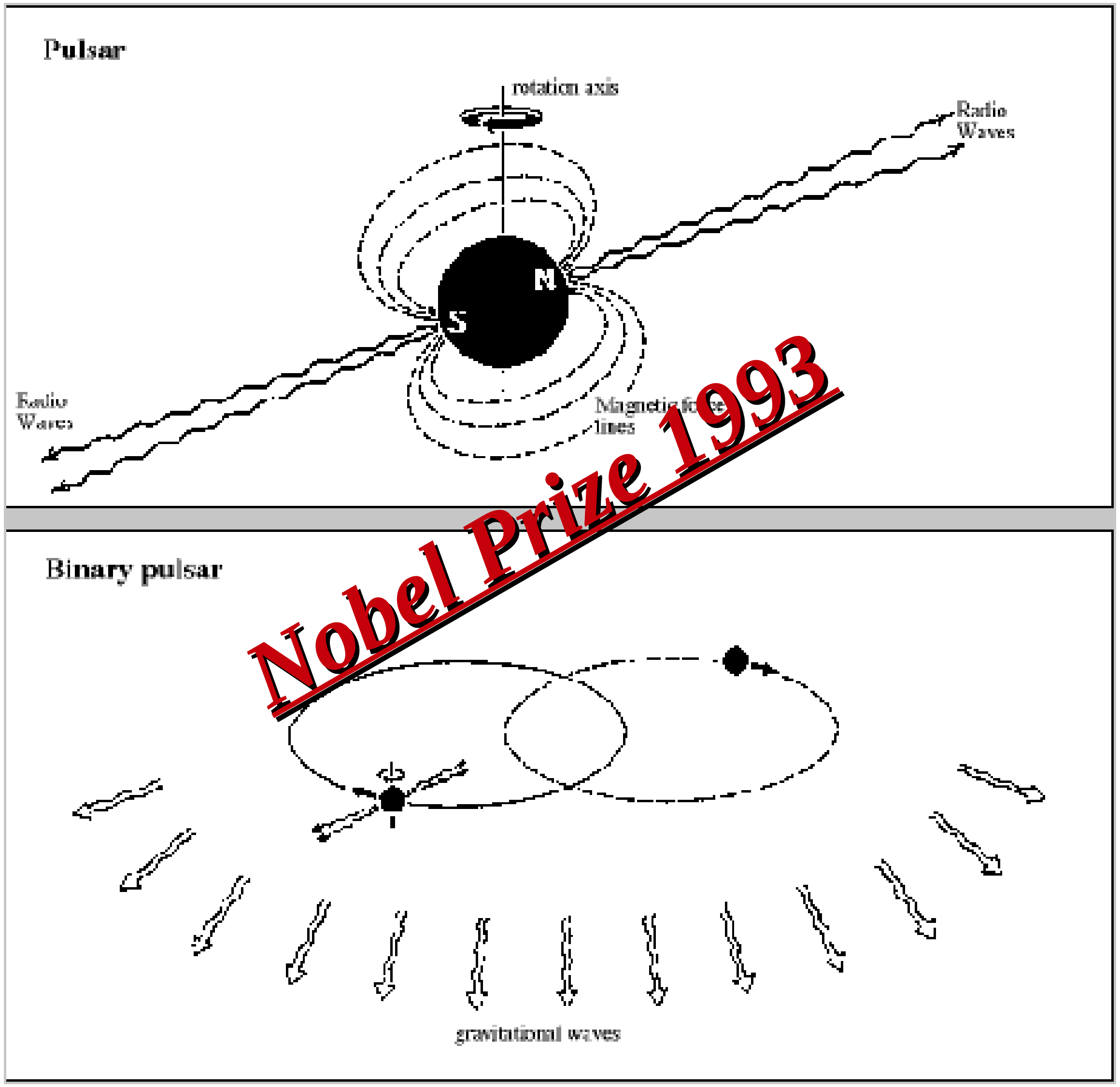
Milli-Hertz Gravitational Waves: *LISA* and *LISA PathFinder*

Alberto Lobo

ICE (CSIC) & IEEC

Preamble: PSRB 1913+16

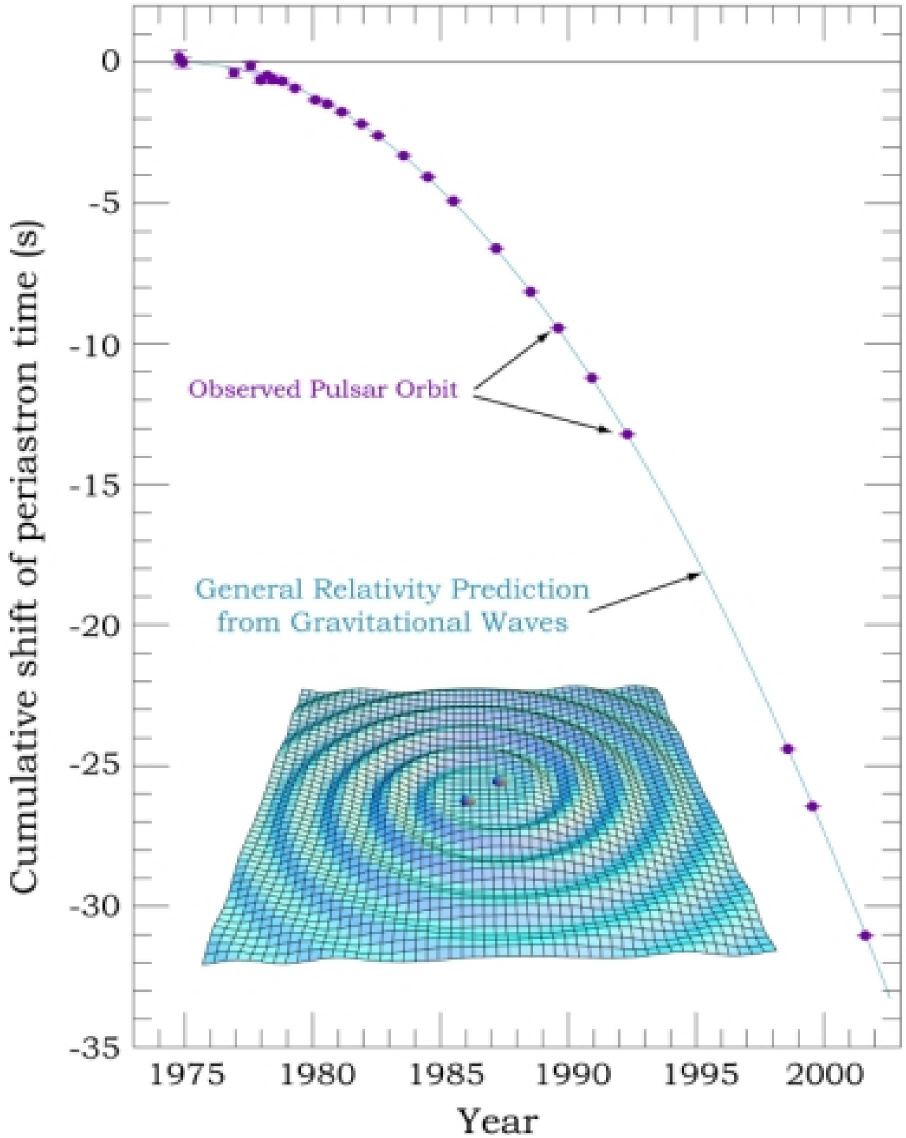
Rusell A. Hulse



Nobel Prize 1993

Joseph H. Taylor, Jr

Preamble: PSRB 1913+16



The binary pulsar 1913+16:

Discovered: Arecibo 1974

Tracking: ~30 years

GR ***prediction***:

$$\dot{E}_{\mathrm{GW}} = -\frac{G}{5\,c^5}\,\dddot{Q}_{ij}\,\dddot{Q}_{ij}$$

Observational ***result***:

$$\frac{\dot{P}_{\mathrm{measured}}}{\dot{P}_{\mathrm{theory}}} = 1.0013 \pm 0.0021$$

Some PSRB 1913+16 parameters

Character	Parameter	Value
Keplerian	Orbital period	$P = 7.7519387743\ (1)$ hours
	Eccentricity	$e = 0.6171338\ (4)$
	Projected semi-major axis	$a \sin i = 2.3417725\ (8)$ light sec
Post-Keplerian	Periastron precession	$\langle\dot{\varphi}\rangle = 4.226595\ (5)$ deg/year
	Time dilation + grav. redshift	$\gamma = 0.0042919\ (8)$ sec
	Orbital period decay rate	$\dot{P} = -2.4056 \pm 0.0051 \times 10^{-12}$
General Relativity	Pulsar mass	$m_p = 1.4414\ (2)\ M_\odot$
	Companion mass	$m_c = 1.3867\ (2)\ M_\odot$
	Orbit inclination	$\sin i = 0.73\ (4)$

PSRB 1913+16 consequences

- *PSRB 1913+16* is a ***strongly relativistic system***
- GR ***correctly predicts all*** post-Keplerian parameters
  - Gravitational redshift and time dilation
  - Perihelion advance
  - Shapiro time delays
  - ***Emission of Gravitational Wave Radiation***

GWs from the binalry pulsar:

- ***Compelling*** evidence of their existence,
- ***Not indirect***, but ***incomplete***

• GW emission frequency:	~ 70 μHz
• Current GW emission amplitude:	~ 2×10^{-23}
• Calculated lifetime:	~ 300,000,000 years

GW Astronomy

Therefore:

- Relevant *GW* sources are ***far*** from Earth
- Detection poses a formidable problem

Benefit of detection:

- *GW*s carry *undistorted news* from source *interiors*

GW sources are often classified in four groups:

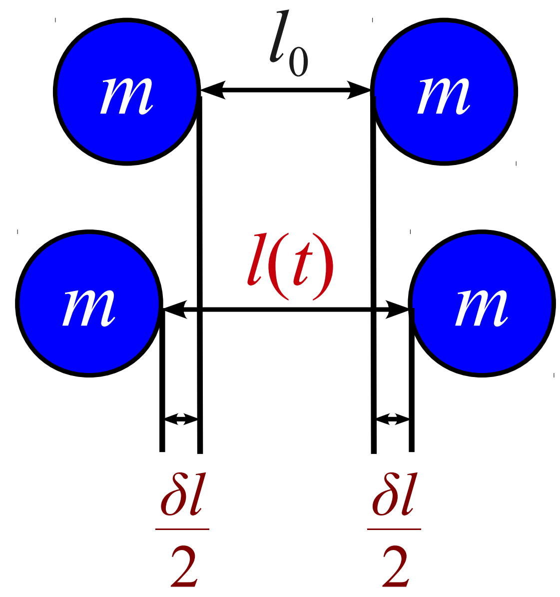
- ***Burst***, or short duration signals
- ***Periodic***, or long duration signals
- ***Stochastic*** backgrounds
- ***Other***, unforeseen signals

GW detection will thus spawn a *new branch* of Astronomy:

GW Astronomy

GW telescopes: basics

Free test masses at rest before *GW* comes:



Incoming GW causes ***relative distance changes***:

$$l(t) = l_0 + \delta l = l_0\left[1 + \frac{1}{2}h(t)\right]$$

where

$$h(t) = \left[h_\times(\boldsymbol{x}_0, t)\cos(2\varphi) + h_+(\boldsymbol{x}_0, t)\sin(2\varphi)\right]\sin^2\theta$$

GW amplitudes are measured in ***metres/metre***.

For envisaged sources, $h \sim 10^{-18} - 10^{-26}$

GW telescopes: basics

Because

$$\delta l(t) = \frac{1}{2}\, l_0 h(t)$$

detection is simpler when l_0 is **very large.**

In the case of interferometric detectors, this entails the use of very long baselines.

But length has impact on the GW frequencies to which the antenna is most sensitive, too:

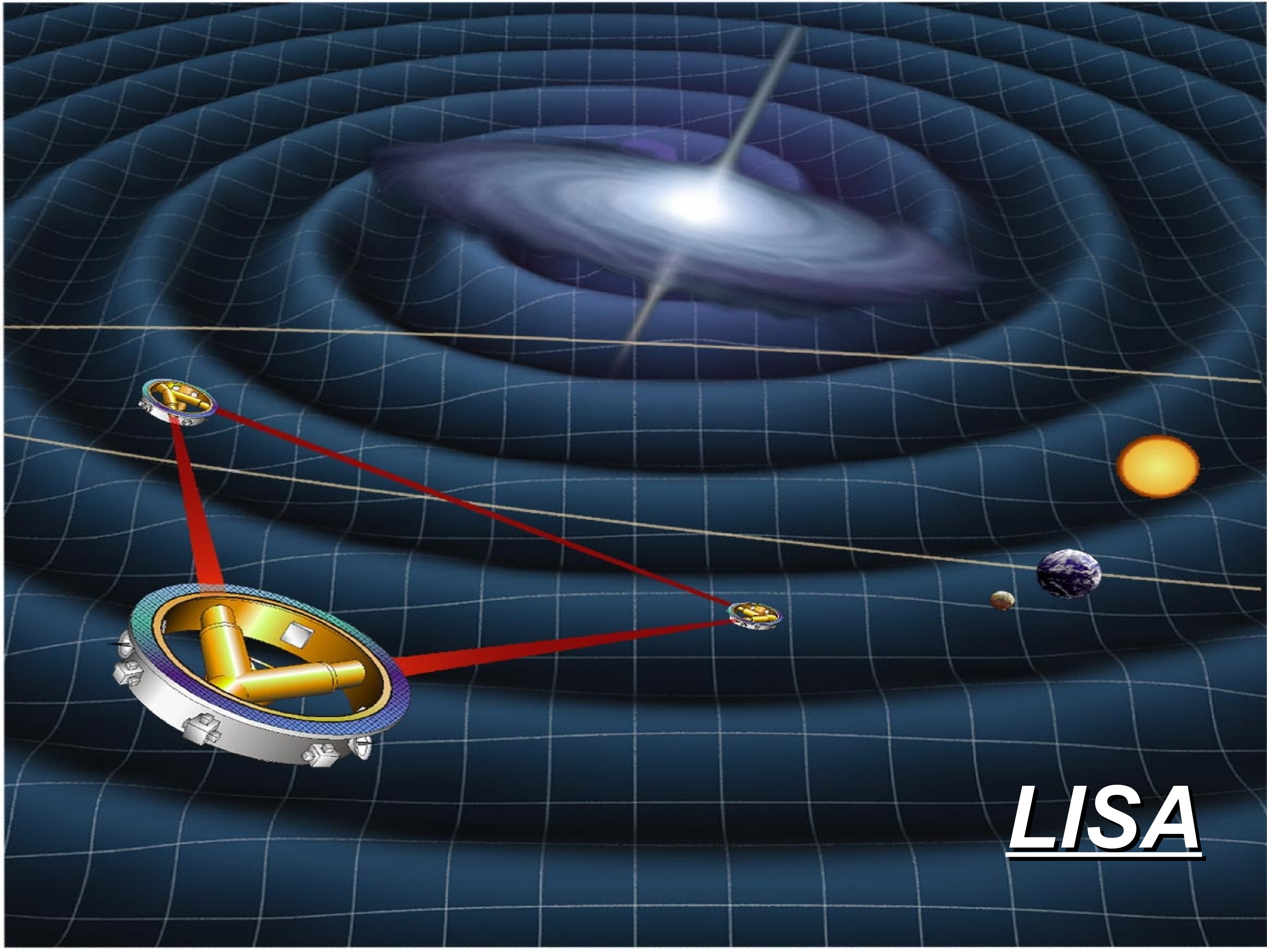
$$\delta\phi = 2\,\frac{\omega_{\rm laser}}{\Omega_{\rm GW}}\, h_0 \sin\frac{\Omega_{\rm GW} L}{2c}\;, \qquad \Omega_{\rm GW} \ll \omega_{\rm laser}$$

Hence optimum arm-length: $L = \dfrac{\lambda_{\rm GW}}{4}$

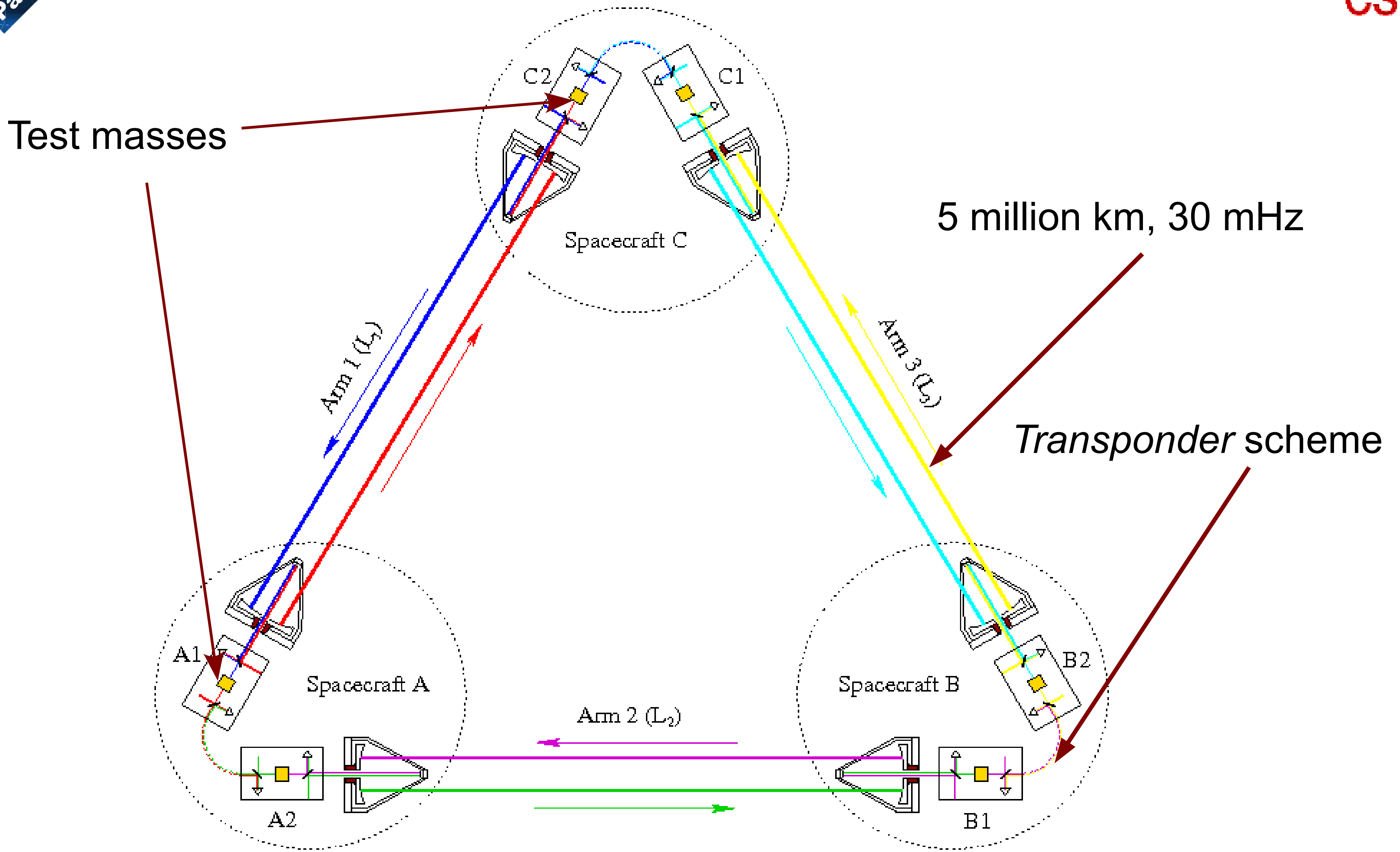
GW telescopes: Earth vs. space based

Ground based (VIRGO & LIGO)	Space based (LISA)
GW freq 10 Hz < f < 2 kHz	GW freq 0.1 mHz < 1 Hz
Main signals are pulsed	Long (years) duration signals
Rates uncertain	Ibid., but some signals guaranteed
SNRs tight	SNRs can be as high as 1000
Data analysis very complex	Data analysis (hopefully) less complex
Data archives huge (because of high freq)	Data archives much more manageable
No hardware limits	Very stringent hardware constraints
Highly serviceable, upgradable	Not serviceable, minor upgrades
Long lifetime	Reduced lifetime

