View Abstract

CONTROL ID: 2258275

TITLE: Possible Space-Based Gravitational-Wave Observatory Mission Concept

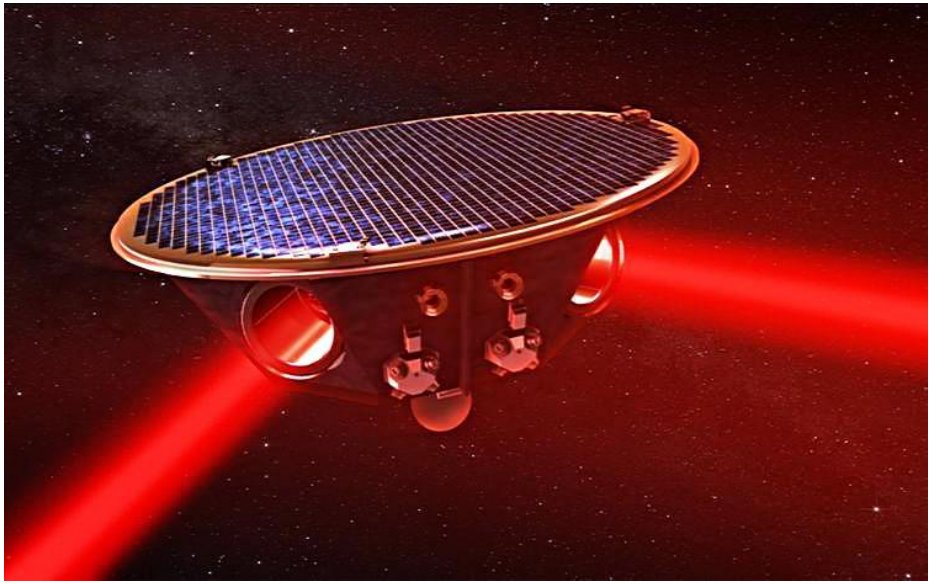
ABSTRACT BODY:

Abstract Body: The existence of gravitational waves was established by the discovery of the Binary Pulsar PSR 1913+16 by Hulse and Taylor in 1974, for which they were awarded the 1983 Nobel Prize. However, it is the exploitation of these gravitational waves for the extraction of the astrophysical parameters of the sources that will open the first new astronomical window since the development of gamma ray telescopes in the 1970's and enable a new era of discovery and understanding of the Universe. Direct detection is expected in at least two frequency bands from the ground before the end of the decade with Advanced LIGO and Pulsar Timing Arrays. However, many of the most exciting sources will be continuously observable in the band from 0.1-100 mHz, accessible only from space due to seismic noise and gravity gradients in that band that disturb ground-based observatories. This talk will discuss a possible mission concept developed from the original Laser Interferometer Space Antenna (LISA) reference mission but updated to reduce risk and cost.

AUTHORS (FIRST NAME, LAST NAME): Jeffrey C. Livas[1]

INSTITUTIONS (ALL): 1. Gravitational Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD, United States.

Possible Space-Based Gravitational Wave Observatory Mission Concept



Minimum Cost 3-arm/6-link LISA-like Mission

Jeff Livas

NASA Goddard Space Flight Center

August 12, 2015

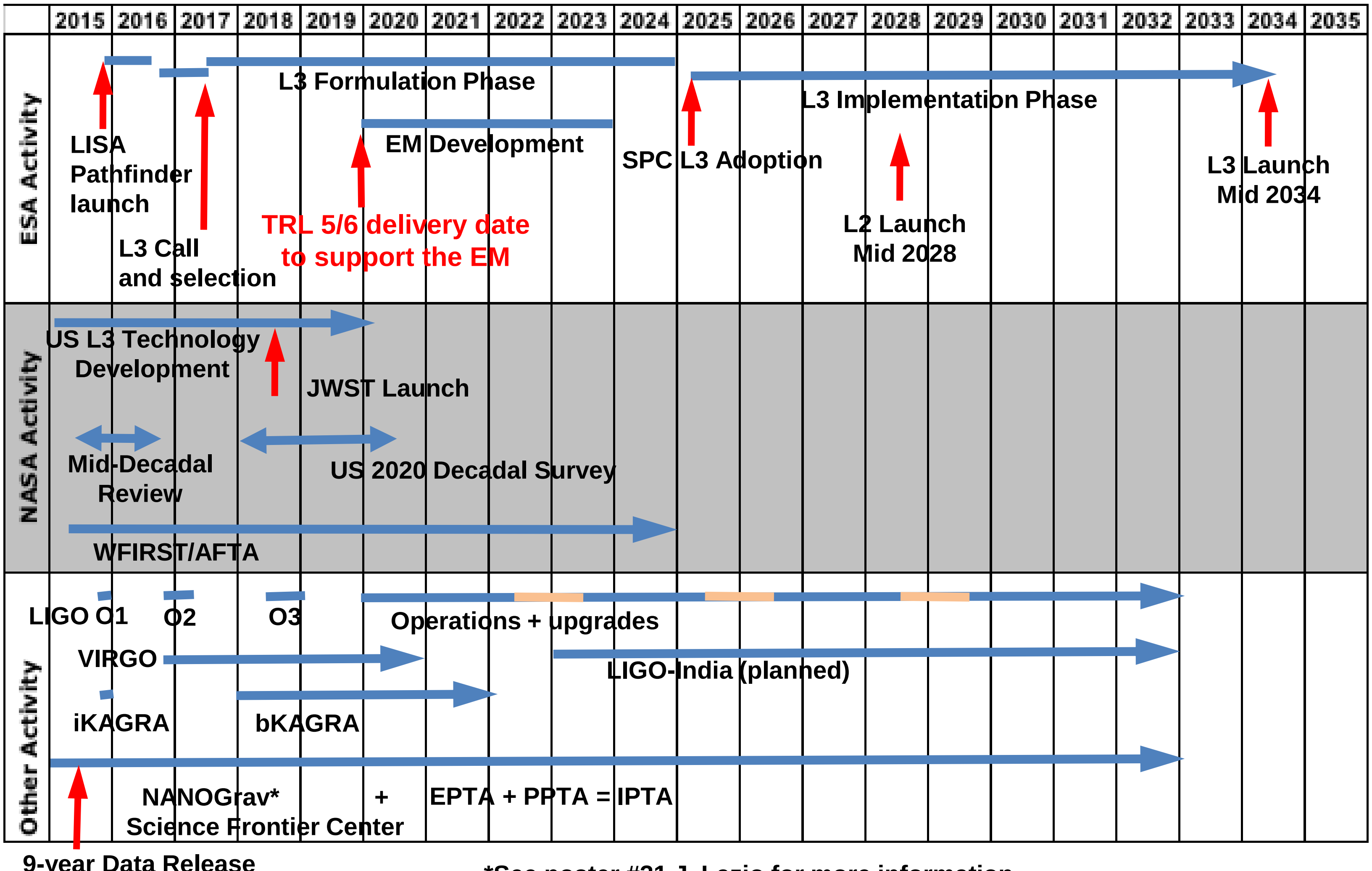
Outline

- **Current US activity**
- **Rough Development Timeline**
- **Range of Mission Designs**
  - Original NGO as proposed
  - SGO-Mid proposed alternative
  - LISA baseline
- **Summary**

Current US Activity

- **Plan of record is a minority partnership for L3**
- **Monitoring ongoing ESA L3 planning activity: Gravitational-wave Observatory Advisory Team (GOAT)**
  - Evaluate technology readiness/concepts for L3
    - Atom interferometry ruled out as not ready
  - Evaluate the success of the LISA Pathfinder mission
- **LISA Pathfinder participation (Nov 2015 launch)**
- **Technology Development and Decadal Survey Preparation**
- **Many details of a US role remain undefined at this stage**
  - Financial contribution
  - Specific technologies

