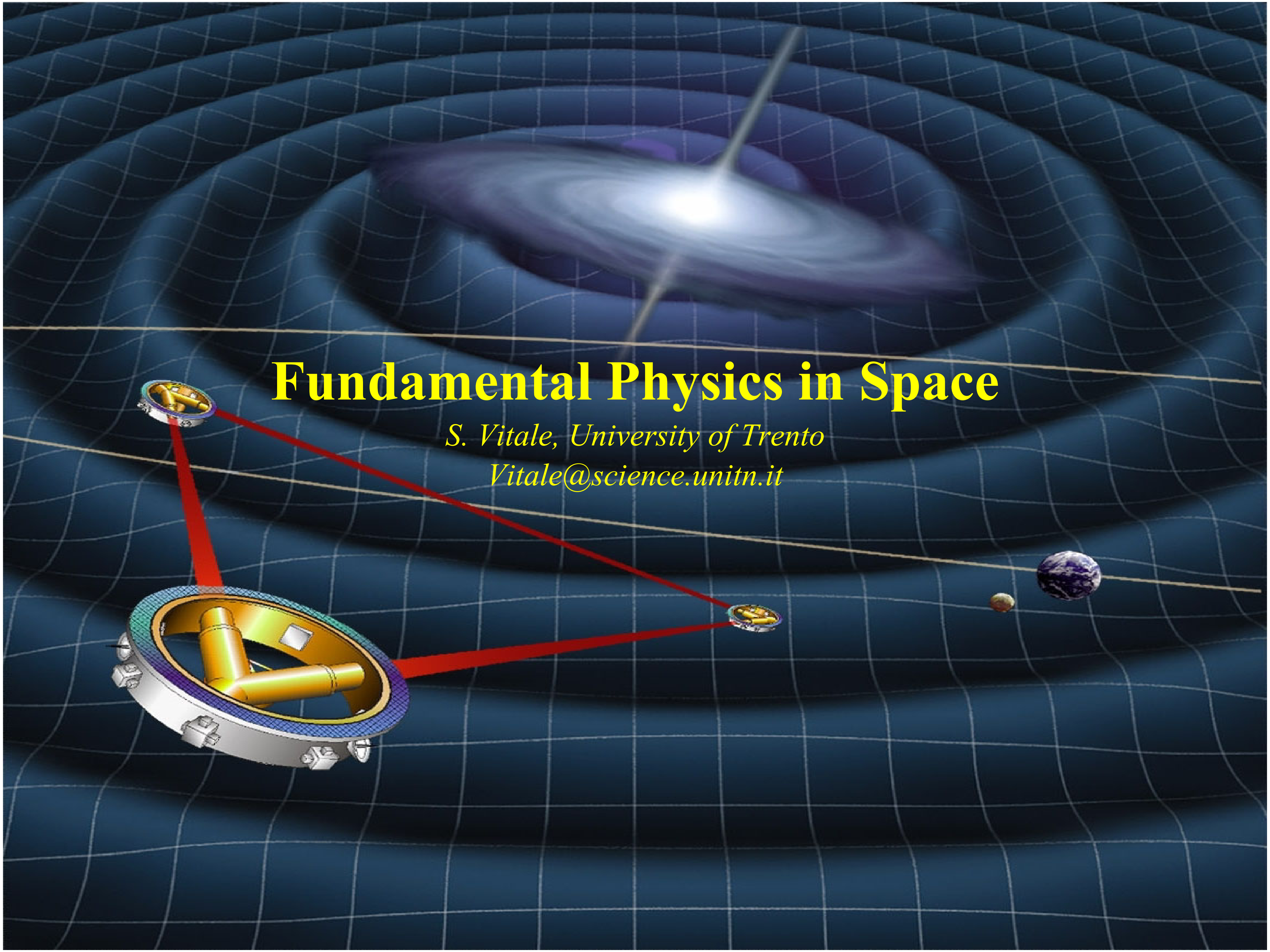


Fundamental Physics in Space

S. Vitale, University of Trento
Vitale@science.unitn.it

Using Space to Investigate Fundamental Laws of Physics:

Quantum measurements, entanglement, de-coherence

Standard (and beyond) Model of Particles and Universe

Classical tests of General Relativity

Quantum–gravity

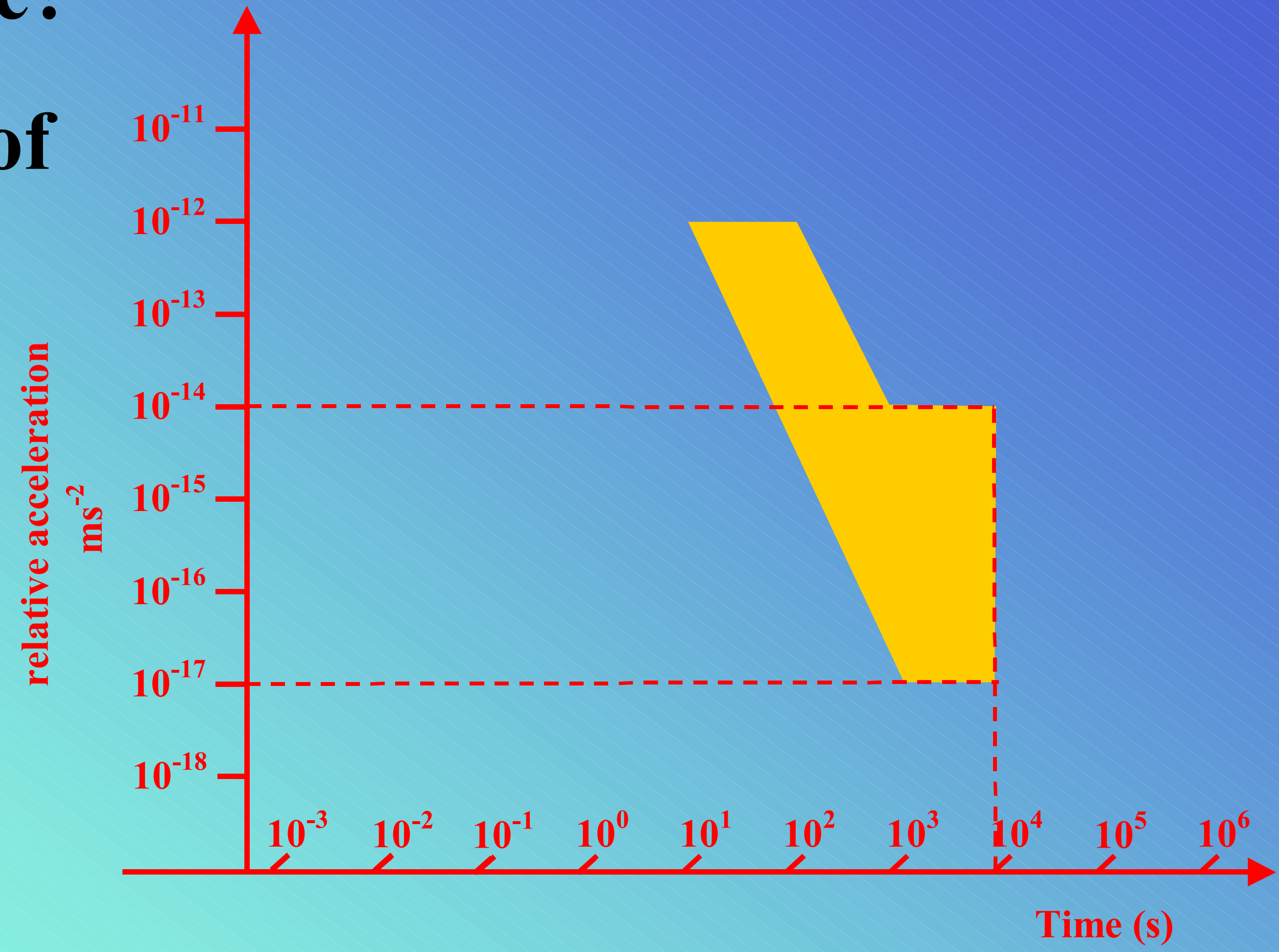
Gravitational Waves, extreme gravitational field and event horizon physics

……..

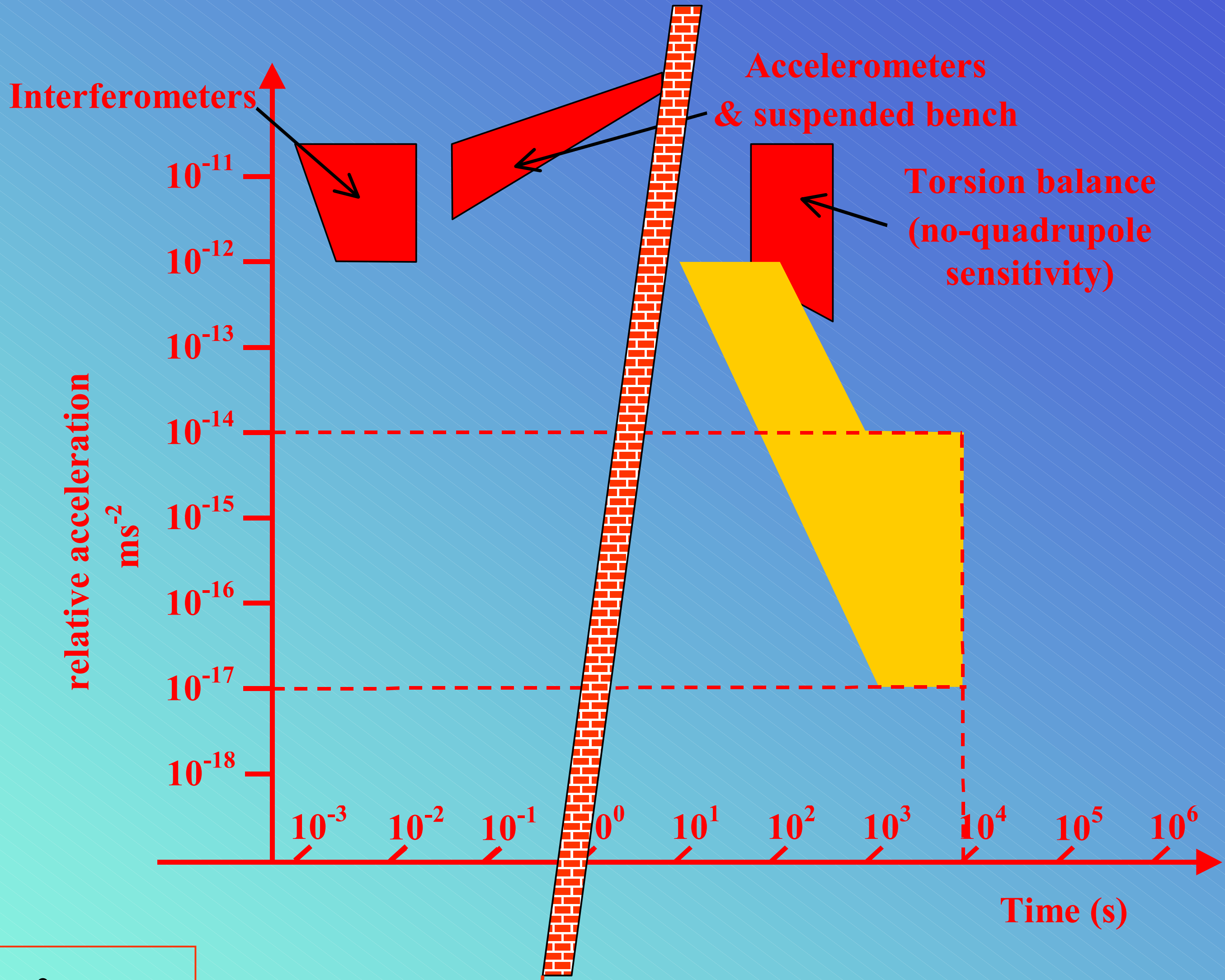
LISA/LISA PF	Gravitational Waves Observatory and the Physics of Black-Holes and Extreme Gravitational Fields
Microscope/GPB (STEP)	High Precision Equivalence Principle Test and the Search for New Long Range Interactions. Tests of General Relativity
HYPER/ACES	Cold-Atoms, Matter-Wave Interferometry and the Next Generation Gravitational Sensors
AMS/EUSO	Anti-matter/Extreme energy cosmic rays

Why Space?

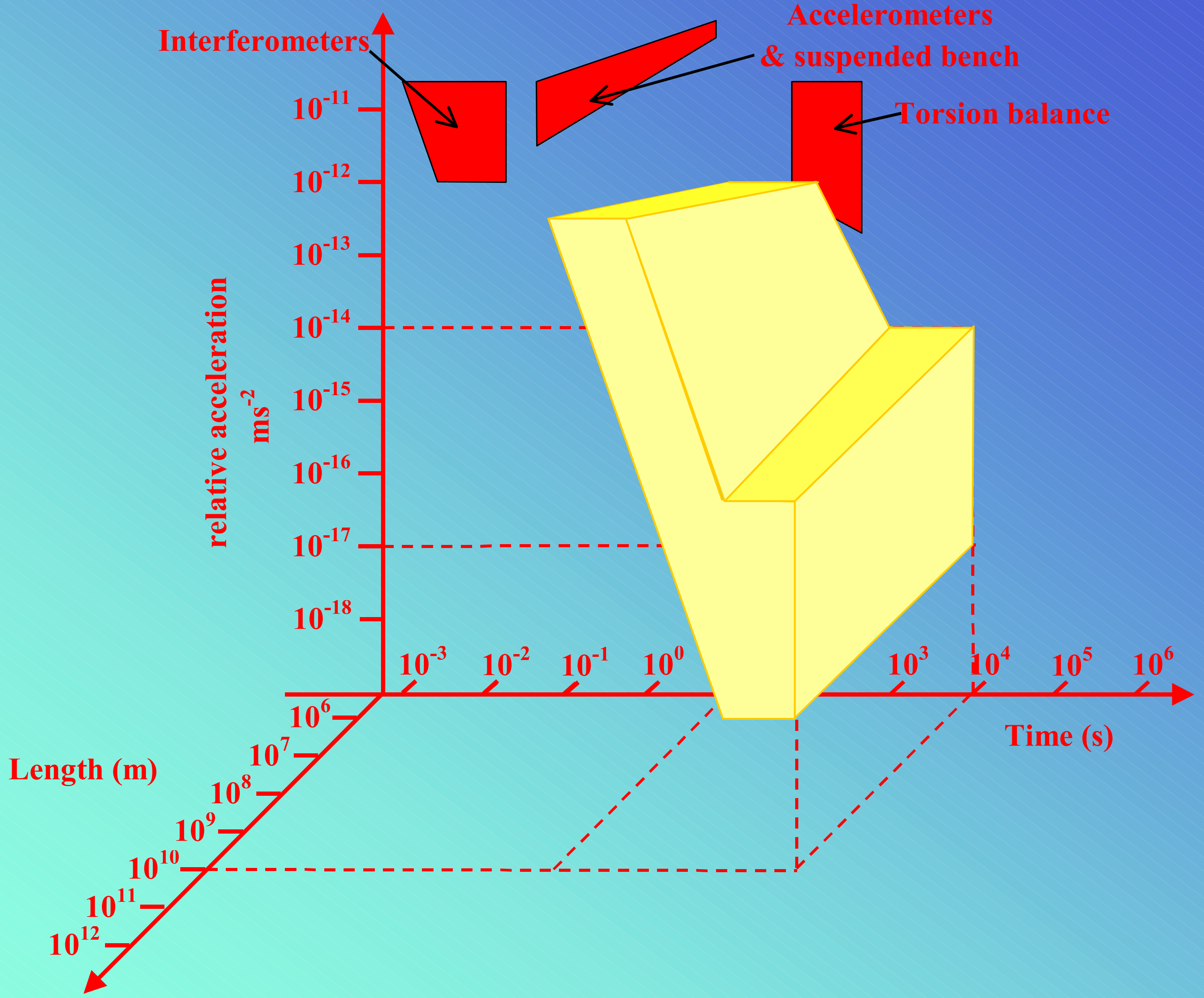
"Purity" of free-fall



Ground

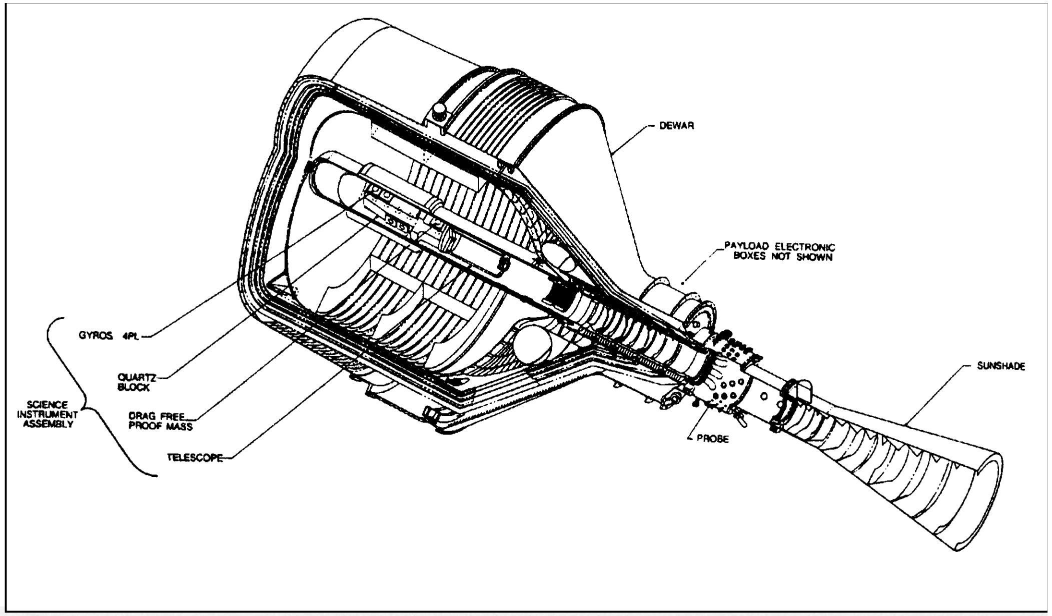


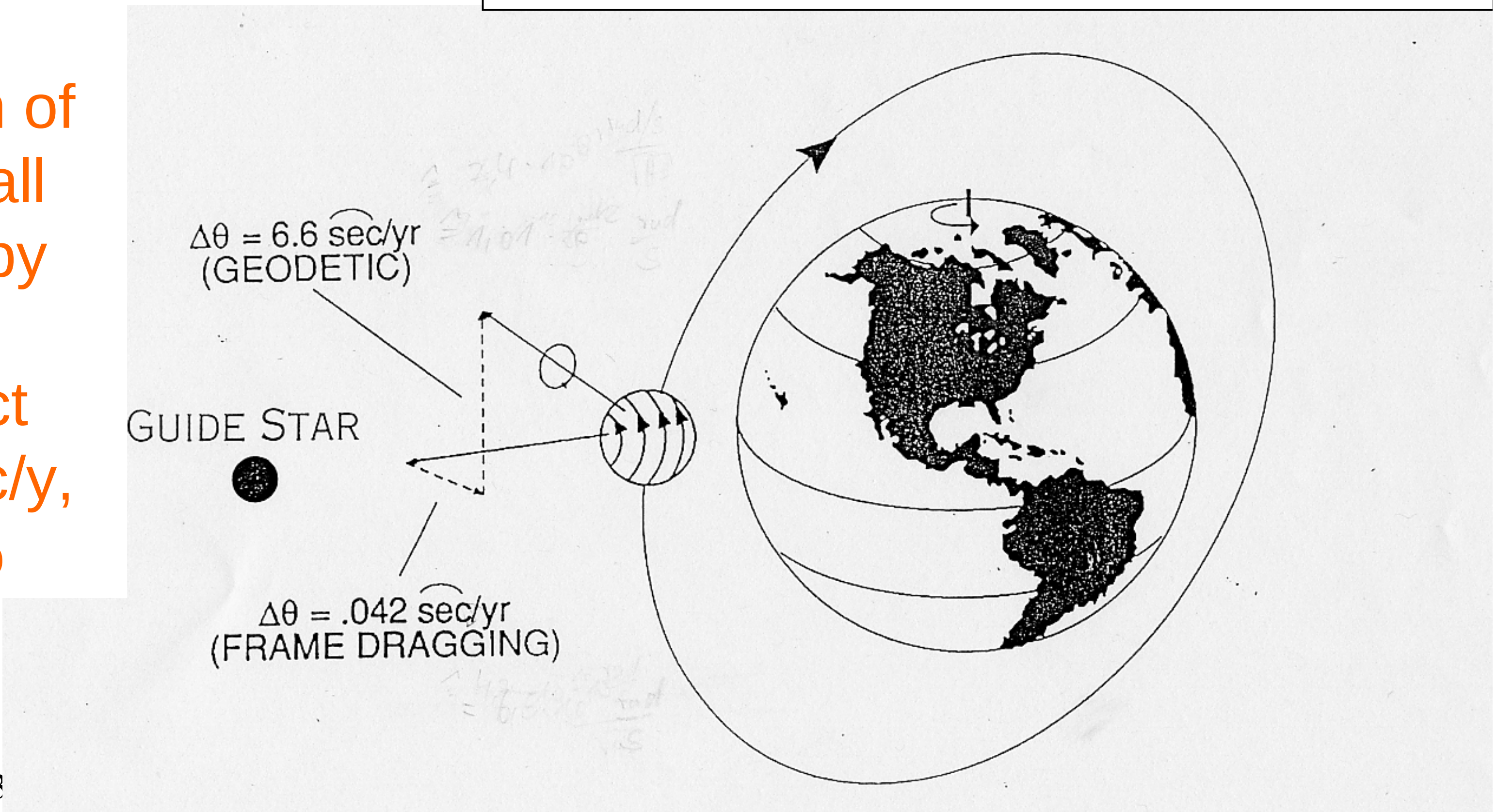
Newtonian quadrupole noise


Interferometers
Accelerometers
& suspended bench
Torsion balance
relative acceleration
ms-2
10-11
10-12
10-13
10-14
10-15
10-16
10-17
10-18
10-3
10-2
10-1
100
103
104
105
106
Time (s)
Length (m)
106
107
108
109
1010
1011
1012

« Gravity Probe B »

- Proposal by L.I. Schiff (Stanford University) & G.E. Pugh 1959/60
- Precession of a spinning ball modified by the Lense-Thirring effect 42 marcsec/y, precision 1%

