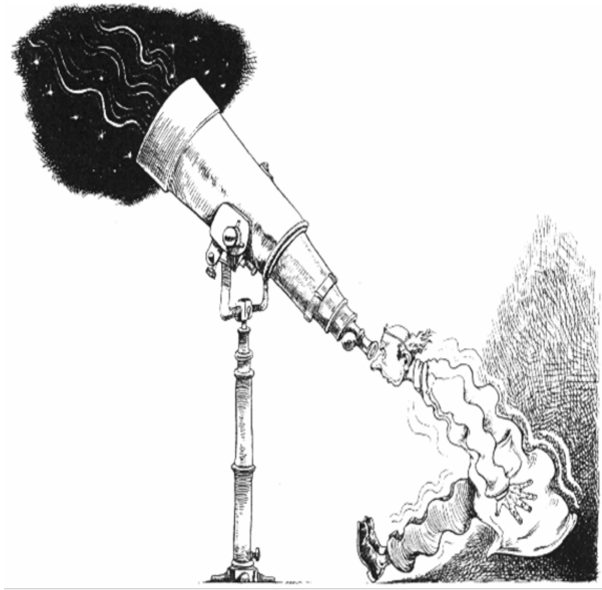
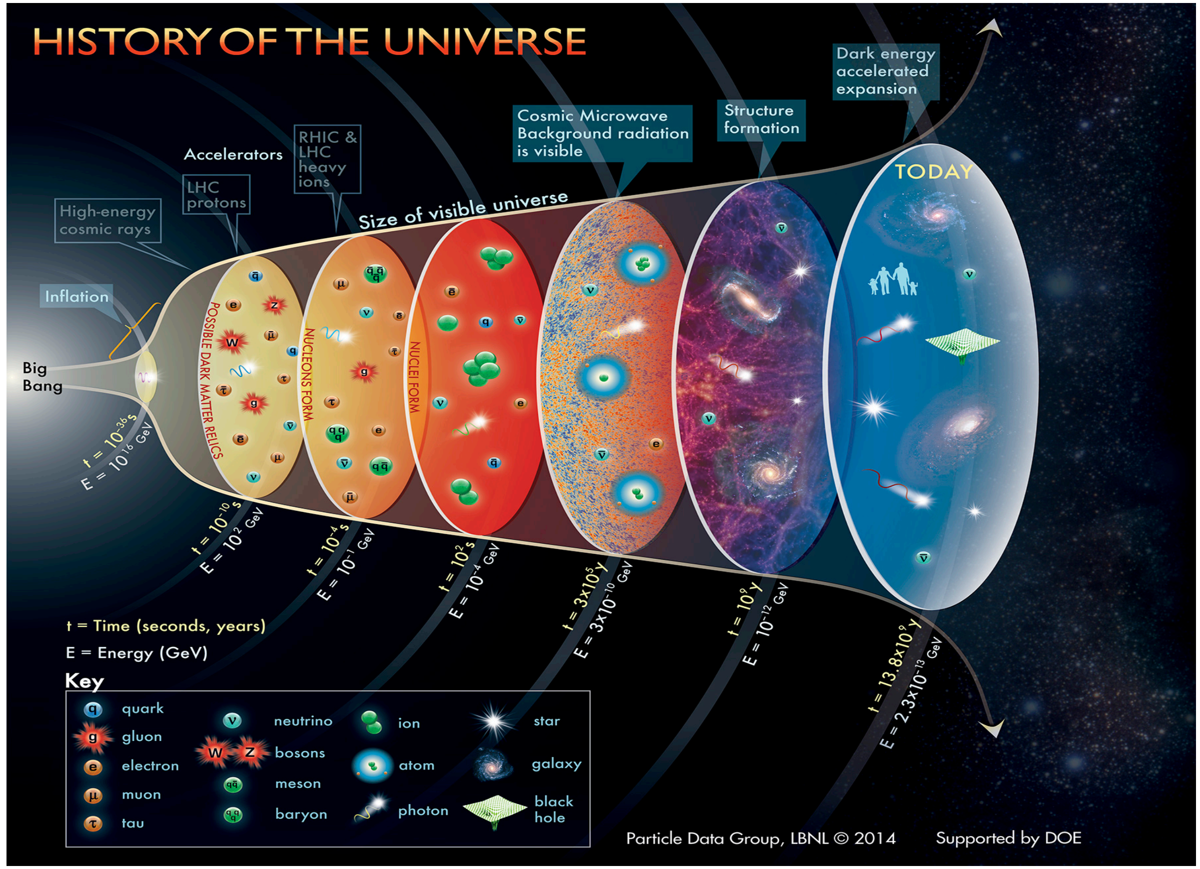
Detectors
and their
Science Goals