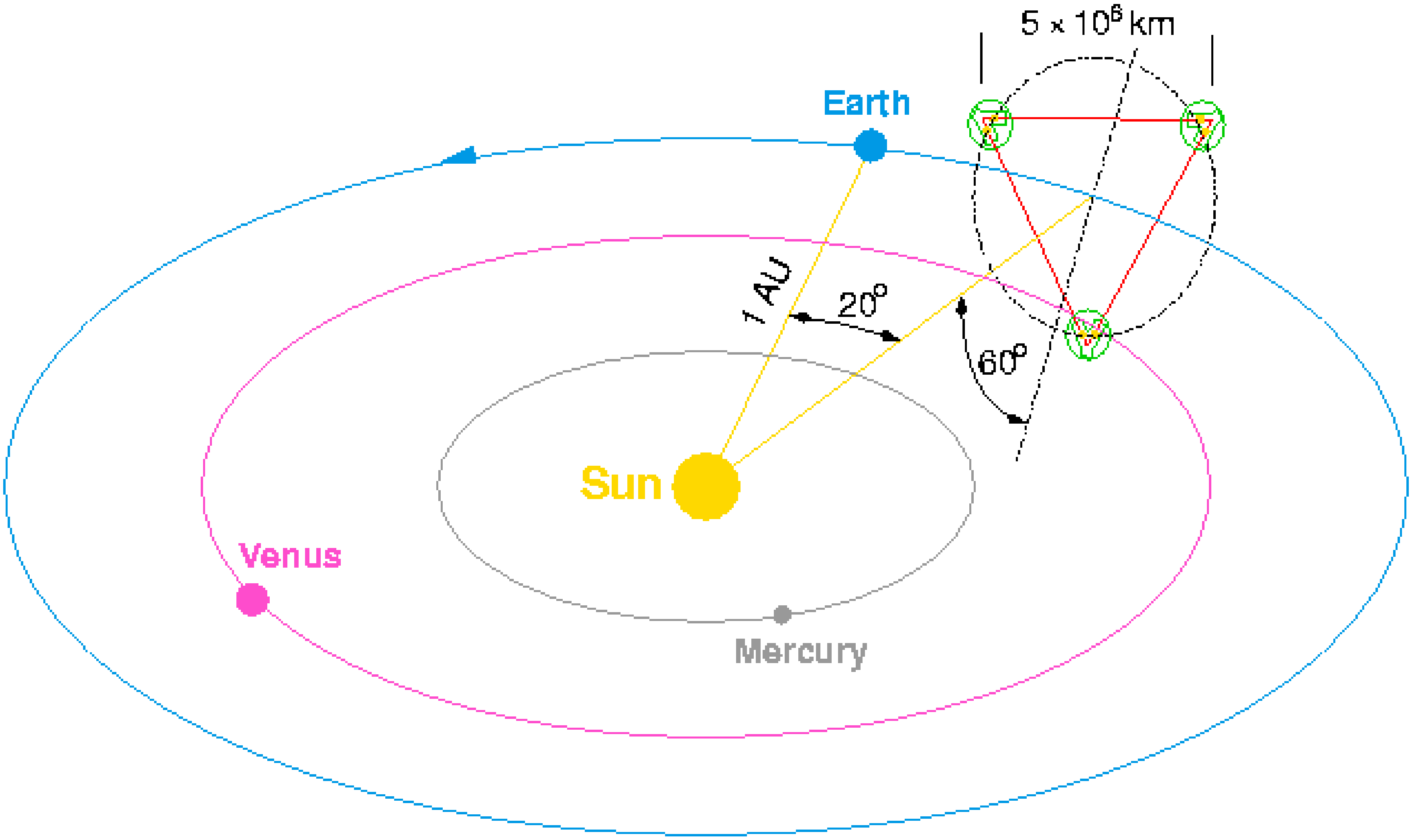
These complement each other in a common objective


LISA

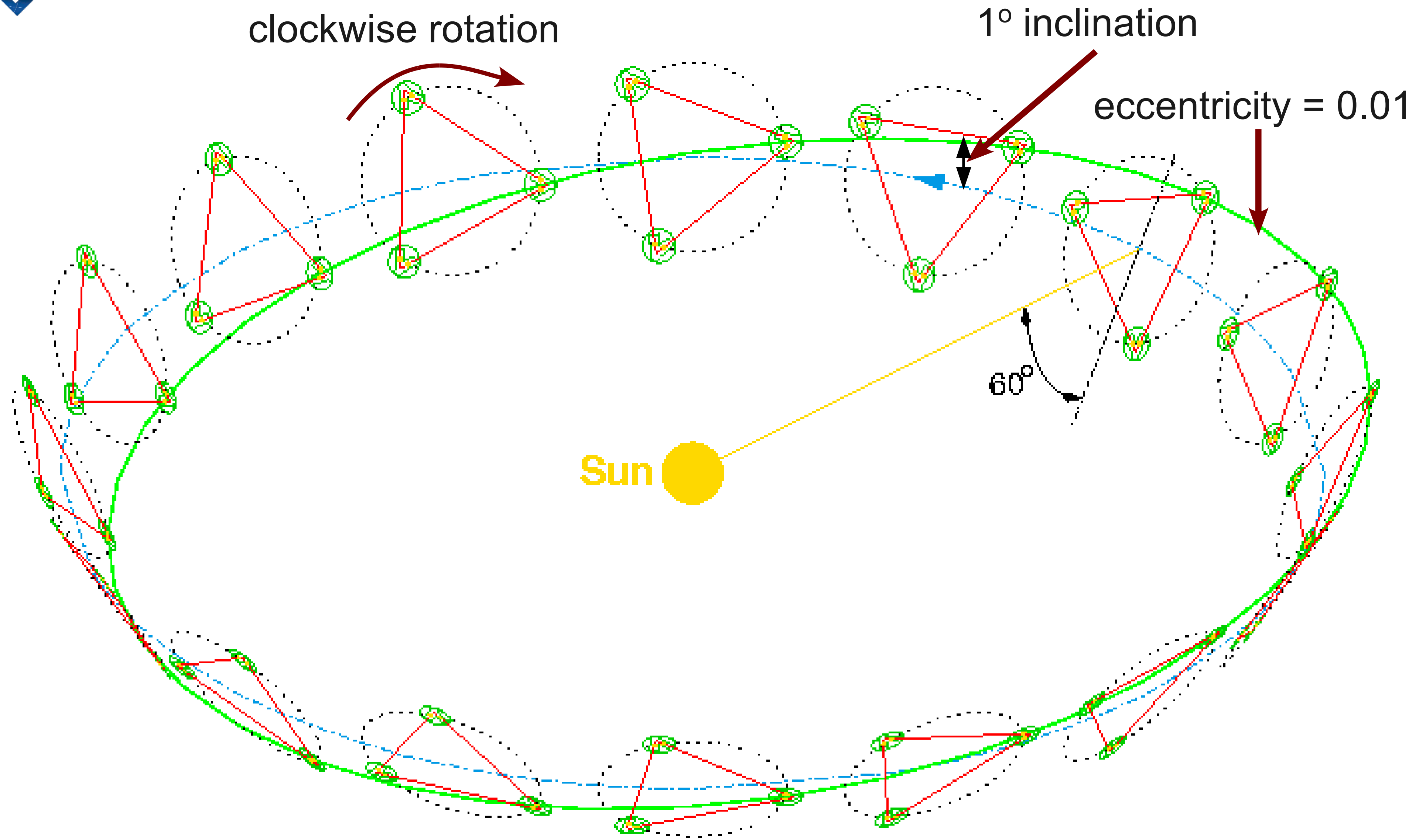
LISA concept

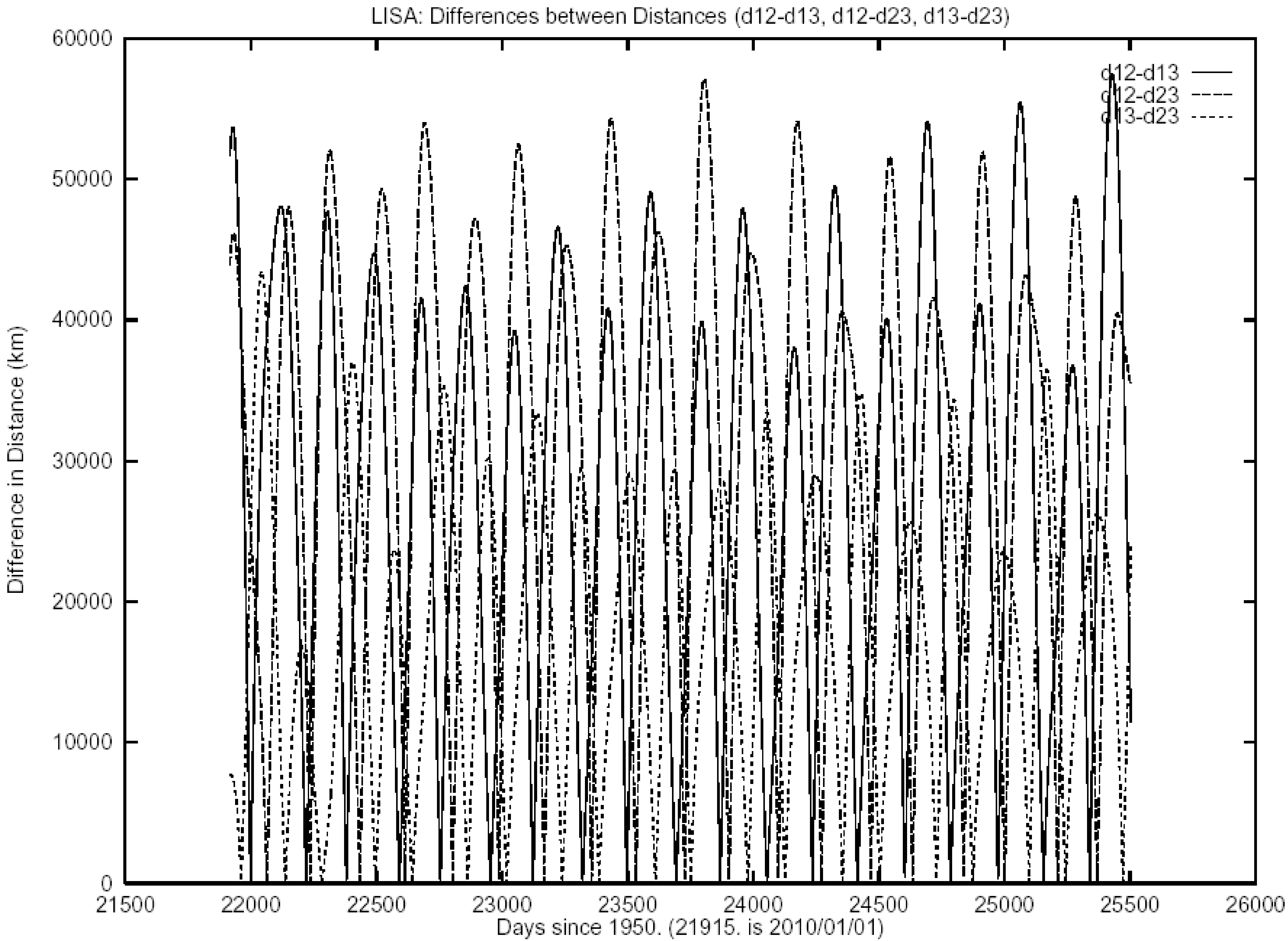


LISA orbit

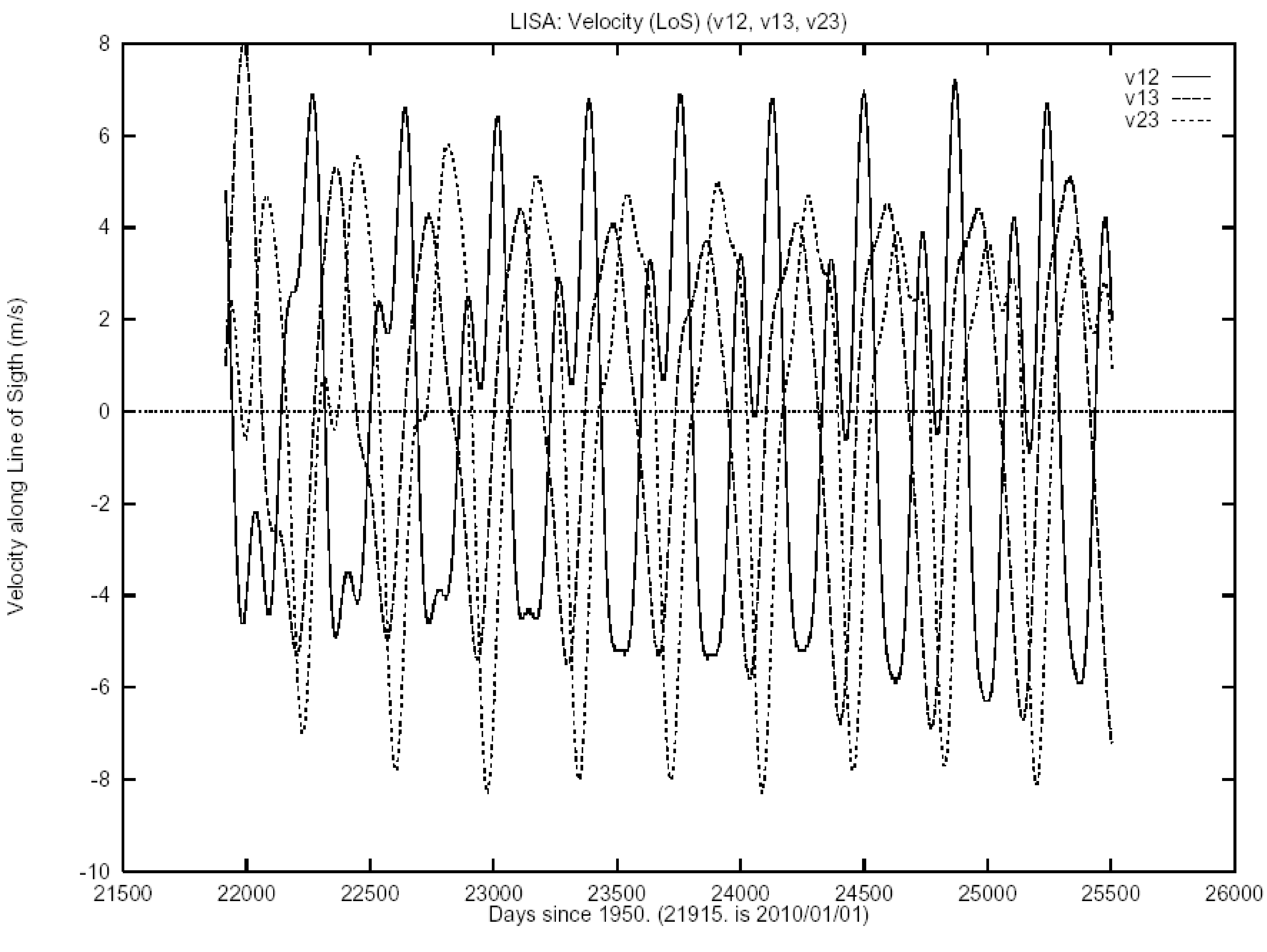


LISA orbit

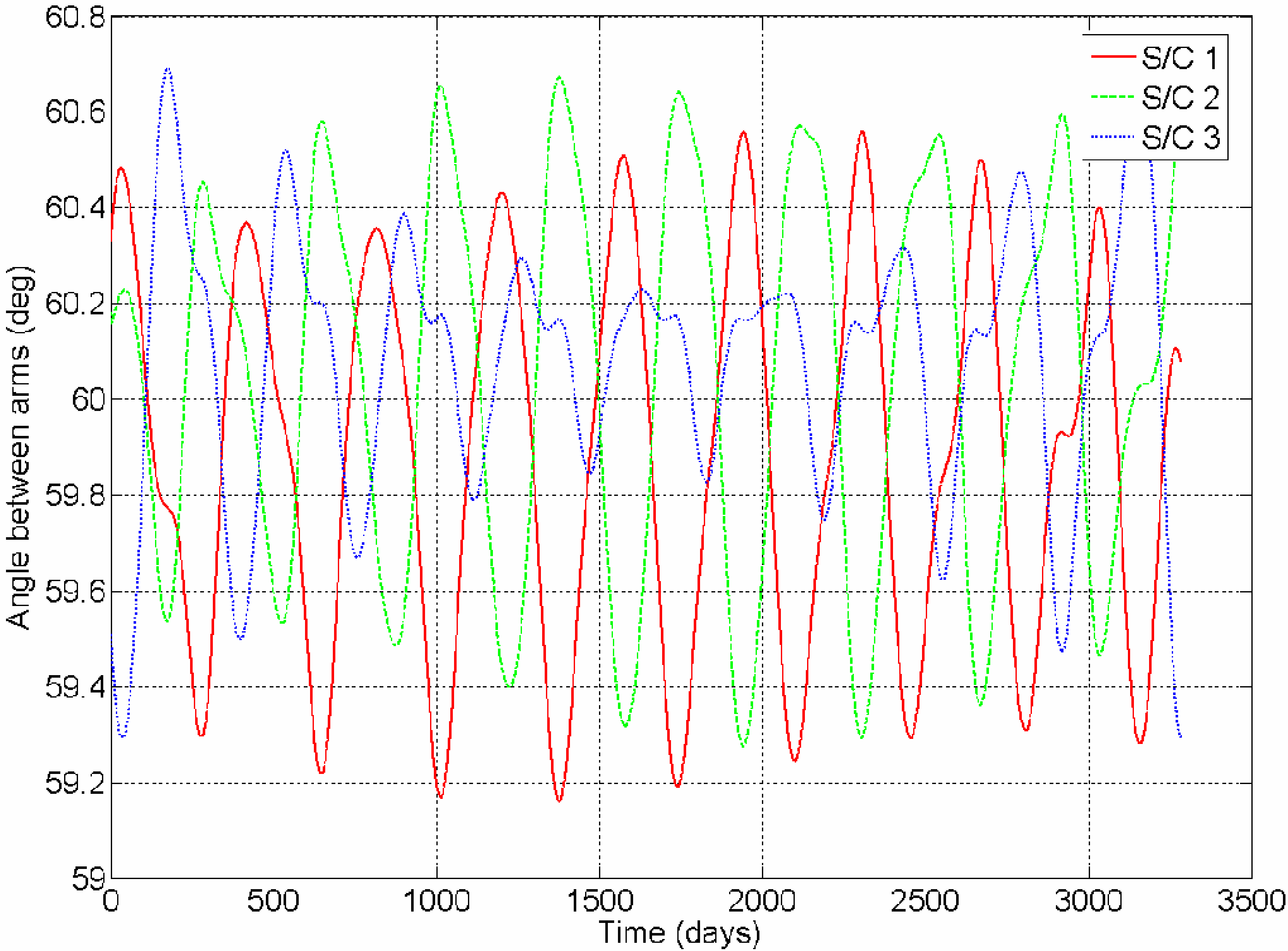




LISA: Differences between Distances (d12-d13, d12-d23, d13-d23)
d12-d13
d12-d23
d13-d23
Difference in Distance (km)
0
10000
20000
30000
40000
50000
60000
21500
22000
22500
23000
23500
24000
24500
25000
25500
26000
Days since 1950. (21915. is 2010/01/01)

