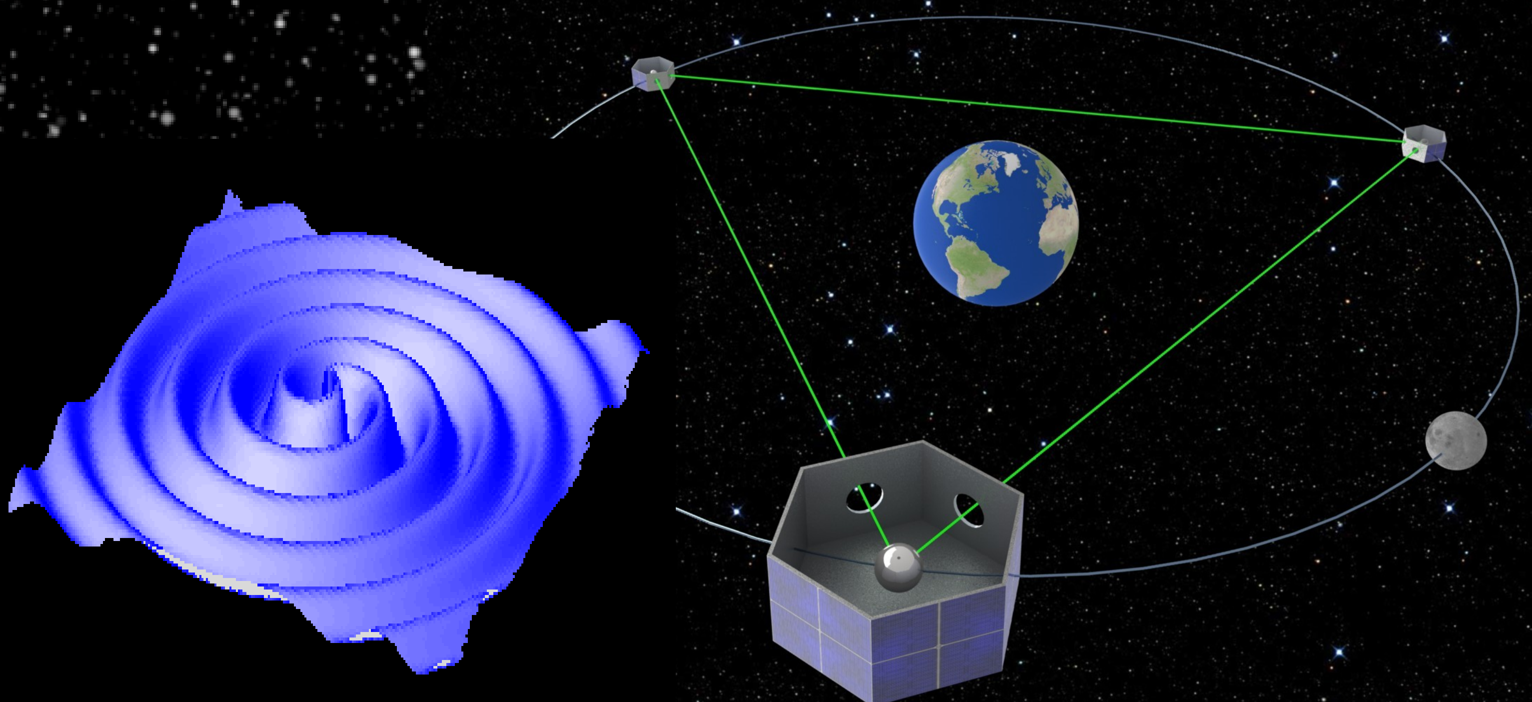
Gravitational Wave Astrophysics
The Next Frontier in Understanding the Universe



LISA-2020 an Intermediate-Scale Space Gravitational Wave Observatory for This Decade

Gravitational Waves
Advanced Detectors Workshop
GWADW 20th -24th May 2013

Sasha Buchman
Stanford University
for the Space Sciences team

LISA-2020 (LAGRANGE based)Collaboration

Stanford	NASA Ames Res. Center	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

MIT	University of Florida
▪ μN thrusters	▪ ATC ▪ DF control

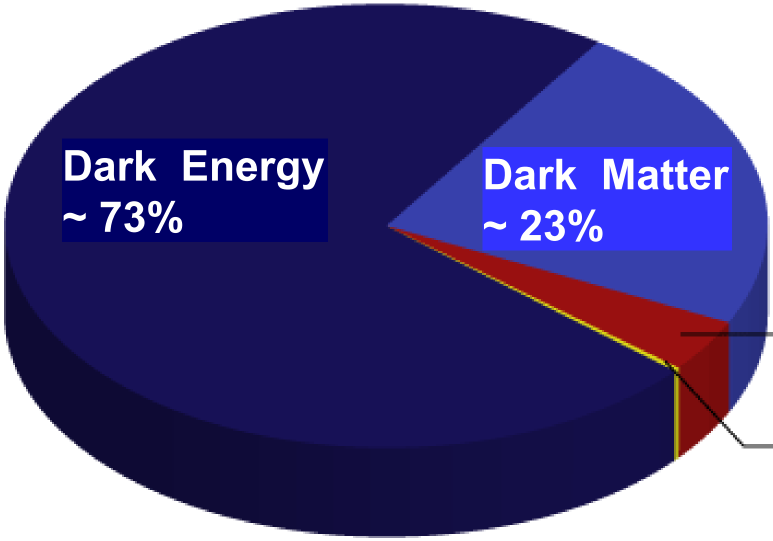
Outline

- **Why Gravitational Wave (GW) Astronomy ?**
- **What Is the Status of GW Astronomy ?**
- **How Do We Go From Here to LISA 2020 ?**

When Can We Fly 'THE NEXT' GWD in Space ?

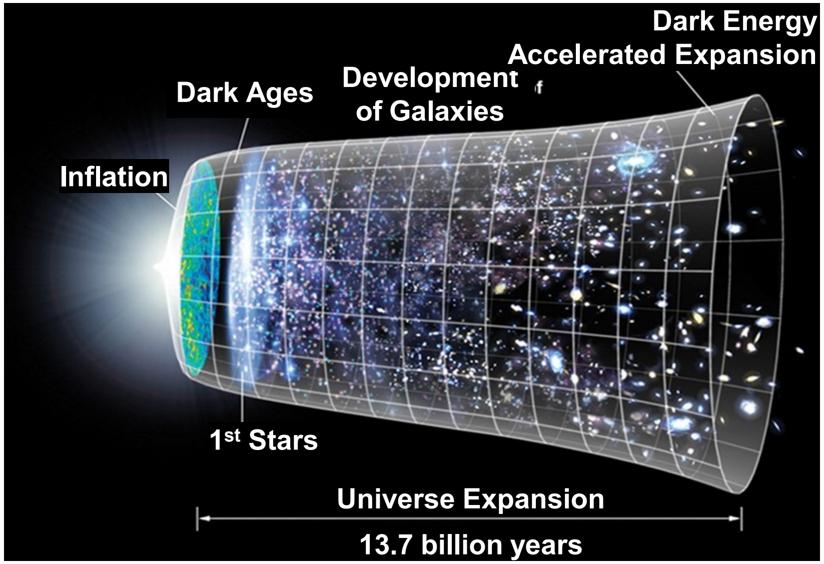
Today's 'DARK' Universe

The Universe as seen by EM



Other non-luminous components
- intergalactic gas 3.6%
- neutrinos 0.1%
- SBHs 0.04%

Luminous matter
- stars & luminous gas 0.4%
- radiation 0.005%



What do we really know?

- Universe known by EM; only ~0.5% of matter
- Continuous '**model improvements**' last 100 years

  BH Universes and paradoxes, CPT & LI violations, Unification ?
- GW '**see and interact**' with 100% of matter
- SM & GR used for converting EM data to Universe picture have 'issues'

Seen in EM "understood" in GR

Why GW Astronomy

- **Gravitational Wave (GW) Astronomy Will Give the Answers About the Universe That EM Cannot Provide**

  Not really supported by the space community

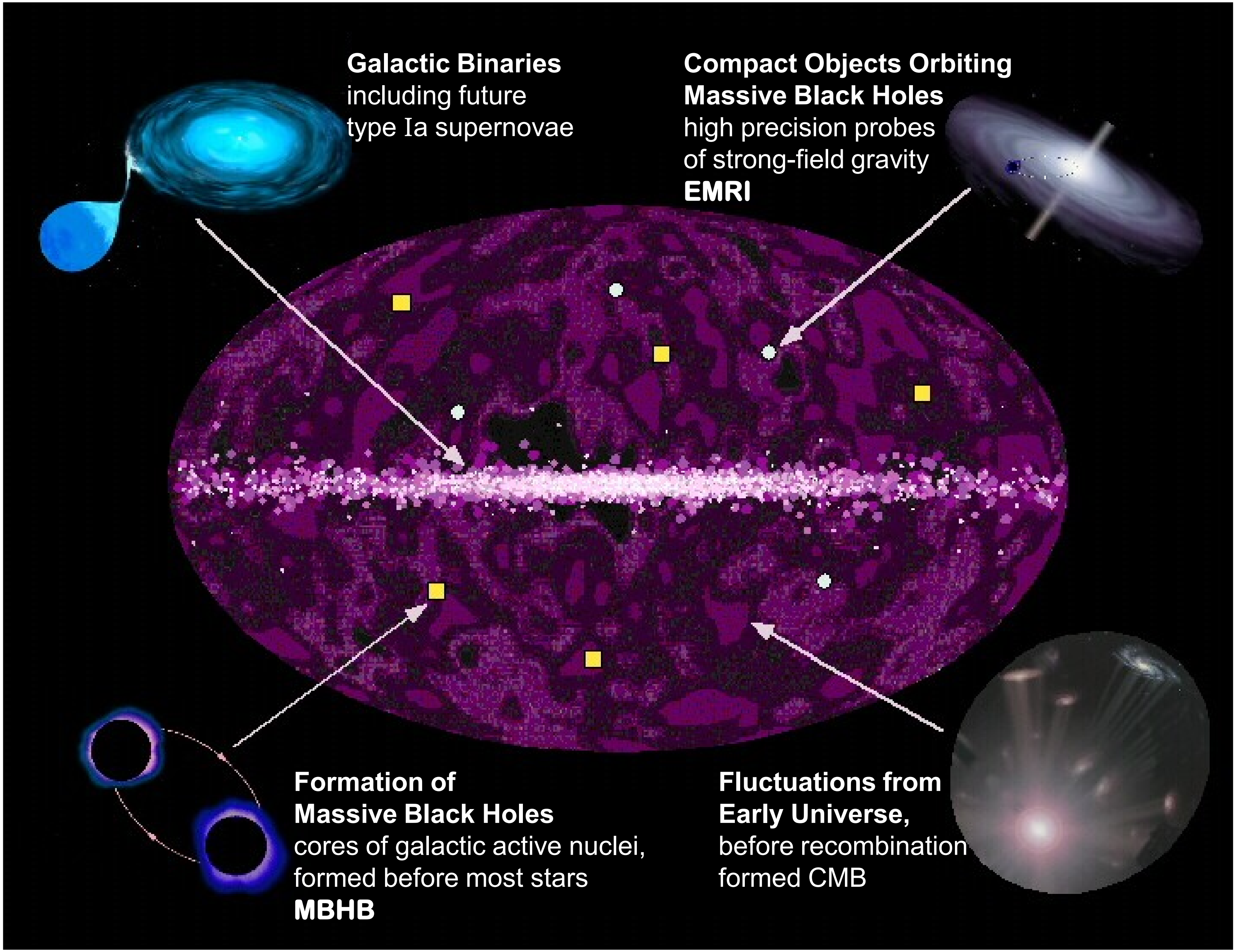
- **The 10^{-4} Hz to 1 Hz is the 'Richest' GW Range**

