KAGAYA studio

宇宙重力波望遠鏡への展開

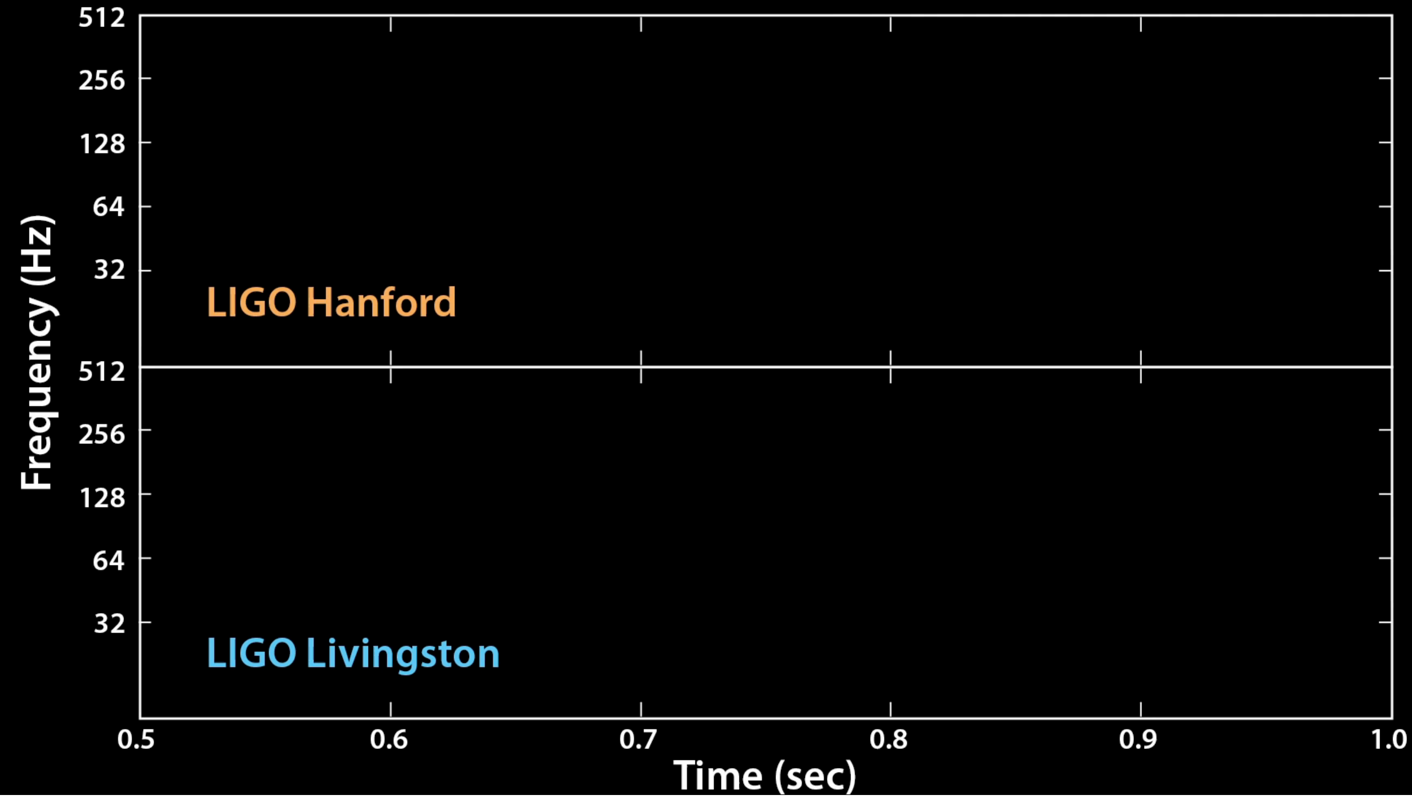
Space Gravitational Wave Observatories

佐藤修一 法政理工

2016 CHANGED EVERYTHING

- LIGO proved:
  - that GWs exist (if you didn't believe binary pulsars!)
  - that laser interferometry can detect them
  - that black holes behave dynamically as GR predicts
  - that even the first GW detection provides science surprises
  - and that the public are wowed by it all!
- LPF showed:
  - that the LISA technology is viable
  - that the LISA community's experimental team is top quality!
- This was reinforced by the strong endorsement to ESA from the GOAT.

aLIGO – GW150914 –



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

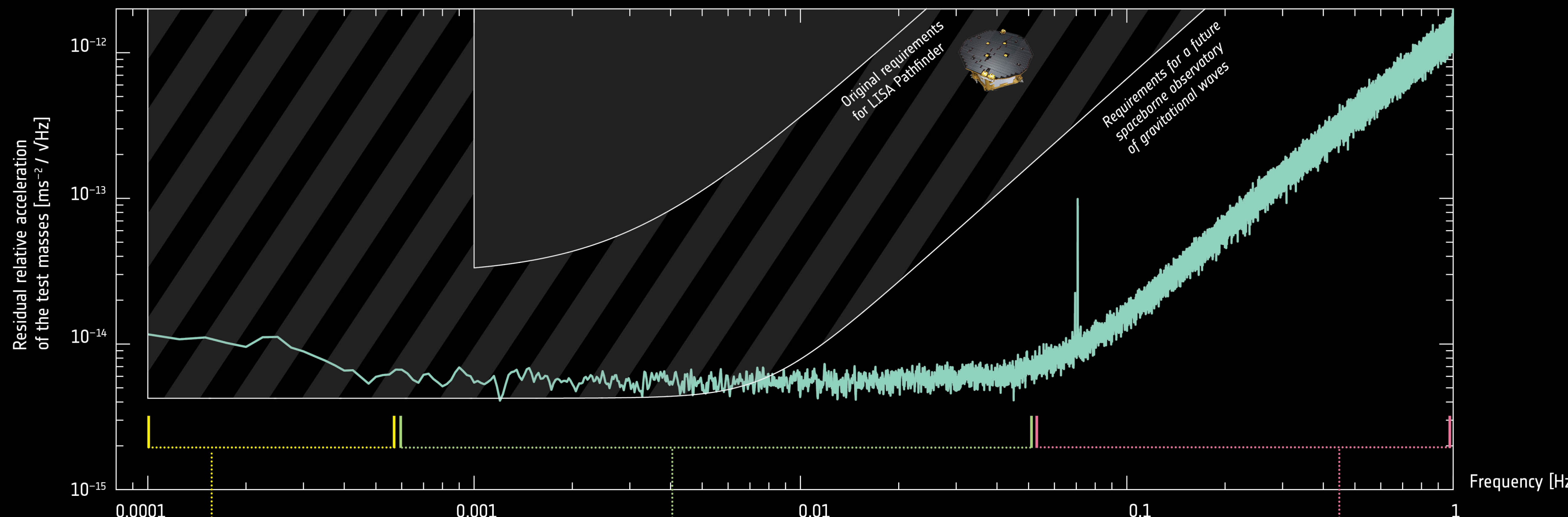
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform

LPF – LISA pathfinder –

DECIGO

→ LISA PATHFINDER EXCEEDS EXPECTATIONS

esa



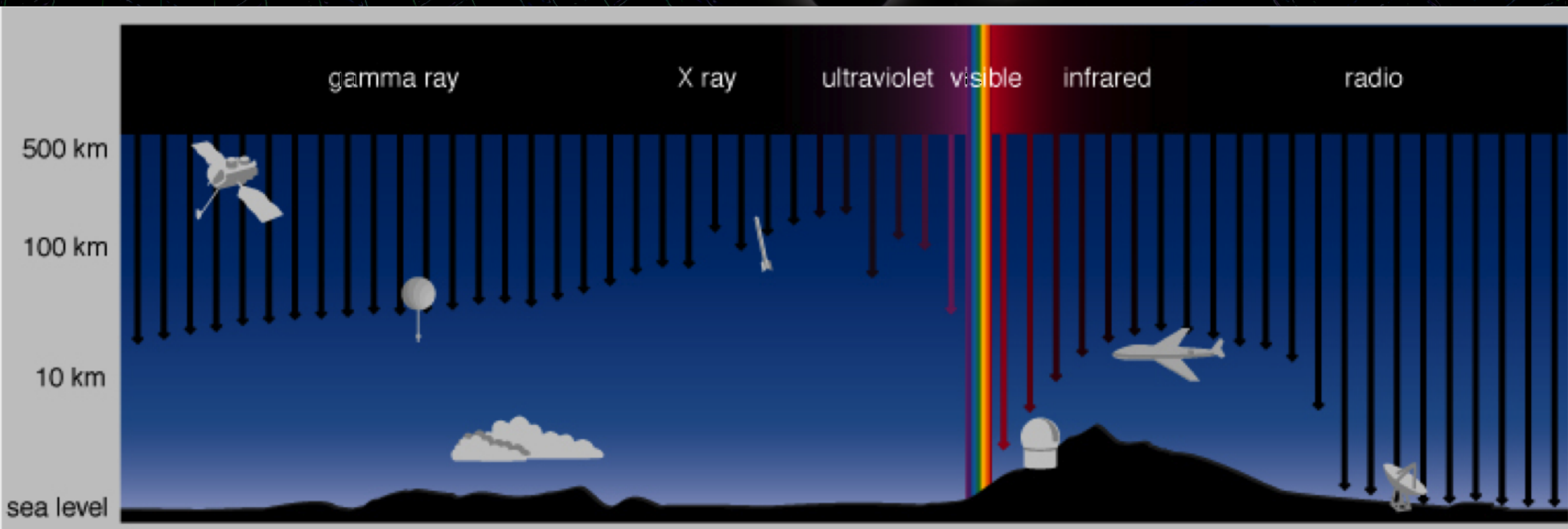
Selected for a Viewpoint in *Physics*

PRL **116,** 231101 (2016) PHYSICAL REVIEW LETTERS week ending 10 JUNE 2016

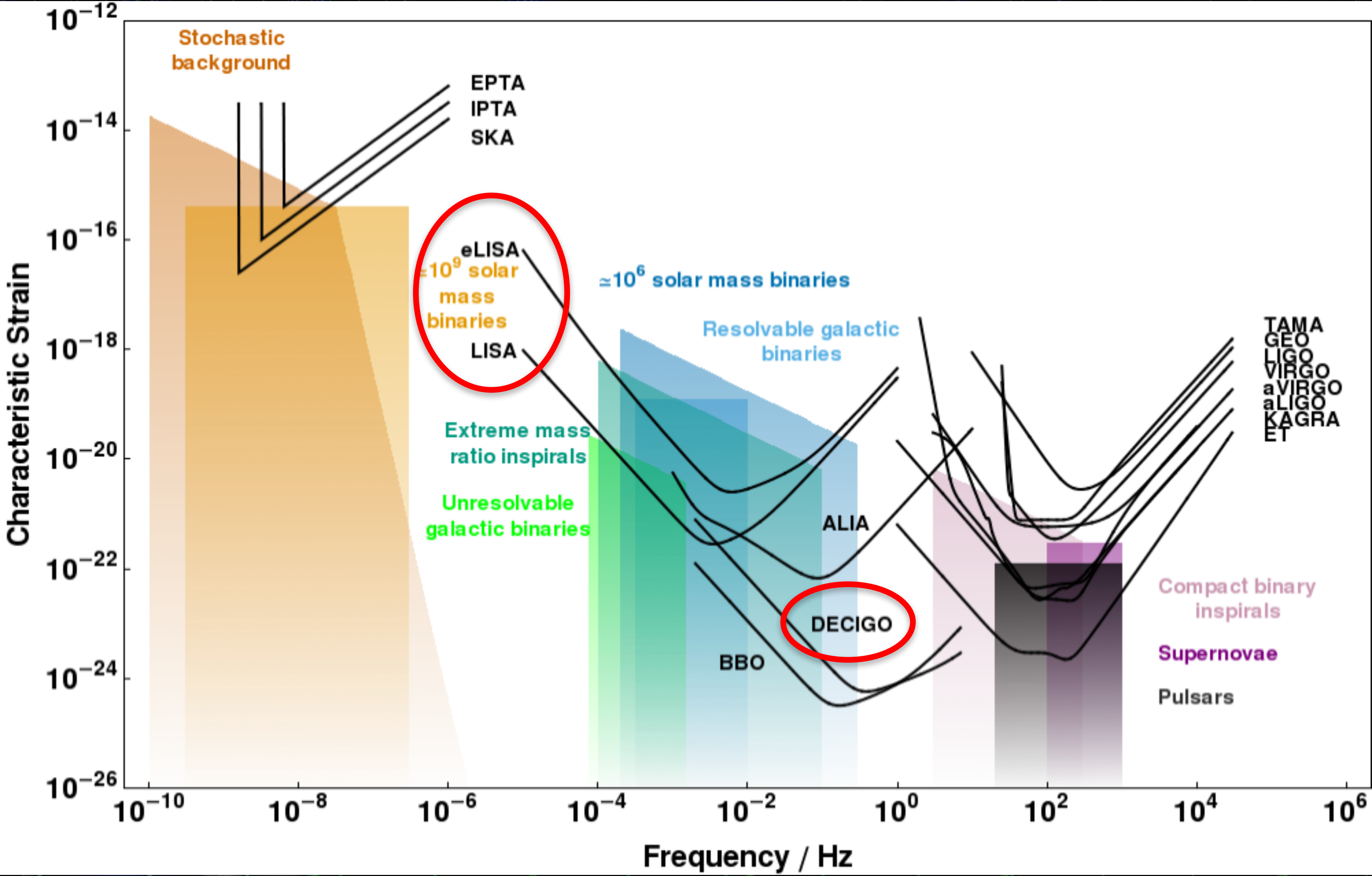
Sub-Femto-*g* Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results

M. Armano,[1] H. Audley,[2] G. Auger,[3] J. T. Baird,[4] M. Bassan,[5] P. Binetruy,[3] M. Born,[2] D. Bortoluzzi,[6] N. Brandt,[7] M. Caleno,[8] L. Carbone,[9] A. Cavalleri,[10] A. Cesarini,[9] G. Ciani,[9,†] G. Congedo,[9,‡] A. M. Cruise,[11] K. Danzmann,[2] M. de Deus Silva,[1] R. De Rosa,[12] M. Diaz-Aguiló,[13] L. Di Fiore,[14] I. Diepholz,[2] G. Dixon,[11] R. Dolesi,[9] N. Dunbar,[15] L. Ferraioli,[16] V. Ferroni,[9] W. Fichter,[17] E. D. Fitzsimons,[18] R. Flatscher,[7] M. Freschi,[1] A. F. García Marín,[2,§] C. García Marirrodriga,[8] R. Gerndt,[7] L. Gesa,[13] F. Gibert,[9] D. Giardini,[16] R. Giusteri,[9] F. Guzmán,[2,||] A. Grado,[19]

