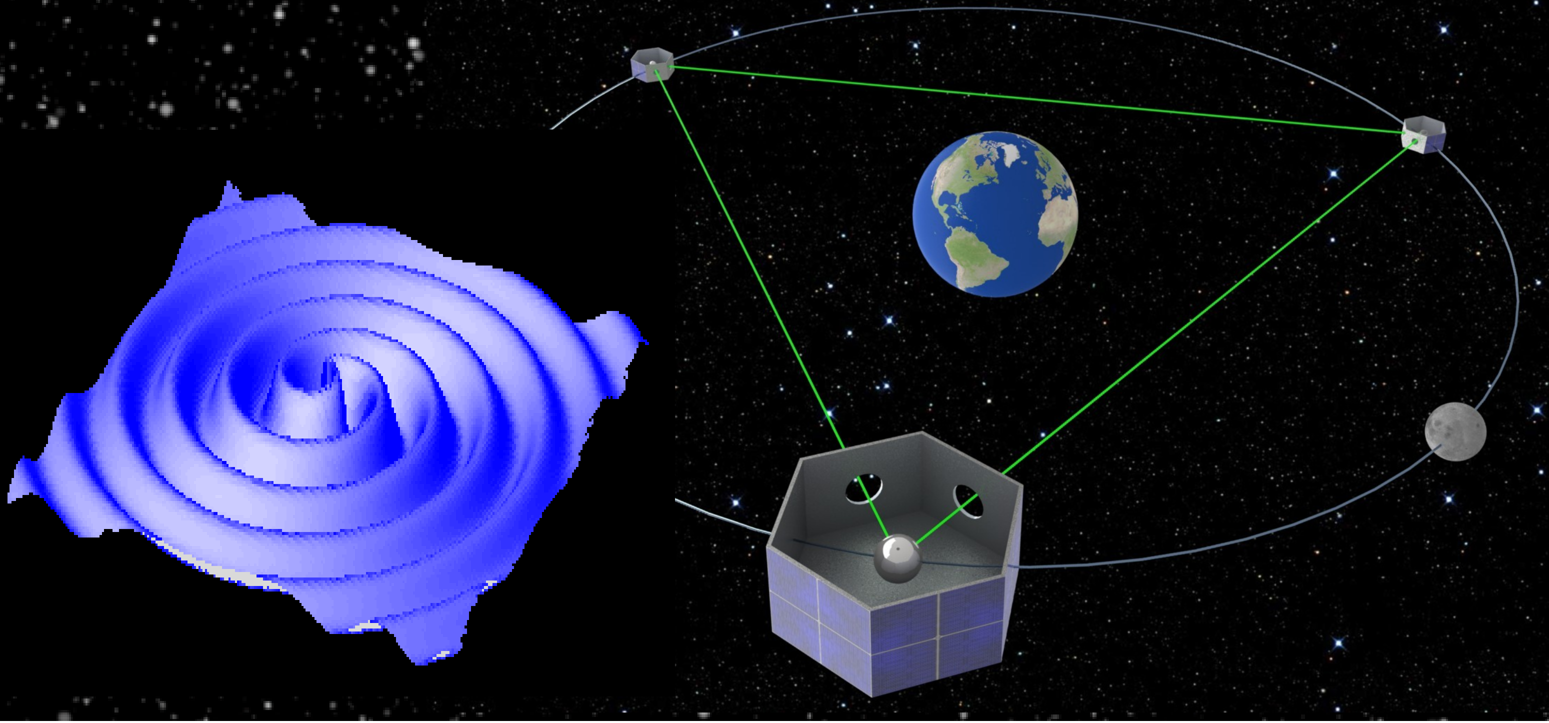
Gravitational Wave Astrophysics
The Next Frontier in Understanding the Universe
An Experimentalist's View



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

Hot topics in Modern Cosmology
Spontaneous Workshop VII
Cargèse, 6 - 11 May 2013

Sasha Buchman
Stanford University
for the Space Sciences team

LISA-2020 Collaboration

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

Outline

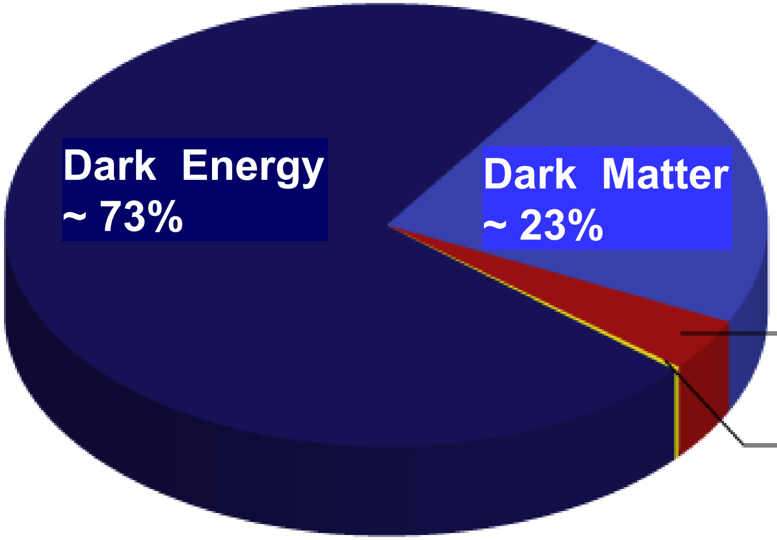
- **Why Gravitational Wave (GW) Astronomy ?**

- **What Is the Status of GW Astronomy ?**

- **How Do We Go From Here for LISA 2020 ?**

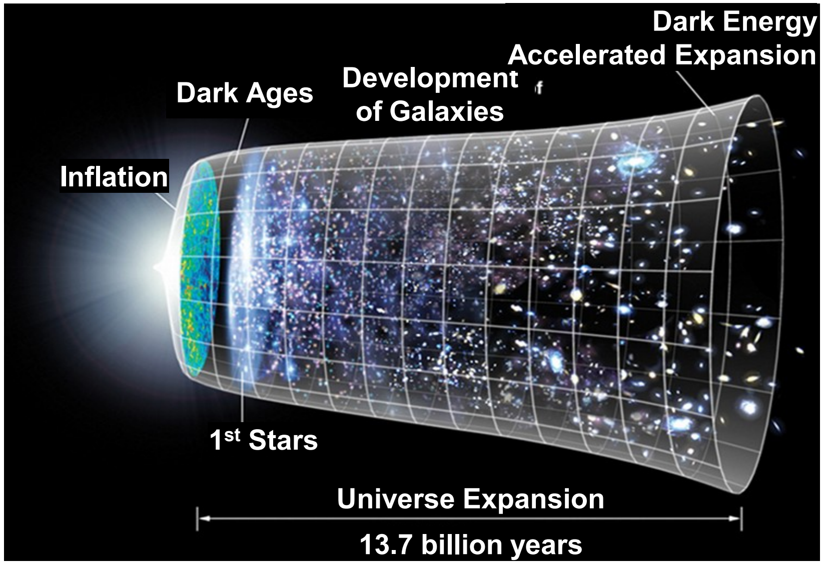
Today’s ‘DARK’ Universe

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 30 years
- ➢ GW sees and interacts with 100% of matter
- ➢ GR used for converting EM to Universe picture has ‘issues’

Seen in EM “understood” in GR

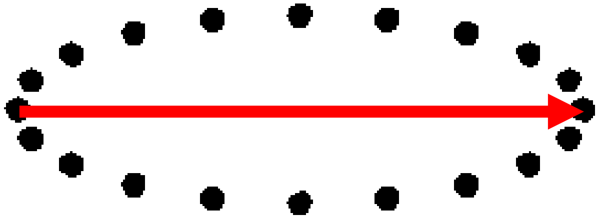
Why GW Astronomy

- Gravitational Wave (GW) Astronomy Will Give the Answers About the Universe That EM Cannot Provide
- The 10^{-4} Hz to 1 Hz is the 'Richest' GW Range

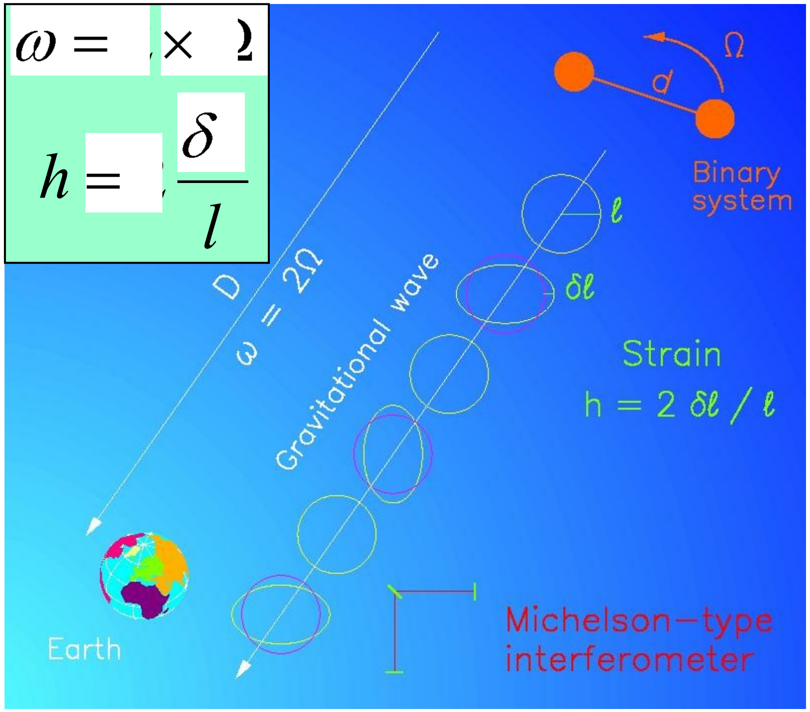
  This Range Requires a Space GW Observatory
- A Laser Interferometer Space Antenna (LISA) Is Necessary and Possible by 2020:
  - Will Achieve the Most Important GW Science
  - At "Affordable Cost" ($500M)
- Support of Science Community is Critical for LISA 2020

GW in General Relativity

- Two independent polarizations oriented at 45
- Transverse to direction of wave
- Area preserving
- Orthogonal changes in length at wave frequency



Plus-polarized GW



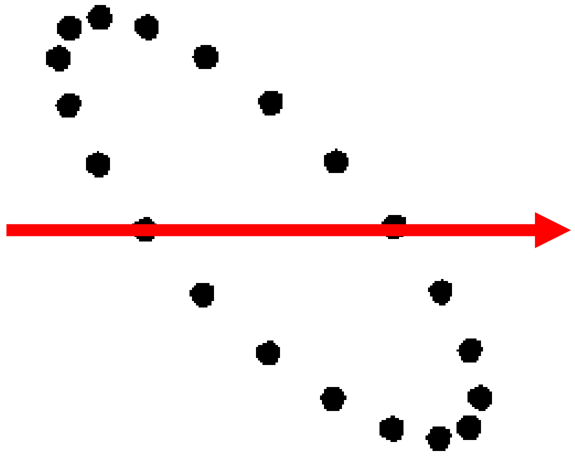
$$\omega = \times$$

$$h = \frac{\delta}{l}$$

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

$$h < \ 0^{-\ 8}$$

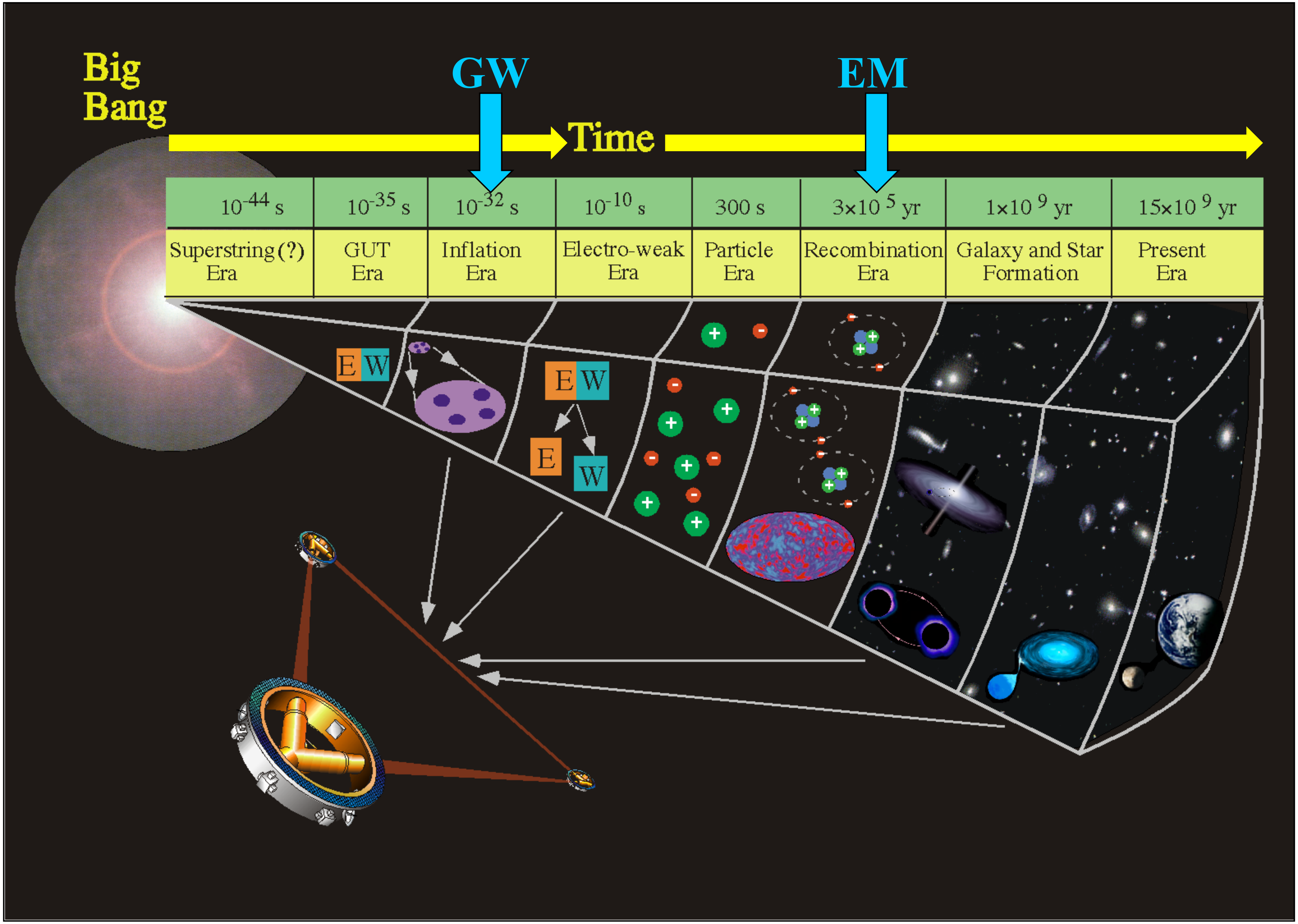
GW



Cross-polarized GW

- **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**

GW Through Time



Big Bang

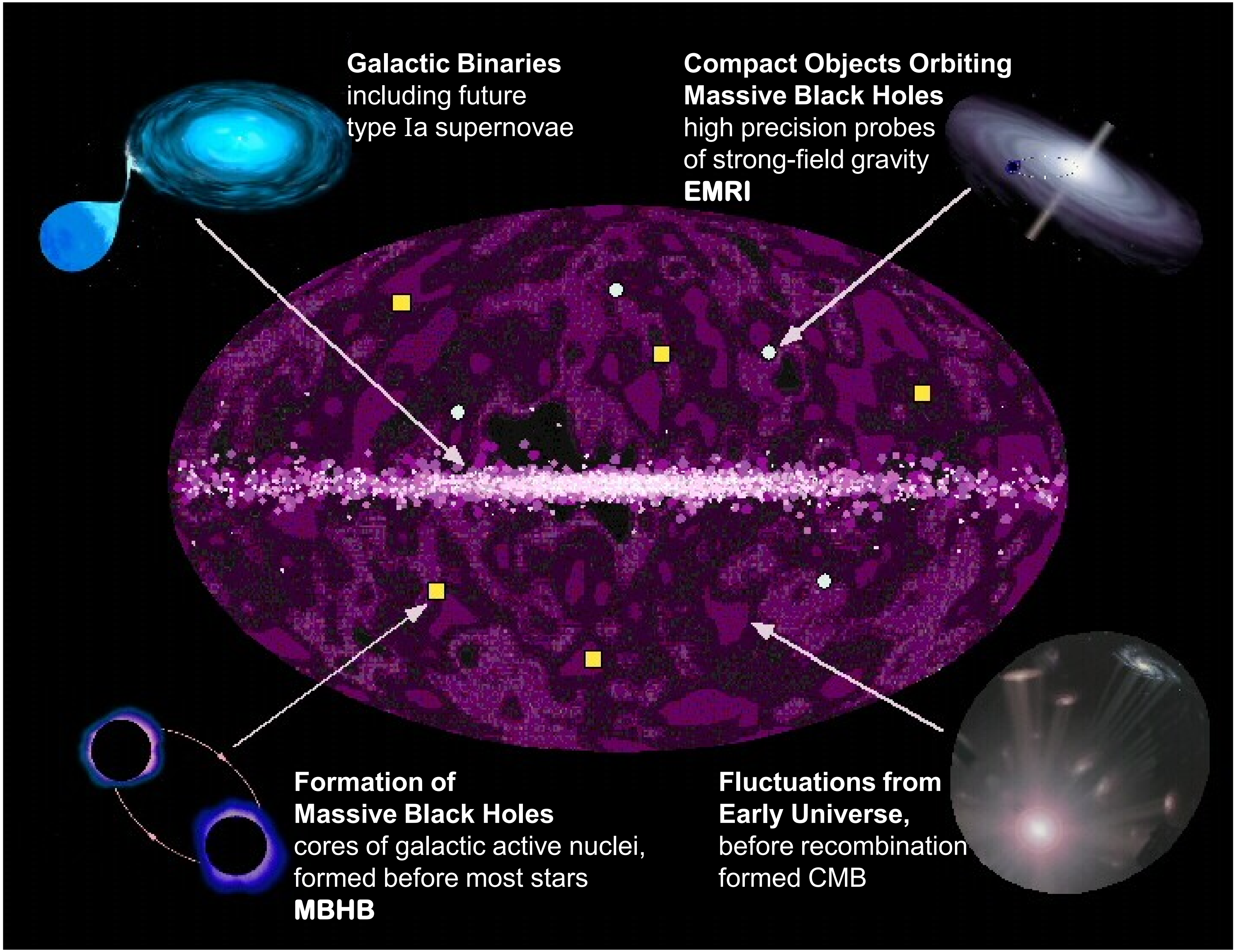
GW

EM

Time

10^{-44} s	10^{-35} s	10^{-32} s	10^{-10} s	300 s	3×10^{5} yr	1×10^{9} yr	15×10^{9} yr
Superstring (?) Era	GUT Era	Inflation Era	Electro-weak Era	Particle Era	Recombination Era	Galaxy and Star Formation	Present Era

