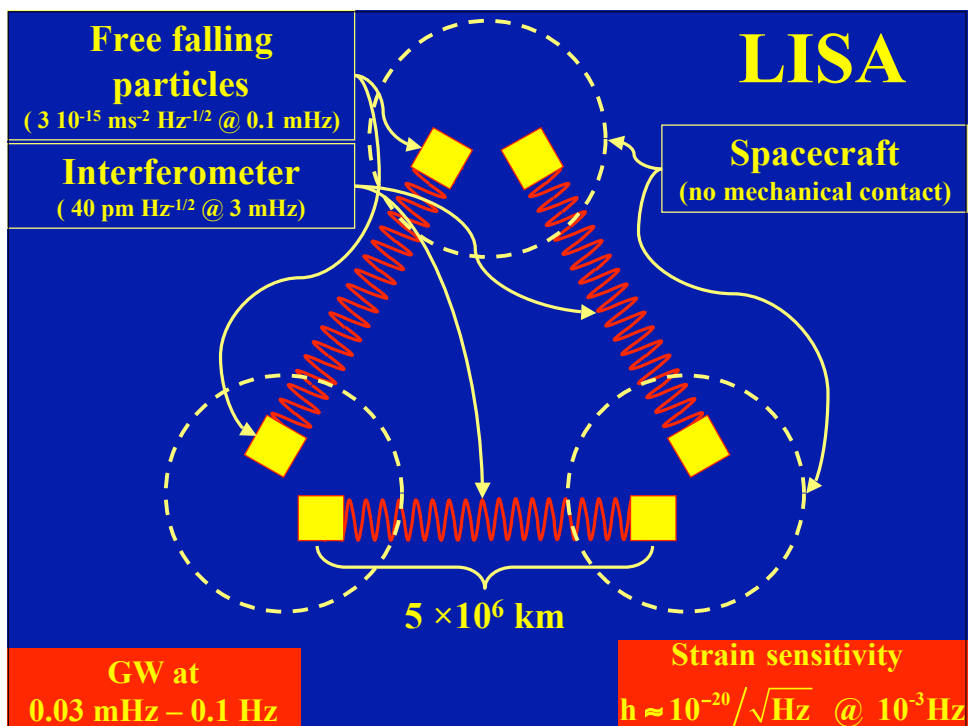
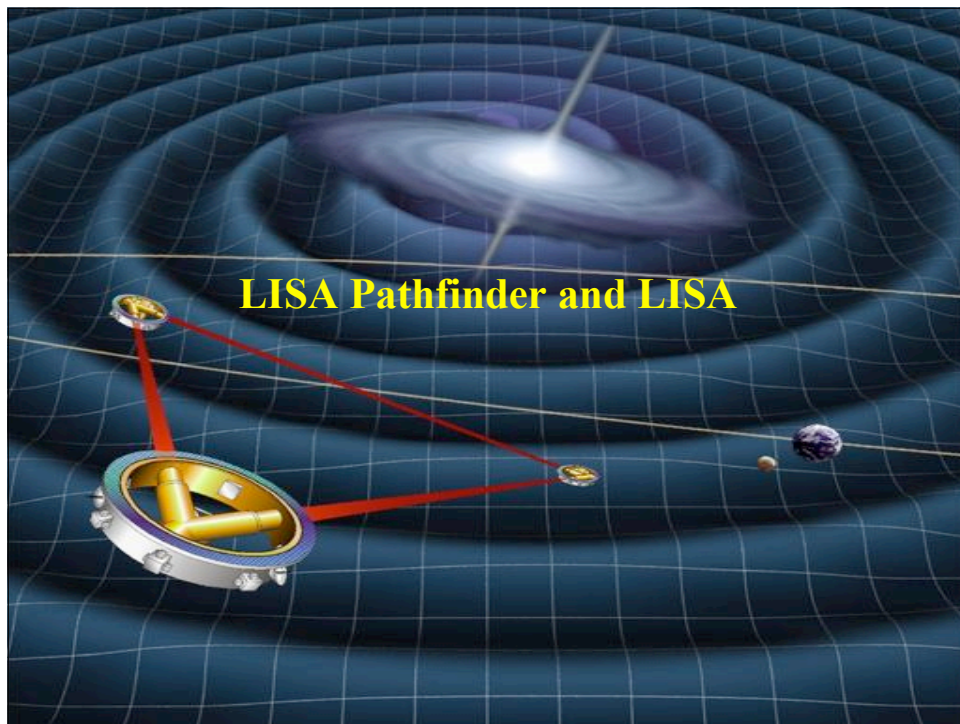
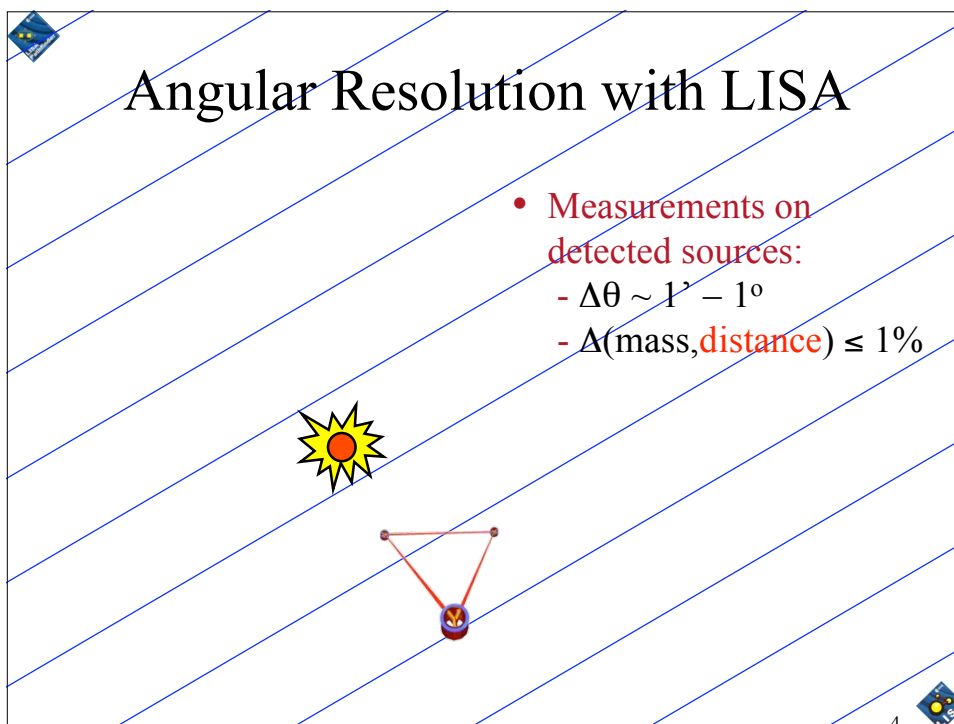
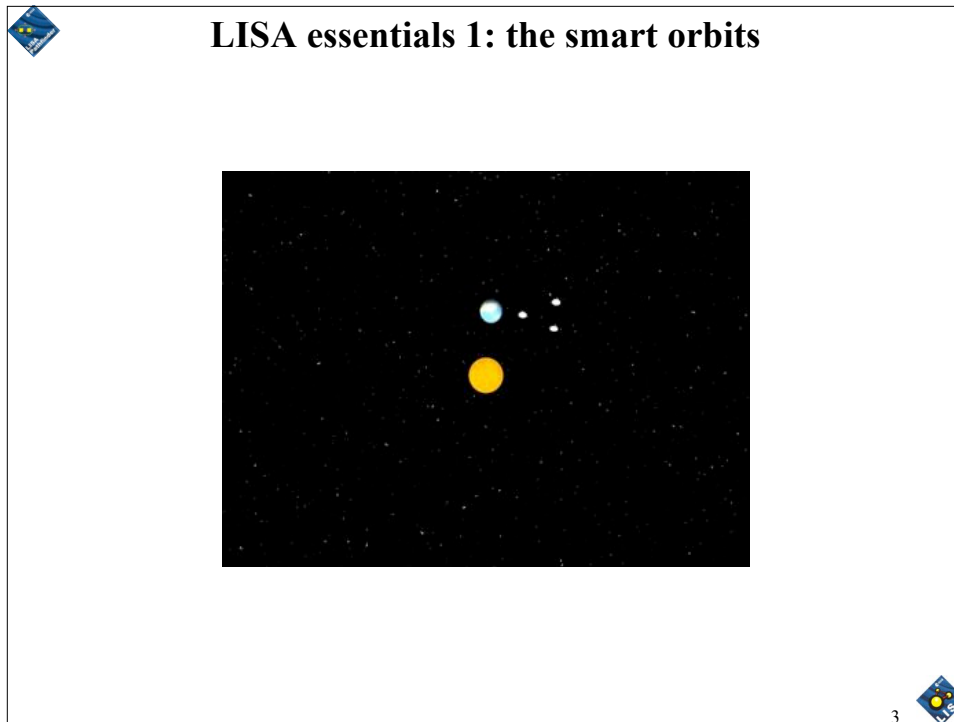
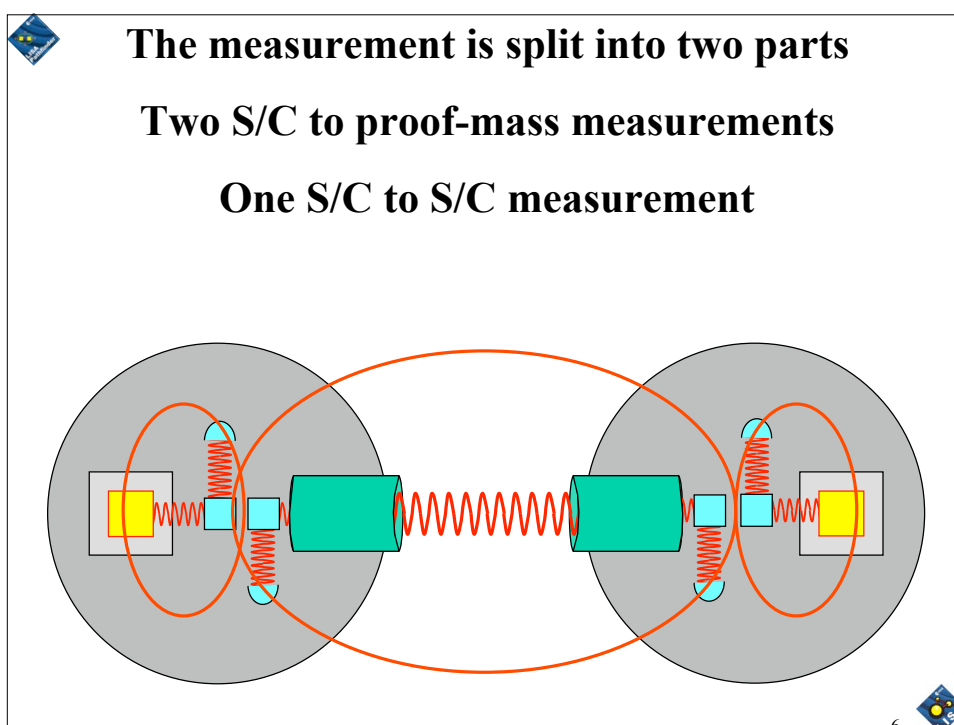
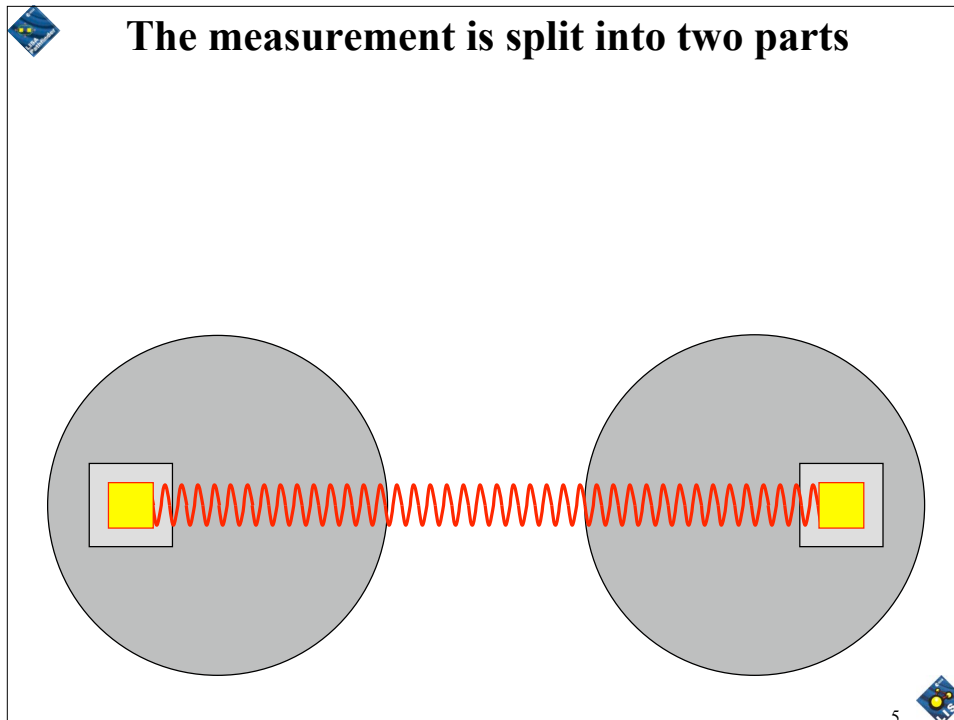








LISA Interferometry

3 5 million km arms: 33 sec 2-way light time
(1st interferometry null at 30 mHz)

Laser divergence:

Telescope $D \sim 30$ cm

SEND 1 W

RECEIVE ~ 200 pW (< 100 pW final)

YAG $1.06 \mu\text{m}$

Arriving Beam ~ 20 km

Shot Noise:

$$S_{\delta L}^{1/2} = \sqrt{\frac{\hbar c}{2\pi} \frac{\lambda}{P_{\text{received}}}} = \sqrt{\frac{\hbar c}{4\pi} \frac{\lambda}{P_{\text{sent}} \eta} \frac{\lambda^2 L^2}{D^4}} \approx 10 \text{ pm/Hz}^{1/2}$$

Laser transponding: outgoing light phase locked to incoming beam

Goal: keep all optical path errors within $40 \text{ pm/Hz}^{1/2}$

7

LISA essentials 2: the laser transponding scheme

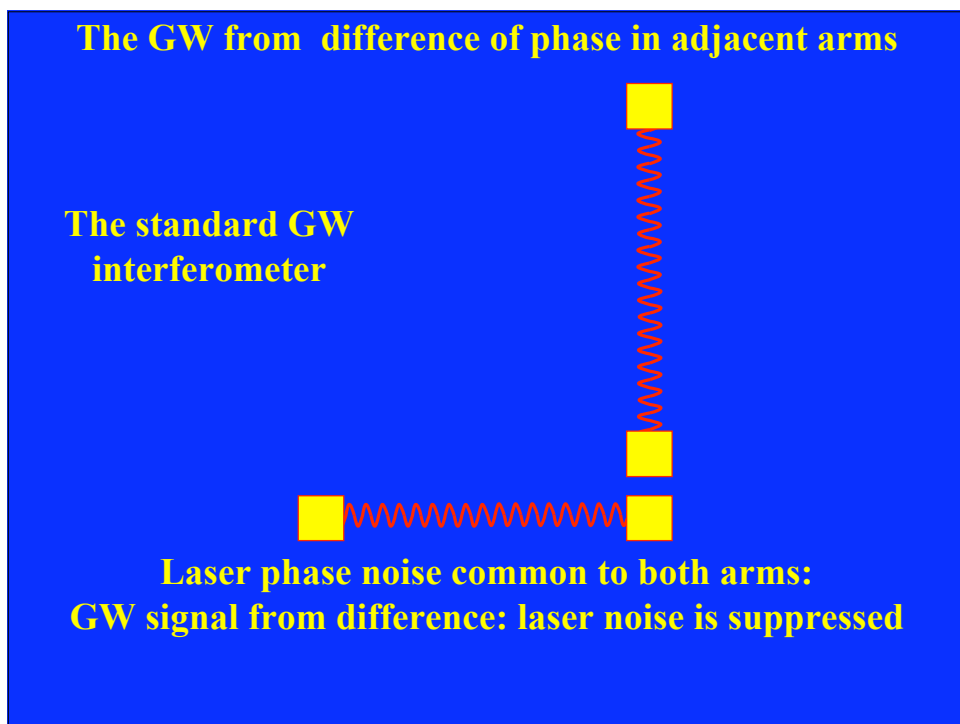
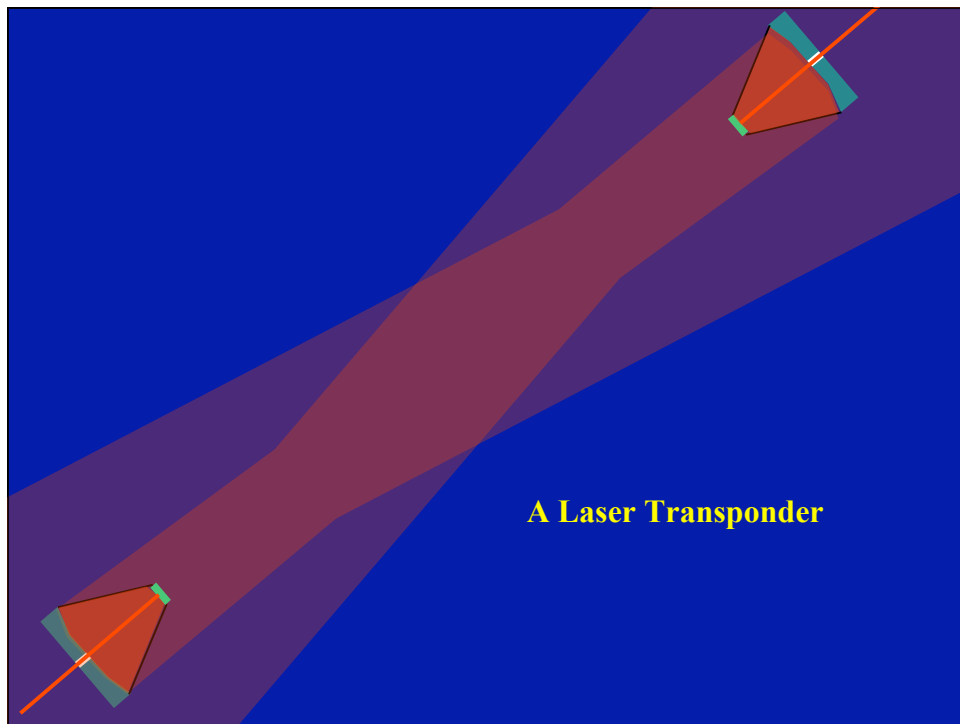
Test mass

