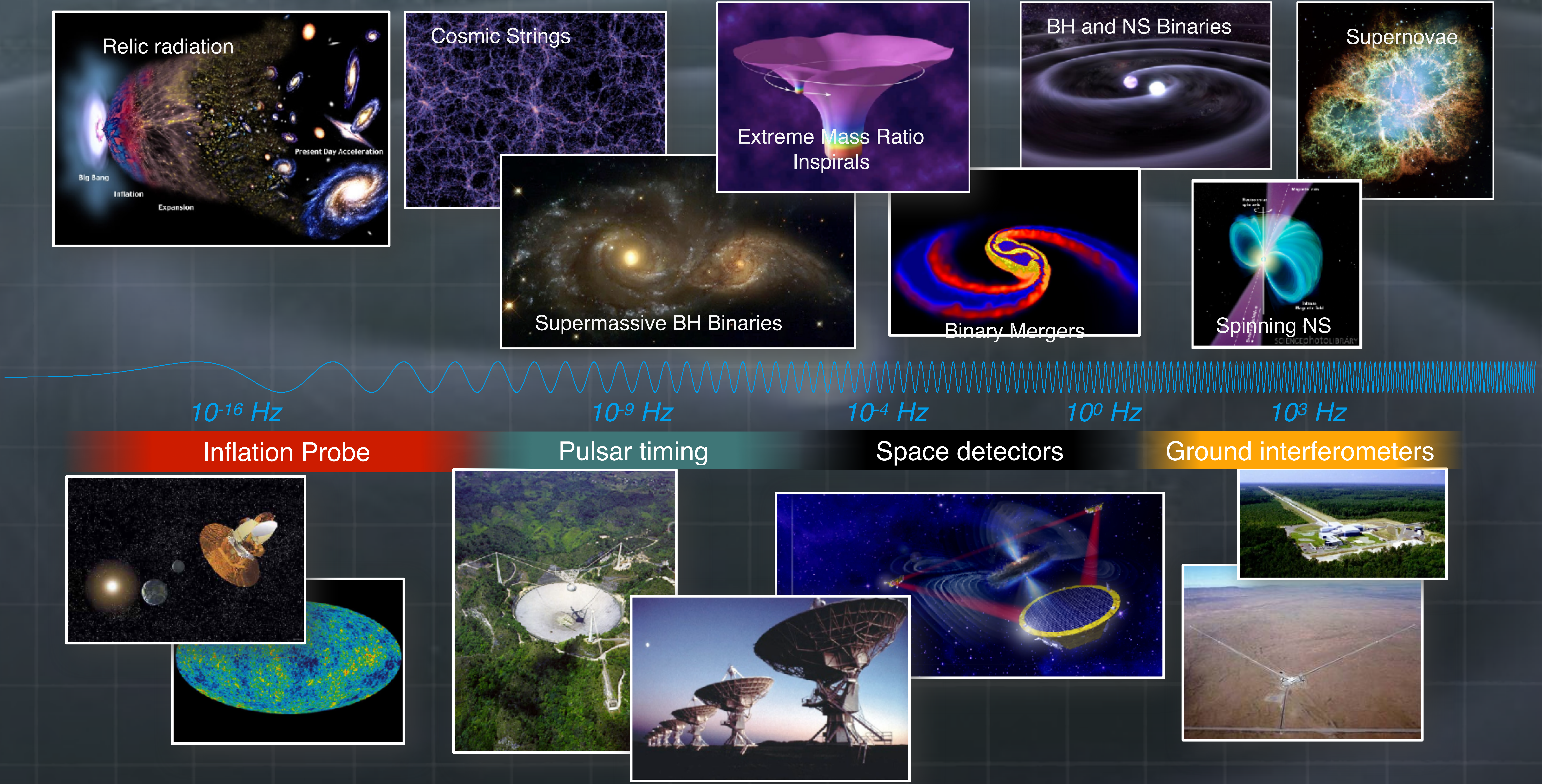
Gravitational Wave Observatories I: History and Status

Neil J. Cornish

eXtreme Gravity Institute

Montana State University

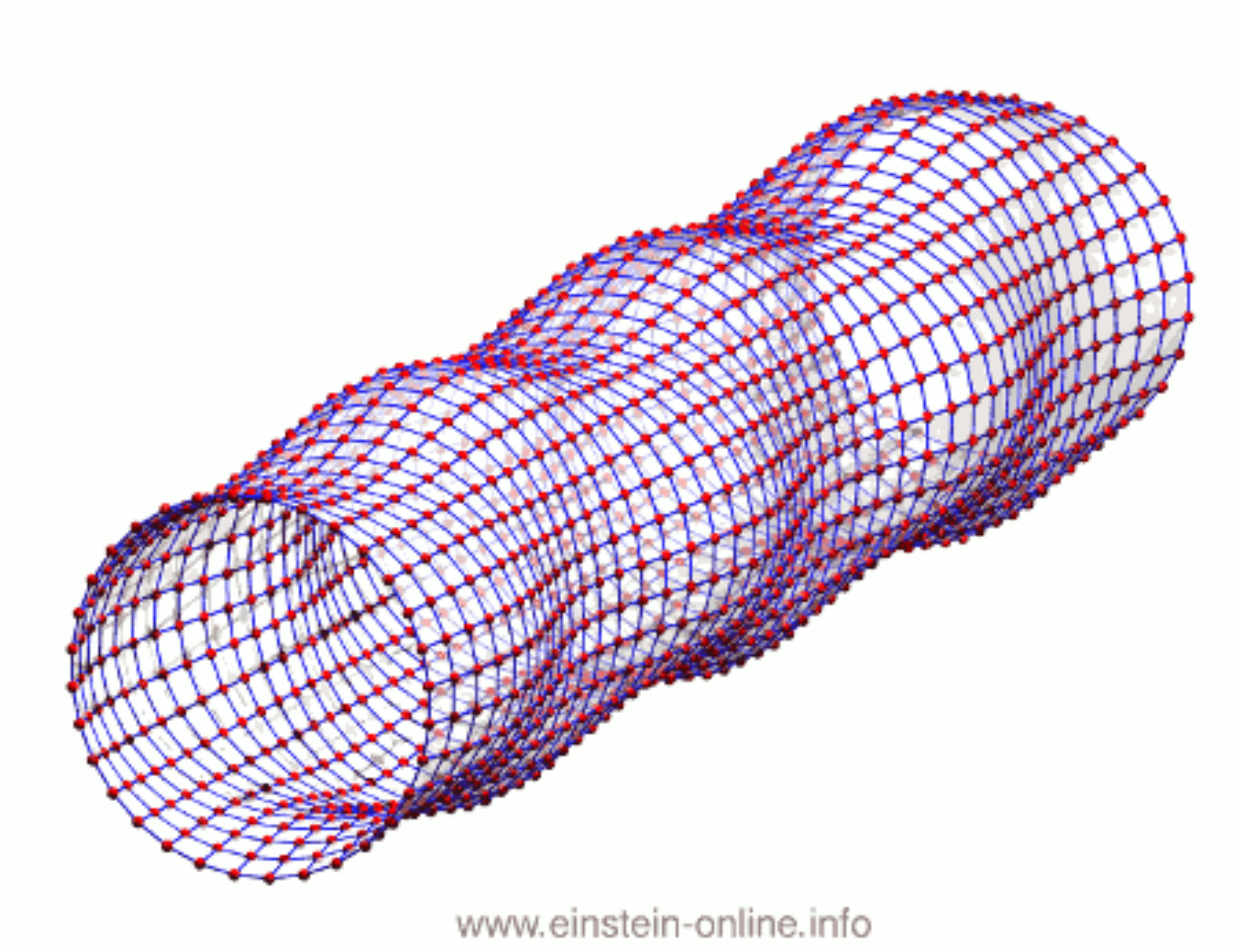
Gravitational Wave Astronomy



Gravitational Wave Detection

Mechanical/Acoustic

Time of flight



Early History

PHYSICAL REVIEW VOLUME 117, NUMBER 1 JANUARY 1, 1960

Detection and Generation of Gravitational Waves*

J. WEBER
University of Maryland, College Park, Maryland
(Received February 9, 1959; revised manuscript received July 20, 1959)

First description of using a mechanical (acoustic) detector

SOVIET PHYSICS JETP VOLUME 16, NUMBER 2 FEBRUARY, 1963

ON THE DETECTION OF LOW FREQUENCY GRAVITATIONAL WAVES

M. E. GERTSENSHTEĬN and V. I. PUSTOVOĬT

First description of using a Michelson interferometer

November 1971 / Vol. 10, No. 11 / APPLIED OPTICS 2495

Photon-Noise-Limited Laser Transducer for Gravitational Antenna

G. E. Moss, L. R. Miller, and R. L. Forward

First experimental tests of a laser interferometer, with input from Chapman and Weiss

Rai Weiss, 1972 design for what became LIGO

QUARTERLY PROGRESS REPORT

No. 105

APRIL 15, 1972

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
RESEARCH LABORATORY OF ELECTRONICS
CAMBRIDGE, MASSACHUSETTS 02139

B. ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

1. Introduction

The prediction of gravitational radiation that travels at the speed of light has been an essential part of every gravitational theory since the discovery of special relativity. In 1918, Einstein,[1] using a weak-field approximation in his very successful geometrical theory of gravity (the general theory of relativity), indicated the form that gravitational waves would take in this theory and demonstrated that systems with time-variant mass quadrupole moments would lose energy by gravitational radiation. It was evident to Einstein that since gravitational radiation is extremely weak, the most likely measurable radiation would come from astronomical sources. For many years the subject of gravitational radiation remained the province of a few dedicated theorists; however, the recent discovery of the pulsars and the pioneering and controversial experiments of Weber[2,3] at the University of Maryland have engendered a new interest in the field.

Weber has reported coincident excitations in two gravitational antennas separated 1000 km. These antennas are high-Q resonant bars tuned to 1.6 kHz. He attributes these excitations to pulses of gravitational radiation emitted by broadband sources concentrated near the center of our galaxy. If Weber's interpretation of these events is correct, there is an enormous flux of gravitational radiation incident on the Earth.

Several research groups throughout the world are attempting to confirm these results with resonant structure gravitational antennas similar to those of Weber. A broadband antenna of the type proposed in this report would give independent confirmation of the existence of these events, as well as furnish new information about the pulse shapes.

The discovery of the pulsars may have uncovered sources of gravitational radiation which have extremely well-known frequencies and angular positions. The fastest known pulsar is NP 0532, in the Crab Nebula, which rotates at 30.2 Hz. The gravitational flux incident on the Earth from NP 0532 at multiples of 30.2 Hz can be 10^{-6} erg/cm^2/s at most. This is much smaller than the intensity of the events measured by Weber. The detection of pulsar signals, however, can be benefited by use of correlation techniques and long integration times.

The proposed antenna design can serve as a pulsar antenna and offers some distinct advantages over high-Q acoustically coupled structures.

2. Description of a Gravitational Wave in the General Theory of Relativity

In his paper on gravitational waves (1918), Einstein showed by a perturbation argument that a weak gravitational plane wave has an irreducible metric tensor in an

GRAVITATIONAL-WAVE ASTRONOMY[1,2]

WILLIAM H. PRESS[3] AND KIP S. THORNE

California Institute of Technology, Pasadena, California

1. INTRODUCTION

The "windows" of observational astronomy have become broader. They now include, along with photons from many decades of the electromagnetic spectrum, extraterrestrial "artifacts" of other sorts: cosmic rays, meteorites, particles from the solar wind, samples of the lunar surface, and neutrinos. With gravitational-wave astronomy, we are on the threshold—or just beyond the threshold—of adding another window; it is a particularly important window because it will allow us to observe phenomena that cannot be studied adequately by other means: gravitational collapse, the interiors of supernovae, black holes, short-period binaries, and perhaps new details of pulsar structure. There is the further possibility that gravitational-wave astronomy will reveal entirely new phenomena—or familiar phenomena in unfamiliar guise—in trying to explain the observations of Joseph Weber.

The future of gravitational-wave astronomy looks bright whether or not

Early claim of detection

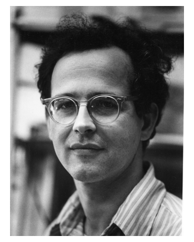
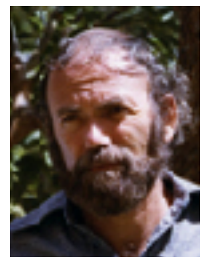
VOLUME 22, NUMBER 24 PHYSICAL REVIEW LETTERS 16 JUNE 1969

EVIDENCE FOR DISCOVERY OF GRAVITATIONAL RADIATION*

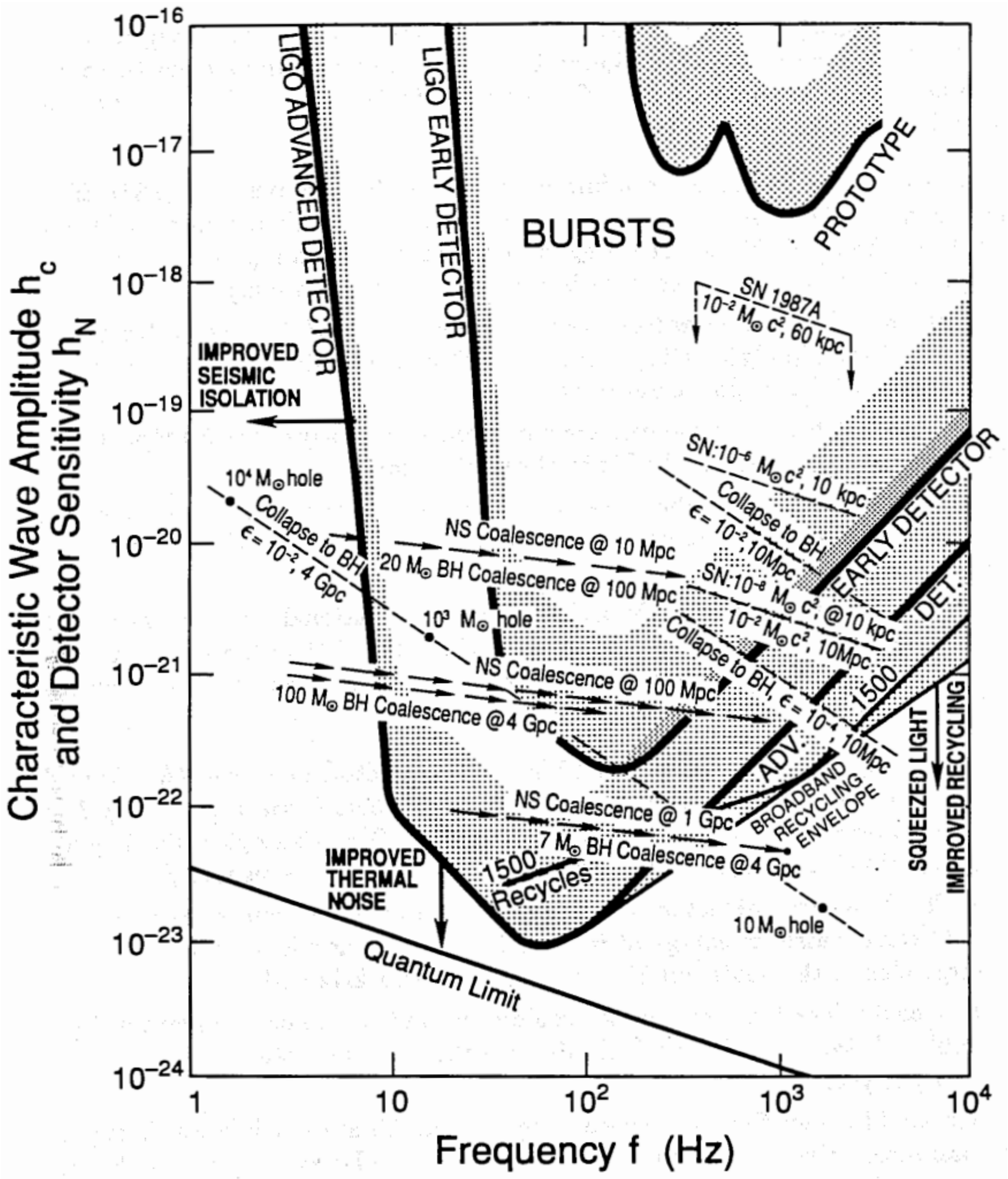
J. Weber
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(Received 29 April 1969)

Coincidences have been observed on gravitational-radiation detectors over a base line of about 1000 km at Argonne National Laboratory and at the University of Maryland. The probability that all of these coincidences were accidental is incredibly small. Experiments imply that electromagnetic and seismic effects can be ruled out with a high level of confidence. These data are consistent with the conclusion that the detectors are being excited by gravitational radiation.

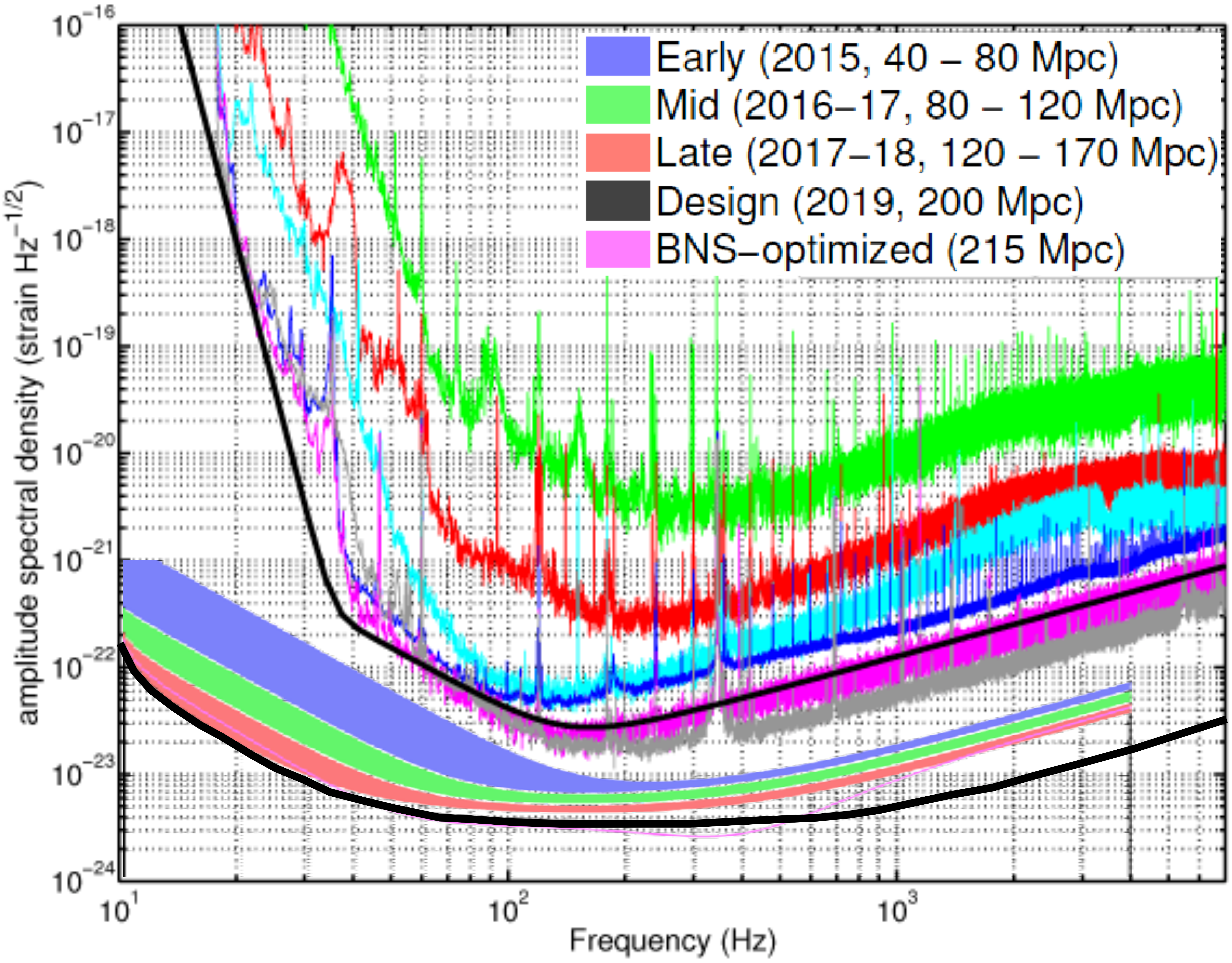
LIGO Timeline

- Conceived in the early 70's, Chapman, Forward, Weiss
- 1984, Caltech and MIT form LIGO collaboration, lead by Drever  Weiss  Thorne 
- 1989 proposal to the National Science Foundation
- 1994 construction approved, Barish  new PI
- 1998 facility construction complete
- 2002 first observing run for the first generation detectors
- 2015 first observing run for the second generation detectors

R. E. Vogt, R. W. P. Drever, K. S. Thorne, F. J. Raab and R. Weiss (Caltech & MIT), “Construction, operation, and supporting research and development of a Laser Interferometer Gravitational-wave Observatory”, proposal to NSF, 1989



LIGO sensitivity over time



GW150914: At last a signal!

