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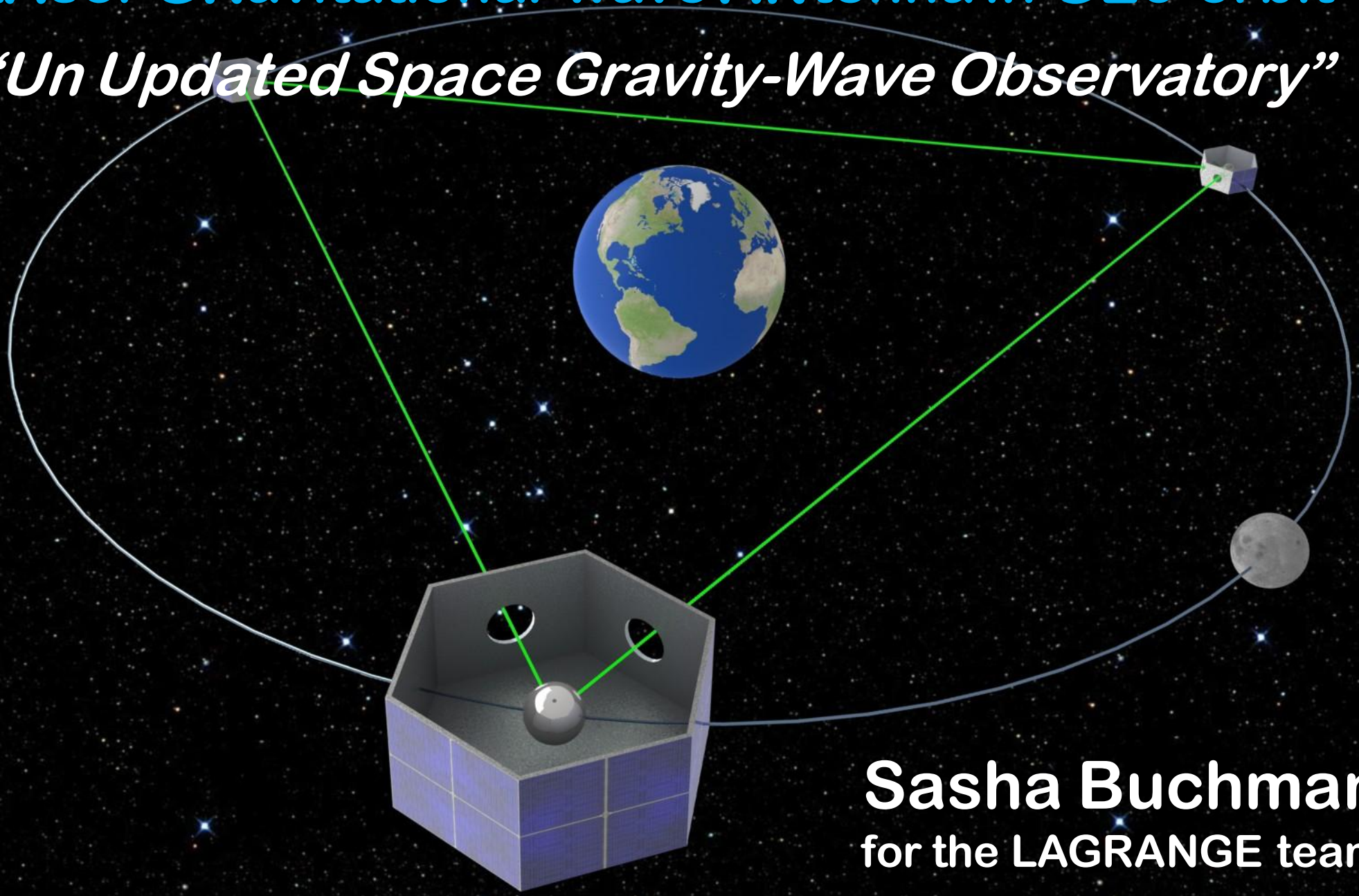
LAGRANGE

LAser GRavitational-wave ANtenna in GEo-orbit

"Un Updated Space Gravity-Wave Observatory"



Sasha Buchman
for the LAGRANGE team

Outline

- **LISA Background and Status**
- **LAGRANGE – An Updated Gravity-Wave Observatory**
- **LAGRANGE - Main Design Features**
- **Technology and Science on Small Sats**

Gravitational Radiation: The Quadrupole

The quadrupole is the first gravitational radiation moment

The leading gravitational radiation term is

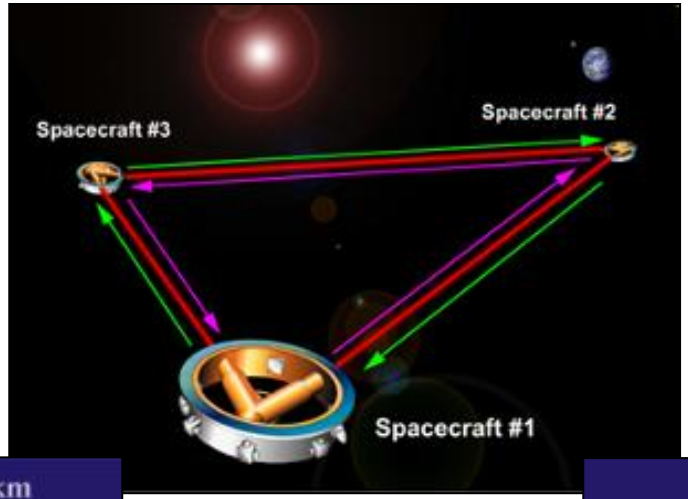
$$h_{\mu\nu} = \frac{2G}{c^4} \cdot \frac{1}{r} \cdot \ddot{Q}_{\mu\nu}$$

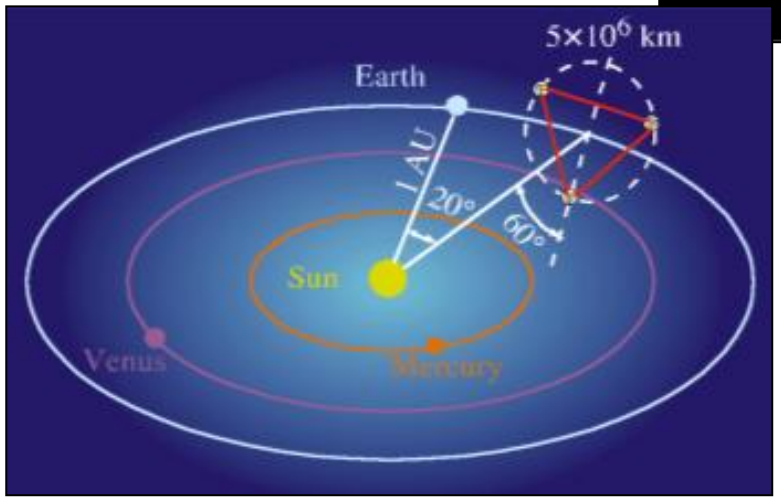
$h_{\mu\nu}$ perturbation from Minkowski space
G gravitational constant
r distance to the source
$Q_{\mu\nu}$ trace-free quadrupole tensor

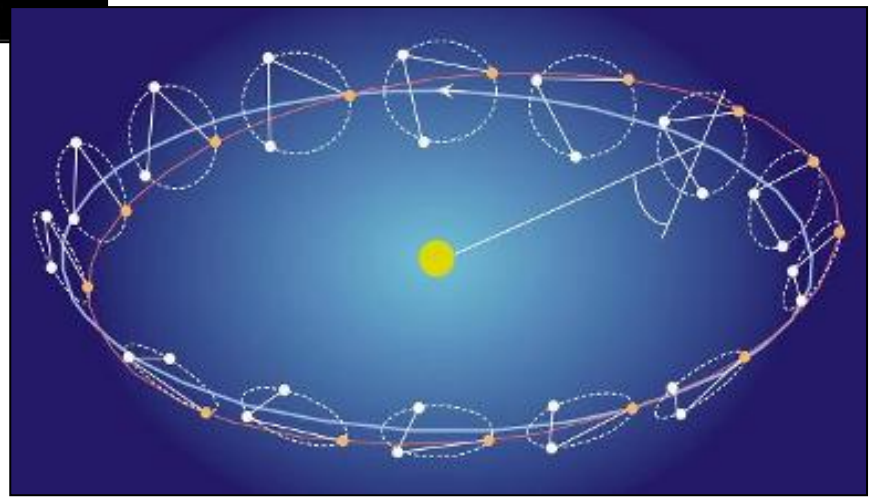
- Space is "stiff" ($2G/c^4 = 1.7\times10^{-44}\ s^2 \cdot kg^{-1} \cdot m^{-1}$)
- The GW perturbation $h_{\mu\nu}$ propagates as 1/r

LISA Concept

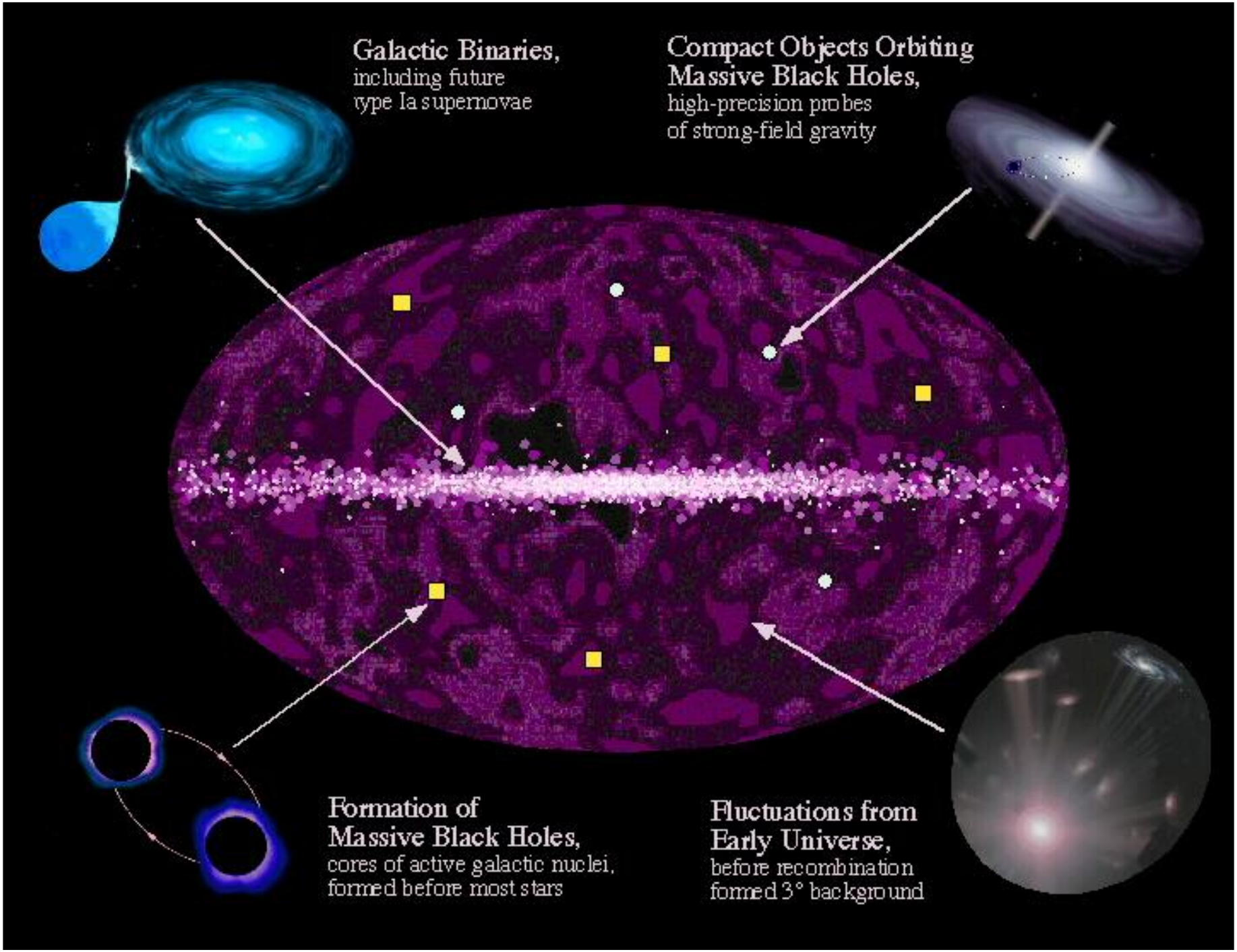
- Three spacecraft in triangular formation separated by 5 million km
- Spacecraft have constant solar illumination
- Formation trails Earth by 20°



