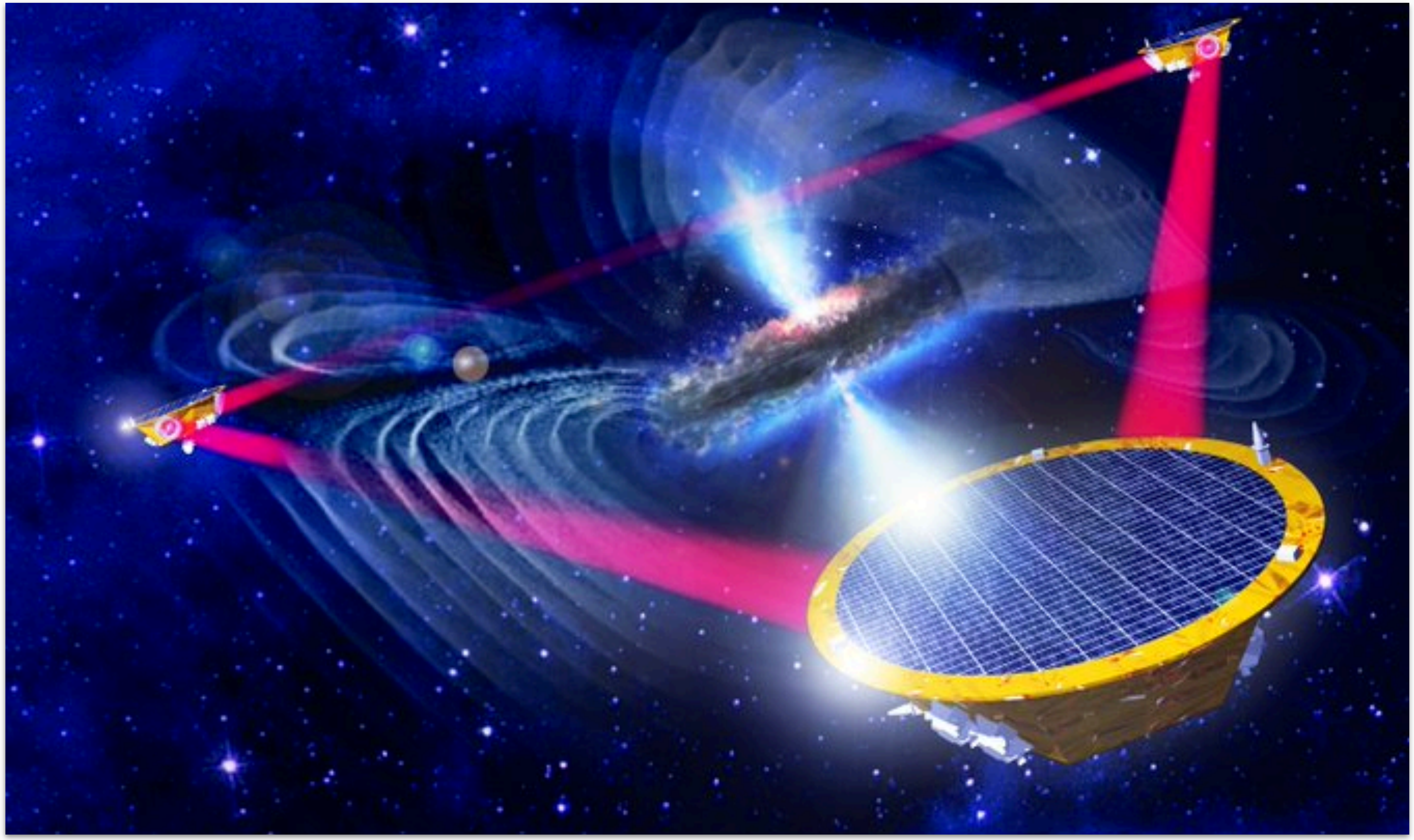


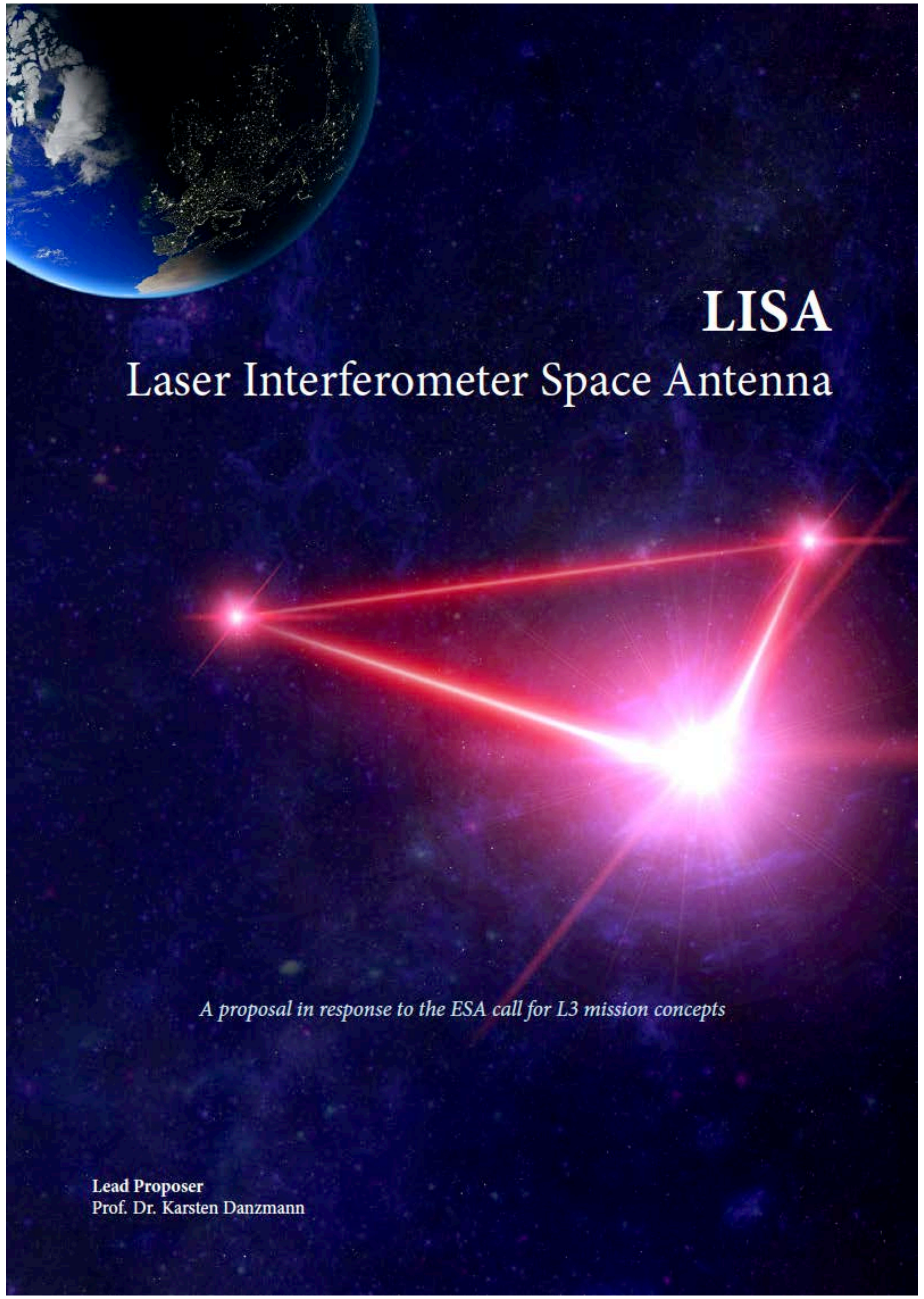
LISA

Overview of the scientific prospects and the Instrument

Guido Mueller

MPI for Gravitational Physics
(Albert-Einstein-Institute)
University of Florida
Leibniz University Hannover

LISA



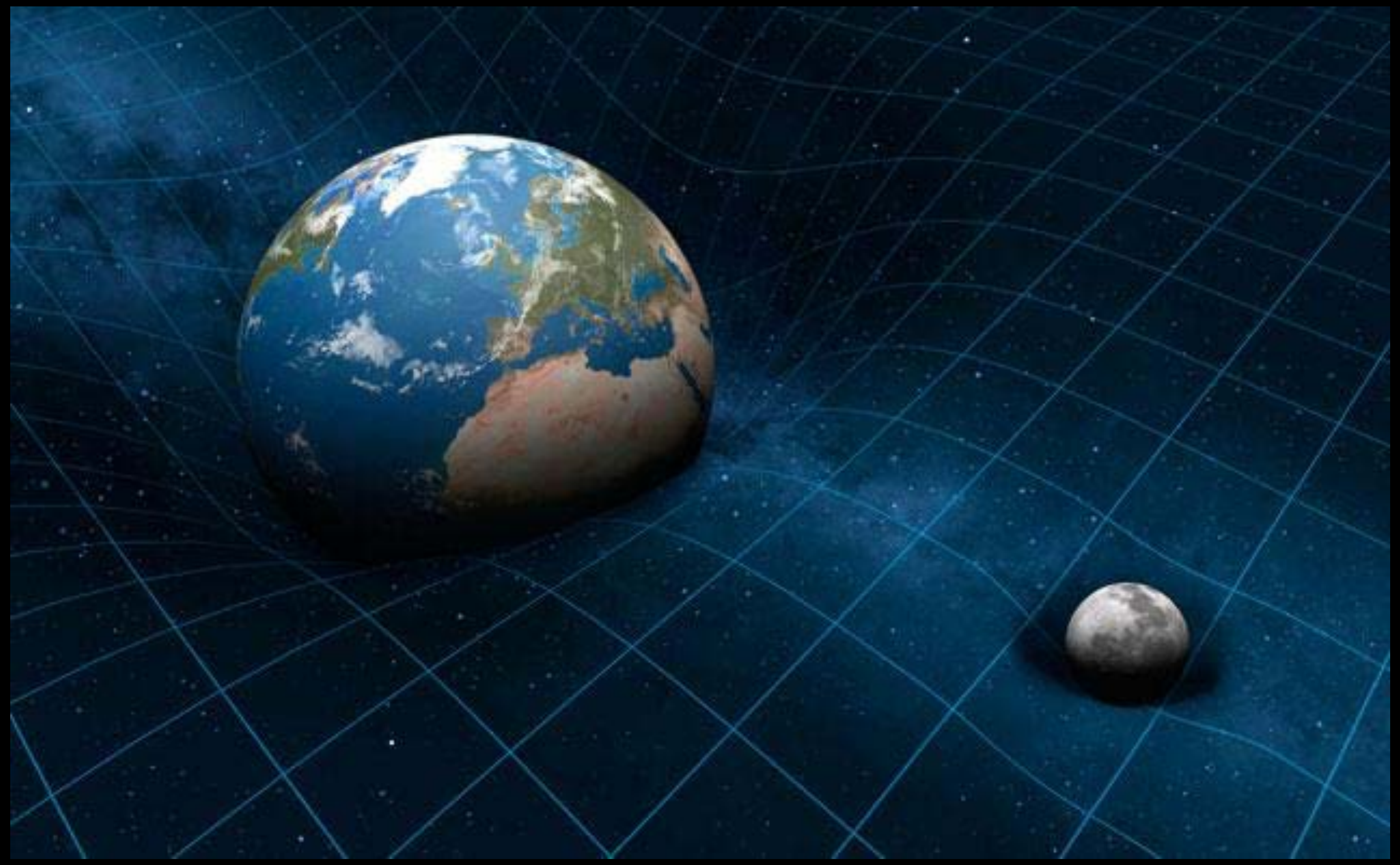
LISA

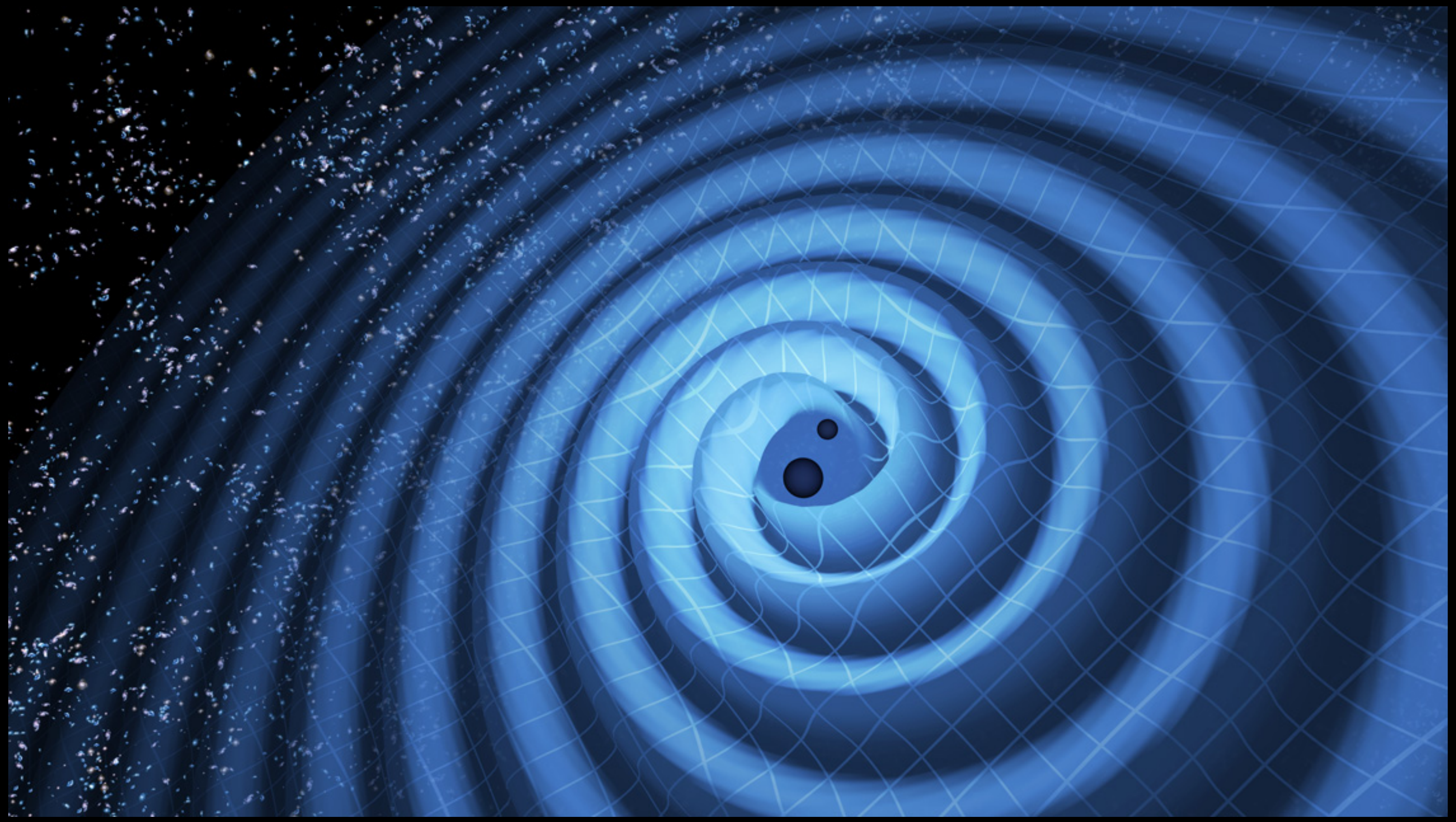
- Initial ideas dating back to the early 1970s
  - Peter Bender et al
- Gained significant momentum in the late 1980s
  - Karsten Danzmann, Tom Prince, Bernie Schutz, Tuck Stebbins et al
  - Early ‘90s: First LISA proposal
- Long history of ups and downs
- Finally enabled by two major breakthroughs:
  - LIGO discovery 2015
  - LISA Pathfinder success in 2016/17
- Proposed in 2017 for ESA’s call for L3 mission concept
  - by LISA Consortium
    - Lead: Karsten Danzmann (AEI Hannover)
      - 30+ yrs history of leading LISA

What are gravitational waves?

Spacetime tells matter how to move;
matter tells spacetime how to curve.

John Wheeler



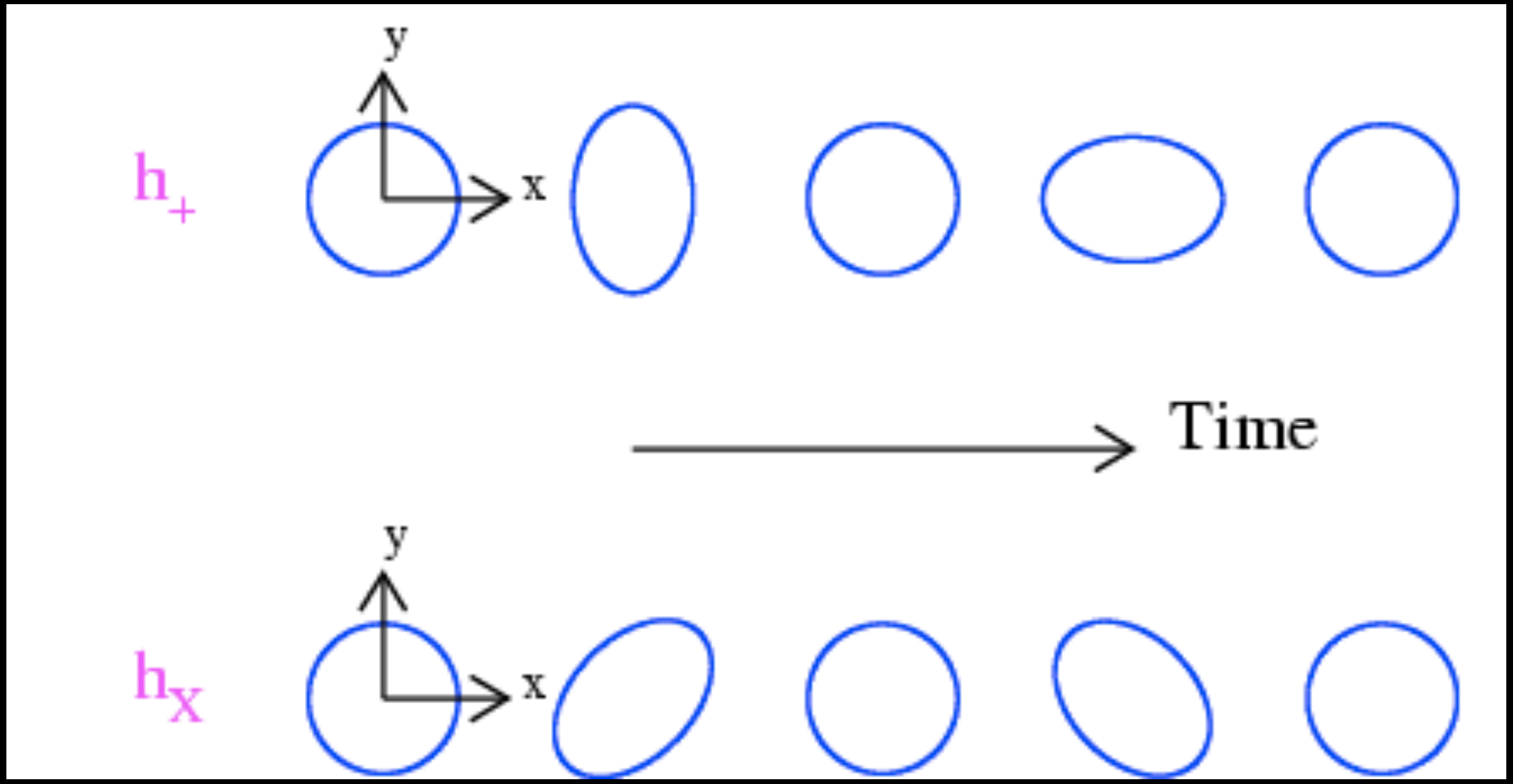


What are gravitational waves?

Strains of space time:

- Stretch and squeeze distances between geodesics
- Modulate light travel times between free falling objects

$$h \approx \frac{\delta l}{L} = \frac{\delta t}{\tau}$$



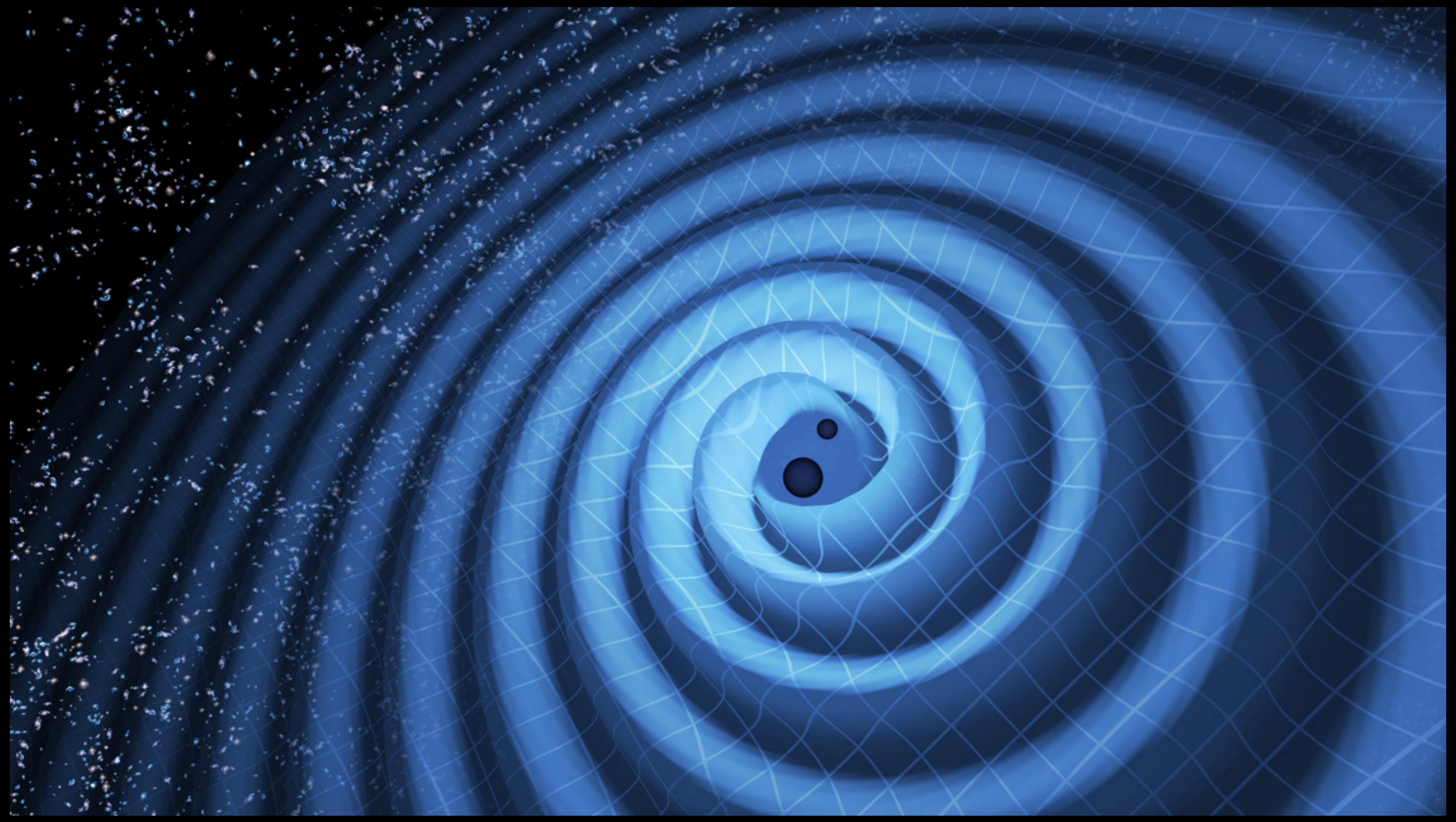
What are gravitational waves?