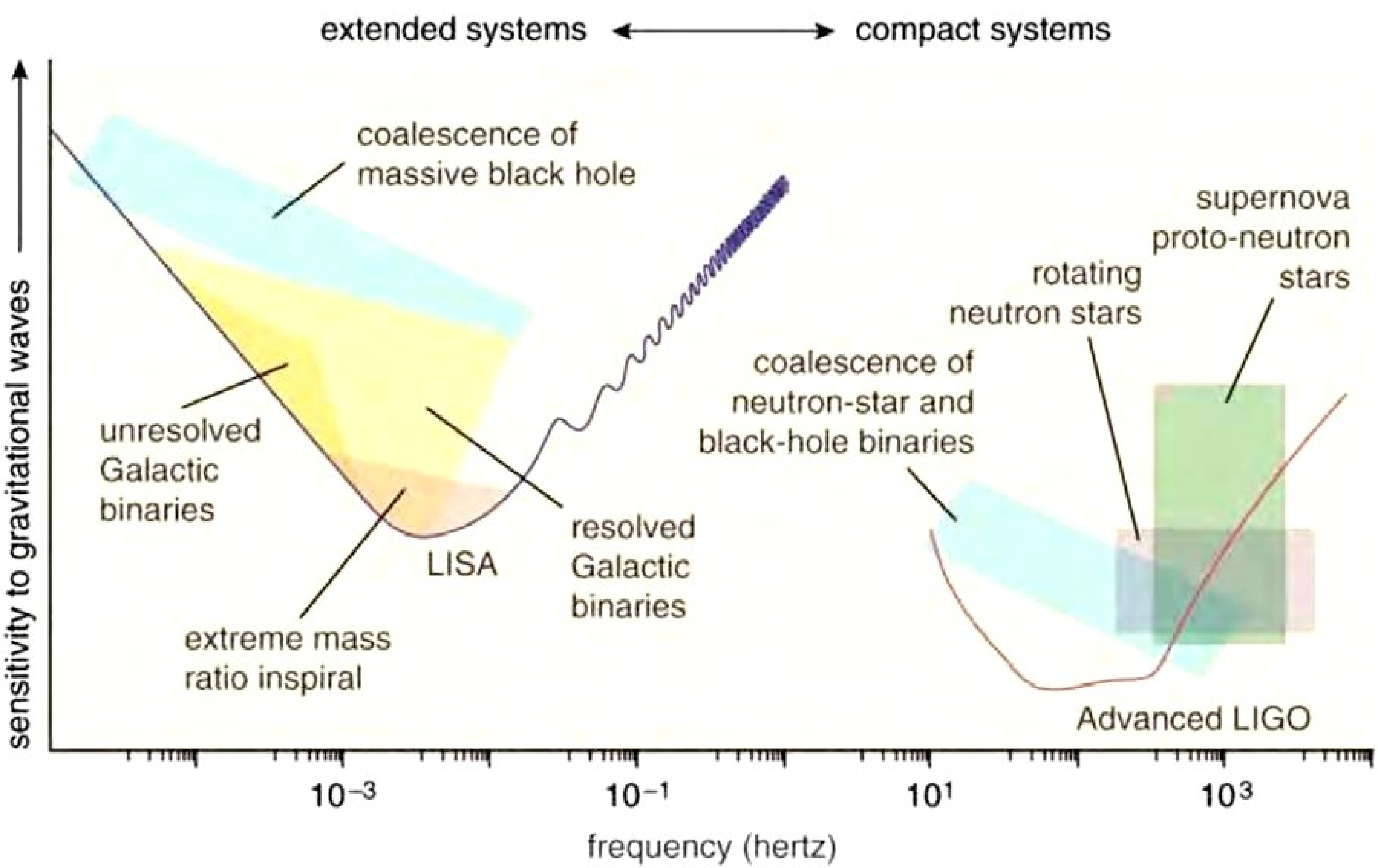


LISA: Velocity (LoS) (v12, v13, v23)
Velocity along Line of Sigth (m/s)
Days since 1950. (21915. is 2010/01/01)
v12
v13
v23
8
6
4
2
0
-2
-4
-6
-8
-10
21500
22000
22500
23000
23500
24000
24500
25000
25500
26000



S/C 1
S/C 2
S/C 3
Angle between arms (deg)
Time (days)
60.8
60.6
60.4
60.2
60
59.8
59.6
59.4
59.2
59
0
500
1000
1500
2000
2500
3000
3500

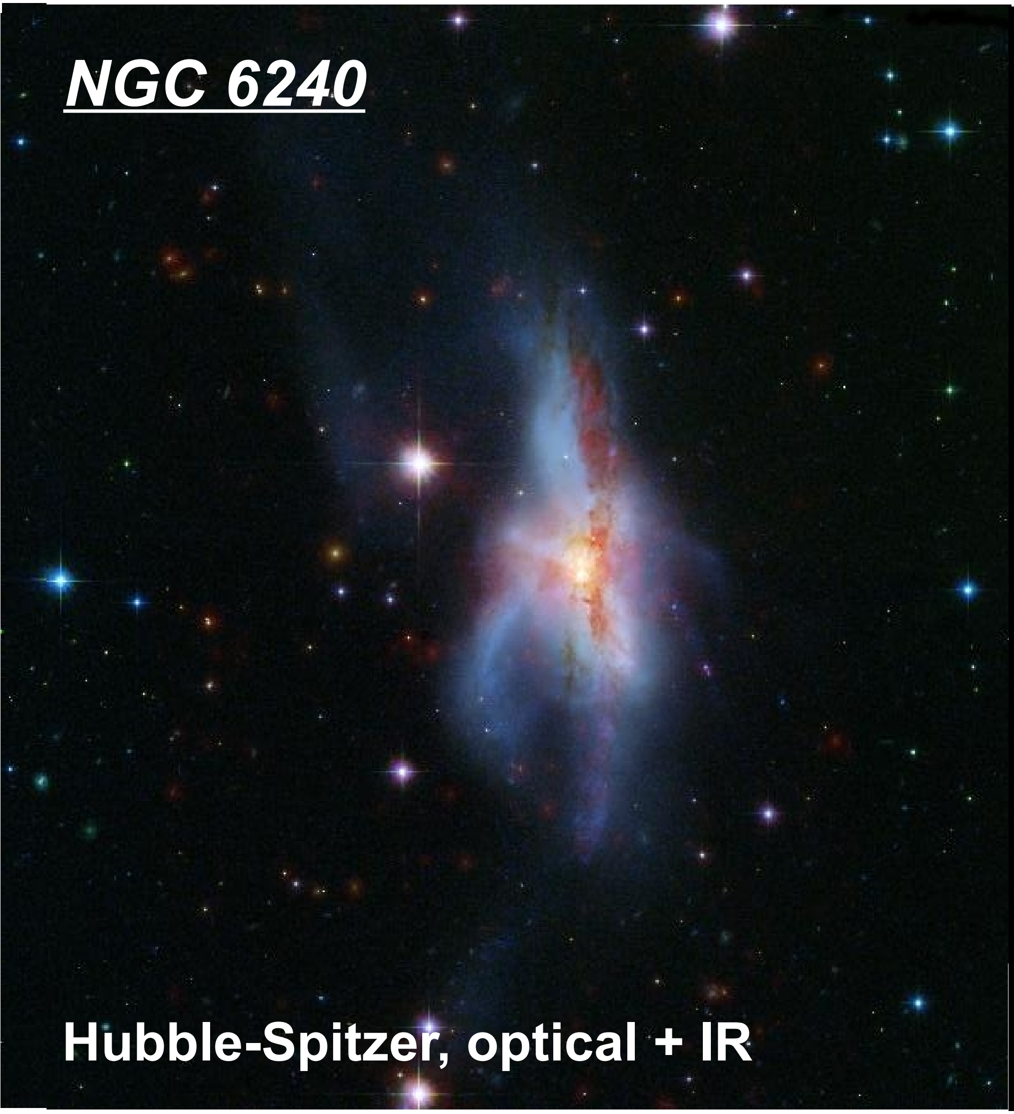
LISA sensitivity

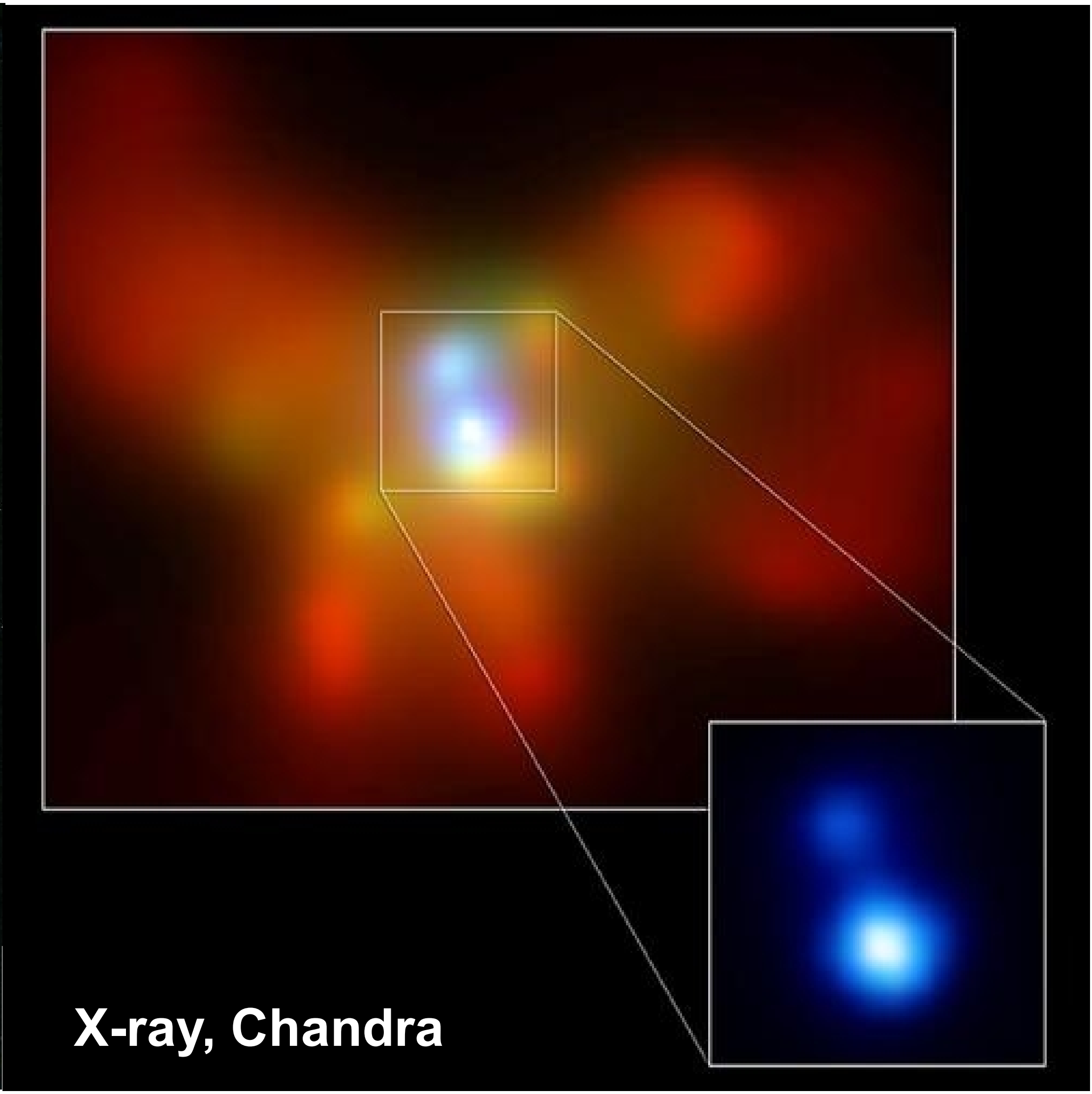


LISA verification binaries

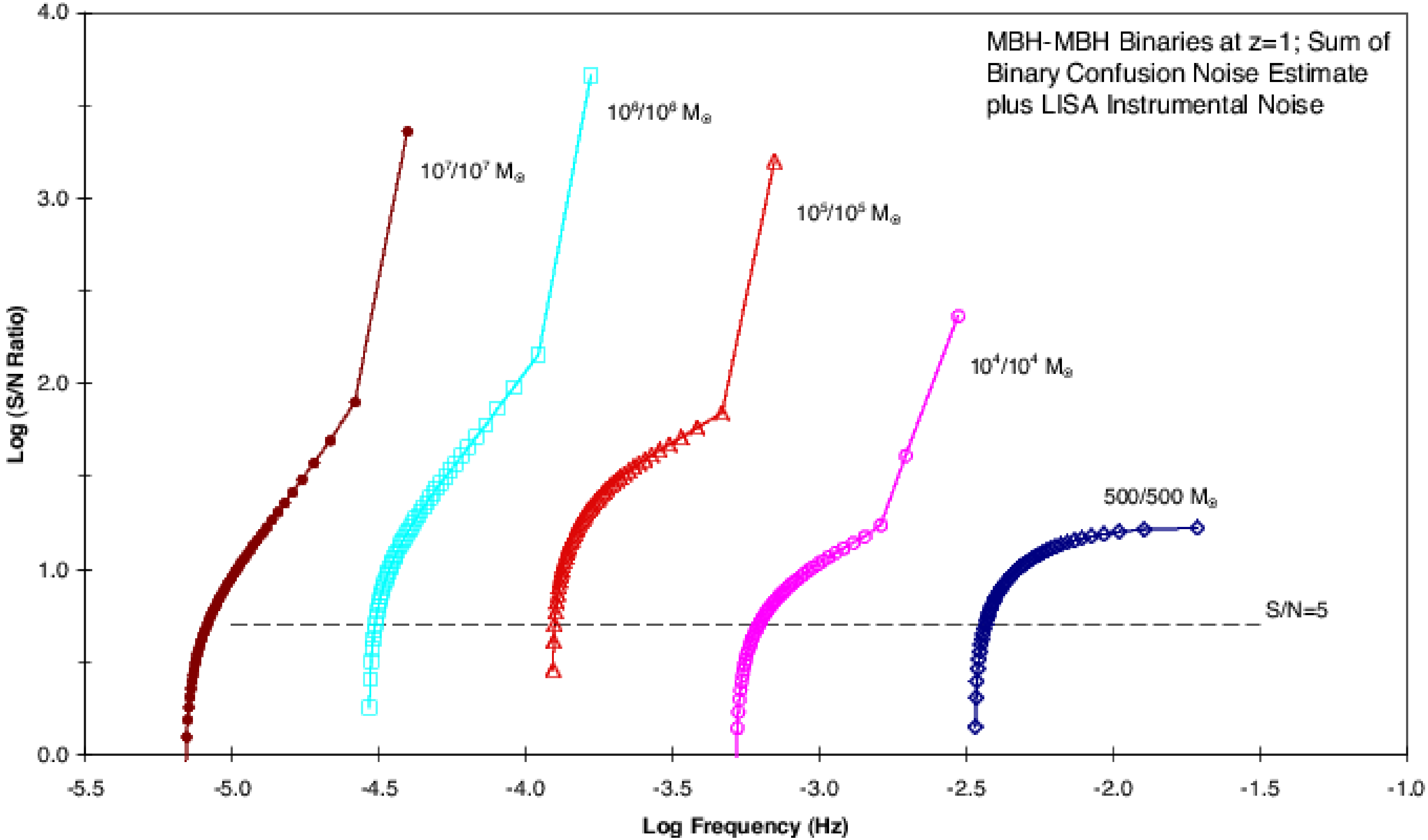
Class	Source	Dist/pc	f/mHz	$M_1/M_\odot$	$M_2/M_\odot$	$\tau/10^8$ y	$h/10^{-22}$
WD+WD	WD 0957-666	100	0.38	0.37	0.32	2	4
	WD 1101+364	100	0.16	0.31	0.36	20	2
	WD 1704+481	100	0.16	0.39	0.56	13	4
	WD 2331+290	100	0.14	0.39	>0.32	<30	>2
WD+sdB	KPD 0422+4521	100	0.26	0.51	0.53	3	6
	KPD 1930+2752	100	0.24	0.50	0.97	2	10
Am CVn	RXJ 0806.3+1527	300	6.2	0.4	0.12	–	4
	RXJ 1914+245	100	3.5	0.6	0.07	–	6
	KUV 05184-0939	1000	3.2	0.7	.092	–	0.9
	AM CVn	100	1.94	0.5	.033	–	2
	HP Lib	100	1.79	0.6	0.03	–	2
	CR Boo	100	1.36	0.6	0.02	–	1
	V803 Cen	100	1.24	0.6	0.02	–	1
	CP Eri	200	1.16	0.6	0.02	–	0.4
	GP Com	200	0.72	0.5	0.02	–	0.3
LMXB	4U 1820-30	8100	3.0	1.4	<0.1	–	0.2
	4U 1620-67	8000	0.79	1.4	<0.03	–	.06
W UMa	CC Com	90	0.105	0.7	0.7	–	6