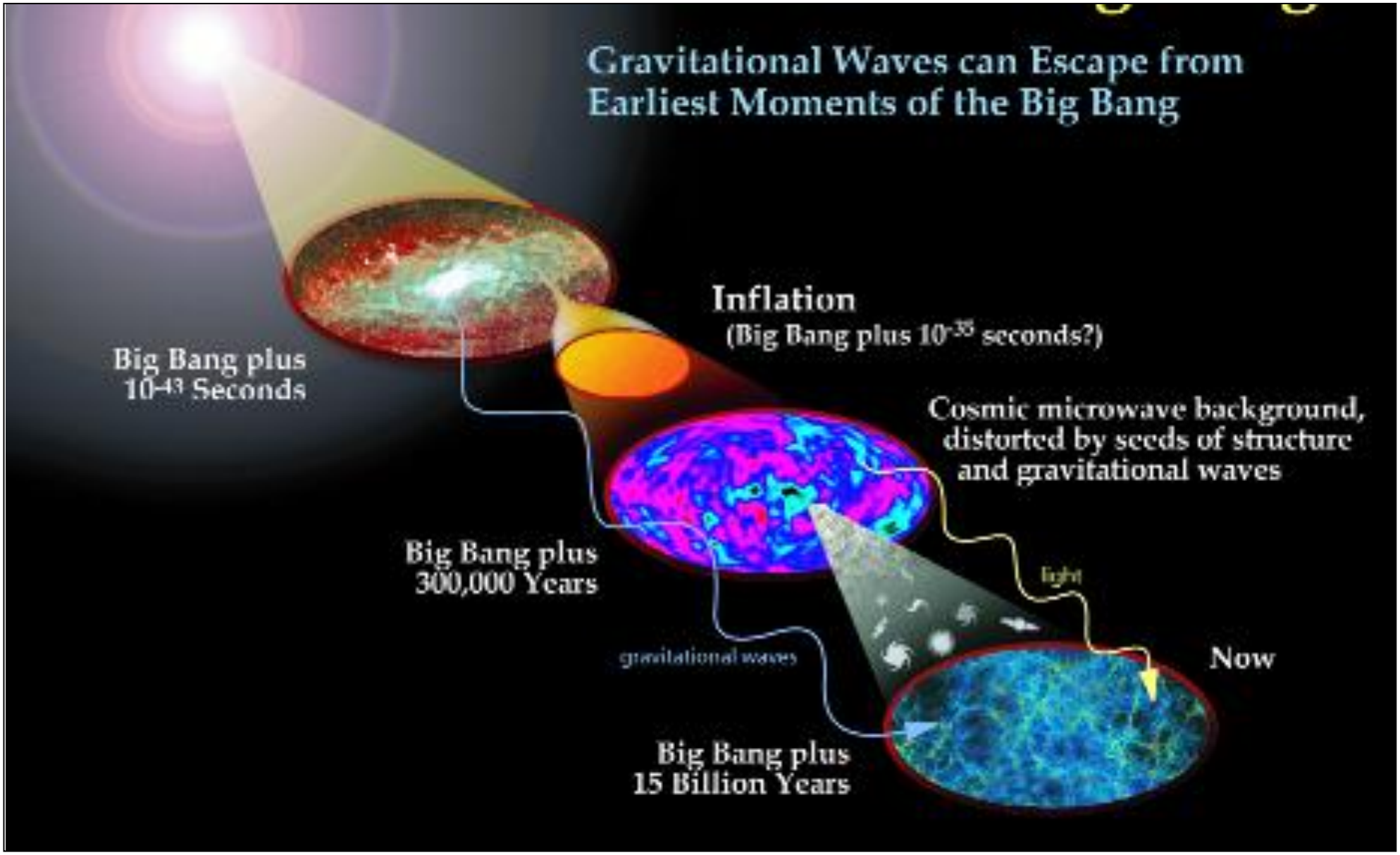




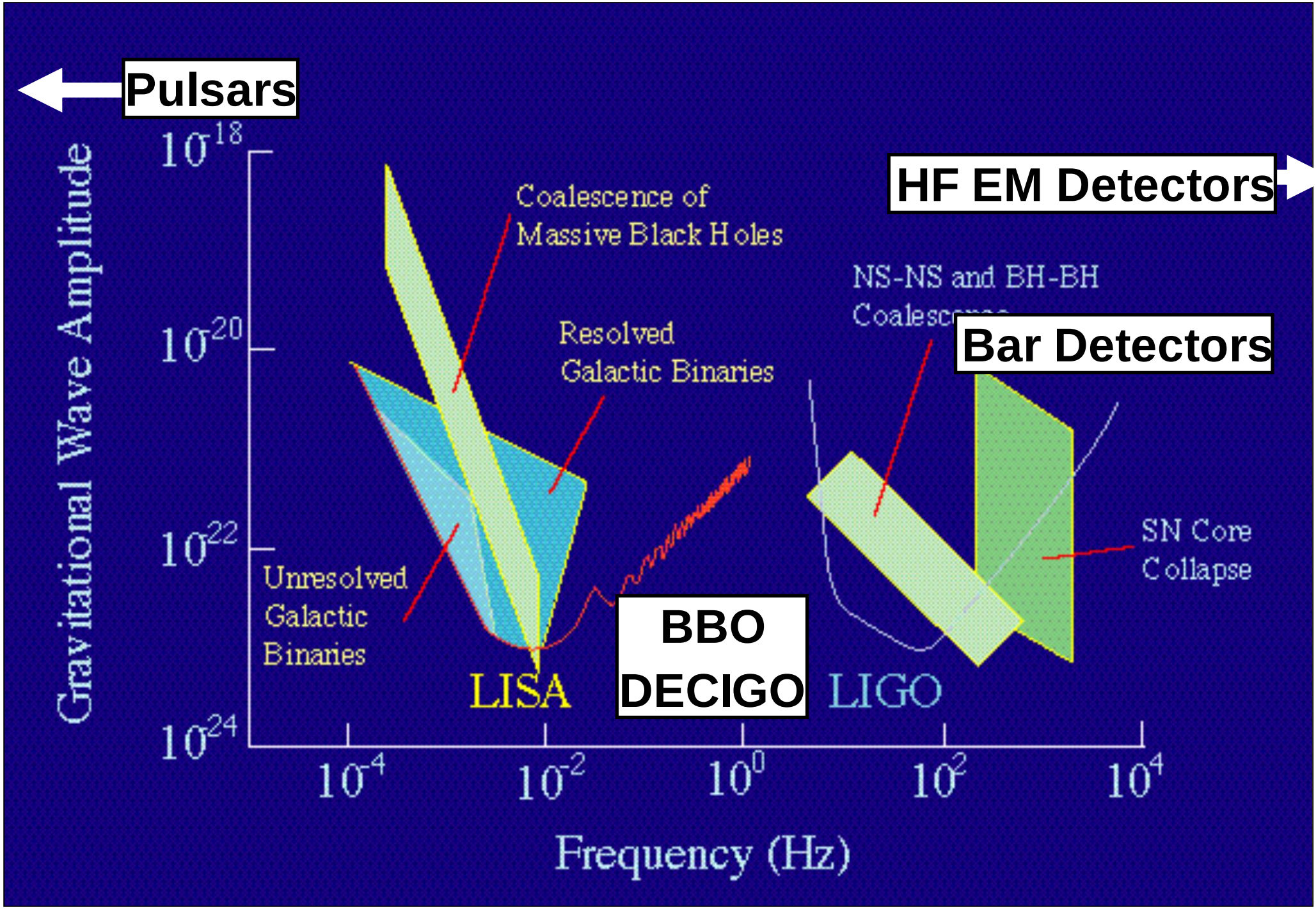
The LISA Gravitational-Wave Sky



Gravitational Waves Through Time

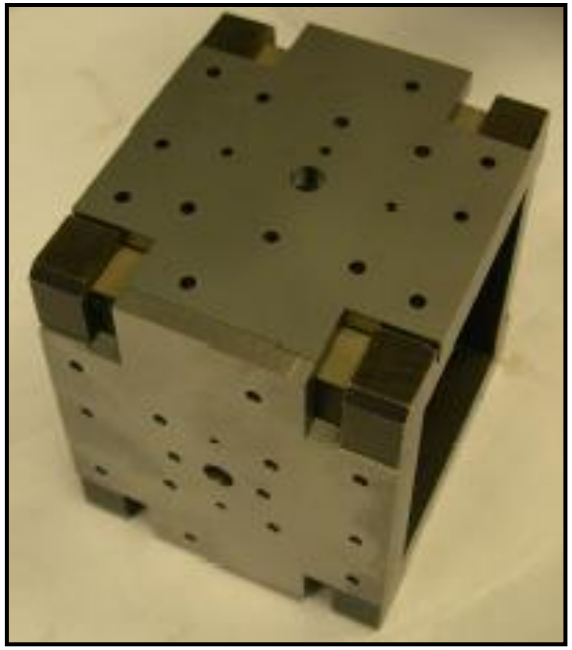


The Gravitational-Wave Spectrum

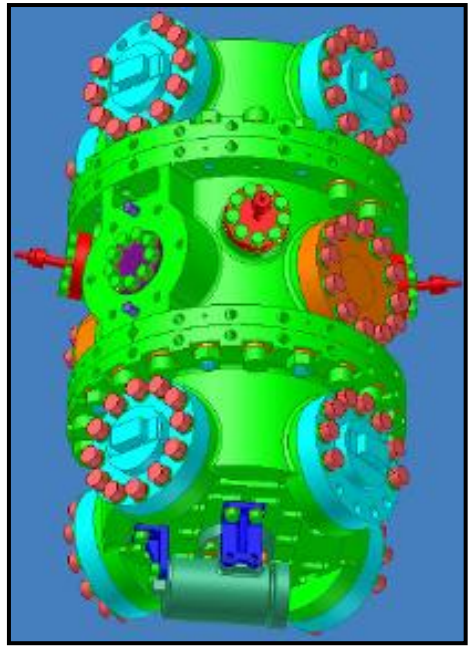


LISA Path Finder (LPF) Development

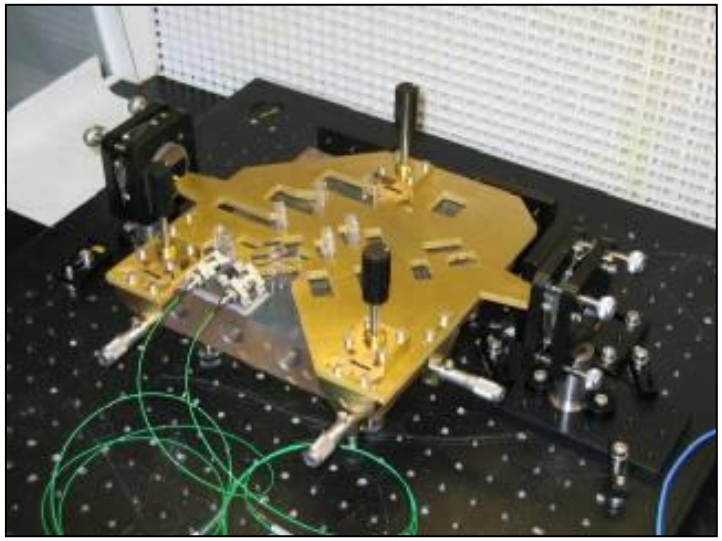
Torsion balance



Housing



GRS



Optical components

Optical bench

LAGRANGE Background

- **LAser GRavitational-wave ANtenna in GEocentric Orbit A response to NASA's Request for Information (RFI) "Concepts for the NASA Gravitational Wave Mission"**
  - **One of 17 submissions**
  - **One of two called "LAGRANGE"**

Conklin, et. al. "LAGRANGE: LAser GRavitational-wave Antenna at GEo-lunar Lagrange points" arXiv:1111.5264v2 [astro-ph.IM] Dec 5, 2011

LISA Status

- **NASA participation in LISA mission terminated 2011**
- **ESA does not choose LISA (NGO) for 2022 L1 launch**
- **LPF to launch 2014**

The SALKS Collaboration for LAGRANGE

Stanford	NASA ARC	Lockheed Martin	KACST of Saudi Arabia	SRI International
science payload lead (GRS / IMS)	science orbit, orb. injection, prop. mod.	telescope, spacecraft	science payload, tech development	µN thrusters