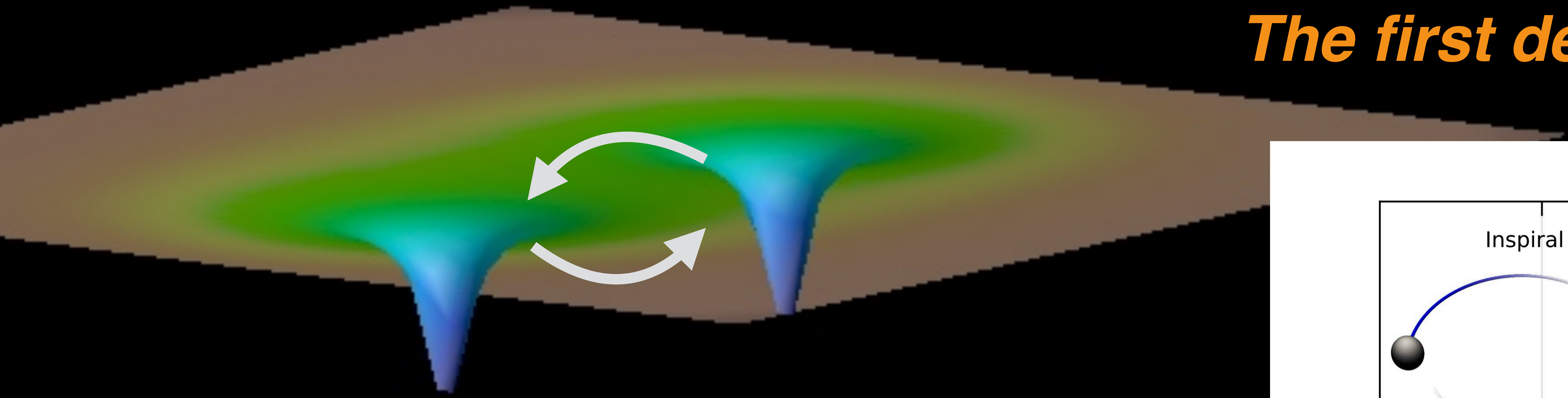
Strains of space time:

- Stretch and squeeze distances between geodesics
- Modulate light travel times between free falling objects

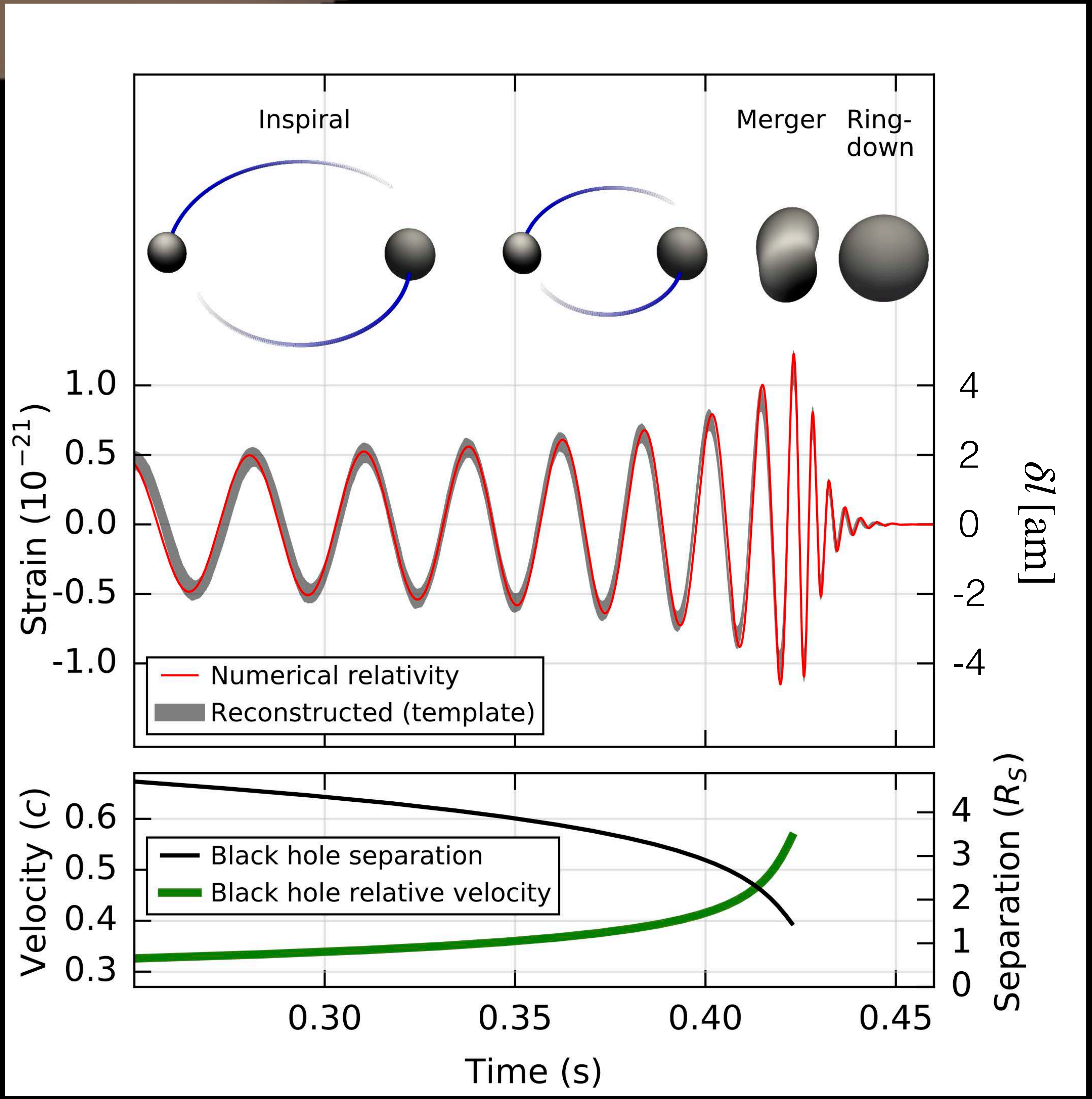
Generated by accelerated masses:

- Compact binary systems
  - Black holes, neutron stars and white dwarfs
- Supernovae, stochastic backgrounds, strings, …





The first detection: GW150914



Typical Strain:

$$h \approx \frac{R_1 R_2}{Dr}$$

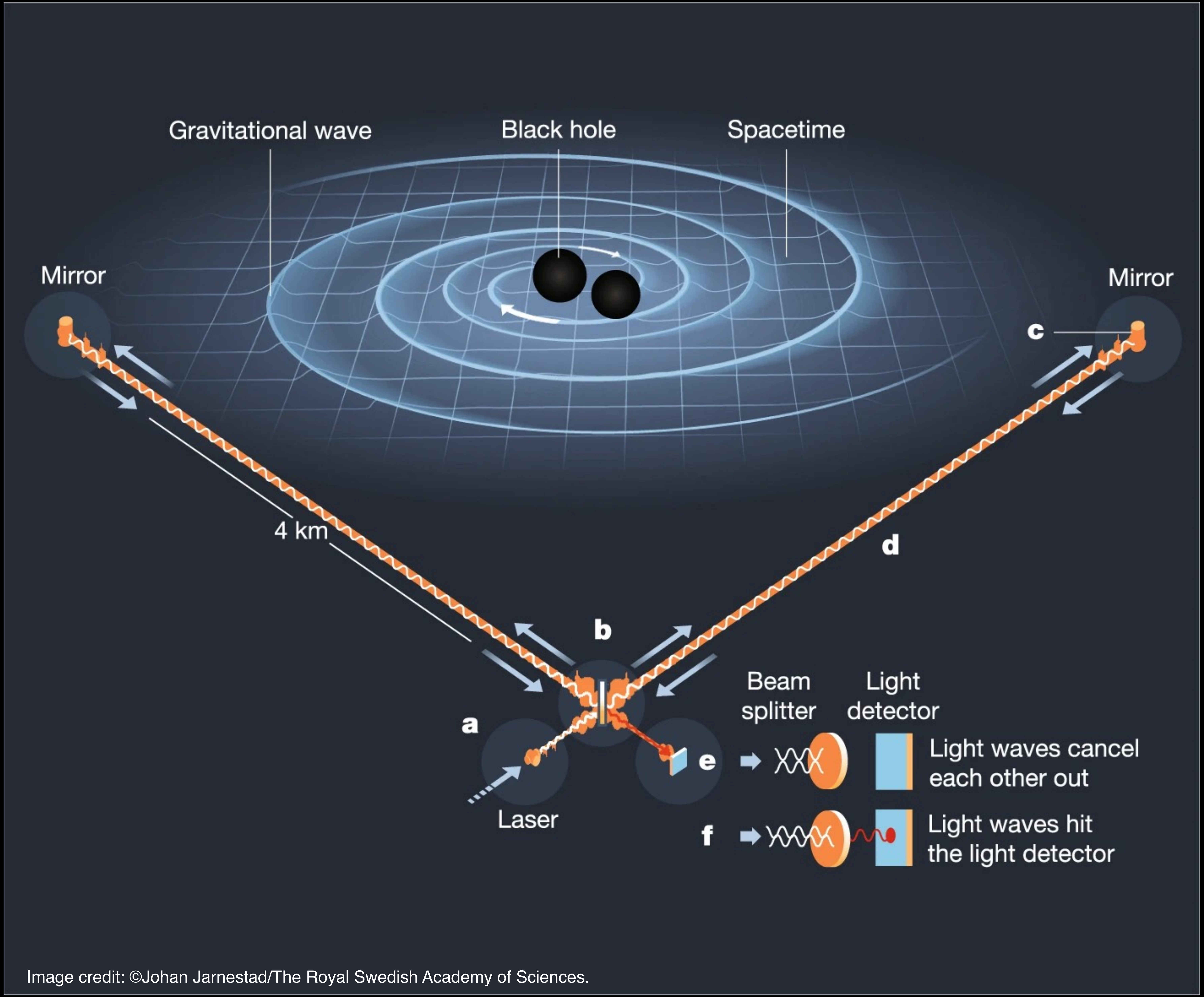
Typical frequency:

$$f \approx \frac{c}{2\pi D}\sqrt{\frac{R_1 + R_2}{2D}}$$

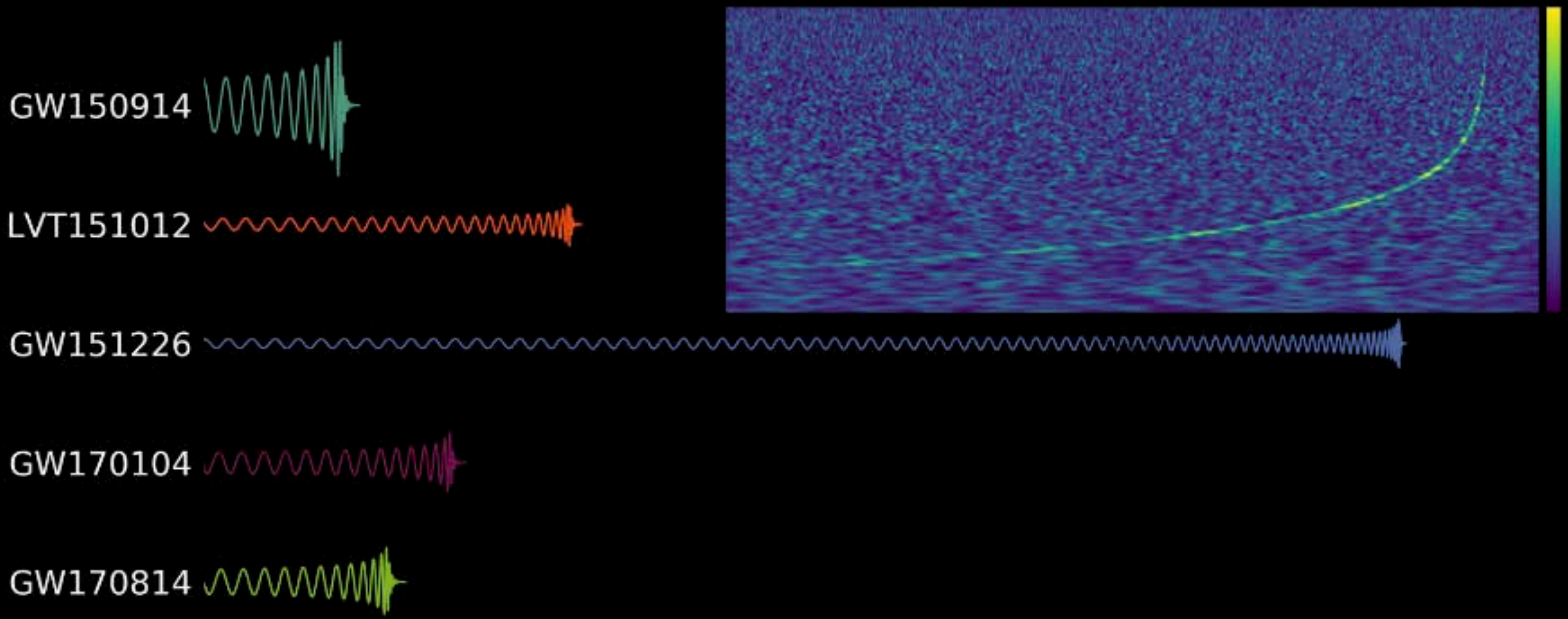
The first detection

Nobel Price 2017:

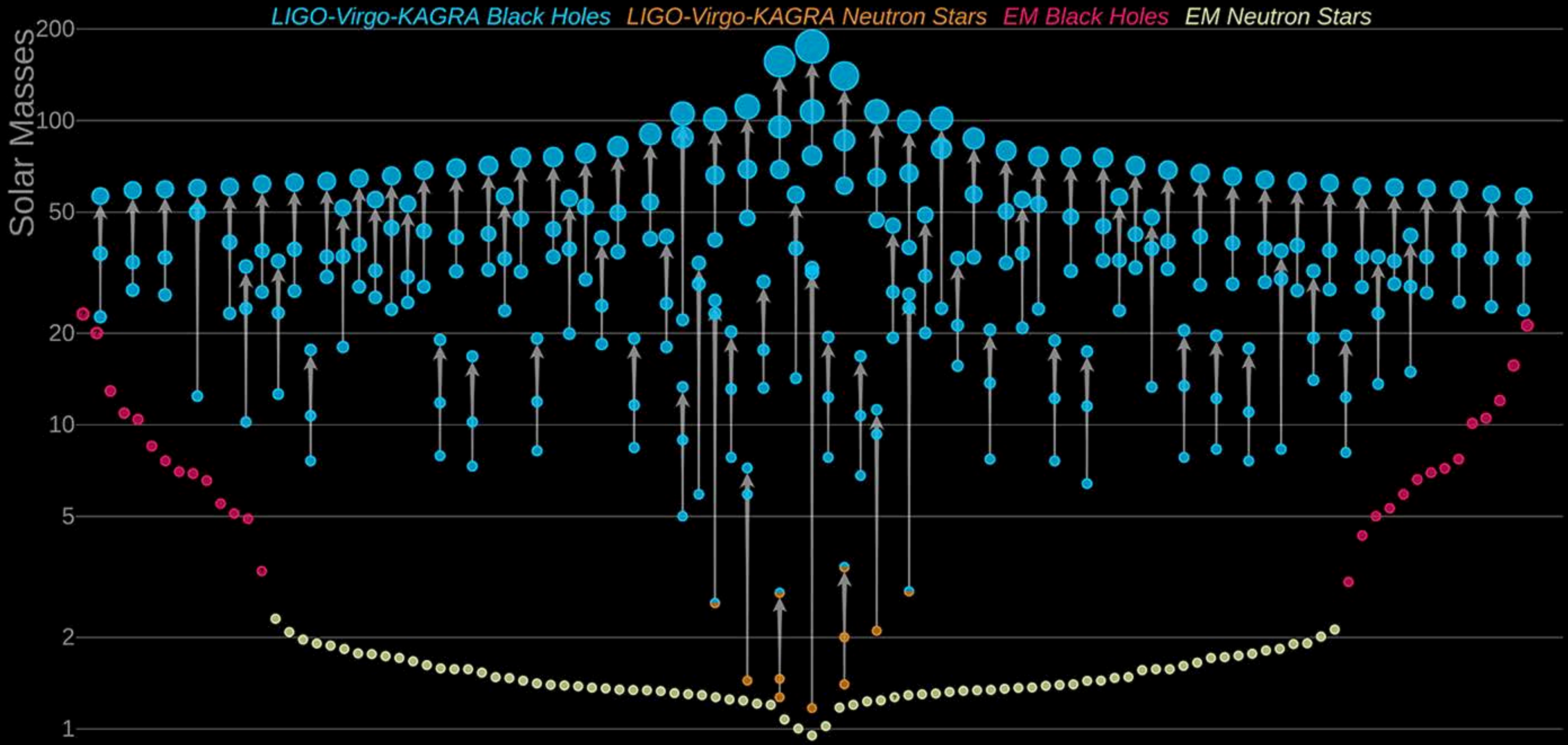
- Rai Weiss
- Kip Thorne
- Barry Barrish



The first few signals:

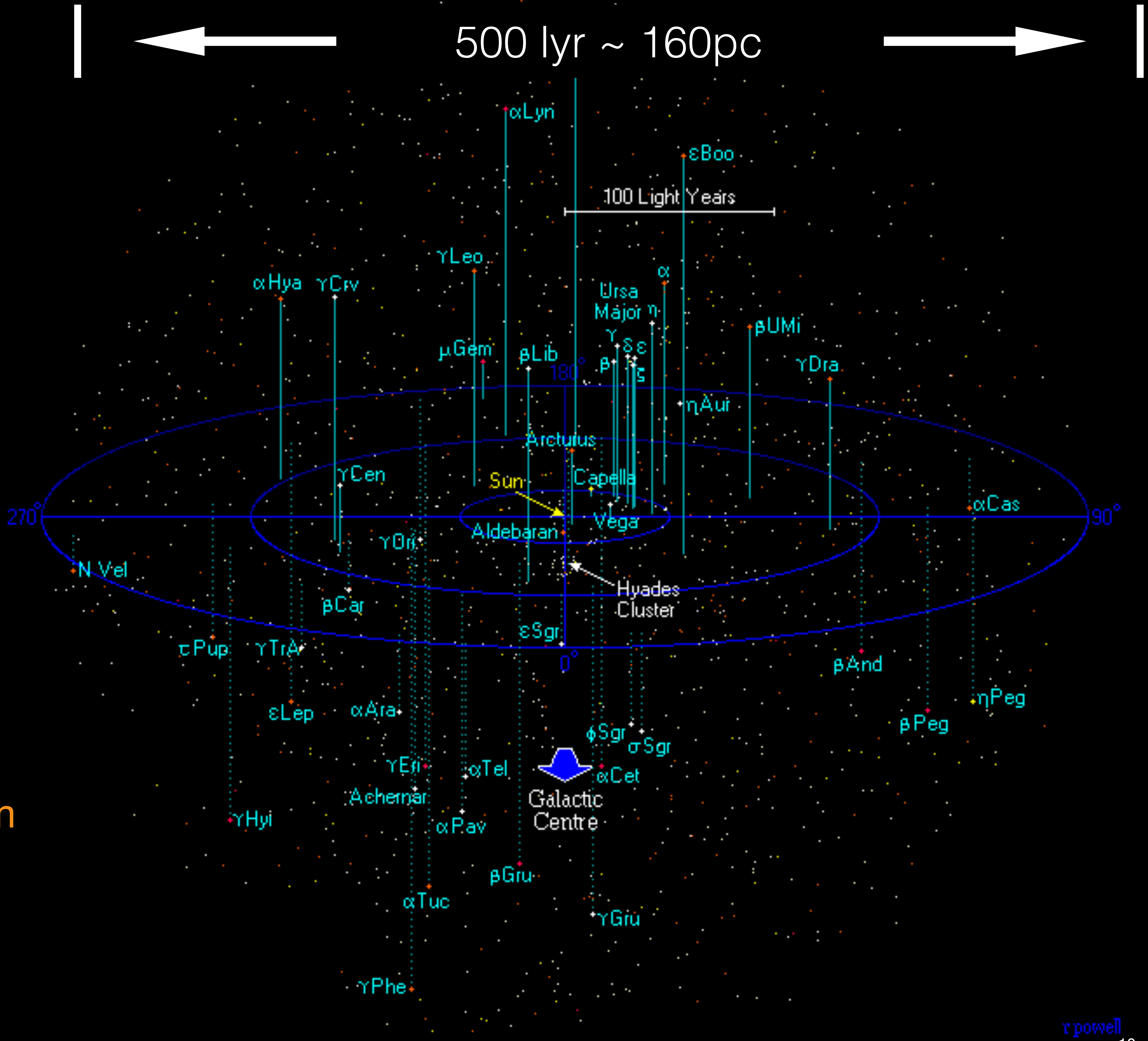


Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

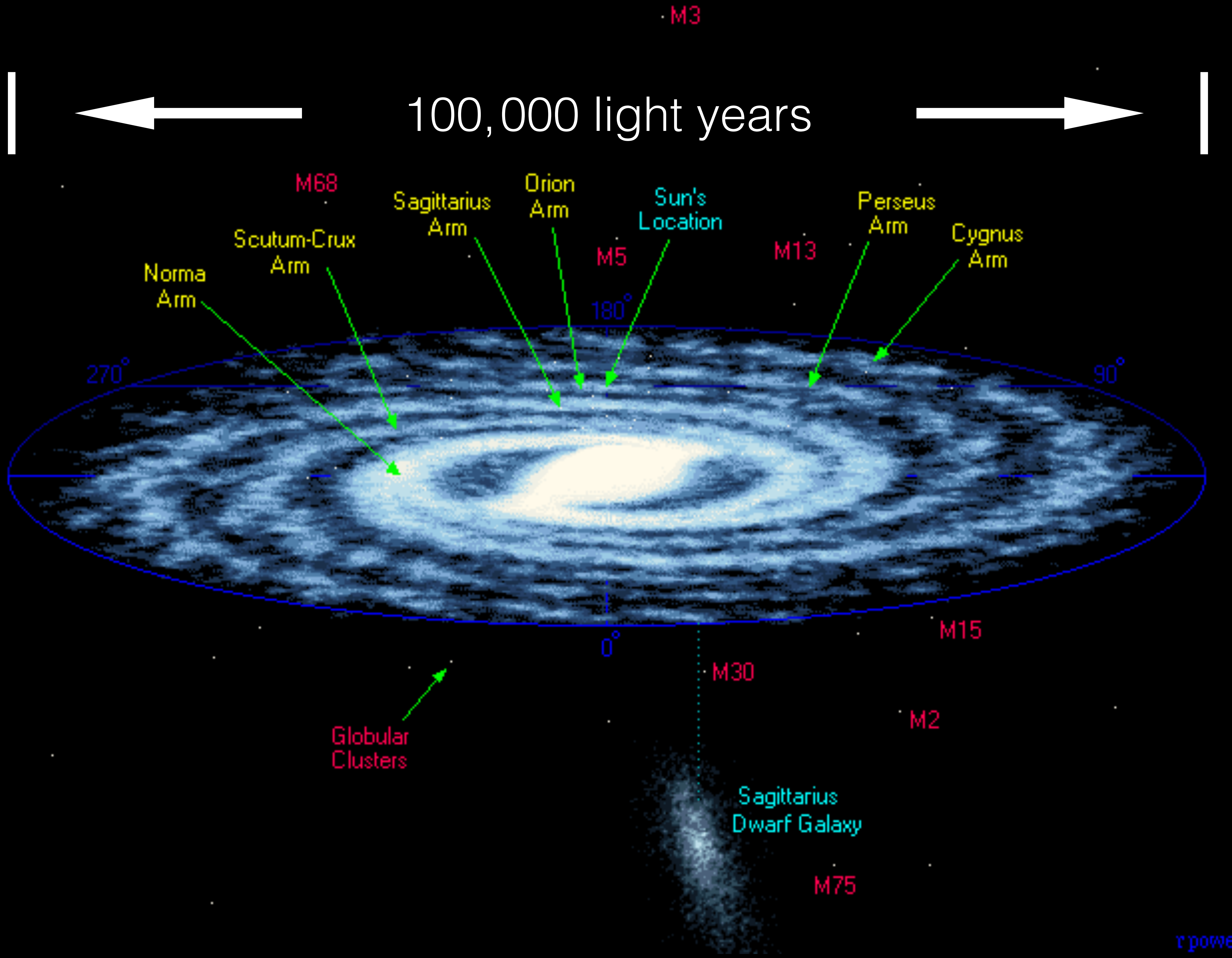
Where was GW 150914 ?



Our backyard:

- Next stars: α-Centauri triple system
- No known BH

Where was GW 150914 ?



Our city:

- Milkyway:
  - 100 billion stars
  - 10 million to 1 billion BHs

Where was GW 150914 ?