Binary system of SMBHs

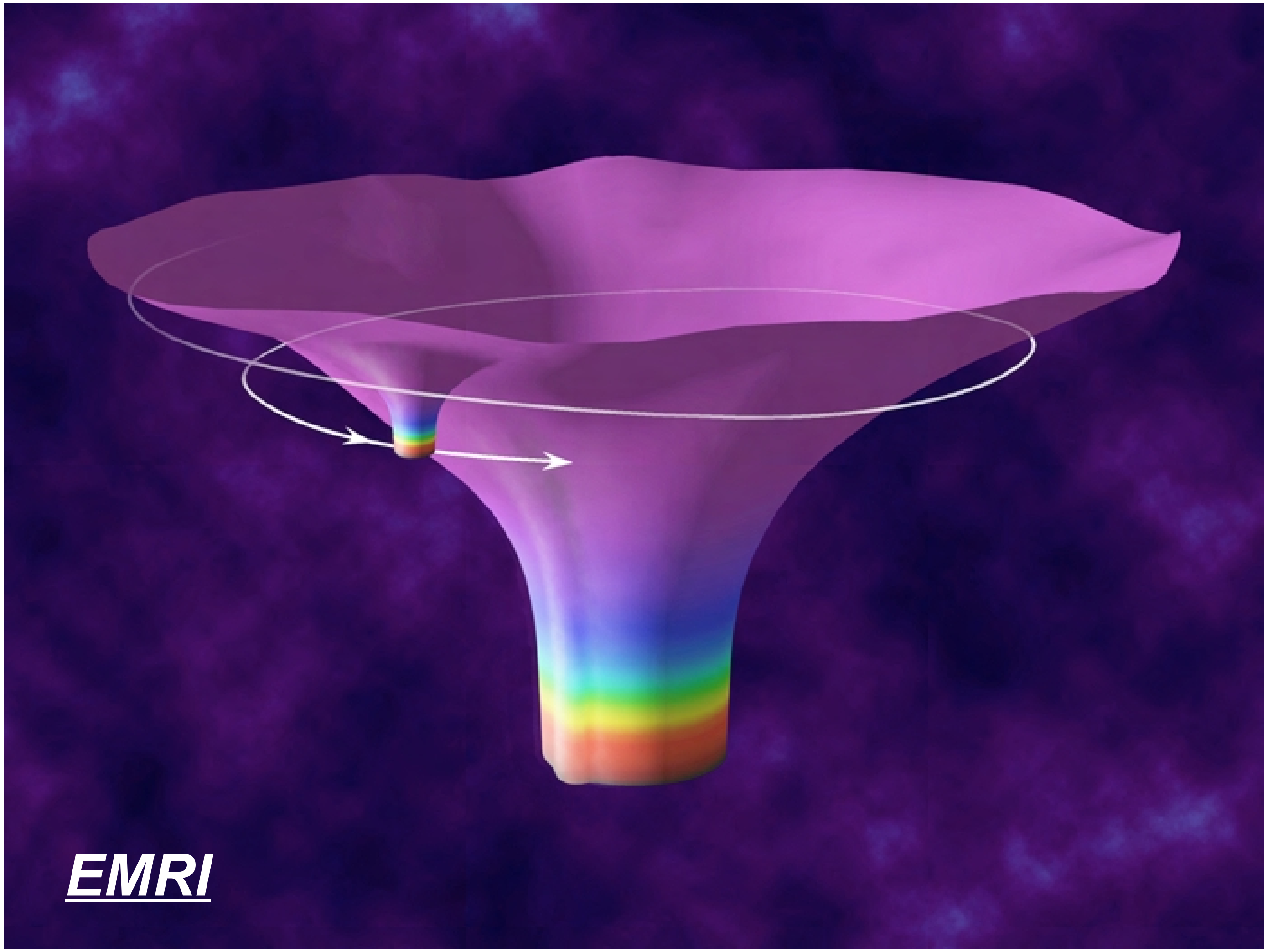




Detectability of SMBH binaries

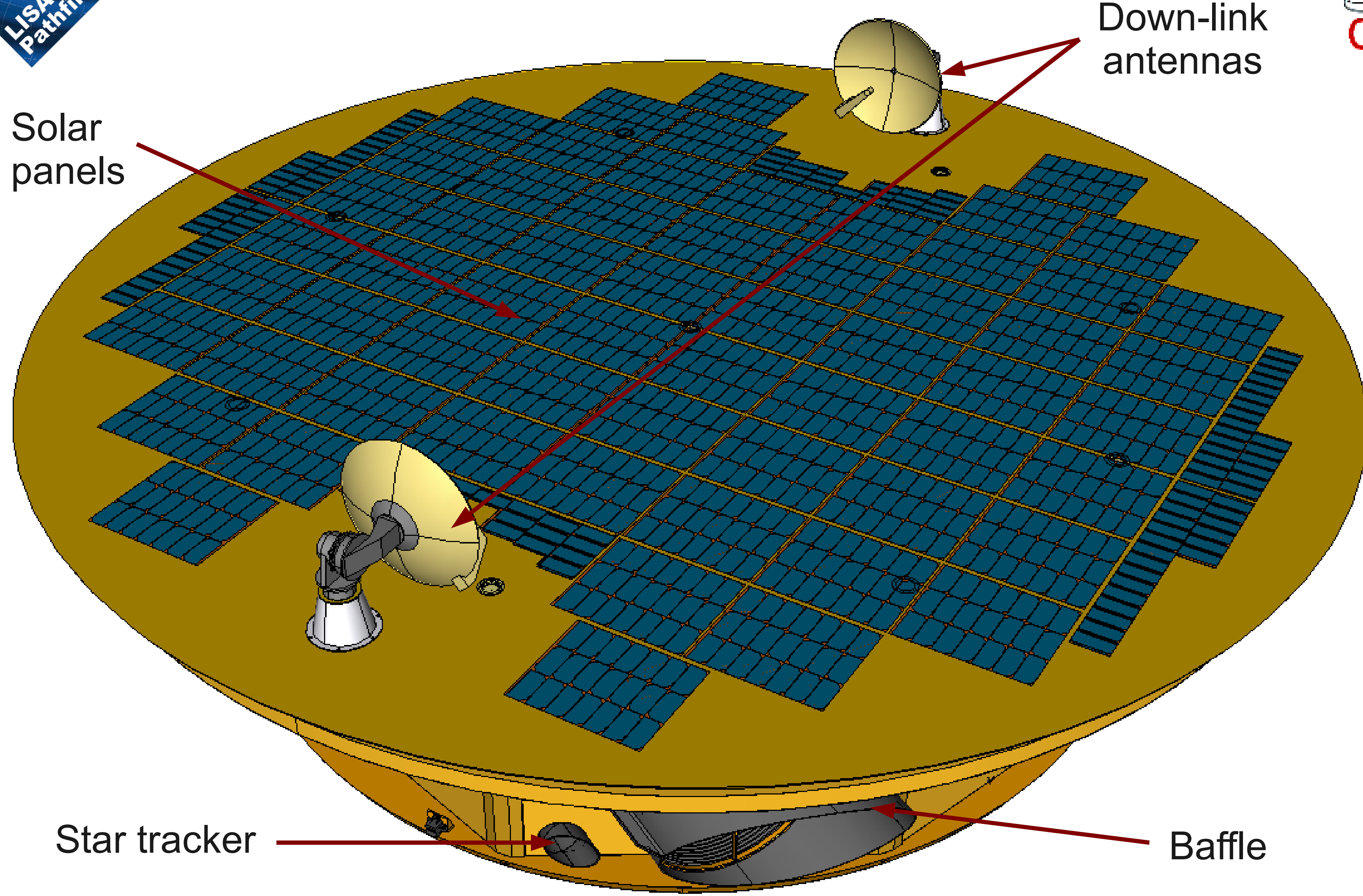


Extreme mass-ratio inspiral

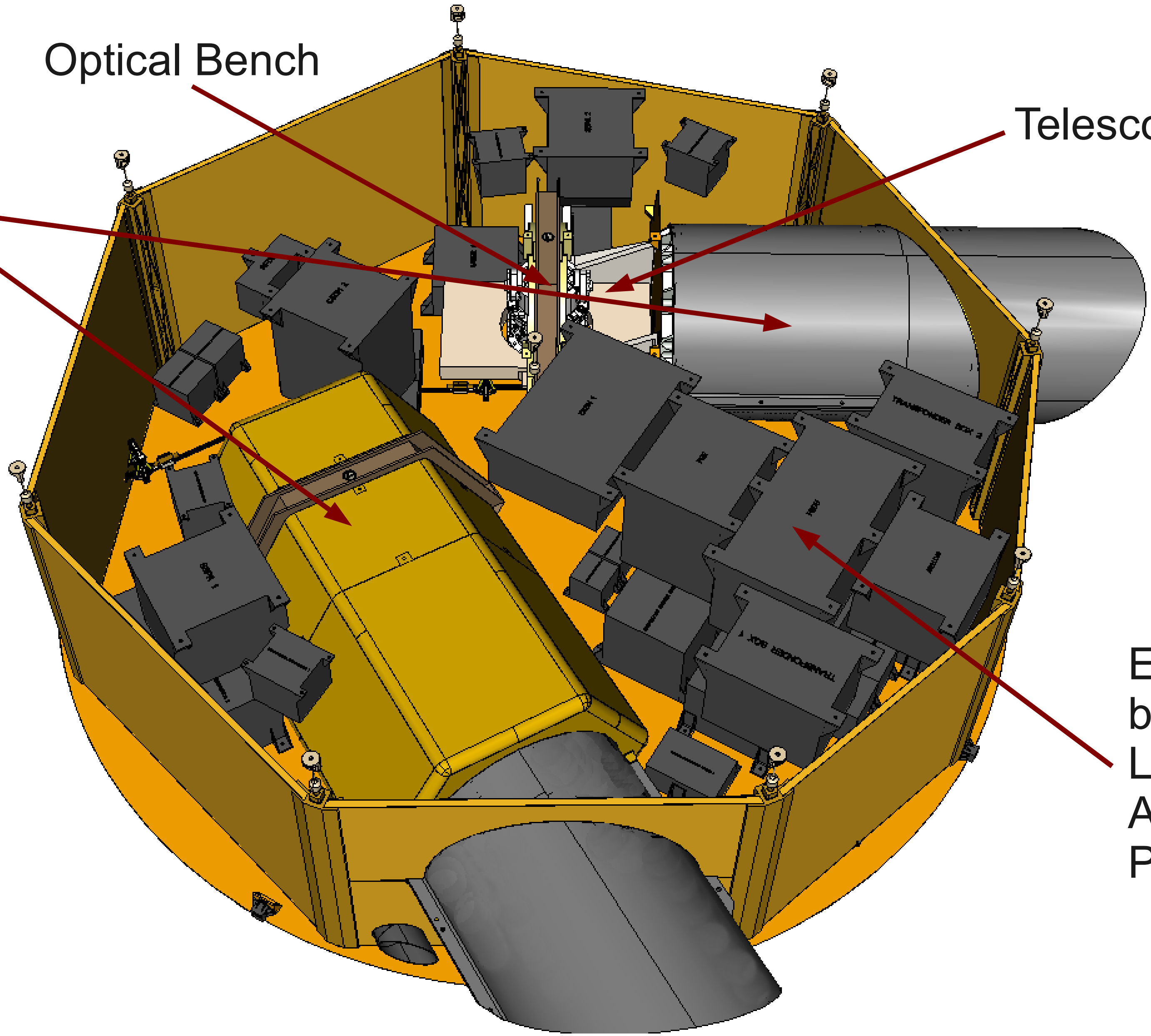


Requires *Numerical Relativity*, lower LISA band

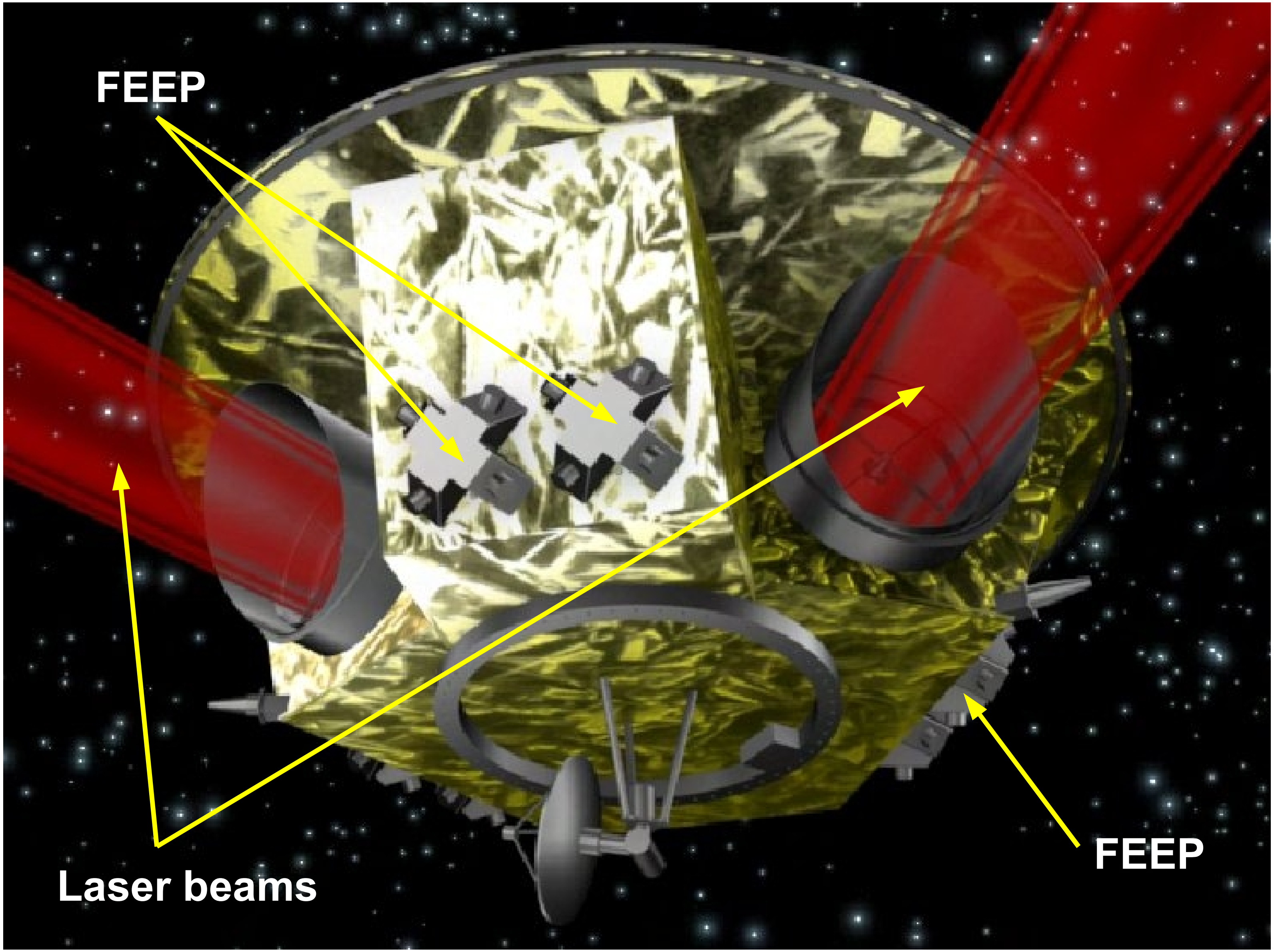
The LISA science-craft



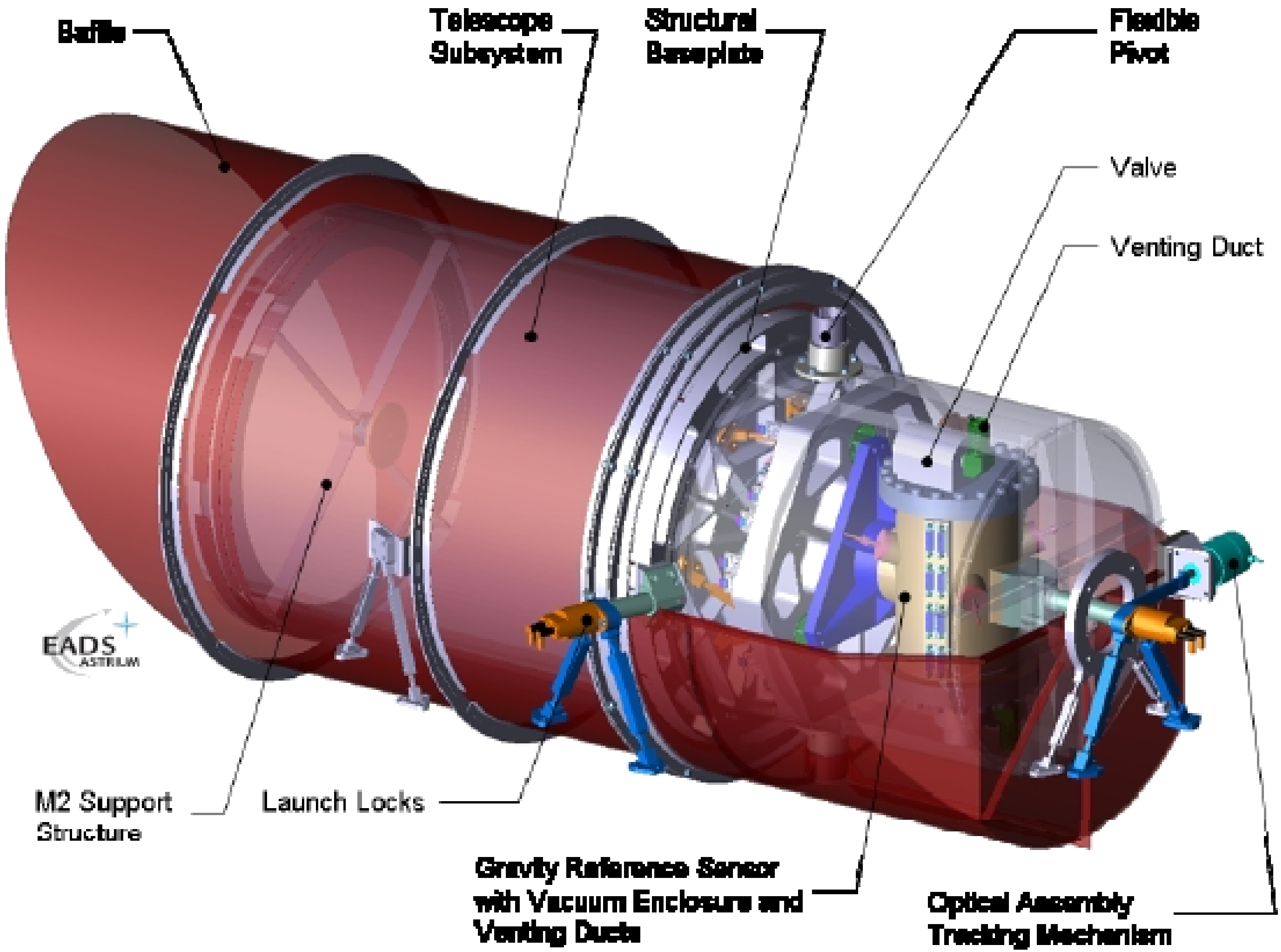
The LISA science-craft



The LISA science-craft



The LISA science-craft



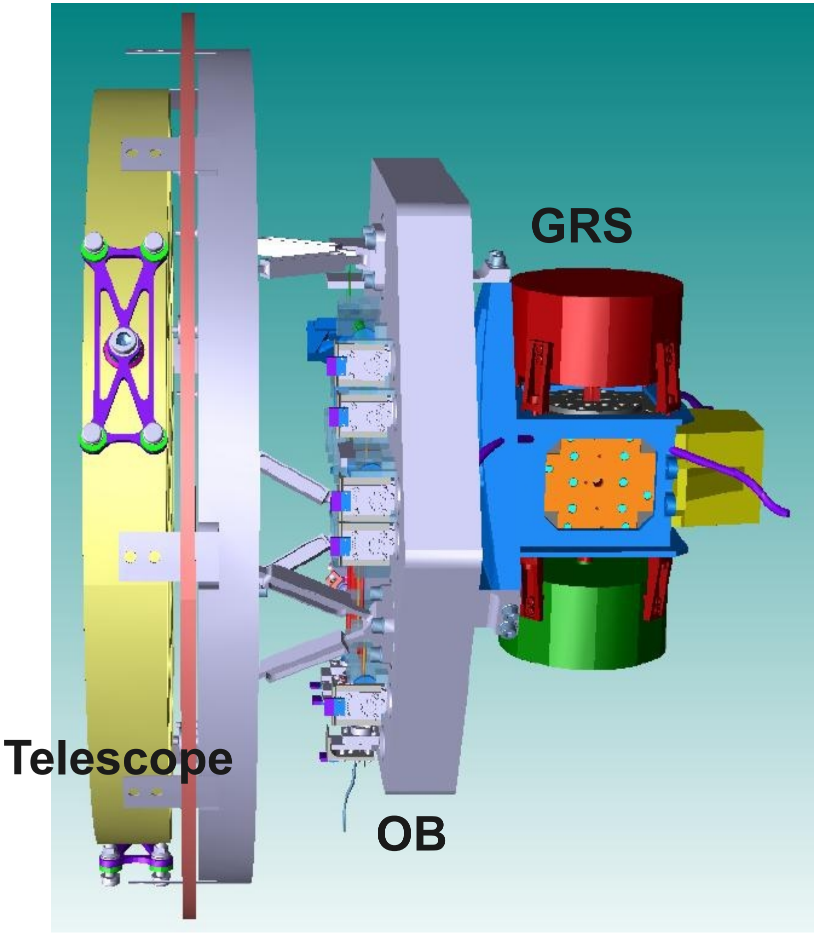
The LISA core instruments

There are two subsystems of major conceptual relevance:

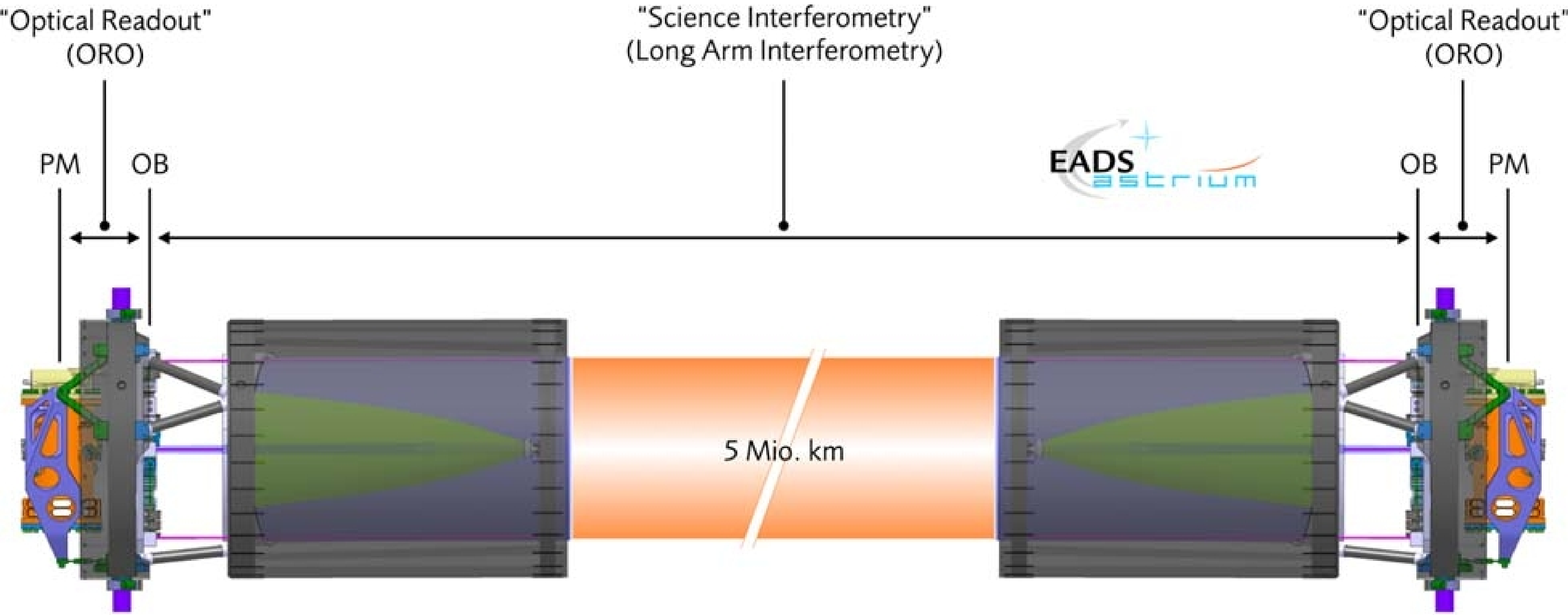
- The *drag-free* subsystem
- The *optical metrology* subsystem

Each of these has in turn various other important subsystems:

- *Drag-free*:
  - TM position sensors (capacitive)
  - Micro-thruster actuators
  - Caging mechanisms
- *Optical Metrology*:
  - Laser assembly
  - Optical bench
  - Phasemeter



LISA interferometry



Time delay interferometry

LISA's laser (1.064 μm) is cavity-stabilised to have frequency fluctuations below

$$S_f^{1/2} < 30 \text{ Hz}/\sqrt{\text{Hz}}$$

within the MBW.

If two interferometer arms have mismatched lengths by ΔL then laser frequency fluctuations δf mimic TM displacements δx:

$$\delta x = \frac{\delta f}{f}\,\Delta L$$

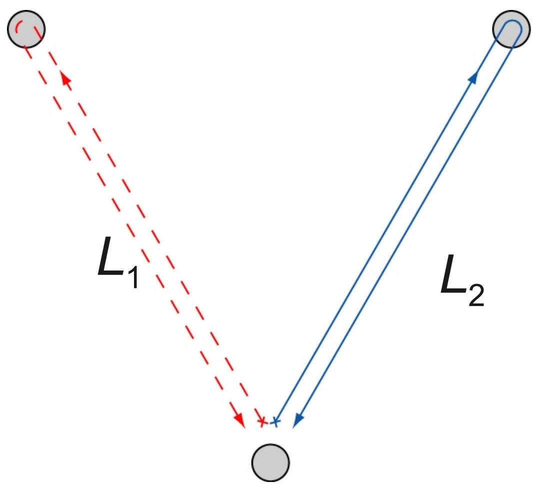
LISA is required to have a displacement noise below **10 pm/√Hz**, hence ΔL *should* be kept below **ΔL < 100 m**.

Yet ΔL gets as large as 60,000 km !!!

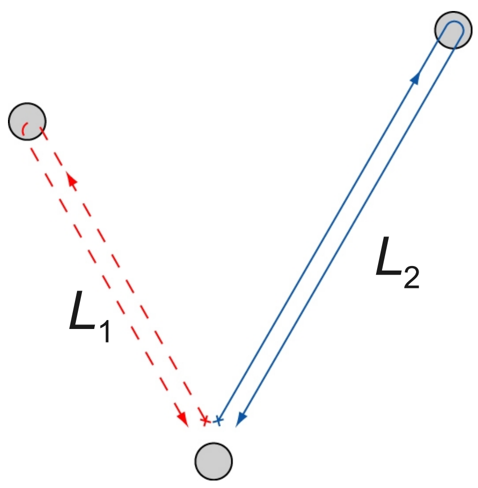
Time delay interferometry

TDI is a ***post-processing technique*** for removing (at least) laser frequency noise.

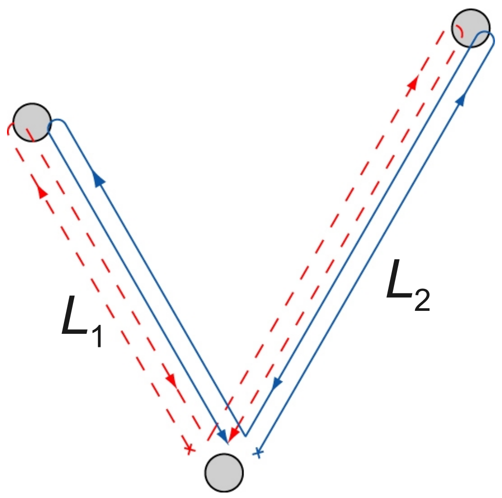
This is done by defining (a wealth of) ***TDI variables*** which contain no frequency noise, yet retain GW signals:



Michelson
(no *f*-noise)



Kennedy-Thorndike
(*f*-noise)



Sagnac
(*f*-noise cancellation)

Time delay interferometry

Let $\phi(t)$ be phase at the beam splitter (vertex). Then, e.g.,

In arm 1: $\phi_1(t) = \phi(t-2L_1) - \phi(t)$

In arm 2: $\phi_2(t) = \phi(t-2L_2) - \phi(t)$

Off-line, the following TDI variable can be constructed:

$$X(t) = [\phi_2(t-2L_1) - \phi_2(t)] - [\phi_1(t-2L_2) - \phi_1(t)]$$

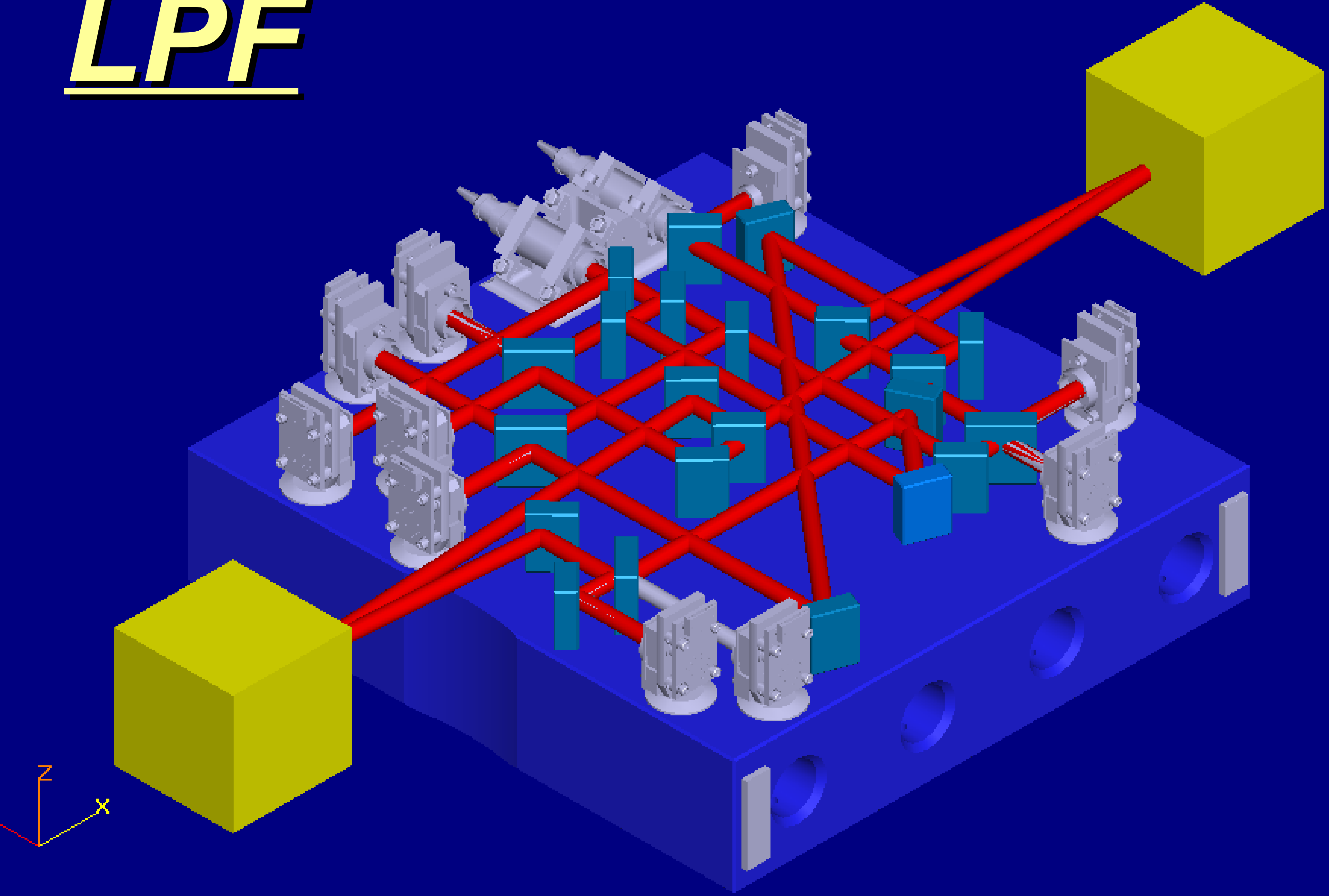
which is readily seen to be free of any phase noise, while still containing (GW) signals.

There are more TDI combinations, but a strong requirement is ***precise knowledge of arm-lenghs*** at the given times.

LISA is really challenging...

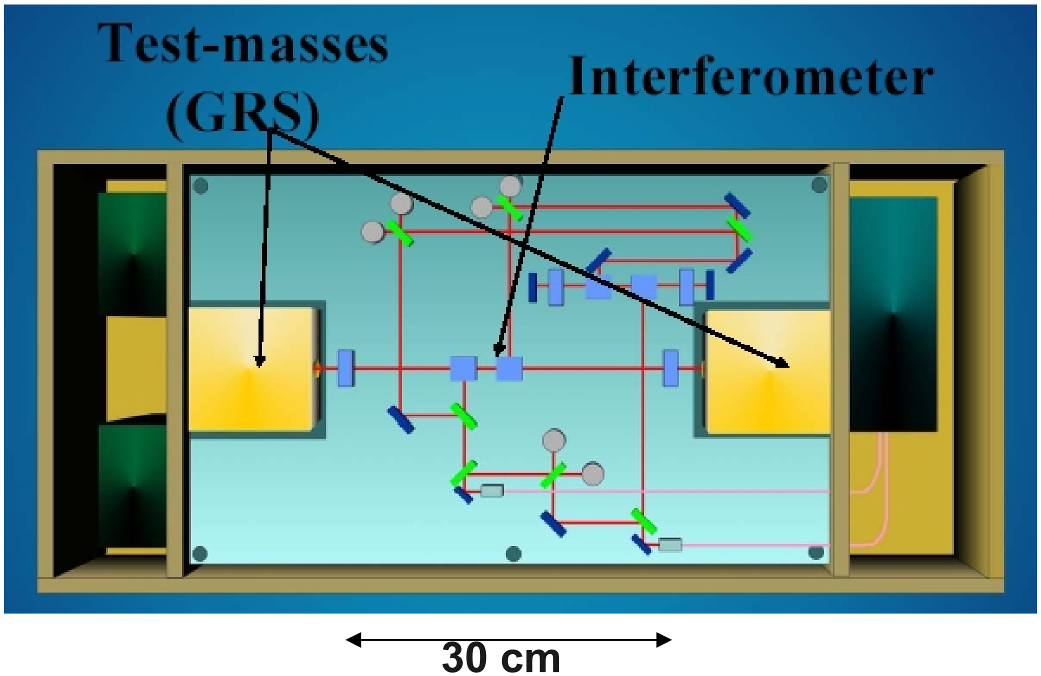
...and expensive!!

LPF



LISA PathFinder

1. One *LISA* arm is *squeezed* to 30 centimetres:



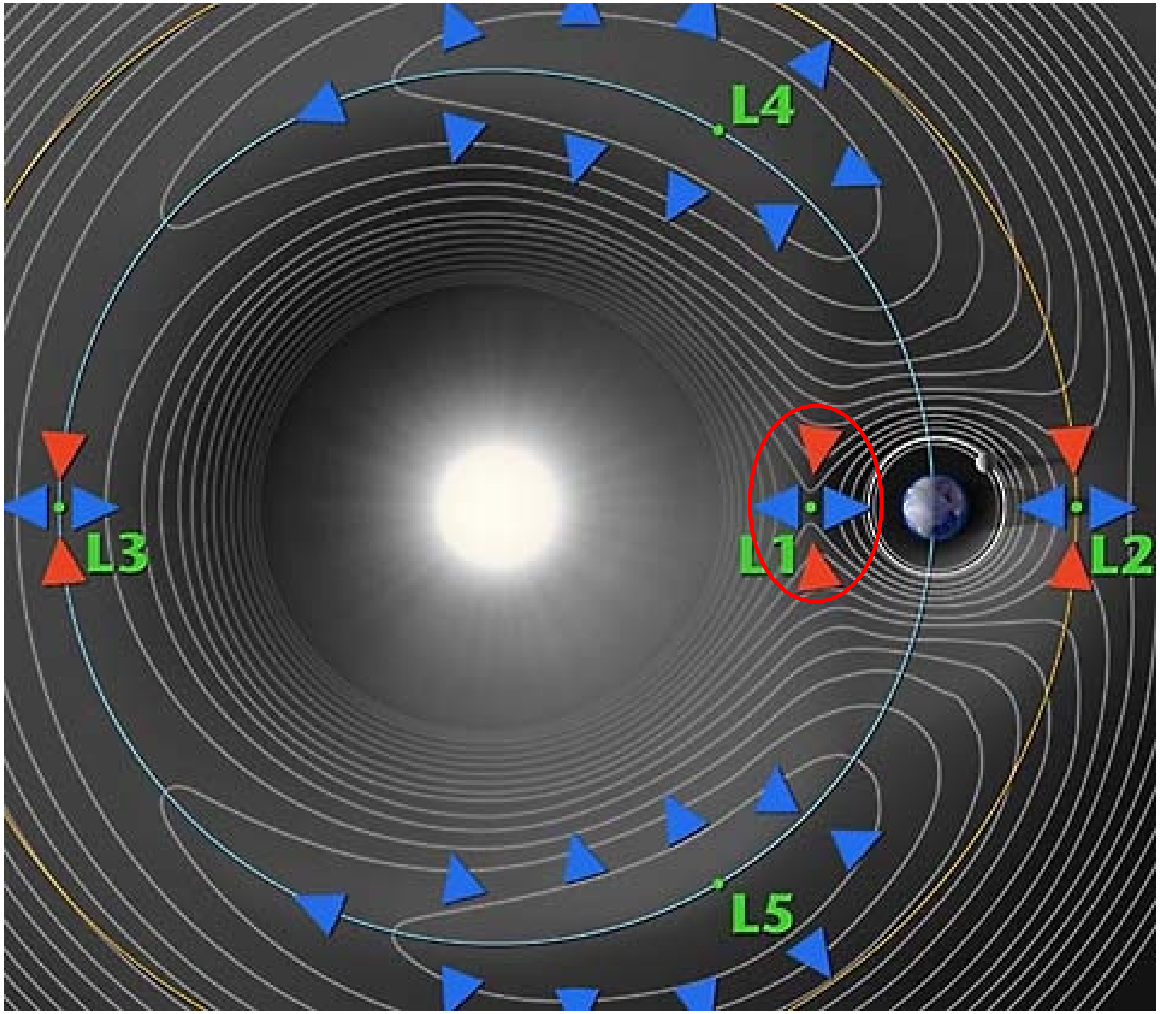
***LTP* Objectives :**

- ***Drag-free***
- ***Interferometry***
- ***Diagnostics***
- ***TM charging***
- ***Telemetry***
- ***Data processing***