  This Range Requires a Space GW Observatory

- **A Laser Interferometer Space Antenna (LISA) Is Necessary and Possible by 2020:**
  - **Will Achieve the Most Important GW Science**
  - **At "Affordable Cost" ($500M)**

- **Support of Science Community Critical for LISA *Series***

The Gravitational-Wave Sky



Conclusion #1

1 Physics & Astrophysics are in a 'DARK' period; GW Astronomy is the most plausible SOLUTION

2 Status and prospects for GW Astronomy

Resolution and Sources of GW

- Earth 10 Hz to 1000 Hz, ~***2016***

  Local (100 MPc range) Medium Resolution

- Astronomical Observations <10^{-7} Hz, ~ ***2017***

  TBD Sources & Resolution

- Space Experiments 10^{-4} Hz - 1 Hz, > ***2030***

  Large # of Sources & Excellent Resolution

GW Space Observatories Issues

With many caveats which are about 50% probable:

- eLISA launch *NOT BEFORE* 2028 (means maybe after 2035)
- NASA - LISA launch *NOT BEFORE* 2030 (means maybe after 2035)

(Approval to Mission; 10 -20 years; Hubble, GP-B, LPF, WST …)

Implications:

- Delay in ‘best’ information required to understand the Universe
- Difficulty motivating students and scientists to join the field
- Old technology and lack of program continuity
- Loss of opportunity to perform in conjunction with LIGO/VIRGO/etc

Few in this audience will have any chance to see LISA type science

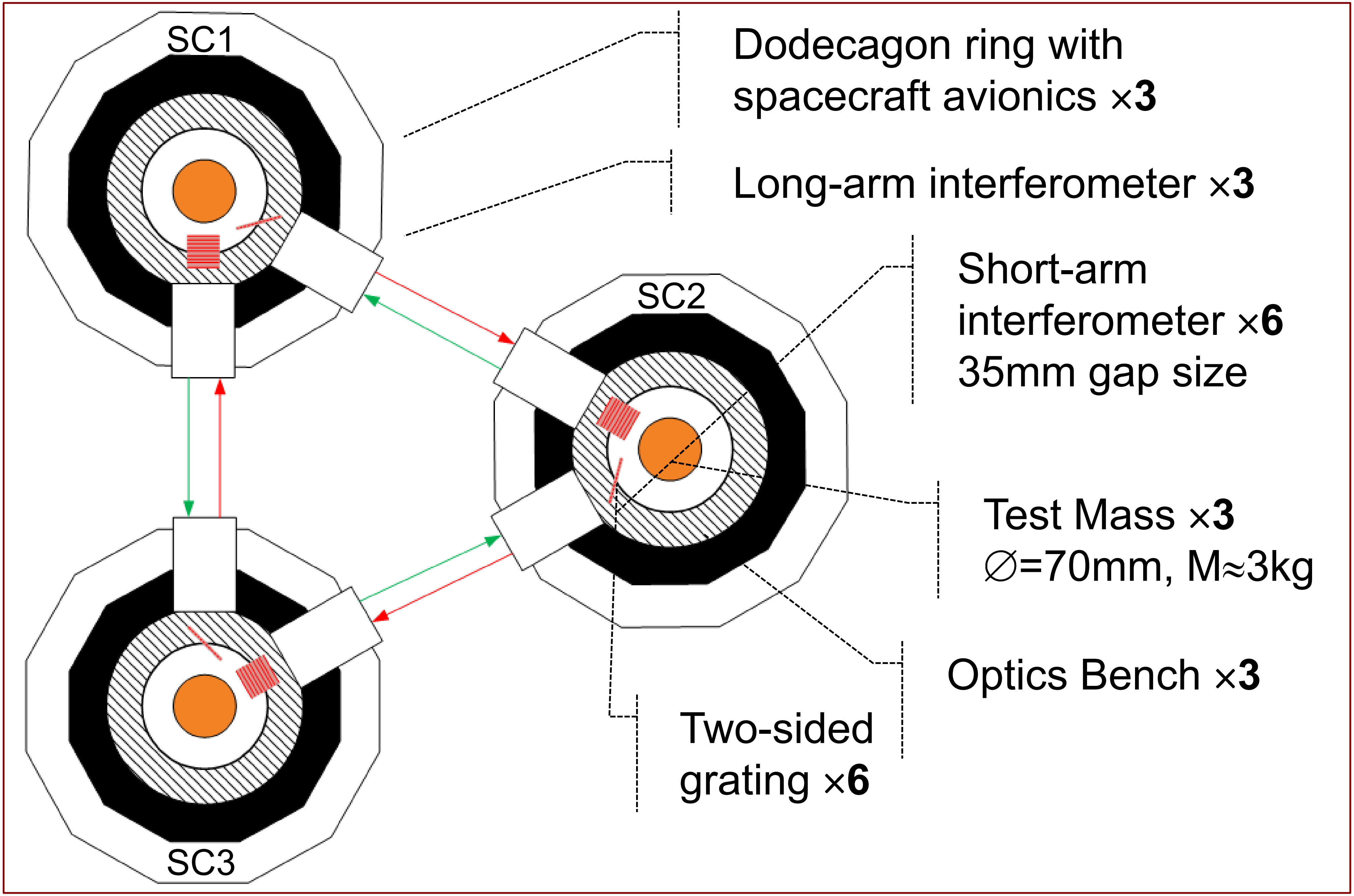
LISA 2020: GW Observatory for This Decade

Cost	Complexity	Comm. Link
Reduce ~ 70%	Reduce ~ 50%	Increase >100

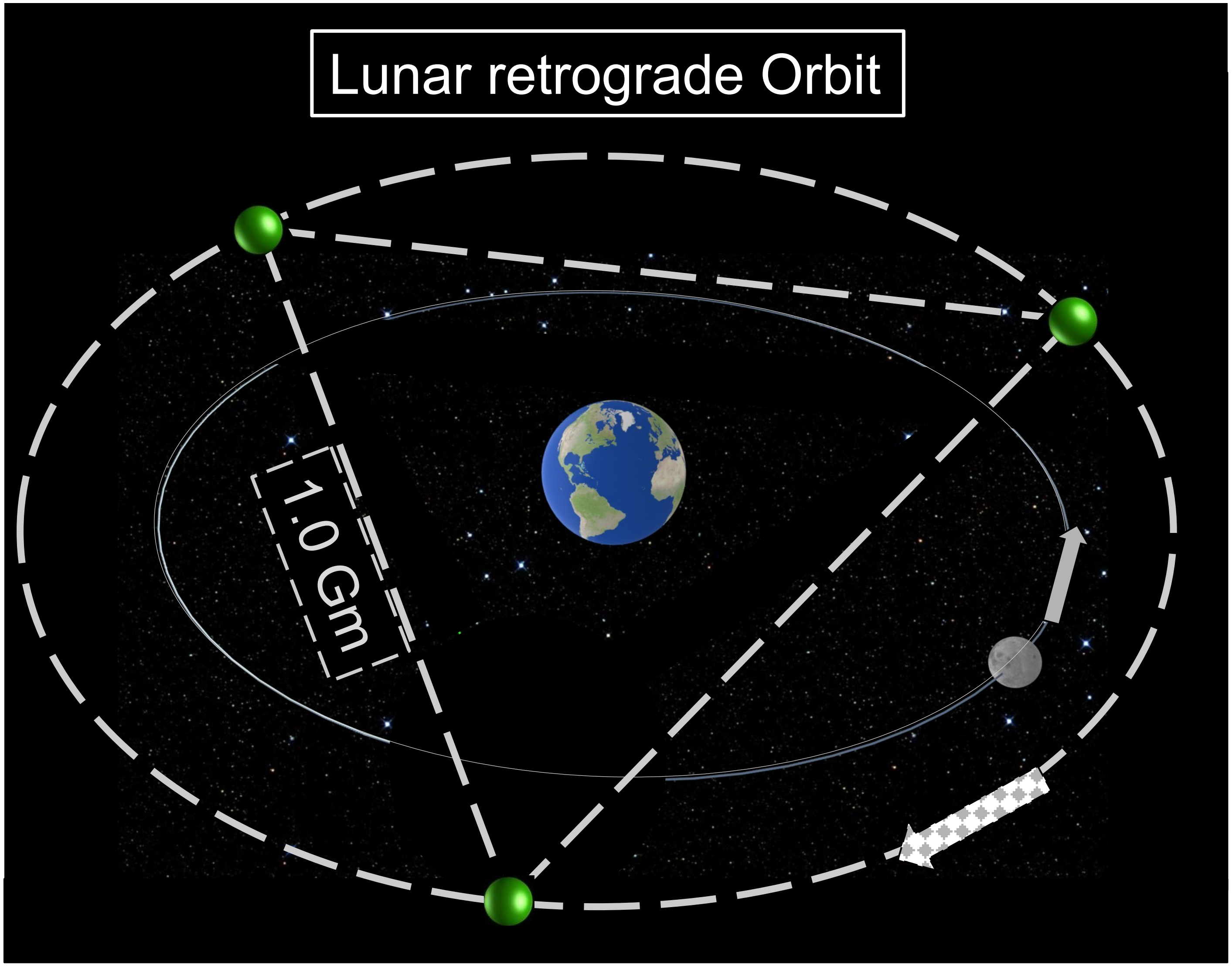
- Geocentric Orbit: ~ 50% Heliocentric cost
- Reduced Requirements ~ ×30
- Small sat approach to tech demonstrations
  - 2013-2017 technology (LISA technology is older than 2000)
  - Parallel, low cost, low risk, on small and cube satellites
  - ~6 technologies at 1 M$ - 4 M$ each
  - Multiple institutions and international partners
- Simplified Robust Inertial Sensor (LPF back-up)
  - Spherical, fully drag-free, optical sensing
- Metrology
  - Reflective Optics with Gratings

LISA-2020 Schematics

Based on LAGRANGE with 1/30 performance



Overview of LISA-2020 Orbits



Geocentric Orbits in Lunar Plane; Arm ~ 1 Gm

Data Rate Estimate for Space Antennas

	GP-B	1 LISA or LISA-2020 SC	3 LISA SC vs GPB
Plan	0.35 GB/day (actual data rate)	0.011 GB/day (NASA) 0.004 GB/day (ESA)	0.033 GB/day (NASA) 0.013 GB/day (ESA)
System			
SC	SC (GPB 6 deg ctrl)	SC (LISA-2020 7 deg ctr) (LISA 7)	≈ (GPB)×3
Temperature	Cryogenics	μK control	≈ (GPB)×3
Propulsion	He thrusters	μN thrusters	≈ (GPB)×3
Pointing	1 telescope	2 telescopes	≈ (GPB)×3**×2**
Test Masses	4 TM × 3 deg ctrl.	2 TM × 6 deg control (coupled)	≈ (GPB)×3**×2**
Read-out	4 SQUID systems	4 pm interferometers	≈ (GPB)×3
BW	Meas BW 12.9 mHz	Meas. BW 0.1-100 mHz	≥ (GPB)×3
Formation	None	N/A	3 SC ???