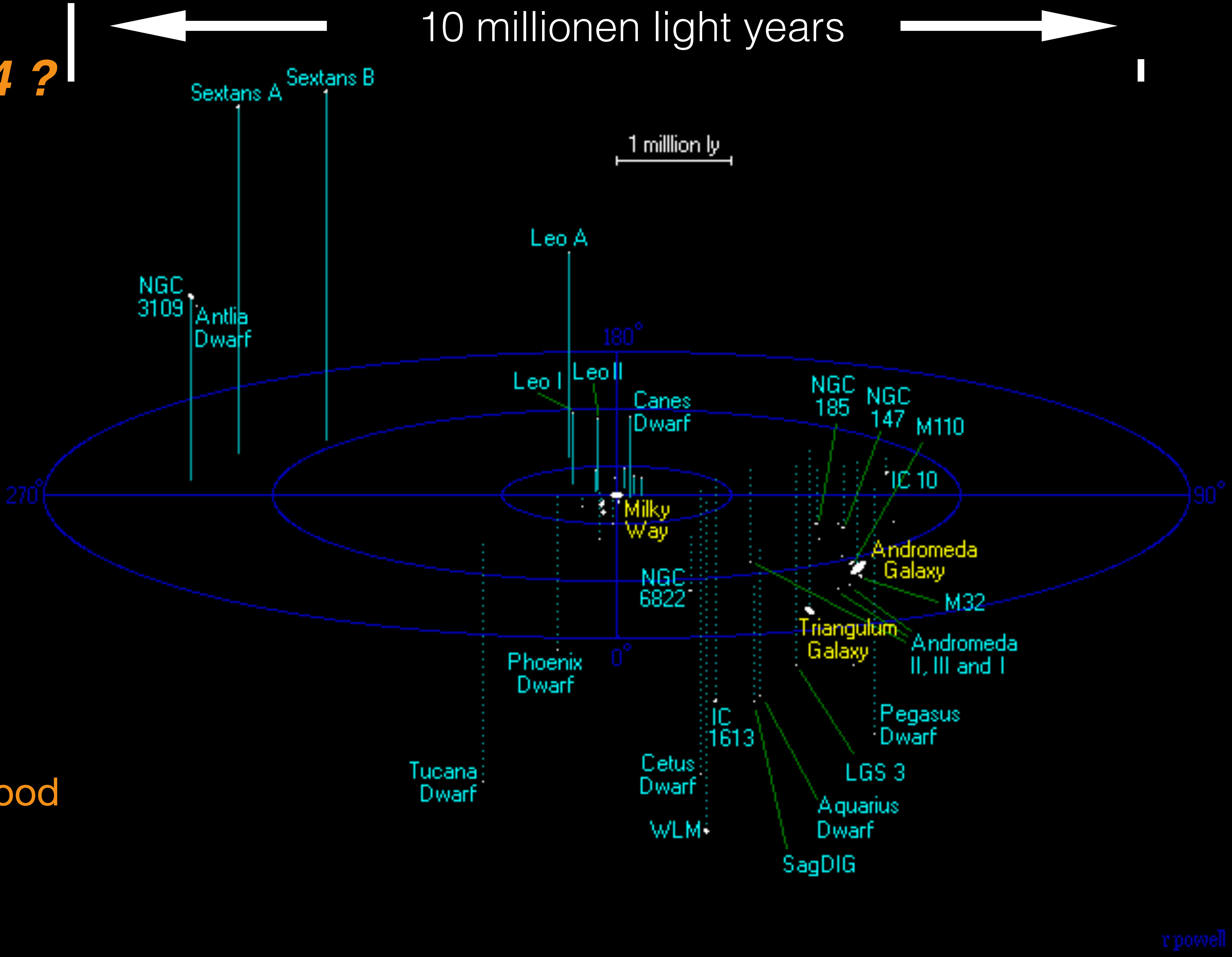
Neighborhood

- 3 large galaxies
- 36 dwarf galaxies
- total of 700 billion stars

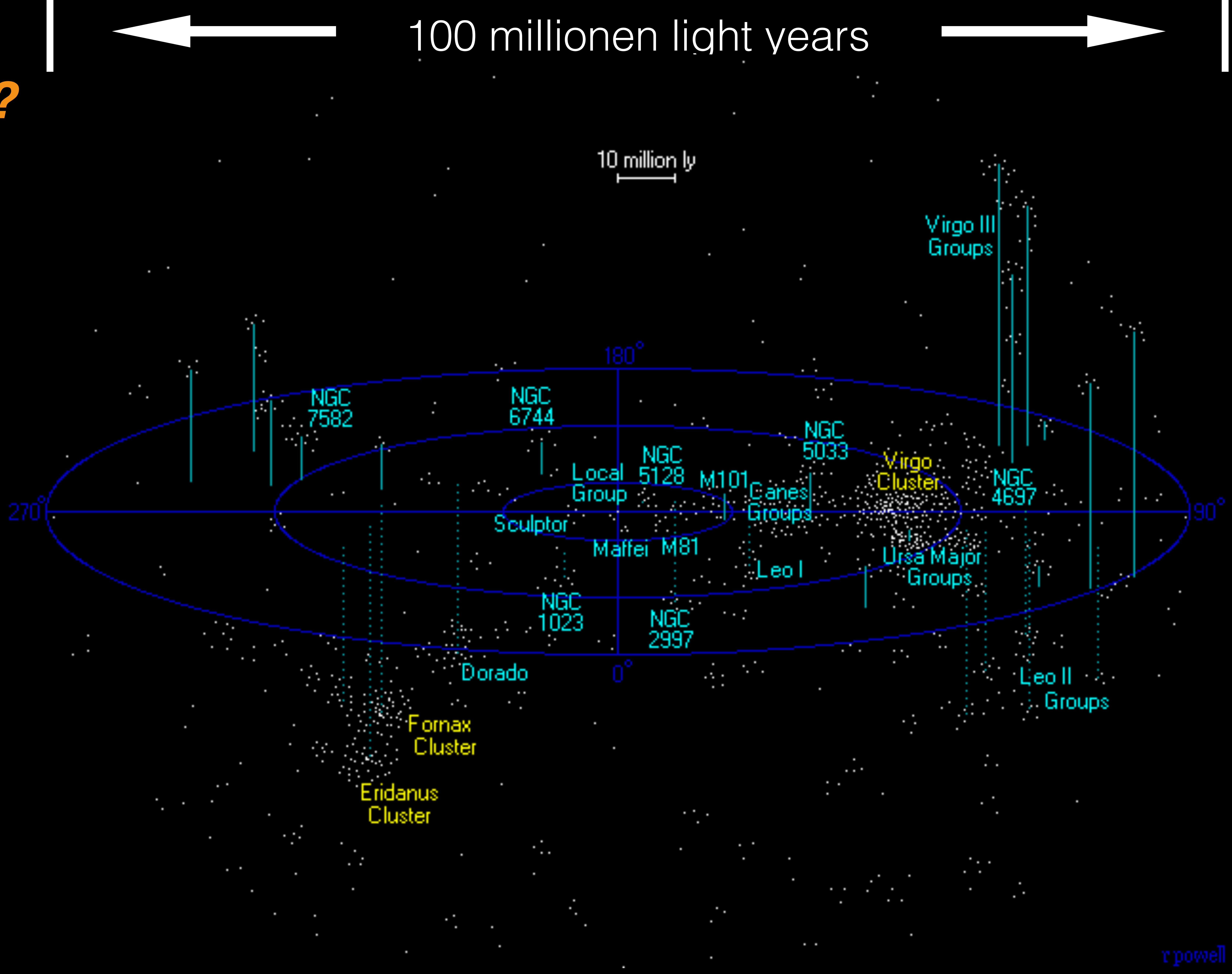
within 5 million ly

And lots of empty space

No gravitational wave event detected within our neighborhood so far.



Where was GW 150914 ?



VIRGO Cluster

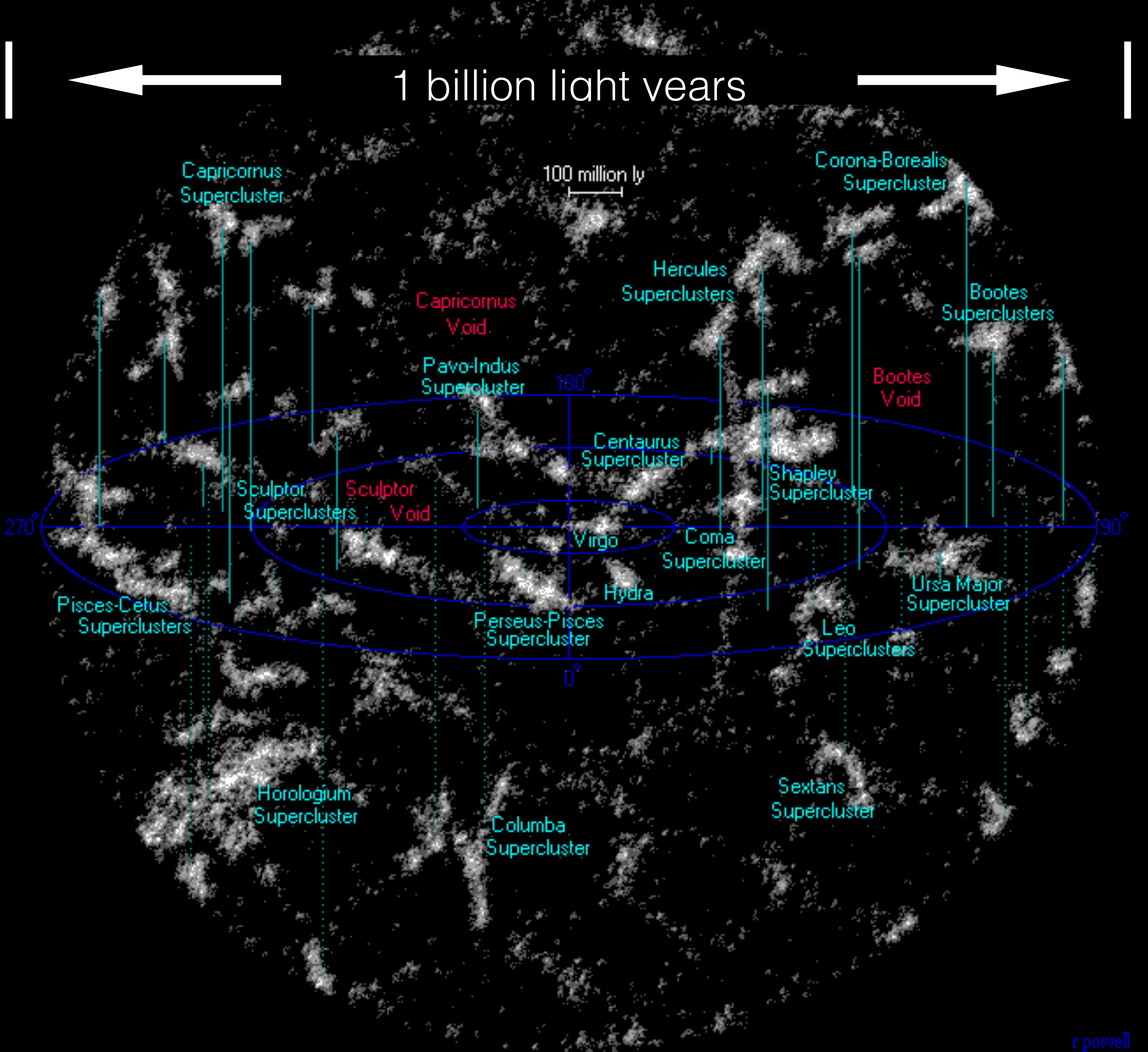
- 160 galaxy groups
- 2500 large galaxies
- 25000 dwarf galaxies
- total of 500 trillion stars

And lots of empty space

LIGO detection GW170817

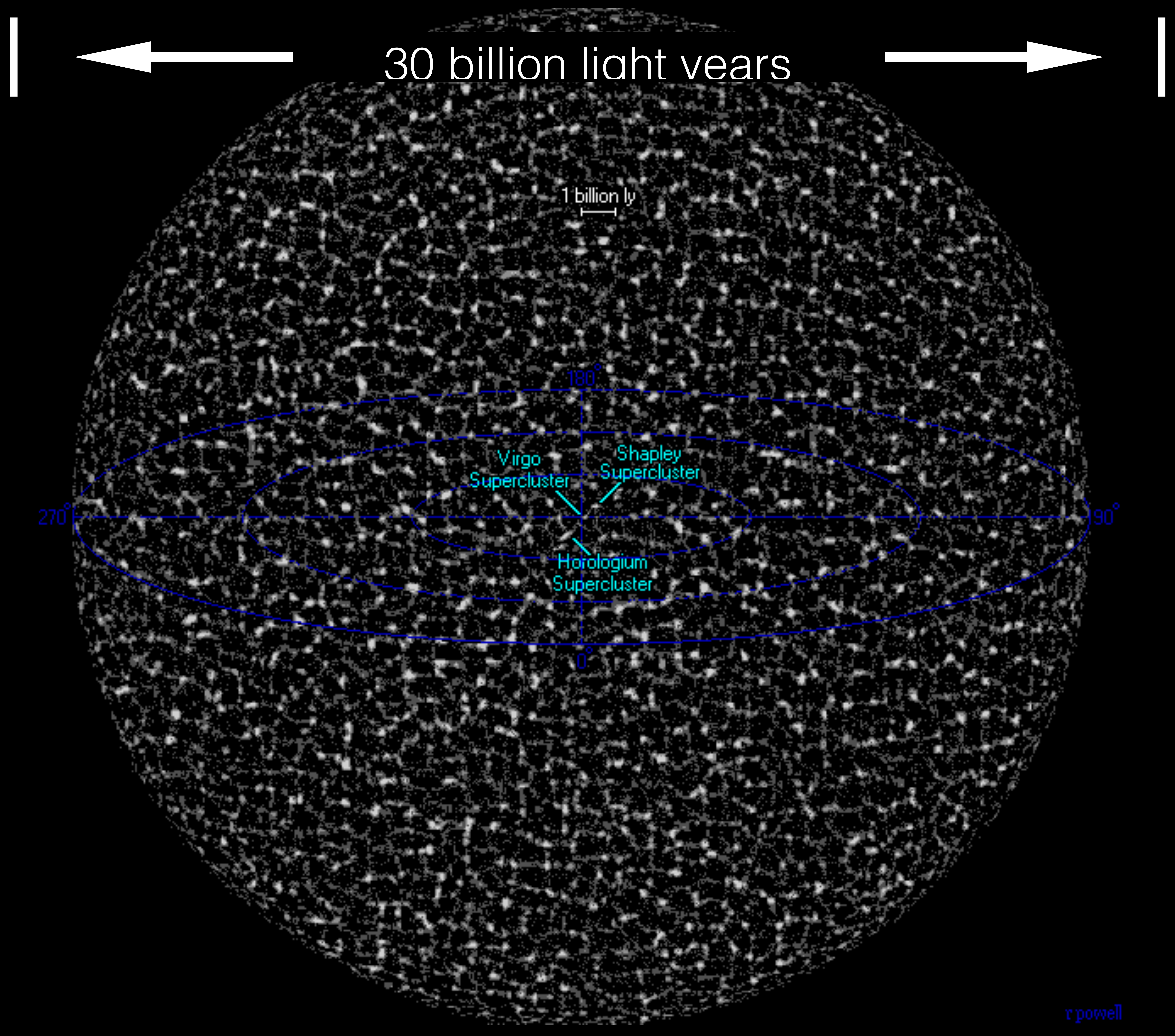
- First NS/NS merger
- 40Mpc distance
- … still outside this cluster

Where was GW 150914 ?



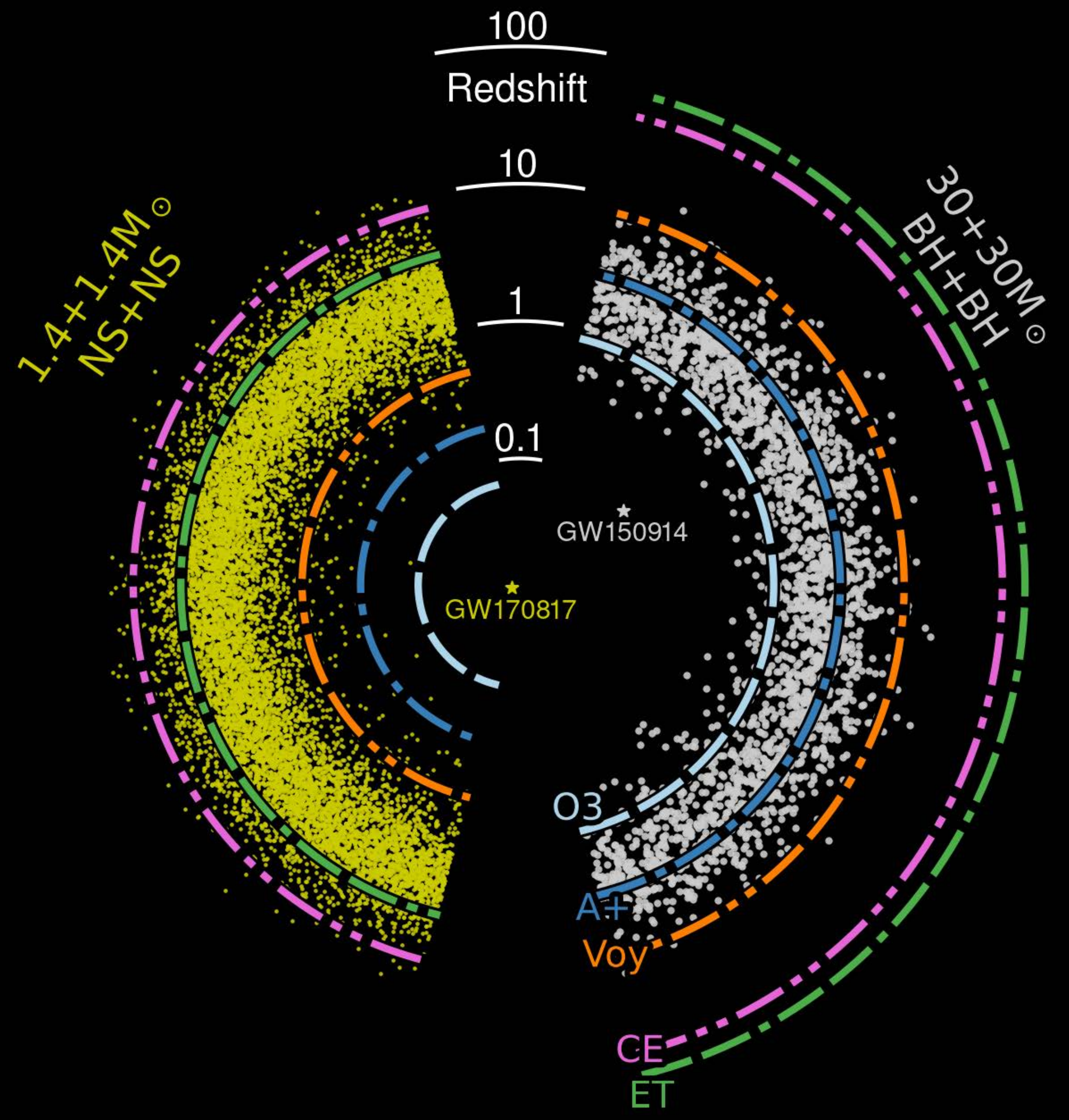
We have to probe well beyond the VIRGO cluster to see significant number of events!

Where was GW 150914 ?

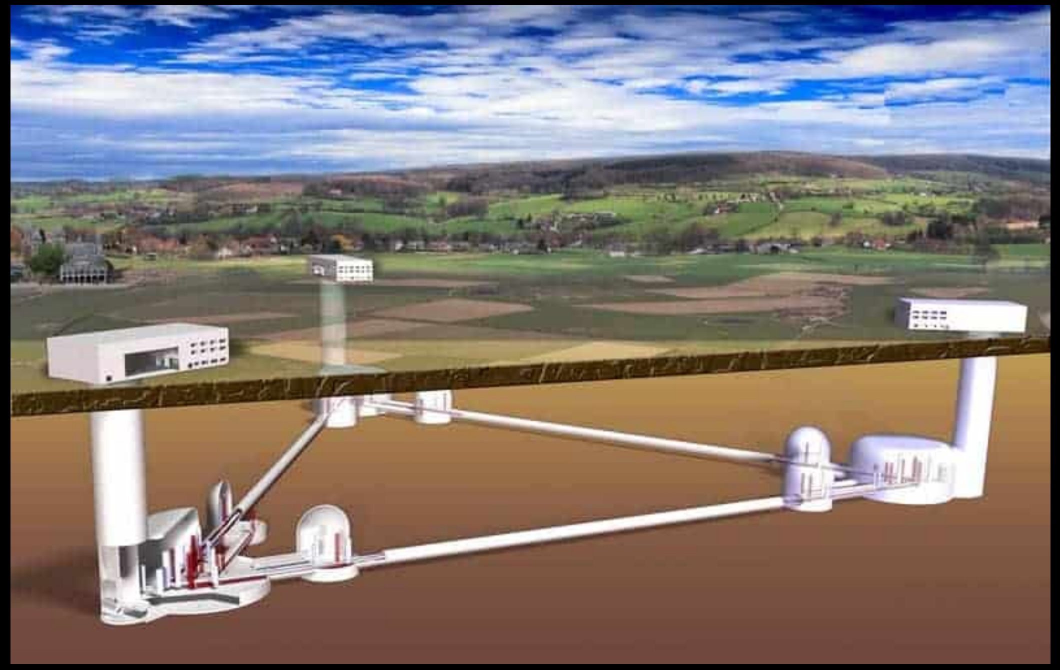


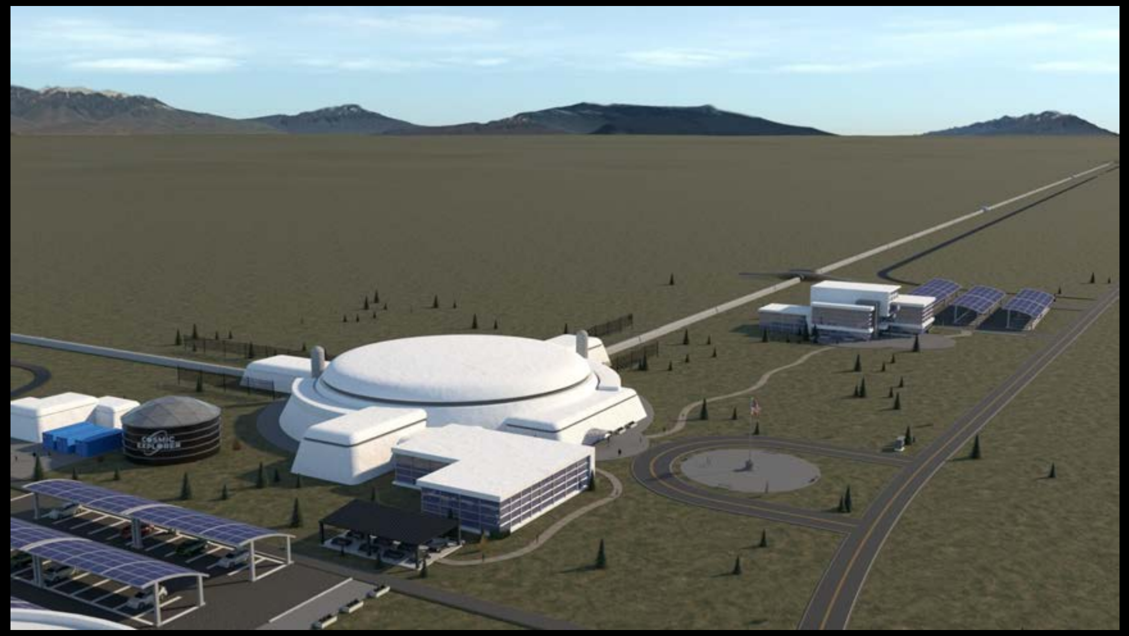
But then it doesn't take much more to listen to the entire visible universe!