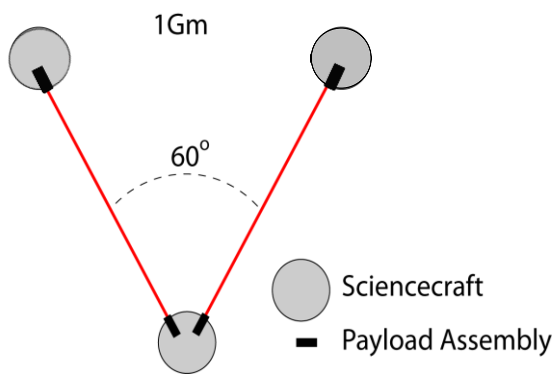
One possible timeline…



*See poster #31 J. Lazio for more information

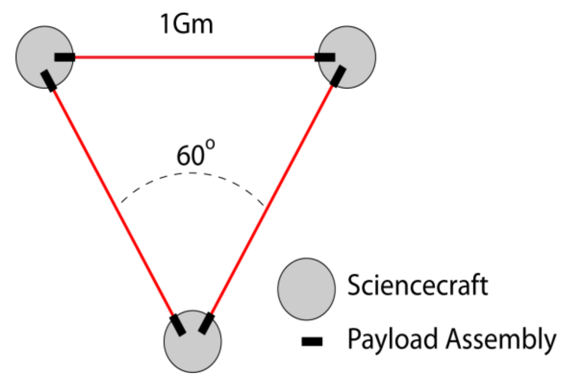
Range of Mission Concepts

NGO[1] (L1 Proposal)



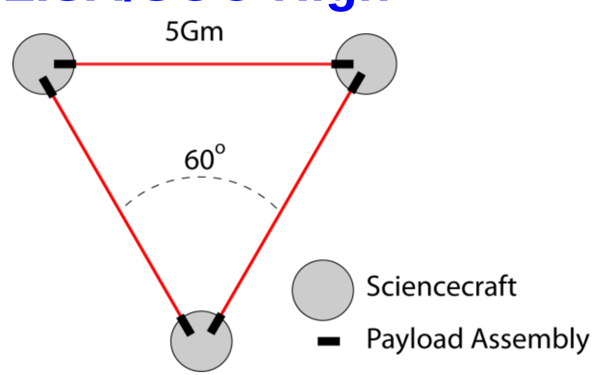
Two-arm version design

SGO[2] Mid



Minimum-cost three arm design with acceptable Decadal-survey science return.

LISA/SGO High



LISA concept with single-agency costing and all know cost reductions.

[1]New GW Observatory
[2]Space-based GW Obs

Architecture Trades

- **Trades that do affect the science performance**
  - Two arms (NGO)
  - Measurement arm length (SGO Mid)
  - Duration of science operation*
  - Orbit: drift-away, or not
  - Telescope diameter
  - Laser power
- **Trades that don't affect the science performance**
  - In-field guiding/backlink fiber
  - Single optical bench
  - Single proof mass
  - Spherical proof mass

Mission Concept Comparison

Parameter	NGO	SGO Mid	LISA
Measurement arm length	1 x 10^6 km	1 x 10^6 km	5 x 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

(Working observatory doing precision parameter estimation: not just detection.)

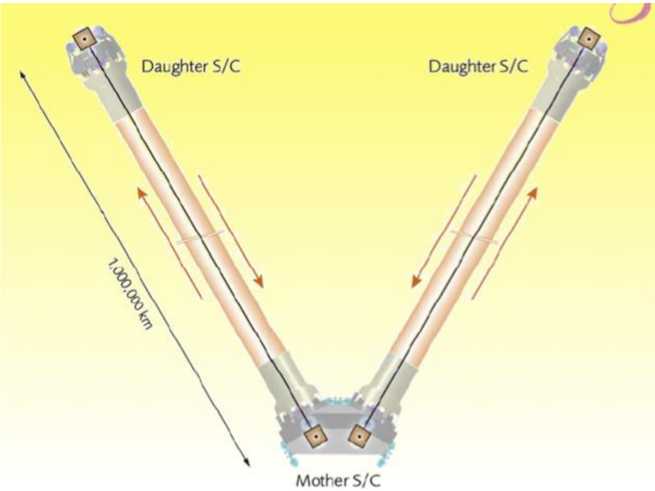
	NGO	SGO Mid	LISA
Massive Black Hole Binary Totals	40-47	41-52	108-220
Detected z > 10	1-3	1-4	3-57
Both mass errors < 1%	13-30	18-42	67-171
One spin error < 1%	3-10	11-27	49-130
Both spin errors < 1%	<1	<1	1-17
Distance error < 3%	3-5	12-22	81-108
Sky location < 1 deg^2	1-3	14-21	71-112
Sky location < 0.1 deg^2	<1	4-8	22-51
Extreme Mass-Ratio Inspirals	12	35	800
Resolved Compact WD Binariess	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 (normalized)	0	0.2	1

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

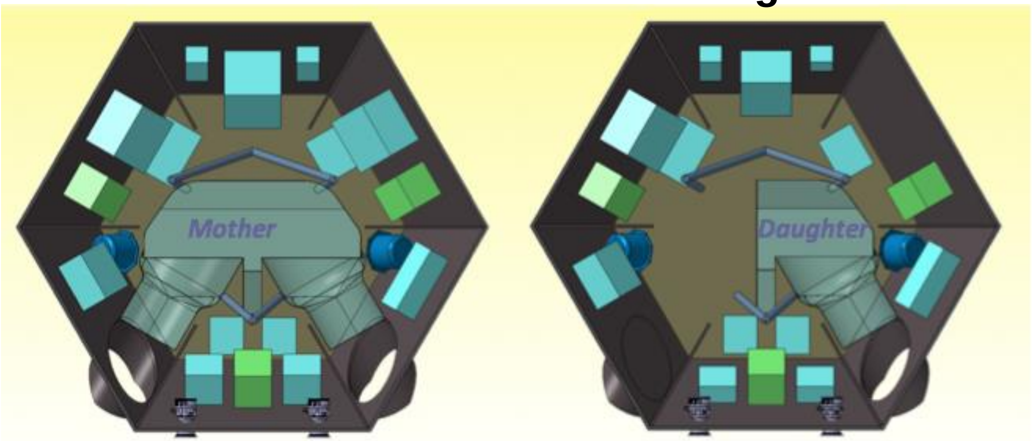
NGO Mission Summary

- **Mission Design**
  - 10^6 km arm-length, 2 arms, 60 deg “V”
  - Mother + 2 x daughter S/C configuration
  - LISA-like payload
    - 20 cm telescope/2W laser
  - 10-degree drift away heliocentric orbit
  - Launch to sub-GTO, separate from LV
    - Two Soyuz-FRG or
    - shared Ariane V
  - Baseline 2 year lifetime + 2 years
    - Limited by communications bandwidth