The Gravitational-Wave Sky



Galactic Binaries
including future
type Ia supernovae

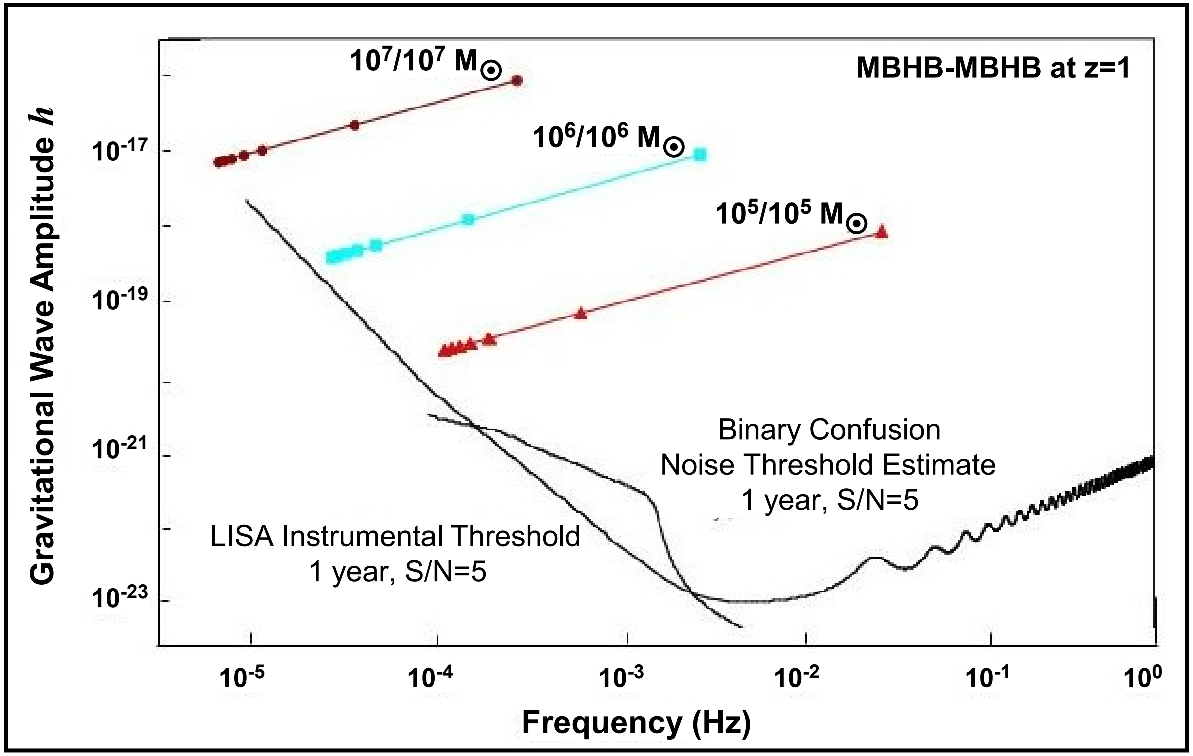
Compact Objects Orbiting
Massive Black Holes
high precision probes
of strong-field gravity
EMRI

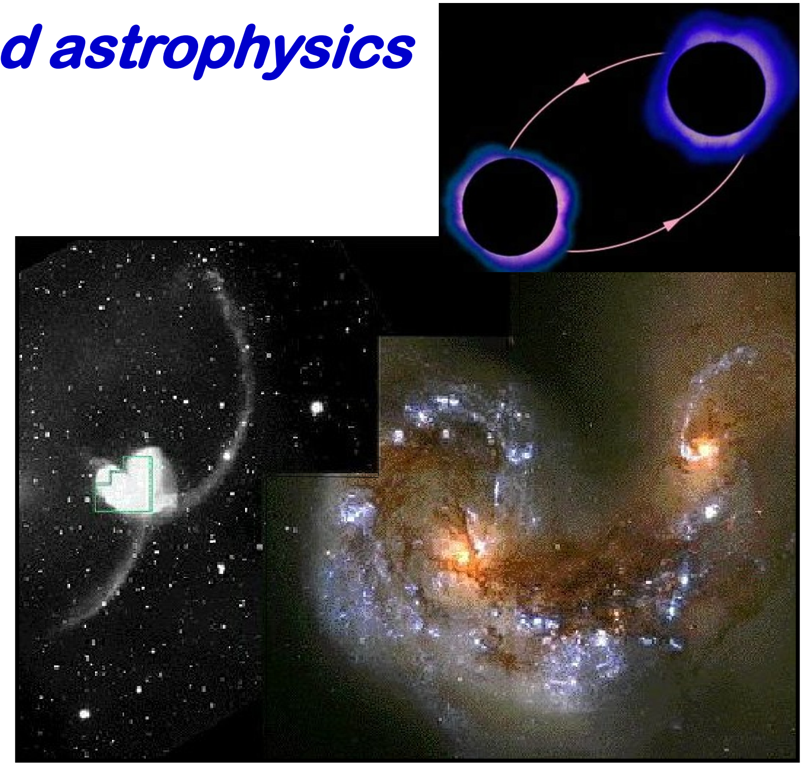
Formation of
Massive Black Holes
cores of galactic active nuclei,
formed before most stars
MBHB

Fluctuations from
Early Universe,
before recombination
formed CMB

MBHB Massive Black Holes Binaries

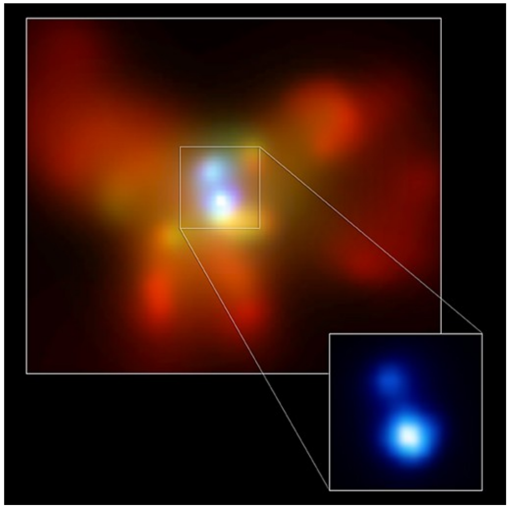
Answers to basic questions in physics and astrophysics





Merging galaxies NGC4038 & NGC4039. Hubble Space Telescope; Courtesy by B. Whitmore, STSI & NASA

- The role of MBH in galaxy evolution
- Fraction of galactic mergers forming MBH
- Timing of the earliest MBH mergers
- Precision tests of dynamical non-linear gravity

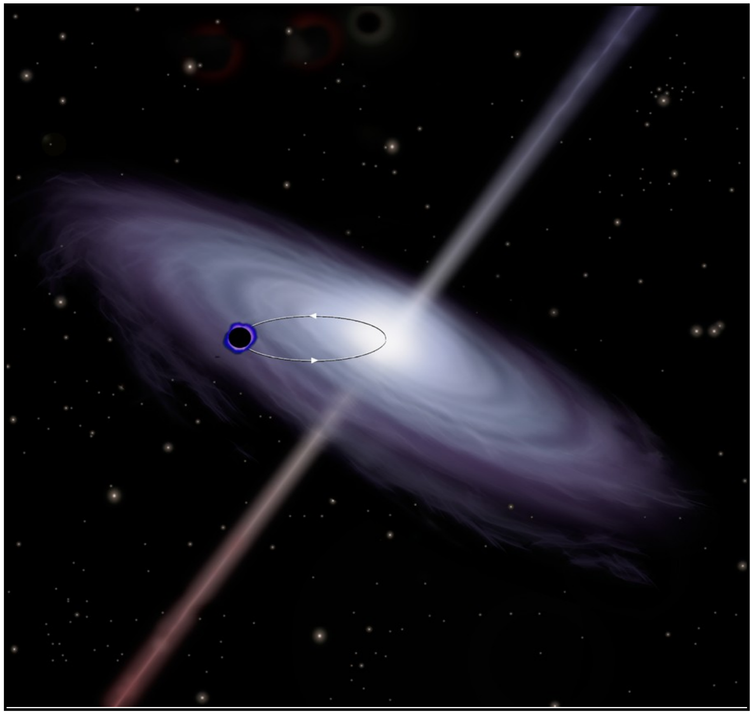


Chandra image of NGC6240 a super MBHB

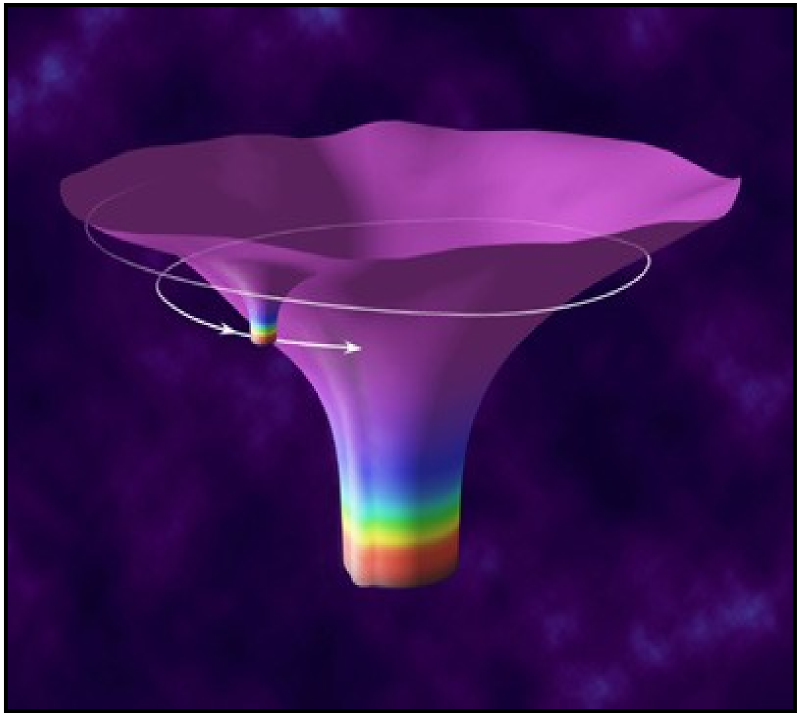
New physics & astrophysics

Probing the Region Near MBH

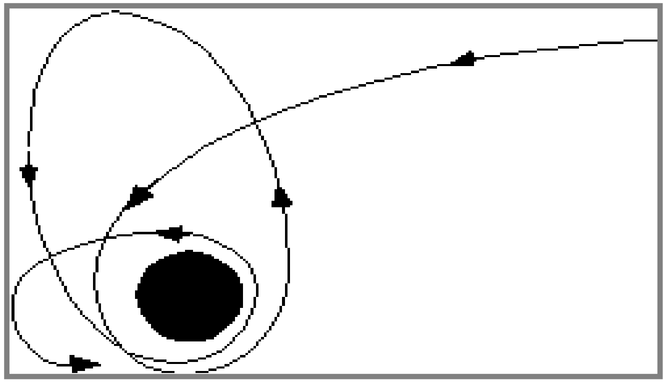
LISA will observe compact stars scattering near MBH



Orbits of compact stars near MBH will evolve rapidly and emit gravitational waves



The warping of space-time caused by a black hole spiraling into a MBH. Courtesy of K. Thorne, Caltech



Stellar-mass black holes orbiting MBH provide precision tests of gravitational theory in the high-field limit

Galactic Sources

LISA will observe thousands of galactic sources

1) Compact Galactic Binary Systems

- White dwarfs
- Neutron stars
- Black holes

LISA measurements

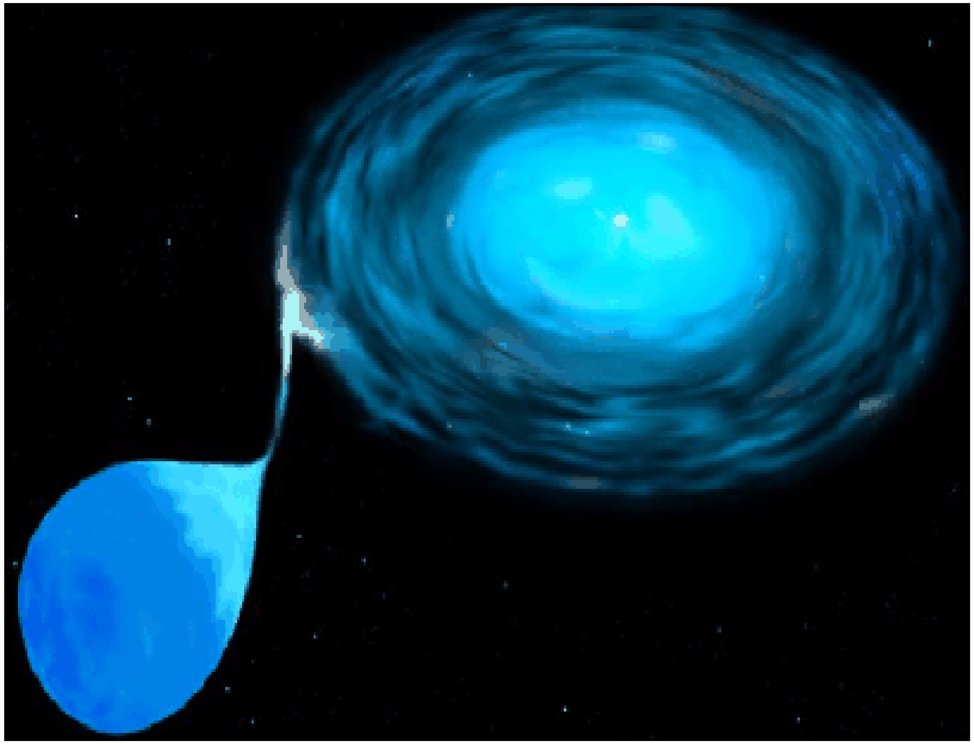
- Direction, distance, orbital period, and masses of ‘strong’ binaries.
- Thousands of systems; most unresolved

2) Type Ia Supernovae

White dwarf binaries lose energy to gravitational waves and collide (Supernova 2002ic – hydrogen blown off by partner onto WD)

