PROGRESS AND PROSPECTS TOWARD A SPACE-BASED GRAVITATIONAL-WAVE OBSERVATORY

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15th Capra Meeting
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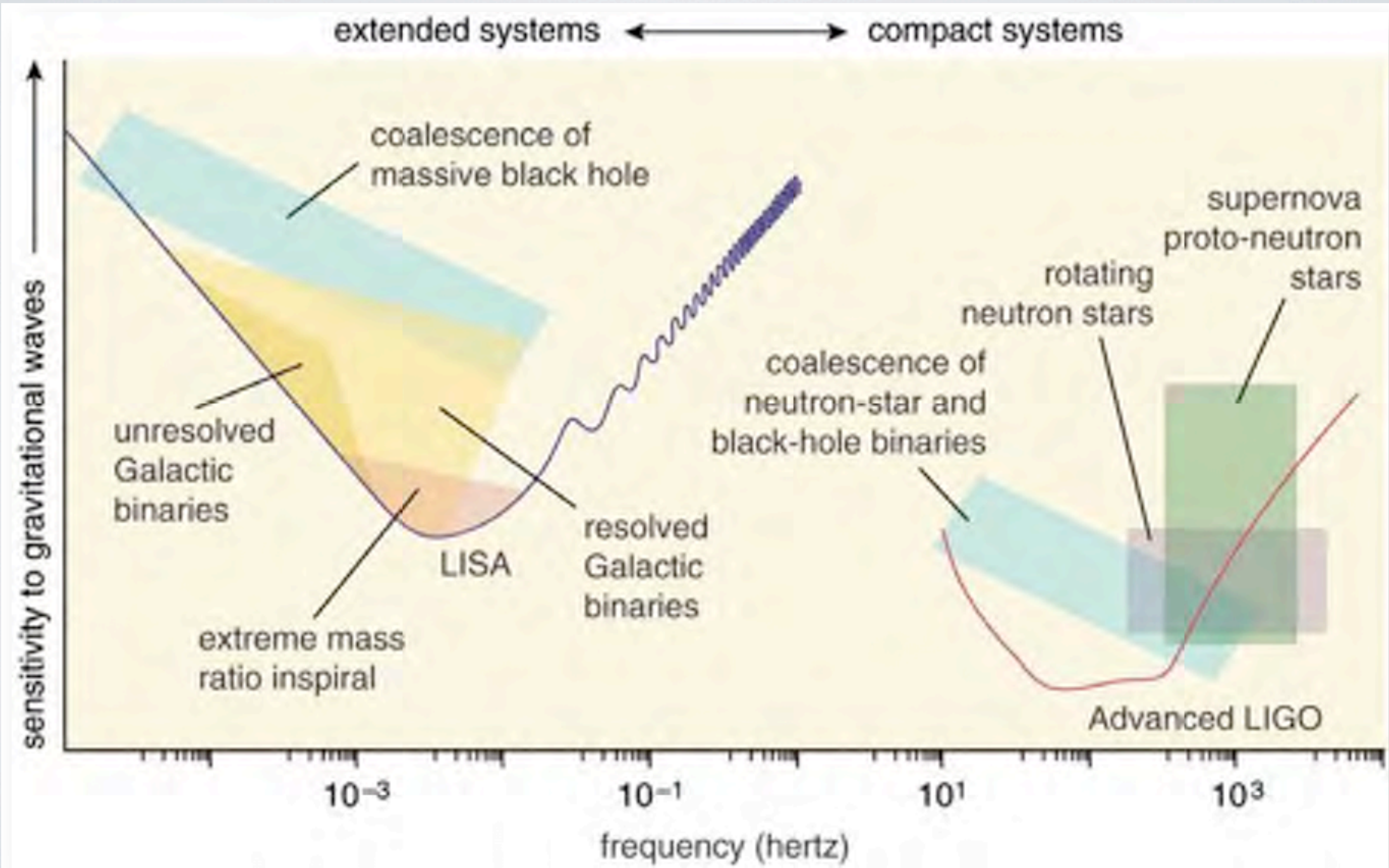
University of Maryland - College Park

Plan: LISA past and future

- No theory here
  - Extreme/Intermediate Mass-Ratio Inspirals (EMRI/IMRI) are an astrophysical testbed for GR
  - Space-based GW observation (ie LISA) needed
- Our old friend LISA before 2010
- LISA 2011-2012
  - (based on GSFC activity and 9th LISA Symposium)
  - Activity in Europe (LISA Pathfinder, NGO, Consortium)
  - Activity in the US (SGO Study)
  - Activity in Asia
- LISA in the future

LISA



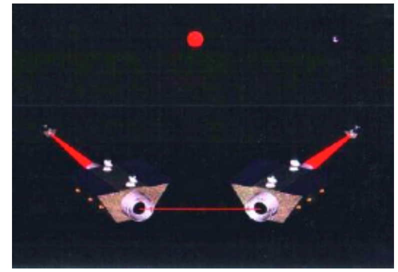
extended systems
compact systems
sensitivity to gravitational waves
coalescence of massive black hole
supernova proto-neutron stars
rotating neutron stars
coalescence of neutron-star and black-hole binaries
unresolved Galactic binaries
resolved Galactic binaries
LISA
extreme mass ratio inspiral
Advanced LIGO
10⁻³
10⁻¹
10¹
10³
frequency (hertz)

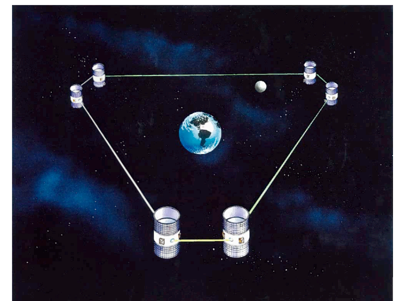
What constitutes LISA?