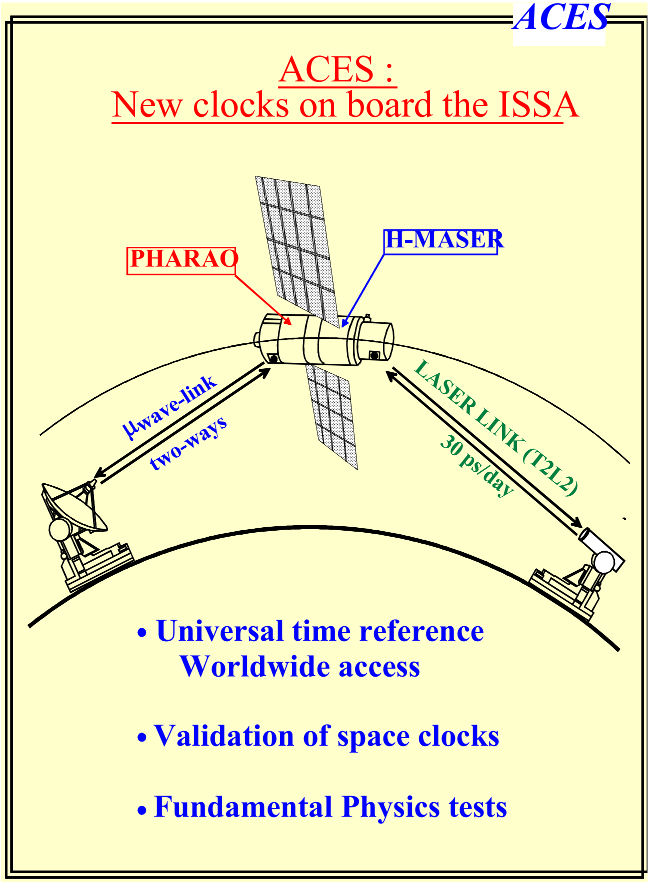




quantum physics in space:

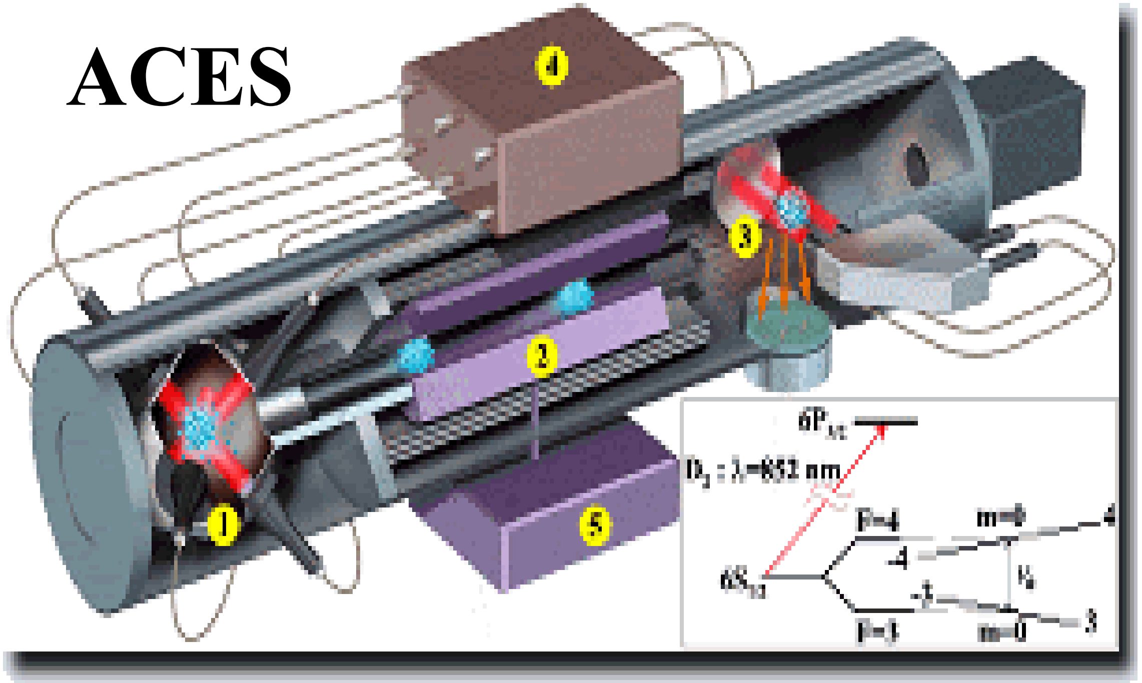
exploiting the ultimate laboratory

$$\dot{\alpha} \approx 10^{-16} y^{-1}; \left(\frac{\Delta\nu}{\nu}\right)_g \approx 10^{-6}; \frac{\Delta c}{\Delta\theta} \approx 10^{-11}$$



Time of flight only possible in 0 g

ACES



CNES/ESA

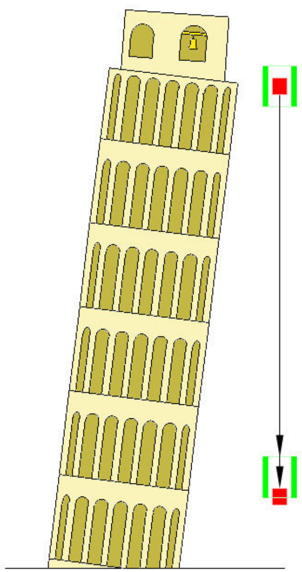
MICROSCOPE

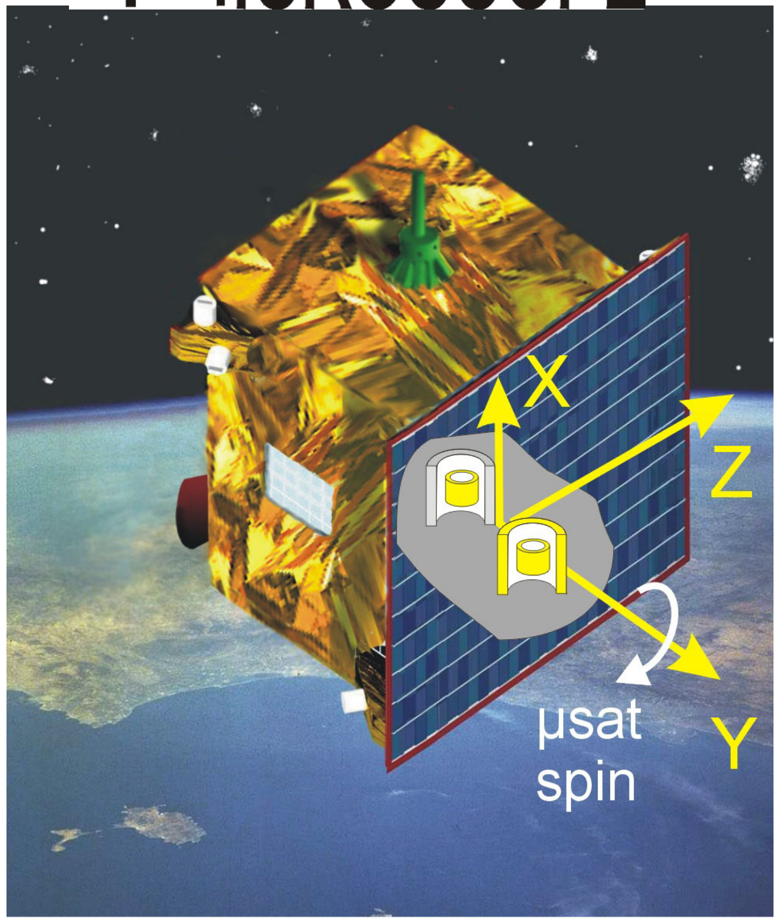
- 2 Differential accelerometers :

  EP test at 10^{-15} or better

  Search for long range forces

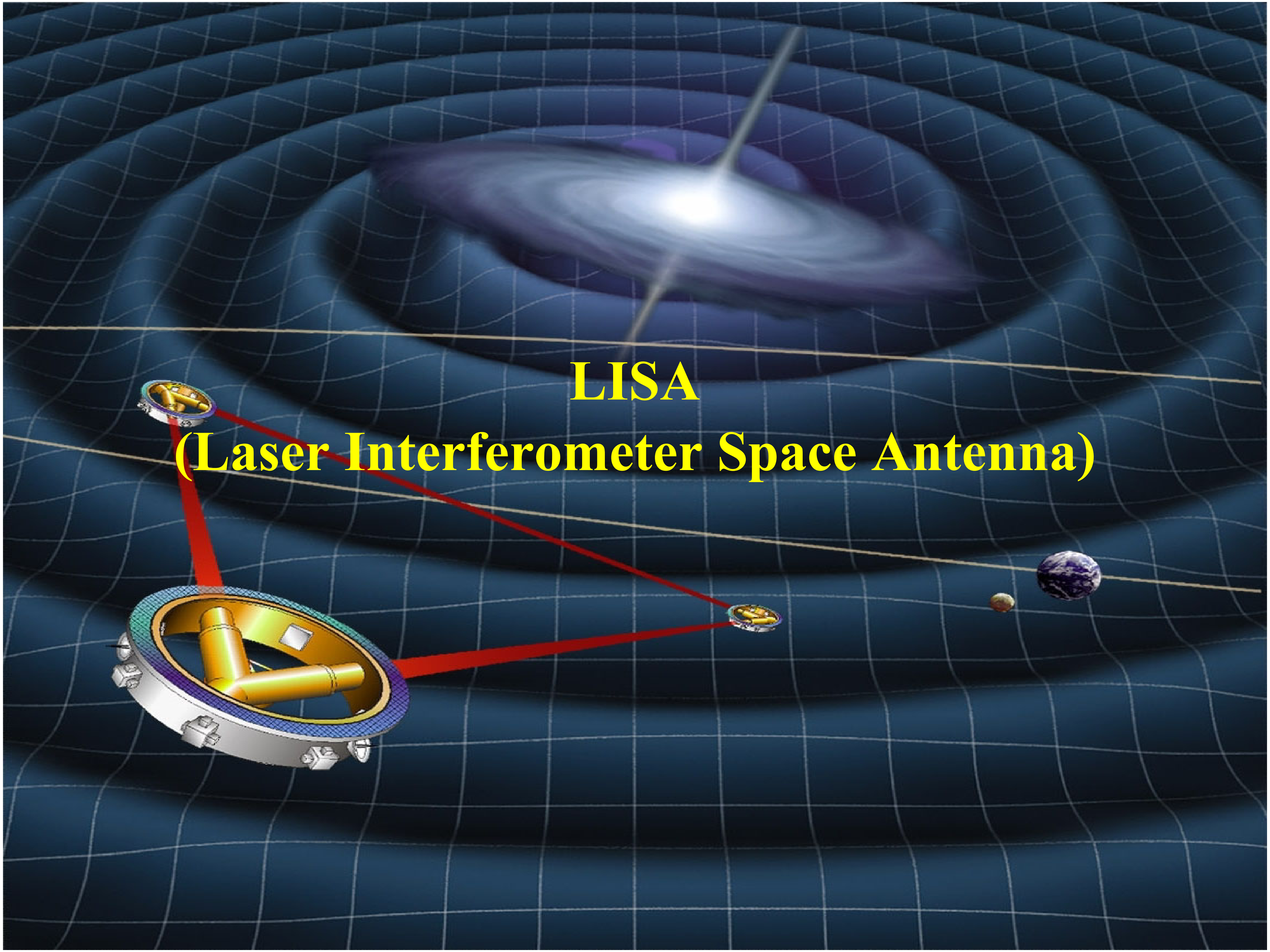
  Predicetd by quantum gravity



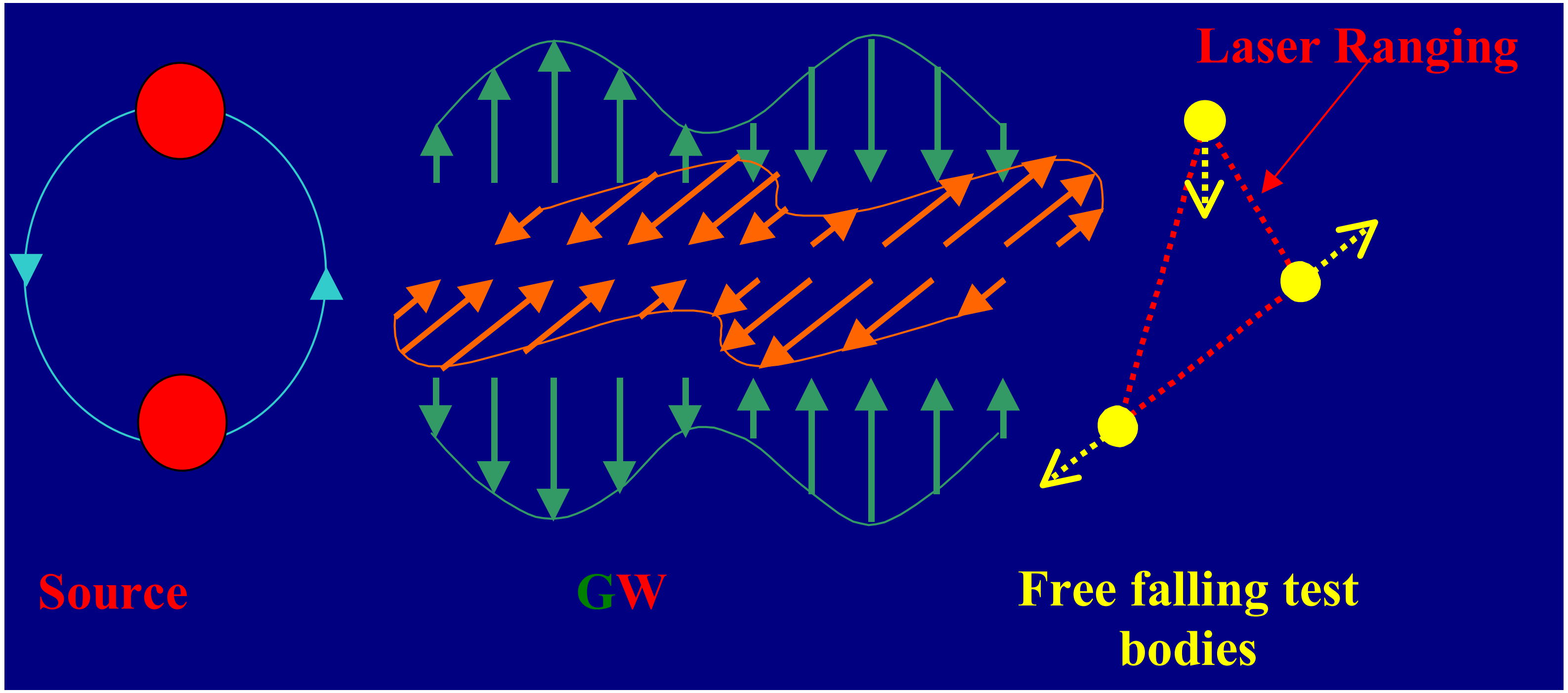


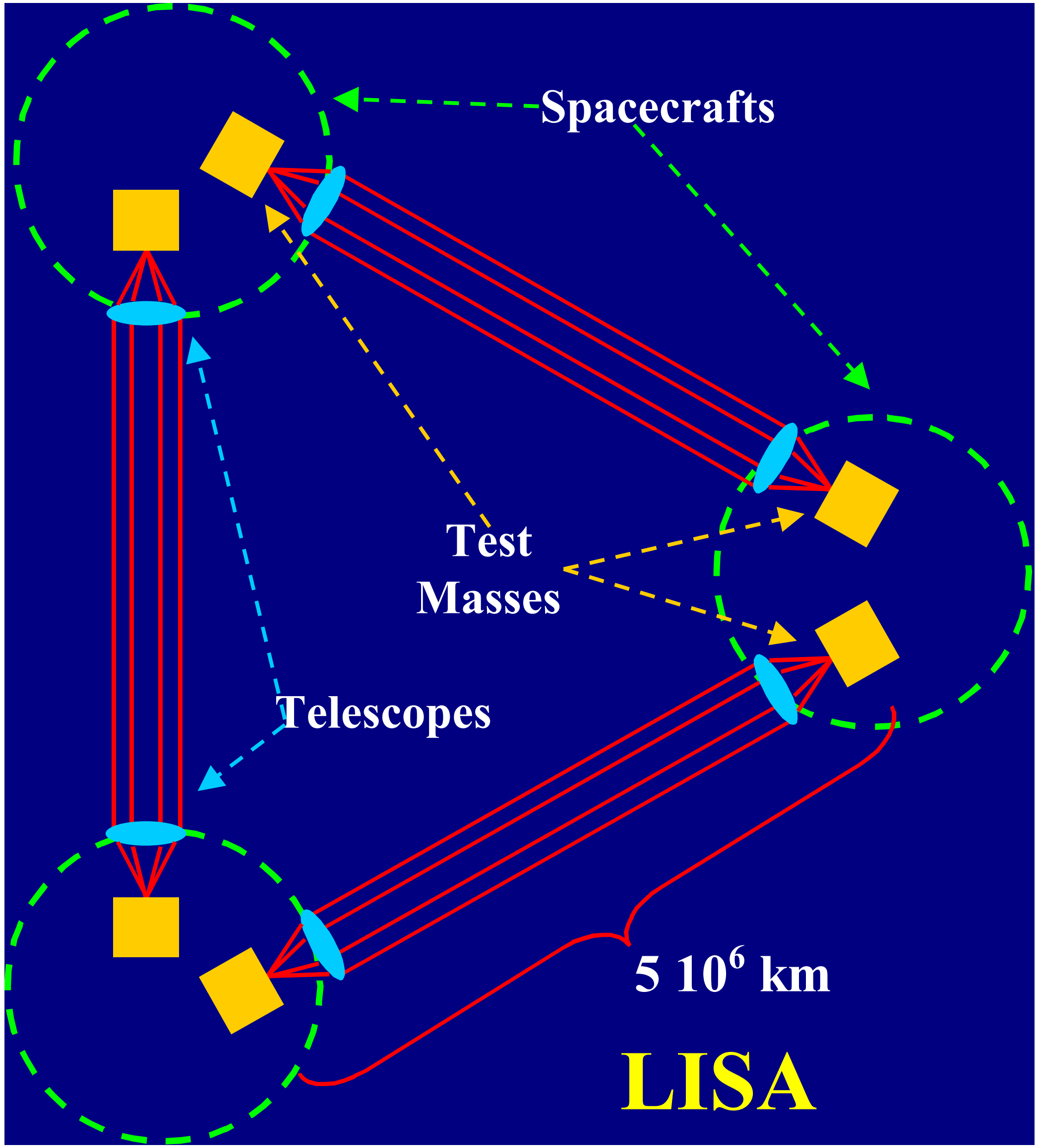
DMPH

ONERA


LISA
(Laser Interferometer Space Antenna)

LISA basics





3 pairs of "free falling" test masses
(3 10^{-15} ms^{-2} $Hz^{-1/2}$ @ 0.1 mHz)

3 "test-mass follower" shielding spacecraft

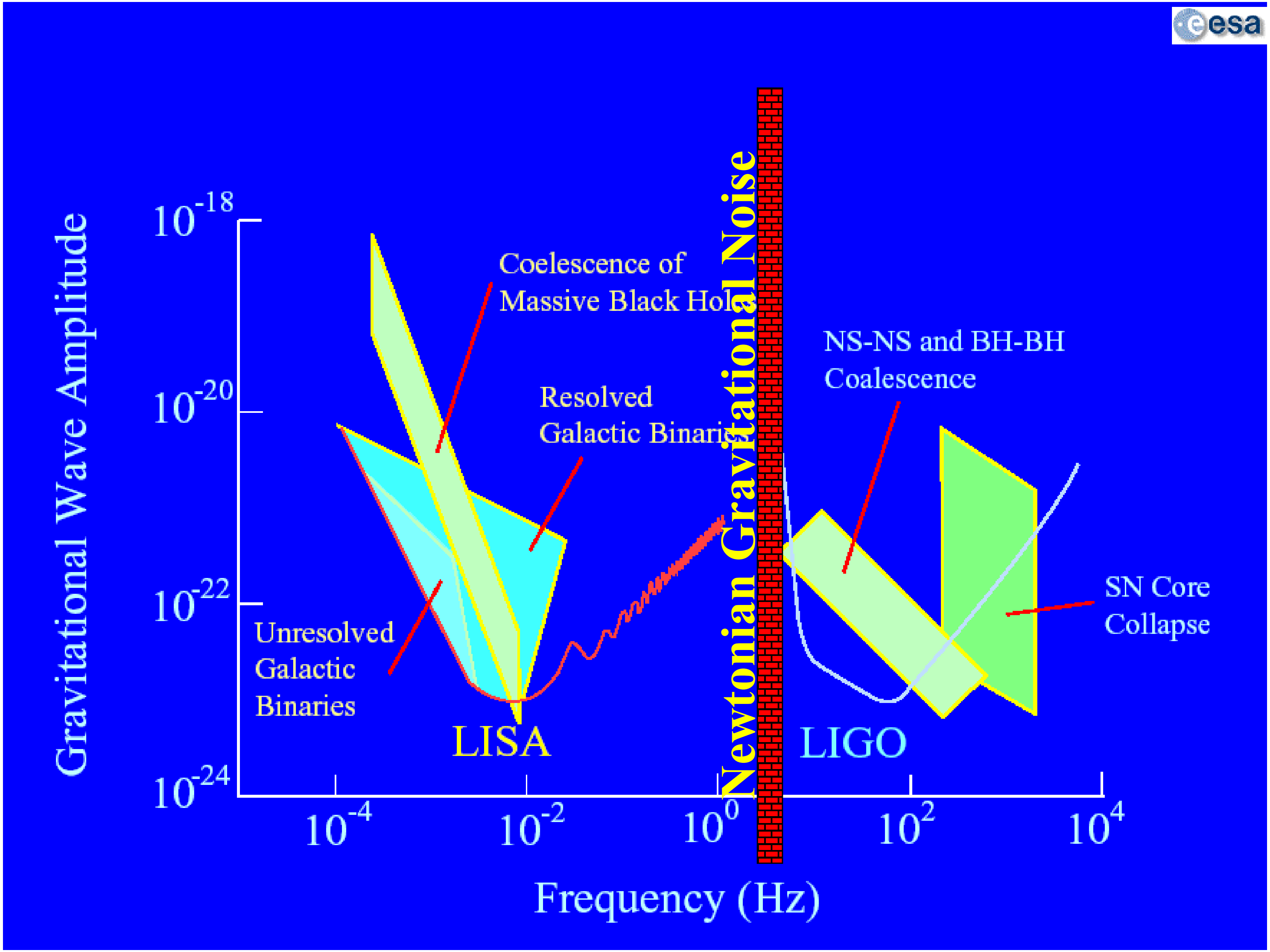
2 semi-independent 5 10^6 km Michelson Interferometers with Laser Transponders

