NASA’s Gravitational-Wave Mission Concept Study

Ira Thorpe & Jeff Livas
For the GW Study Team

Physics of the Cosmos Program Analysis Group Meeting
August 14th, 2012
Washington, DC

Talk Overview

Ira

- Description of the Study Process
- Summary of Community Response
- Assessment of Science Potential
- Discussion of “architecture space” for GW missions

Jeff

- Risk Considerations
- Cost Estimates
- Technology Development
- Conclusions

Goals of the Study

- Explore options for achieving all or part of the LISA science objectives identified as a priority in the 2010 Astrophysics Decadal Survey.
    - Ability to address science goals
    - Cost
    - Risk
    - Technical readiness
- Generalize results of specific options so that future concepts can be efficiently evaluated.

Study Personnel

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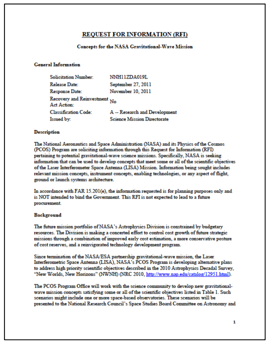
Study Timeline

RFI Released



REQUEST FOR INFORMATION (RFI)

Concepts for the NASA Gravitational-Wave Mission

General Information

Solicitation Number:	NNH11ZDA019L
Release Date:	September 27, 2011
Response Date:	November 10, 2011
Recovery and Reinvestment Act Action:	No
Classification Code:	A -- Research and Development
Issued by:	Science Mission Directorate

Description

The National Aeronautics and Space Administration (NASA) and its Physics of the Cosmos (PCOS) Program are soliciting information through this Request for Information (RFI) pertaining to potential gravitational-wave science missions. Specifically, NASA is seeking information that can be used to develop concepts that meet some or all of the scientific objectives of the Laser Interferometer Space Antenna (LISA) Mission. Information being sought includes relevant mission concepts, instrument concepts, enabling technologies, or any aspect of flight, ground or launch systems architecture.

In accordance with FAR 15.201(e), the information requested is for planning purposes only and is NOT intended to bind the Government. This RFI is not expected to lead to a future procurement.

Background

The future mission portfolio of NASA's Astrophysics Division is constrained by budgetary resources. The Division is making a concerted effort to control cost growth of future strategic missions through a combination of improved early cost estimation, a more conservative posture of cost reserves, and a reinvigorated technology development program.

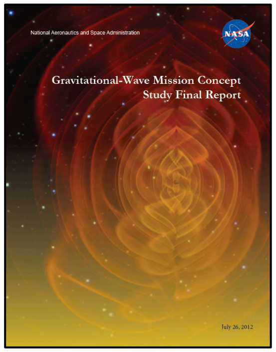
Since termination of the NASA/ESA partnership gravitational-wave mission, the Laser Interferometric Space Antenna (LISA), NASA's PCOS Program is developing alternative plans to address high priority scientific objectives described in the 2010 Astrophysics Decadal Survey, "New Worlds, New Horizons" (NWNH) (NRC 2010, http://www.nap.edu/catalog/12951.html).

The PCOS Program Office will work with the science community to develop new gravitational-wave mission concepts satisfying some or all of the scientific objectives listed in Table 1. Such scenarios might include one or more space-based observatories. These scenarios will be presented to the National Research Council's Space Studies Board Committee on Astronomy and

1

Workshop

Final Report Delivered



National Aeronautics and Space Administration

Gravitational-Wave Mission Concept Study Final Report

July 26, 2012

Sept. 27th

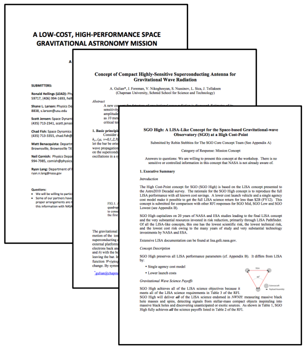
Nov. 10th

Dec. 20-21

March 5th

April 5th

July 26th



A LOW-COST, HIGH-PERFORMANCE SPACE GRAVITATIONAL ASTRONOMY MISSION

Concept of Compact Highly-Sensitive Superconducting Antenna for Gravitational Wave Radiation

A. Gulian*, J. Foreman, V. Nikoghosyan, S. Nussinov, L. Sica, J. Tollaksen
(Chapman University, Schmid School for Science and Technology)

SGO High: A LISA-Like Concept for the Space-based Gravitational-wave Observatory (SGO) at a High Cost-Point

Submitted by Robin Stebbins for The SGO Core Concept Team (See Appendix A)

Category of Response: Mission Concept

Answers to questions: We are willing to present this concept at the workshop. There is no sensitive or controlled information in this concept that NASA is not already aware of.

1. Executive Summary

Introduction

The High Cost-Point concept for SGO (SGO High) is based on the LISA concept presented to the Astro2010 Decadal survey. The rationale for the SGO High concept is to reproduce the full LISA performance with all known cost savings. A lower cost launch vehicle and a single agency cost model make it possible to get the full LISA science return for less than $2B (FY12). This concept is submitted for comparison with other RFI responses for SGO Mid, SGO Low and SGO Lowest (see Appendix B).

SGO High capitalizes on 20 years of NASA and ESA studies leading to the final LISA concept and the very substantial resources invested in risk reduction, primarily through LISA Pathfinder. Of all the LISA-like concepts, this one has the lowest scientific risk, the lowest technical risk, and the lowest cost risk owing to the many years of study and very substantial technology investments by NASA and ESA.

Extensive LISA documentation can be found at lisa.gsfc.nasa.gov.

Concept Description

SGO High preserves all LISA performance parameters (cf. Appendix B). It differs from LISA by:

- Single agency cost model
- Lower launch costs

Gravitational Wave Science Payoffs

SGO High achieves all of the LISA science objectives because it meets all of the LISA science requirements in Table 3 of the RFI. SGO High will deliver *all* of the LISA science endorsed in *NWNH*: measuring massive black hole masses and spins, detecting signals from stellar-mass compact objects inspiraling into massive black holes and discovering unanticipated or exotic sources. As shown in Table 1, SGO High fully achieves *all* the science payoffs listed in Table 2 of the RFI.

RFI Responses Due

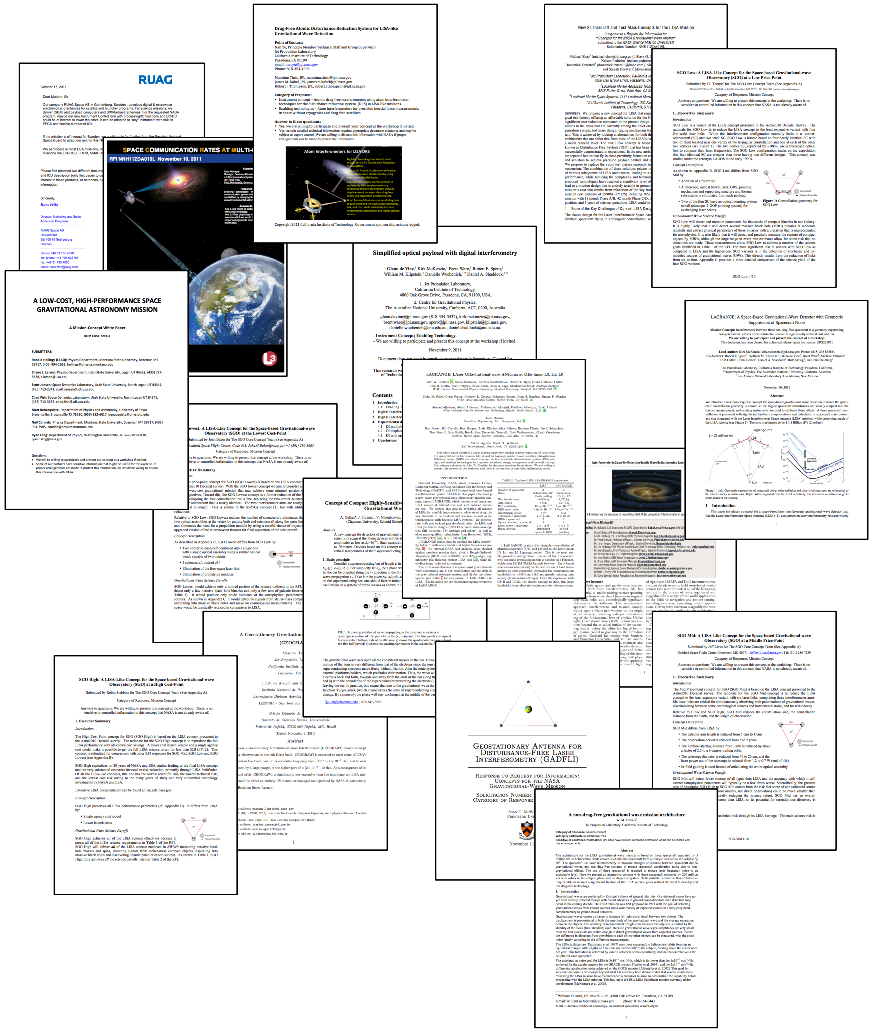
TEAM X
Jet Propulsion Laboratory

Team-X Studies

- SGO Mid/High
- LAGRANGE/ McKenzie
- OMEGA Instrument
- OMEGA Mission

RFI Submissions

- 17 Submissions Received
  - 12 mission concepts
  - 3 instrument concepts
  - 2 technologies
- Initial analysis by core team
  - Is it relevant?
  - What are the essential features?
  - Is the information complete?
  - Valid sensitivity curves?
  - Group for analysis
  - Preliminary science assessment



Group 1: LISA-like

	SGO High	SGO Mid	SGO Low	SGO Lowest	Shao
Constellation	3-S/C triangle (six 5 Gm links)	3-S/C triangle (six 1 Gm links)	4-S/C Vee (four 1 Gm links)	3-S/C in-line (one 4 Gm link one 2 Gm link)	3-S/C triangle (six 5 Gm links)
Inertial Reference	LPF design(2 per S/C)	LPF design (2 per S/C)	LPF design (1 per S/C)	LPF design (1 per S/C)	Torsion pendulum
Displacement Measurement	LISA IMS (40cm, 1.2W)	LISA-like IMS (25cm, 0.7W)	LISA-like IMS (25cm, 0.7W)	LISA-like IMS (25cm, 0.7W)	unspecified
Cruise / Science / Extended (mo)	14 / 60 / 42	21/24/ 24	21/24/24	18/2/0	unspecified
Estimated cost	$1.6B	$1.4B	$1.4B	$1.2B	$1B

Included in Team-X Study

NOTE: Information is as-submitted by RFI respondents

Group 2: Non drag-free

	LAGRANGE (McKenzie)	Folkner, et al.
Orbit	Earth-Sun L2 + Heliocentric	Heliocentric
Constellation	3-S/C 164^o triangle (four 20Gm links	3-S/C triangle (six 260Gm links)
Force measurement system	Solar wind monitor, radiation monitor, accelerometer	Solar wind monitor, radiation monitor
Displacement Measurement	LISA-like IMS (40cm, 1.2W)	LISA-like IMS (30cm, 1.0W)
Cruise / Science / Extended (mo)	? / 24 / 0	?/36/ ?
Estimated cost	$1.1B	$1.0B

Included in Team-X Study

NOTE: Information is as-submitted by RFI respondents

Group 3: Geocentric

	GEOGRAWI	GADFLI	OMEGA	LAGRANGE (Conklin)
Orbit	Geostationary	Equatorial, geostationary	600,000 km geocentric, earth-moon plane (retrograde)	Earth-Moon L3, L4, L5
Constellation	3-S/C triangle (73 Mm)	3-S/C triangle (73 Mm)	6-S/C triangle (1 Gm)	3-S/C triangle (0.7 Gm)
Inertial Reference	Spherical (1 per S/C)	LPF design (2 per S/C)	ONERA design (1 per S/C)	Spherical (1 per S/C)
Displacement Measurement	LISA IMS (40cm, 1.2W)	LISA-like IMS (25cm, 0.7W)	Lightweight IMS (30cm, 0.7W)	LISA-like IMS (20cm, 1W)
Cruise / Science / Extended (mo)	? / 24 / ?	?/24/ ?	12/36/ ?	? / 60 / ?
Estimated cost	$1.1B	$1.2B	$0.3B	$1.0B