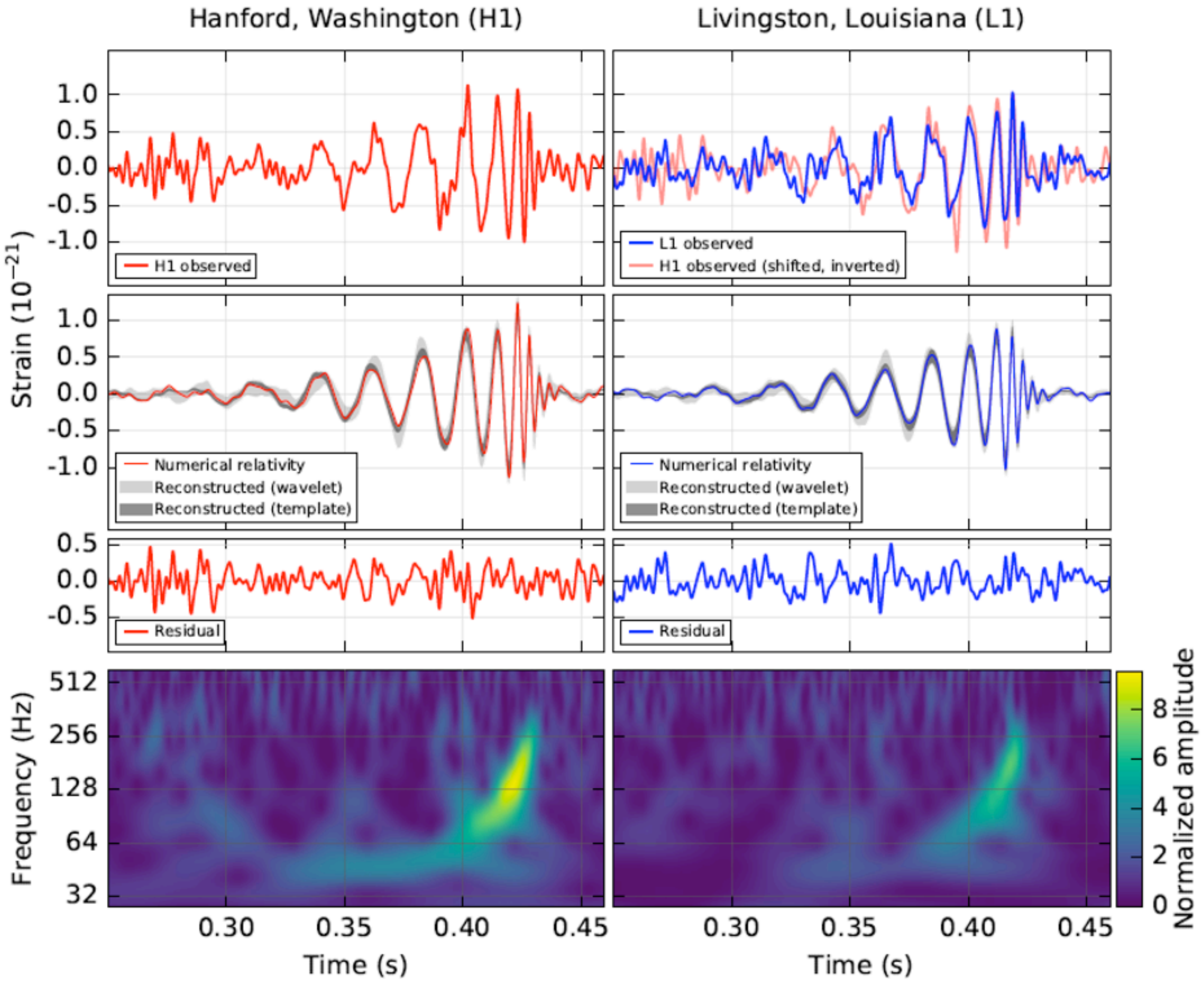
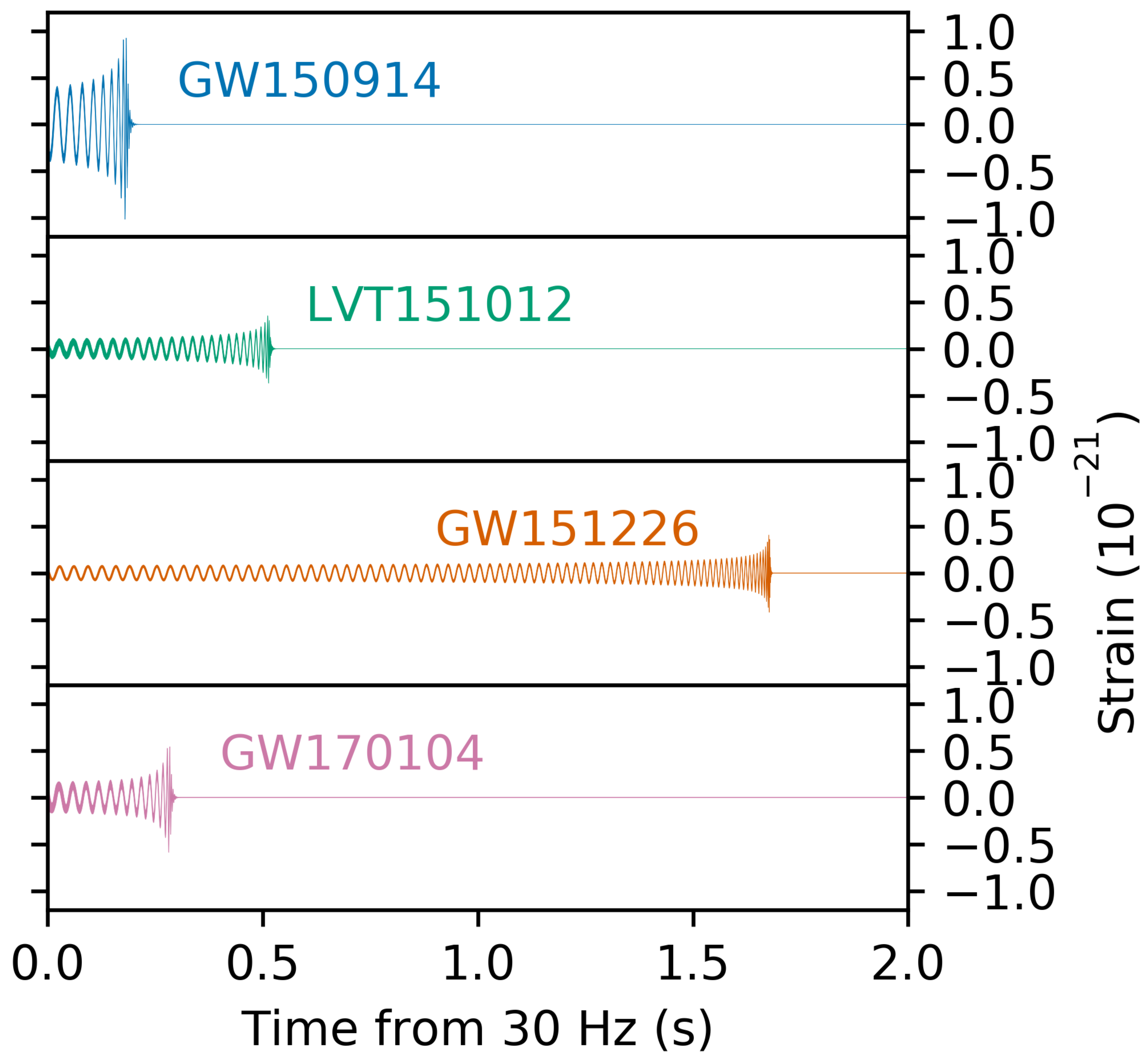
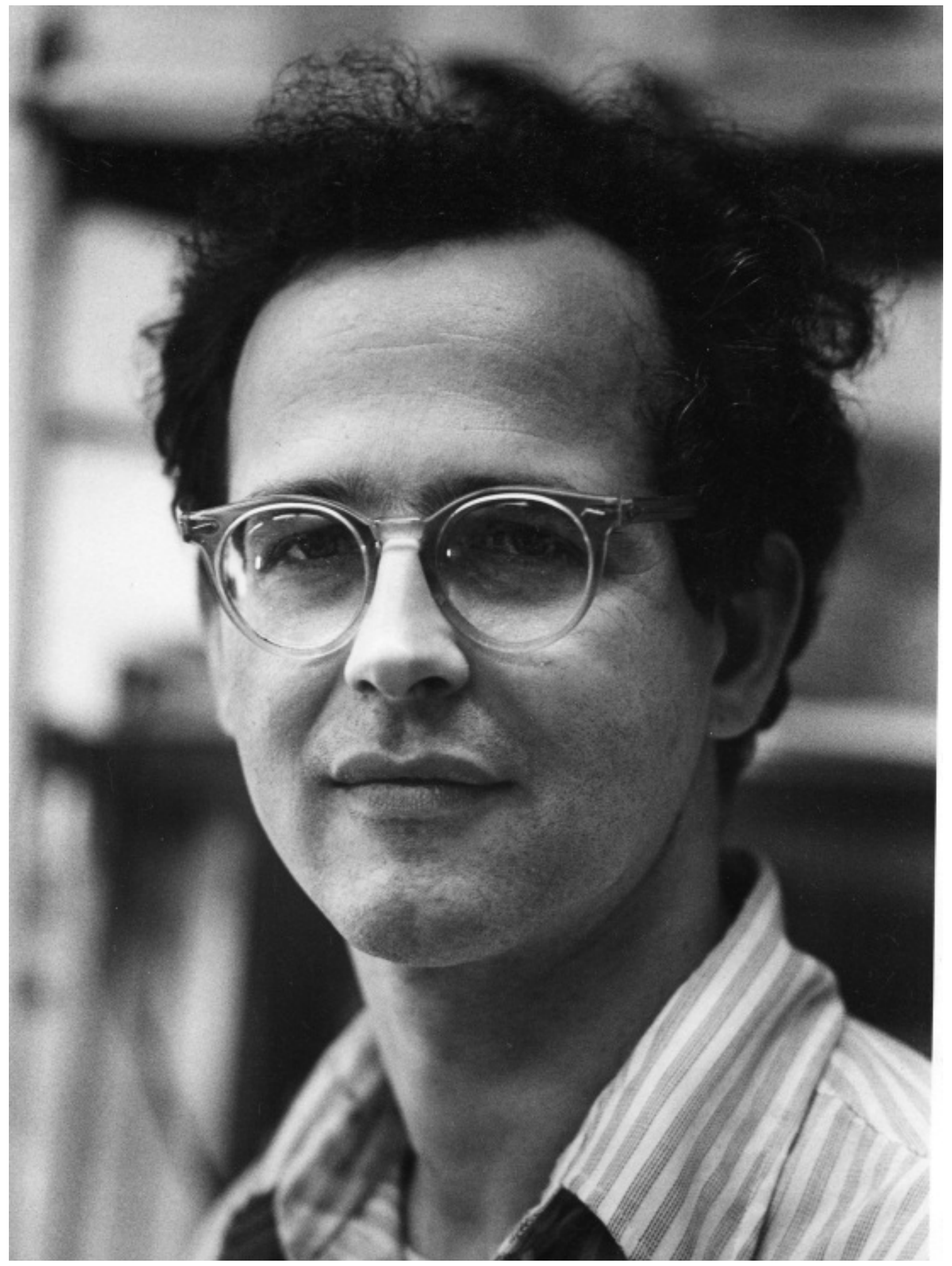


FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series



GW150914: A story 40+ years in the making

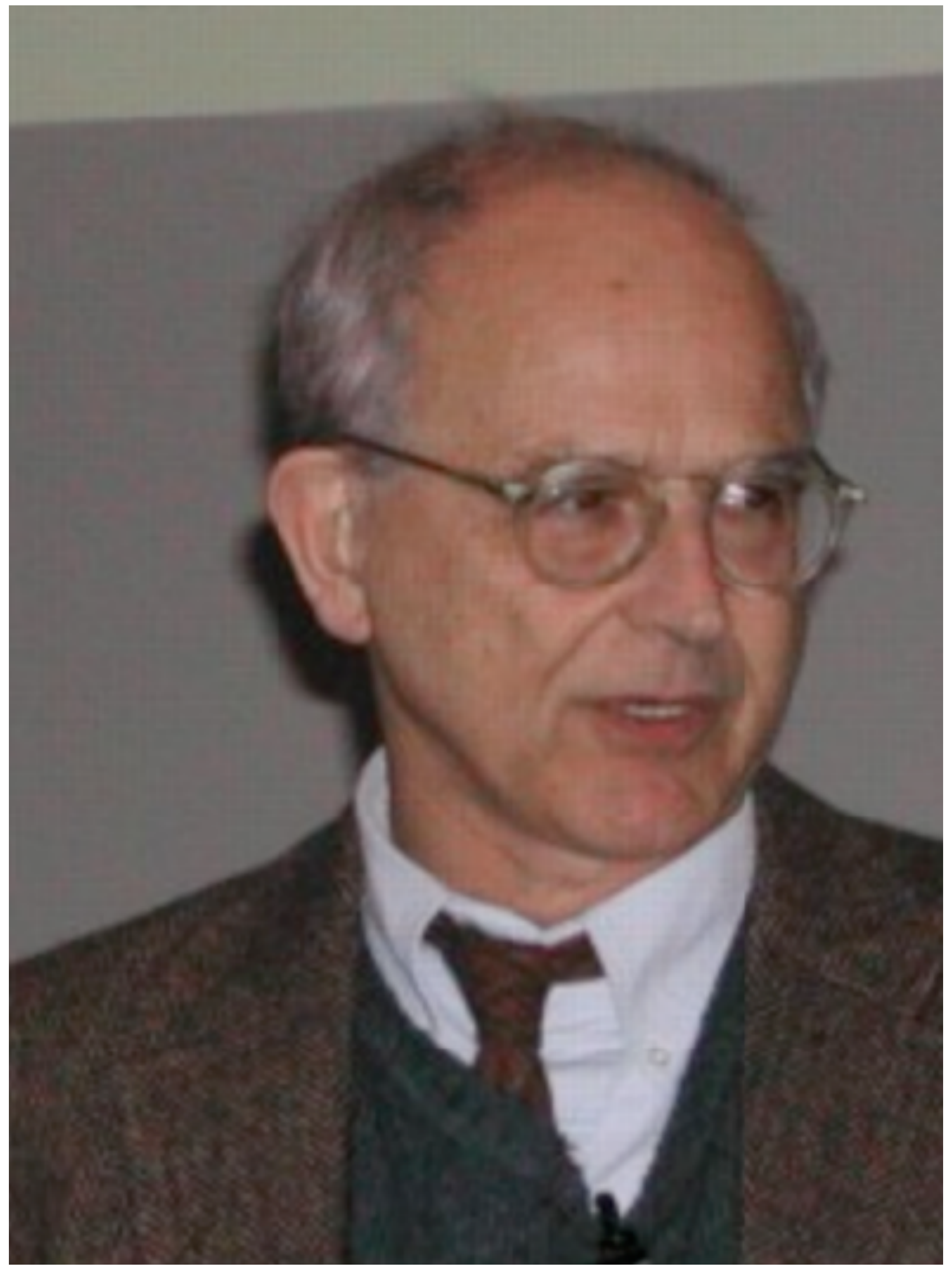


Rai Weiss

Kip Thorne

Ron Drever

GW150914: A story 40+ years in the making



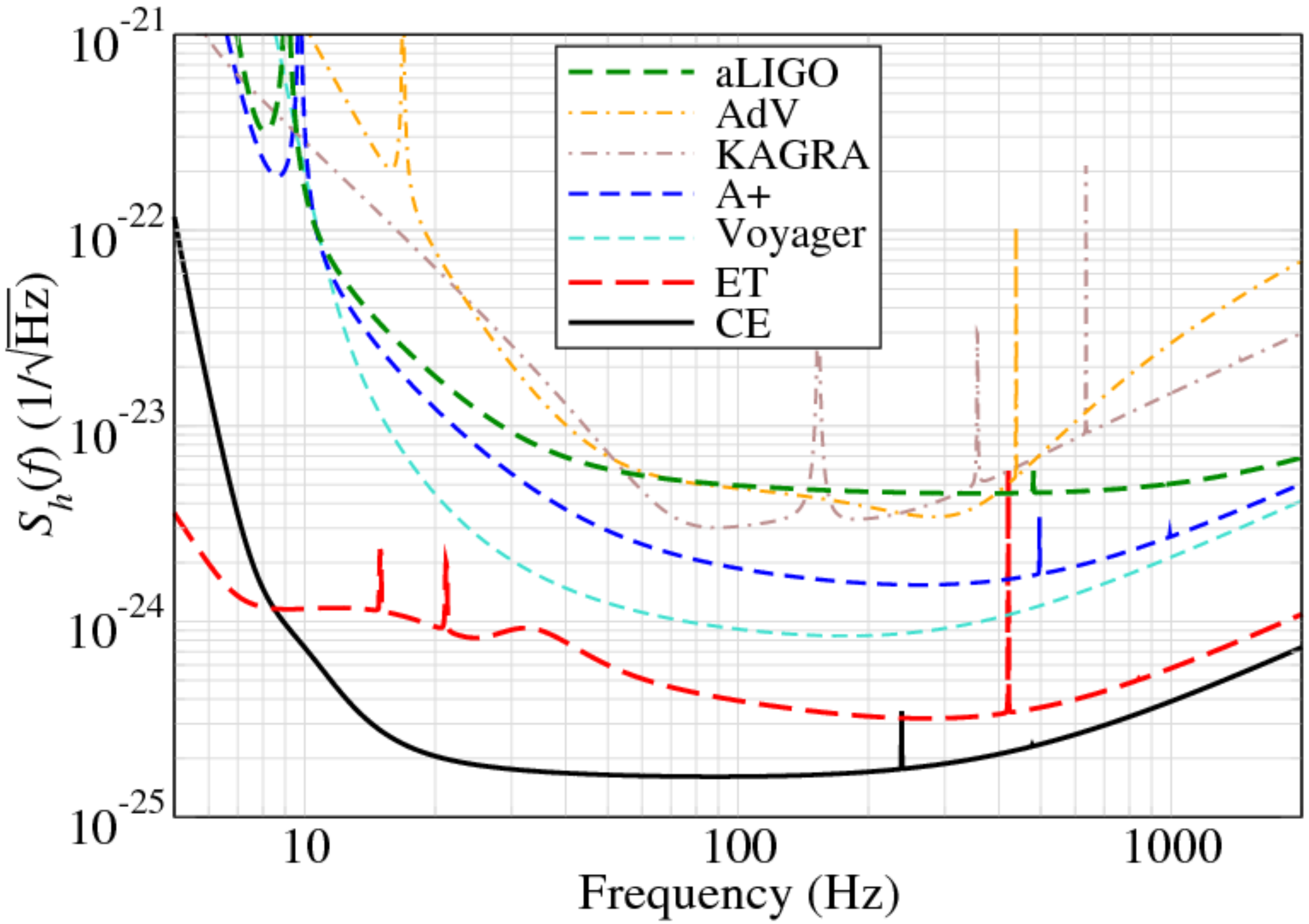
Rai Weiss

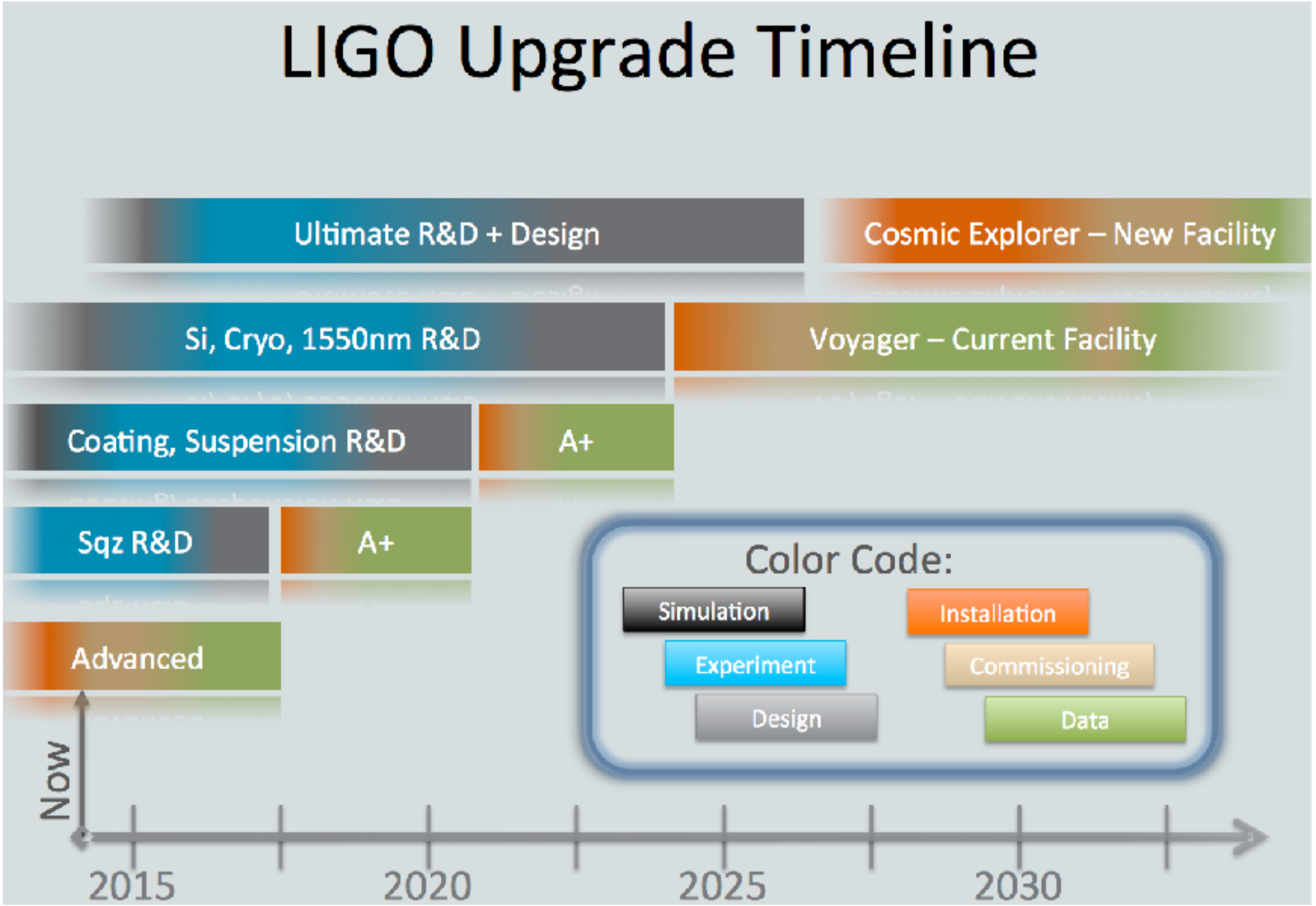
Kip Thorne

Ron Drever


GEO
VIRGO
LIGO H1
LIGO L1
LIGO-India
2023+
KAGRA
2017+
Next steps - a worldwide network

3rd and 4th generation ground-based instruments





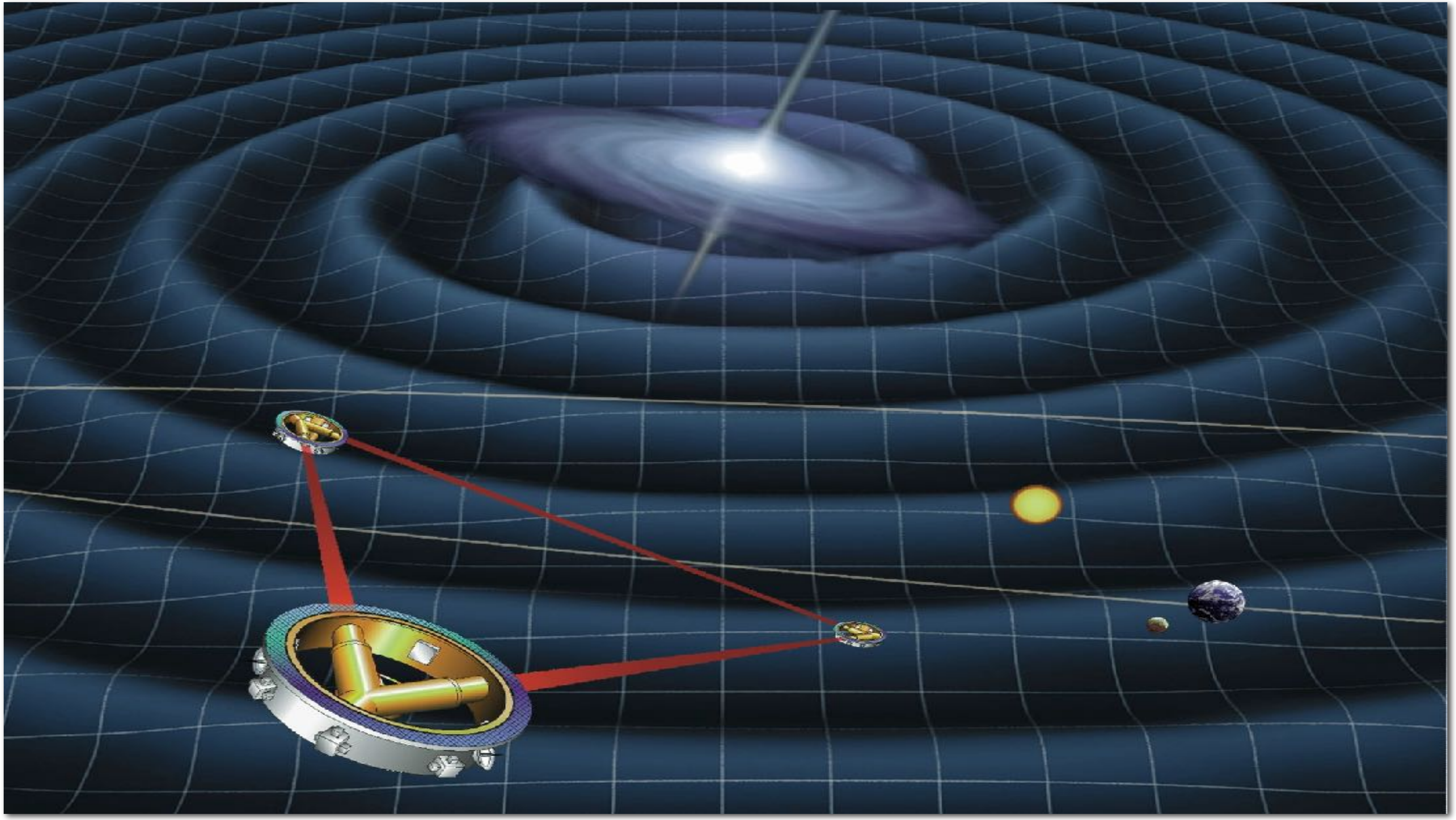
A+: aLIGO upgrade, freq. dep. squeezing, heavier mirrors, more powerful lasers

Voyager: aLIGO upgrade, same facility, cryogenic, more powerful lasers

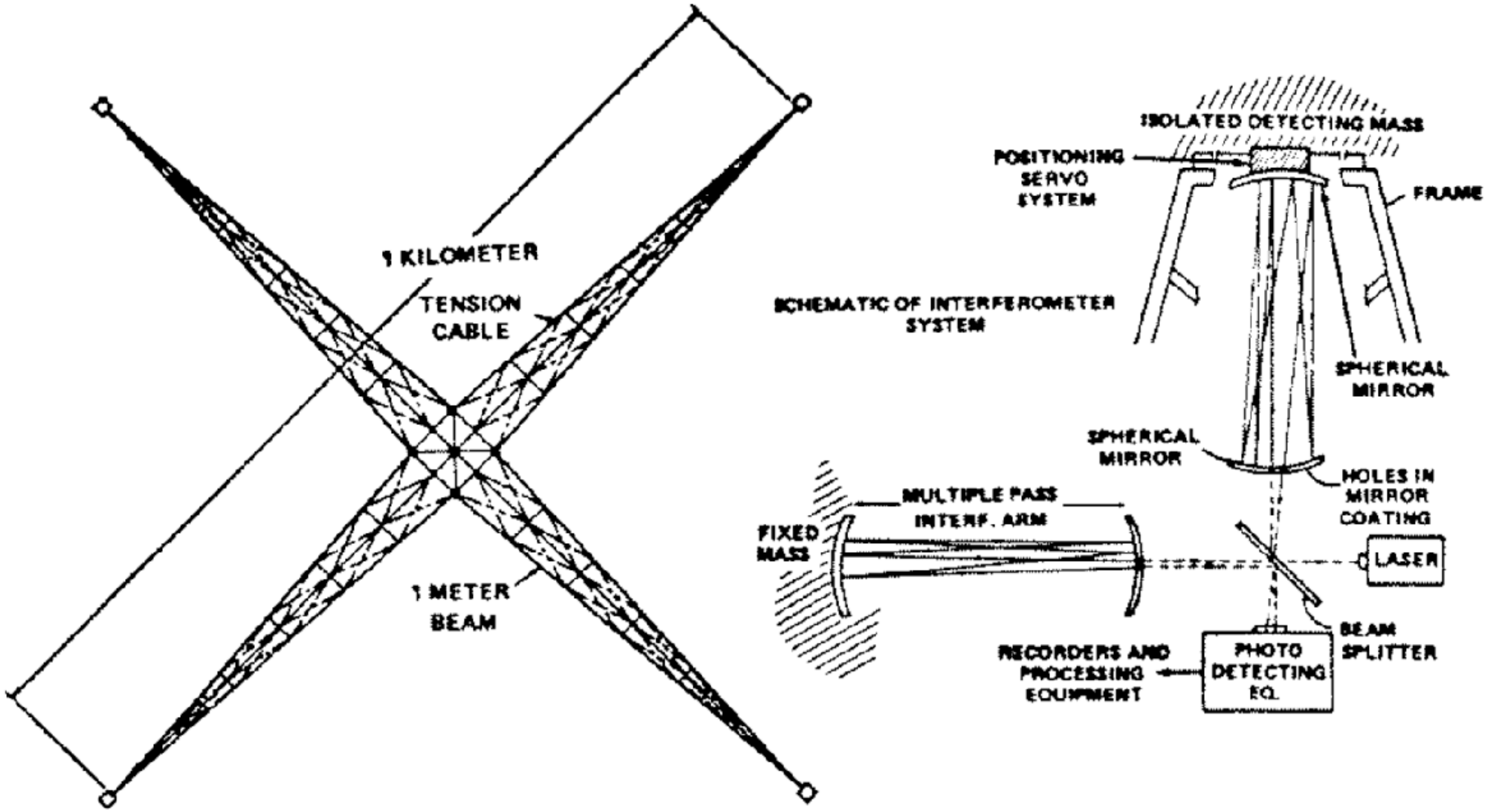
Einstein Telescope: Underground, 10 km, triangular, cryogenic