LISA measurements

- Direction and time of collision, for the ~ 500 type Ia supernovae



Physics, Astrophysics and *Calibration*

Known Binary Calibration Sources for LISA

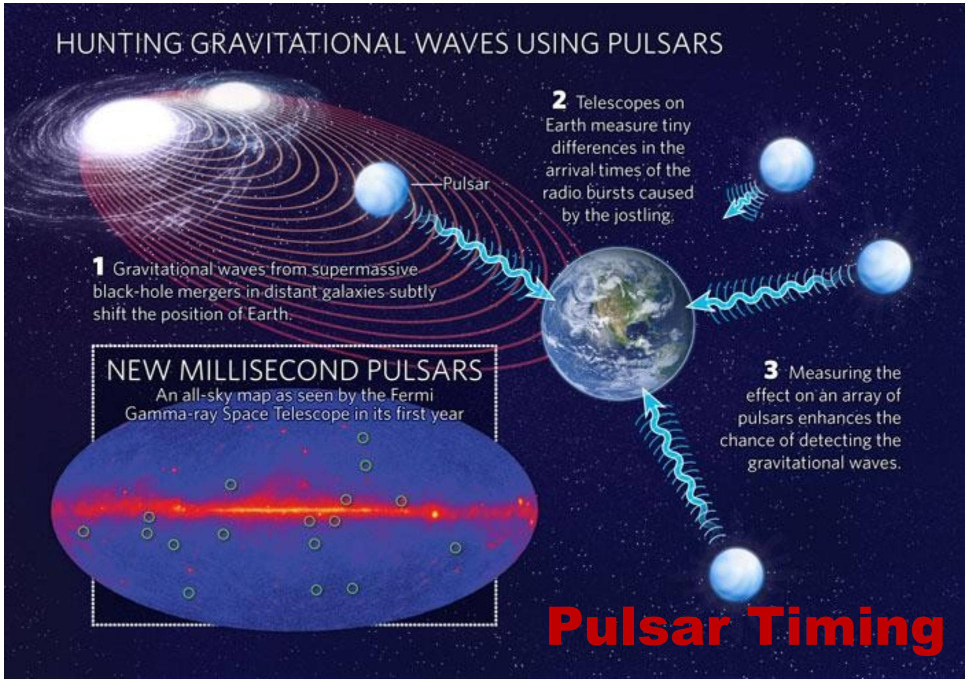
class	source	dist pc	$f = 2/P_b$ mHz	M_1 $M_\odot$	M_2 $M_\odot$	τ_{mrg} 10^8y	h
WD+WD	WD 0957-666	100	0.38	0.37	0.32	2	4×10^{-22}
	WD 1101+364	100	0.16	0.31	0.36	20	2×10^{-22}
	WD 1704+481	100	0.16	0.39	0.56	13	4×10^{-22}
	WD 2331+290	100	0.14	0.39	> 0.32	< 30	$> 2 \times 10^{-22}$
WD+sdB	KPD 0422+4521	100	0.26	0.51	0.53	3	6×10^{-22}
	KPD 1930+2752	100	0.24	0.5	0.97	2	1×10^{-21}
AM CVn	RXJ0806.3+1527	300	6.2	0.4	0.12	–	4×10^{-22}
	RXJ1914+245	100	3.5?	0.6	0.07	–	6×10^{-22}
	KUV05184-0939	1000	3.2	0.7	0.092	–	9×10^{-23}
	AM CVn	100	1.94	0.5	0.033	–	2×10^{-22}
	HP Lib	100	1.79	0.6	0.03	–	2×10^{-22}
	CR Boo	100	1.36	0.6	0.02	–	1×10^{-22}
	V803 Cen	100	1.24	0.6	0.02	–	1×10^{-22}
	CP Eri	200	1.16	0.6	0.02	–	4×10^{-23}
	GP Com	200	0.72	0.5	0.02	–	3×10^{-23}
LMXB	4U1820-30	8100	3.0	1.4	< 0.1	–	2×10^{-23}
	4U1626-67	3-8000	0.79	1.4	< 0.03	–	6×10^{-24}
W UMa	CC Com	90	0.105	0.7	0.7	–	6×10^{-22}

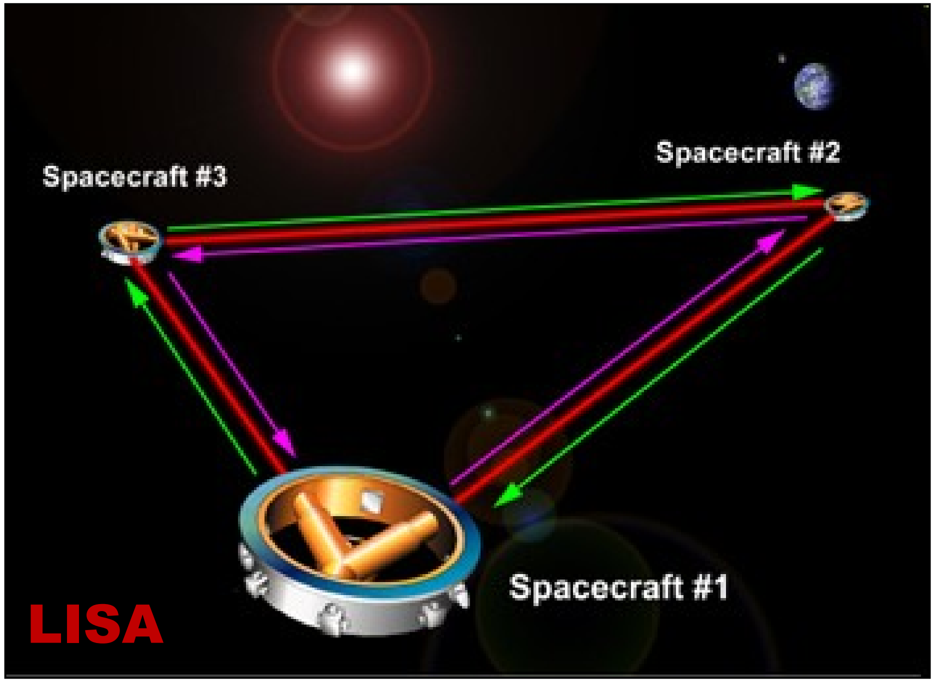
How Do We Measure the GW Spectrum ?

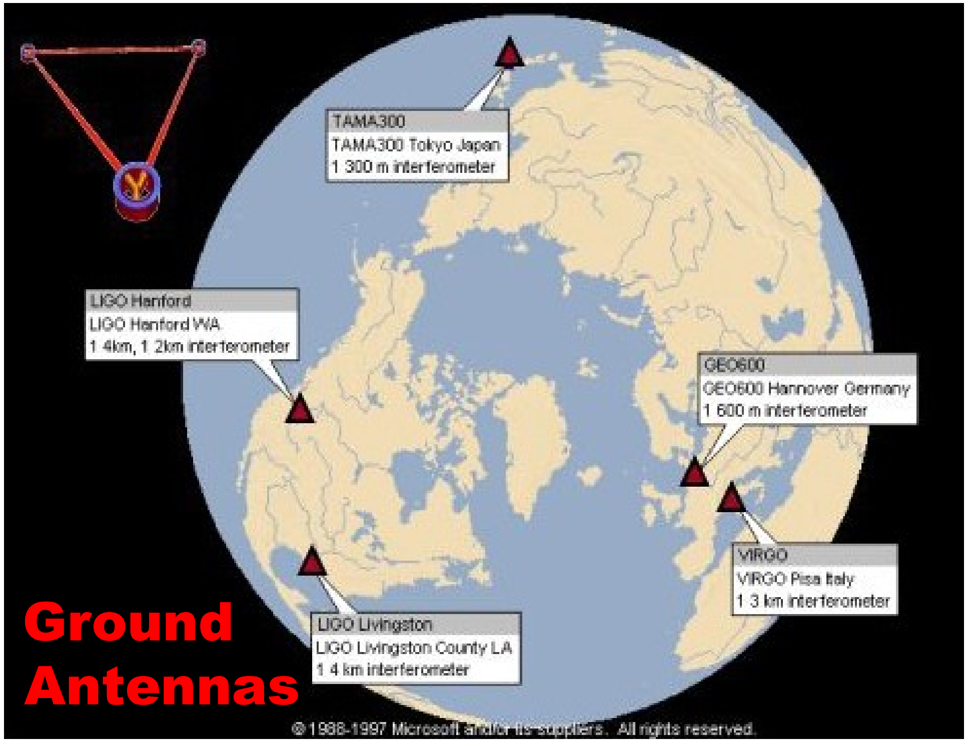
- **Astronomy <10^{-7} Hz, ~2017**
  - ***Pulsar Timing***
  - ***CMB Polarization: WMAP, Boomerang***
- **Earth 10 Hz - 1 kHz, ~2016**

  Gravitational Wave Observatories
  - ***LIGO, VIRGO, GEO 600, Other..***
- **Space 10^{-4} Hz - 1 Hz > 2030**

  Gravitational Wave Observatories
  - ***LISA, LISA-2020***







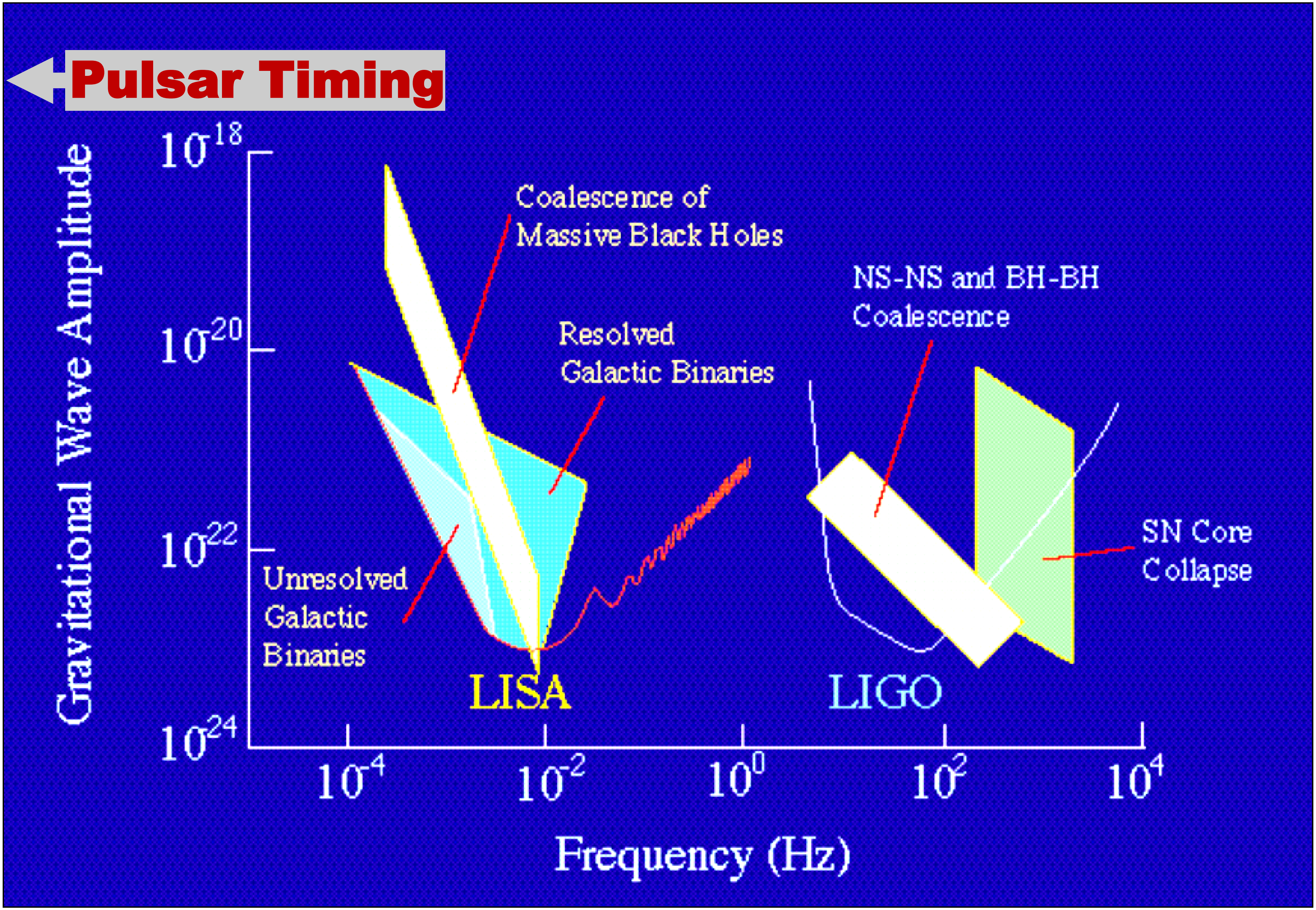
Detection of GW

Three Elements for Maximizing GW Detection

1. Free Floating Test Masses (TM) ≥ 2
2. Minimize δl → by best sensitivity measurement
3. Maximize l → by largest 'baseline'

	TM	δl	l
Astronomy	**Pulsars**	**~ 10m**	**> 10^{17} m**
Space	**Drag-free TM**	**~ 10^{-11} m**	**~ 10^{9} m**
Earth	**Seismically Isolated TM**	**~ 10^{-18} m**	**≤ 4× 10^{3} m**

The GW Spectrum



Conclusion #1

① Physics & Astrophysics are in a 'DARK' period; GW Astronomy is a very 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)**

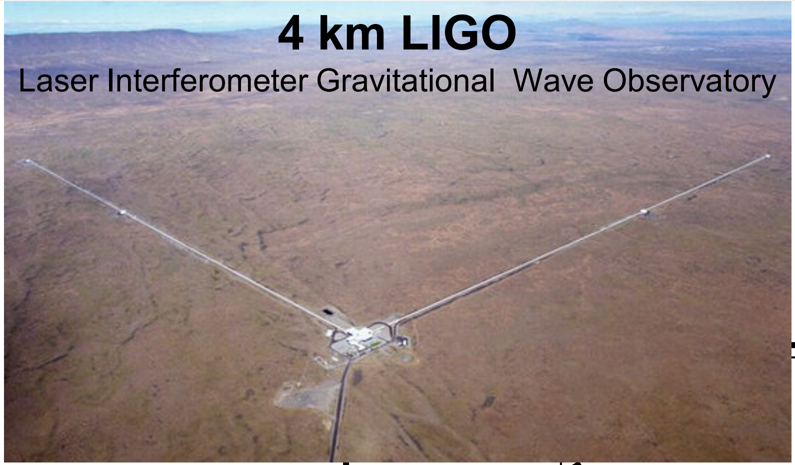
(Plan to Mission >10 years; Hubble, GP-B, LPF, WST …)

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**

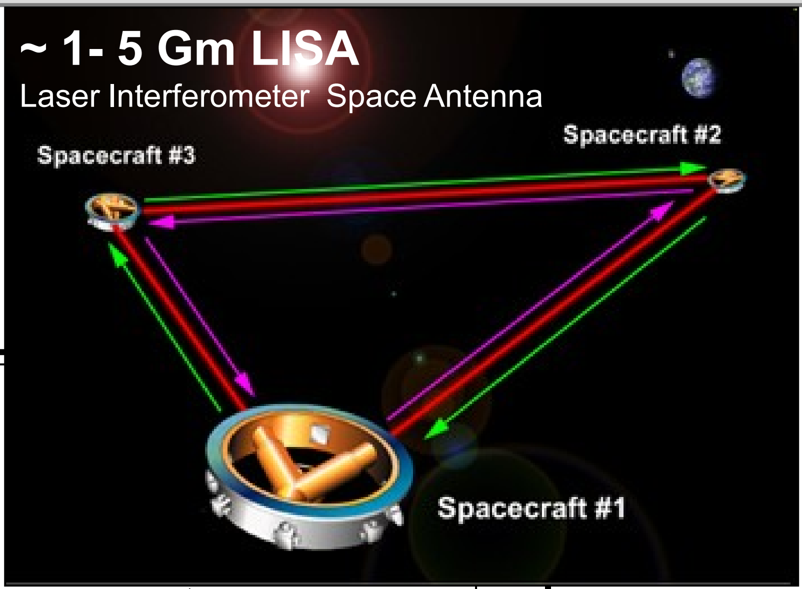
Few in this audience will have any chance to see LISA type science