NGO Layout

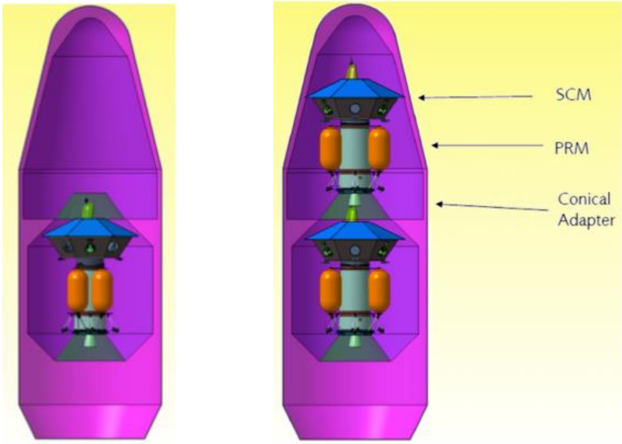


Mother **Daughter**



Figures from K. Danzmann ESA presentation

Soyuz Launch Stack

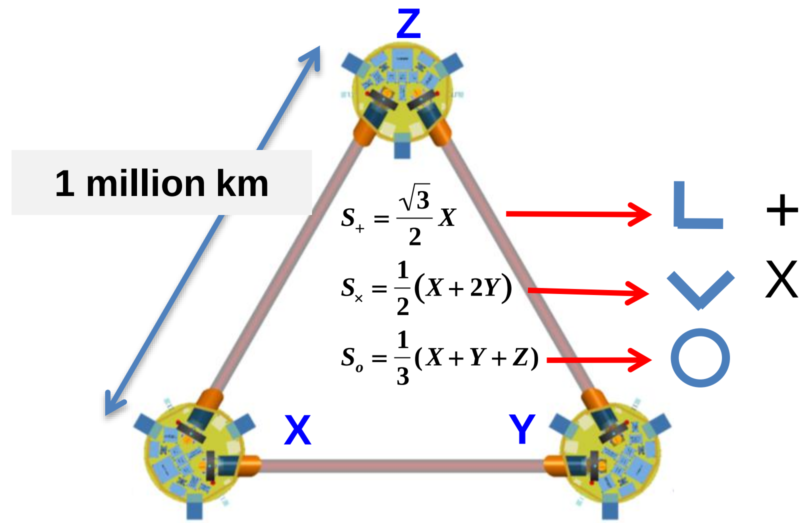


Mother **2 Daughters**

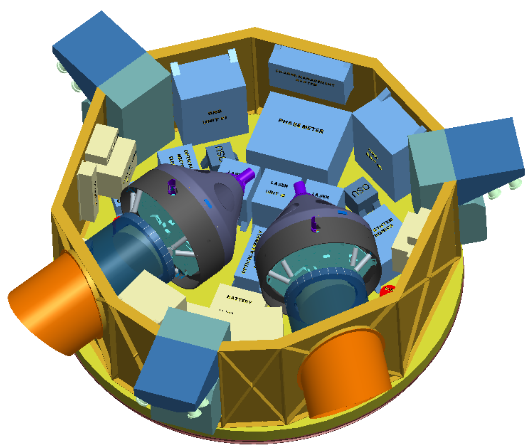
SGO-Mid Mission Summary

- **Mission Design**
  - 10^6 km arm-length, 3 arms, 60 deg triangle
  - 3 identical spacecraft
  - LISA-like payload
    - 25 cm telescope/1 W laser
  - 9-21 degree drift away heliocentric orbit
  - Direct injection to escape, 18 mo transfer
    - Single EELV (e.g. Falcon 9 Block 3)
  - Baseline 2 year lifetime + 2 years
    - Limited by communications bandwidth

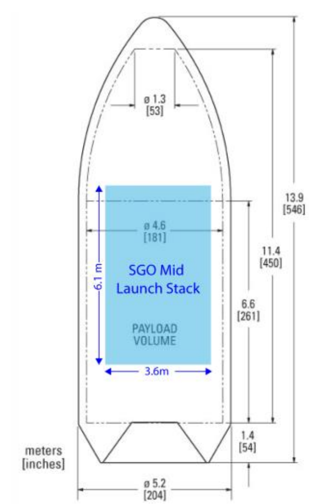
SGO Layout



"Sciencecraft"



Single EELV Launch Stack

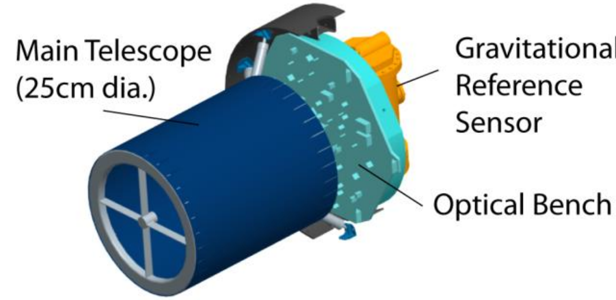


No ITAR or EAR protected information

Payload Integrated with Bus

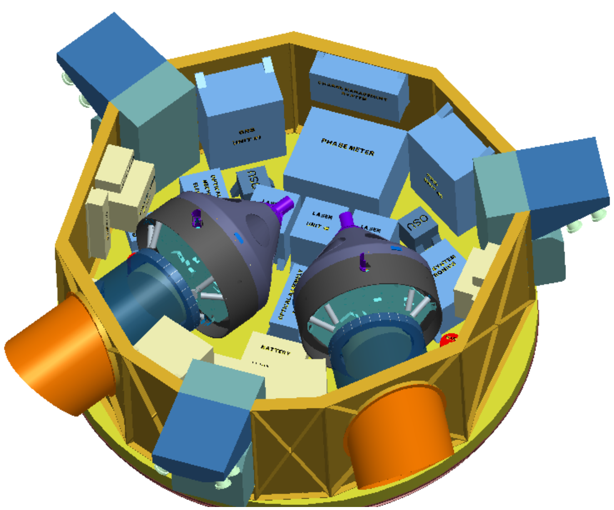
Payload systems

- **Interferometer Measurement System (IMS)**
  - **Laser**
  - **Telescope**
  - **Optical bench**
- **Disturbance Reduction System (DRS)**
  - **Gravitational Reference Sensor (GRS)**
  - **µN thrusters**
  - **Control laws**