Kostas Kokkotas

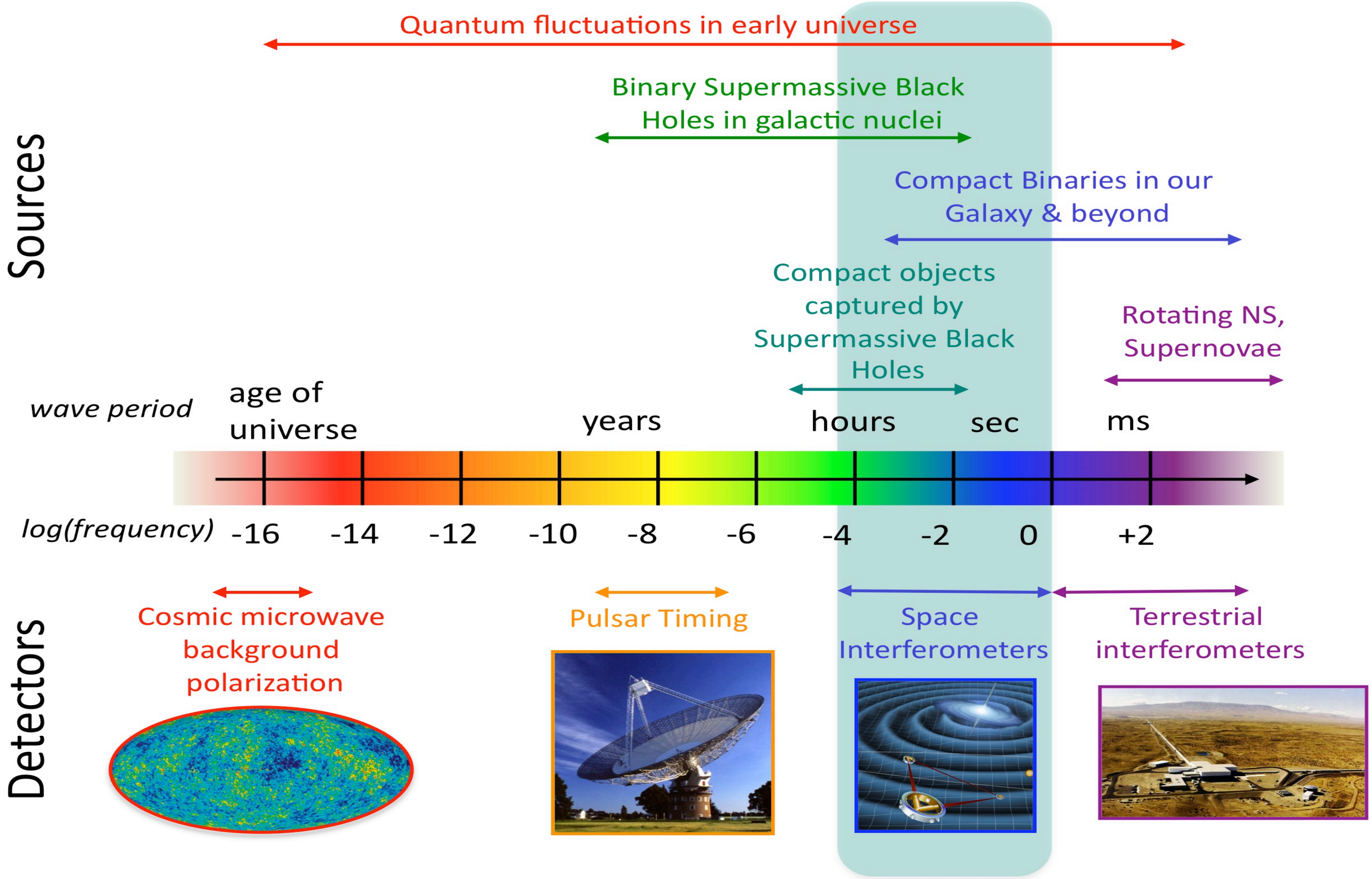
THE "STORY" OF THE UNIVERSE…

…WAS ALWAYS VIOLENT

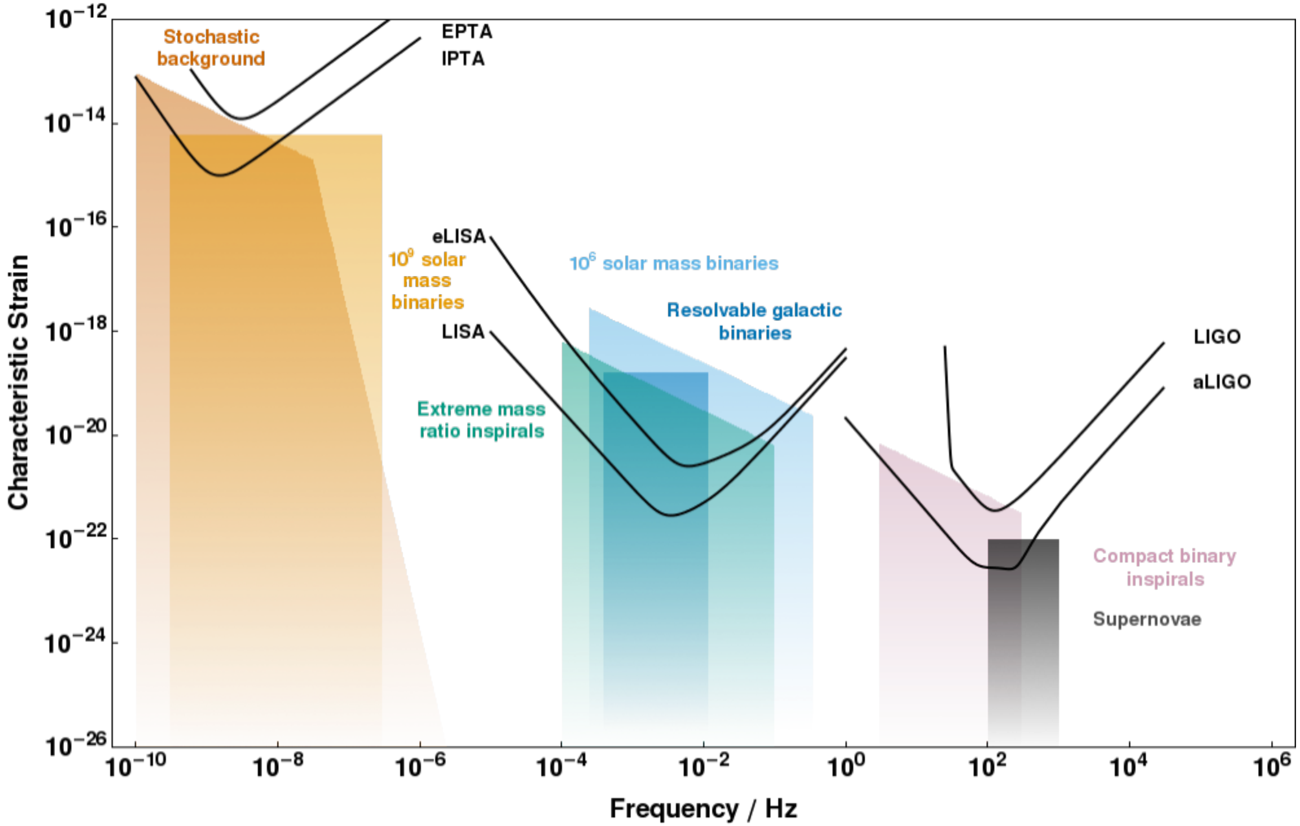


VIOLENT PHENOMENA ARE ALWAYS ASSOCIATED WITH THE EMISSION OF GRAVITATIONAL WAVES

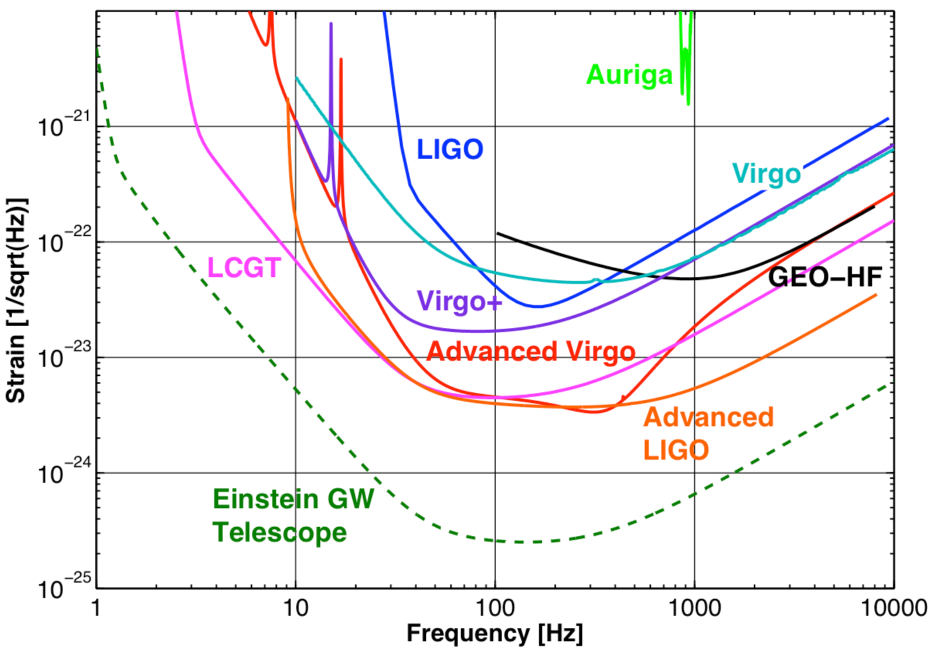
The Gravitational Wave Spectrum

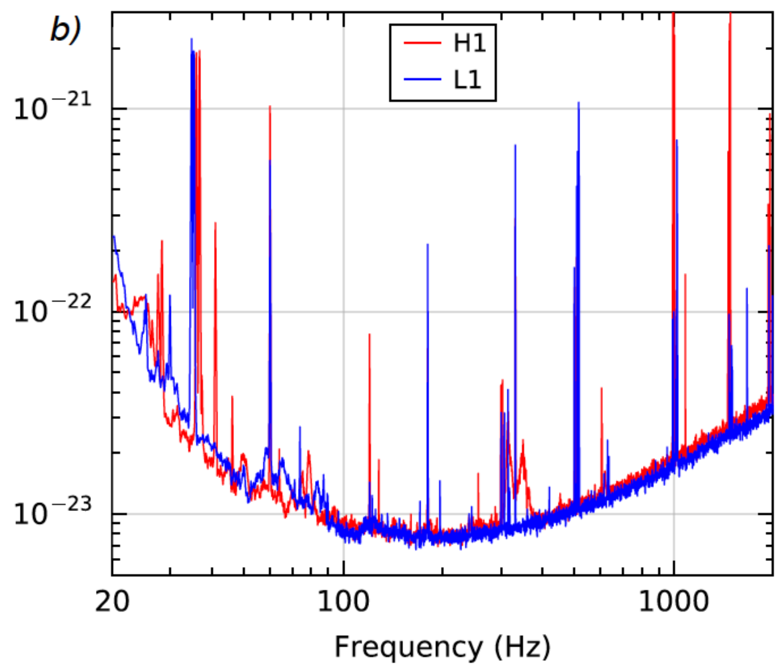


ΑΝΙΧΝΕΥΤΕΣ σ’ όλο το ΒΑΡΥΤΙΚΟ ΦΑΣΜΑ

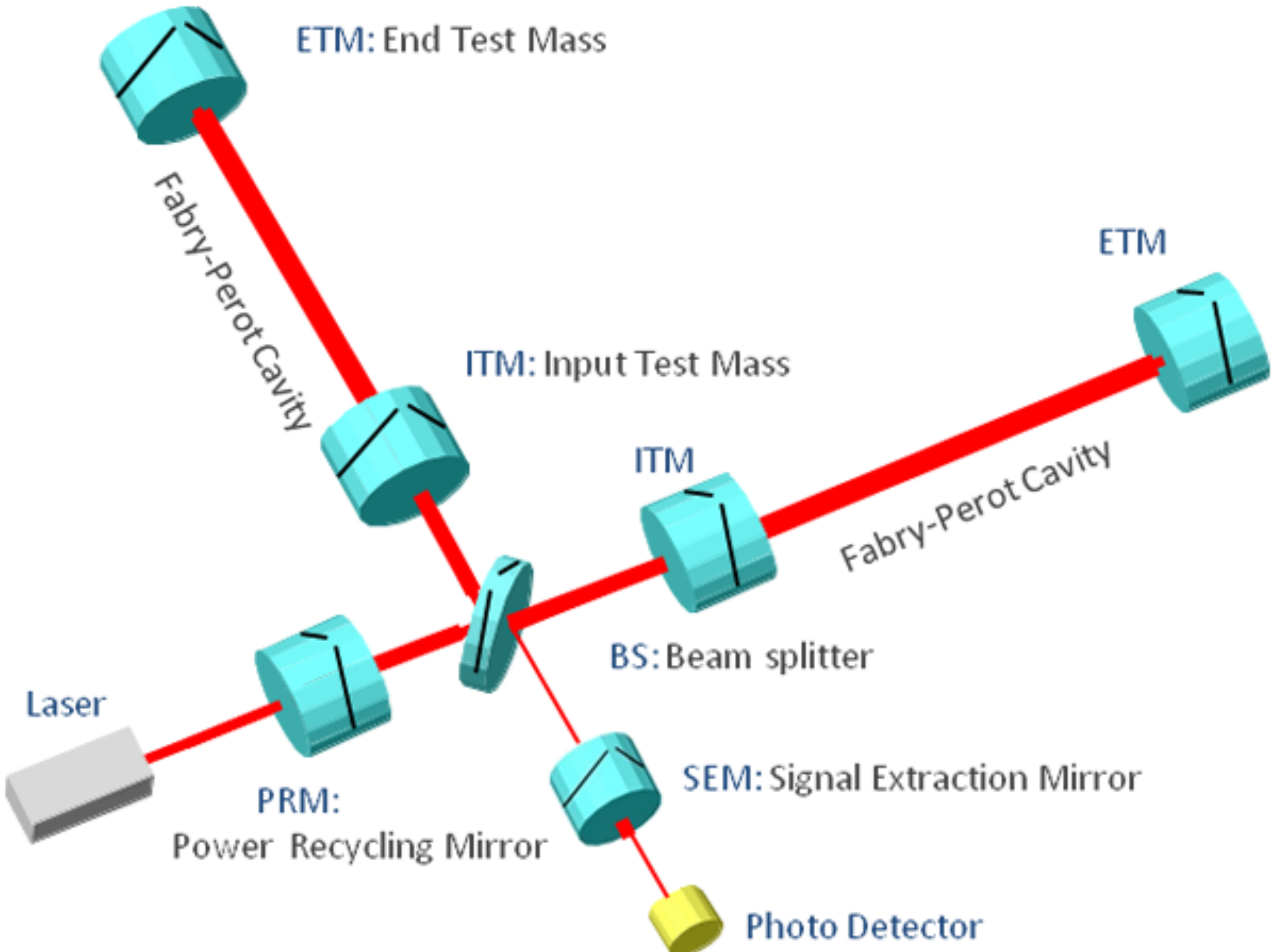


Detector Sensitivity



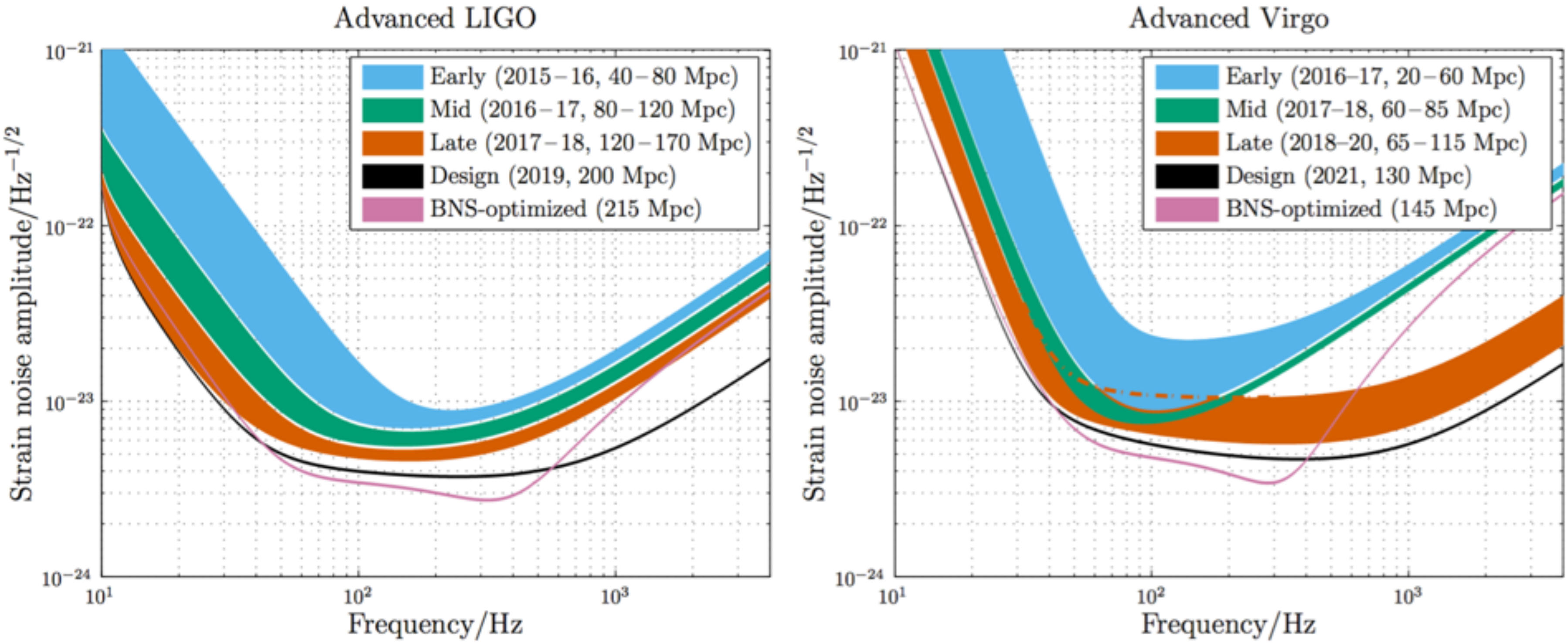


Interferometers



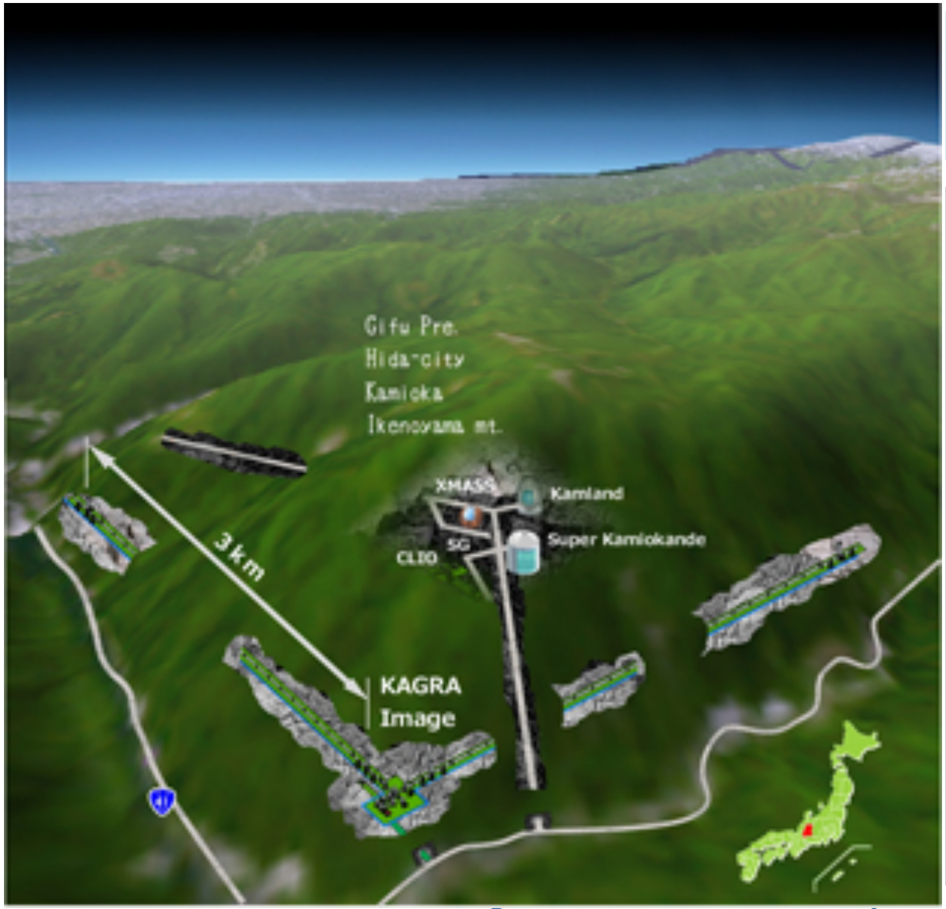
Immediate Future

Detector Sensitivity for Binary Neutron Star Mergers



KAGRA

Large-scale Cryogenic Gravitational-wave Telescope



The construction has started in April 2012.

- KAGRA consists of a modified Michelson interferometer with two 3-km long arms, located in the ground under Kamioka mine.
- The mirrors are cooled down to cryogenic temperature of -250 Celsius degree (20 Kelvin). Sapphire is chosen for the material of the mirror.

INDIGO

The Indian Initiative in GW Observations

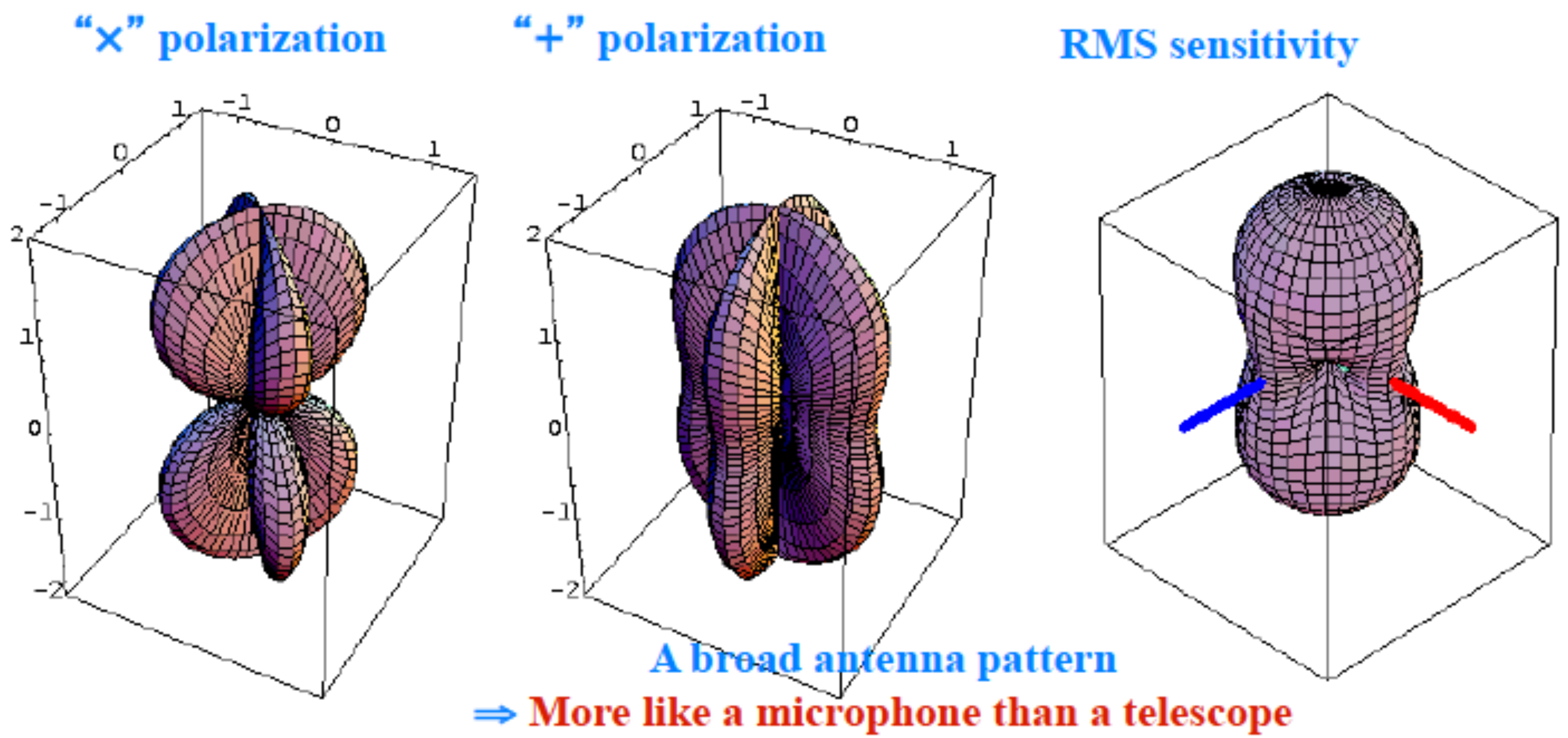
A week after the announcement of GW discovery the Indian Government approved the project ($205m in 10years)

Antenna Pattern of a Laser Interferometer

