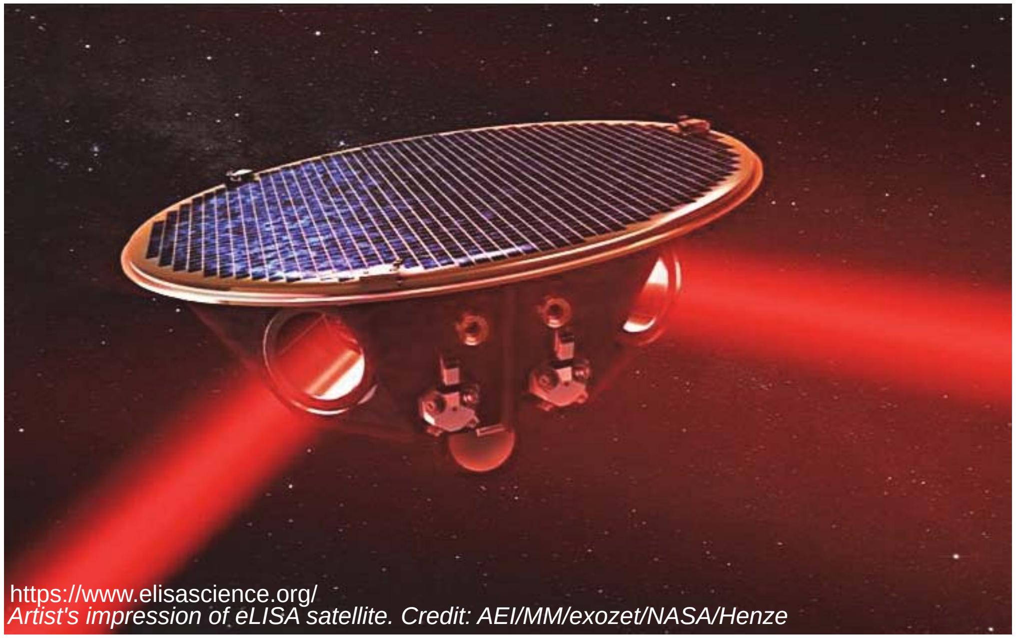
Space-based Gravitational-wave Observatories (SGOs)



Artist's impression of eLISA satellite. Credit: AEI/MM/exozet/NASA/Henze

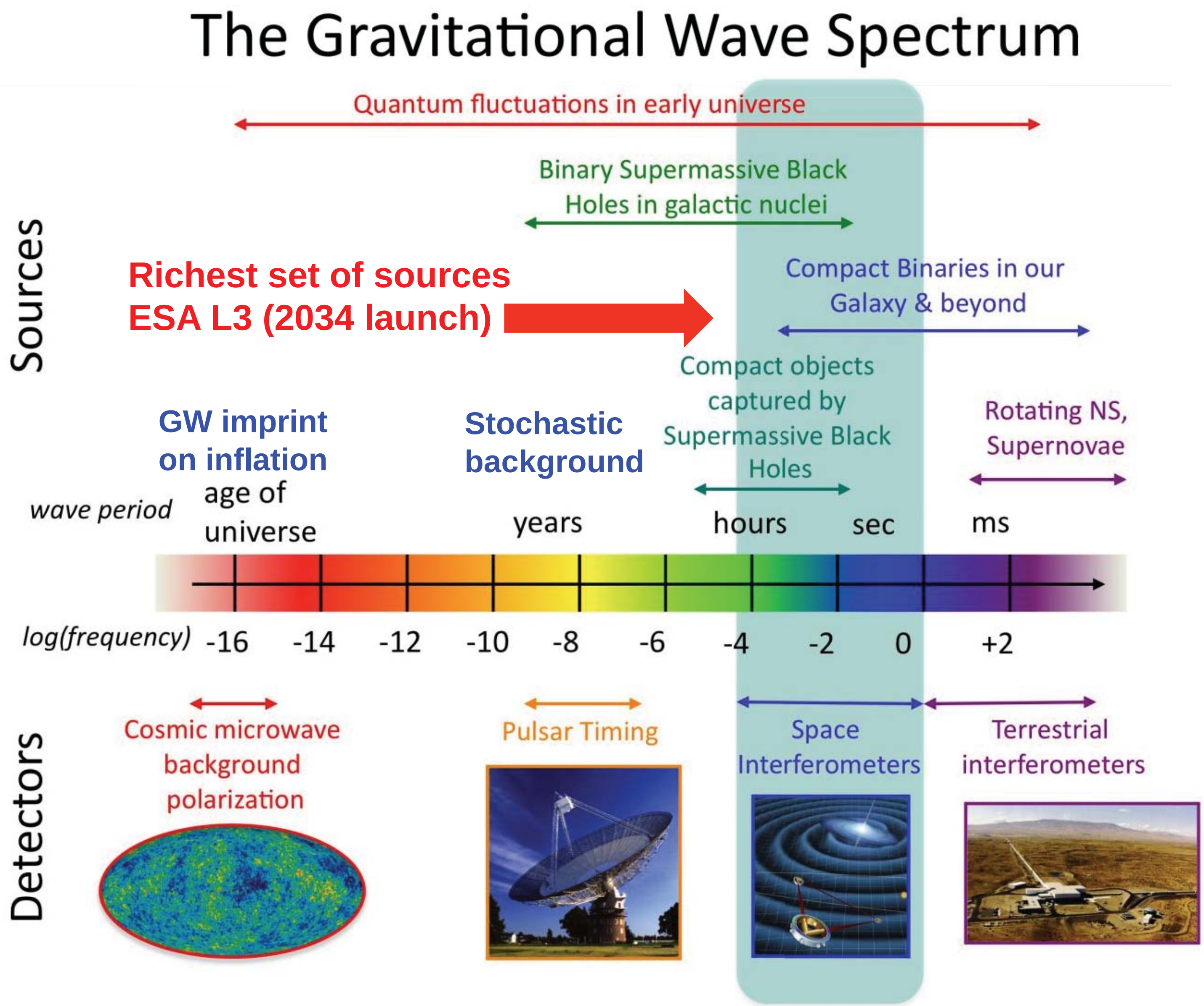
Presented by Jeff Livas
NASA Goddard Space Flight Center
Greenbelt, MD 20771

IEEE AVFOP Conference: Atlanta, GA 11 Nov 2014

Outline

- Why are SGOs important?
- Basic GW physics
- Science
- Mission description
- How it works – more detail
- Program status
- Summary

Why is this important?

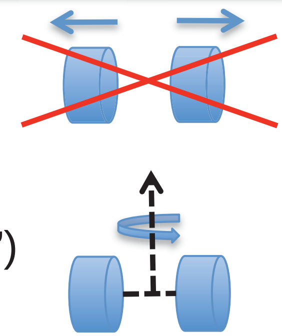


BICEP-2/Planck **Detection 2018-20?** **Detection 2017-18?**

Image credit: NASA

Measurement Challenge

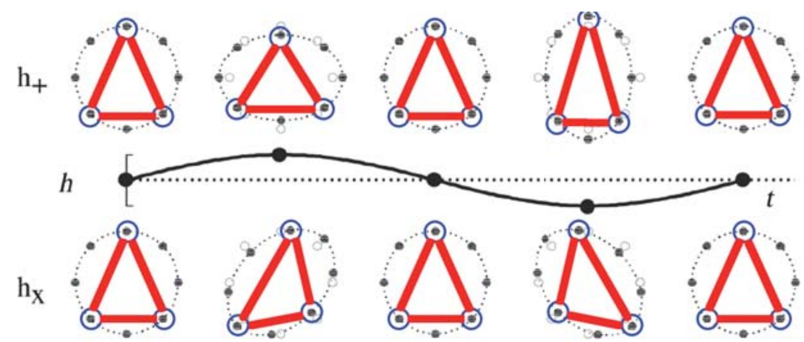
- **Lowest order radiator is a quadrupole**
  - Dipole radiation forbidden by conservation of momentum
  - Simplest quadrupole is a pair of masses rotating around their common center of mass (a "dumbell")
- **What is to be measured**
  - Time-varying strain ($\Delta L/L$) in spacetime typically ~10^{-21} /√Hz = 10 pm/10 Gm/√Hz
  - Variations are periodic or quasi-periodic between 10^{-4} and 1 Hz, observable for months to centuries
- **Measurement concept**
  - Measure distance changes between free-falling mirrors
    - o Test masses are the mirrors
    - o Interferometric measurement of distance changes
  - Preferred measurement conditions
    - o A long measurement path to make ΔL large
    - o A very quiet place to avoid disturbances to the test masses: SPACE!