Telescope Assembly

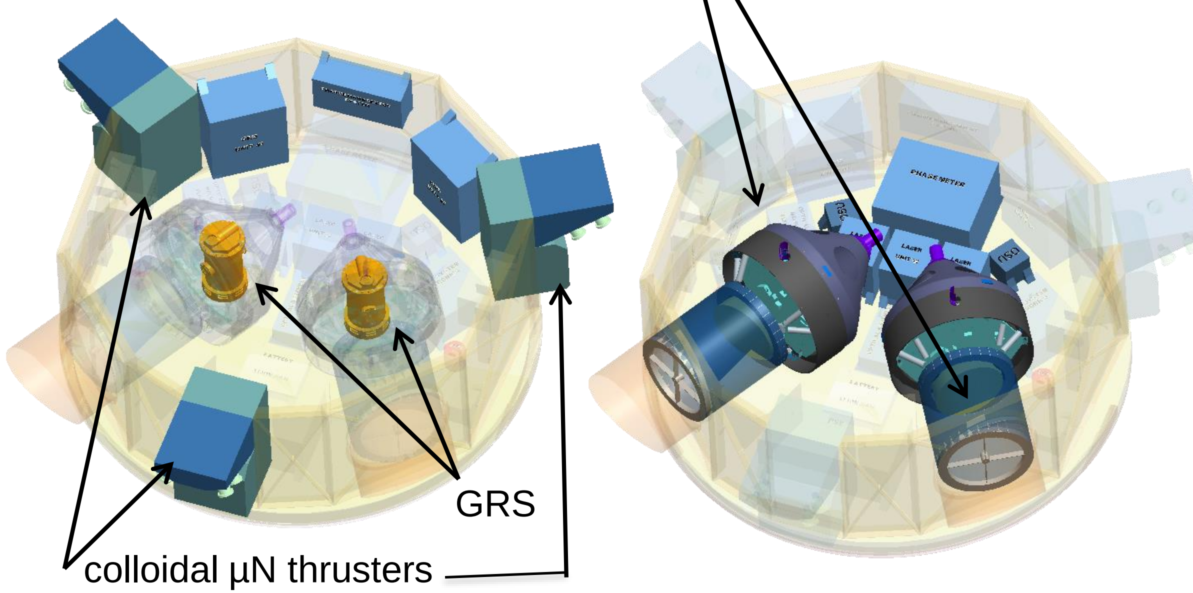
Full Spacecraft Bus



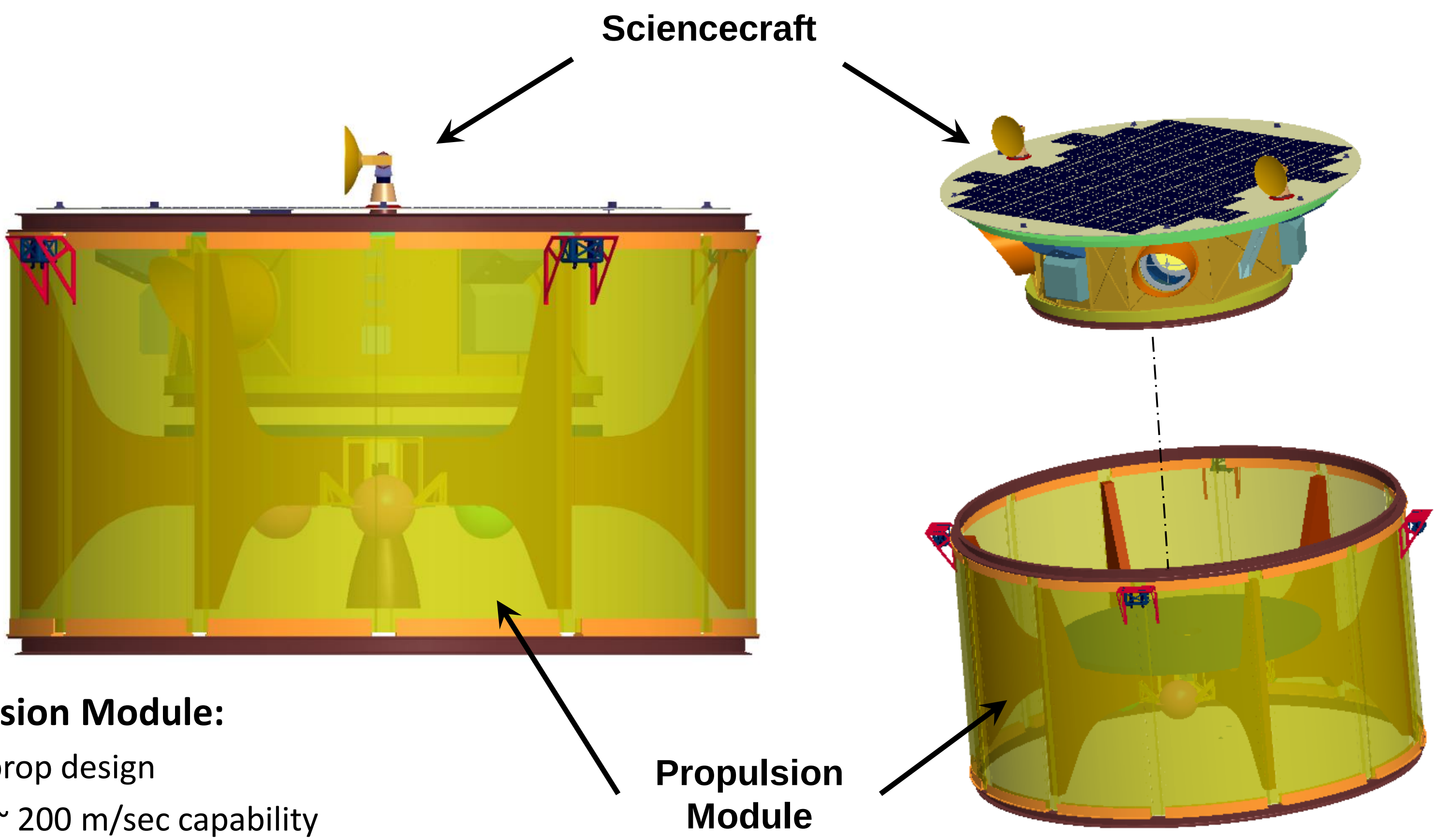
(Note: solar array not shown)

DRS Detail

IMS Detail



Prop Module/Cruise Configuration



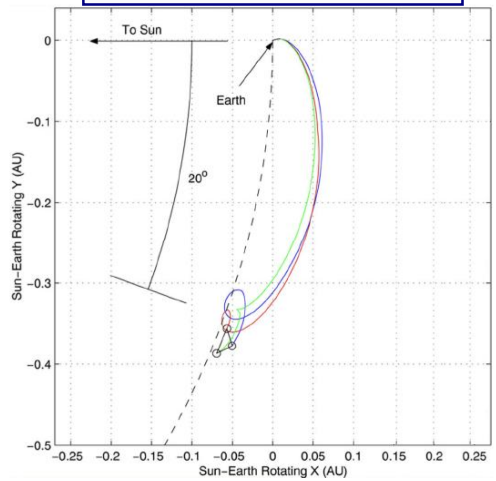
Propulsion Module:

- Bi-prop design
- Δv ~ 200 m/sec capability
- 6 coarse sun sensors
- 2 star tracker heads
- 2 omni antennas