Cosmic Explorer: New facility, 40 km arms, squeezing etc

Space Interferometers



Gravitational Wave Interferometer: 1974



“LIGO in space”

1978 Design - 16.5 t, $49.5M. Shuttle Launched. To be built in space. Aluminum extruding machine.

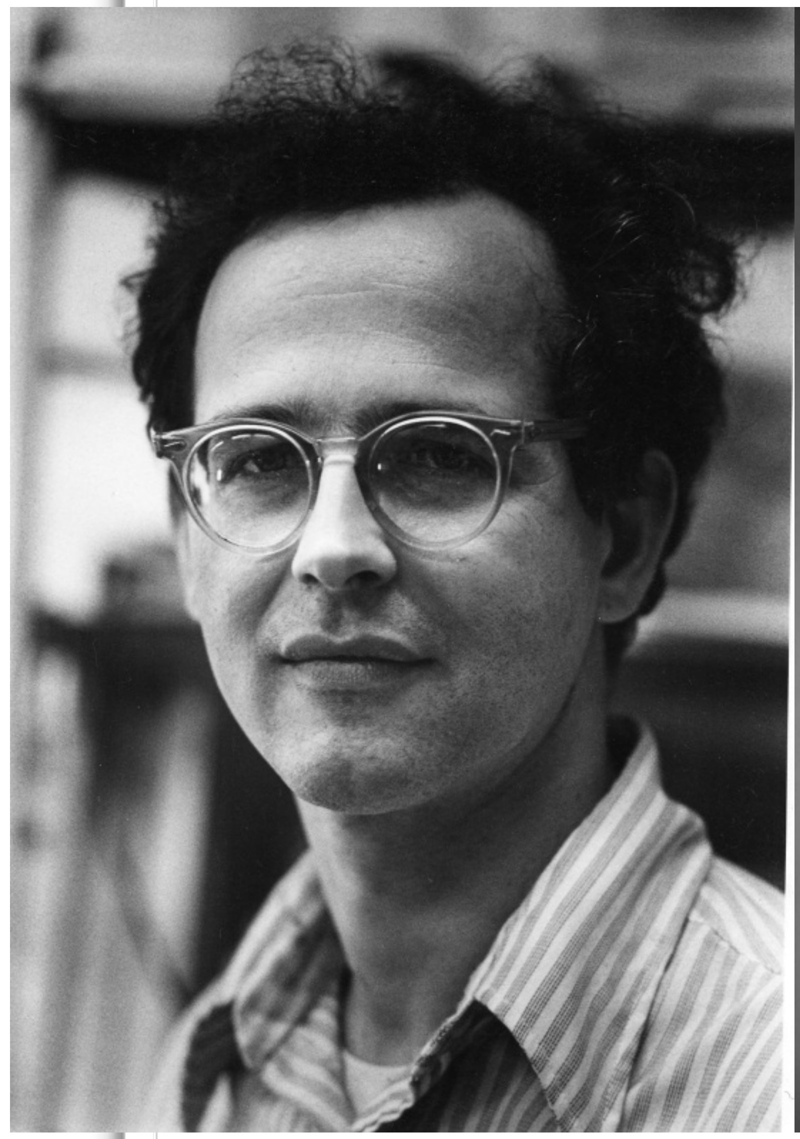
The Weiss Report: 1975

MANAGEMENT AND OPERATIONS

WORKING GROUP FOR SHUTTLE ASTRONOMY

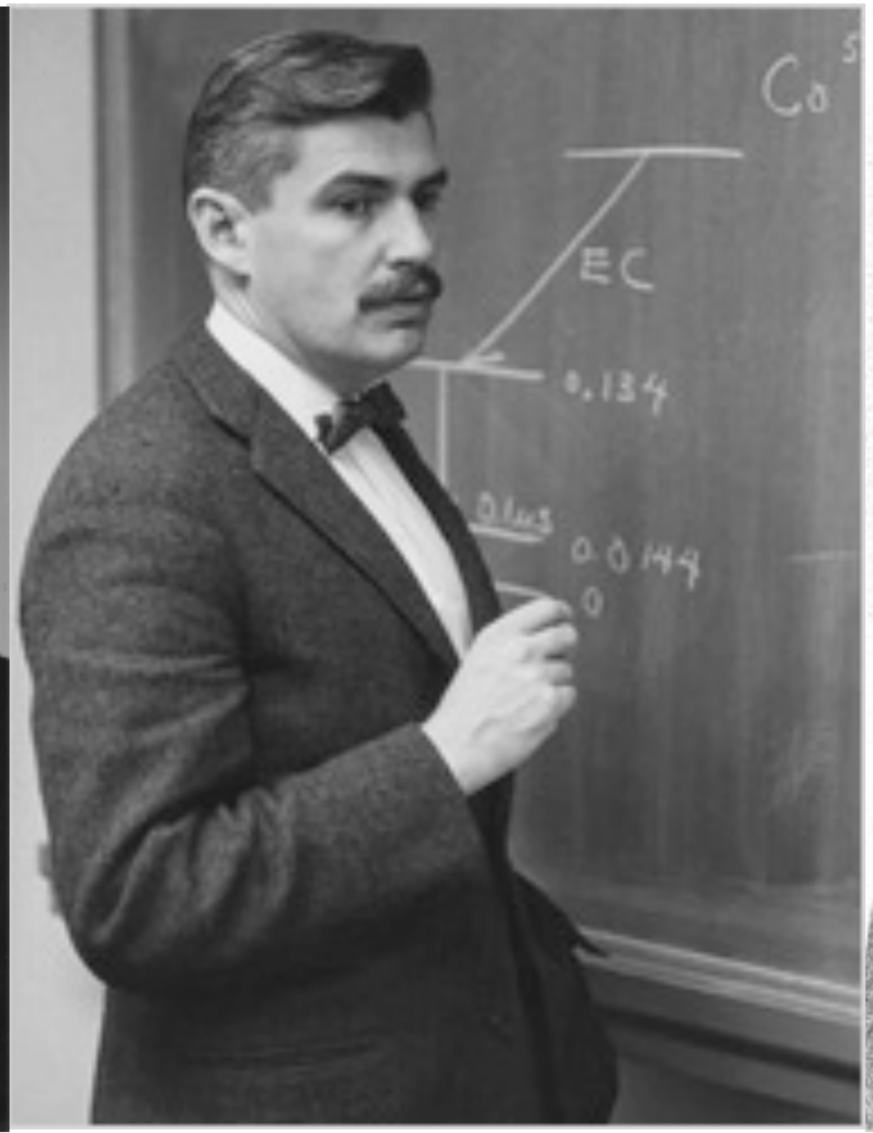
REPORT OF THE SUB-PANEL ON RELATIVITY AND GRAVITATION

Weiss



Bender

Pound

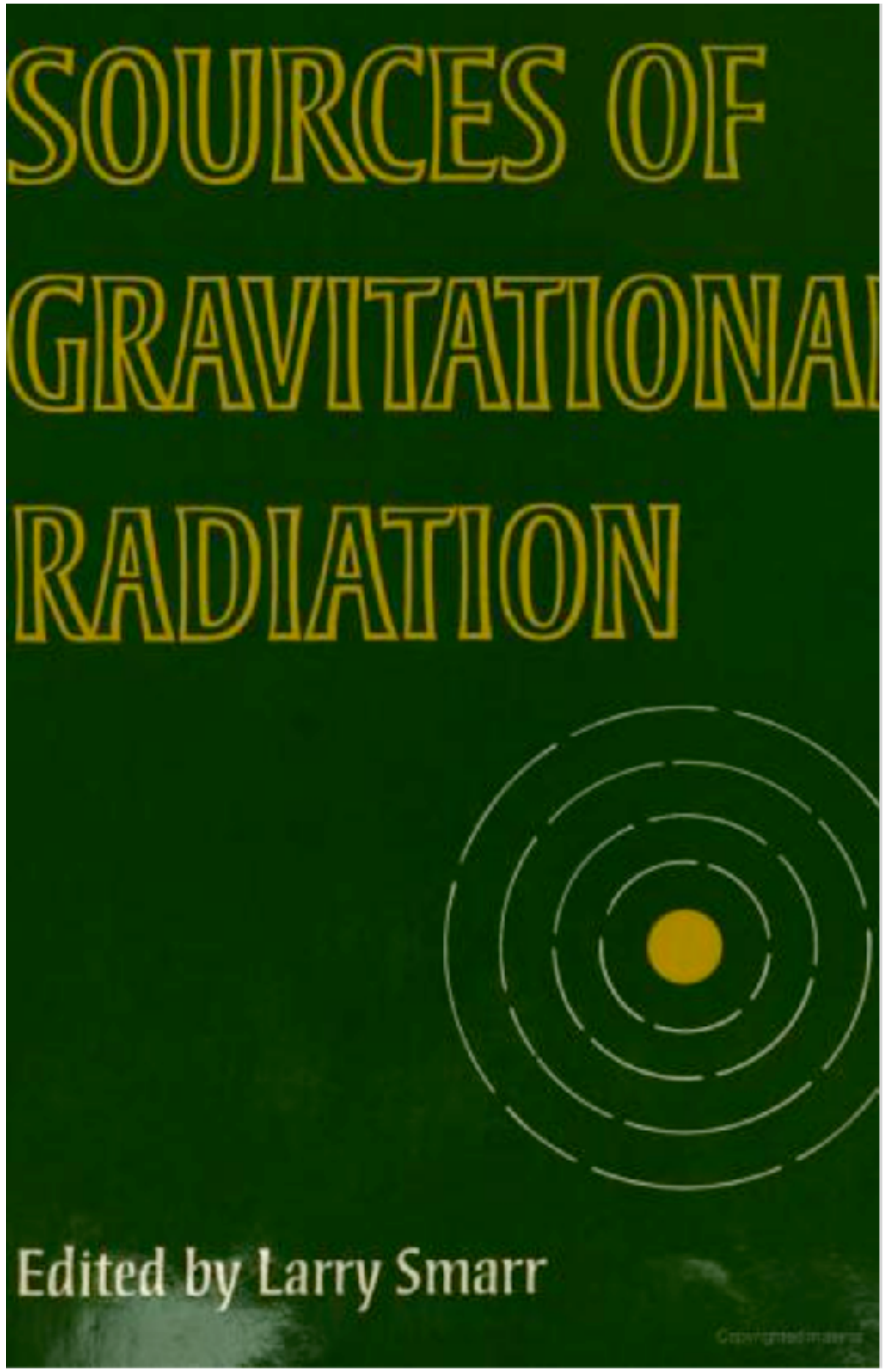


Misner

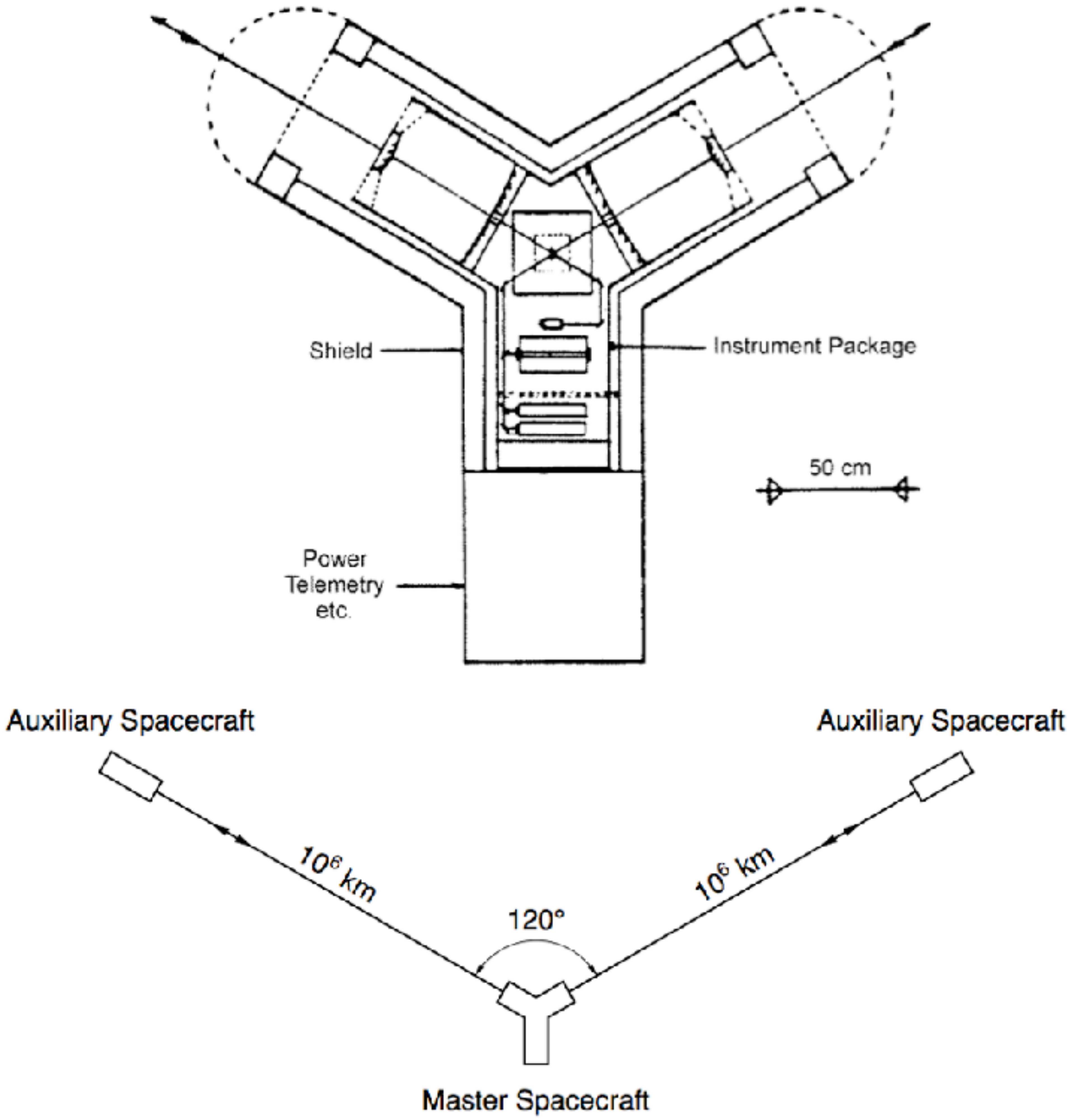
The Weiss Report: 1975

TABLE OF CONTENTS

Battelle Workshop, Seattle July 24-August 4, 1978

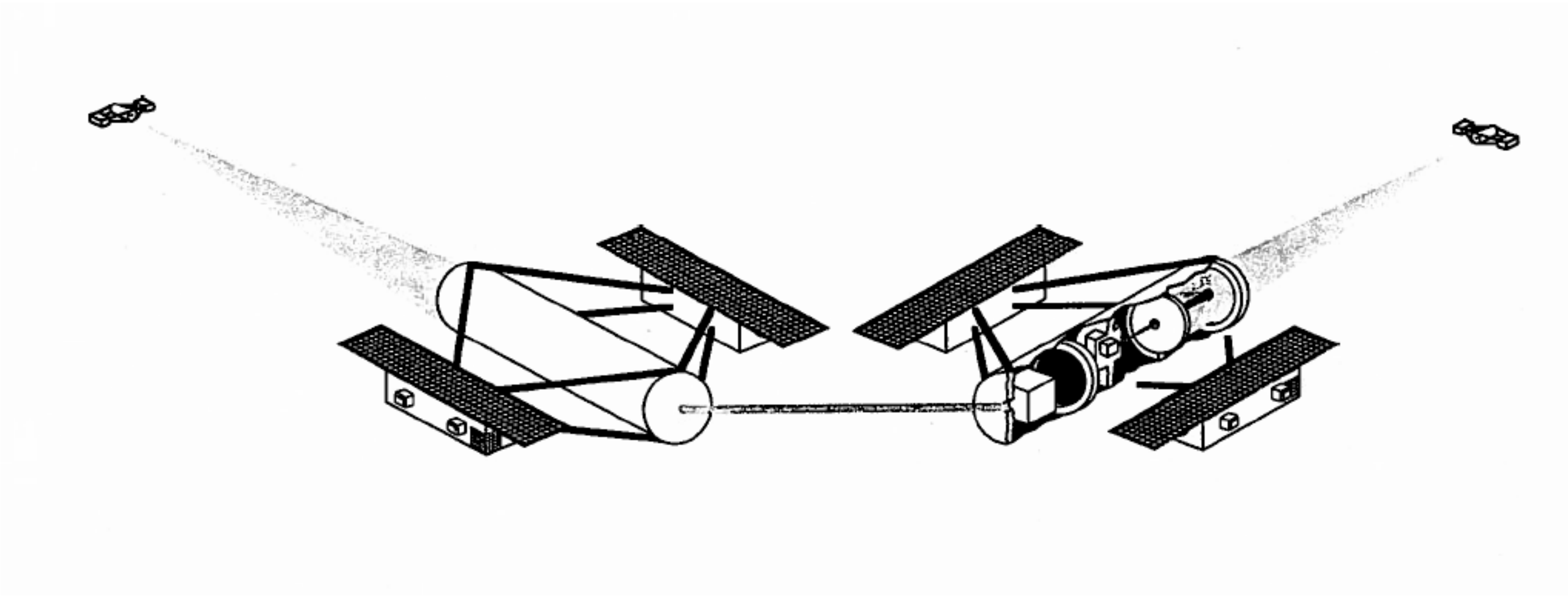


Laser Antenna for Gravitational-radiation Observation in Space (LAGOS): 1981



Faller & Bender 1981
Faller, Bender, Hall, Hils & Vincent 1985

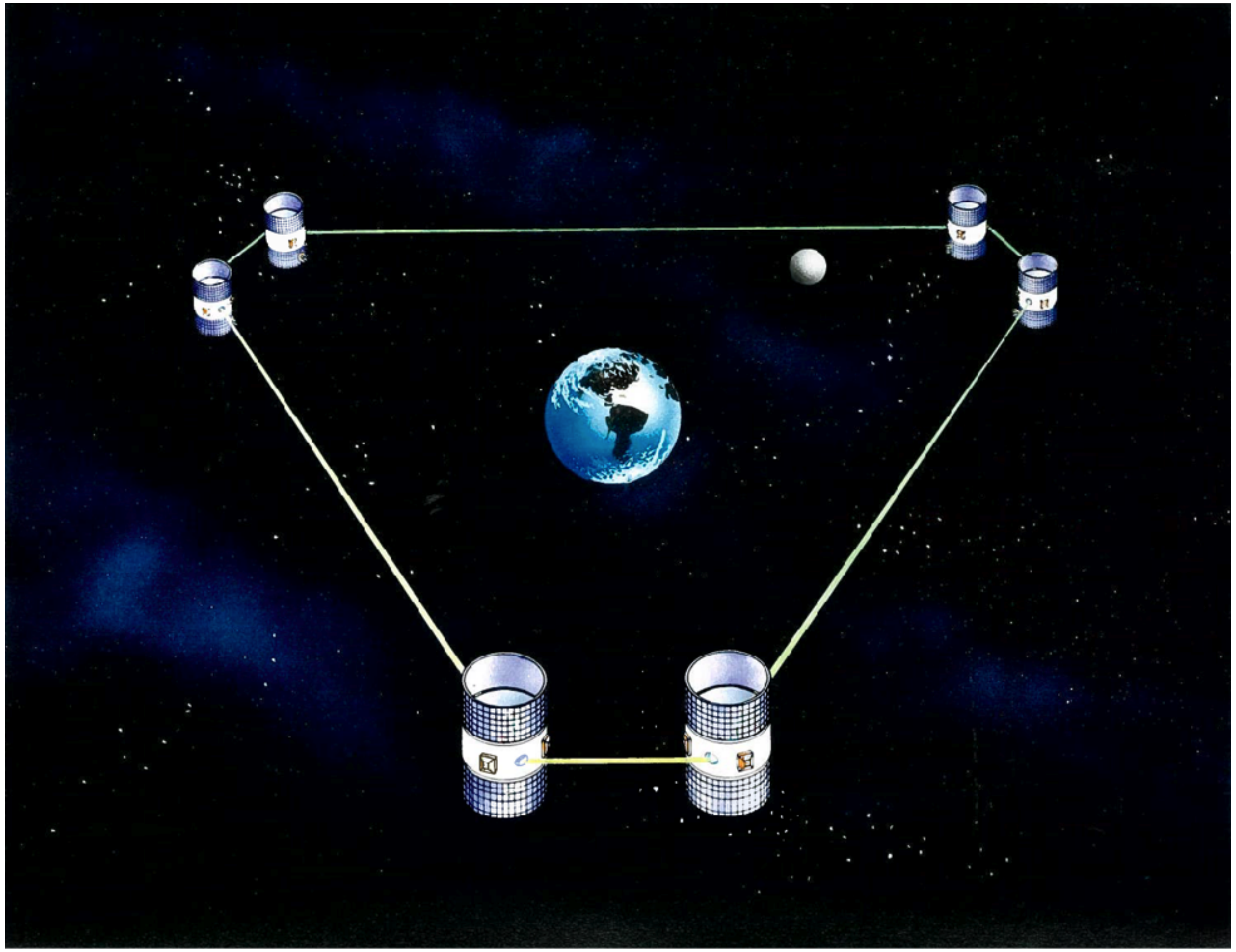
Laser Interferometer Space Antenna (LISA): 1993



ESA M3 candidate May1993

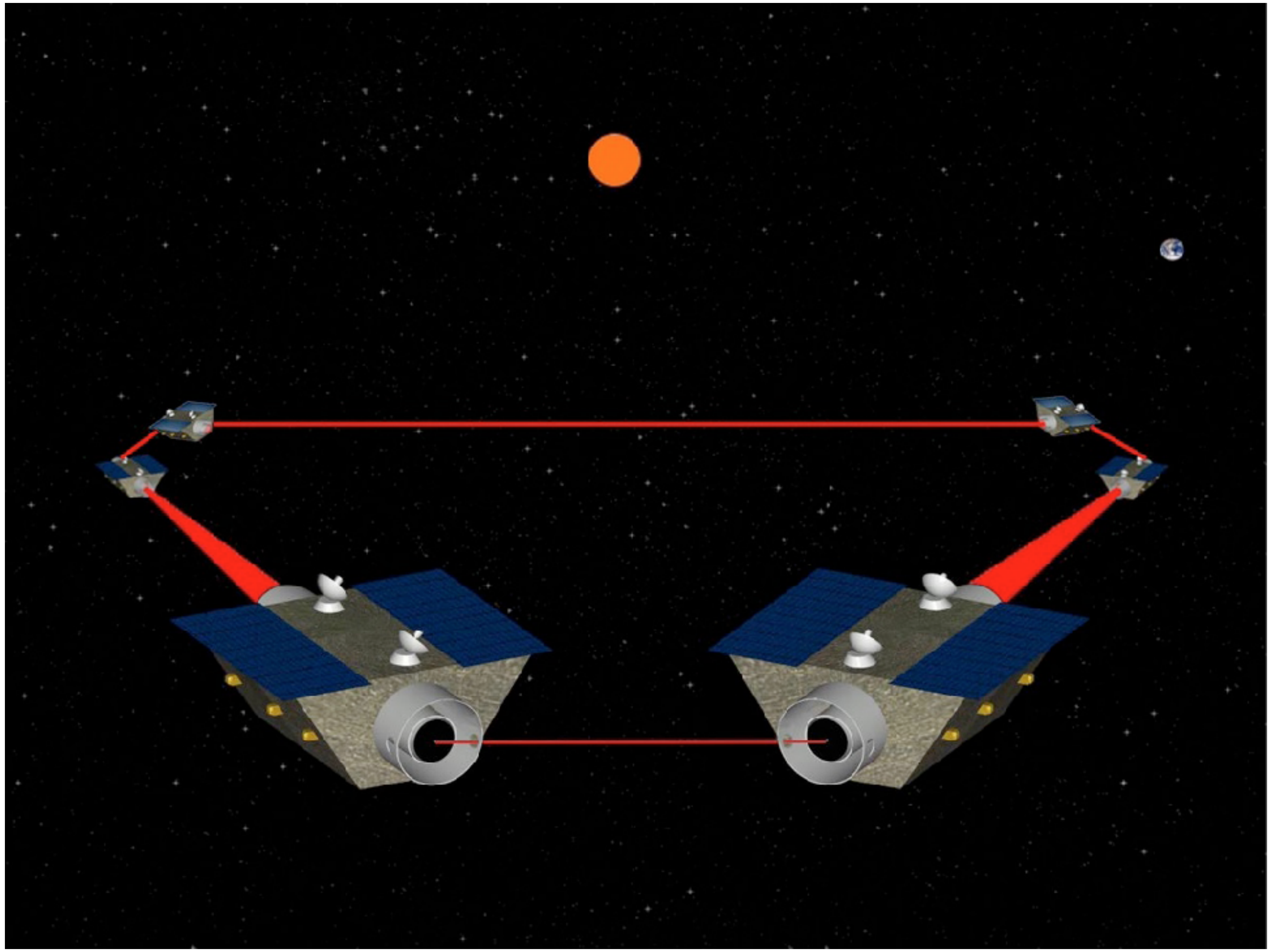
(Jim Hough came up with the LISA acronym in 1992)