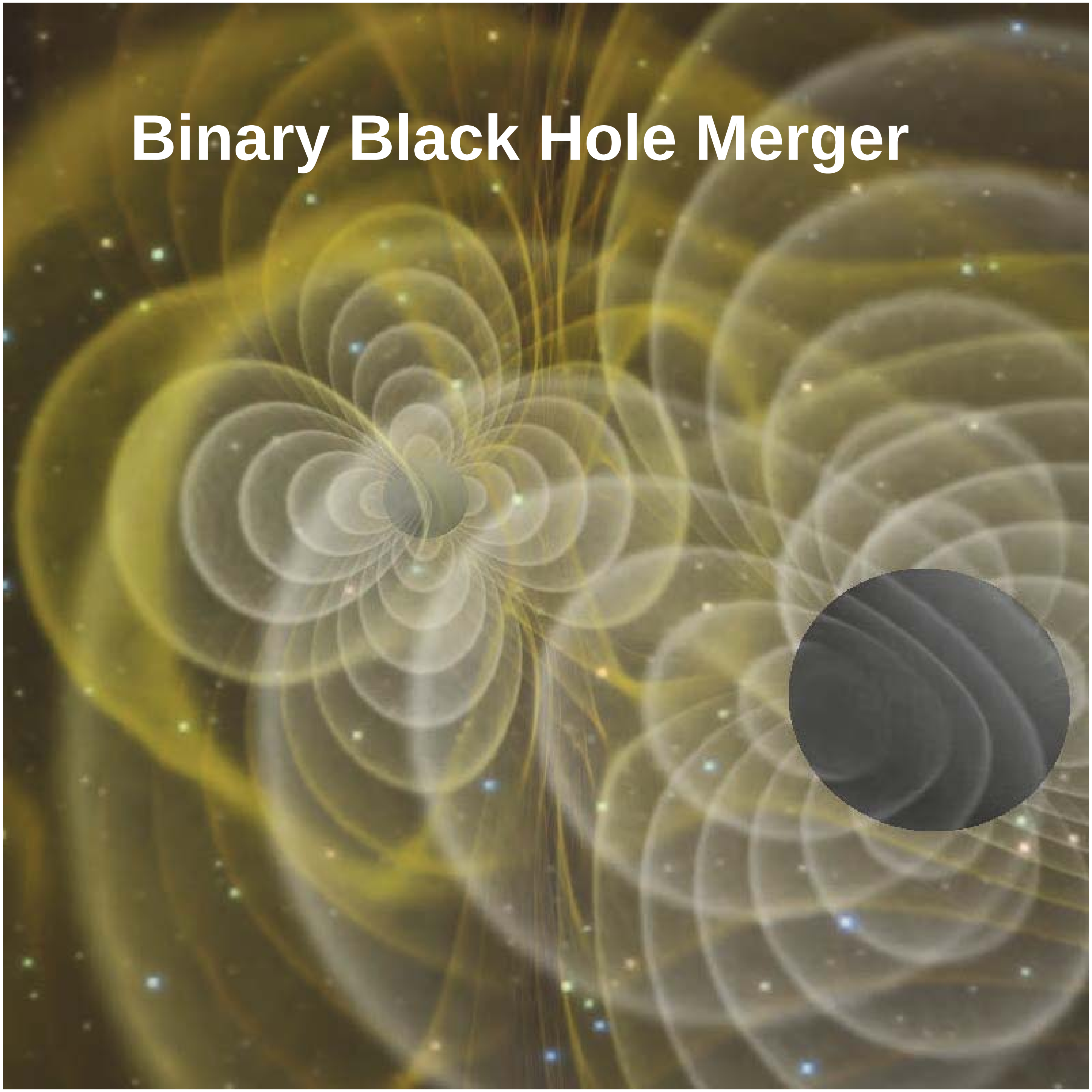


h_+ Polarization

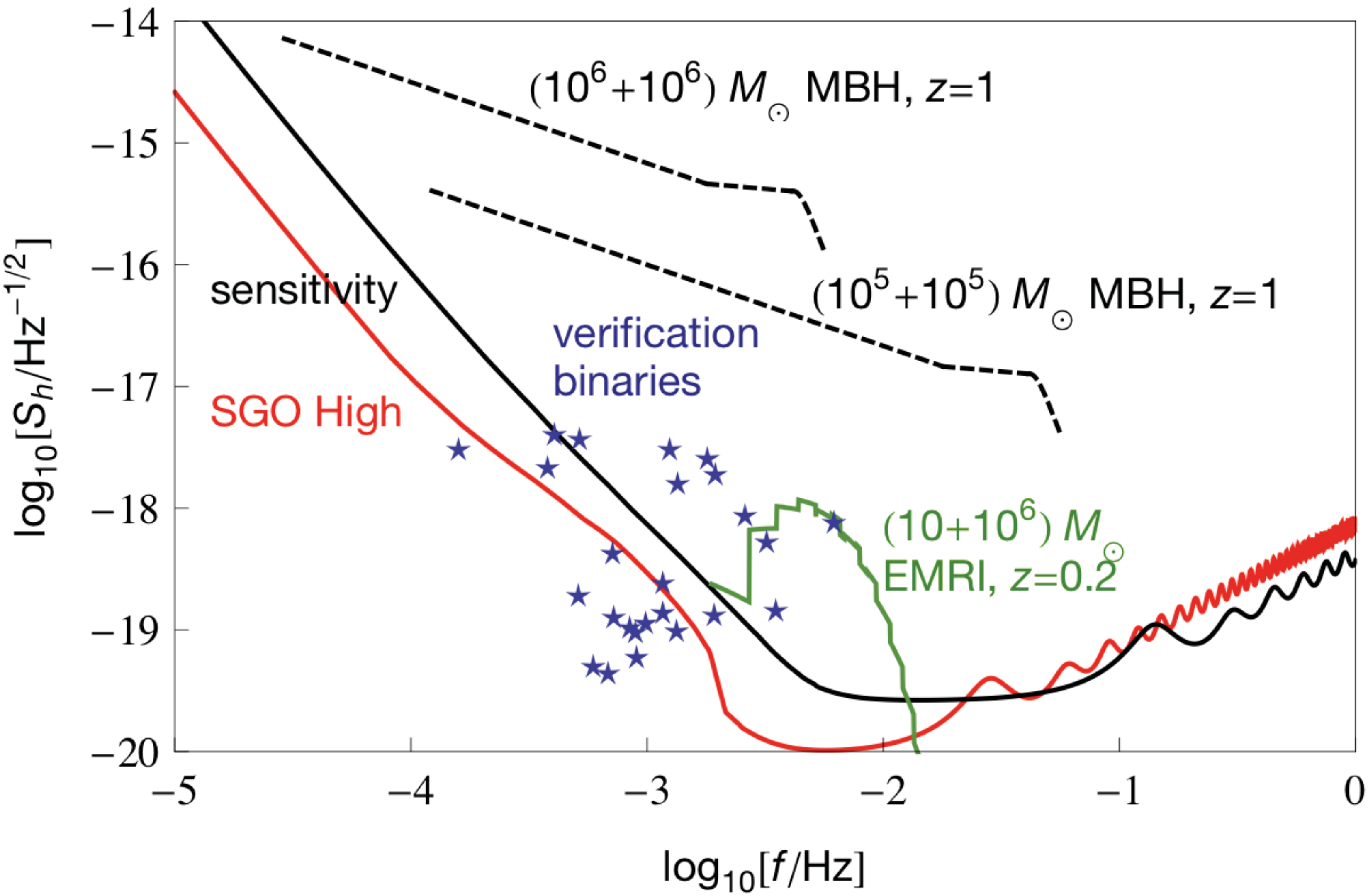
h_x Polarization

Constellation Response




Binary Black Hole Merger

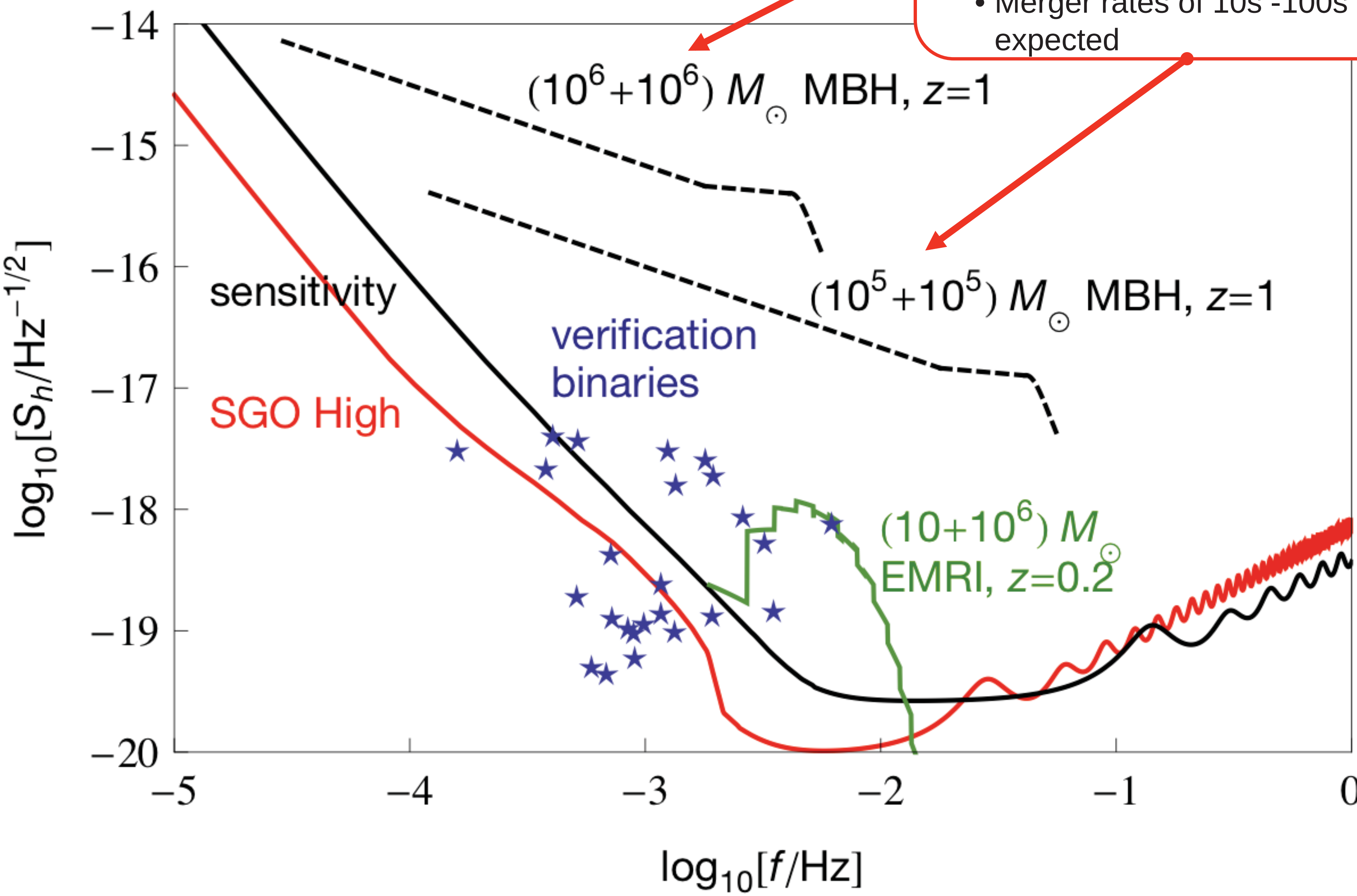
Science Overview



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



Science Overview

Supermassive Black Hole Mergers
- Formation and growth of massive black holes: galaxy mergers
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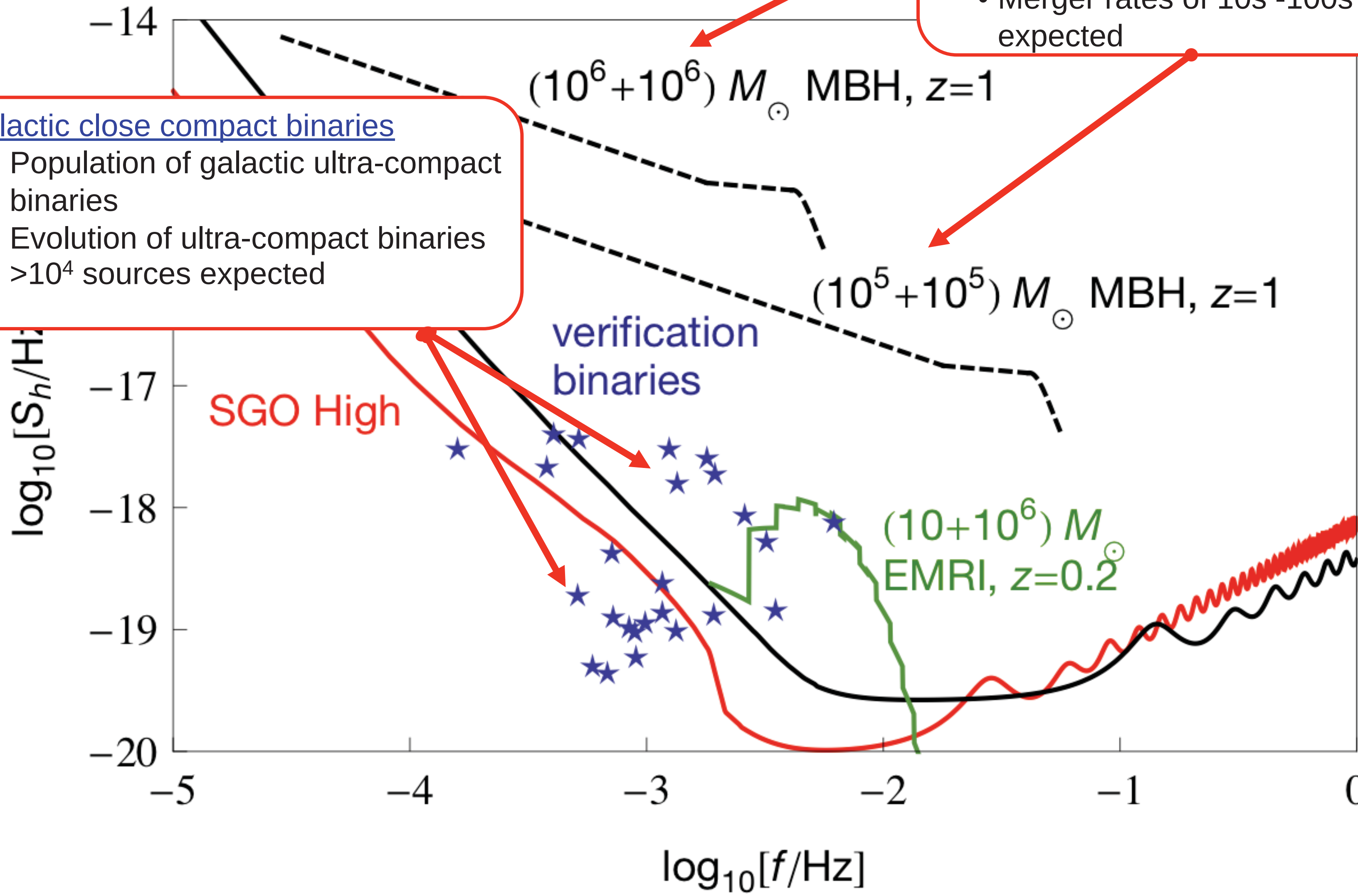
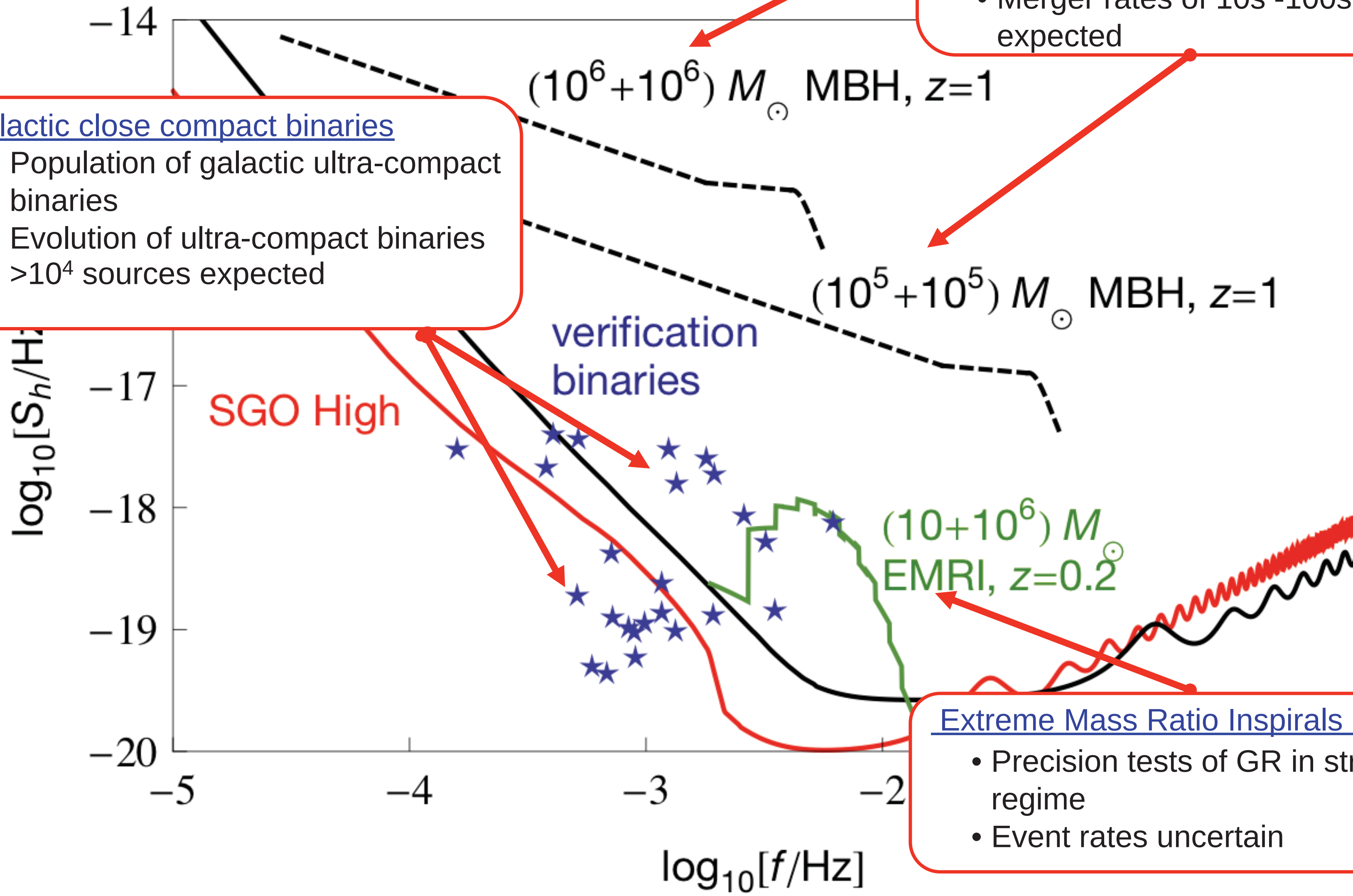
Galactic close compact binaries
- Population of galactic ultra-compact binaries
- Evolution of ultra-compact binaries
- >10^4 sources expected



Science Overview



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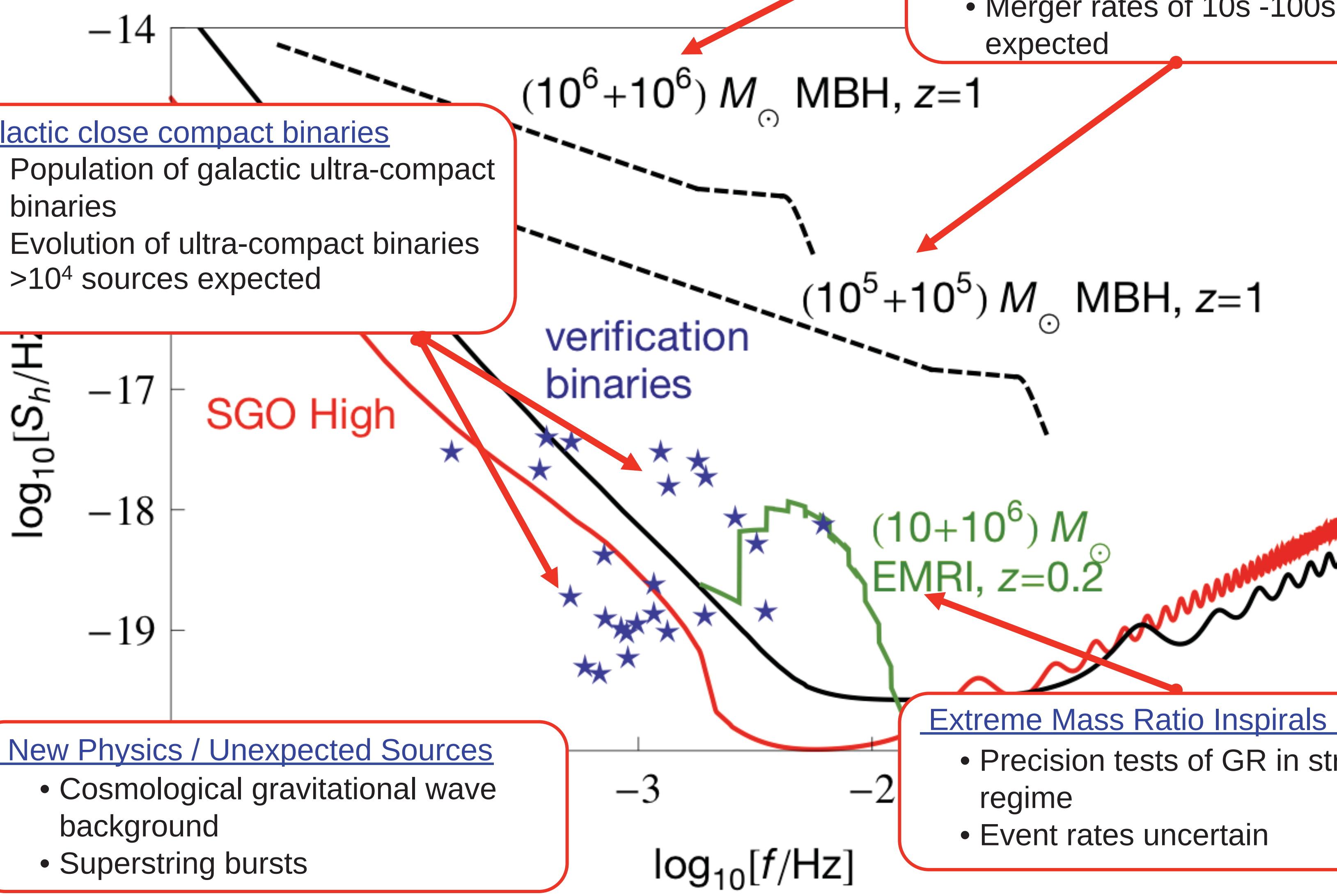
Extreme Mass Ratio Inspirals (EMRIs)
- Precision tests of GR in strong-field regime
- Event rates uncertain

Science Overview



Supermassive Black Hole Mergers
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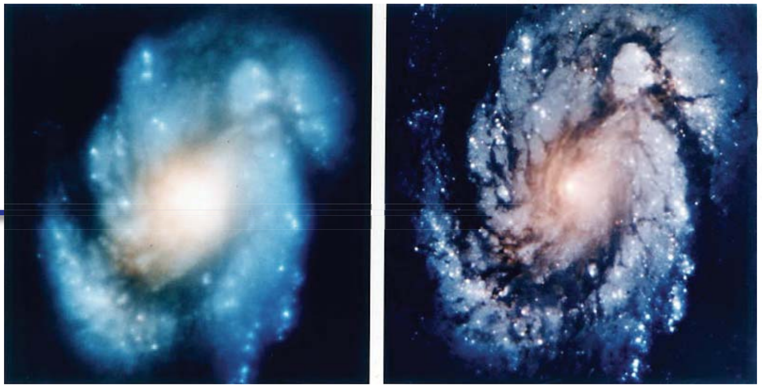
New Physics / Unexpected Sources
- Cosmological gravitational wave background
- Superstring bursts