Included in Team-X Study

NOTE: Information is as-submitted by RFI respondents

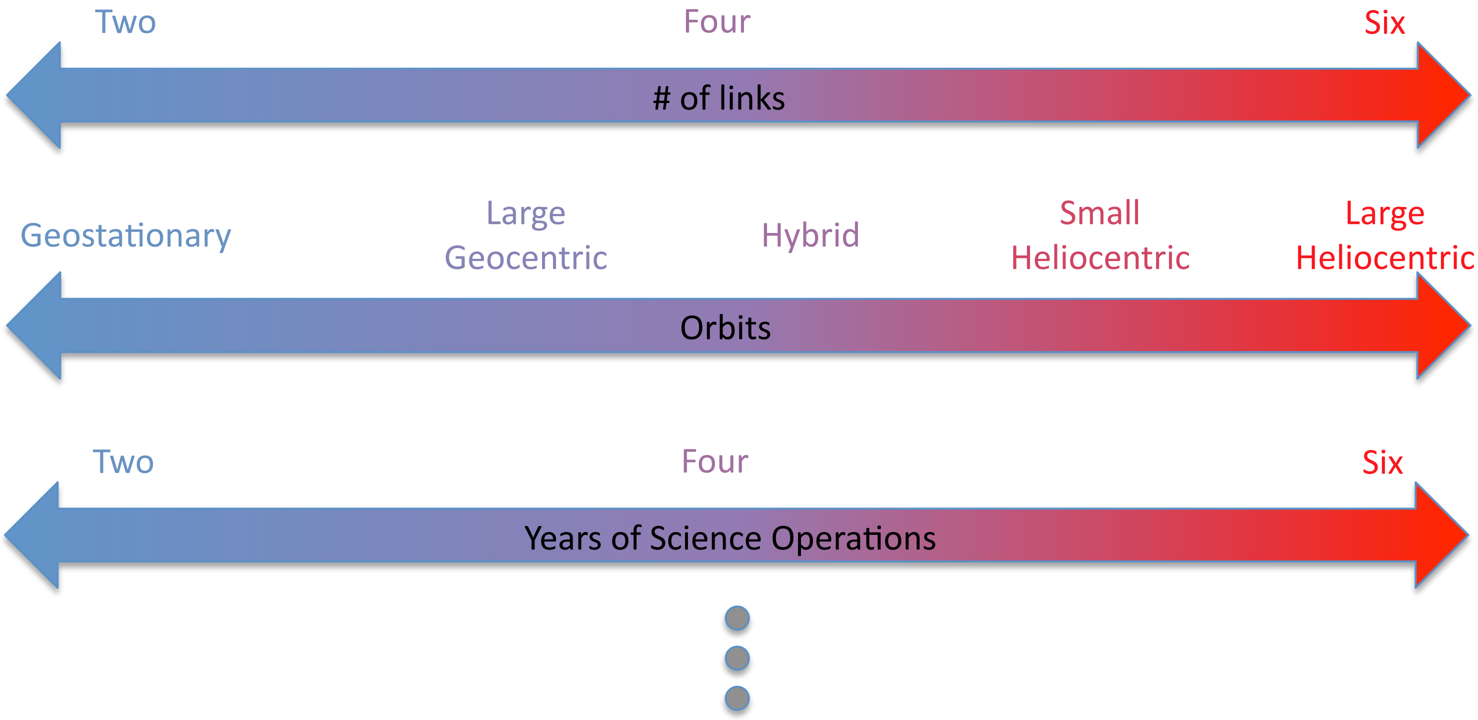
Group 4: Other

	InSpRL	Yu, et al.	Gulian, et al.
Key Idea	Atom-interferometry for inertial reference and time of flight	Atom interferometry for inertial reference	Superconducting detector
Constellation	2 S/C in-line (two 500km links)	LISA-like	Not specifcied
Cruise / Science / Extended (mo)	Not specified	LISA-like	Not-specified
Estimated cost	$0.7B	N/A	Not specified

NOTE: Information is as-submitted by RFI respondents

Rationale for Team-X Study

- Each mission concept represents a point in a multi-dimensional “architecture space”
- Study missions to cover interesting regions of that space
- Draw abstract conclusions about architecture choices as opposed to specific mission concepts.



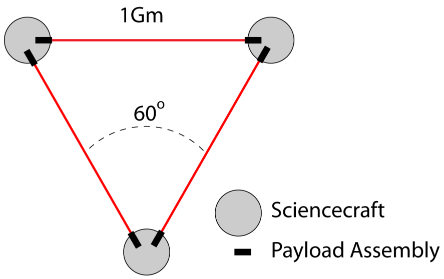
Two
Four
Six
# of links

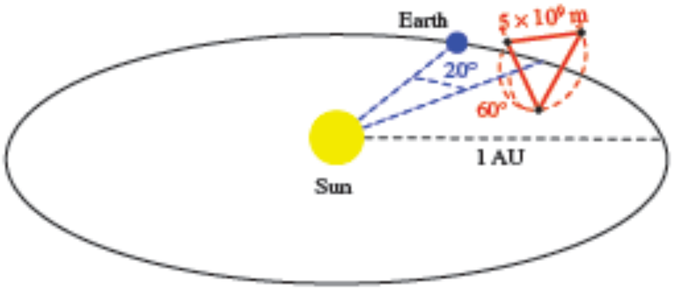
Geostationary
Large Geocentric
Hybrid
Small Heliocentric
Large Heliocentric
Orbits

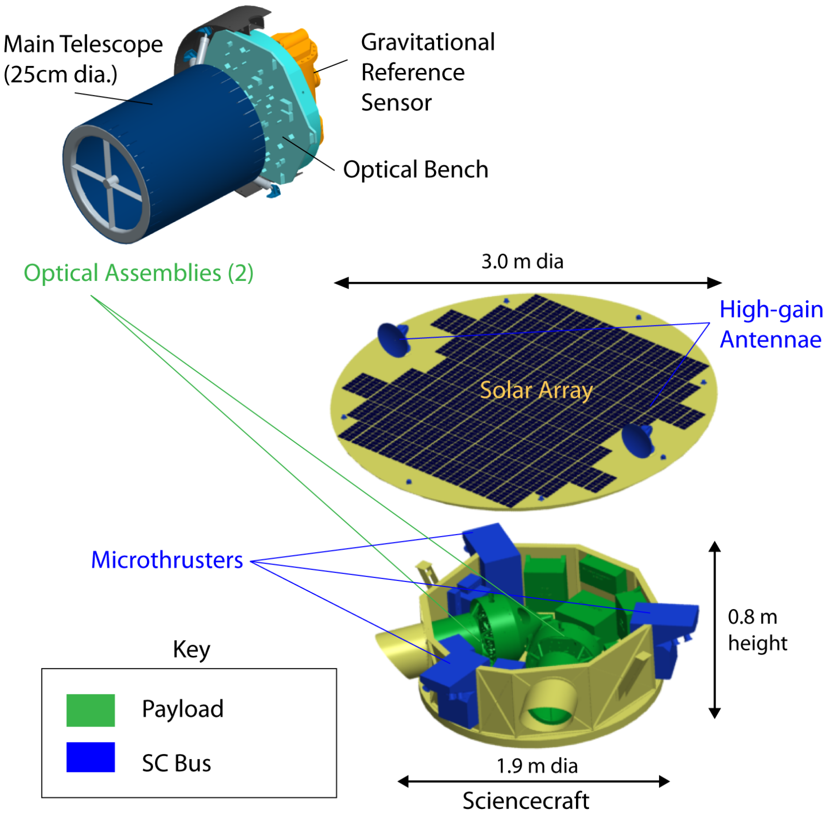
Two
Four
Six
Years of Science Operations

Concept 1: SGO Mid

LISA-like design with shorter arms, smaller telescope, smaller laser, drift-away orbits…



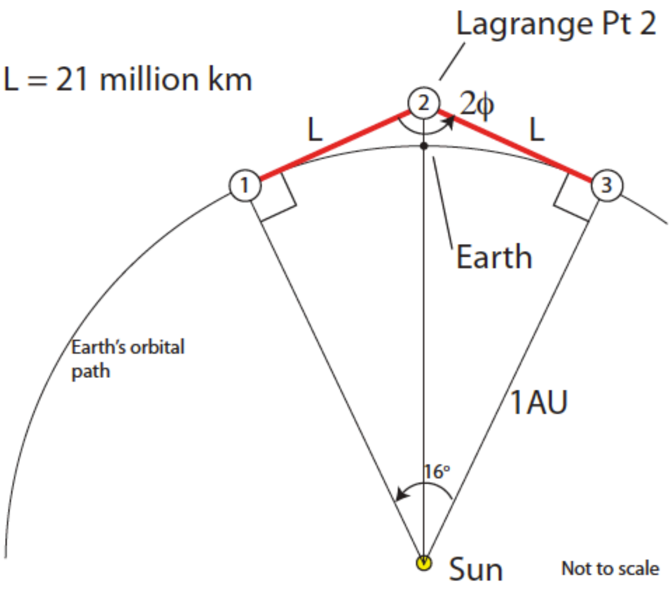


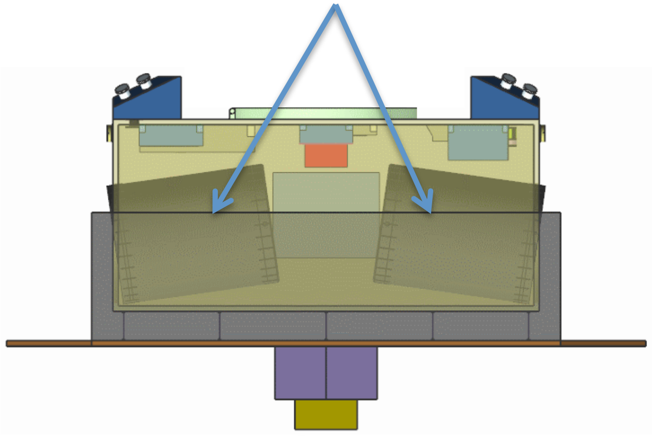


SGO High (LISA as single-agency) studied as delta

Concept 2: LAGRANGE

Eliminate drag-free inertial reference in favor of geometric suppression and force measurement system



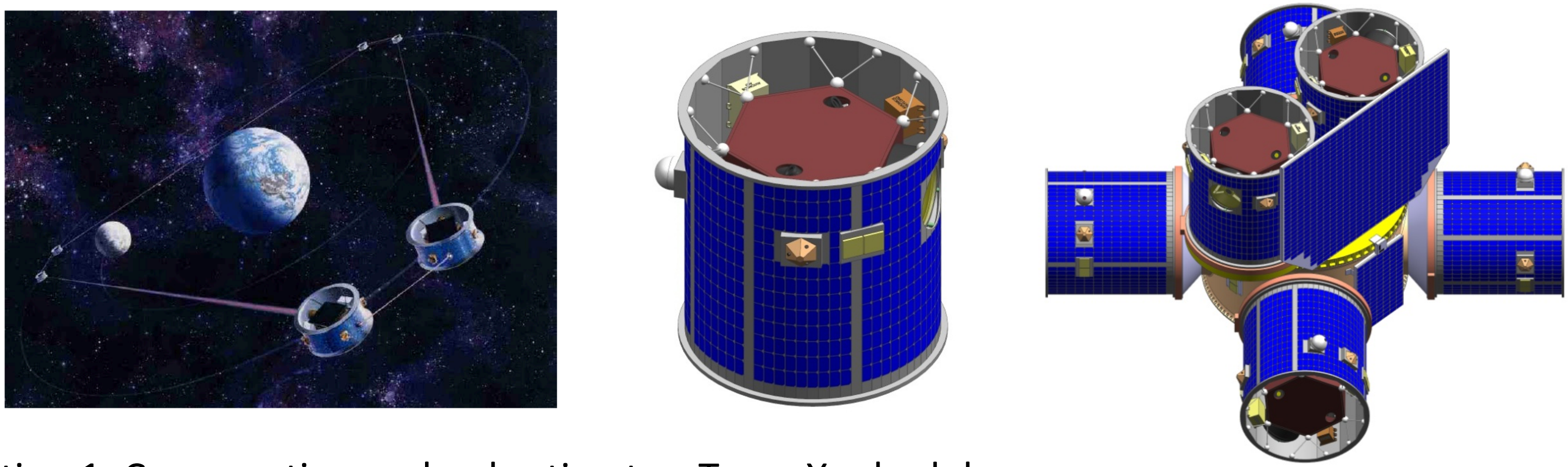


Telescopes

Solar wind & radiometer instruments

Concept 3: OMEGA

Geocentric constellation of six spacecraft (two per vertex) in 6×10^5 km orbit. Single launch and serial deployment by a carrier S/C. Lightweight payload and S/C



Option 1: Conservative payload estimates, Team-X schedule
Option 2: Aggressive payload estimates, customer schedule

NOTE: Spacecraft design reflects Team-X modifications to RFI submission design.