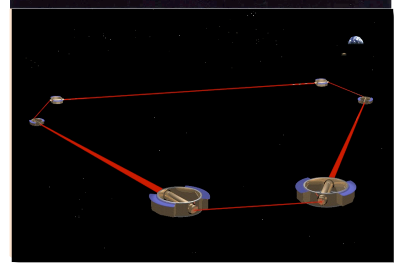
- Drag–free control
  - Free–falling test mass
  - Precision stationkeeping
- Continuous laser ranging
- Heliocentric orbits
  - Constellation in equilateral triangle
  - Highly stable orbits, without orbital stationkeeping
  - Benign environment
  - Million–kilometer arms (**LISA=5M km**)
- Laser frequency noise subtraction (TDI)
  - Michelson's white–––light fringe condition through post–processing
- Sensitive to MBH mergers, galactic binaries, **… and EMRI's**

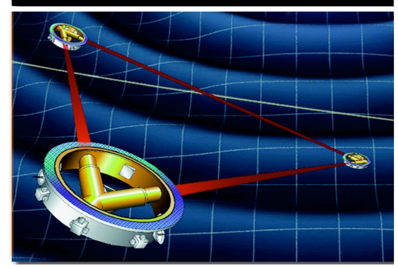
A Brief History of LISA

- 1974 – 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
- 2012 – ESA L1 downselect









Progress toward LISA

- **Technology**
  - LISA Pathfinder
  - Other technology: progress on many fronts
  - Now high-level of technical readiness, but awaiting LPF result
- **Science**
  - Enriched understanding of astrophysics of all sources
  - Advances in theoretical understanding waveforms
  - Demonstration of data analysis challenges in MLDC
  - Broader appreciation of overall science opportunity
- **LISA in 2010**
  - Equal NASA / ESA partnership
  - NASA subject to decadal survey review; ESA subject to Cosmic Visions L1 downselect
  - launch around ~2020

LISA Pathfinder

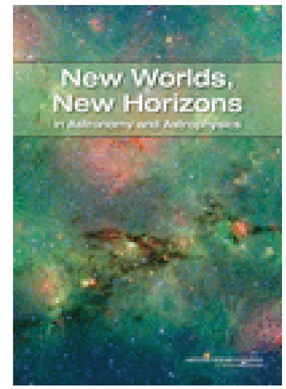
- To demonstrate critical LISA technologies in a space environment:
  - Gravitational Reference Sensing
  - Drag-free attitude control
  - Micro-Newton thrusters
  - Interferometry with free-falling mirrors
- Lead by European Space Agency (ESA)
  - mainly European payload: LISA Test Package
  - with smaller NASA contribution (ST7)
  - ~$700 million invested (my rough est.)

LPF transfer orbit thermal testing

- Status
  - much of LISA technology already demonstrated in development
  - Issue resolved with test mass launch lock
  - EU thruster issues: now selecting between cold-gas and FEEP thrusters
  - Integration going into "hibernation" until Dec 2013
  - Launch in 2014

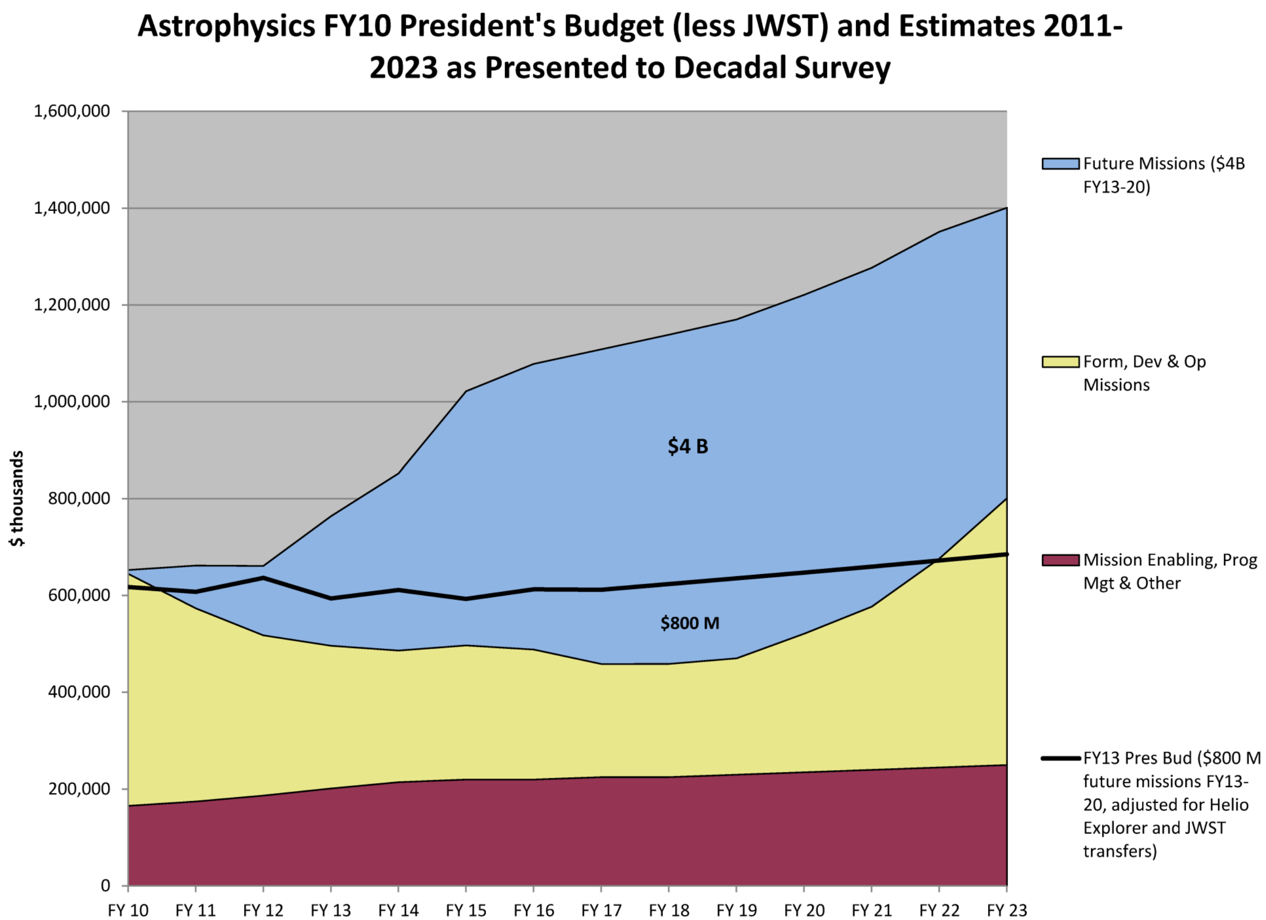
2010 Decadal Survey Results

- Recommended large space projects
  1. Wide Field IR Survey Telescope (WFIRST) ($1.6B)
  2. Explorer program augmentation ($400M)
  3. LISA [ESA partnership] ($1.4B for US)
  4. International X-ray Observatory (IXO) ($3.1B) [ESA partnership]
- A strong astrophysics community endorsement for LISA as a major mission!
- ... provides 2010-2020 roadmap for NASA (funds permitting)