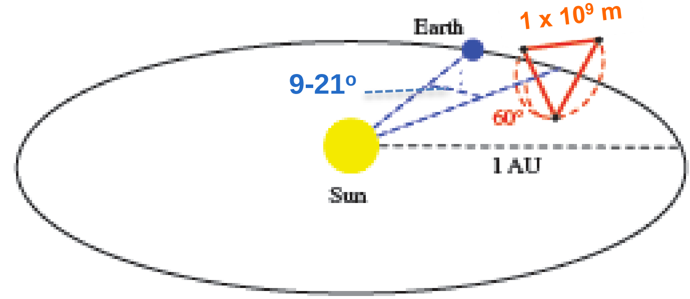
Mission Timeline

Falcon Heavy EELV

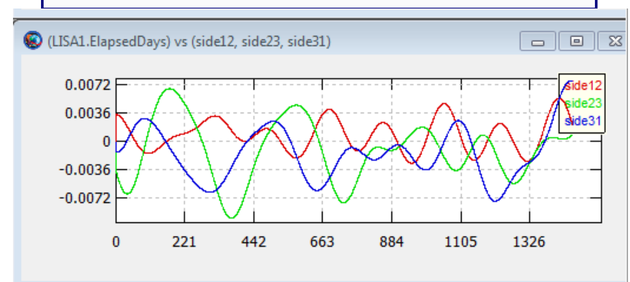
Cruise Trajectories

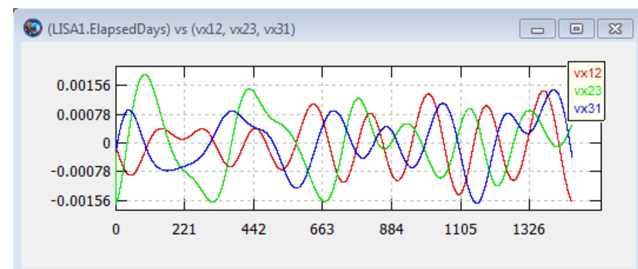


Science Orbits

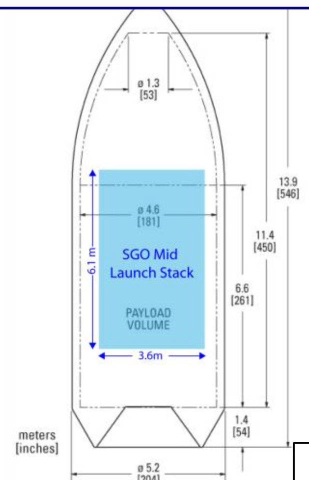


Doppler/Arm length changes

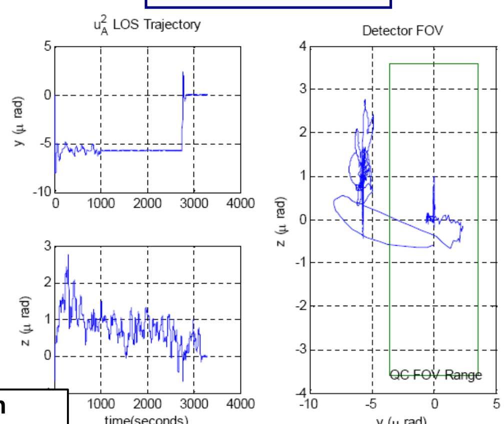




Stack in Falcon 5 m PLF



Acquisition



4 month commissioning

Mission Timeline

Launch and Early Operation Stack Separation

Sciencecraft Separation (x3) Element Commissioning

Acquisition

Constellation Commissioning

24 months science operations: orbits optimized for 48 months

End of Mission

Pre-Launch	18 month cruise	Science Operations

Considerations for a Mission

- **Need one that does the science, <u>and gets selected</u>**
- **To get "adopted" by ESA**
  - Fit within the available cost cap
  - Allows assignment of responsibilities, including US
  - Recognizes European investments (LPF)
- **To get "started" by NASA**
  - Acceptable and affordable role for NASA
  - Suitable endorsement by 2020 decadal review
  - Acceptable to the "stakeholders" (e.g. ESA, NASA, member states)

Costs

- **Estimate of contributions that could be available for L3**
  - ESA cap is 1B€, ~$1.2B
  - Member states contribution is ~250-300M€, ~$360M
  - 20% NASA contribution is $316M
  - Total: $1.9B
- **Cost estimates from 2012 Study**
  - SGO Mid: $1.4B (study team), $1.9B (Team X)
  - LISA: $1.7B (study team), $2.1B (Team X)
- **A NASA contribution of $500M would cover all options.**

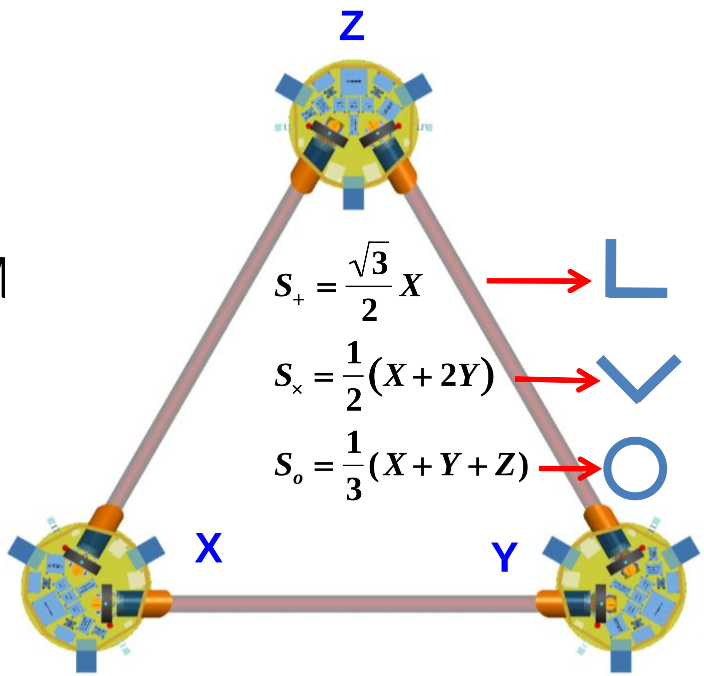
Summary

- **Space-based gravitational-wave work continues**
  - Spectacular science receives top ratings in reviews
  - Science return can be calculated from the design
  - Issue is funding, not technology
- **Current opportunity is partnership with ESA on an L3 mission for 2034 launch**
  - 20+ year scientific collaboration on both sides of the Atlantic
  - Requires successful LISA Pathfinder technology demo on track for a Nov 2015 launch
  - NASA role remains to be well defined
- **US technology development targeted at TRL-5/6 level for ~ 2019 for key technologies**
  - Includes hardware, astrophysics, and data analysis work
- **Full LISA design returns best science for cost, risk**
  - SGO-Mid carried as a de-scope

Backup Slides

How the science instrumentation works

- **The Constellation is the instrument**
  - Orbits passively maintain formation
  - "Sciencecraft" house test masses and interferometry
- **Interferometer Measurement System (IM**
  - Active transponder, phase-locked laser ranging system
  - Phasemeter records fringe signal
  - Laser frequency noise correction by pre-stabilization and post processing
- **Disturbance Reduction System (DRS)**
  - Free-falling test masses don't contact the sciencecraft
  - Drag-free stationkeeping reduces sciencecraft test mass relative motion and force gradients
  - Design to limit thermal, magnetic, electrostatic, mechanical, self-gravity disturbances

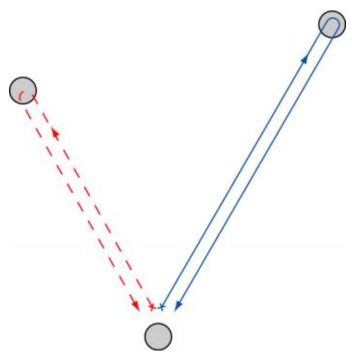


Frequency Noise Suppression: Time Delay Interferometry (TDI)

- An interferometer arm length mismatch ΔL will allow frequency noise to mimic a displacement noise, δx.
- A sensitivity requirement of δx <10 pm/√Hz implies that the interferometer arm lengths must be equal to better than 100 m
- LISA arm lengths may differ by as much as 1% or 10,000 km!

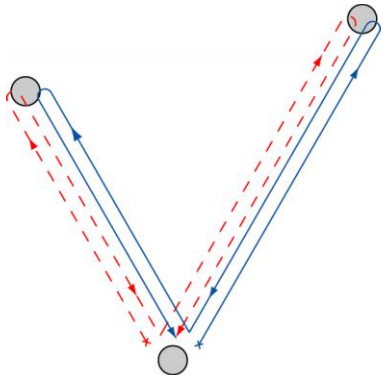
$$\delta x = \frac{\delta \nu}{\nu} \Delta L$$

1



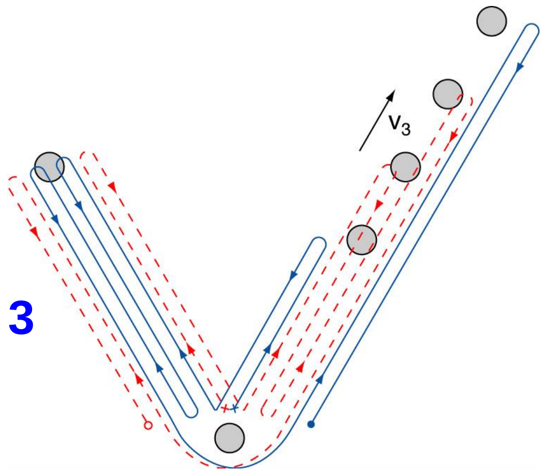
- Unequal-arm Michelson interferometer
- Output corrupted by laser frequency noise