The strain x(t) measured by a detector is mainly dominated by noise n(t), such that even in the presence of a signal h(t) we have

$$x(t) = n(t) + h(t) \quad \text{where } h(t) = F_+(t;\psi)h_+(t;\psi) + F_\times(t;\psi)h_\times(t;\psi)$$

F_+ and **F_x** are the strain antenna patterns. They depend on the orientation of the detector and source and on the polarization of the waves



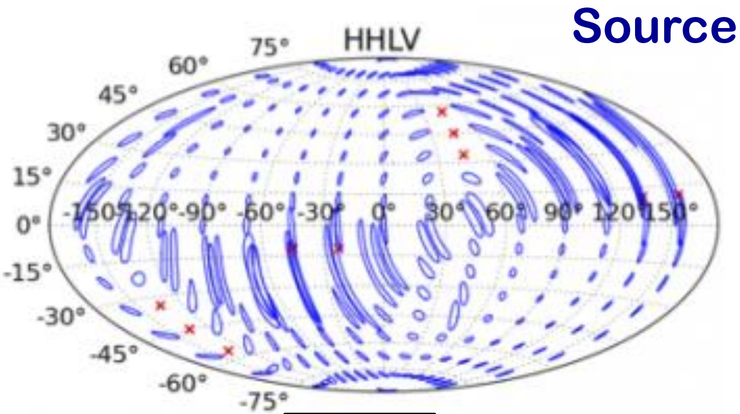
Multiple Detectors



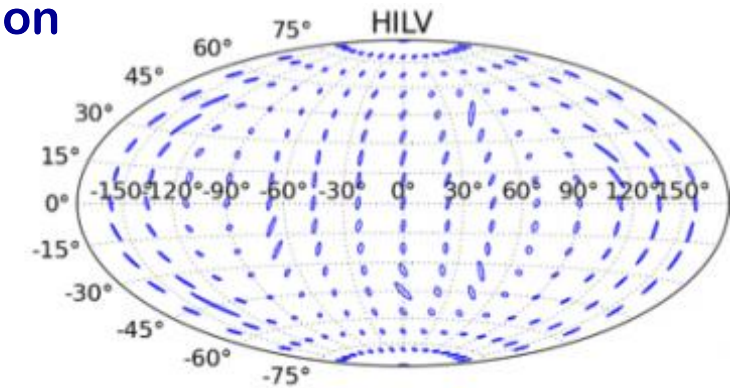
- ✓ Multiple interferometers are needed to **confidently detect** and **locate** the sources of GWs (except continuous signals), since directional observations cannot be made with a single detector like LIGO, which is sensitive to large portions of the sky at once.
- ✓ GWs have a finite speed and are expected to travel at the speed of light. This will induce **a detection delay** (up to about **10 milliseconds**) between the two LIGO detectors. Using this delay and the delay between LIGOs, Virgo, KAGRA, IntiGO will help pinpoint the sky location of the GW source.
- ✓ Multiple detectors also help sort out candidate GW **events that are caused by local sources**, like trees falling in the woods or even a technician dropping a hammer on site.

Why too many detectors?