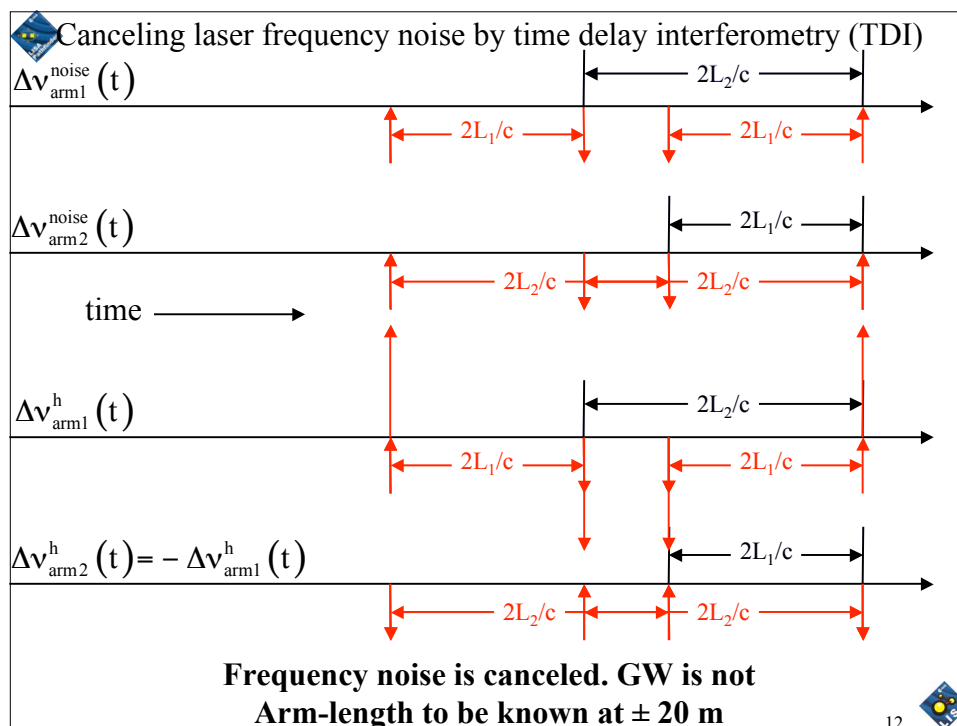
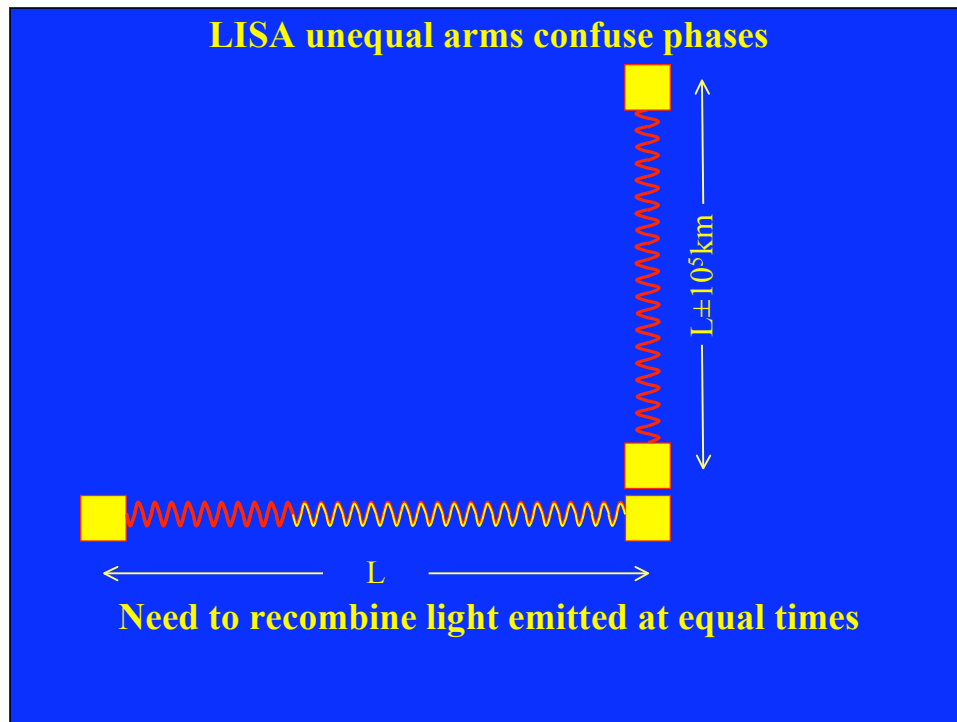
Test mass

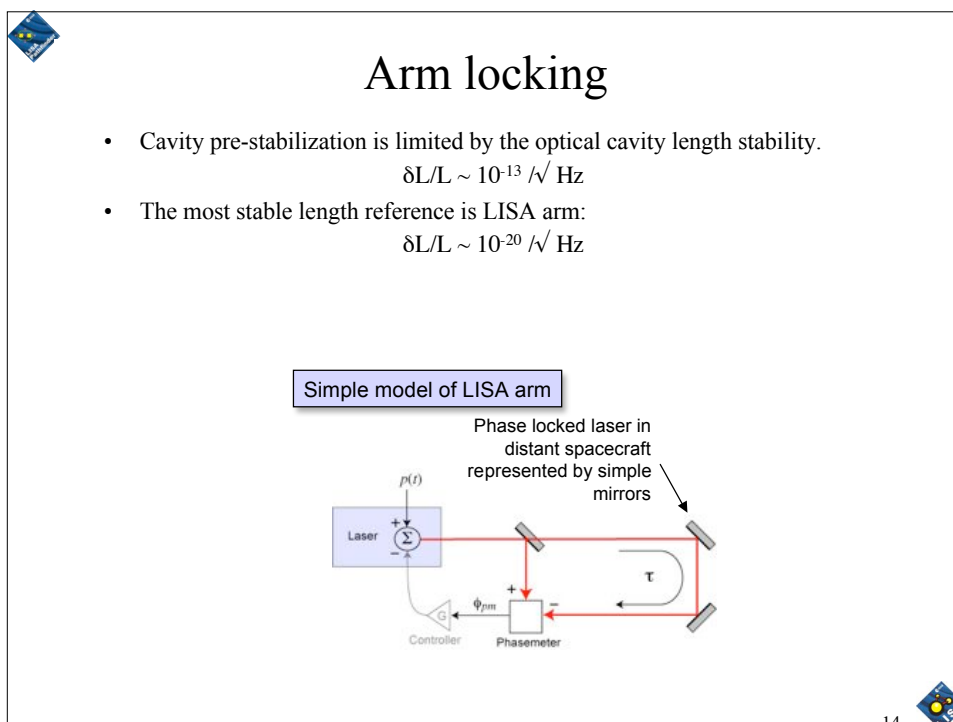
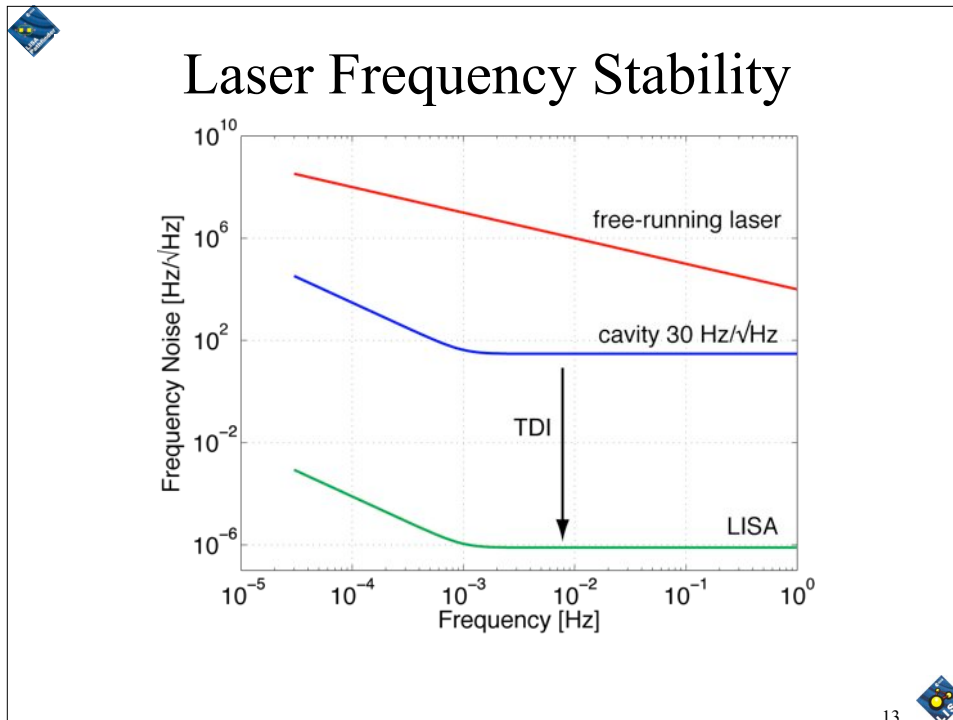
$5 \times 10^6 \text{ km}$

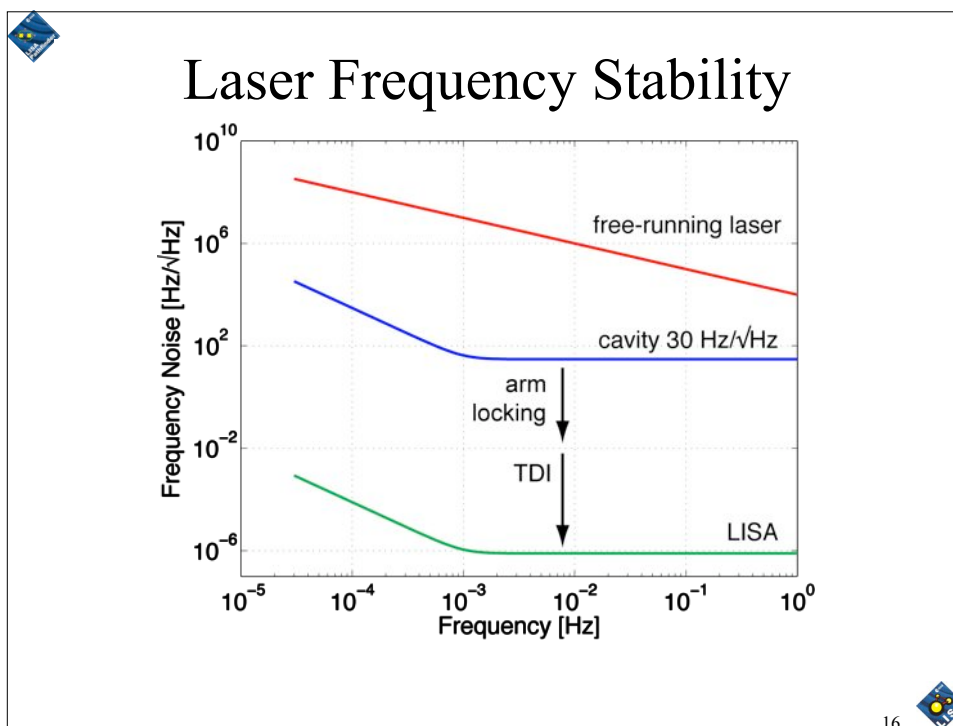
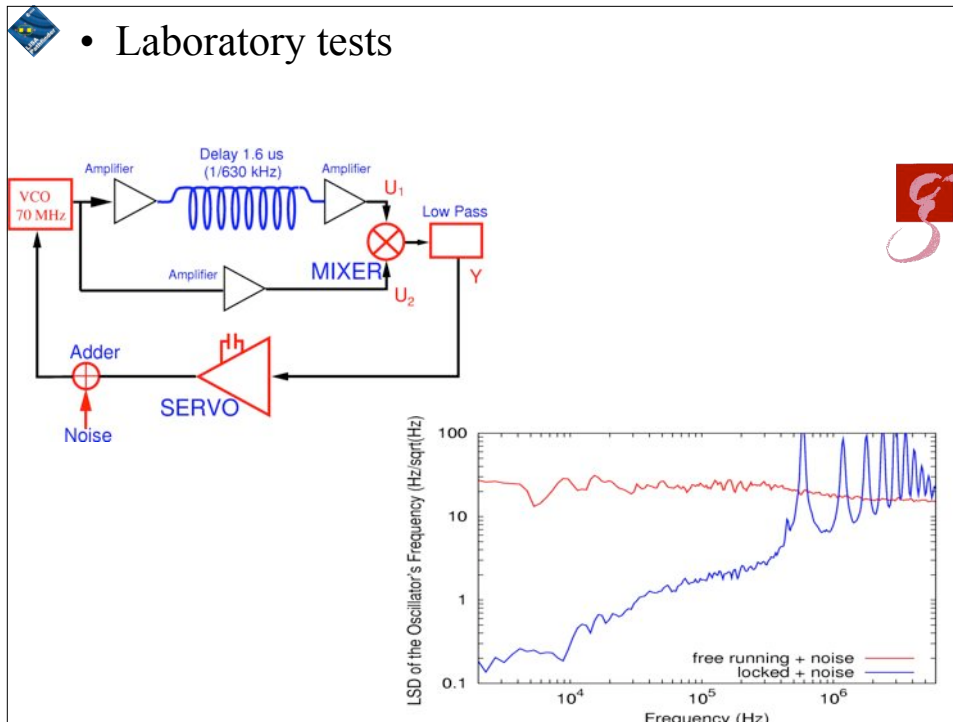
Power loss due to beam divergence makes interferometry by reflection impossible

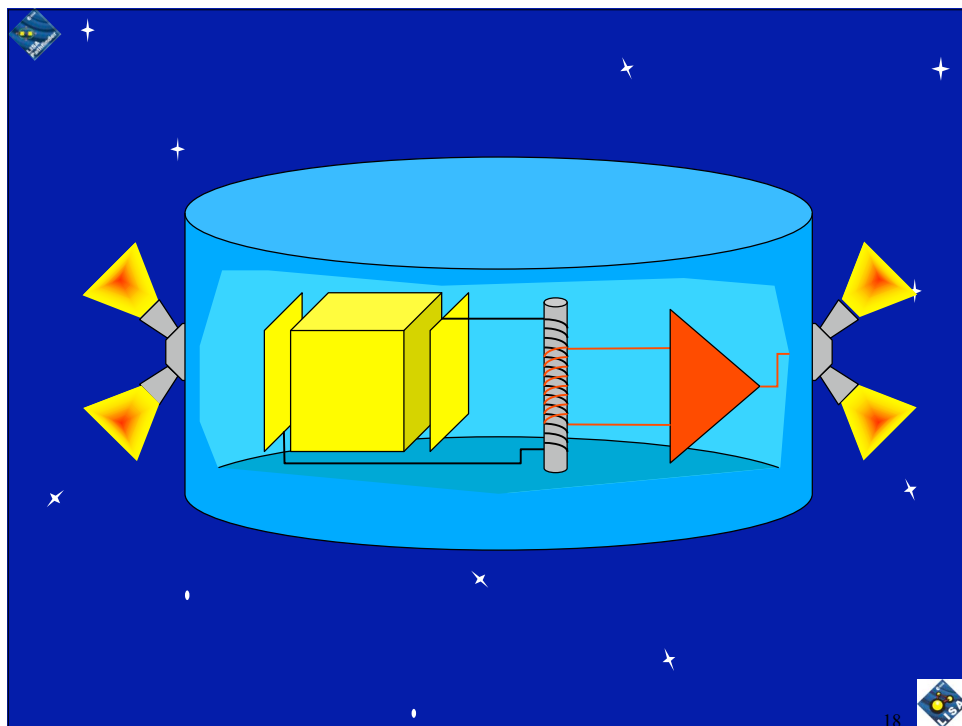
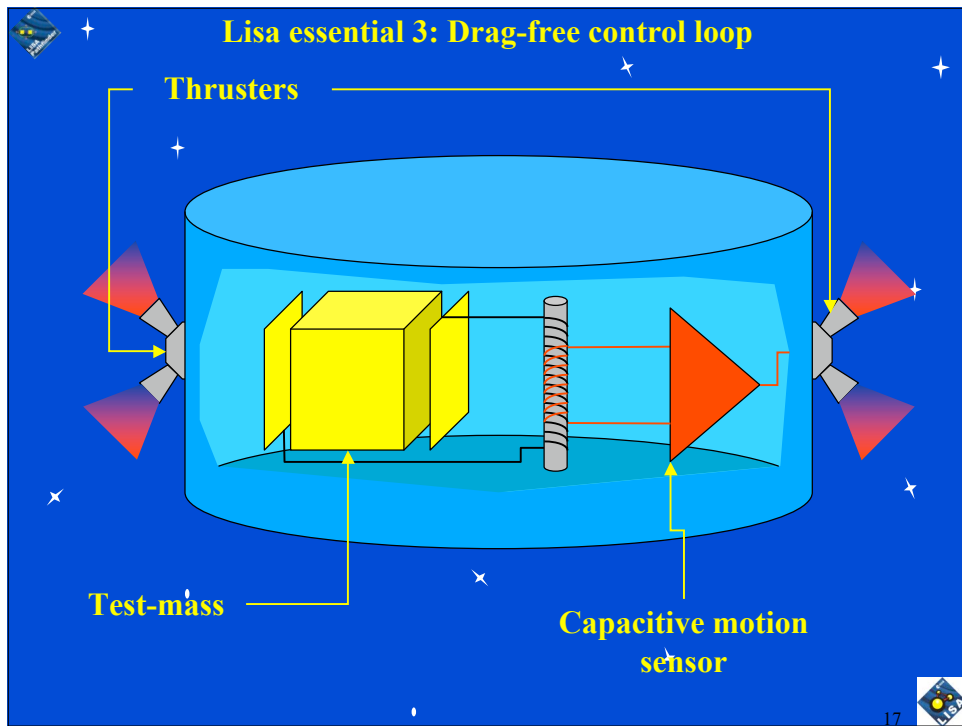
8