GW Interferometers



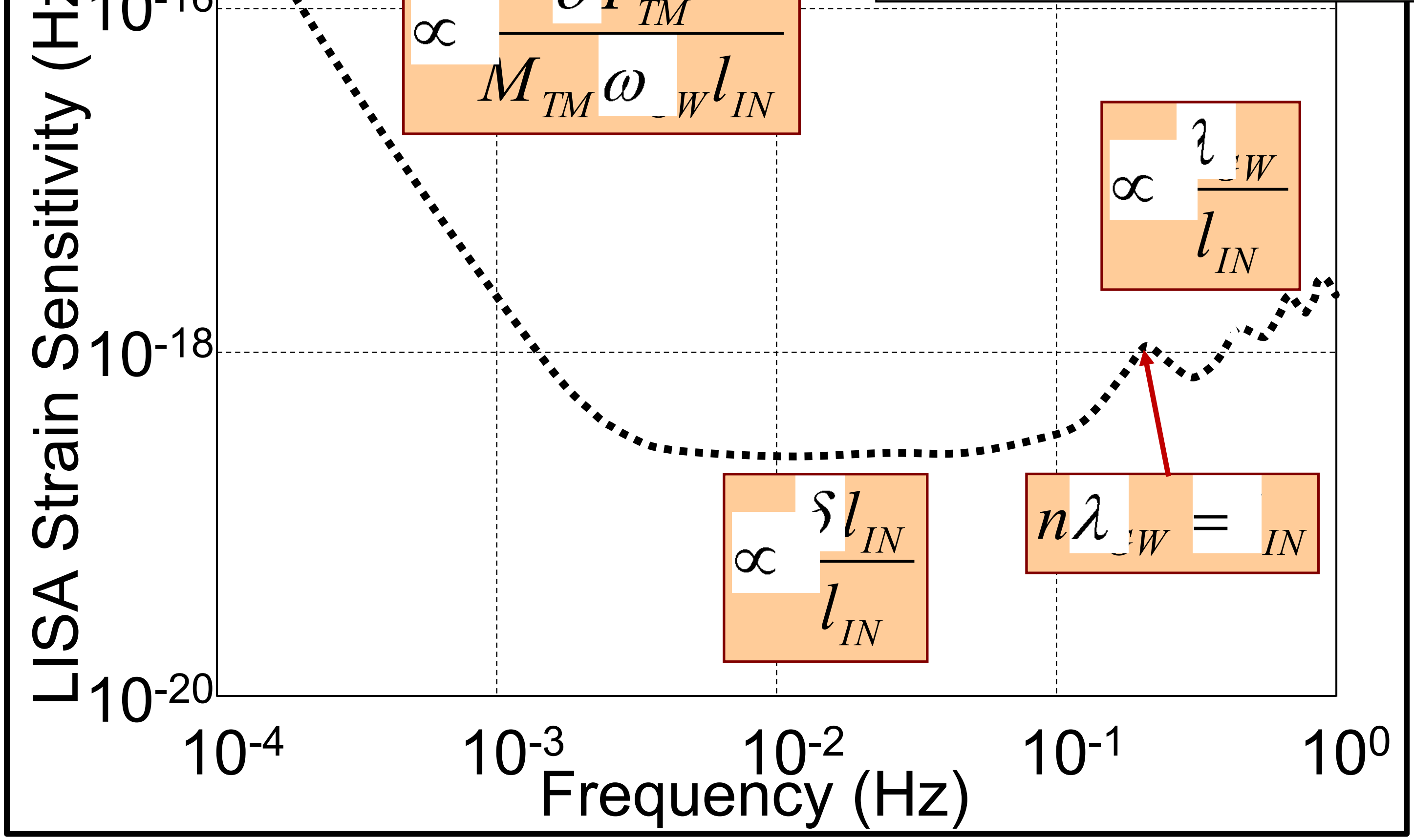
4 km LIGO

Laser Interferometer Gravitational Wave Observatory



~ 1- 5 Gm LISA

Laser Interferometer Space Antenna



$$\propto \frac{\delta F_{TM}}{M_{TM}\,\omega_{GW}\,l_{IN}}$$

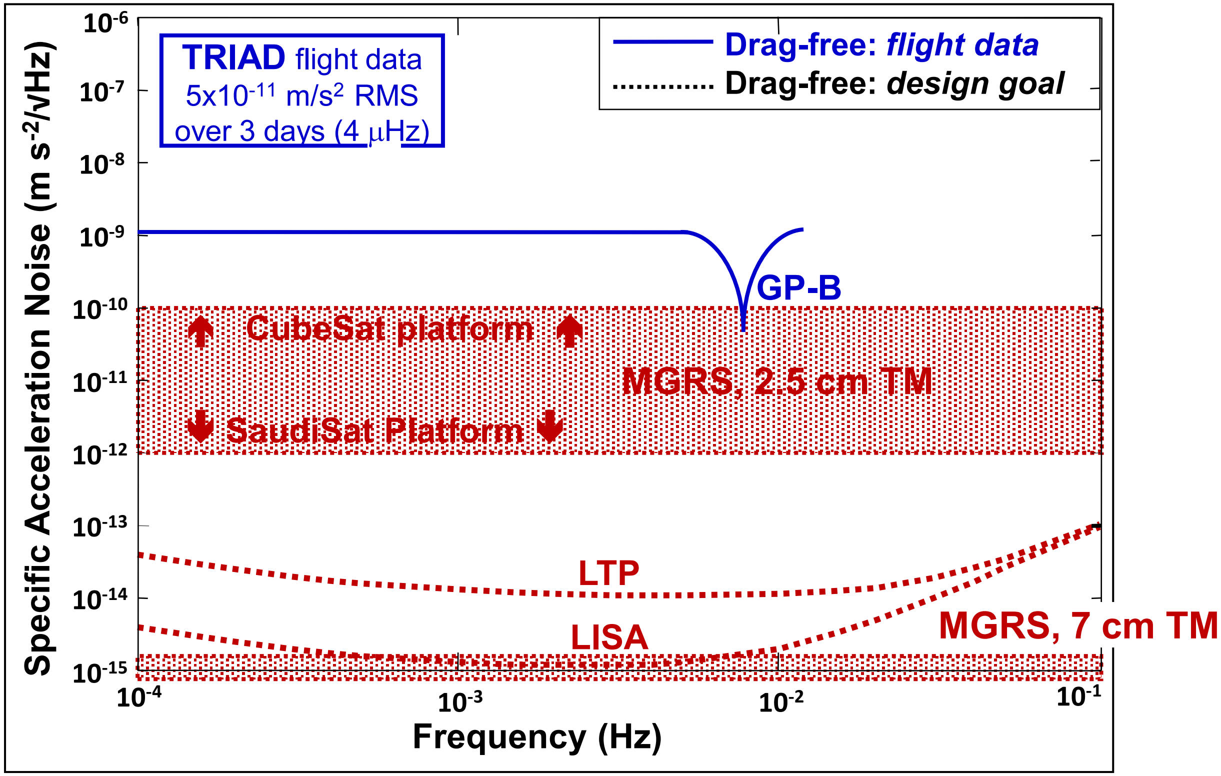
$$\propto \frac{\lambda_{GW}}{l_{IN}}$$

$$\propto \frac{\delta l_{IN}}{l_{IN}}$$

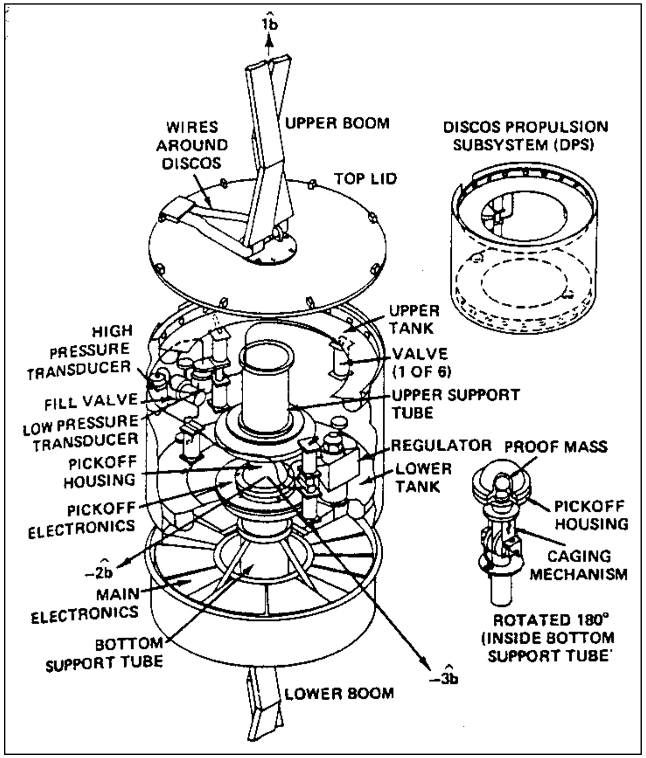
$$n\lambda_{GW} = l_{IN}$$

Space 'Mirror': Drag-Free 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**

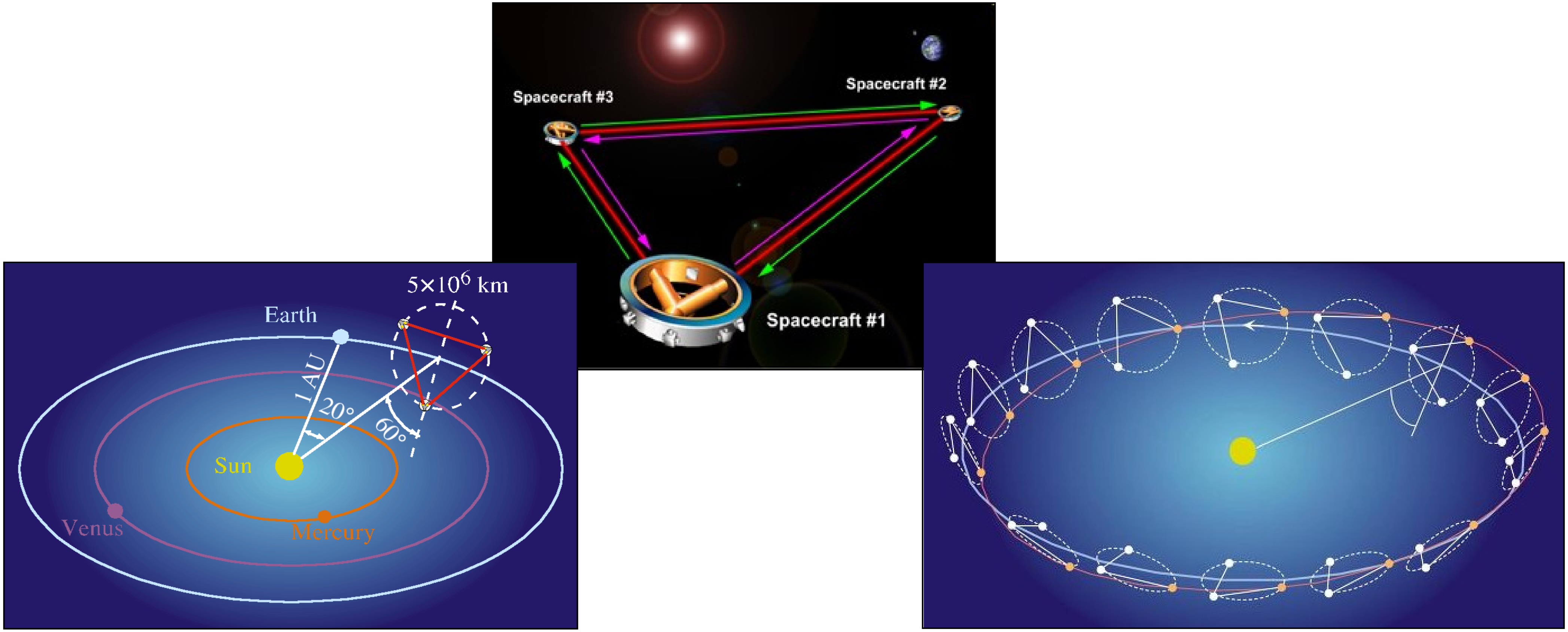
Applications of Drag-free Technology

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

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

LISA Concept

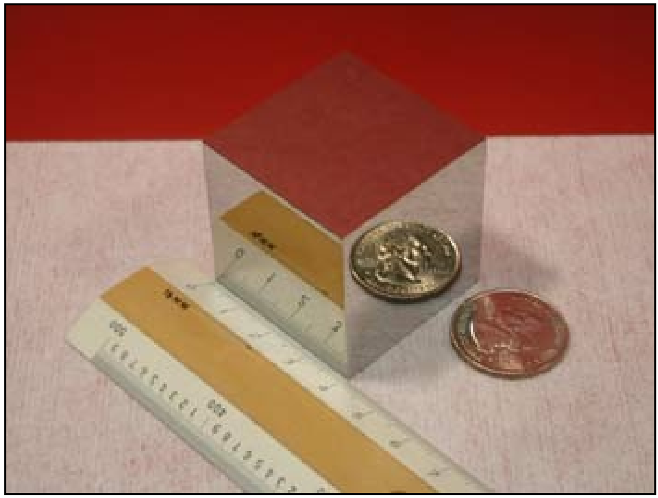
- Three spacecraft in triangular formation separated by 5 million km
- Spacecraft have constant solar illumination
- Formation trails Earth by 20°



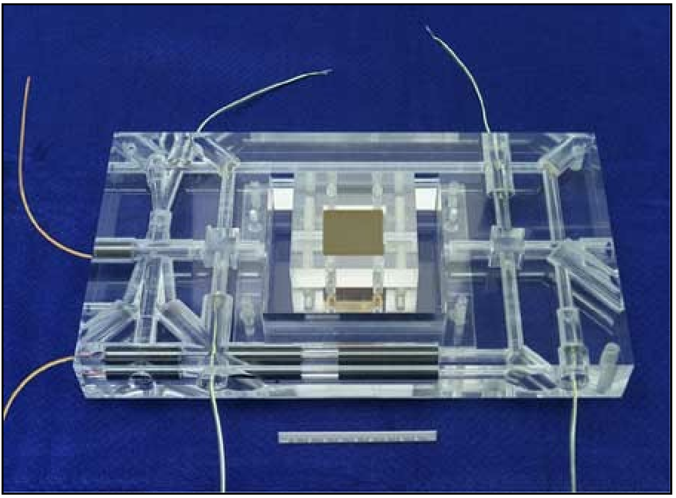
Orbit position and velocity modulate GW amplitude and phase