Spectrum of Electromagnetic wave

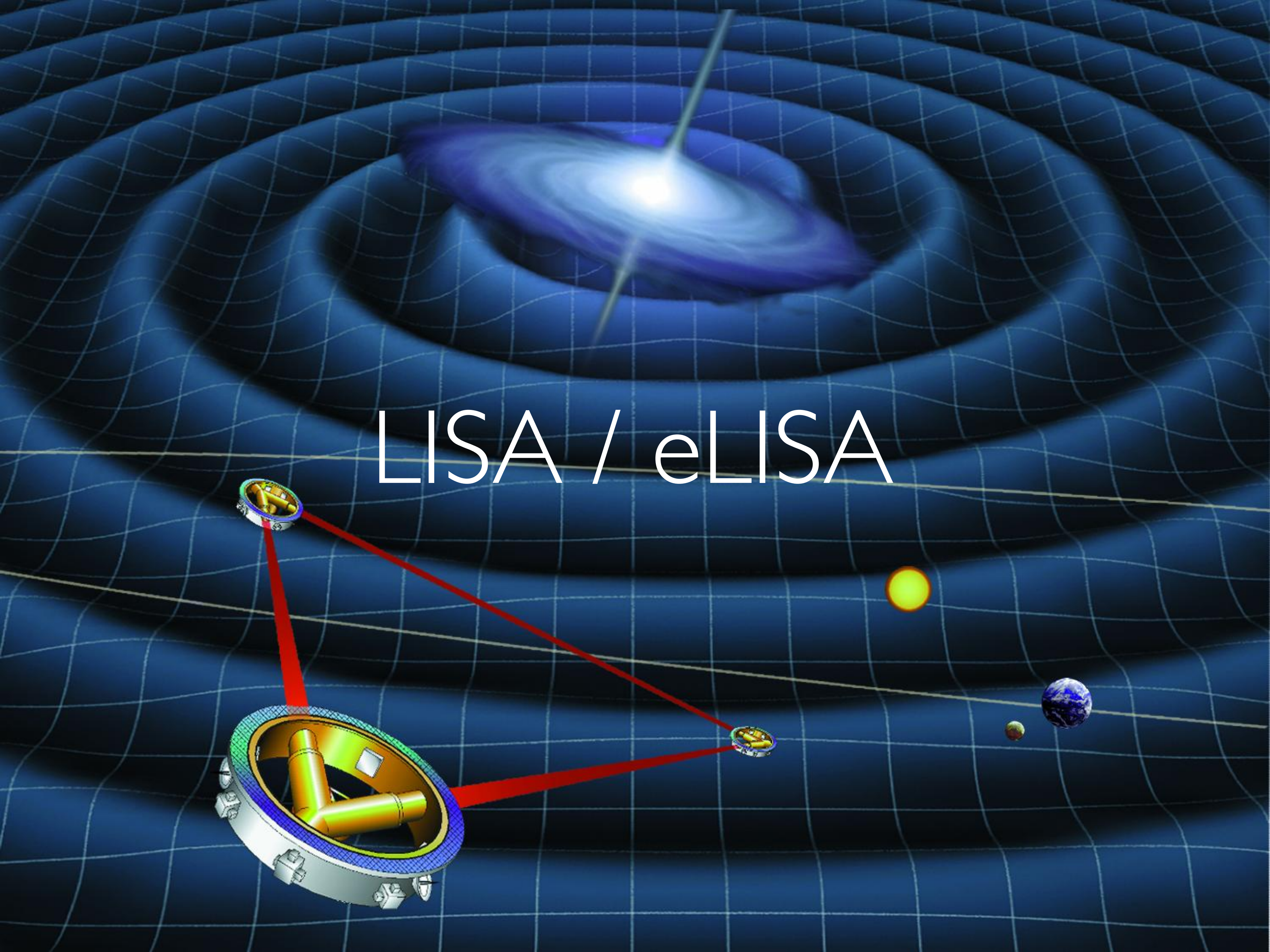


Spectrum of gravitational wave



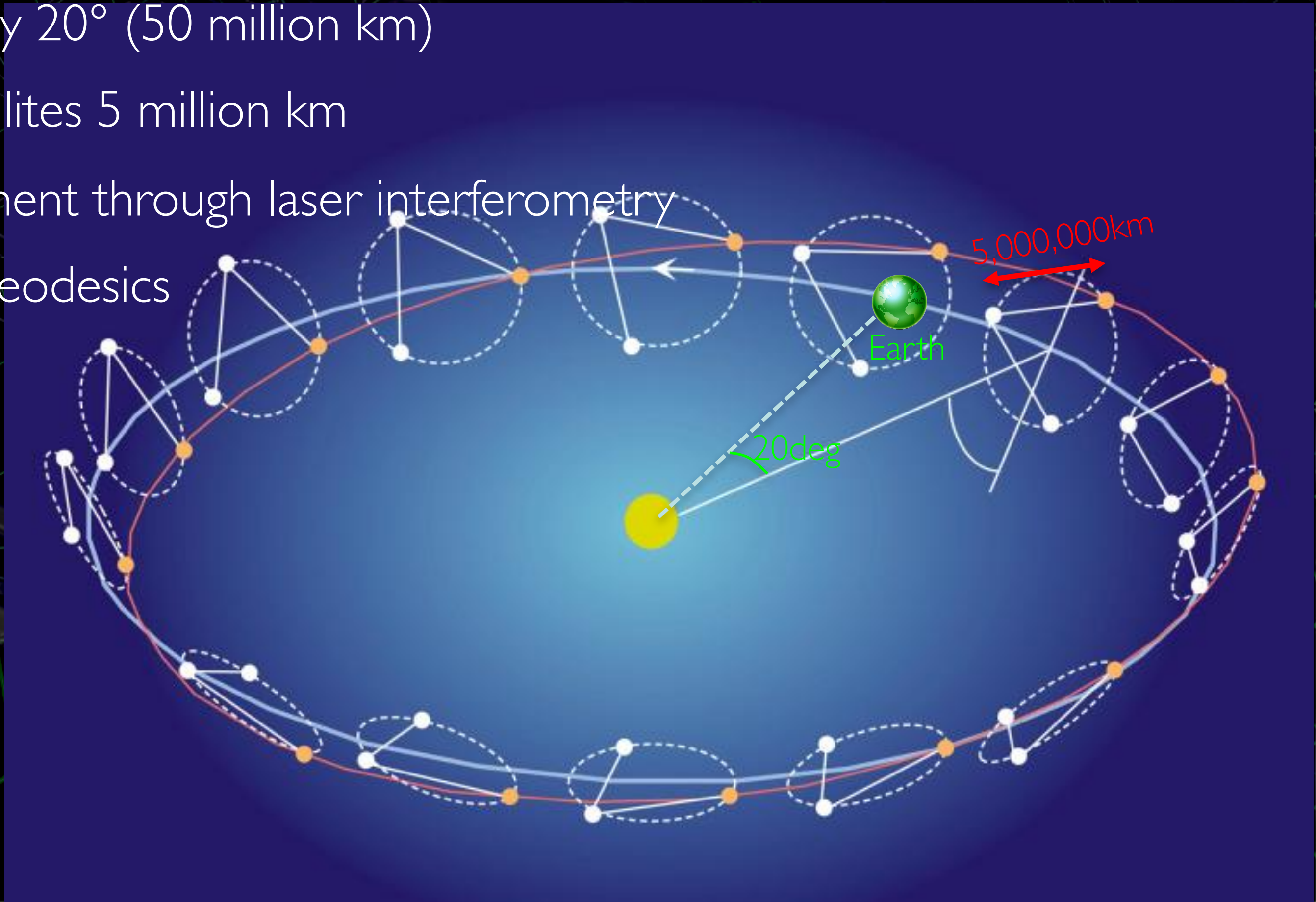
Outline

- LISA / eLISA
- LISA pathfinder
- DECIGO
- B-DECIGO


LISA / eLISA

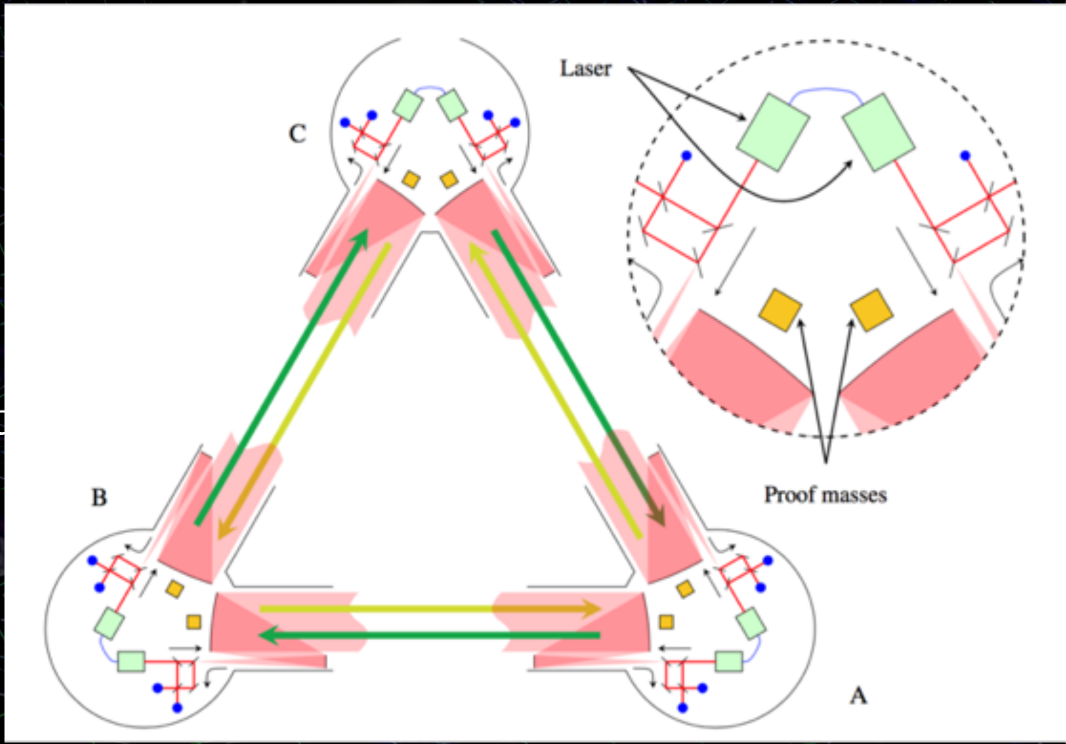
Classic LISA – *Mission overview* –

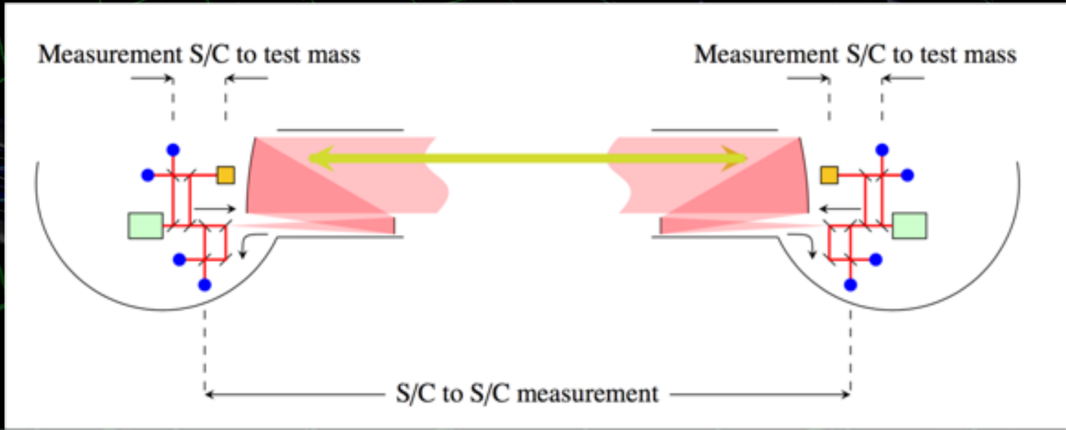
- Laser Interferometer Space Antenna
- Joint ESA/NASA mission
  - to detect and observe low- frequency gravitational waves
  - f = 0.1 mHz ... 100 mHz
- 3 drag-free S/C in a heliocentric orbit
  - trailing the Earth by 20° (50 million km)
- Distance between satellites 5 million km
- pm accuracy measurement through laser interferometry
- Reference masses on geodesics



Classic LISA – *Mission overview* –

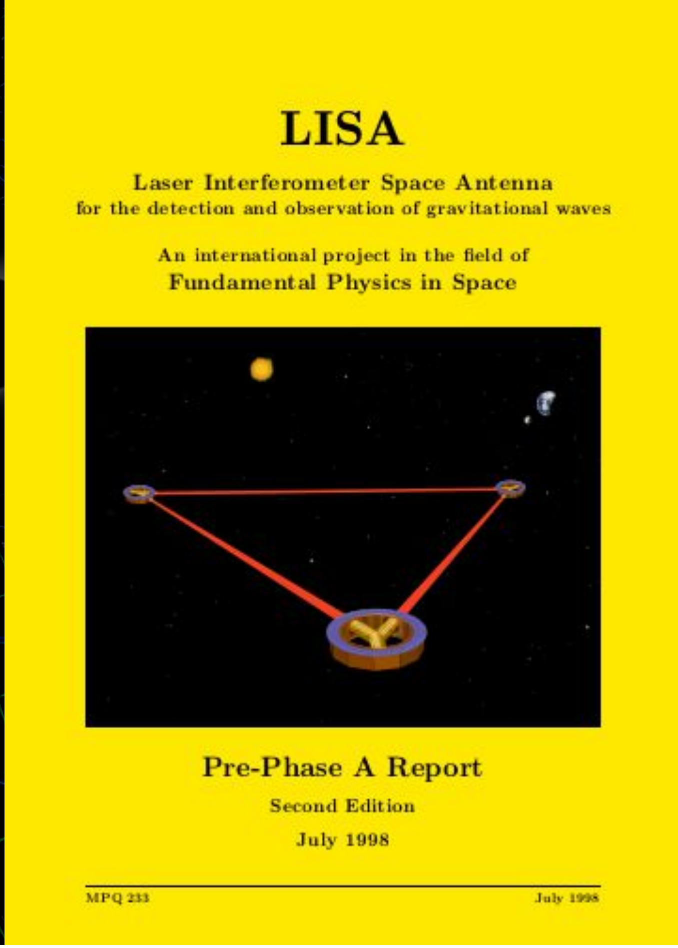
- Baseline : 5,000,000km = 5Gm
- Test mass : ~2kg
- Light source : 2W – 1064nm
- 20cm telescope
- 3 S/C in triangular formation
- Optical transponder interferometry
- Test mass to test mass measurement
    - Test mass to SC
    - SC to SC
- Combine 6 links on ground
- Time Delay Interferometry
- Launch with Ariane-V





Classic LISA – *History* –

- 1992 : Proposed as M3 mission in Horizon 2000
- 1996 : Cost reduction to 3 S/C
- 1998 : Pre-Phase A report
- 2011 : LISA Redefinition study for ESA L1
  - Mission concept : NGO (eLISA)
- 2012 : ESA L1 SPC Decision -JUICE
- 2013 : New ESA Call for Large Missions L2 and L3
- 2013 : Selected as Science Theme for ESA L3
  - L2 : "The Hot and Energetic Universe" Athena in 2028
  - L3 : "The Gravitational Universe" eLISA in 2034
- 2015 : LPF launch
- 2016 : Call for L3 mission


LISA

Laser Interferometer Space Antenna
for the detection and observation of gravitational waves

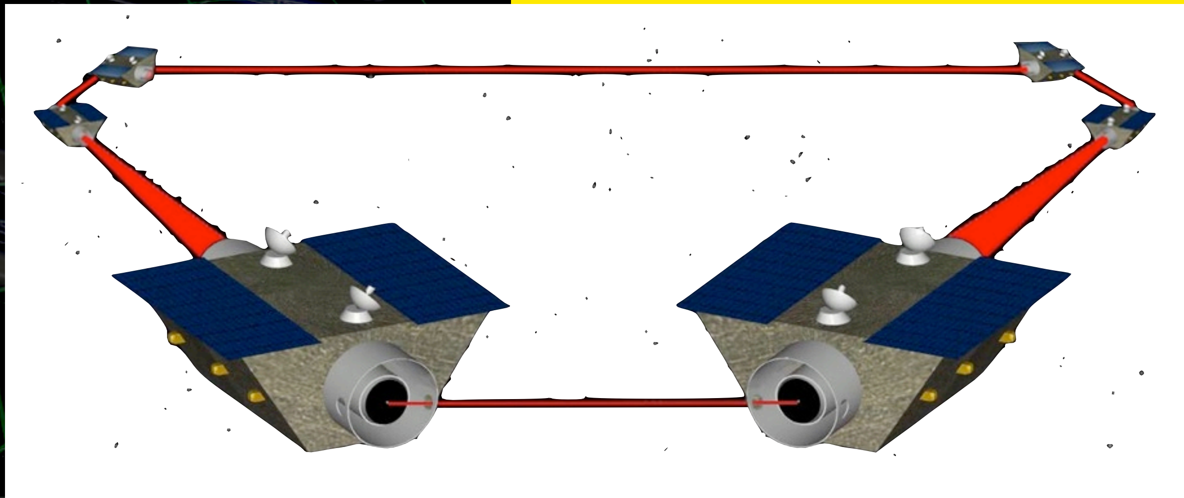
An international project in the field of
Fundamental Physics in Space