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

Not just detection…

- Detection already happened (direct + indirect…)
- Study growth of cosmic structure
- Test of GR in strong field limit
- Precise parameter estimation, including distances



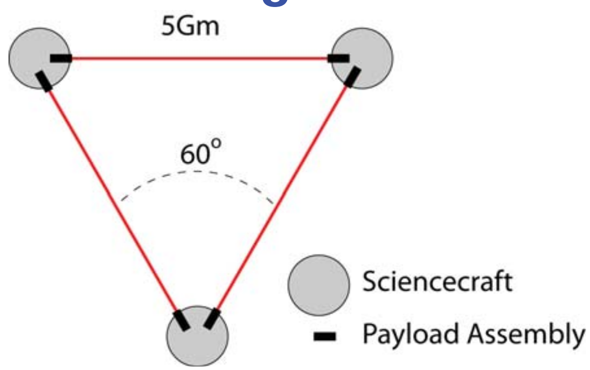
Quality vs Quantity

Number of Sources Observed	Classic LISA	SGO-Mid
Massive Black Hole Mergers	108-230	41-52
Detected @ Z>10	3-57	1-4
Both mass errors < 1%	67-171	18-42
One spine error < 1%	49-130	11-27
Both spin errors < 1%	1-17	<1
Distance error < 3%	81-108	12-22
Sky location < 1 deg^2	71-112	14-21
Sky location < 0.1 deg^2	22-51	4-8
Extreme-Mass-Ratio-Inspirals	800	35
Resolved Ultra Compact Binaries	40,000	7,000
Interacting UCB's	1,300	100
Detached UCB's	40,000	8,000
Sky location < 1 deg^2	13,000	2,000
Sky loc < 0.1 deg^2 + distance error < 10%	8,000	800
Stochasitc Bkgnd relative to LISA	1.00	0.20

Table courtesy Robin T. Stebbins
With assistance from R. Lang, N. Cornish, and S. Larson

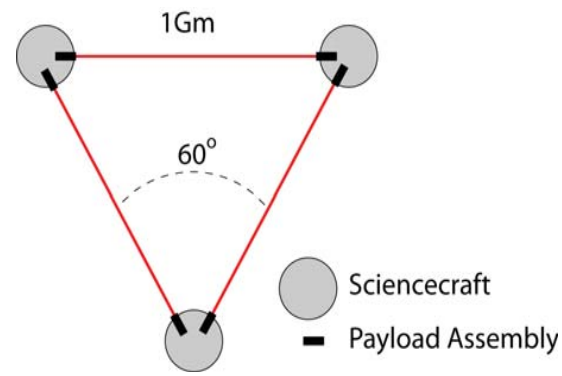
SGO Mission Concepts

SGO High



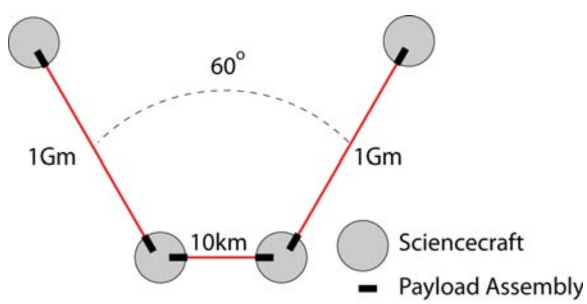
LISA concept with single-agency costing and all know cost reductions.