Source Localization



LIGO I
LIGO II
VIRGO

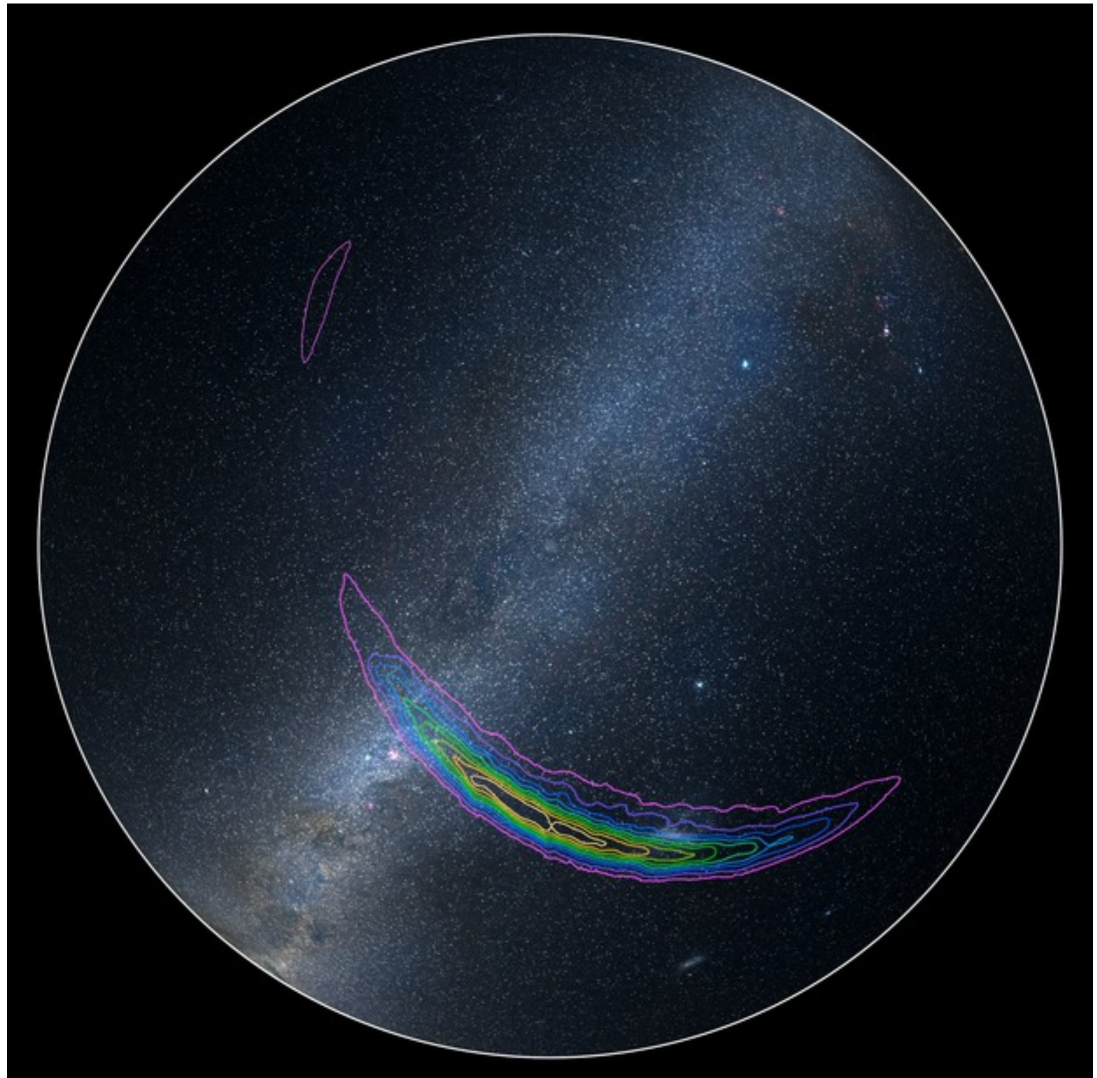


LIGO I
LIGO II
VIRGO
INDIGO

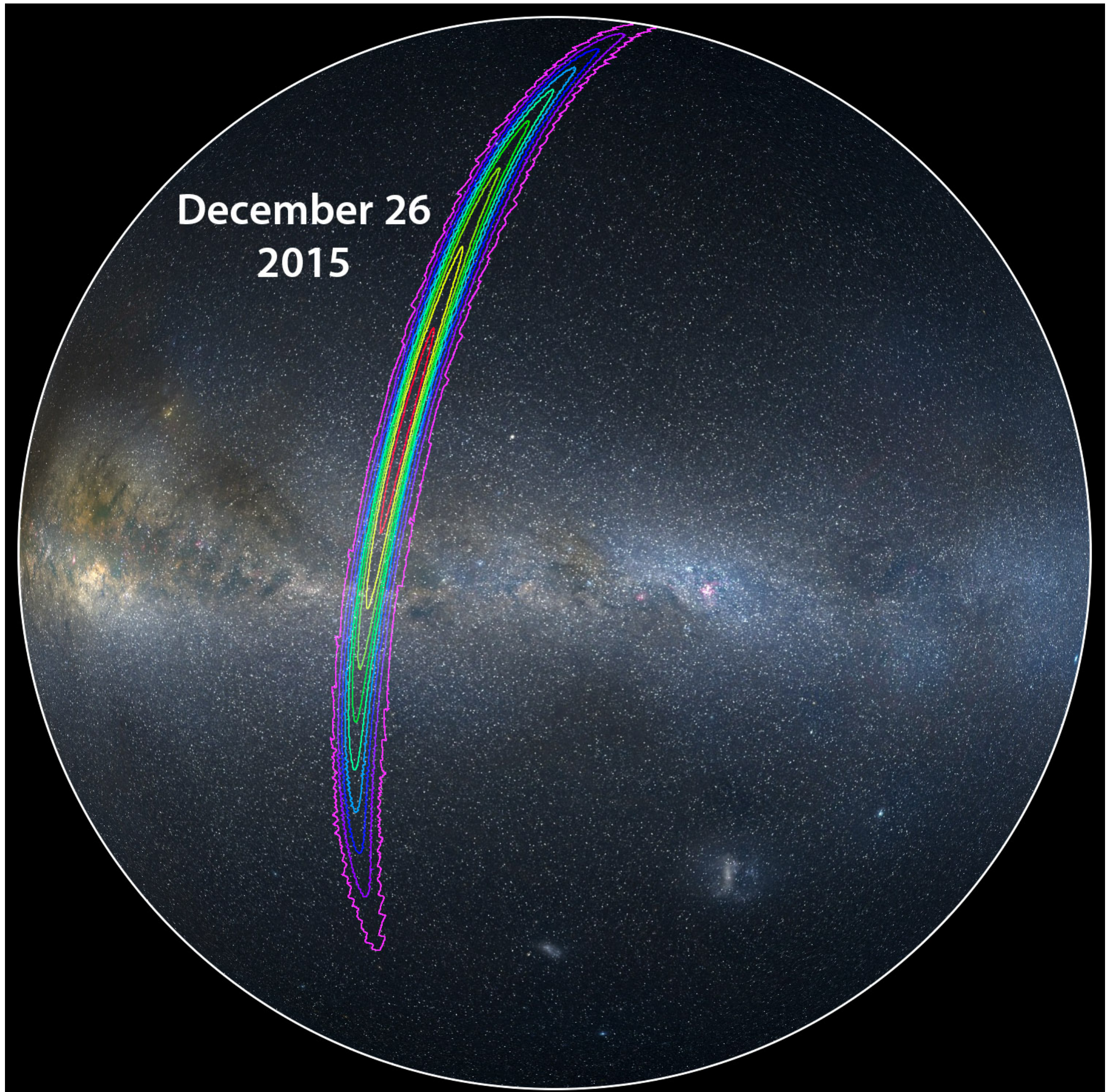
- ✓ **Confidently detect** & **locate** the sources of GWs
- ✓ **The detection delay** (~**10 milliseconds**) between LIGOs, Virgo, KAGRA, IntiGO will help pinpoint the sky location of the GW source.
- ✓ Sort out candidate GW **events that are caused by local sources**.