Pre-Phase A Report

Second Edition

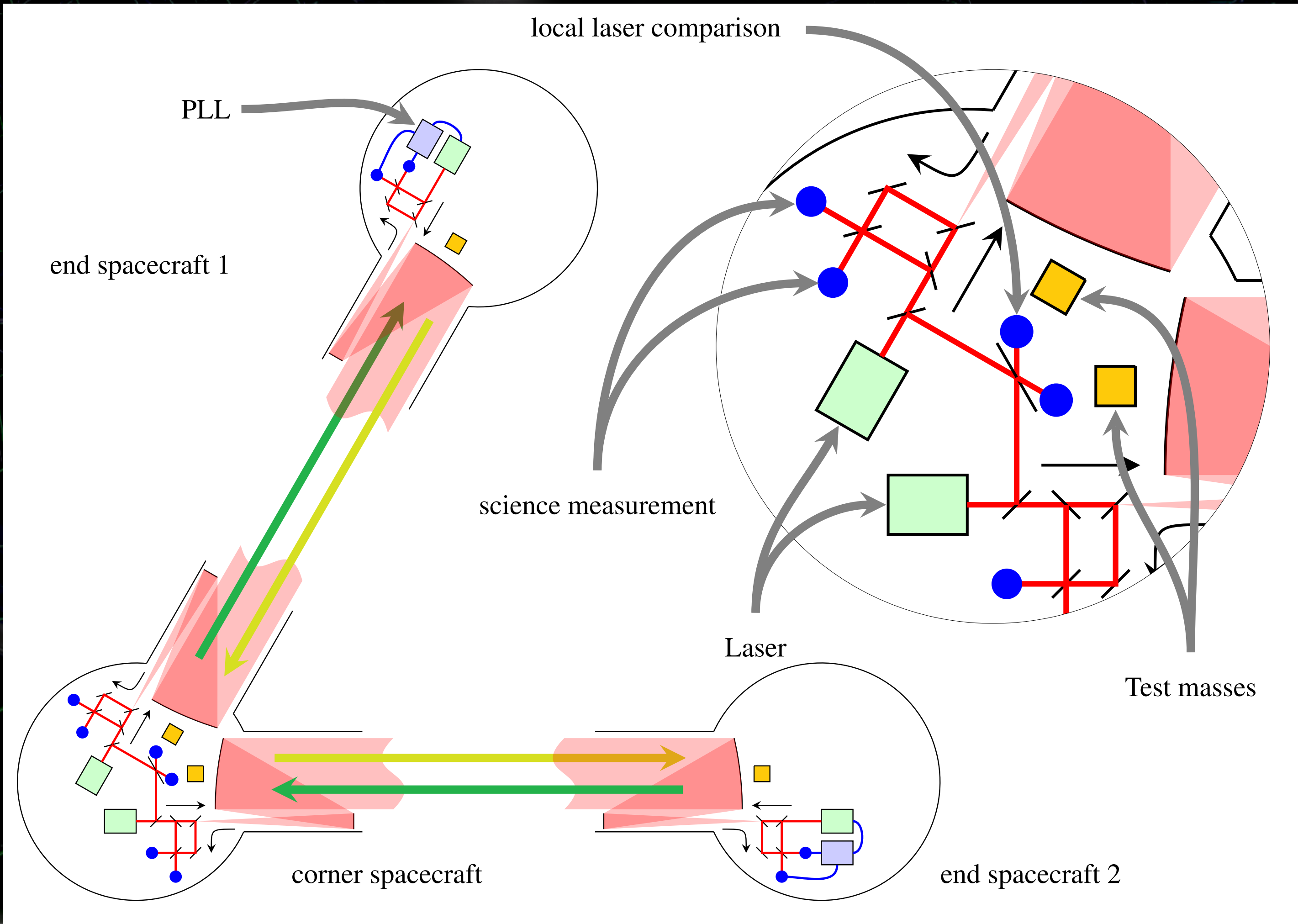
July 1998

MPQ 233 July 1998

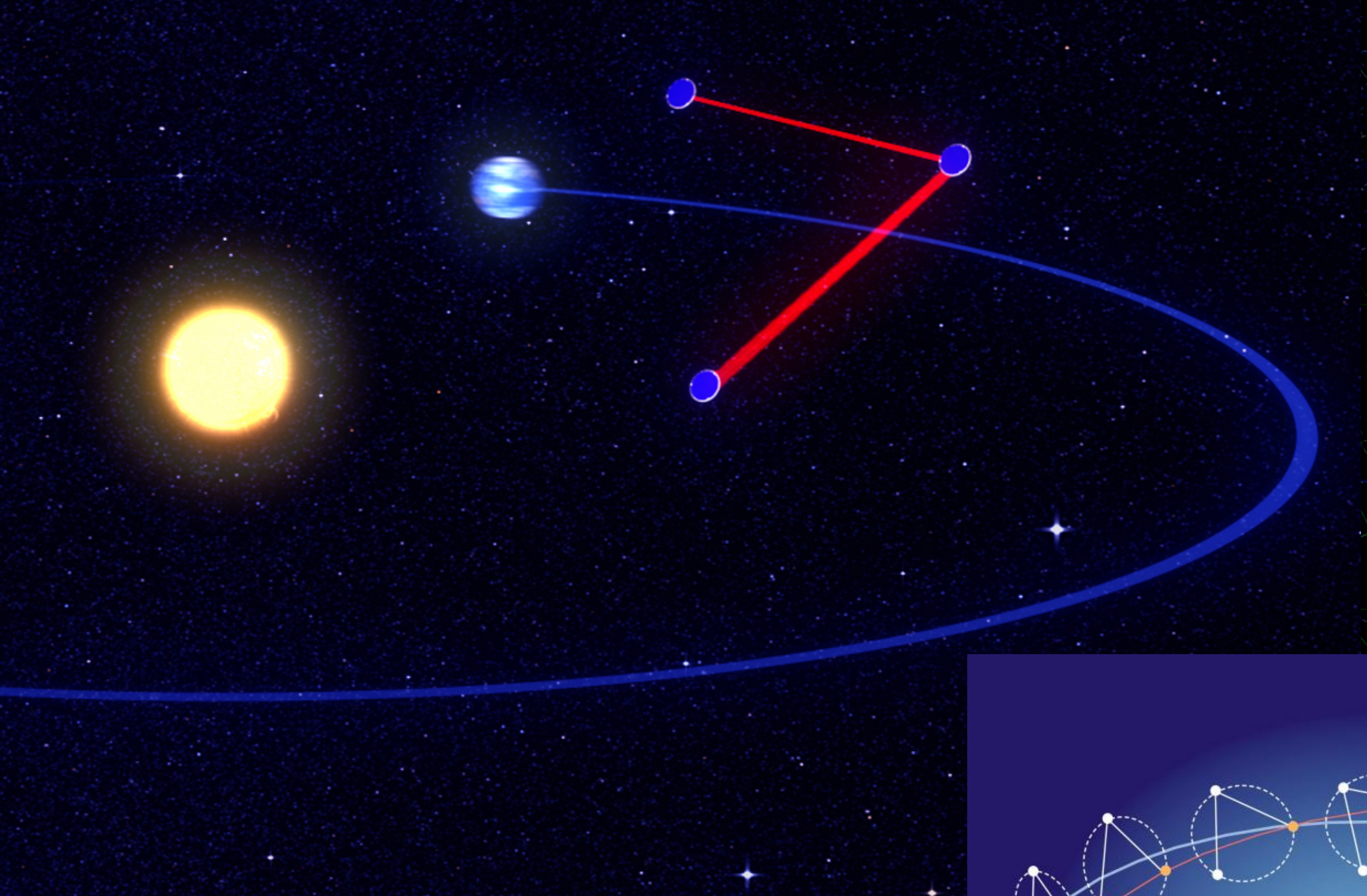


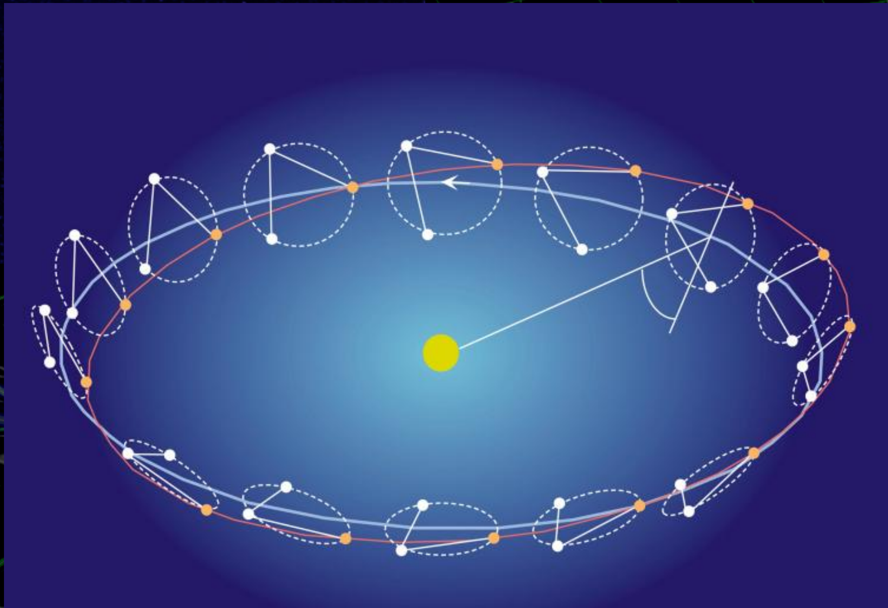
eLISA – *Mission overview* –

- evolving LISA
- Baseline : 1,000,000km （1Gm）
- 1 interferometer
- 2 optical links
- Launch with Soyuz



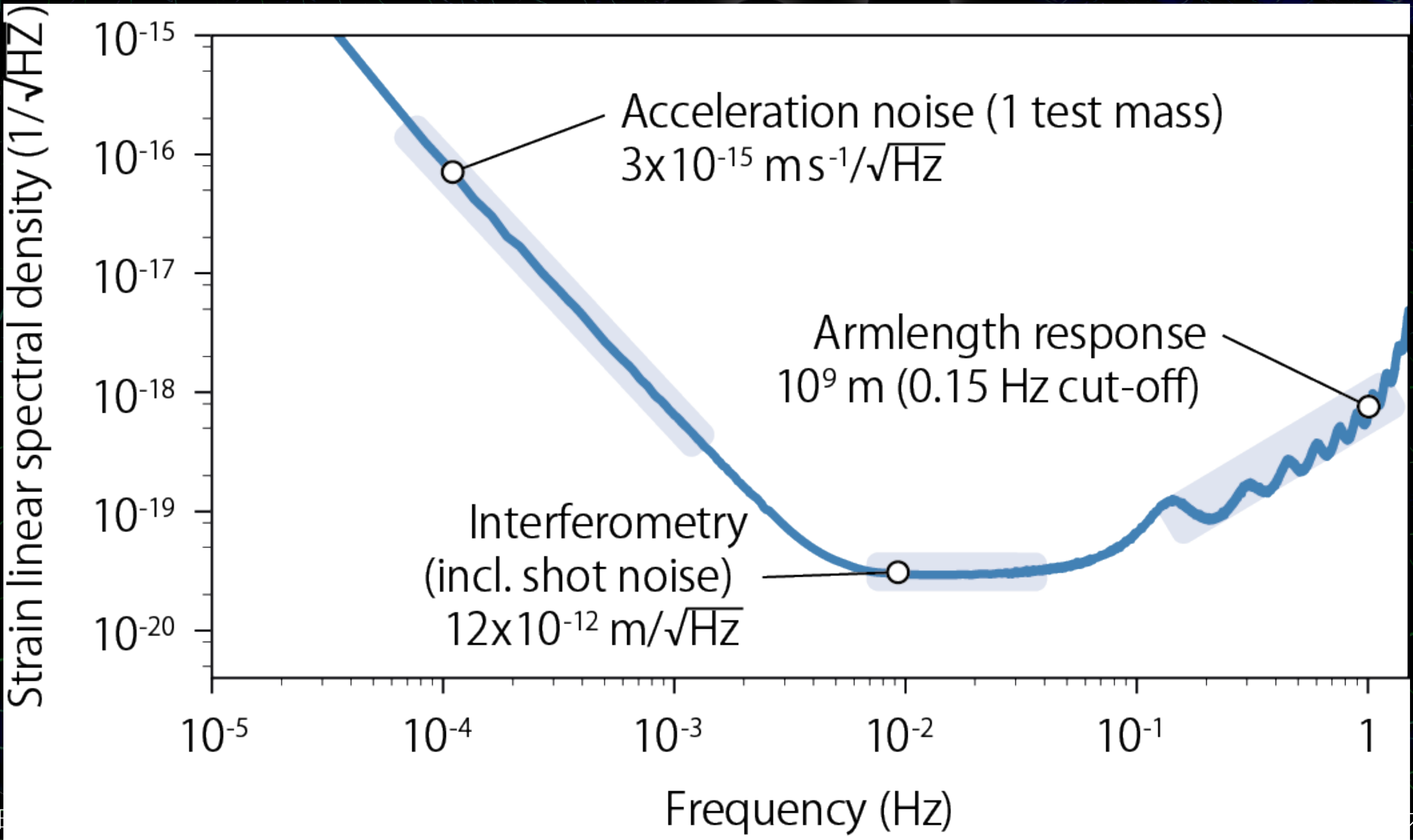
eLISA – *Orbit* –



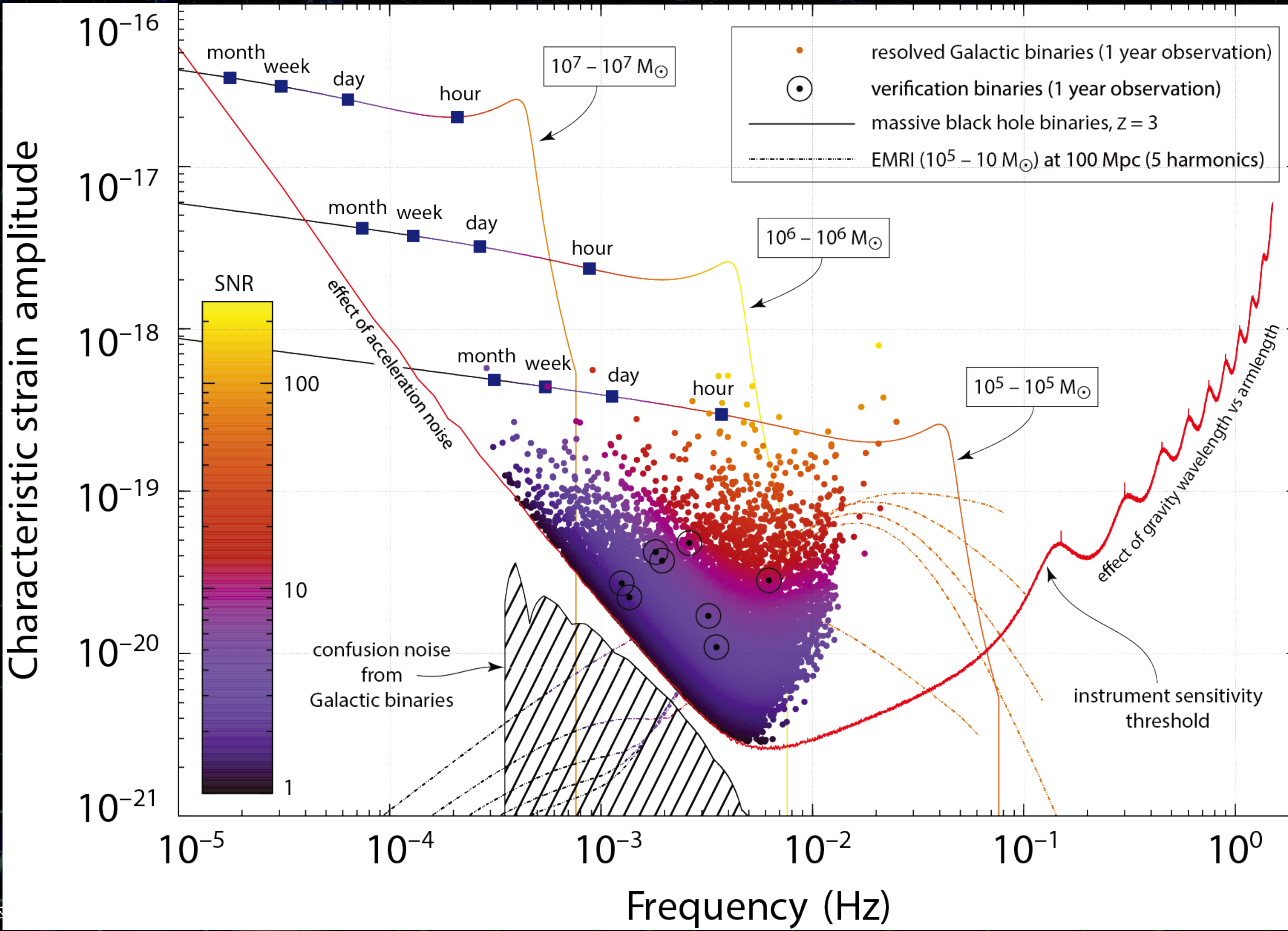


eLISA – *Mission requirement* –

- Displacement noise : 1.2×10^{-11} m/rHz
- Acceleration noise : 3.0×10^{-15} m/s^2/rHz

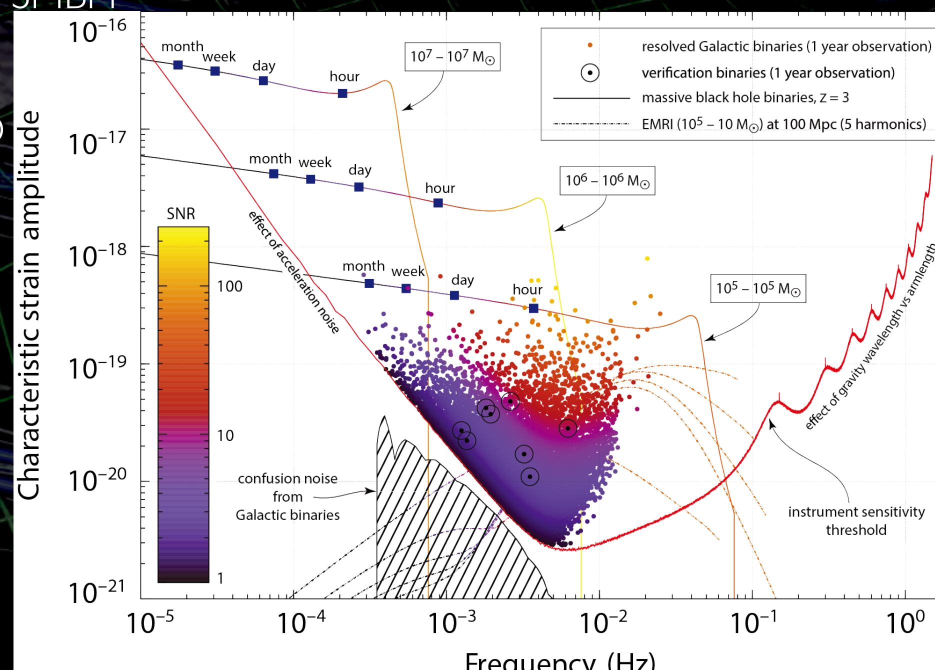


eLISA – *Science case* –



eLISA – *Science case*–

- Compact white dwarf binaries (CWDs)
  - Some $10^{3\text{-}4}$ are expected to be resolved over 10^7 Galactic binaries
- Compact neutron-star and black-hole binaries
  - Next to NS/NS binary system
- Massive black hole binaries (MBHBs)
  - Cosmological merger history of MBH
  - Dynamics of galaxy formation and evolution
- Extreme mass ratio inspirals (EMRIs)
  - Precise map of the spacetime geometry of the SMBH
- Gravitational wave backgrounds
  - astrophysical or cosmological nature, like BWD



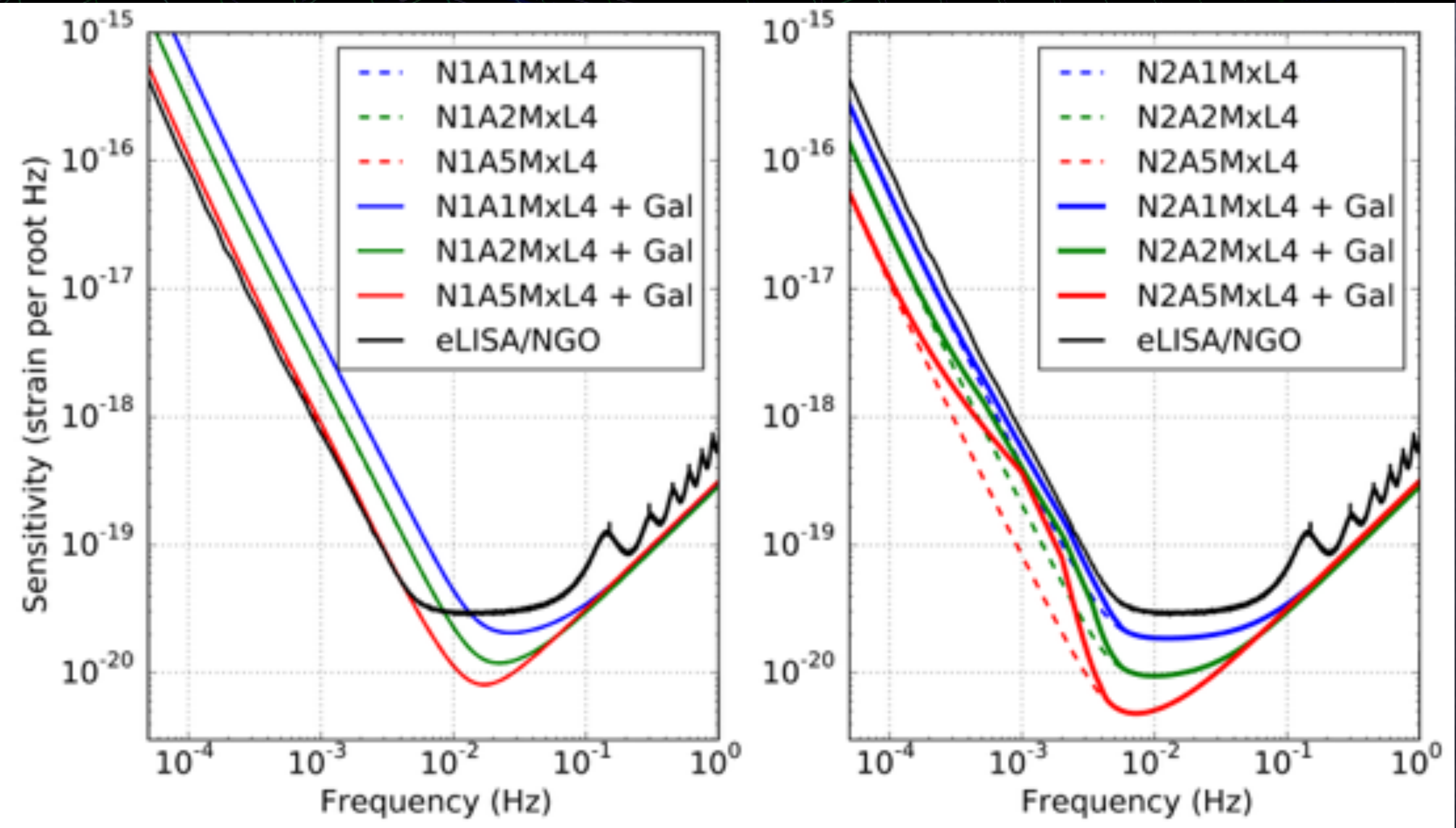
eLISA – *Perspective* –

- 2016 : eLISA design/mission not selected yet
  - Options analyzed by Gravitational Wave Advisory Team (GOAT)
- 2016 : Call for mission concepts for L3
- 2017 : Mission proposal
- 2020 : Phase-A completed
- 2022 : Technology matured
- 2024 : Phase-B1 completed
- 2034 : Launch as L3 @ ESA