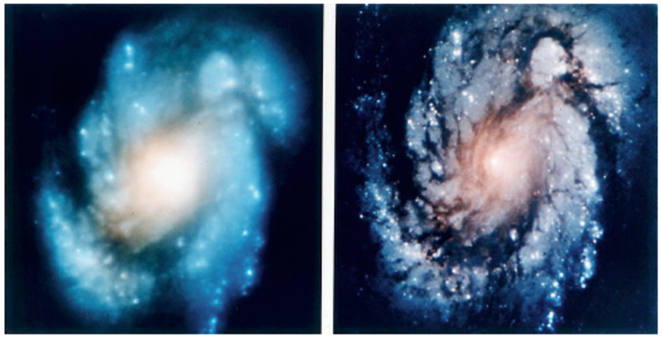
Science Performance Analysis

Decadal Endorsement

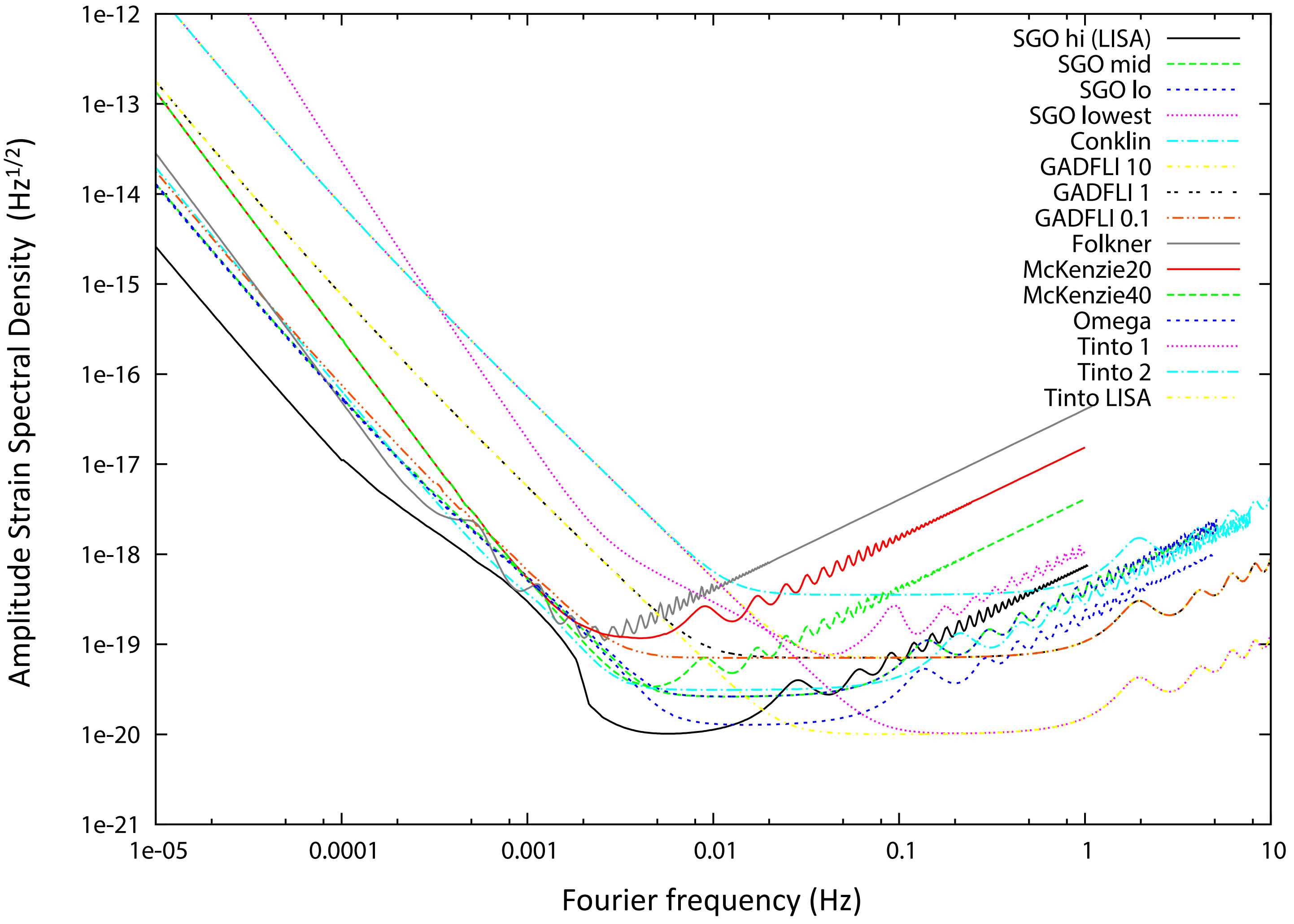
- Measurements of black hole mass and spin will be important for understanding the significance of mergers in the building of galaxies;
- Detection of signals from stellar-mass compact stellar remnants as they orbit and fall into massive black holes would provide exquisitely precise tests of Einstein's theory of gravity; and
- 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.

Science Assessment Activities

- Validate sensitivity curves
- Preliminary analyses for most concepts (data quantity)
- Detailed analysis for a few concepts (data quality)

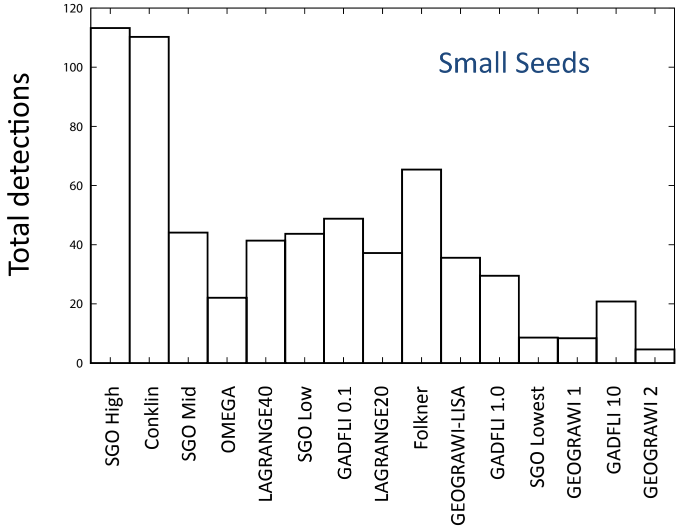


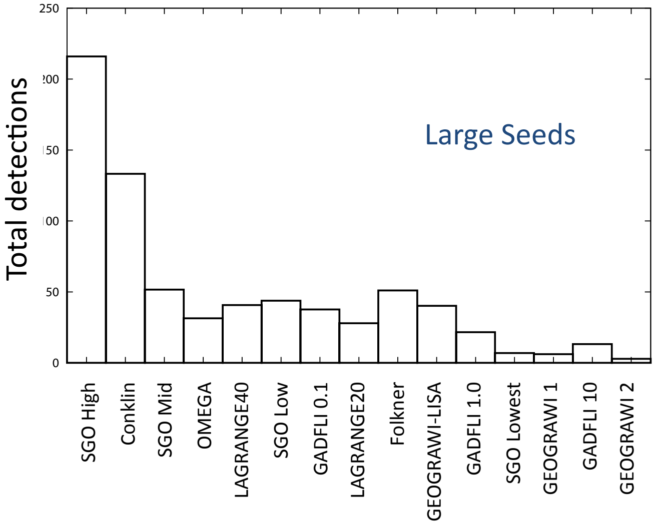
Sensitivity Curve Comparison

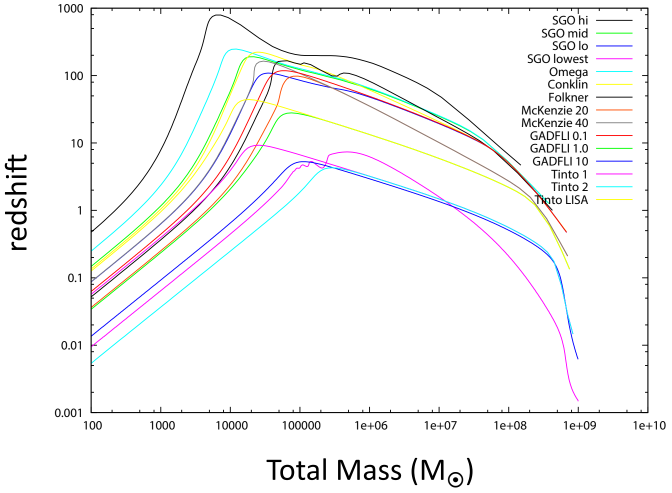


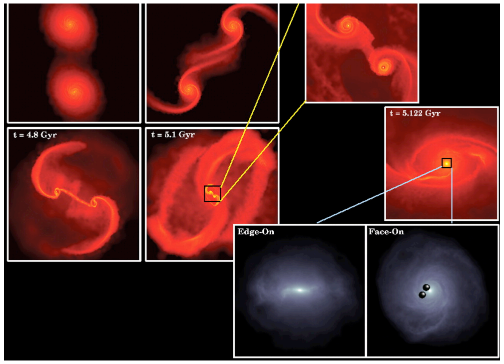
Massive Black Hole Binaries

Structure formation, Black Hole growth, Black Hole seeds, GR tests, cosmology…



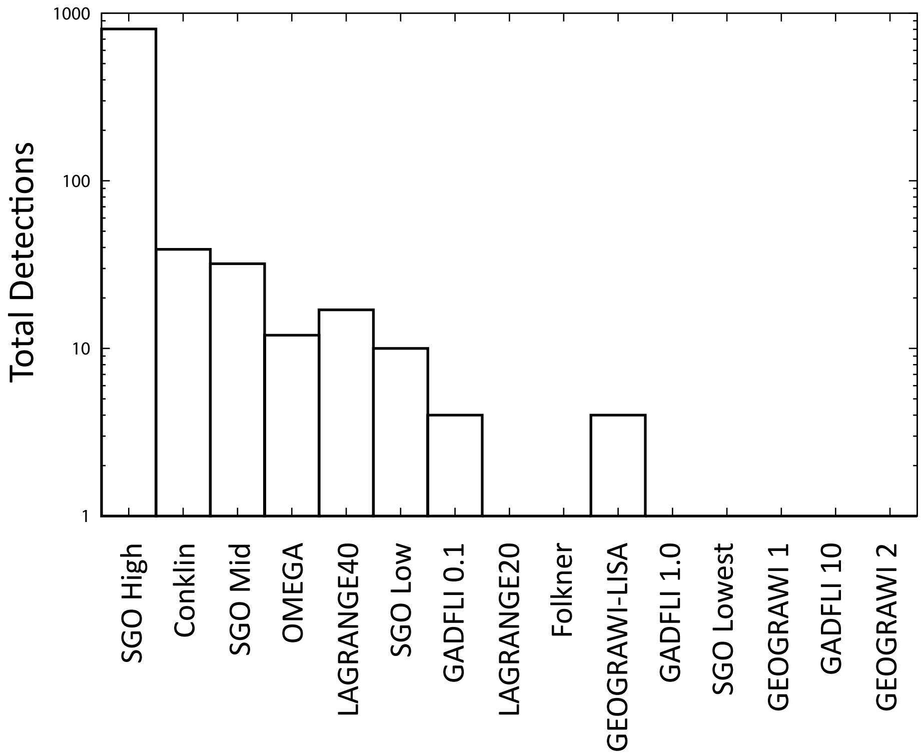


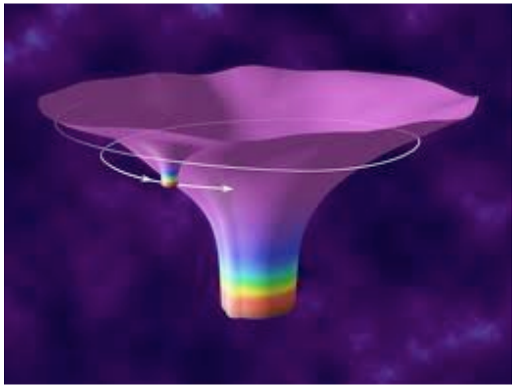


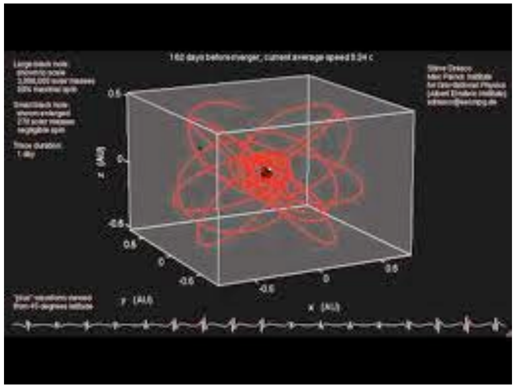


Extreme Mass Ratio Inspirals (EMRIs)