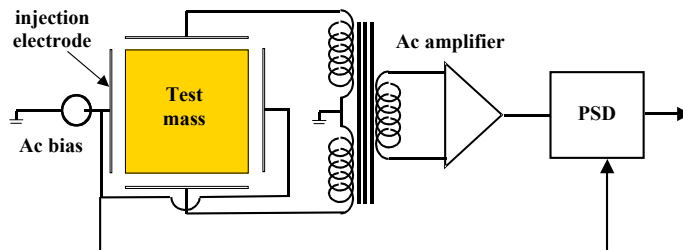






 The drag-free key elements: 1 the displacement

sensor

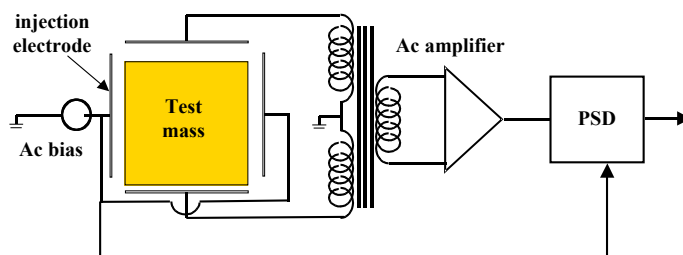


19



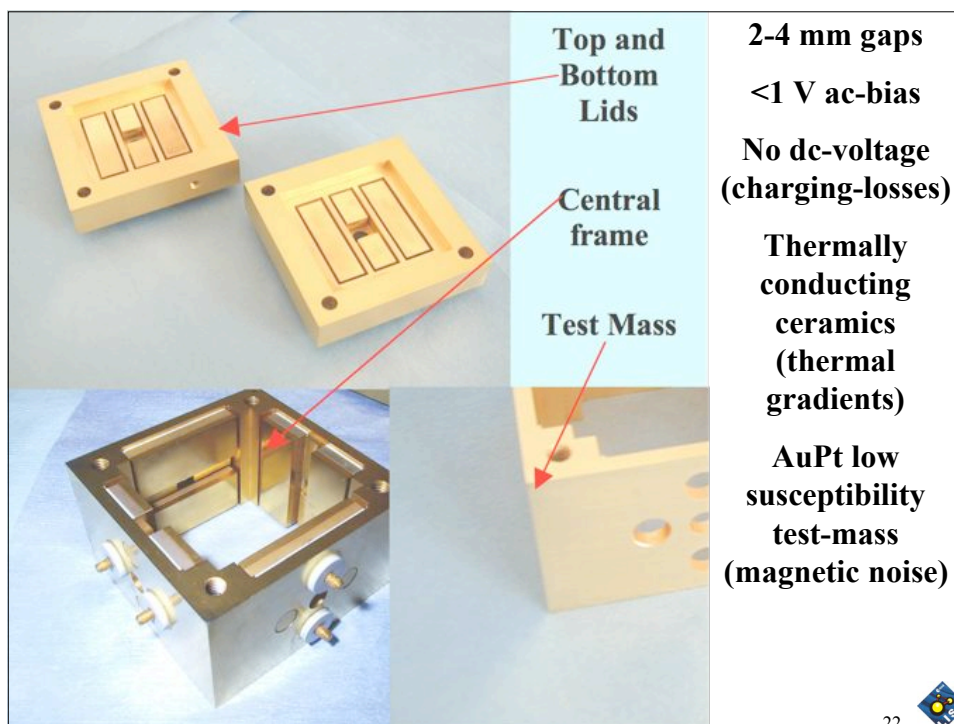
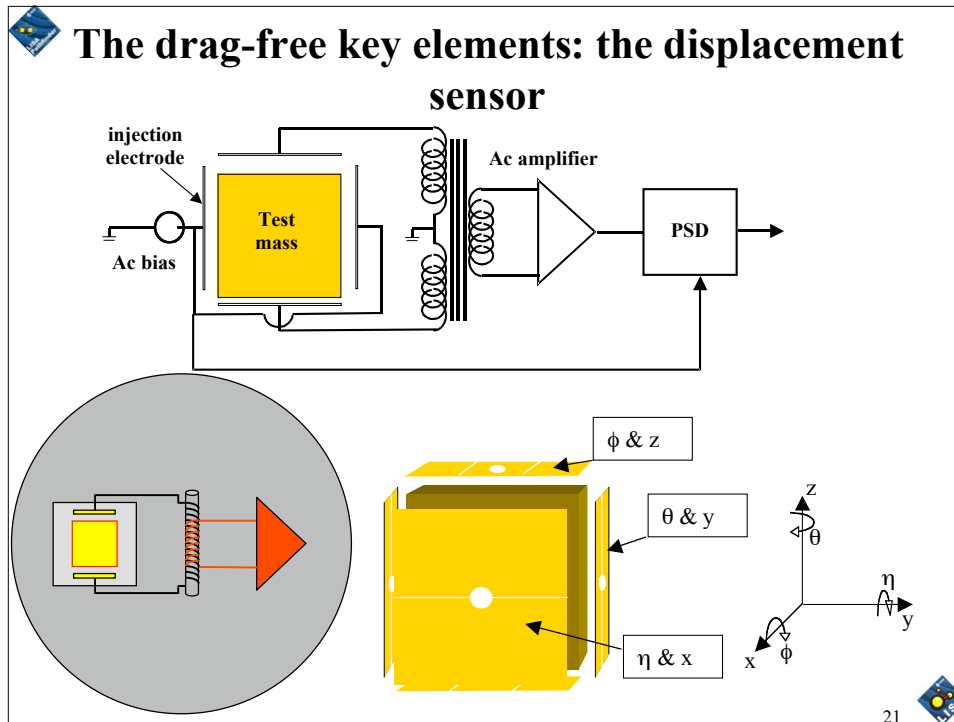
 The drag-free key elements: 1 the displacement

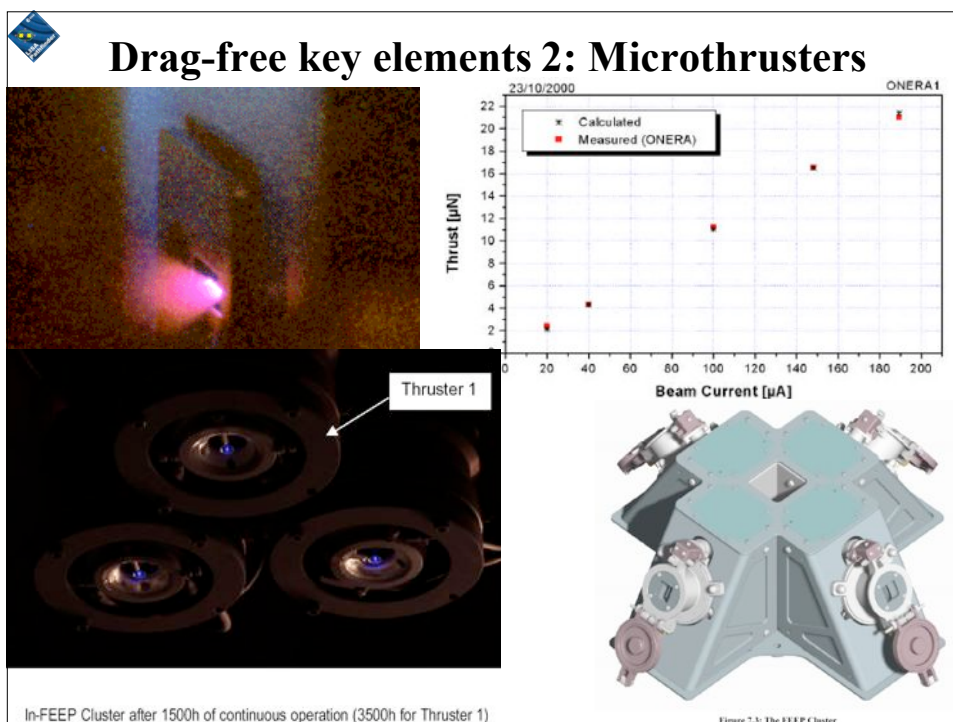
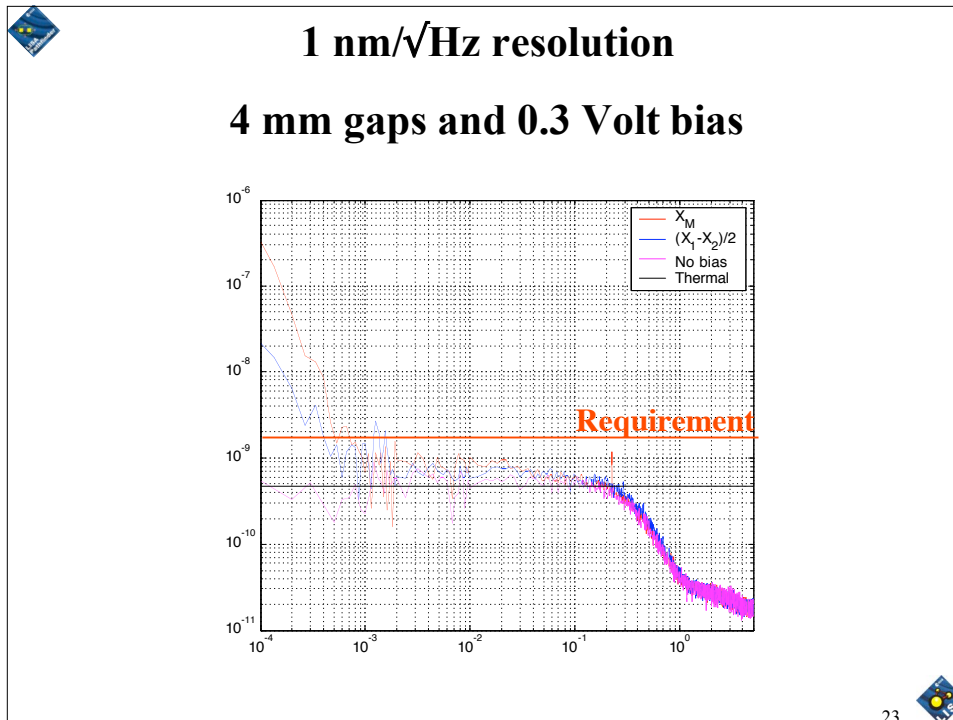
sensor

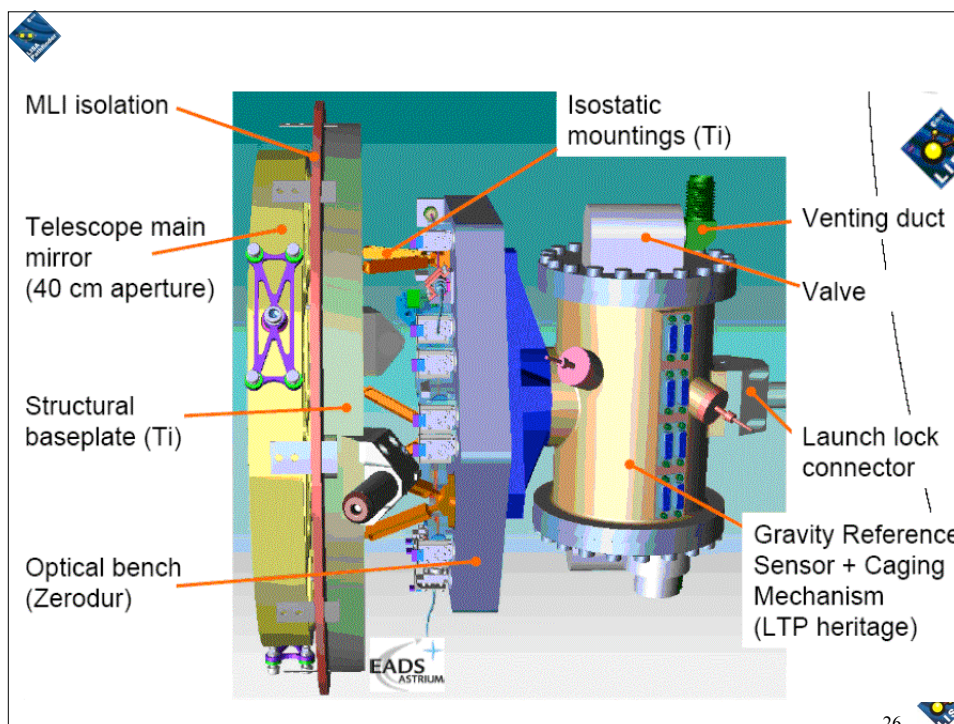
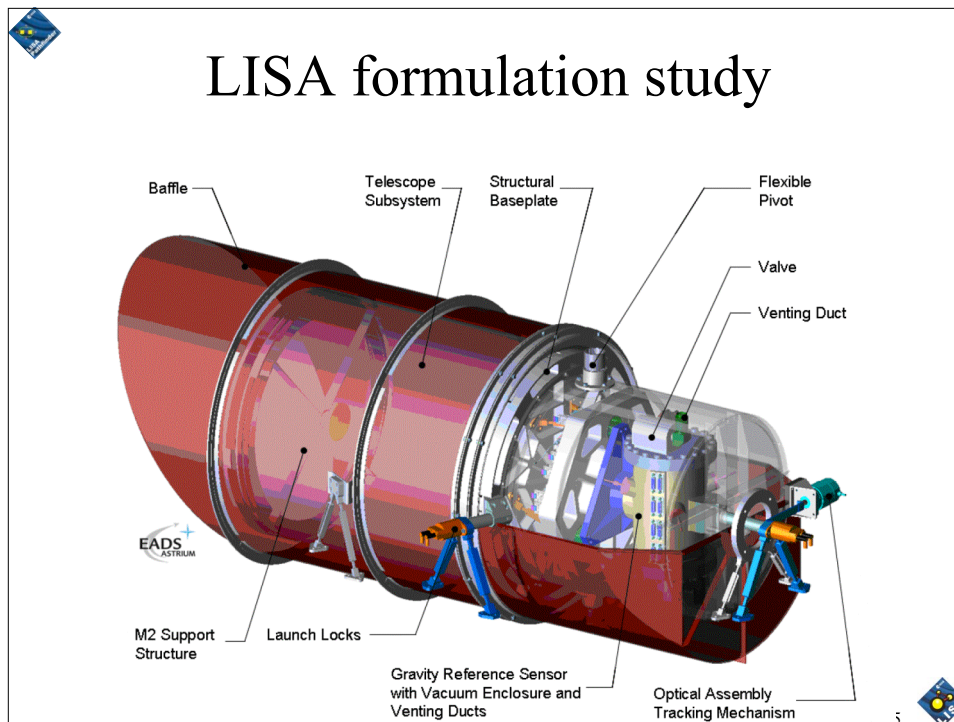