(40 pm $Hz^{-1/2}$)

Goal: GW at

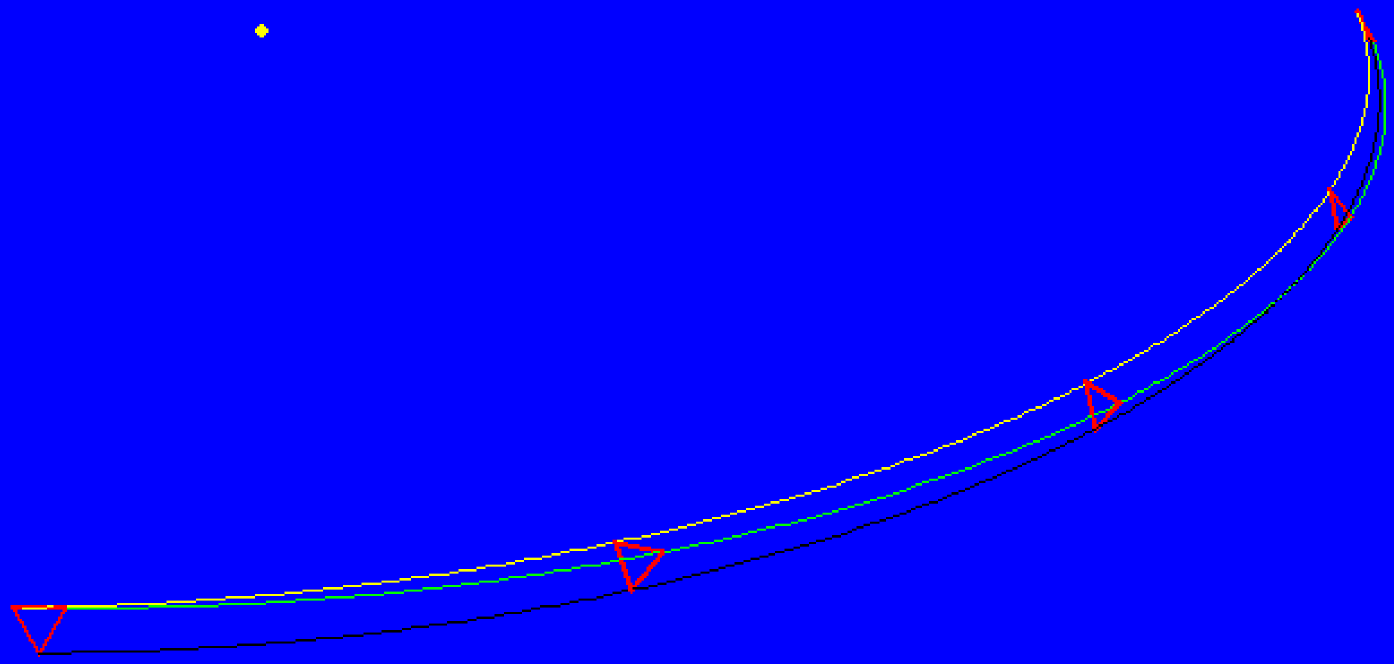
0.1 mHz – 0.1 Hz

$$\text{Strain sensitivity} \approx 3\times10^{-21}/\sqrt{\text{Hz}} \quad @ \; 10^{-3}\text{Hz}$$

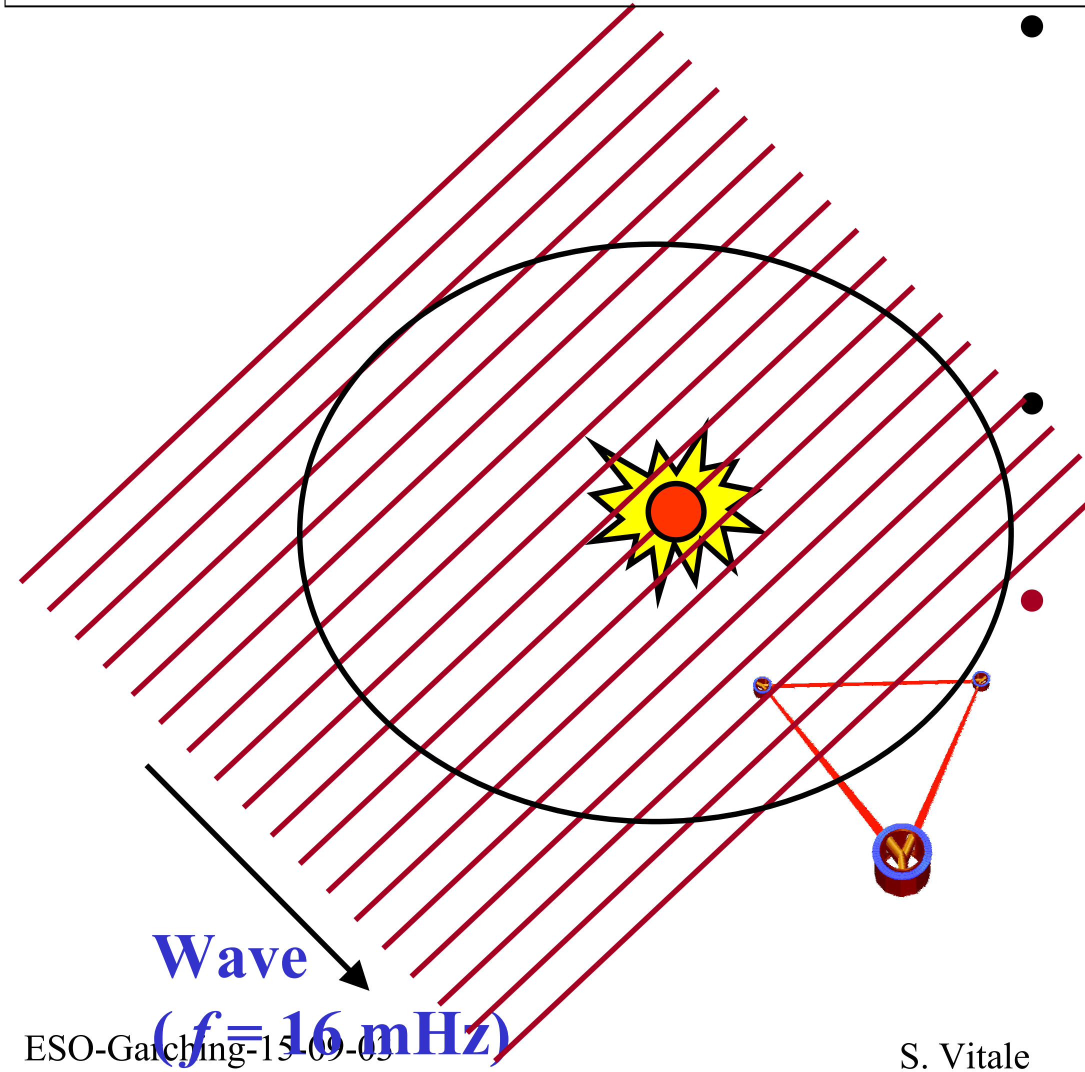


esa
Gravitational Wave Amplitude
10^{-18}
10^{-20}
10^{-22}
10^{-24}
Coelescence of
Massive Black Holes
Resolved
Galactic Binaries
Unresolved
Galactic
Binaries
LISA
Newtonian Gravitational Noise
NS-NS and BH-BH
Coalescence
SN Core
Collapse
LIGO
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency (Hz)

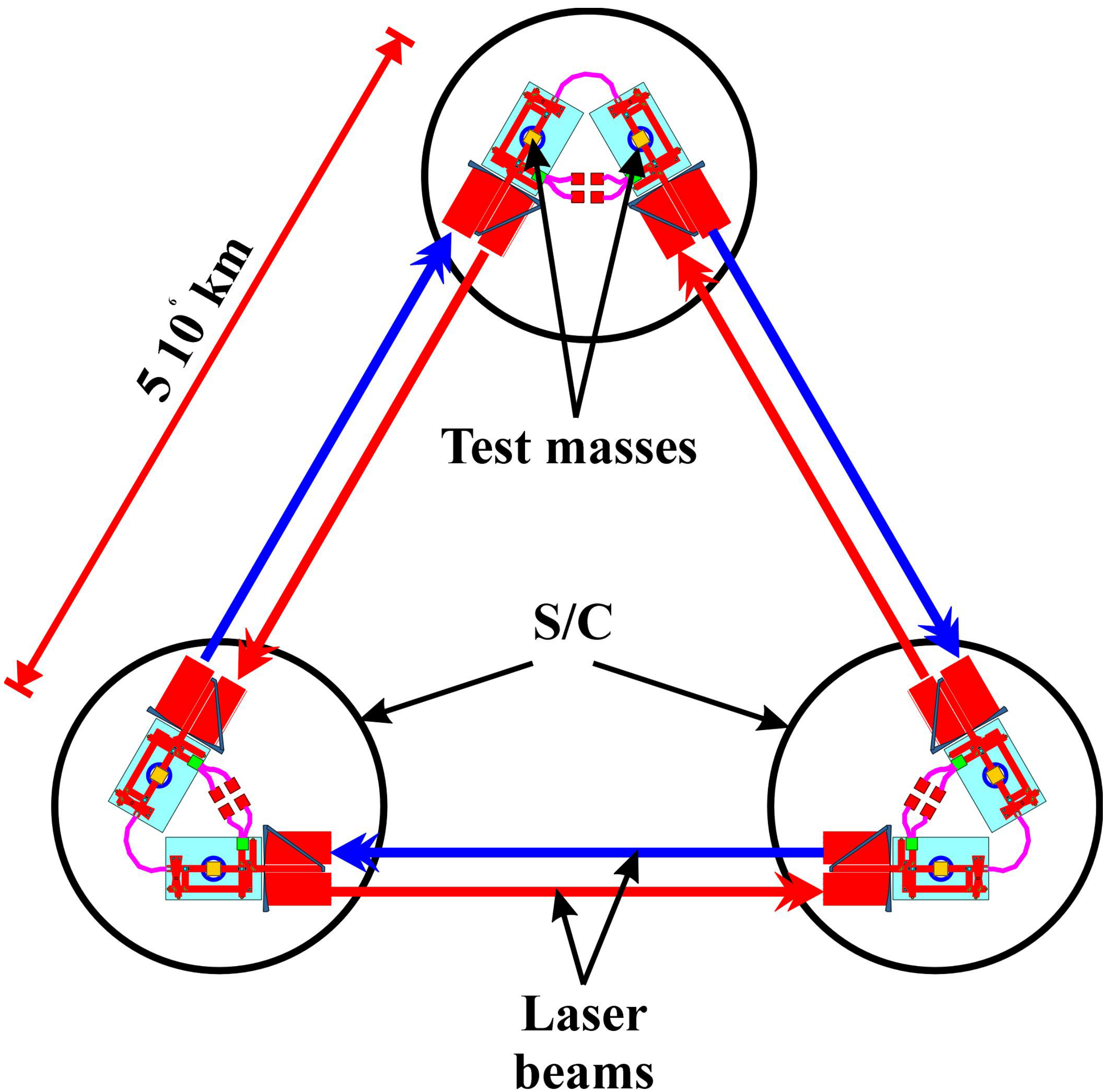
LISA essentials 1: the smart orbits



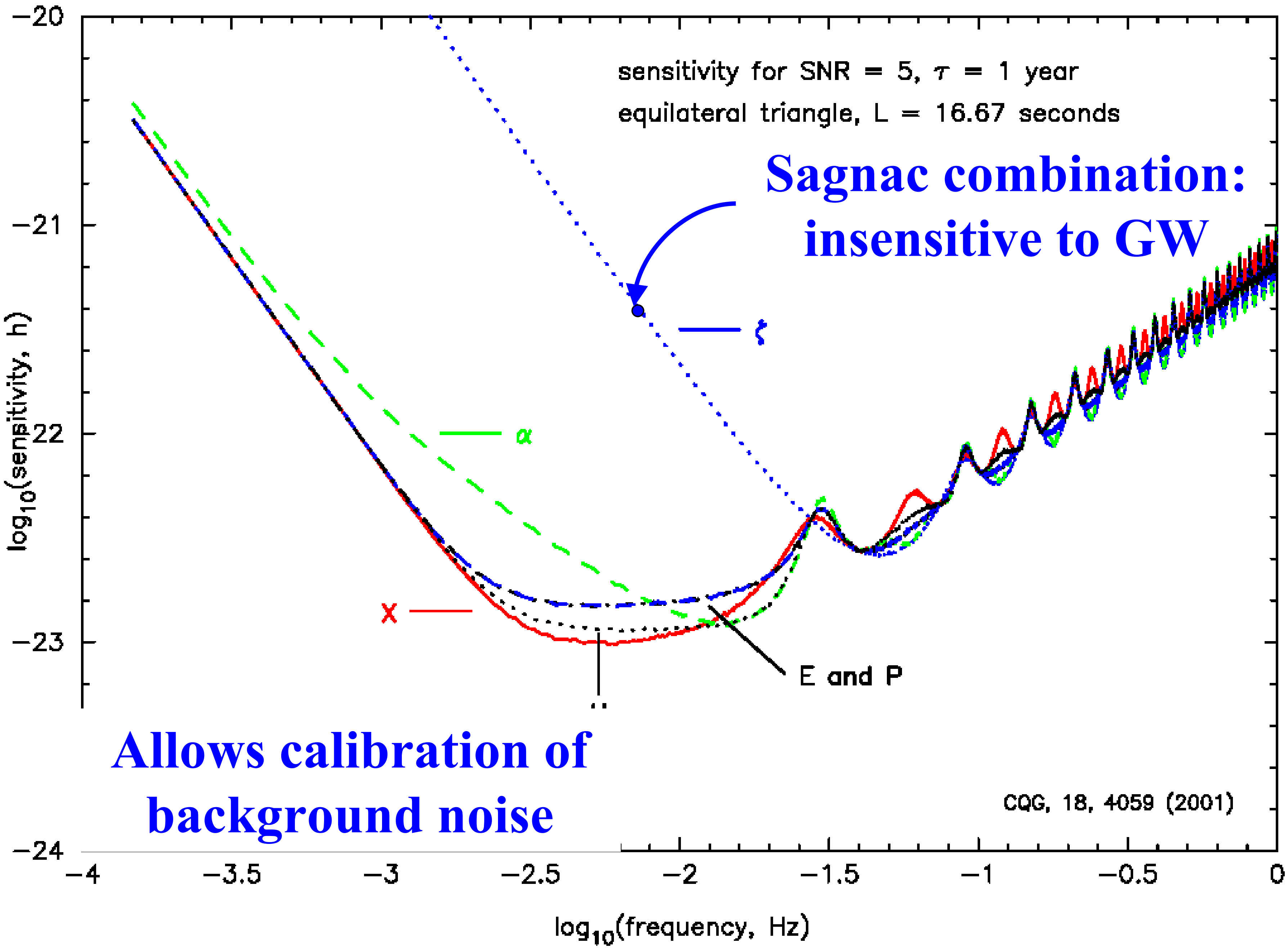
Angular Resolution with LISA

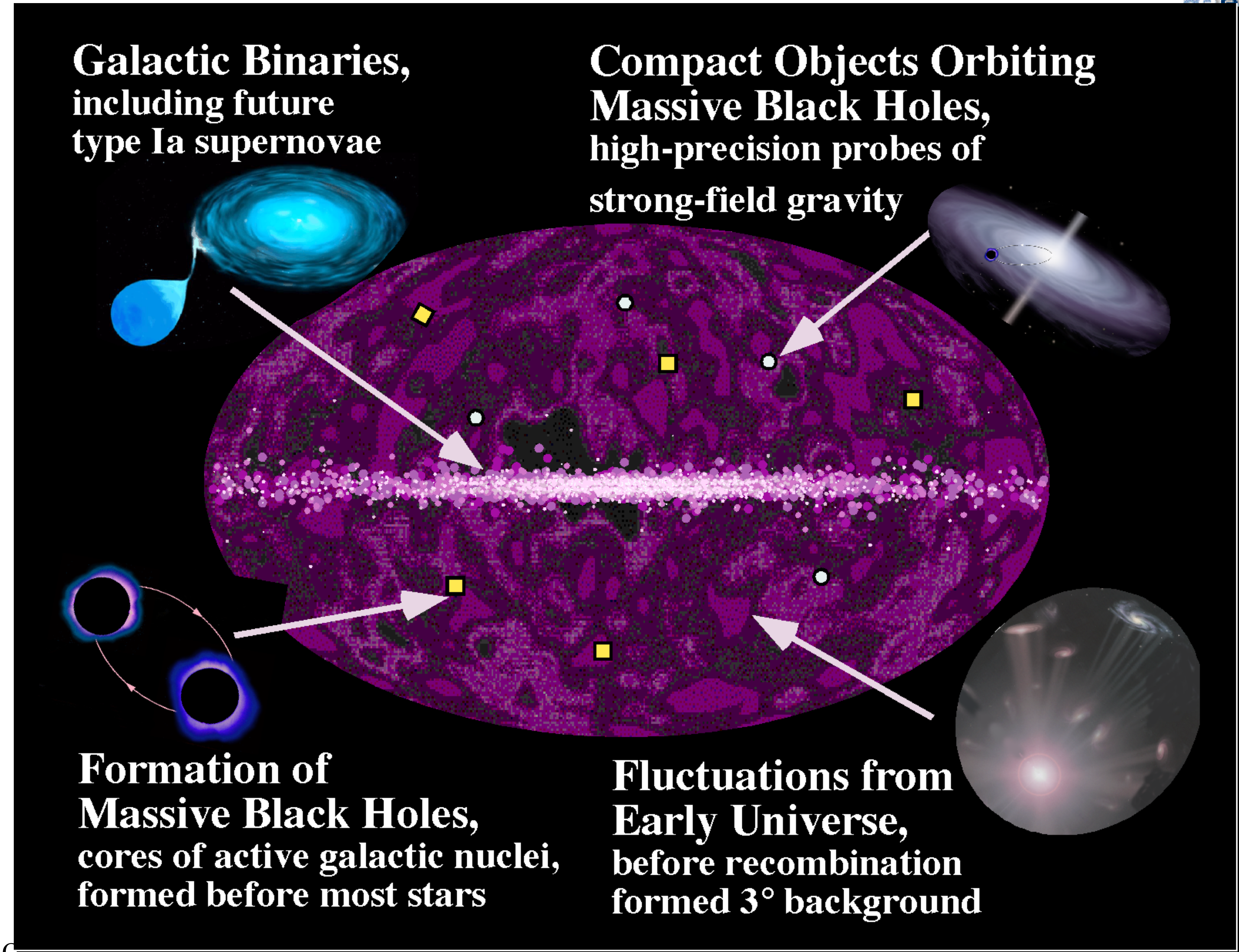


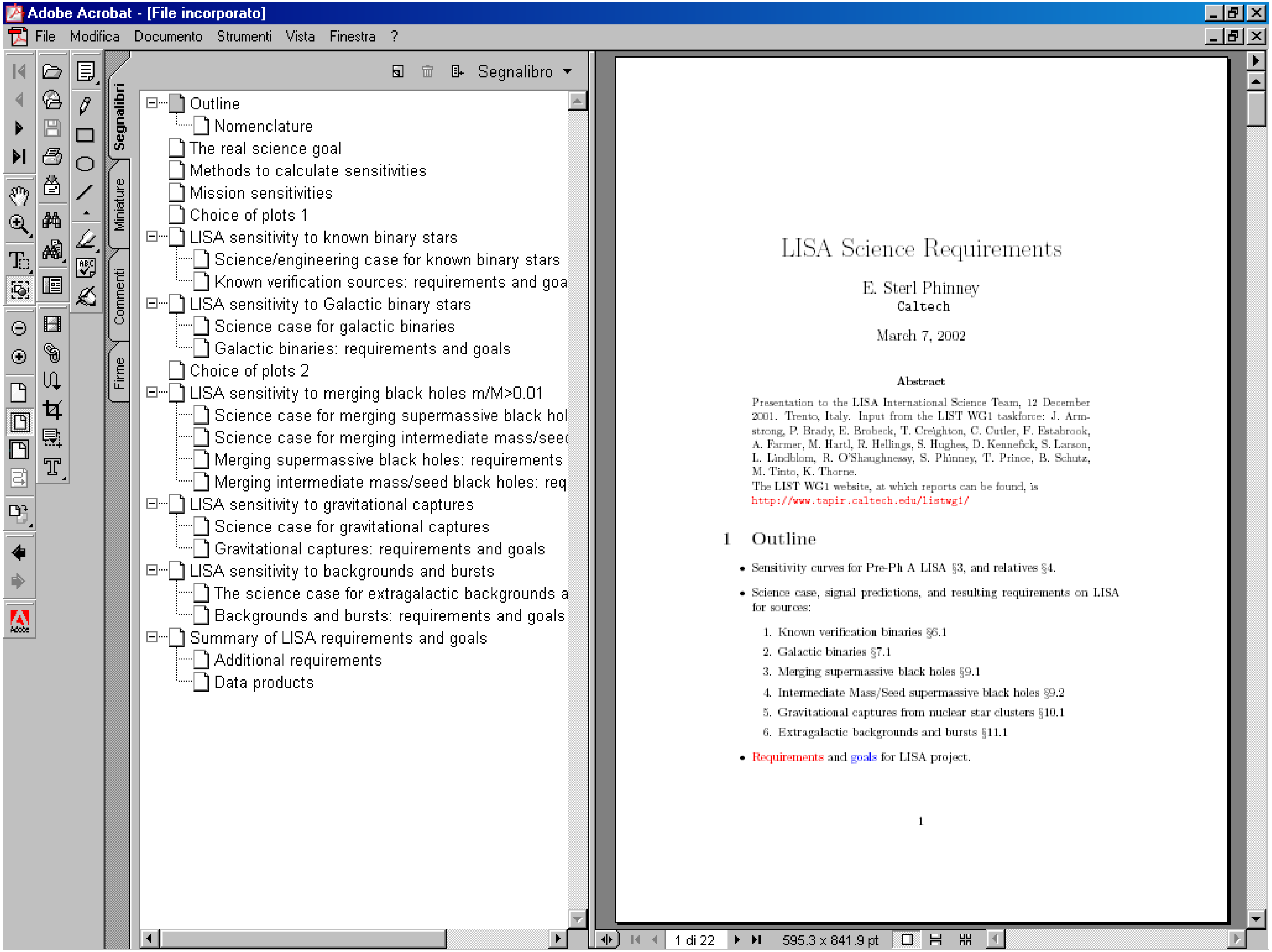
- Using phase modulation due to orbital motion is equivalent to aperture synthesis.
- Gives diffraction limit $\Delta\theta = \lambda / 1\text{ AU}$.
- Measurements on detected sources:
  - $\Delta\theta \sim 1' - 1^{o}$
  - $\Delta(\text{mass,distance}) \leq 1\%$