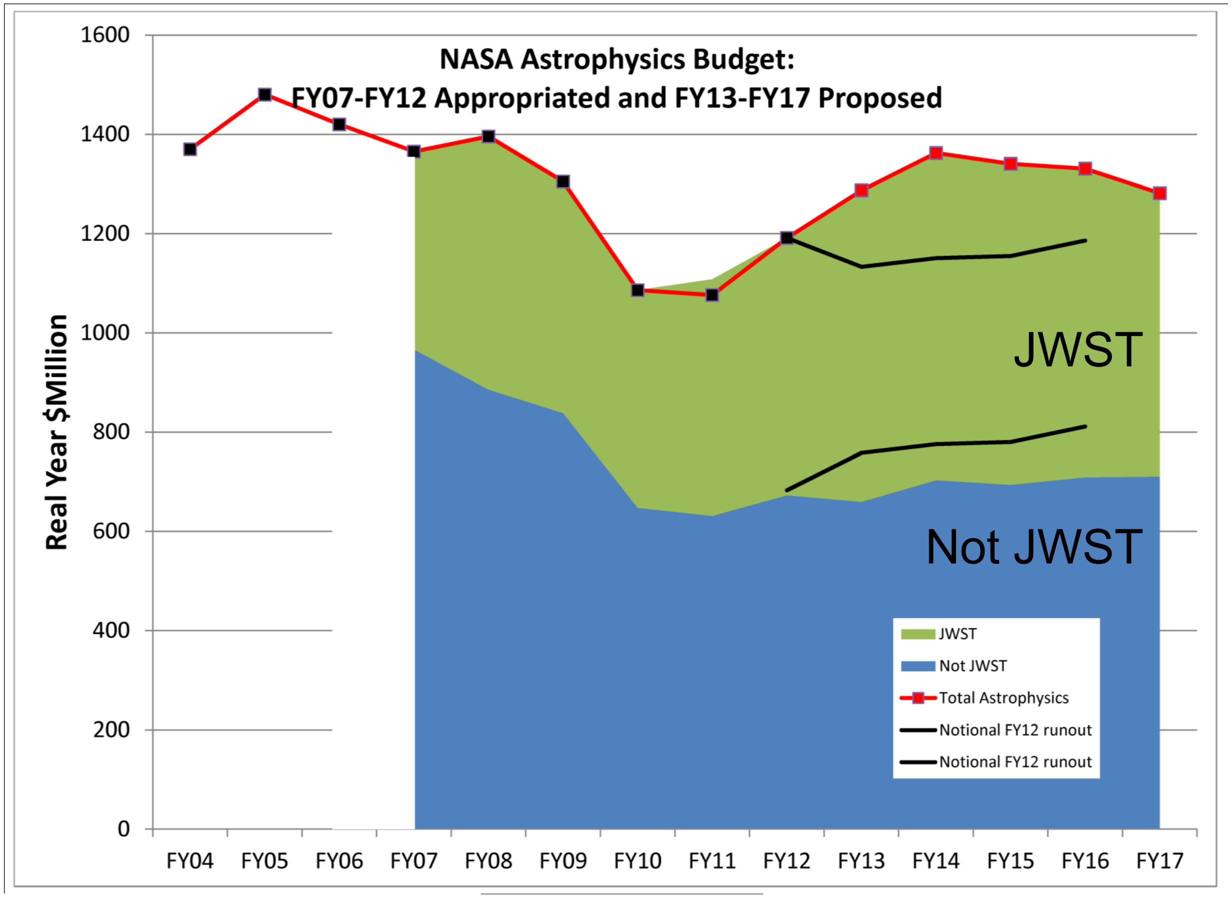
New Worlds, New Horizons in Astronomy and Astrophysics
Committee for a Decadal Survey of Astronomy and Astrophysics; National Research Council (2010)

er, about those funds...



Shown by Paul Hertz, Associate Administrator for NASA Science Mission Directorate (SMD), to Committee on Astronomy and Astrophysics, June 4 2012 (see http://sites.nationalacademies.org/BPA/BPA_048755)

past and future astrophysics funding



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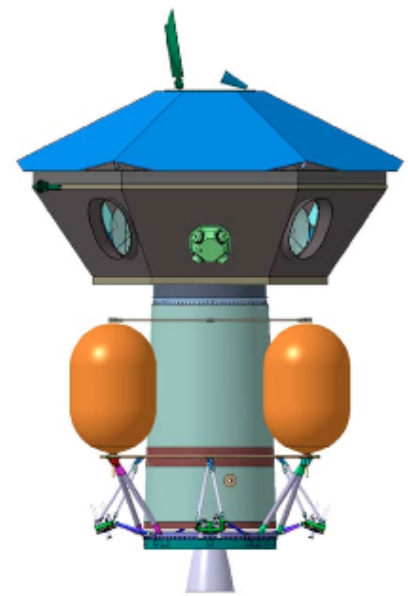
Not adjusted for inflation!

Big Question: What happens after JWST launch?

LISA 2011-2012: Europe

- Objective: Cosmic Visions L1 selection, spring 2012
  - Candidates: LISA, IXO, Jupiter probe
  - Became: "NGO", "Athena", "Juice"
- Constraints:
  - No critical contribution from NASA (March 2011)
  - 850M Euro cost cap for ESA
  - but often ~200M Euro member state contrib
  - Launch by 2022
- LISA->eLISA aka NGO
  - Highly developed concept: extensive science case and technical detail in the "Yellow Book" http://sci2.esa.int/cosmic-vision/NGO_YB.pdf



an NGO/eLISA spacecraft

LISA 2011-2012: designing eLISA

- Challenge: limit ESA costs
  - Payload to be provided by member states
  - Maximal reuse of LPF design
  - Launch savings
- Launch -> 2 Soyuz rockets
  - mass barely fits --> limited orbit options
  - --> smaller (1M km) arms
    and drift away orbits (innovation!)
- Payload reduction
  - smaller arms allow smaller telescopes
  - can only afford 2 arms (in mass and Euros)
- Lifetime reduction: 2 yrs of science

EMRIs with LISA and eLISA

- International science community eLISA study
  - Massive effort in April/May 2011
  - Continued until late fall “Yellow Book” completion
- EMRI detection rates (SNR 20)
  - LISA: 10–1000 per yr
  - eLISA: 1–100 per yr
  - factor of 10 sensitivity loss
- EMRI events
  - eLISA also has shortened lifetime
  - factor of ~30 loss in count
- eLISA would *probably* detect EMRIs