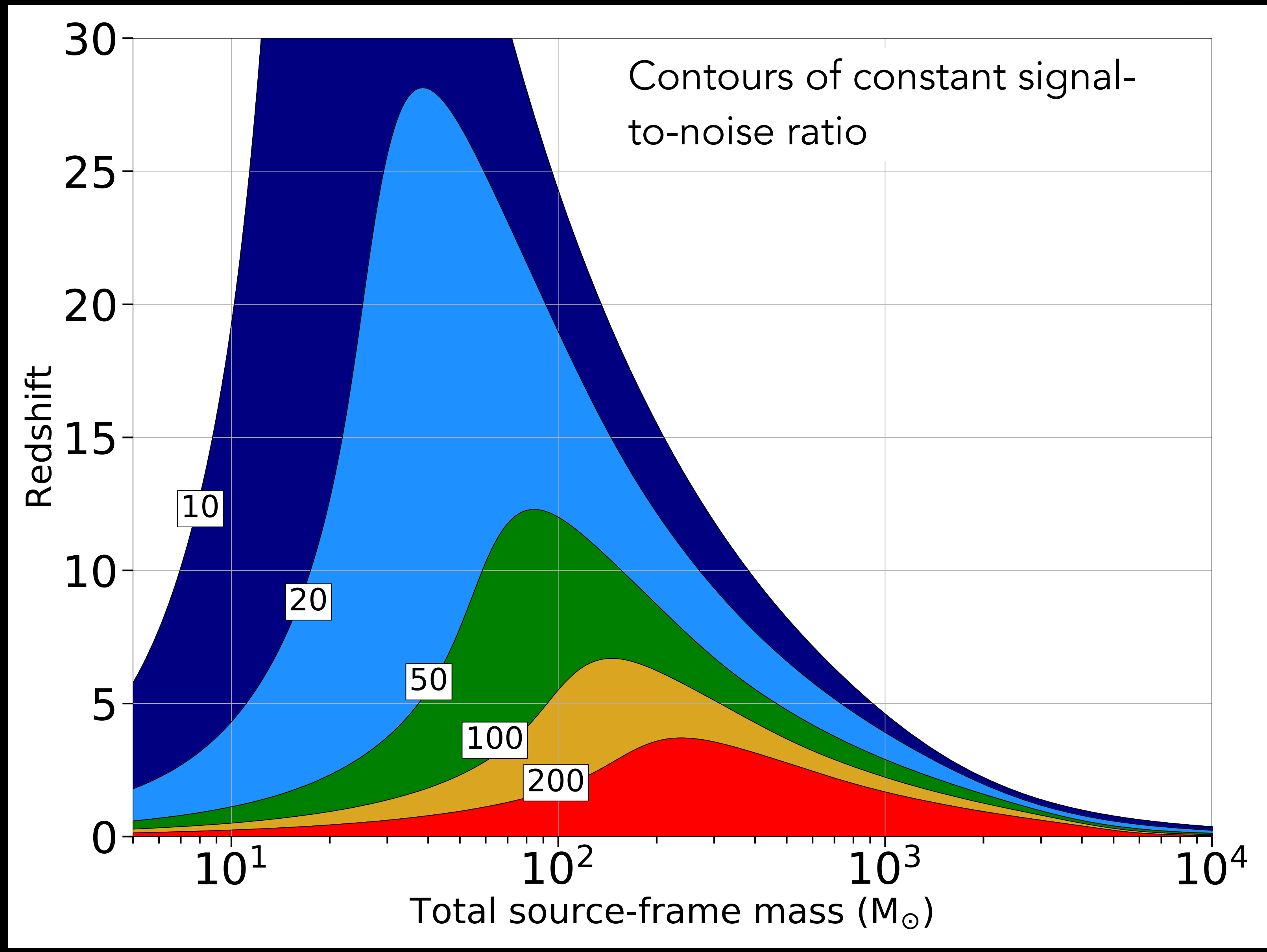
From Advanced LIGO, VIRGO, KAGRA

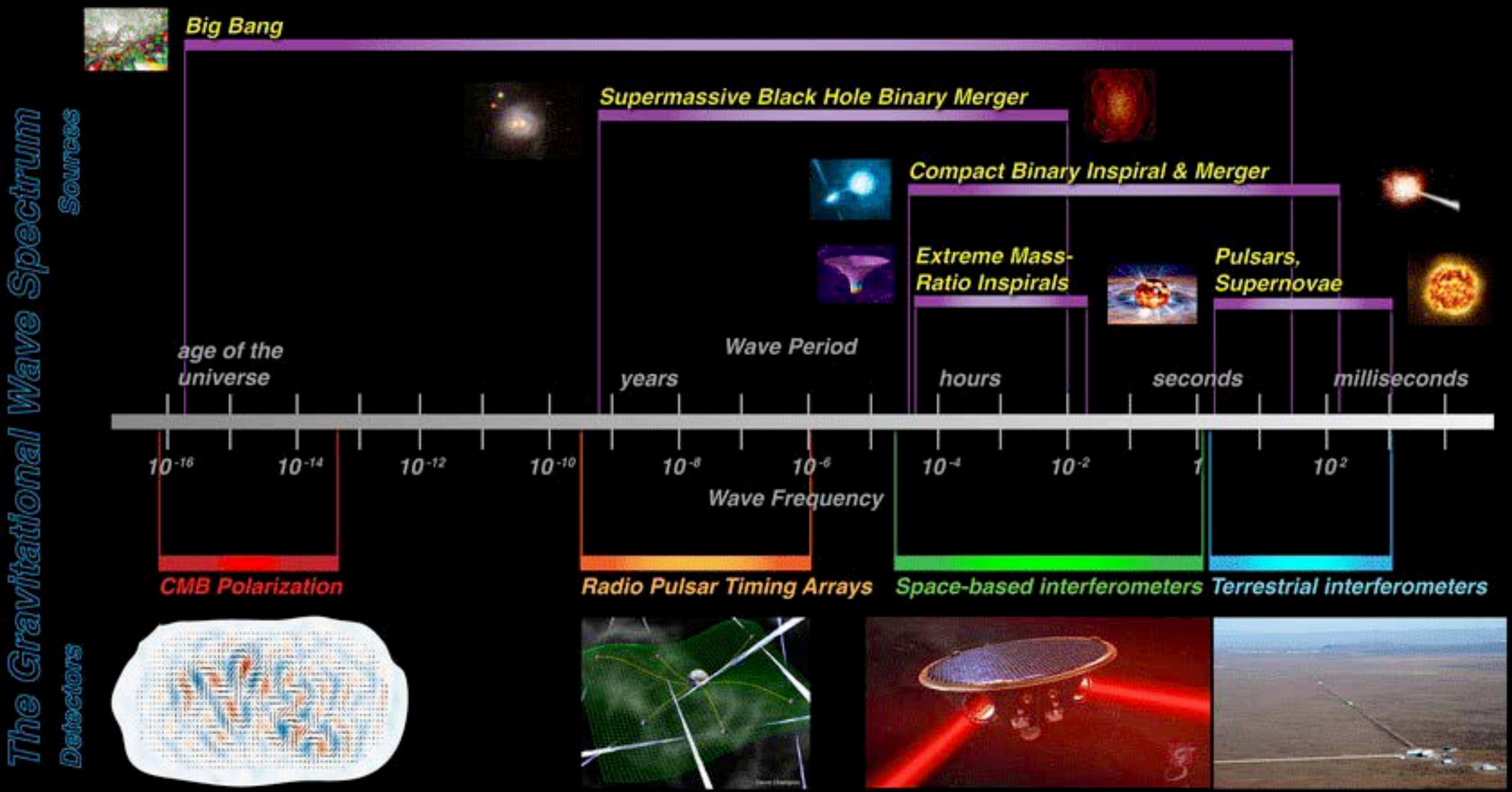


To Einstein Telescope and Cosmic Explorer



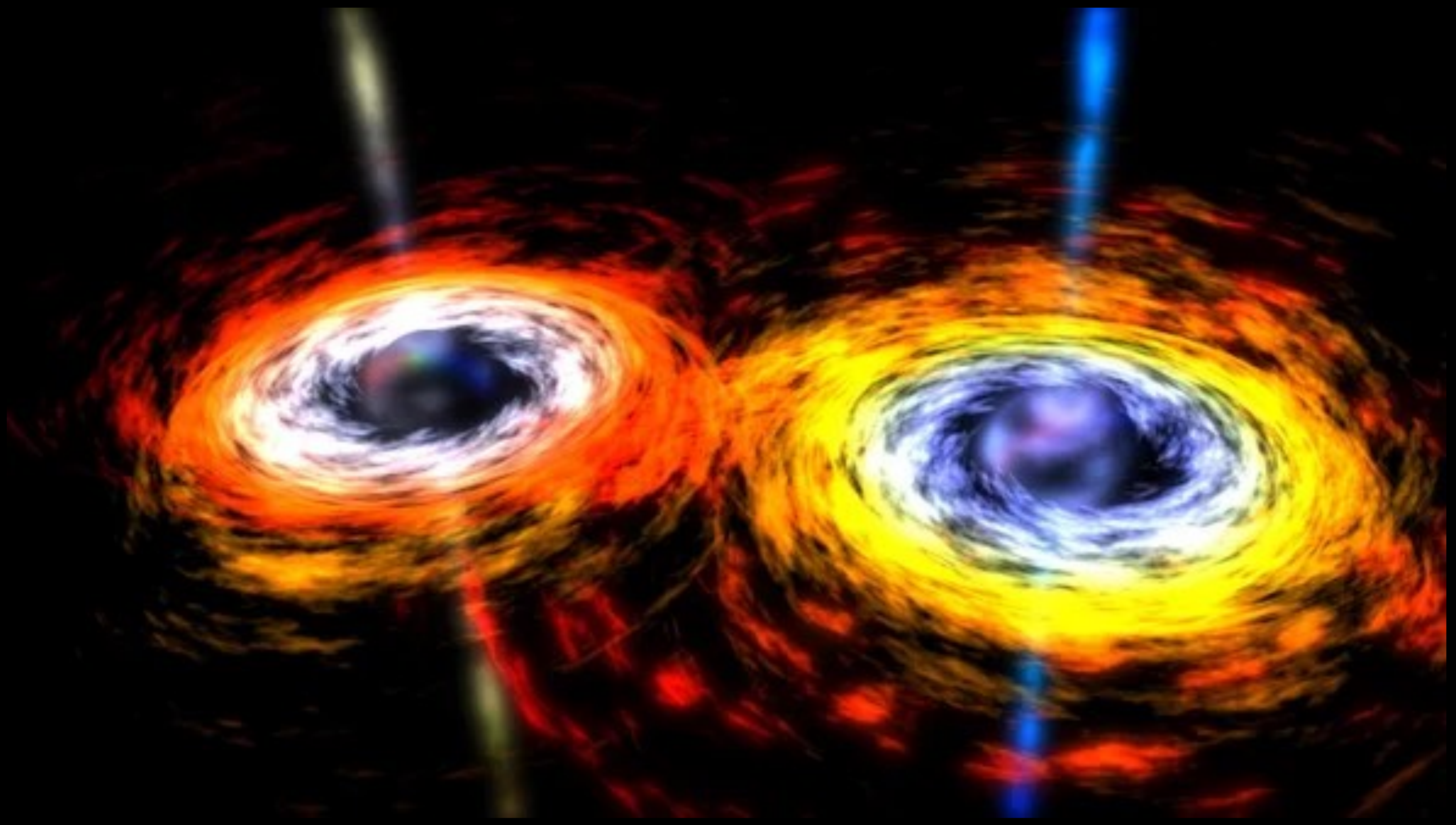





The Gravitational Wave Spectrum
Sources
Detectors
Big Bang
Supermassive Black Hole Binary Merger
Compact Binary Inspiral & Merger
Extreme Mass-Ratio Inspirals
Pulsars, Supernovae
age of the universe
Wave Period
years
hours
seconds
milliseconds
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
Wave Frequency
CMB Polarization
Radio Pulsar Timing Arrays
Space-based interferometers
Terrestrial interferometers

LISA:

- Typical source:
  - Two 10^6 solar mass BHs
  - 10 R_s separation
    - Time to collascence: 1d
  - 300 Gly (z=10) away

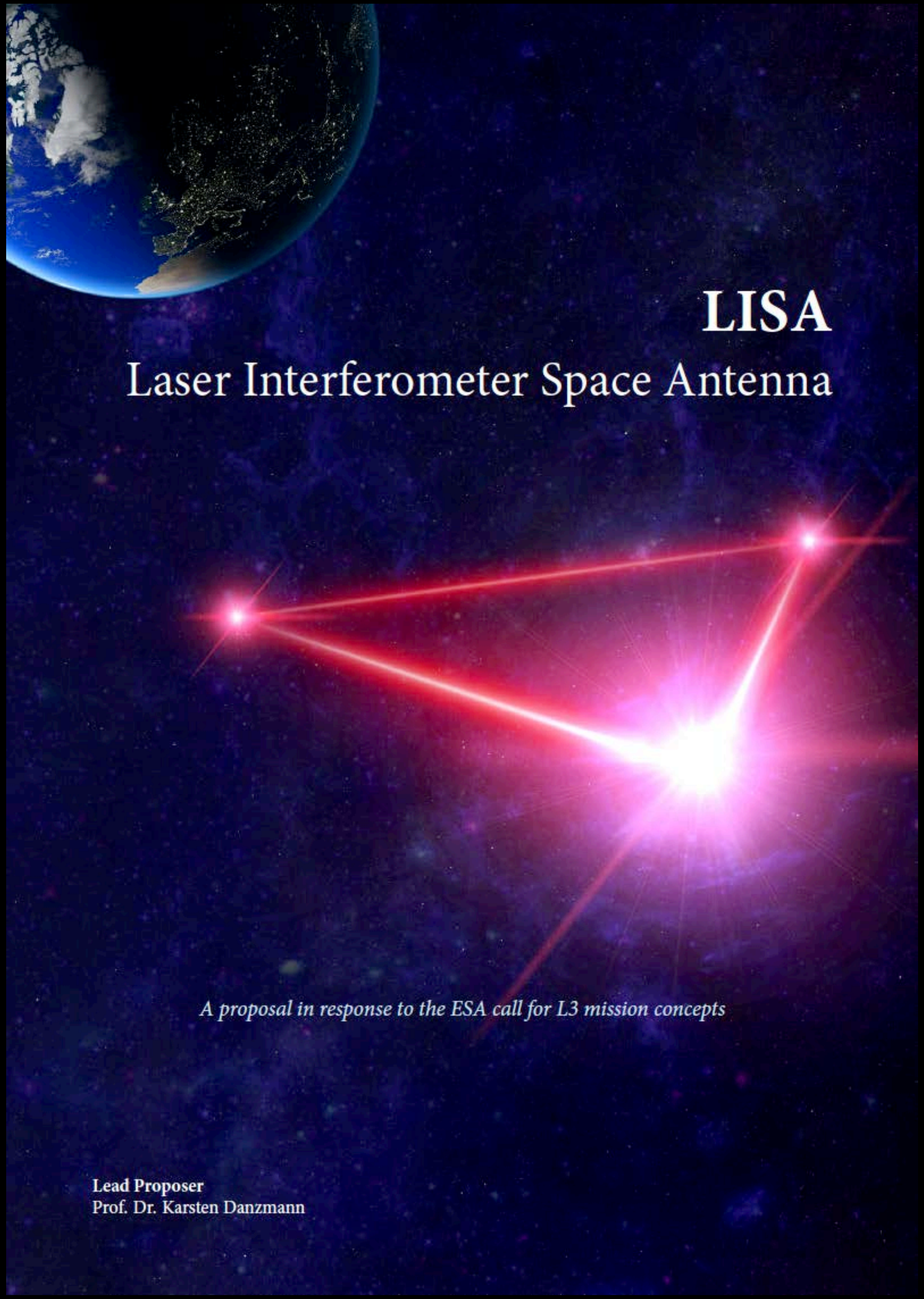


Typical Strain:

$$h \approx \frac{R_1 R_2}{Dr} \approx 10^{-19} \quad \Rightarrow \quad h = \frac{\delta l}{L} \approx \frac{250\,\mathrm{pm}}{2.5\,\mathrm{Gm}}$$

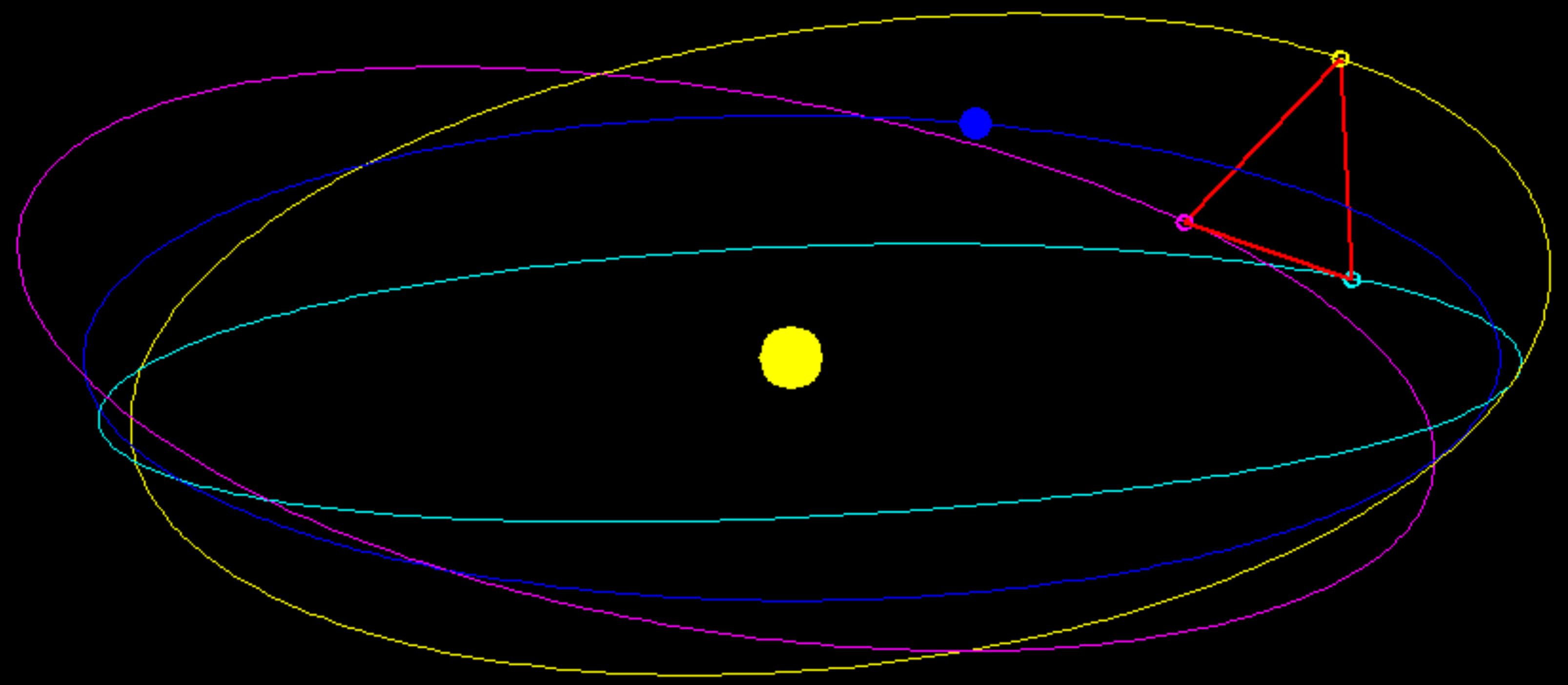
Typical frequency:

$$f \approx \frac{c}{2\pi D}\sqrt{\frac{R_1 + R_2}{2D}}\frac{1}{1+z} \approx 0.05\,\mathrm{mHz}$$



LISA:

- 3 S/C in heliocentric orbits
    - 30 Gm behind Earth
    - 100s signal travel time Earth - LISA
- Near equilateral triangle
    - $L = 2.5\,\mathrm{Gm} \pm 30\,\mathrm{Mm}$
    - $\alpha = 60^\circ \pm 1^\circ$

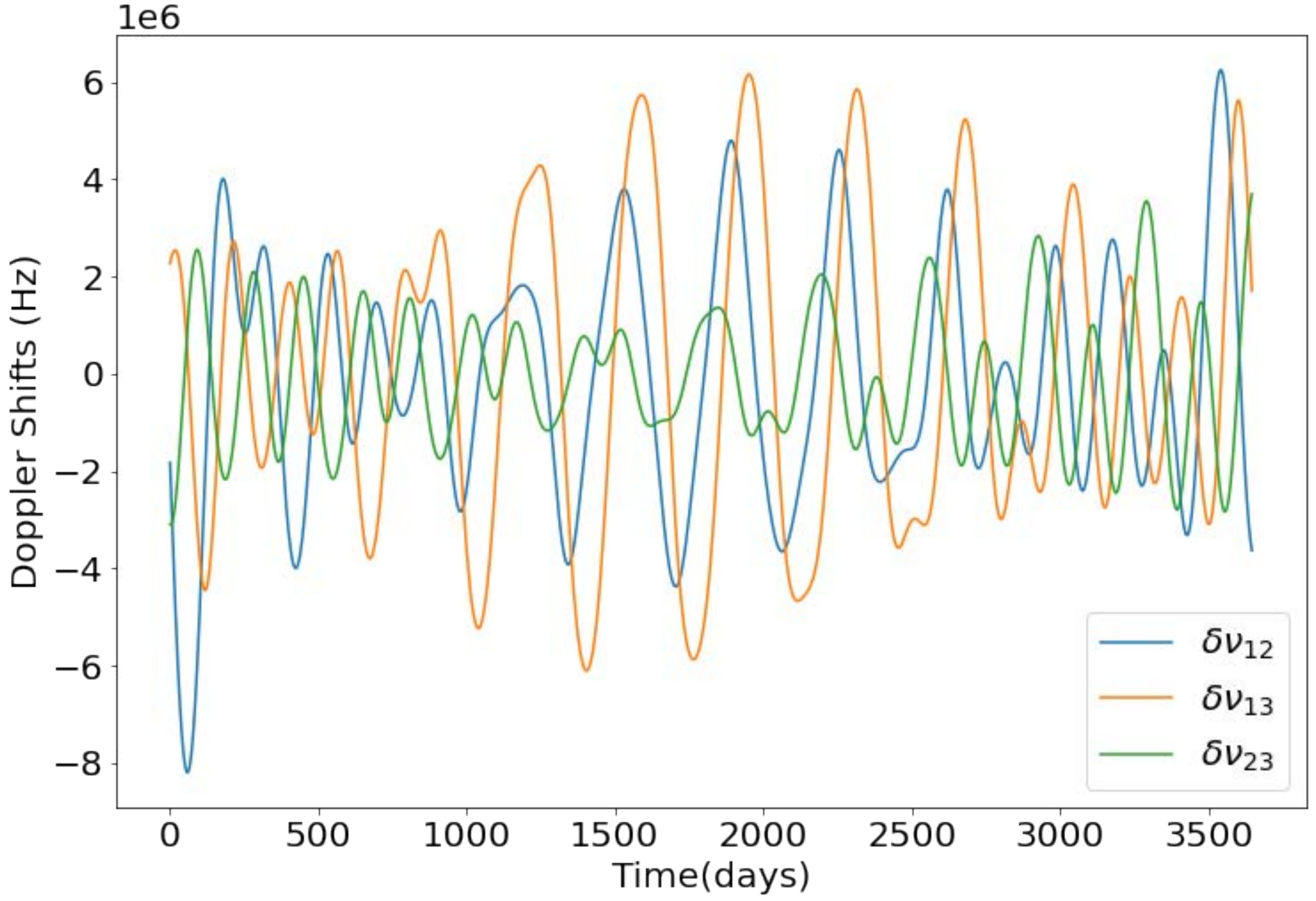


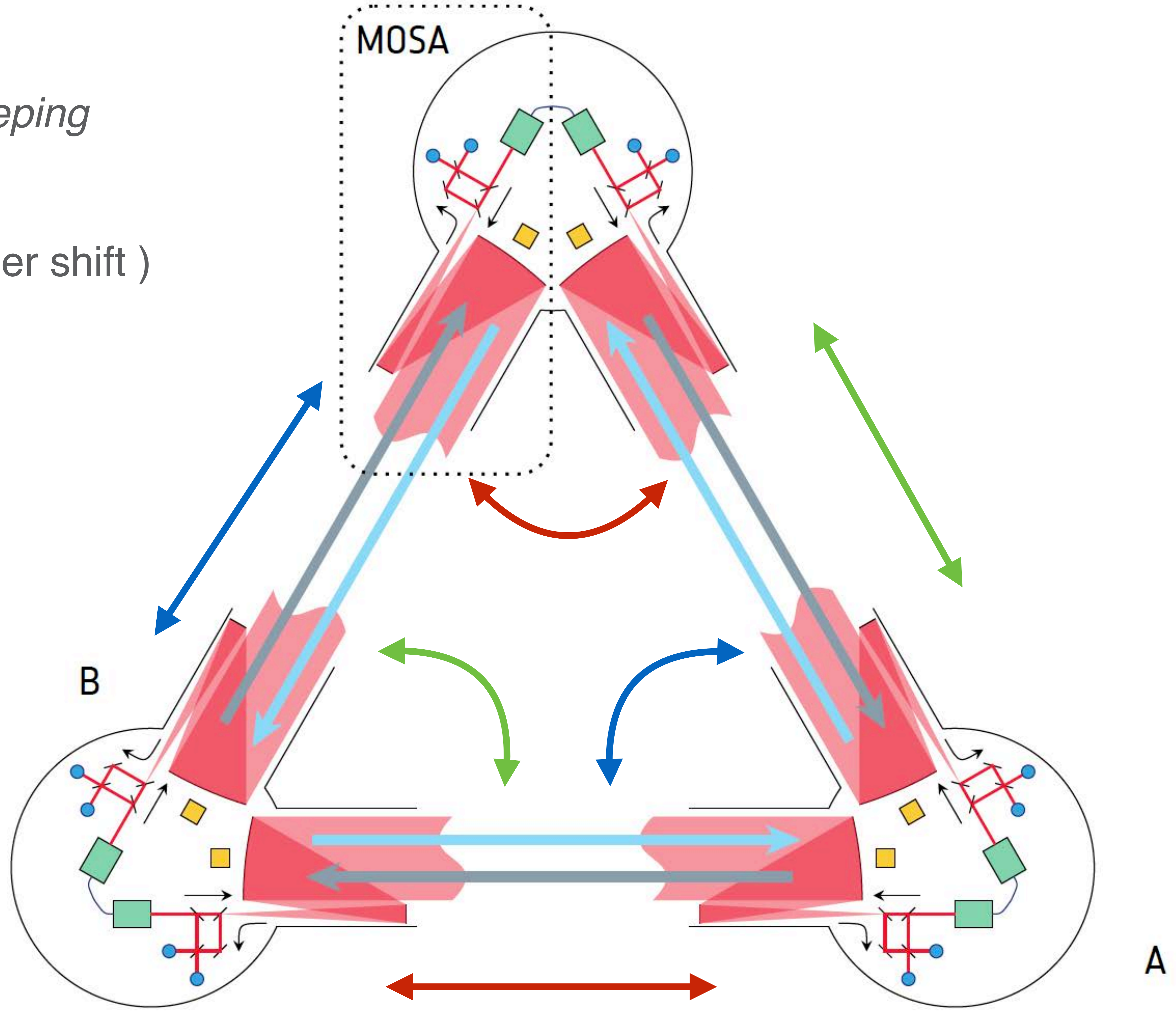
Nicolas Douillet - ARTEMIS

LISA Mission Concept

LISA's magic orbits:

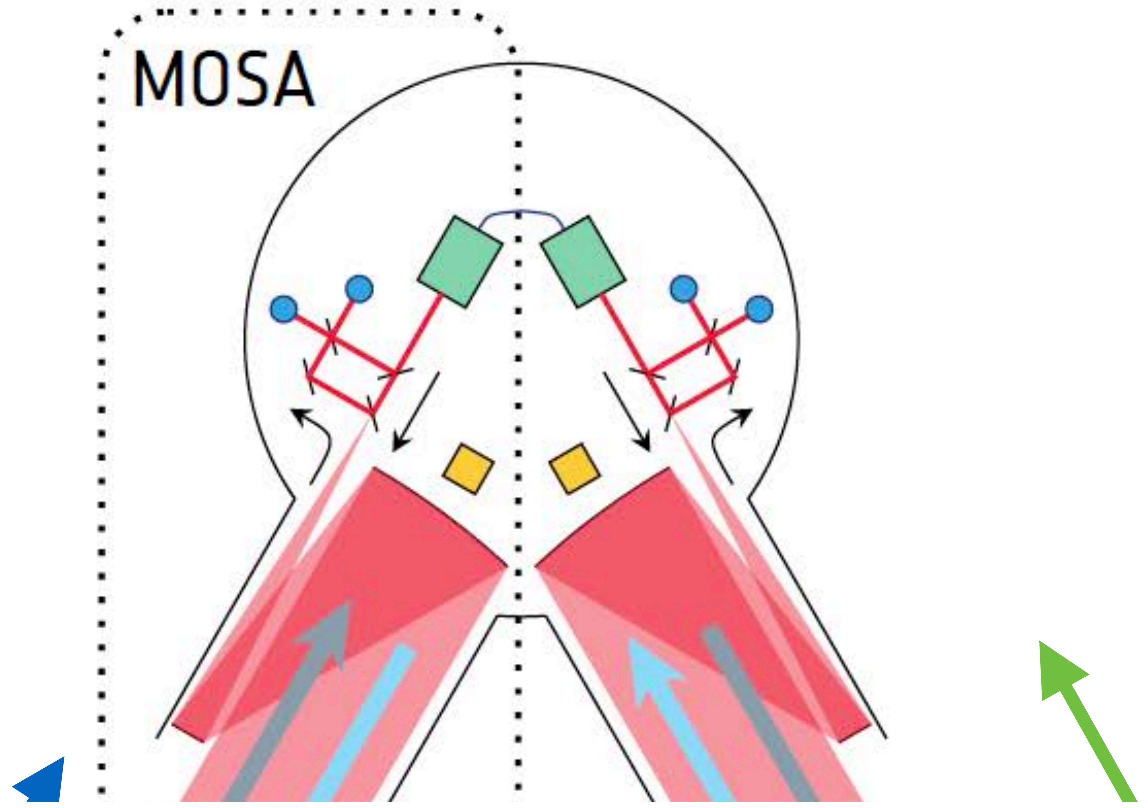
- *Maintain equilateral triangle* ***as much as possible*** *w/o station keeping*
  - ***Separation variation:*** $\approx 1\,\%$ ***, angular variation:*** $\pm 0.8^\circ$
  - ***Relative speed between S/C:*** $< 10\,\mathrm{m/s}$ ($\approx 10\,\mathrm{MHz}$ Doppler shift)