Strong gravity probe, GR tests, compact object astrophysics …







Galactic Binaries

Stellar evolution, compact object demographics, E/M counterparts, Milky Way structure, fundamental physics…

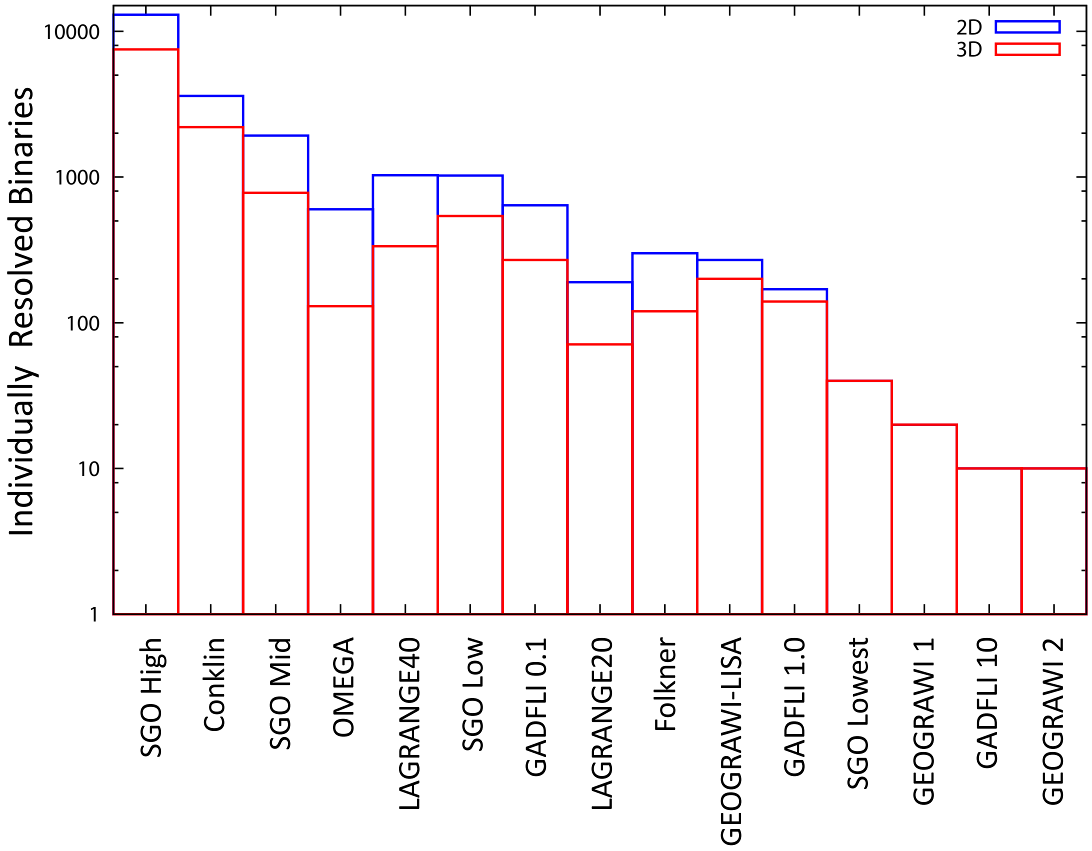
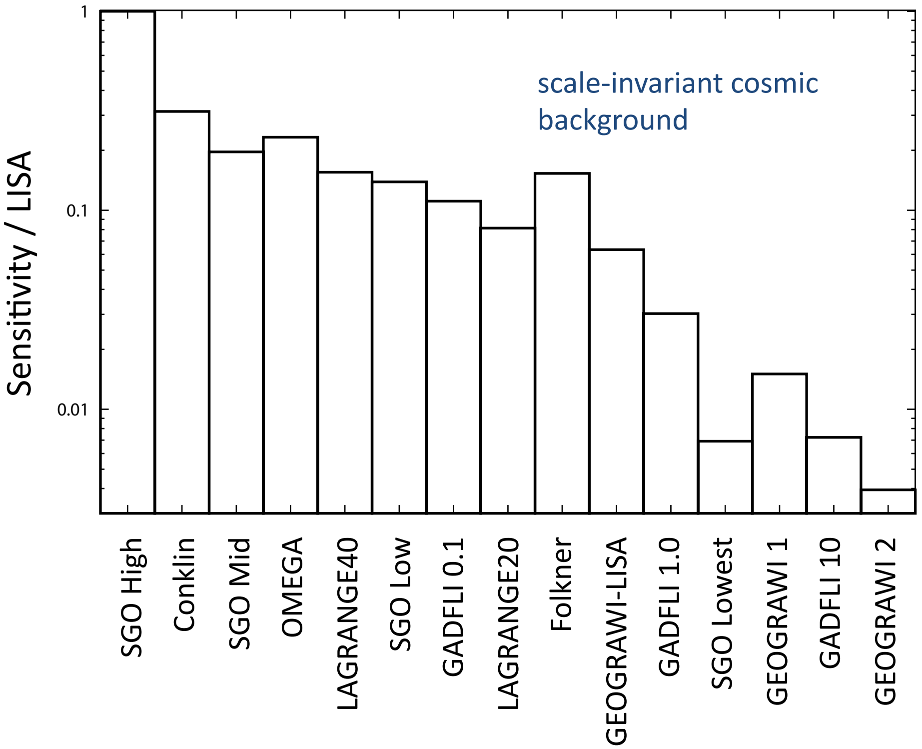
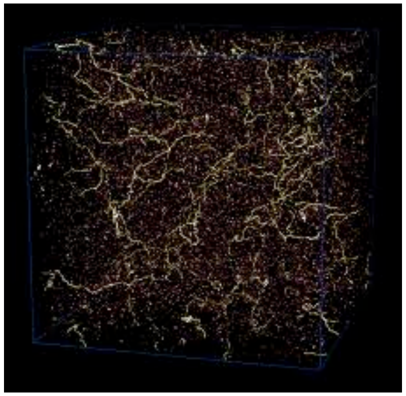


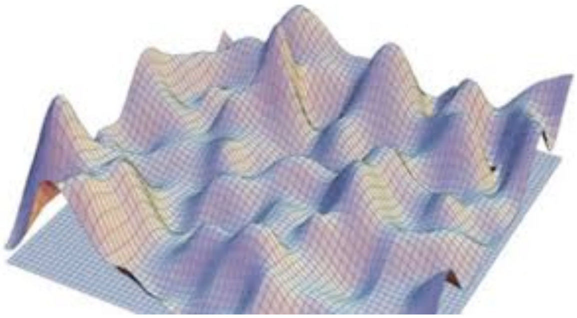

Image: NASA/GSFC/D. Berry

Discovery Space

Stochastic backgrounds, cosmic-strings, unknown unknowns…

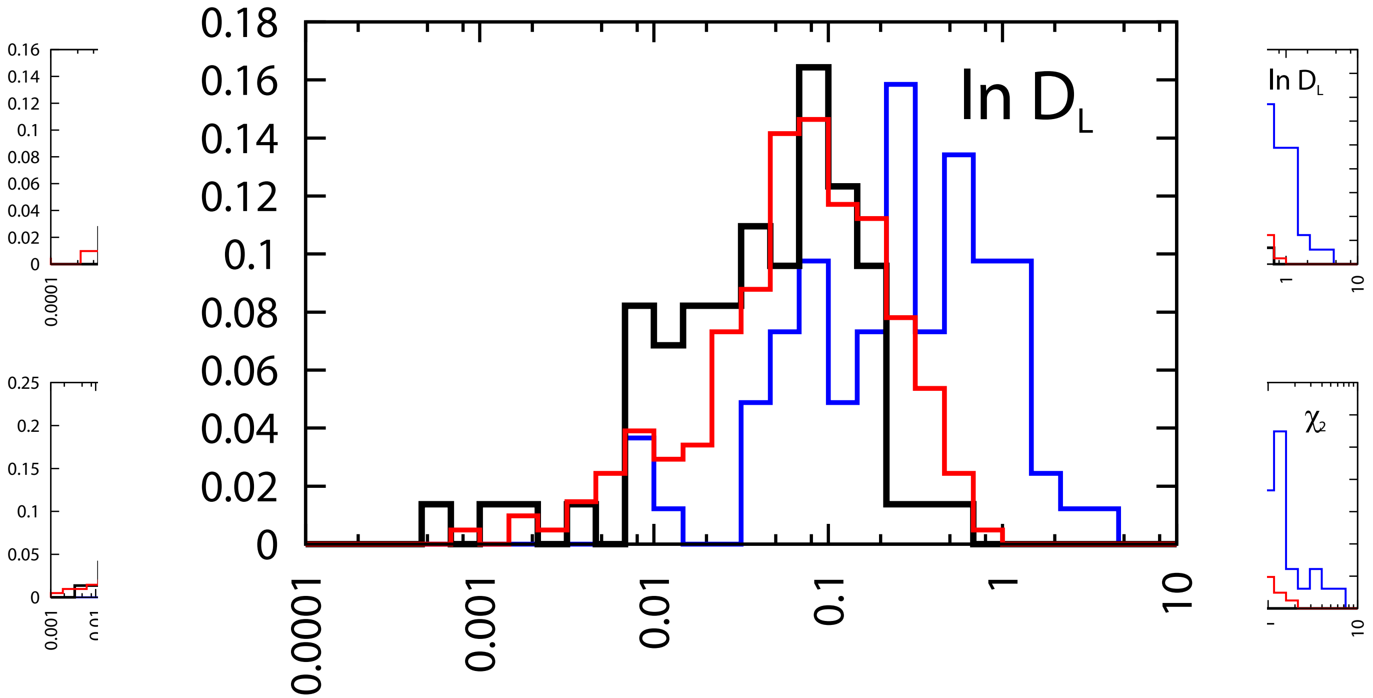






Black Hole Parameter Estimation

Not just how many, but how well-measured (masses, spins, distance, sky position…)



OMEGA

SGO-Mid

LAGRANGE

Science Summary for Team-X Missions

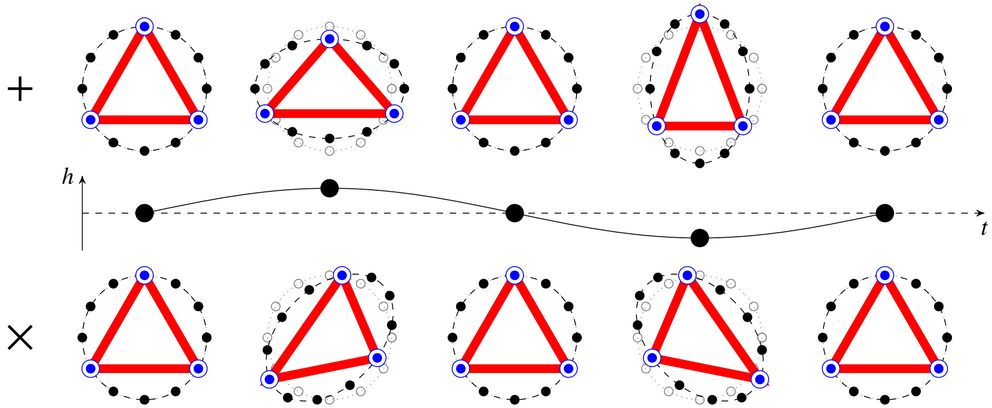
Metric of choice depends on science interests. Uncertainties reflect our astrophysical ignorance and hence the discovery potential.