POSITIONING THE SOURCE GW150914

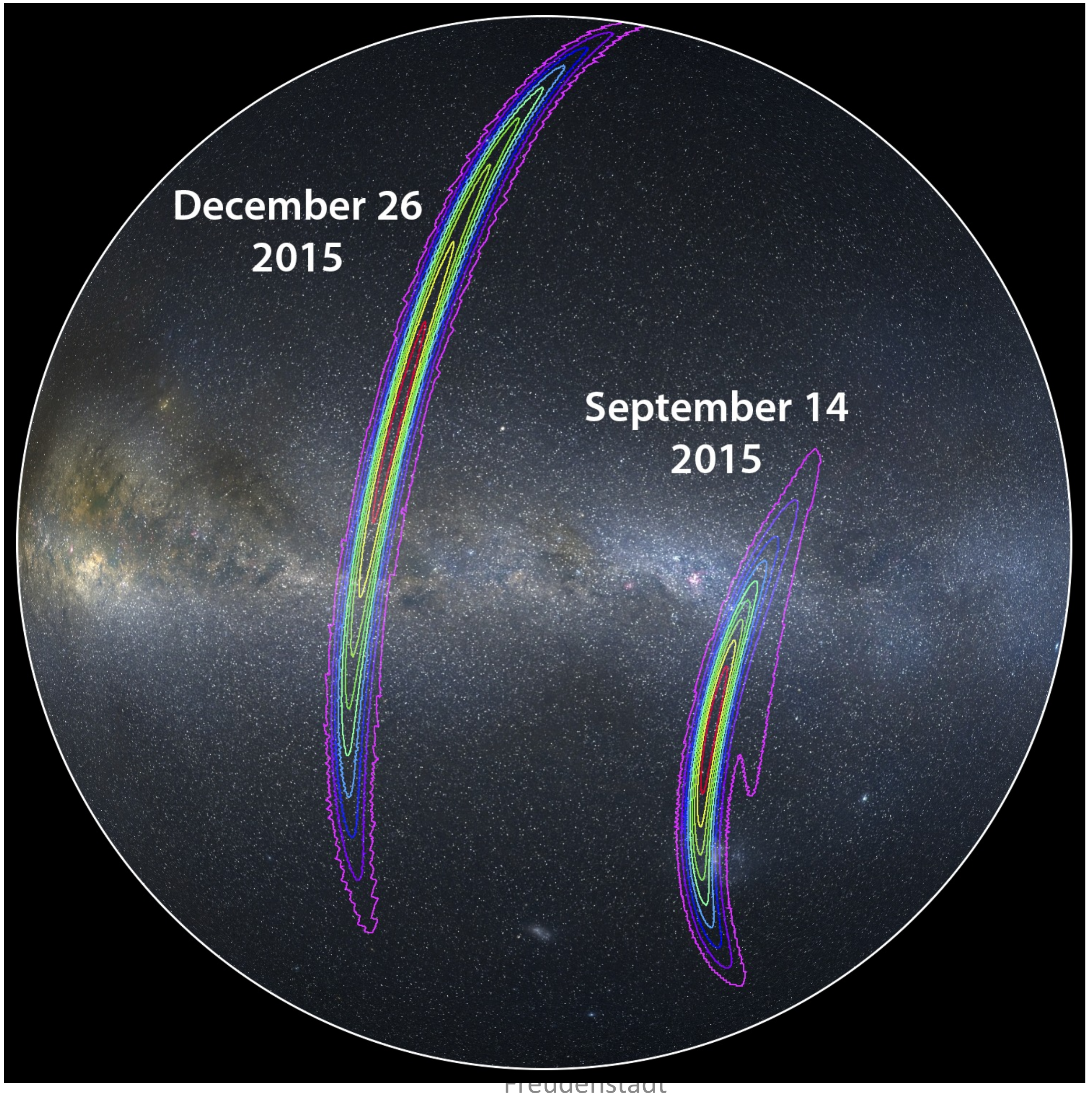
600 deg²

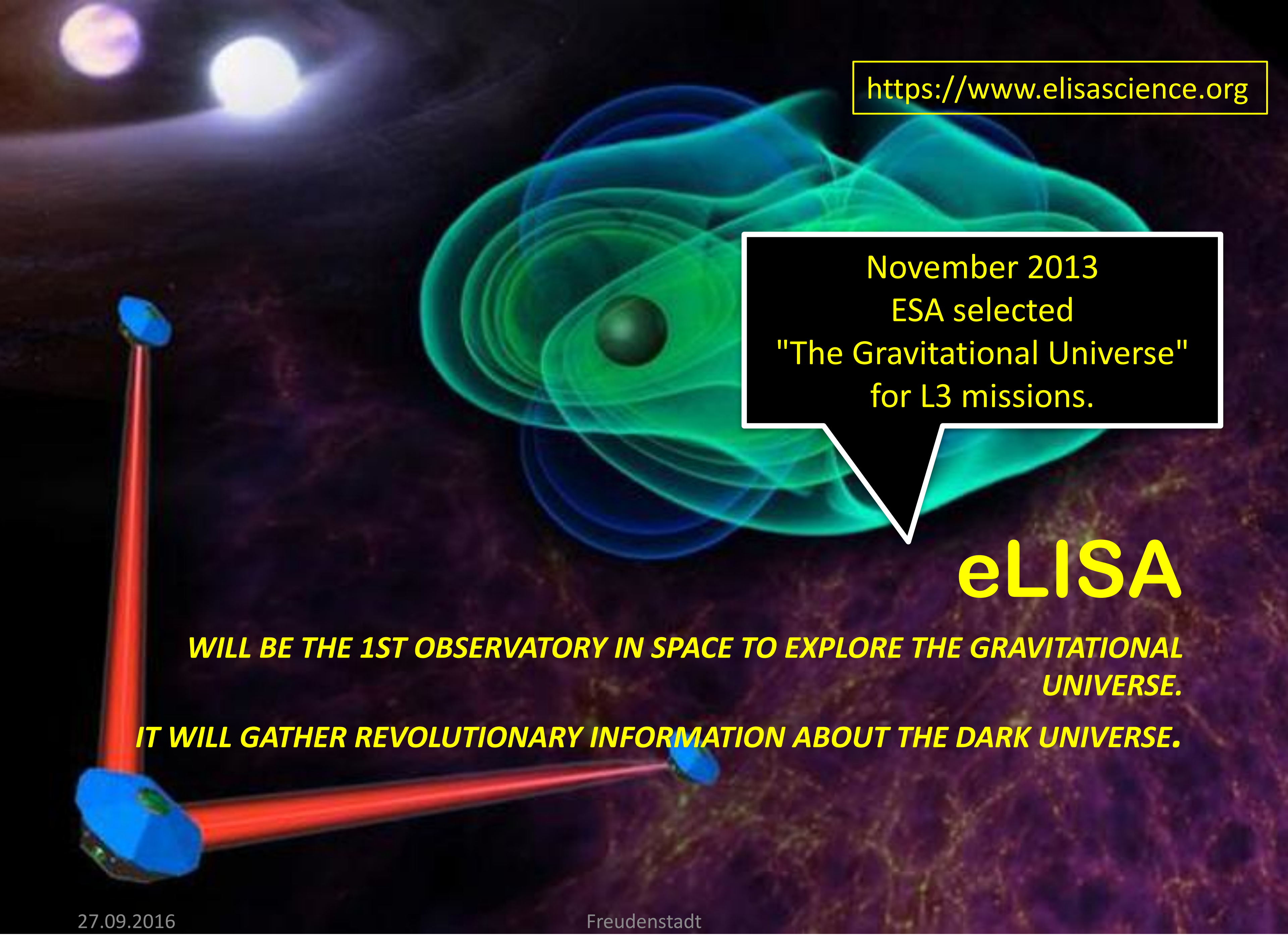


POSITIONING THE SOURCE GW151226

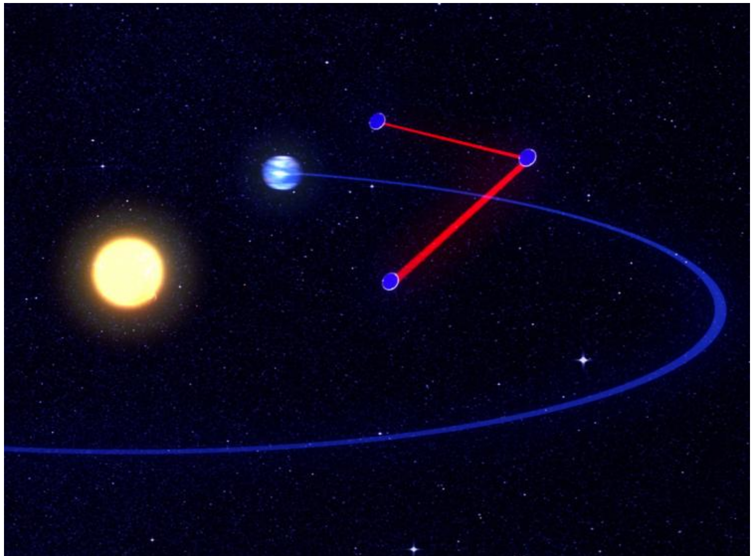


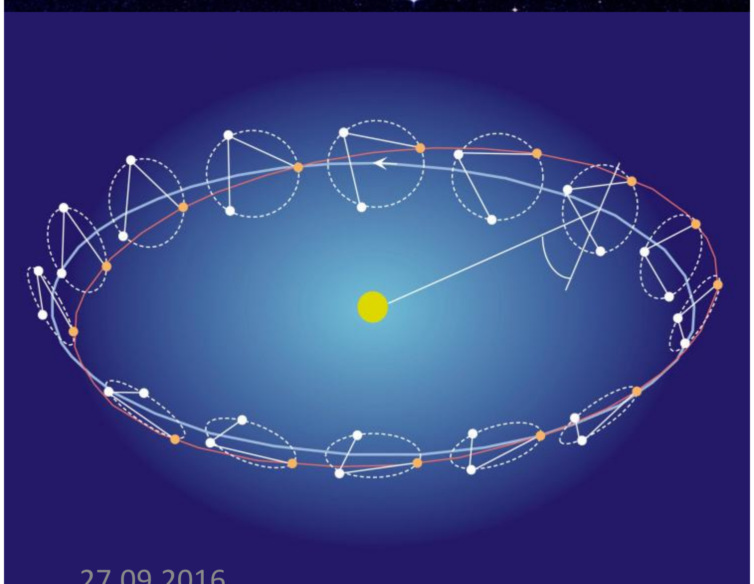
POSITIONING THE SOURCE GW151226




https://www.elisascience.org
November 2013
ESA selected
"The Gravitational Universe"
for L3 missions.
eLISA
WILL BE THE 1ST OBSERVATORY IN SPACE TO EXPLORE THE GRAVITATIONAL UNIVERSE.
IT WILL GATHER REVOLUTIONARY INFORMATION ABOUT THE DARK UNIVERSE.

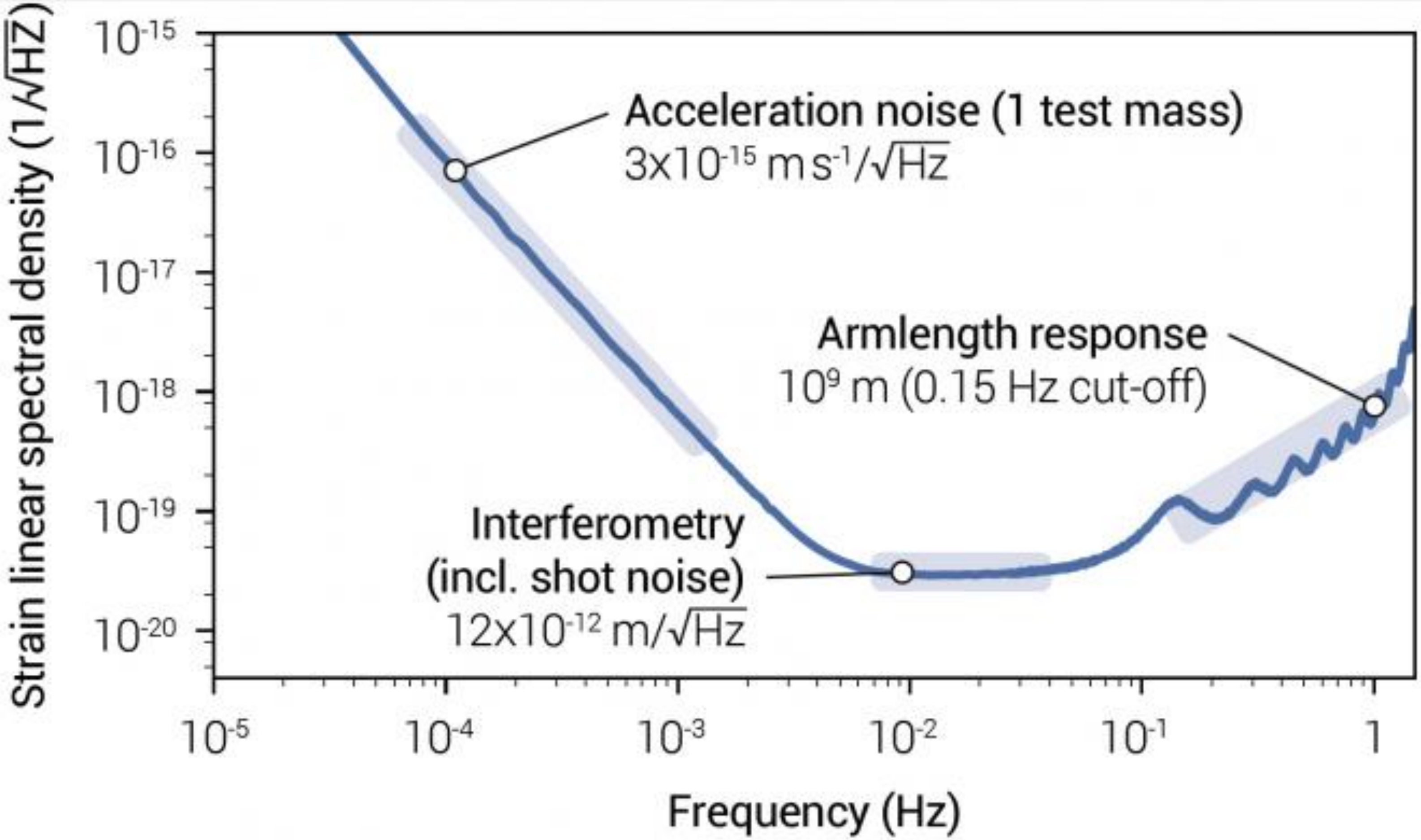
eLISA :Mission design





- ✓ The 3 eLISA spacecraft will be placed in orbits that form a triangular formation with center 20° behind the Earth and side length 1 million km.
- ✓ Each spacecraft will be in an individual Earth-like orbit around the Sun.
- ✓ The eLISA orbits ensure a stable thermal environment, minimising thermal disturbances on the spacecraft and the inertial test masses.
- ✓ Another key technology of eLISA are free-falling test masses inside each spacecraft. The test masses will be undisturbed by forces other than gravitation.