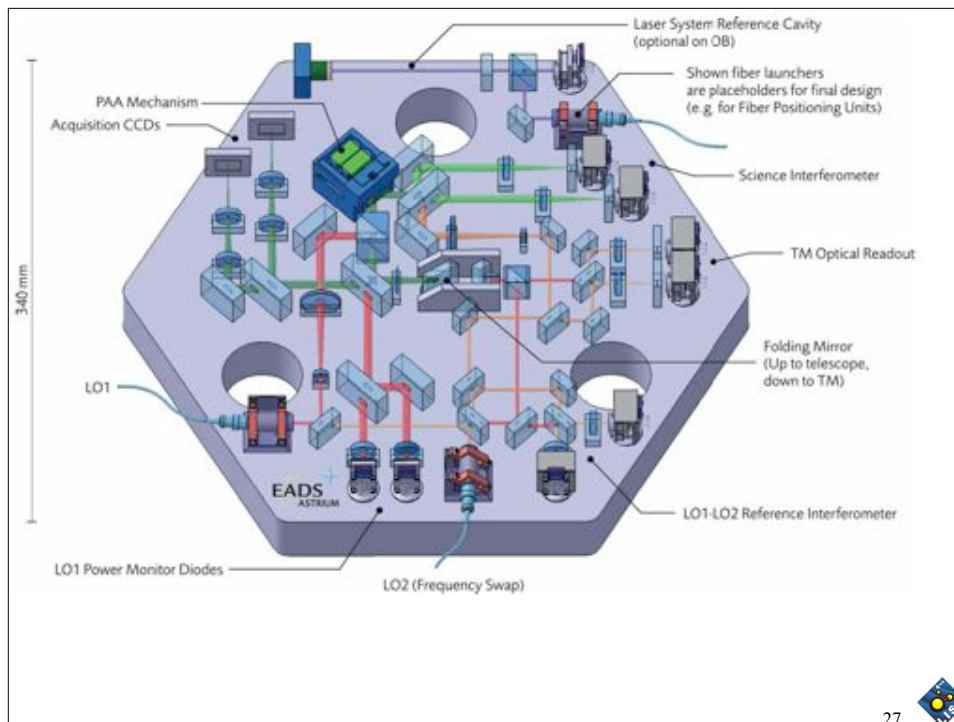
20



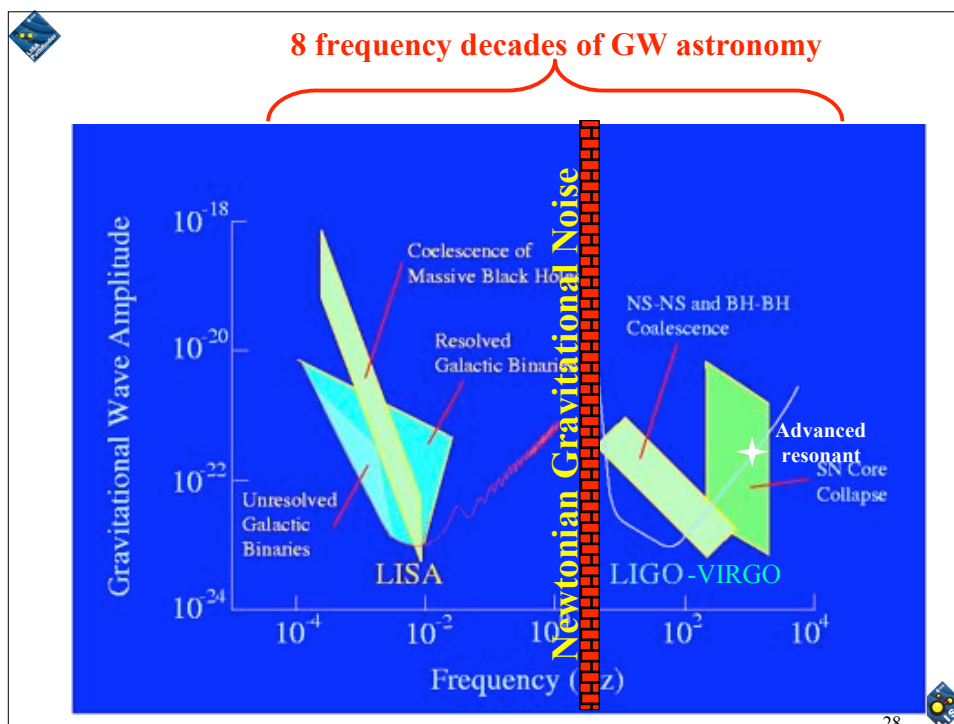








27



28

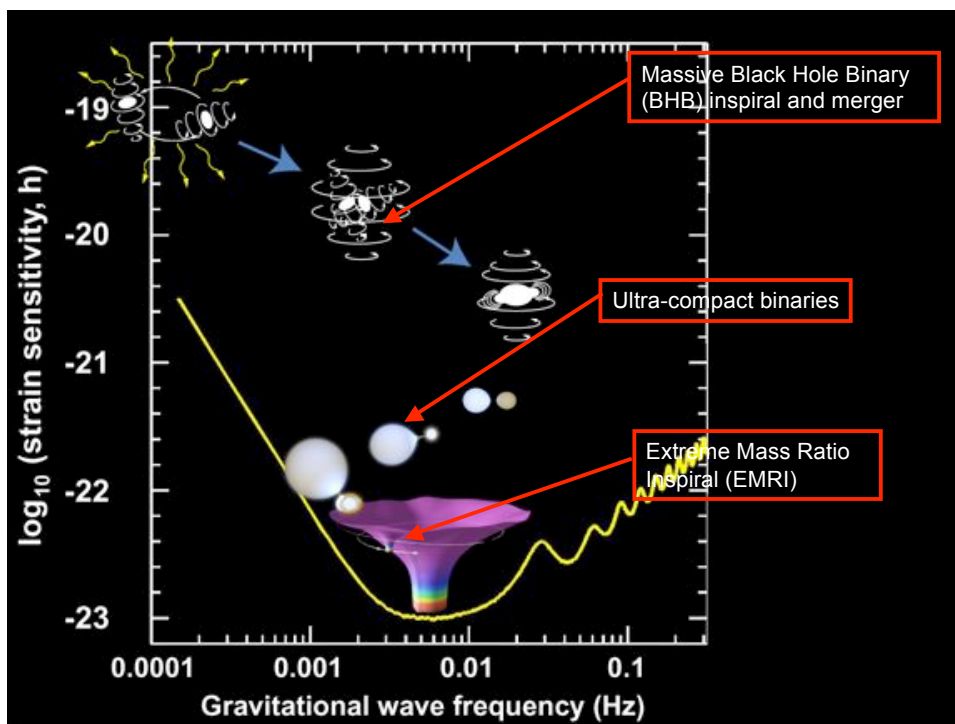
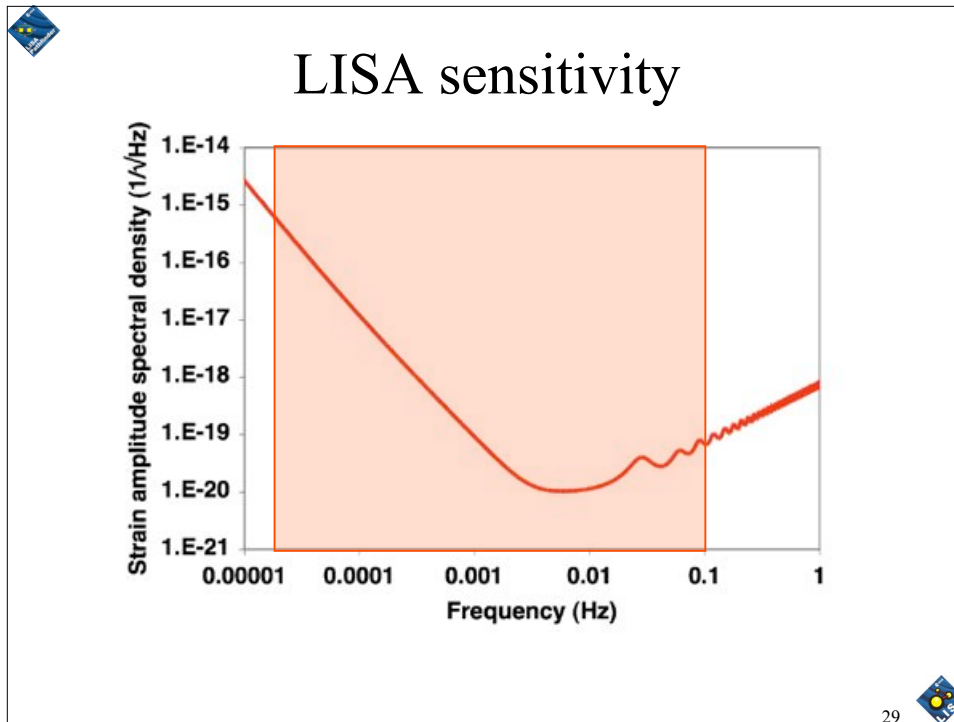


Table 4-1. LISA science objectives and supporting science investigations.

Science Objectives	Science Investigations
Understand the formation and growth of massive black holes	Search for a population of seed black holes at early epochs
	Search for remnants of the first (Pop III) stars through observation of intermediate-mass black hole captures, also at later epochs
Trace the growth and merger history of massive black holes and their host galaxies	Determine the relative importance of different black hole growth mechanisms as a function of redshift
	Determine the merger history of 1×10^4 to $3 \times 10^5 M_\odot$ black holes from the era of the earliest known quasars ($z \sim 6$)
	Determine the merger history of 3×10^5 to $1 \times 10^7 M_\odot$ black holes at later epochs ($z < 6$)
Explore stellar populations and dynamics in galactic nuclei	Characterize the immediate environment of MBHs in $z < 1$ galactic nuclei from EMRI capture signals
	Study intermediate-mass black holes from their capture signals
	Improve our understanding of stars and gas in the vicinity of galactic black holes using coordinated gravitational and electromagnetic observations

LISA objectives 1/2

31



Survey compact stellar-mass binaries and study the morphology of the Galaxy	Elucidate the formation and evolution of Galactic stellar-mass binaries: constrain the diffuse extragalactic foreground
	Determine the spatial distribution of stellar mass binaries in the Milky Way and environs
	Improve our understanding of white dwarfs, their masses, and their interactions in binaries and enable combined gravitational and electromagnetic observations
Confront General Relativity with observations	Detect gravitational waves directly and measure their properties precisely
	Test whether the central massive objects in galactic nuclei are the black holes of General Relativity
	Make precision tests of dynamical strong-field gravity
Probe new physics and cosmology with gravitational waves	Study cosmic expansion history, geometry and dark energy using precise gravitationally calibrated distances in cases where redshifts are measured
	Measure the spectrum of, or set bounds on, cosmological backgrounds
Search for unforeseen sources of gravitational waves	

LISA objectives 2/2

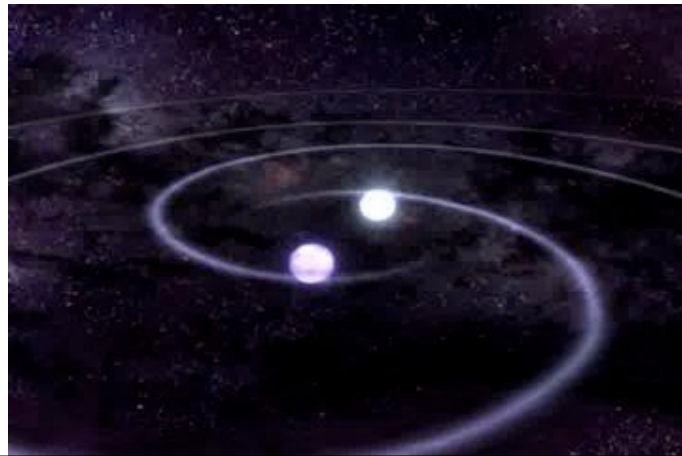
32



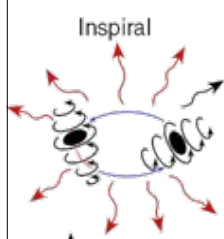
Binary Star in our Galaxy (White Dwarfs, Neutron Stars)

Very bright signal (>100 times larger than noise)

Of some of them we know everything: they're out and waiting for being observed



class	source	dist (pc)	$f=2/P_\delta$ (mHz)	M_1 $M_\odot$	M_2 $M_\odot$	h	SNR (1 Year)
WD + WD	WD 0957-666	100	0.38	0.37	0.32	4.00E-22	4.1
	WD1101+364	100	0.16	0.31	0.36	2.00E-22	0.4
	WD 1704+481	100	0.16	0.39	0.56	4.00E-22	0.7
	WD2331+290	100	0.14	0.39	>0.32	2.00E-22	0.3
WD+sdB	KPD 0422+4521	100	0.26	0.51	0.53	6.00E-22	2.9
	KPD 1930 +2752	100	0.24	0.5	0.97	1.00E-21	4.1
AM CVn	RXJ0806.3+1527	300	6.2	0.4	0.12	4.00E-22	173.2
	RXJ1914+245	100	3.5	0.6	0.07	6.00E-22	195.0
	KUV05184-0939	1000	3.2	0.7	0.092	9.00E-23	27.3
	AM CV n	100	1.94	0.5	0.033	2.00E-22	35.6
	HP Lib	100	1.79	0.6	0.03	2.00E-22	32.0
	CR Boo	100	1.36	0.6	0.02	1.00E-22	10.6
	V803 Cen	100	1.24	0.6	0.02	1.00E-22	9.2
	CP Eri	200	1.16	0.6	0.02	4.00E-23	3.3
	GP Com	200	0.72	0.5	0.02	3.00E-23	1.1
LMXB	4U1820-30	8100	3	1.4	< 0.1	2.00E-23	5.7
	4U1626-67	<8000	0.79	1.4	< 0.03	6.00E-24	0.2
W UMa	CC Com	90	0.105	0.7	0.7	6.00E-22	0.5



Signals from binary inspiral

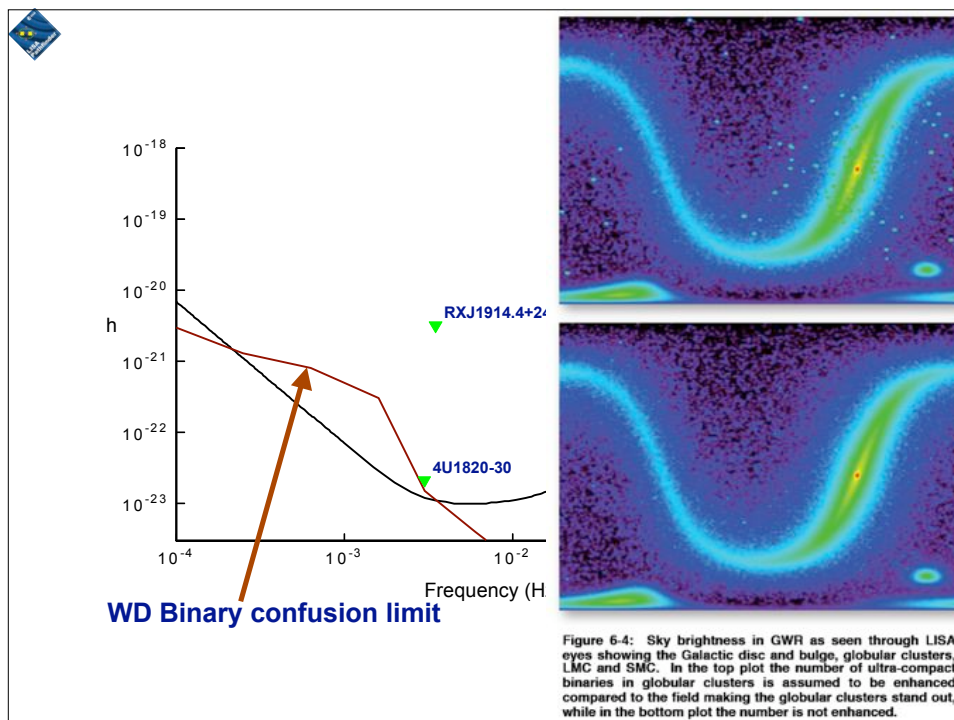


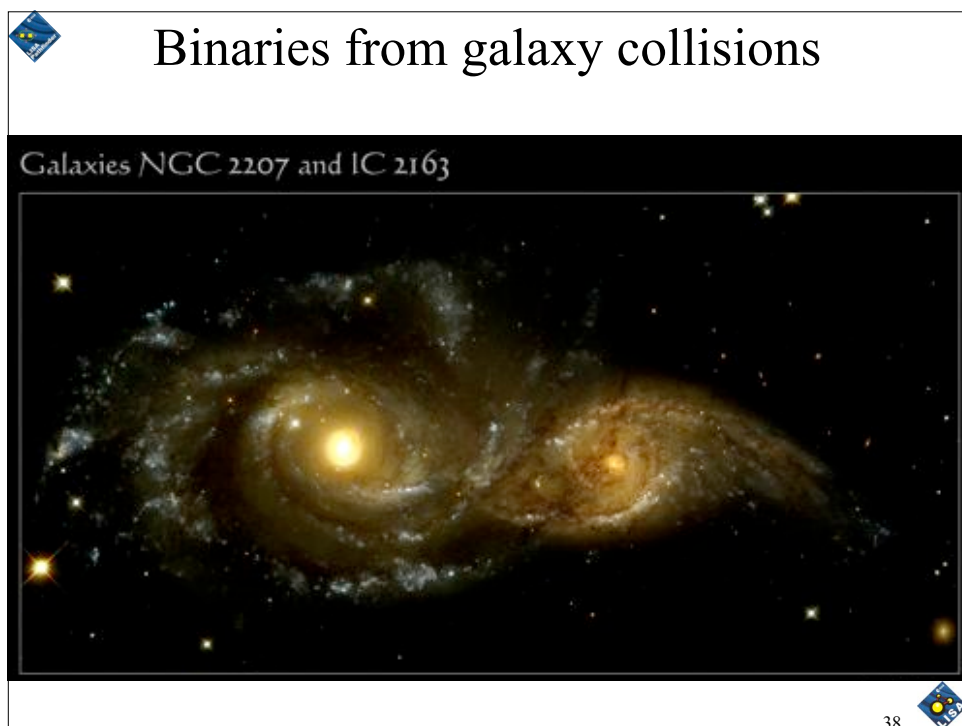
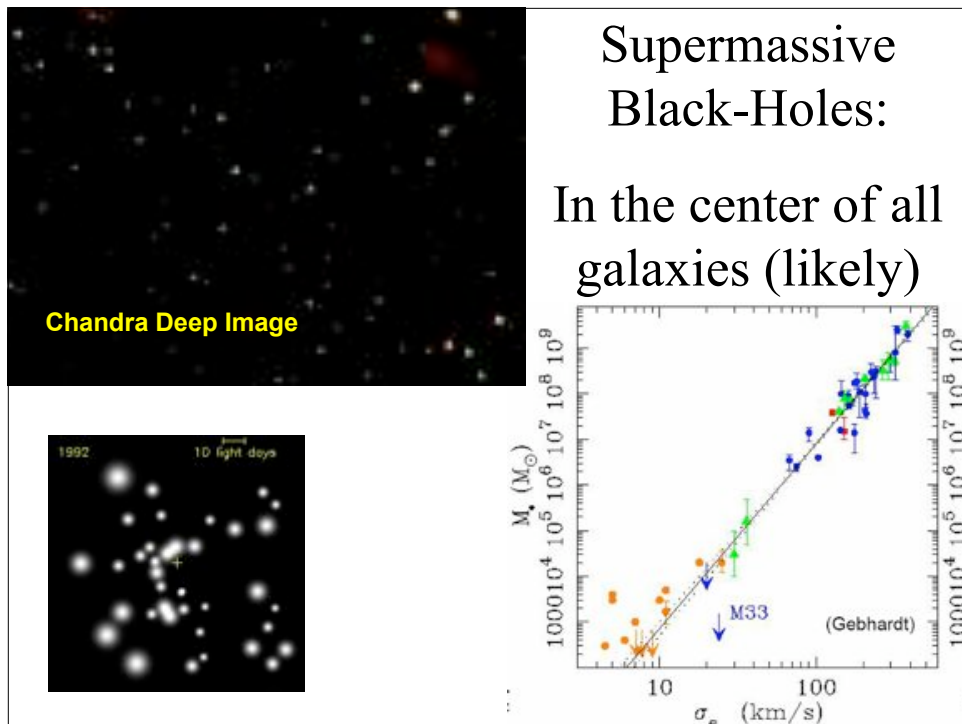
Galactic WD (/NS) binaries