2. *Relax sensitivity* by one order of magnitude, also in band:

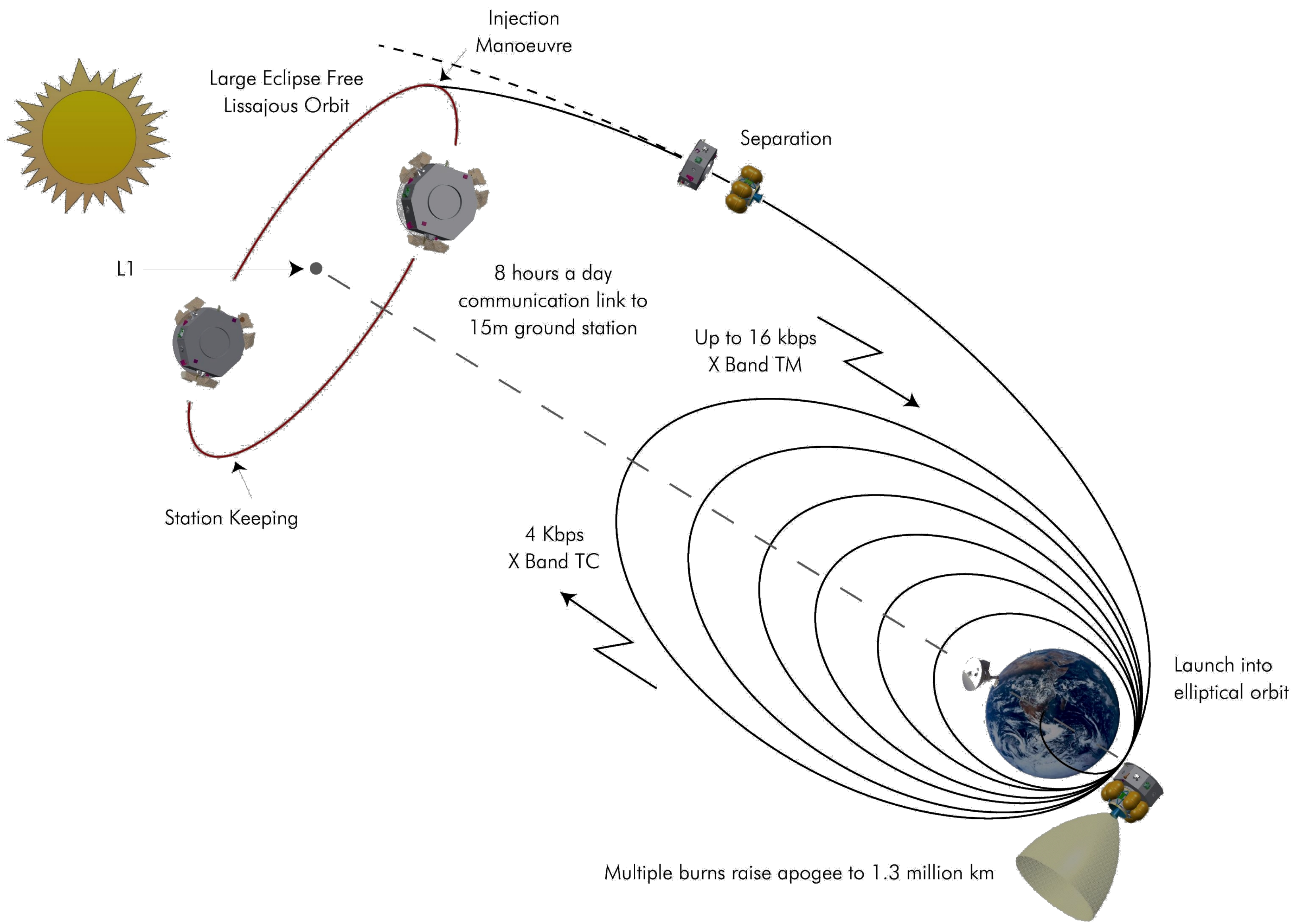
$$S_{\Delta a}(\omega) \leq 3\times 10^{-14}\left[1+\left(\frac{\omega/2\pi}{3\,\mathrm{mHz}}\right)^2\right]\,\mathrm{m\,s^{-2}\,Hz^{-1/2}}\ ,\quad 1\,\mathrm{mHz}\ \leq \omega/2\pi \leq 30\,\mathrm{mHz}$$