Something more than "an interferometer": 6 independent beams


Sagnac combination: insensitive to GW
Allows calibration of background noise
sensitivity for SNR = 5, τ = 1 year
equilateral triangle, L = 16.67 seconds
ζ
α
X
E and P
CQG, 18, 4059 (2001)
log10(sensitivity, h)
log10(frequency, Hz)
−20
−21
−22
−23
−24
−4
−3.5
−3
−2.5
−2
−1.5
−1
−0.5
0

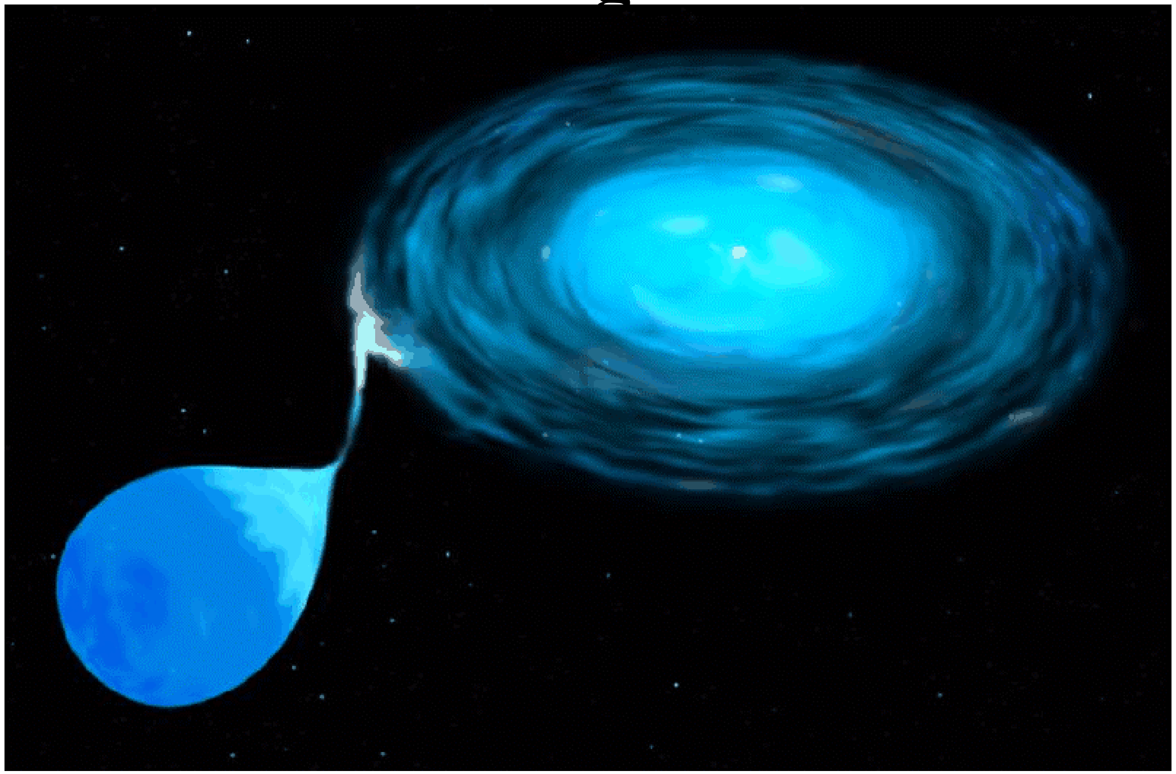

Galactic Binaries,
including future
type Ia supernovae
Compact Objects Orbiting
Massive Black Holes,
high-precision probes of
strong-field gravity
Formation of
Massive Black Holes,
cores of active galactic nuclei,
formed before most stars
Fluctuations from
Early Universe,
before recombination
formed 3° background


Adobe Acrobat - [File incorporato]
File Modifica Documento Strumenti Vista Finestra ?
Segnalibri
Miniature
Commenti
Firme
Segnalibro
Outline
Nomenclature
The real science goal
Methods to calculate sensitivities
Mission sensitivities
Choice of plots 1
LISA sensitivity to known binary stars
Science/engineering case for known binary stars
Known verification sources: requirements and goa
LISA sensitivity to Galactic binary stars
Science case for galactic binaries
Galactic binaries: requirements and goals
Choice of plots 2
LISA sensitivity to merging black holes m/M>0.01
Science case for merging supermassive black hol
Science case for merging intermediate mass/seec
Merging supermassive black holes: requirements
Merging intermediate mass/seed black holes: req
LISA sensitivity to gravitational captures
Science case for gravitational captures
Gravitational captures: requirements and goals
LISA sensitivity to backgrounds and bursts
The science case for extragalactic backgrounds a
Backgrounds and bursts: requirements and goals
Summary of LISA requirements and goals
Additional requirements
Data products
LISA Science Requirements
E. Sterl Phinney
Caltech
March 7, 2002
Abstract
Presentation to the LISA International Science Team, 12 December 2001. Trento, Italy. Input from the LIST WG1 taskforce: J. Armstrong, P. Brady, E. Brobeck, T. Creighton, C. Cutler, F. Estabrook, A. Farmer, M. Hartl, R. Hellings, S. Hughes, D. Kennefick, S. Larson, L. Lindblom, R. O'Shaughnessy, S. Phinney, T. Prince, B. Schutz, M. Tinto, K. Thorne.
The LIST WG1 website, at which reports can be found, is
http://www.tapir.caltech.edu/listwg1/
1 Outline
• Sensitivity curves for Pre-Ph A LISA §3, and relatives §4.
• Science case, signal predictions, and resulting requirements on LISA for sources:
1. Known verification binaries §6.1
2. Galactic binaries §7.1
3. Merging supermassive black holes §9.1
4. Intermediate Mass/Seed supermassive black holes §9.2
5. Gravitational captures from nuclear star clusters §10.1
6. Extragalactic backgrounds and bursts §11.1
• Requirements and goals for LISA project.
1
1 di 22
595.3 x 841.9 pt

Galactic Binaries

SNR up to 500 in 1 year. Angular esolution 10^{-3} – 10^{-2} srad at SNR ≈10

Some are standard candles: everything known about the signal.



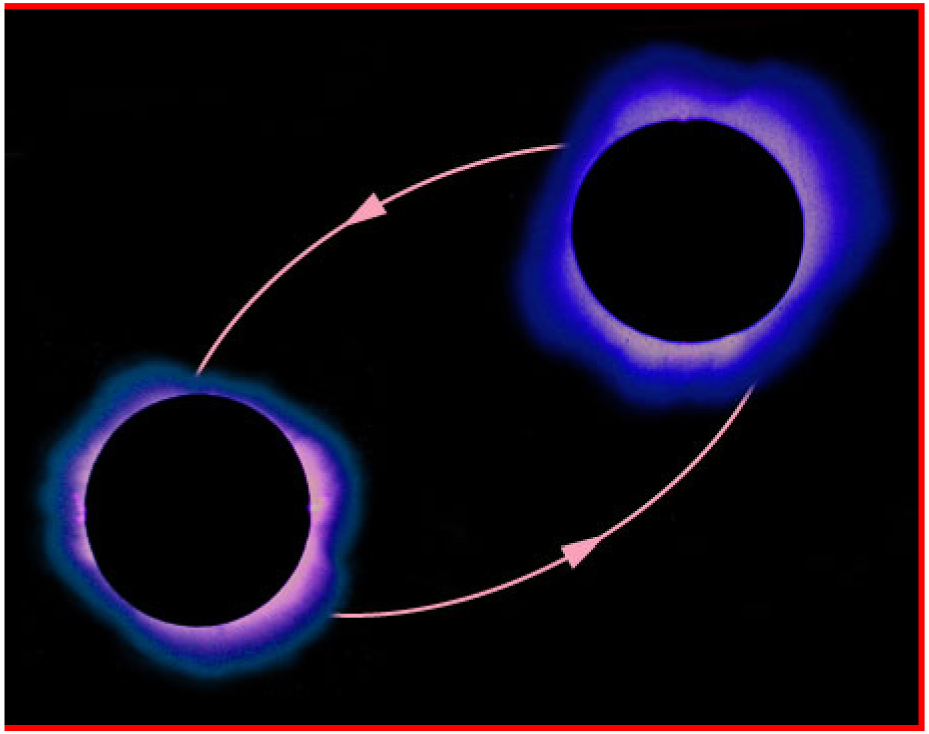
LISA calibration binaries

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}

7.1 Science case for galactic binaries

Astronomy of exotic (past or present) interacting binary stars.

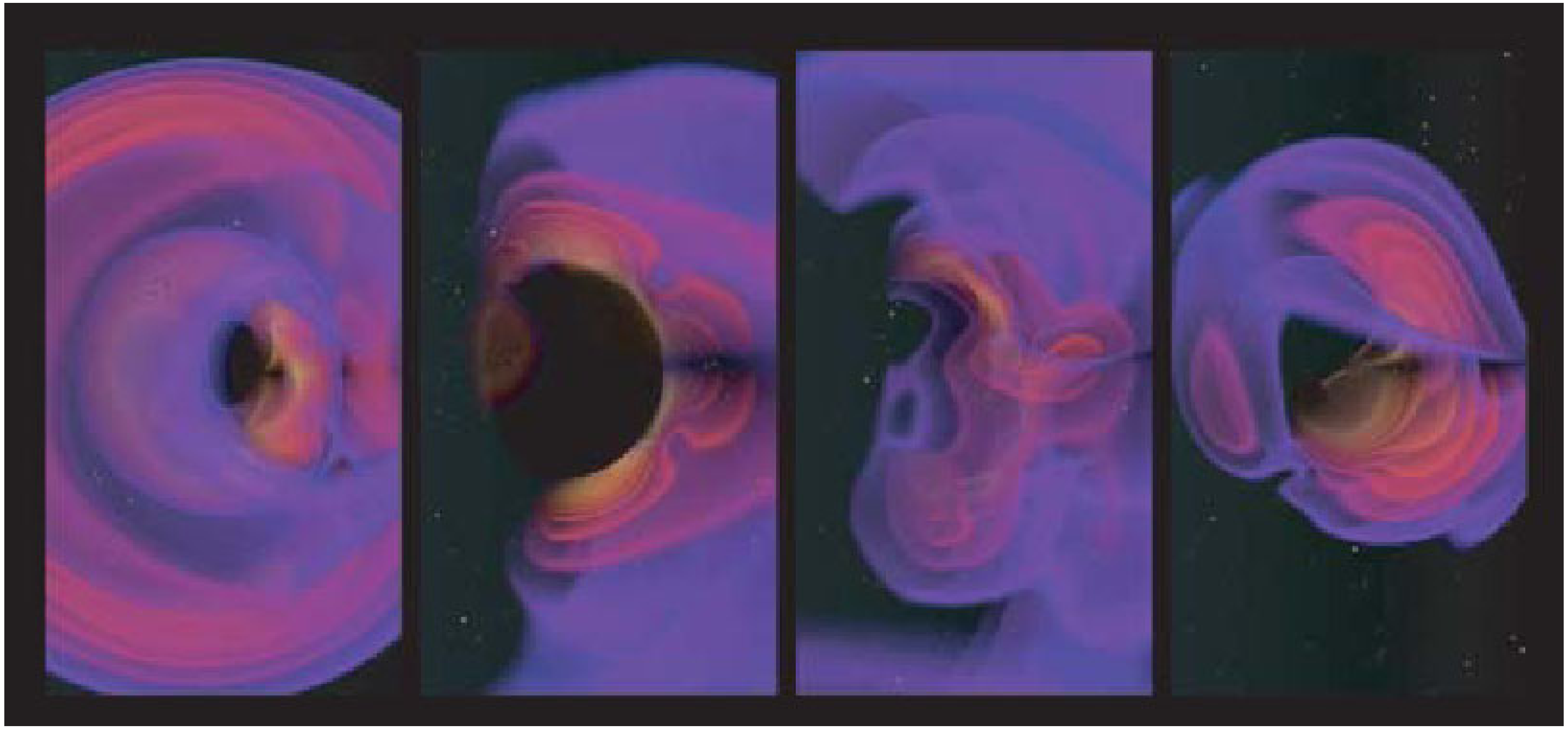
- Binary star map of Galaxy & beyond w/inclinations, orientations: star formation clues?
- Discovery space for exotic binaries hard/impossible to find electromagnetically.
- Identification/study of white dwarf tides/mergers: SN Ia, AIC (accretion induced collapse to NS), rare novae connection?
- Probe strong interior magnetic fields of WD (rotating quadrupoles).
- Galactic background at $3 \times 10^{-5}\text{Hz} < f < 3 \times 10^{-4}\text{Hz}$ gives binary star formation history of the galaxy.
- Chirp mass distribution, $\dot{f} < 0$ distribution give tests of binary star evolution theories, especially crucial but poorly understood angular momentum transfer before, during and after common-envelope evolution.



Massive black hole binaries from merging galaxies cores

SNR up to 2000 in one year at z ≈1 – 3

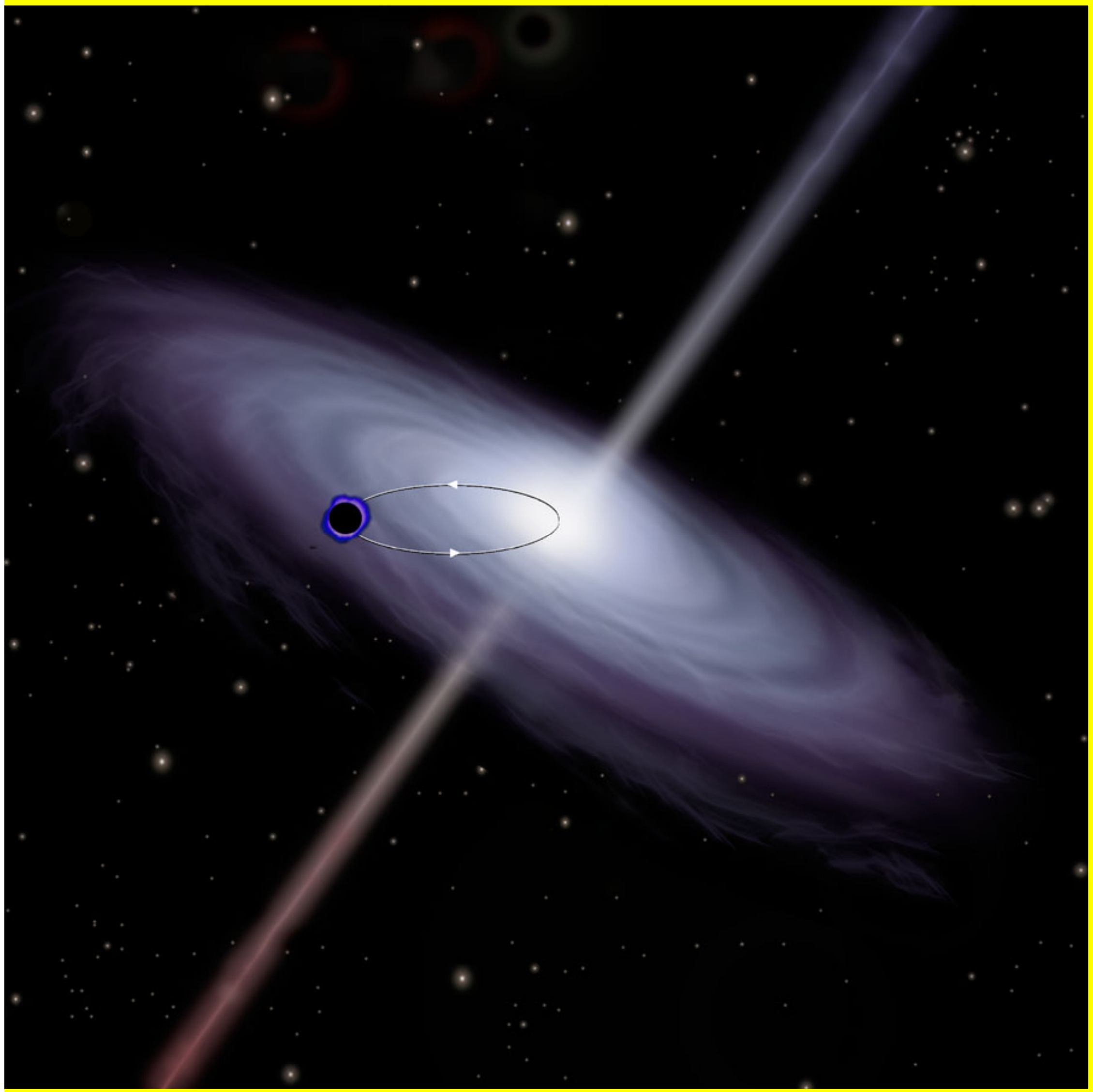
Angular resolution few’-few°



Binary SMBH-SMBH

9.1 Science case for merging supermassive black holes

- Precision tests of dynamical nonlinear gravity through comparison with precise numerical simulation of Einstein's equations. Cosmic censorship in horizon merger, ringdown. [ground-based detectors will do this with substantially lower precision with stellar mass BHs, however].
- Determine precision masses, spins for supermassive black holes in galactic nuclei (PN inspiral).
- Determine precision distances to supermassive black holes, get redshifts (if cosmography well-determined). Or if electromagnetic signal gives redshift, determine cosmography.
- Determine combination of merger history of galaxies and protogalactic lumps with nuclear stellar/gas dynamics (black hole binaries vs triples vs clusters, ejection of nuclear stars).



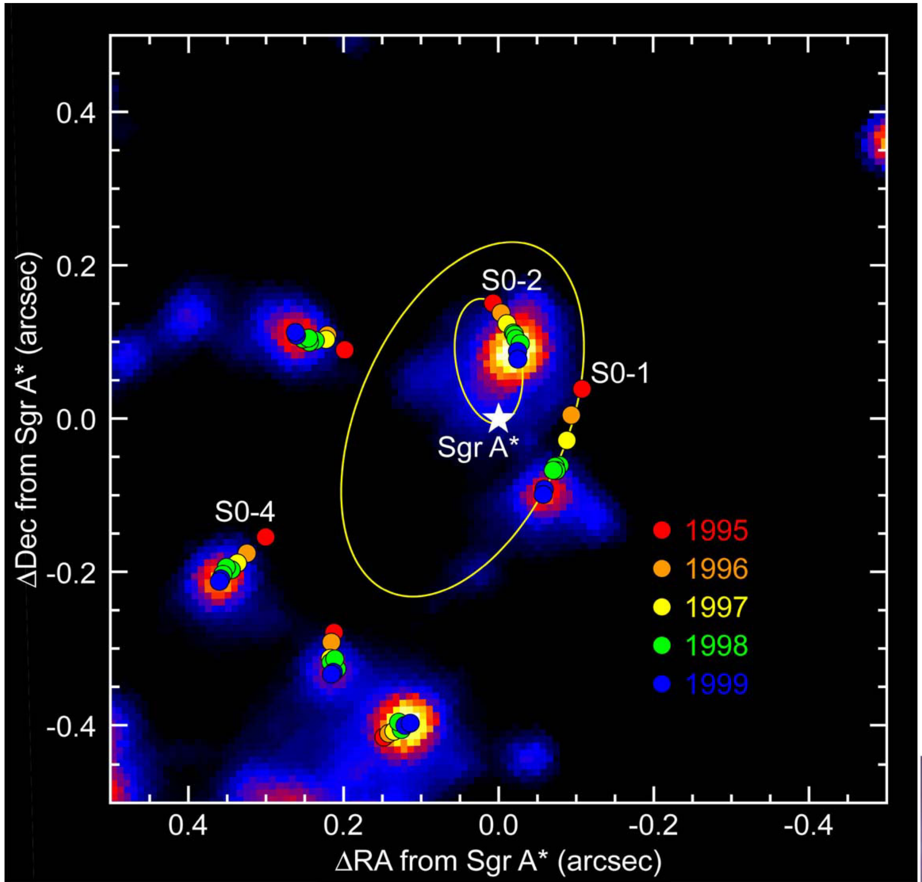
Gravitational capture

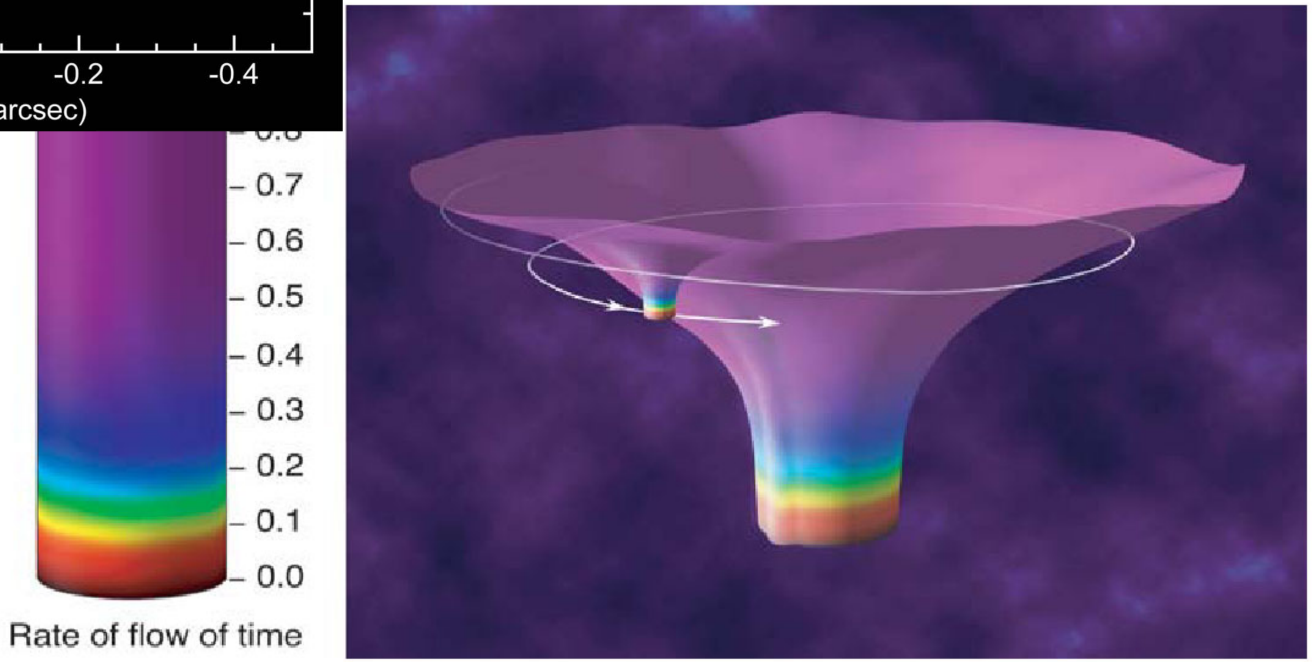
High rate. SNR 10-20

Map of the event horizon

Proof of no-hair theorem

Direct proof of BH



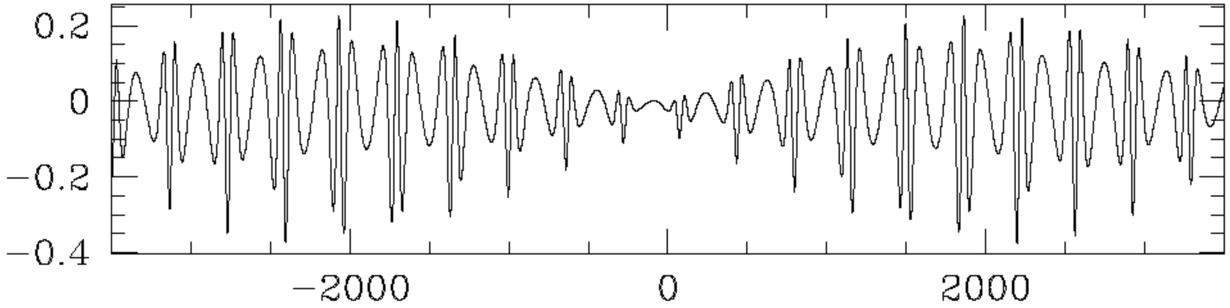


ESO-Garching-15-09-03

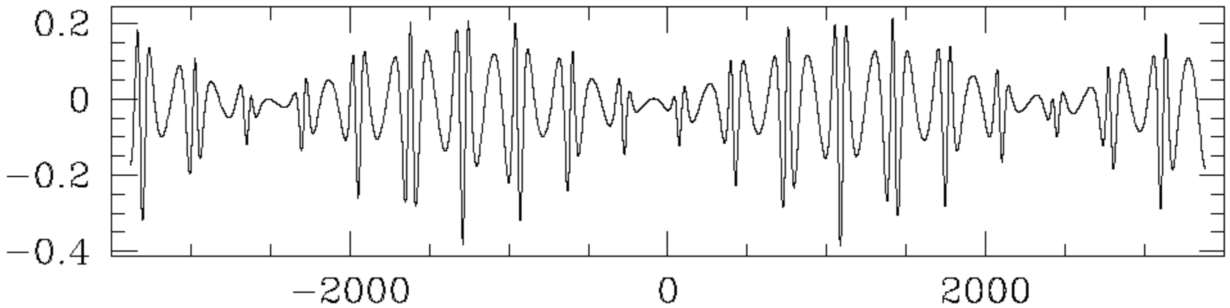
The science case for gravitational capture