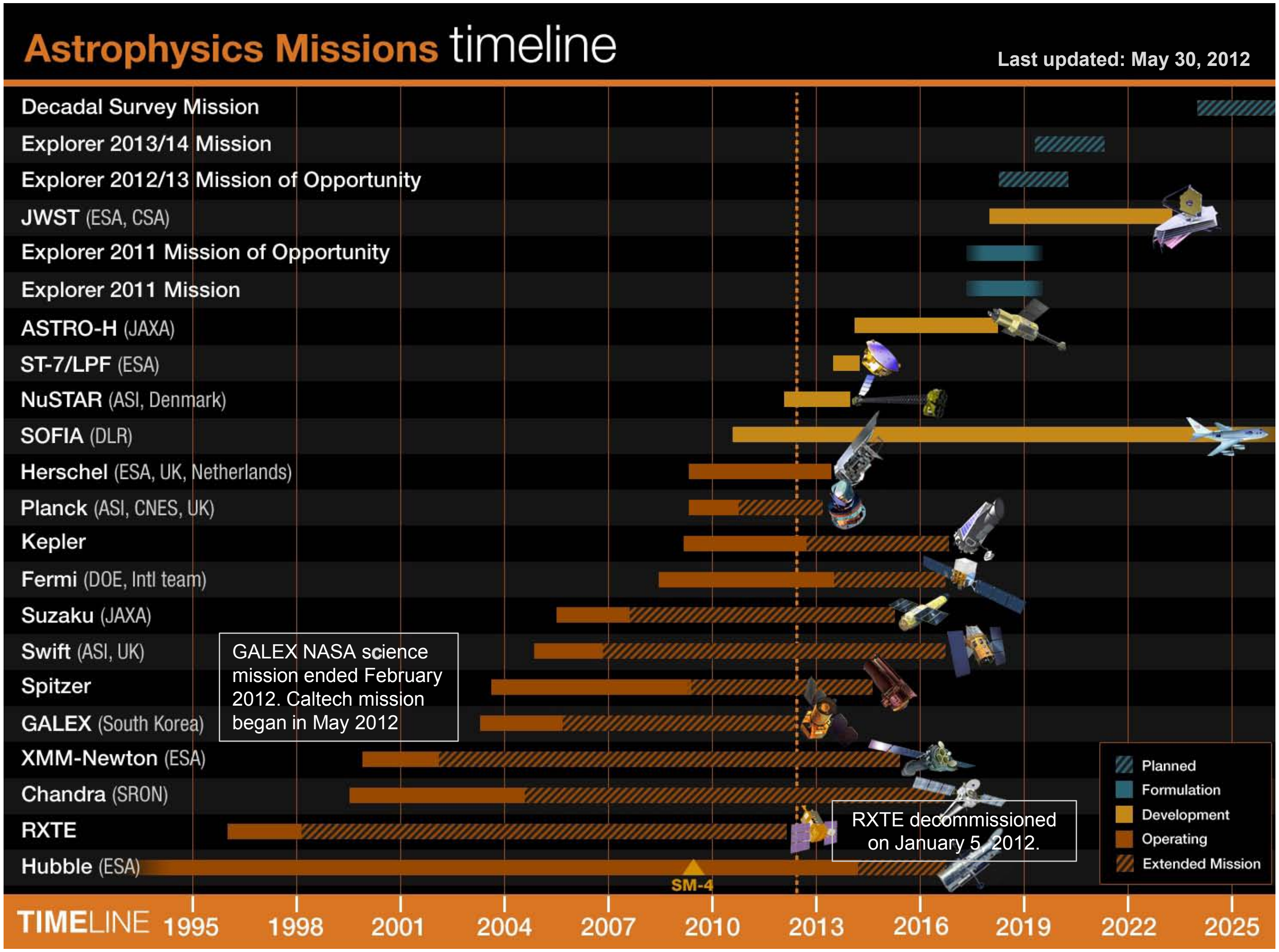
Cosmic Visions L1 downselect

- JUICE selected over NGO
  - concerns about NGO cost an schedule
  - NGO given top science ranking
  - and noted for European “strategic value”
- Europeans remain united behind NGO/eLISA concept
- Will coordinate through a European “eLISA Consortium”
  - **”As the eLISA mission, despite not being selected, was reported to have been unanimously ranked first by ESA´s scientific review committee in terms of scientific interest, strategic value for science and strategic value for the projects in Europe, the community is in good spirits: this is the first time that any space agency committee has ranked a gravitational wave observatory as its highest scientific priority.” (see: http://mpiz-koeln.mpg.de/7789)**
- Next opportunity may be Cosmic Visions “L2”
  - Call for concepts may come in 2014
  - Launch would nominally be expected around 2028
  - The program may be restructured for the next 2025+ decade.

LISA 2011–2012: US Study

- NASA Astrophysics expects insufficient funds for decadal science program
- EU proceeding alone
- LISA and x-ray mission demoted from “projects” to “studies” through the Physics of the Cosmos (PCOS) program
- NASA launches a 9-month study to explore cheaper ways to achieve some of decadal endorsed science

LISA 2011-2012: US Study Context



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LISA 2011-2012: Goals of the US Study

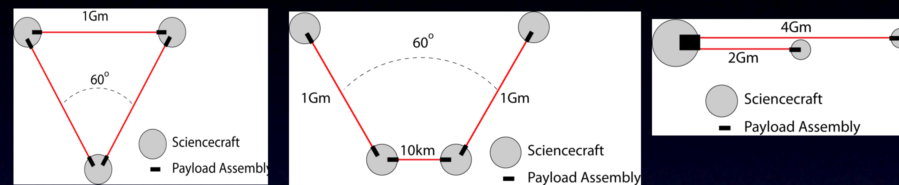
- Develop mission concepts that will accomplish some or all of the LISA science objectives at lower cost points.
- Explore how mission architecture choices impact science, cost and risk.
- Big Questions
  - Are there concepts at $300M, $600M or $1B?
  - What is the lowest cost GW mission?
  - Is there a game-changing technology that hasn't been adequately considered?

Elements of the Study

- Request for Information (RFI) – due Nov. 10th.
- Core Team – ~25 GSFC, JPL & university scientists and engineers critically reviewing RFI responses
- Science task force – ~15 volunteer scientists evaluating science performance of concepts
- Community Science Team (CST) – 10 scientists, Rai Weiss, Ned Wright co-chairs
- Public workshop – December 20-21st
- Concurrent engineering studies by JPL's Team-X in March and April
- Final Report to NASA Headquarters – July 6th
- Presentation to the Committee on Astronomy and Astrophysics (CAA) of the National Research Council (NRC)

RFI response concepts

- LISA-like(4)
- Geocentric(4)
- Non-drag-free(2)
- Other (2, incl AI)