Type	Birth rate (year ⁻¹)	Resolved systems	With frequency change
(wd, wd)	2.9×10^{-2}	12 163	560
AM CVn	1.8×10^{-3}	10 117	49
(ns, wd)	1.4×10^{-4}	21	3
(ns, ns)	3.2×10^{-5}	1	0
(bh, wd)	3.8×10^{-5}	1	0
(bh, ns)	1.0×10^{-5}	0	0
Total		22 303	614

(Nelemans et al, 2001; Nelemans, 2002)

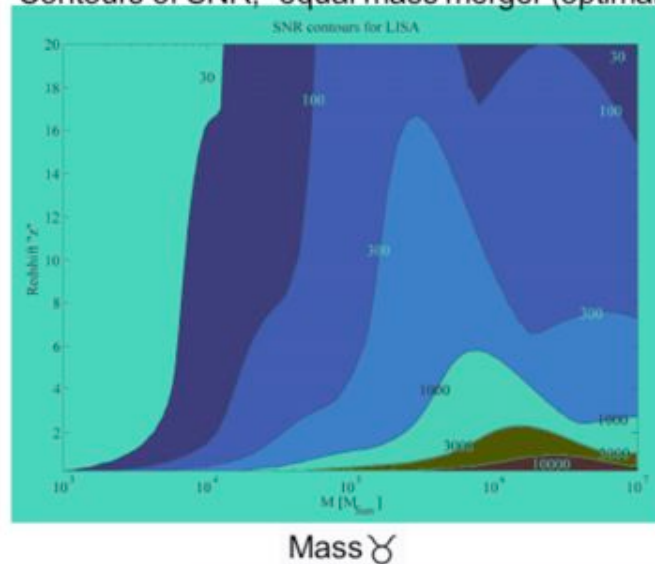
- Map (partially 3D) of WDs in the galaxy
- For ~100 systems, studies of:
 - Tidal interaction
 - Mass transfer
- If follow-on optical observations are available (for some objects): information on M-R relation (Cooray and Seto, 2004)





Massive Binary Black Holes: strong signals

Contours of SNR, equal mass merger (optimal)



Visible
from
“every
where”
in the
Univer
se

Absolute Distances from Black Hole Binaries

Waveforms of black hole binaries give precise, gravitationally calibrated distances to high redshift

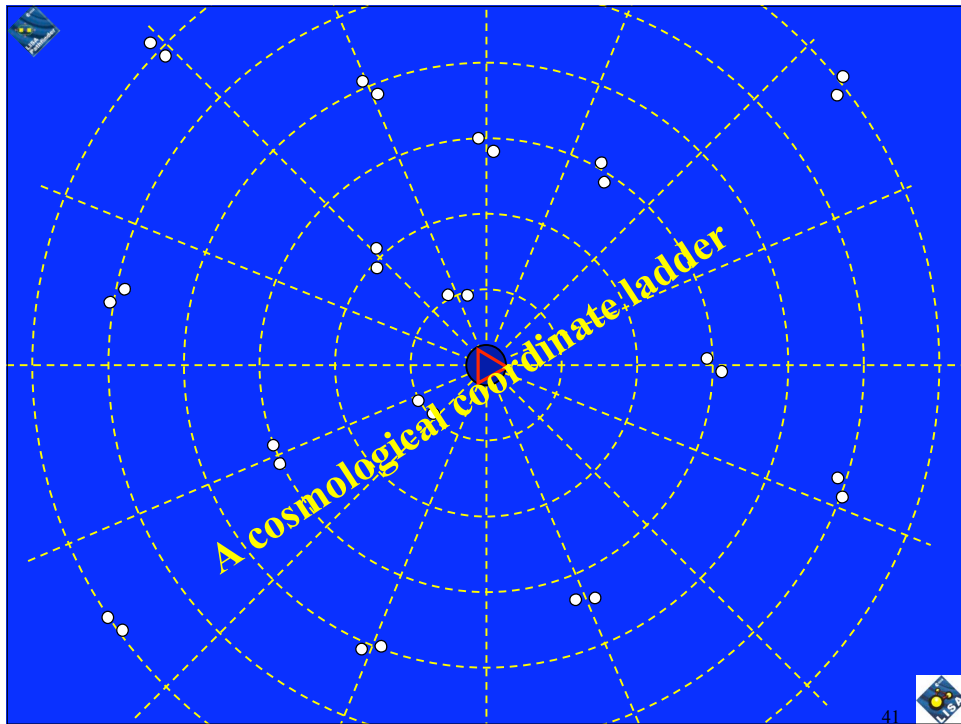


Absolute luminosity distances can be derived directly from

- amplitude
- orbital frequency
- chirp time

$$\text{Distance} \approx c \frac{1}{\text{frequency}^2 \times t_{\text{chirp}} \times \text{amplitude}}$$

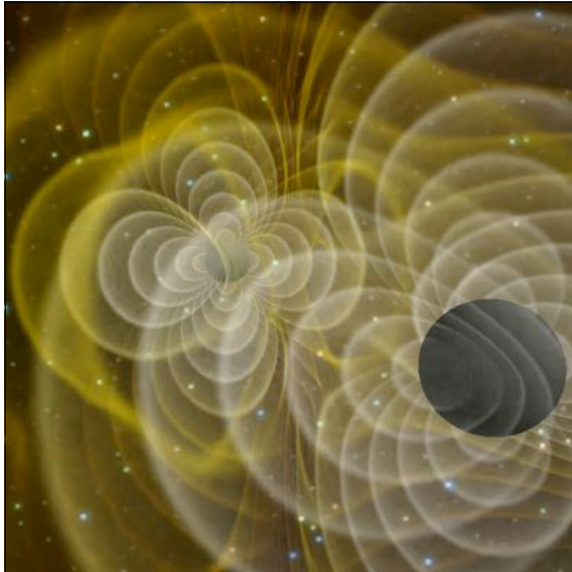
1. Distances accurate to 0.1% to 2% per event
2. Absolute, physical calibration using only gravitational physics



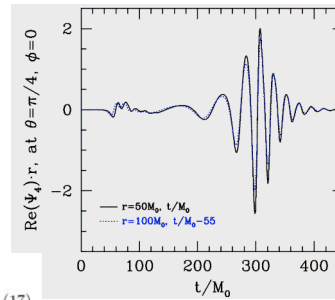
Visible signals from gravitational wave sources

LISA sources have possible electromagnetic counterparts over a wide variety of wavebands and timescales; an exploratory bonanza for wide field synoptic imaging and spectroscopy

- ✂ Black-hole mergers in real time
 - hours to weeks notice within 1°
- ✂ Precursor, prompt and afterglow emission from gas around black hole mergers
- ✂ Tidally heated, eclipsing and accreting white dwarf binaries (several known already)
- ✂ Nuclear starbursts



A recent result in numerical relativity:



Although the mass of the system must decrease because of radiative losses,

$$M_i = M_1 + M_2 > M_f ,$$

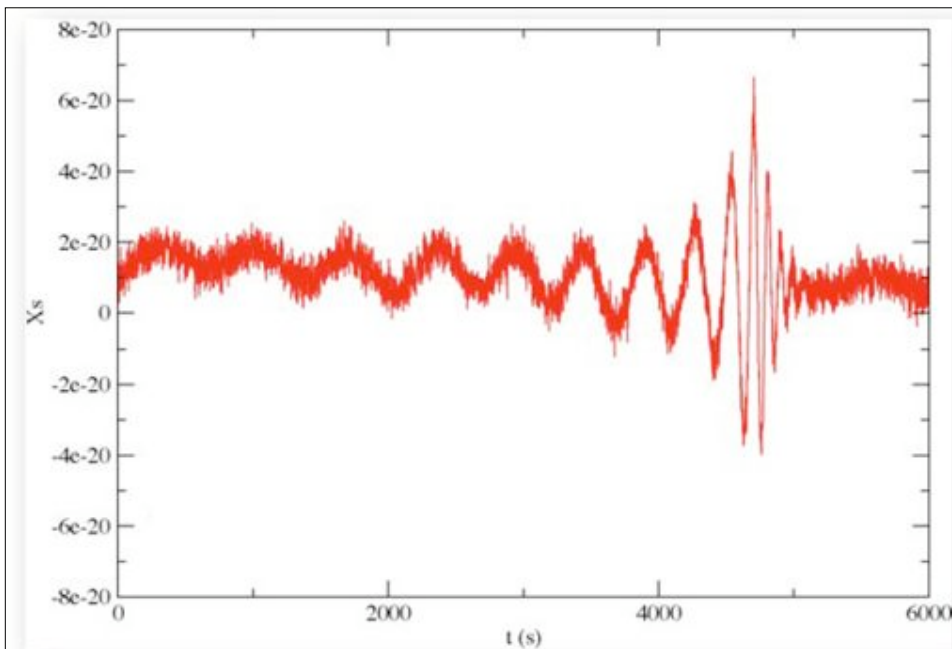
(17)

the area of all event horizons in the system must *increase* during the coalescence:

$$A_i = A_1 + A_2 < A_f .$$

(18)

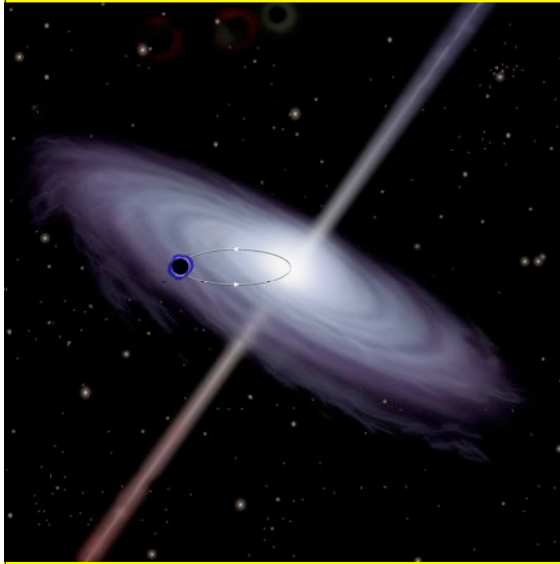
43



$2 \times 10^5 M_\odot$ at $Z=5$ + Simulated noise

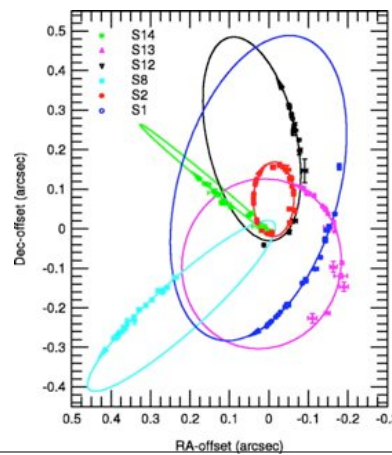
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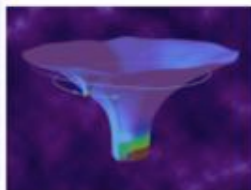
Capture of small Black-Hole by a super- massive one

A Map of the Horizon



How well does General Relativity describe real black holes?

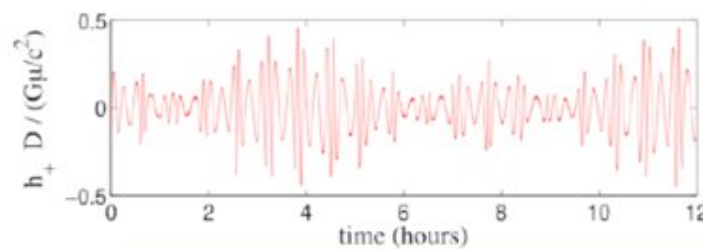
*Waveforms of Extreme Mass Ratio Inspirals (EMRIs)
test the unique Kerr black hole solutions of GR*



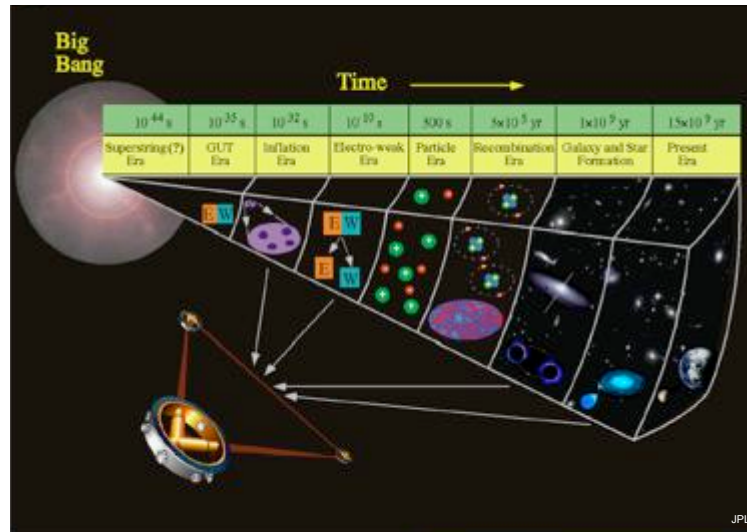
~ 10^5 orbits of each source

Rich waveforms test:

- "No-hair Theorem" of General Relativity to ~1% accuracy
- Response of dynamical tide on horizon to ~10%



Gravitational Waves through Time



47

Primordial Gravitational Waves

- Production: Fundamental Physics in early Universe
 - Inflation, phase transitions, topological defects, brane-worlds, strings
- Non-thermal spectrum gives energies and masses
- Expressed as fraction of closure density
- Poorly constrained

$10^{-14} \approx \Omega_{gw} < 10^{-5}$
 LISA sees $\Omega_{gw} > 10^{-11}$ Simple Inflation Nucleosynthesis
 (max.) Bound
 Covers 6 out of 9 orders of magnitude!

48



Mock LISA Data Challenge

[MLDC HOME](#)

[LISA Data Analysis](#)

[Challenge Participants](#)

[Round 2](#)

[Round 1](#)

[Community Resources](#)

[Who we are](#)

Mock LISA Data Challenge

In support of the Laser Interferometer Space Antenna (LISA) gravitational wave observatory, we are conducting several rounds of mock data challenges. The LISA Mock Data Challenges were proposed and discussed at meetings organized by the US and European LISA Project that were attended by a broad cross section of the international gravitational-wave community. These challenges are meant to be blind tests, but not really a contest. These serve the dual purposes of fostering the development of LISA data analysis tools and capabilities, and of demonstrating the technical readiness already achieved by the gravitational-wave community in distilling a rich science payoff from the LISA data output.