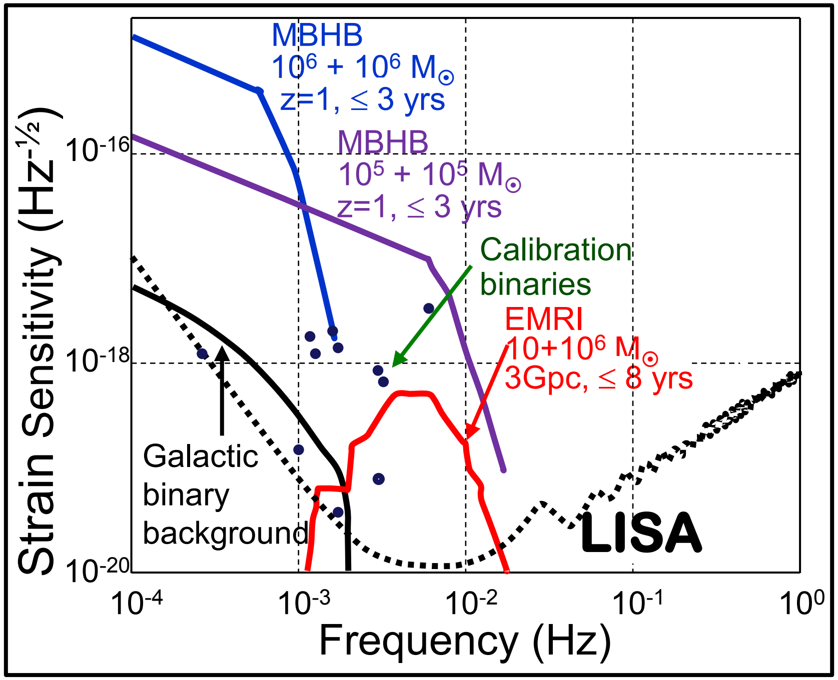
GPB data rate ≤ 1 LISA/LISA-2020 SC data rate
LISA/LISA-2020 data rate ≥ 3 × GP-B data rate ≥ 1 GB/day
Estimated LISA/LISA-2020 data rate / Planned LISA data rate (ESA)* ≥ 77

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

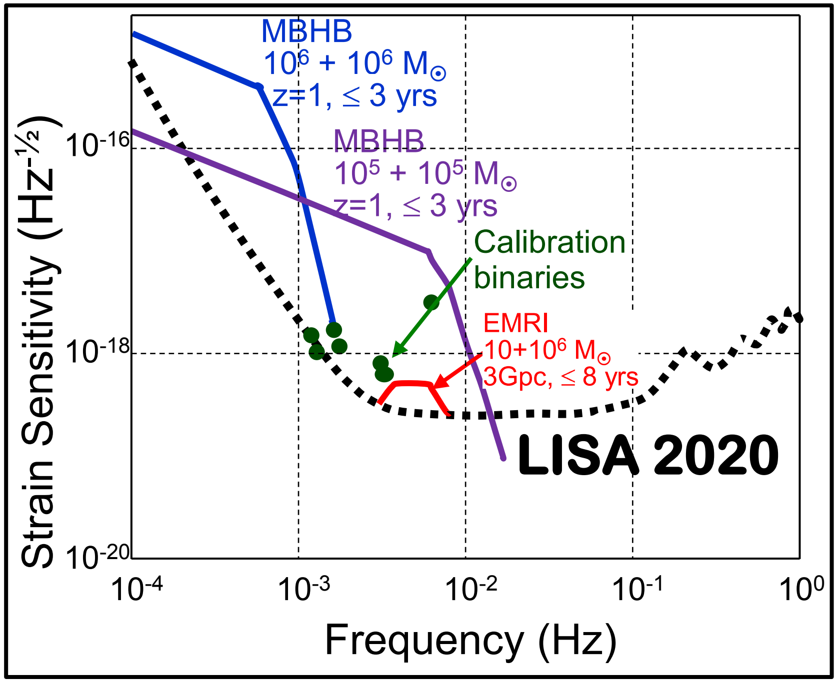
Comm Link Increase > 100

LISA & LISA 2020

- **LISA:** 10^{-4} – 1 Hz **GW in Space**
  Laser Interferometer Space Antenna
  "Standard" since 1995
  - **Based on 20 yrs of studies by LISA team**
  - **Heliocentric Orbit with Three 5 Gm Arms**
  - **$\delta h/h \approx 10^{-20}$**
  - **Cost > 2 G€**
  - **Launch AFTER 2030**



- **LISA 2020:** 10^{-4} – 1 Hz **GW in Space**
  - **Based on 10 yrs of studies by SU team**
  - **Geocentric Orbit with Three ~1 Gm Arms**
  - **$\delta h/h \approx 3\times10^{-19}$**
  - **Cost ≈ 1/2 G$**
  - **Launch Around 2020**



LISA & LISA-2020

	Orbit (Gm)	TM ($ms^{-2}Hz^{-1/2}$)	Metrology ($pm\ Hz^{-1/2}$)
LISA 2020	0.7-1.0 Geocentric	10^{-13} Sphere × 1	240 Reflective
LAGRANGE	0.7-1.0 Geocentric	3×10^{-15} Sphere × 1	8 Reflective
LISA	5.0 Heliocentric	3×10^{-15} Cube × 2	20 Transmissive

Metric	LISA	LISA-2020
Total MBHB	**110-220**	**20-40**
MBHB z > 10	3-60	1-4
EMRIs	800	≤ 10
Total WDB	**$4\ 10^4$**	**≤ 3×10^3**
WDB with 3D	8×10^3	≤ 10^2
Stochasic Background	1.0	≤ 0.2

Principal Cost Savings Relative to LISA

1. **Orbit change: Geocentric (0.7 Gm – 1.0 Gm arm length)**
   - Requires 1 small propulsion module instead of 3
   - Launch mass savings: ~ 3,000 kg
   - Reduced operations & communications complexity
   - Other orbits possible Earth-Sun L1?
2. **Reduced S/C mass from simplified payload components**
   - 1 GRS, 1 Laser, 1 optics bench, smaller (20 cm) telescopes
     - 2 Lasers budgeted for redundancy (4 in LISA)
     - No credible TM failure mechanism
     - TM sensing, charge control, spin-up, and drag-free have redundancy
   - Launch mass savings: ~ 150 kg $\times$ 3 spacecraft
   - Any 'available ' compact TM technology OK.
3. **LISA-2020 wet launch mass: ~2,000 kg (~5,000 kg for LISA)**
   - Historic trends show cost scales with mass
   - Complex payloads are hard to cost