- Measure $M = M_0$, $a/M = S_1$ to $< 1\%$.
- Measure higher mass and current multipoles M_2, S_3, etc to sufficient precision to test "no hair theorem" (e.g. Kerr predicts $M_2 = Ma^2$; uniform density slowly rotating Newtonian star, radius R, has $M_2 = (25/8)(R/M)Ma^2$.).
  - No hair satisfied: highest precision probe of strong field nonlinear gravity yet envisaged. [Note: black holes almost certainly have non-Abelian hair, and "no hair theorem" strictly false for fields beyond E&M. QCD hair not detectable -femtometer multipoles! But in some models fields in dark hidden sectors of string theory could make measurable effects on bothrodesy.]
  - No hair not satisfied: discovery of hypothetical new types of massive compact bodies —e.g. soliton stars, naked singularities. Inversion of multipoles gives detailed map of spacetime.
- Measure to high precision the orbiting body's tidal extraction of rotational energy and angular momentum from the black hole (via its $\sim 5 - 10\%$ effect on the rate of inspiral).
- Astrophysical parameters: mass, spin, distance of supermassive bodies, mass, orbital eccentricity, inclination all to better than a few %. Infer population and evolution of supermassive black holes and their surrounding star clusters (mass segregation, IMF, density structure).

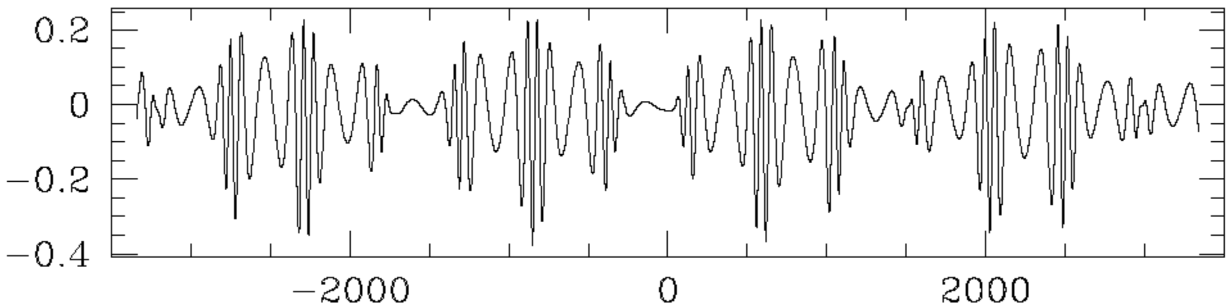
a/M=0.5, a=12, e=0.4, i=0.785; 20 radial periods



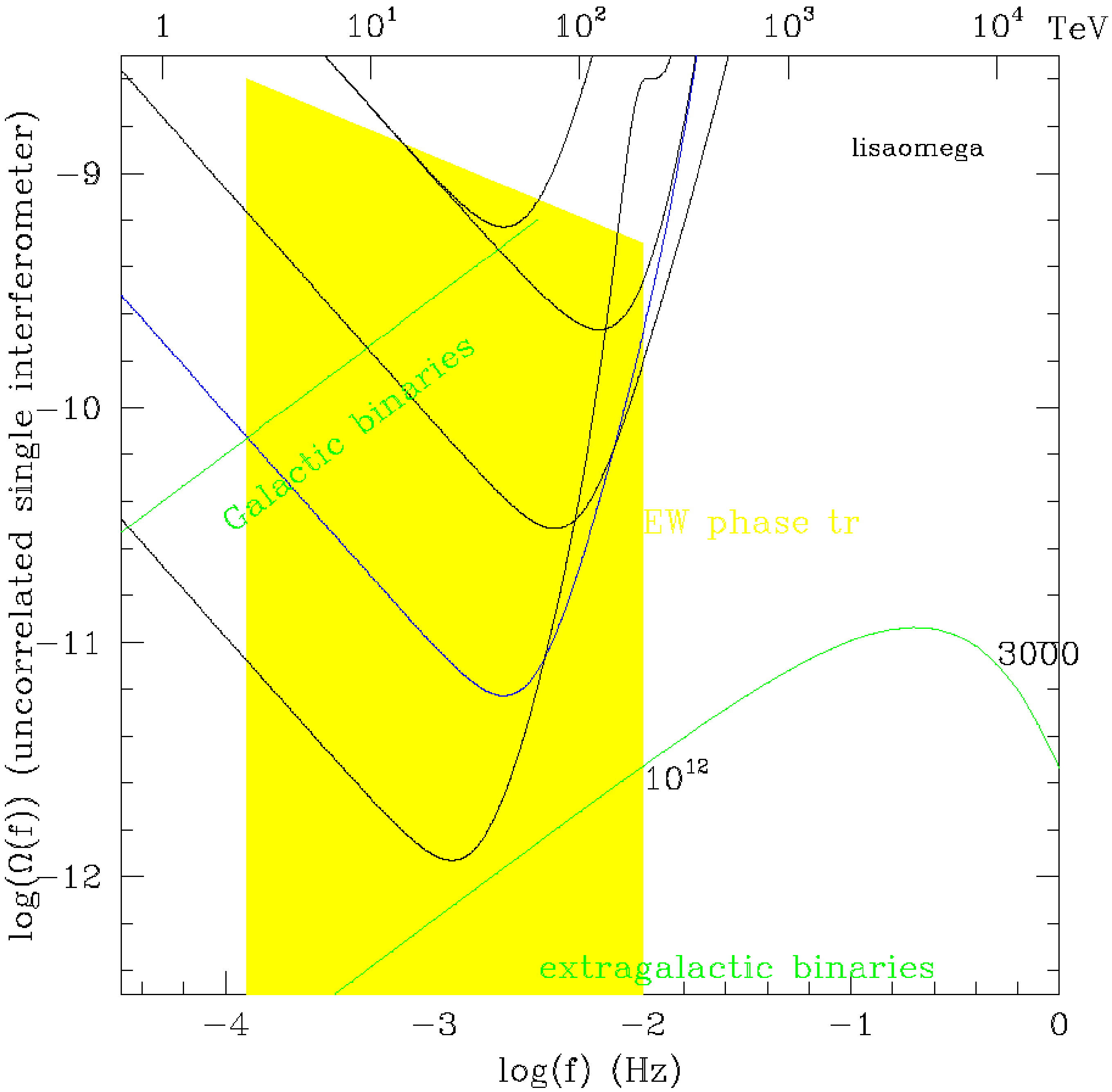
a/M=0.95, a=12, e=0.4, i=0.785; 20 radial periods



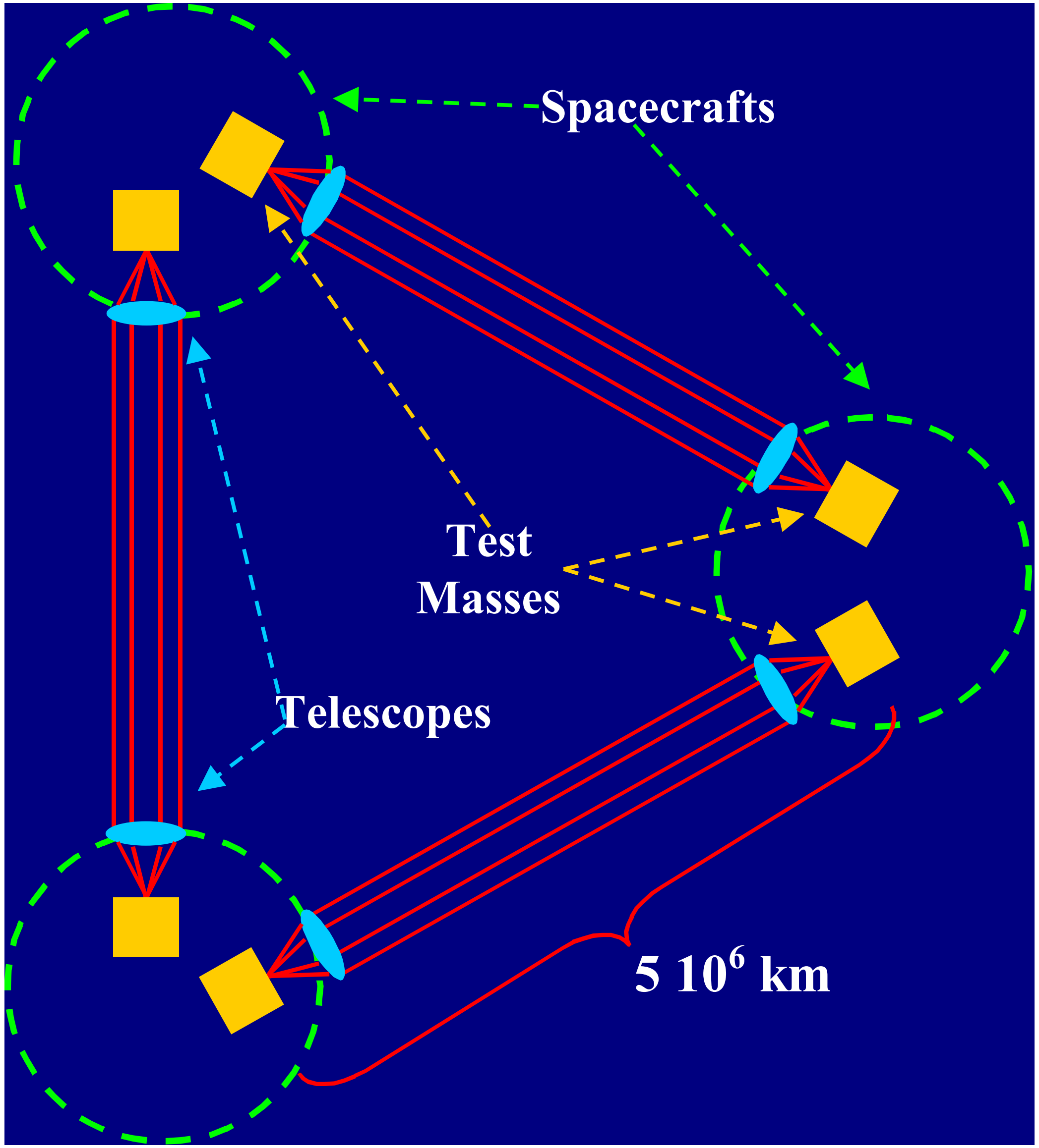
a/M=−0.95, a=12, e=0.4, i=0.785; 14 radial periods



Signal extraction challenging



Stochastic Background

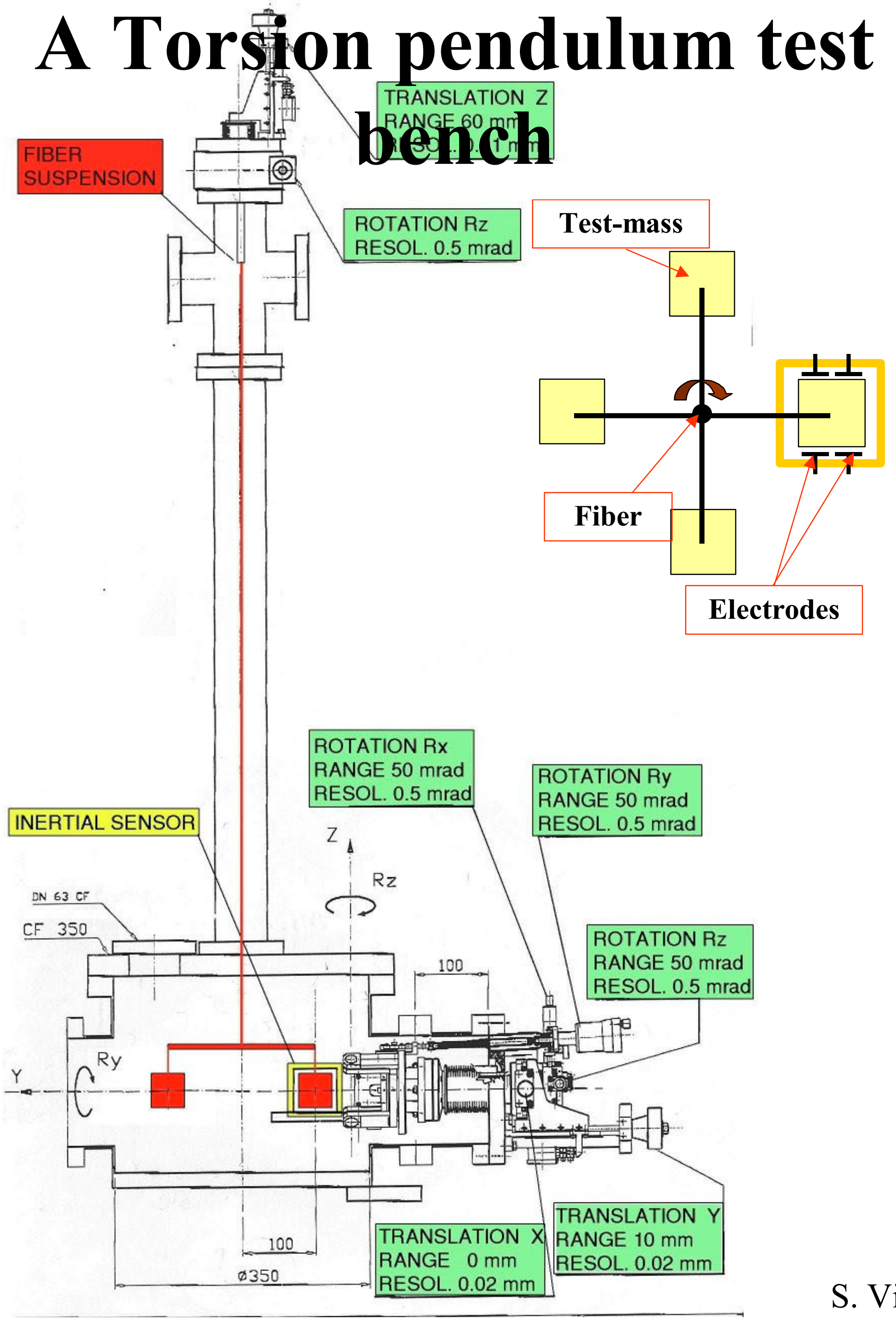


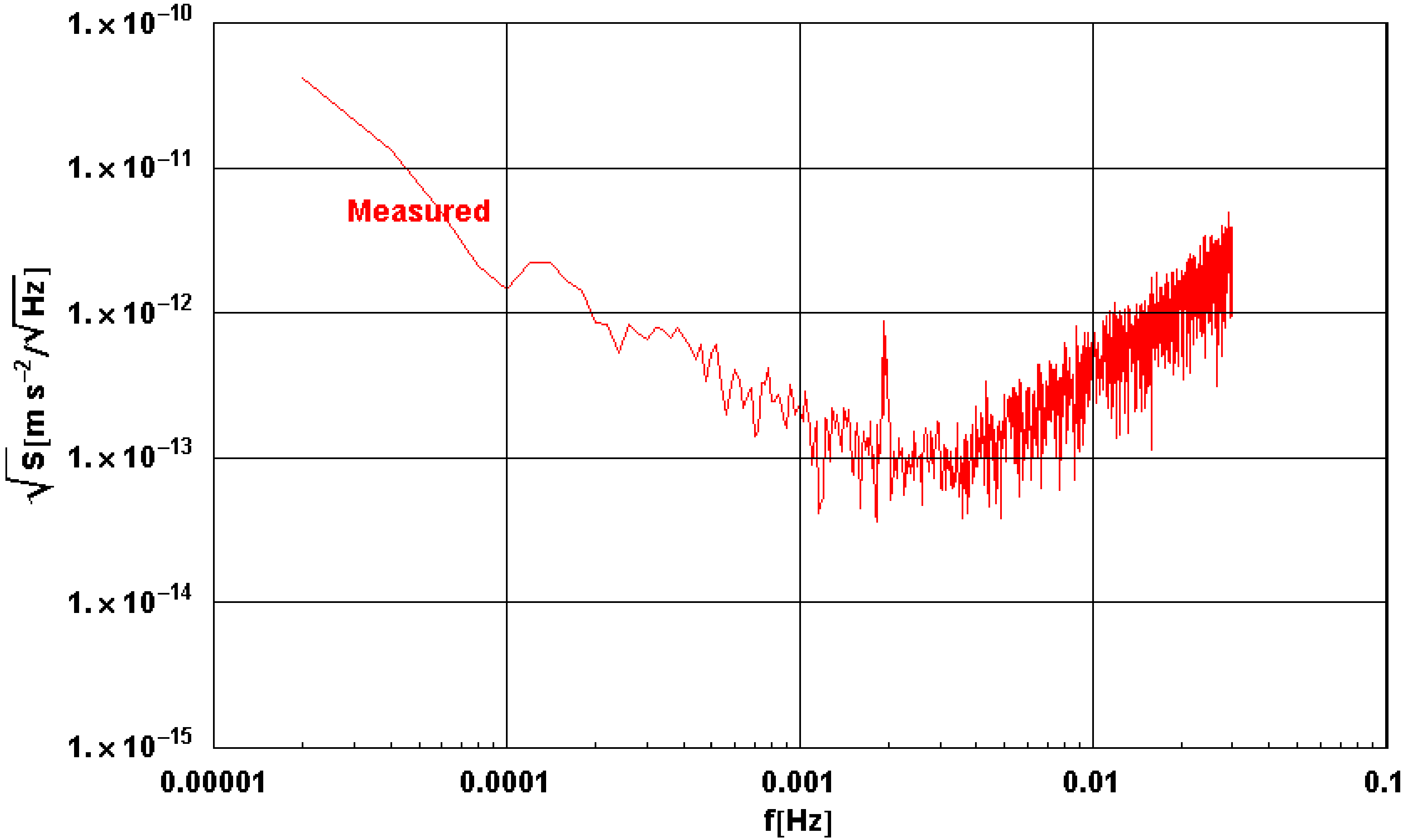
3 pairs of "free falling" test masses
(3 10^{-15} ms^{-2} $Hz^{-1/2}$ @ 0.1 mHz)

Can it be achieved?

Can it be tested?