SGO Mid



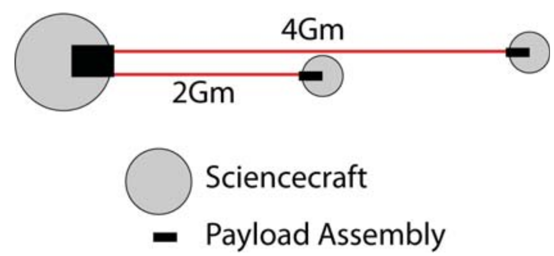
Minimum-cost three arm design with acceptable Decadal-survey science return.

SGO Low



Two-arm version of SGO Mid

SGO Lowest

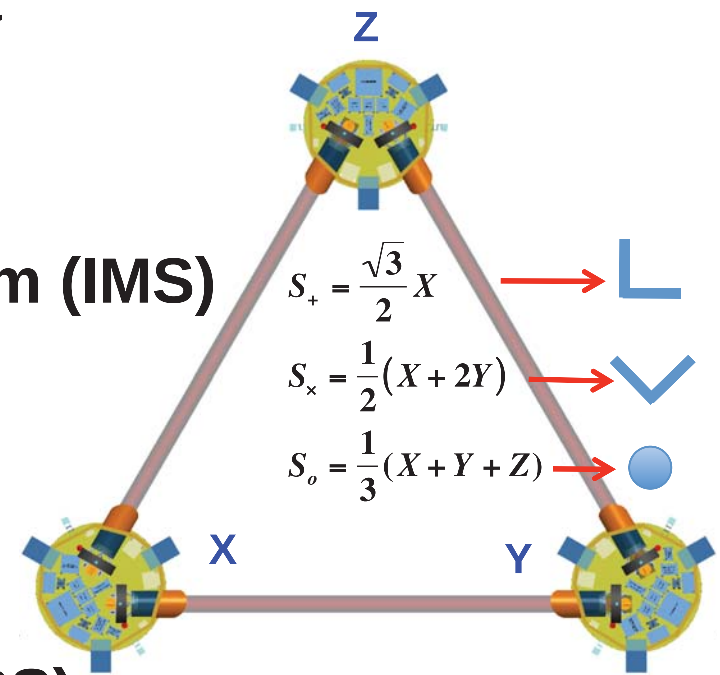


Minimum two-arm mission

Study final report is available here:
http://pcos.gsfc.nasa.gov/studies/gravitational-wave-mission.php

How the science instrumentation works

- **The Constellation is the instrument**
  - Orbits passively maintain formation
  - “Sciencecraft” house test masses and interferometry
- **Interferometer Measurement System (IMS)**
  - Active transponder, phase-locked laser ranging system
  - Phasemeter records fringe signal
  - Laser frequency noise correction by pre-stabilization and post processing

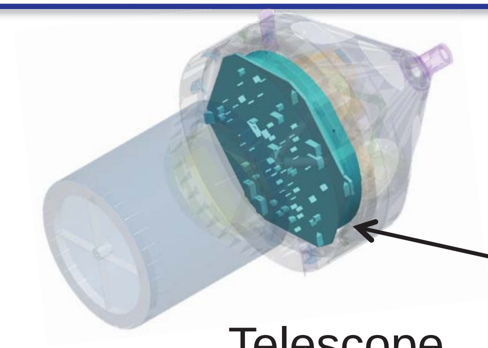


- **Disturbance Reduction System (DRS)**
  - Free-falling test masses don’t contact the sciencecraft
  - Drag-free stationkeeping reduces sciencecraft test mass relative motion and force gradients
  - Design to limit thermal, magnetic, electrostatic, mechanical, self-gravity disturbances

Payload Integrated with Bus

Payload systems

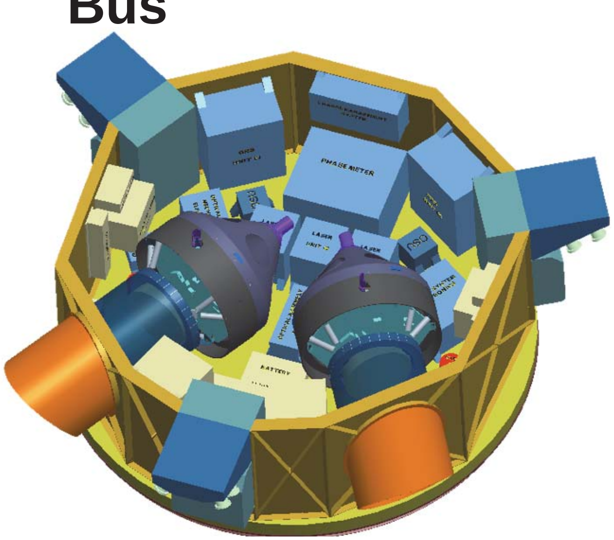
- **Interferometer Measurement System (IMS)**
  - **Laser**
  - **Telescope**
  - **Optical bench**
- **Disturbance Reduction System (DRS)**
  - **Gravitational Reference Sensor (GRS)**
  - **μN thrusters**
  - **Control laws**



Optical bench mounted in Telescope Assembly

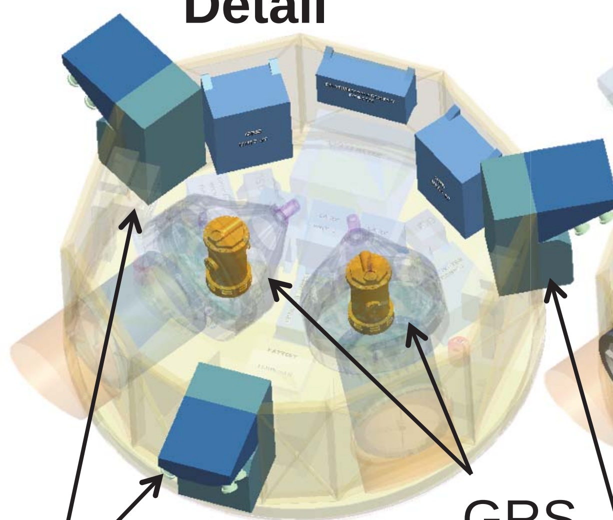
Telescope Assembly

Full Spacecraft Bus



(Note: solar array not shown)

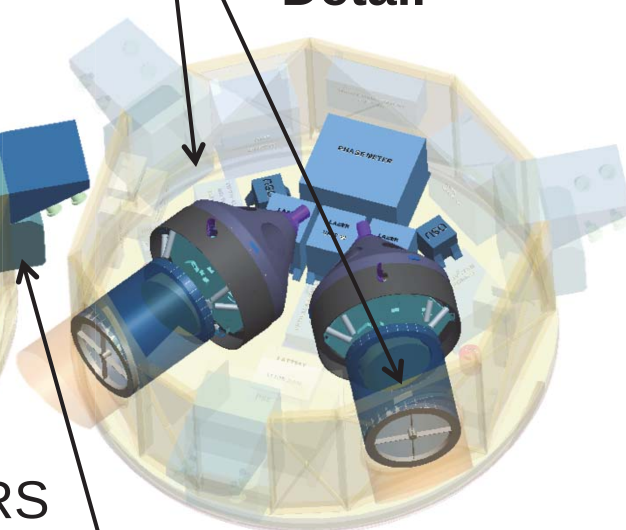
DRS Detail



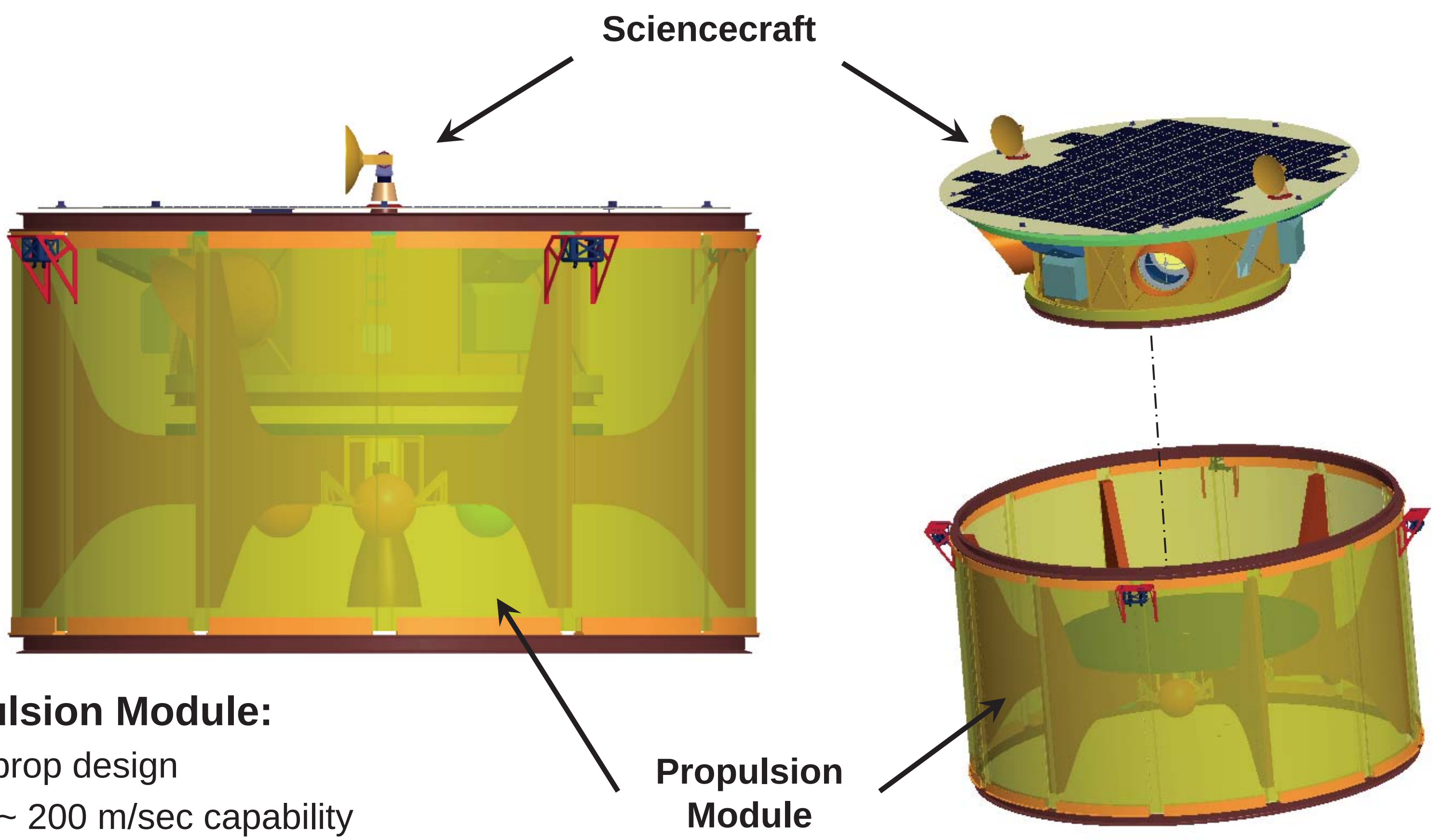
GRS

colloidal μN thrusters

IMS Detail



Prop Module/Cruise Configuration



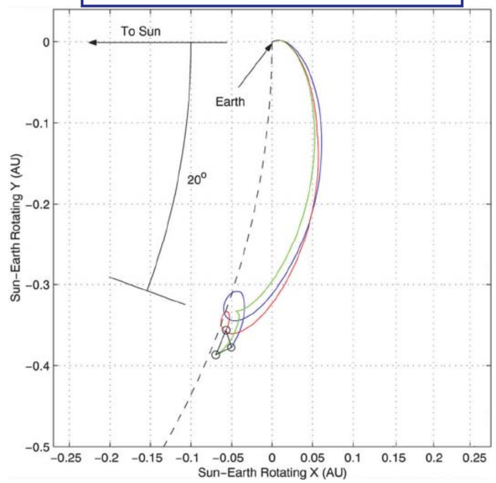
Propulsion Module:

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

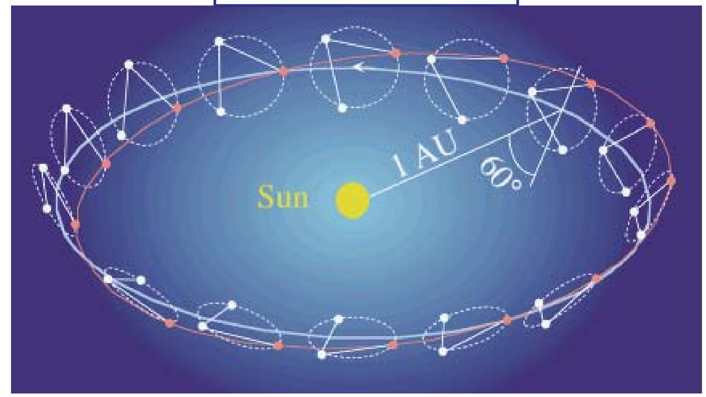
Mission Timeline

Falcon Heavy EELV

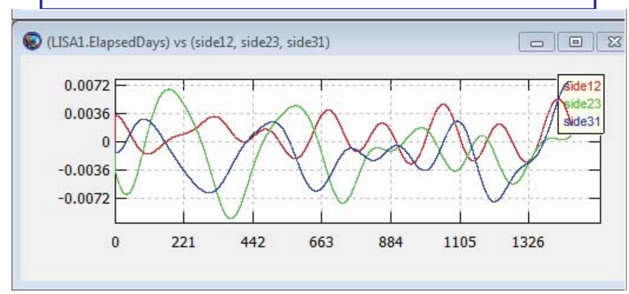
Cruise Trajectories

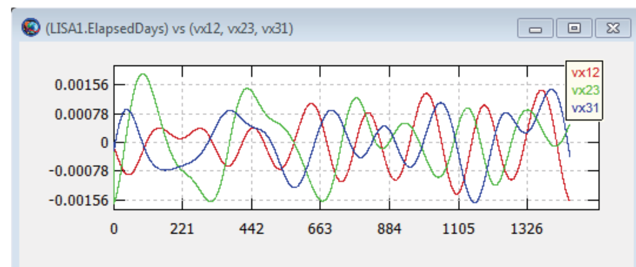


Science Orbits

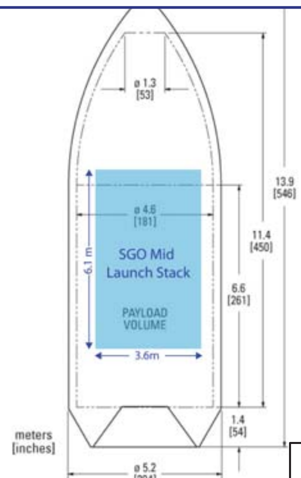


Doppler/Arm length changes

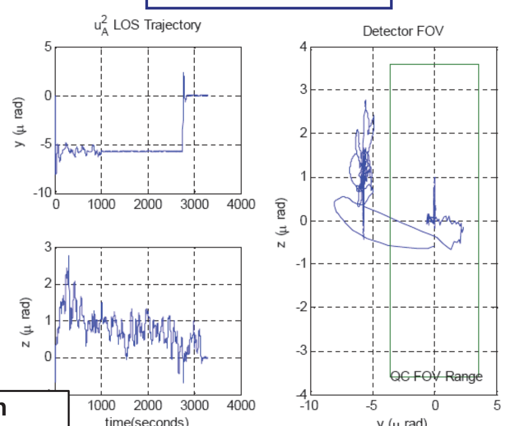




Stack in Falcon 5 m PLF

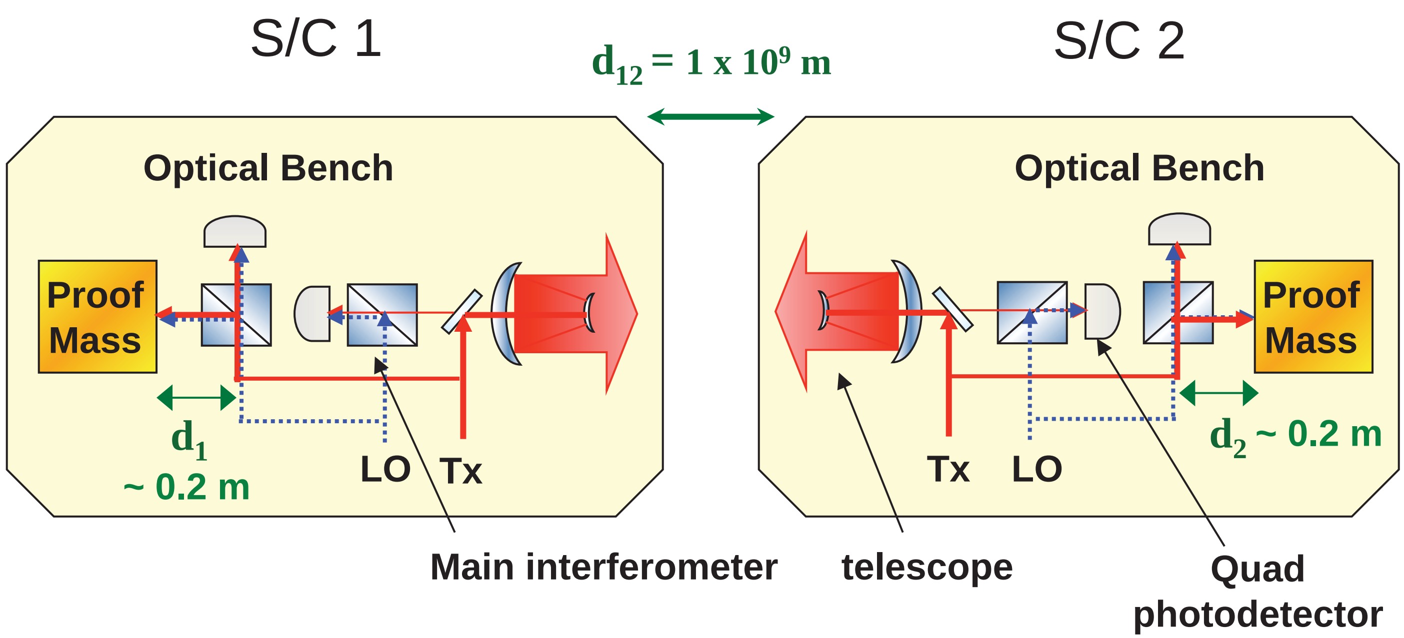


Acquisition



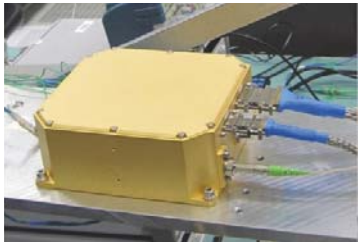
Inter-Spacecraft Distance Measurement

- Test-mass to test-mass measured in 3 parts:
  - 2 × test-mass to spacecraft measurements (short-arm: LPF tests this)
  - 1 × spacecraft to spacecraft interferometer (long-arm)

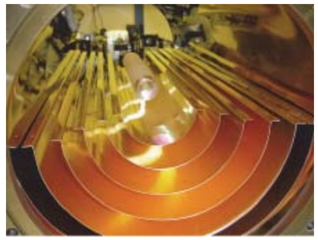


Interferometry Measurement System

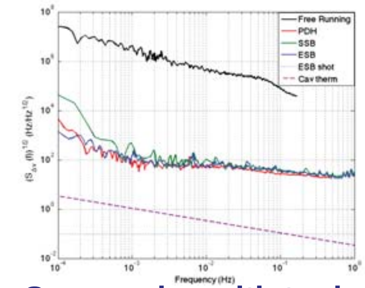
LASER



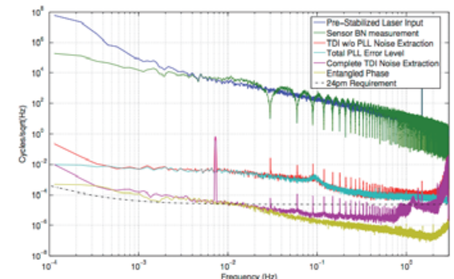
Seed laser with LPF heritage



Cavity pre-stabilization

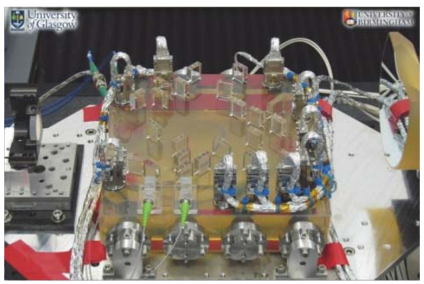


Same noise with tuning
US Patent 7,970,025



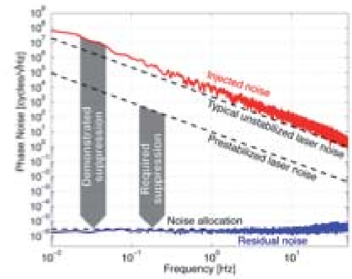
TDI demonstrated with realistic delays using electronic signals

OPTICAL BENCH

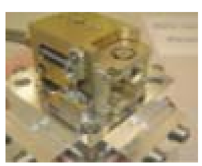


Optical bench with LPF heritage

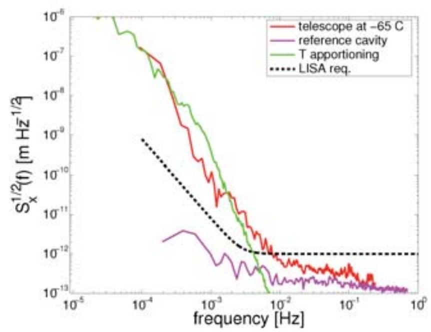
Low noise quad detector
US Patent 8,598,673 B2