Metric	SGO High	SGO Mid	LAGRANGE (McKenzie)	OMEGA
Total MBH detected	108-220	41-52	37-45	21-32
MBH w/ $z > 10$	3-57	1-4	1-5	1-6
MBH w/ mass errors < 1%	67-171	18-42	8-25	11-26
MBH w/ both spins < 1%	1-17	< 1	0	< 1
MBH w/ distance < 3%	81-108	12-22	2-6	10-17
MBH w/ location < 1 deg^2	71-112	14-21	2-4	15-18
MBH w/ location < 0.1deg^2	22-51	4-8	<1	5-8
Total EMRIs (*/÷ 10)	800	35	20	15
Total WD binaries (resolved)	4×10^4	7×10^3	5×10^3	5×10^3
WD binaries with 3D position	8×10^3	8×10^2	5×10^2	1.5×10^2
Stochasic Background	1.0	0.2	0.15*	0.25

Science Findings

- Several mission concepts, including those studied by Team X, were found to be capable of delivering a significant fraction of the LISA science related to massive black hole mergers and galactic binaries.
- The science of compact object captures (EMRI systems) may be at risk due to significantly reduced detection numbers relative to the LISA mission.
- *Concepts with three arms significantly improve parameter estimation over two-arm designs for black holes and enhance the ability to detect un-anticipated signals.*
- Additional years of science observations produce more science return for very modest expense.
- Gravitational-wave astrophysics and data analysis research has had a major impact on the anticipated science return from gravitational wave missions and has the potential to continue doing so.

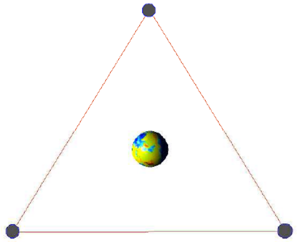
GW Mission “Architecture” choices

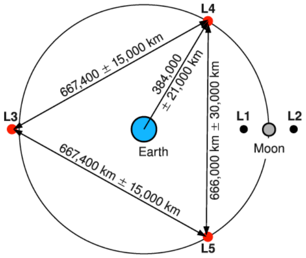


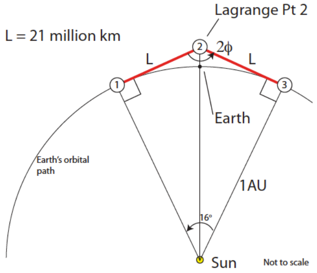
- What are the nominal trajectories of the test masses?
  - Orbit choices / Mission design
- What physical objects define the inertial test particles?
  - Inertial Reference Design
- How are time-of-flight measurements realized?
  - Time of flight measurement design
- What spacecraft requirements result?
  - Flight System Design

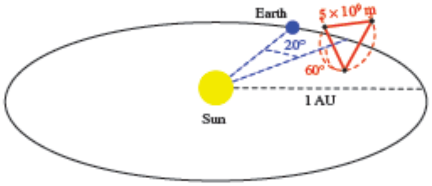
Orbits & Trajectories

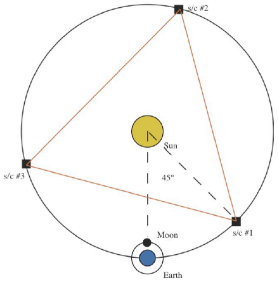
- Impacts
  - Payload requirements: Doppler shifts, pointing angles, etc.
  - Spacecraft requirements: thermal environment, radiation, communications
  - Science: modulation for parameter estimation & sky coverage
  - Mission design: Launch vehicle, propulsion module(s)
- Choices
  - “small” geocentric (geostationary)
  - Large geocentric
  - geo-/heliocentric hybrids
  - Heliocentric drift away
  - Stationary Heliocentric
  - Large Heliocentric











Orbits & Trajectories Findings

- Choices of orbits and trajectories have an immediate impact on propulsion requirements, but they also have consequences for the payload, flight system, and launch vehicle.

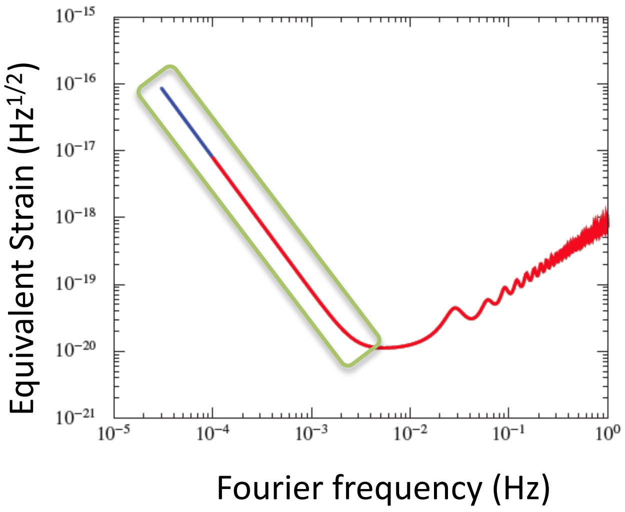
- *Contrary to expectations, high geocentric orbits have no significant propulsion savings over heliocentric orbits.*

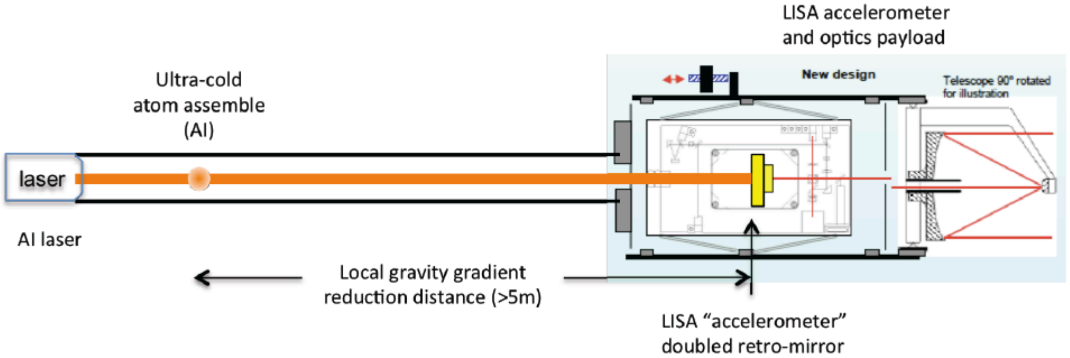
- Heliocentric missions are favored with respect to spacecraft thermal stability related to solar flux.

- Stable orbits, possibly with stationkeeping, allow extended missions.

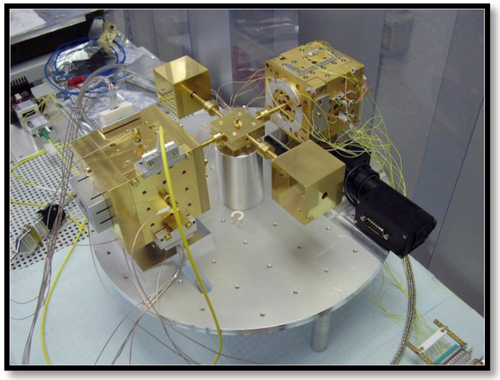
Inertial Reference

- Importance
    - reference point for GW measurement
    - Determines sensitivity at low frequencies
- Options
    - Drag-free test mass (LISA, **LPF**, many submissions)
    - Use S/C, measure and correct non-inertial forces
    - Atom interferometers





Proposed Atom Interferometer Inertial Sensor (Yu, et al.)



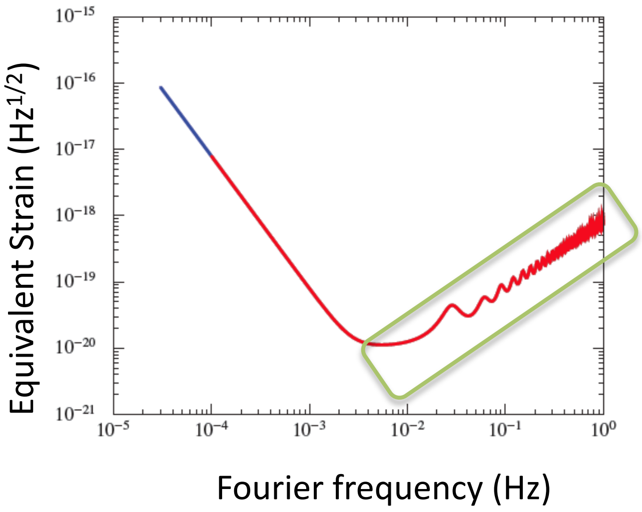
LPF inertial sensor in ground-testing

Inertial Reference Findings

- The estimated cost of the inertial reference instrumentation for the missions studied by Team X does not vary significantly and is not a major contributor to the overall mission cost.
- *The LPF GRS is the most highly developed inertial reference, and therefore the least risky.*
- The non-drag-free approach is potentially interesting in the unlikely event that a serious flaw with the drag-free design is uncovered by LPF. However, the non-drag-free approach brings a different set of risks, some of which are potentially severe, that would require further study if this approach is to be pursued.
- Refinement or enhancement of GRS technologies have the potential to reduce risk, reduce cost, or improve measurement performance but will not enable a Probe-class mission.

Time of Flight Measurement

- Importance
  - Used to detect geodesic deviation
  - Determines high-frequency sensitivity
- Choices
  - Laser Interferometry (LIGO, LISA, all but one RFI concept)
  - Atom Interferometry (Saif, et al.)



Time of Flight Measurement Findings

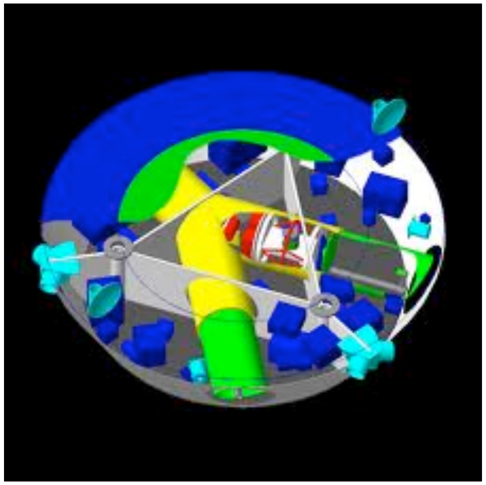
- *The LISA-derived Interferometric Measurement System (IMS) employed by SGO High and SGO Mid is a well-developed, low-risk concept capable of meeting the measurement requirements.*

- The non-drag-free approach brings an additional risk associated with relative motion between the spacecraft center of mass and the fiducial optic. Mitigating this effect may place severe requirements on the thermal, mechanical, and gravitational stability of the spacecraft. Further study would be required to assess this.

- Refinement or enhancement of core interferometry technologies have the potential to reduce risk, reduce cost, or improve measurement performance but will not enable a Probe-class mission.