LPF orbit

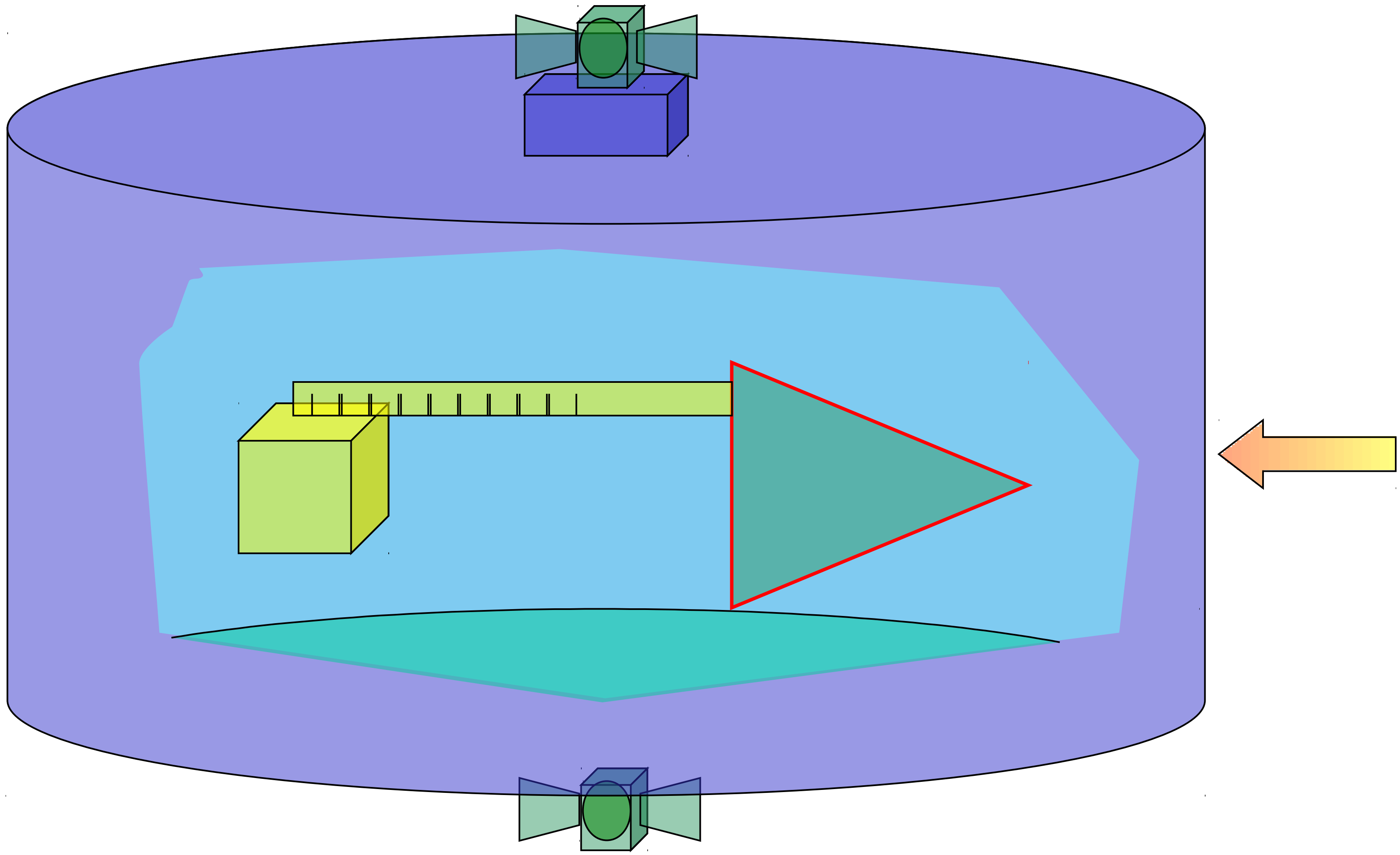


- *Lagrange L1*
- Travel time: ~3 months
- Mission lifetime: ~6 months

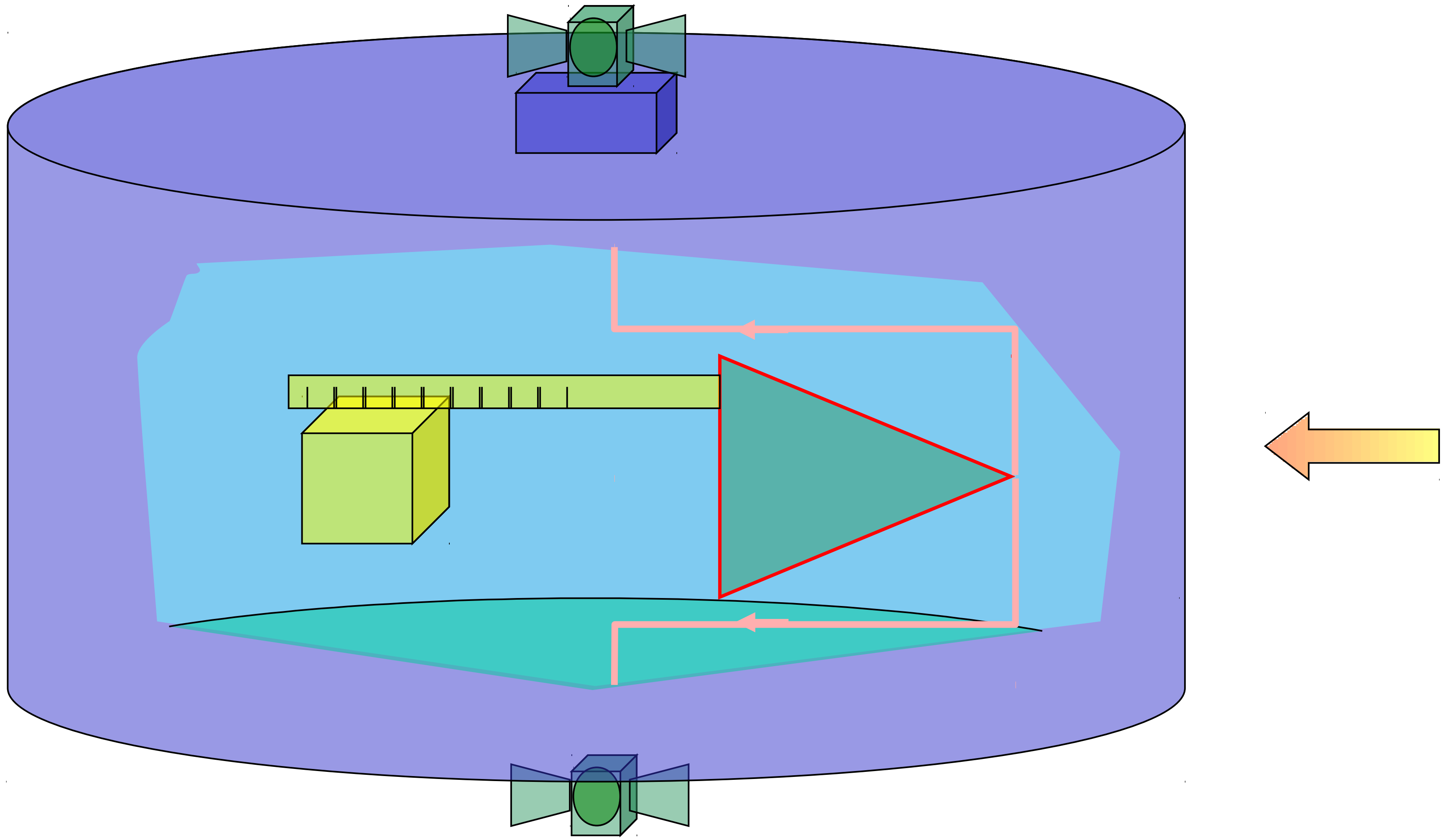
LPF orbit injection manoeuvres



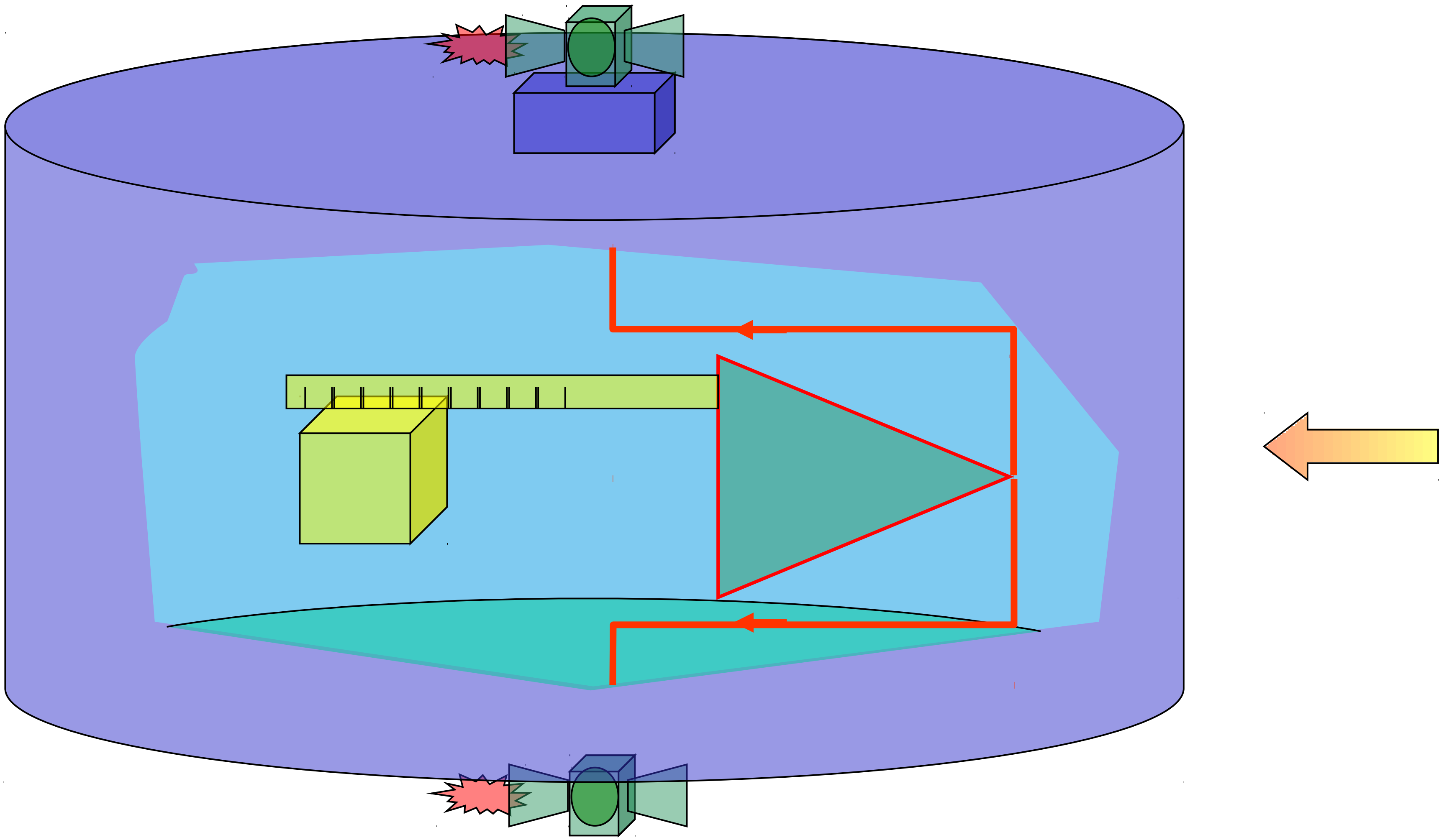
Drag-free sequence



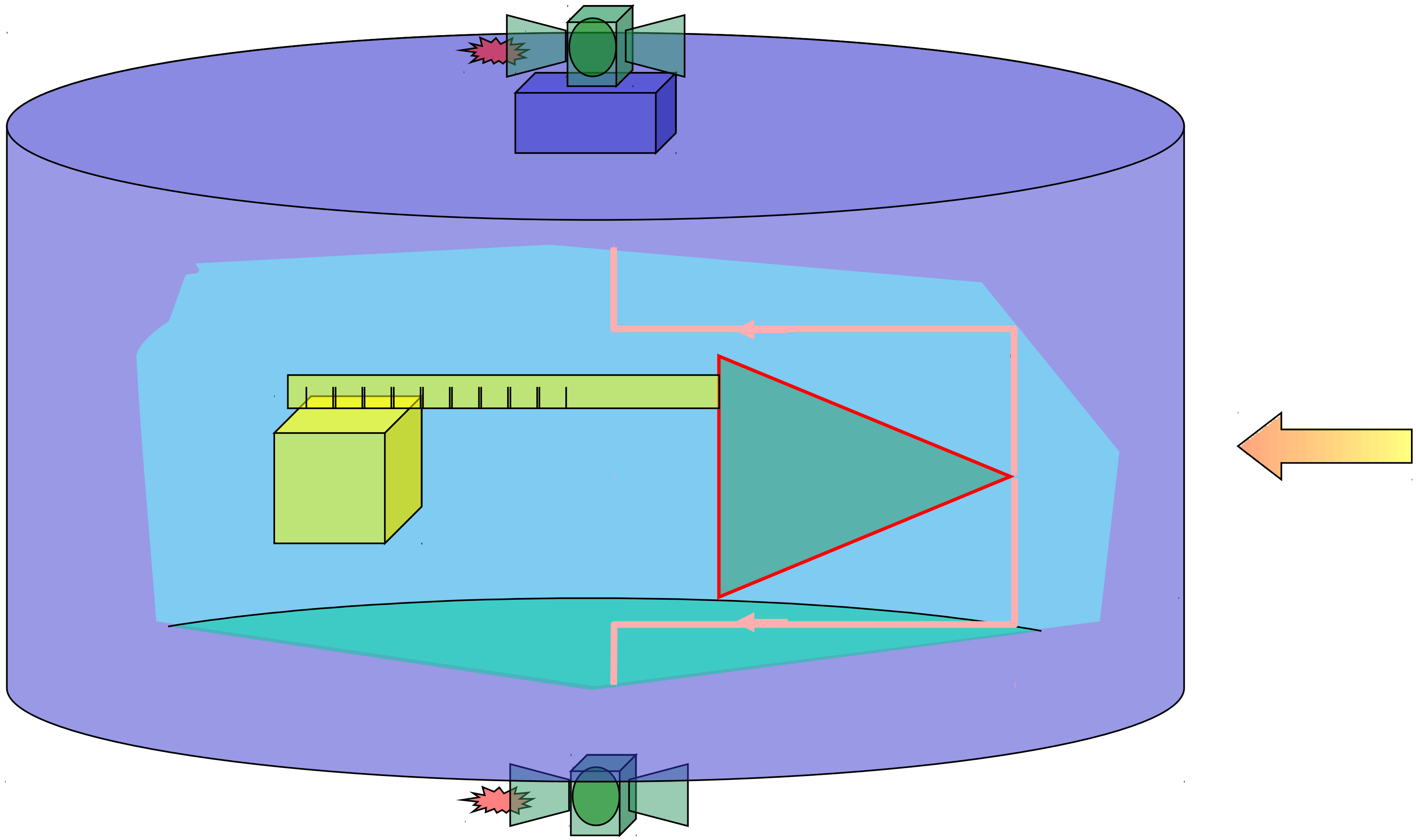
Drag-free sequence



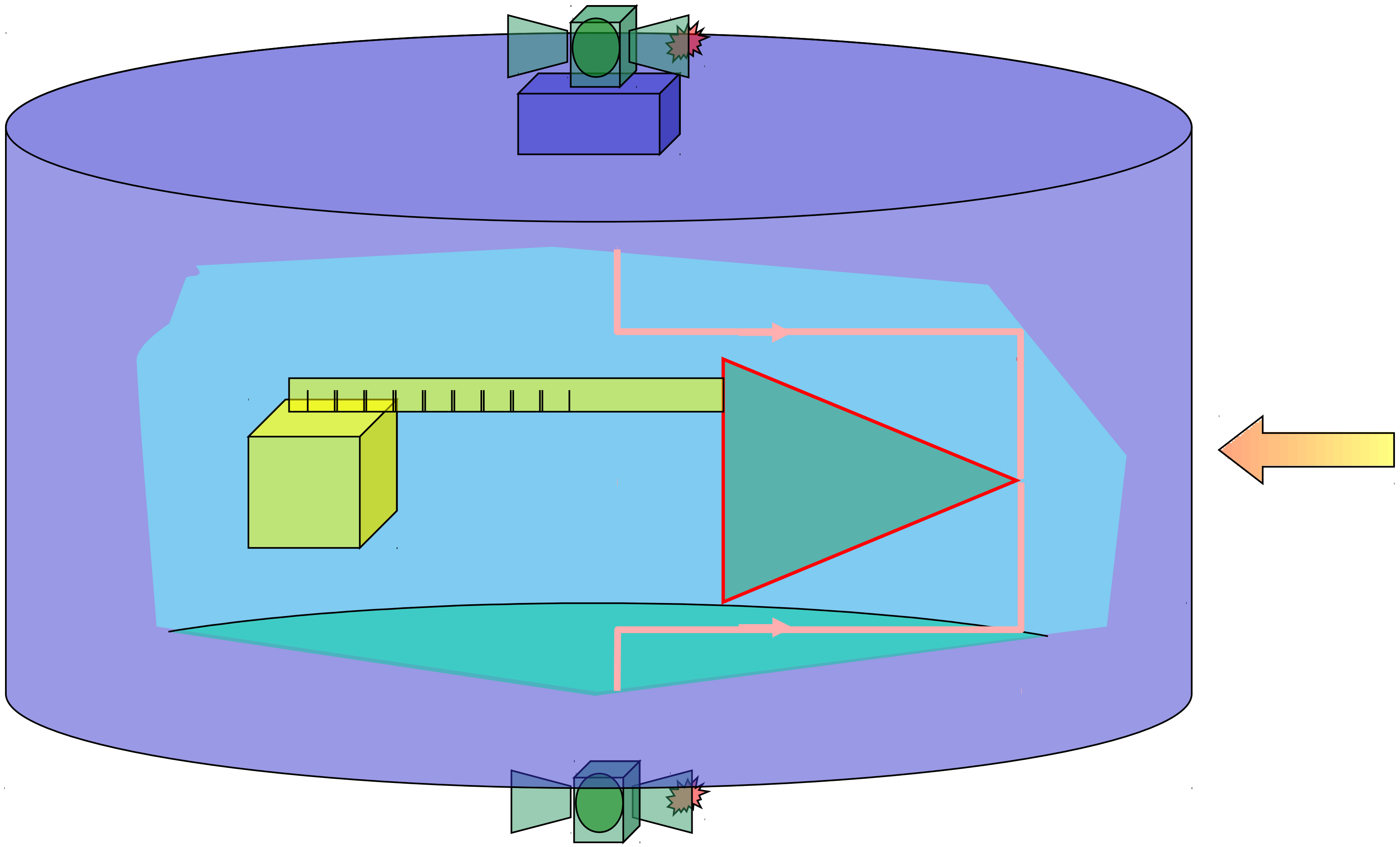
Drag-free sequence



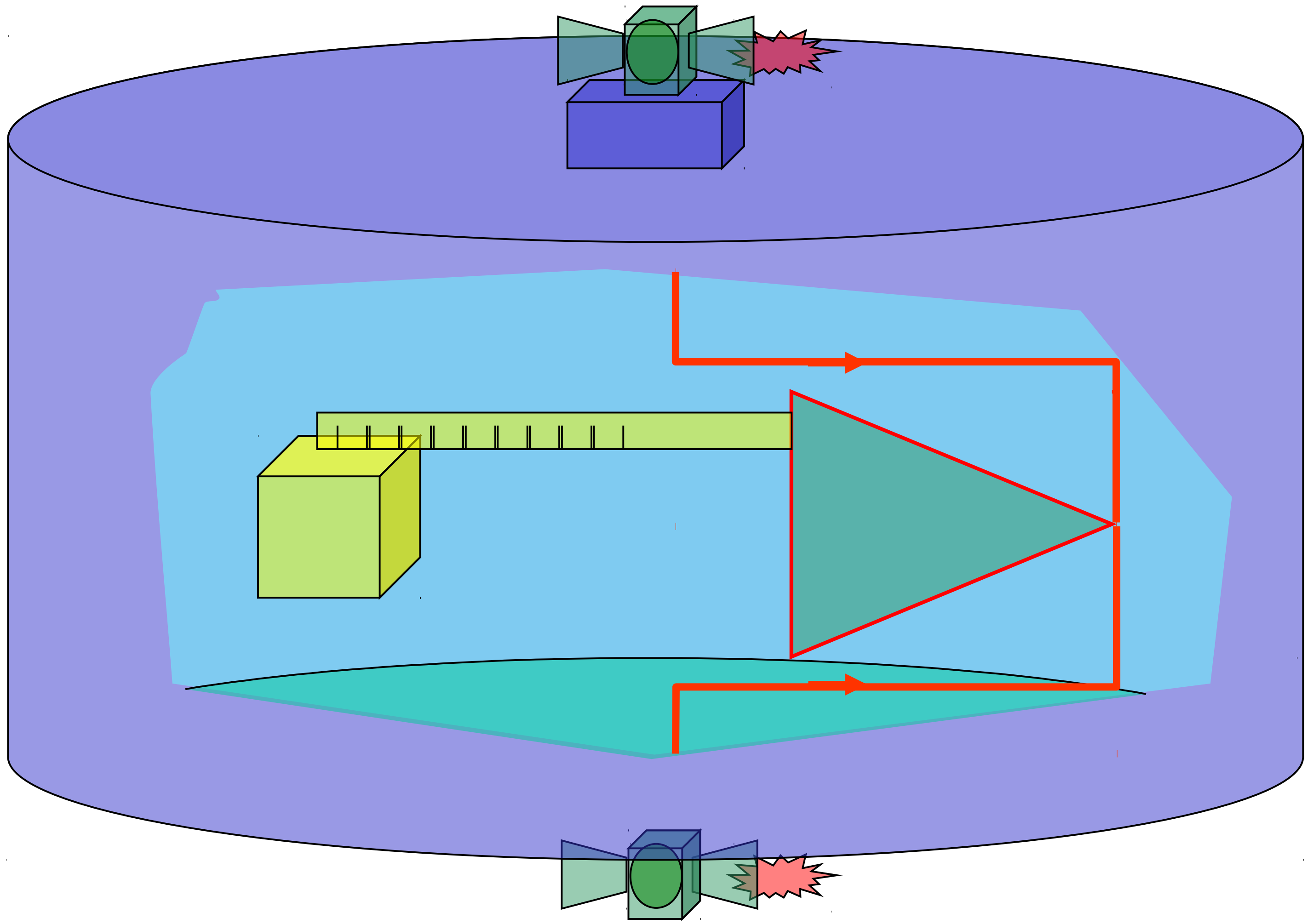
Drag-free sequence



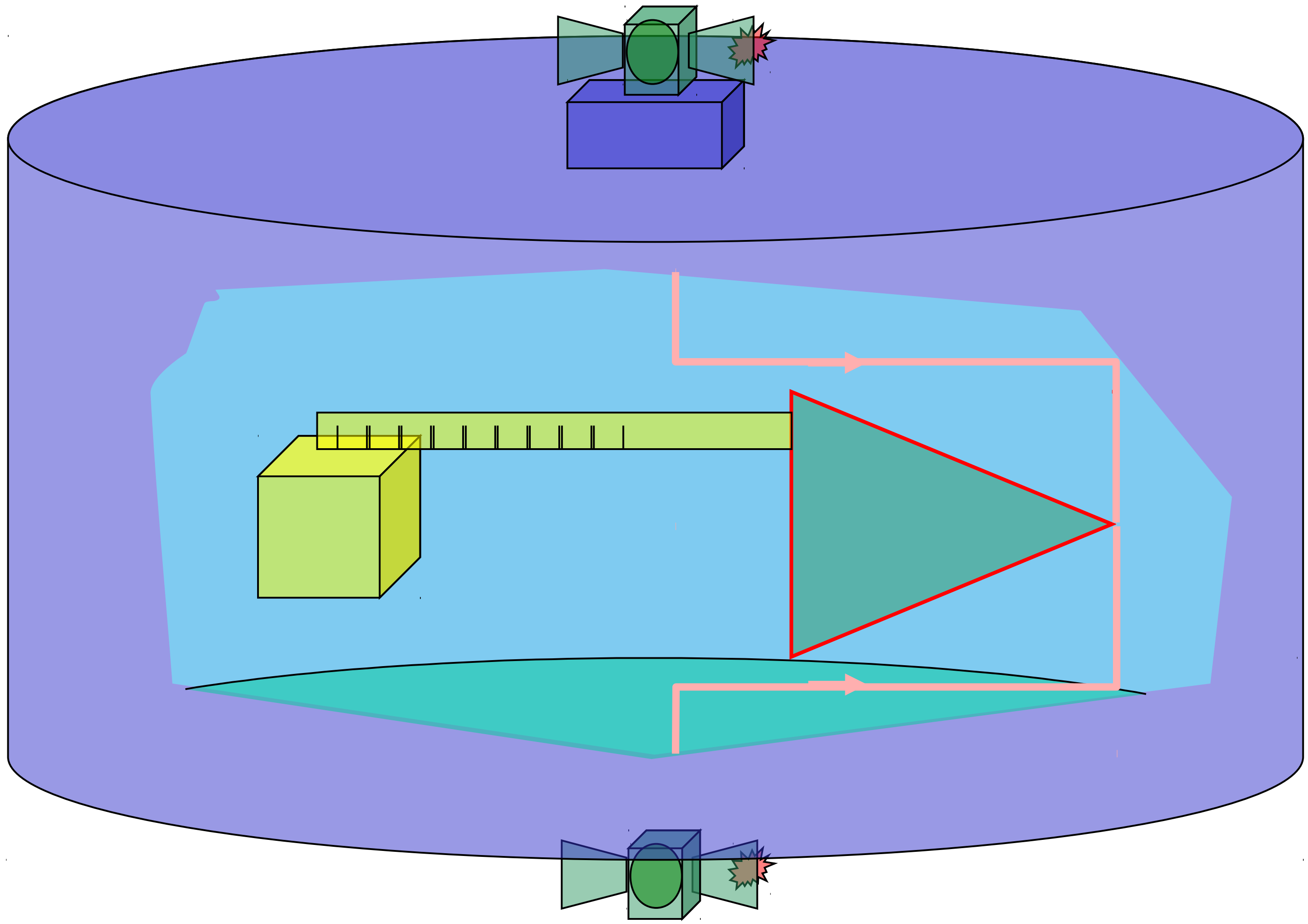
Drag-free sequence



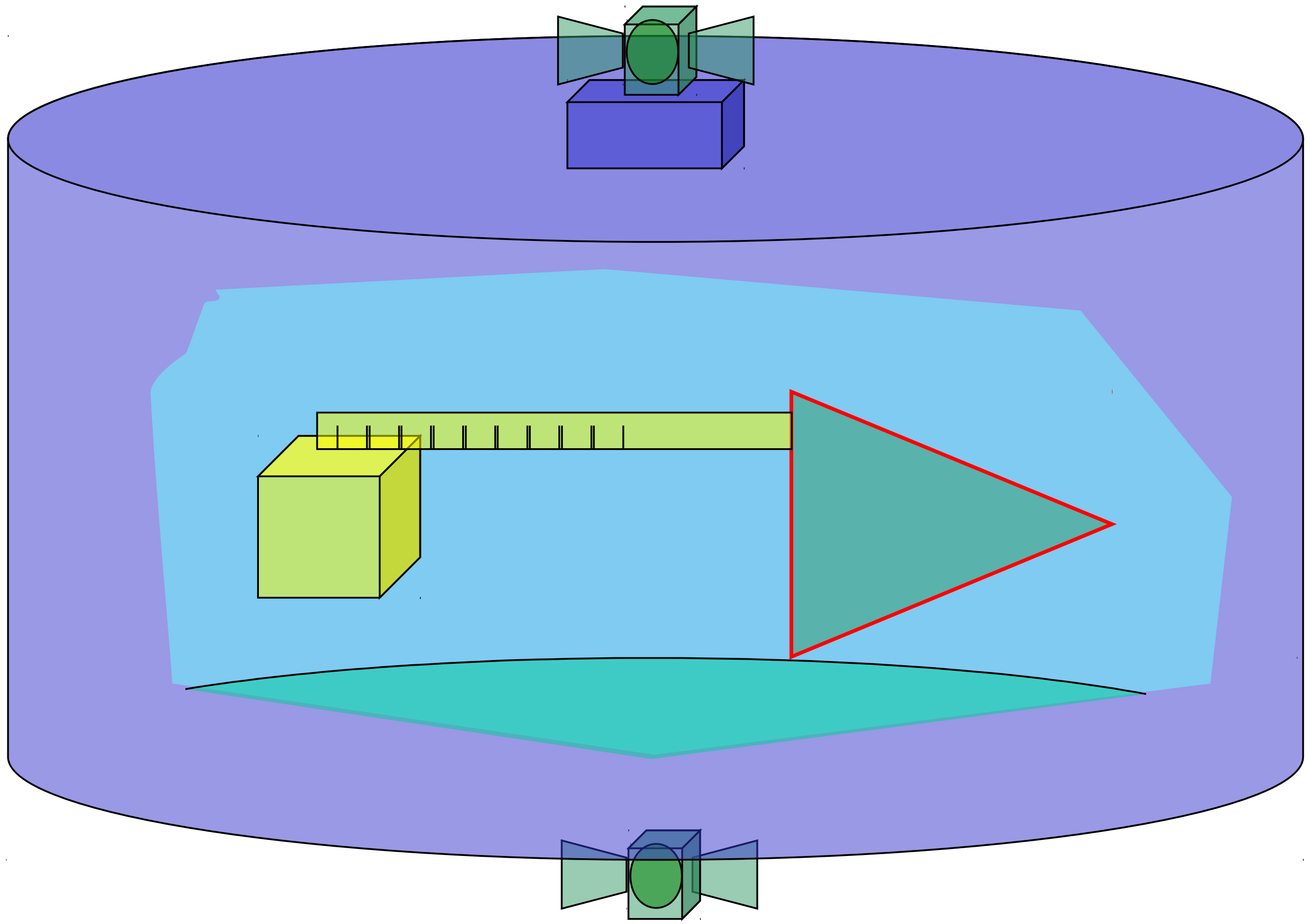
Drag-free sequence



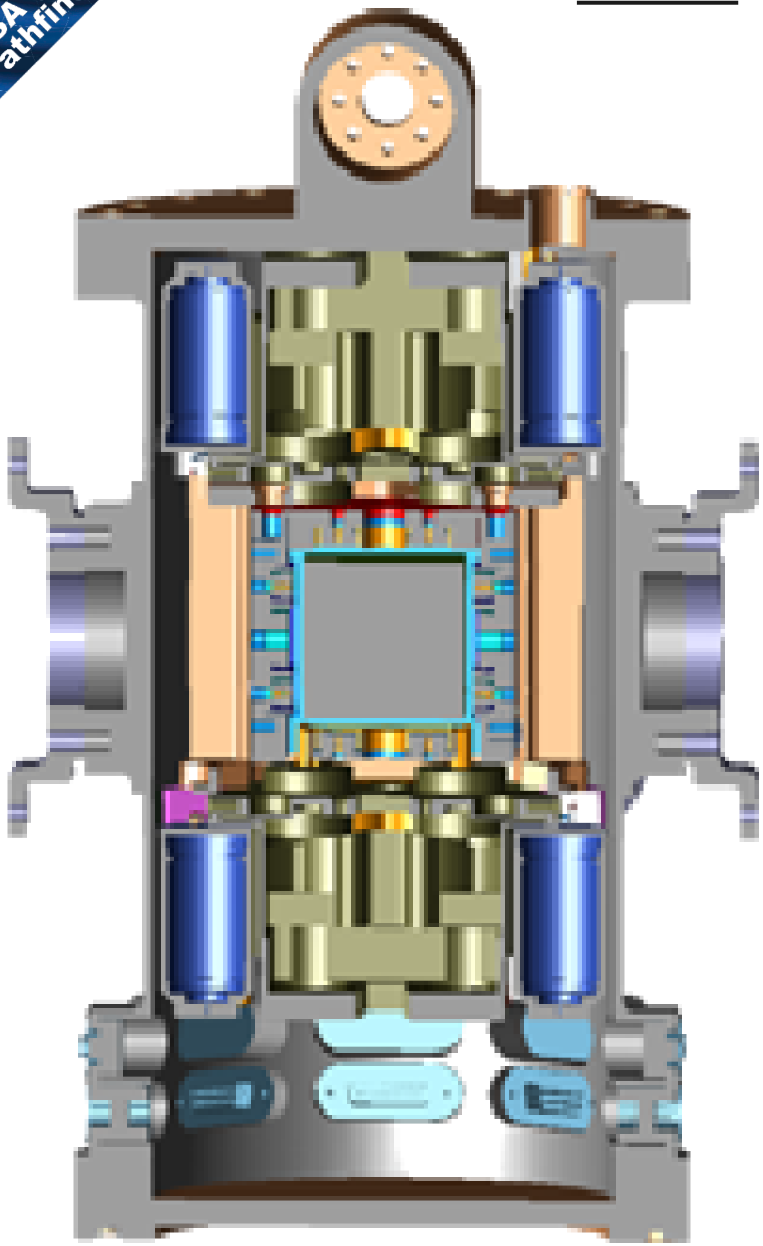
Drag-free sequence



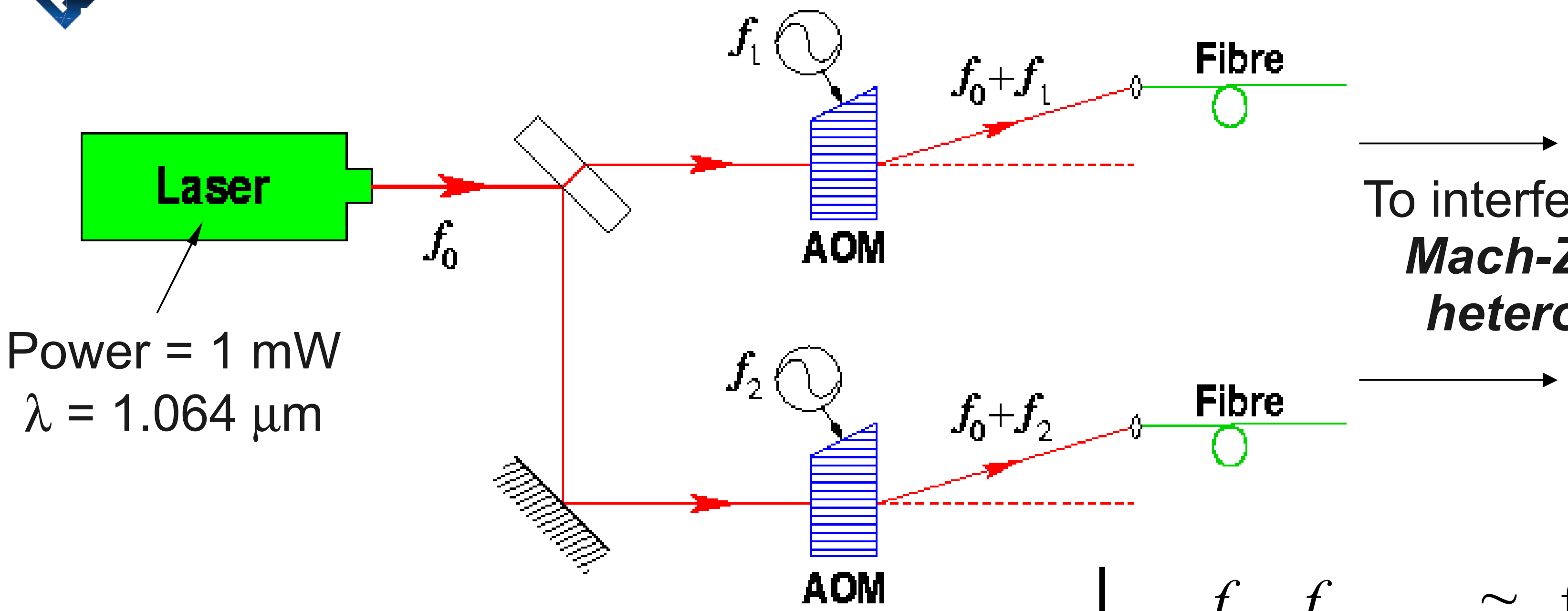
Drag-free sequence



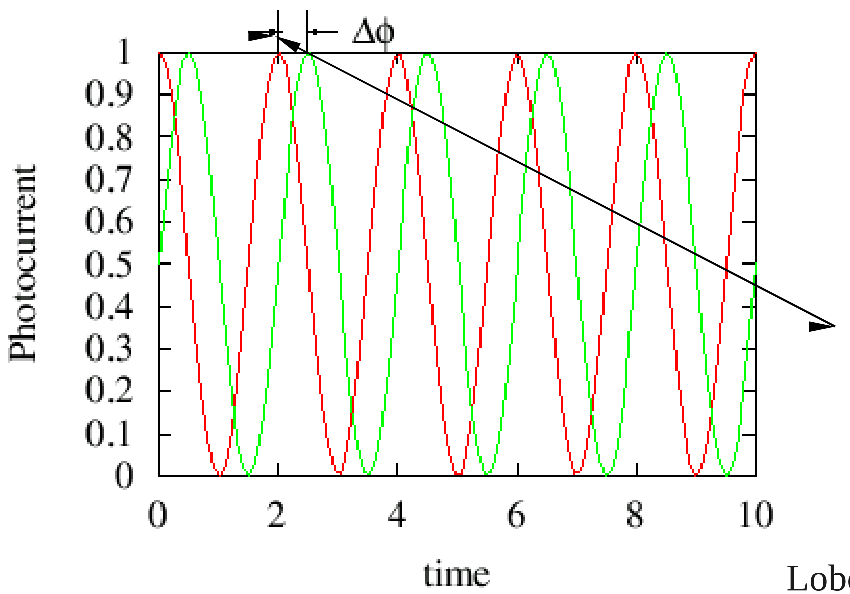
GRS



The LPF laser and phase-meter



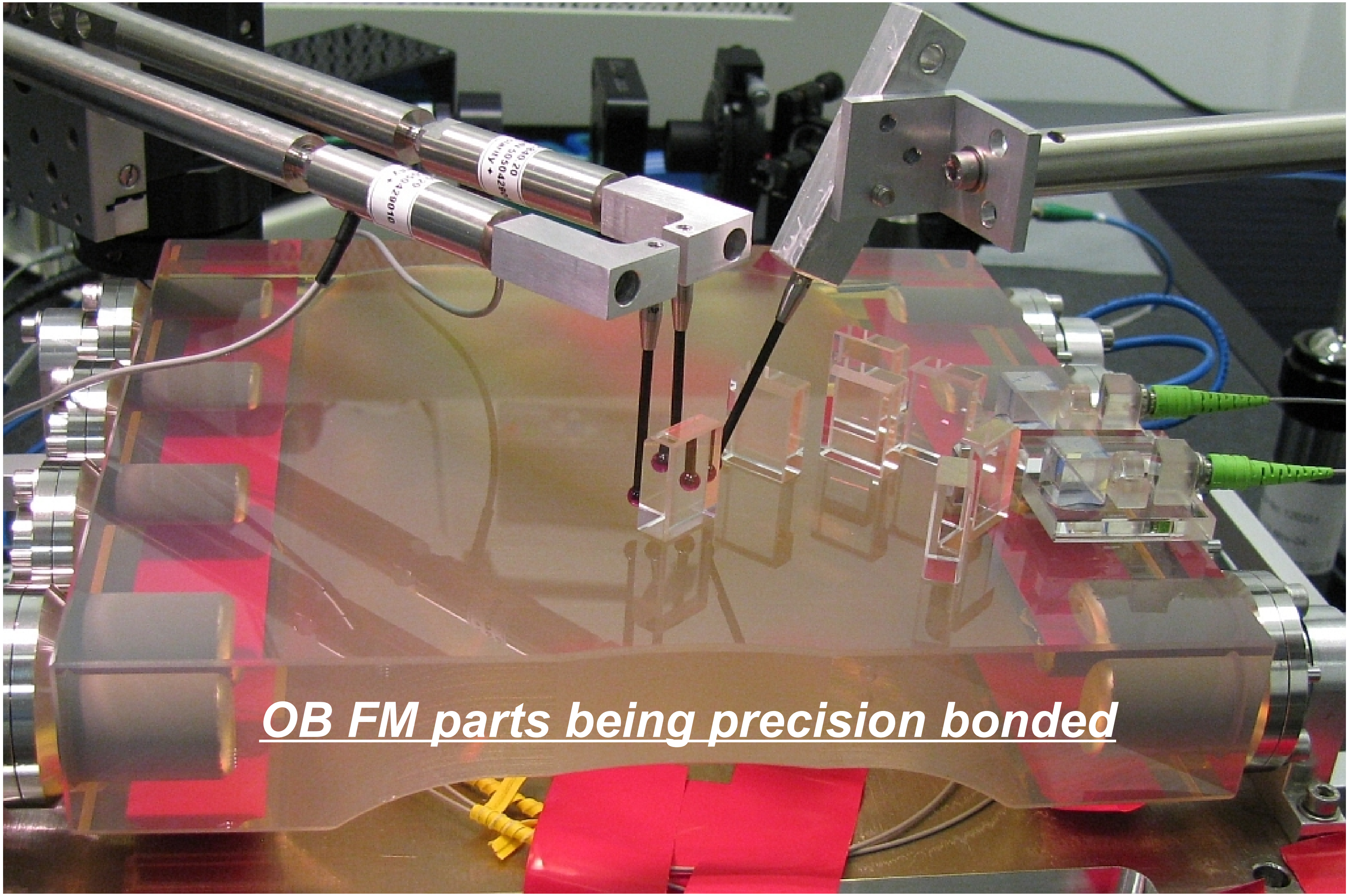
$$f_1,\ f_2 \simeq \text{few MHz}$$
$$f_{\rm het} = f_1 - f_2 \simeq 1\ \text{kHz}$$

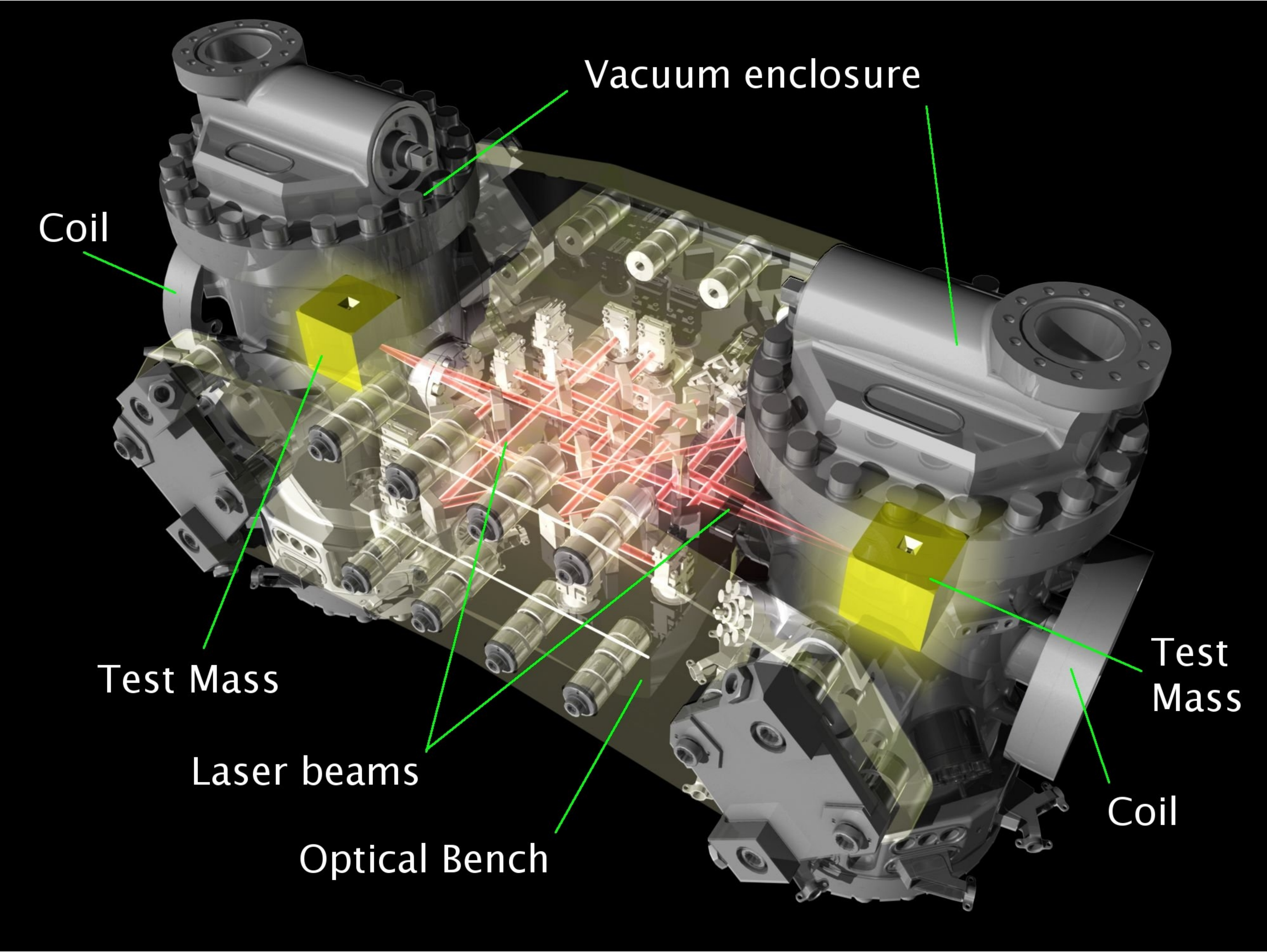


Signal:

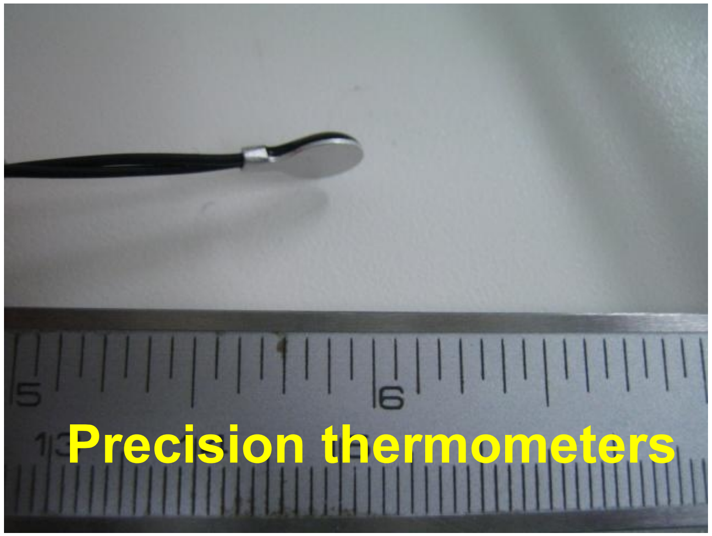
$$\cos\left[\Delta\phi(t)\right] = \cos\left[2\pi\left(f_{\rm het}\,t - \frac{\Delta l(t)}{\lambda}\right)\right]$$