eLISA : Sensitivity

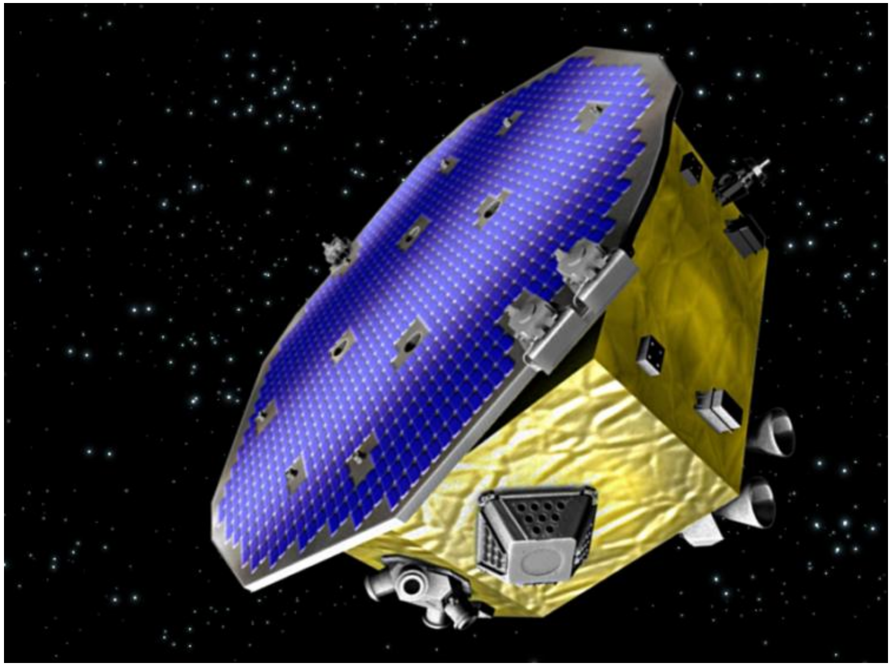


Time, sky and polarisation averaged eLISA sensitivity.
The noise spectrum (strain sensitivity) is plotted as a linear spectral density.

eLISA : Pathfinder

LISA Pathfinder is the precursor mission for all LISA-like missions.

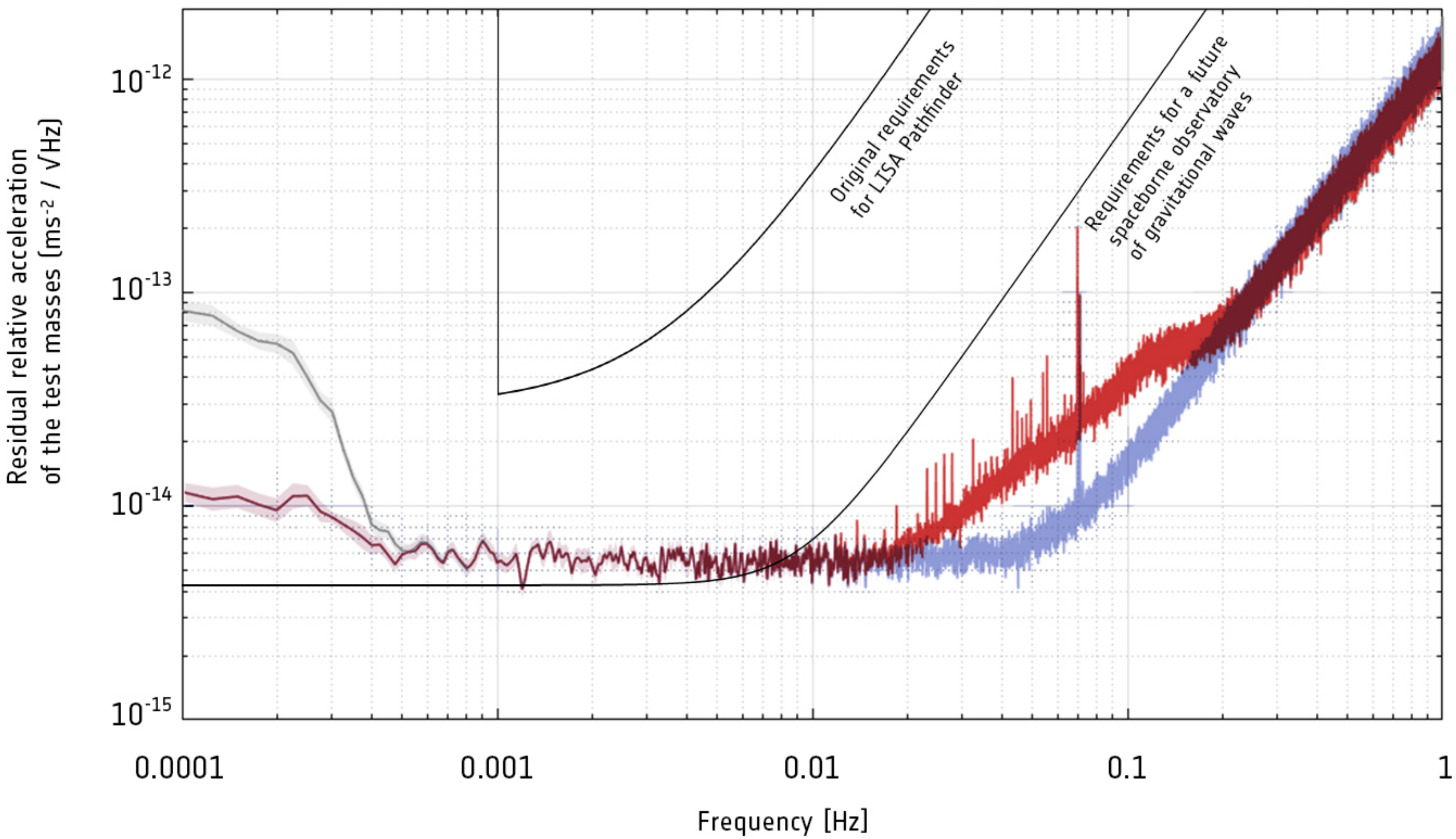
LPF was launched in December 2015.



LISA Pathfinder (LPF) placed two test masses in a nearly perfect gravitational free-fall, controlled and measured their relative motion with unprecedented accuracy.

LISA Pathfinder technologies are not only essential for eLISA, they also lie at the heart of any future space-based test of Einstein's General Relativity.

7th of June 2016 :
LISA pathfinder Exceeds expectations

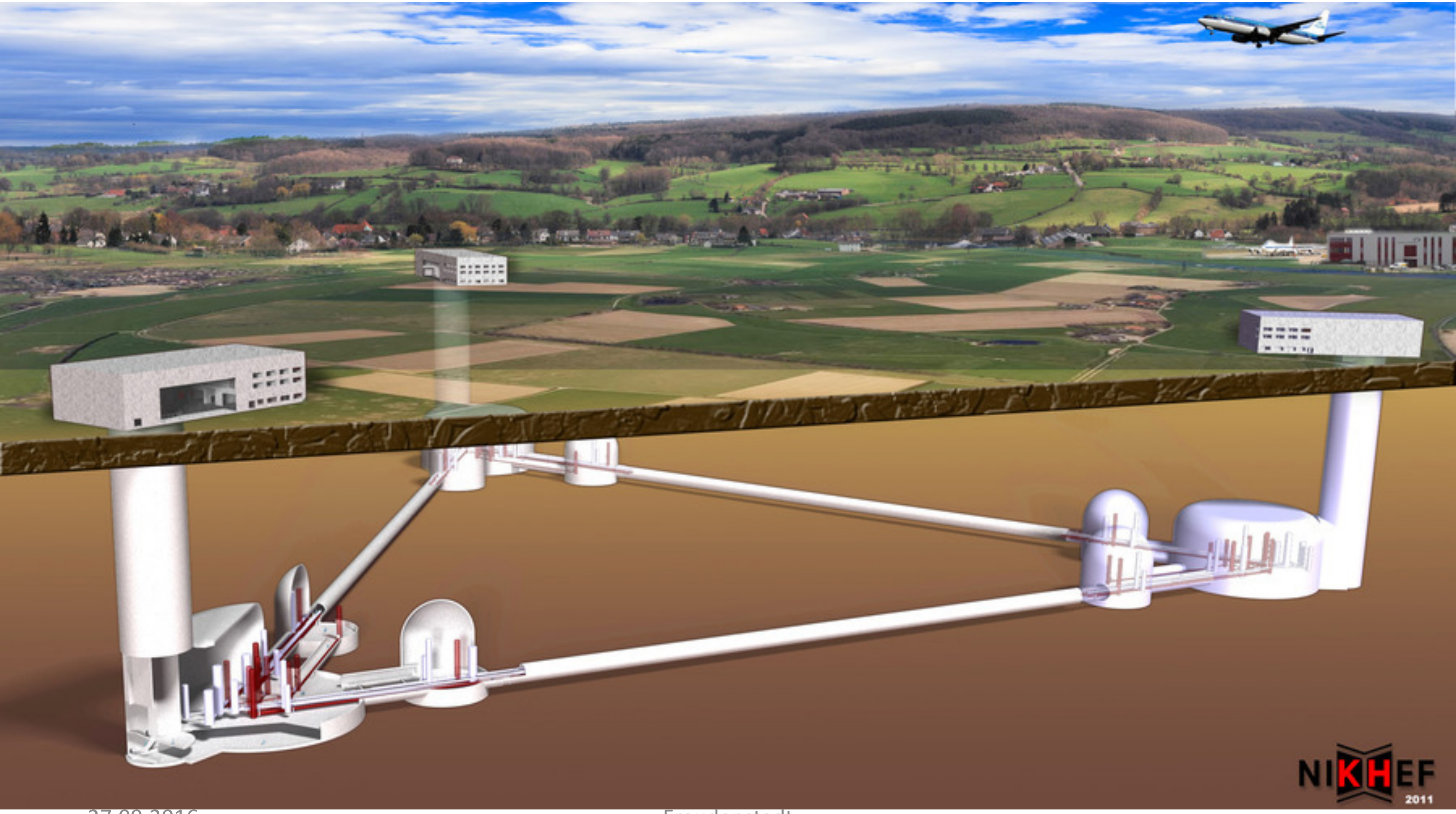


This residual relative acceleration of the two test masses on LISA Pathfinder as a function of frequency.