Flight System Design

- Standard Mission: instrument is payload in the spacecraft
- GW Mission: *constellation of spacecraft is the instrument*
- Tightly integrated design
  - Thermal
  - vibrational
  - Self-gravity



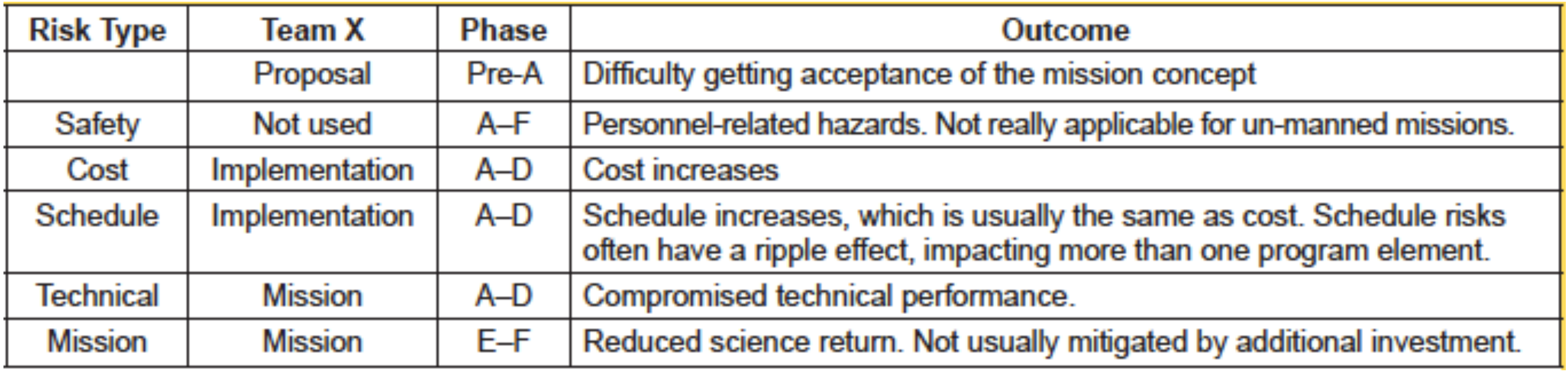
Flight System Findings

- All mission concepts considered require a spacecraft bus with unusual requirements on mechanical stability, thermal stability and gravitational stability. Meeting these requirements leads to a payload and bus that are tightly integrated during design, development, test, and operations.
- The design of the flight system influences the potential for extended operation of the mission.
- Of the missions studied by Team X, the flight systems of SGO High and SGO Mid are most mature and appear lowest risk.
- The requirements placed on the spacecraft bus for a non-drag-free design are different than those for a drag-free design and are less well understood. Further work would be necessary to determine the exact nature of these requirements and the resulting implications for the flight system.

Speaker change…

Risk Assessment

- Why important?
  - Trading cost for risk is one way to reduce cost
  - Need to identify risks and balance them against cost
- Team X considered some Proposal, Cost, Schedule, and Mission Risks, as well as some Technical and Technology Development Risks
- Team X did NOT consider heritage and maturity of concepts, nor did they consider science instrumentation risks
- Risks are categorized by how the outcome affects a mission:



Risk Type	Team X	Phase	Outcome
	Proposal	Pre-A	Difficulty getting acceptance of the mission concept
Safety	Not used	A–F	Personnel-related hazards. Not really applicable for un-manned missions.
Cost	Implementation	A–D	Cost increases
Schedule	Implementation	A–D	Schedule increases, which is usually the same as cost. Schedule risks often have a ripple effect, impacting more than one program element.
Technical	Mission	A–D	Compromised technical performance.
Mission	Mission	E–F	Reduced science return. Not usually mitigated by additional investment.

Risks Common to All (Team X studied) Missions

- Mission Risks
  - Astrophysical event rates are lower than expected

Only mitigation is to increase mission lifetimes

- Instrumentation risk
  - Photoreceiver development

Likely a misunderstanding: baseline photoreceivers meet all performance requirements

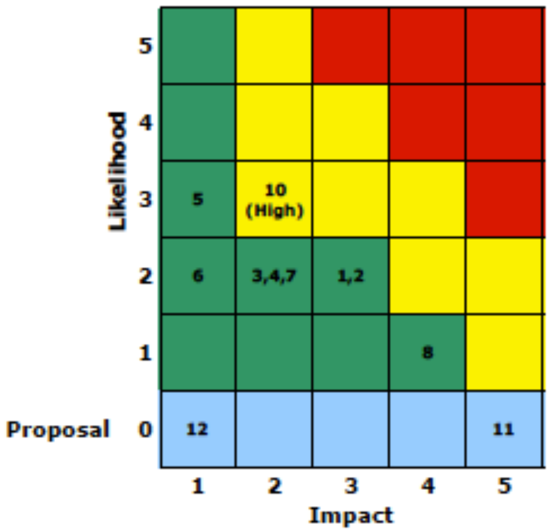
- Proposal risk
  - Not possible to do a credible mission test under flight-like conditions

No mitigation possible other than careful test planning

Risk Assessment: All risks compared

Team X assessment plus Core Team

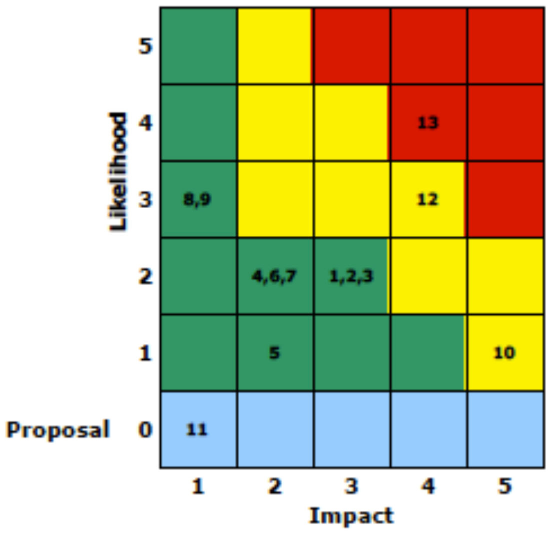
SGO-Mid/(High)



Likelihood	1	2	3	4	5
5					
4					
3	5	10 (High)			
2	6	3,4,7	1,2		
1				8	
Proposal 0	12				11

Impact

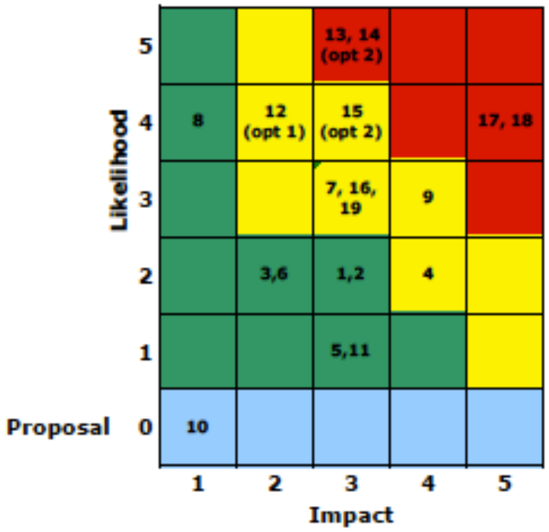
LAGRANGE



Likelihood	1	2	3	4	5
5					
4				13	
3	8,9			12	
2		4,6,7	1,2,3		
1		5			10
Proposal 0	11				

Impact

OMEGA



Likelihood	1	2	3	4	5
5			13, 14 (opt 2)		
4	8	12 (opt 1)	15 (opt 2)		17, 18
3			7, 16, 19	9	
2		3,6	1,2	4	
1			5,11		
Proposal 0	10				

Impact

High Risks

Risk	Title	Likelihood	Impact
LAGRANGE-12	Thermal-elastic effects	4	4
OMEGA(2)-13	Staffing/destaffing	5	3
OMEGA(2)-14	Schedule too short	5	3
OMEGA-17	Optical filter required	4	5
OMEGA-18	Fiber phase noise	4	5

Risk Findings

- A three-arm design has lower risk than a similar two-arm design, allowing for graceful degradation
- Three dual-string spacecraft appear to be more robust than six single-string spacecraft for most mission failures
- A non-drag-free architecture introduces significant additional risk
- Overlapping construction of multiple units adds significant schedule risk.

Cost Estimates

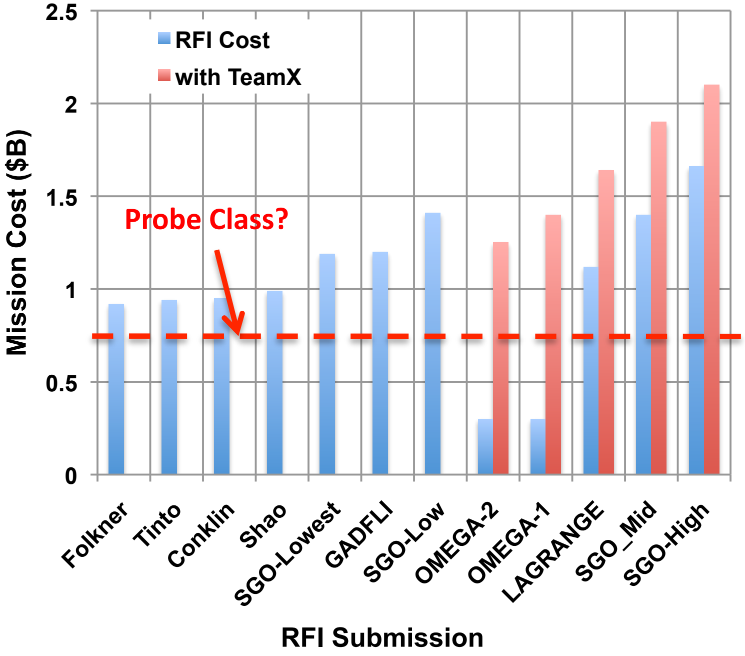
- Common assumptions for uniformity:
  - Class B (single fault tolerant by design)
  - All technologies assumed to be TRL 6
  - Only NLS-II launch vehicles considered
  - Mass margins of 53%
  - power margins of 43%
  - 30% cost reserve added to Phase A-E
  - single-center, in-house build

- Team X process:
  - uses JPL-proprietary databases
  - bottom up estimates from discipline leads, including labor hours
  - Analogous and parametric models used where COTS not available
  - Tools estimate associated costs such as management, system engineering, mission assurance, etc

Cost Estimates

Mission	White Paper	Team X Estimate	$M/yr Science Ops
SGO High	$1.7B	$2.1B	$0.42B
SGO Mid	$1.4B	$1.9B	$0.95B
LAGRANGE	$1.1B	$1.6B	$0.82B
OMEGA Option 1		$1.4B	$1.4B
OMEGA Option 2	$0.3B	$1.2B	$1.2B

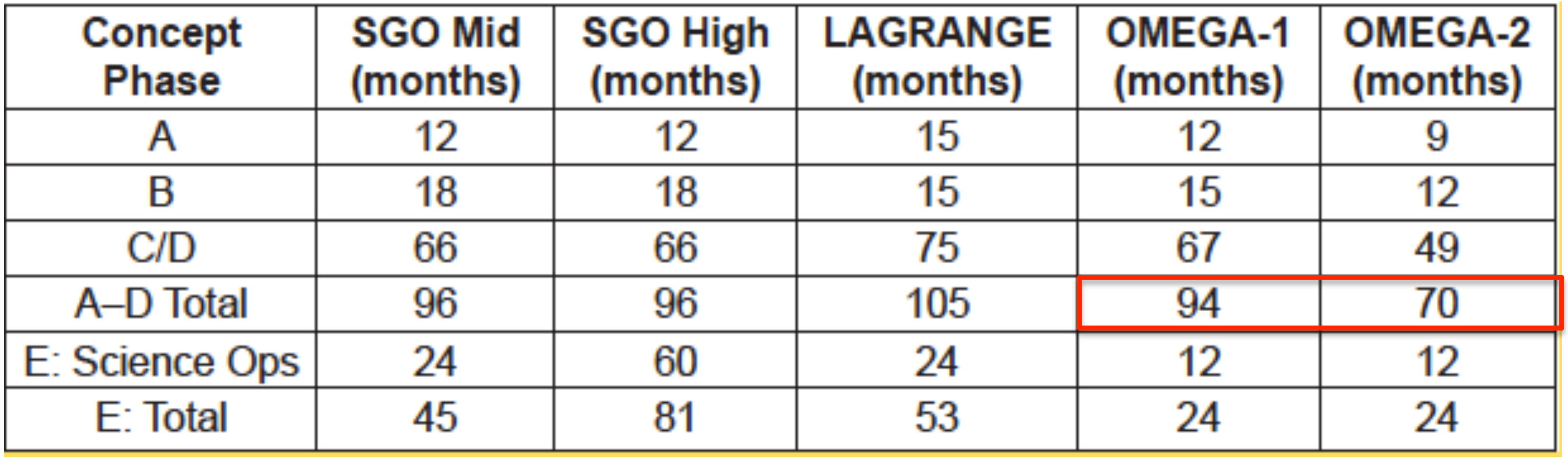
Units are $FY12



Probe Class?