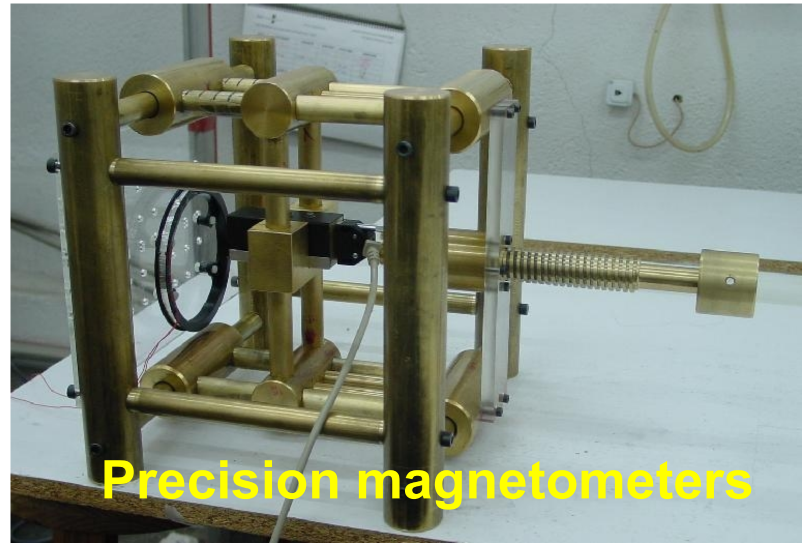
The LPF optical bench

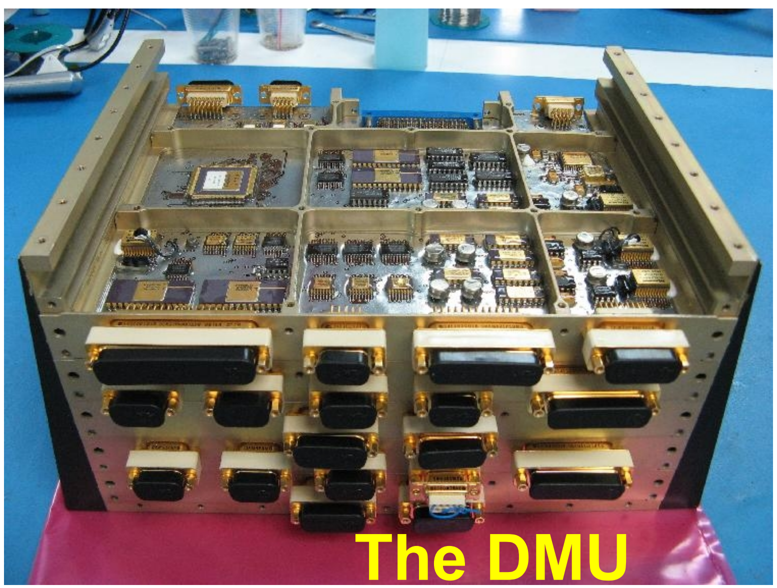


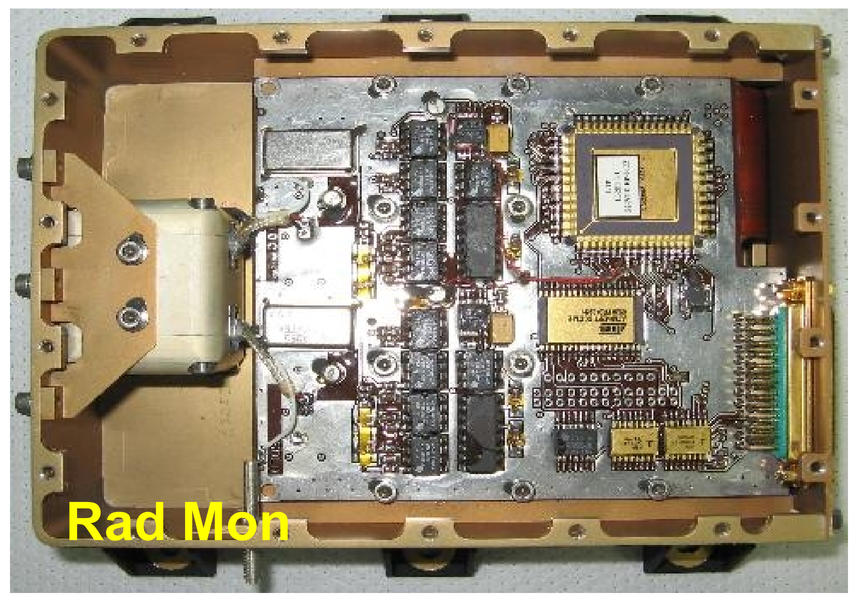

Vacuum enclosure
Coil
Test Mass
Test Mass
Laser beams
Optical Bench
Coil

Spanish contributions to LPF (IEEC-ICE)









The LPF Spacecraft and propulsion module

Final remarks

- GWs are a unique and unexplored new way to scrutinise the Universe
- GWs are the last open issue in GR so far
- GW detection is a very challenging problem: almost 50 years since first attempts by Joe Weber
- LISA has received substantial support from the Astro-2010 Decadal Survey last August-13
- LISA strongly depends on success of LISA PathFinder, scheduled for a 2013 launch. System integration begins January 2011.
- Important parts of LPF will be transferred to LISA, including:
  - ►Local metrology system
  - ►Most of LPF GRS
  - ►Diagnostics items

  while other parts need feasible improvement with affordable effort. Some of these are already under study, while the mission formulation (Astrium Germany) is essentially complete

End of presentation