2



- Equal-arm (Sagnac) interferometer (TDI combination X)
- Output immune to laser frequency noise: synthesized equal arms

3

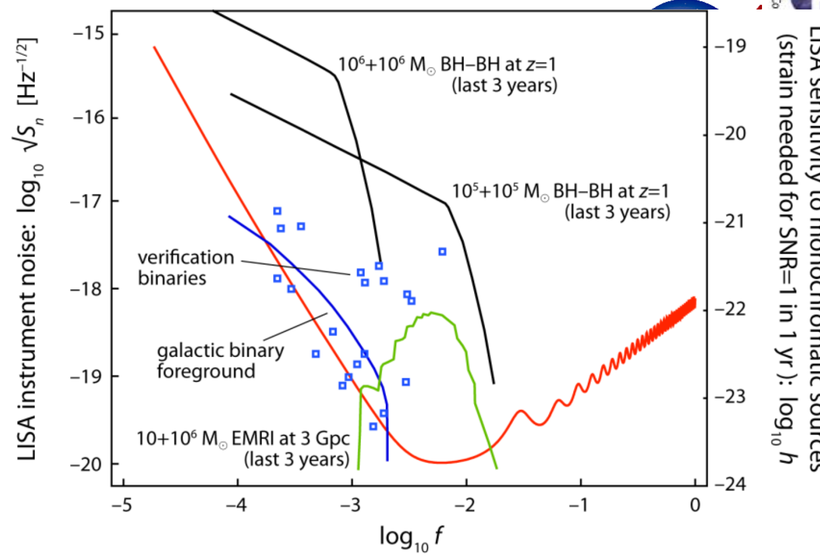


- Constant spacecraft velocity introduces an arm length mismatch to the synthesized interferometer.
- ΔL ~ 20m/s x 6.7 s ~ 130 m
- Output immune to laser frequency noise: synthesized equal arms

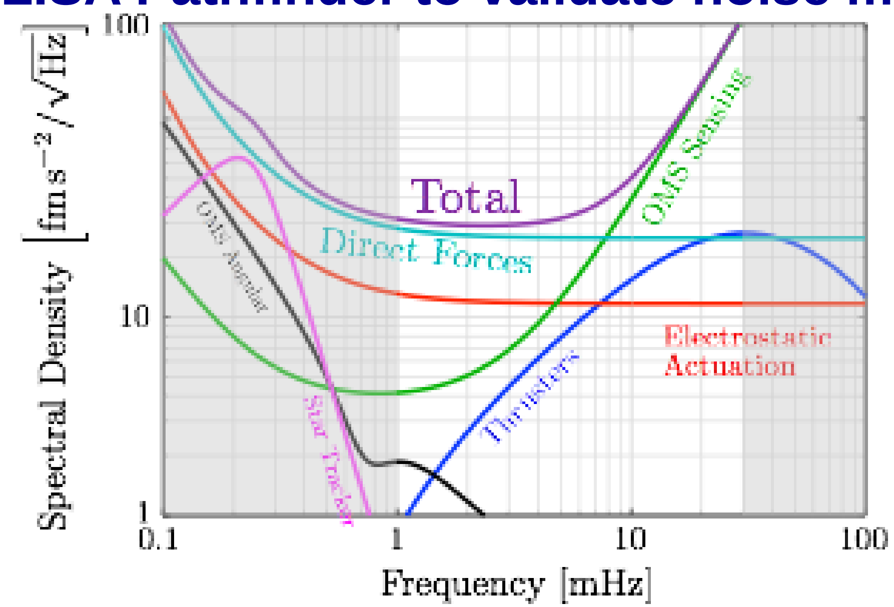
D.A. Shaddock, et al; PRD **68**, 061303 (2003).

Instrument Performance

- **The instrument performance is determined by:**
  - **Displacement noise from the Interferometric Measurement System (IMS)**
  - **Acceleration noise from the Disturbance Reduction System (DRS)**
  - **Arm Length (1 x 10^6 km)**
- **The arm length also determines the instrument response function and is optimized for the science requirements.**



LISA Pathfinder to validate noise model



Summary of IMS subsystem noise allocations

	$\times 10^{-12}\frac{m}{\sqrt{Hz}}\sqrt{1+\left(\frac{2\,mHz}{f}\right)^4}$	
Effect	**Total per group (pm/√Hz)**	**Sub - Allocation**
Total IMS Error/Noise Budget	**12.0**	
Total of subsystem allocations	**11.7**	
Subsystem Allocations		
Shot noise	**7.7**	
Pathlength noise	**7.0**	
Pointing Errors		5.3
Telescope pathlength stability		1
Optical bench pathlength stability		4.5
Measurement noise	**5.4**	
Photoreceiver errors		3
Residual laser frequency noise		2
Residual clock frequency noise		3
Phasemeter noise		1
Intensity noise		1
Phase reconstruction		1
straylight		2