Updated Gravity-Wave Observatory

Cost	Complexity	Comm Link
Reduce 50%	Reduce ~50%	Increase >10^2

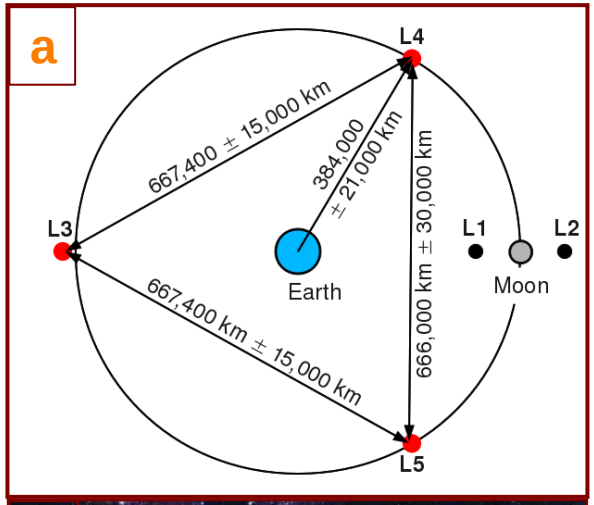
- **Geocentric Orbit ~ 50% Heliocentric cost , ≥ 100 Comms**
- **Simplified Robust Inertial Sensor (LPF back-up)**
  - Spherical, fully drag-free, optical sensing
- **Metrology**
  - Optical Reflective with Gratings
- **Small sat approach to tech demonstrations**
  - 2013-2017 technology (LISA technology is older than 2000)
  - Parallel, low cost, low risk, on small and cube satellites
  - ~6 technologies at 1 M$ - 4 M$ each
  - Multiple institutions and international partners

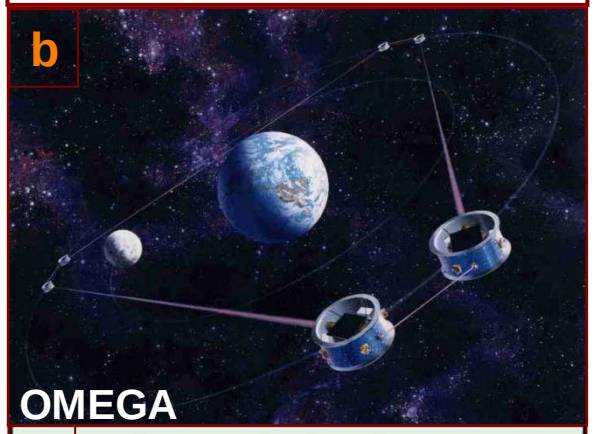
Design Overview

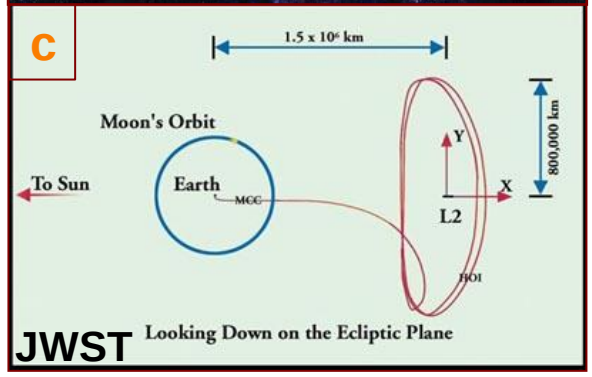
- **Geocentric orbit:** 3 identical drag-free spacecraft & payloads instable; equilateral triangle (6 links)

	Orbit	Type	Arm length	To Earth
a	EM - L3, L4, L5		0.67 Gm	0.4 Gm
b	Lunar retrograde	OMEGA	1.0 Gm	0.58 Gm
c	SE – L2 Halo	JWST	1.39 Gm	1.5 Gm

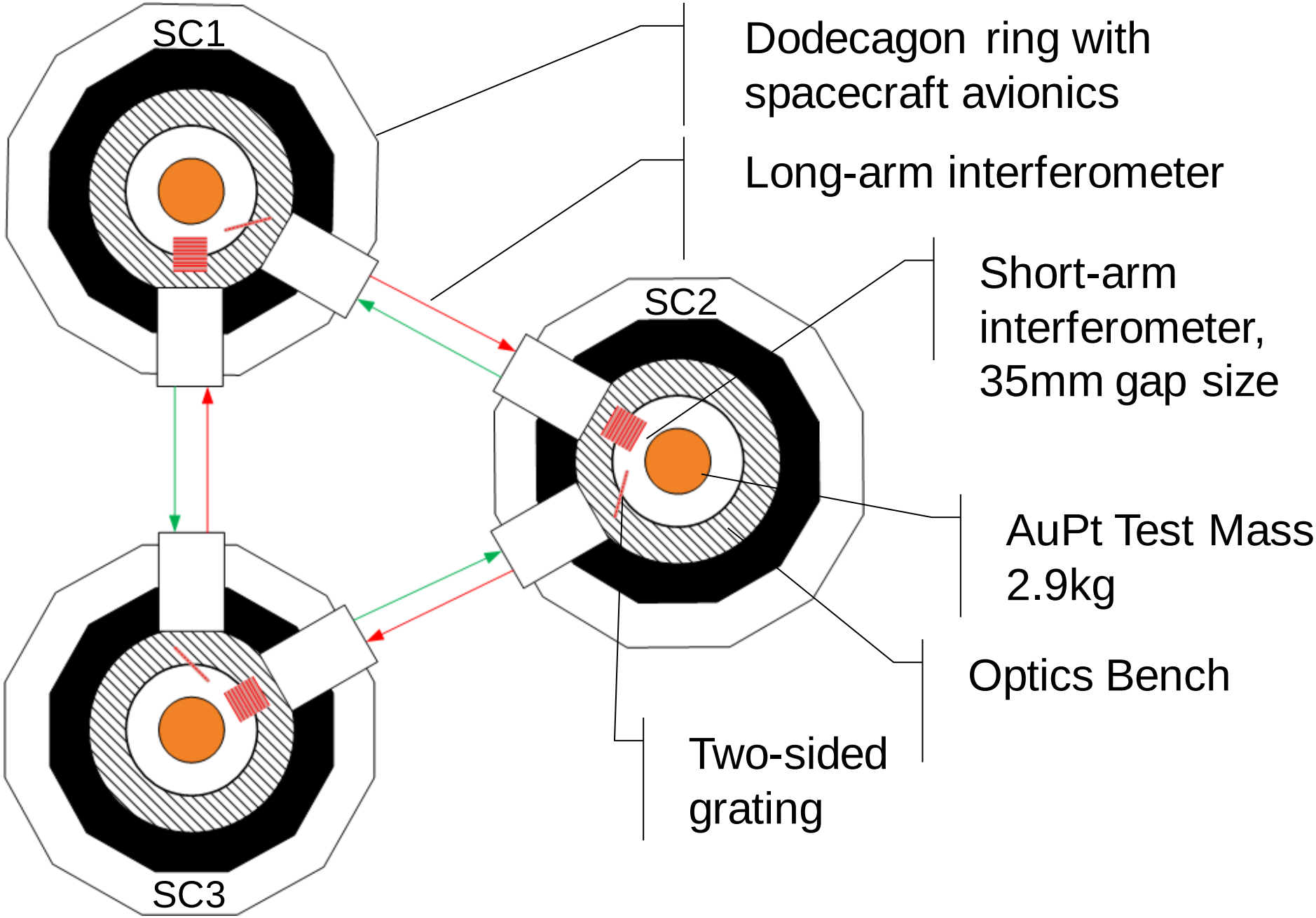
- **Minimum complexity**
  - 1 spherical TM with no forcing
  - 1 laser per S/C
  - Flight proven technology with high TRL (Honeywell gyro, DISCOS, GP-B, LISA)
- **Continuous, simultaneous, fast communications**
  - Fixed antennas on each S/C
  - Mbps by NASA GN (11 m class), ~1 hour data latency
  - Critical for mission success (GP-B, LIGO)
- **Performance maintains LISA science**
- **5 year mission lifetime**



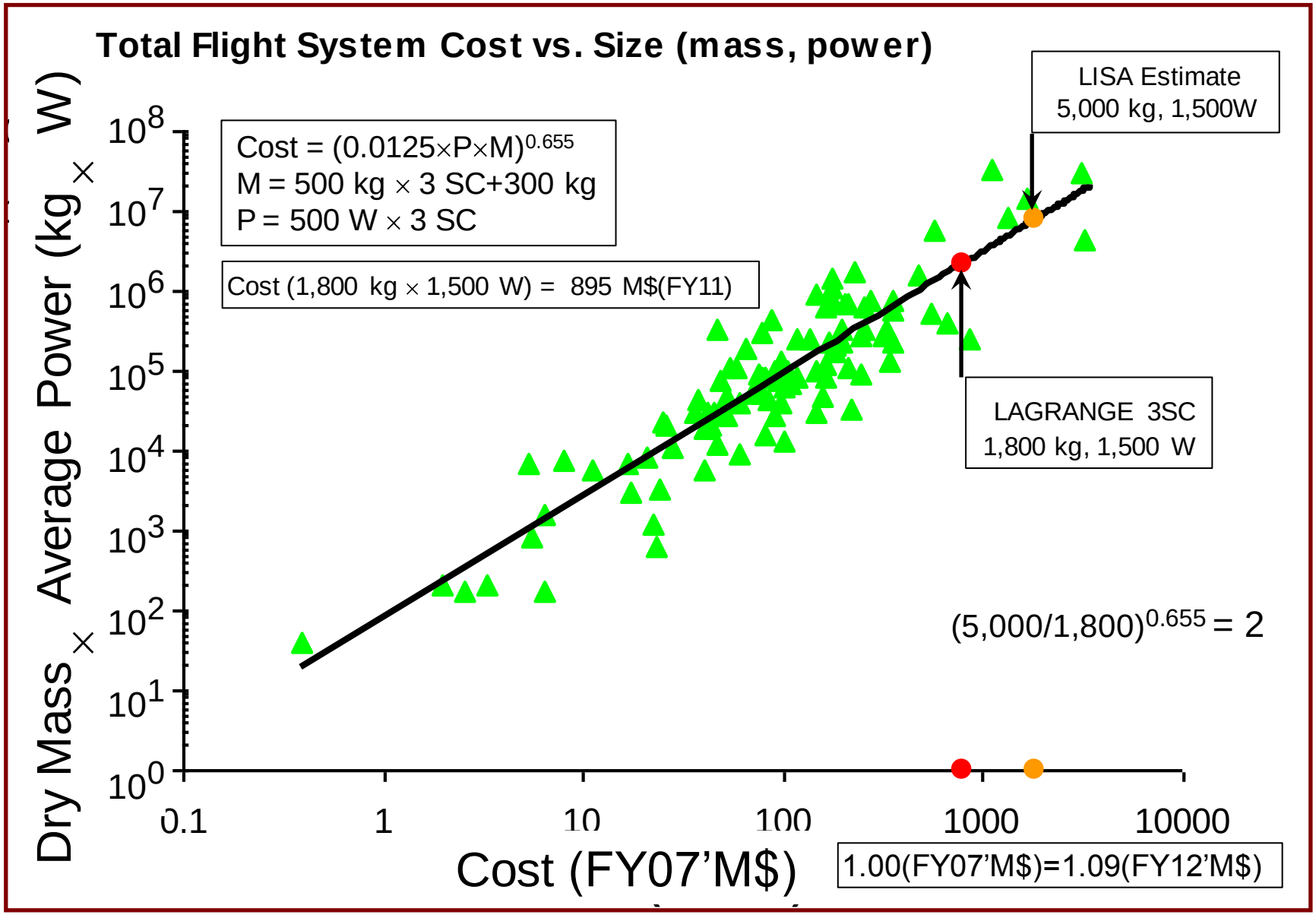




System Overview



LAGRANGE Cost Estimate



Data Rate Estimate for Space Antenna

	GP-B	1 LISA SC	3 LISA SC vs GPB
Plan	**0.35 GB/day (actual data rate)**	**0.004 GB/day**	**0.013 GB/day**
System			
SC	SC (GPB 6 deg ctrl.)	SC (LISA 7 deg ctr.)	≈ (GPB)×3
Temperature	Cryogenics	μK control	≈ (GPB)×3
Activation	He thrusters	μN thrusters	≈ (GPB)×3
Pointing	1 telescope	2 telescopes	≈ (GPB)×6
Test Masses	4 TM × 3 deg ctrl.	2 TM × 6 deg control	≈ (GPB)×3
Read-out	4 SQUID systems	4 pm interferometers	≈ (GPB)×3
BW	Meas. BW 12.9 mHz	Meas. BW 0.1-100 mHz	≥ (GPB)×3