Cost Estimates: Importance of Schedule

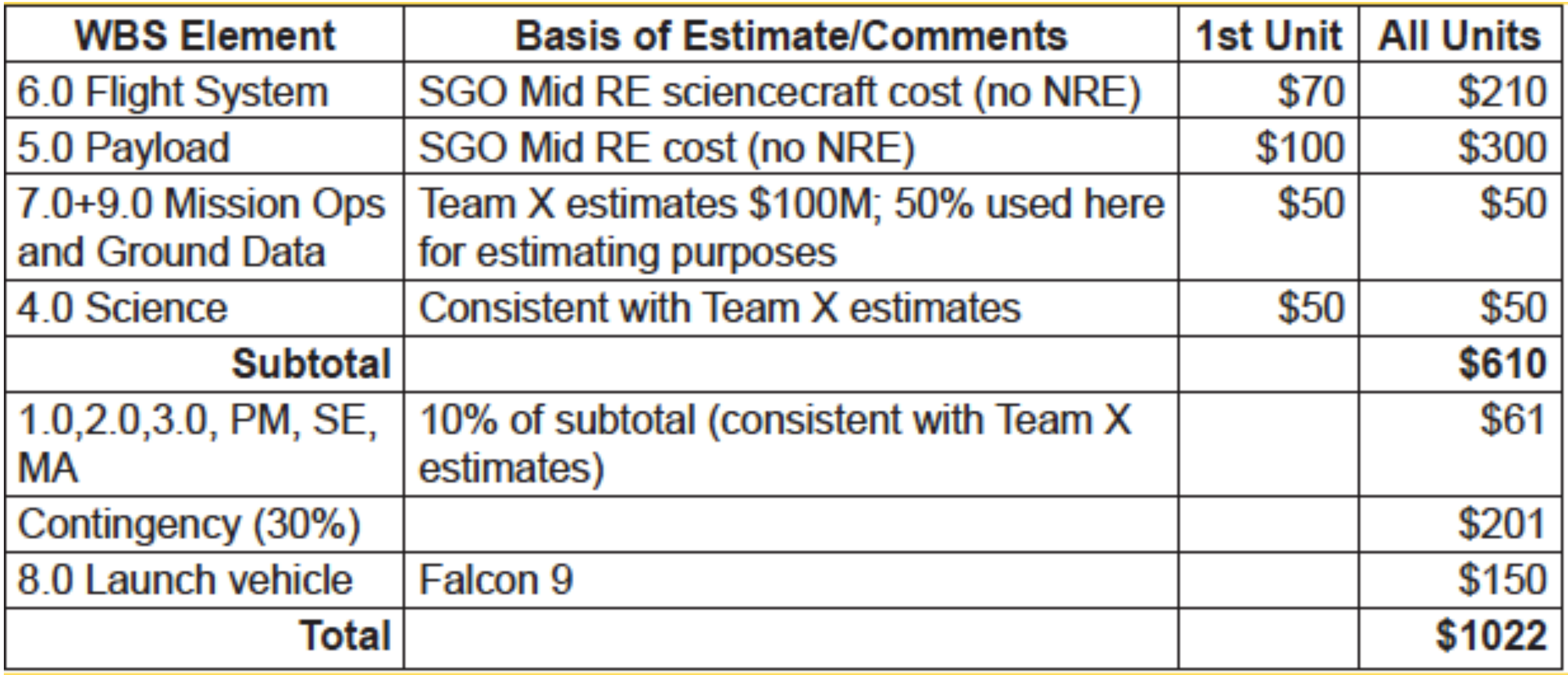
- Schedule strongly affects cost estimates
  - Marching army costs and overhead included
- Omega-2 schedule not formally supported by Team X; estimate developed anyway to explore trade space
- Estimated phase C/D burn rate of ~ $100M/yr
  - Measure of how scheduled risk may convert to cost growth



Concept Phase	SGO Mid (months)	SGO High (months)	LAGRANGE (months)	OMEGA-1 (months)	OMEGA-2 (months)
A	12	12	15	12	9
B	18	18	15	15	12
C/D	66	66	75	67	49
A–D Total	96	96	105	94	70
E: Science Ops	24	60	24	12	12
E: Total	45	81	53	24	24

Cost Estimates: Generic Mission Estimate

- Lowest cost mission possible using Team X data
- Assumptions:
  - No NRE (mass produced, off-the-shelf)
  - Single launch
  - (no separate cruise vehicle or prop module)
  - Three identical spacecraft



WBS Element	Basis of Estimate/Comments	1st Unit	All Units
6.0 Flight System	SGO Mid RE sciencecraft cost (no NRE)	$70	$210
5.0 Payload	SGO Mid RE cost (no NRE)	$100	$300
7.0+9.0 Mission Ops and Ground Data	Team X estimates $100M; 50% used here for estimating purposes	$50	$50
4.0 Science	Consistent with Team X estimates	$50	$50
Subtotal			**$610**
1.0,2.0,3.0, PM, SE, MA	10% of subtotal (consistent with Team X estimates)		$61
Contingency (30%)			$201
8.0 Launch vehicle	Falcon 9		$150
Total			**$1022**

Cost Findings

- The choice of heliocentric versus geocentric mission designs does not seem to be a significant cost driver
- Reducing a three-arm design to two arms will not necessarily reduce the cost significantly
- Eliminating a drag-free inertial reference achieves at most modest savings
- Optimizing the build plan could be a source of modest saving
- In all cases, the Team X estimated costs were found to be well over $1B, thus putting the mission in the Flagship class

Technology Development: Importance

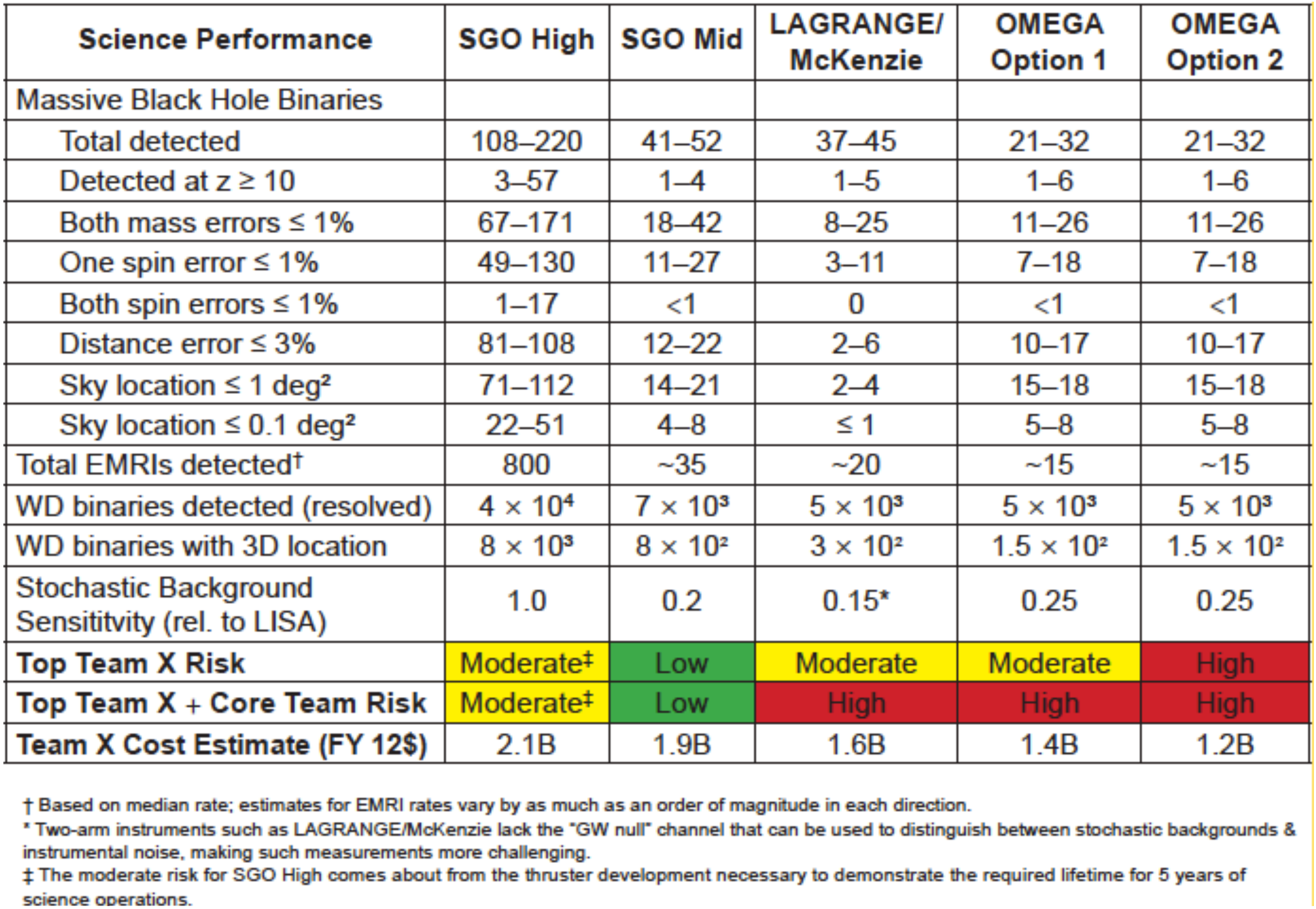
- Existing workshare agreement (2004)
    - ensures coverage of all critical technologies by at least one partner
    - Encourages both partners to pursue as many development activities as possible
- European investment >> US investment
    - LISA Pathfinder
    - Separate ESA-sponsored tech development funding program for universities (~ 10M Euro/yr for > 5 years)
    - ESA Member State National investments
- Strategy depends on partnership *best to be flexible!*
    - ESA or NASA led or equal partners
    - bi- or multi-lateral?
    - Focus on system-level work (i.e. testbeds)
    - Science source work is also critical (parameter estimation, data analysis and understanding of sources)

Technology Findings

- No new or unproven technology is needed to enable a LISA-like mission such as SGO High or SGO Mid
- Refinement and enhancement of core LISA technologies could provide cost, risk or performance benefits that integrate to a moderate effect on the mission as a whole, but will not enable a Probe-class mission
- *Coordinated and sustained US investment in core LISA technologies will preserve the US research capability and support mission opportunities on a variety of time scales for a variety of partnering arrangements*
- System testbeds for drag-free control and interferometric measurement are a good investment, providing an arena in which to develop technologies, gain insight into the measurement process, and develop techniques that could eventually be applied to future integration and testing

Summary of Missions considered by Team X:

Science return, risk, and cost



Science Performance	**SGO High**	**SGO Mid**	**LAGRANGE/ McKenzie**	**OMEGA Option 1**	**OMEGA Option 2**
Massive Black Hole Binaries					
Total detected	108–220	41–52	37–45	21–32	21–32
Detected at $z \geq 10$	3–57	1–4	1–5	1–6	1–6
Both mass errors ≤ 1%	67–171	18–42	8–25	11–26	11–26
One spin error ≤ 1%	49–130	11–27	3–11	7–18	7–18
Both spin errors ≤ 1%	1–17	<1	0	<1	<1
Distance error ≤ 3%	81–108	12–22	2–6	10–17	10–17
Sky location ≤ 1 deg^2	71–112	14–21	2–4	15–18	15–18
Sky location ≤ 0.1 deg^2	22–51	4–8	≤ 1	5–8	5–8
Total EMRIs detected[†]	800	~35	~20	~15	~15
WD binaries detected (resolved)	4×10^4	7×10^3	5×10^3	5×10^3	5×10^3
WD binaries with 3D location	8×10^3	8×10^2	3×10^2	1.5×10^2	1.5×10^2
Stochastic Background Sensititvity (rel. to LISA)	1.0	0.2	0.15[*]	0.25	0.25
Top Team X Risk	Moderate[‡]	Low	Moderate	Moderate	High
Top Team X + Core Team Risk	Moderate[‡]	Low	High	High	High
Team X Cost Estimate (FY 12$)	2.1B	1.9B	1.6B	1.4B	1.2B

[†] Based on median rate; estimates for EMRI rates vary by as much as an order of magnitude in each direction.