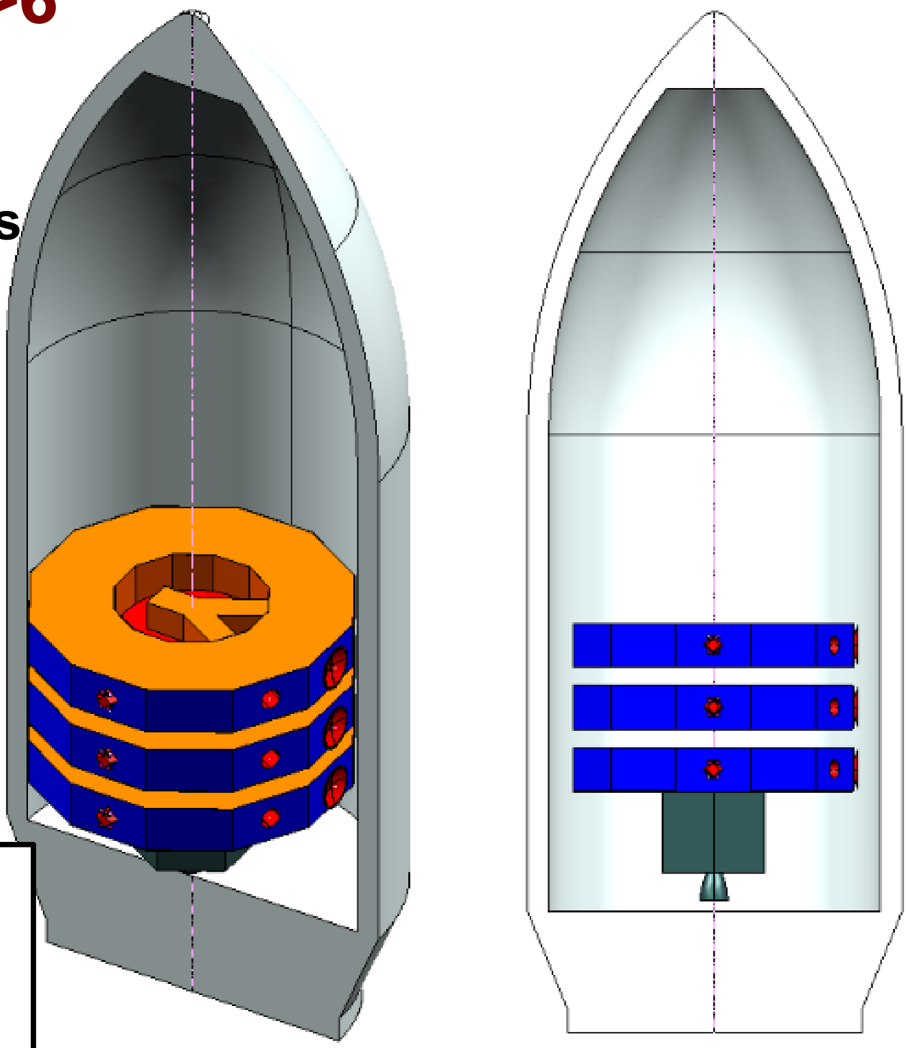
Spacecraft & Mission Design by LM

Off the shelve but too large

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**



Concept of 3 SC & 1 Propulsion module In Launch Fairing

LISA-2020 GWD Concept Study

LISA-2020 concept with heritage

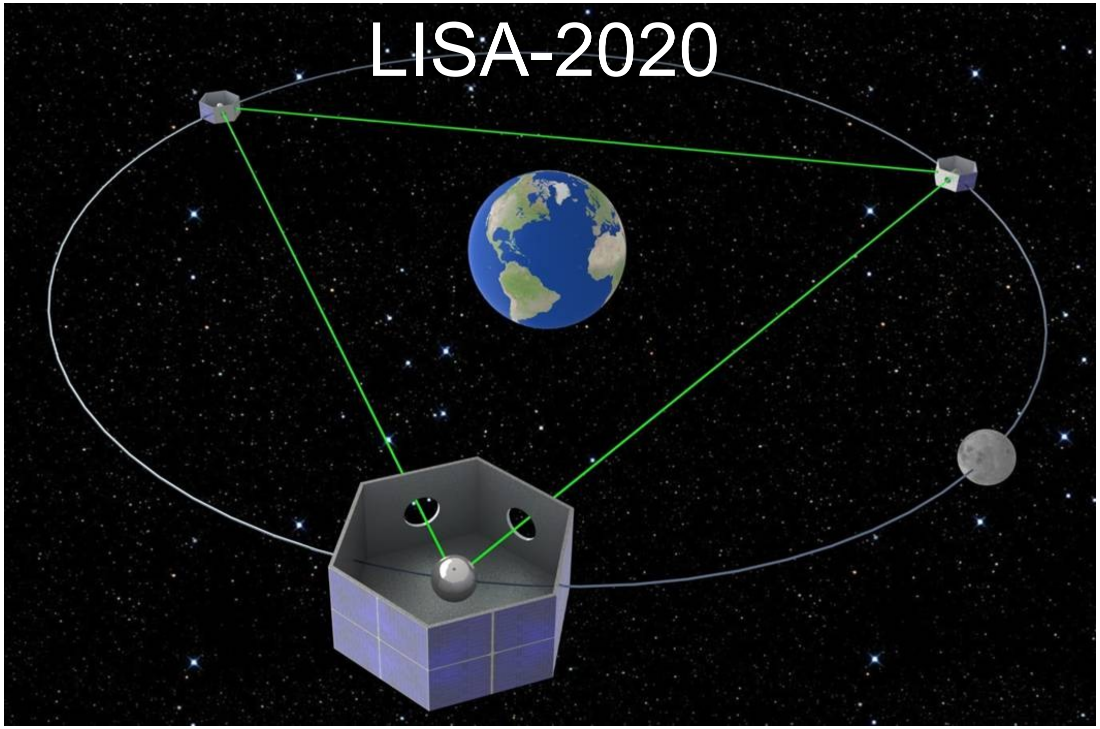
2 t launch
3 00 kg
3 00 W

Honeywell, DISCOS, LPF, ST-7, GP-B, STAR

- **3 drag-free spacecraft in geocentric orbit**
- **Minimized payload: 1 test-mass (sphere), 1 laser, 2 telescopes**
- **Small sat approach to tech demonstrations**

LISA-2020 maintains LISA science ~ 50%

- **50% Complexity**
- **30% Cost**
- **10,000% Communications Band**



For and Against LISA 2020

- **Advantages**
  - GW Science ~2020
  - Technology
  - GW Community
- **Obstacles**
  - Funding
  - Competition
    - EM Astronomy has **Data**
    - Planetary Science
  - Inadequate EPO

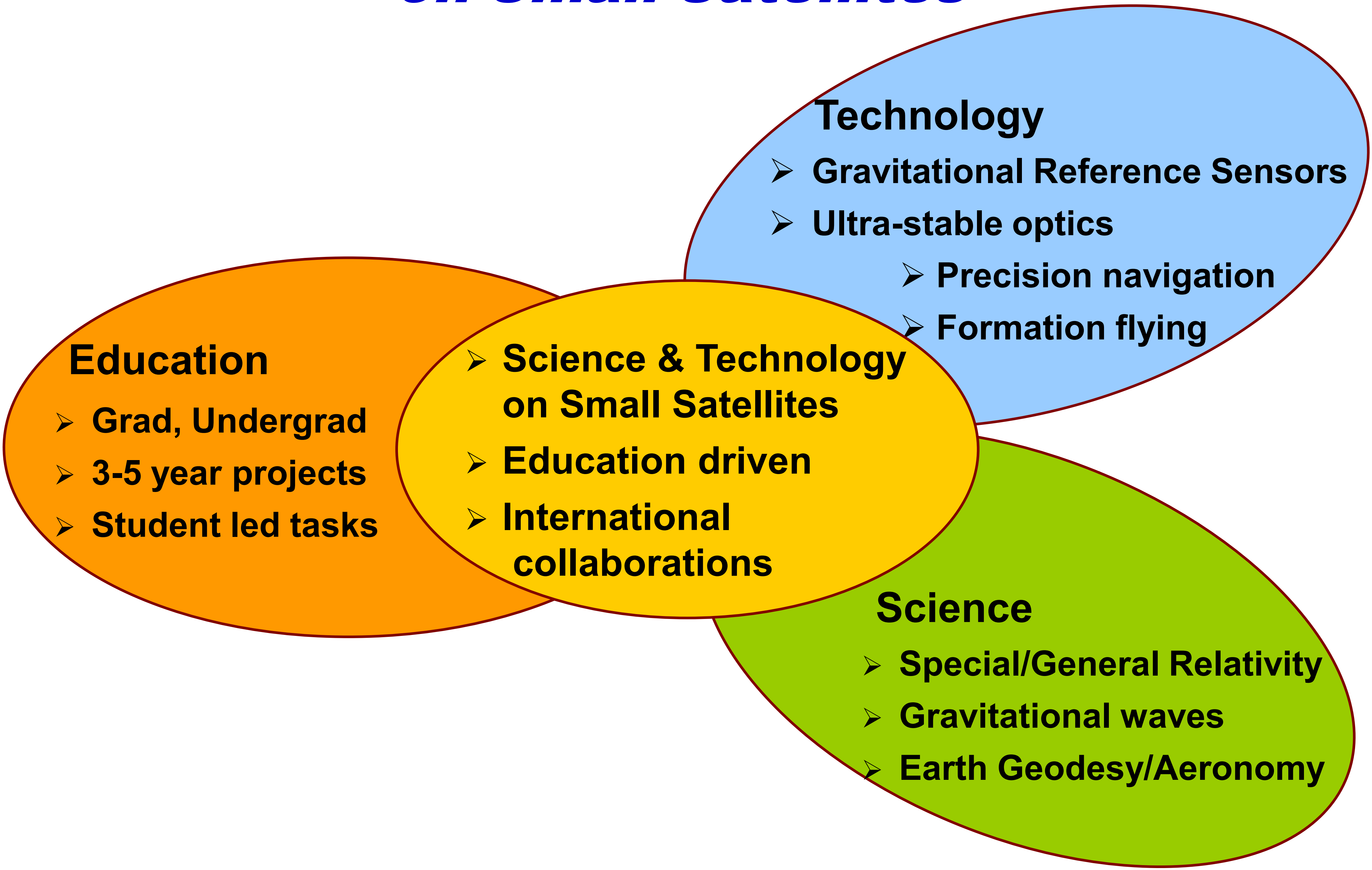
Conclusion #2

1 Physics & Astrophysics are in a 'DARK' period; GW Astronomy is a very plausible SOLUTION

2 A LISA-2020 Type Geocentric Medium GW Antenna Can Provide Excellent GW Data ~2020

3 Technology Development on Small Satellites

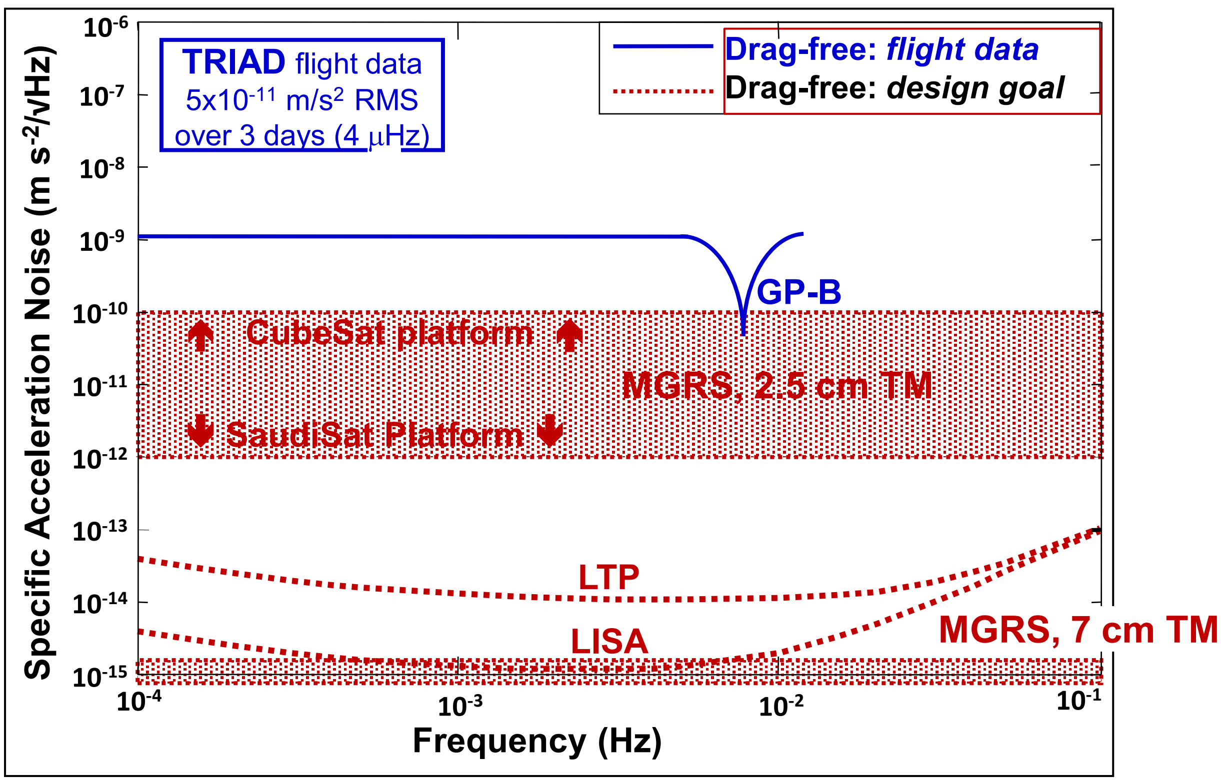
Science & Technology Implementation on Small Satellites

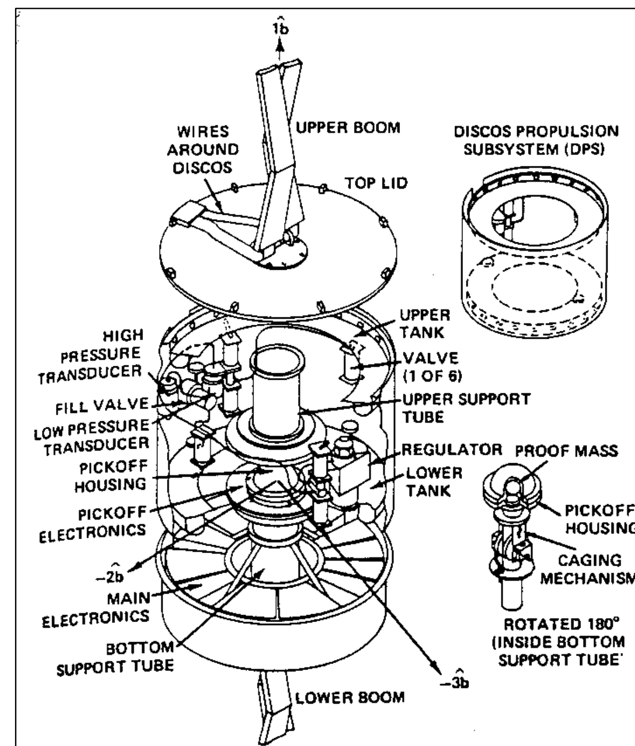


Stanford Spherical 6 DOF TM Performance

1. **Control Spacecraft to follow TM**
2. **Reduce External Disturbances**
   - Aerodynamic Drag
   - Magnetic Torques
   - Radiation Pressure
   - Gravitational Torques