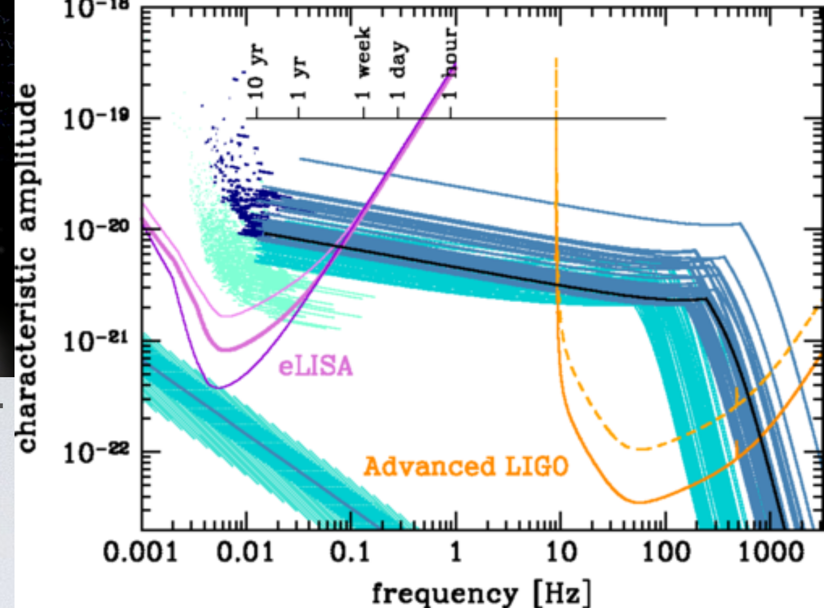
  +14 months to orbit

eLISA – *Options* –

- Arm length L= 1, 2, 5 Gm
- Low-frequency noise at the LISA requirement level of LPF or10 times worse
- 4 or 6 links
- 2 or 5 year mission
- Laser power of 0.7 W or 2 W
- Telescope mirror size of 25, 28 or 40 cm



eLISA – aLIGO+LPF Impact –



LIGO + LPF: IMPACT

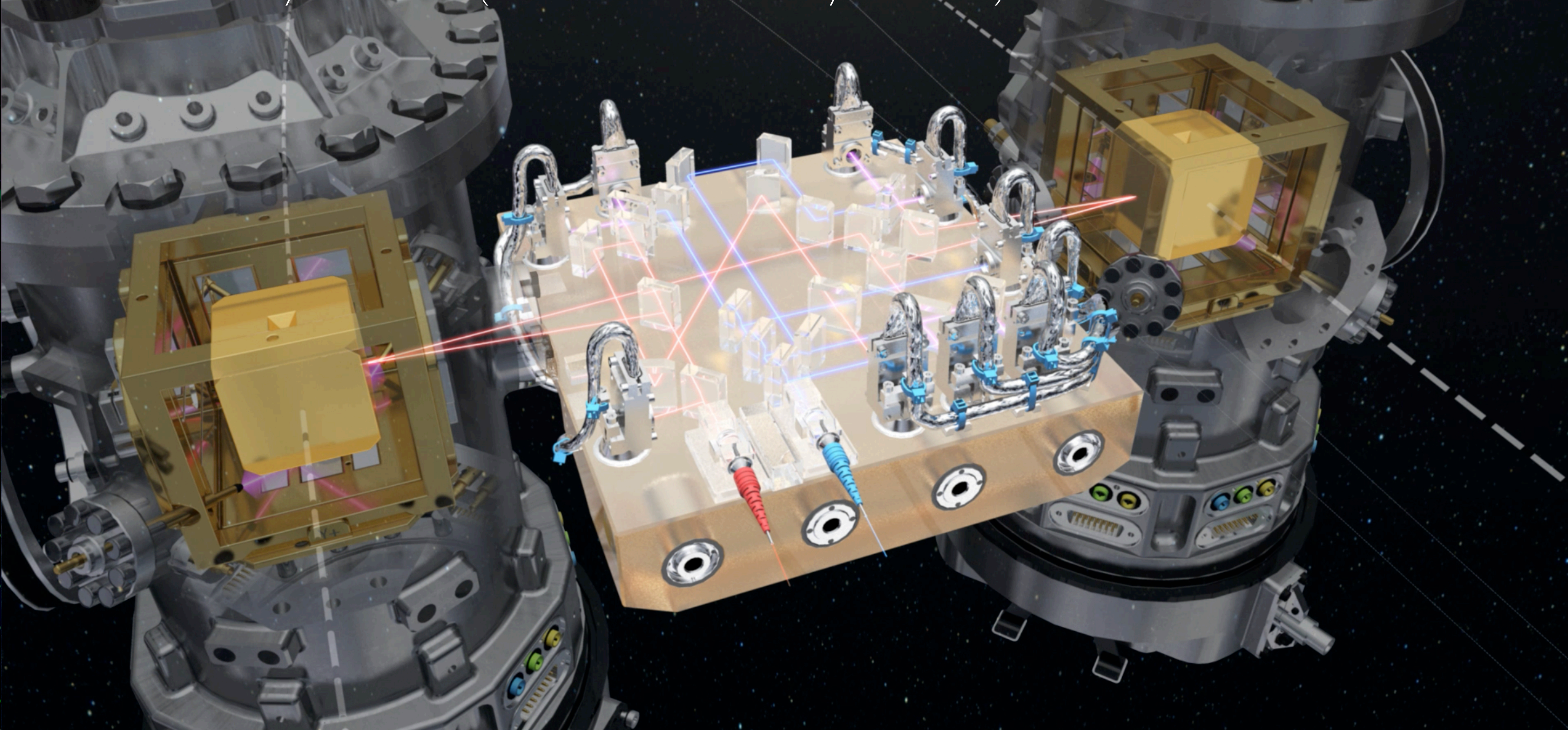
The GW game has changed

- Strong international interest: NASA, JAXA, China
- Strong motivation for bringing L3 closer
- Strong motivation for doing a 3-arm, 6-link mission
- Realisation that there is joint science to be done by ground-based and space-based observatories
- Confirmation that GW observations do astronomy as well as probe the fundamental nature of spacetime


LISA Pathfinder

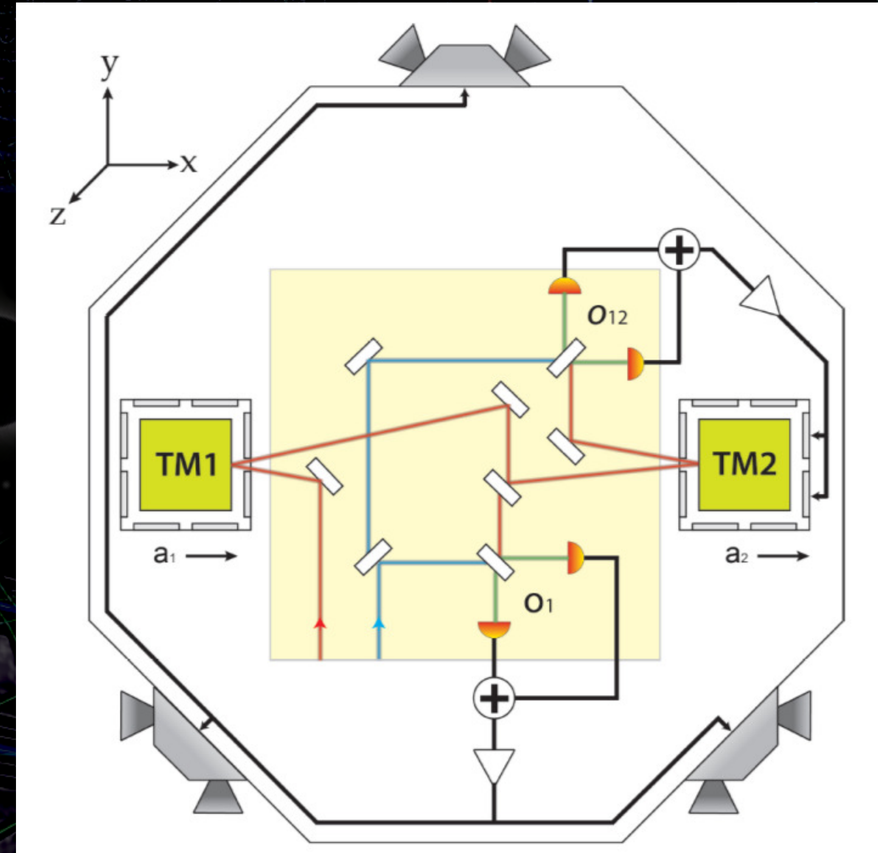
LISA pathfinder – *Concept* –

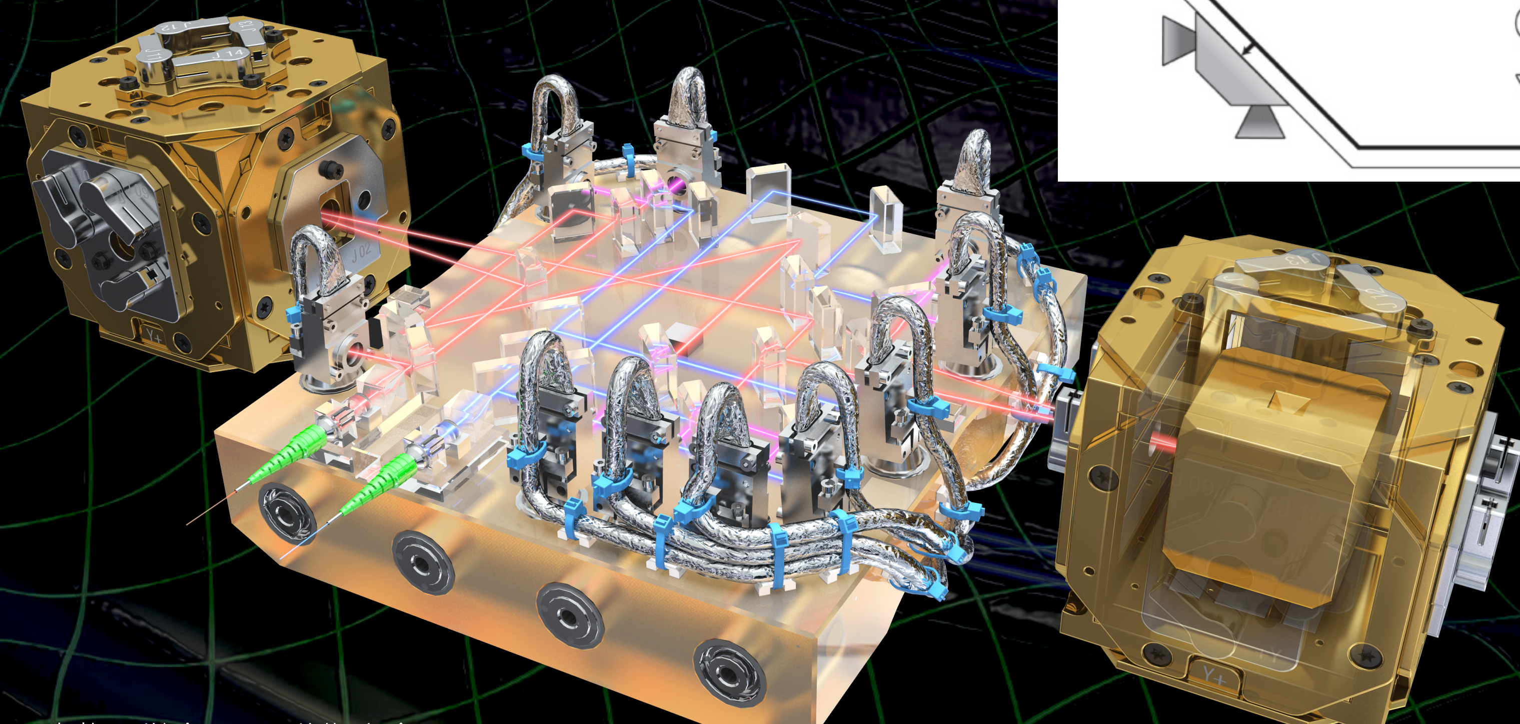
- Technology demonstration for LISA
  - Test of most of the local measurement (95 % of noise)
  - Same hardware/processes with LISA to carry them at TRL 8-9.
  - In-orbit consolidation test for our physical model of free fall
- ESA spacecraft
  - European Payload Mission (LISA Technology Package : LTP)
  - NASA Payload Mission (Disturbance Reduction System : DRS)



LISA pathfinder – *Concept* –

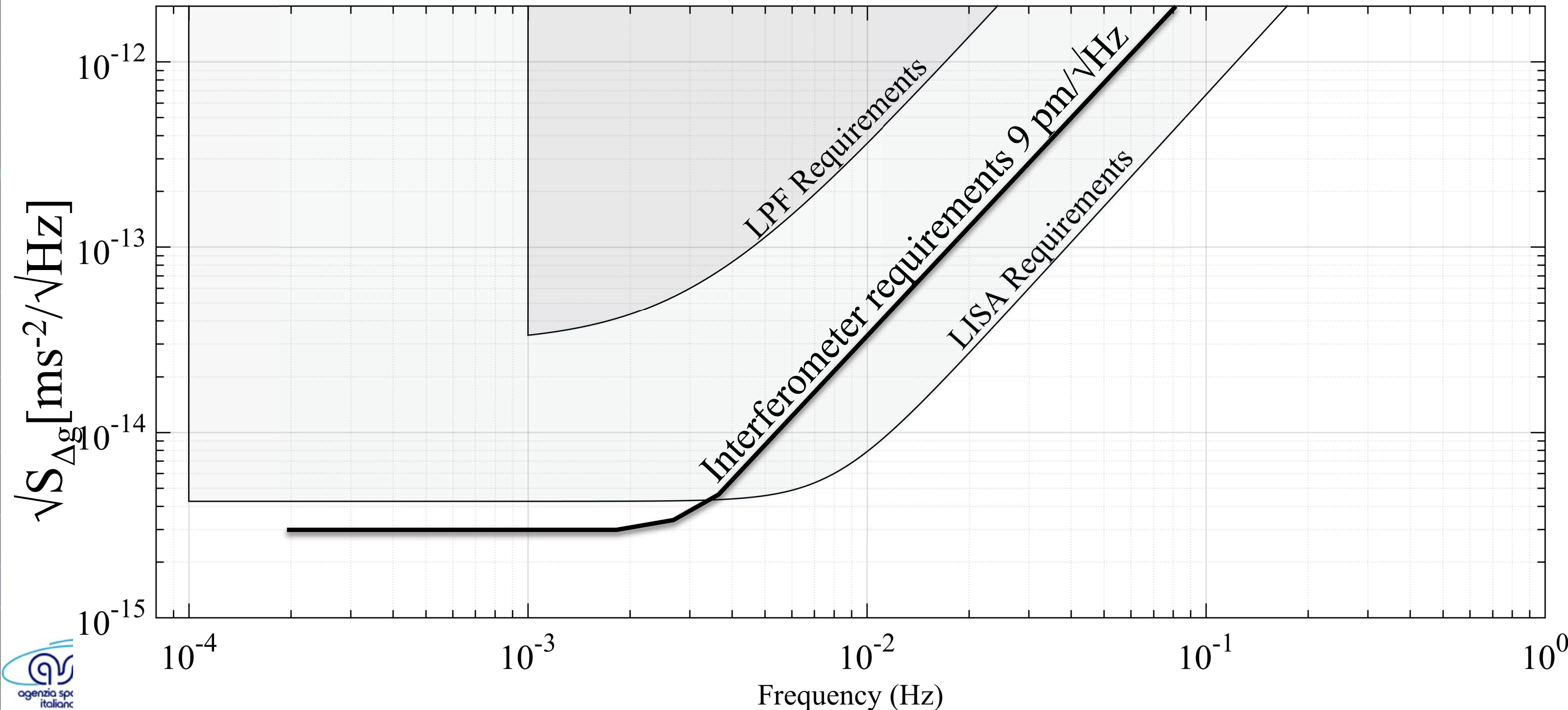
- One LISA link inside a single spacecraft
- 2 Test masses
- 4 interferometers
- Satellite chases one test mass
- Second test-mass forced to follow the first





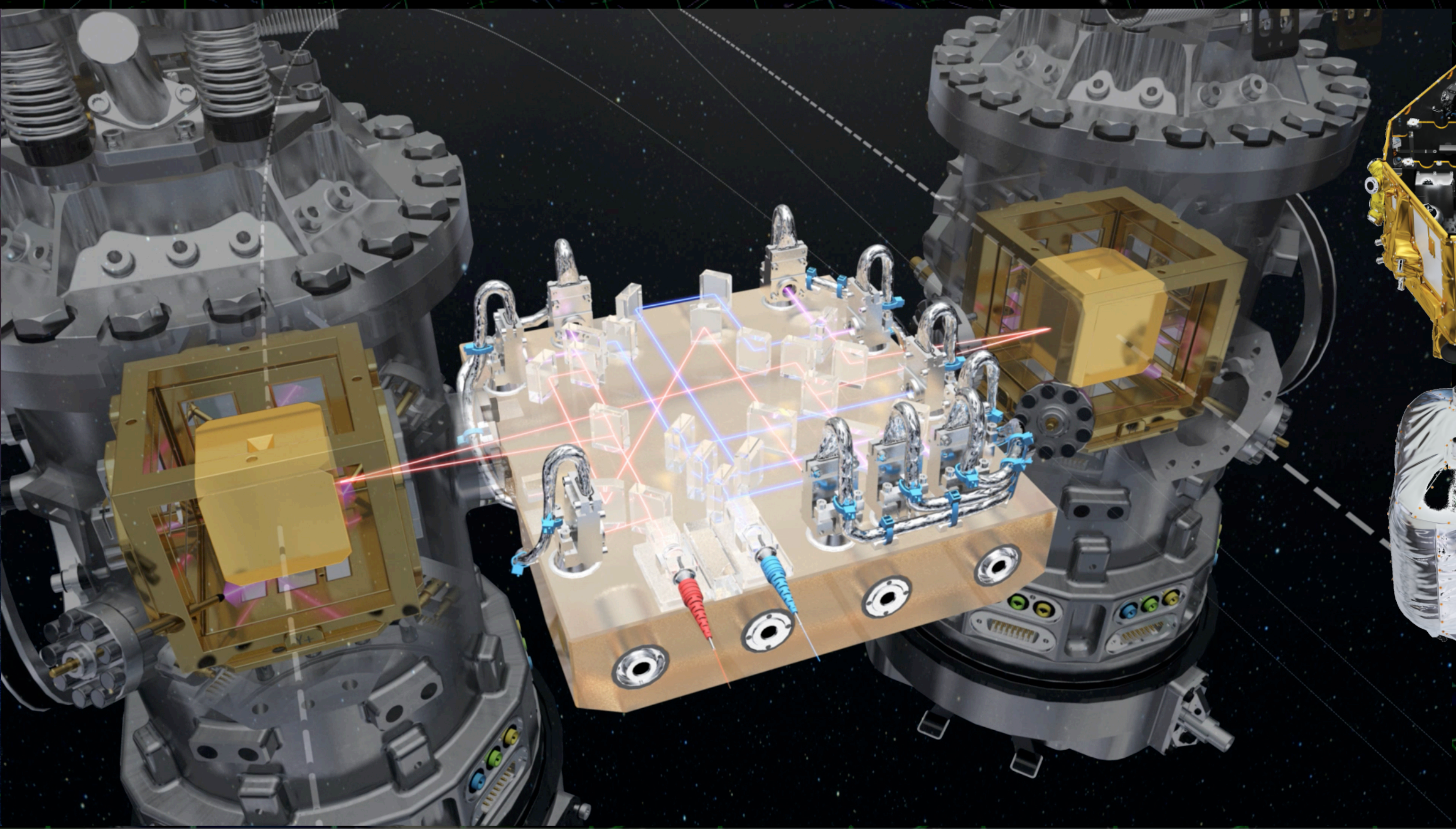
LISA pathfinder – *Mission requirement* –