Spaceborne Astronomical Gravitational-wave Interferometer To Test Aspects of Relativity and Investigate Unknown Sources (SAGITTARIUS): 1993



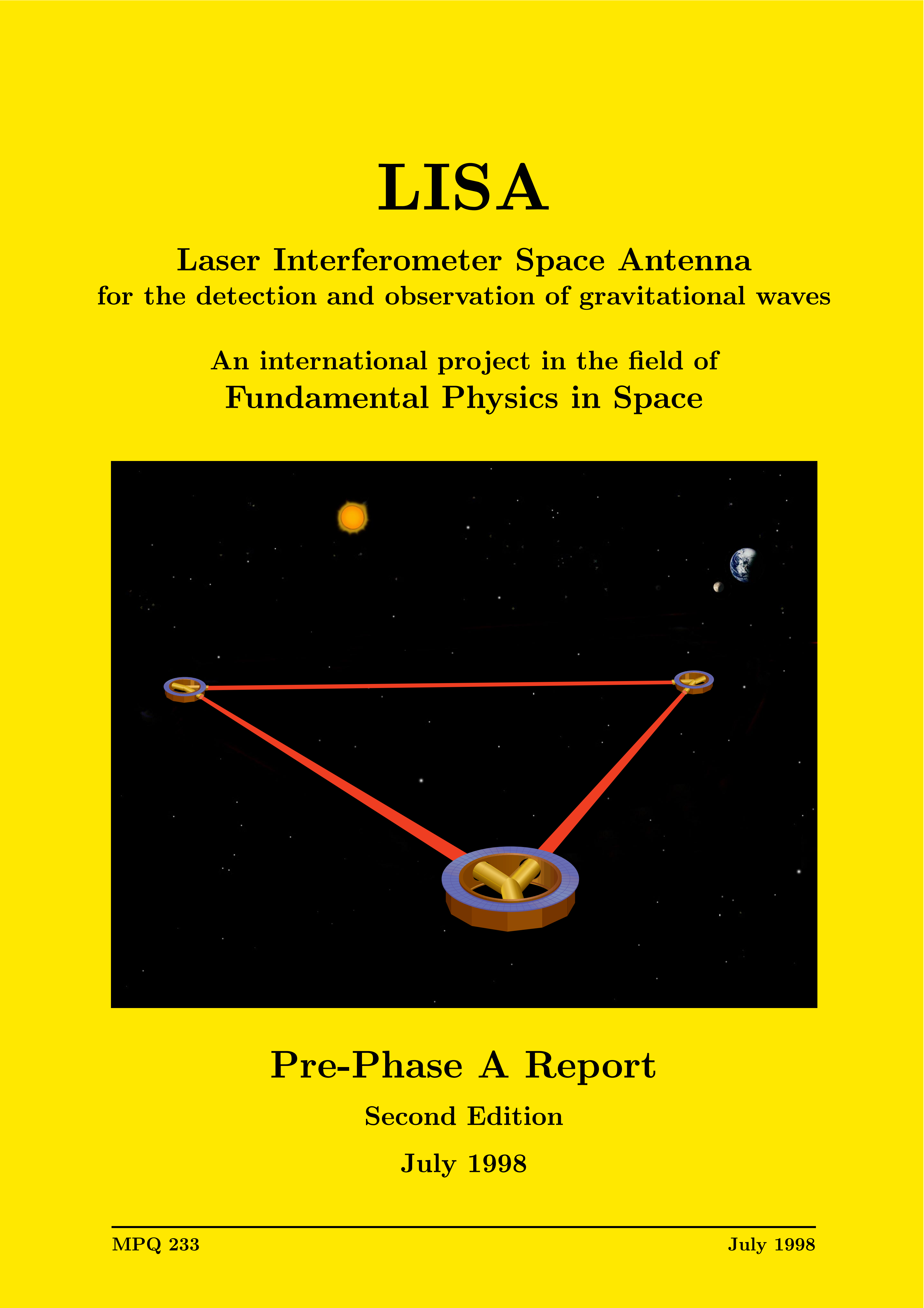
ESA M3 candidate (Hellings) 1993

Laser Interferometer Space Antenna for Gravity (LISAG): 1993



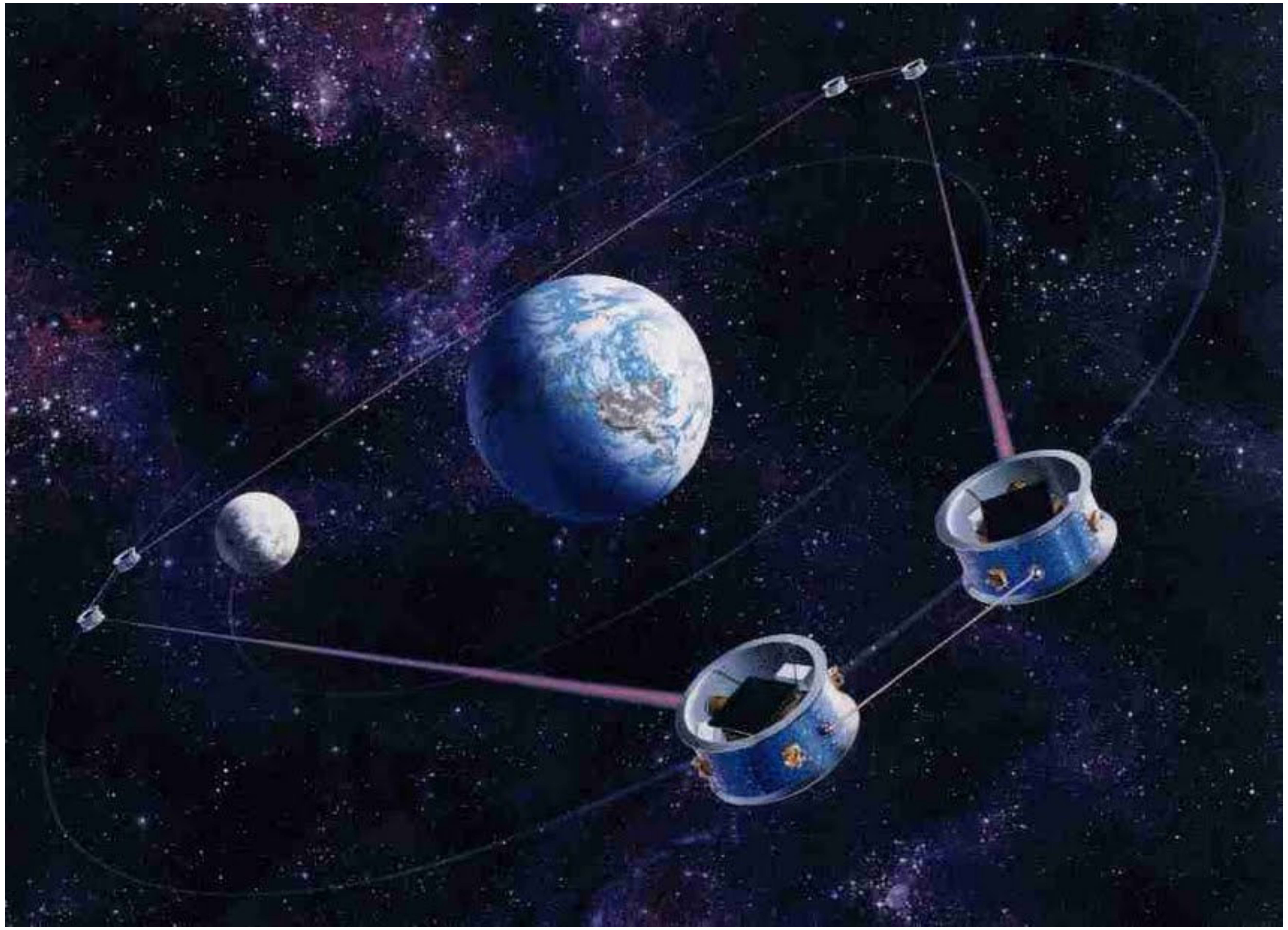
ESA Cornerstone candidate December 1993

Laser Interferometer Space Antenna (LISA)



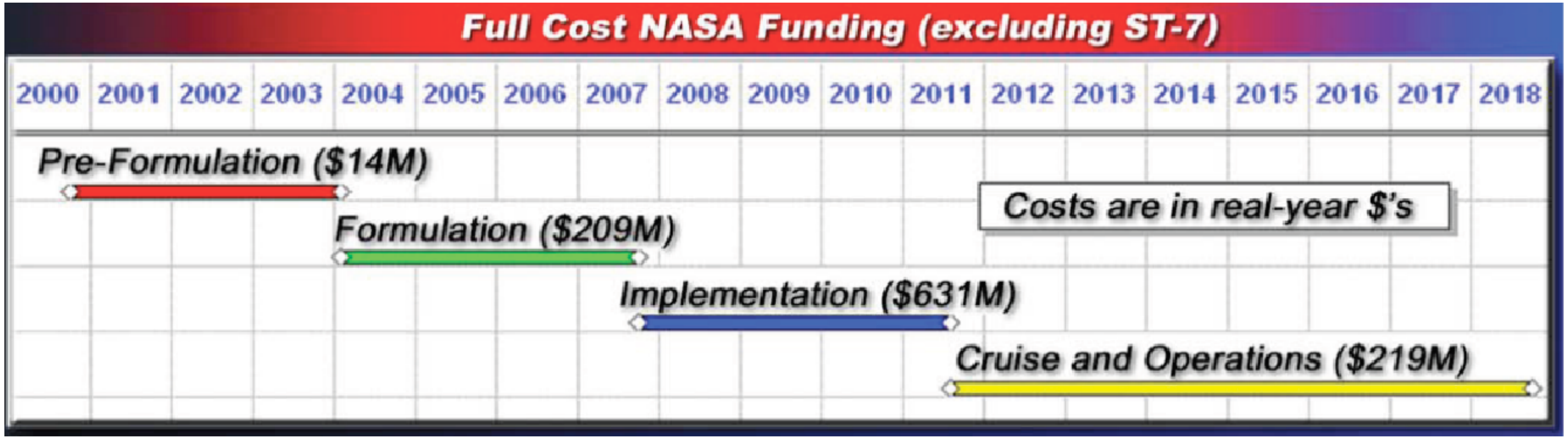
NASA/ESA joint study1996, Yellow Book 1998

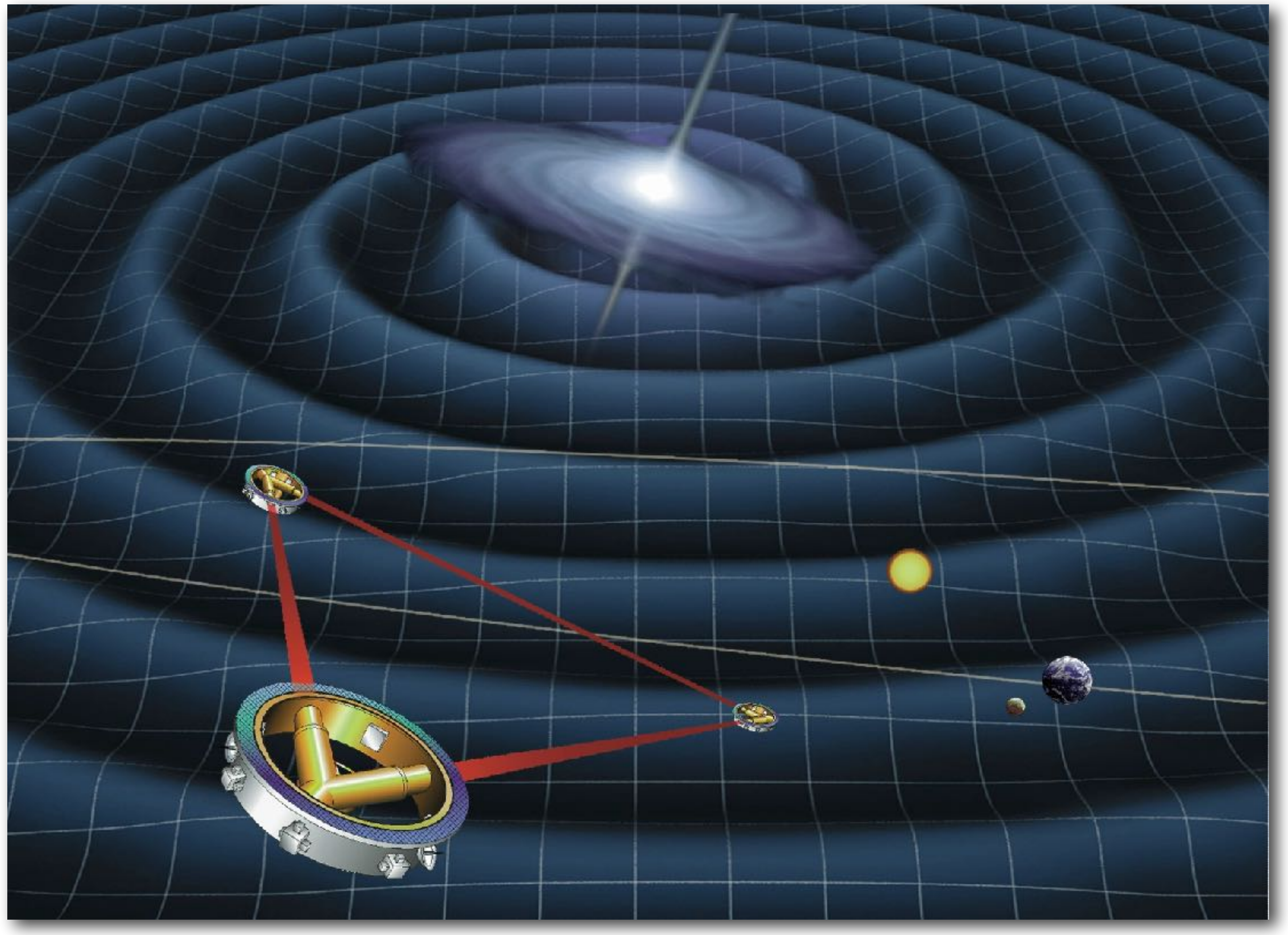
Orbiting Medium Explorer for Gravitational-wave Astrophysics (OMEGA):1998

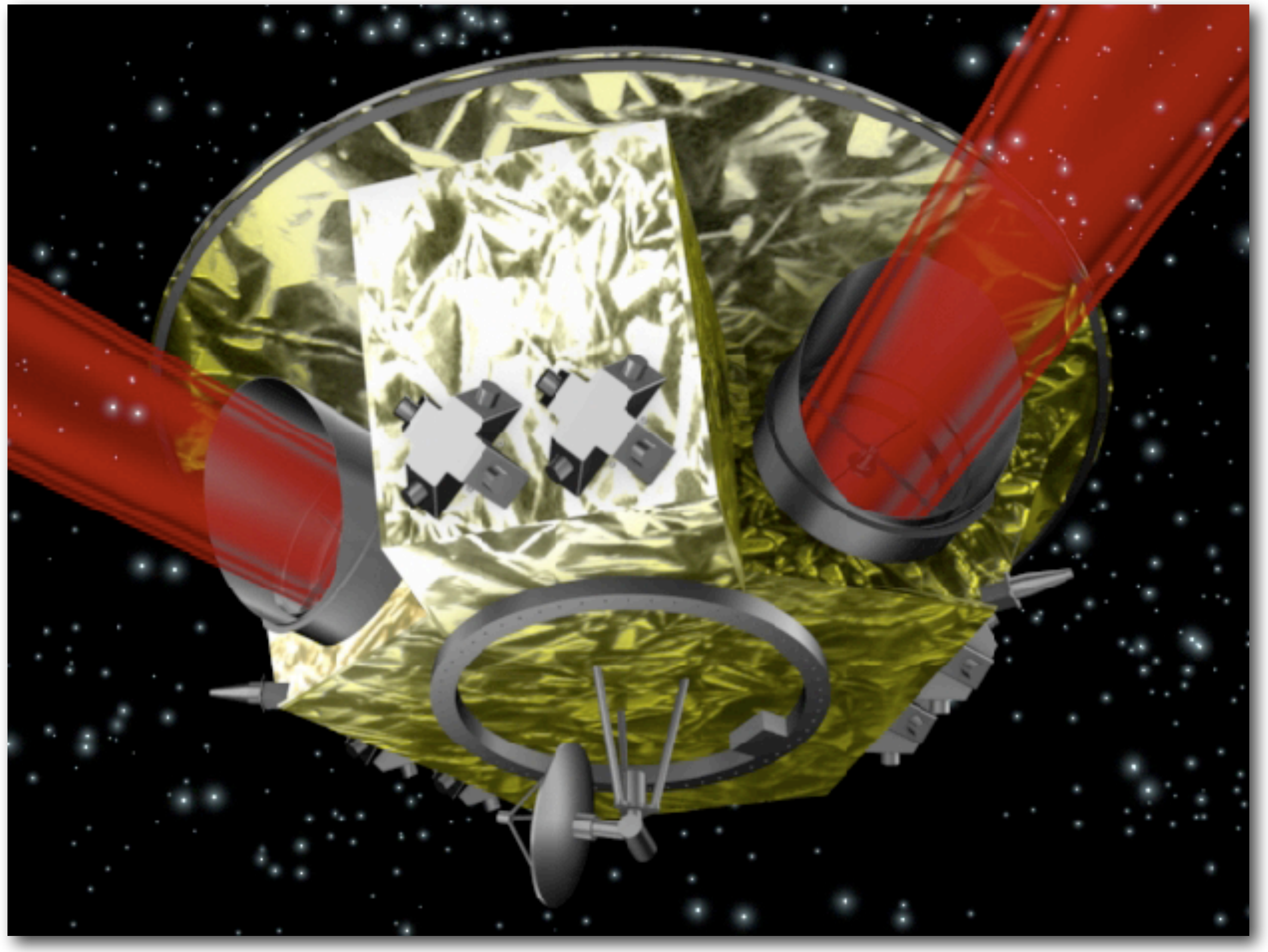


1998 NASA MIDEX proposal (Hellings et al)

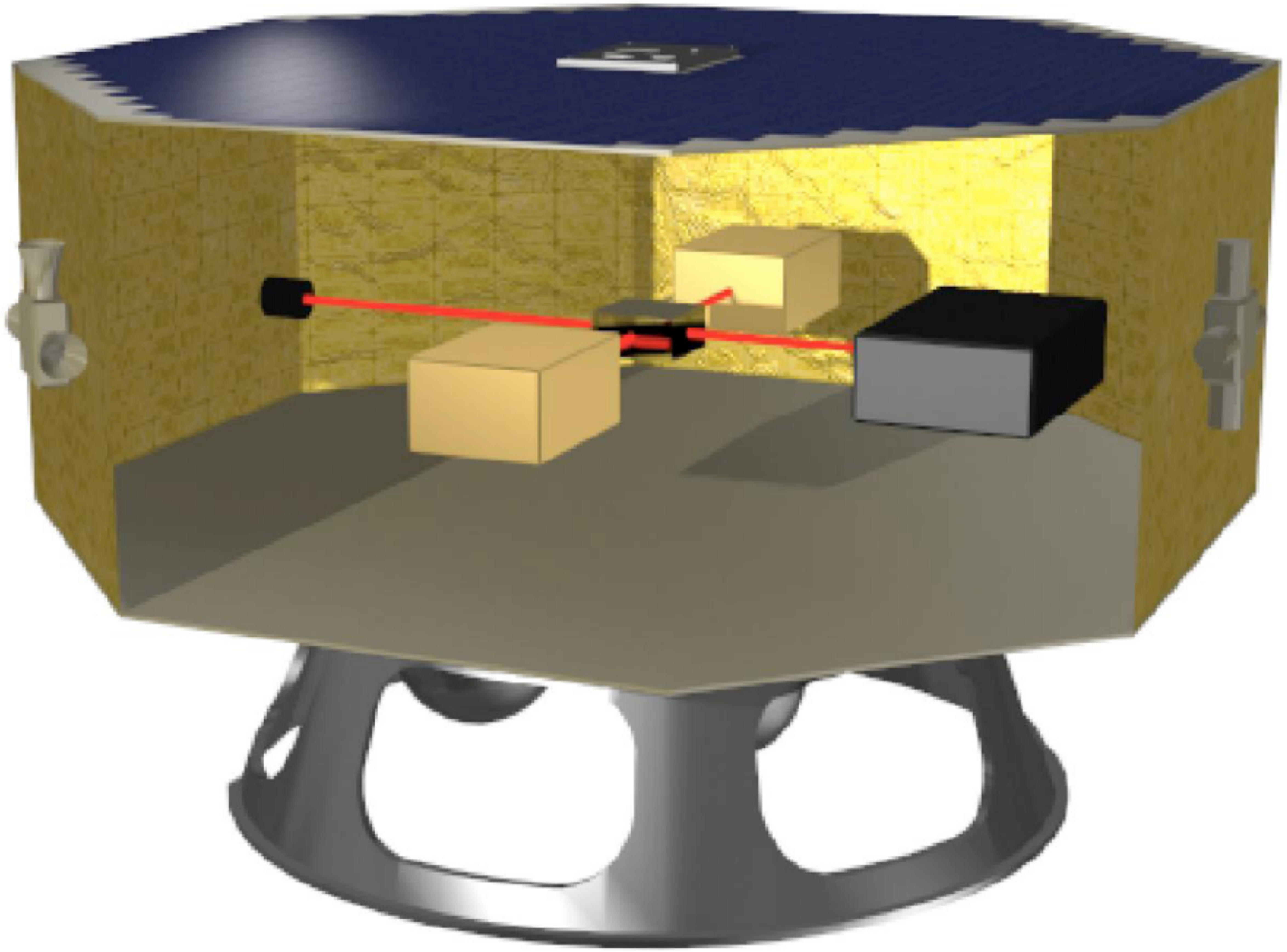
ESA/NASA LISA mission: official start 2001