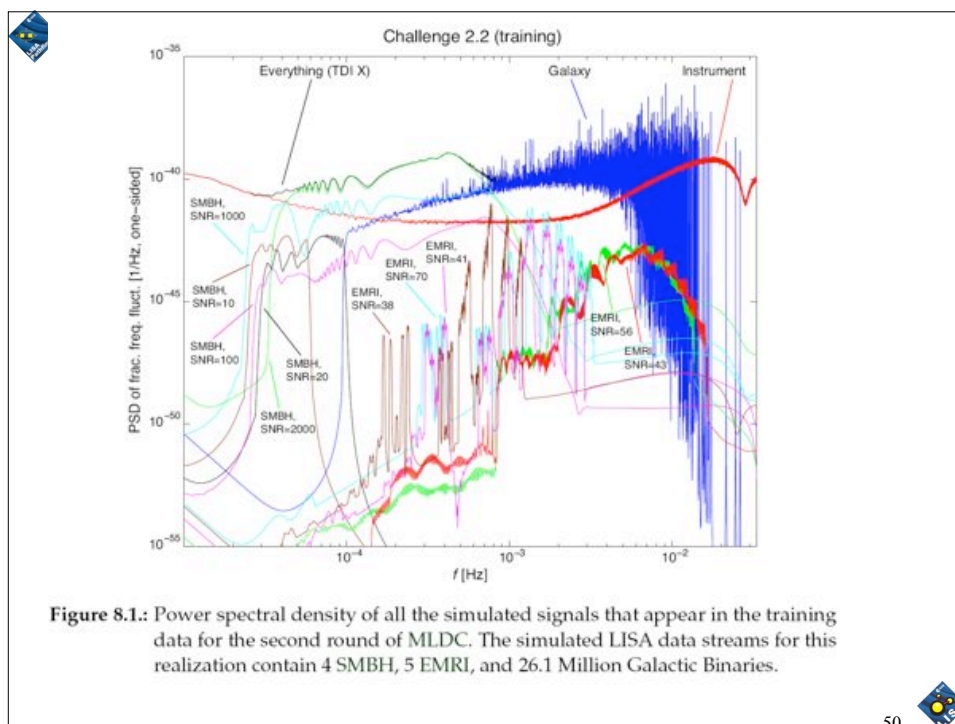
The Mock LISA Data Challenge (MLDC) Taskforce has been working since the beginning of this year to formulate challenge problems of maximum efficacy, to establish criteria for the evaluation of the analyses, to develop standard models of the LISA mission (orbit, noises) and of the LISA sources (waveforms, parameterization), to provide computing tools such as LISA response simulators, source waveform generators, and a Mock Data Challenge file format, and more generally to provide any technical support necessary to the challengers, including moderated discussion forums and a software repository.

WHAT'S NEW:

- **Round 2 revised.** The blind challenge data sets were revised. (Mar 2, 2007).
- **EMRIs rereleased.** New Ch 1.3 data sets now available (Mar 2, 2007).
- **Round 2 released.** Round 2 data sets are now available. (Jan 31, 2007).
- **Round 1 Analysis Submitted.** Round 1 Analysis submitted for GWDW11 Proceedings. (Jan 25, 2007).
- **Round 1 Results.** Preliminary Round 1 results presented at

<http://astrogravs.nasa.gov/docs/mldc/>



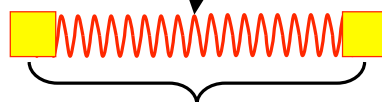


Is LISA feasible?



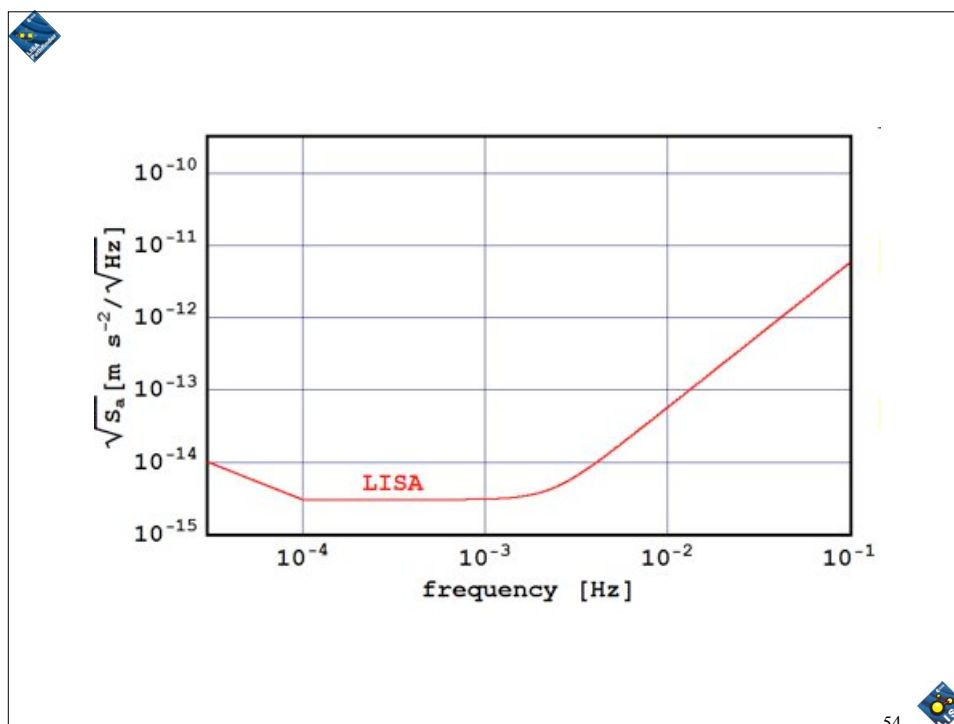
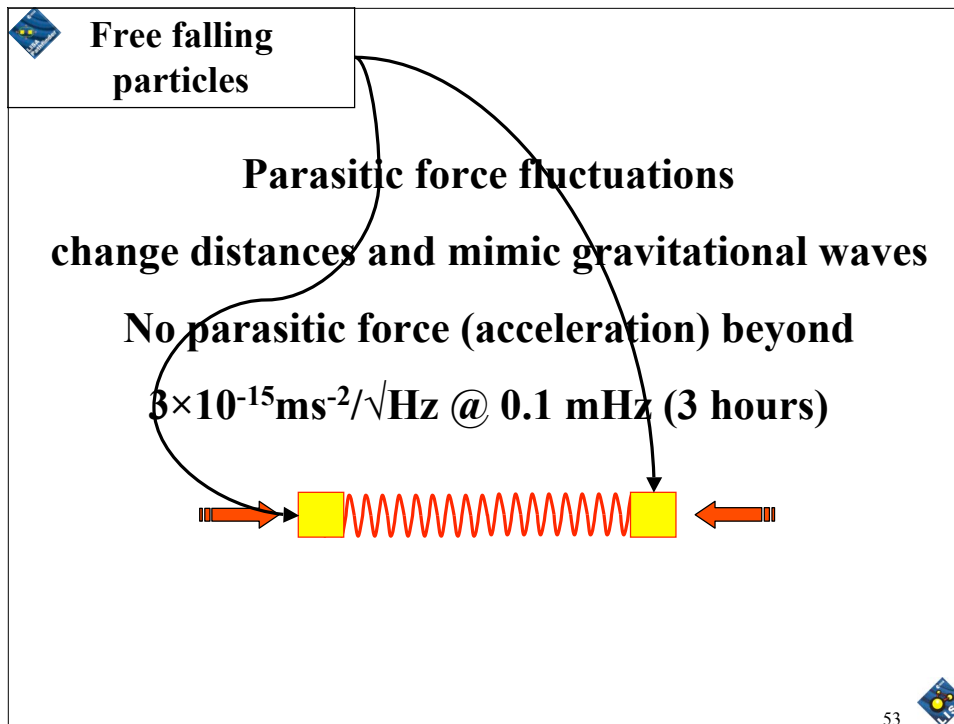
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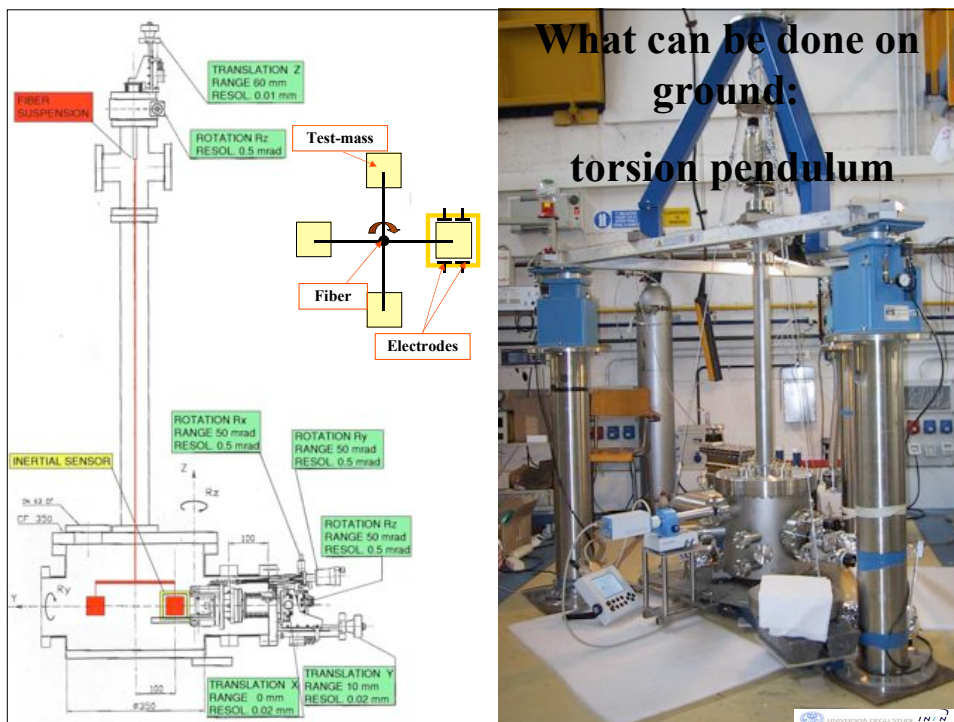
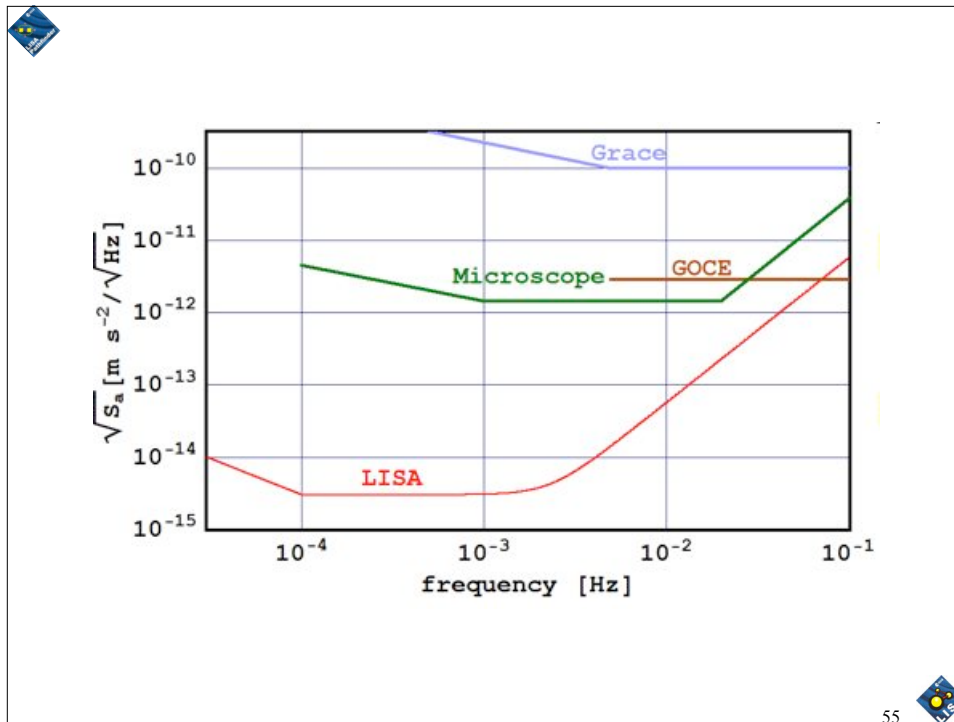
Interferometer
(40 pm Hz^{-1/2} @ 3 mHz)

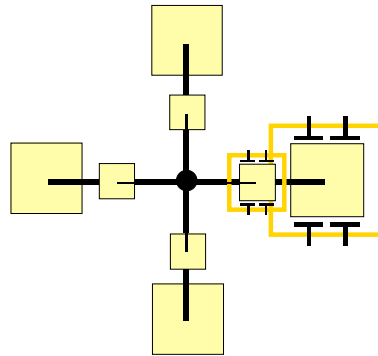


5×10^6 km

52

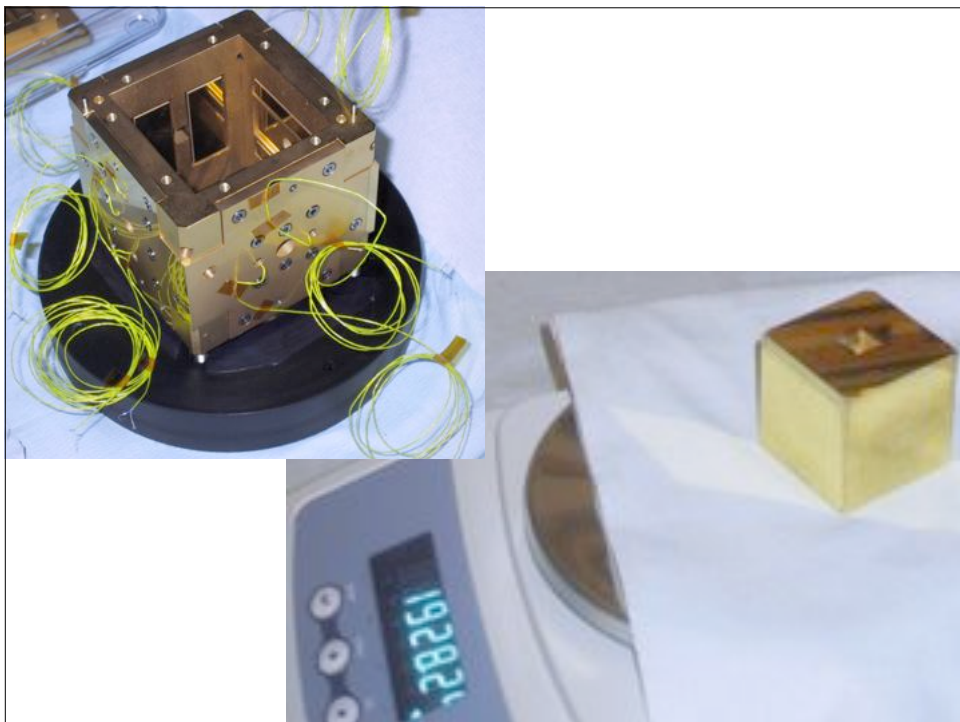


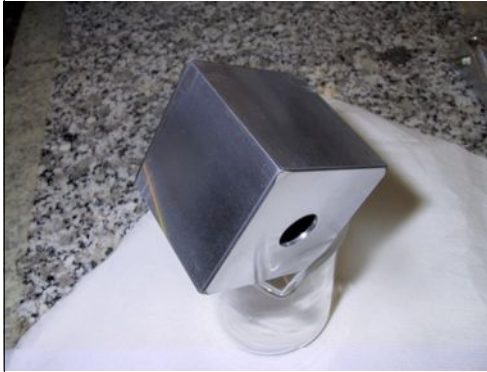




Achieving free motion in the horizontal plane (0 g)

57

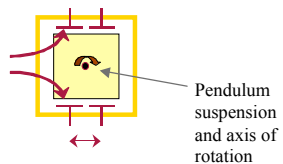




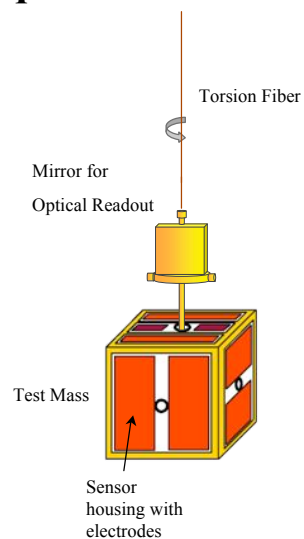
**Hollow proof-mass
for torsion
pendulum testing**