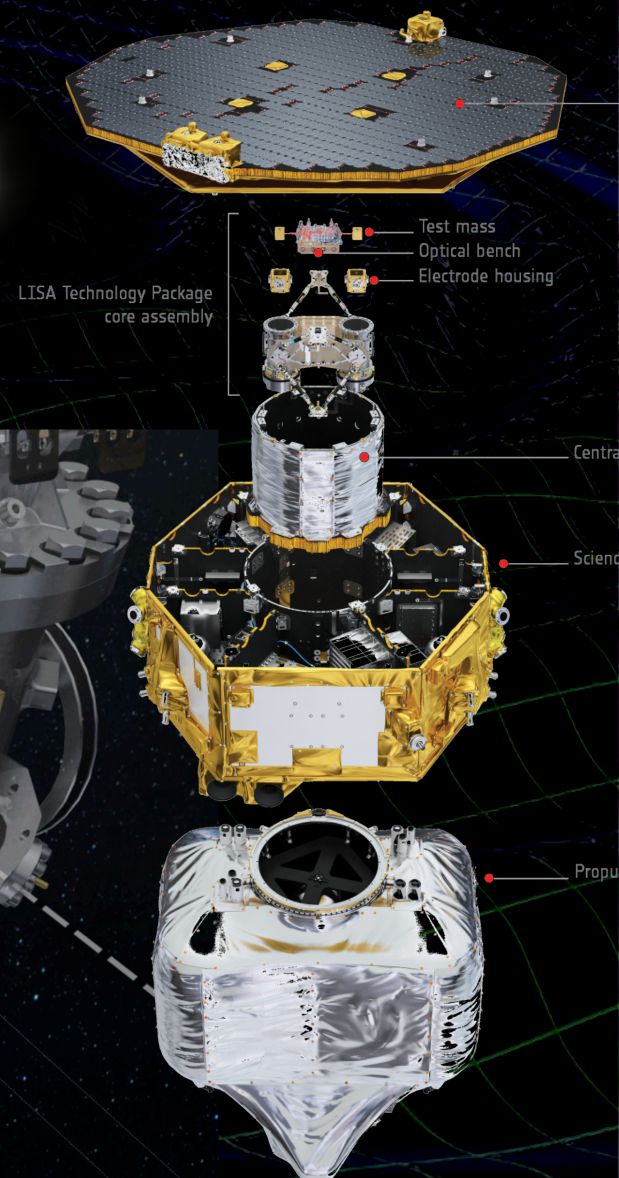
- LPF amplitude requirement relaxed : single spacecraft experiment more noisy
- Frequency requirement relaxed to cut down ground testing time
- Interferometer requirements to allow for margin and to match LISA sensitivity range



LISA pathfinder – *The LTP* –

- Test masses gold-platinum, 46mm, highly non-magnetic
- Electrode housing
- UV light : neutralize the cosmic ray charging
- Caging mechanism
- Vacuum enclosure
- Ultra high mechanical stability optical bench

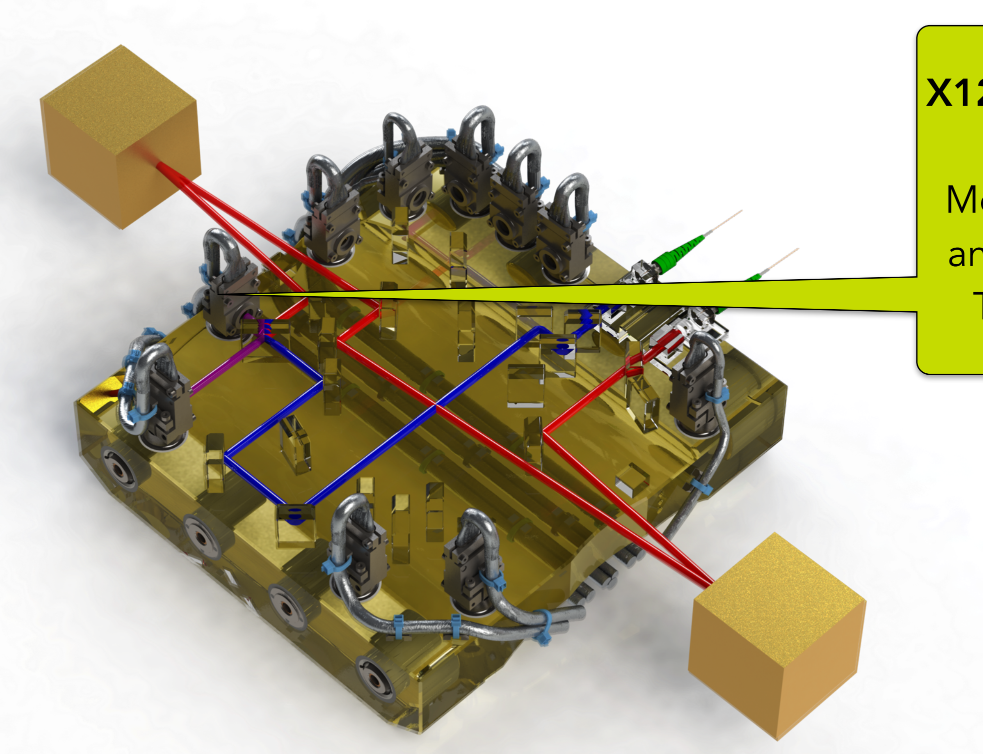




@ 宮崎大学木花キャンパス

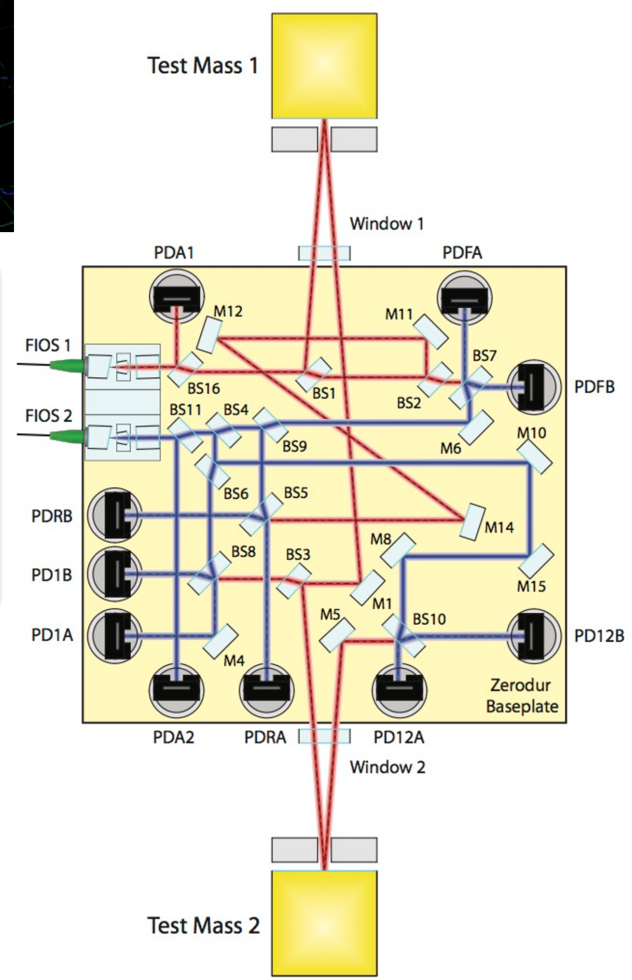
LISA pathfinder – *Interferometer* –

- 4 Interferometers of the Optical Metrology System
  - X1 Interferometer : Measures position and orientation of TM1
  - X12 Interferometer : Measures position and orientation of TM2 w.r.t. TM1
  - Reference Interferometer : Measures phase fluctuations common to both optical fibers
  - Frequency Interferometer : Measures fluctuations of laser frequency



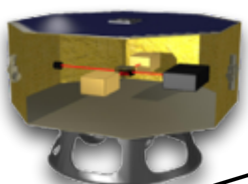
X12 Interferometer

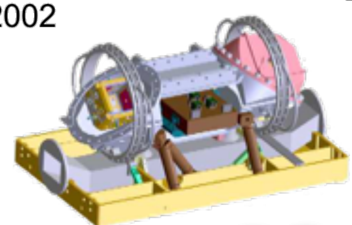
Measures position and orientation of TM2 w.r.t. TM1

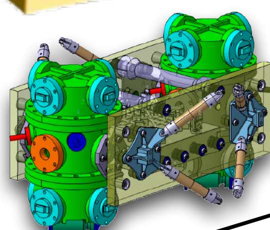


LISA pathfinder – *History* –

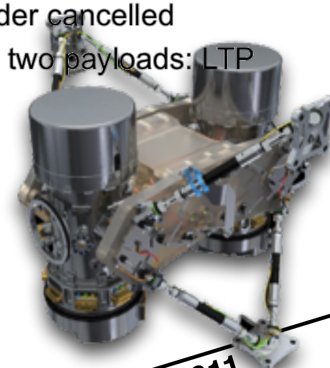
- First proposed as **ELITE** (European LIsa TEchnology) in 1998
  - Homodyne interferometer
  - Launch date 2002

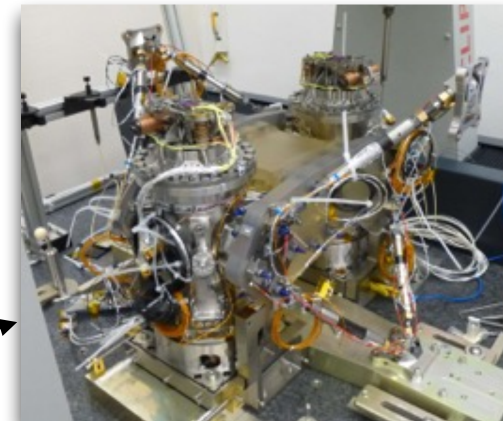






- After initial study, SMART-2 was descoped and renamed **LISA Pathfinder**
  - Darwin Pathfinder cancelled
  - Single s/c, with two payloads: LTP and DRS

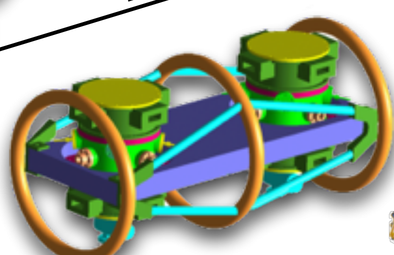




1998 — 2002 — 2004 — 2006 — 2011 — 2015

- Several design changes were made over the years….

  ….although the underlying concept has been stable since the beginning



- The LISA Technology Package (LTP) was delivered in May 2015

- DRS was descoped in 2005
  - DRS inertial sensor and interferometer cancelled
  - DRS now uses the LTP inertial sensor

- ELITE proposal was refined and proposed to ESA in 2000 as **SMART-2**
  - Included LISA Pathfinder, ST-7 DRS, Darwin Pathfinder
  - Launch date 2006

lisa pathfinder

S
W
IABG
iABG
S
SOUTH
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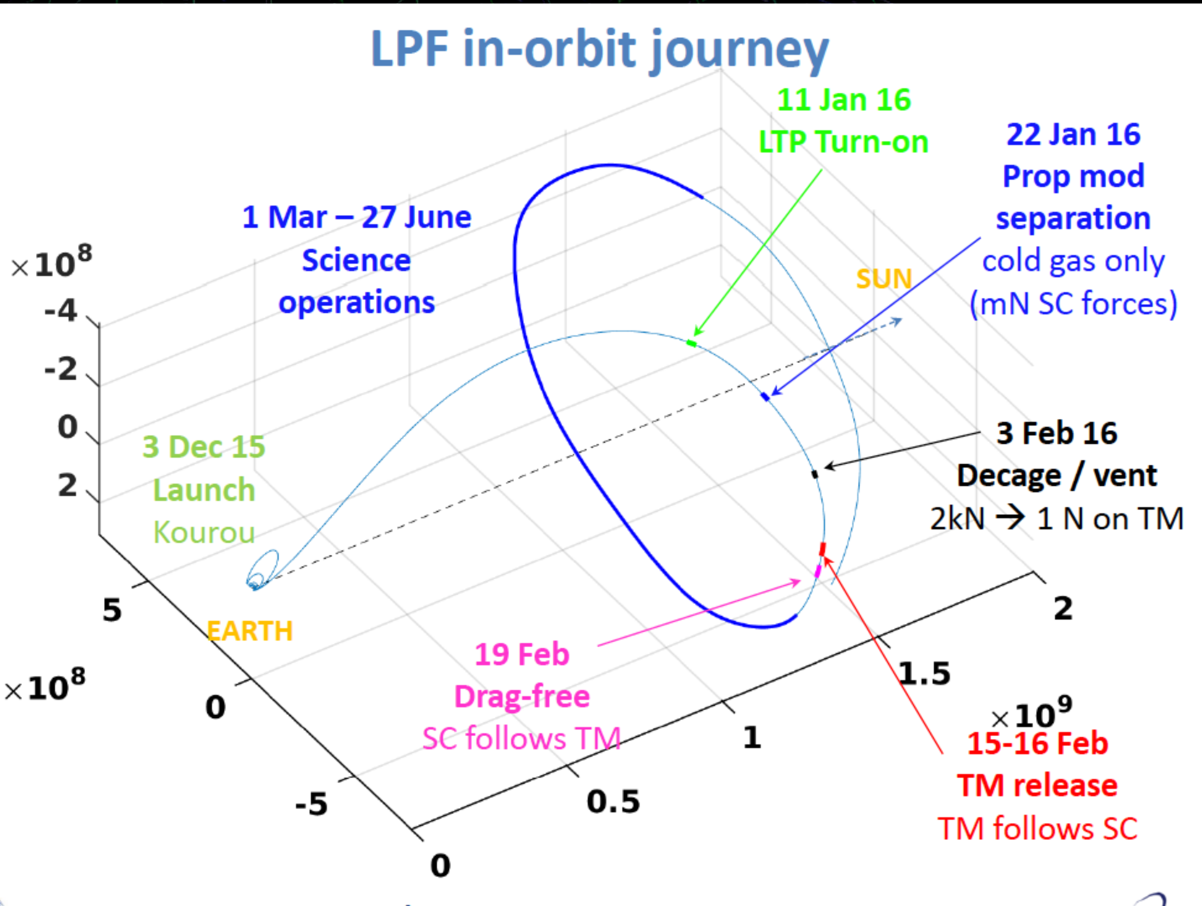
WEST
esa
LISA PATHFINDER
Gravitational wave detection technology for LISA

LISA pathfinder – *Launch* –

- 2015.12.3 @ Guiana Space Centre, Kourou

LISA pathfinder – *Journey to L1* –

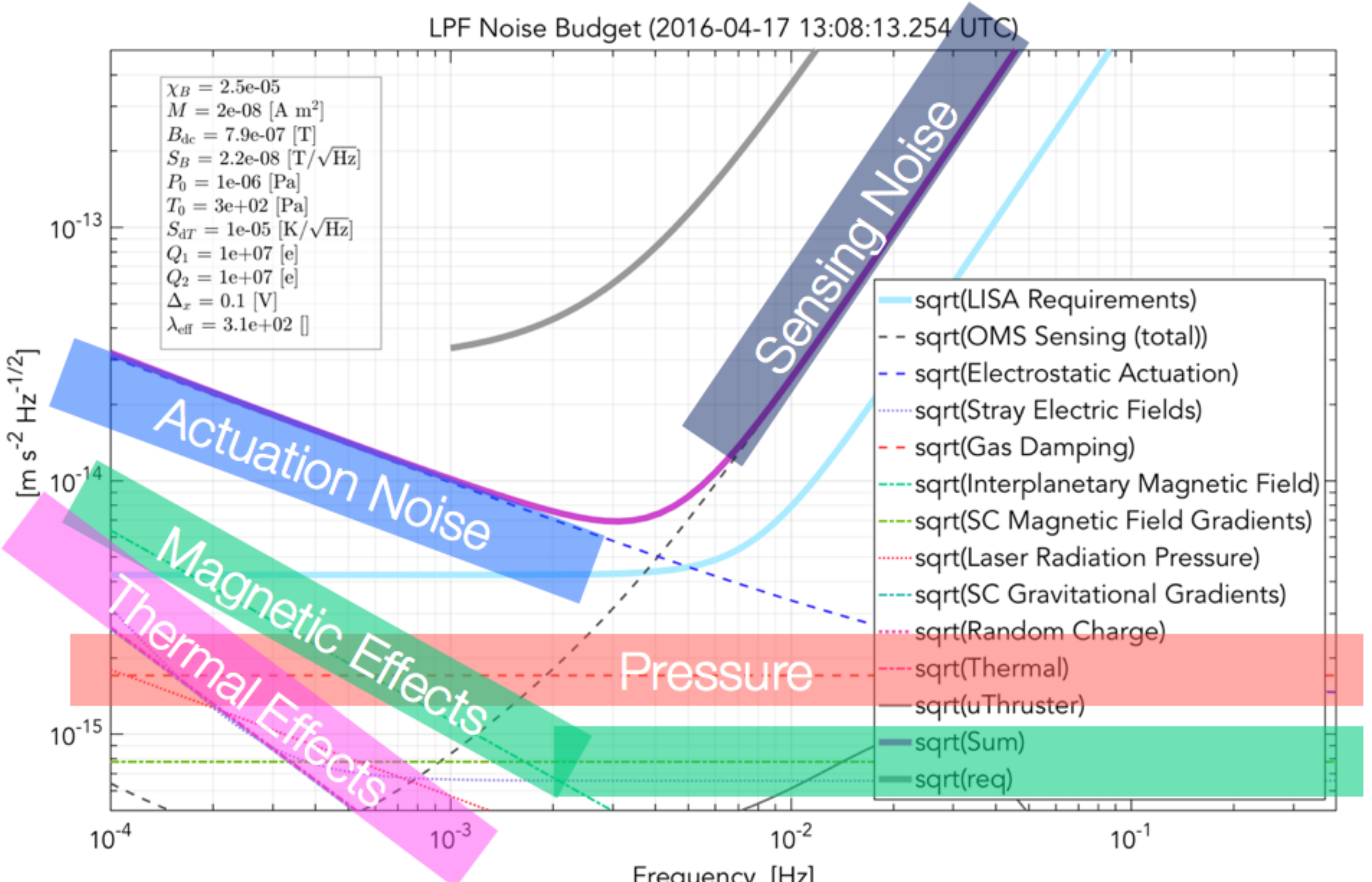
- Orbit raised via 6 apogee raising manoeuvres
- Transfer to Lagrange Point (L1) took ~50 days
- Separation of propulsion module on 2 February
- Final Orbit :
  - 500,000km x 800,000km around L1
  - Orbital Period of 6 months