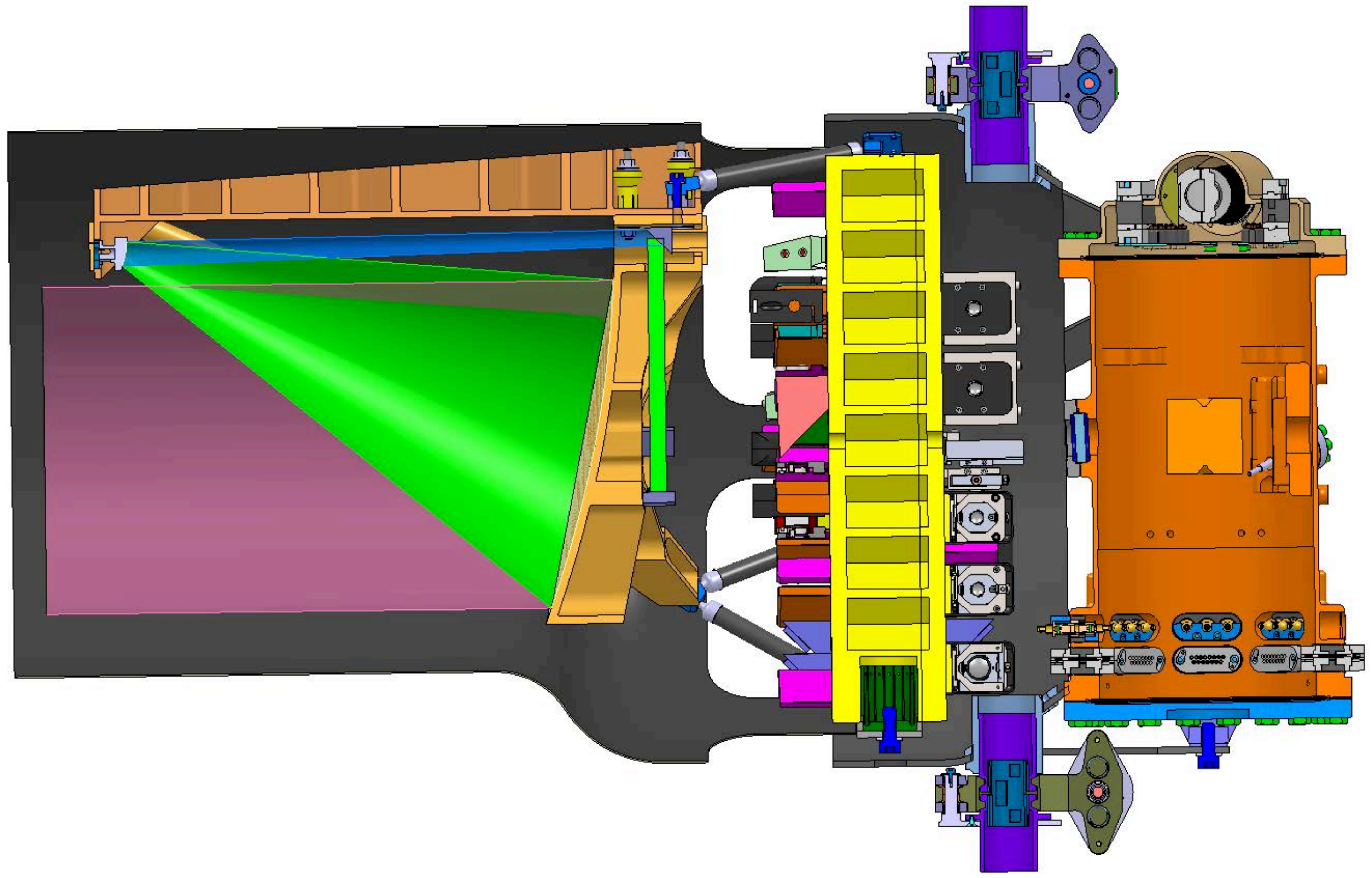


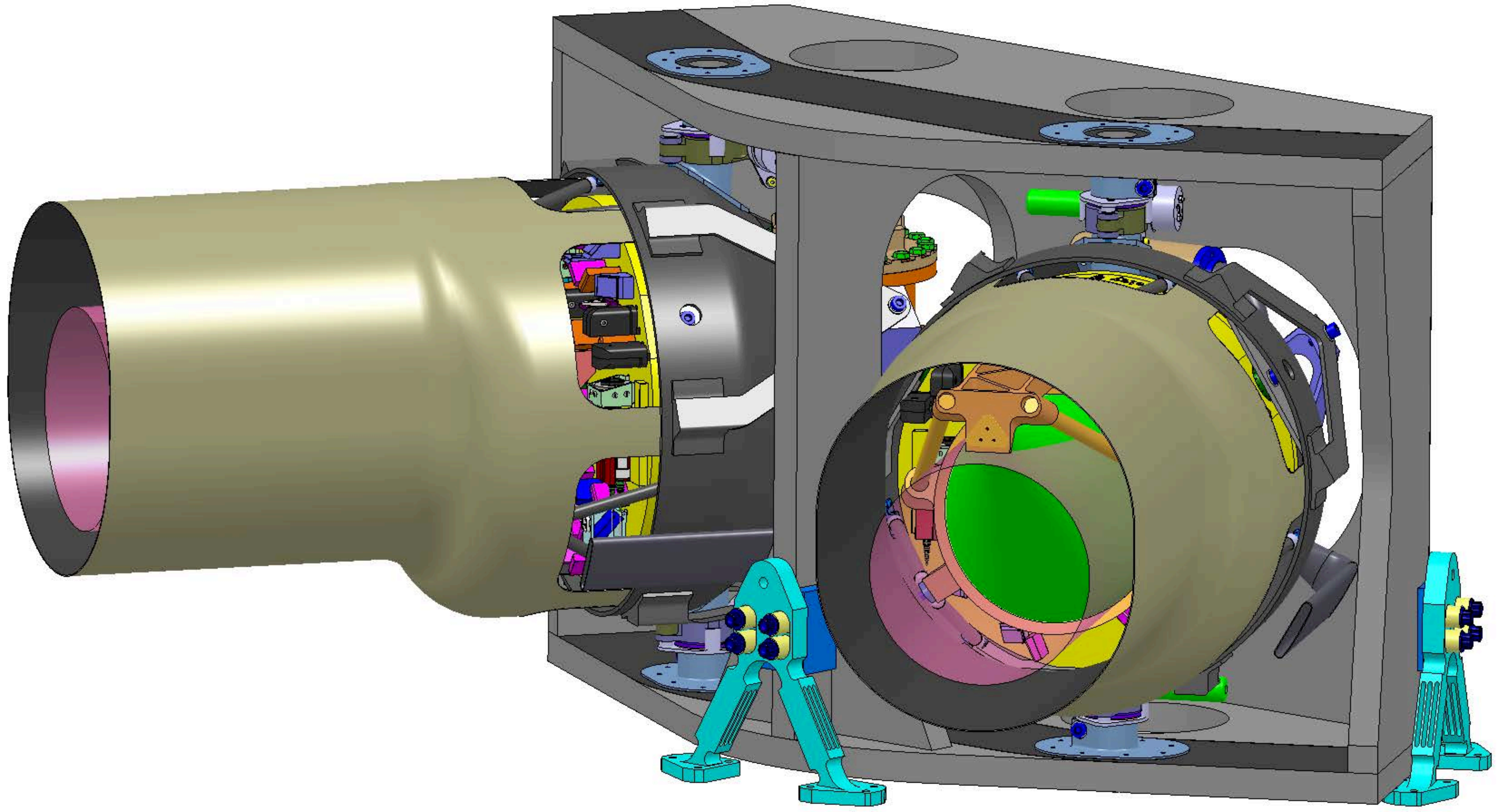


Each S/C contains

- *2 Moving Optical Sub Assemblies (MOSA)*
  - *Free falling test mass inside their electro-static housings*
  - *Optical Bench with several actuators (Mechanisms) and detectors*
  - *30-cm off-axis telescope*





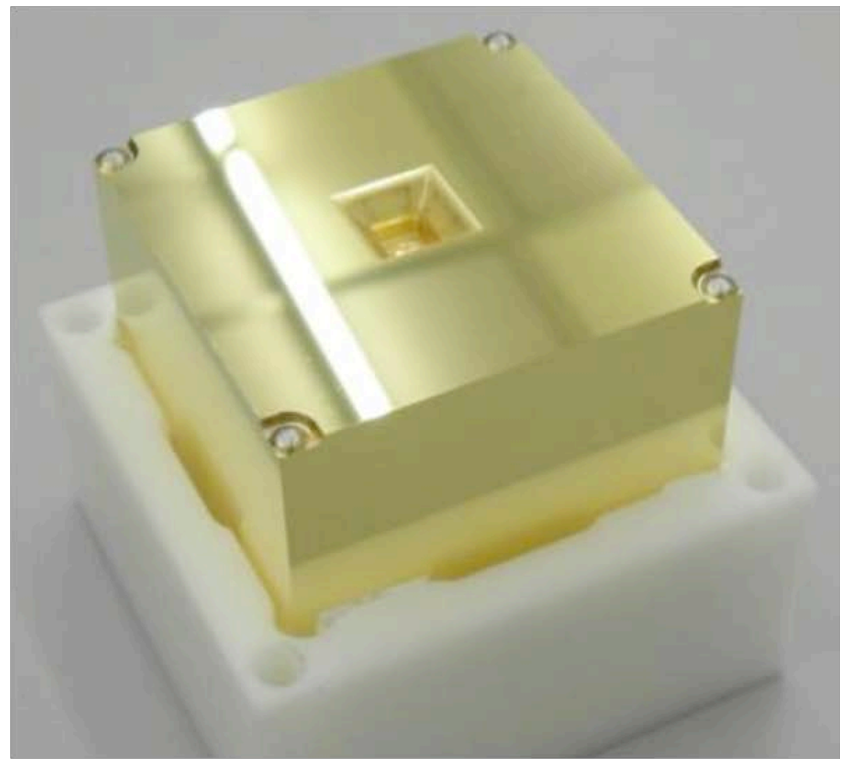


A

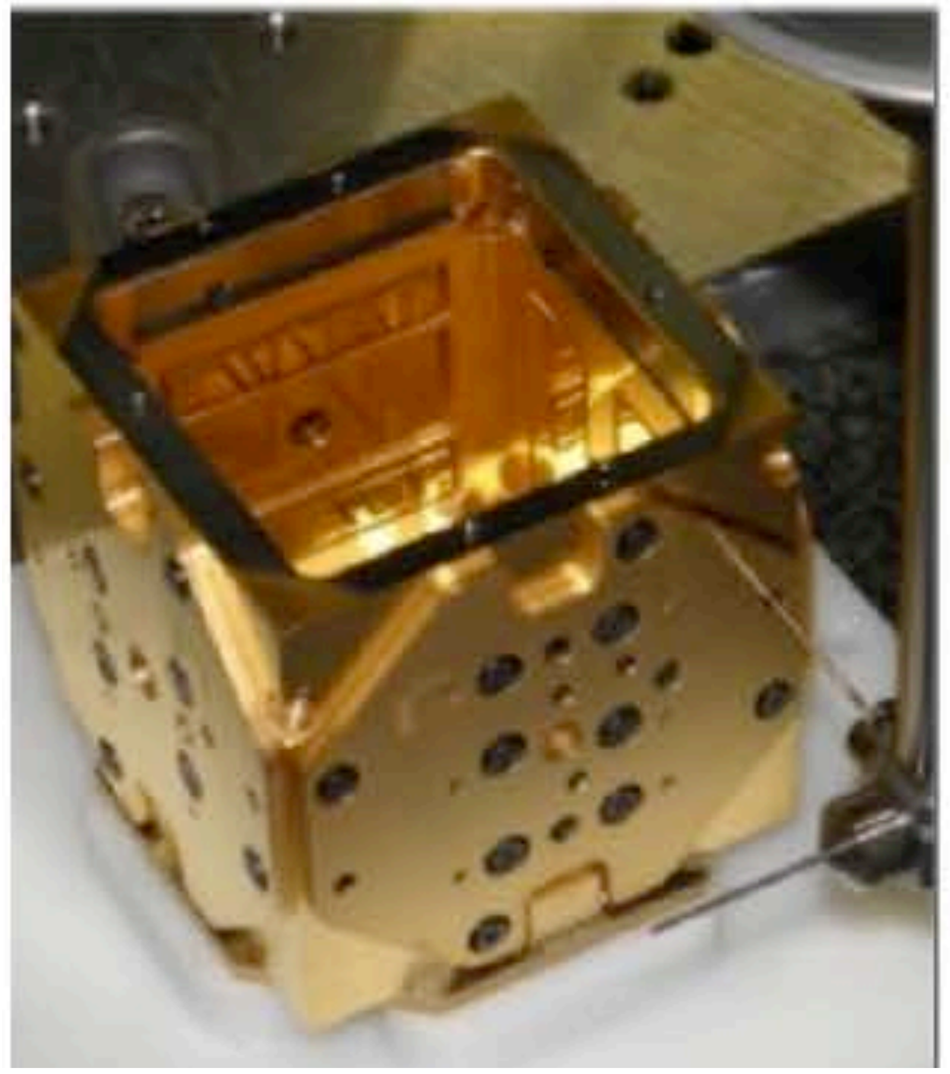
LISA - Mission Concept

Basic Concept

- *S/C in drag free motion in each interferometer direction*
  - *follows each free falling test mass along its sensitive direction*
- *Test mass follows S/C in all other degrees of freedom*
- *S/C will be aligned against incoming laser fields*

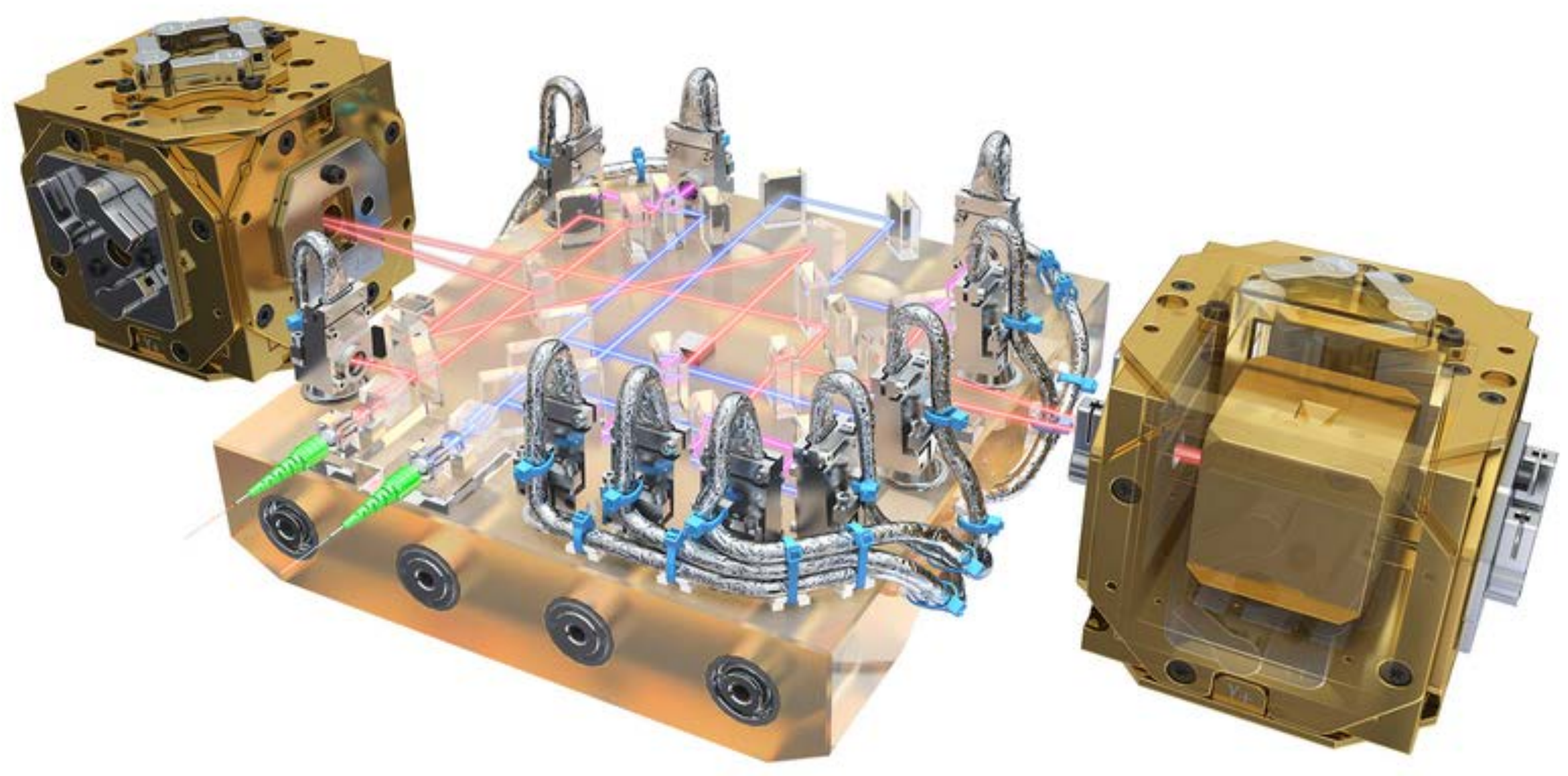


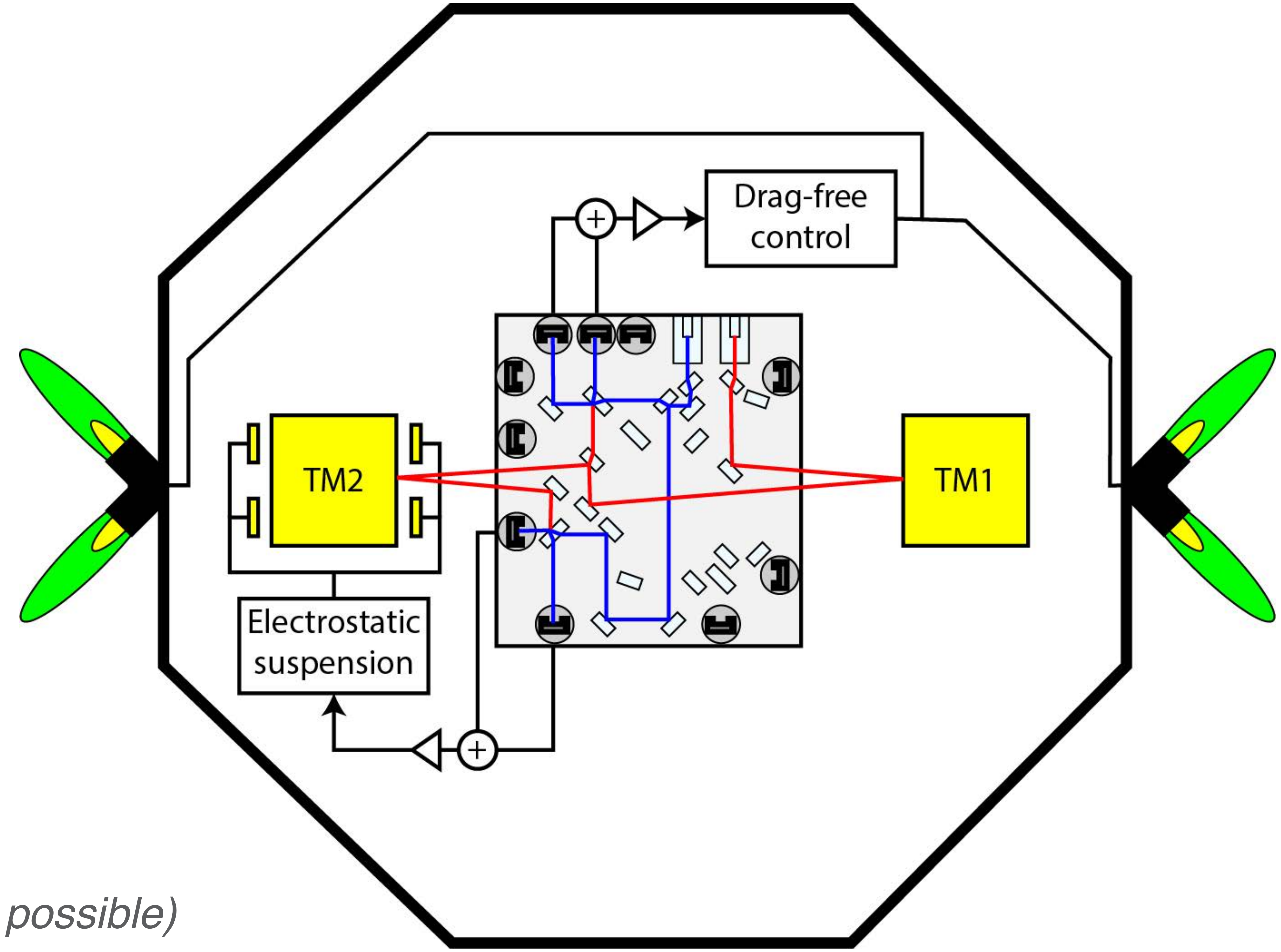
- *Each test mass inside own electro-static housing*
  - *Capacitive sensing (nm/√Hz sensitive)*
  - *Electro-static actuation to control test mass*
    - *Position perpendicular to optical axis*
    - *Orientation in all three angles*



LISA Pathfinder (LPF)

Demonstrate this idea in dedicated space mission

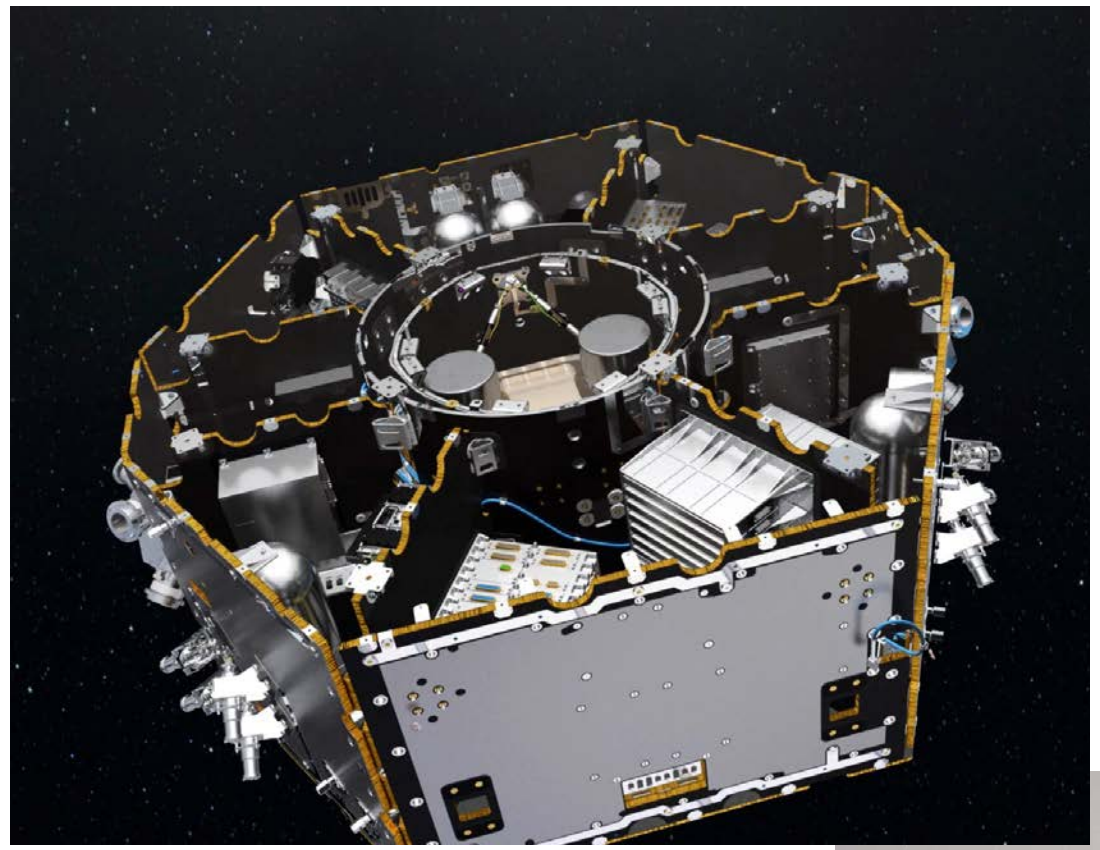




LPF: Shrink the 2.5Gm to 40cm

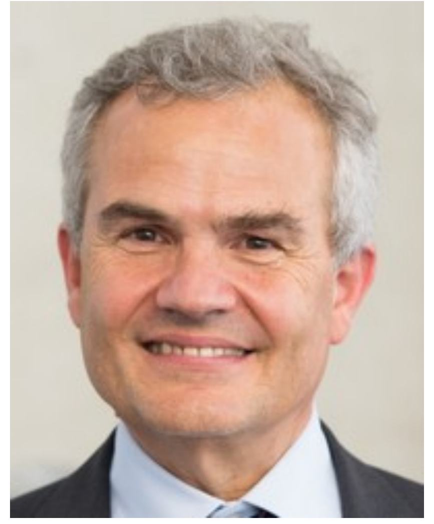
- *Two independent test masses separated by OB*
- *Two interferometer:*
  - *Test mass to test mass distance*
  - *Test mass to optical bench distance*
- *Drag-free operation*
  - *Steer S/C around free falling test masses (as much as possible)*

LISA Pathfinder (LPF)