LISA Phasemeter development meets multiple requirements

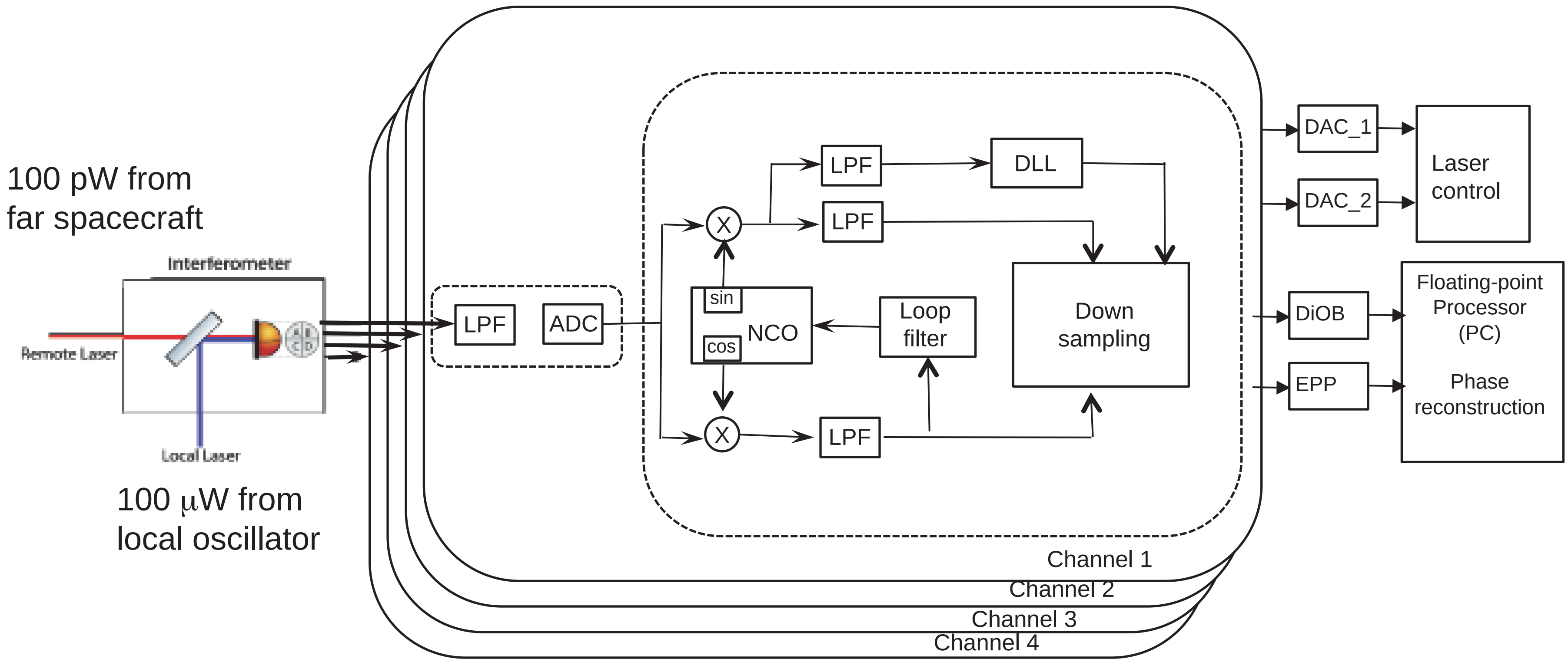


Pointing mechanisms tested



Prototype telescope spacer demonstrates dimensional stability and for studying scattered/stray light

Front-end Phasemeter Architecture

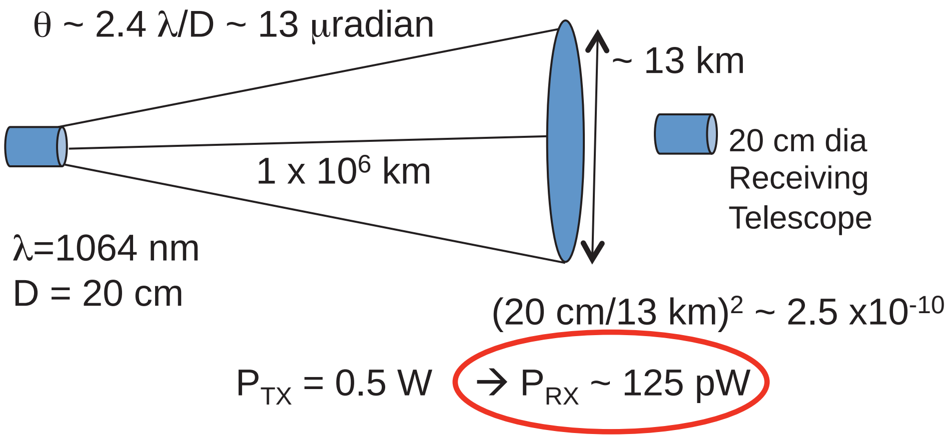


- Low noise quad photodiode* serves two functions
  - Differential wavefront sensing of quadrant pairs determines S/C pointing
  - Sum is main science signal

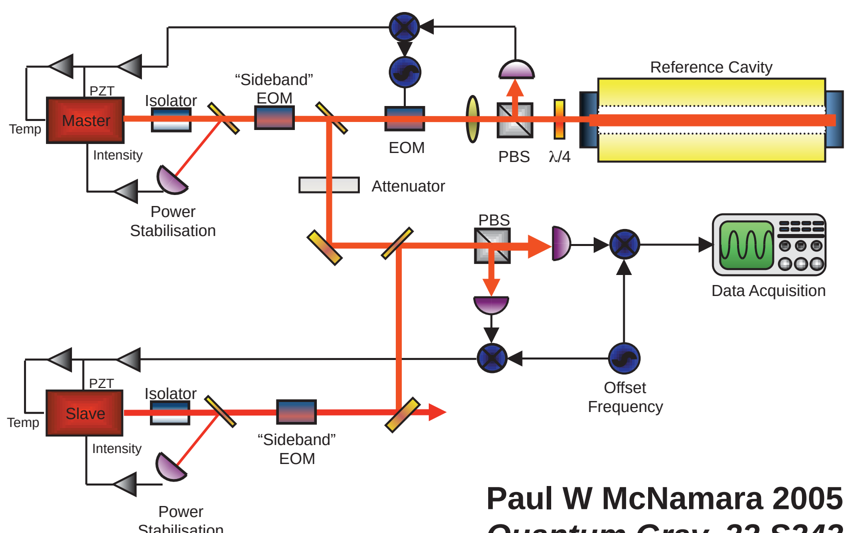
*Joshi, A. et al. Proc. SPIE 8453, 84532G (25 Sep 2012);
doi: 10.1117/12.918285

Weak Light Phase Locking

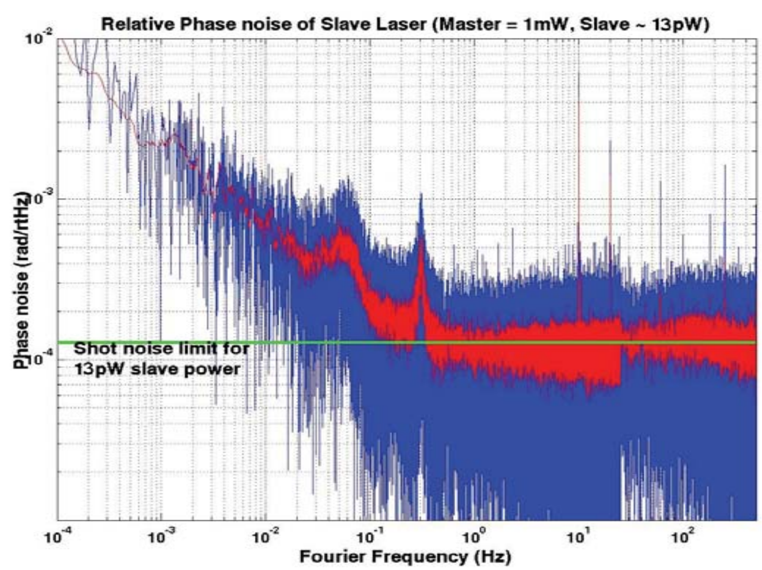
SGO received power budget:



- **Phase lock Successful at lower power than requirements**
  - **Master Oscillator = 1 mW vs 3-10 mW**
  - **Slave laser power = 13pW vs ~ 100 pW**
  - **Laser power step attenuated– not variable**
- **Shot noise limit for 13pW = 1.3x10^{-4} rad/√Hz**



Paul W McNamara 2005 *Class. Quantum Grav. 22 S243-S247*

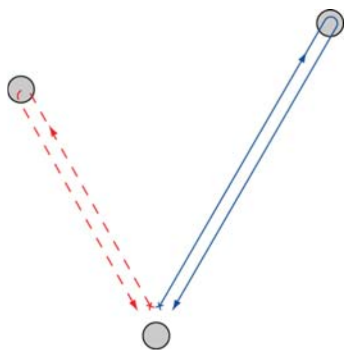


Frequency Noise Suppression: Time Delay Interferometry (TDI)

- **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!**

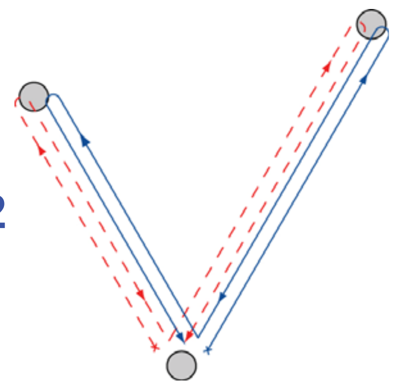
$$\delta x = \frac{\delta \nu}{\nu}\Delta L$$

1



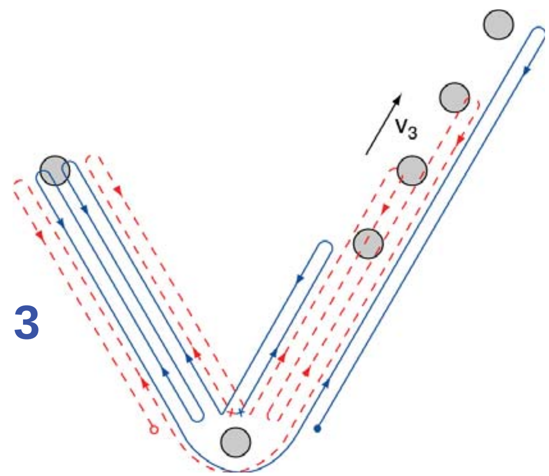
- **Unequal-arm Michelson interferometer**
- **Output corrupted by laser frequency noise**

2



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

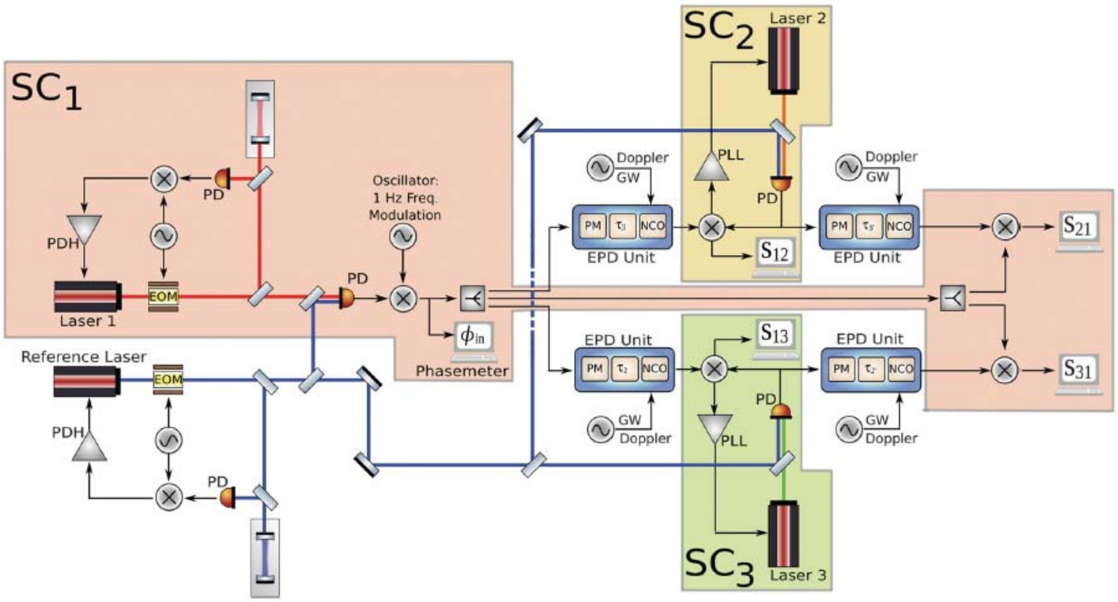
3



- **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**

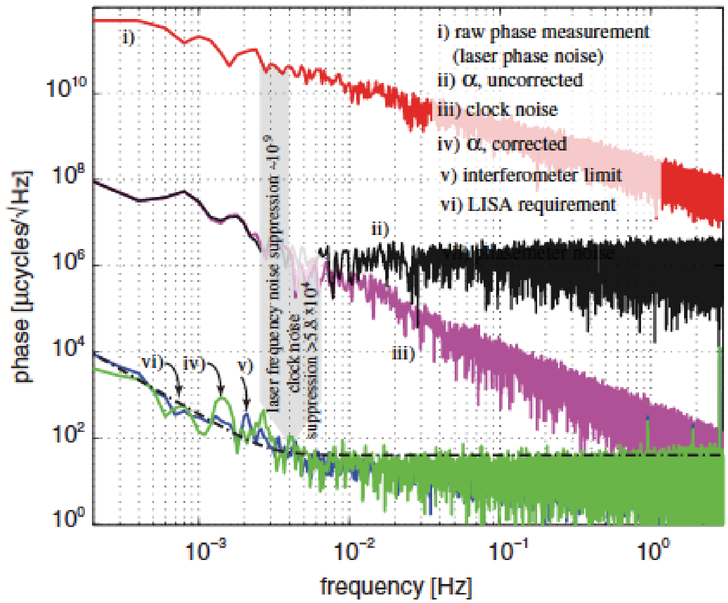
D.A. Shaddock, et al; PRD **68**, 061303 (2003).