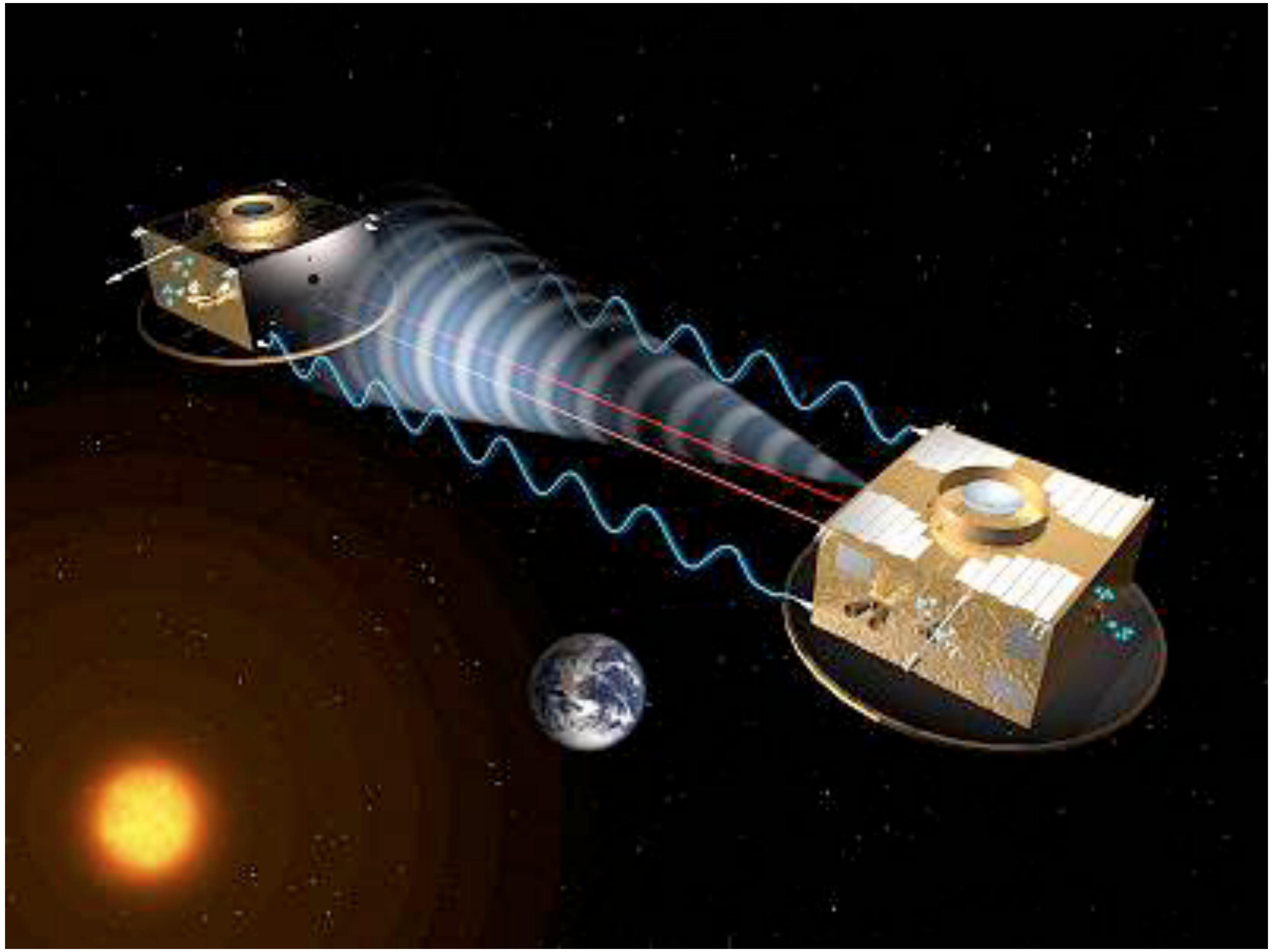


Pathfinder: European LIsa TEchnology (ELITE): 1998



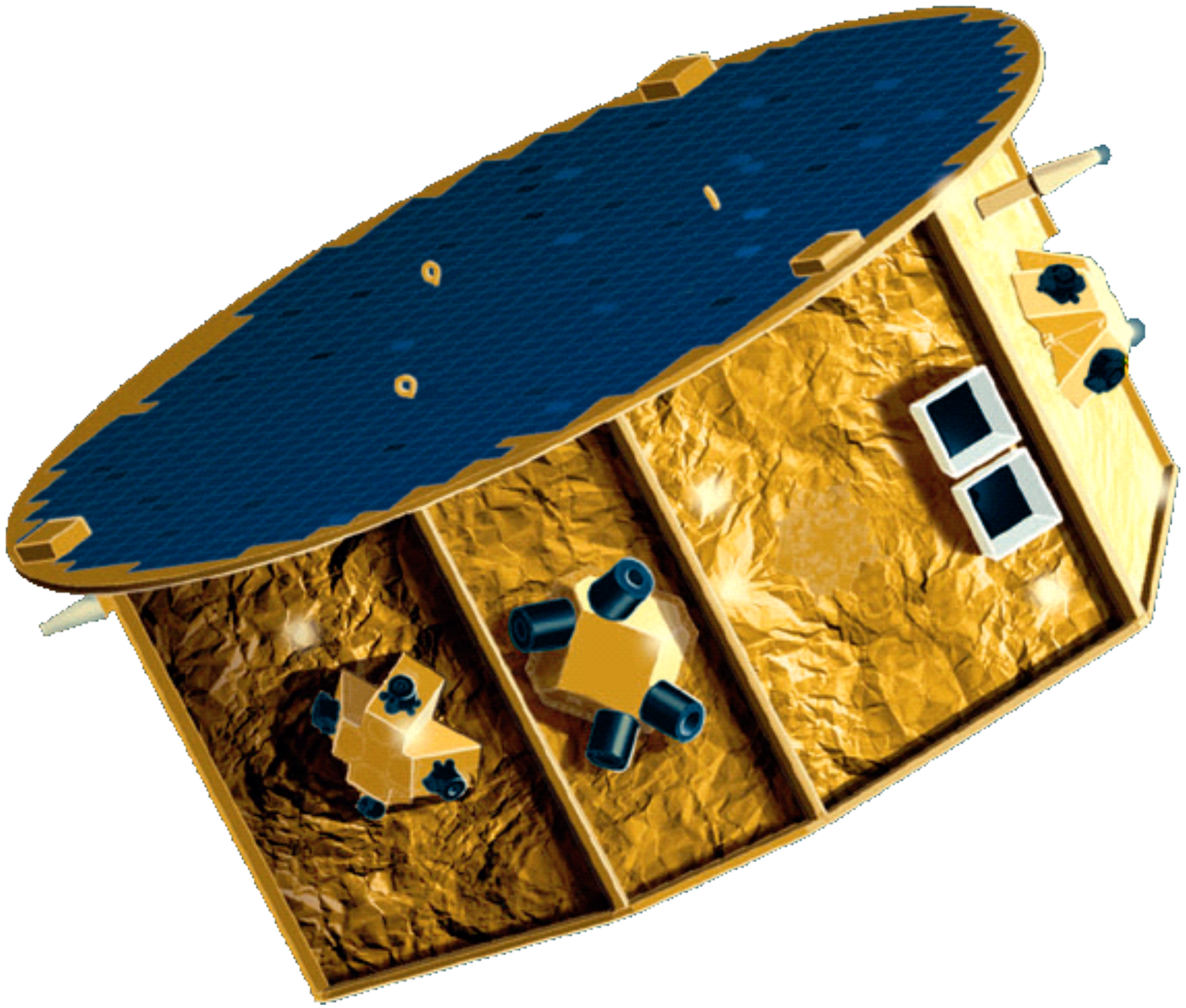
For launch in 2002

Small Missions for Advanced Research in Technology-2 (SMART-2): 2000



LISA/Darwin Pathfinder. For Launch in 2006

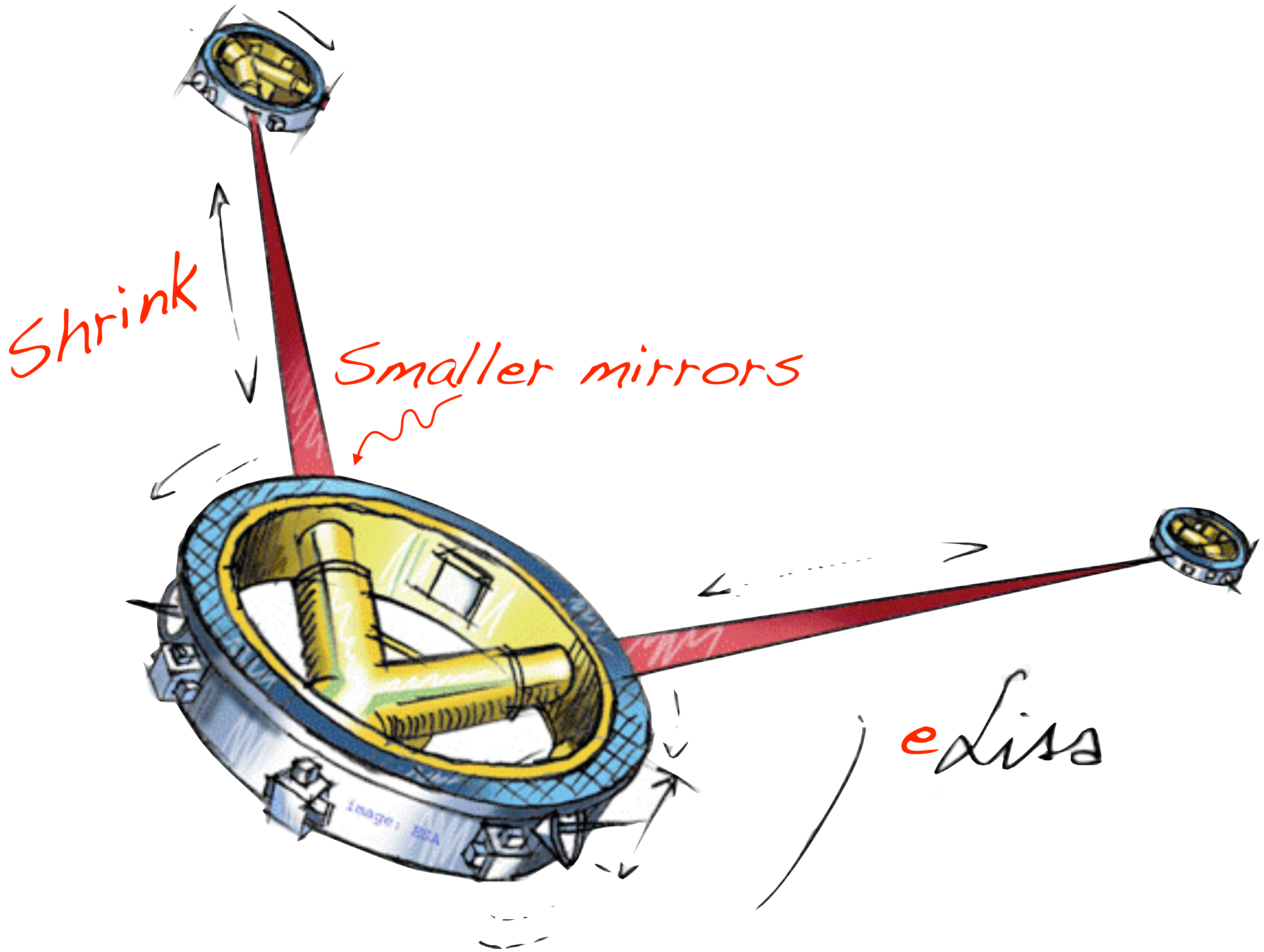
LISA Pathfinder - Space Technology Mission 7: Approved 2002



SMART-2 Descoped to single spacecraft. For launch in ~~2006~~ 2015

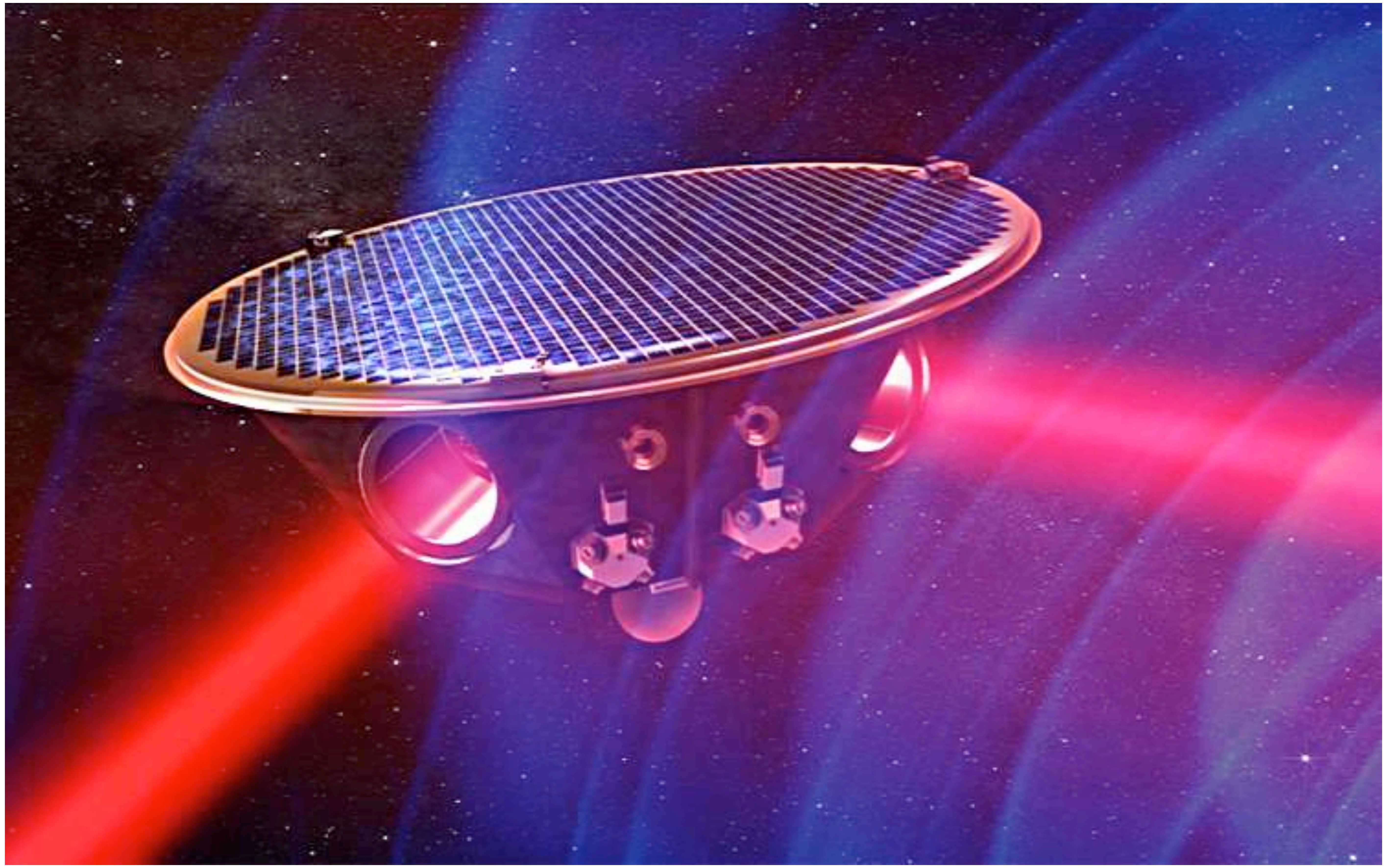
March 2011, The Divorce

eLISA - Descoped LISA proposed for ESA-lead mission (2011)

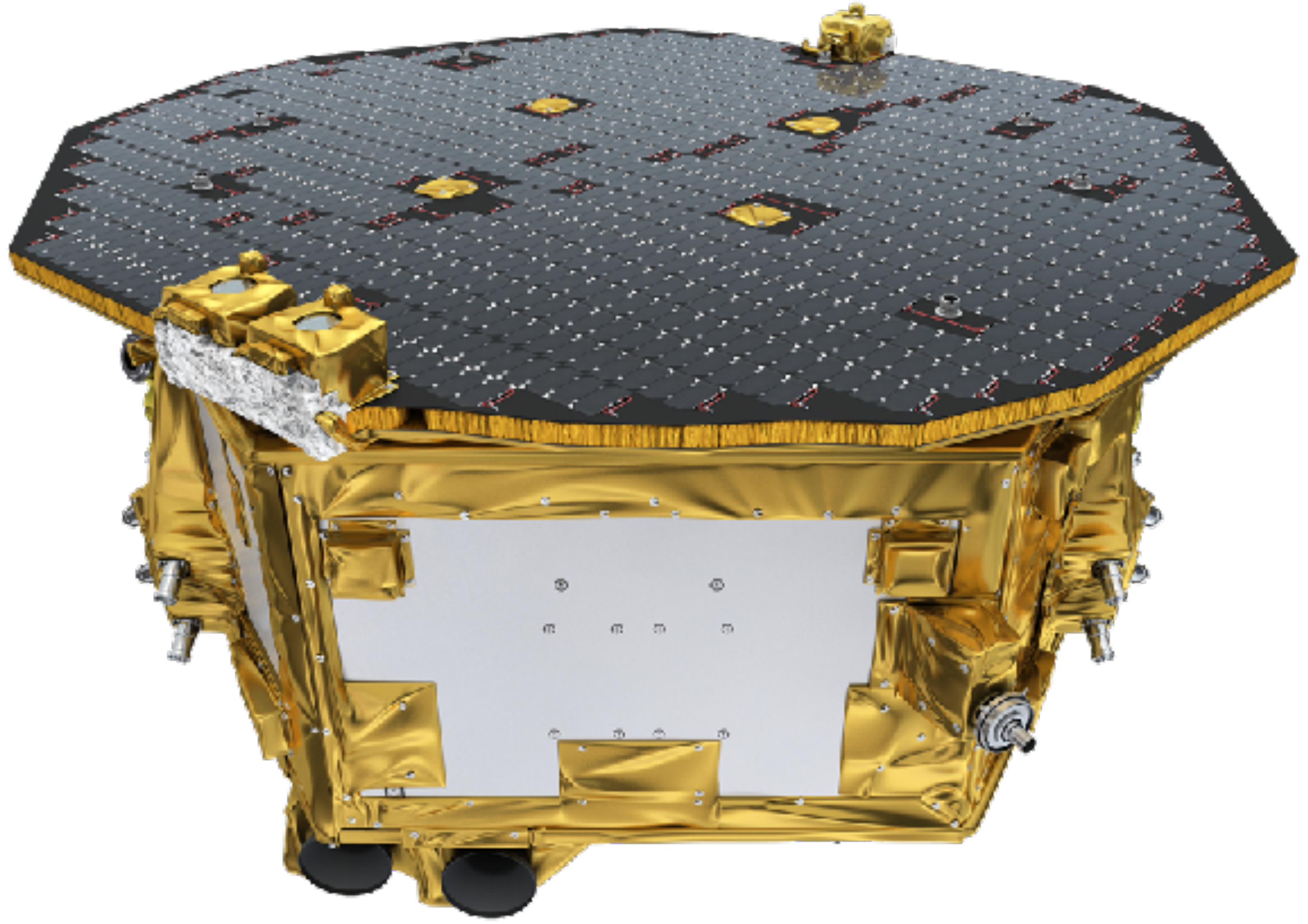


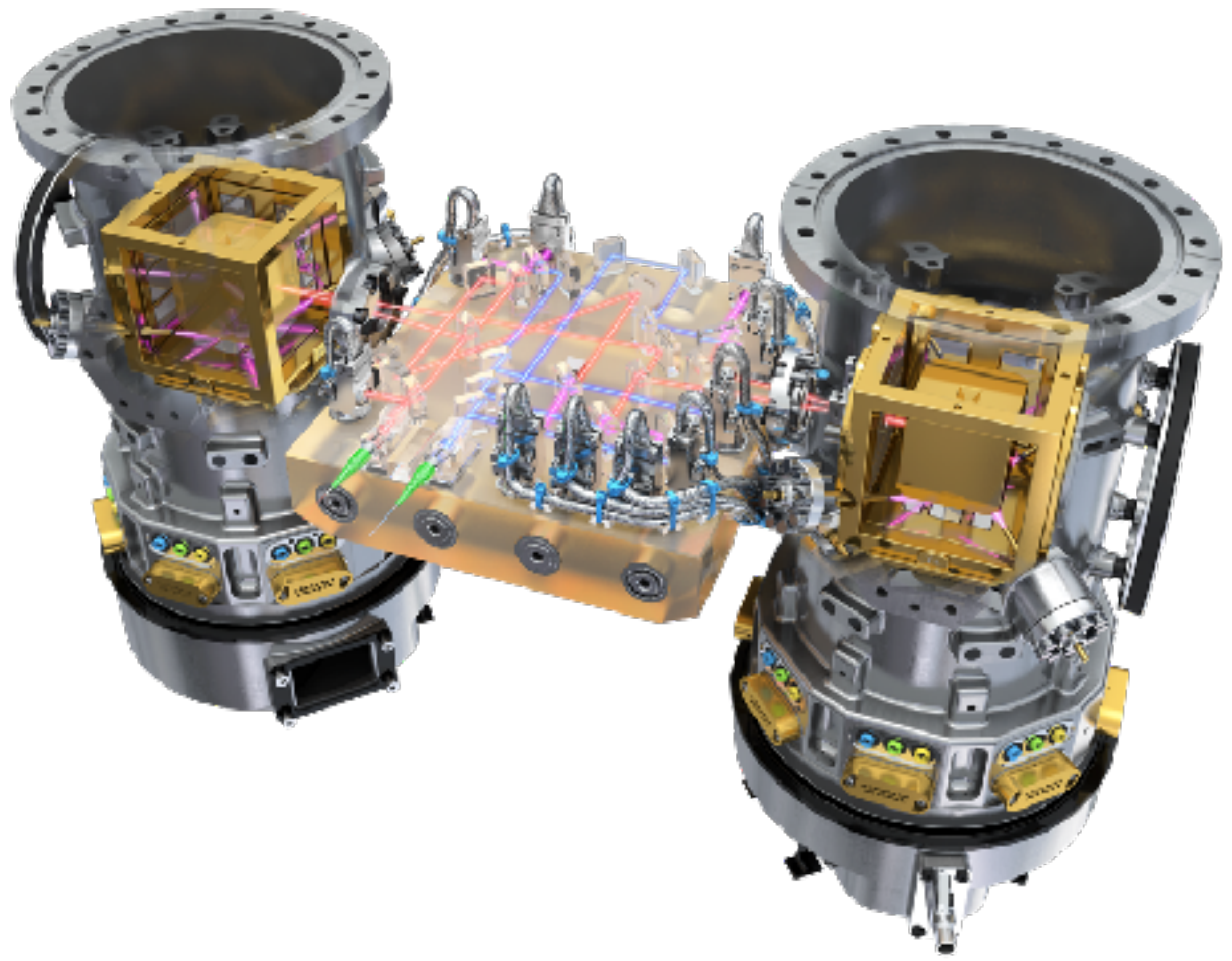
Cosmic Visions L1 Candidate

The Gravitational Universe selected as L3 science theme (2013)