GPB data rate ≤ 1 LISA SC data rate

LISA data rate ≥ 3 × GP-B data rate = 1 GB/day

LISA Estimated data rate ≥ 1 GB/day

LISA Estimated data rate / Planned rate ≥ 100

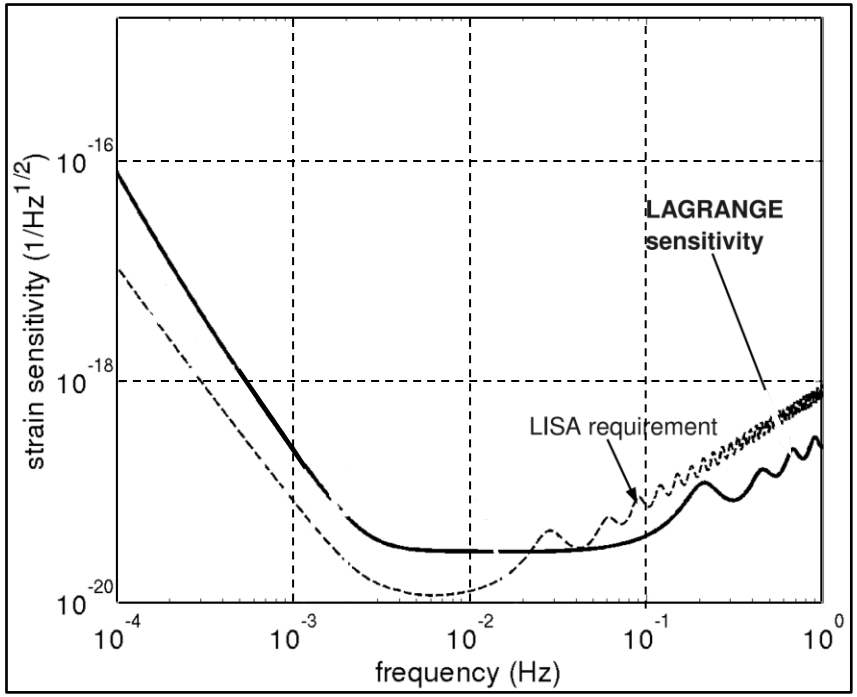
7 kbit/s for 8 hours every 2 days = 0.013 GB/day | **ESA web site**

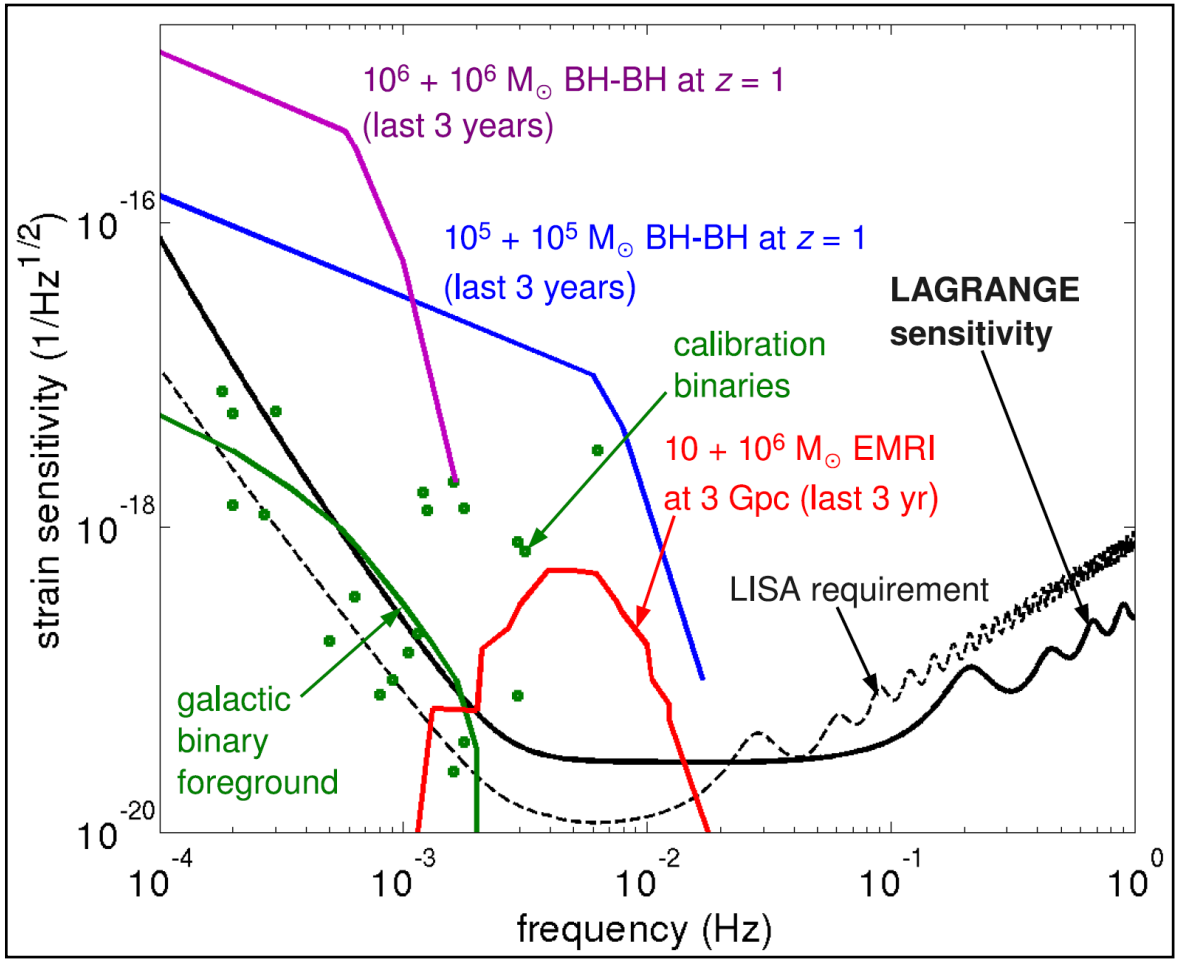
Principal Cost Savings Relative to LISA

1. **Orbit change: Geocentric (0.7 Gm – 1.4 Gm arm length)**
   - Requires 1 small propulsion module instead of 3 large modules
   - Launch mass savings: ~ 2,500 kg
   - Reduced operations & communications complexity
2. **Reduced S/C mass from reduced payload components**
   - 1 GRS, 1 Laser, 1 optics bench, smaller (20 cm) telescopes
     - Reliable TM caging mechanism
     - TM sensing, charge control, spin-up, and drag-free have redundancy
   - Launch mass savings: ~ 150 kg × 3 spacecraft
3. **LAGRANGE wet launch mass: ~2,000 kg (~5,000 kg for LISA)**
   - Historic trends show cost scales with mass

LAGRANGE Performance (EM L2, L3, L4)

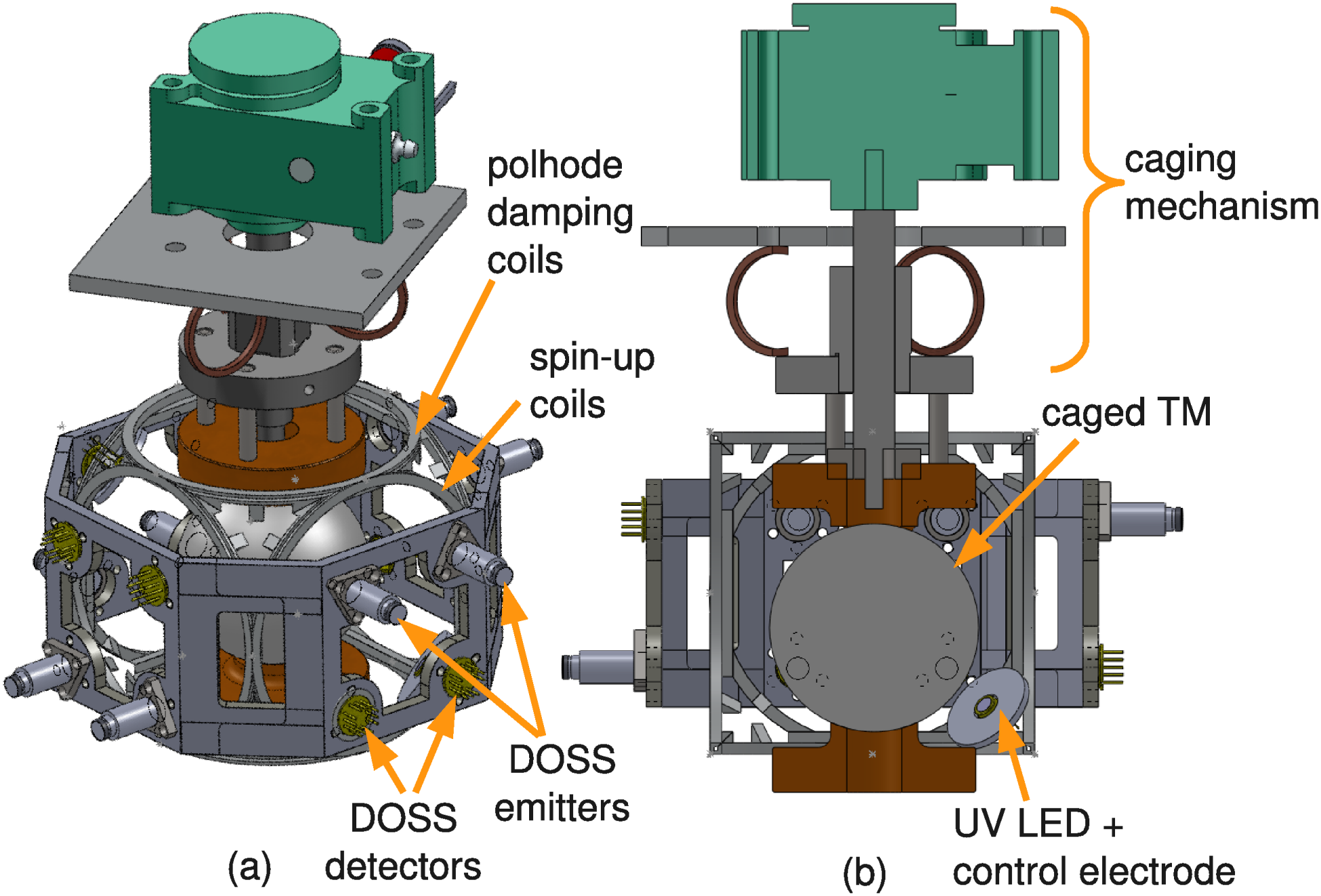
- **Arm length: 0.67 Gm – 1.39 Gm**
- **Metrology: 8 pm/Hz$^{1/2}$ at 3 mHz**
- **Acceleration noise: 3×10^{-15} m/sec^2**
  Must be over-designed
- **Sensitivity 2x less than LISA below 20 mHz**
- **Below 2 mHz galactic binary confusion sets limit**





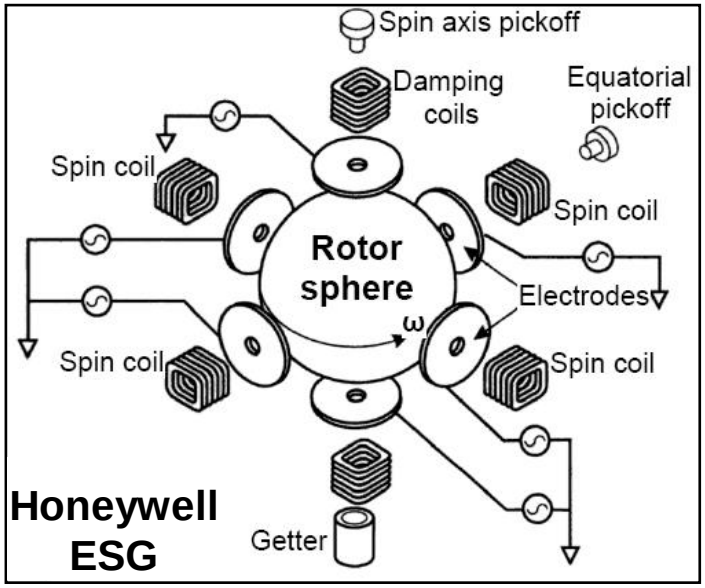
LAGRANGE maintains all important LISA science objectives