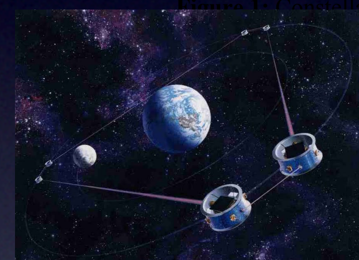
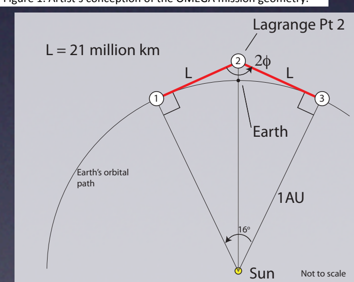
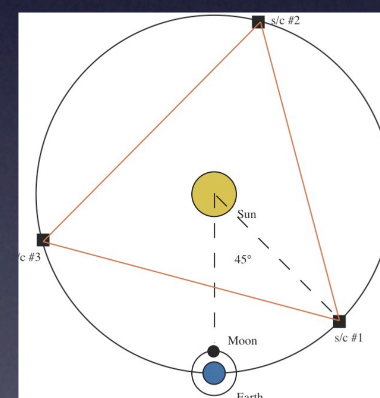
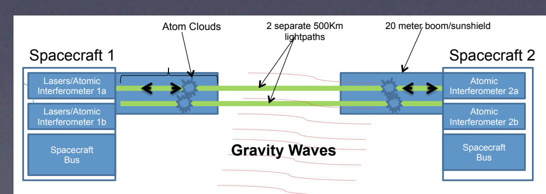


Figure 1. Artist's conception of the OMEGA mission geometry.







LISA-like Concepts

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}

No-Drag-Free Concepts

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}

Geocentric Concepts

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}

Other Concepts

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}

Architecture Choices – Mission Design

- Heliocentric – fixed, drift-away, in-line, L2/leading/trailing, 1 AU
- Geocentric – OMEGA, geosync, L3/L4/L5, LEO
- Compare delta-v, constellation stability, propellant, thermal, modulation of science signal, comm

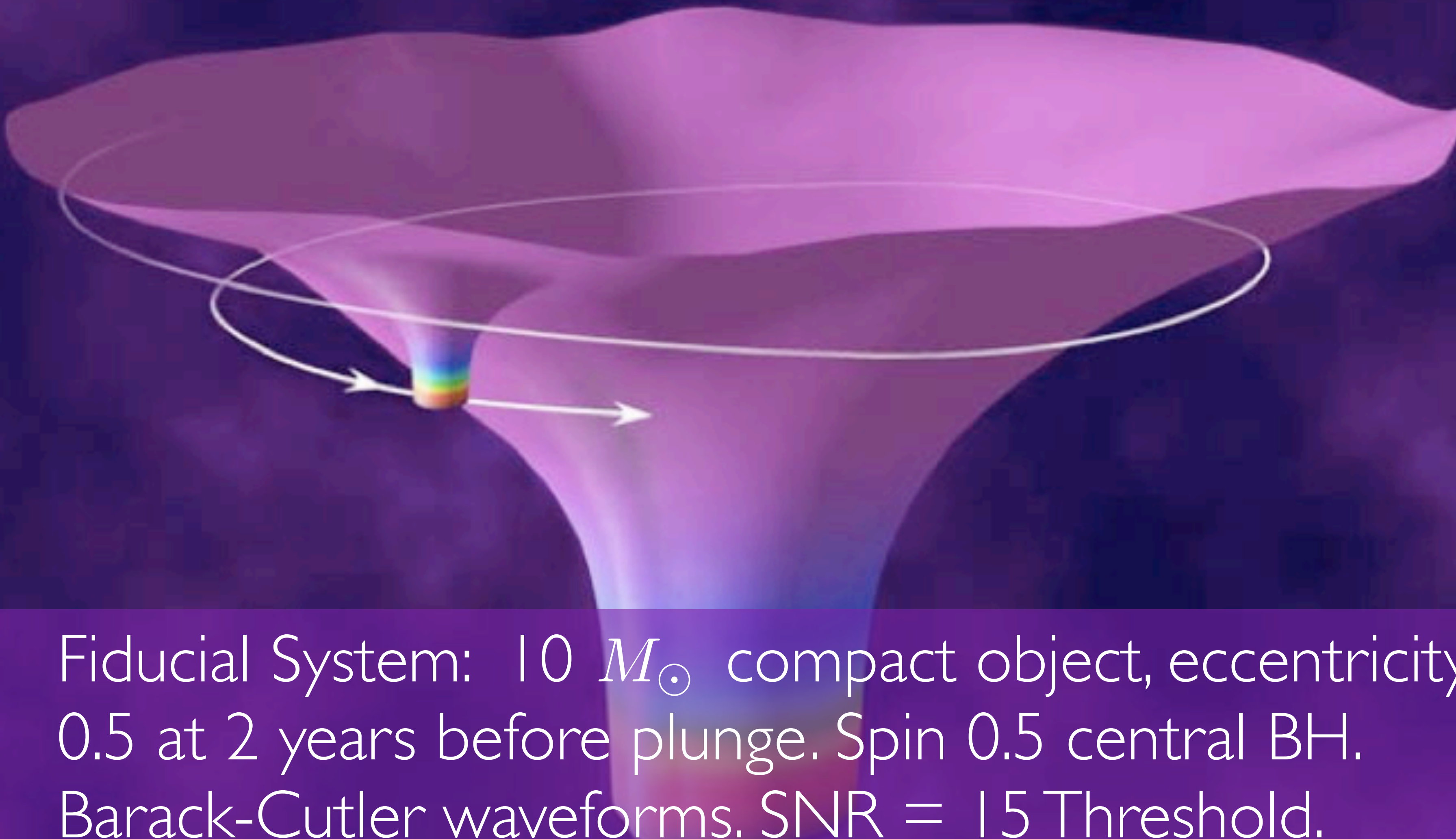
Architecture Choices – Inertial Reference

- Proof mass – cubical, parallelepiped or spherical free-falling, or torsion pendulum
- Spacecraft center-of-gravity (aka no-drag-free) with modeled corrections
- Atom interferometry – atoms as proof masses, atoms as secondary inertial reference
- Payload as separated spacecraft

Architecture Choices – Measurement Strategies

- Laser interferometry with laser heterodyne phase comparison – free-space or digital interferometry
- Laser interferometry with atom interferometer phase comparison
- Laser and clock frequency noise correction – 3 spacecraft & TDI, or very much better phase reference (AI)