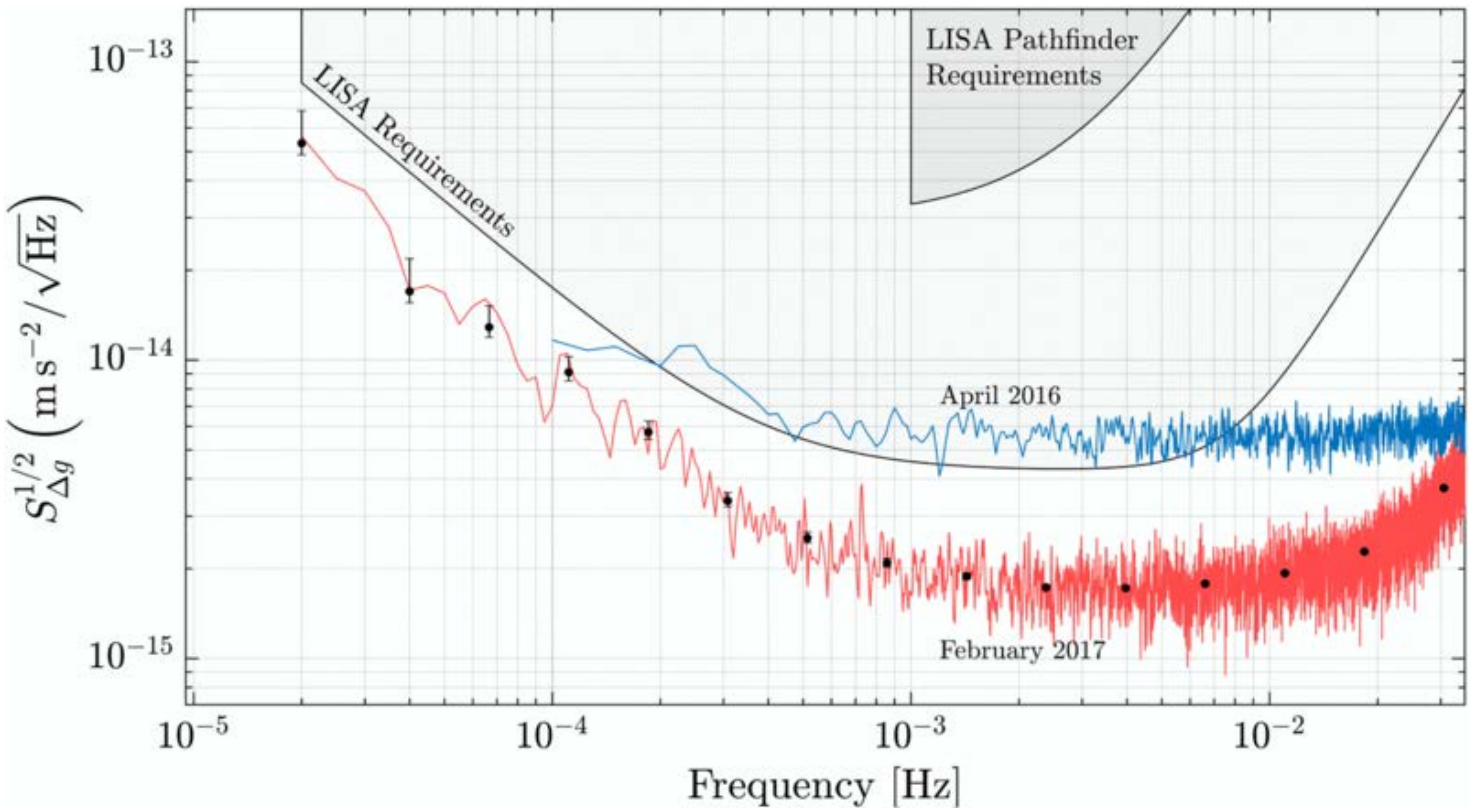


Launched December 2015

Karsten Danzmann



Stefano Vitale



GRS performance: 3 times below LISA requirement

- *Limited at high frequencies by gas pressure*
- *Limited at low frequencies by actuation noise*

LISA - Mission Concept

Gravitational Reference Sensor (GRS):

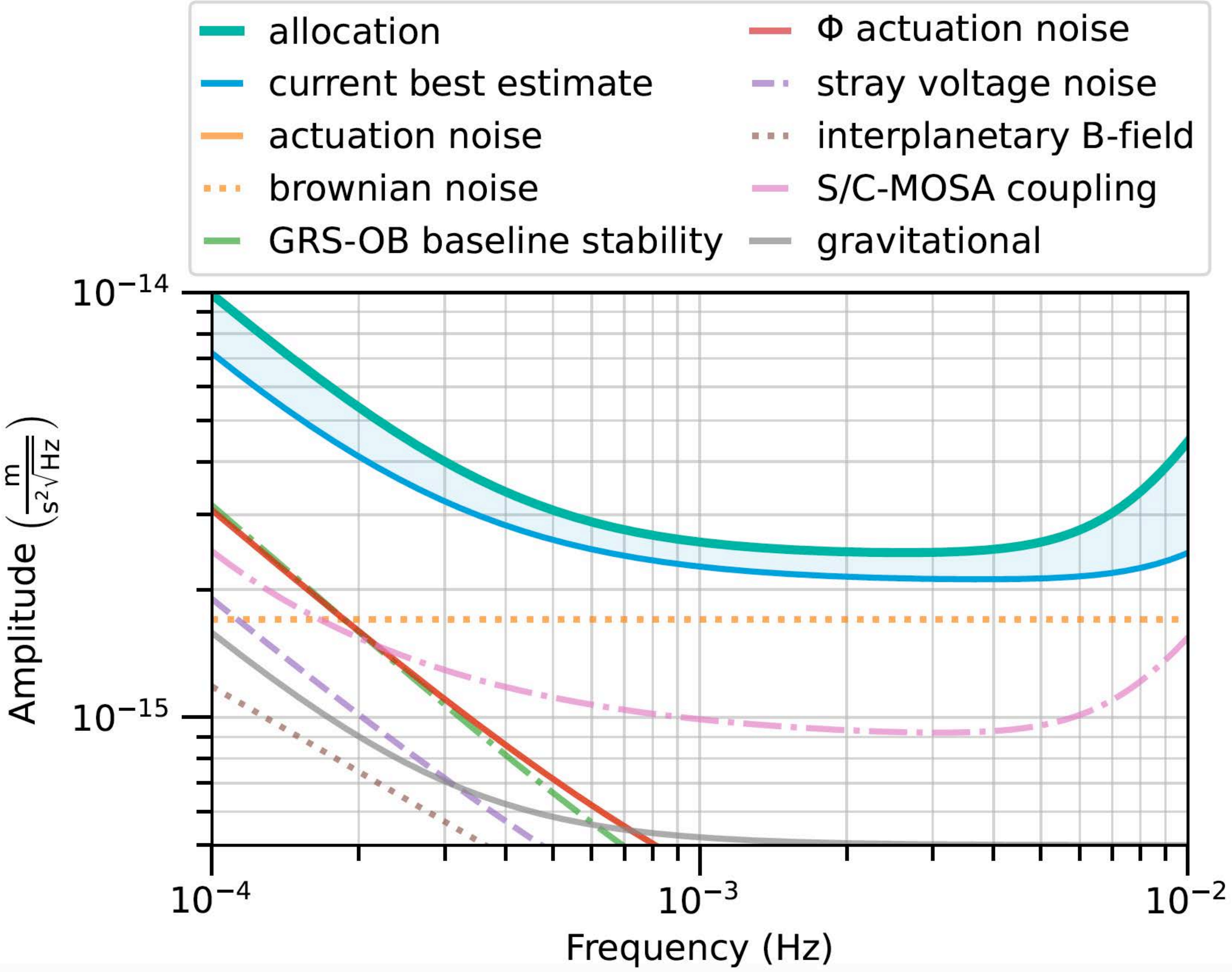
- *Will be mostly a rebuild of the LPF GRS*
- *Very well understood performance model*

Expected improvements:

- *Lower gas pressure —> lower Brownian noise*
- *Larger gaps —> lower Brownian noise*
- *Better S/C motion sensing*
  - *Potential for post-processing improvements*

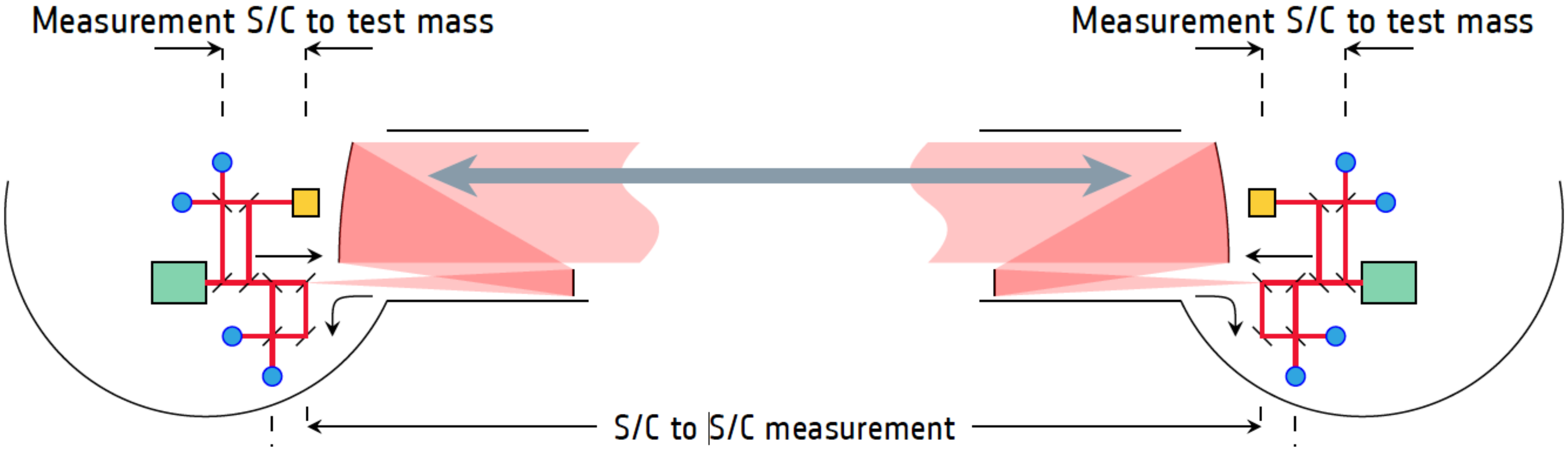
Additional challenges:

- *MOSA actuation*
  - *S/C-MOSA coupling via force gradients*
  - *Gravitational coupling*
- *Drag-free operation in 2-dimensions*



LISA Mission Concept

How do we measure the relative TM motion over 2.5Gm with the required sensitivity?



TMI: Test mass interferometer

- TM to OB distance
- Local interferometer
    - Similar to LPF

SCI: Science interferometer

- OB to OB distance
- pm-sensitivity over 2.5Gm
    - While S/C move by m/s

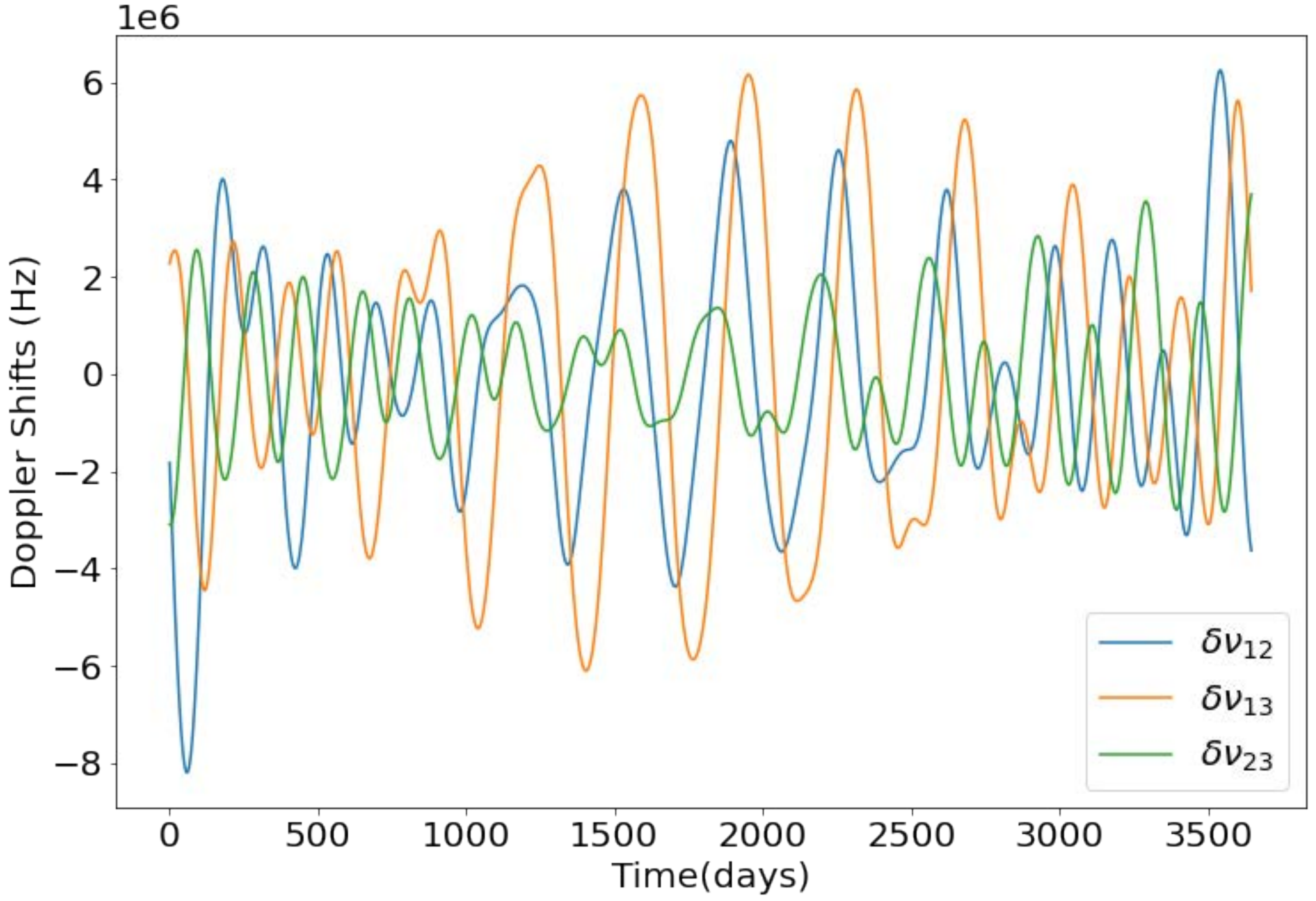
TMI: Test mass interferometer

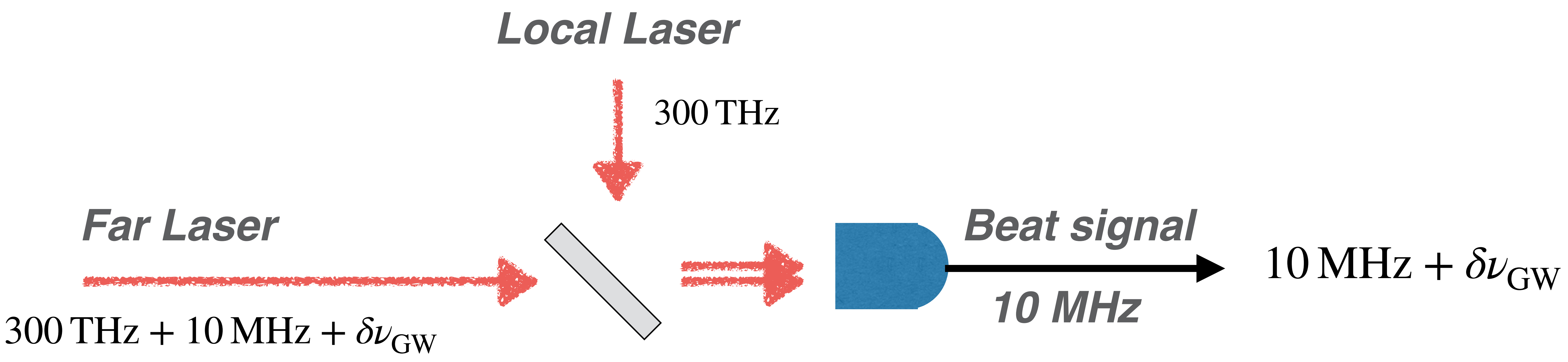
- TM to OB distance
- Local interferometer
    - Similar to LPF

LISA Mission Concept

LISA's magic orbits:

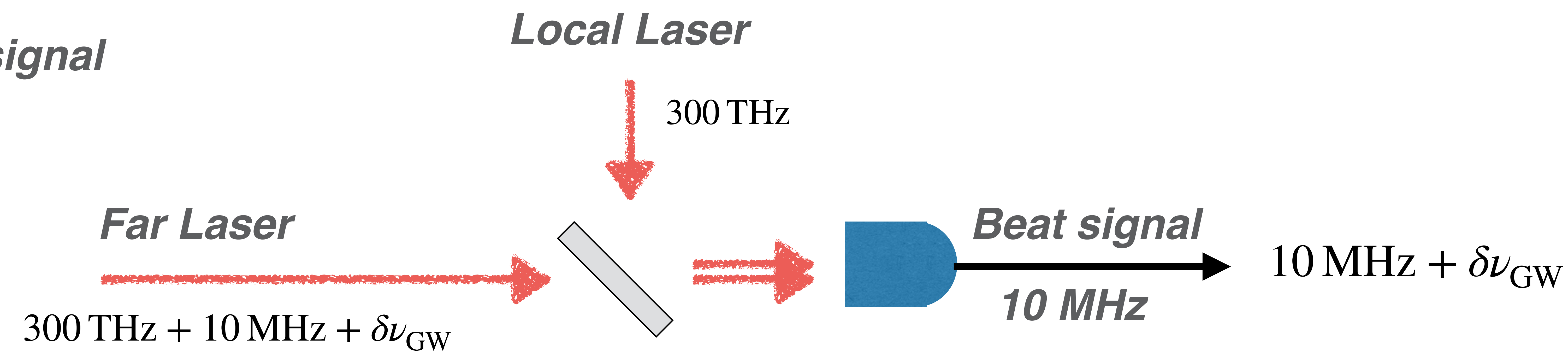
- *Maintain equilateral triangle* ***as much as possible*** *w/o station keeping*
    - ***Separation variation:*** $\approx 1\,\%$ ***, angular variation:*** $\pm 0.8°$
    - ***Relative speed between S/C:*** $< 10\,\mathrm{m/s}$ ($\approx 10\,\mathrm{MHz}$ Doppler shift)
        - ➡ ***Signal: Phase modulated laser beat signal***





LISA Mission Concept

- *Signal: Phase modulated laser beat signal*



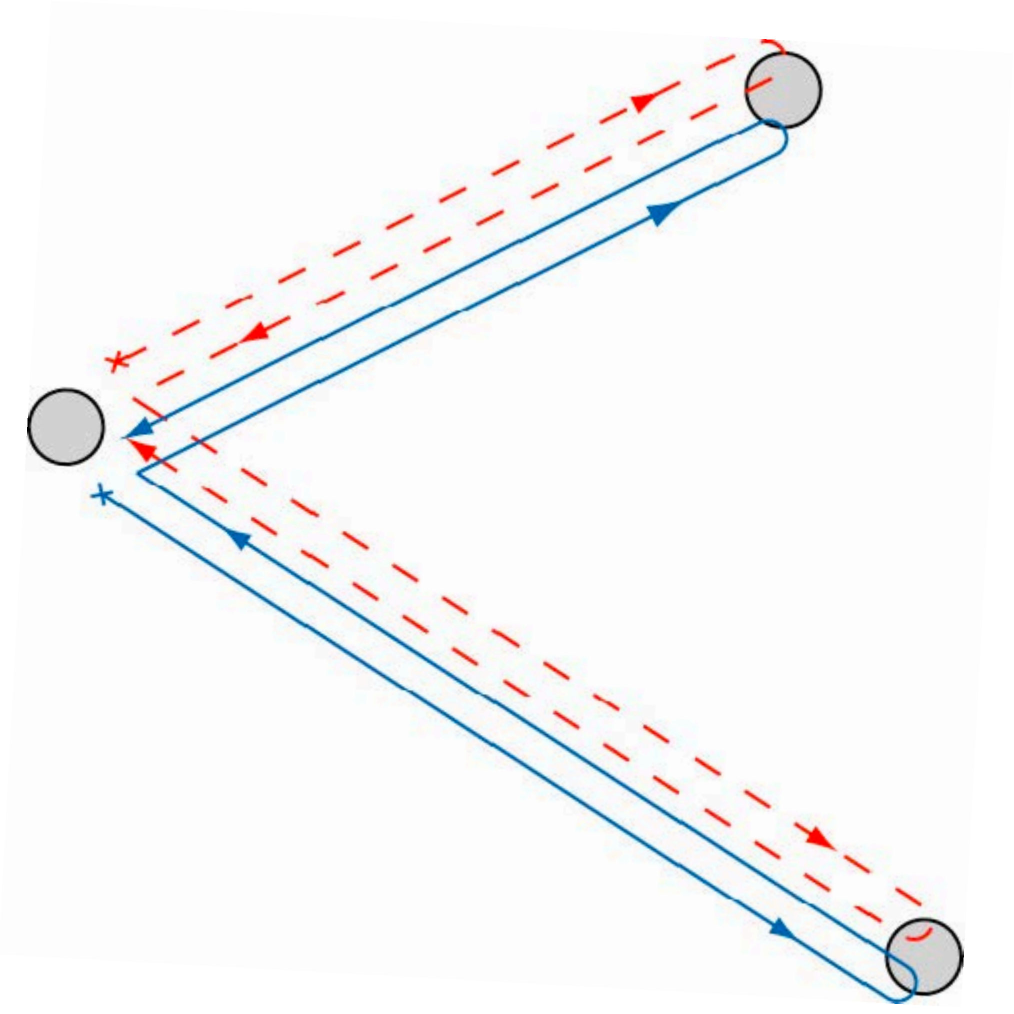
LISA is an unequal arm interferometer:

- *Limited by laser frequency noise*

$$\delta l_{\delta\nu} = \frac{\delta\nu}{\nu}\Delta L$$

Solution:

- *Create artificial equal arm interferometer*
  - *Time Delay Interferometry (TDI)*

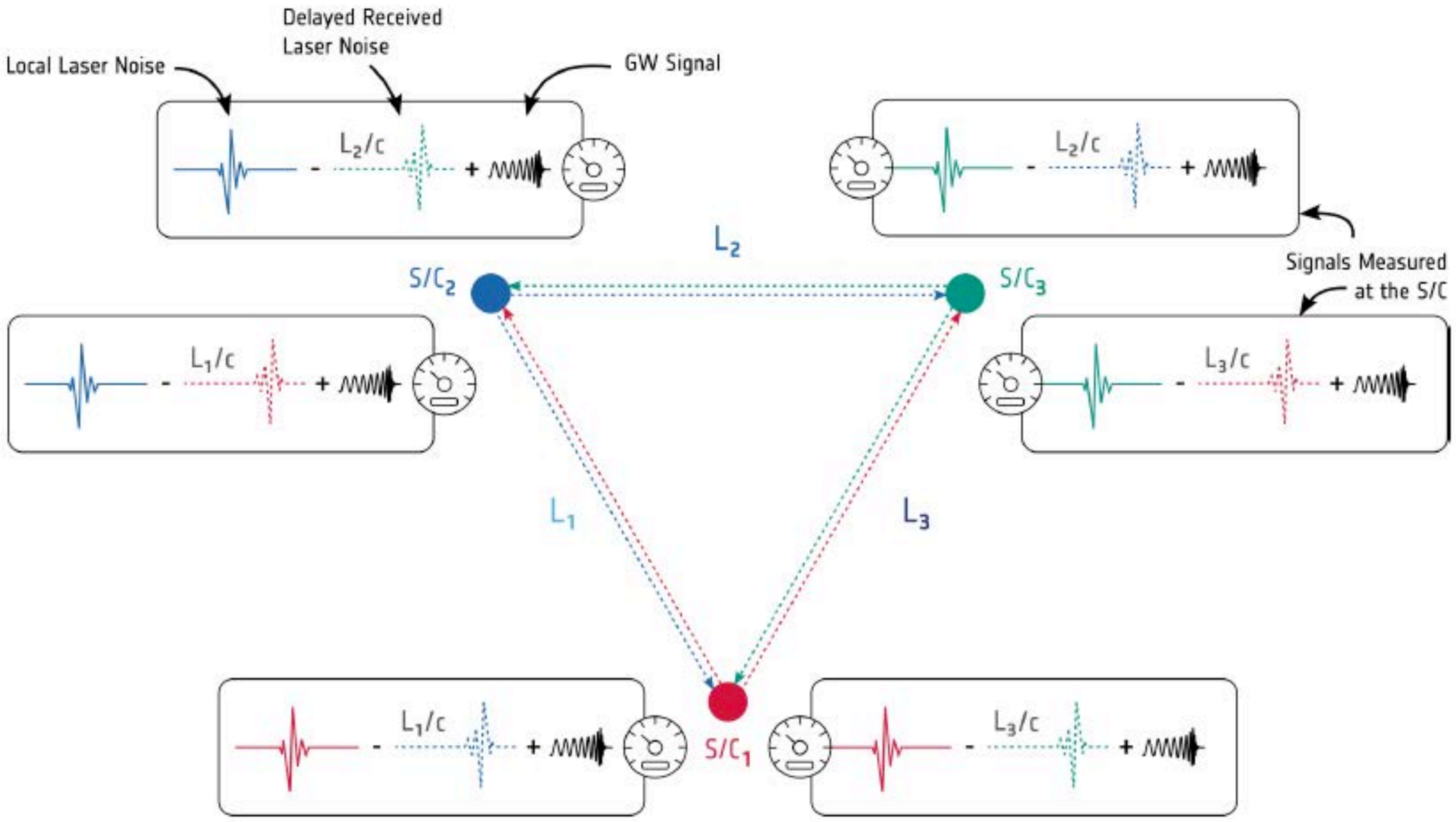


LISA Mission Concept

Time delay interferometry:

- *LISA measures laser beat signals:*
  - *Measures same laser noise locally twice and - delayed - on both far S/C*
- *LISA times these measurements with 3ns = 1m accuracy relative to each other*
- *On ground: Form linear combinations between up-sampled and time-shifted data streams which cancel laser noise*
- *Artificial equal-arm interferometer:*

$$\delta l_{\delta\nu} = \frac{\delta\nu}{\nu}\Delta L = \frac{30\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}}{300\,\mathrm{THz}} 1\,\mathrm{m} = 10^{-13}\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$$