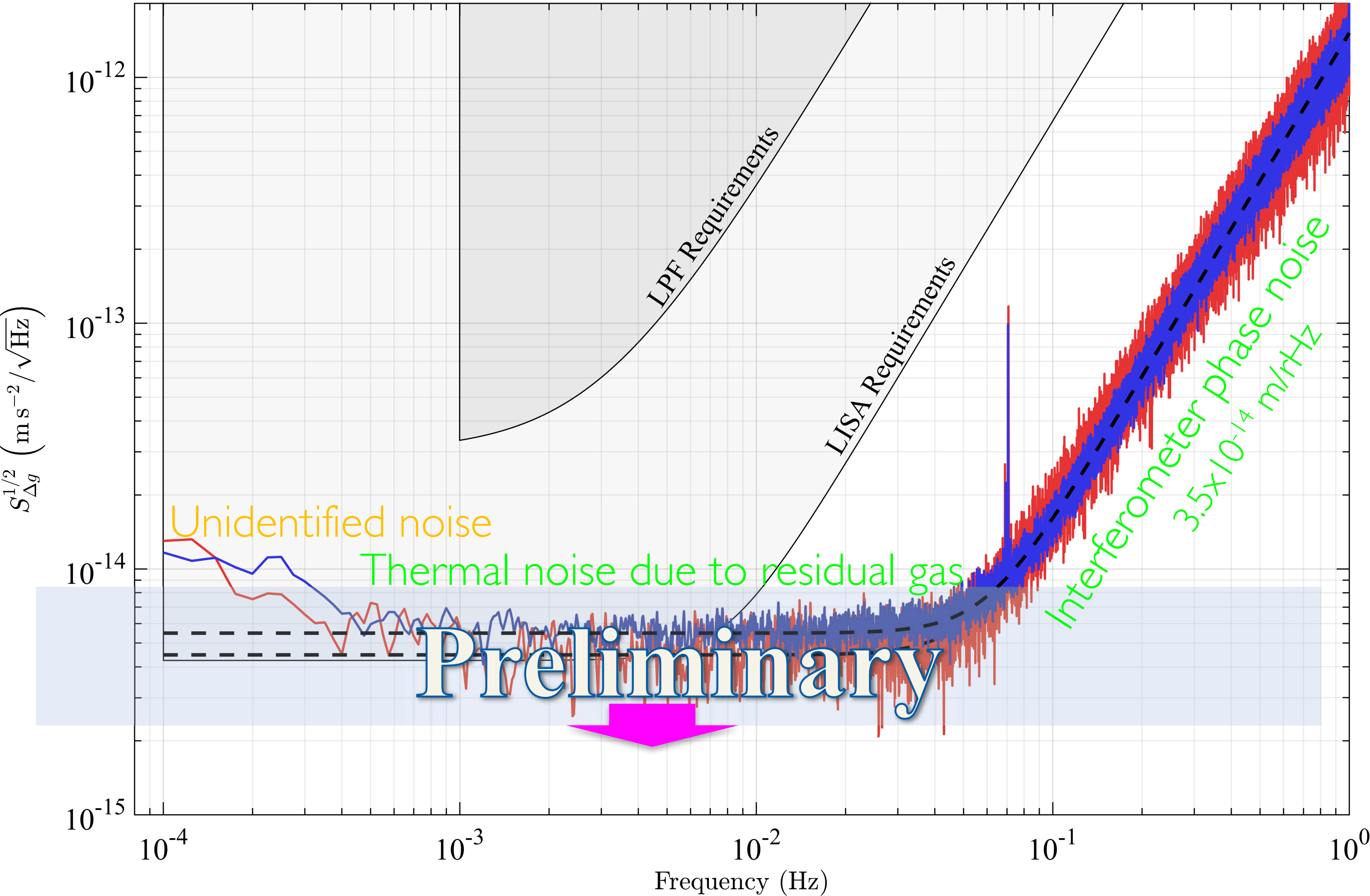
LISA pathfinder – *Timeline* –

- 2015.12.3 : Launch of LISA Pathfinder
- 2016.1.11 : Switch-on of the LISA Technology Package
- 2016.2.2 : Release of test mass launch locks and opening of venting valve
- 2016.2.15 & 16 : Test mass release → free floating test masses
- 2016.2.18 : Alignment of the laser interferometer
- 2016.2.22 : First entry to Science Mode
- 2016.3.1 : Start of Science Operations
- 2016.6.25 : End of LTP Science Ops & start of DRS Ops
- 2016.6.27 : DRS Commissioning, Phase 2
- 2016.12 : End DRS Operations, start extended mission
- 2017.5 : End of mission

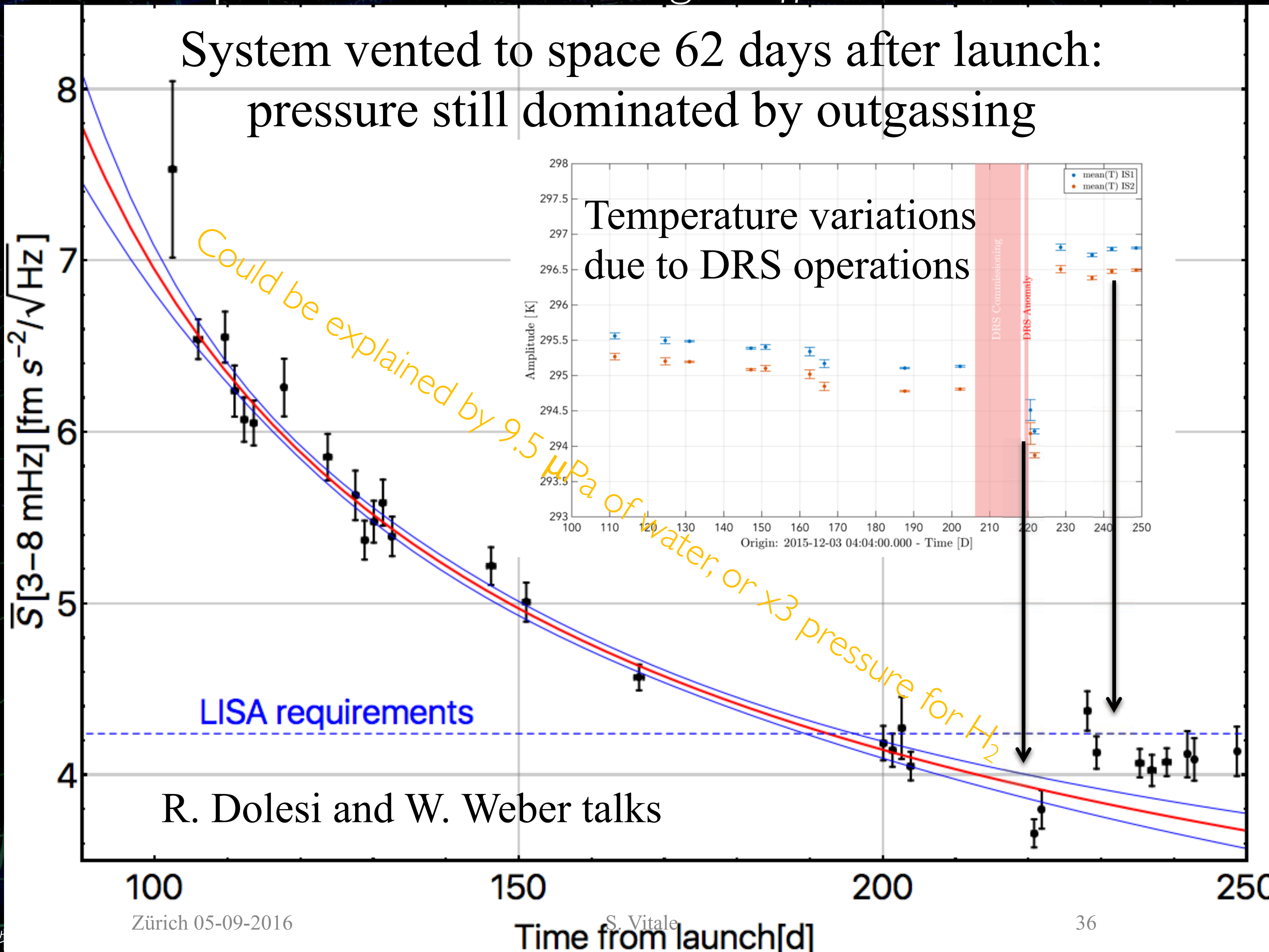
LISA pathfinder – *Noise budget prior to launch* –



LISA pathfinder – *Acceleration noise spectrum*–



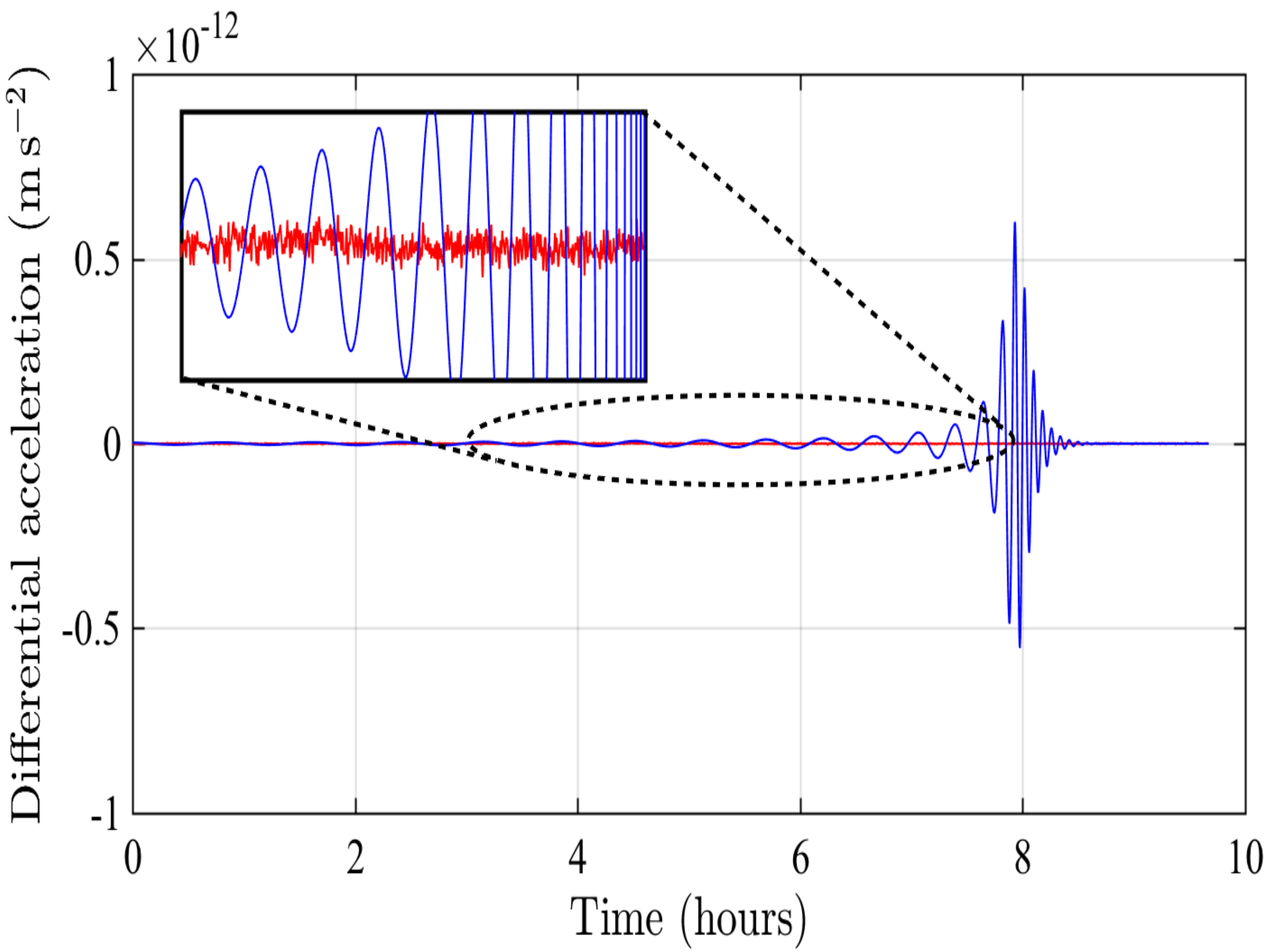
LISA pathfinder – *Residual gas effect* –



LISA pathfinder – *Expected LISA signal* –

Simulated LISA acceleration signal for two $5\times10^5\ M_\odot$ black-holes with their galaxies merging at z=5

LISA Pathfinder acceleration data



DECIGO

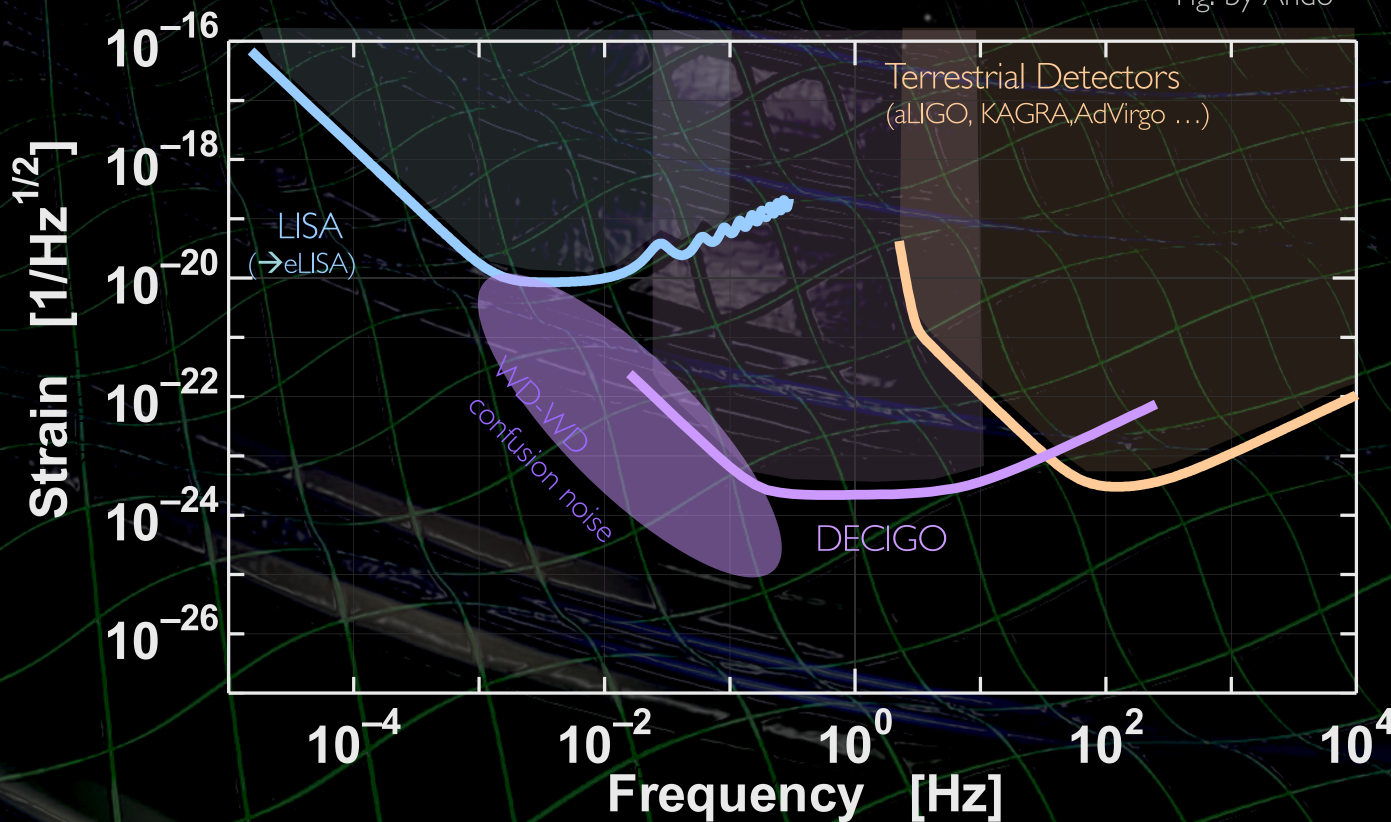
日本物理学会 2016 秋期大会

23 Sep. 2016 @ 宮崎大学木花キャンパス

DECIGO – *The idea* –

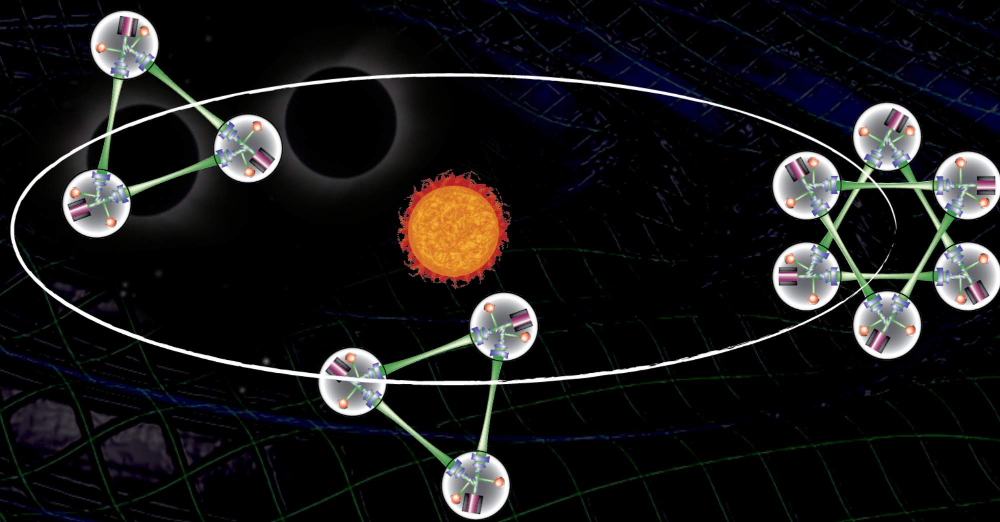
- DECi-hertz Interferometer Gravitational wave Observatory
  - Seto, Kawamura and Nakamura, PRL87, 221103(2001)
  - Bridges the gap between LISA and terrestrial detector
  - Low confusion noise → Potentially high sensitive instruments