From amplitude and phase LISA determines direction to <1

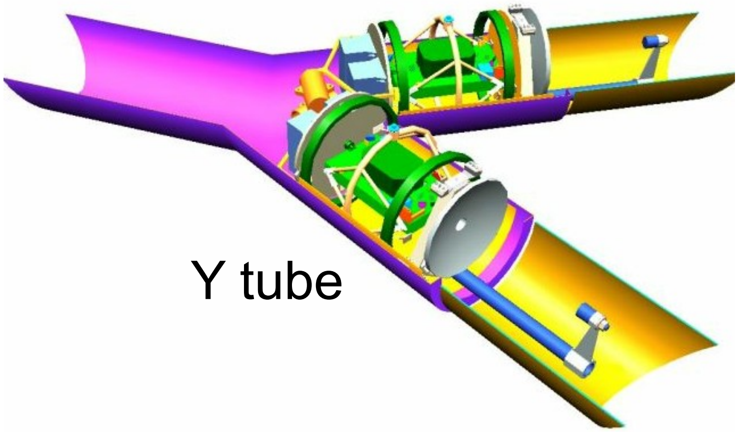
LISA Systems



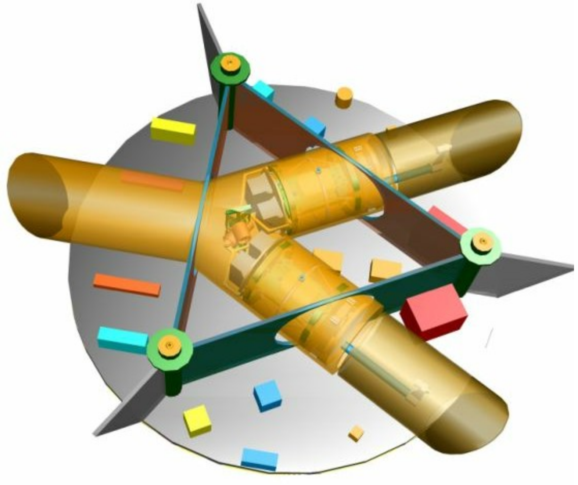
Test mass



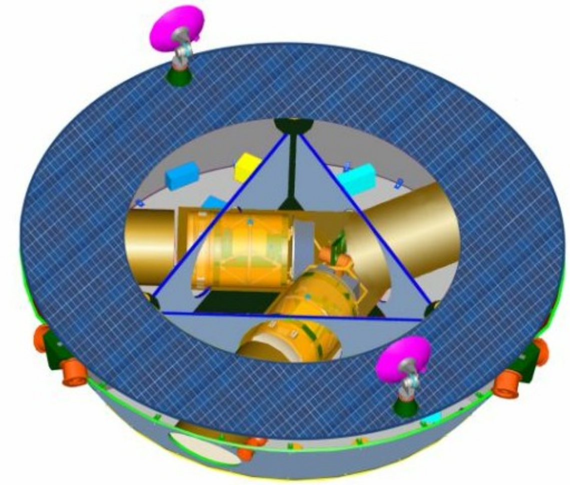
Optical bench



Y tube

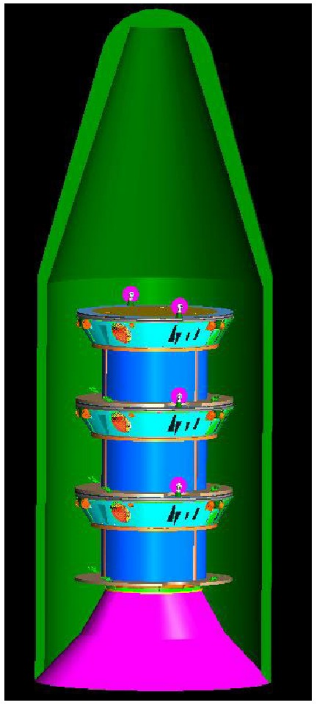


Payload



Spacecraft

Propulsion module



Launch configuration

LISA 2020: GW Observatory for This Decade

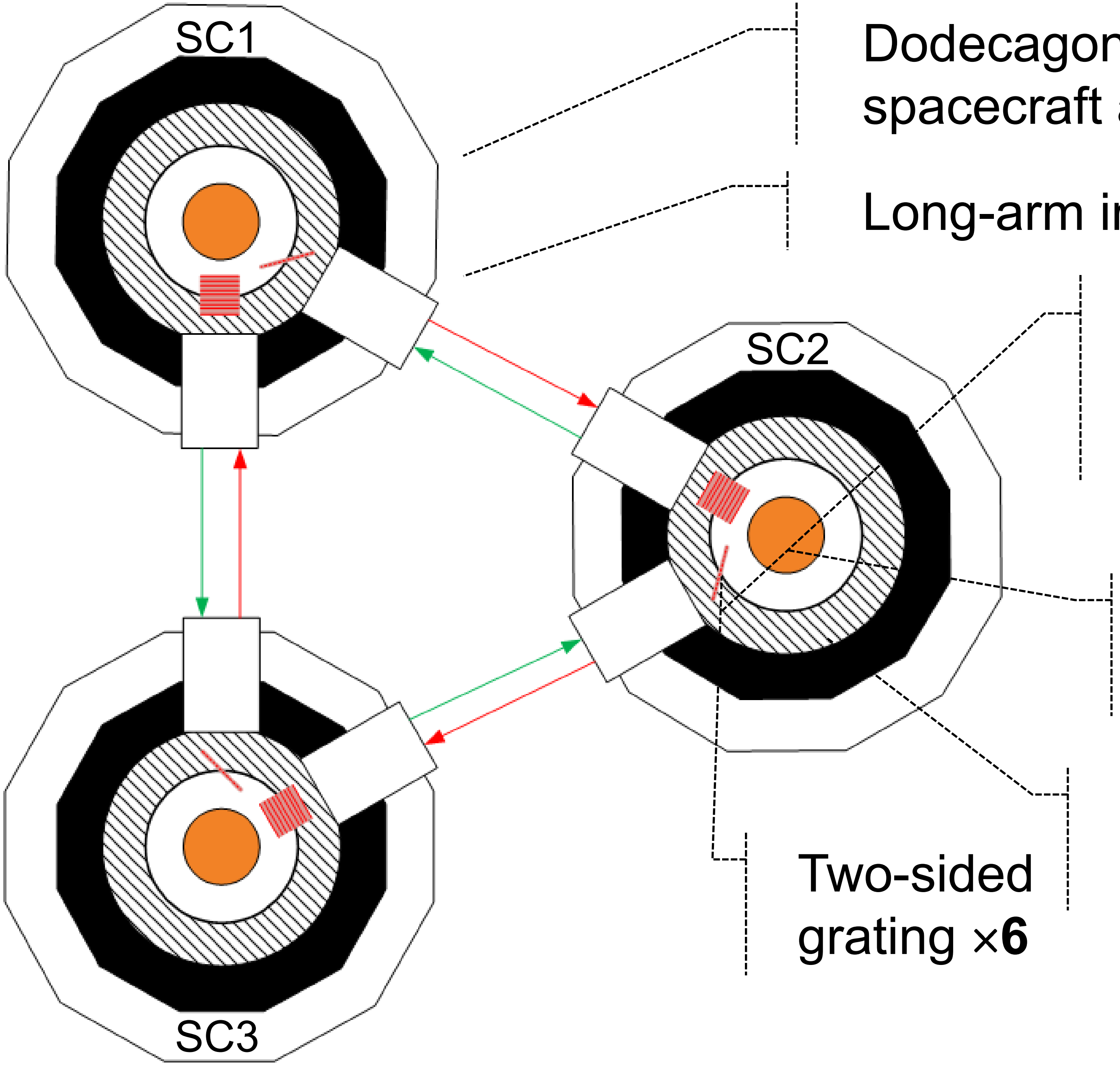
Cost
Reduce ~ 70%

Complexity
Reduce ~ 50%

Comm. Link
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**
  - **Optical Reflective with Gratings**

System Overview



Dodecagon ring with spacecraft avionics ×**3**

Long-arm interferometer ×**3**

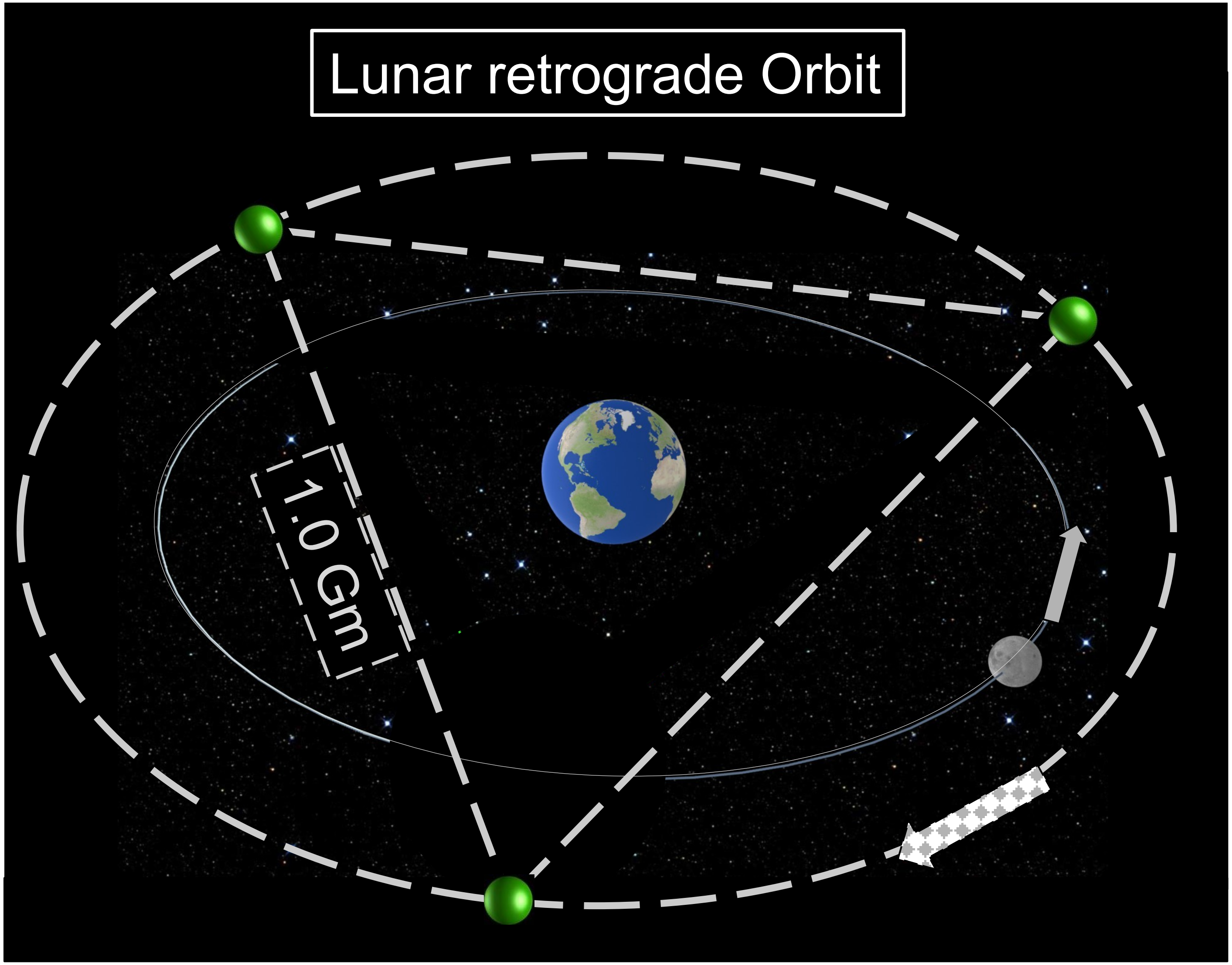
Short-arm interferometer ×**6**
35mm gap size

Test Mass ×**3**
∅=70mm, M≈3kg

Optics Bench ×**3**

Two-sided grating ×**6**

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

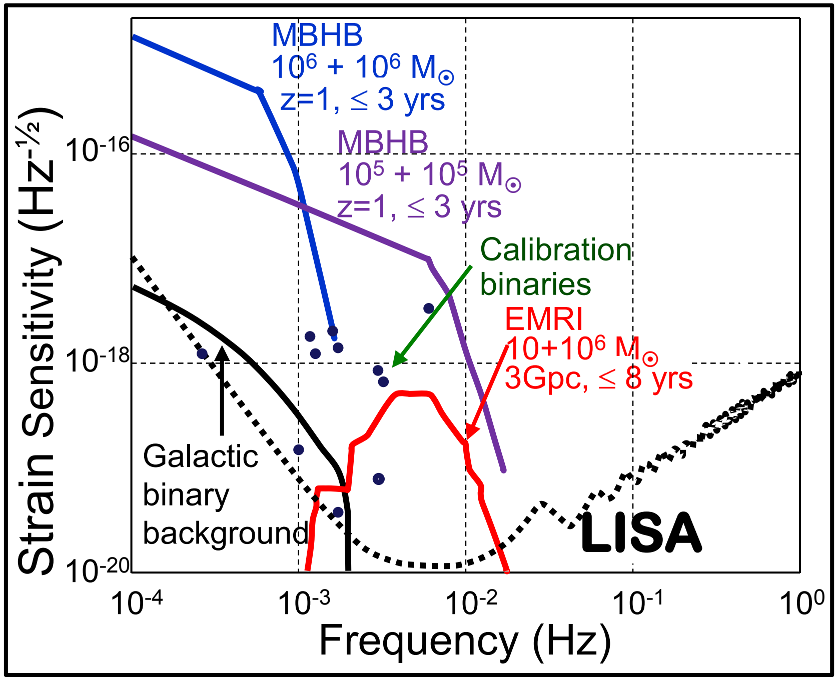
Comm Link
Increase > 100

LISA & LISA 2020

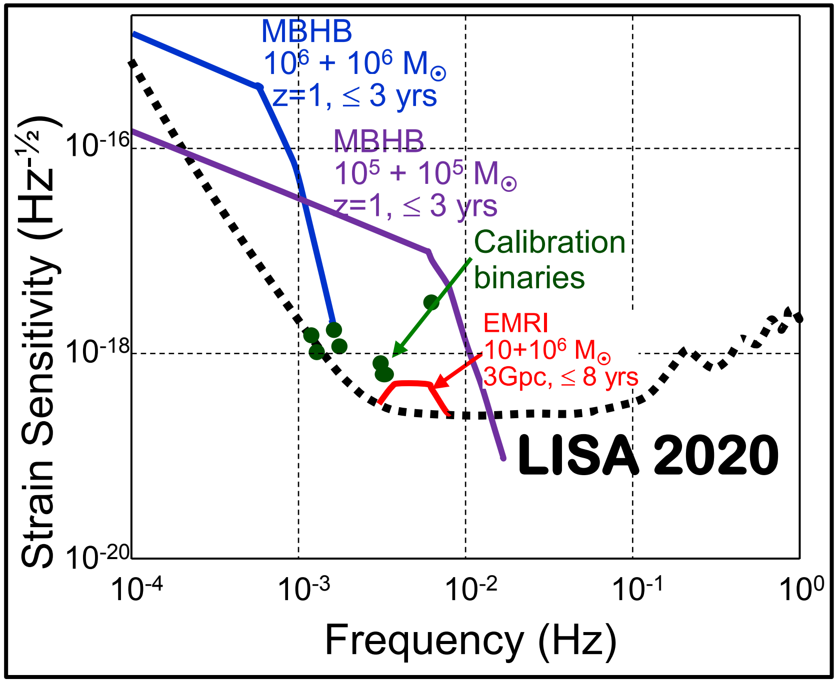
- **LISA:** 10^{-4} – 1 Hz **GW in Space**

  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** ($\mathrm{ms^{-2}Hz^{-1/2}}$)	**Metrology** ($\mathrm{pm\ Hz^{-1/2}}$)
LISA 2020	0.7-1.0 Geocentric	10^{-13} Sphere × 1	240 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

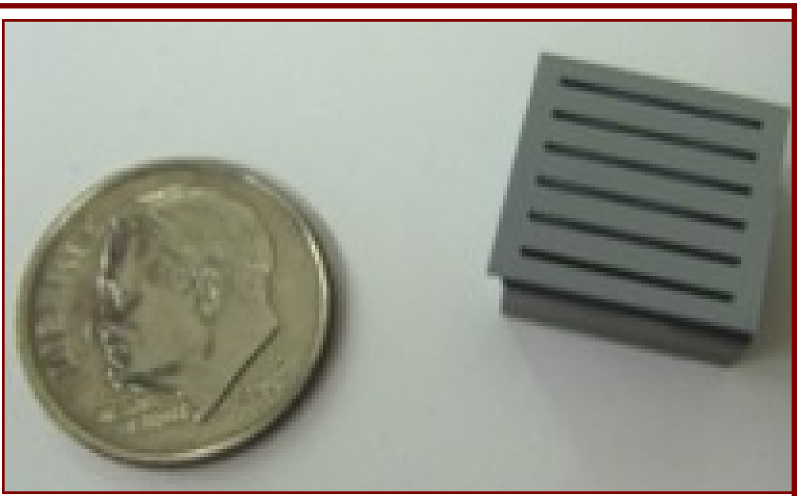
Principal Cost Savings Relative to LISA

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
2. **Reduced S/C mass from reduced 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 × 3 spacecraft
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

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)**

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

LISA-2020 Gravity-wave Concept Study

LISA-2020 concept with heritage

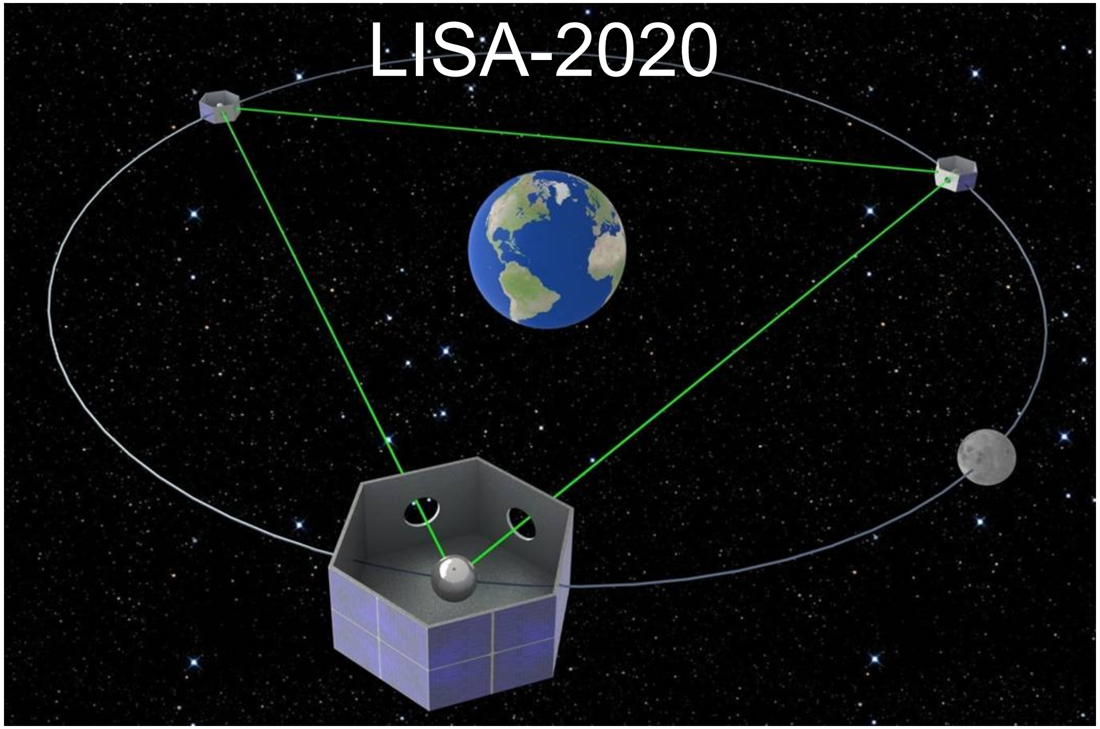
2 t launch
3[redacted]00 kg
3[redacted]00 W