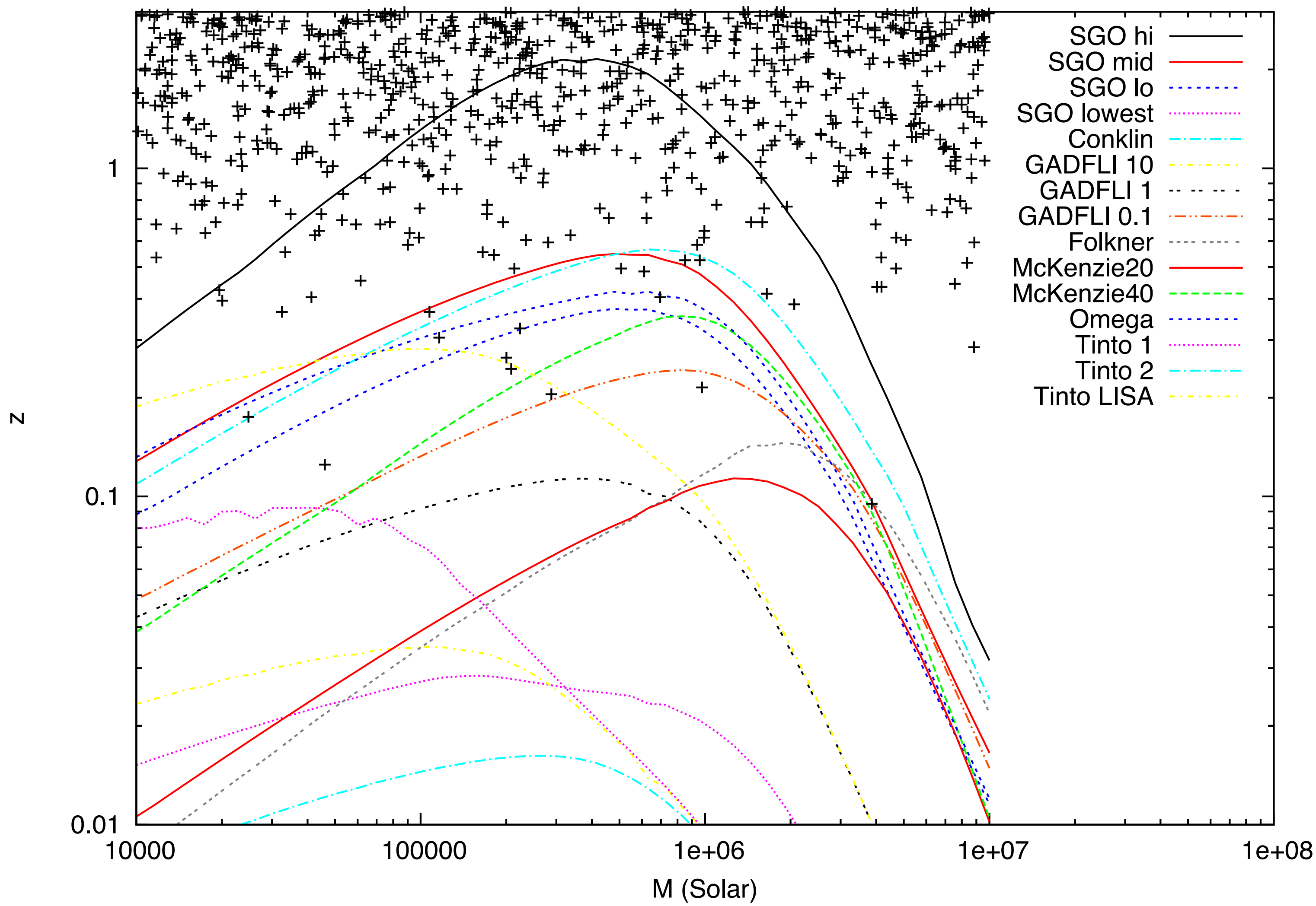
EMRI Horizons



Fiducial System: 10 $M_\odot$ compact object, eccentricity 0.5 at 2 years before plunge. Spin 0.5 central BH. Barack-Cutler waveforms. SNR = 15 Threshold.

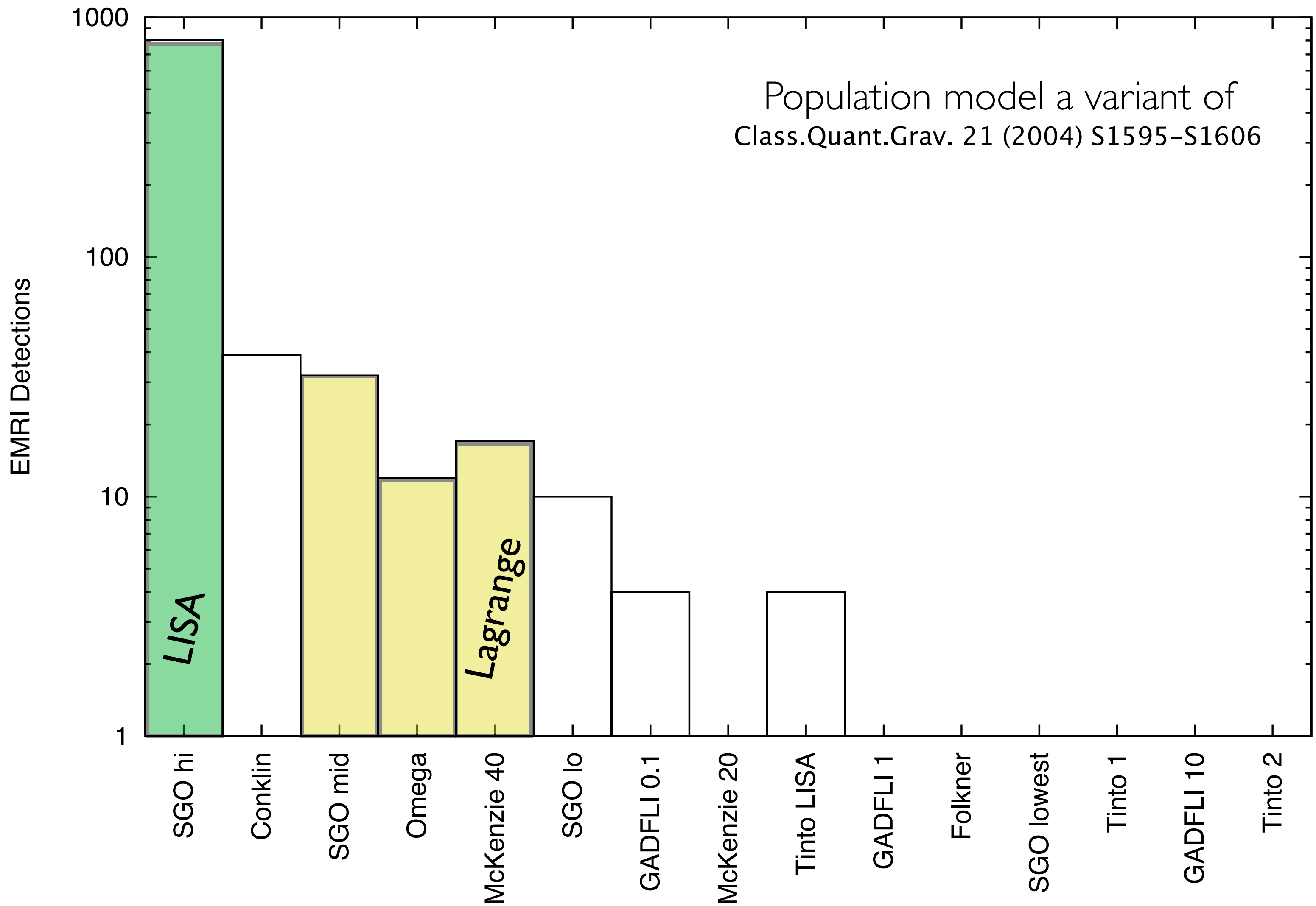
Preliminary:Neil Cornish, GW Mission CST