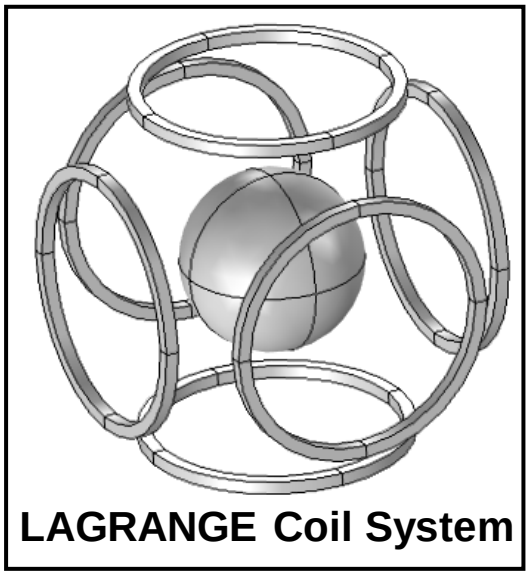
Modular Gravitational Reference Sensor



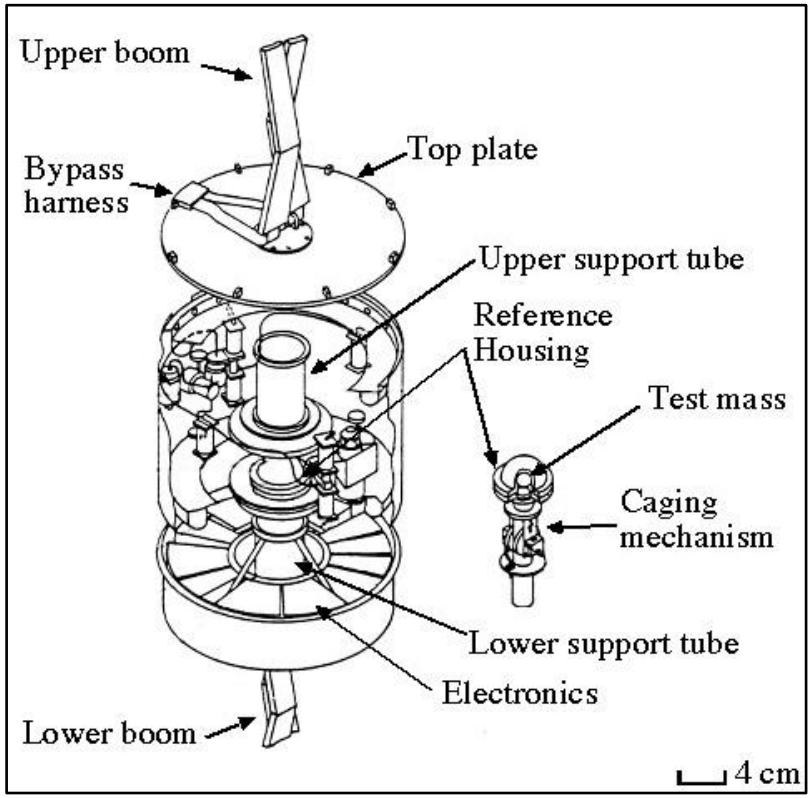
Spherical Test Mass Heritage

➢ Spin-up & Polhode-damping Based on Honeywell Gyros

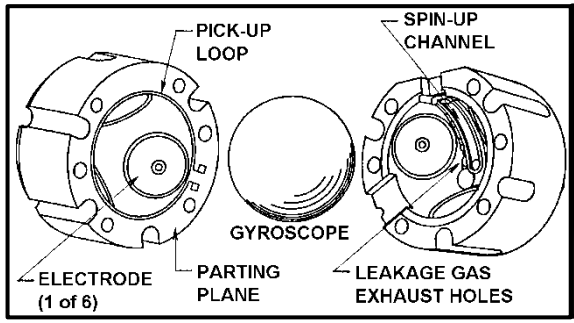




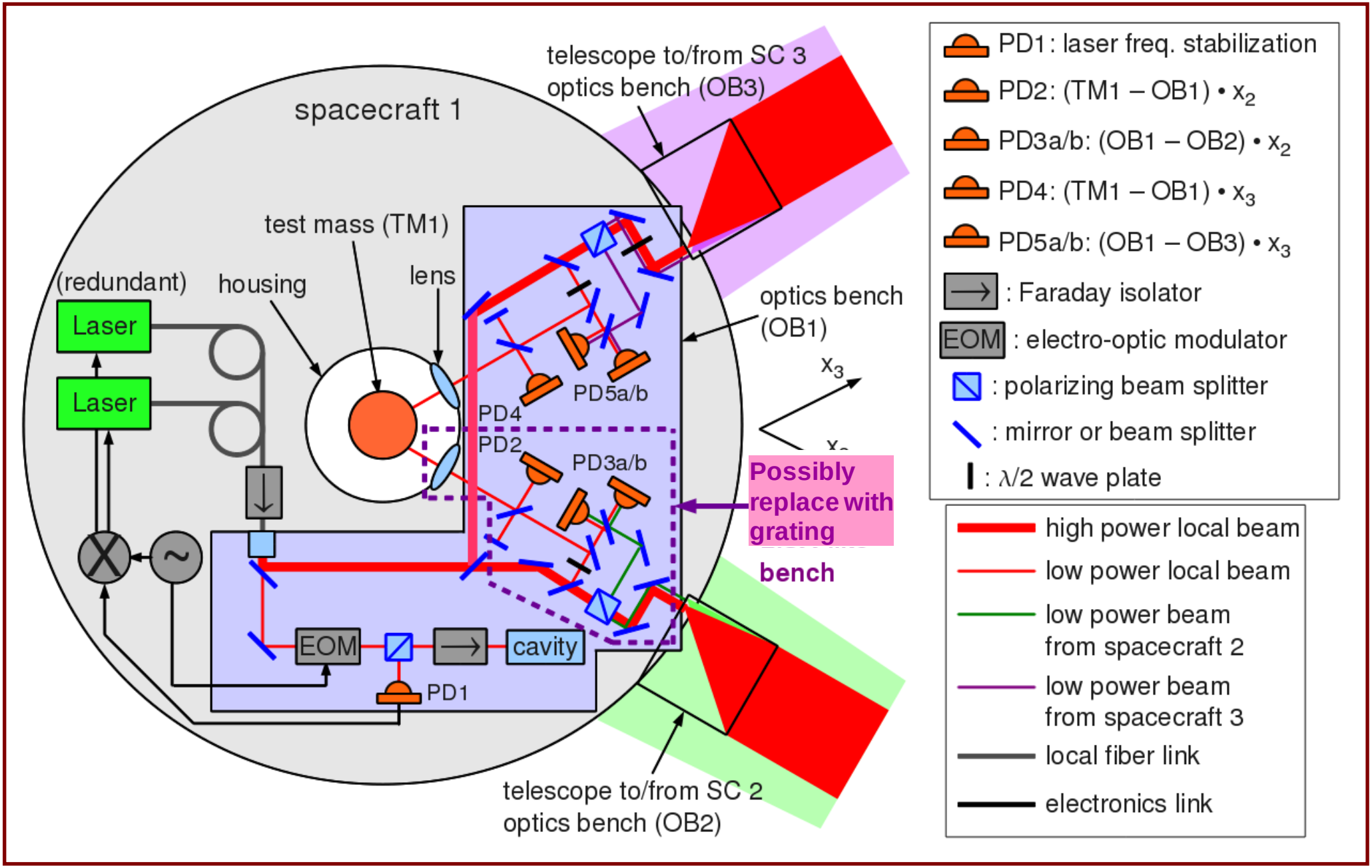
➢ Materials & Caging Based on DISCOS



➢ Manufacturing & UV Control Based on GP-B

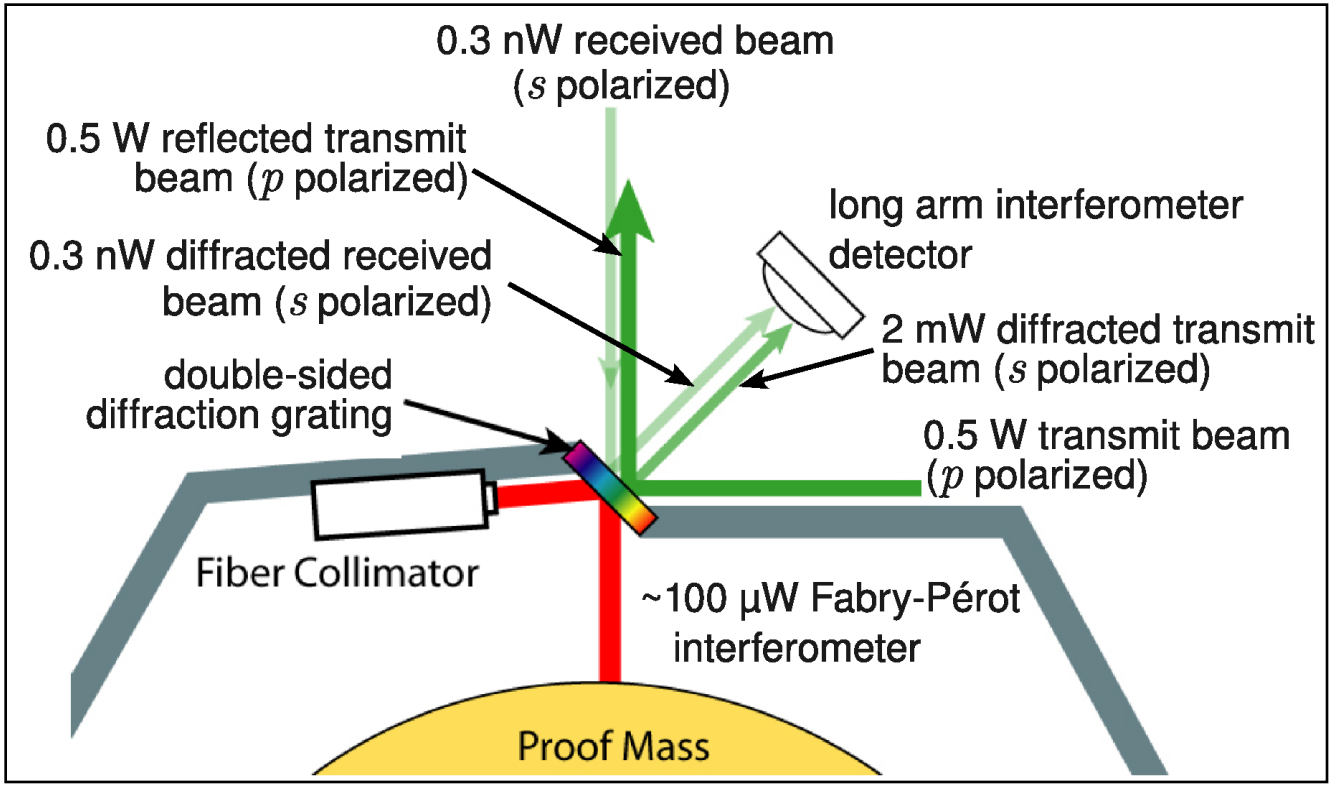


LISA-like Optical Bench



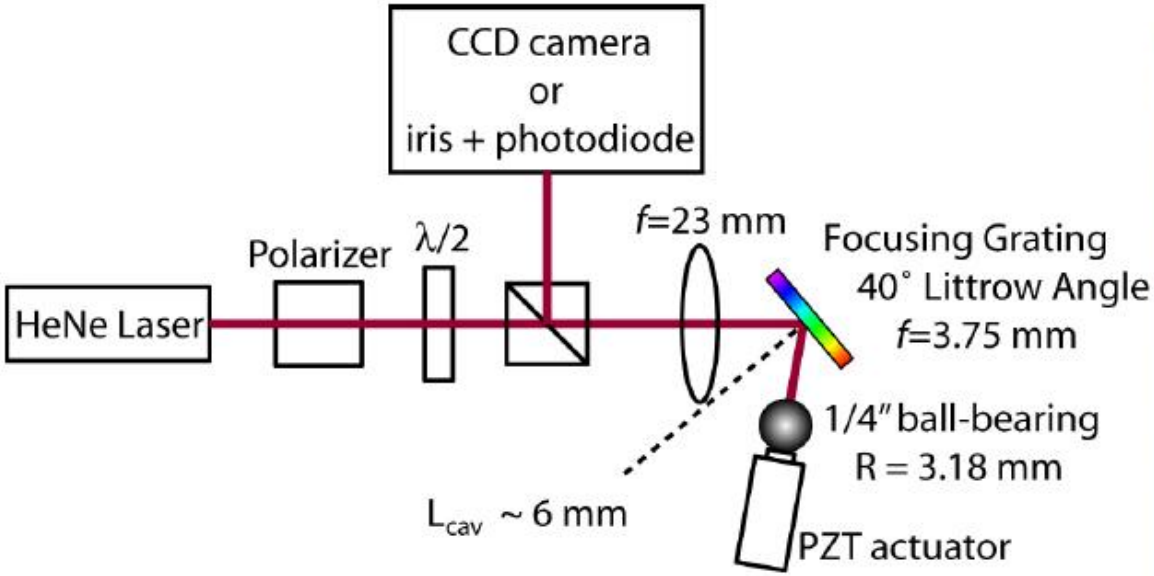
Interferometry with a Diffraction Grating

- **Double sided diffraction grating on low CTE material**
  - Small, ~ mm relay region between long & short arm interferometers
  - CTE < *dn/dT*
  - Fewer components → smaller optics bench
- **Sensitivity to grating motion: 1 µcycle/pm (similar to LISA req.)**