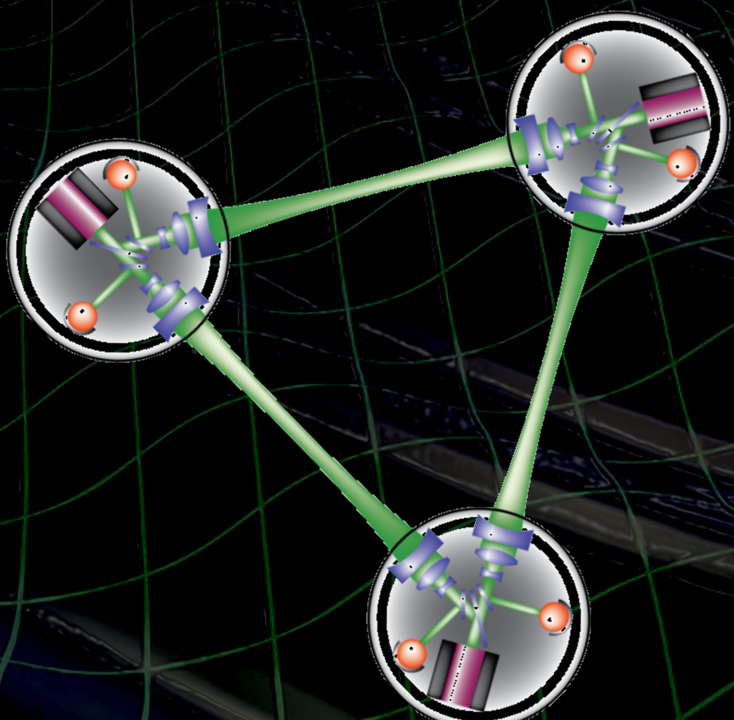
Fig. by Ando



DECIGO – *Pre-conceptual design* –

- Interferometer parameters
  - Arm length: 1000 km
  - Mirror diameter: 1 m
  - Mirror mass: 100 kg
  - Laser wavelength : 515 nm
  - Laser power: 10 W
  - Finesse: 10





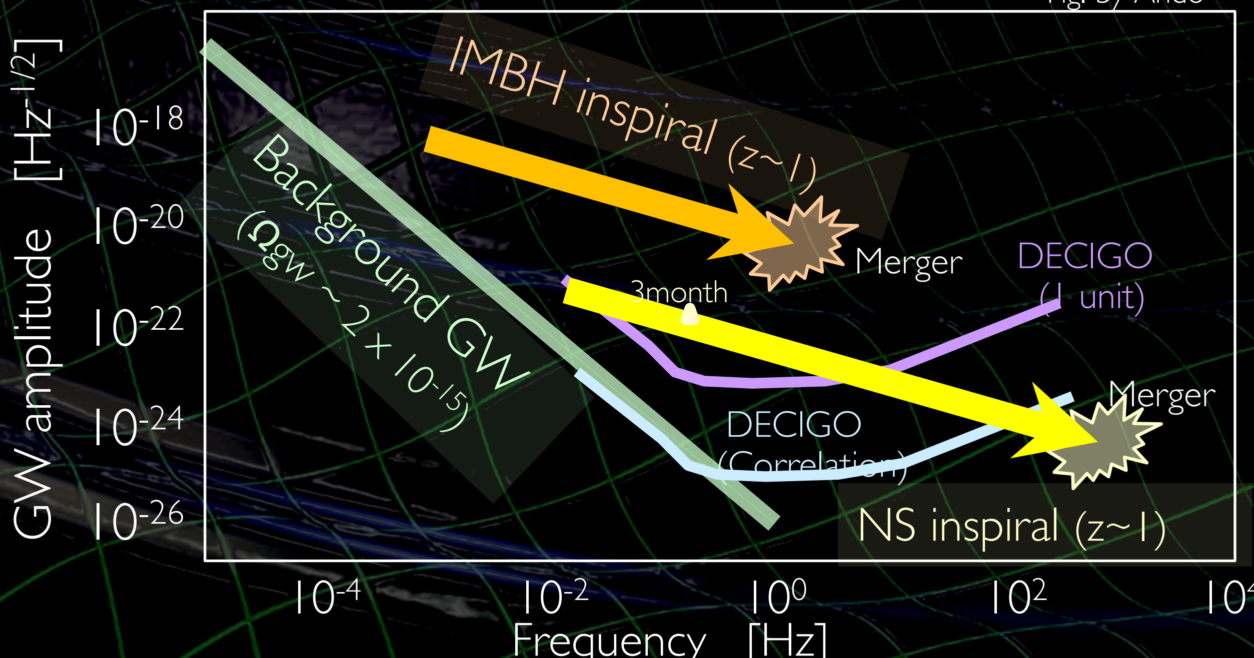
- Interferometer topology
  - Differential FP interferometer
  - Three interferometers for redundancy
  - Drag-free controlled S/Cs

- Constellation
  - 4 interferometer units
  - 2 overlapped units → Cross correlation
  - 2 separated units → Angular resolution

DECIGO – *Science case* –

- BNS Inspirals
  - From cosmological distance
  - Cosmology (Inflation, Dark energy)
- IMBH Inspirals and Mergers
  - Formation history of SMBH
  - Galaxy formation
- Stochastic background
  - Fundamental physics

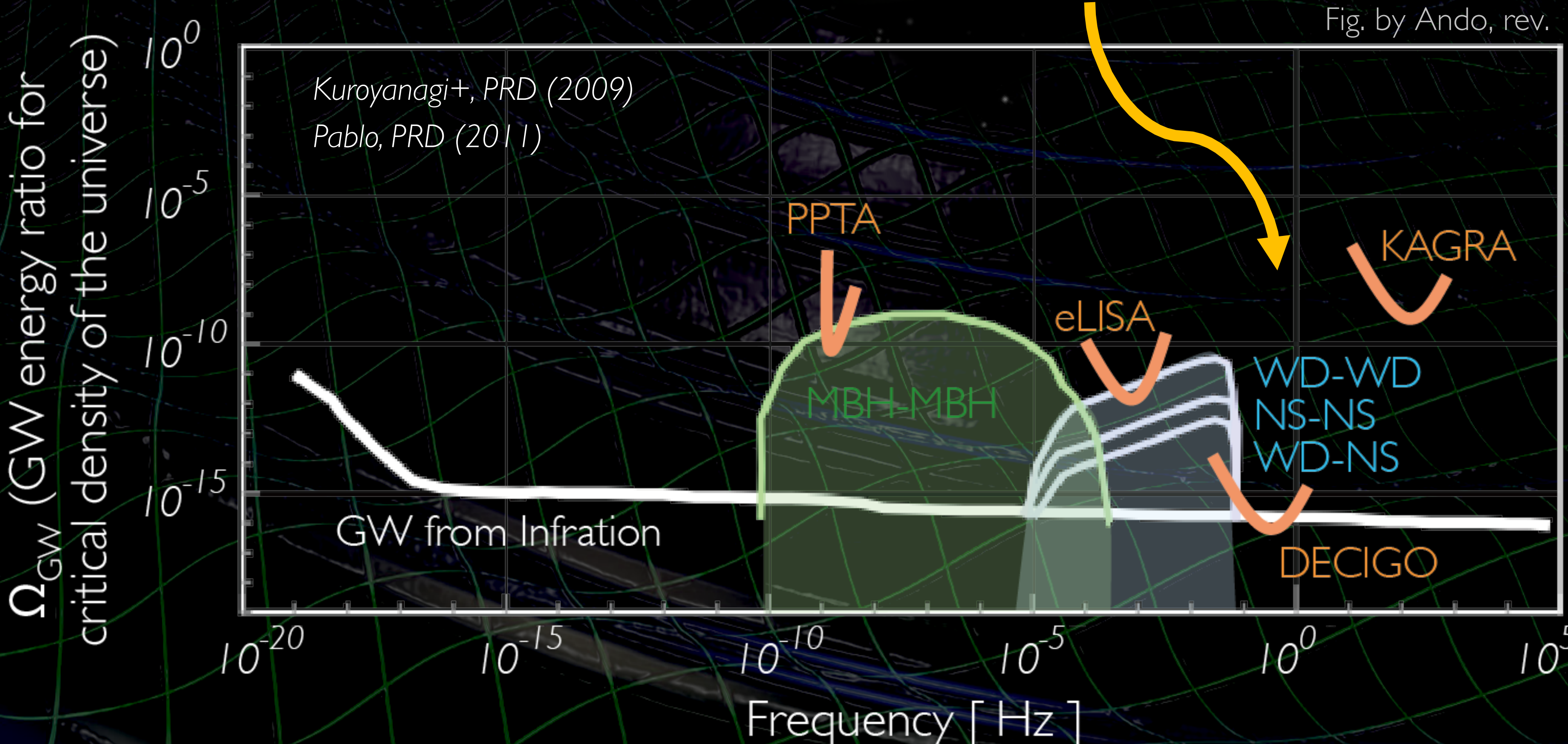
Fig. by Ando



DECIGO – *Access to very beginning of the Universe* –

DECIGO band is open window
for direct observation of the early universe.

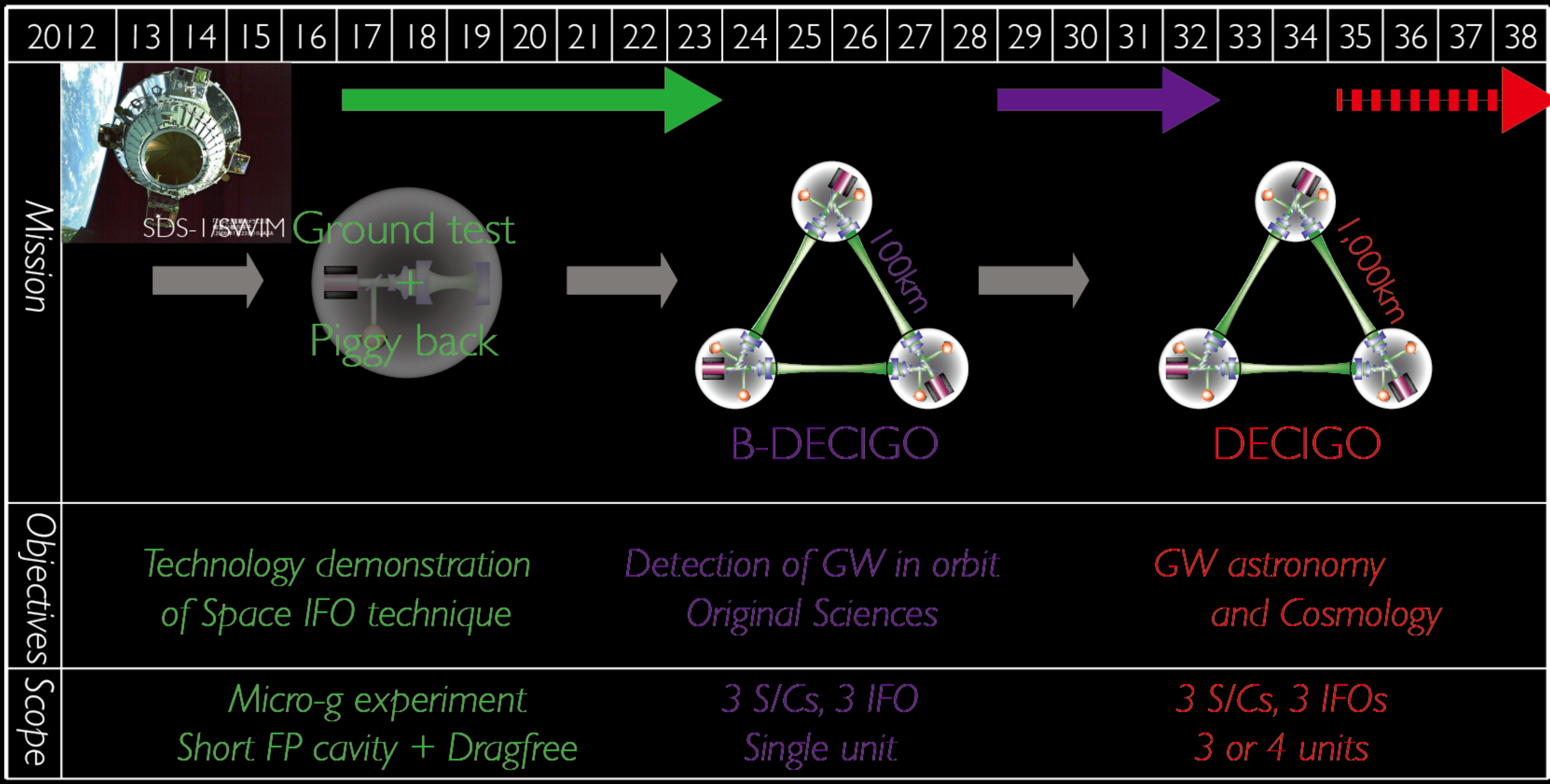
Fig. by Ando, rev.



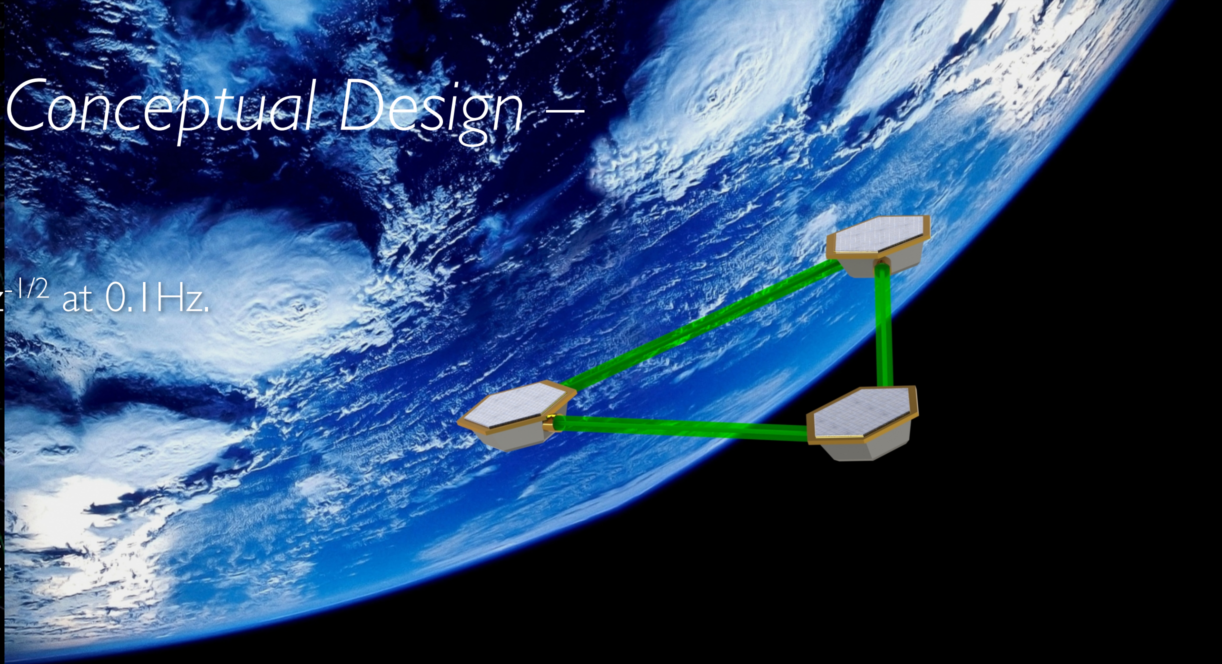

B-DECIGO

B-DECIGO – *Revised Roadmap* –

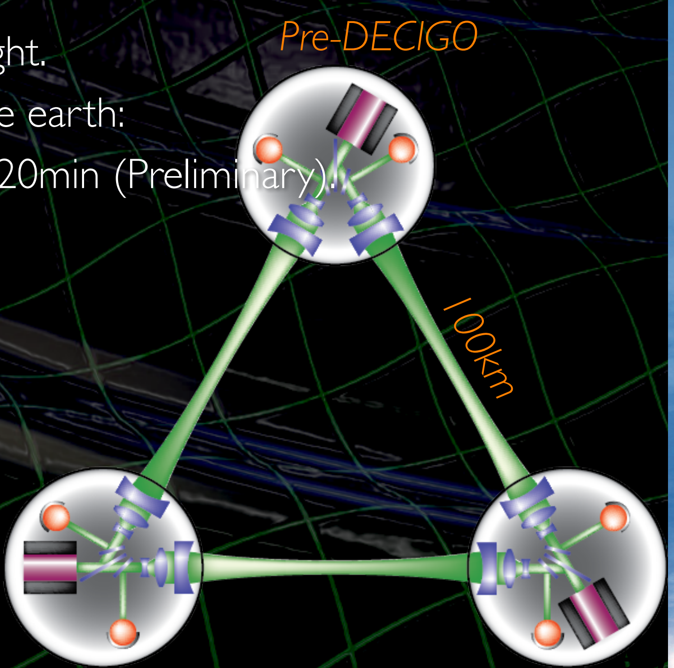
Fig. by Kawamura, rev.