GP-B Flight Gyroscope **2004**





TRIAD Sensor **1972**

Applications of Drag-free Technology

	Category	Application	Drag-free Performance ($m/sec^2Hz^{1/2}$), frequency (Hz)	Metrology (m)
Capability of Cubesat with 2.5 cm TM	Navigation	Autonomous, fuel efficient orbit maintenance	$\leq 10^{-10}$, near zero frequency [a,b]	≤ 10 absolute
		Precision real-time on-board navigation	$\leq 10^{-10}$, near zero frequency [a]	≤ 10 absolute [a]
		Formation flying	$\leq 10^{-10}$, near zero frequency [a]	$\leq 10^{-9}$ differential [a]
	Earth & Planetary Science	Aeronomy	$\leq 10^{-10}$, 10^{-2} to 1 Hz [a]	1 absolute [a]
		Geodesy, GRACE	10^{-10}, 10^{-2} to 1 Hz [a, b, c]	10^{-6} differential [a]
		Future Earth geodesy	$\leq 10^{-12}$, 10^{-2} to 1 Hz [a]	$\leq 10^{-9}$ differential [a]
	Fundamental Physics	Equivalence Principal tests	$\leq 10^{-10}$, 10^{-2} to 1 Hz [a]	$\leq 10^{-10}$ differential [a]
		Tests of general relativity	$\leq 10^{-10}$, near zero frequency [a]	≤ 1 absolute [a]
7 cm TM	Astrophysics	Gravitational waves	3×10^{-15}, 10^{-4} to 1 Hz	$\leq 10^{-11}$ differential

Notes: [a] Performance to be demonstrated by the drag-free CubeSat; [b] demonstrated; [c] non-drag-free

Courtesy John Conklin

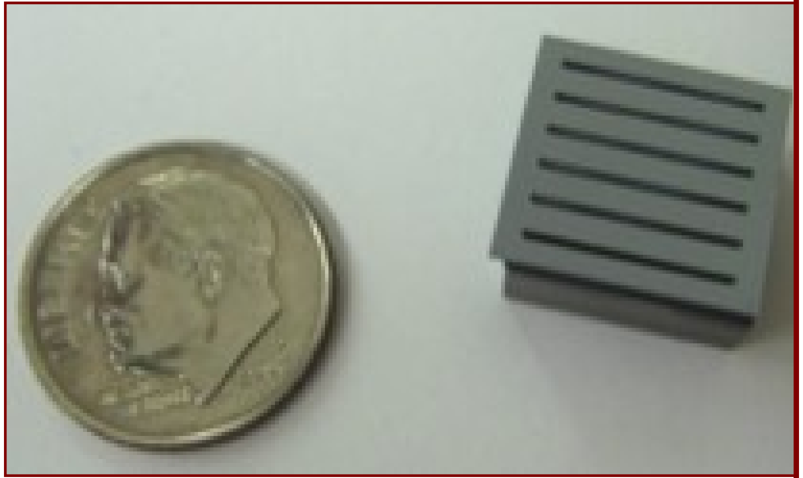
Advantages of a Spherical TM

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. **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)**

NEGATIVE: The Mirror Moves

Micronewton Thrusters Design

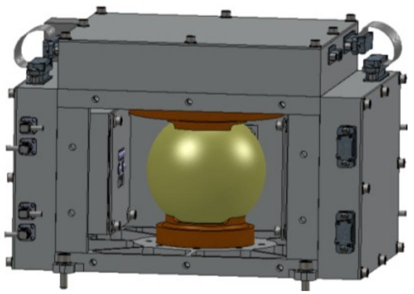
- **Drag-free & attitude via µN thrusters**
- **No existing thruster meets LISA noise, max thrust, and lifetime requirements**
  - LPF evaluating alternates to FEEPs
- **MIT & SRI micro-fabricated ion thrusters as attractive alternative to Busek CMNT or Italian/Austrian FEEPs**



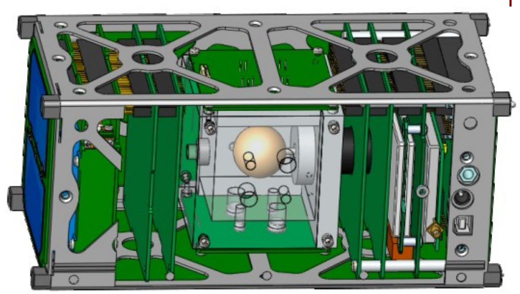
  - Micro-fabricated emission sites produce ions & electrons
  - "Digital propulsion": 100's – 1,000's of independent emitters / cm^2
    - Single unit can produce forces + torques
  - Huge dynamic range: ion production physics unchanged over 10^{-9} to 1 N
  - Up to 10,000 sec Isp
  - Prototype: 1 nN to 5 µN thruster ion source tested to 40 hr of operation
  - Can be demonstrated on a 1U CubeSat
  - MIT – uses capillarity; no moving parts

Thrusters are a problem

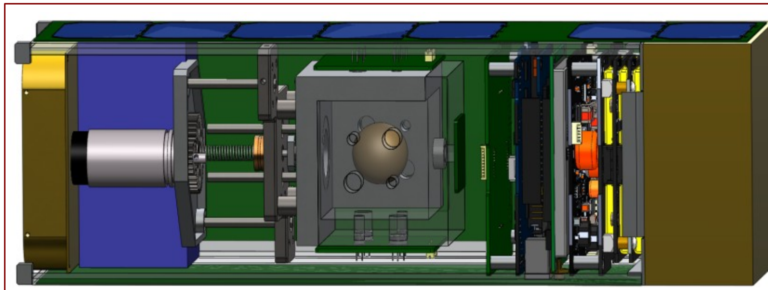
Small Sats Technology Program



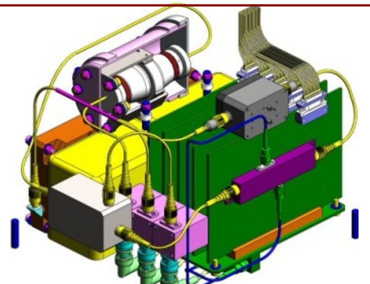
UV LED Sat -2013



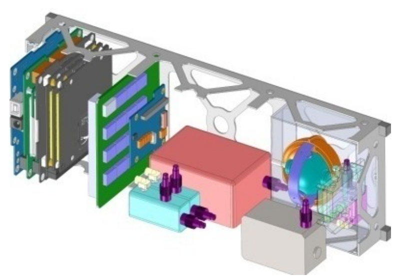
DOSS Sat - 2014



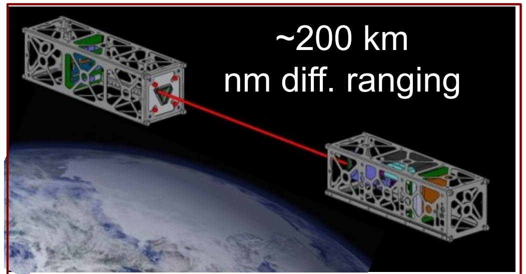
Drag-Free CubeSat - 2015 NEXT
ARC-SU-KACST Flight



Optical Sat – 2015
(Lab development)



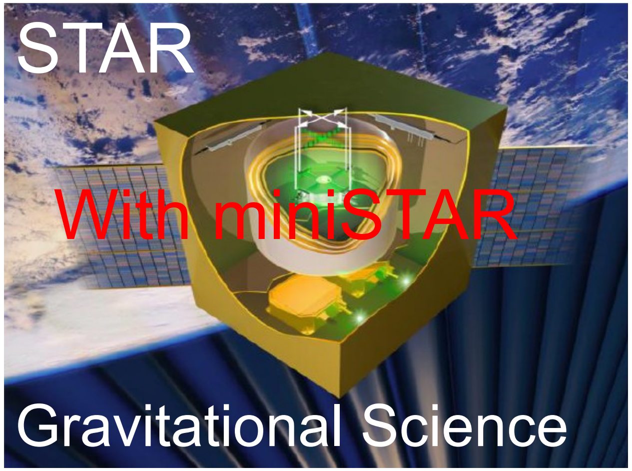
Mini STAR– 2015
(Lab development)

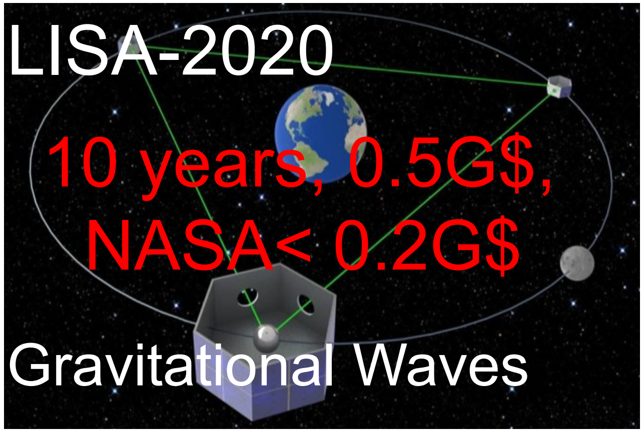


Laser Ranging – 2016
(Lab development)

df/f ~ 10^{-12}
1mm optical cavity
1 mm gas cell
25 cm^3, 25 g, <100 mW

Mini clock Sat – 2016
(Lab development)