A Torsion pendulum test bench

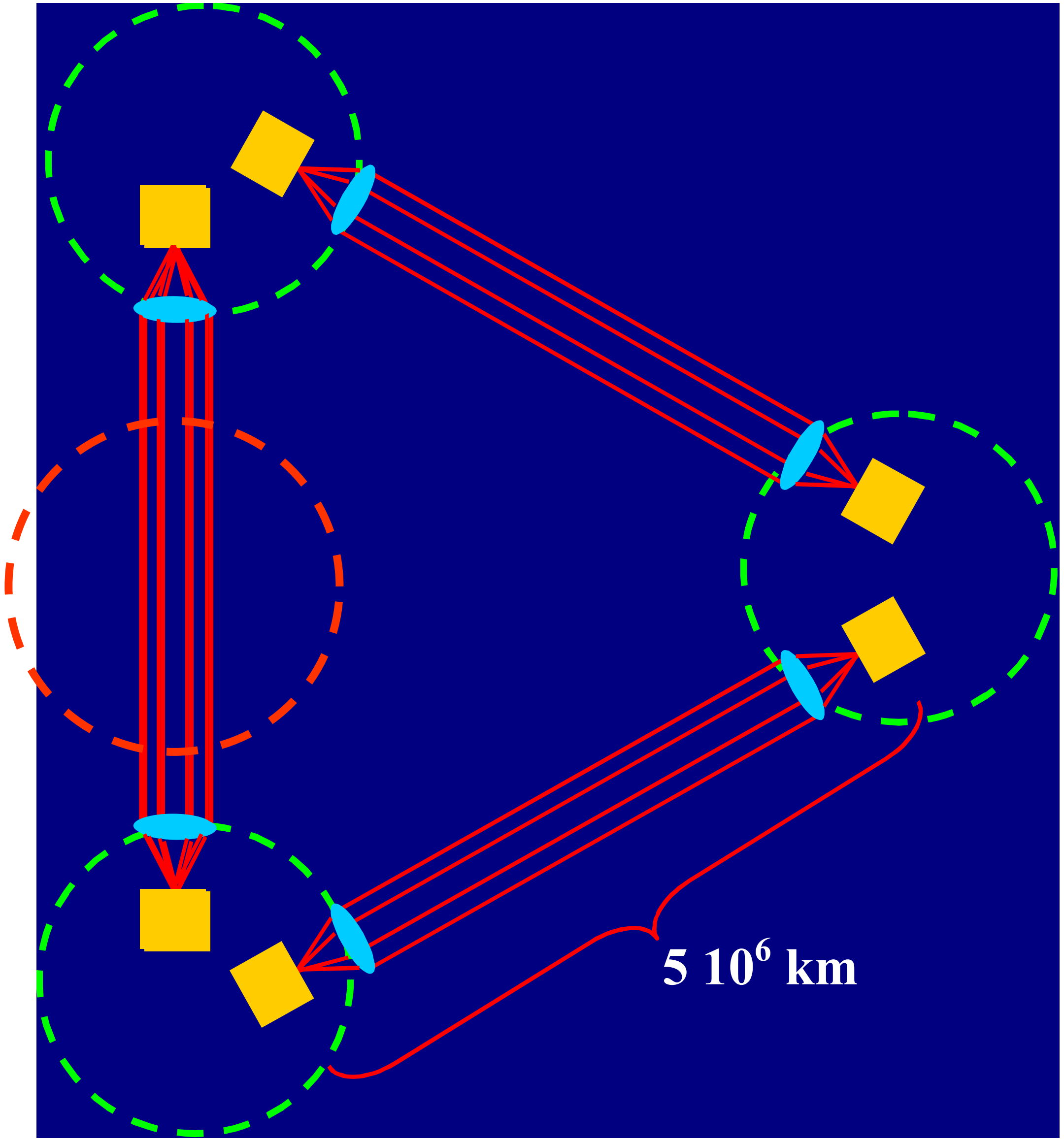




$1.\times 10^{-10}$
$1.\times 10^{-11}$
$1.\times 10^{-12}$
$1.\times 10^{-13}$
$1.\times 10^{-14}$
$1.\times 10^{-15}$
$\sqrt{S[m\,s^{-2}/\sqrt{Hz}]}$
Measured
0.00001
0.0001
0.001
0.01
0.1
f[Hz]

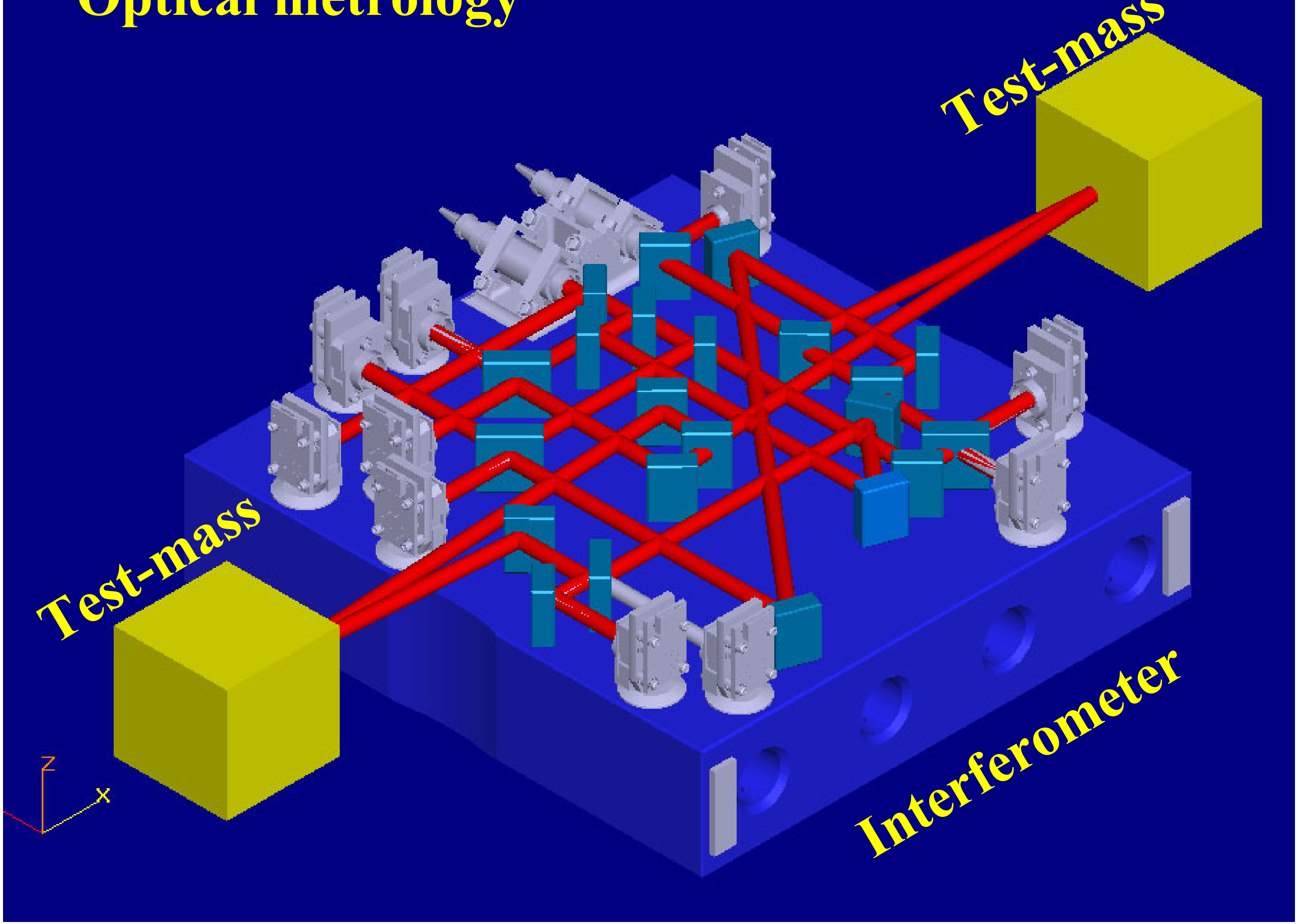
LISA Path Finder (SMART-2) In-flight test:

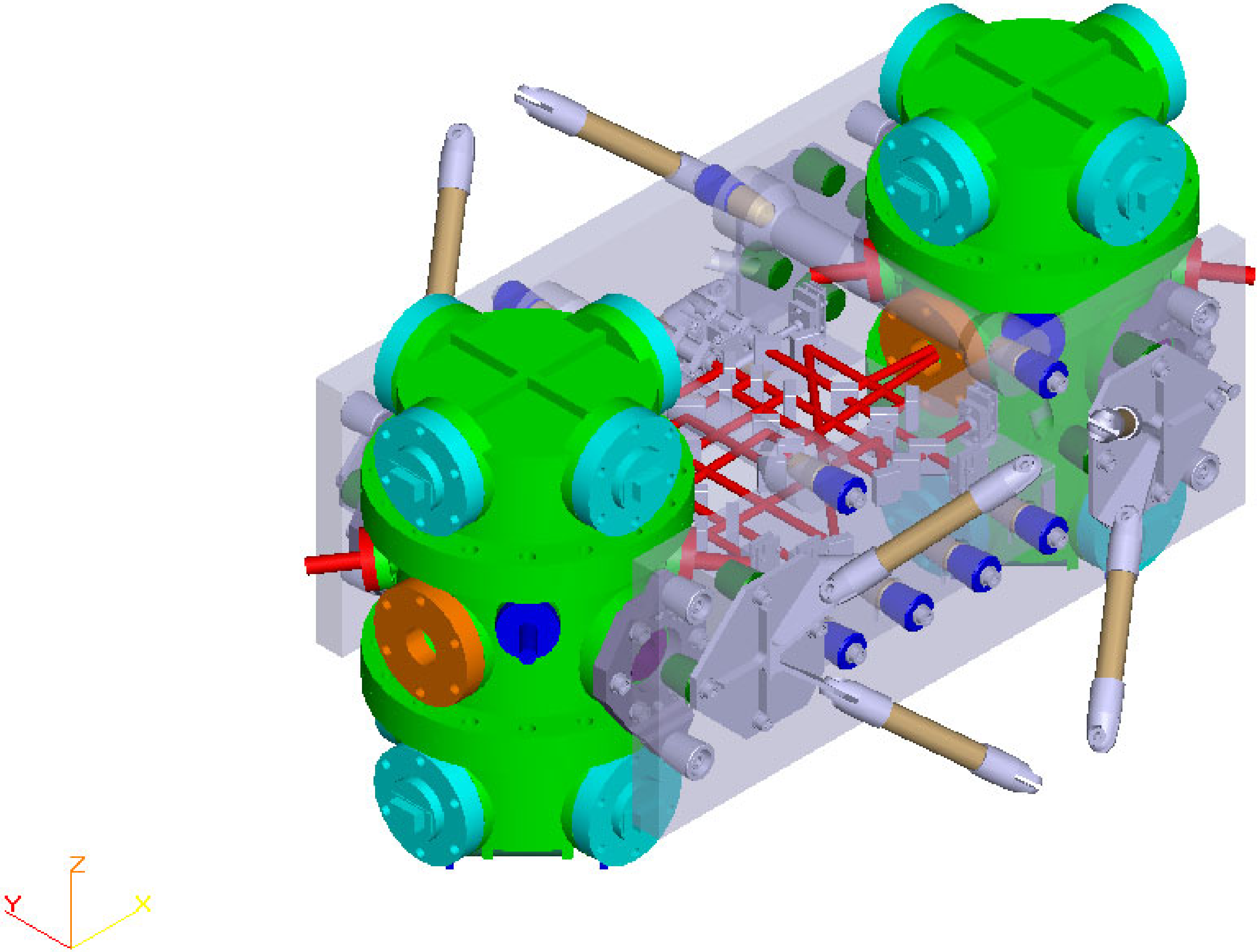
squeezing 1 LISA's arm to 35 cm
One order of magnitude from LISA goals



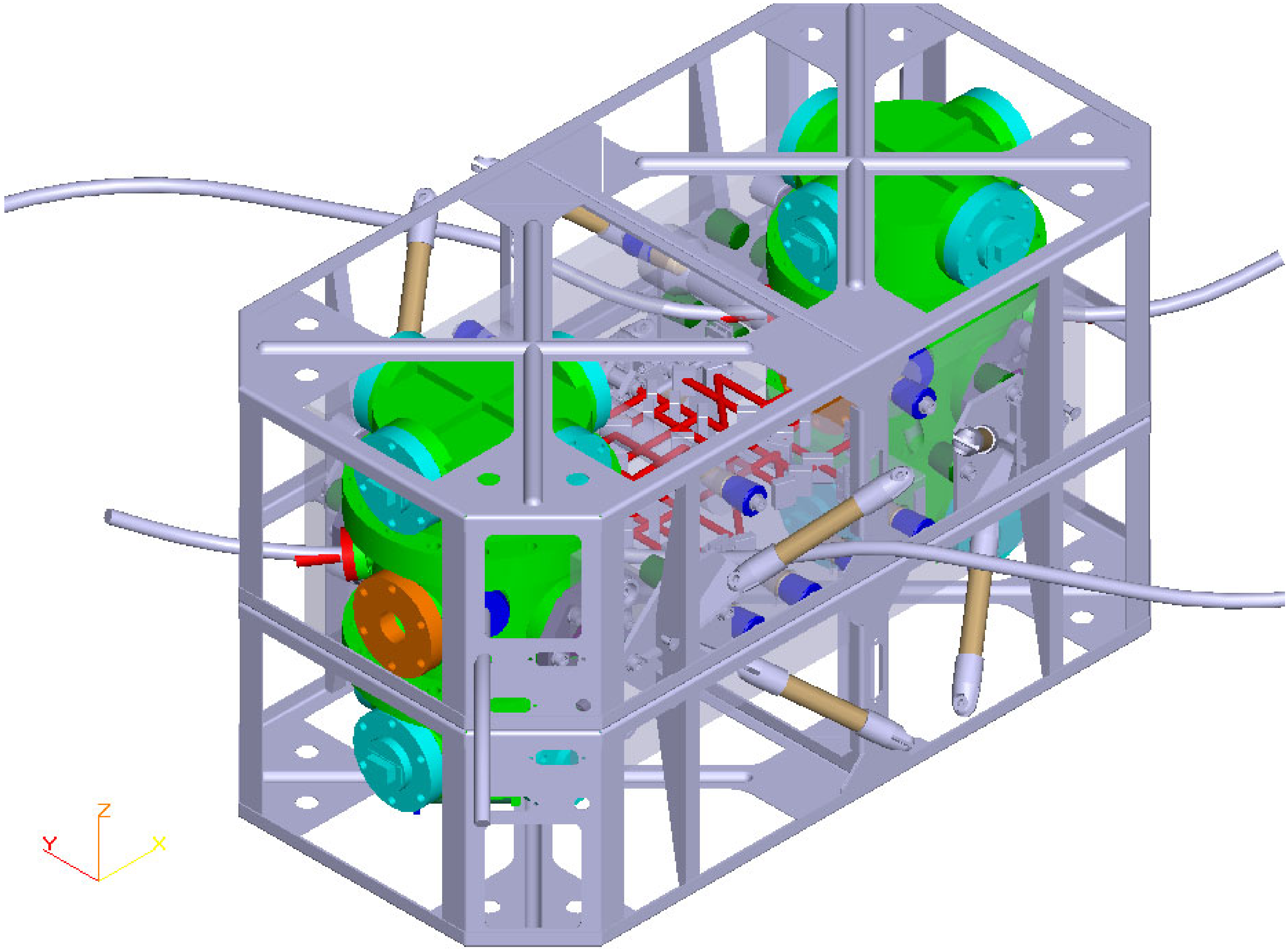
$$\delta a \leq 3 \cdot 10^{-14} \frac{ms^{-2}}{\sqrt{Hz}} \qquad 1\ mHz \leq f \leq 30\ mHz$$

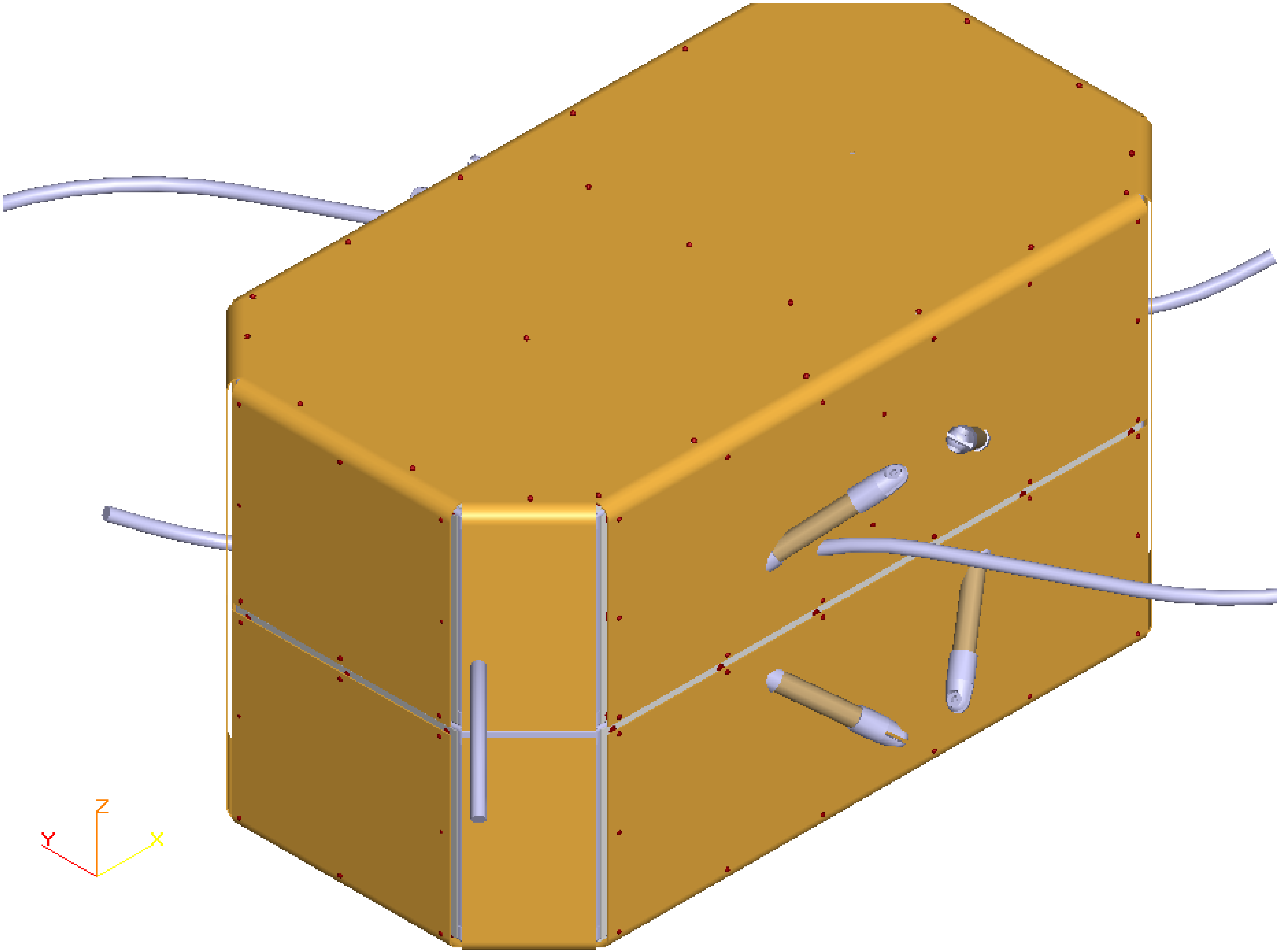
Optical metrology



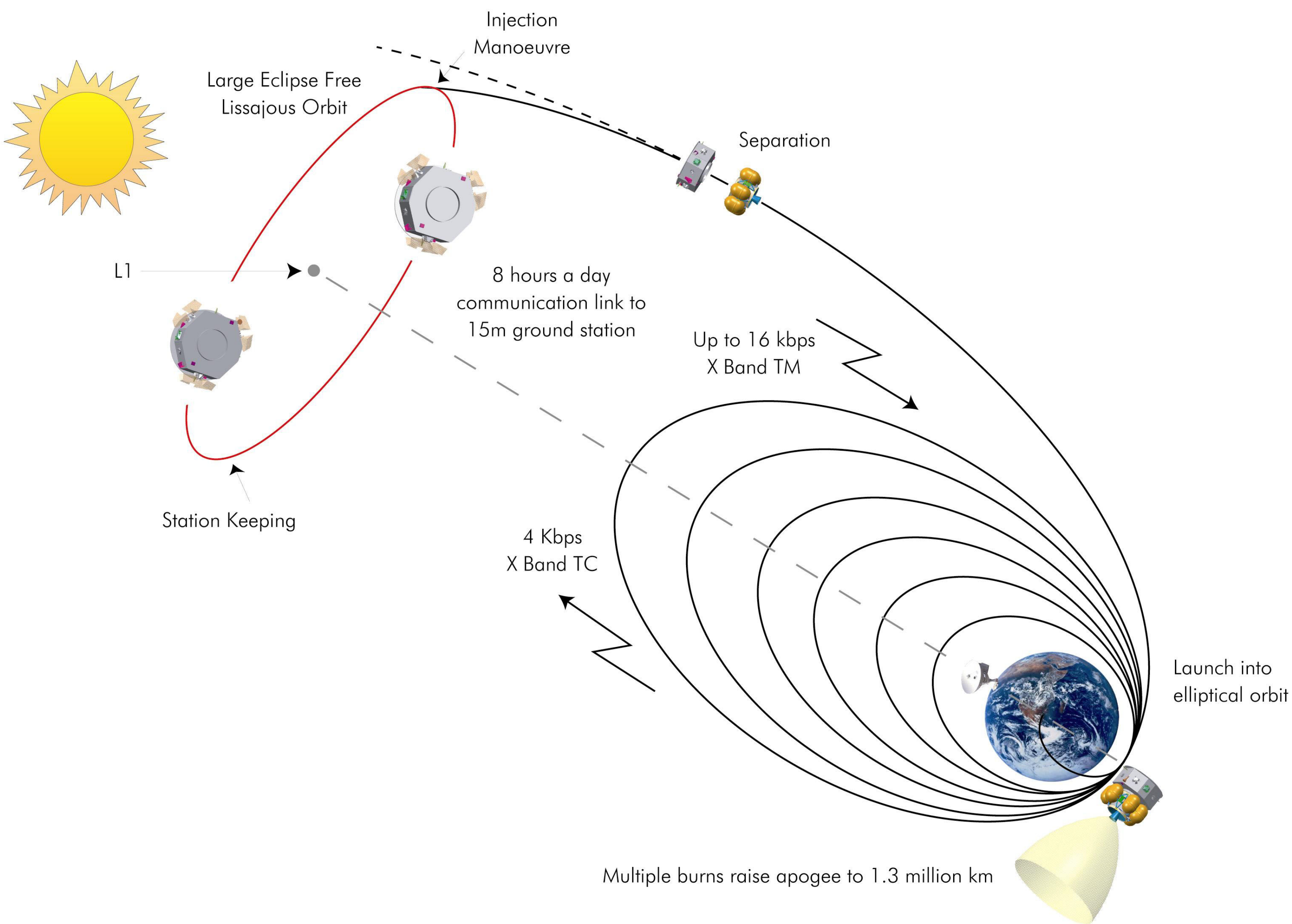


Z
Y
X


Z
Y
X



Z
Y
X



Injection
Manoeuvre
Large Eclipse Free
Lissajous Orbit
Separation
L1
8 hours a day
communication link to
15m ground station
Up to 16 kbps
X Band TM
Station Keeping
4 Kbps
X Band TC
Launch into
elliptical orbit
Multiple burns raise apogee to 1.3 million km

Testing quality of free fall

10^{-12}

$$\sqrt{S_F}\left(\frac{N}{\sqrt{Hz}}\right)$$

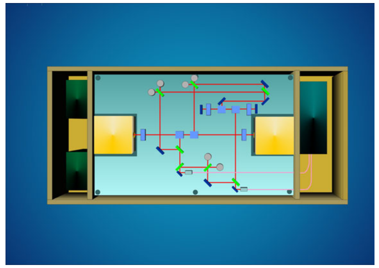
10^{-13}

10^{-14}

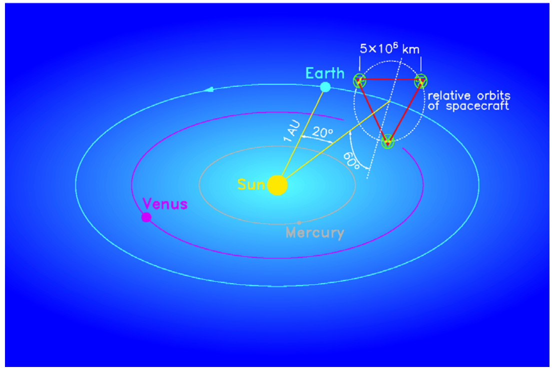
10^{-15}

Torsion pendulum

(surface disturbances)



LISA PF



LISA

Beyond Einstein Program - Microsoft Internet Explorer

File Modifica Visualizza Preferiti Strumenti ?