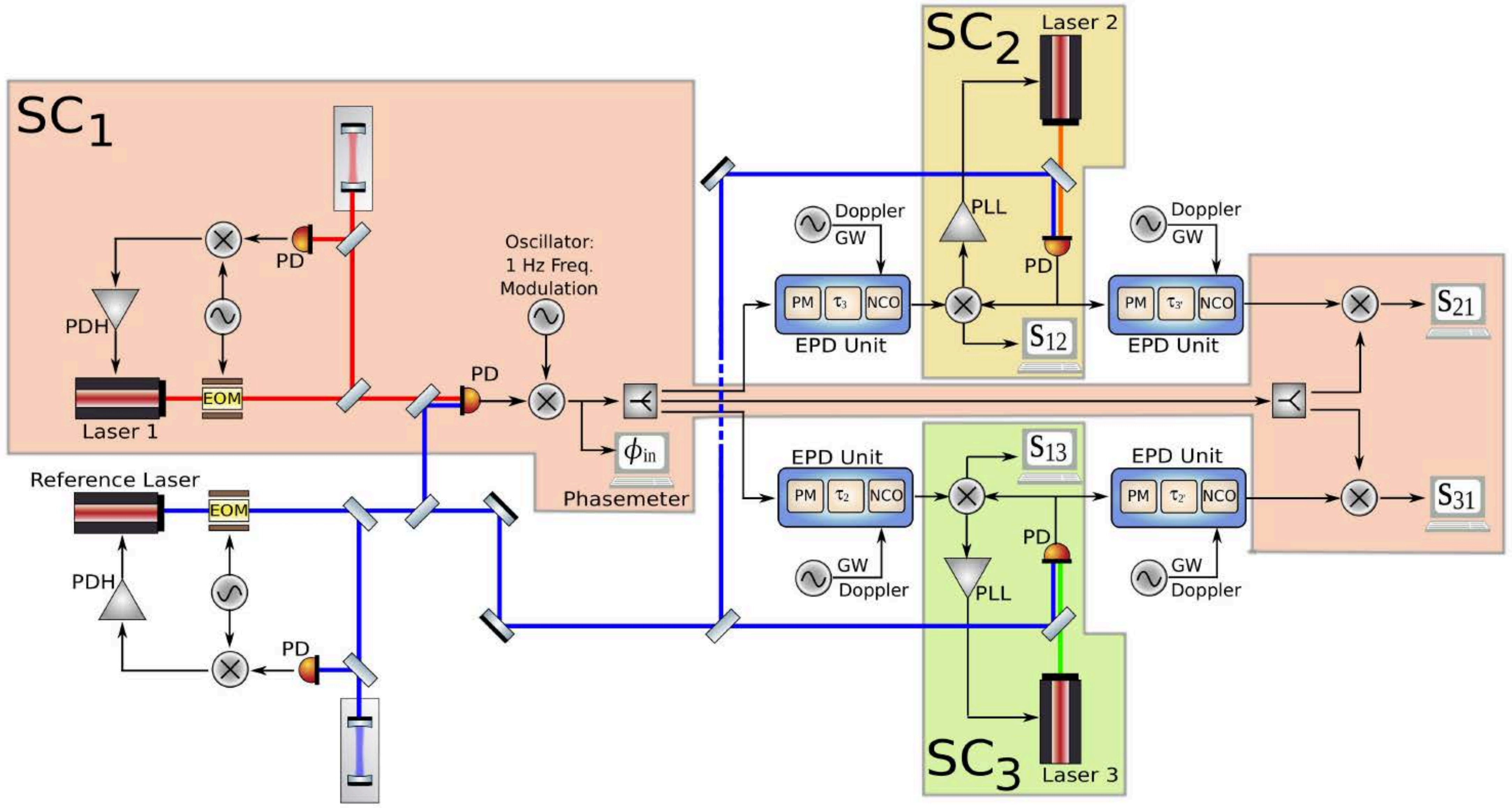


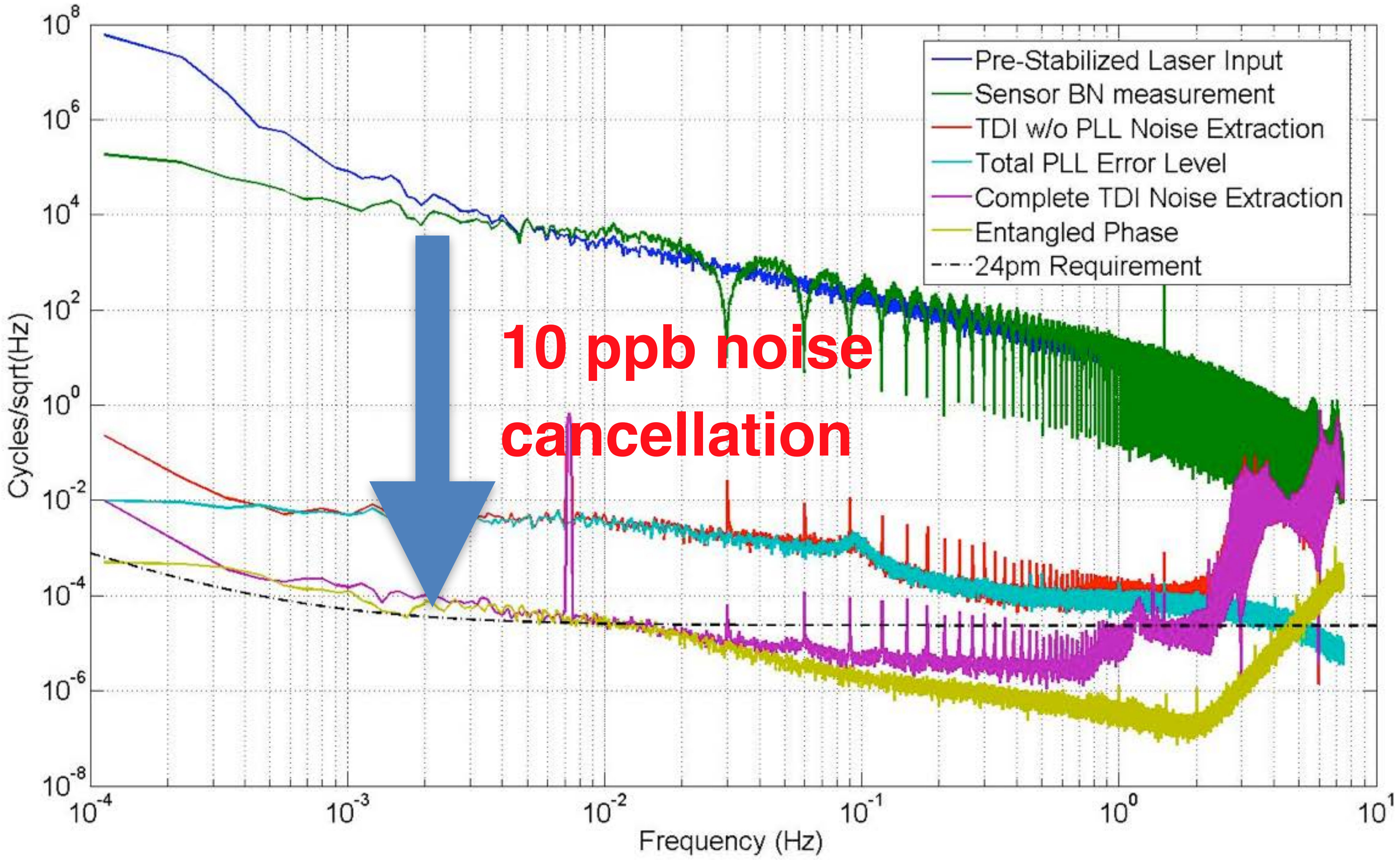
LISA is a laser interferometer but also a timing experiment!

LISA Mission Concept

UF: LISA Testbed 2012

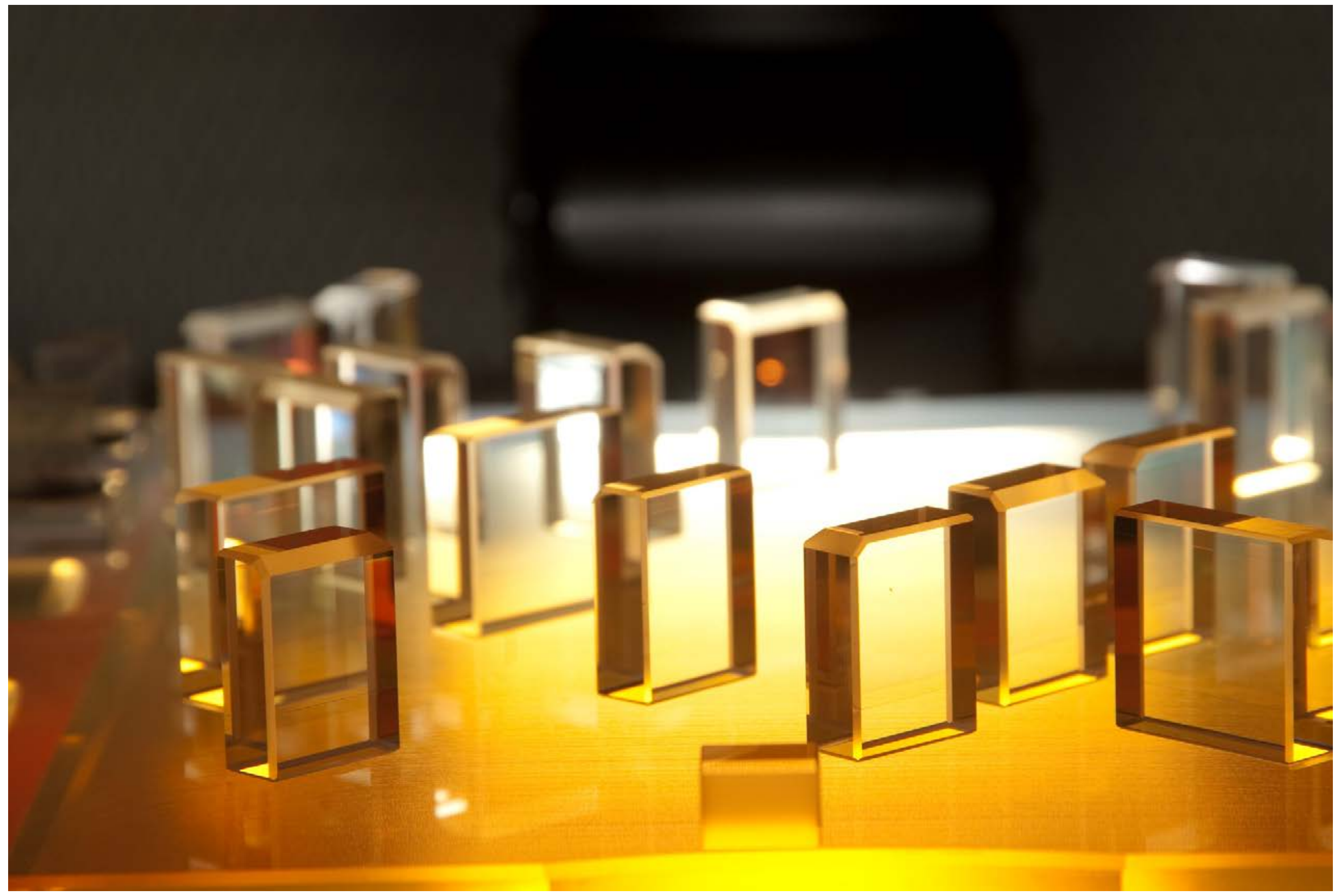
- *Demonstrated TDI in an electro-optical experiment with 16s (faked-) light travel times (old LISA: 5Gm)*
- *Nearly reached LISA requirements in 2012 (limited by timing jitter in ADCs)*

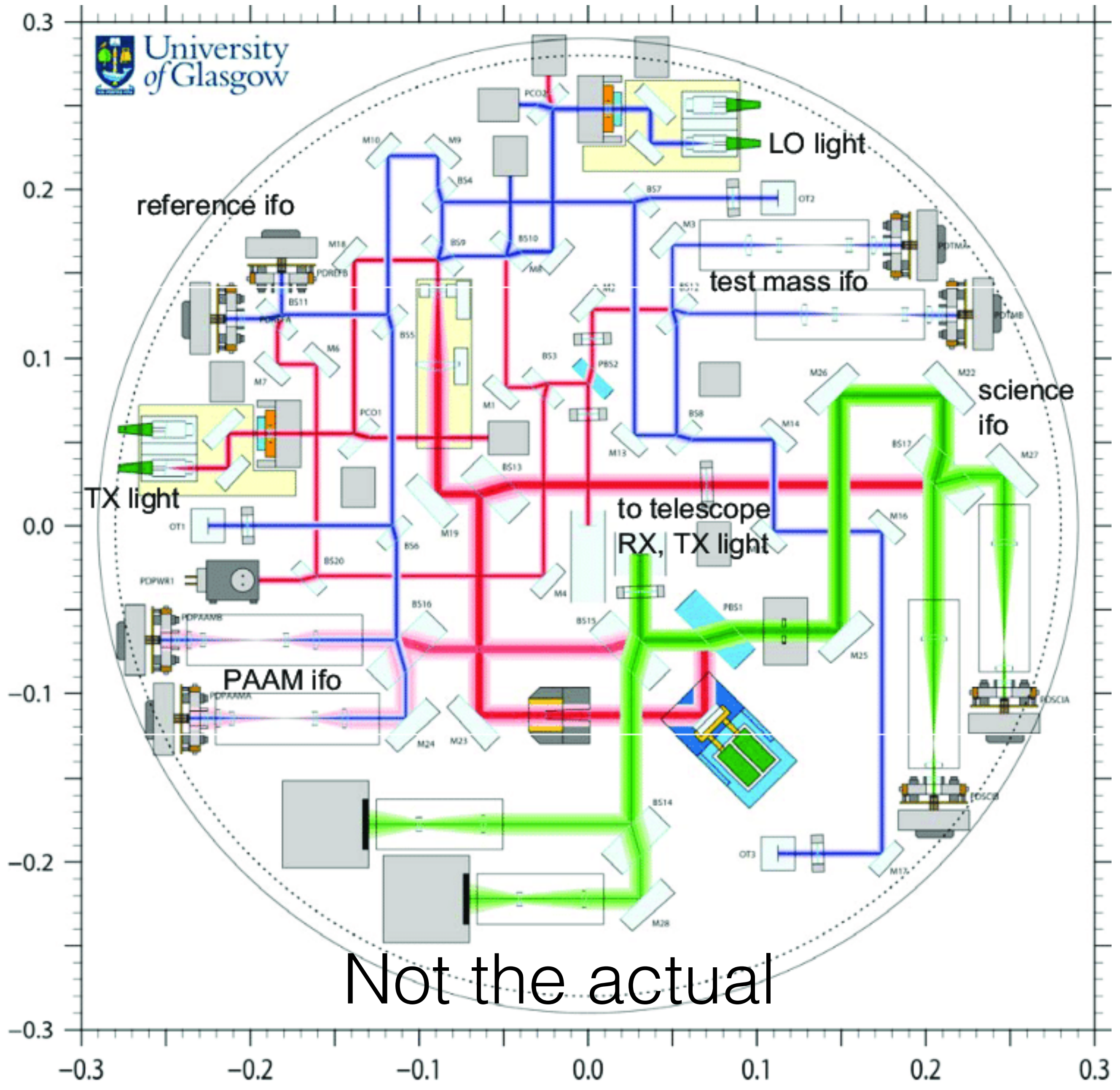


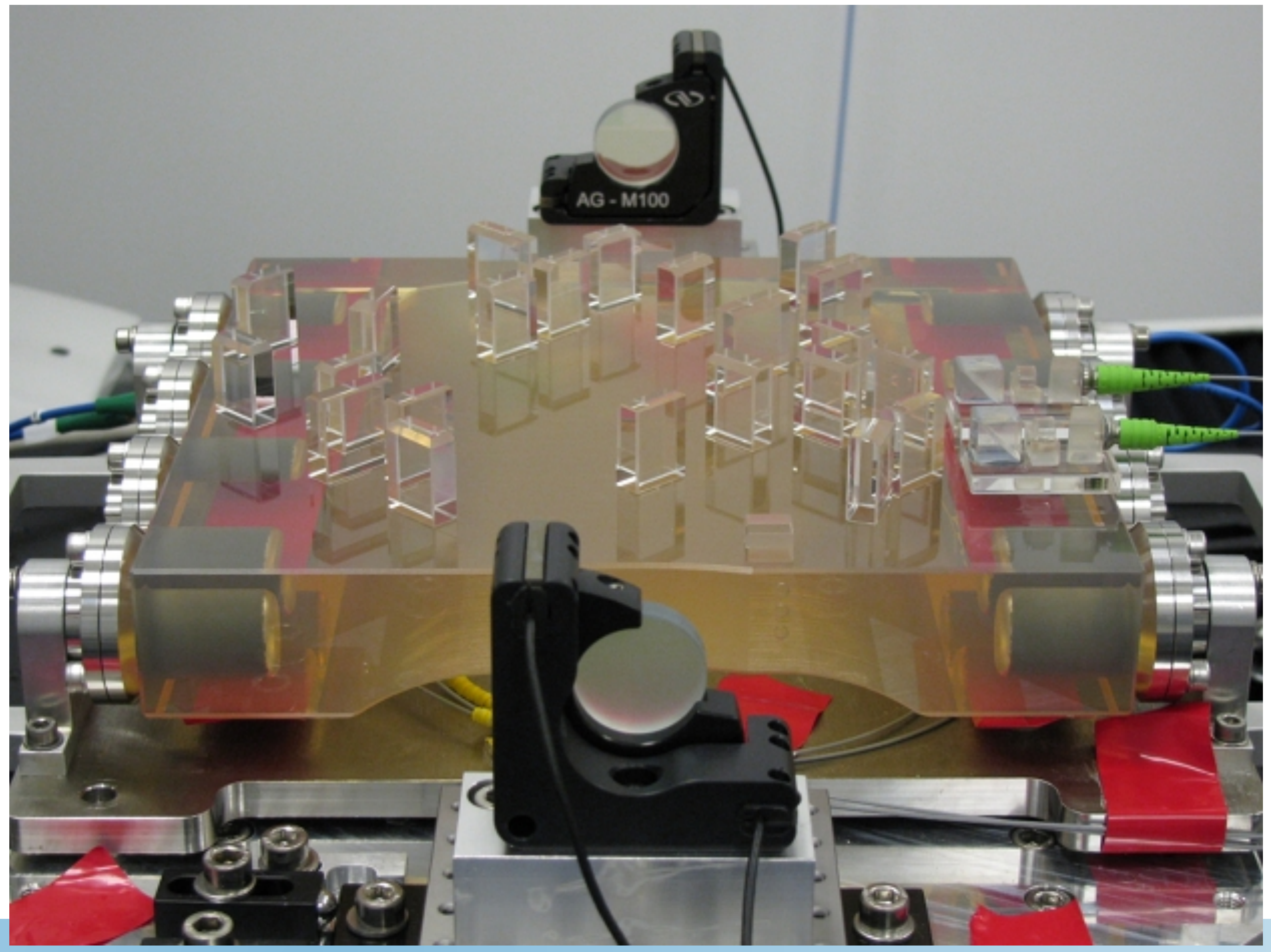


LISA - Mission Concept

- *Optical Bench:*
  - *All mirrors/beam splitters hydroxide bonded with* $< 10\,\mu\mathrm{rad}$ and $10\,\mu\mathrm{m}$ *precision on Zerodur baseplate*
  - *Larger version of LPF bench*
  - *Includes: QPDs, PAAM, BAAM, FSU, CAS, BL, …*
  - *Optical interfaces with Telecope and Test mass*



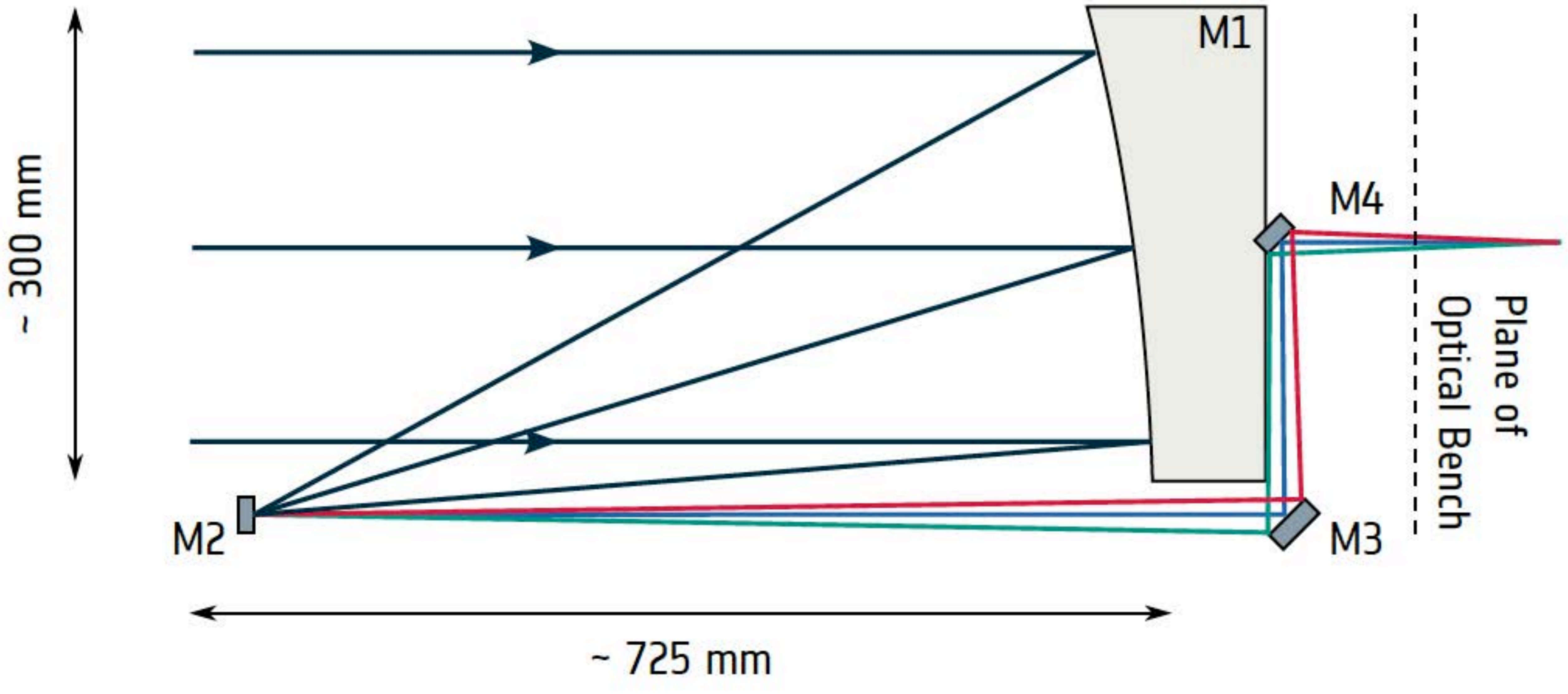


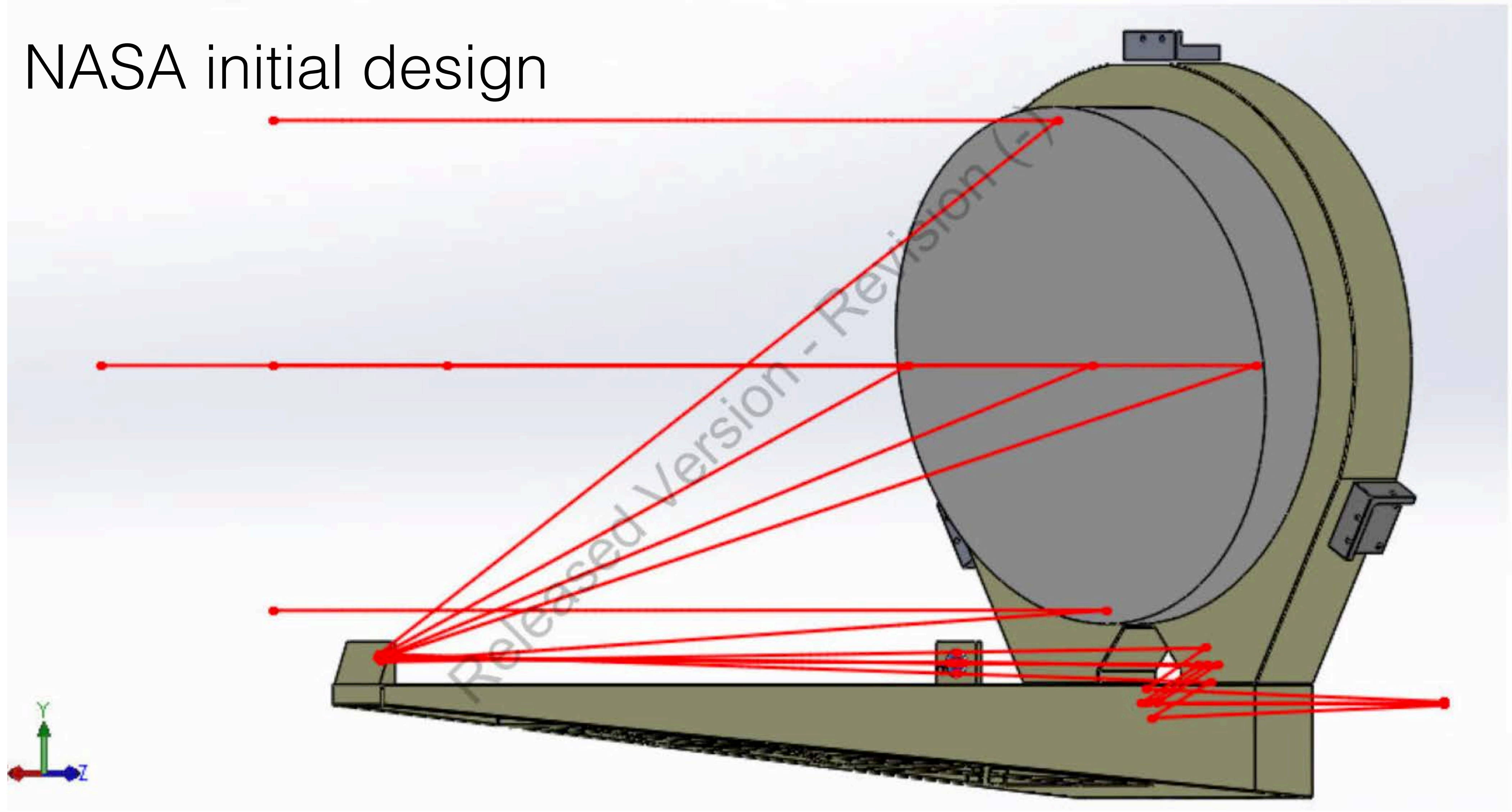


LISA - Mission Concept

30 cm off-axis telescope

- *Magnification: 134*
- *30cm Primary, few cm beam sizes on M2, M3, M4*
- *on axis beam exchange with OB*
- *Wavefronterror < 30 nm*
- *Optical path length variations < 1 pm/√Hz*