TDI Experimental Demonstration



Mitryck, et al. PRD **86**, 122006 (2012) testbed with electronic delays

- **Laser frequency noise suppression of ~ 10^9**
- **Clock noise suppression of ~ 6×10^4**



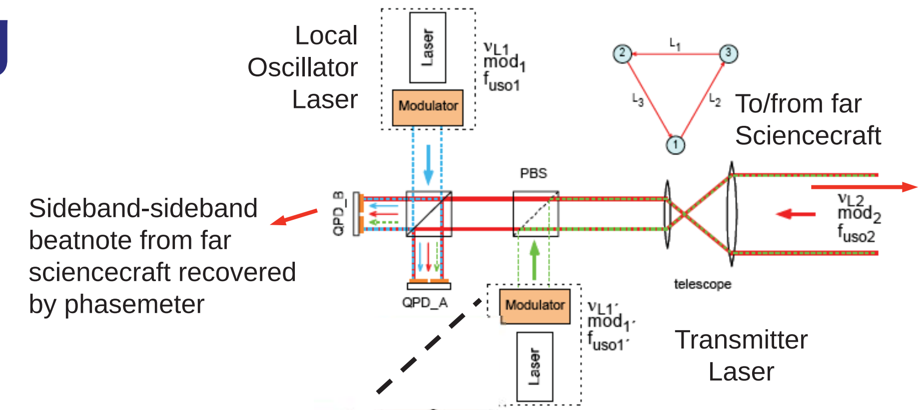
Laser frequency noise can be reduced with margin

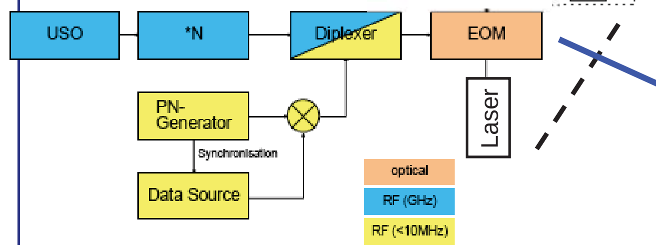
de Vine, et al. PRL **104**, 211103 (2010) static test bed

Inter-Sciencecraft Signaling: Clock noise and ranging

- **Requirement 1:**
- **Implementation: clock-coherent side tone**
  - **8 GHz nominal sidetones (~2 MHz offsets in send vs receive)**
  - **1% of power in sidebands**
  - **Sideband-sideband beat detection**
- **Requirement 2:**
- **Implementation: inter-spacecraft comm**
  - **1% modulation on main science beam (carrier)**
  - **Manchester encoding (2 Mchips/s)**
  - **13-bit Gold code yields 2 m range accuracy**
  - **~100 bps required (400 kbps capable)**

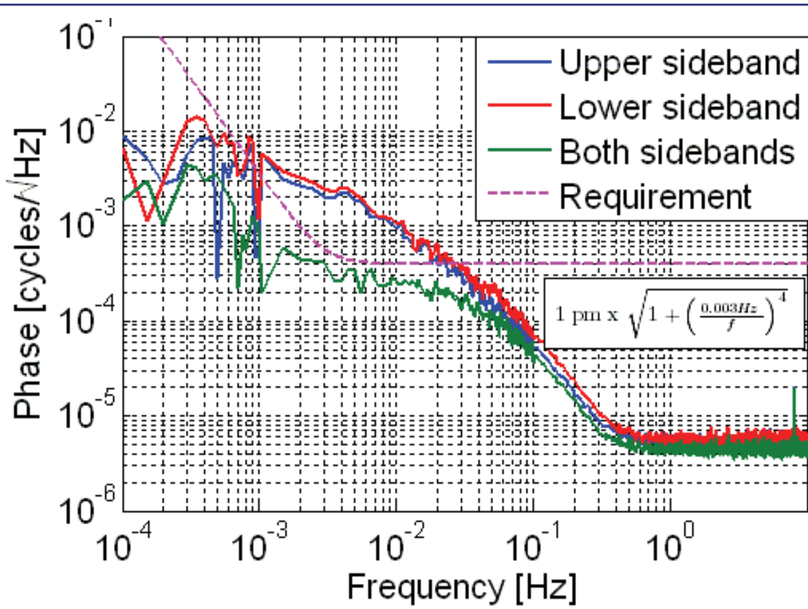
Phase modulator supports clock noise rqmts

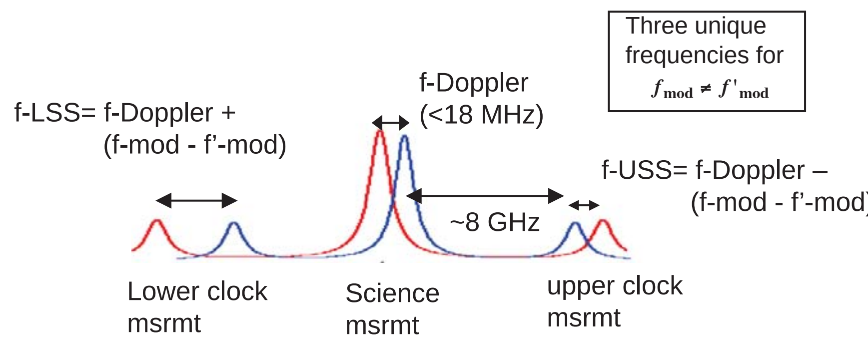




Ultra-stable oscillator (USO) modulated onto main science beam

Fiber-coupled electro-optic modulator (EOM)

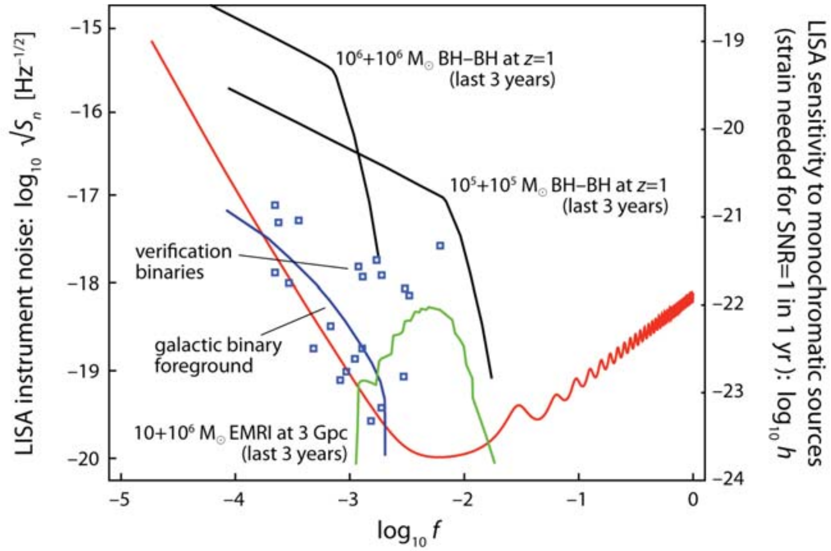




Using sideband-sideband beatnotes (instead of carrier-sideband) allows high modulation frequency and low photoreceiver BW

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.**



Summary of DRS Subsystem allocations

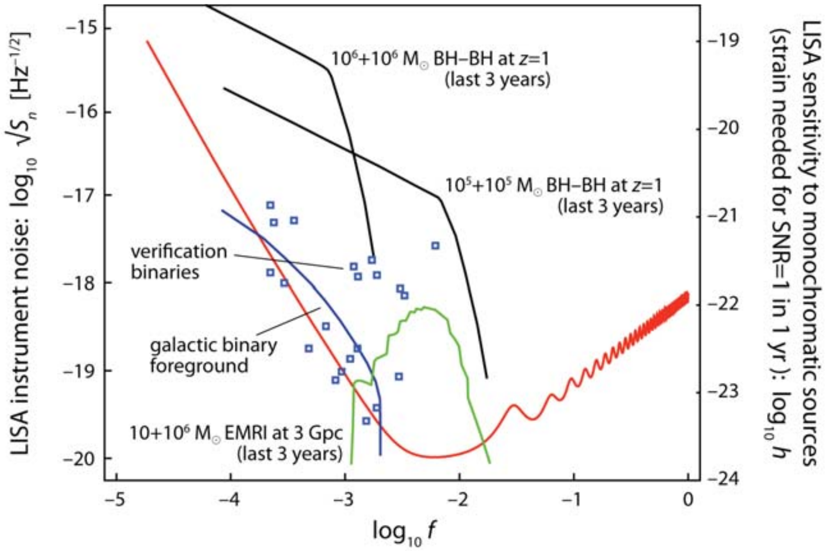
	$\times 10^{-16} \frac{m}{s^2\sqrt{Hz}} \sqrt{1+\left(\frac{f}{8\,mHz}\right)^4} \sqrt{1+\left(\frac{0.1\,mHz}{f}\right)}$	
Effect	**Total per group**	**Per group**
Total Acceleration noise Budget	**30.0**	
Total of subsystem allocations	**19.5**	
Disturbance Groups		
Electrostatics		12.0
Brownian		9.1
Spacecraft magnetic		7.0
Spacecraft coupling		6.0
Spacecraft cross coupling		4.5
Thermal		4.0
Interplanetary Magnetic		4.0
Misc small effects		4.0

Summary of IMS subsystem noise allocations

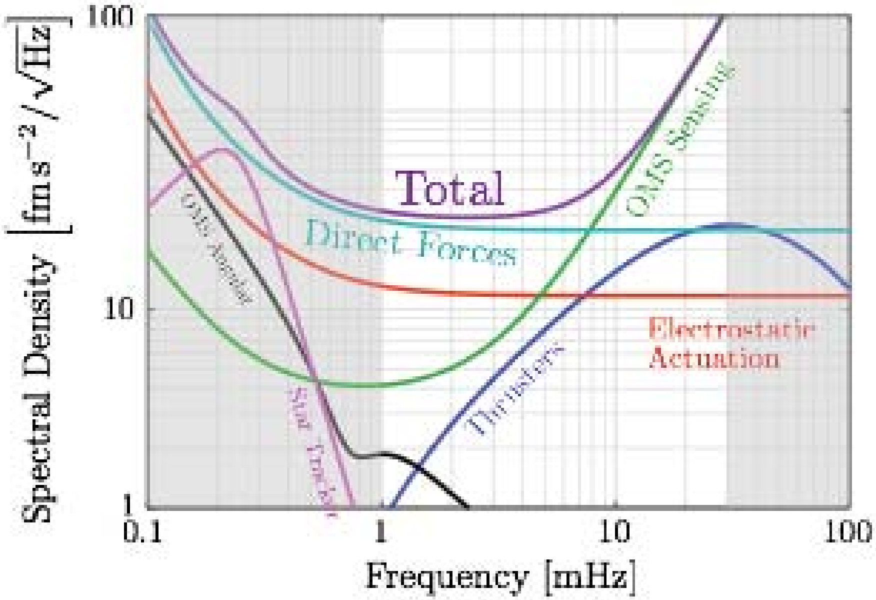
	$\times 10^{-12} \frac{m}{\sqrt{Hz}} \sqrt{1+\left(\frac{2\,mHz}{f}\right)^4}$	
Effect	**Total per group (pm/√Hz)**	**Sub - Allocation**
Total IMS Error/Noise Budget	**12.0**	
Total of subsystem allocations	**11.7**	
Subsystem Allocations		
Shot noise	**7.7**	
Pathlength noise	**7.0**	
Pointing Errors		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