B-DECIGO – *Pre Conceptual Design* –

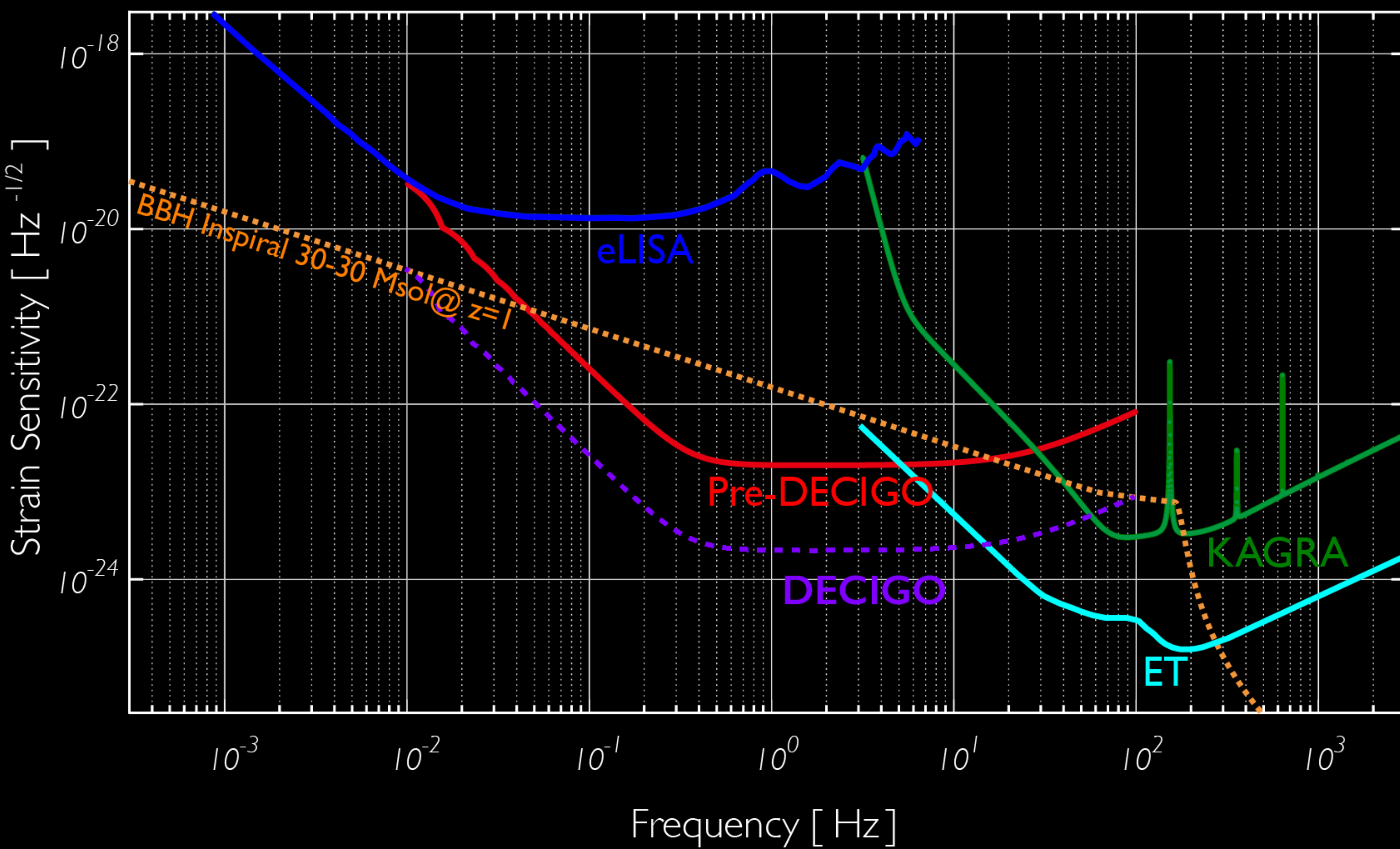


- Mission Requirement
  - Strain sensitivity of 2×10^{-23} $Hz^{-1/2}$ at 0.1Hz.
  - 3-years observation period.
- Conceptual Design
  - Laser interferometer by 3 S/C
  - Baseline : 100 km
  - Laser source : 1W, 515nm
  - Mirror : 300mm, 30kg
  - Drag-free and Formation flight.
  - Record-disk orbit around the earth:
  - Altitude 2000km, Period ~120min (Preliminary).

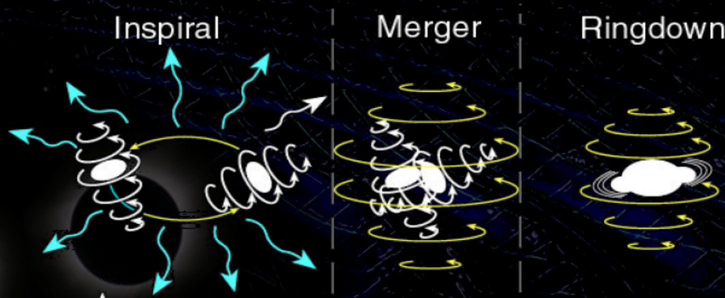


B-DECIGO – *Sensitivity Curve* –

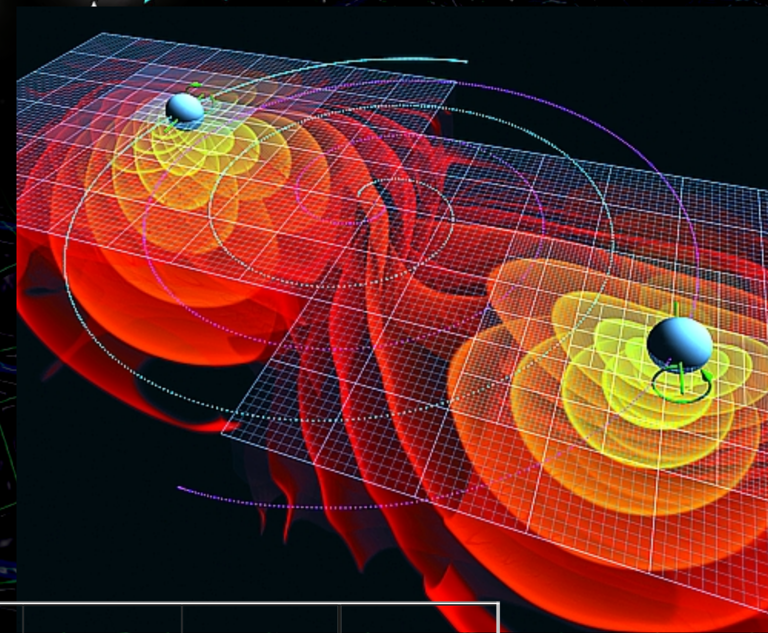
T. Nakamura et al., Prog. Theor. Exp. Phys. 093E01 (2016)



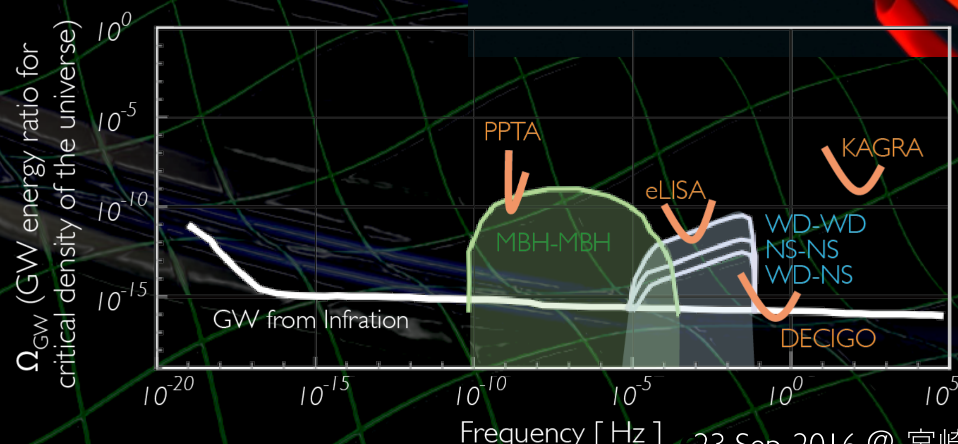
B-DECIGO – *Science Case* –



- Inspiral of Compact Binaries
  - High rate ~10^6 binaries/yr.
  - Estimation of binary parameters and merger time.
  - Astronomy by GW only and GW-EM observations.



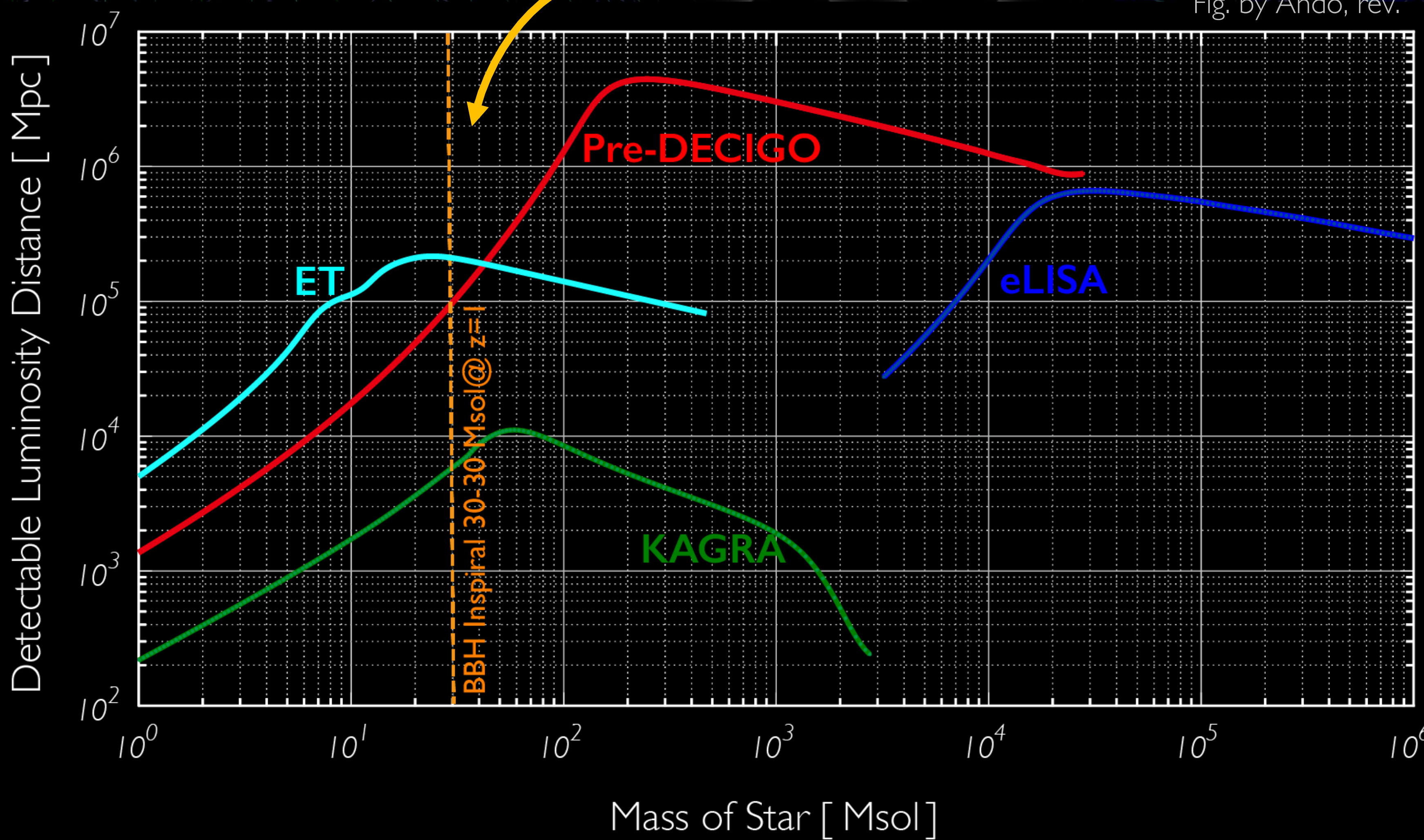
- Inspirals and Mergers of IMBHs
  - Cover most of the universe.
  - Formation history of SMBH and galaxies.
- Foreground Understandings for DECIGO
  - Parameter estimation and subtraction of binaries.
  - Characteristics of foreground
  - Is the any eccentric binaries?



B-DECIGO – *Observable Range* –

30$M_\odot$ BBH Merger : 100 Gpc (z>10) range
with SNR~8 (optimal direction/polarization).

Fig. by Ando, rev.

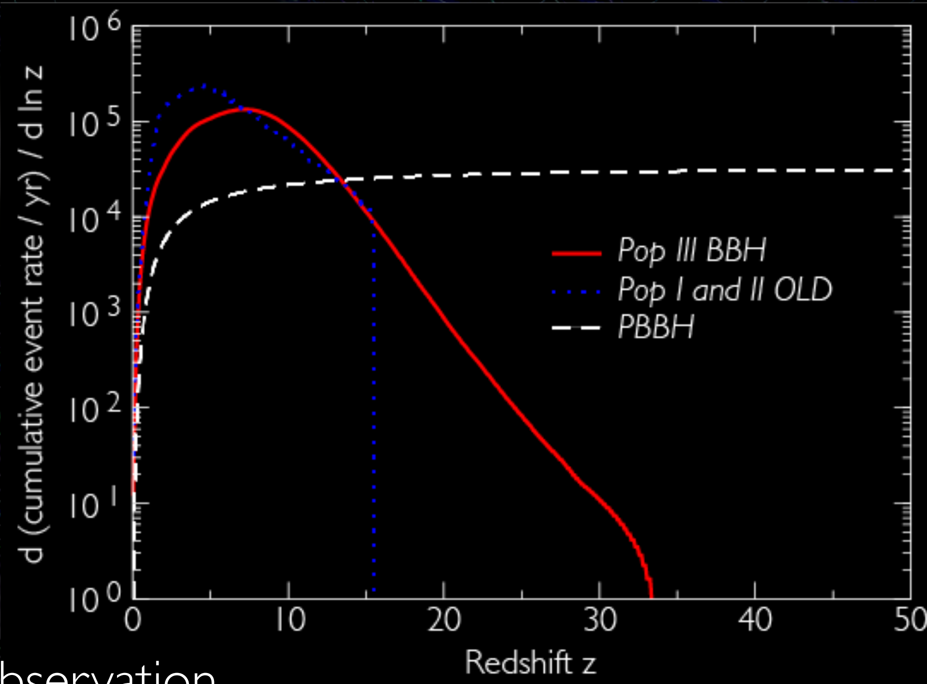


B-DECIGO – *Compact Binaries* –

T. Nakamura et al., Prog. Theor. Exp. Phys. 093E01 (2016)

- BBH
  - Observable range ~Tpc
  - Detection Rate will be ~ 4 x10^4 -10^6 evevts/yr
  - Possible to identify the origin of BBH

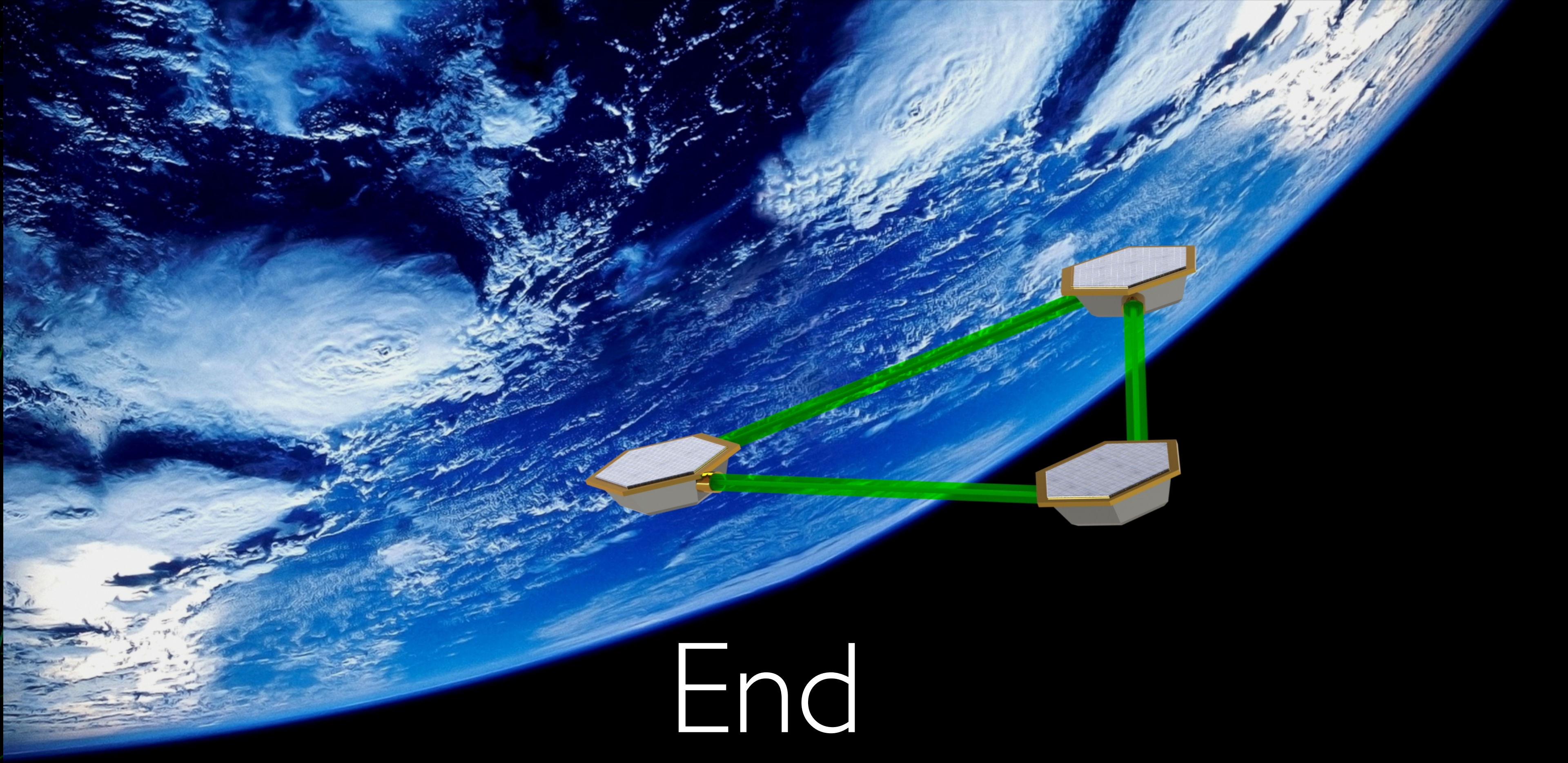
    Pop-III, Pop-I/II, or Primordial BH.



- BNS
  - Range for BNS is ~2Gpc
  - Higher rate expected.
- With low-freq. GW observations, longer observation
  - Improved parameter estimation accuracy with lager cycle number (~10^5) :
  - Localization, Merger time → Alerts for GW-EM.
  - Mass, Distance, Spin → Origin and nature of BBH.

Conclusion

- aLIGO observed GW150914
- LISA pathfinder exceeds expectations
- Strong motivation for LISA
- Strong motivation for DECIGO / B-DECIGO



End