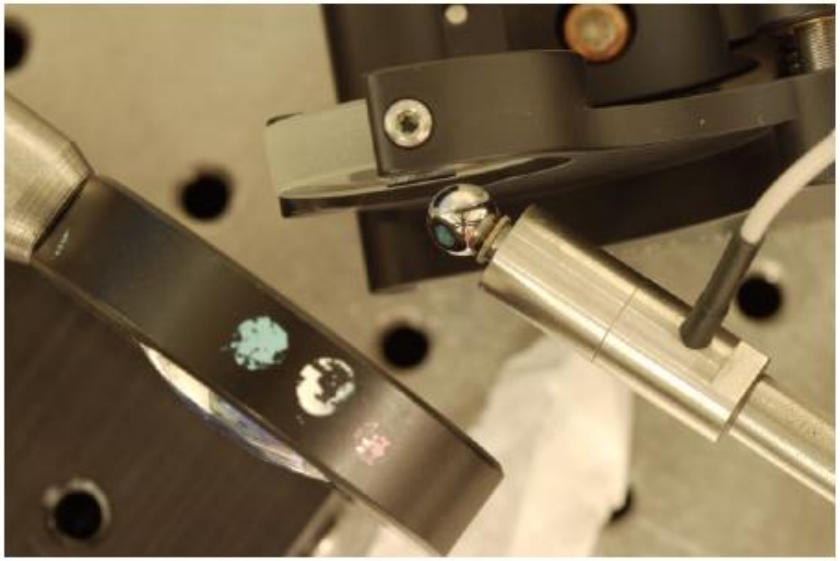


Grating-Sphere Cavity

Mode matching and stable low finesse cavity demonstrated



(a) Layout of the spherical grating cavity



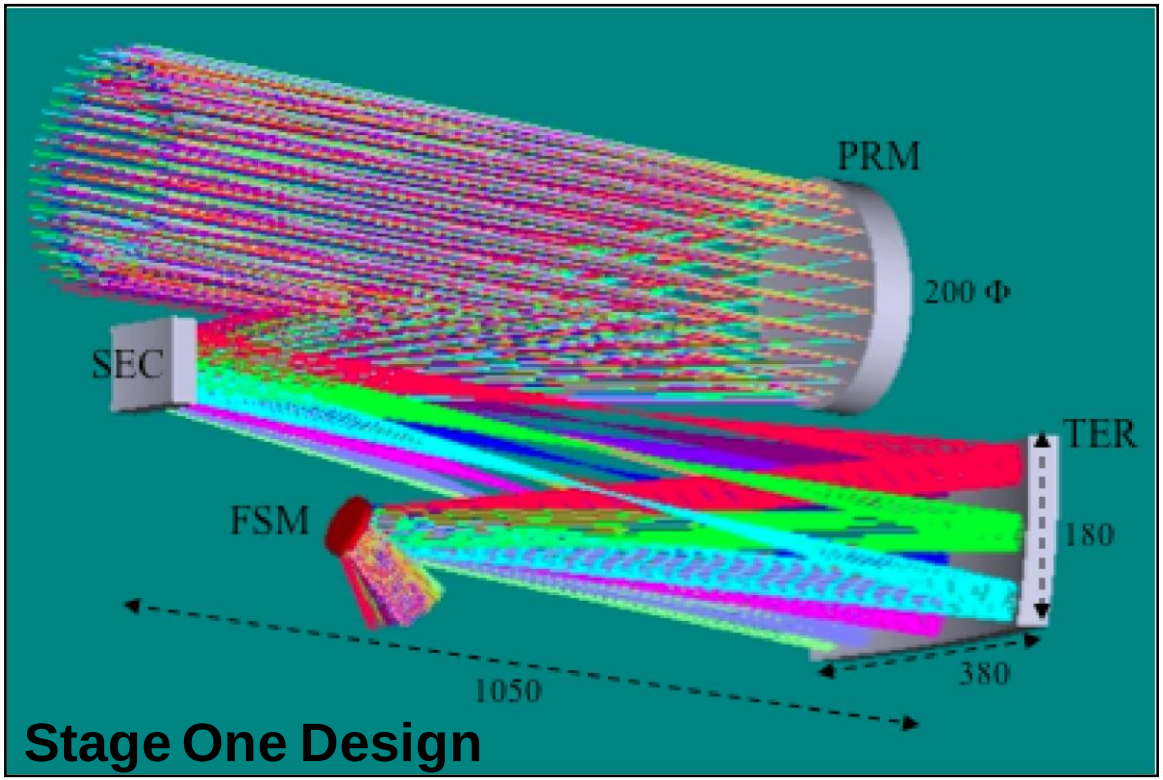
(b) Picture of the cavity

Figure A.1: Schematic and photograph of focusing grating cavity used to demonstrate successful mode-matching using a spherical end-mirror.

Telescope Design by Lockheed Martin

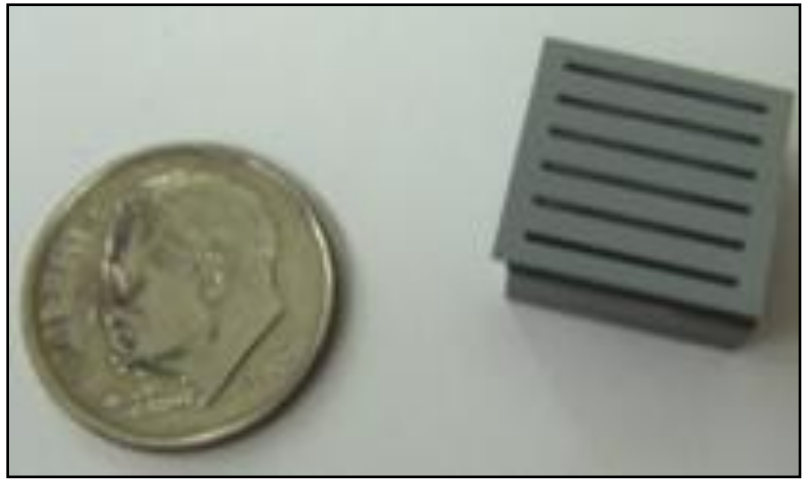
Based on Telescopes Flown

- 20 cm aperture
- ±2.5 deg beam steering
- 5 pm path-length stability
- Composite metering structure
- Off-axis, 2-stage design
- Stage one is 6:1 3-mirror Anastigmat
  - Leads to ±15 deg steering mirror near exit pupil
- mK temperature control
- Off-axis TMA TRL9
  - mK temp control, low CTE composite, pm path length combo TRL 4



Stage One Design

Micronewton Thrusters SRI Design



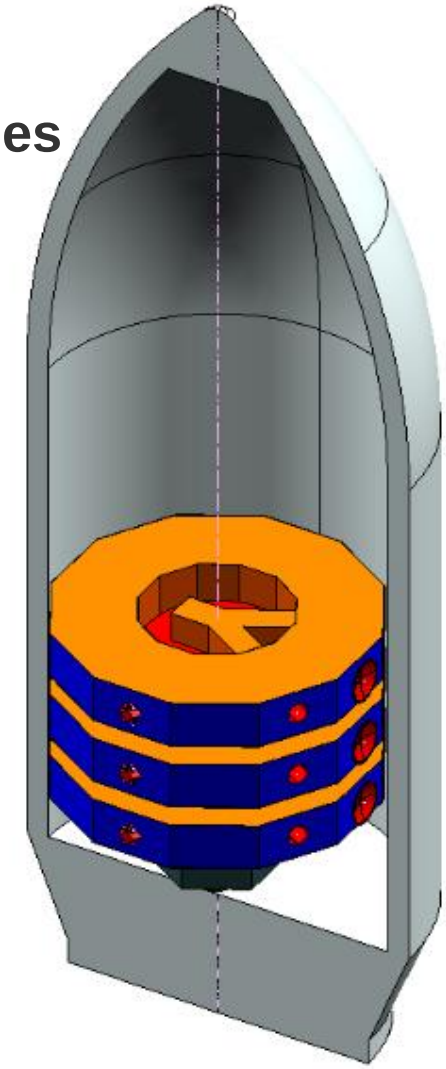
- **Drag-free & attitude via μN thrusters**
- **No existing thruster meets LISA noise, max thrust, and lifetime requirements**
  - NGO evaluating alternates to FEEPs
- **SRI micro-fabricated ion thruster attractive alternate to Busek CMNT or Italian/Austrian FEEPs**
  - Micro-fabricated emission sites produce ions & electrons
  - "Digital propulsion": 100's – 1,000's of independent emitters / cm^2
    - Single unit can produce forces + torques
  - Huge dynamic range: ion production physics unchanged over 10^{-9} to 1 N
  - Up to 10,000 sec Isp
  - Prototype: 1 nN to 5 μN thruster ion source tested to 40 hr of operation
  - Can be demonstrated on a 1U CubeSat
- **FEEP or Cold gas alternatives**

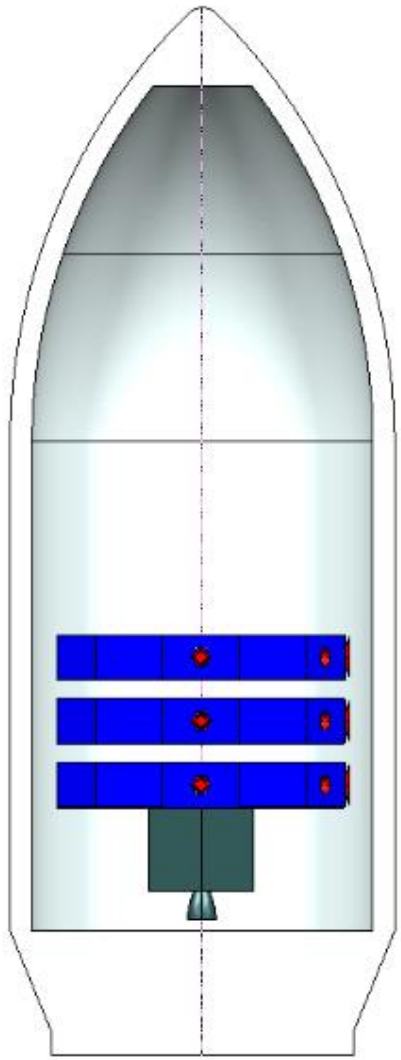
Spacecraft & Mission Design by LM

S/C based on existing LM S/C, TRL >6

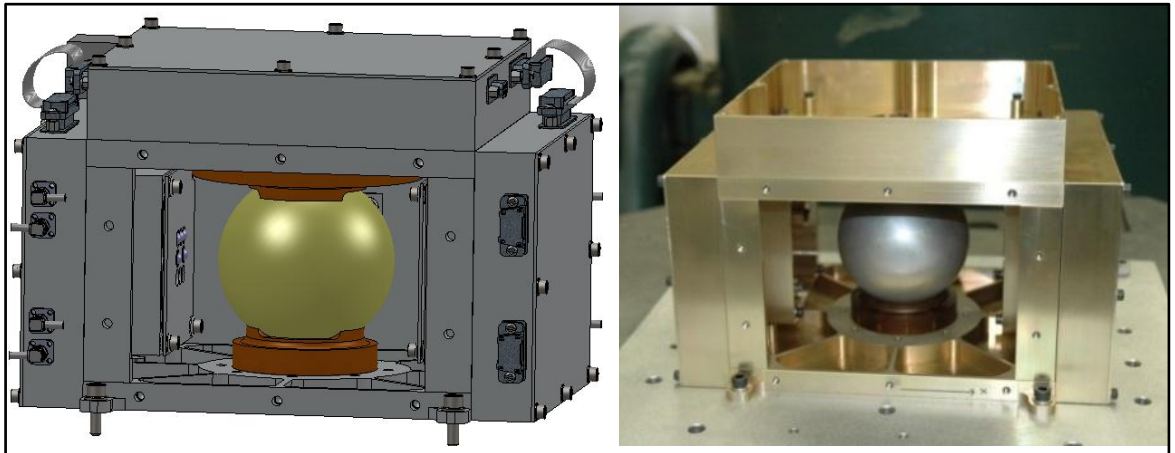
- ~3 m × 0.7 m, 300 kg, 500 W
- Fixed 10 W antenna between telescopes

- **Thermal design: GRS 10 μK at 1 mHz**
  - ±50 K at exterior at 27.3 period
  - Thermal load radiated top/bottom
  - Payload at center
- **Launch mass: 2,070 kg**
- **4-7 month cruise**
- **5 year lifetime**
- **$950M FY12**