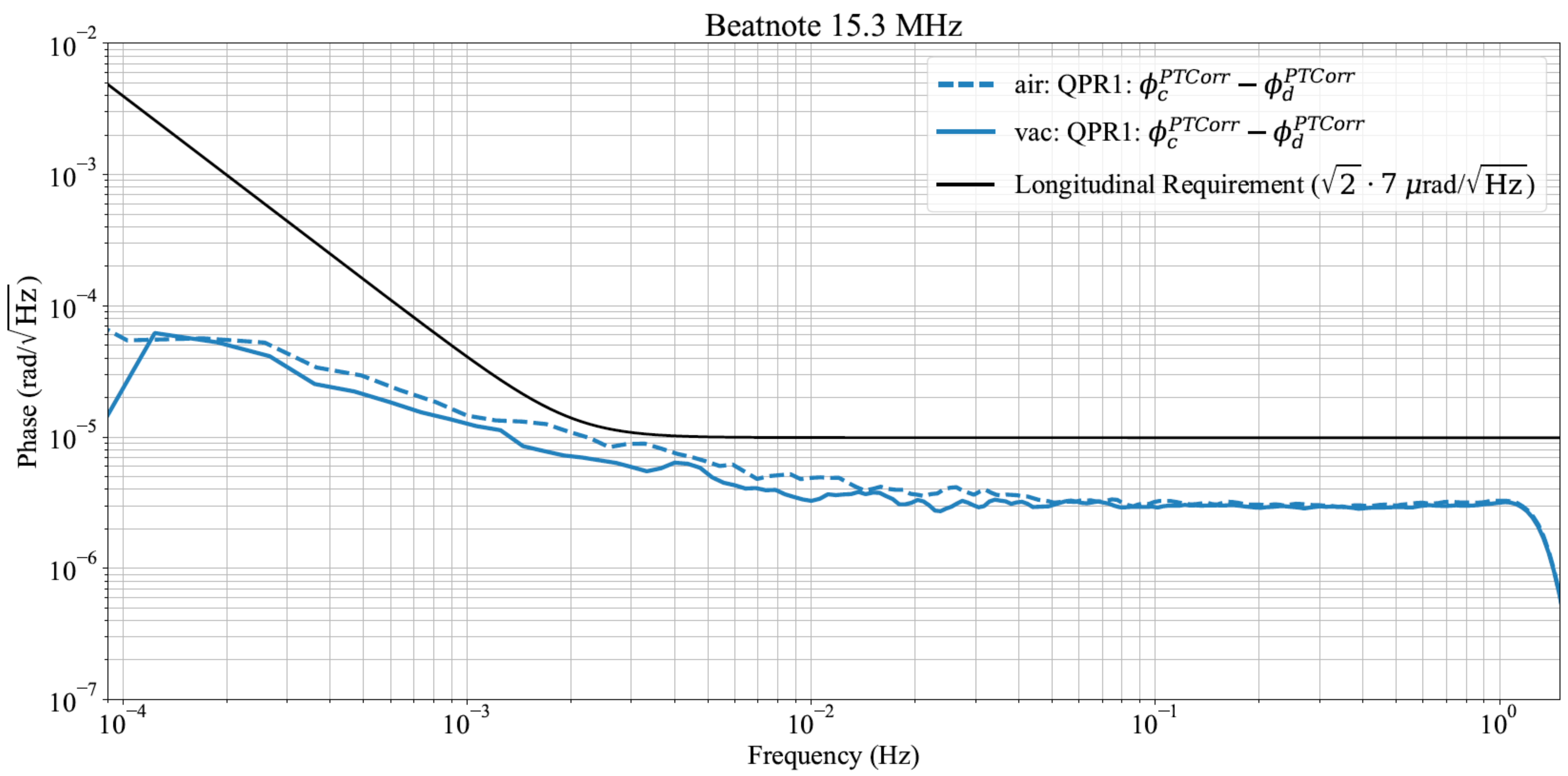
Prototypes:

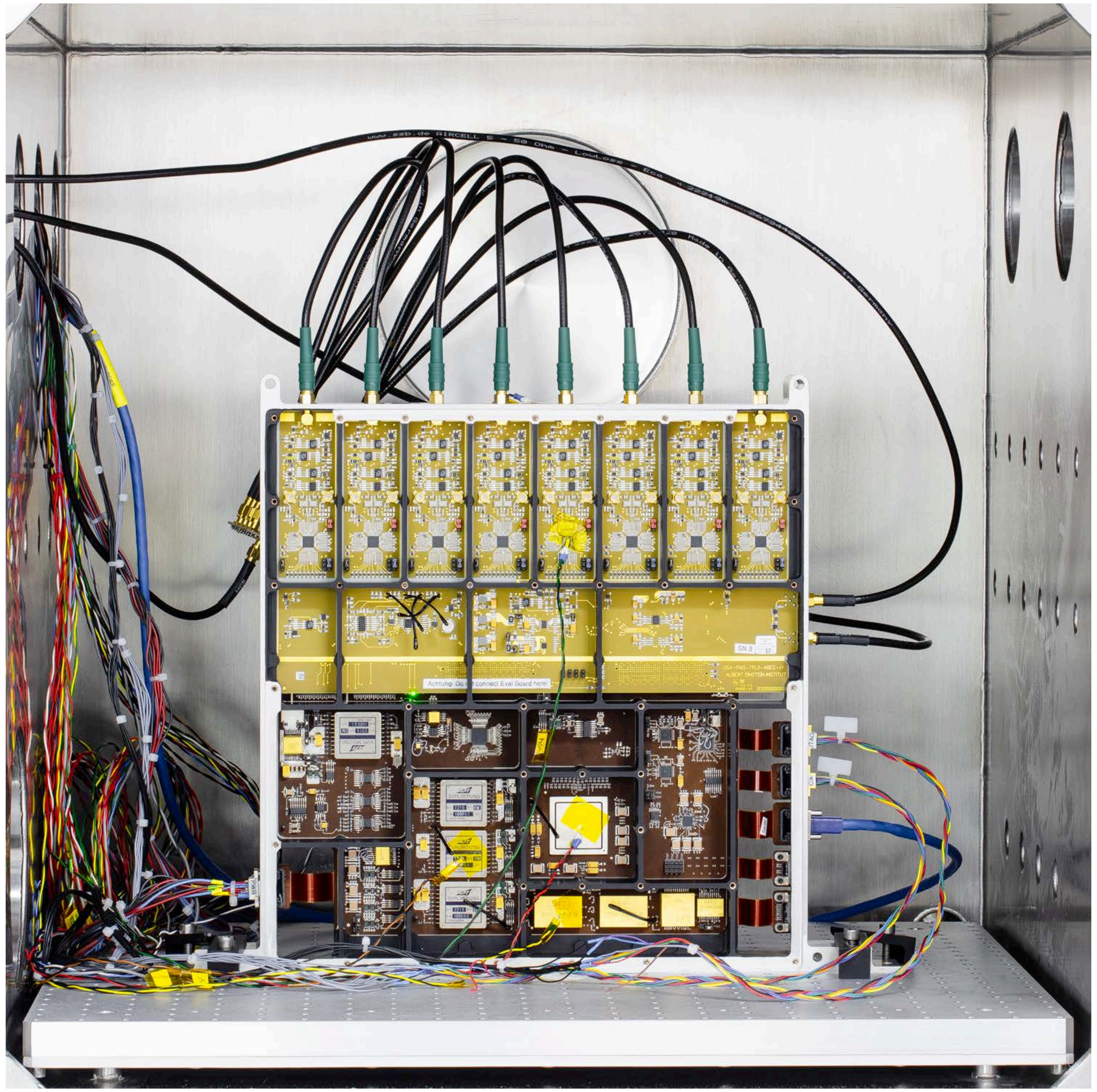
- Structural Thermal Model (STM) currently tested at University of Florida for
  - sub-pm stability
  - Effective CTE
- Engineering Development Unit (EDU)
  - Nearly finished
  - Soon to be delivered to GSFC/NASA

LISA - Mission Concept

Additional payload items

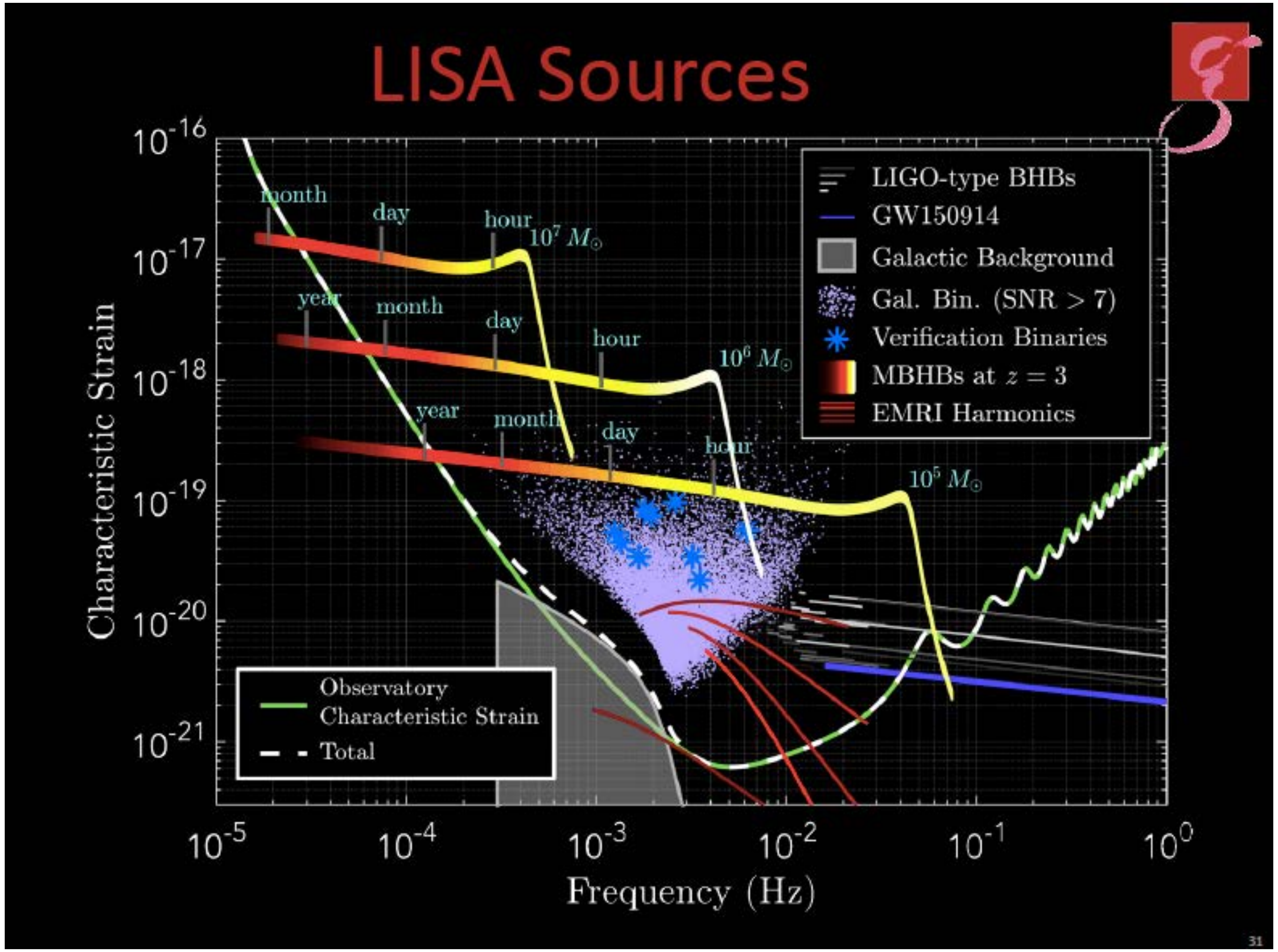
- *2 Laser systems: 2W, 1064nm (US)*
  - *fiber connected to OB*
- *Phase Measurement System (PMS)*
- *Environmental Sensing system*
- *…*





Phasemeter Prototype

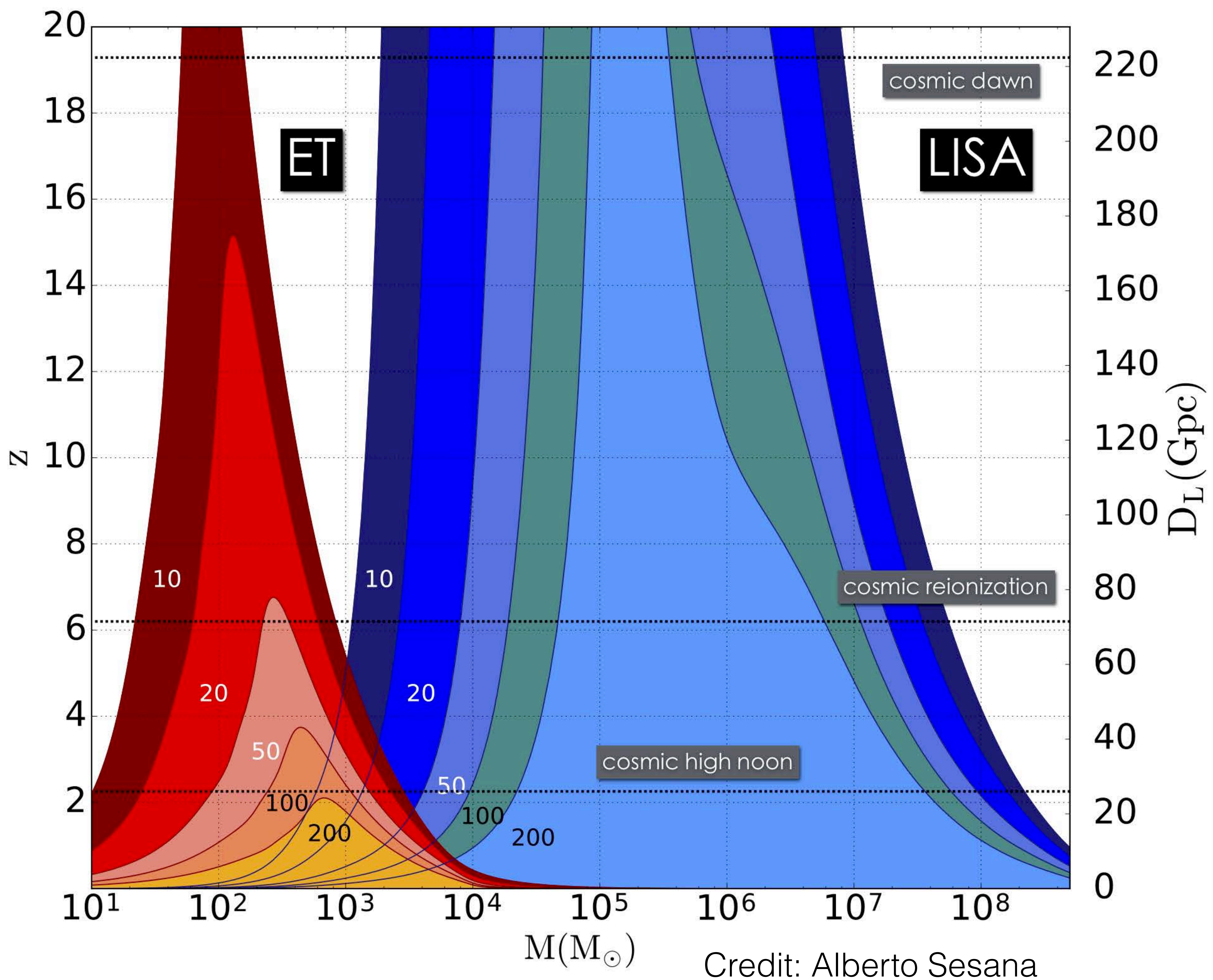
LISA - Scientific Goals



- *Compact galactic binaries:*
  - *Study formation and evolution*
  - *Distribution within Milky Way Galaxy*

- *Massive Black Hole Binaries*
  - *Trace their origin, growth and merger history across cosmic epochs*
  - *Study growth mechanism of MBH dating back to earliest quasars*
  - *Search for see black holes at cosmic dawn*

LISA - Scientific Goals



Credit: Alberto Sesana

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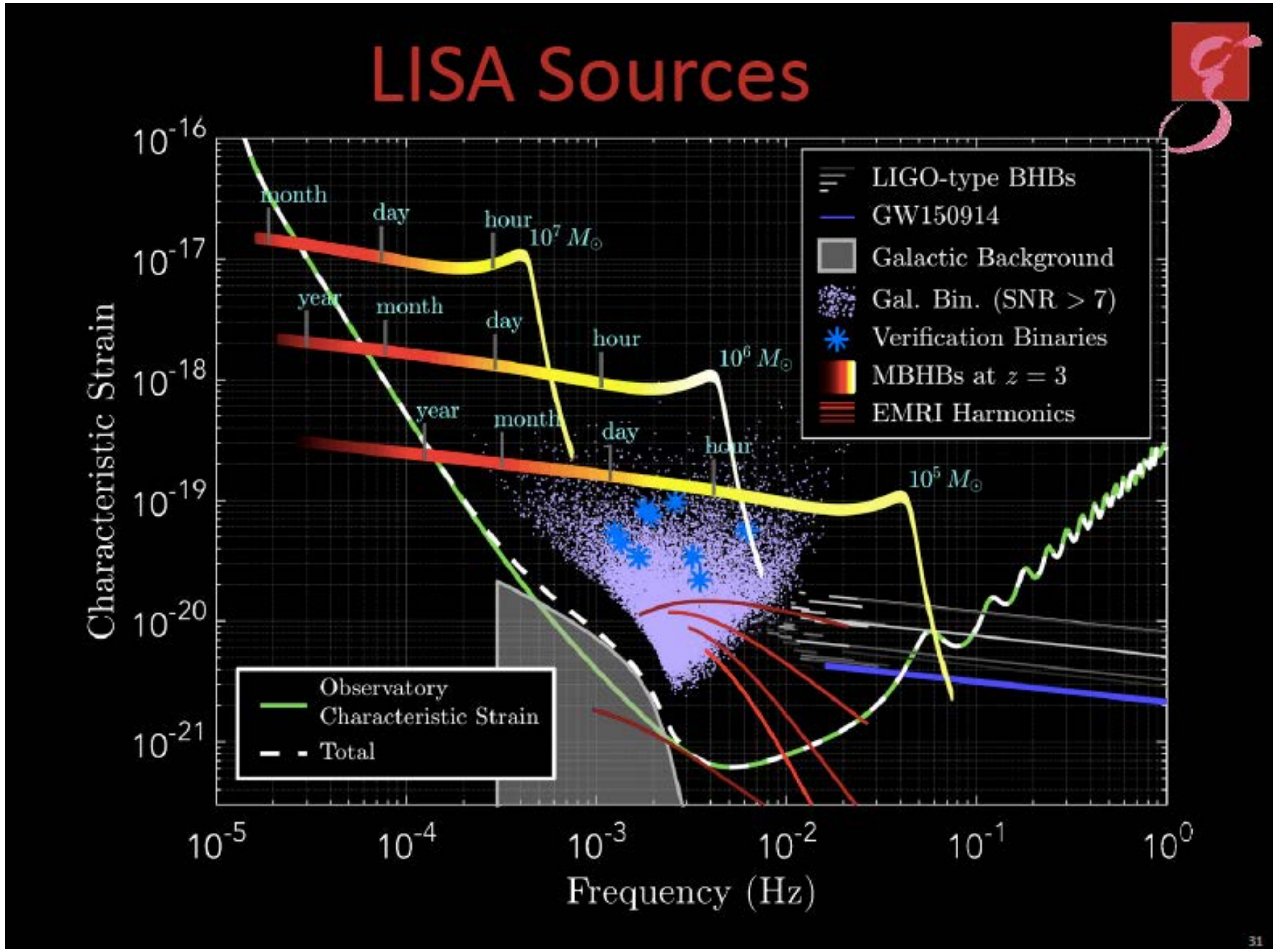
LISA - Scientific Goals



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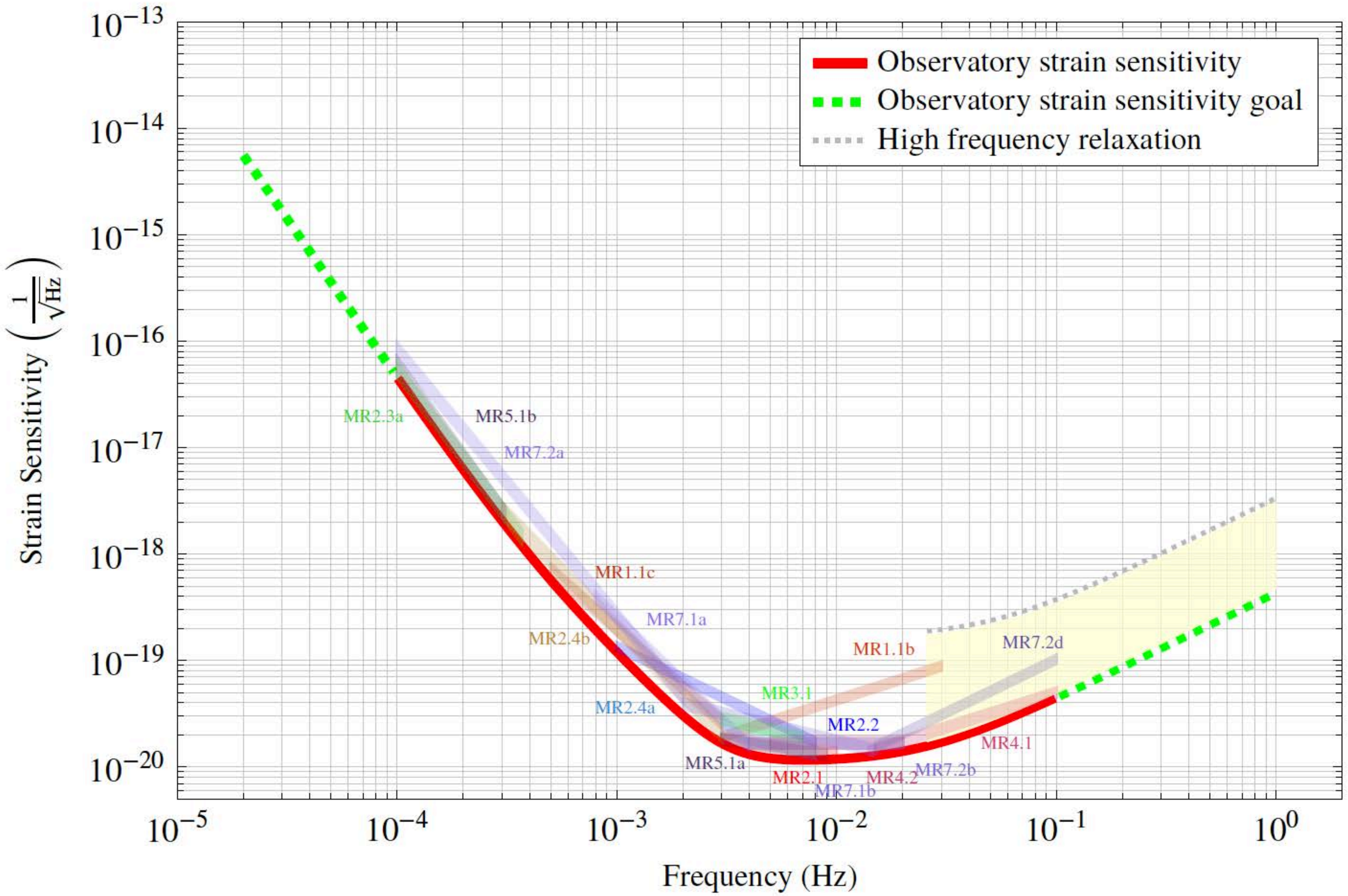
  - *Search for see black holes at cosmic dawn*
- *Extreme and intermediate mass-ratio inspirals*
  - *Probe the properties and immediate environments of black holes in the local Universe*
- *Probe the rate of expansion of the Universe with standard sirens (Multi-messenger astronomy)*
- *Stochastic gravitational wave background*
  - *Early Universe and TeV-scale particle physics*
- *….*

LISA - Scientific Goals

Science Requirements Document (SRD)

- Defines science requirements in terms of
  - Strain sensitivity
  - Duty cycle
  - GW - Polarisation
  - Mission lifetime (4.5 yrs of science, ext: 10 yrs)
  - Data Products
  - …
- Links them to scientific investigations/studies
  - Led initially by LISA Science Team
    and it's working groups



Governing Document:

- Violations of the SRD can lead to reassessment of LISA

Project Status

Implementation Schedule – ESA Major Milestone Dates – Proposed (TBC)

esa

Review	Date	Instrument Level
Adoption	25. January 2024	
Prime Kick-Off	Oct/Nov 2024	
Mission SRR (after co-engineering)	April 2025	Q2/2023
Mission PDR	Nov 2027/Feb 2028	TBD
Mission CDR	January 2031	Q4/2027
Target for Launch	2035	

- LISA Adoption during ESA-SPC January meeting
- Following adoption, the LISA Science Team (LST) will be selected
  - LST is expected to set up working groups which target specific science investigations
  - LISA Consortium will be heavily involved in scientific work
    - LISA Consortium Is currently being restructured to adapt to new structure