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



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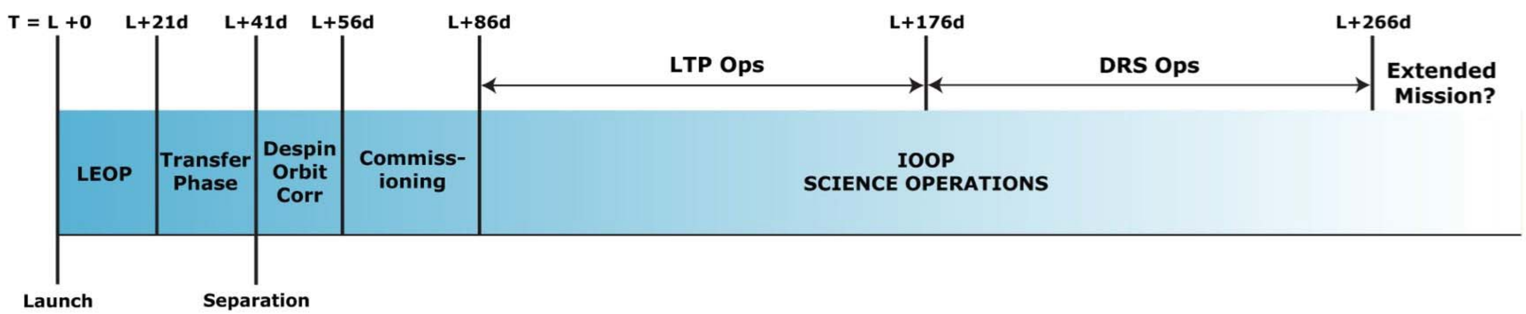
LPF Status

- Propulsion module complete
- Spacecraft bus near complete
  - cold-gas thruster system currently being integrated
- Major system tests complete
  - thermal
  - electro-magnetic
  - vibration/shock
- On-track for July 2015 launch
  - Lissajous orbit around L1
  - 90 days LTP Ops
  - 90 days DRS Ops



Summary

- **Space-based gravitational-wave work continues**
  - Science receives top ratings in reviews
  - LPF is progressing for launch in July 2015
  - 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
- **Successful LISA Pathfinder technology demo required**
- **US technology development targeted at TRL-5 level for ~ 2020 for key technologies**

BACKUP SLIDES

Context and Status of SGO-Mid

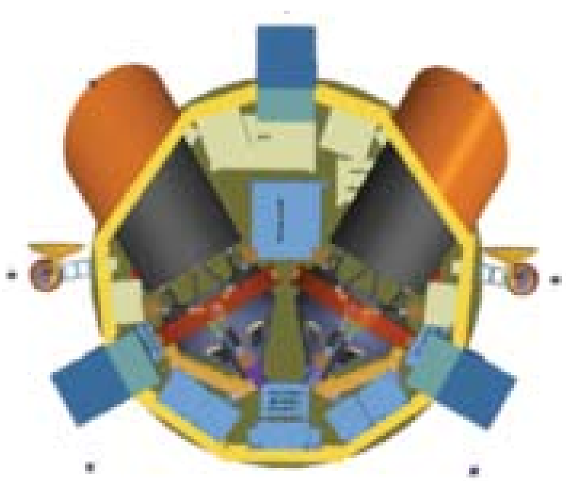
- **No official project office at NASA**
  - Study team under Physics of the Cosmos Program office
- **No LISA International Science Team (LIST)**
  - University engagement is critical
  - Community engagement through PhysPAG
- **Technology development for L3 mission contribution**
  - laser -- photoreceiver
  - telescope -- micro-newton thruster
  - phasemeter
- **Participation on LPF science team**
  - ST-7 experiments -- mission data analysis operations
- **Developing a reference mission and science case**

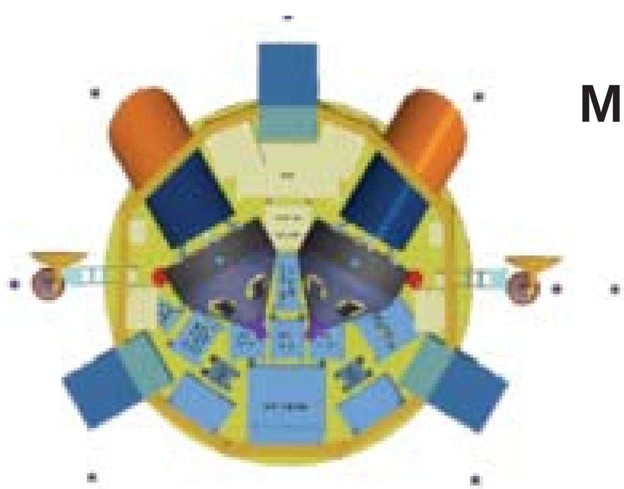
SGO-High vs Mid (vs LISA baseline)

- **SGO High differs from LISA by:**
  - **Preserves all LISA performance parameters**
  - **Single agency cost model (not joint mission)**
  - **Lower cost launch vehicle (shared launch on a Falcon Heavy)**
  - **Demonstrated improvements in photoreceiver performance**
  - **More economical trajectories to the operational orbits**

- **SGO Mid differs from LISA by:**
  - **Detector arm length reduced from 5 Gm to 1 Gm**
  - **Science operations reduced from 5 to 2 years.**
  - **Nominal starting distance from Earth is reduced by about a factor of 2.5 to a 9-degree trailing orbit.**
  - **Telescope diameter is reduced from 40 to 25 cm, and the laser power out of the telescope is reduced from 1.2 to 0.7 W (end of life).**
  - **In-field guiding is used instead of articulating the entire optical assembly**

High





Mid

LISA vs SGO-high vs SGO-mid

Parameter	LISA Concept	SGO High	SGO Mid
Arm length (meters)	5×10^9	5×10^9	1×10^9
Constellation	Triangle	Triangle	Triangle
Orbit	22° heliocentric, earth-trailing	22° heliocentric, earth-trailing	Heliocentric, earth-trailing, drifting-away 9°- 21°
Trajectory	Direct injection to escape, 14 months	Direct injection to escape, 14 months	Direct injection to escape, 18 months
Interferometer configuration	3 arms, 6 links	3 arms, 6 links	3 arms, 6 links
Launch vehicle	Medium EELV (e.g., Atlas V 431)	Medium EELV (e.g., Falcon Heavy shared launch)	Medium EELV (e.g., Falcon 9 Block 3)
Baseline/Extended Mission Duration (years)	5/3.5	5/3.5	2/2
Telescope Diameter (cm)	40	40	25
Laser power out of telescope end of life (W)	1.2	1.2	0.7
Measurement system modifications	Baseline/Reference	Baseline/Reference (Same as LISA Concept)	In-field guiding, UV-LEDs, no pointing
Motivation:	Science performance, two agencies	LISA performance with all known economies	Lowest cost 6 links
Approximate Cost (FY12 $B)	1.82	1.66	1.40

Orbits/trajectory

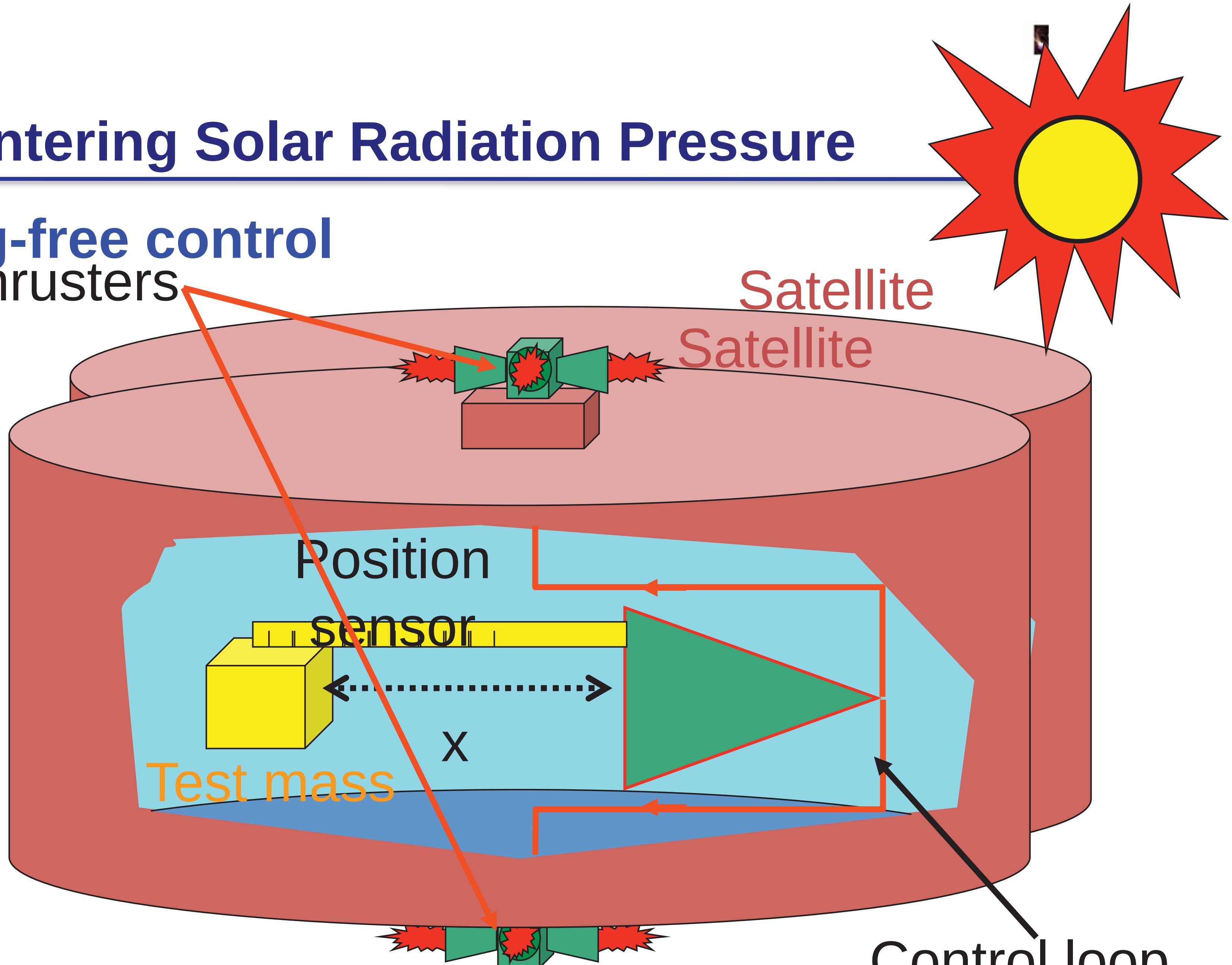
- **2 year drift-away**
  - ~ 6 deg/year drift rate starting at 9 degrees
  - 2 year end of mission similar to nominal SGO-high orbital station (but orbit optimized for 4 years)
  - EOL communications requirements similar to SGO-high
- **Stable constellation geometry simplifies measurement**
  - $\Delta L/L$ ~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

Countering Solar Radiation Pressure

Drag-free control



Courtesy K. Danzmann