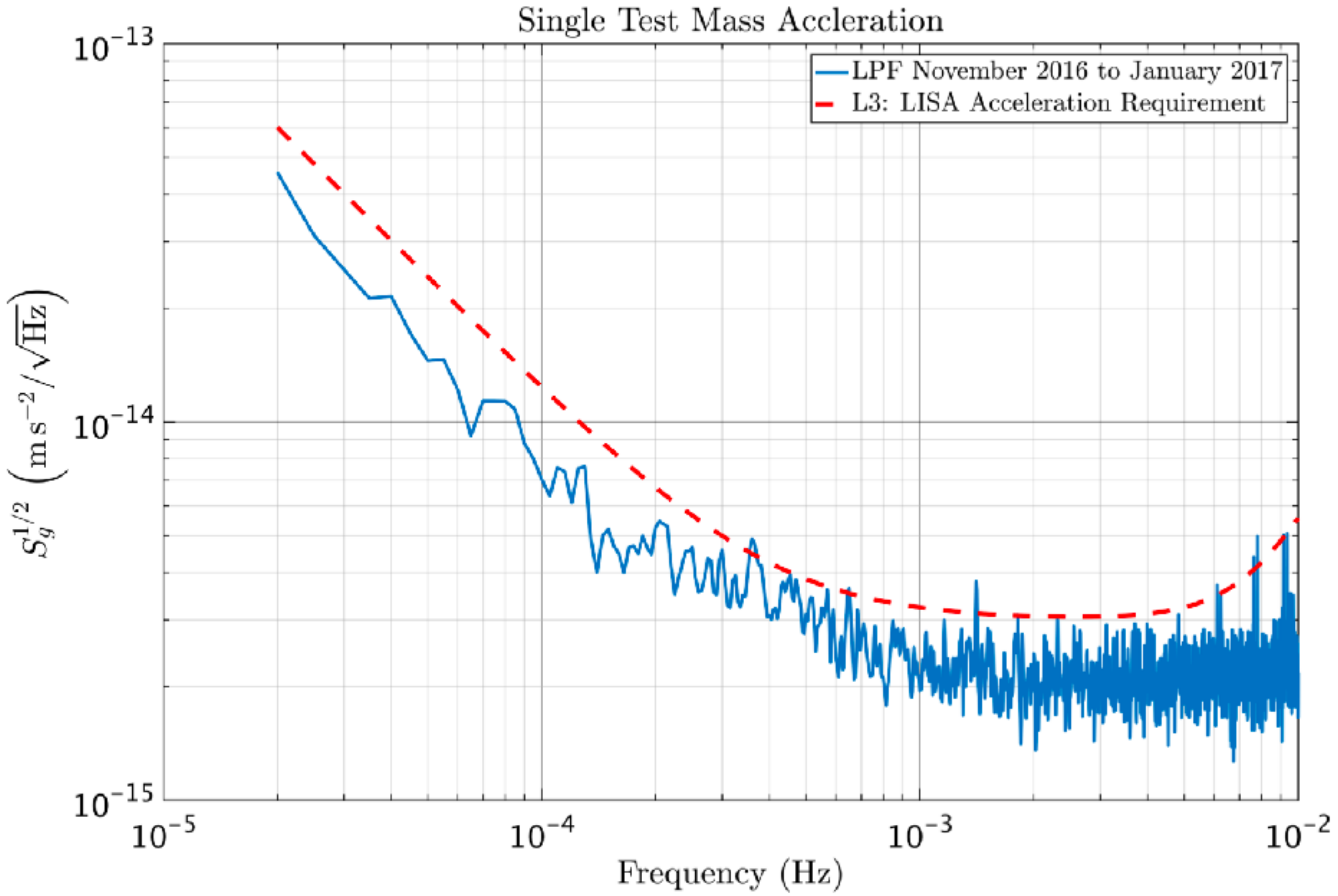


eLISA as candidate mission concept: Launch in 2034

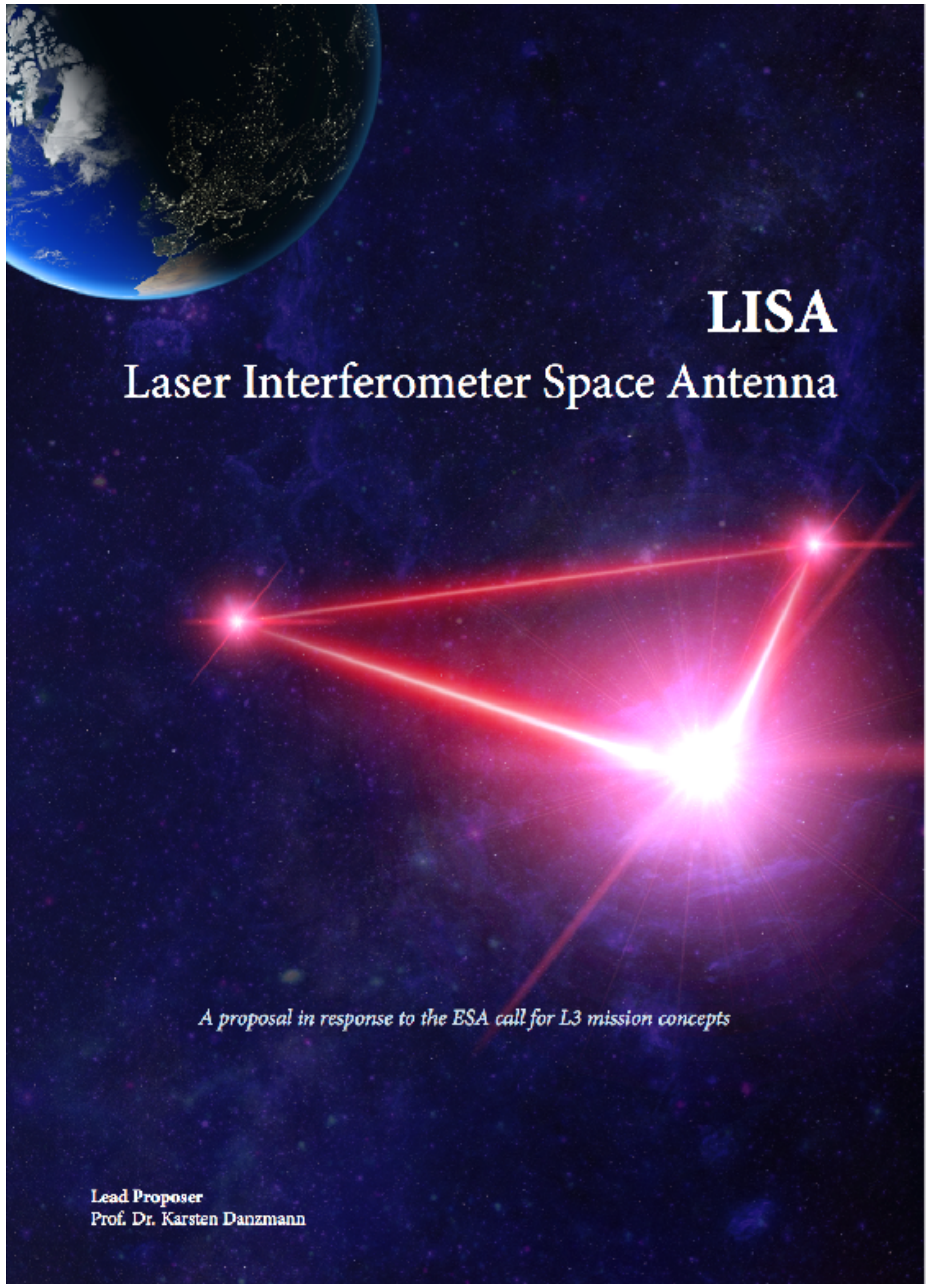


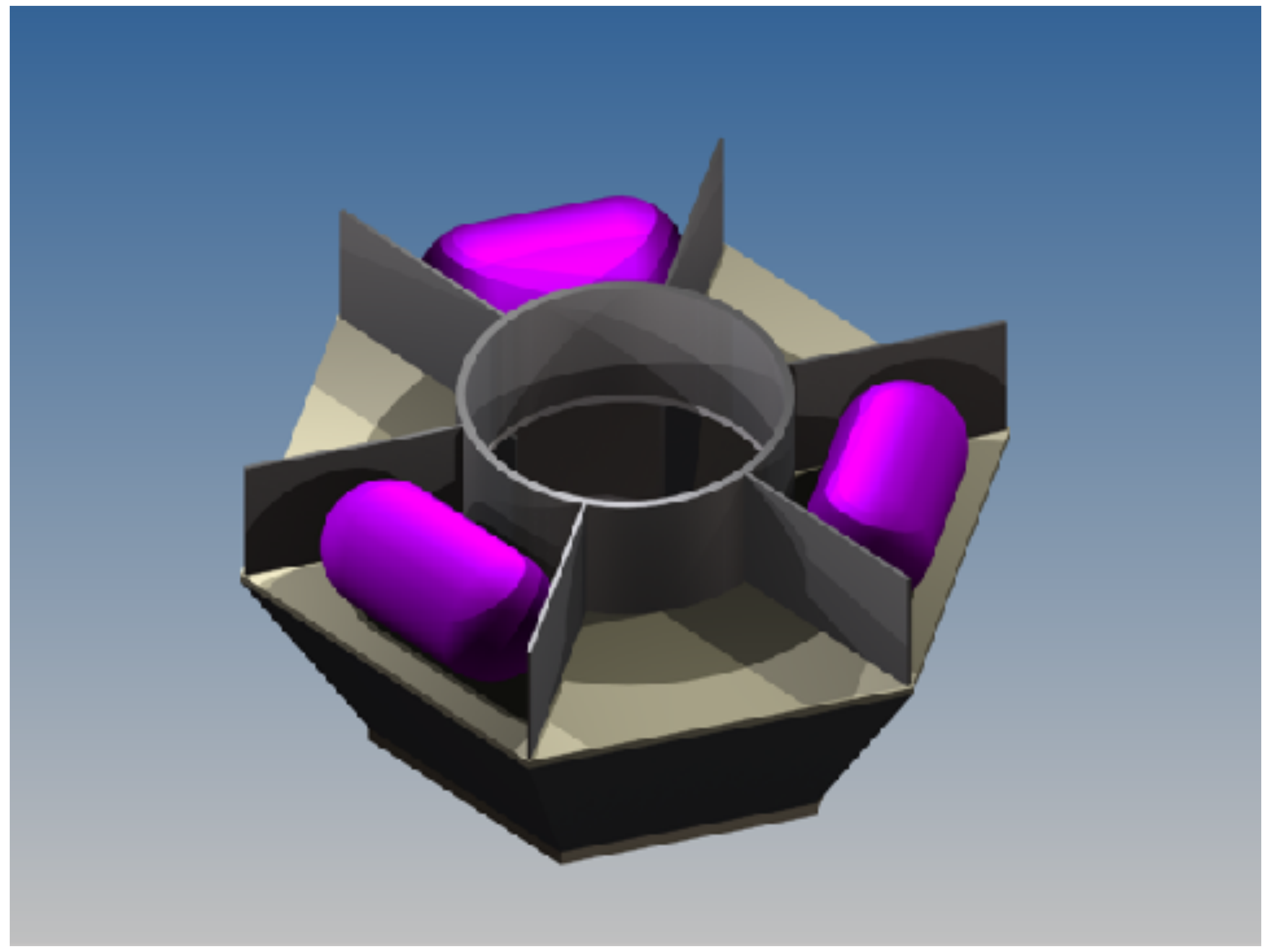


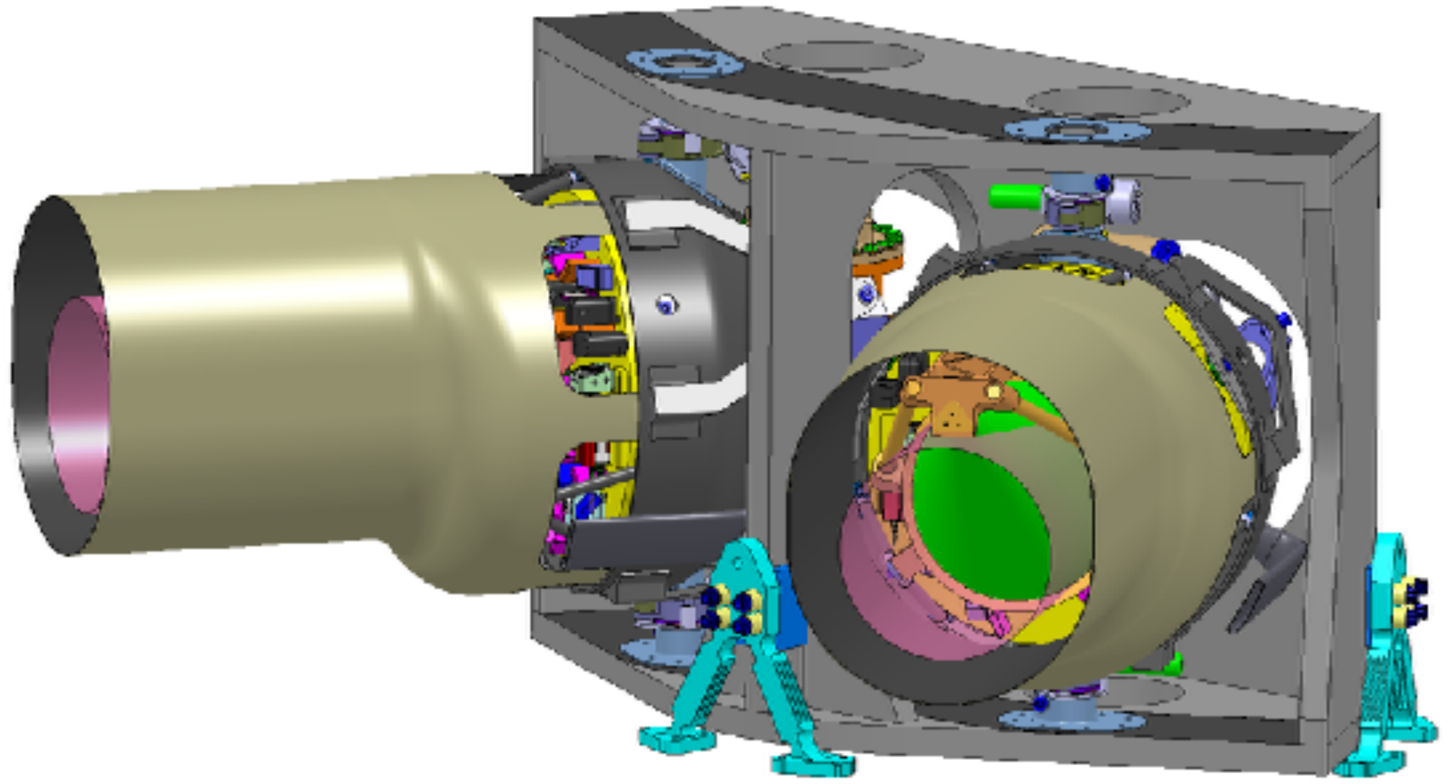
Near perfect free-fall demonstrated by the LISA Pathfinder mission in 2016

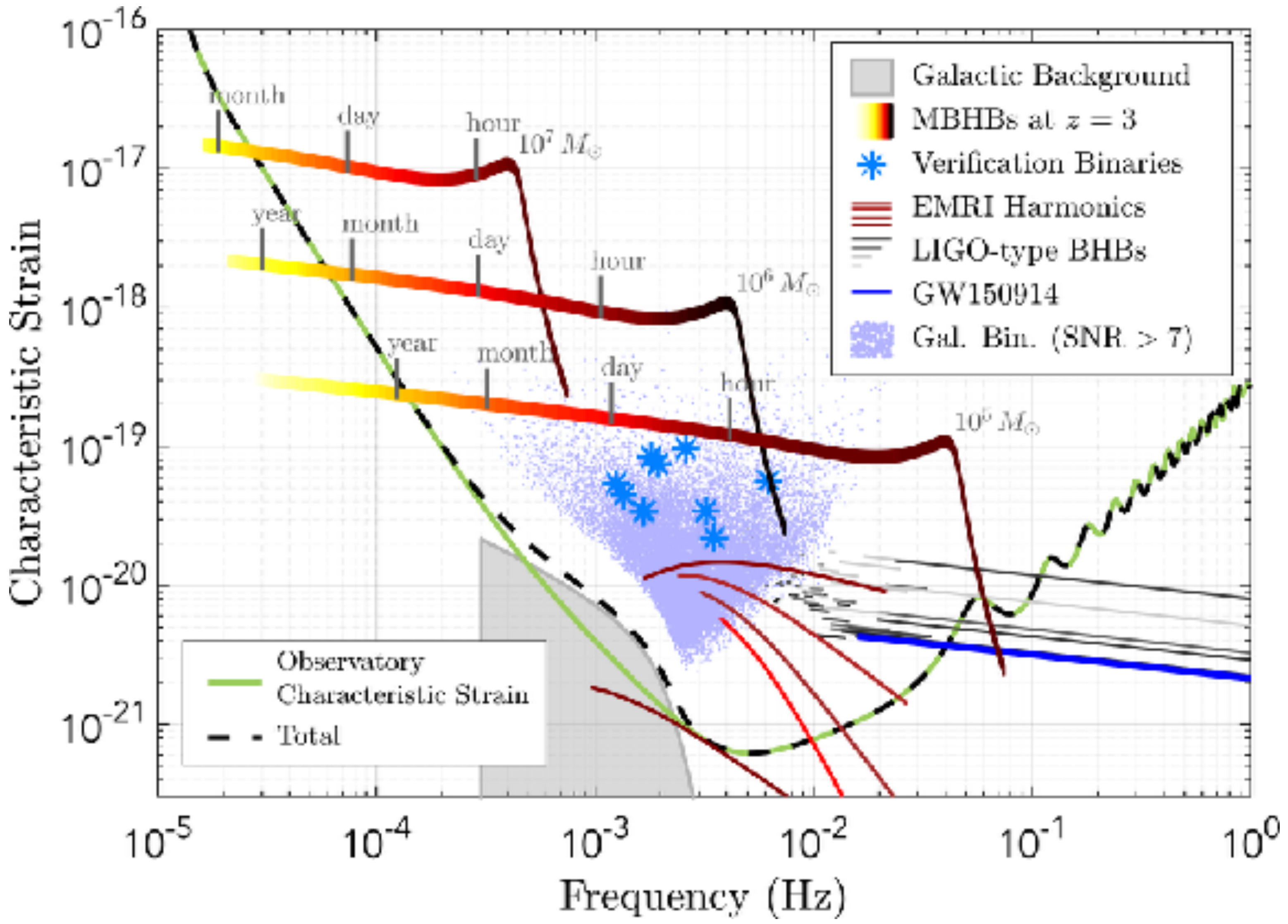


January 2017, LISA mission proposed for ESA L3 science theme



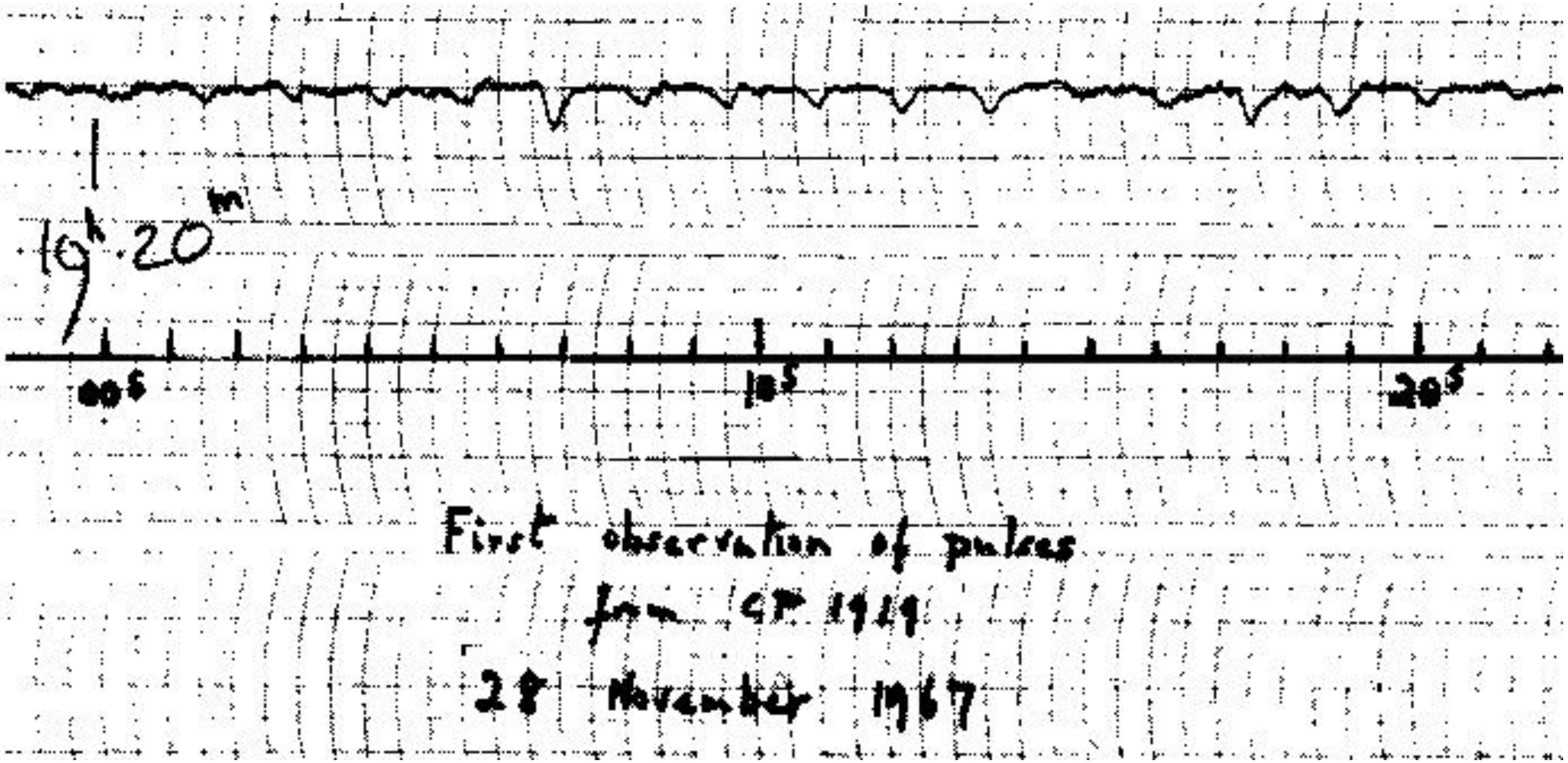






Pulsar Timing

The History and Future of Pulsar Timing



Bell & Hewish - discovered first radio pulsar PSR B1919+21 in 1967

Steve Detweiler - Inventor of Pulsar Timing Detection

THE ASTROPHYSICAL JOURNAL, 234:1100–1104, 1979 December 15

PULSAR TIMING MEASUREMENTS AND THE SEARCH FOR GRAVITATIONAL WAVES

STEVEN DETWEILER
Department of Physics, Yale University
Received 1979 June 4; accepted 1979 July 6

1948-2016

ABSTRACT

Pulse arrival time measurements of pulsars may be used to search for gravitational waves with periods on the order of 1 to 10 years and dimensionless amplitudes $\sim 10^{-11}$. The analysis of published data on pulsar regularity sets an upper limit to the energy density of a stochastic background of gravitational waves, with periods ~ 1 year, which is comparable to the closure density of the universe.

Subject headings: cosmology — gravitation — pulsars — relativity

Uses spacecraft doppler tracking GW response formula from Estabrook and Walhquist (1975)

Mentions earlier paper by Sazhin (1978) that considered a particular line-of-sight detection PTA geometry

Steve Detweiler - Inventor of Pulsar Timing Detection

THE ASTROPHYSICAL JOURNAL, 234:1100–1104, 1979 December 15

PULSAR TIMING MEASUREMENTS AND THE SEARCH FOR GRAVITATIONAL WAVES

STEVEN DETWEILER
Department of Physics, Yale University
Received 1979 June 4; accepted 1979 July 6

Under some circumstances it is possible to differentiate with certainty the effects on the residual caused by a gravitational wave from those caused by some pulsar phenomenon. For example, the cross-correlation of the signals from a number of pulsars could determine that an anomalous residual was produced by an event in the solar system rather than on the pulsar.

1948-2016

Suggests cross-correlation of pulsar signals to detect GWs

The paper discusses possible sources and sets the first upper limits. Limits were weak since pulsars then were poorly timed $\delta t \sim 100\,\mathrm{ms}$

1982 - Discovery of the first milli-second Pulsar, PSR B1937+21

letters to nature

Nature **300**, 615 - 618 (16 December 1982); doi:10.1038/300615a0

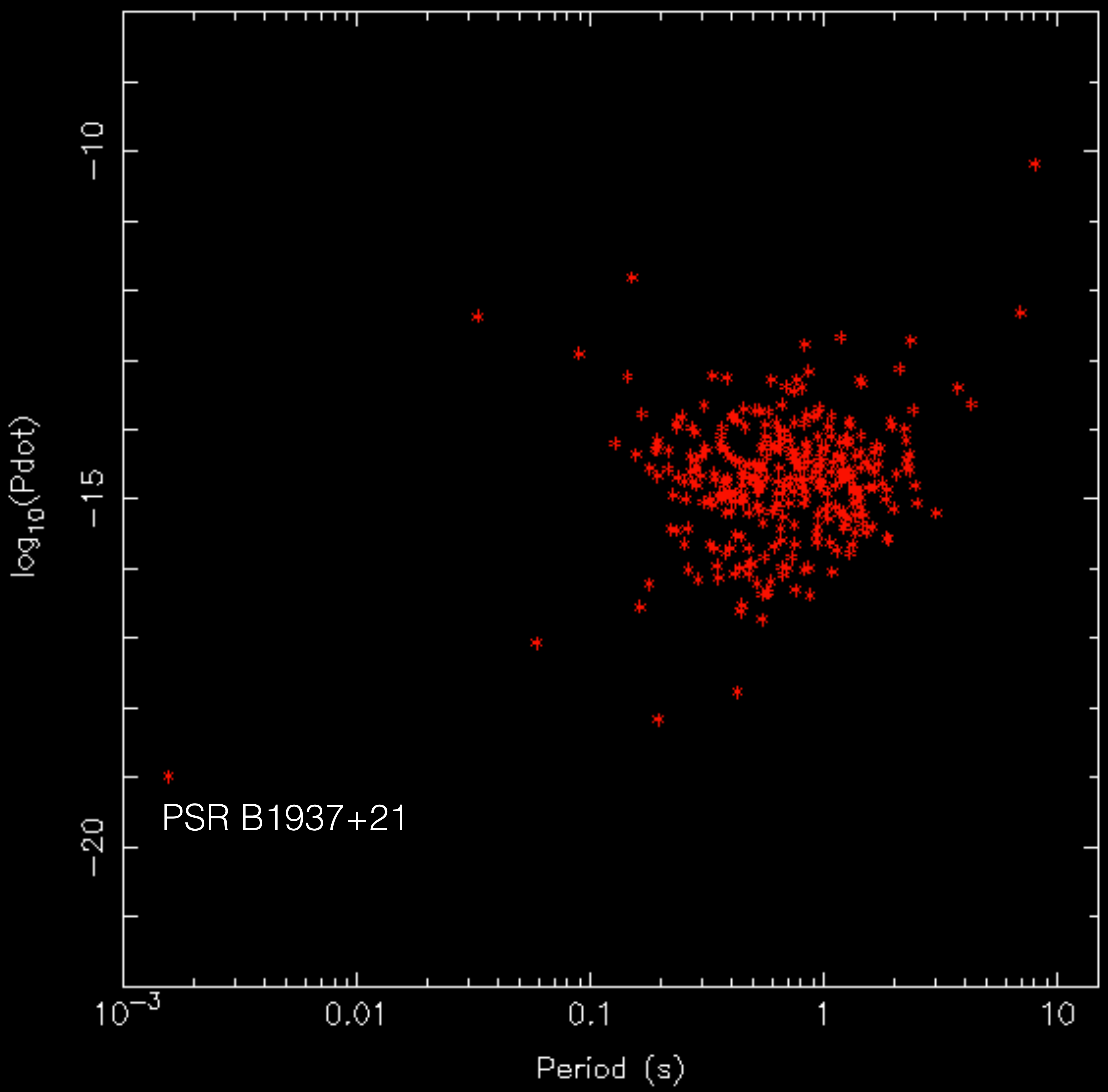
A millisecond pulsar

D. C. BACKER[*], SHRINIVAS R. KULKARNI[*], CARL HEILES[*], M. M. DAVIS[†] & W. M. GOSS[‡]

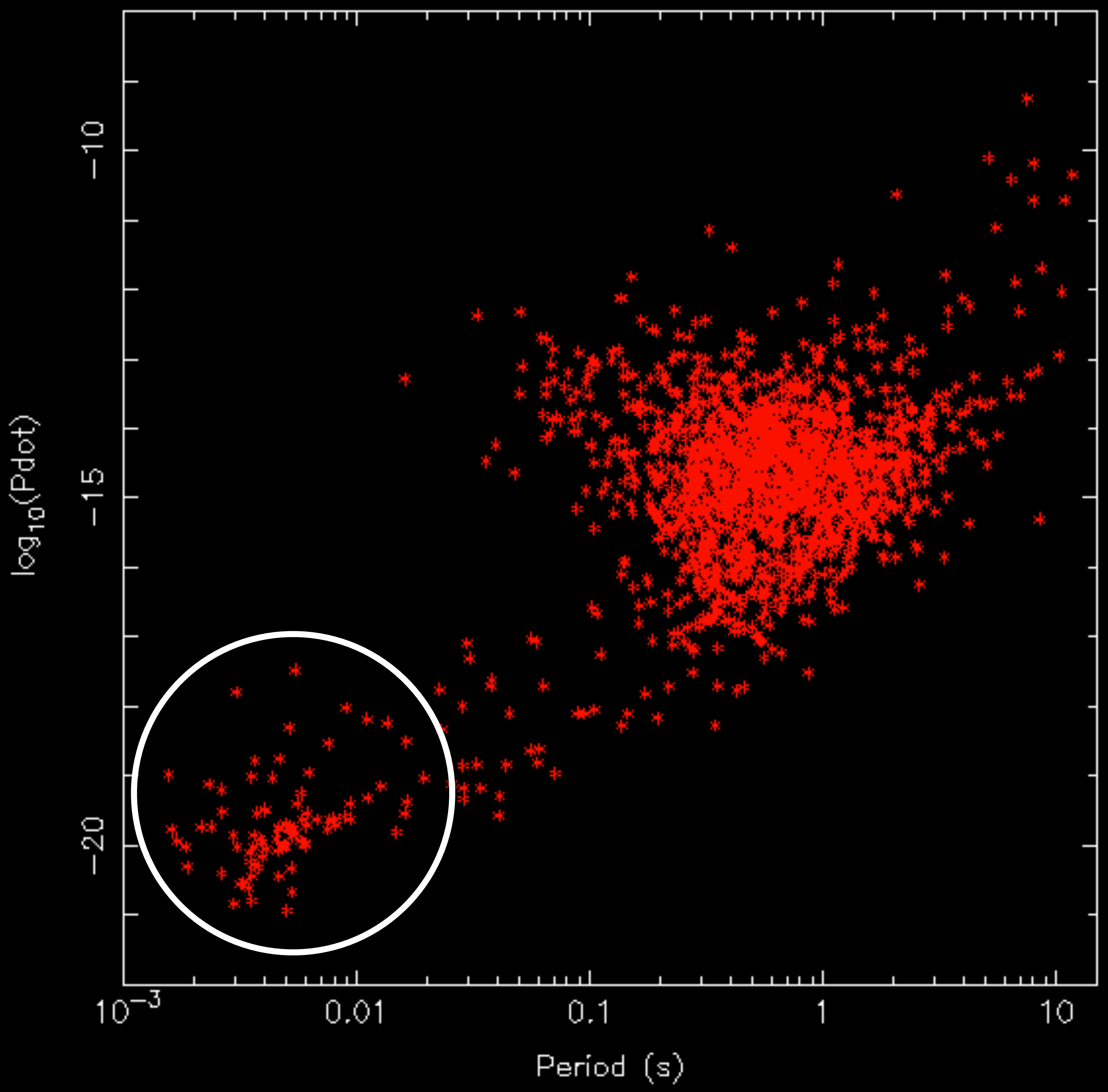
[*]Radio Astronomy Laboratory and Astronomy Department, University of California, Berkeley, California 94720, USA
[†]National Astronomy and Ionosphere Center, Arecibo, Puerto Rico
[‡]Kapteyn Laboratorium, Groningen, The Netherlands