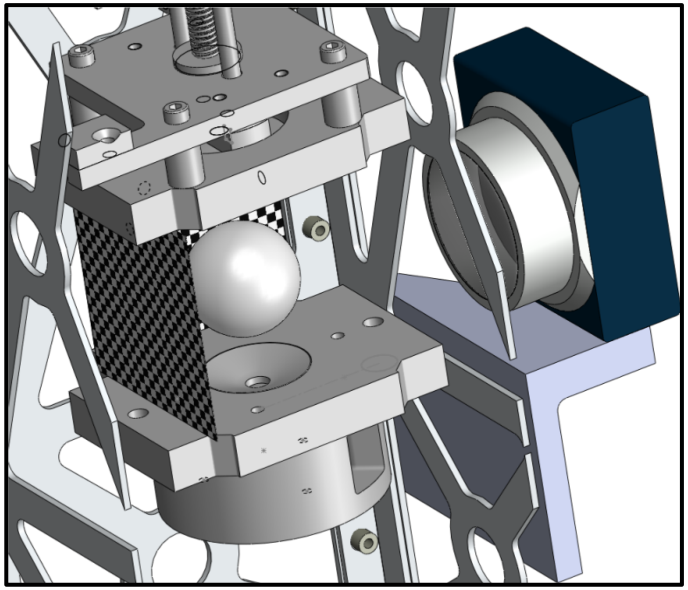


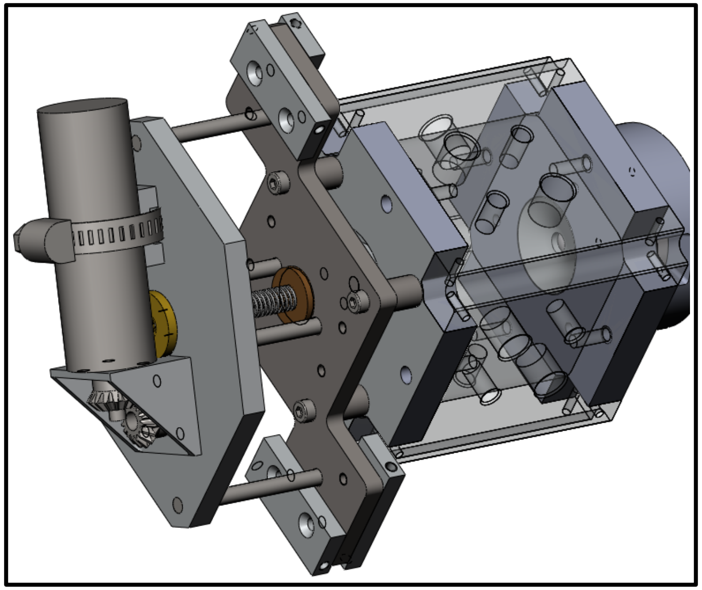


Caging System - April 2013 Parabolic Flight

MGRS, 2.5 cm TM, for Parabolic Flight Caging Test

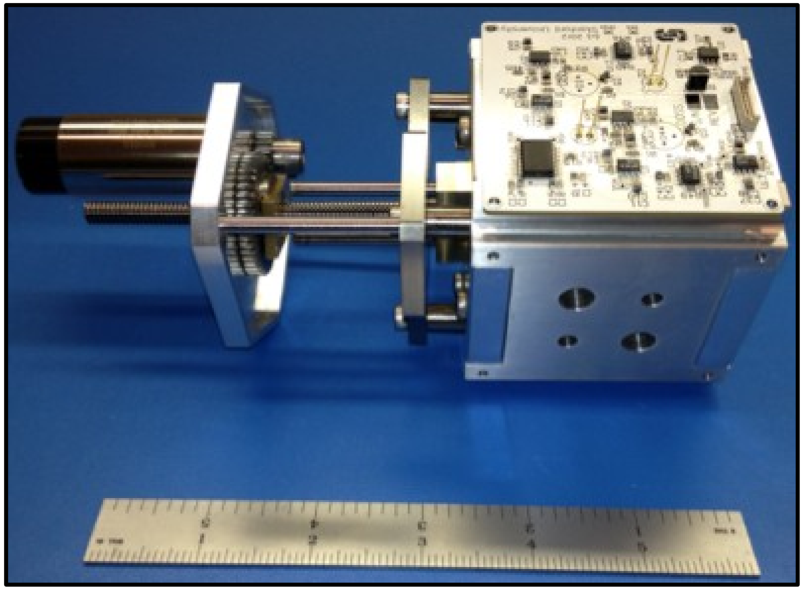
3 U Caging Fixture





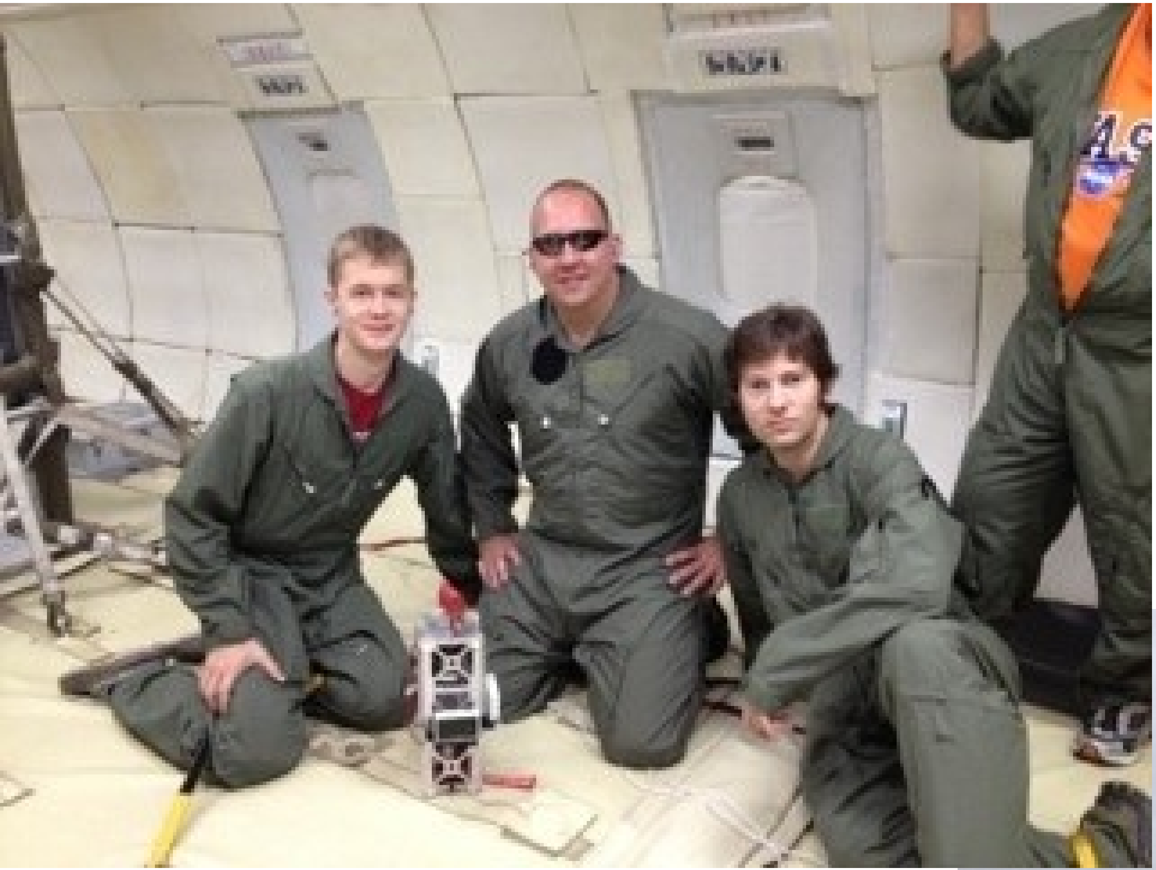
Caging System Schematics

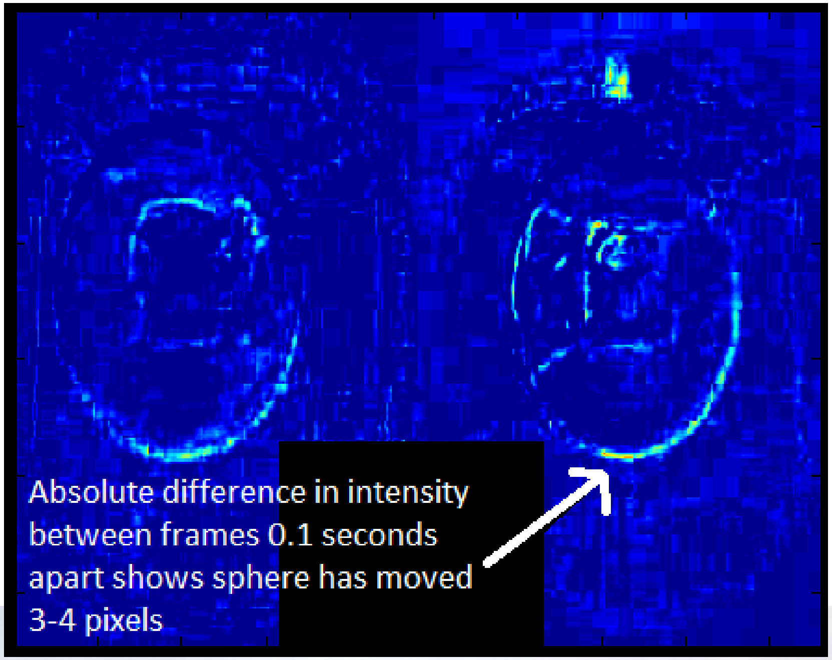
Housing



MGRS, Mechanical

Caging System - April 2013 Parabolic Flight





Flight Team (from left)
April 22nd – 25th

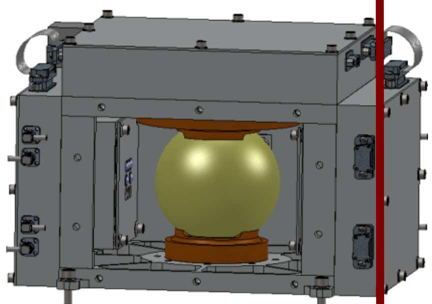
- **Andreas Zoellner**
- **Kirk Ingold**
- **Eric Hultgren**