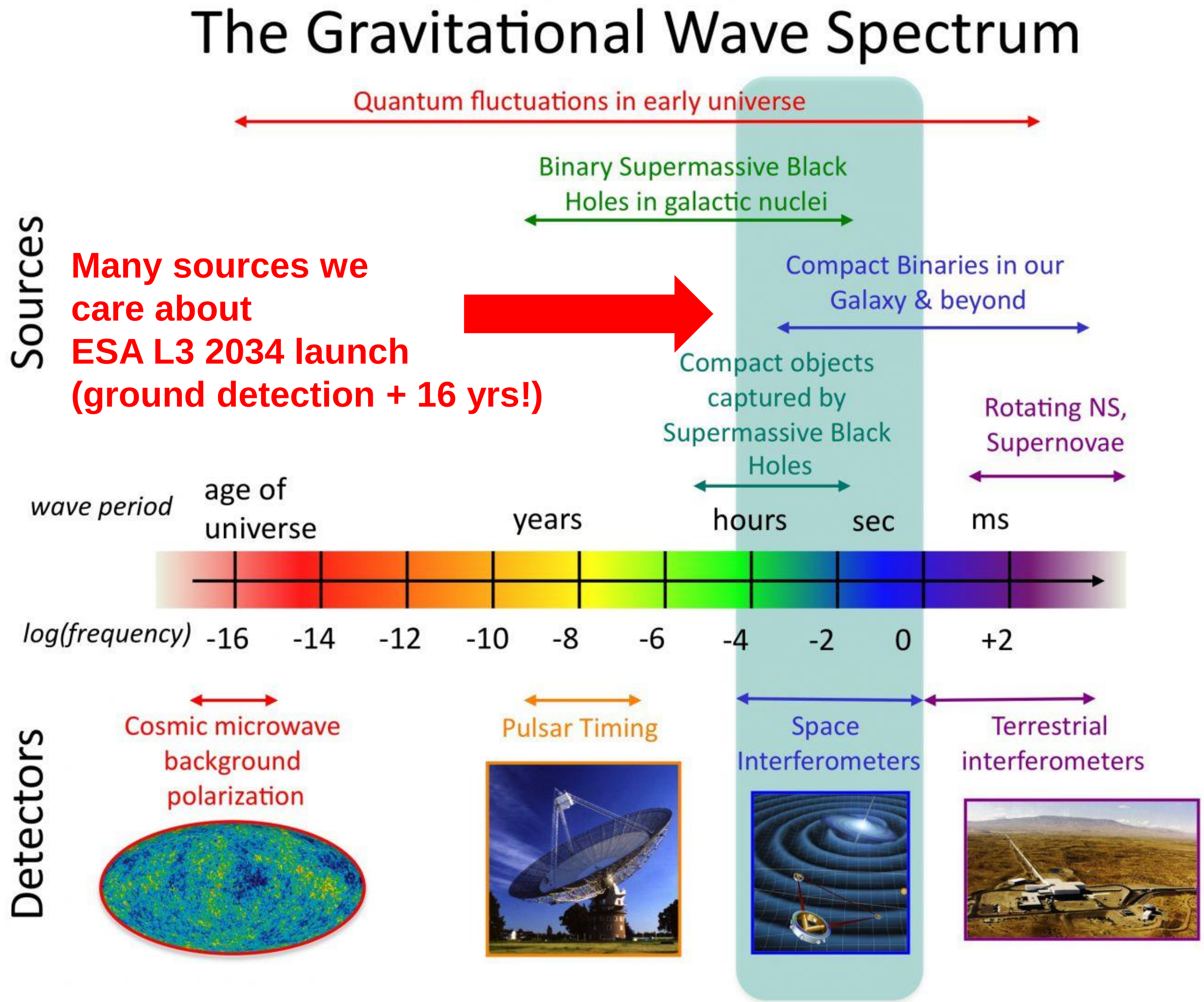
Orbits/trajectory

- **2 year drift-away**
  - ~ 6 deg/year drift rate starting at 9 degrees
  - 2 year end of mission similar to nominal SGO-high orbital station (but orbit optimized for 4 years)
  - EOL communications requirements similar to SGO-high
- **Stable constellation geometry simplifies measurement**
  - $\Delta L/L$ ~0.010, relative to 10^6 km
  - $\Delta\alpha$ ~ +/- 0.6° relative to 60°
  - Δv ~ +/- 1.6 m/s
  - Point ahead ~ +/- 0.55urad out of plane
  - Point ahead ~ +/- 0.004 urad in plane, relative to ~ -0.3 urad
- **18 month trajectory from escape**
  - For shared launch, second stage has 2 restarts
  - Drop off shared package at GTO, then go to escape
  - Optimized ΔV ~ 130 m/s (each), ~ 200 m/s for extended launch window and margin

Operations / Science Data

- **Simple Operations**
  - No instrument pointing or scheduling of observation time
  - LISA observes "all the sky, all the time"
    - Scheduled interruptions approximately every 2 weeks for HGA re-pointing and to switch laser offset frequencies
- **Routine Communications Strategy**
  - Ka-Band downlink every 2 days with one spacecraft (6 days for the constellation)
  - Up to 8-hr contacts with DSN 34m at 90 kbps (allows downlink of 6 days telemetry generated at 5 kbps)
  - Special merger events may require more frequent contact and continuous operation for up to ~ 4 days to preempt schedule interruptions and com
- **Science Data**
  - 5 kbps = 1 kbps science data + 4 kbps science housekeeping and engineering data, 15 kbps total for the constellation
  - **No on-board science processing**
  - Mission Ops Team forwards downlinked data to Science Data Centers

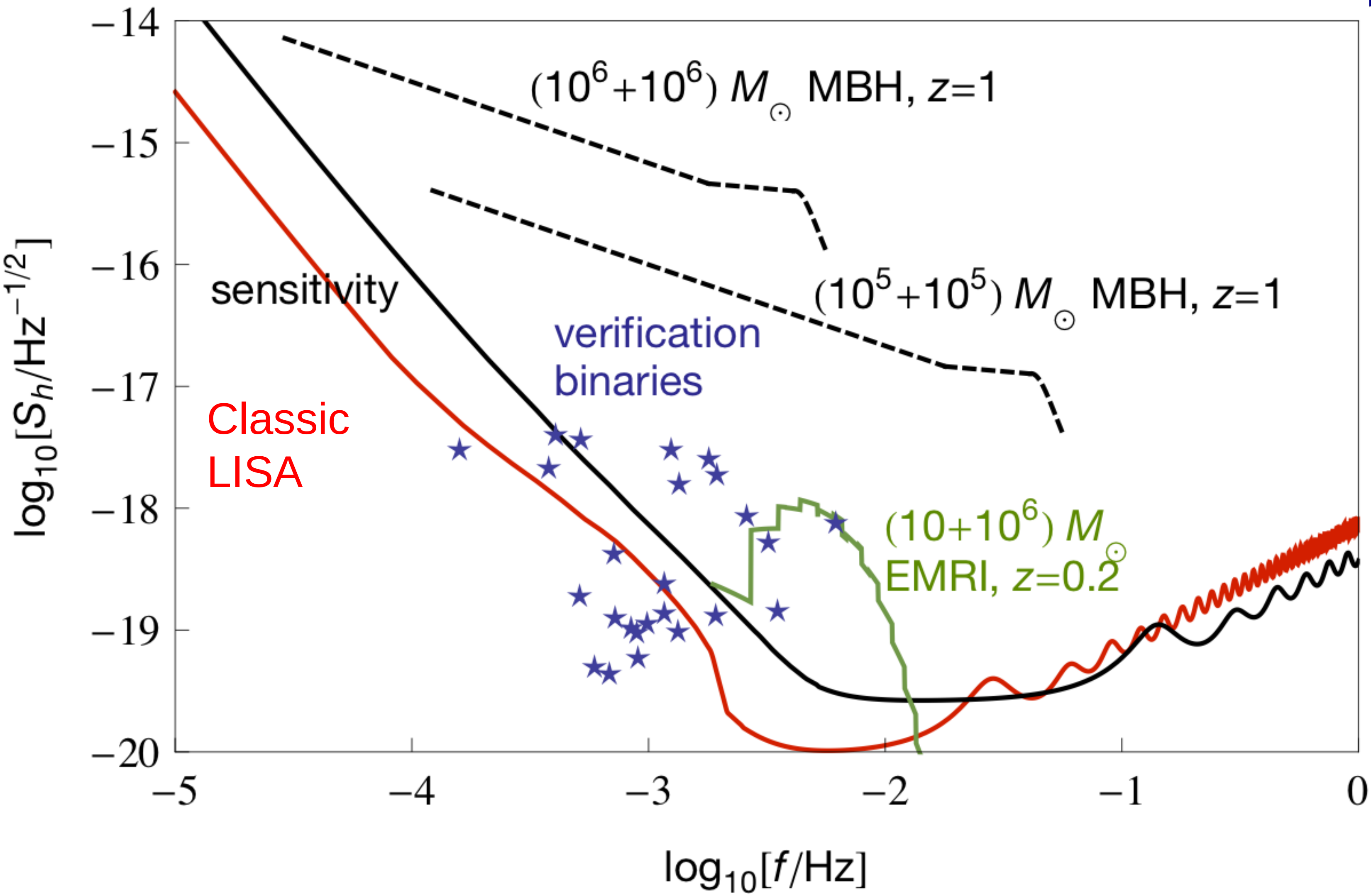
Why is this important?



Many sources we care about
ESA L3 2034 launch
(ground detection + 16 yrs!)