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

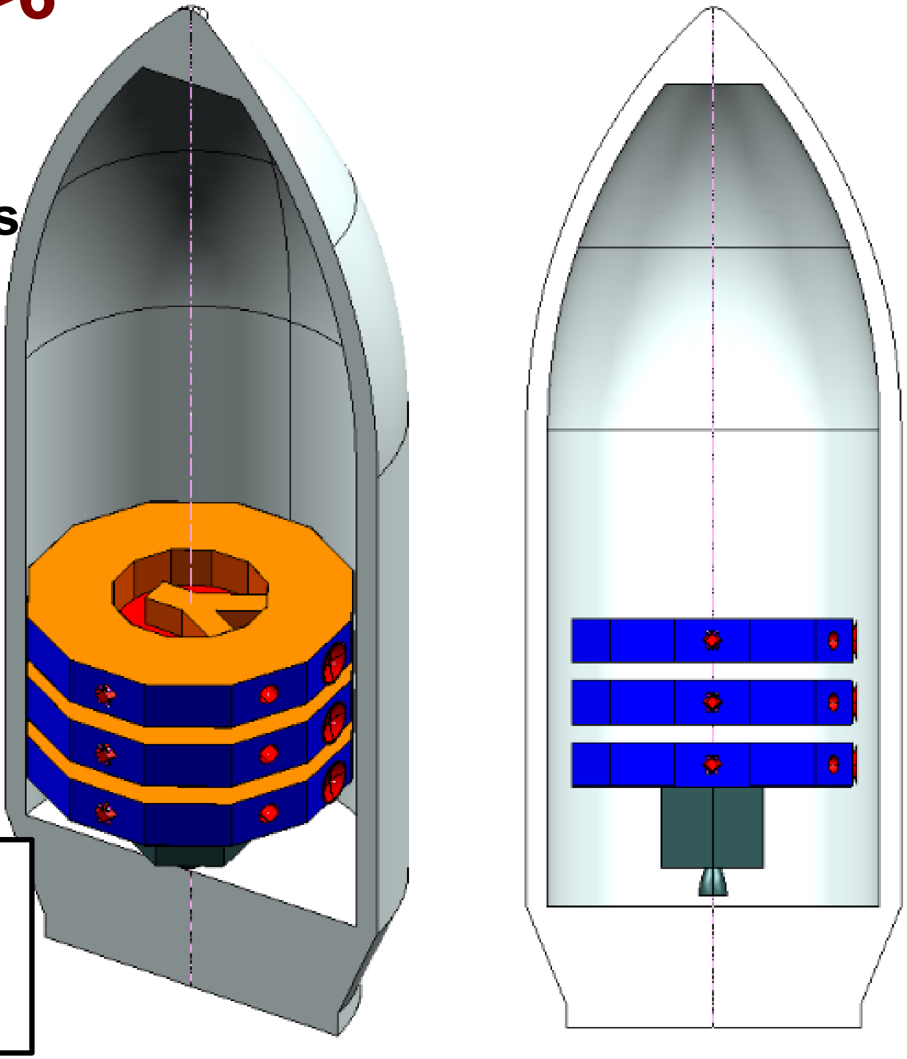
Spacecraft & Mission Design by LM

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

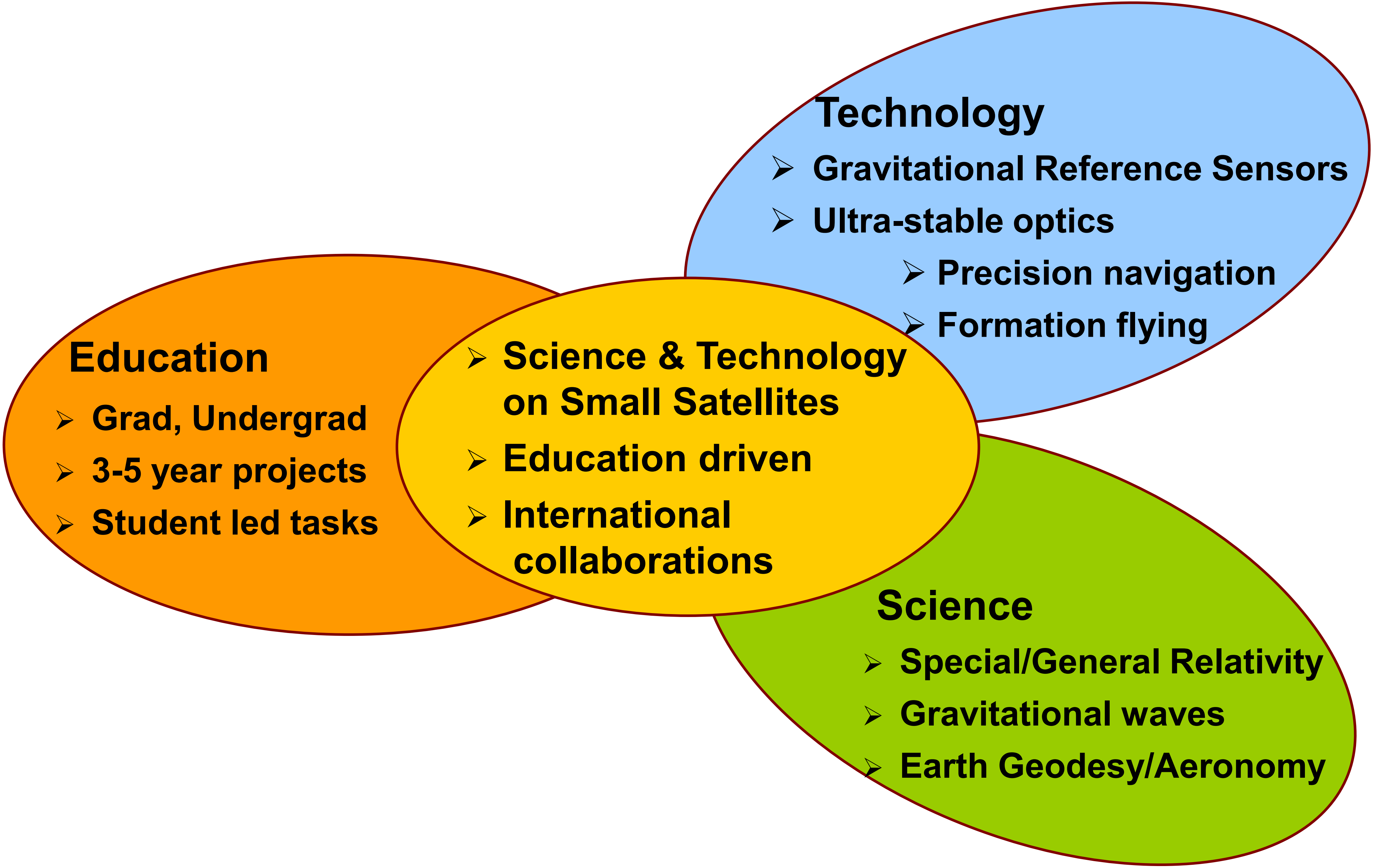
Conclusion #2

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



Technology

- Gravitational Reference Sensors
- Ultra-stable optics
- Precision navigation
- Formation flying

Education

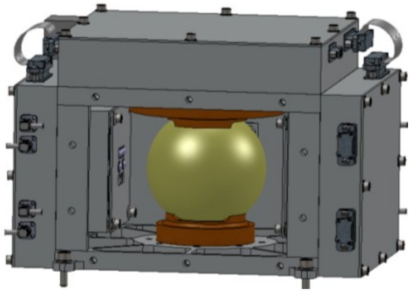
- Grad, Undergrad
- 3-5 year projects
- Student led tasks

- Science & Technology on Small Satellites
- Education driven
- International collaborations

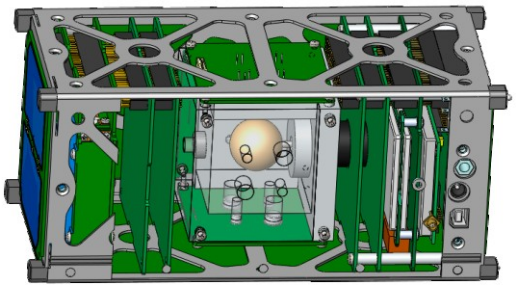
Science

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

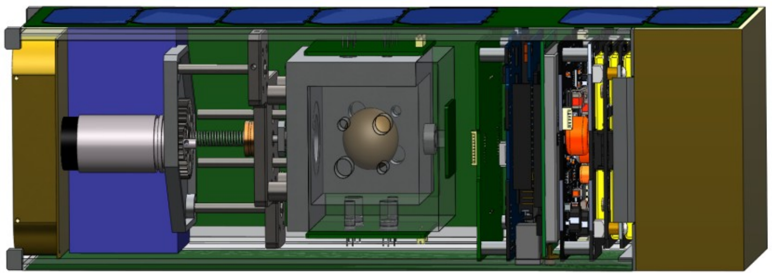
Small Sats Technology Program



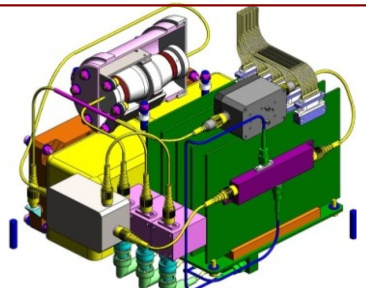
UV LED Sat -2013



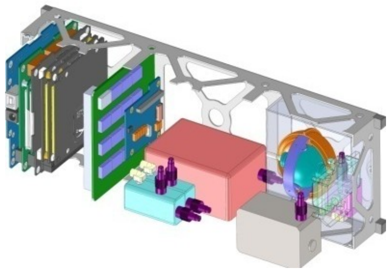
Shadow Sat - 2014
(partially-funded)



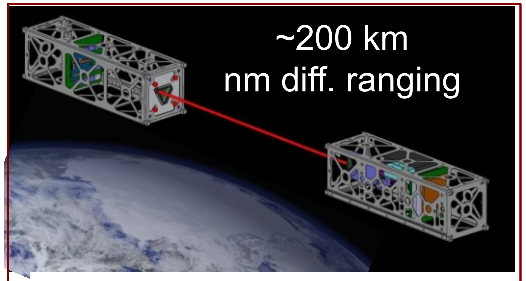
Drag-Free CubeSat - 2014 NEXT
ARC-SU-KACST Flight



Optical Sat – 2015
(Lab development)



Mini STAR– 2015
(Lab development)



Laser Ranging – 2016
(Lab development)

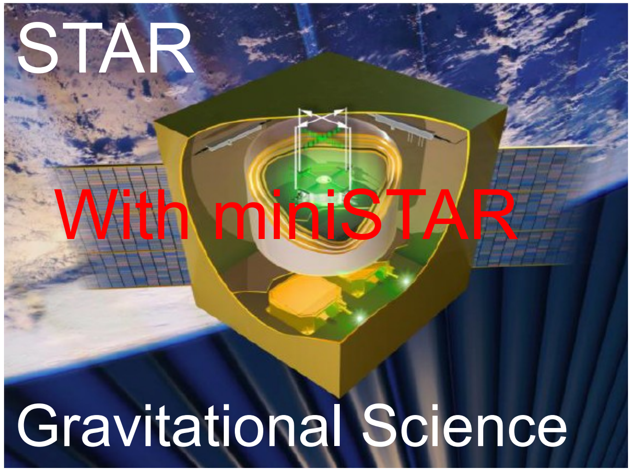
df/f ~ 10^{-12}
1mm optical cavity
1 mm gas cell
25 cm^3, 25 g, <100 mW

Mini clock Sat – 2016
(Lab development)

GRACE follow-on

With Cube-sats

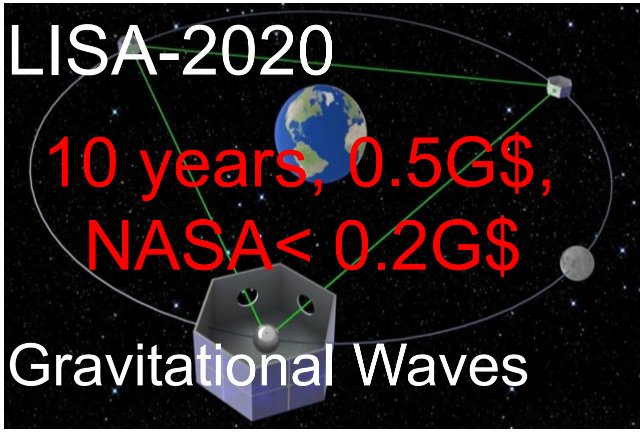
Geodesy, Aeronomy



STAR

With miniSTAR

Gravitational Science



LISA-2020

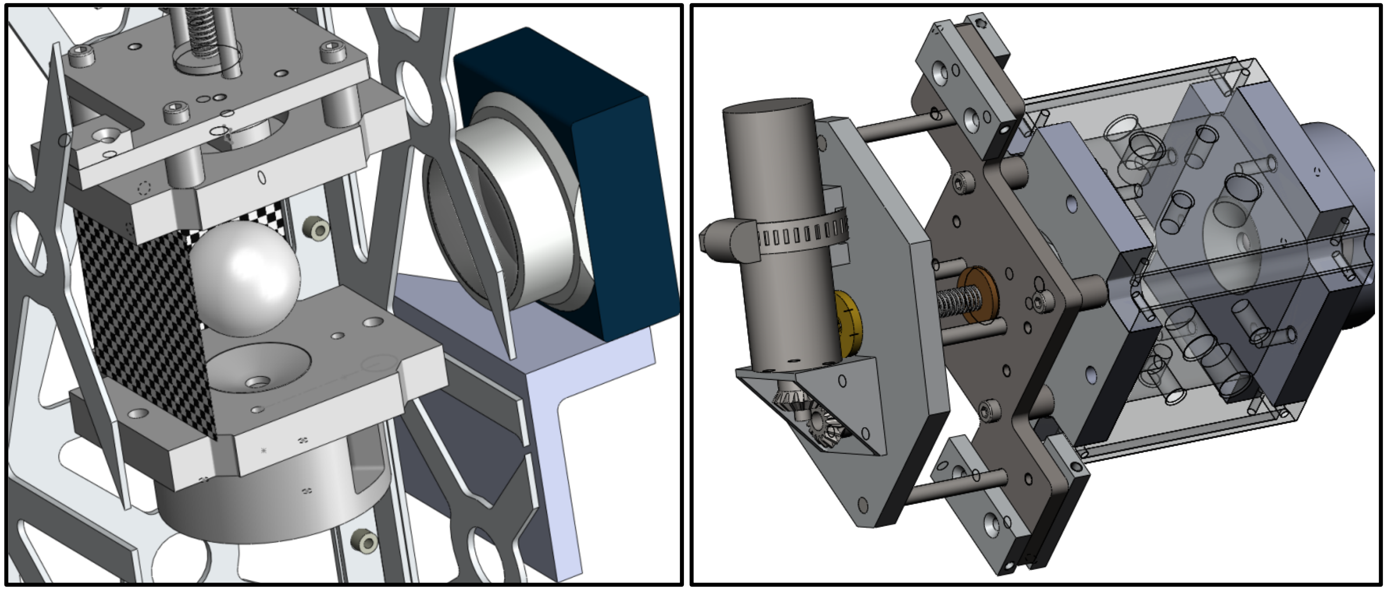
10 years, 0.5G$,
NASA< 0.2G$

Gravitational Waves

Caging System - April 2013 Parabolic Flight

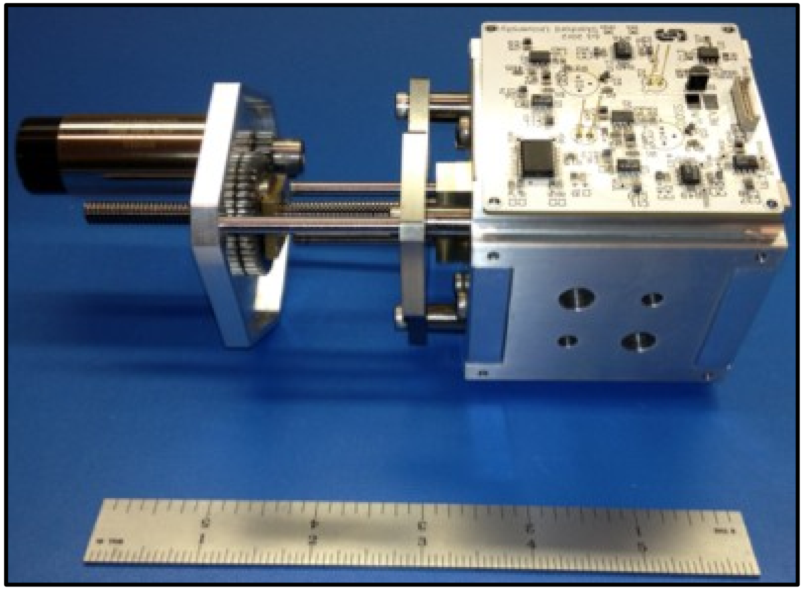
MGRS, 2.5 cm TM, for Parabolic Flight Caging Test