Indietro Cerca Preferiti Cronologia

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Site Map

structure and evolution of the universe

BEYOND EINSTEIN

FROM THE BIG BANG TO BLACK HOLES

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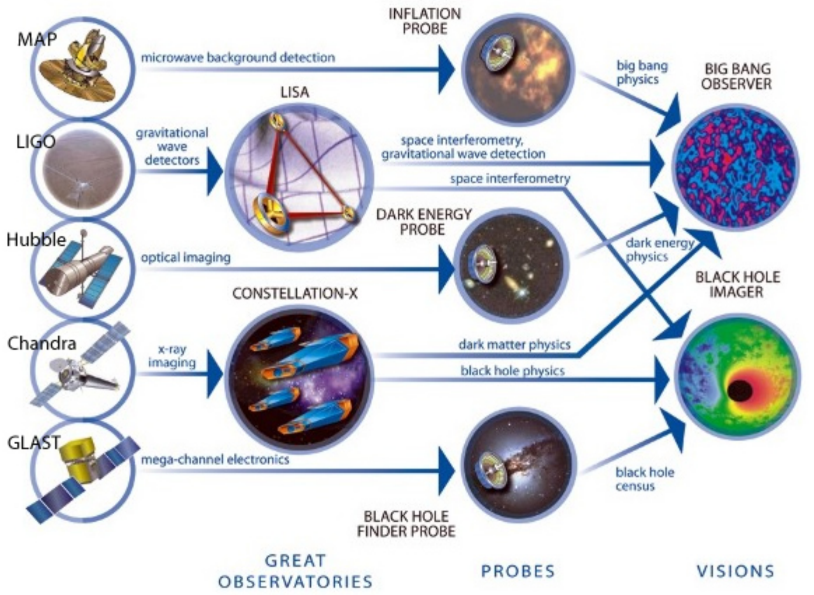
The Program

The *Beyond Einstein* program has three linked elements which advance science and technology towards two visions: to detect directly gravitational wave signals from the earliest possible moments of the Big Bang, and to image the event horizon of a black hole. The central element is a pair of Einstein Great Observatories, Constellation-X and LISA. These powerful facilities will blaze new paths to the questions about black holes, the Big Bang, and dark energy. They will also address other central goals of contemporary astrophysics (discussed in Part II of the 2003 Roadmap). The second element is a series of competitively selected Einstein probes, each focused on one of the science questions. The third element is a program of technology development, theoretical studies, and education, to support the Probes and the vision missions: the Big Bang Observer and the Black Hole Imager. The program offers competitive opportunities for mission leadership, technology development, and groundbreaking scientific research, with goals that excite the public.

Beyond Einstein Program



Internet

ESO-

LISA-TRIP

SUMMARY

Assessment of Risk

Achieving technology roadmap: Medium

Formulation in addition to technology development: Medium

Implementation: Medium

The Big Bang Observer:
Direct detection of gravitational waves from the birth of the Universe to the present

P.I.: E. S. Phinney

US Co-Is: Peter Bender, Saps Buchman, Robert Byer, Neil Cornish, Peter Fritschel, William Folkner, Stephen Merkowitz

Foreign Co-P/Is: Karsten Danzmann, Luciano DiFiore, Seiji Kawamura, Bernard Schutz, Alberto Vecchio, Stefano Vitale

Collaborators: John Armstrong, Fabrizio Barone, Charles Bennett, Jordan Camp, Joan Centrella, David Chernoff, Adrian Cruise, Curt Cutler, Frank Estabrook, Jens Gundlach, Gerhard Heinzel, Ronald Hellings, Craig Hogan, James Hough, Scott Hughes, Andrew Jaffe, Barry Kent, William Kinney, Alberto Lobo, Nergis Mavalvala, Thomas Prince, Michael Sandford, Bangalore Sathyaprakash, David

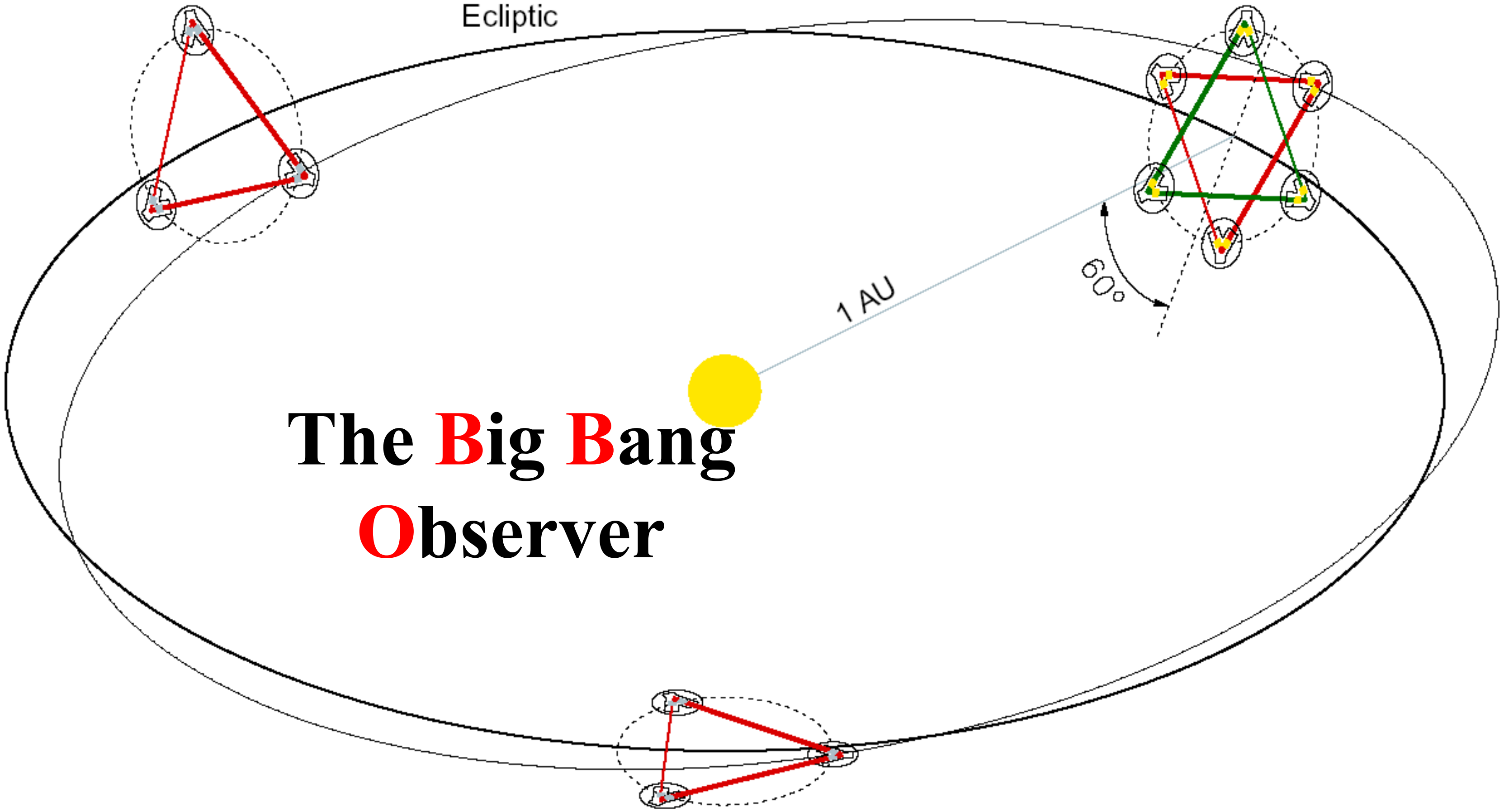
I. Introduction: Primary and Secondary Science Objectives

NASA's 2002 SEU Roadmap *Beyond Einstein* highlights three major unanswered questions raised by Einstein's general theory of relativity:

1. *What powered the Big Bang?*
2. *What happens to space, time and matter at the edge of a black hole?*
3. *What is the mysterious dark energy pulling the Universe apart?*

The prime scientific objective of the Big Bang Observer (BBO) mission is the direct detection of relic gravitational waves from inflation. When combined with cosmic microwave background inferences about gravitational waves 17 orders of magnitude lower in frequency, the BBO measurements will enable quantitative testing of the theory of inflation (§II.1), addressing the first question above (SEU Objective 1 and RFAs 1a).

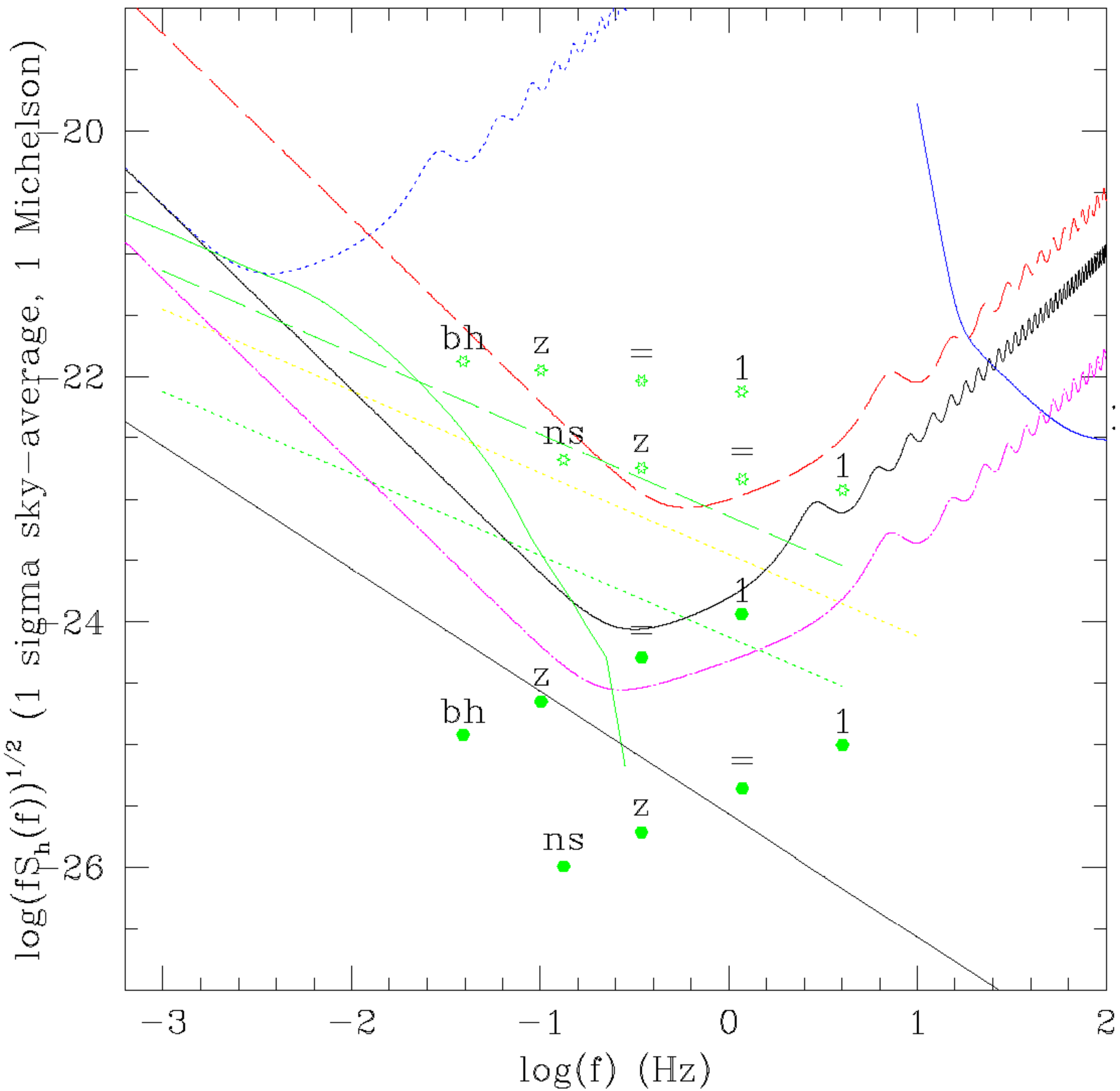
Gravitational waves from inflation have been propagating essentially unchanged (Weinberg 2003) since the universe was $\lesssim 10^{-35}$s old, with temperature $kT \sim 10^{14}$GeV. At



The Big Bang Observer

Table 1: Possible BBO Configurations

name	Laser power W	Laser λ μm	opt eff	arm length km	mirror dia m	Acc noise vs LISA
BBO-lite	100	1.06	0.3	2×10^4	3	0.1
BBO	300	0.5	0.3	5×10^4	3.5	0.01
BBO-grand	500	0.5	0.5	2×10^4	4	0.001

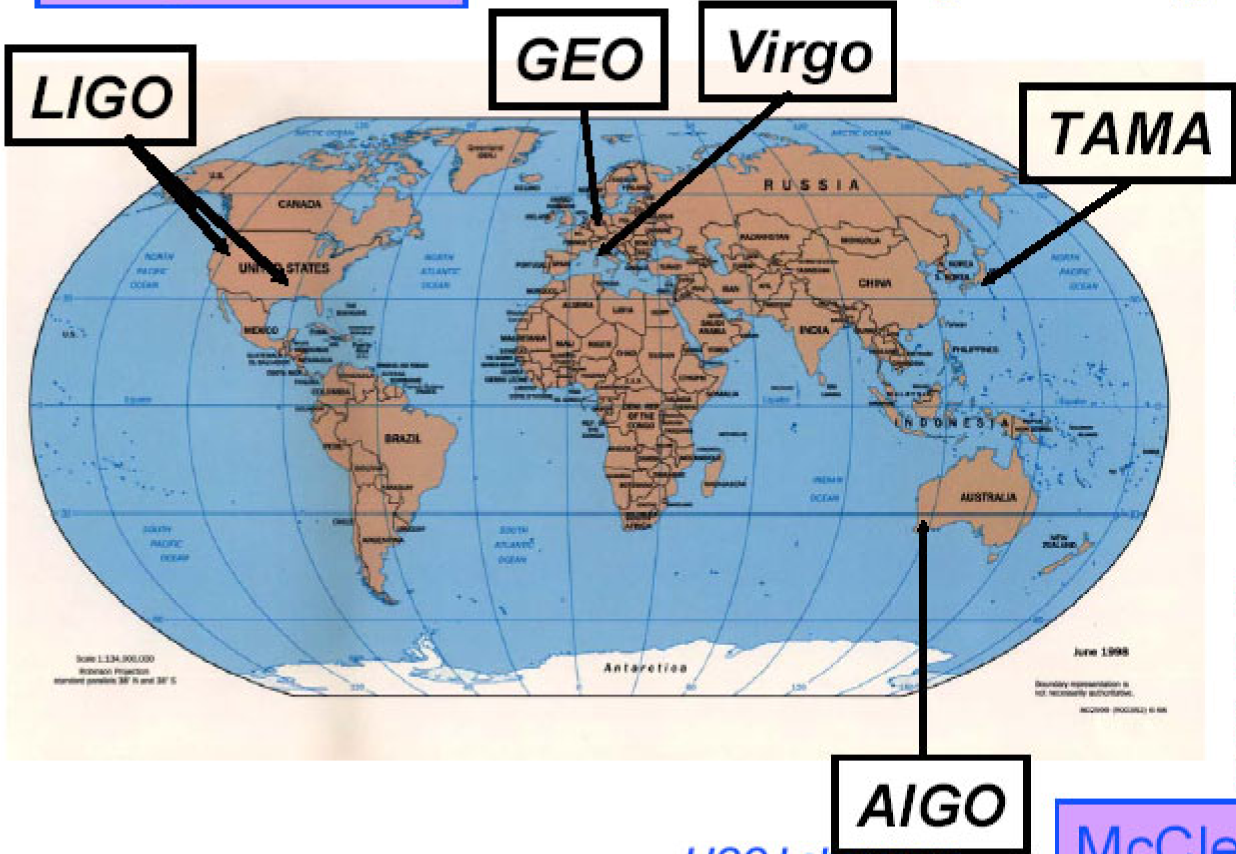

log(fS_h(f))^{1/2} (1 sigma sky-average, 1 Michelson)
-20
-22
-24
-26
-3
-2
-1
0
1
2
log(f) (Hz)
bh
z
=
1
ns
z
=
1
1
=
z
bh
1
=
z
ns

LIGO

An International Network of Interferometers

Hough, Willke

Simultaneously detect signal (within msec)



detection confidence

locate the sources

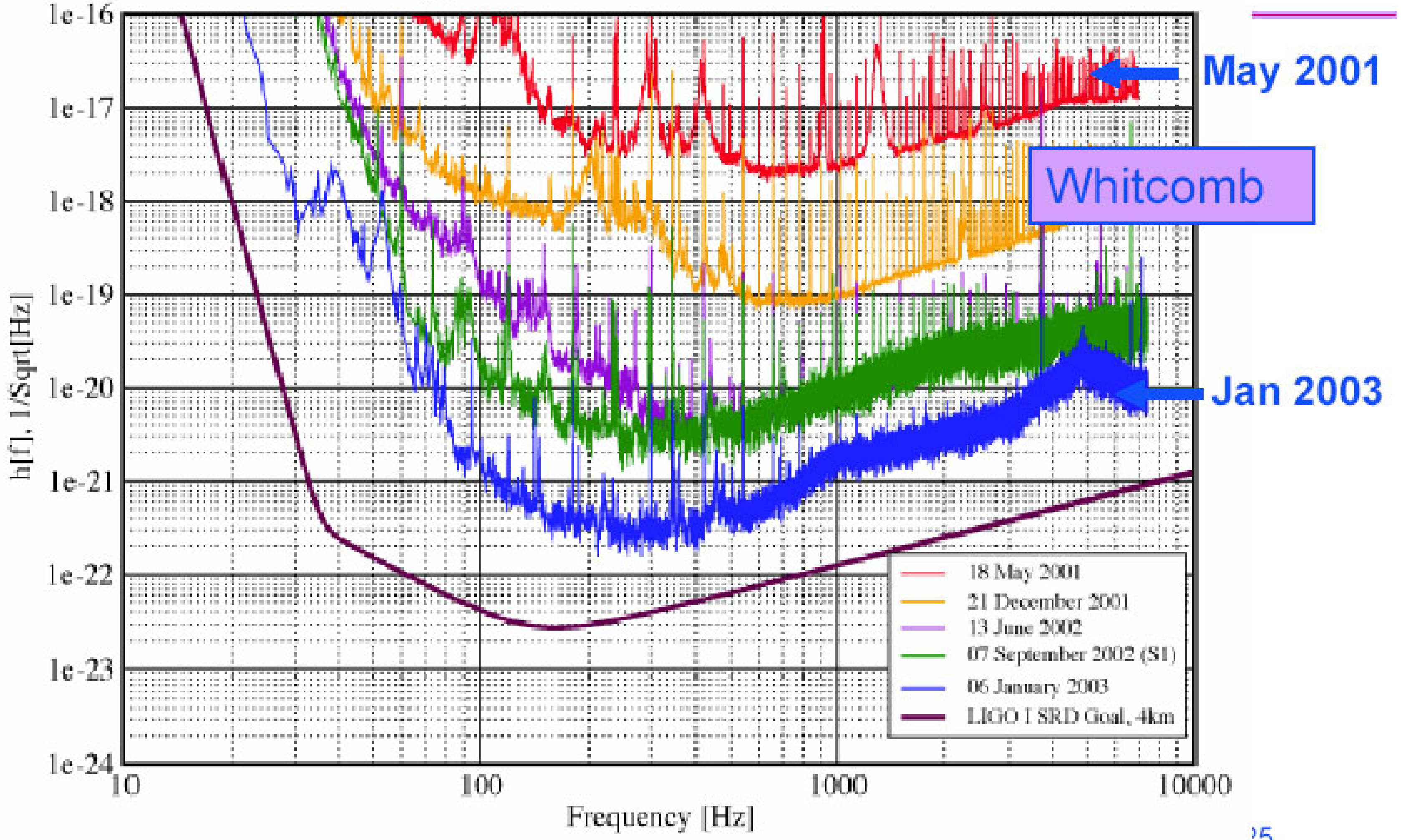
decompose the polarization of gravitational waves