Flight4-22a.m4v

UV LED Small Satellite

Technology Objectives

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



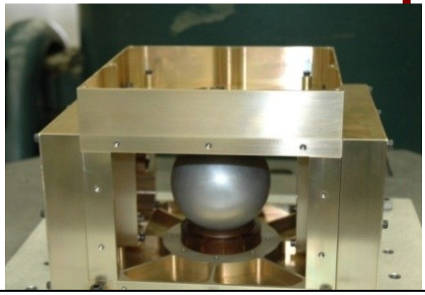
Mission Design

55 kg
50 W
Saudi Sat 3

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

Payload

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



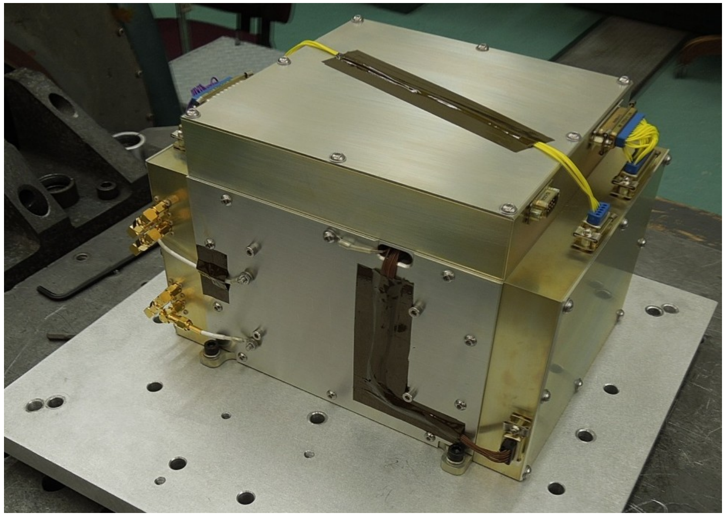
222×277×180 mm; 6.5 kg

Management

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

Demonstrates unconventional international collaboration

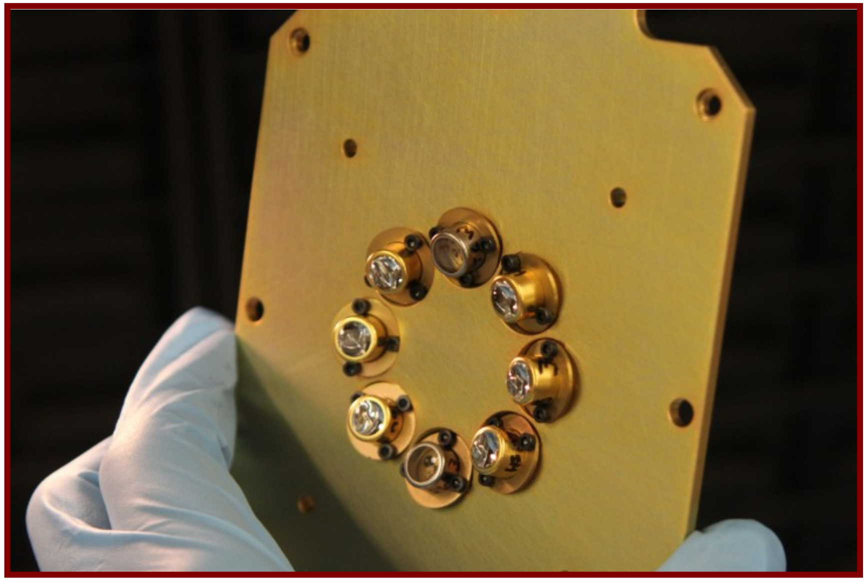
UV LED Instrument Integration and Test



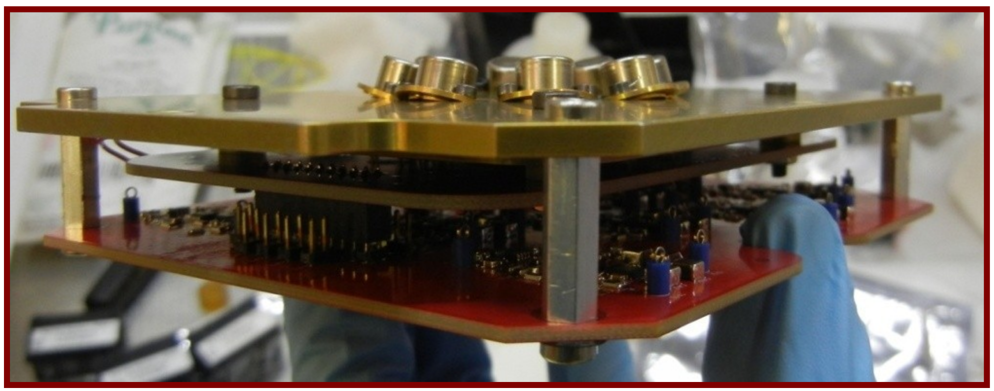
Thermovac chamber testing

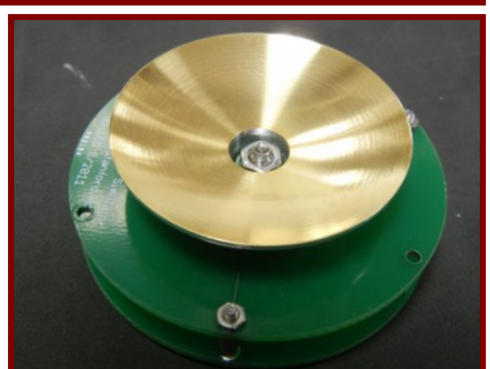
Integration of Flight Model at ARC

UV LED Instrument Components; 2013 Launch



▪ Payload completion:	May 2013
▪ PL-SC Com Interface:	May 2013
▪ Spacecraft CDR:	May 2013
▪ Payload Integration:	Jun 2013
▪ Russian launch:	Nov 2013

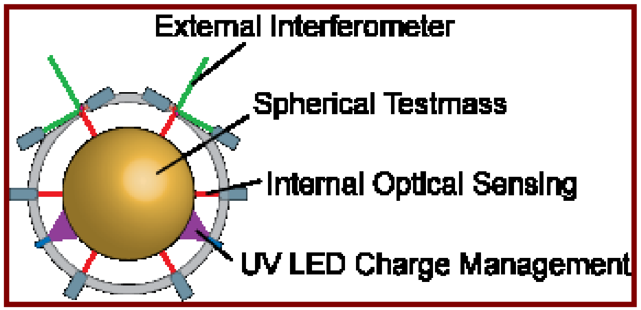




Differential Optical Shadow Sensor (DOSS)

Technology Objectives

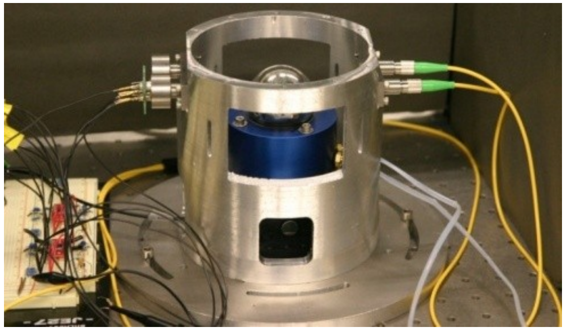
- Raise TRL level for miniature high-sensitivity displacement sensor
  - nm/Hz$^{1/2}$ sensitivity
  - No forcing
  - Non-contact



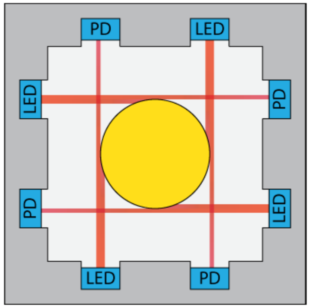
Mission Design

2 kg
4 W
3U Cube

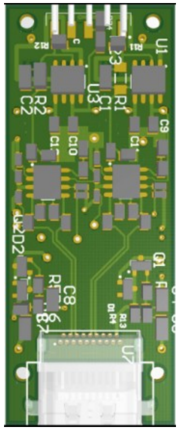
- 3U CubeSat
- Any orbit
- Launch ~ 2014
- 1 month ops
- Payload funded



Payload

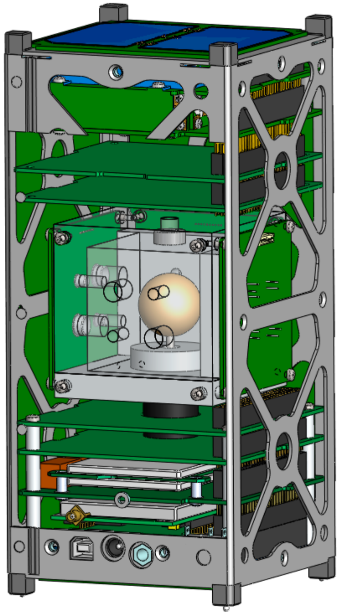


- Light source:
  - SLED, 1545 nm
- InGaAs quad-photodiode
- Ultra-low current Difet amp