3 U Caging Fixture



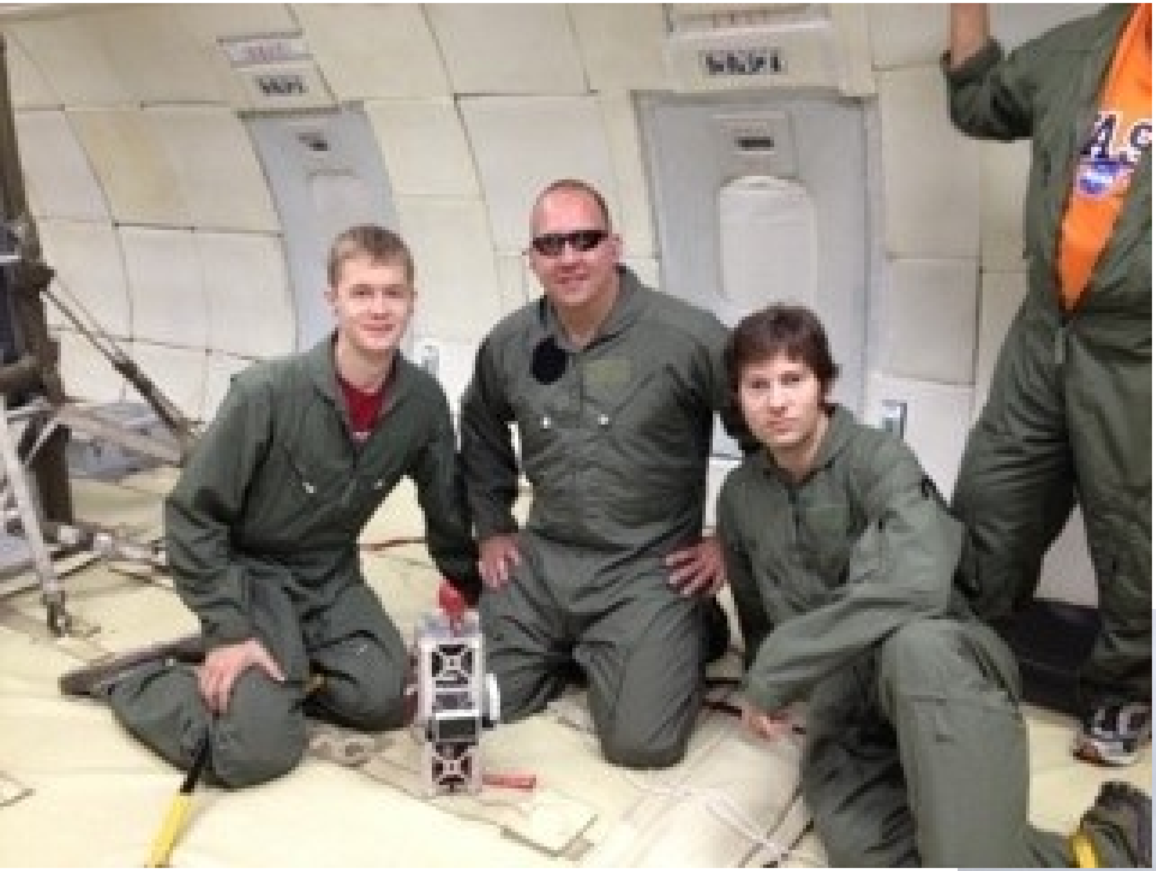
Caging System Schematics

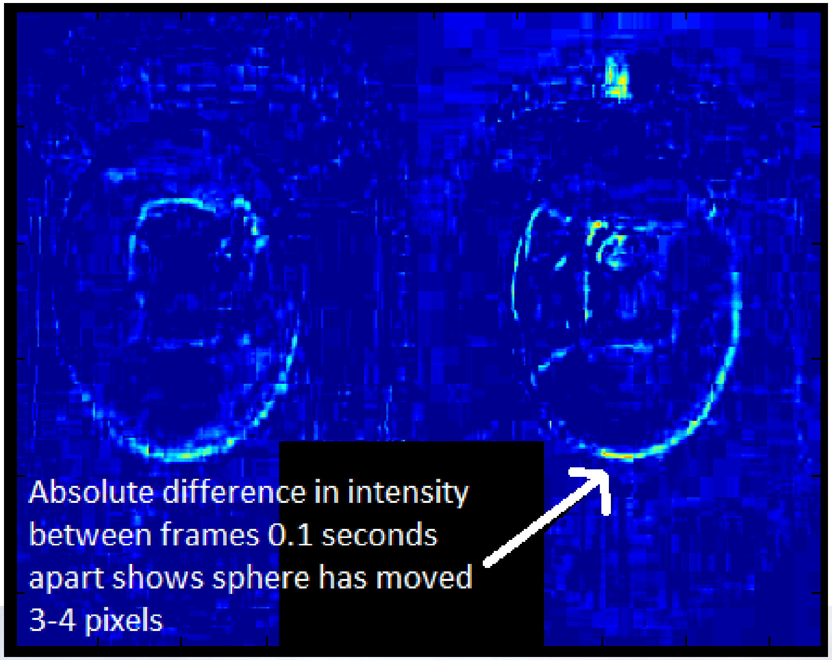
Housing



MGRS, Mechanical

Caging System - April 2013 Parabolic Flight





Absolute difference in intensity between frames 0.1 seconds apart shows sphere has moved 3-4 pixels

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

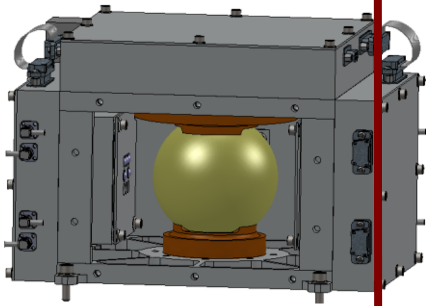
- **Andreas Zoellner**
- **Kirk Ingold**
- **Eric Hultgren**

Flight4-22a

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



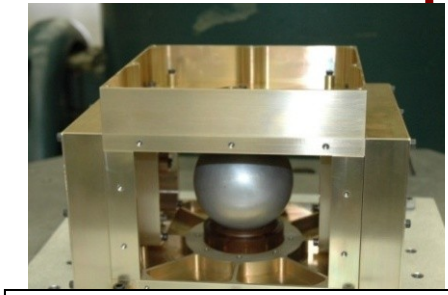
Mission Design

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



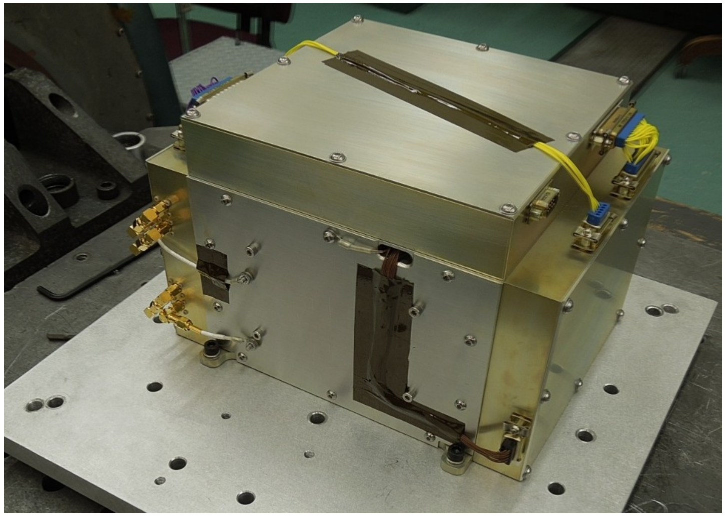
222×277×180 mm; 6.5 kg

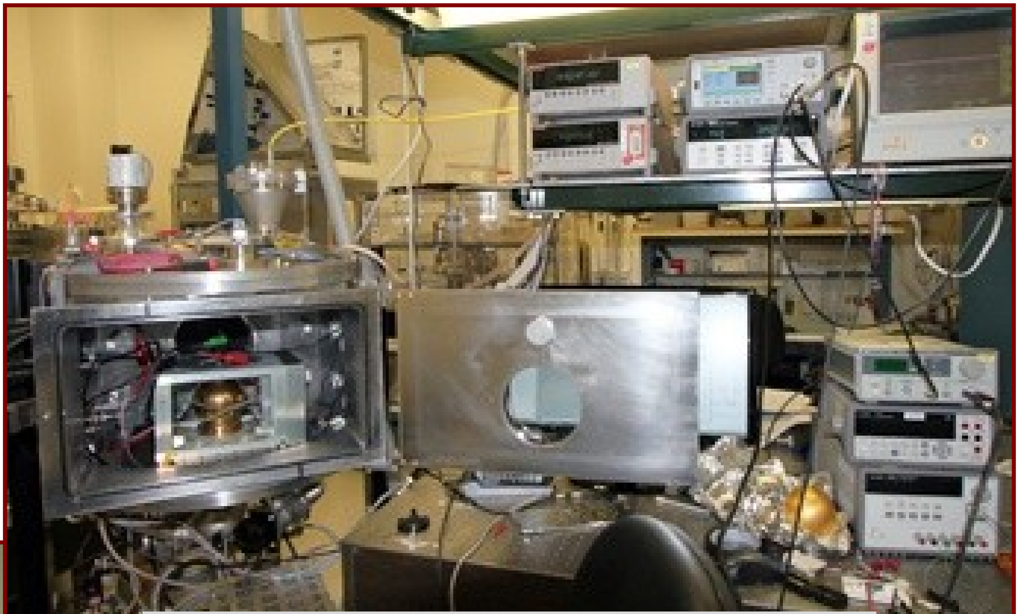
Management

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

Demonstrates unconventional international collaboration

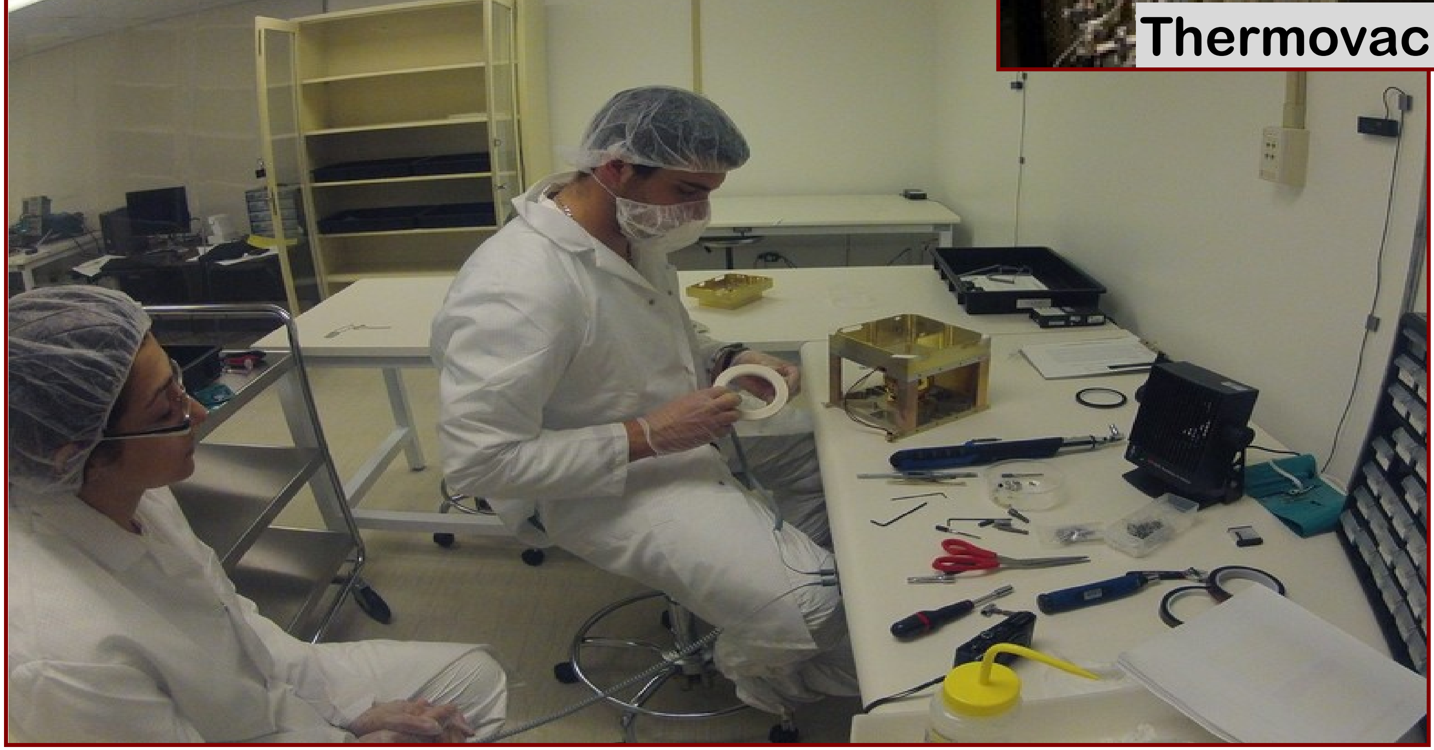
UV LED Instrument Integration and Test



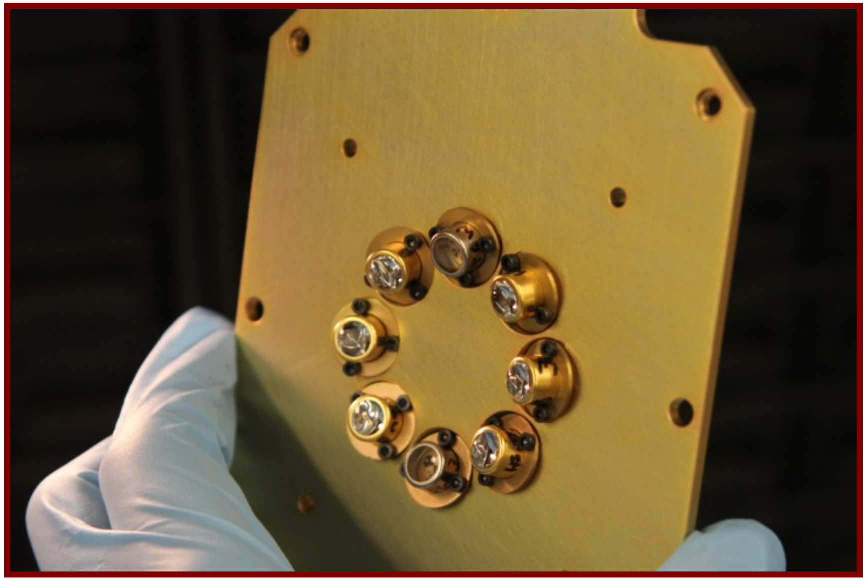


Thermovac chamber testing

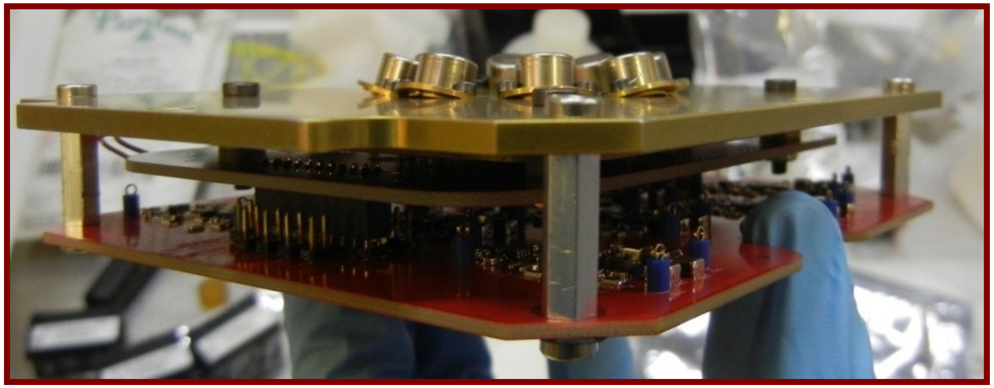
Integration of Flight Model at ARC

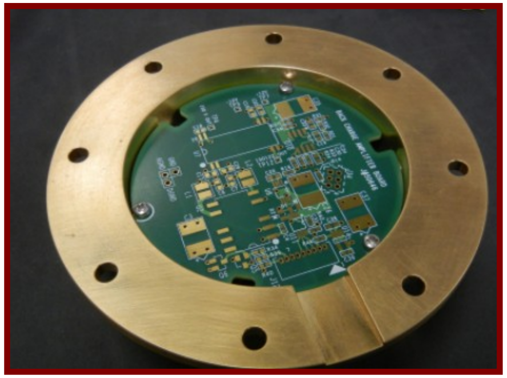


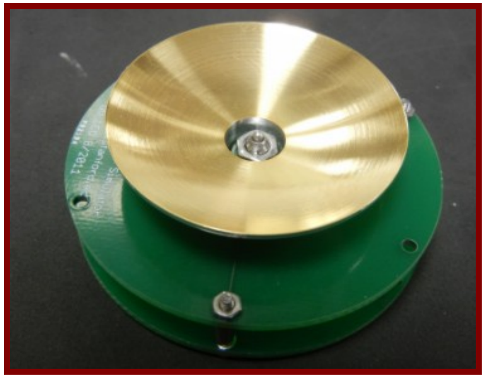
UV LED Instrument Components; 2013 Launch