The radio properties of 4C21.53 have been an enigma for many years. First, the object displays interplanetary scintillations (IPS) at 81 MHz, indicating structure smaller than 1 are s, despite its low galactic latitude (–0.3°)[1]. IPS modulation is rare at low latitudes because of interstellar angular broadening. Second, the source has an extremely steep ($\sim\nu^{-2}$) spectrum at decametric wavelengths[2]. This combination of properties suggested that 4C21.53 was either an undetected pulsar or a member of some new class of objects. This puzzle may be resolved by the discovery and related observations of a fast pulsar, 1937+214, with a period of 1.558 ms in the constellation Vulpecula only a few degrees from the direction to the original pulsar, 1919+21. The existence of such a fast pulsar with no evidence either of a new formation event or of present energy losses raises new questions about the origin and evolution of pulsars.

Milli-second Pulsars, 1982 to now



1982



Now

Hellings & Downs, 1983

THE ASTROPHYSICAL JOURNAL, **265**:L39–L42, 1983 February 15

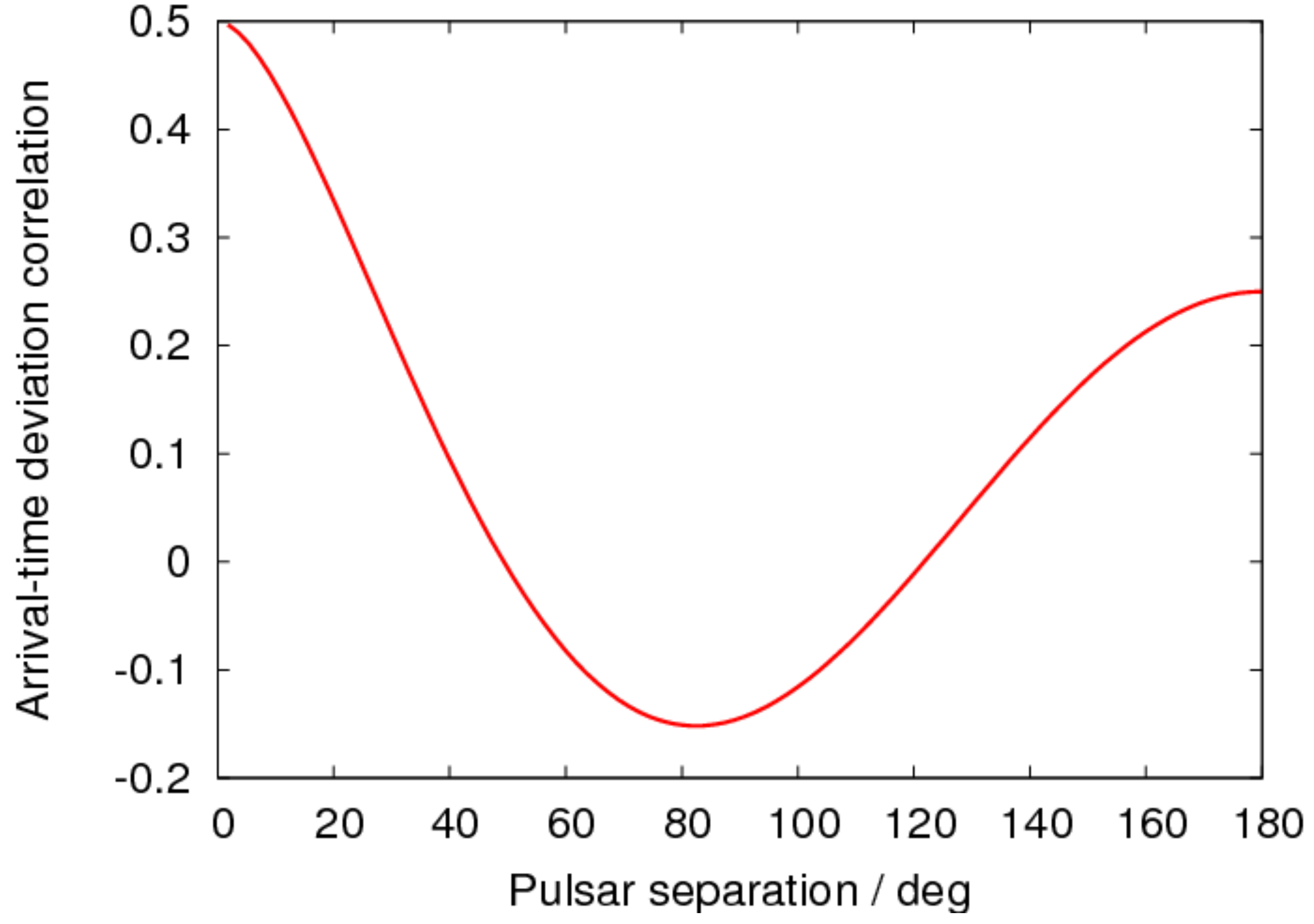
UPPER LIMITS ON THE ISOTROPIC GRAVITATIONAL RADIATION BACKGROUND FROM PULSAR TIMING ANALYSIS[1]

R. W. HELLINGS AND G. S. DOWNS
Jet Propulsion Laboratory, California Institute of Technology
Received 1982 October 1; accepted 1982 October 20

ABSTRACT

A pulsar and the Earth may be thought of as end masses of a free-mass gravitational wave antenna in which the relative motion of the masses is monitored by observing the Doppler shift of the pulse arrival times. Using timing residuals from PSR 1133+16, 1237+25, 1604−00, and 2045−16, an upper limit to the spectrum of the isotropic gravitational radiation background has been derived in the frequency band 4×10^{-9} to 10^{-7} Hz. This limit is found to be $S_E = 10^{21} f^3$ ergs cm^{-3} Hz^{-1}, where S_E is the energy density spectrum and f is the frequency in Hz. This would limit the energy density at frequencies below 10^{-8} Hz to be 1.4×10^{-4} times the critical density.

Subject headings: cosmology — gravitation — pulsars



Bound used classic (un-recylced) pulsars $\delta t \sim 10\,\mu\mathrm{s} \rightarrow 2\,\mathrm{ms}$

Indirect Detection of Gravitational Waves (by mid ‘80s)

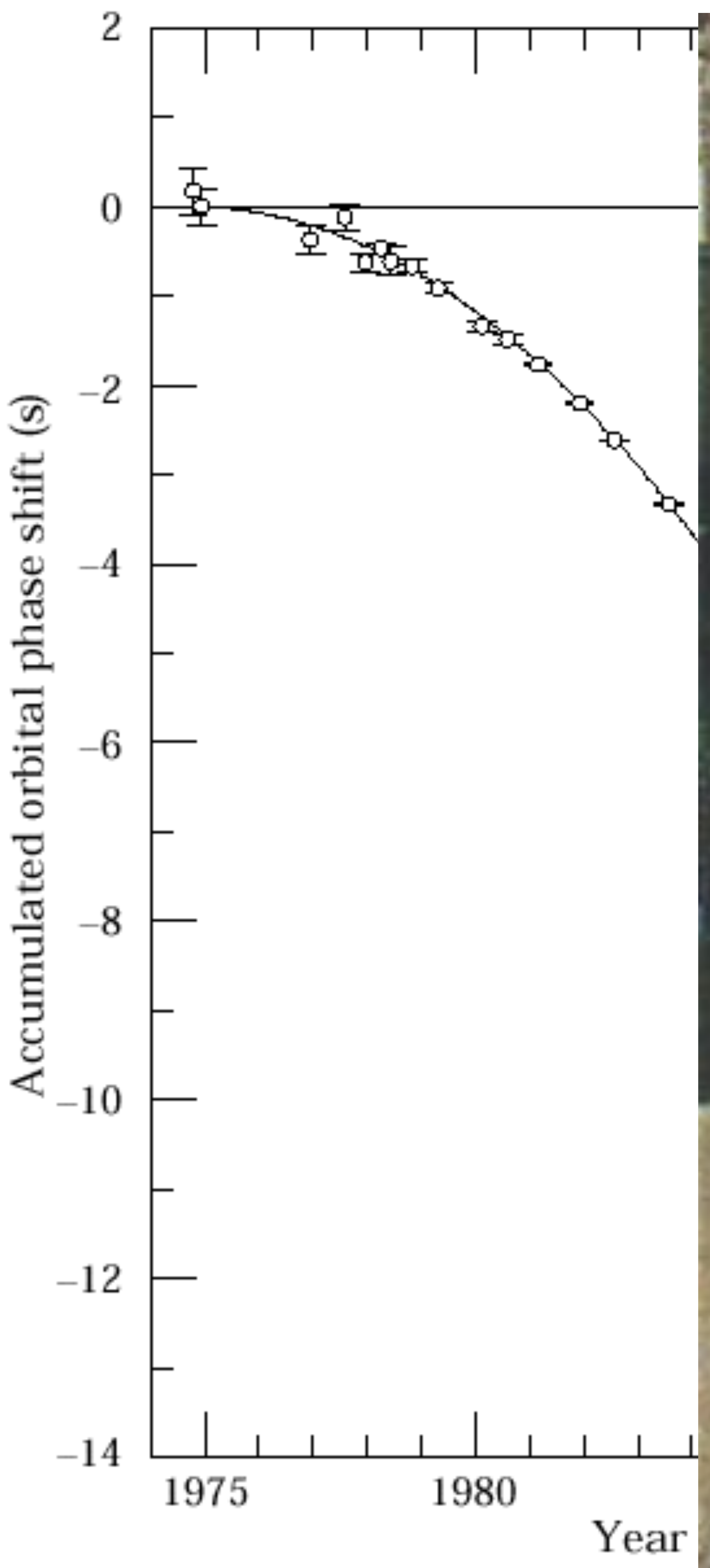
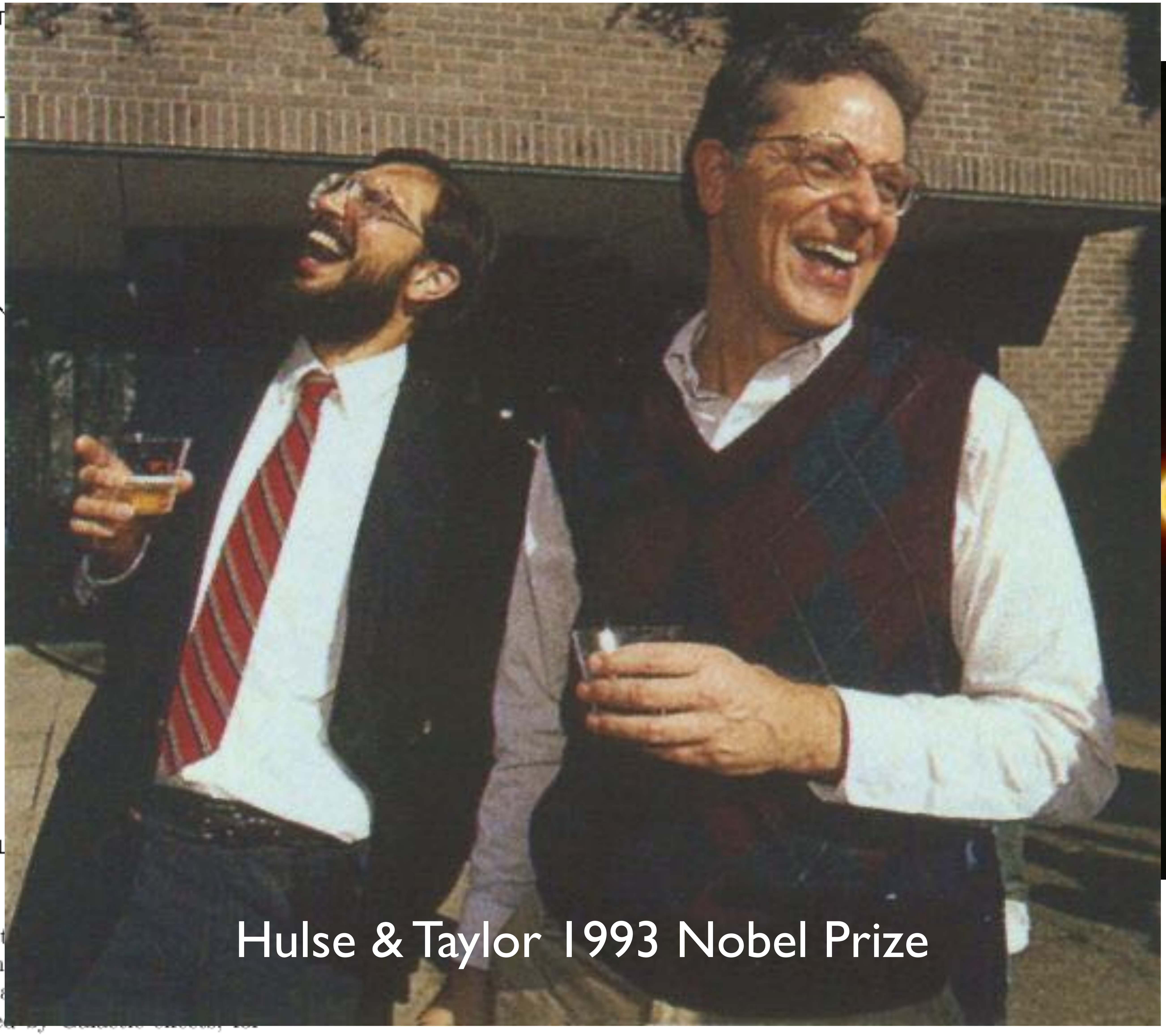
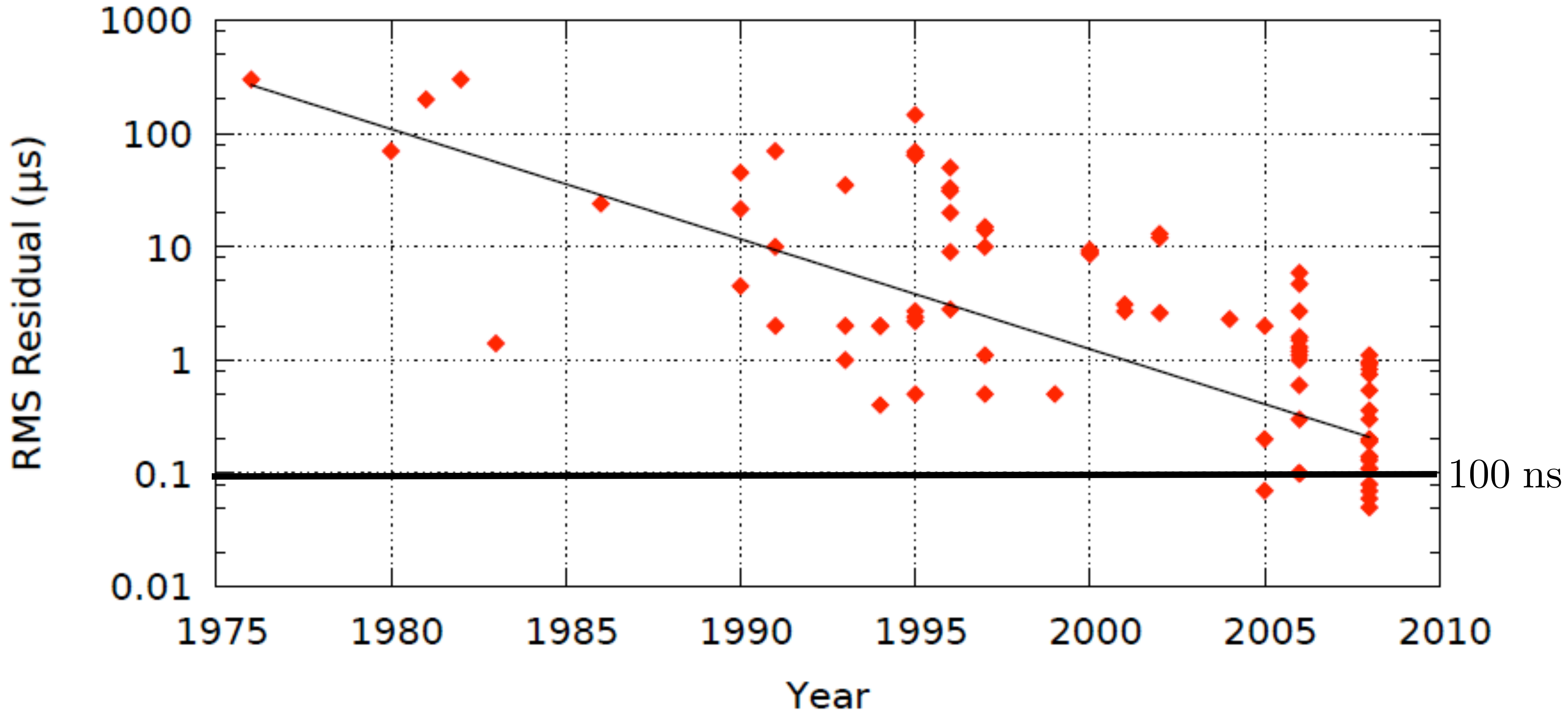
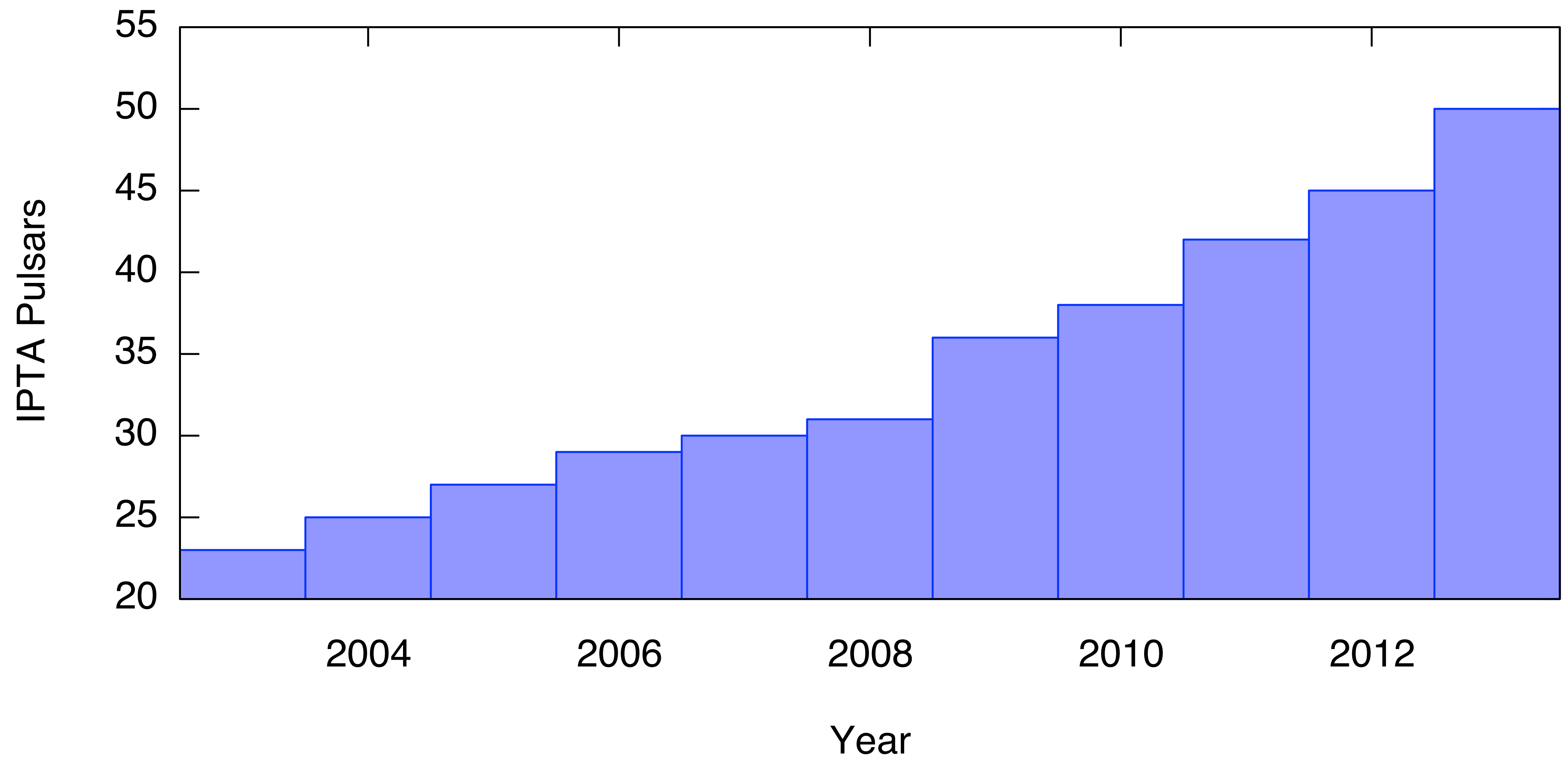


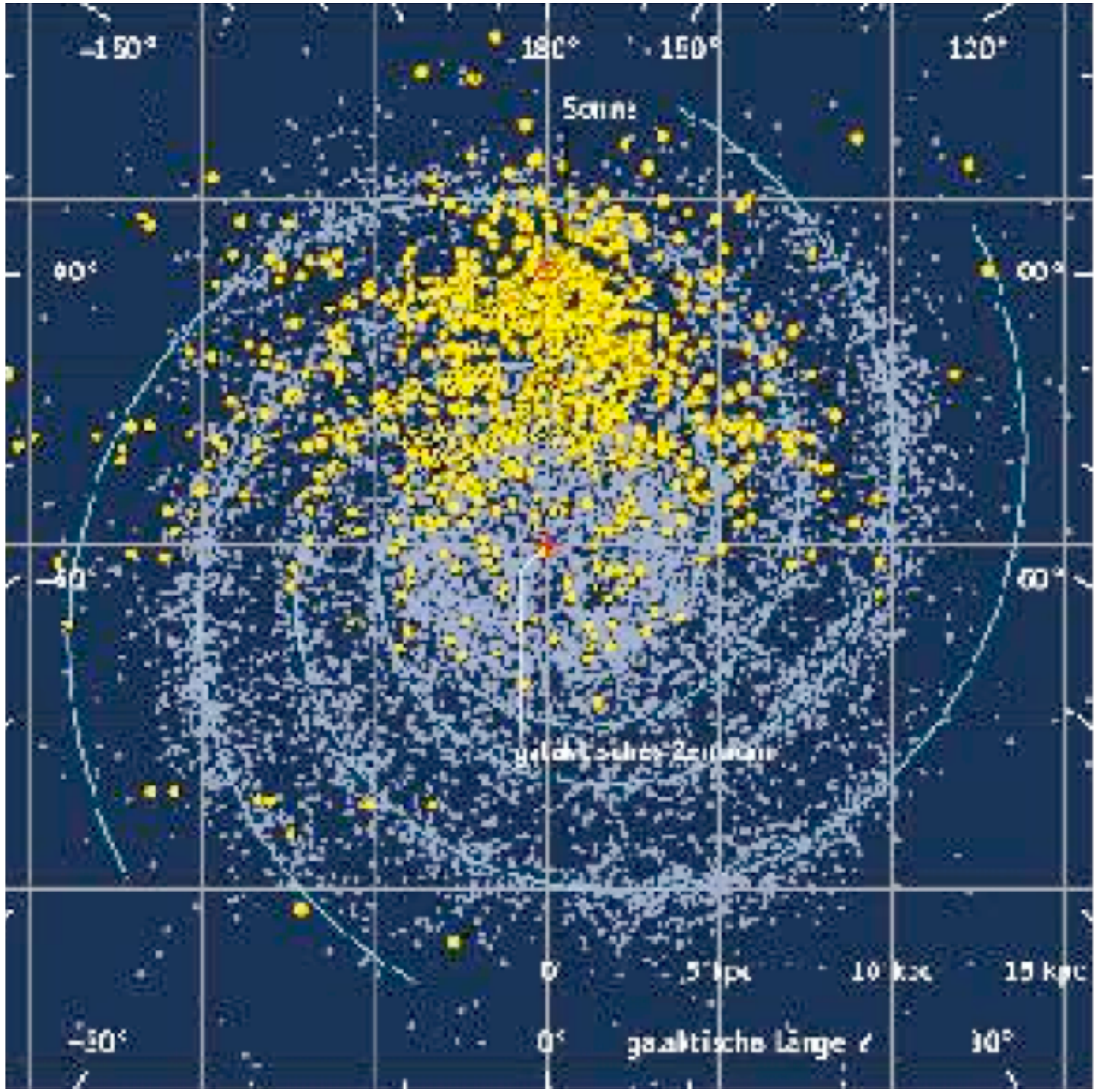
Figure 14.1: Accumulated shift of t
passage in the PSR 1913+16 system
orbit with a constant period. The para
general relativistic prediction, modifie
orbital period decay from gravitational radiation damping forces.