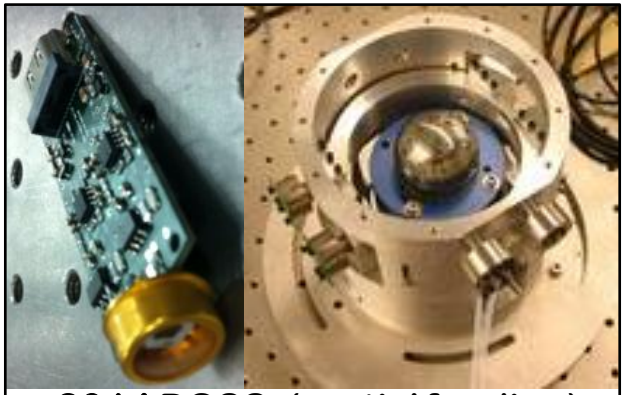




Small Sats Tech Demo Program

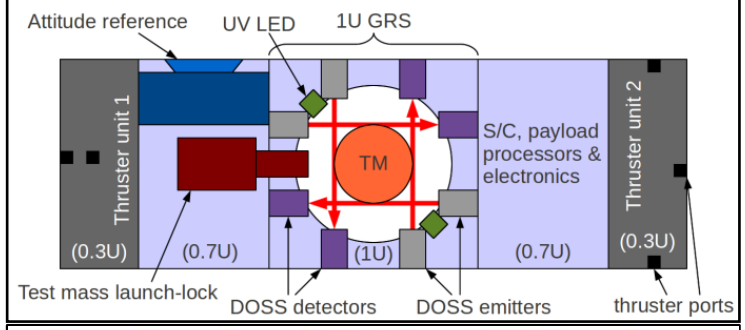


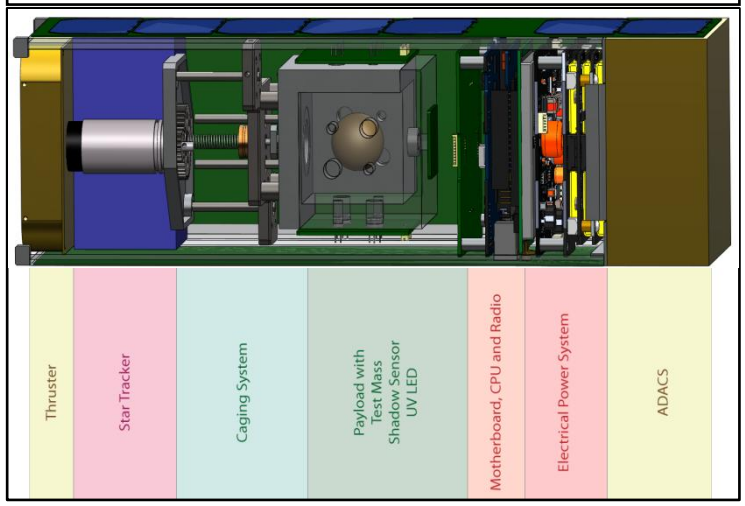
2013 UV LED Sat –(payload 6/2012)

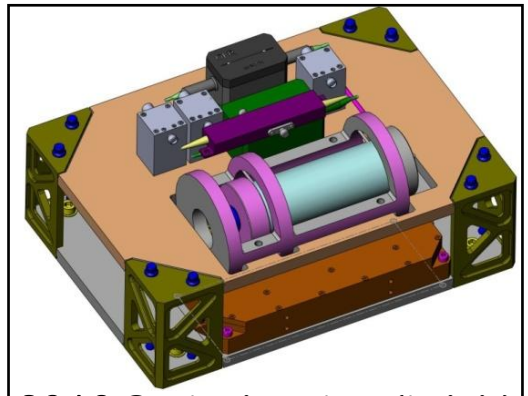


2014 DOSS- (partial funding)

2015 Drag-free CubeSat - (in lab)







2016 Optical cavity –(in lab)

Science & Technology Implementation on Small Satellites

Technology

- Gravitational Reference Sensors
- Ultra-stable optics
  - Precision Navigation
  - formation flying

Education

- Grad, Undergrad
- 3-5 year projects
- Student led tasks

Science & Technology

on Small Satellites

Education driven

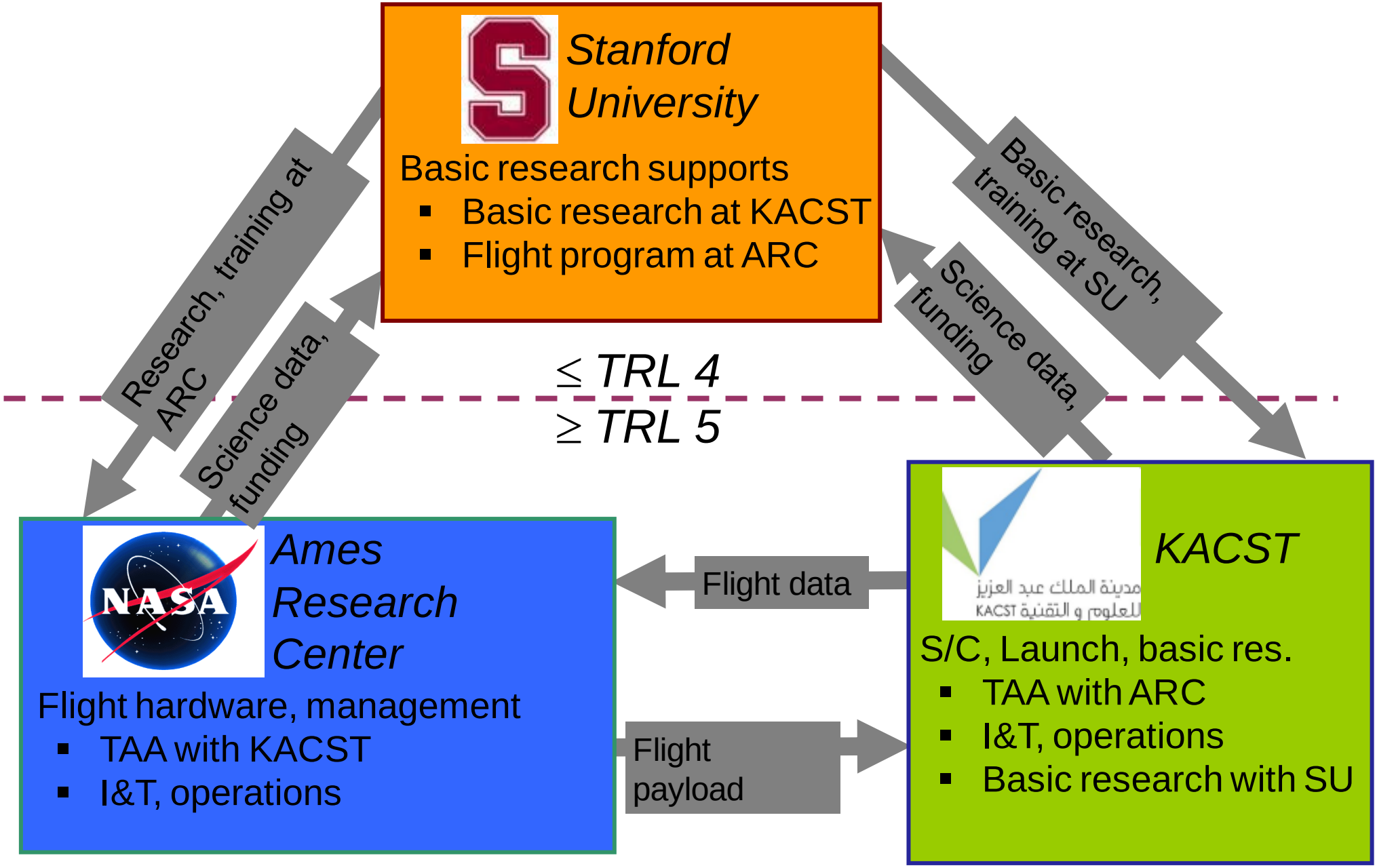
International collaborations

Science

- Special/General Relativity
- Gravitational waves
- Earth Geodesy/Aeronomy

Collaboration: Stanford – ARC – KACST

"Non Conventional Collaboration" on UV-LED SAT

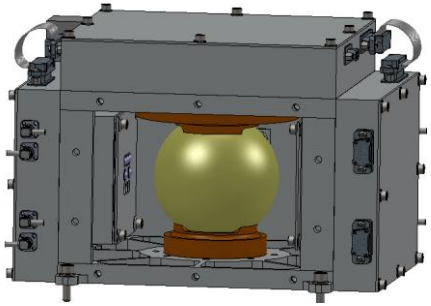


UV LED Small Satellite

55 kg
50 W
Saudi Sat 3
Launch 2013

Technology Objectives

- Raise TRL levels (4/5 → 8/9) for
  - Deep UV LEDs
  - ac charge control
- Beneficiaries:
  - LISA
  - GRACE follow-on
  - Drag-free CubeSat



Mission Design

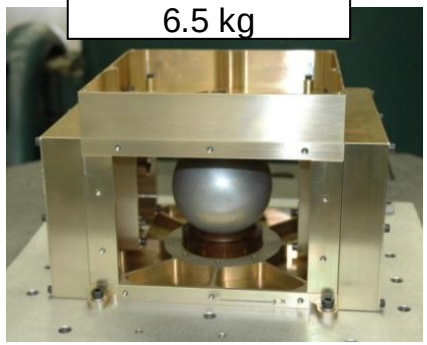
- Spacecraft: Saudi Sat
- Russian launch in 2013
- 2 month mission
- Fully funded ($1.5M)

Demonstrates unconventional international collaboration

Payload

- Isolated "test mass"
- 16 UV LEDs & photodiodes
- Charge amp
- Voltage bias plates
- ac charge control electronics

222×277×180 mm
6.5 kg



Management

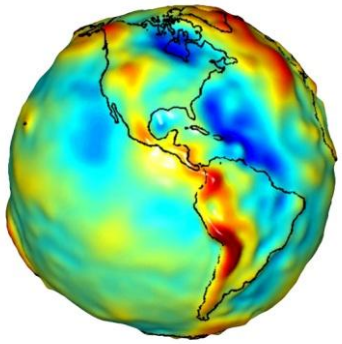
- NASA ARC: Flight payload, PM, SE, SMA
- Stanford: Payload design, SOC
- KACST: Spacecraft, Launch, MOC

The Drag-free CubeSat

4 kg
6 W
3U Cube
Launch 2015

Science

- Earth Aeronomy, space weather
- Demo < 10^{-12} m/sec^2 for future
  - Geodesy
  - Earth observation
  - Gravity science
  - Gravity-waves

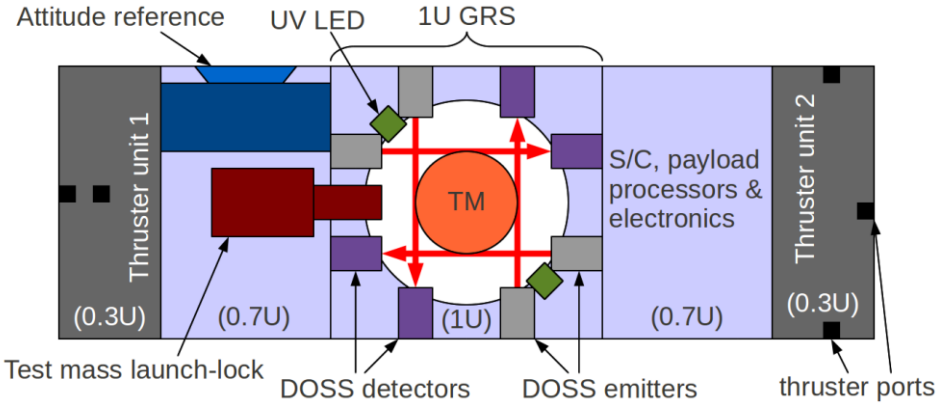


Mission Design

- 3U CubeSat
- Secondary launch via P-POD
- Launch ~ 2015
- 1-2 month drag-free ops in LEO
- Target program: Franklin/Edison

Payload

- Drag-free sensor + micro-thrusters



Management

- NASA ARC: PM, SE, SMA, mission operations
- Stanford: Payload design, drag-free control, data analysis