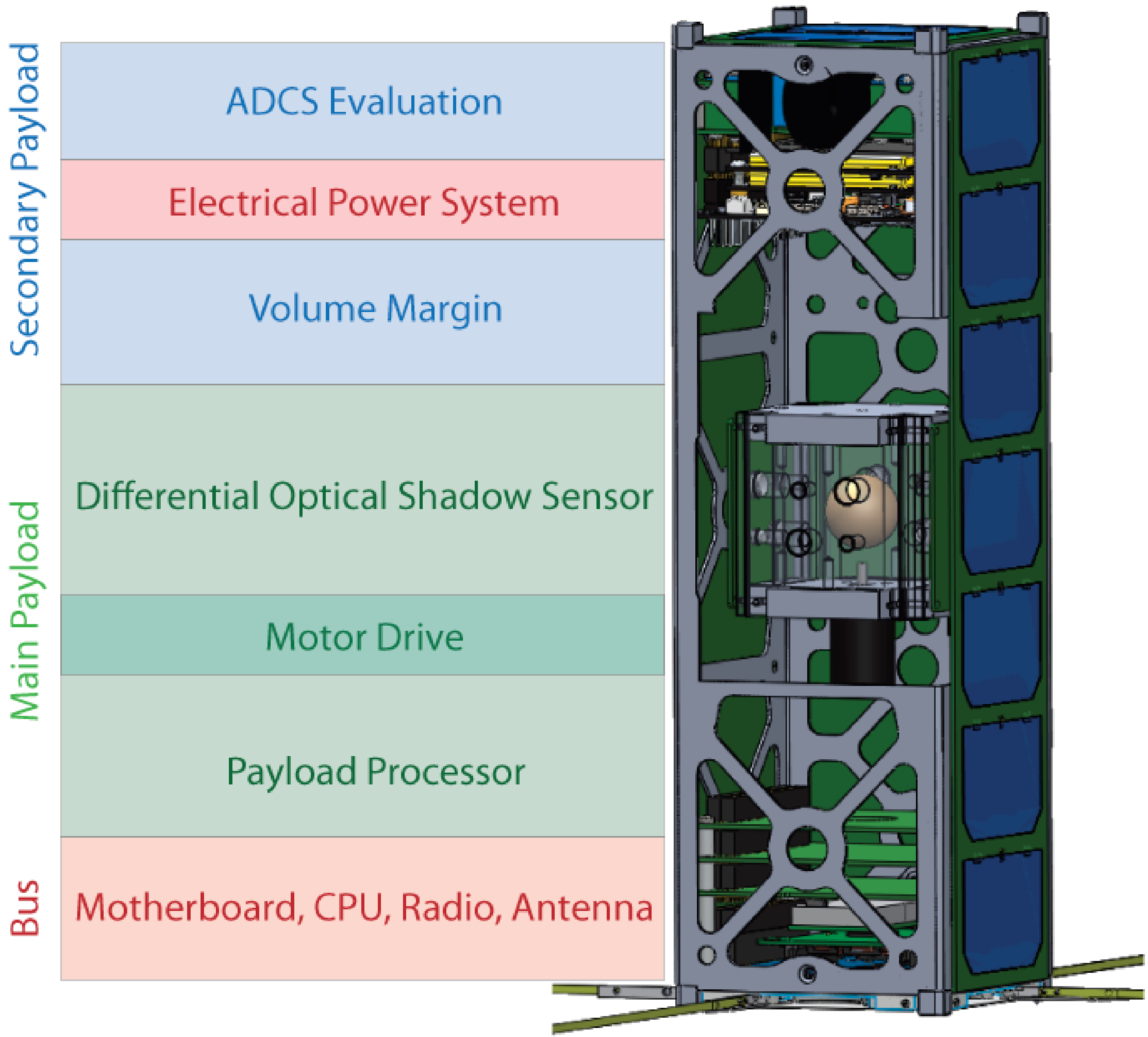


Management

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



DOSS & ADCS on 3U Cubesat; 2014 Launch

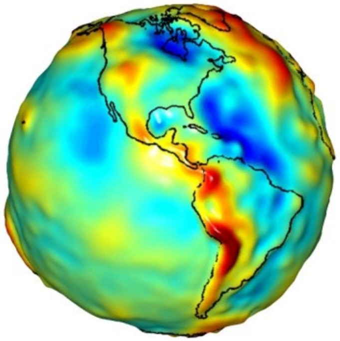


The Drag-free CubeSat

4 kg
6 W
3U Cube

Science

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

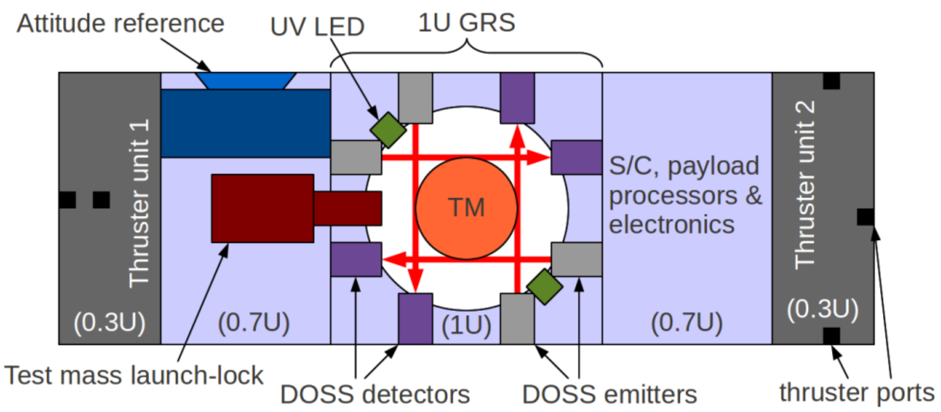


Mission Design

- 3U CubeSat
- Secondary launch via P-POD
- Launch ready ~ 2015
- 1-2 month drag-free ops in low g environment < 10^{-8} m/s^2

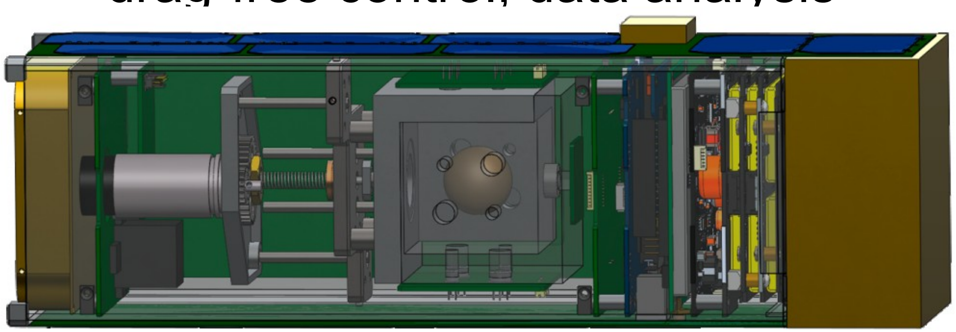
Payload *(back-up version)*

- Drag-free sensor + micro-thrusters



Management

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



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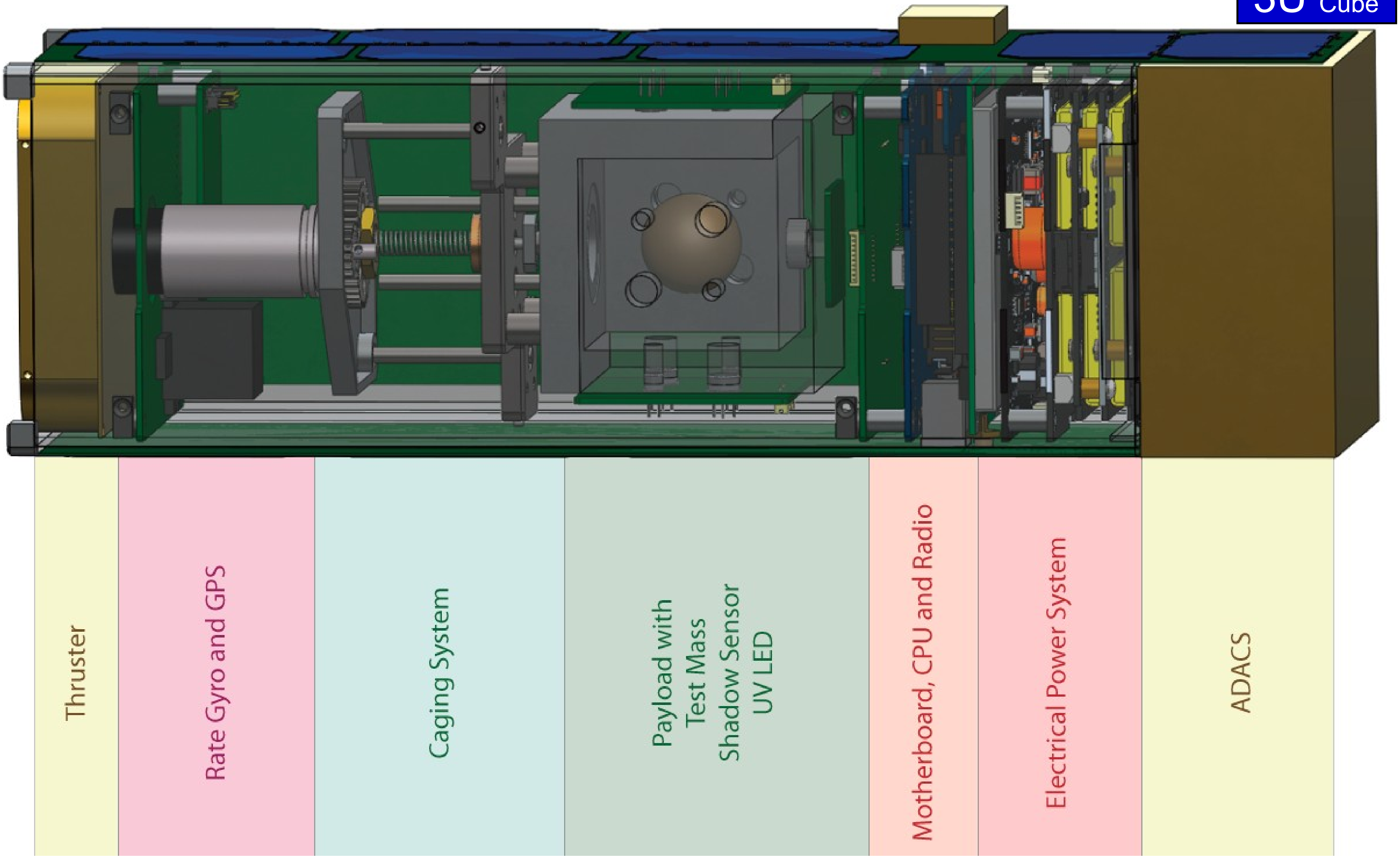
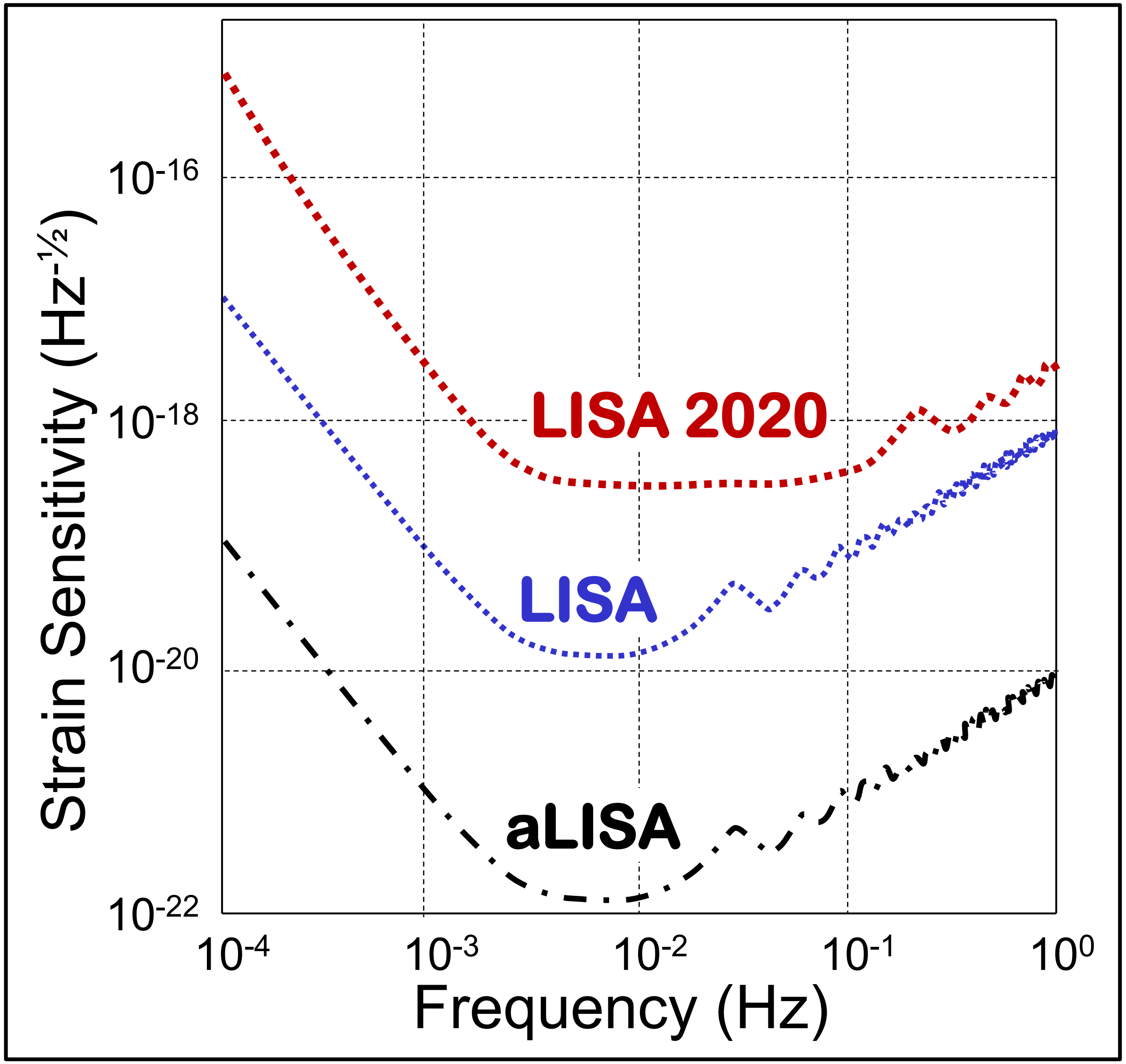


GWD in Space

- **LISA 2020: ~2020**
- **LISA: ~2030**
- **aLISA : ~2045**



Conclusions

1 Physics & Astrophysics are in a 'DARK' period; GW Astronomy is a very plausible SOLUTION

2 A LISA-2020 Type Geocentric Medium GW Antenna Can Provide Excellent GW Data ~2020

3 Technology Development on Small Sats Provides the Road to LISA-2020 & Significant Science

Thank you for your attention