[*] Two-arm instruments such as LAGRANGE/McKenzie lack the "GW null" channel that can be used to distinguish between stochastic backgrounds & instrumental noise, making such measurements more challenging.

[‡] The moderate risk for SGO High comes about from the thruster development necessary to demonstrate the required lifetime for 5 years of science operations.

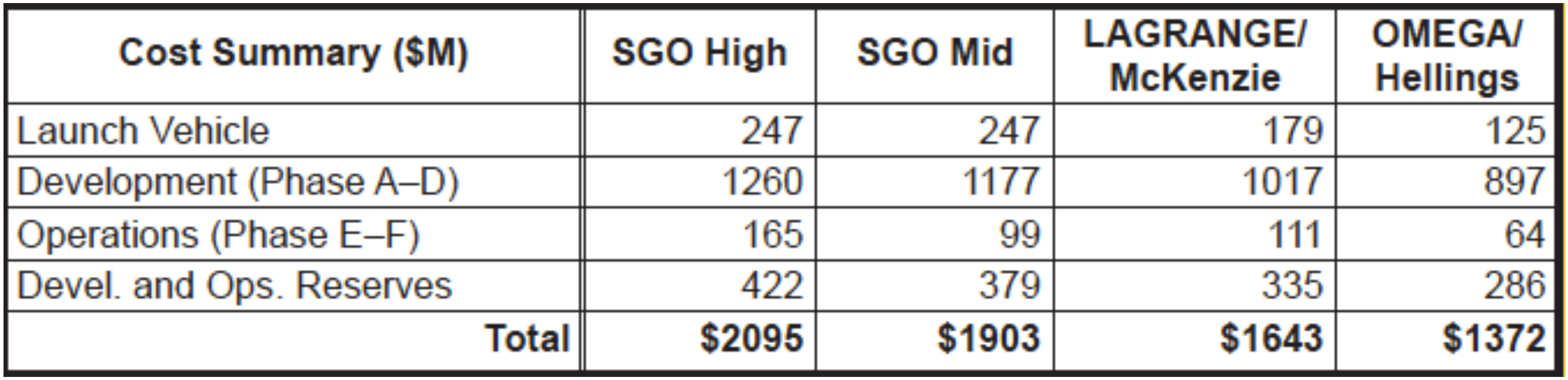
General Findings

- Scientifically compelling missions can be carried out for less than the full LISA cost. No concepts were found near or below $1B
- Scaling the LISA architecture with three arms down to the SGO Mid concept preserves compelling science, reduces cost, and maintains low risk
- Eliminating a measurement arm reduces costs moderately, reduces science, and increases mission risk
- More drastic changes, such as eliminating drag-free operation or adopting a geocentric orbit, significantly increase risk, and the associated cost savings are uncertain
- Scientific performance decreases far more rapidly than cost
- We have found no technology that can make a dramatic reduction in cost
- There is an urgent need for NASA to prepare for the imminent exploration of the Universe with gravitational waves, leading to revolutionary science. The US needs a sustained and significant program supporting technology development and science studies to participate in the first space-based gravitational-wave mission

Backup Slides

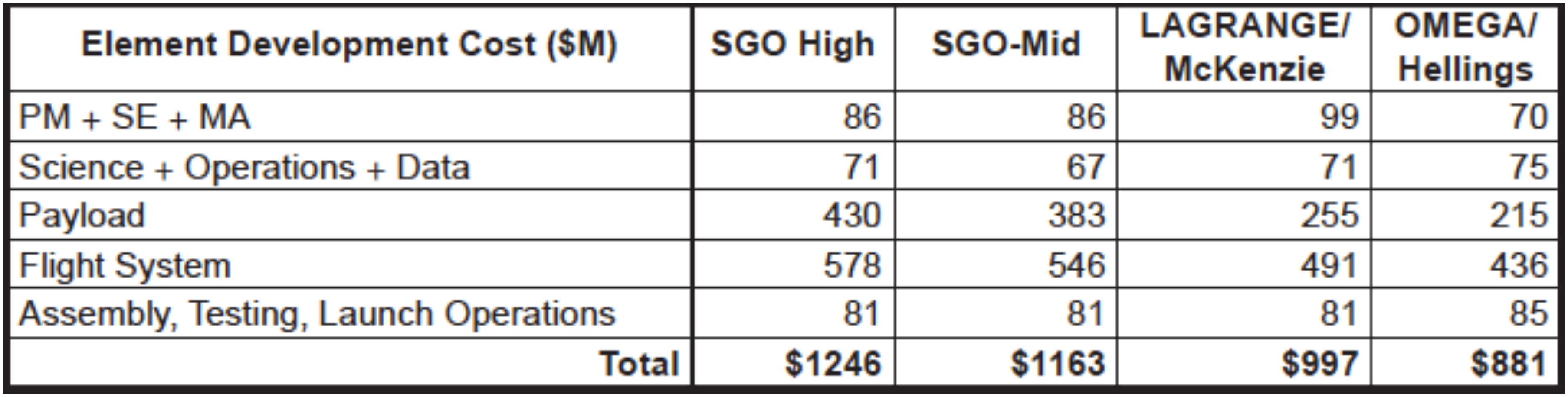
Cost Estimates: Breakdowns

Team X Mission Segment Cost Breakdown



Cost Summary ($M)	SGO High	SGO Mid	LAGRANGE/ McKenzie	OMEGA/ Hellings
Launch Vehicle	247	247	179	125
Development (Phase A–D)	1260	1177	1017	897
Operations (Phase E–F)	165	99	111	64
Devel. and Ops. Reserves	422	379	335	286
Total	**$2095**	**$1903**	**$1643**	**$1372**

Team X Mission Mission Component Development Cost Breakdown



Element Development Cost ($M)	SGO High	SGO-Mid	LAGRANGE/ McKenzie	OMEGA/ Hellings
PM + SE + MA	86	86	99	70
Science + Operations + Data	71	67	71	75
Payload	430	383	255	215
Flight System	578	546	491	436
Assembly, Testing, Launch Operations	81	81	81	85
Total	**$1246**	**$1163**	**$997**	**$881**

Cost Estimates: PI vs Team X estimates

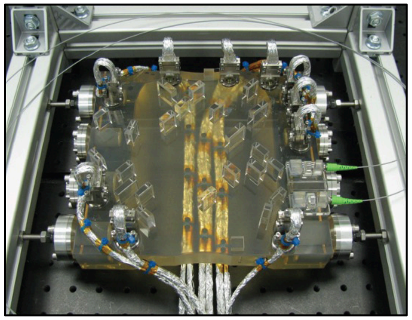
- **For SGO Mid: Team X vs RFI Team cost differences**

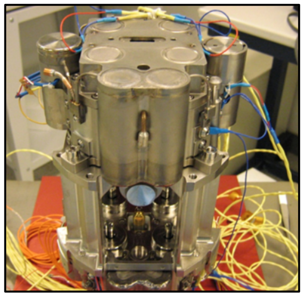
Contribution	**Cost delta ($M)**
NLS-II vs Falco:n Heavy launch vehicle difference	$164
Learning curve for RE costs	$285
Team X 30% cost reserves vs white paper 20%	$105
Misc small differences	$52
Total	$500

- **For Omega: Team X vs RFI Team cost differences**

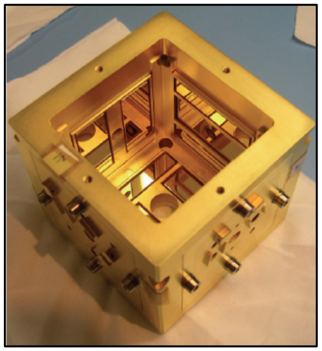
Contribution	**Cost delta ($M)**
Sciencecraft cost	$380
Payload costs	$180
Launch vehicle (NLS-II)	$80
Assembly, test, and launch operations	$80
Contingency	$200
Total	$920

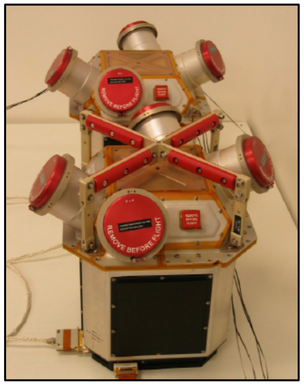
Technology Status

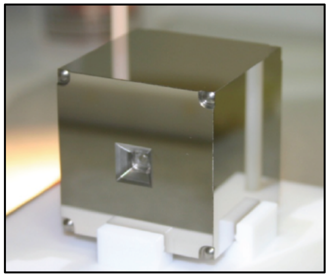




- Drag-free Inertial Reference Technologies
  - GRS: flight model for LPF
  - Micronewton thrusters
    - CMNT flight model for LPF, lifetime for LISA
    - FEEPs undergoing qualification
  - Control laws: both NASA and ESA have developed



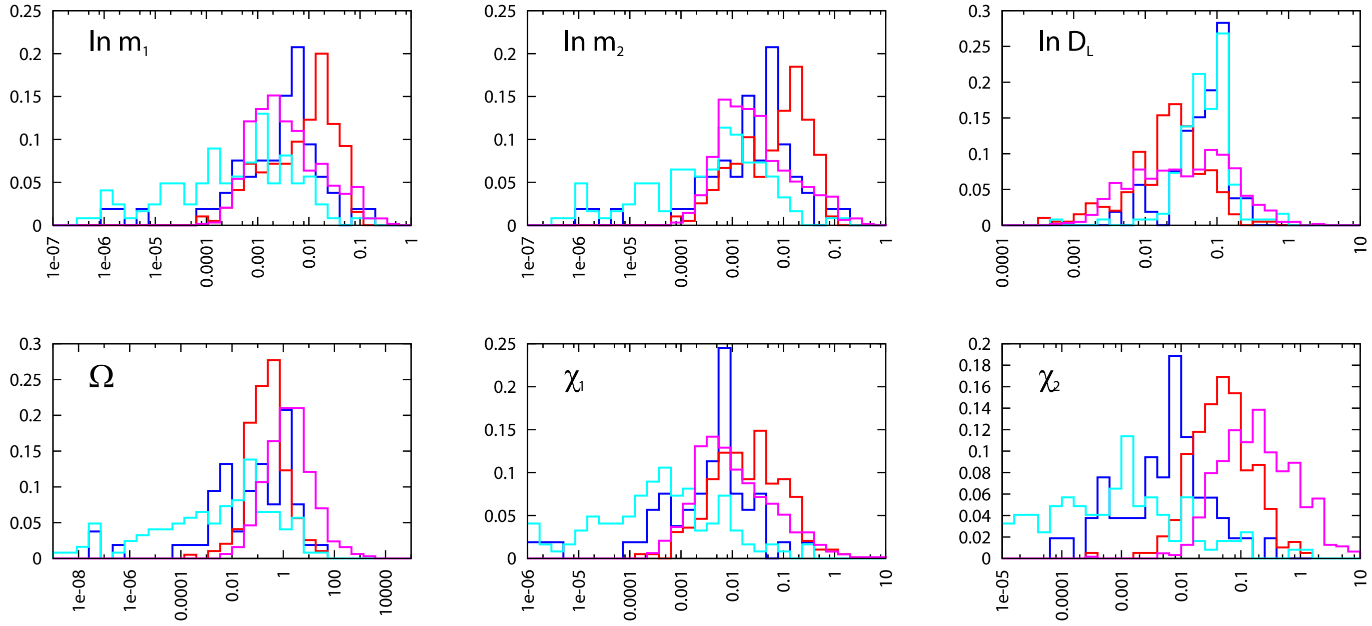




- Interferometric Distance Measurement Technologies
  - Phasemeter
    - NASA at ~ TRL 5, close to 6
    - ESA accelerated development
  - Photoreceivers: baseline meets requirements, advanced devices at early stage but promise improvement
  - Laser system: most components demonstrated, complete system level demo still needed
  - Optical bench: LPF flight model delivered, LISA bench designed
  - Telescope: US, ESA studies in progress

Black Hole Parameter Estimation

- Intriguing results
  - Very small constellations benefit from rapid modulation of the GW signal
  - Very large constellations benefit from arm-length effects



SGO High, Large Seeds

SGO High, Small Seeds

GADFLI, Large Seeds

GADFLI, Small Seeds