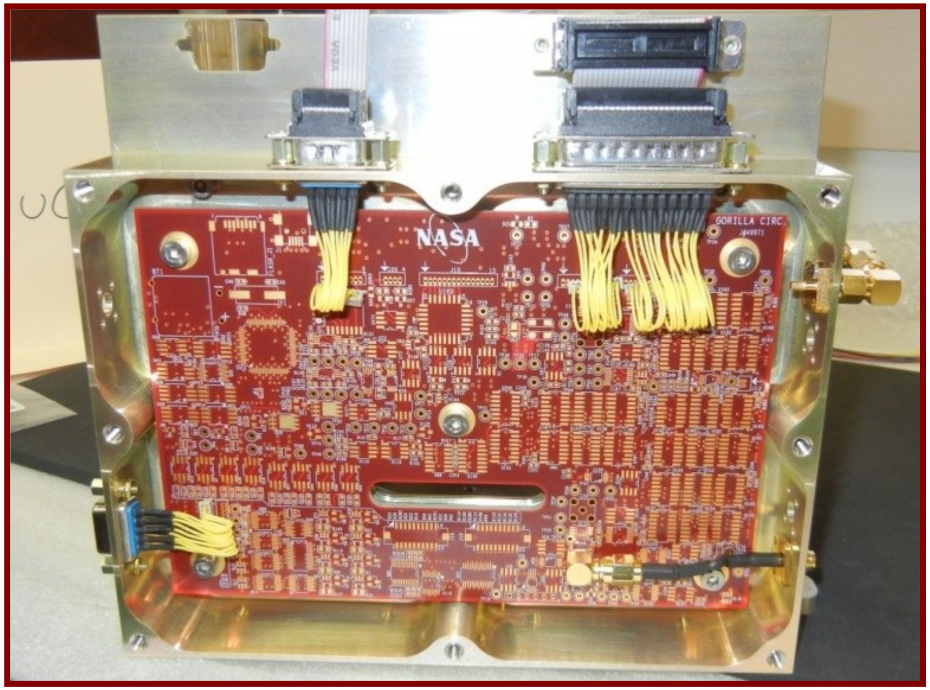


- Payload completion: May 2013
- Spacecraft CDR: May 2013
- Payload Integration: Jun 2013
- Russian launch: Nov 2013

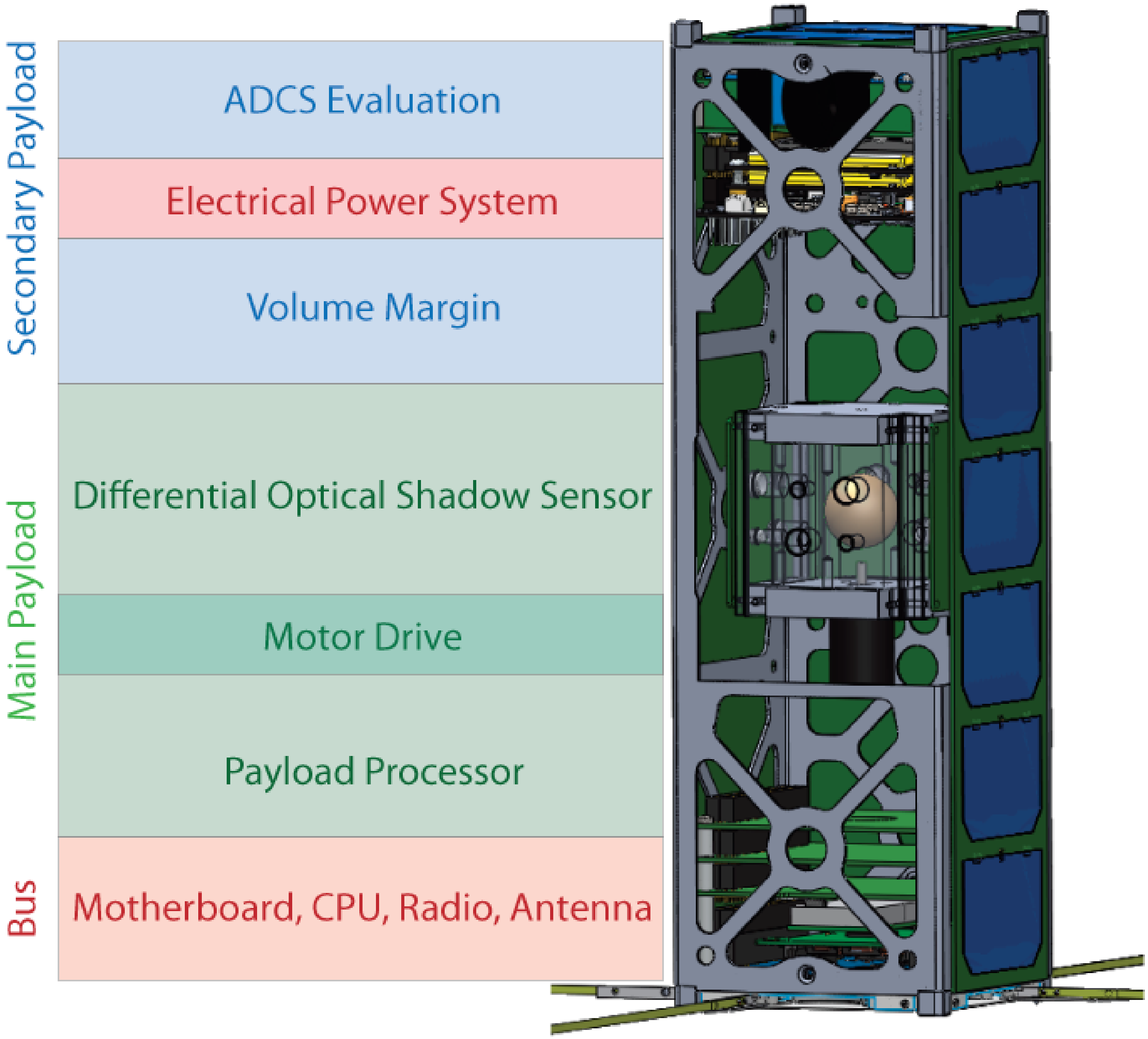








DOSS & ADCS on 3U Cubesat; 2014 Launch



Secondary Payload
- ADCS Evaluation
- Electrical Power System
- Volume Margin

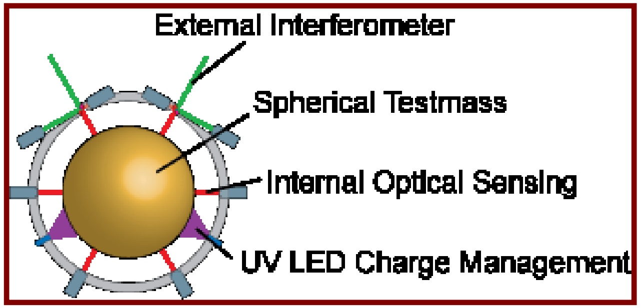
Main Payload
- Differential Optical Shadow Sensor
- Motor Drive
- Payload Processor

Bus
- Motherboard, CPU, Radio, Antenna

Differential Optical Shadow Sensor (DOSS)

Technology Objectives

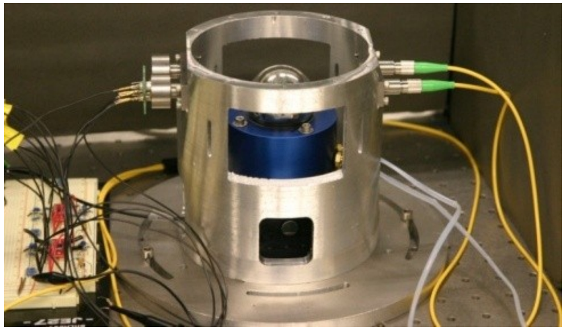
- Raise TRL level for miniature high-sensitivity displacement sensor
  - nm/Hz$^{1/2}$ sensitivity
  - No forcing
  - Non-contact



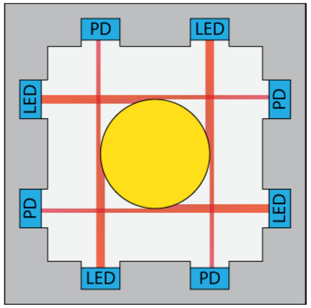
Mission Design

2 kg
4 W
3U Cube

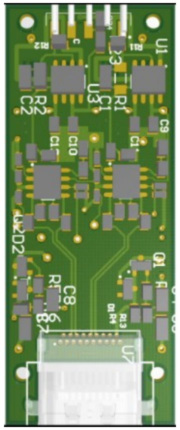
- 3U CubeSat
- Any orbit
- Launch ~ 2014
- 1 month ops
- Payload funded



Payload

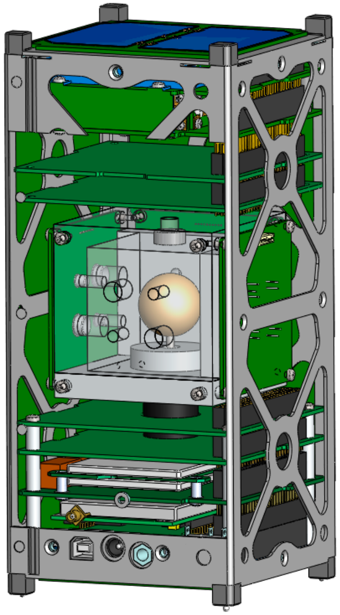


- Light source:
  - SLED, 1545 nm
- InGaAs quad-photodiode
- Ultra-low current Difet amp



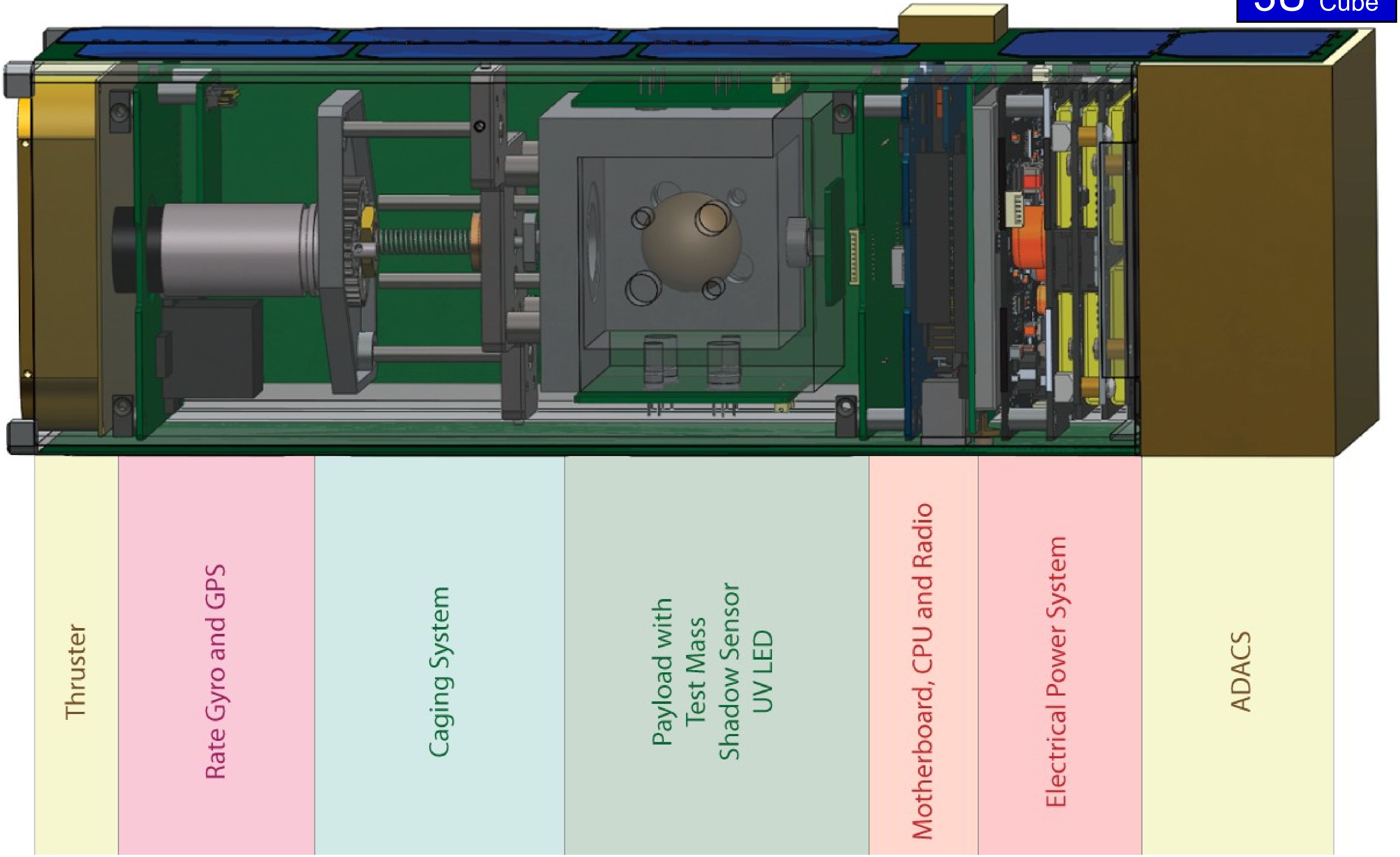
Management

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



The Drag-free CubeSat

4 kg
6 W
3U Cube



Thruster

Rate Gyro and GPS

Caging System

Payload with
Test Mass
Shadow Sensor
UV LED

Motherboard, CPU and Radio

Electrical Power System

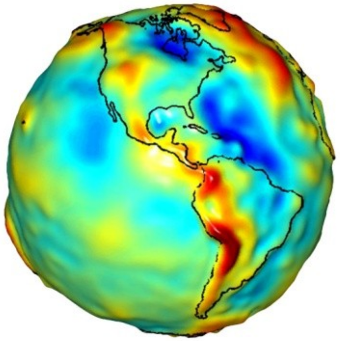
ADACS

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

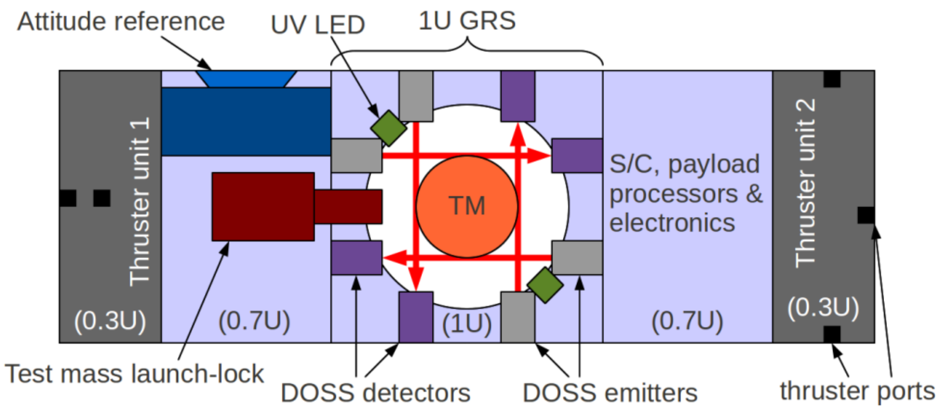


Mission Design

- 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

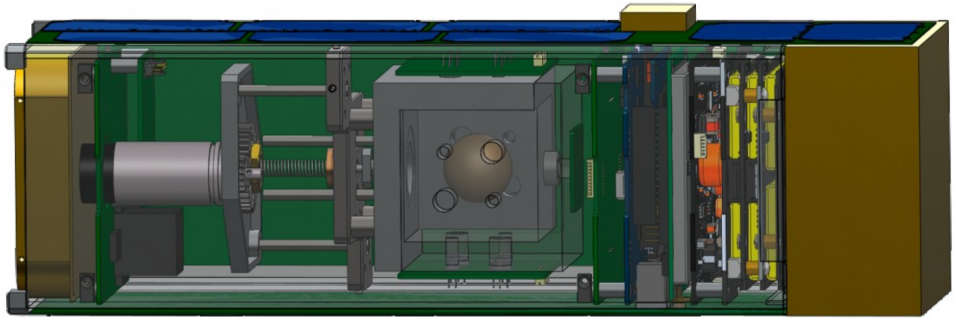
Payload (back-up version)

- Drag-free sensor + micro-thrusters



Management

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



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