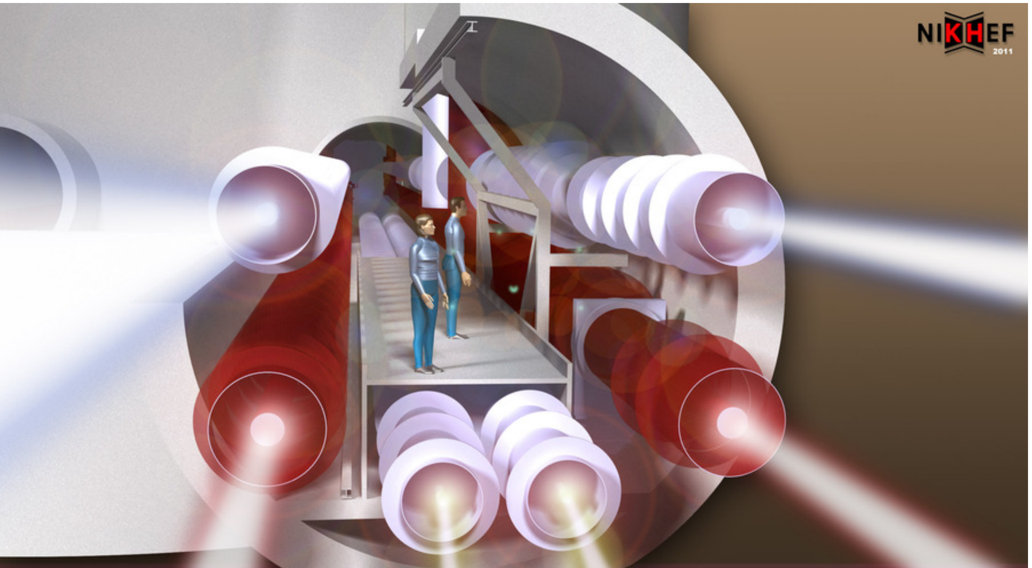
eLISA : Science Goals

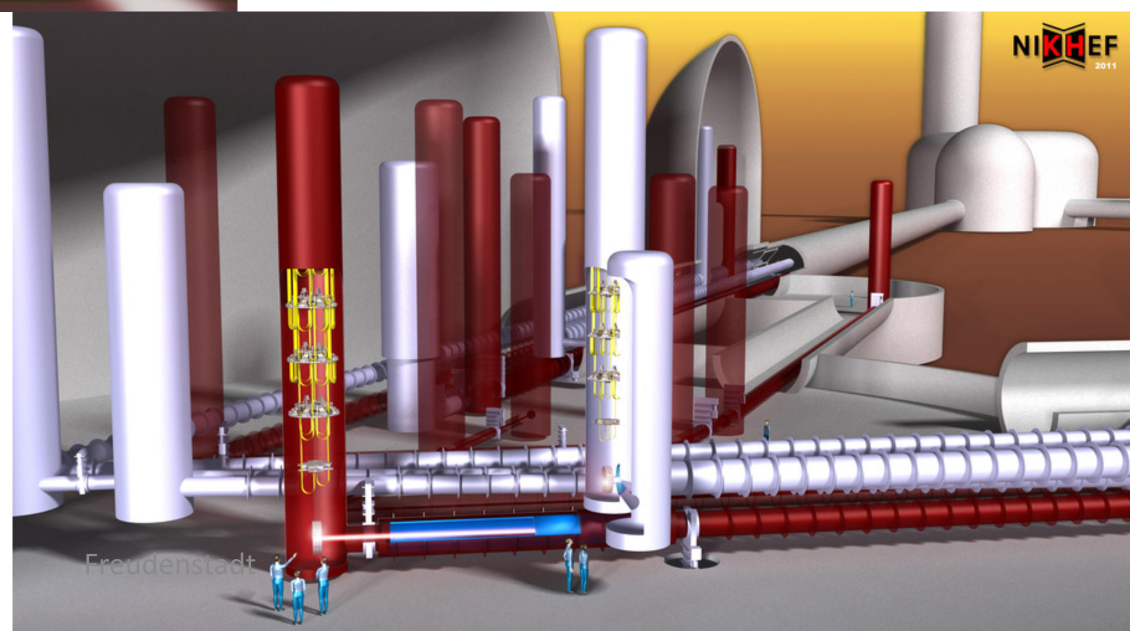
- eLISA will detect all **binary black hole mergers** even when the black holes are not active.
- eLISA will provide both the **widest and deepest survey** of the sky ever
- eLISA will offer a unique, new way to probe both cosmic dawn and high noon, to address a number of unanswered questions:
  - *When did the first Black holes form in pre-galactic haloes?*
  - *What is their initial mass and spin?*
  - *What is the mechanism of black hole formation in galactic nuclei?*
  - *How do black holes evolve over cosmic time due to accretion and mergers?*
  - *What can we learn about galaxy hierarchical assembly?*

ET : design

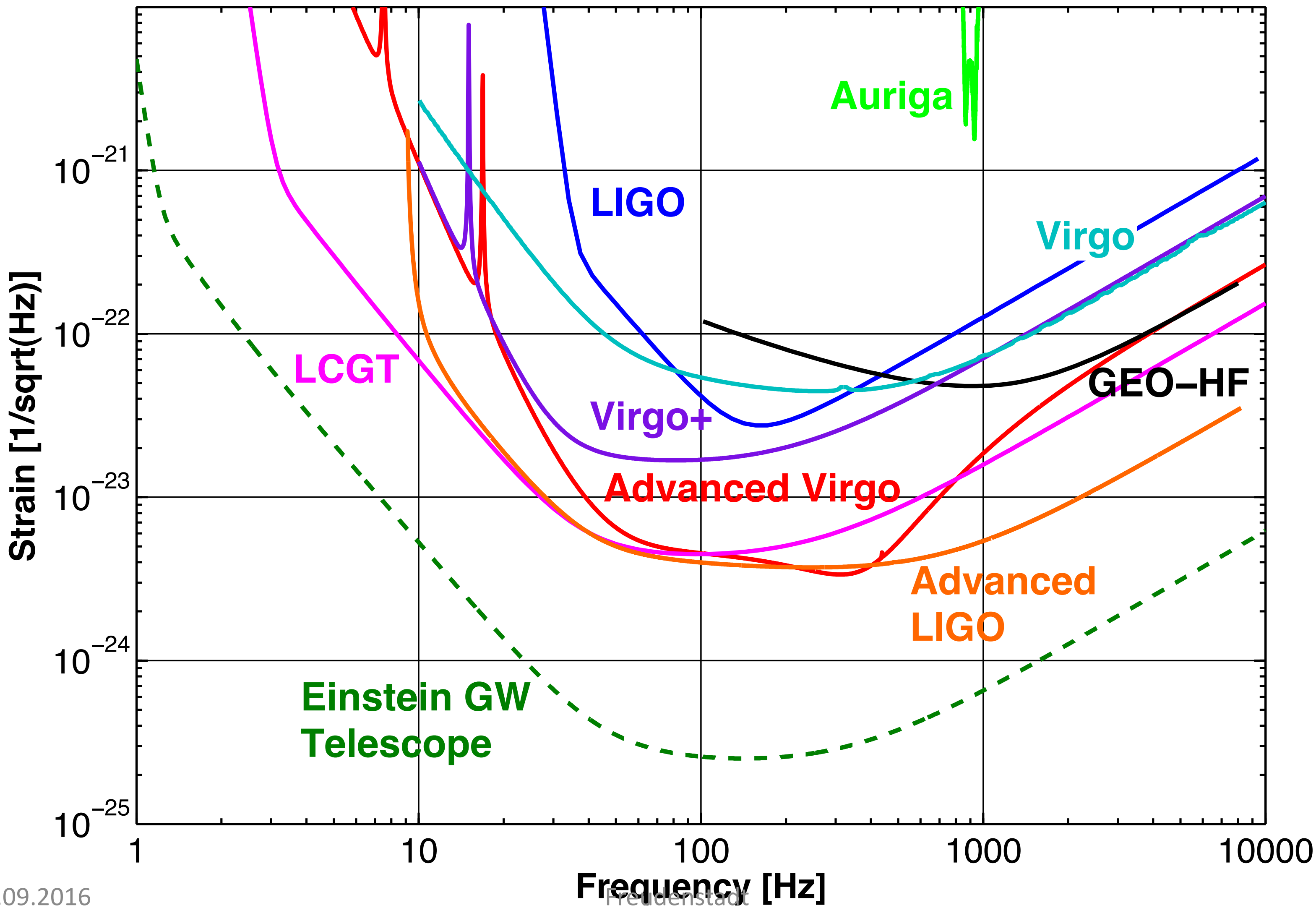


ET : design





ET: Sensitivity



ET: Observations

- BH collisions when the Universe was still in its infancy assembling the first galaxies
- NS collisions when star formation in the Universe was at its peak
- Formation of BHs and NSs in supernovae and collapsars in the local neighbourhood
- stochastic backgrounds of cosmological and astrophysical origin

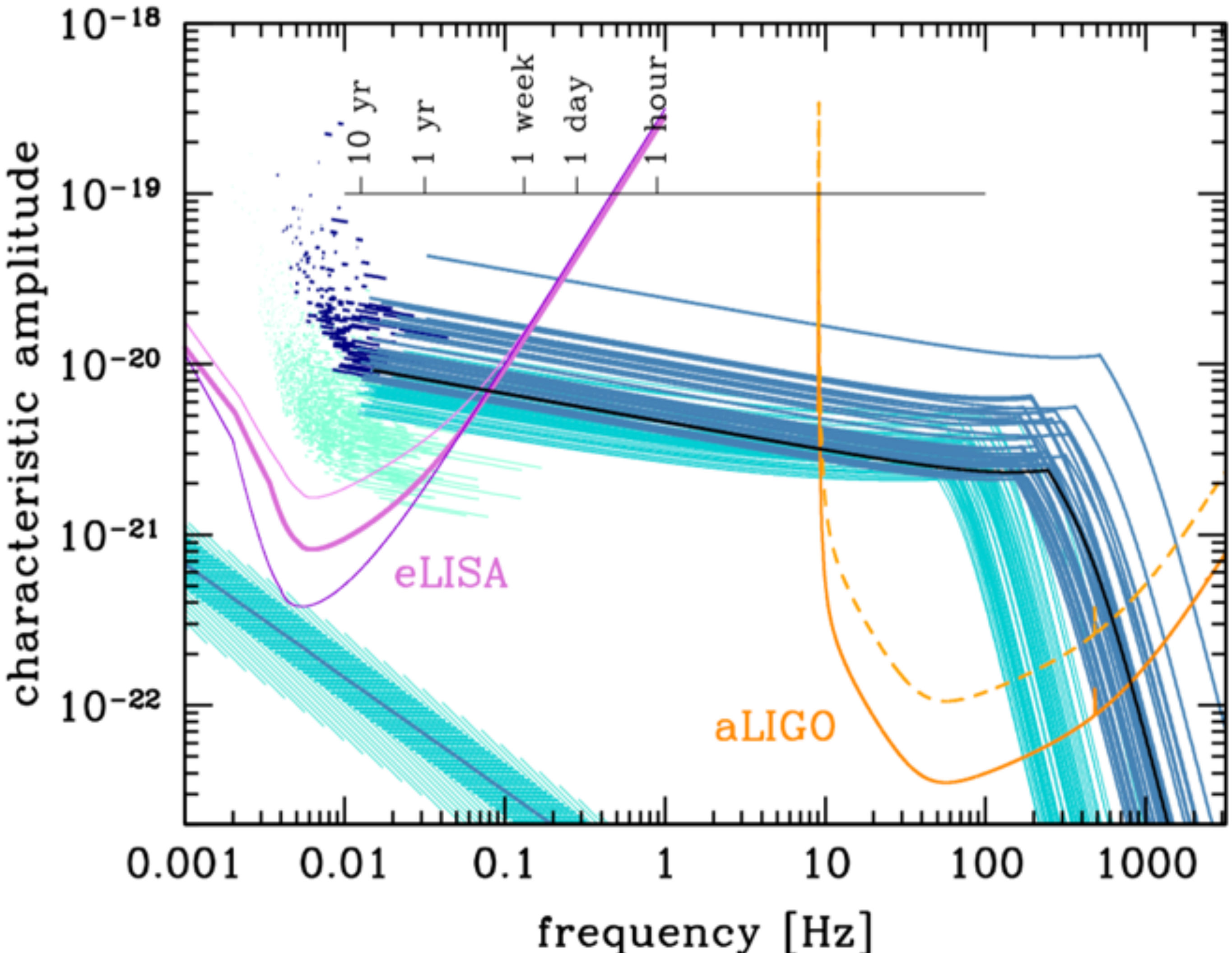
ET: New Insights

- the secret births and lives of black holes and neutron stars, their demographics, populations and their masses and spins
- dark energy and its variation with redshift
- equation of state of matter at supra-nuclear densities
- early history of the Universe's evolution