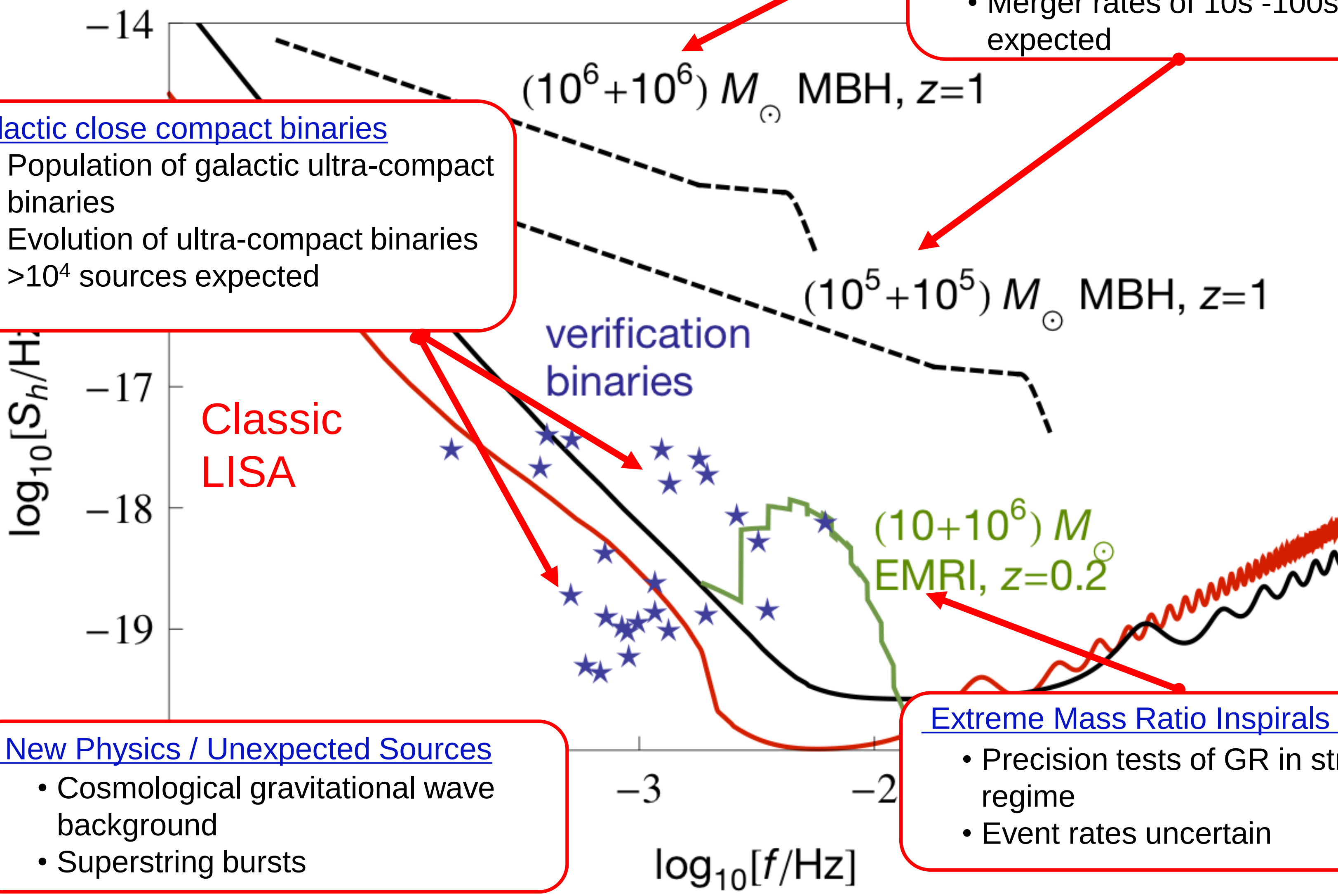
CMB Polarization **Detection 2018?** **Detection 2017-18?**

Science Overview



Ref: http://lisa.nasa.gov/Documentation/LISA-LIST-RP-436_v1.2.pdf

Science Overview



Supermassive Black Hole Mergers
- Formation and growth of massive black holes: galaxy mergers
- Dynamical strong-field gravity
- Merger rates of 10s -100s yr^{-1} expected

Galactic close compact binaries
- Population of galactic ultra-compact binaries
- Evolution of ultra-compact binaries
- $>10^4$ sources expected

New Physics / Unexpected Sources
- Cosmological gravitational wave background
- Superstring bursts

Extreme Mass Ratio Inspirals (EMRIs)
- Precision tests of GR in strong-field regime
- Event rates uncertain

Ref: http://lisa.nasa.gov/Documentation/LISA-LIST-RP-436_v1.2.pdf

Gravitational Wave
Mission Concept Development Team

Study Manager: **Ken Anderson, NASA/GSFC**

Study Scientist: **Tuck Stebbins, NASA/GSFC**

Community Science Team

Rainer Weiss, MIT (Co-chair)
Edward Wright, UCLA (Co-chair)
Peter Bender, University of Colorado
Joan Centrella, NASA/GSFC
Neil Cornish, Montana State University
Jens Gundlach, University of Washington
Ronald Hellings, Montana State University
Guido Mueller, University of Florida
Holger Mueller, U. C. Berkeley
Thomas Prince, Caltech

Science Task Force

Neil Cornish, Montana State University (Chair)
John Baker, NASA/GSFC
Matthew Benacquista, University of Texas Brownsville
Emanuele Berti, University of Mississippi
Curt Cutler, NASA/JPL
Ron Hellings, Montana State University
Ryan Lang, Washington University
Shane Larson, Utah State University
Tyson Littenberg, NASA GSFC
Jeffrey Livas, NASA/GSFC
Sean McWilliams, Princeton University
James Ira Thorpe, NASA/GSFC
Michele Vallisneri, NASA/JPL

Core Team

Petar Arsenovic, NASA/GSFC
John Baker, NASA/GSFC
Peter Bender, University of Colorado
Edward Brinker, NASA/GSFC
Jordan Camp, NASA/GSFC
John Crow, NASA/GSFC
Curt Cutler, NASA/JPL
Glenn deVine, NASA/JPL
Robert Gallagher, NASA/GSFC
William Klipstein, NASA/JPL
Steve Leete, NASA/GSFC
Jeff Livas, NASA/GSFC
Kirk McKenzie, NASA/JPL
Guido Mueller, University of Florida
Juergen Mueller, NASA/JPL
Kyle Norman, NASA/GSFC
Kenji Numata, NASA/GSFC
Babak Saif, NASA/GSFC
Robert Spero, NASA/JPL
James Ira Thorpe, NASA/GSFC
Michele Vallisneri, NASA/JPL
Brent Ware, NASA/JPL
Gary Welter, NASA/GSFC
John Ziemer, NASA/JPL

What happened to LISA?

- **Summary of the timeline:**
  - March 2011: ESA ended the partnership to pursue a joint gravitational wave mission
  - NASA pursued mulitple alternate options including
    - Minority role in the ESA-led mission (~ 2022 selection for 2034 launch)
    - A NASA-led mission based on a down-scaled concept
    - A joint mission at some future date (after 2020)
    - Concept is Space-based Gravitational-wave Observatory (**SGO-Mid**)
- **Nov 2013: Selection of L2/L3 *science themes*:**
  - L2 is the "Hot and Energetic Universe" for an expected 2028 launch
  - L3 is the "Gravitational Universe" for an expected 2034 launch
- **June 2014: selection of Athena as the mission for L2**
- **Selection of an L3 Mission Concept in 2016 (moved up from 2022)?**
  - NGO is the ESA name for the original proposed mission
  - Evolved LISA (eLISA) is the leading mission contender
  - US would contribute technology as a minority partner
- **Technologies under development:**
  - Phasemeter -- Micro-Newton thruster -- optical bench
  - Laser -- Telescope -- photoreceiver