Timing accuracy and number of good pulsars have been increasing with time

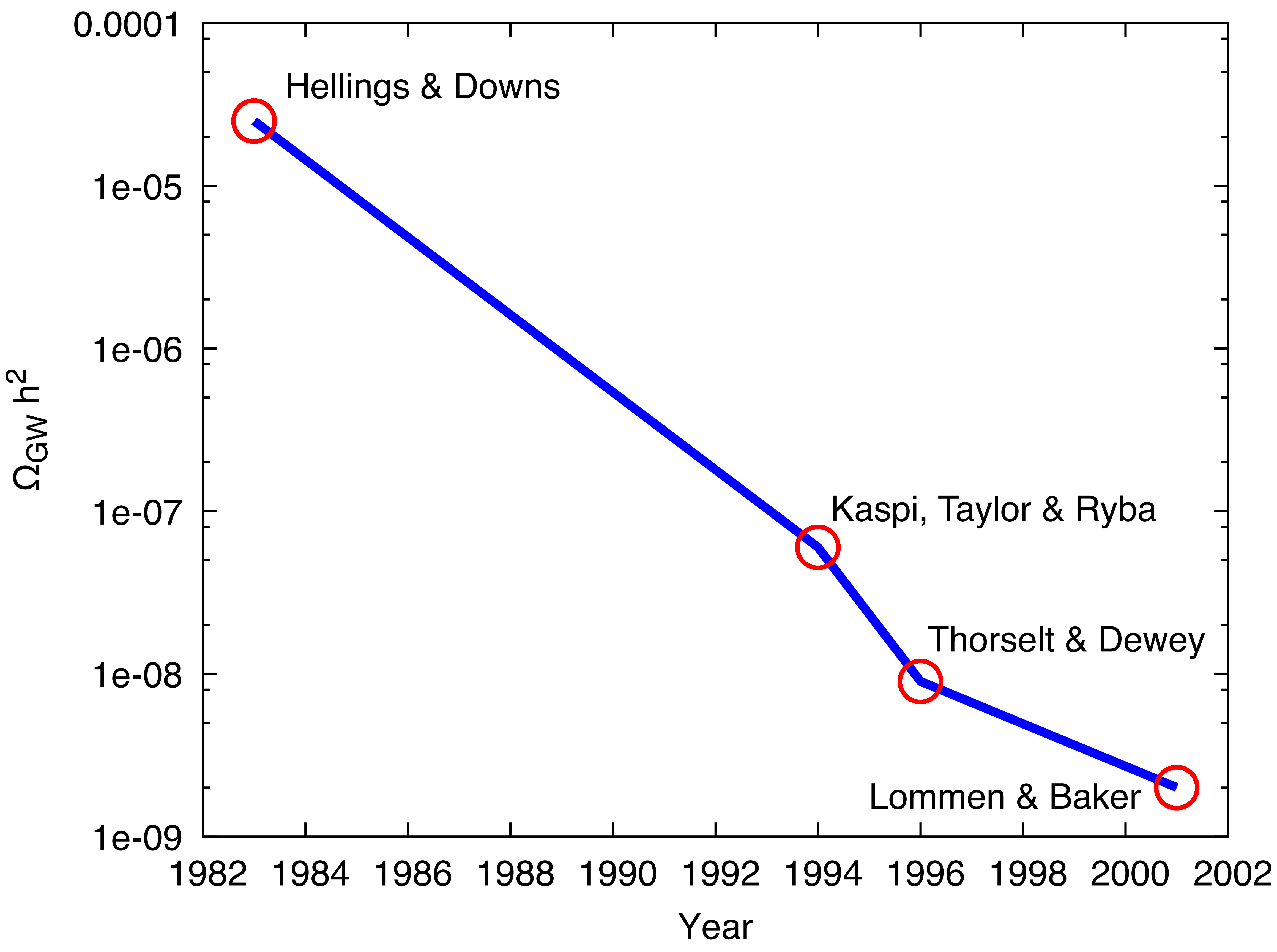


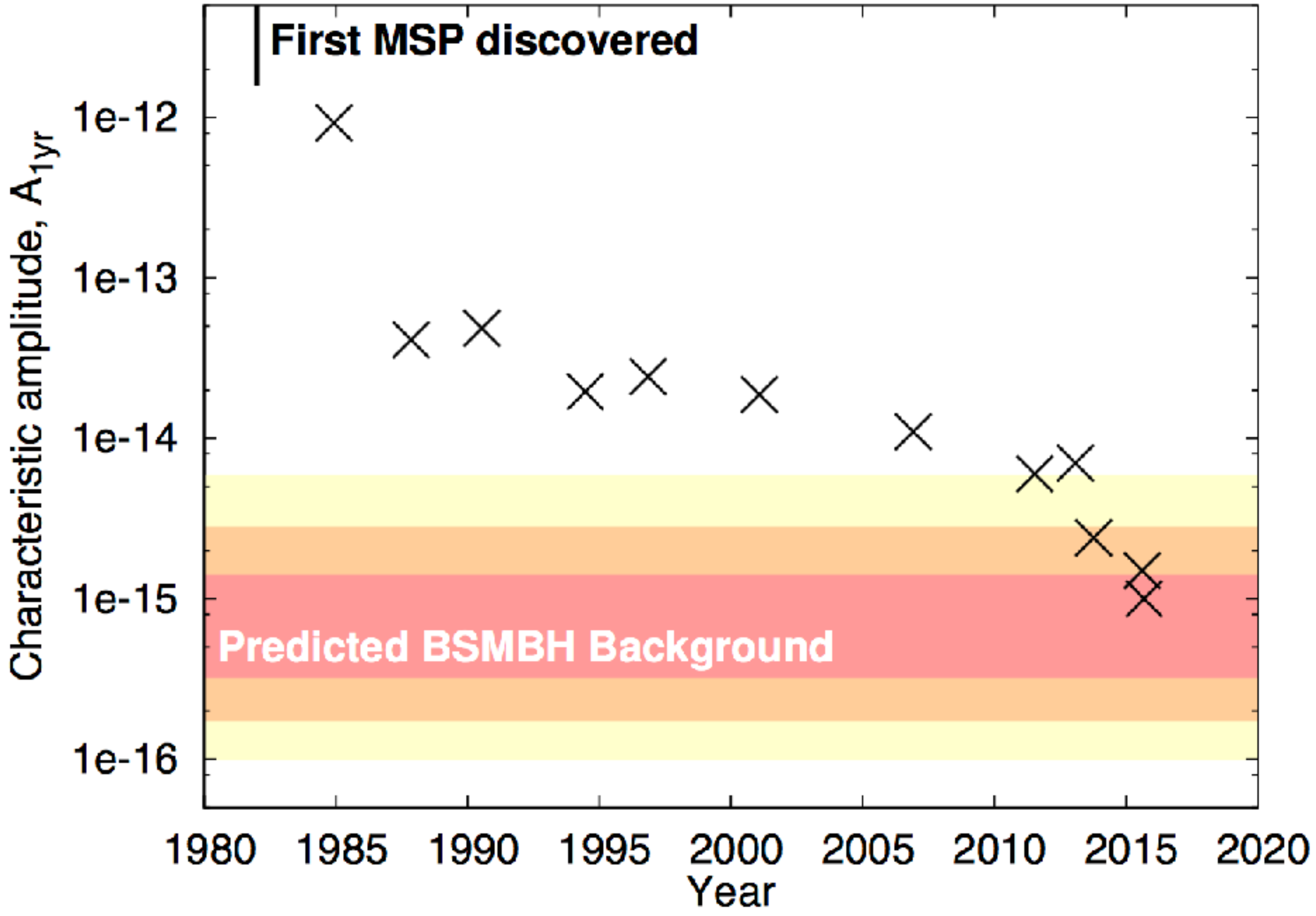




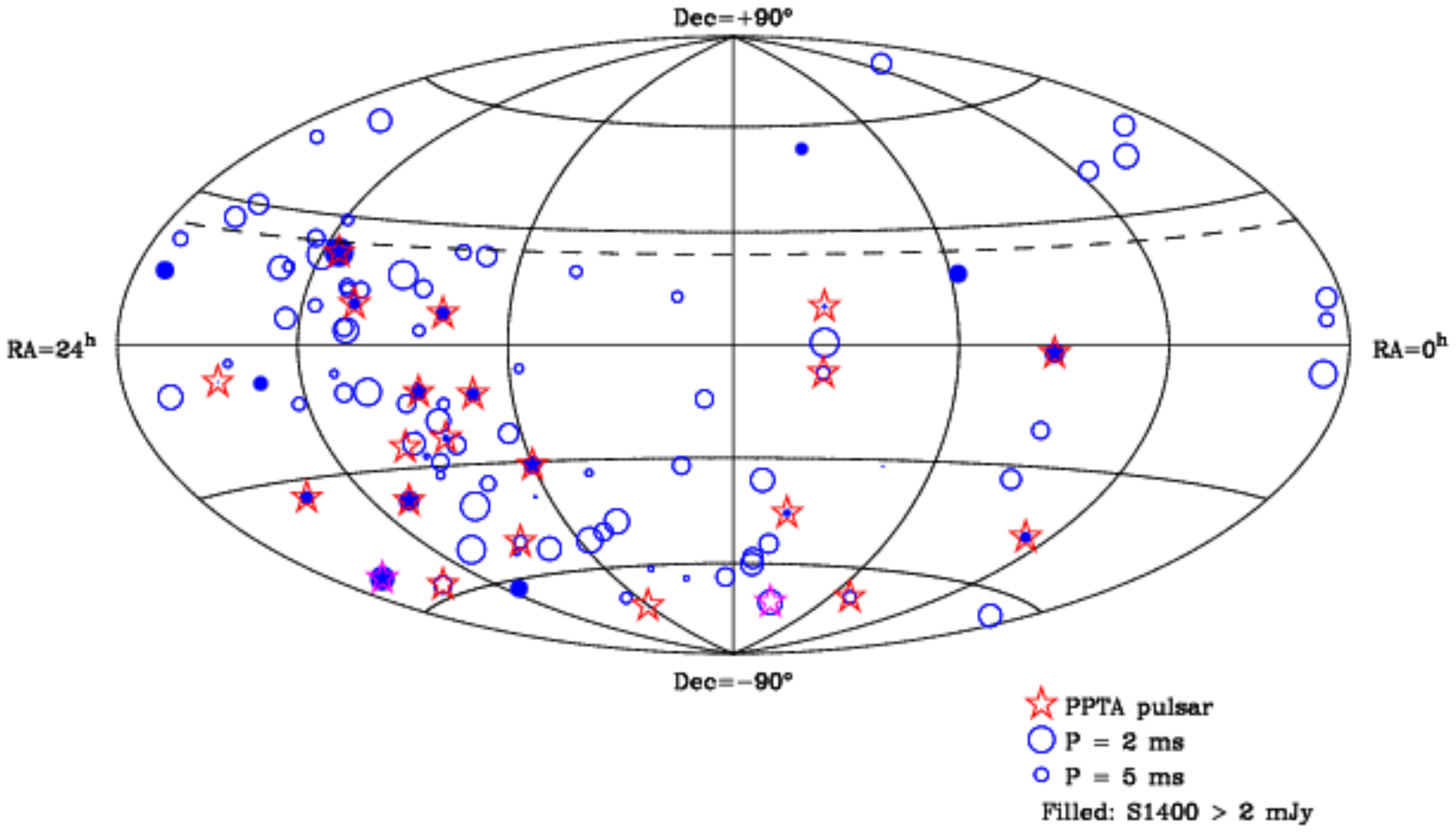
Galactic Scale Detector

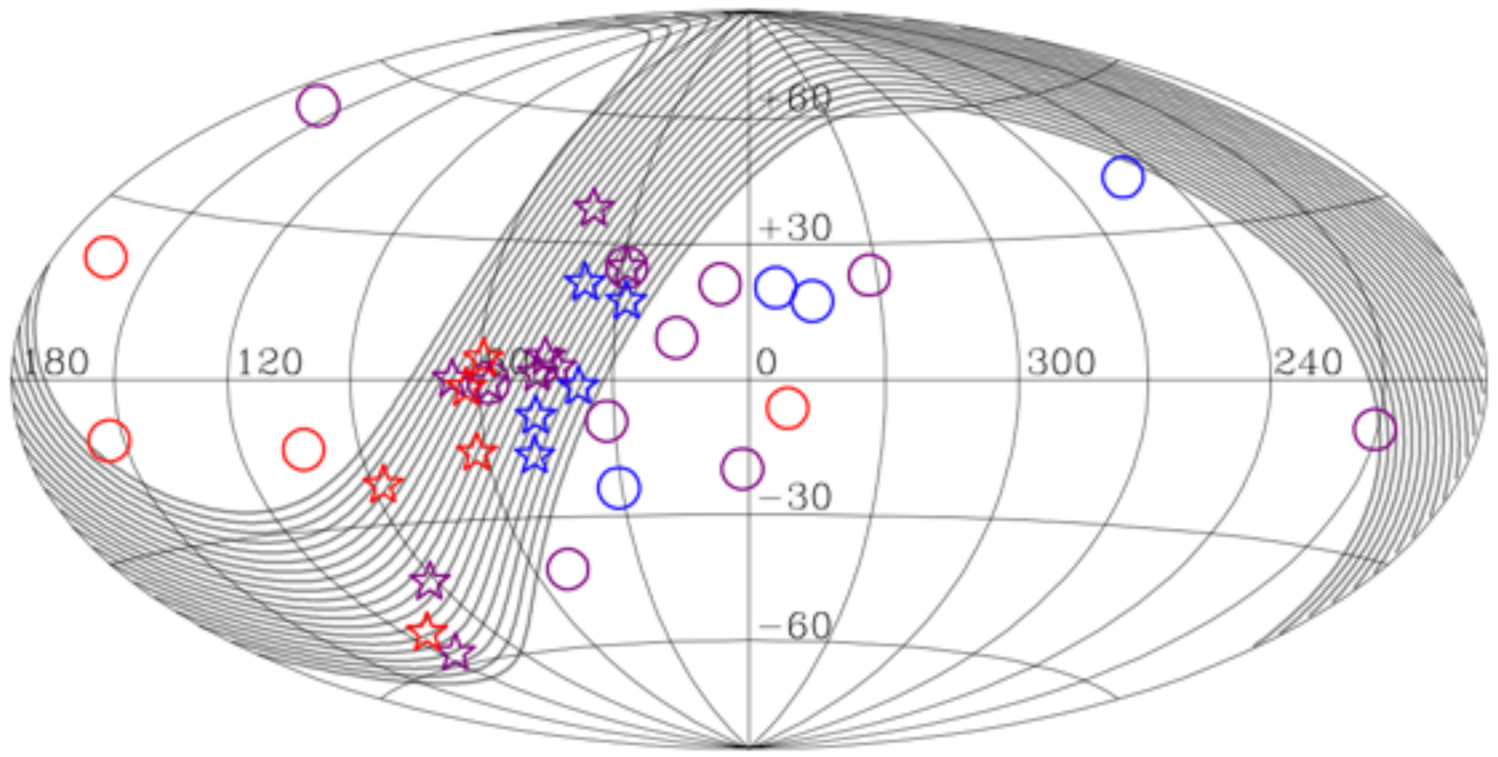
Improving upper bounds





Parkes Pulsar Timing Array

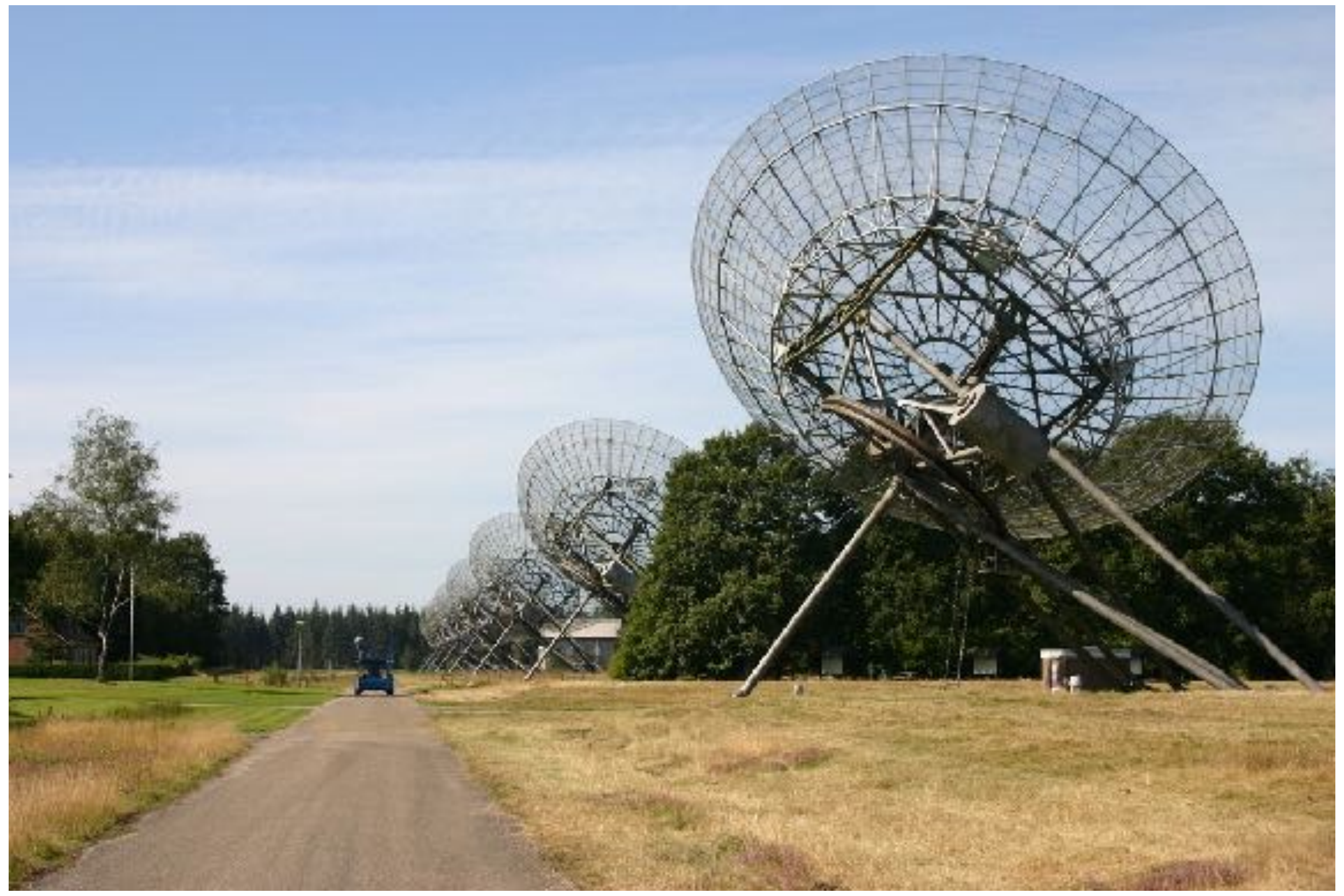


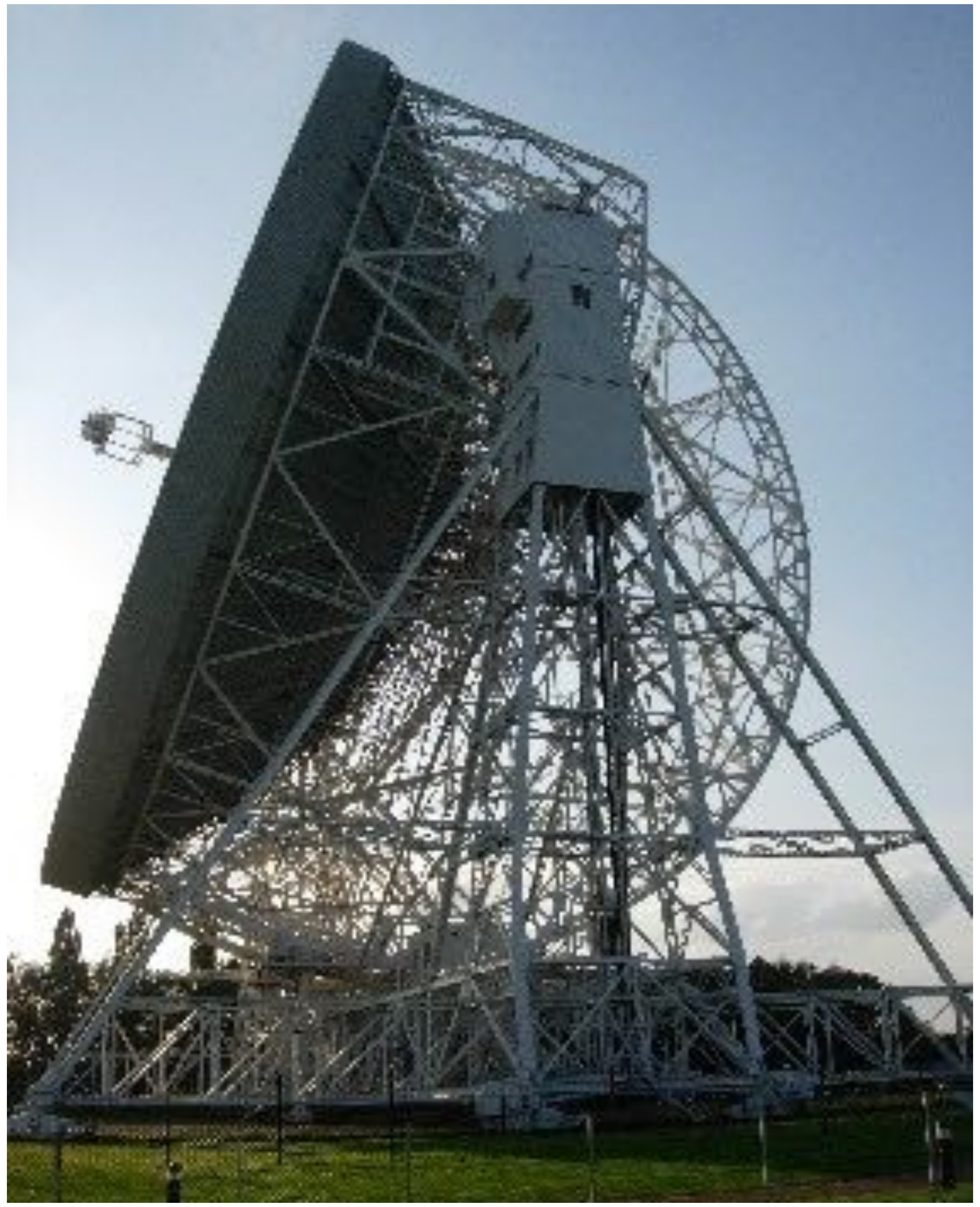


NANOGrav

European Pulsar Timing Array

EPTA





The International Pulsar Timing Array

EPTA

PPTA

NANOGrav

Next steps: Chime, FAST, MeerKAT, and the SKA