The single mass configuration: surface forces generate torques

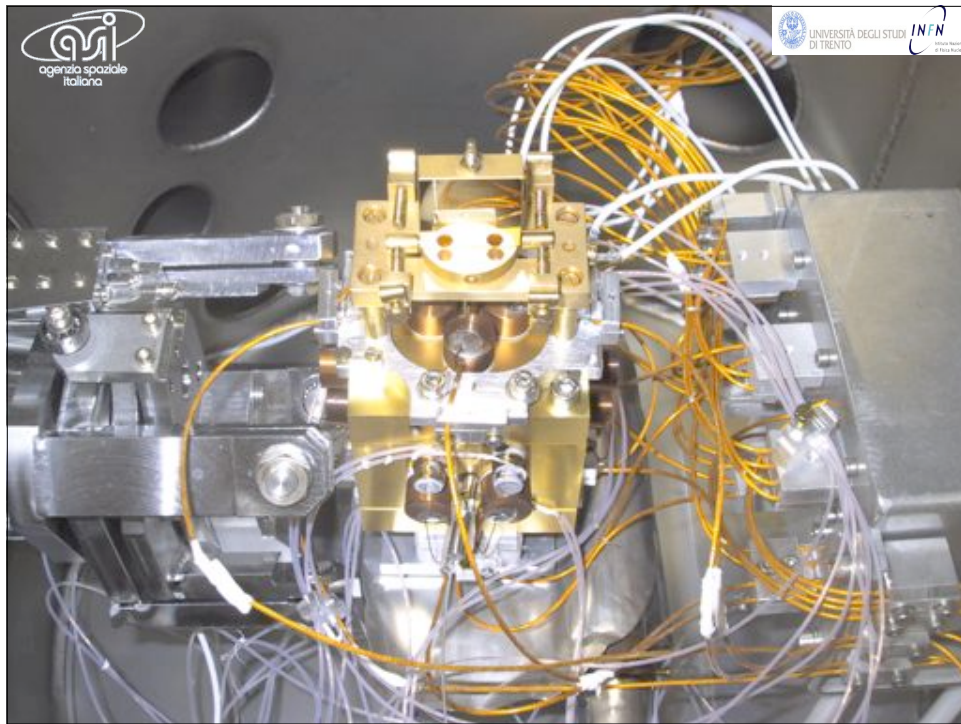


Pendulum
suspension
and axis of
rotation

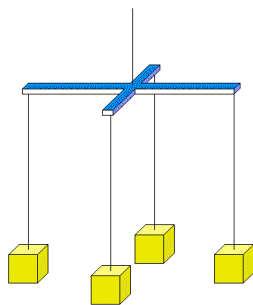


60





Two-degrees of freedom roto-translational pendulum

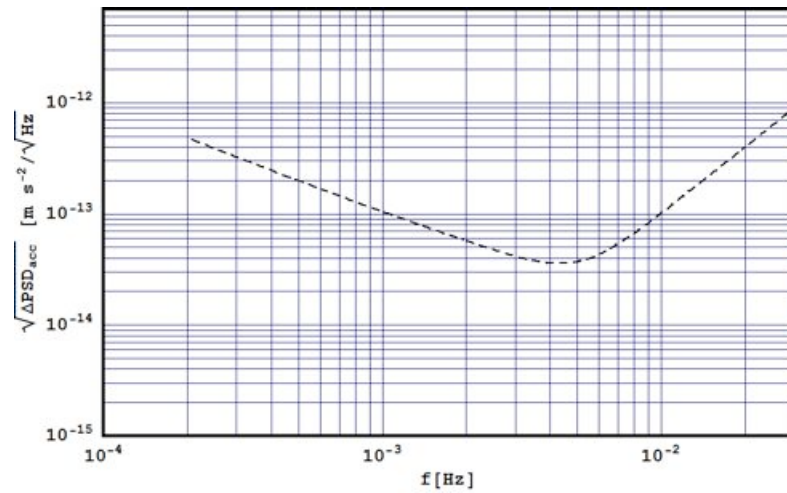


62





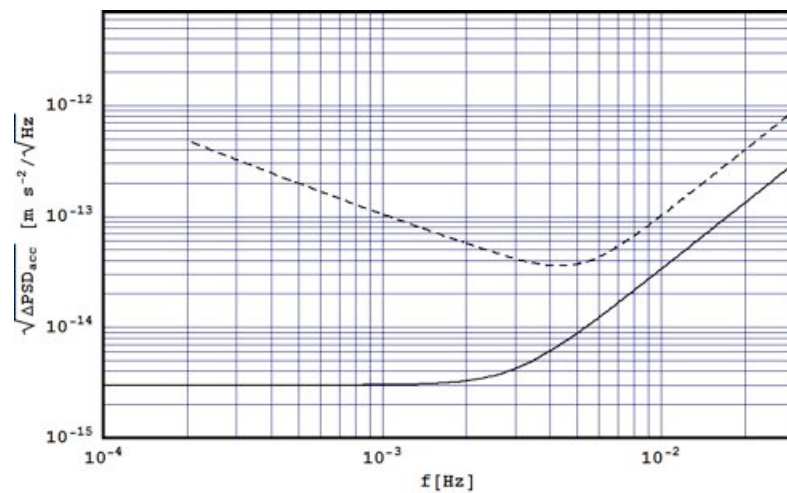
Pendulum data converted into acceleration



63

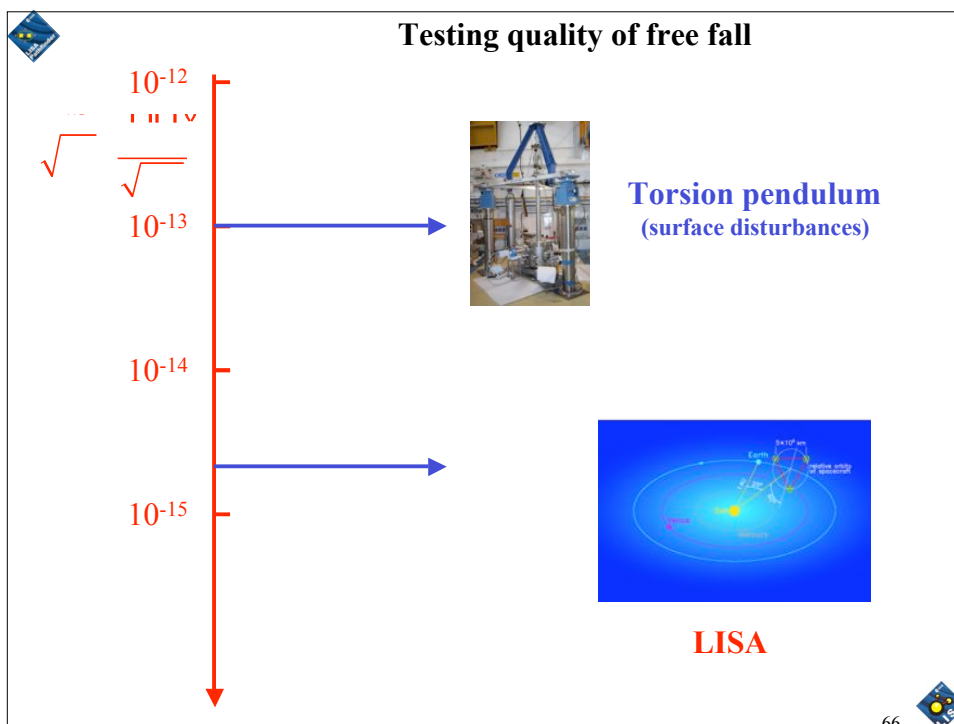
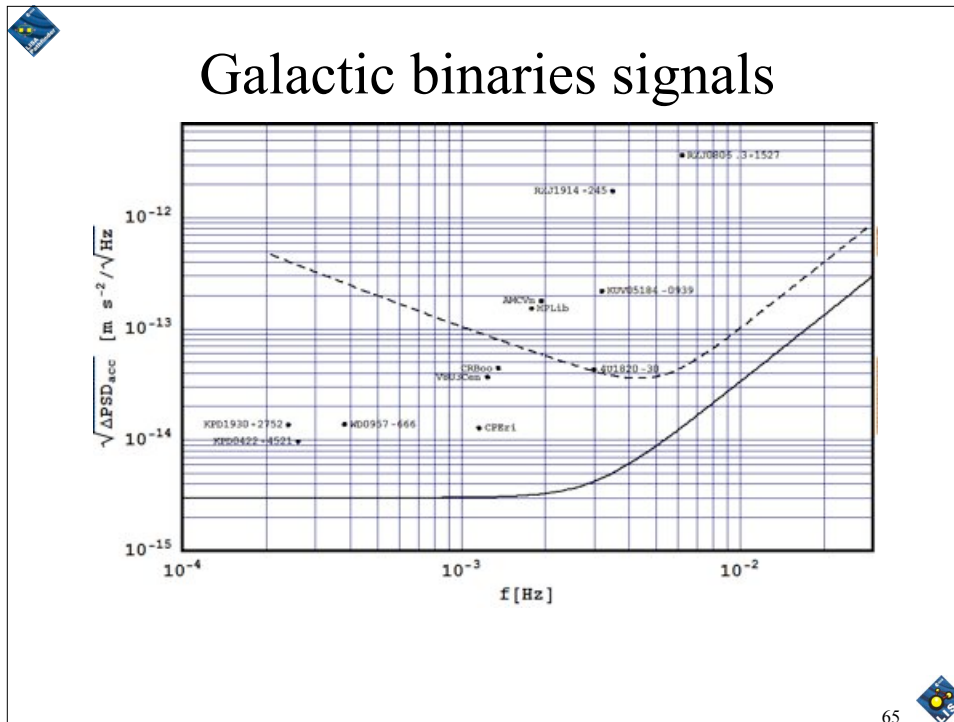


LISA requirements



64

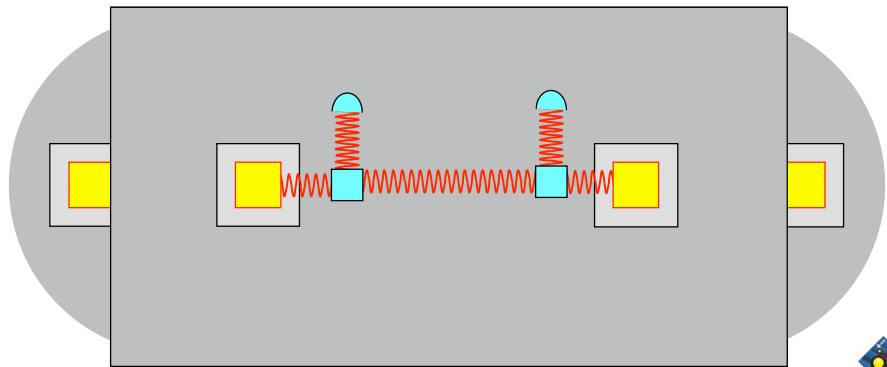






LISA Pathfinder

- One 5-million-kilometer LISA arm squeezed into one S/C
- Demonstrate relative acceleration within a factor ≈ 10

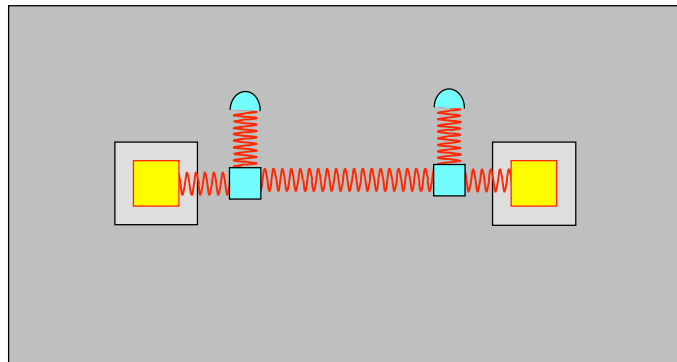


67



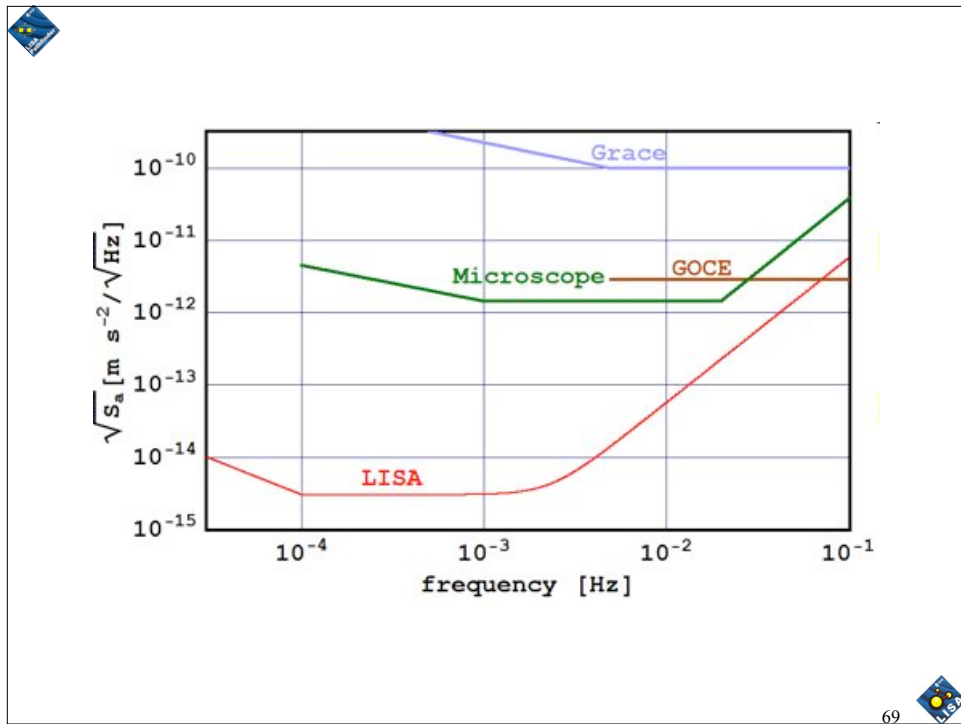
LISA Pathfinder

- One 5-million-kilometer LISA arm squeezed into one S/C
- + validation of the entire S/C to proof-mass measurement

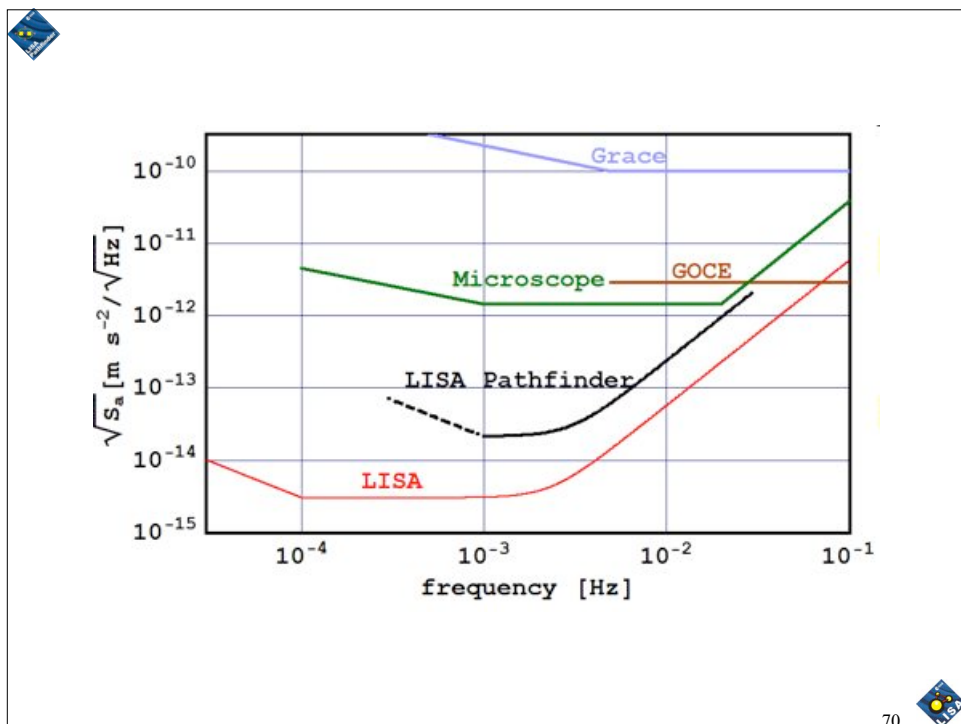


68

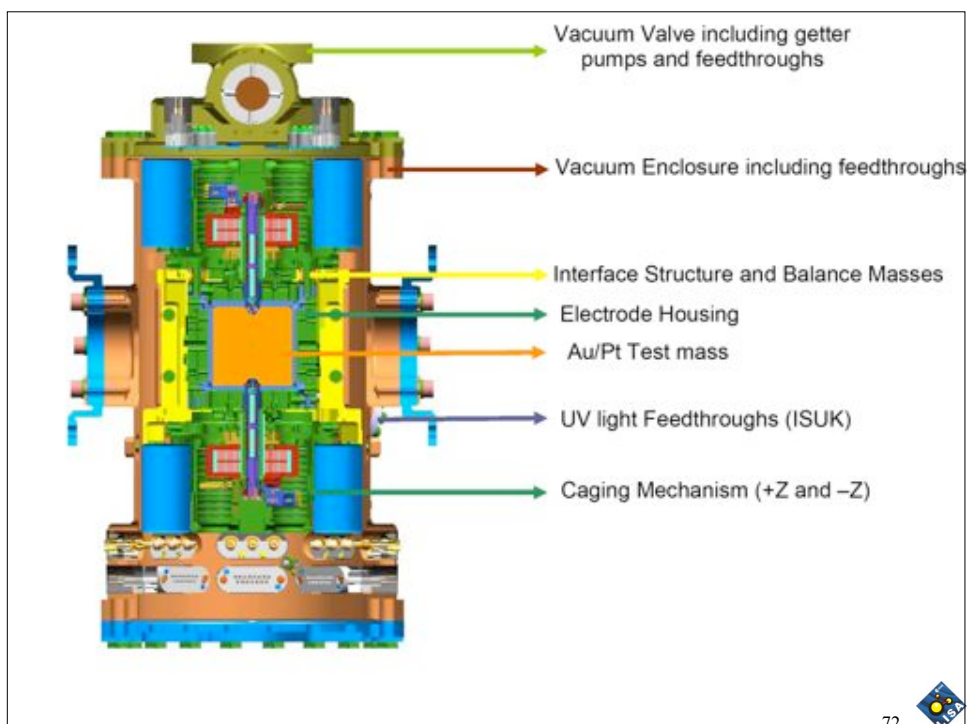
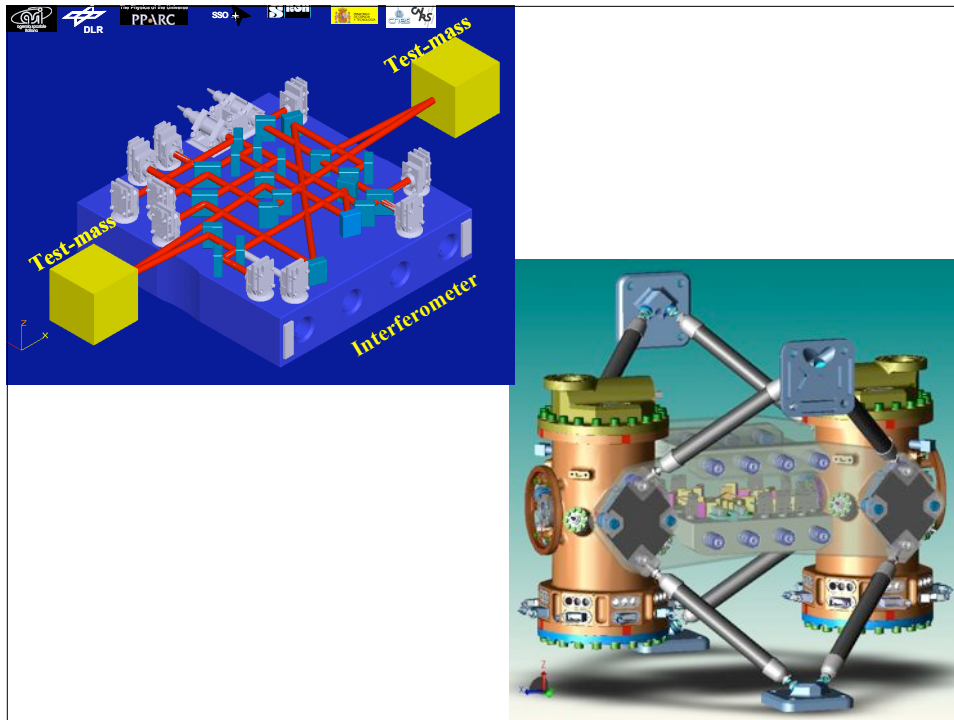