McClelland

LIGO Hanford Observatory

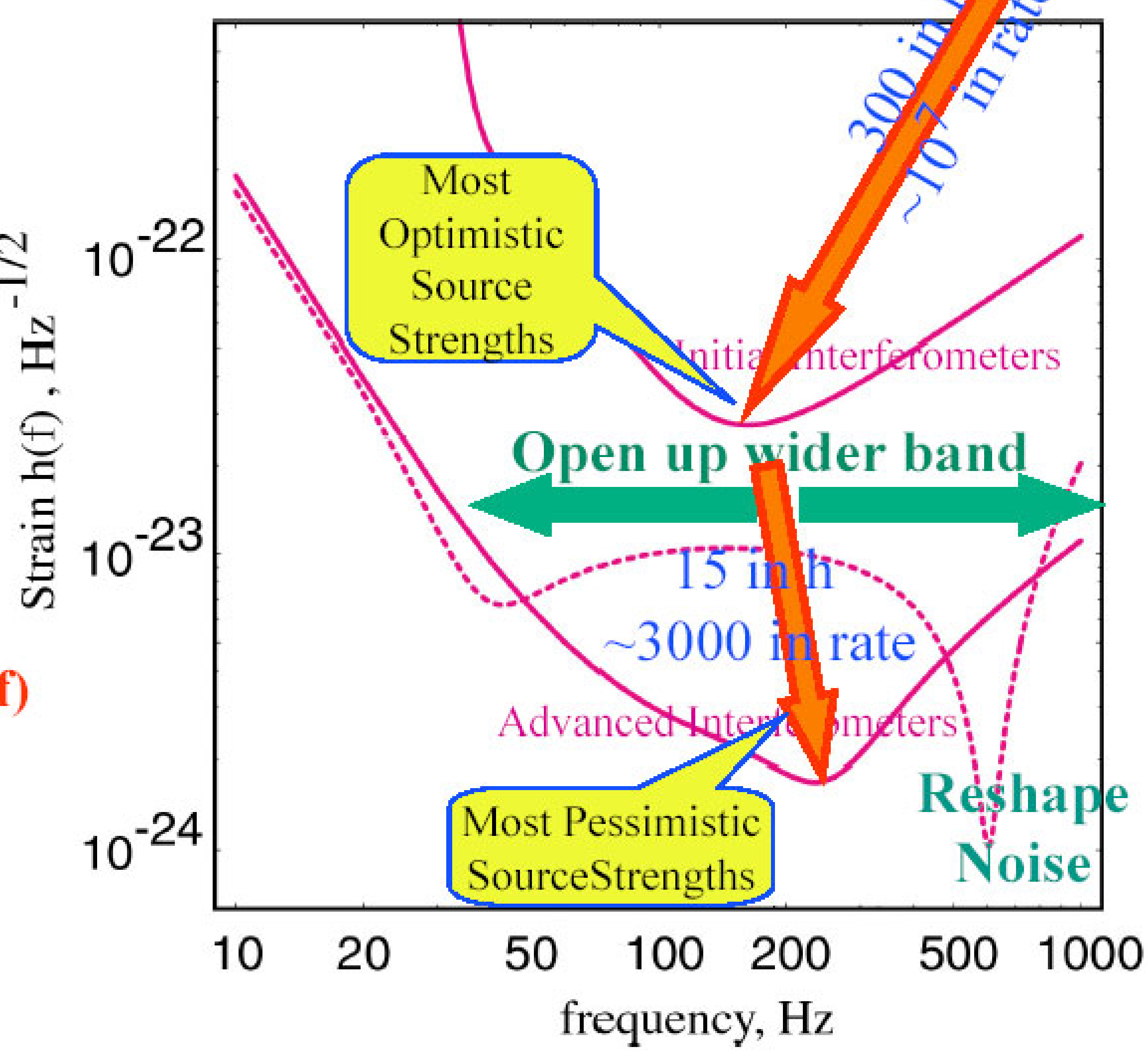
LIGO-G030250-01-M LIGO Laboratory 18

LIGO Sensitivity Livingston 4km Interferometer



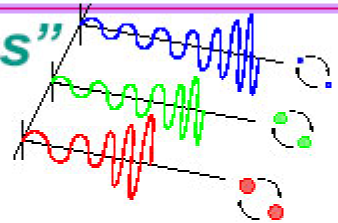
From Initial Interferometers to Advanced

$h_{rms} = h(f) \sqrt{f} \sim 10\ h(f)$

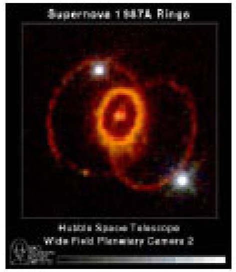


Astrophysical Sources of Gravitational Waves

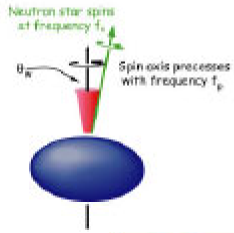
- Compact binary inspiral: *"chirps"*
  - » NS-NS waveforms are well described
  - » BH-BH need better waveforms
  - » search technique: matched templates



Thorne

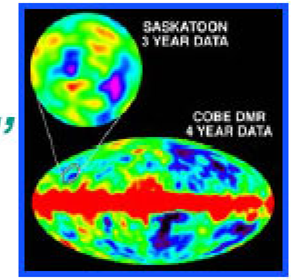


- Supernovae / GRBs: *"bursts"*
  - » burst signals in coincidence with signals in electromagnetic radiation
  - » Challenge to search for untriggered bursts



- Pulsars in our galaxy: *"periodic signals"*
  - » search for observed neutron stars (frequency, doppler shift)
  - » all sky search (computing challenge)
  - » r-modes

- Cosmological Signals *"stochastic background"*



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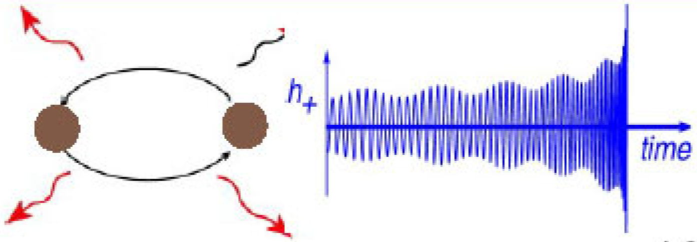
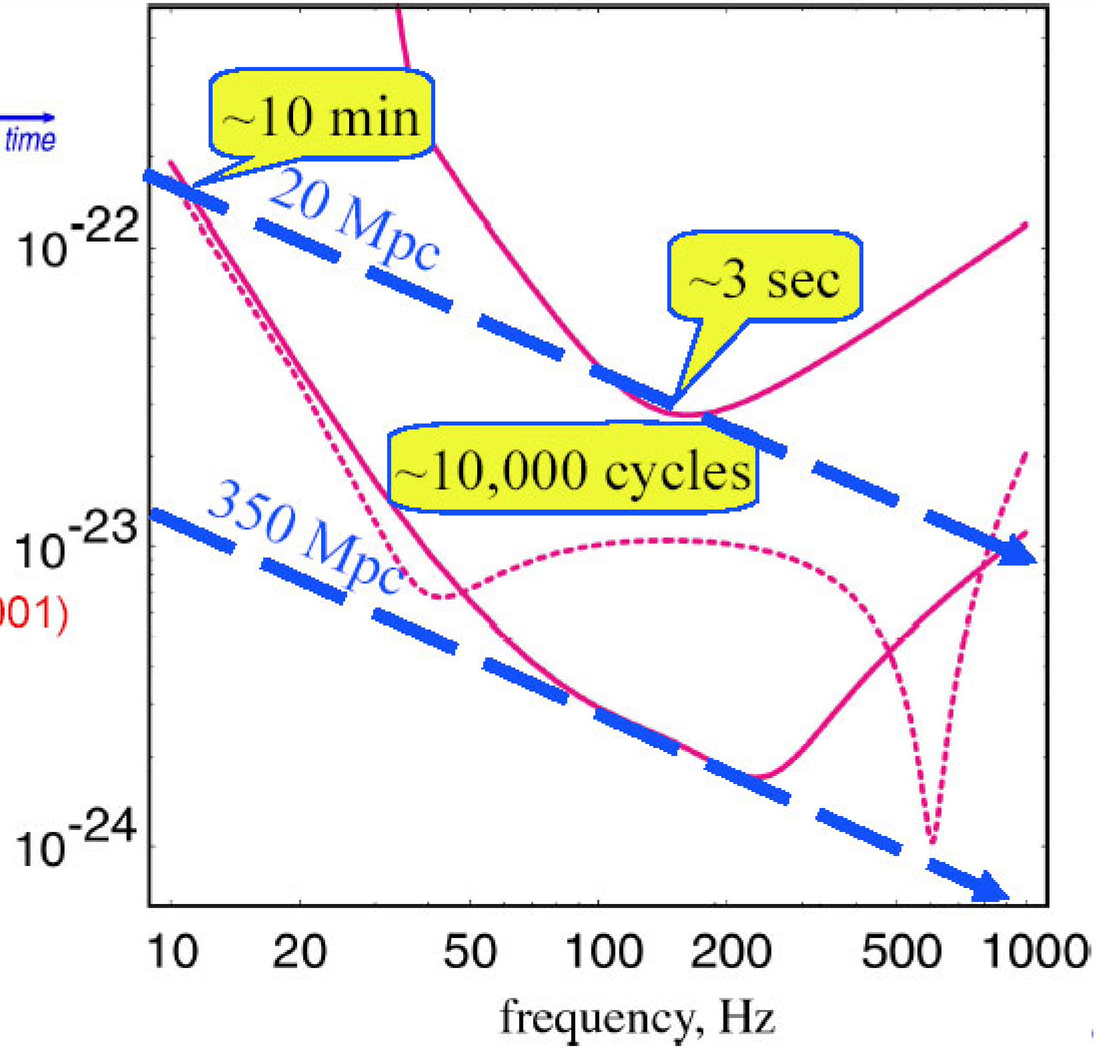
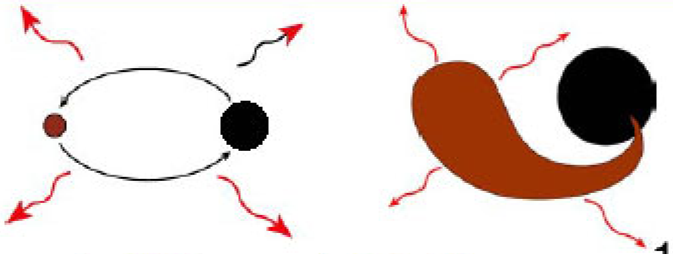
Neutron Star / Neutron Star Inspiral
(our most reliably understood source)



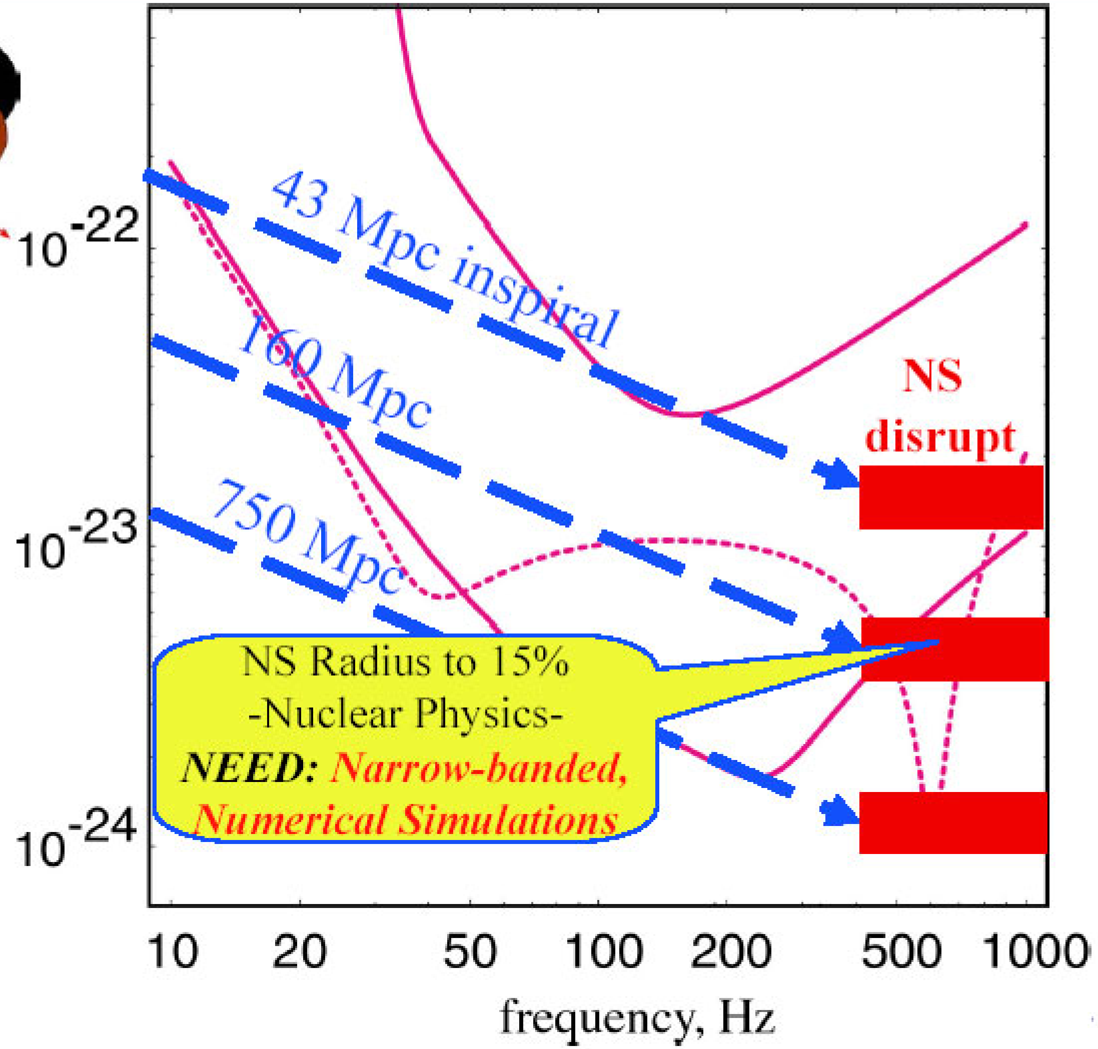
- **1.4 Msun / 1.4 Msun NS/NS Binaries**
- **Event rates**
  - » V. Kalogera, R. Narayan, D. Spergel, J.H. Taylor *Astrophys J,* 556, 340 (2001)
- **Initial IFOs**
  - » Range: 20 Mpc
  - » 1 / 3000 yrs to **1 / 4yrs**
- **Advanced IFOs -**
  - » Range: 350Mpc
  - » **2 / yr to 3 / day**



Neutron Star / Black Hole Inspiral and NS Tidal Disruption

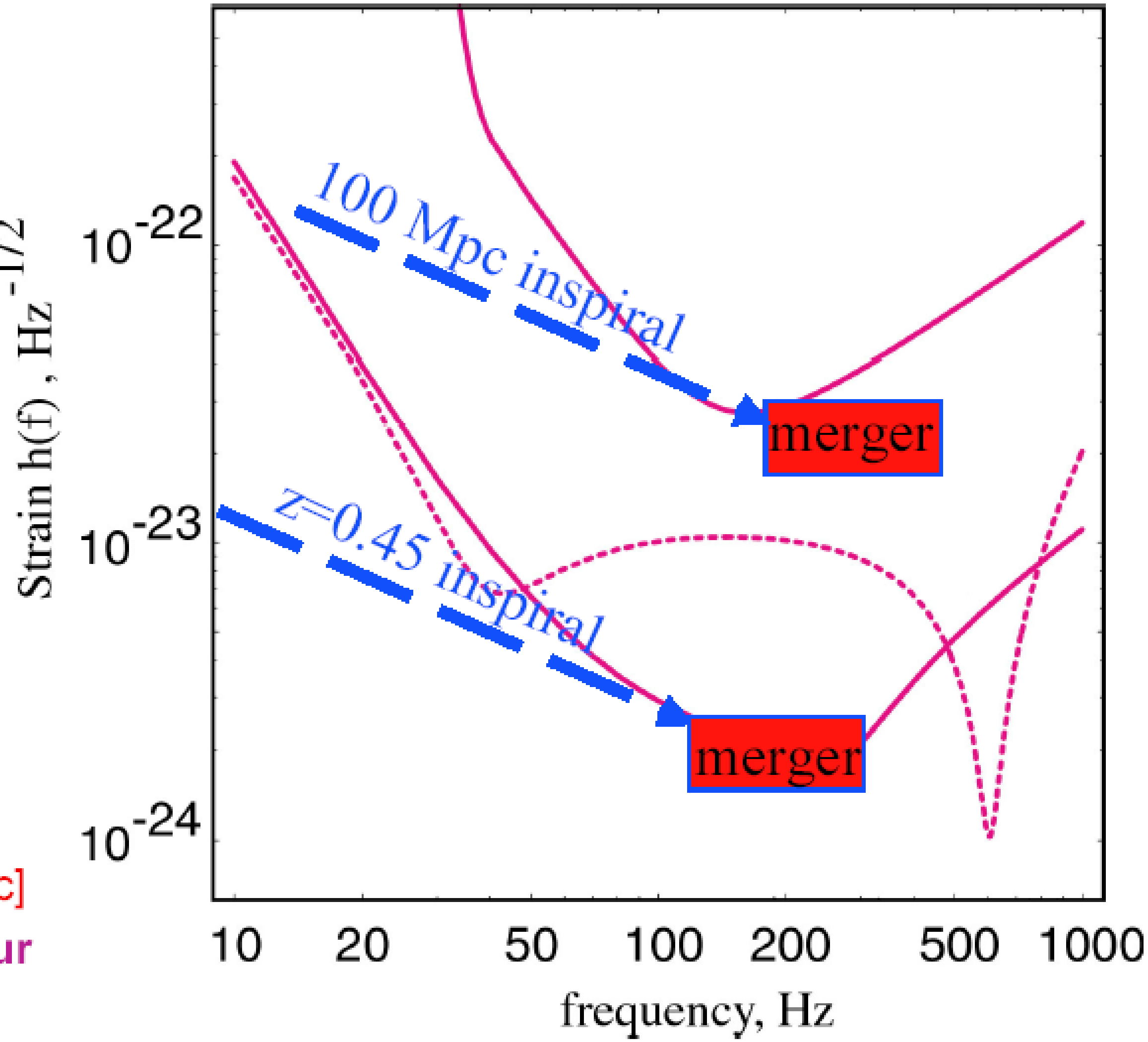


- **1.4Msun / 10 Msun NS/BH Binaries**
- **Event rates**
  - » Population Synthesis [Kalogera's summary]
- **Initial IFOs**
  - » Range: 43 Mpc
  - » 1 / 5000 yrs to **1 / 3yrs**
- **Advanced IFOs**
  - » Range: 750 Mpc
  - » **1 / yr to 4 / day**



Black Hole / Black Hole Inspiral and Merger

- **10Msun / 10 Msun BH/BH Binaries**
- **Event rates**
  - » Population synthesis [Kalogera's summary]
- **Initial IFOs**
  - » Range: 100 Mpc
  - » ~1 / 250 yrs to **~2 / yr**
- **Advanced IFOs -**
  - » Range: z=0.45 [1.7 Gpc]
  - » **~1/ month to ~1 / hour**



LIGO Plans

schedule

1996	Construction Underway (mostly civil)
1997	Facility Construction (vacuum system)
1998	Interferometer Construction (complete facilities)
1999	Construction Complete (interferometers in vacuum)
2000	Detector Installation (commissioning subsystems)
2001	Commission Interferometers (first coincidences)
2002	Sensitivity studies (initiate LIGO I Science Run)
2003+	LIGO I data run (one year integrated data at $h \sim 10^{-21}$)
2007	Begin 'advanced' LIGO installation

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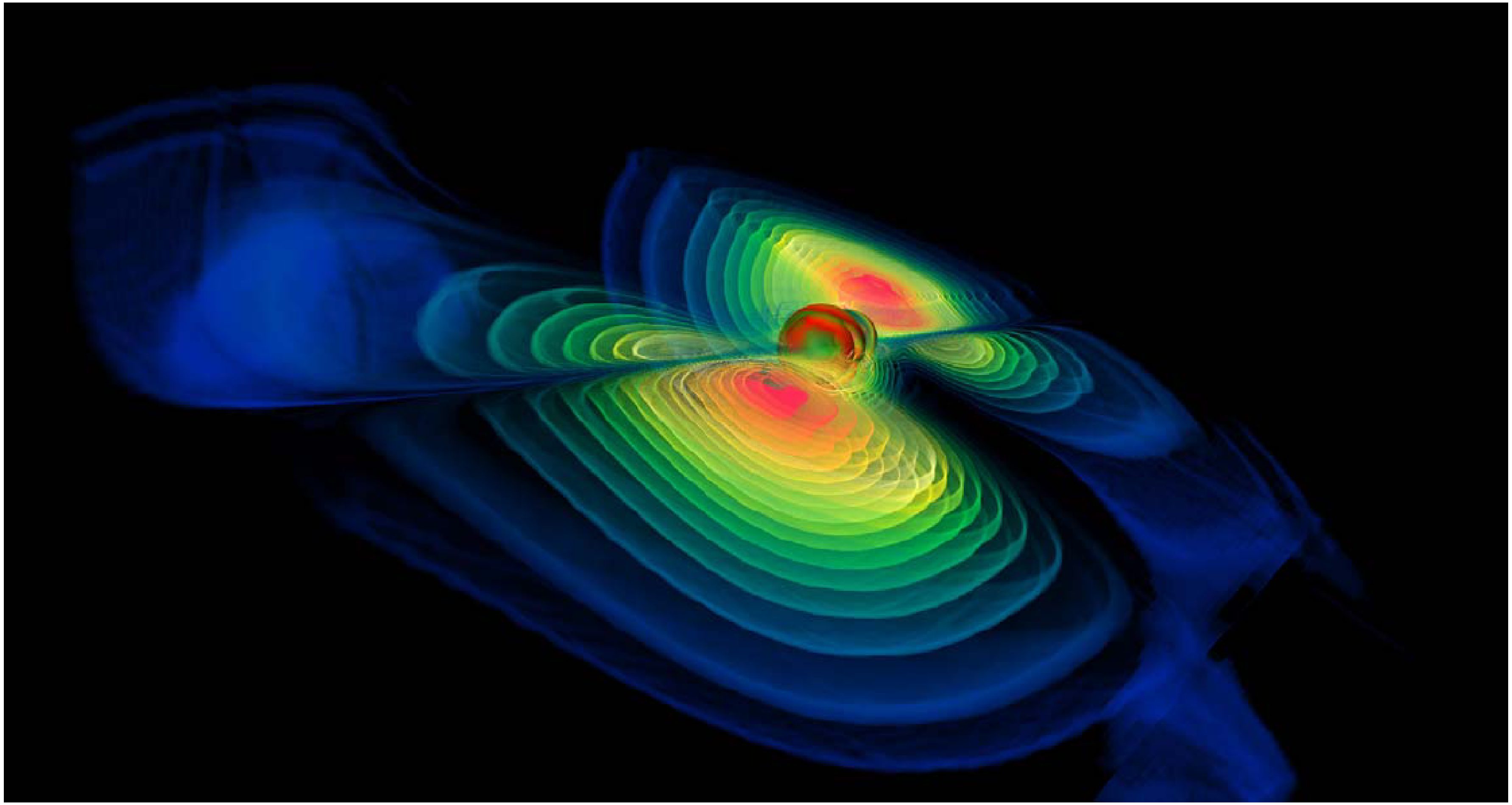
LIGO-G030250-01-M *LIGO Laboratory* 27



"Colliding Black Holes"

Credit:
National Center for Supercomputing Applications (NCSA)