Looking forward to results from a gravity-wave space antenna

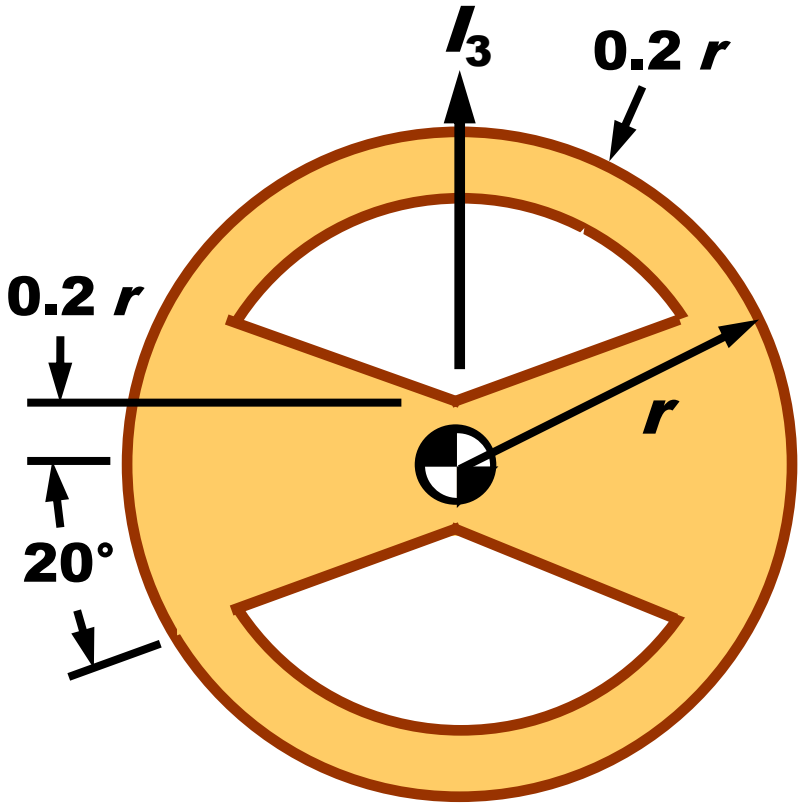
Thank you

Advantages of a Spherical GRS

1. **No TM forcing or torquing**
   - Neither electrostatic support nor capacitive sensing required, reducing disturbances & complexity
2. **Large gap (35 mm)**
   - Disturbances reduced and/or spacecraft requirements relaxed
3. **A long flight heritage**
   - Honeywell gyros, Triad I (5×10^{-11} m/sec^2), GP-B (4×10^{-11} m/sec^2 Hz$^{1/2}$)
4. **Scalability**
   - Performance can be scaled up or down by adjusting TM and gap size
5. **Simplicity**
   - No cross coupling of degrees of freedom
6. **Simple flight-proven caging mechanism (DISCOS)**

Test Mass Geometry

- **TM hollowed out: 70%/30% Au/Pt**
  - $\Delta I / I > 0.1 \rightarrow$ polhode > 0.3 - 1 Hz for spin = 3 - 10 Hz
  - Density loss < 20%
  - Symmetric $\rightarrow$ IMS modulation is sinusoidal
- **Carbide coated (e.g. SiC, ZrC)**
  - Hard (no sticking), Reflective,
  - Conductive, Allows UV charge control
  - Patches consistent or better than gold
- **External geometry requirements**
  - Spherical to ~ 30 nm
    - GP-B, Honeywell rotor ~ 10 nm
  - Mass unbalance < 300 nm
    - GP-B rotor ~ 10 nm



Optimal Geometry

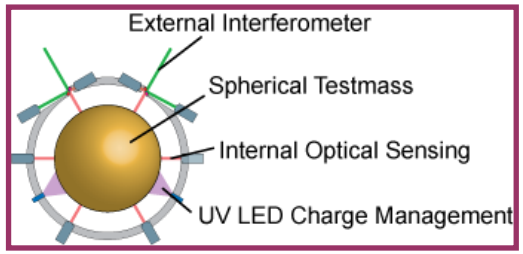
LISA Interferometric Measurement System

- **IMS follows LISA scheme with some differences**
- **1 W Nd:YAG (1064 nm), split to feed both arms**
- **Split interferometry: long-arm / short-arm interferometers**
  - Short-arm (TM to optics bench): Michelson or gravity Fabry-Pérot cavity
  - Long-arm (optics bench to remote optics bench):
    local & received laser phase difference (PBS or diffraction grating)
- **Laser pre-stabilization by optical cavity or iodine cell**
- **Single TM requires no back-link → 4 phase measurements (6 for LISA)**
- **150 MHz Doppler frequency**
  - Requires modified LISA phasemeter
  - Alternate: frequency shift low-power local beam with AOM (or EOM)
    - Requires clock with ~10^{-14} accuracy (e.g. space qualified H maser)
- **6 µrad point-ahead angle: LISA PAAM (TRL 4)**

Differential Optical Shadow Sensor (DOSS)

Technology Objectives

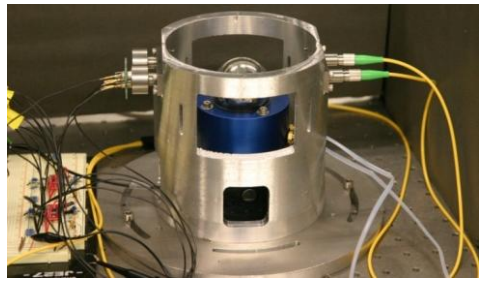
- Raise TRL level for miniature high-sensitivity displacement sensor
  - nm/Hz$^{1/2}$ sensitivity
  - No forcing
  - Non-contact



Mission Design

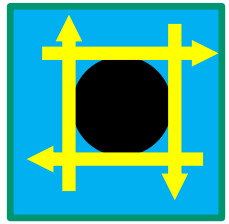
2 kg
4 W
2U Cube
Launch 2014

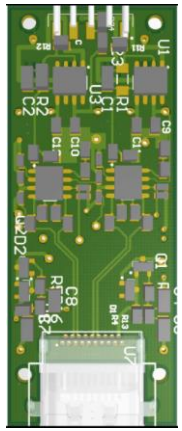
- 2U CubeSat
- Any orbit
- Launch ~ 2014
- 1 month ops
- Payload funded



Payload

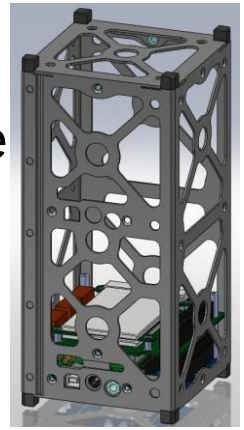
- Light source:
  - SLED, 1545 nm
- InGaAs quad-photodiode
- Ultra-low current Difet amp





Management

- Stanford & KACST: Payload, CubeSat structure
- I&T & Launch: pending



Fiber-coupled Optical Cavity Small Sat

Technology Objectives

- Raise TRL levels for:
  - Frequency stabilized laser
  - Fiber coupled optical train
- Beneficiaries:
  - STAR, GRACE follow-on, LISA

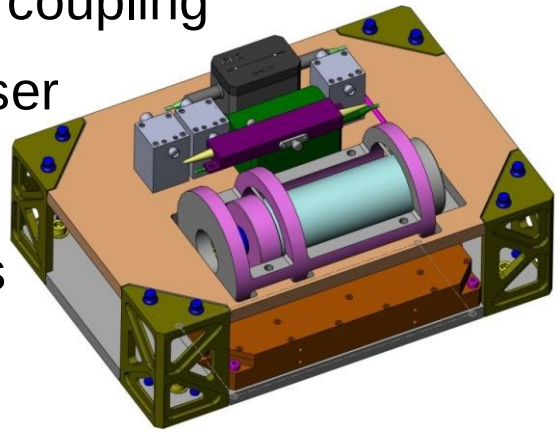
Mission Design

- Saudi-sat compatible secondary
- Any orbit, slow tumble OK
- Launch ~ 2015
- 1 month mission lifetime

55 kg
50 W
Saudi Sat 3
Launch 2016

Payload

- High-finesse Optical cavity
- Optical fiber coupling
- Low-cost laser
- Modulator
- photodiodes



Management

- NASA ARC: PM, SE, SMA, ops
- Stanford: Payload design, science
- KACST: Spacecraft

Space-Time Asymmetry Research (STAR)

Science

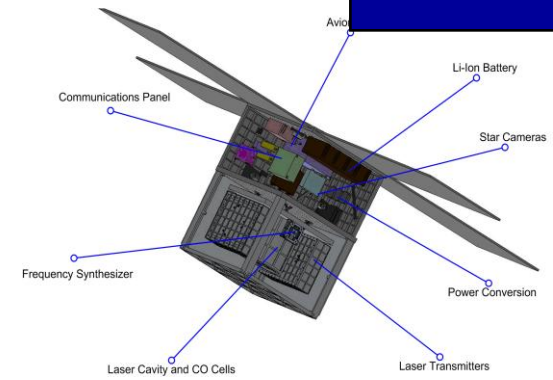
"*Deviations from Einstein's predictions would cause us to rethink one of the foundational pillars of all of physical science*" – Astro2010 decadal

- STAR will measure:
  - Isotropy of speed of light to 10^{-17}
  - The direction of anisotropy
  - Dependence on boost velocity

Mission Design

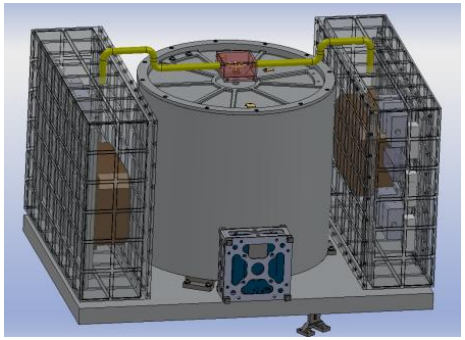
180 kg
150 W
ESPA
2018

- ESPA compatible on EELV
- Circular sun-sync 650 km orbit
- Launch ~ 2016
- 2-year lifetime
- Class D mission

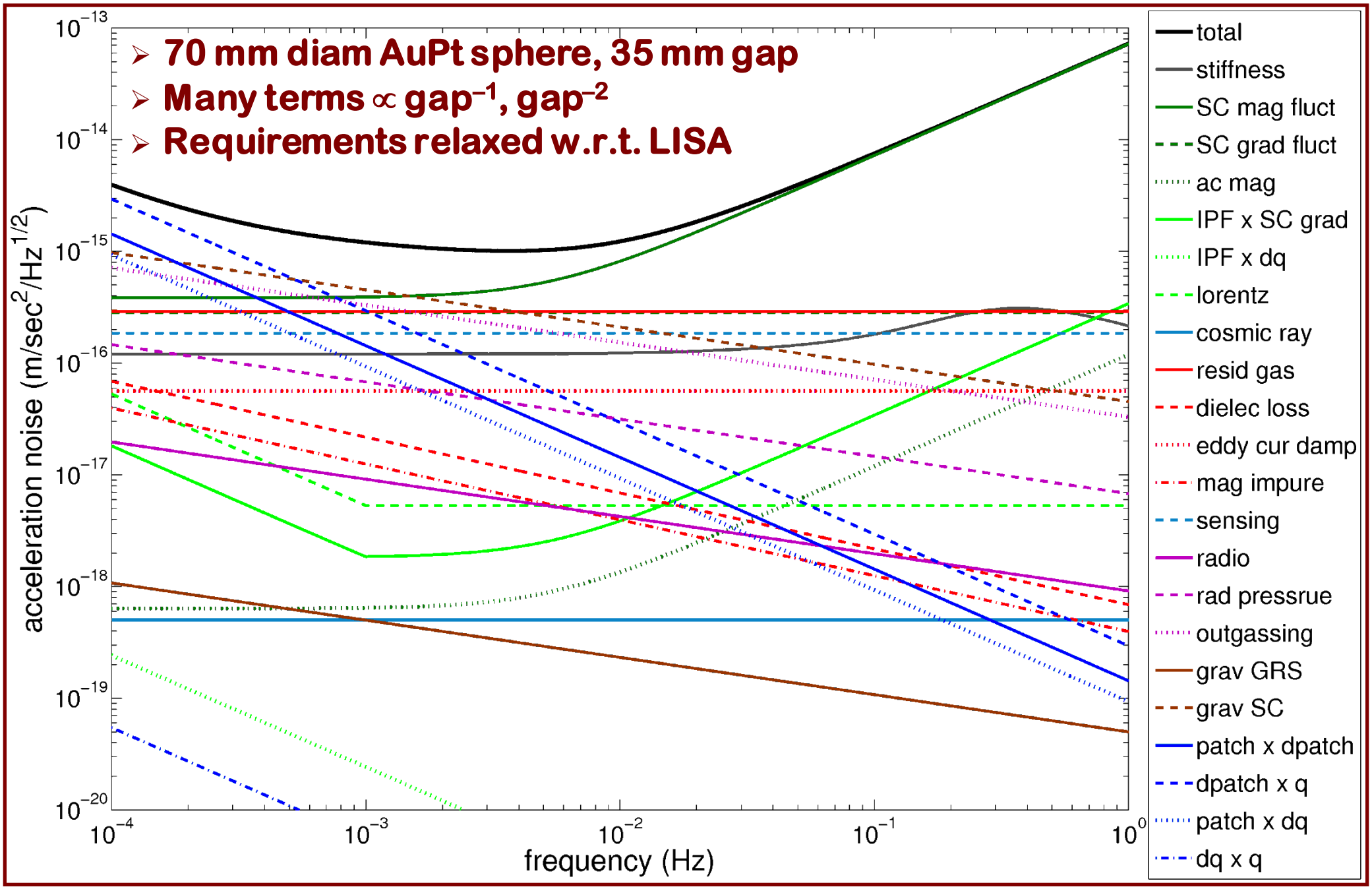


Payload

- Molecular clocks
- Orthogonal optical cavities
- Low-noise comparator
- Multi-layer thermal enclosure



Management

- NASA ARC: PM, SE, SMA, ops
- Stanford: Payload design, science
- KACST: Spacecraft & Launch
- DLR: molecular clocks

Acceleration Noise Budget