EMRI Horizons



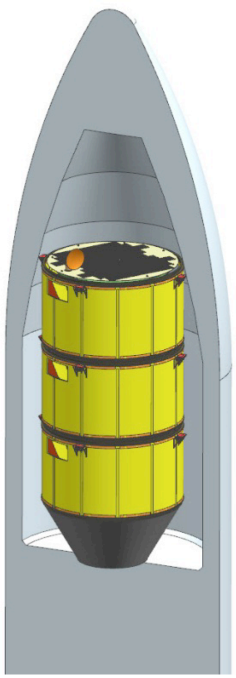
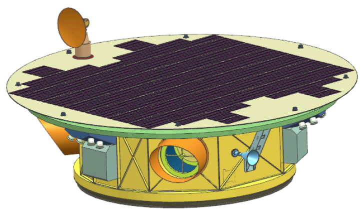
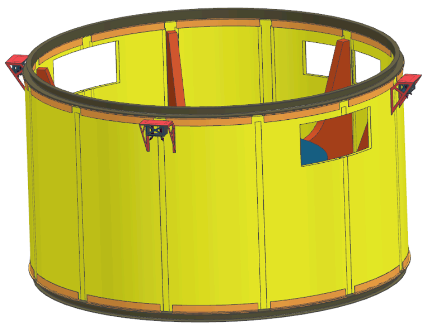
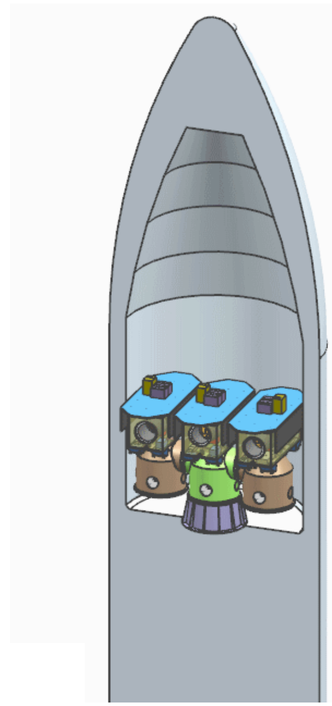
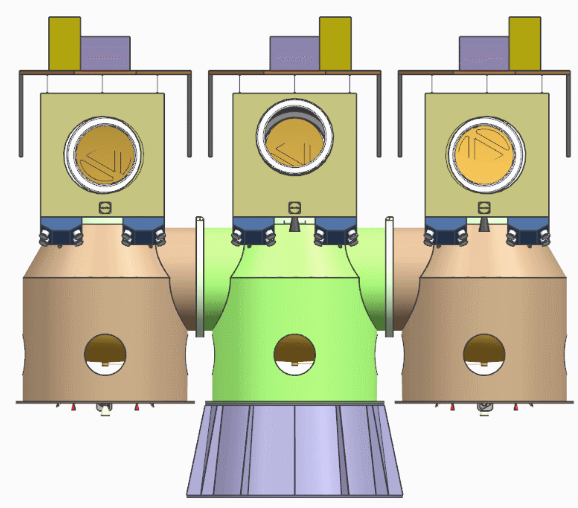
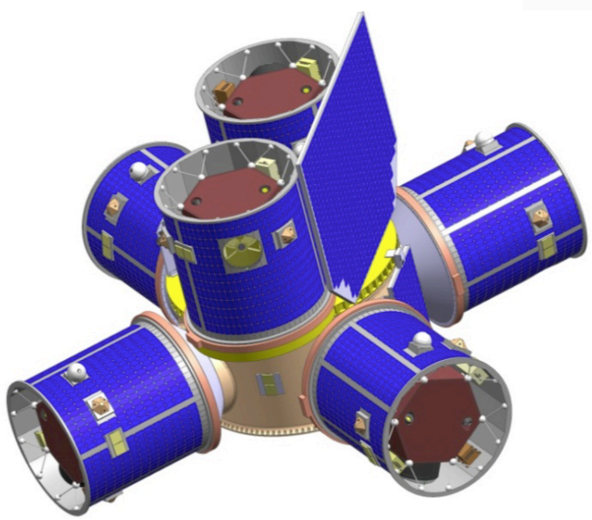
Preliminary:Neil Cornish, GW Mission CST