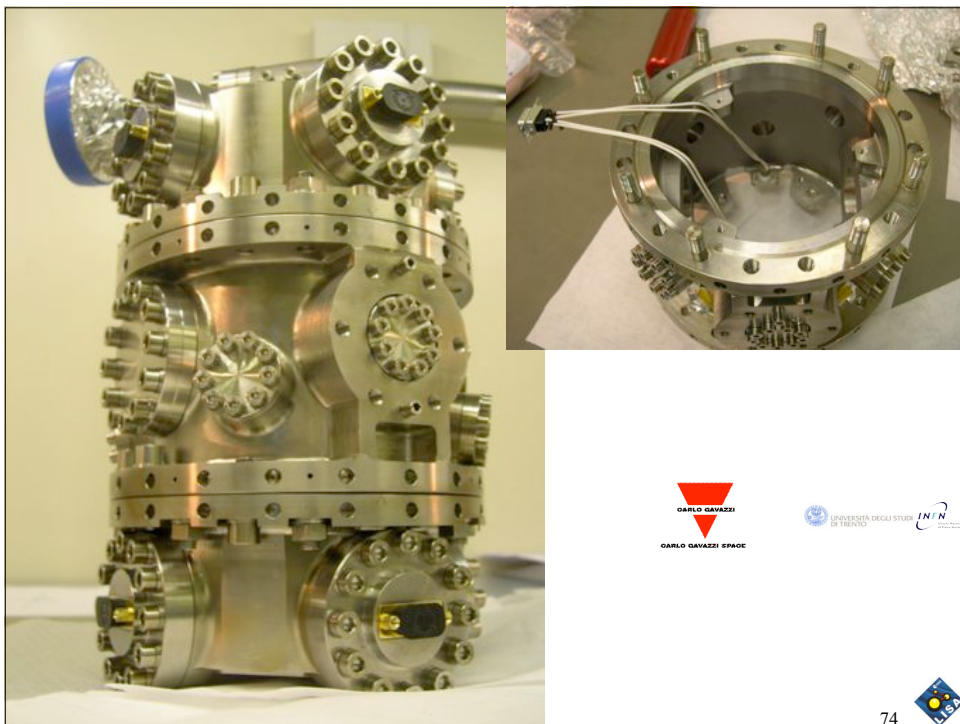
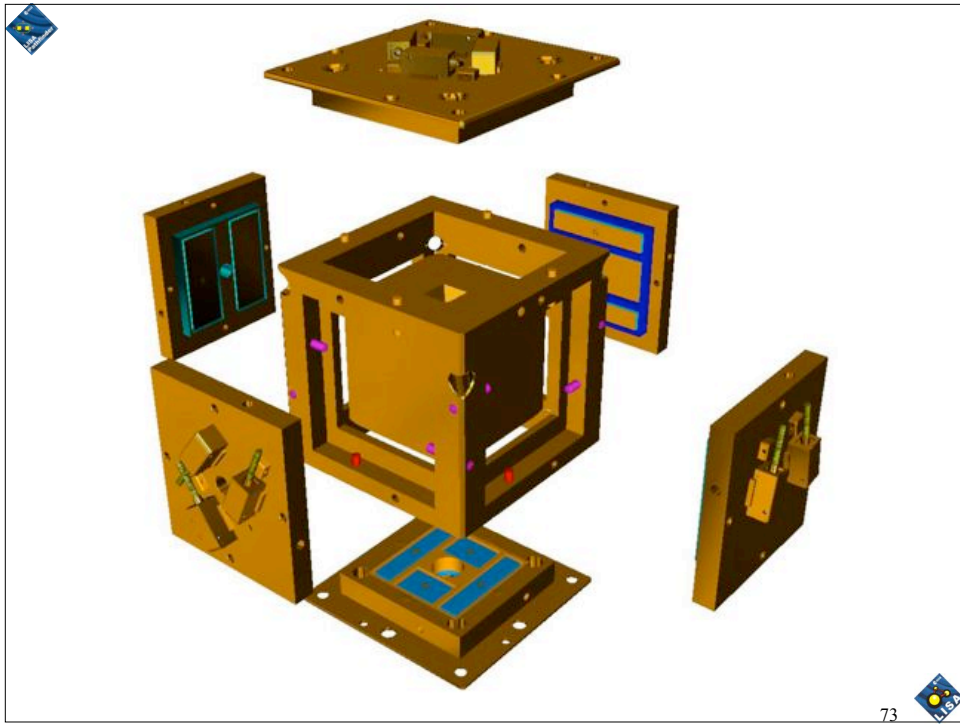


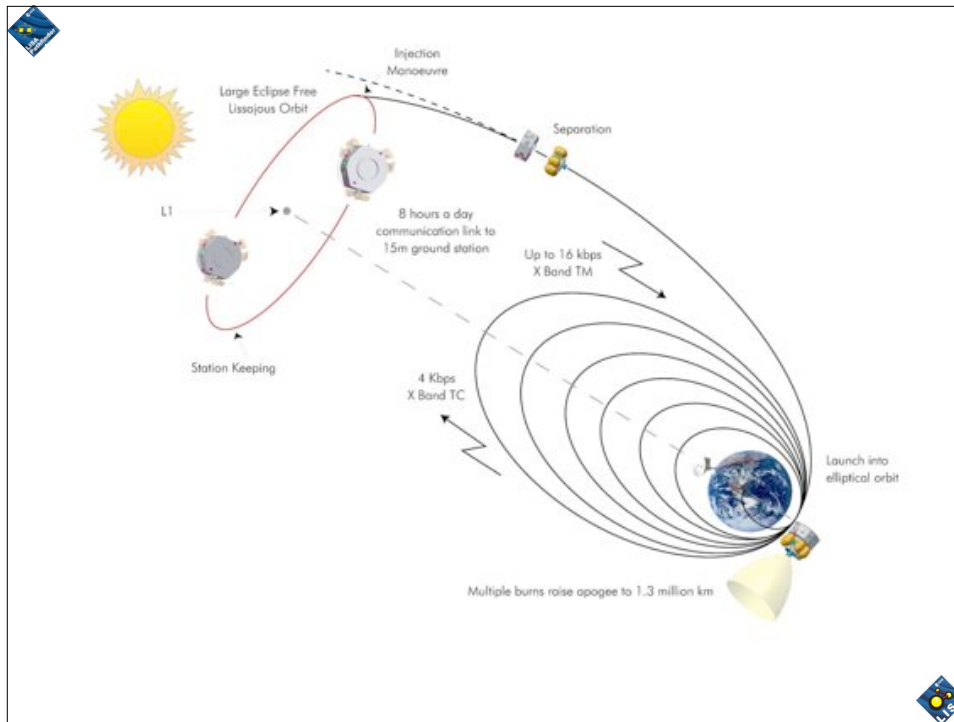
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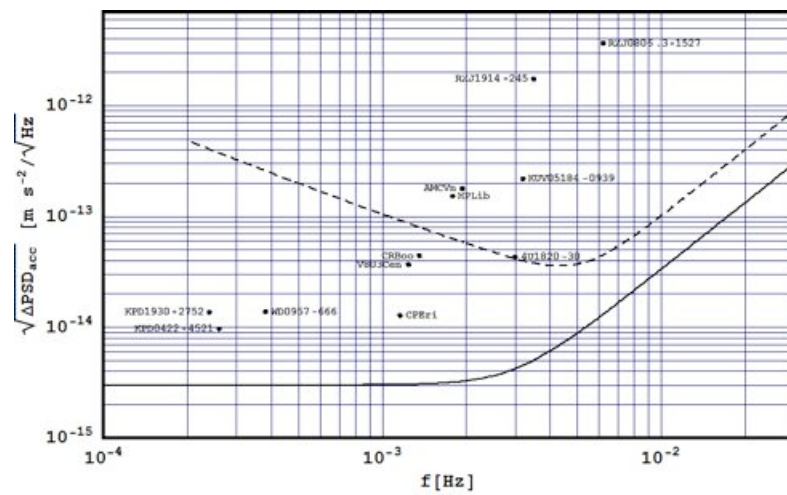
70





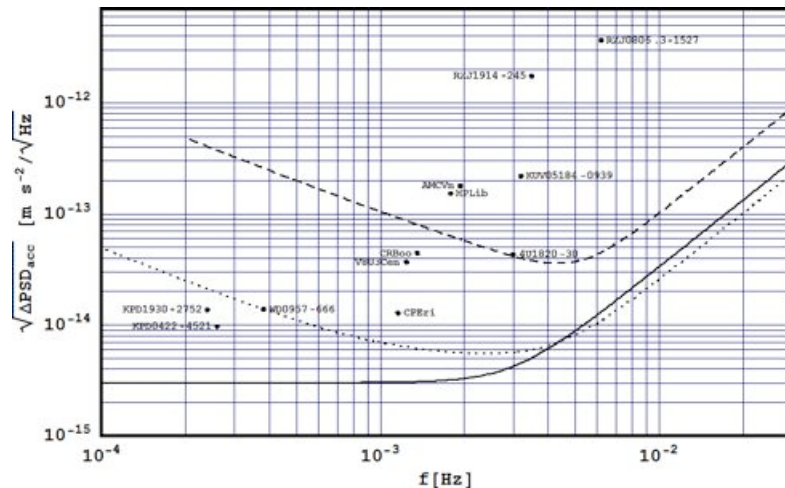


Pendulum: surface forces





LISA Pathfinder a full test



77



Science Objectives

6.5 Mission goal: the physical model

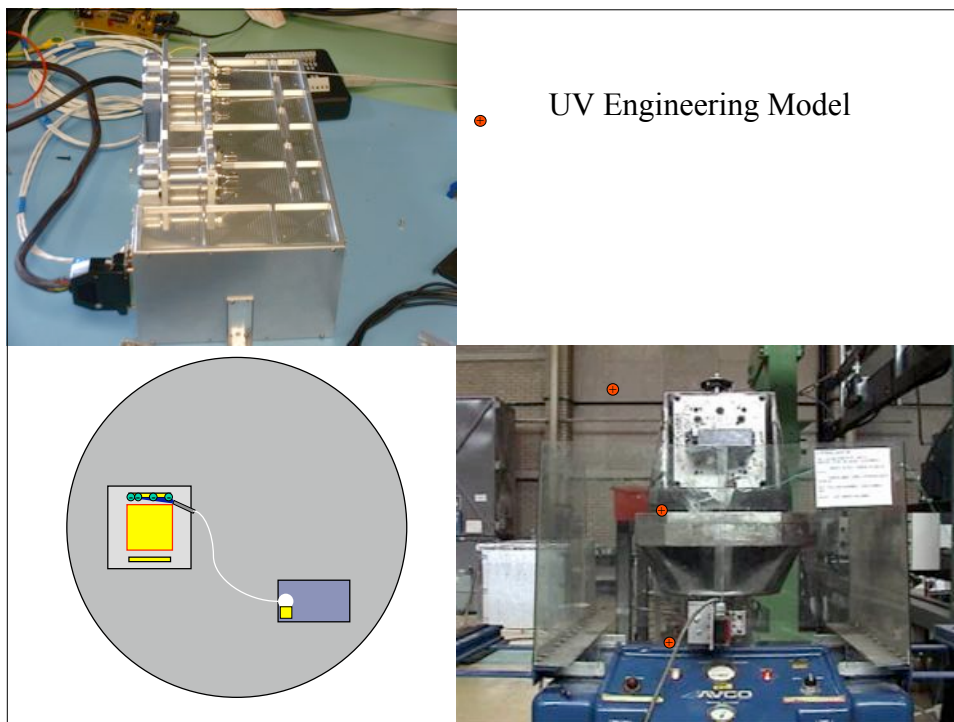
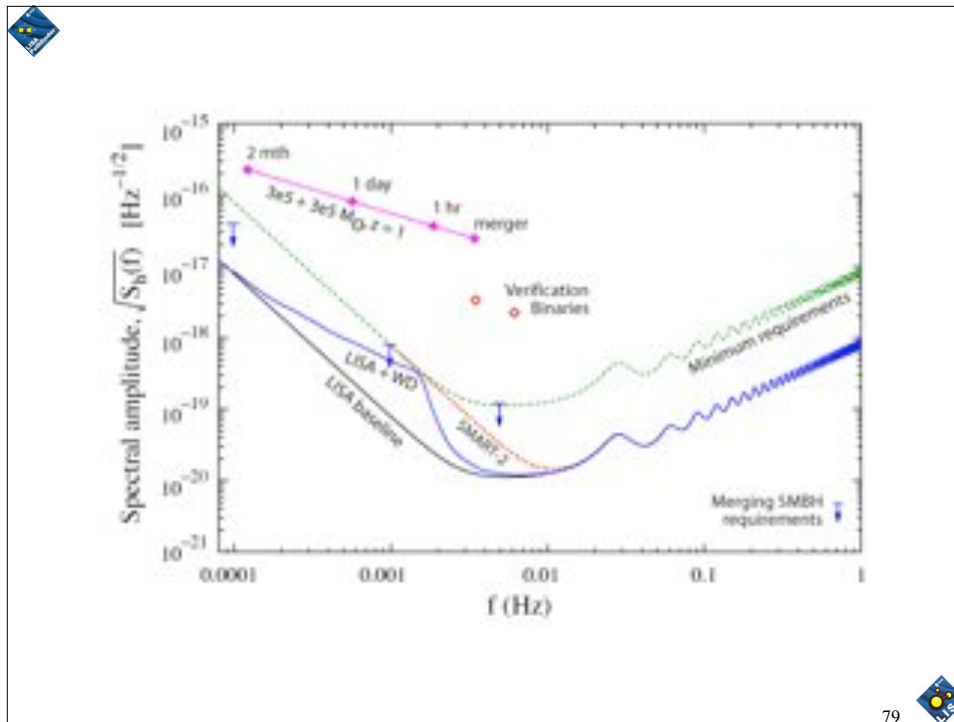
The final objective of LISA Pathfinder is to confirm the overall physical model of the forces that act on a test-mass in interplanetary space. To fulfil this program, the mission is not going to just make a measurement of acceleration but will implement a full menu of measurements:

- Measurement of acceleration noise between 0.0001 and 1 Hz.
- Measurement of dc-forces
- Measurement of force gradients
- Calibration of control loop transfer functions
- Characterization of thrust and thrust noise of micro-thrusters
- Measurement of interferometer performance and interferometer cross-talk
- Measurement of all cross-talk coefficients among different degrees of freedom
- Test of continuous charge measurement
- Test of continuous discharging and of discharging induced noise
- Test of magnetic induced noise
- Test of thermally induced acceleration noise
- Characterization of charging environment.

At the end of this set of measurements, the noise model will be verified down to painstaking detail.

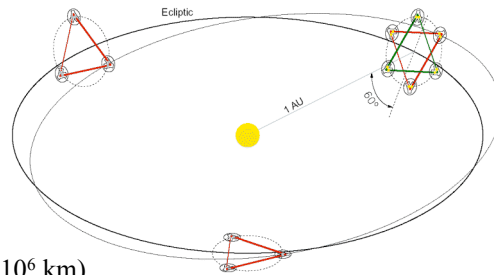
78







The Big Bang Observer



- Shorter arms ($5 \cdot 10^4$ km, not $5 \cdot 10^6$ km)
- More light (300 W, not 1 W)
- Bigger telescopes (3 m, not 30 cm)
- Better force isolation ($.03 \text{ fm/s}^2/\text{Hz}^{1/2}$, not $3 \text{ fm/s}^2/\text{Hz}^{1/2}$)
- Multiple constellations for noise discrimination

→ Need to subtract off signals from ALL NS-NS, BH-BH mergers in universe in order to see background of gravitational radiation from big bang Wow!

→ year 2025 (???)

81