EMRI Detections



Preliminary:Neil Cornish, GW Mission CST

Implementation Strategies

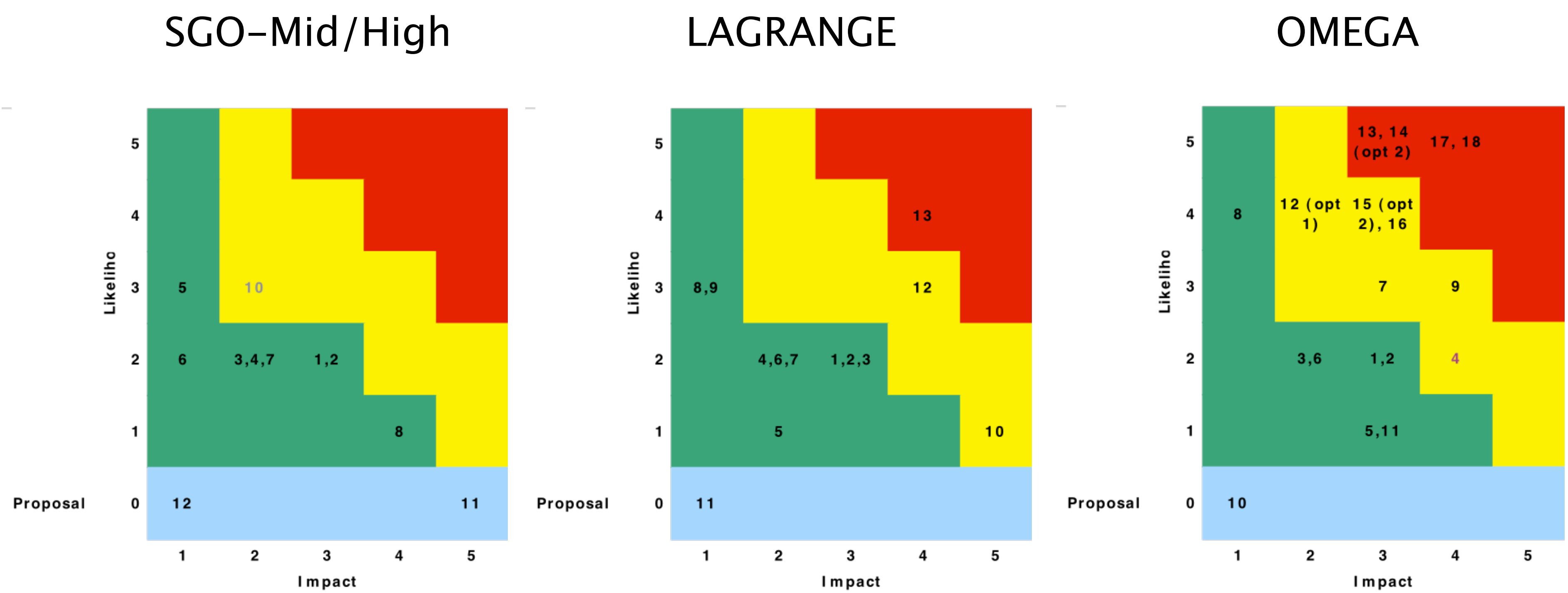

Implementation Strategies

Parameter	SGO Mid	LAGRANGE	OMEGA
Mass Margin	53%	53%	53%
Payload mass (kg), power (W) CBE	216.5 kg, 233 W	99.7 kg, 99.3 W	Option 1: 64.3 kg, 80W; Option 2: 55 kg, 54W
Mass rack-up			
Science-craft type 1	717 kg (3)	531 kg (2)	147 kg (6)
Science-craft type 2		586 kg (1)	
Propulsion Module type 1 +	661 + 139 (3)	224 + 174 (2)	374 + 465.5 (1)
Prop		591 + 114 (1)	
Propulsion module type 2 +	?	32 kg	28 kg
Prop	4553 kg	3182 kg	2347 kg
LV Adapter			
Launch Mass Wet			
Launch Vehicle	Atlas V 551; 6075 kg	Atlas V 511; 3285 kg	Falcon 9 Block 2; 2490 kg

Team X Costs

- Team-X is very conservative.
- Cost estimates range from $1.2B to 2.1B.
- Per science year costs
  - SGO-hi $450M/yr
  - SGO-mid/Lagrange ~$800-900/yr
  - Omega ~$1,300M/yr
- Important cost drivers
  - Payload and S/C development, launch vehicle, operations: all relevant (modest) cost levers
  - Non-recurring costs (NRE) and recurring costs (RE) are important.
  - Serial vs parallel construction of multiple units (~ $150M/yr)
  - The details matter

Risk



- These are a combination of Team-X and Core Team risks.
- Risk rises rapidly with modest (<10%) cost reductions.
- SGO-Mid considered "very low risk" by TeamX
- This assessment is not complete.

US Study: incomplete results

- The CST prefers SGO-Mid (3 arms, LISA-like, 1 Mkm, drift-away).
  - Represents a cost-science trade from LISA
  - Concepts with lower cost ests. incur new risk
- Big Questions
  - We found no concepts at $300M, $600M or $1B.
  - The lowest cost GW mission is ~$1.4B (±0.2).
  - We found no game-changing technology that hasn't been adequately considered.
- Heliocentric is a better choice than geocentric.
- No-drag-free achieves only modest savings while incurring substantial risk. [Cost model is uncertain.]
- Science:long-baseline and geocentric concepts have mitigating MBH+MBH parameter estimation effects

U.S. LISA outlook

- LISA science is still a high NASA priority
- Next major mission in Astrophysics starts after 2018.
- The Astrophysics Division anticipates that a "probe-class" mission could be started ~2017.
- The Division will not commit to a 'large' mission until after Astro2020. 'Commit' means the Confirmation Review at the end of Phase B.
- A partnership with ESA seems most likely. That would require:
  - Rebuilding a partnership
  - Reliably coordinating two agencies' programs
  - US investment in LISA science and technology would need to grow soon.

LISA 2011-2012: Japan

- (based on LISA Symposium talks)
- Japan is pursuing most/all areas of LISA technology
- Primary concept is DECIGO:
  - viewed as post-LISA (2030s?)
  - higher-freq deci-Hz band
- DECIGO Pathfinder:
  - LPF-like tests on a small satellite
  - Considered a strong candidate in coming small-mission call
- (unofficially) Japan could be interested in contributing to an international LISA-like mission

LISA 2011–2012: China

- (based on talks at Paris LISA Symposium)
- "Space Science and Technology in China: A Roadmap to 2050"
  - Chin. Acad. of Sci. document (2010)
  - Strategic Goal 1: includes...
    - directly detecting black holes
    - gravitational waves
- Nat'l Space Science Center (est 2011): Space Science Strategy Pioneer Project
  - incl series of space-projects leading to a future LISA-like mission
  - Step 1 2011–2015: ground studies
  - Step 2 2016–2020: pending, space technology?

LISA 2011-2012: China

- Gravitational wave mission studies
  - 2008-2010: Feasibility studies based on ALIA concept (Bender 2005). "cLISA"
  - 2010-2012: Preliminary engineering studies
  - 2011-2015: Program of experimental and theoretical studies in key areas of science and technology. Accepted as part of national program in 2011. Seems to have significant funds.
- GW detection group:
  - includes 8 universities, research centers, and aerospace co.
  - addressing a full range of topics related to LISA science and technology

LISA 2011-2012: China

- cLISA concept
  - viewed as a post-LISA (>2030?) concept
  - moderately improve over LISA sens on high-freq side and lower floor
  - emphasis includes IMRIs
  - appears promising for EMRIs too
- China looking for international partnerships

LISA Prospects

- Status
  - Great strides have been made in LISA technology and science
  - Over $1 billion probably invested already
  - Strong momentum in Europe
  - Growing worldwide investment/interest:EU,US,Japan,China,India?
- Coming events:
  - LISA Pathfinder results in 2015 should mitigate persisting concerns about technical novelty
  - Ground-based detections should ease concerns about conceptual novelty
- The future LISA
  - LISA: Now refers to the general class of LISA-like missions
  - Competition for (scarce!?!) funds in US and Europe
  - No mission likely to launch before 2025 (ie start before 2018)
  - We now understand a larger variety of LISA-like mission options
  - A Europe-led international collaboration seems promising for launch in late 2020s
  - Work must begin now to prepare a international joint concept for competition later this decade!
  - Next LISA Symposium: Florida 2014