ET: Fundamental Physics

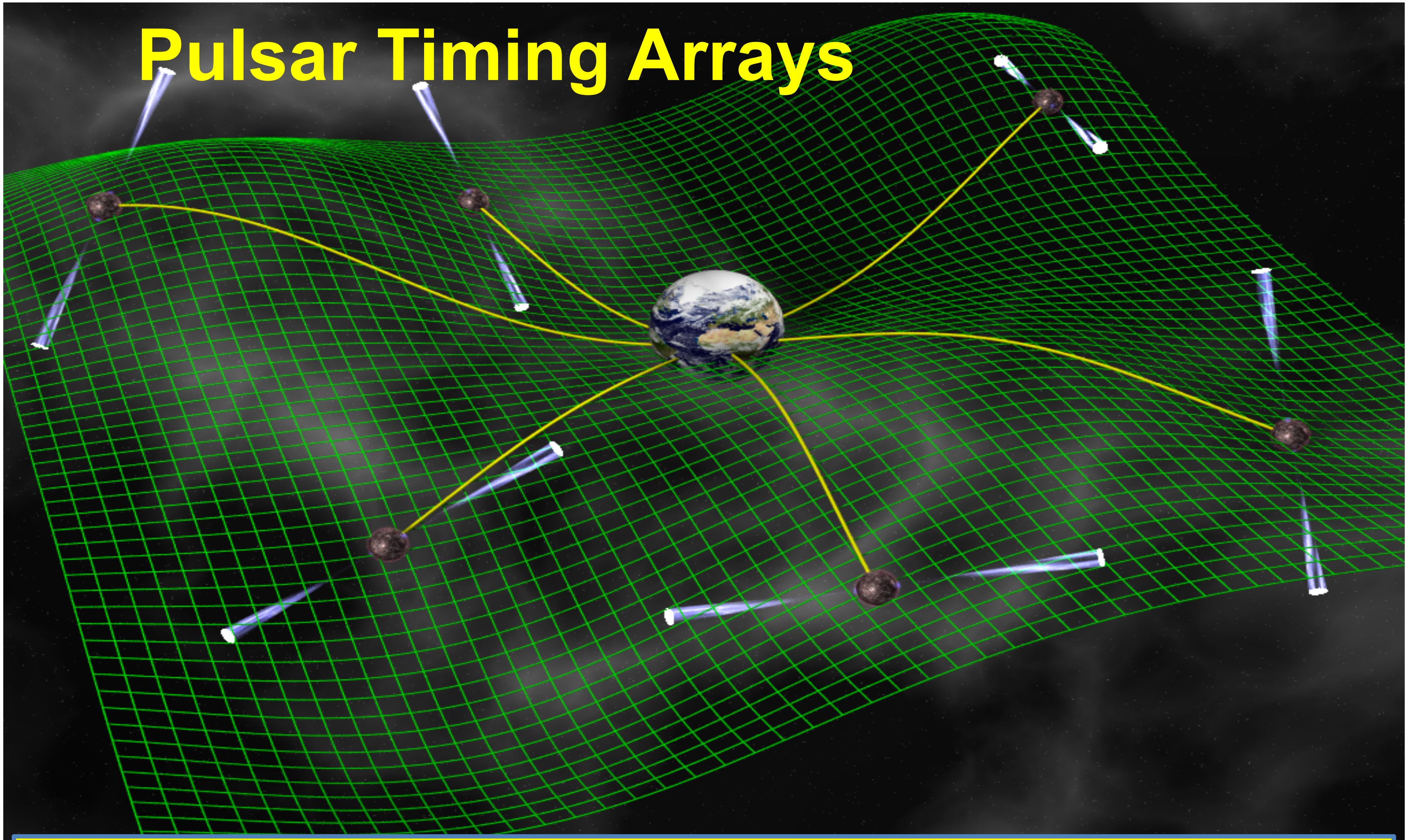
- **Properties of GWs**
  - Testing GR beyond the quadrupole formula
    - Binary pulsars consistent with quadrupole formula; they don't measure properties of GW
  - How many polarizations are there?
    - In Einstein's theory only two polarizations; a scalar-tensor theory could have six
  - Do gravitational waves travel at the speed of light?
    - There are strong motivations from string theory to consider massive gravitons
    - Binary pulsars constrain the speed to few parts in a thousand
    - GW observations can constrain to **1 part in 10^{18}**
- **EoS of dark energy**
  - Black hole binaries are standard candles/sirens
- **EoS of supra-nuclear matter**
  - Signature of EoS in GW emitted when neutron stars merge
- **Black hole no-hair theorem and cosmic censorship**
  - Are BH (candidates) of nature BH of general relativity?
- **An independent constraint/measurement of neutrino mass**
  - Delay in the arrival times of neutrinos and GWs

Brave New World of BBH Mergers



Intermediate mass BHs> $100M_{\odot}$

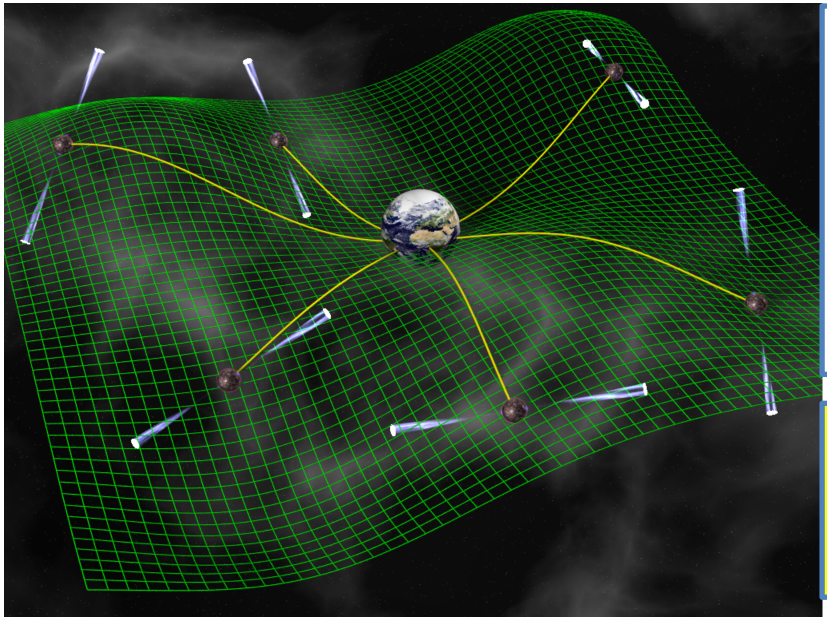
Sesana arXiv:1602.06951



Available pulsar data have already placed limit of about **h<10^{-13}** on the amplitude of such low-frequency GWs

Pulsar Timing Arrays

10-1000 μHz



A different approach to detecting GWs is used by pulsar timing arrays, such as the

- European Pulsar Timing Array (EPTA)
- North American Nanohertz Observatory for GW (NANOGrav)
- Parkes Pulsar Timing Array (PPTA)

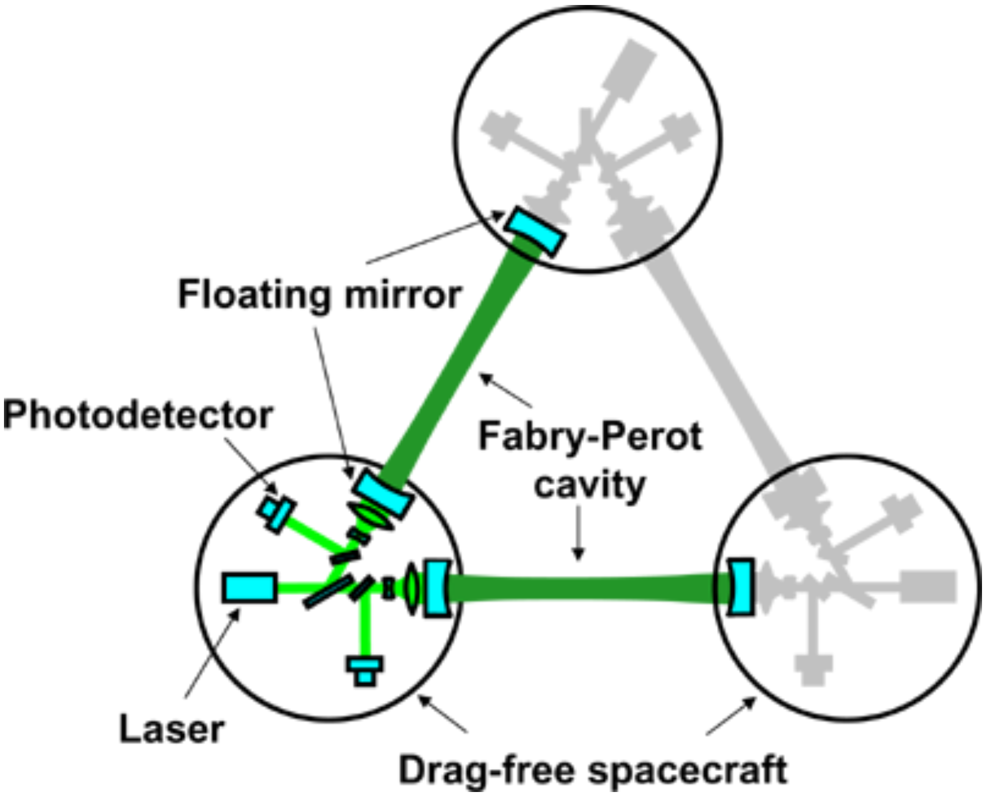
Available pulsar data have already placed limit of about **$h<10^{-13}$** on the amplitude of such low-frequency GWs

- These projects propose to detect GWs by looking at the effect these waves have on the incoming signals from an array of 20–50 well-known millisecond pulsars.
- As a GW passing through the Earth contracts space in one direction and expands space in another, the times of arrival of pulsar signals from those directions are shifted correspondingly.
- By studying a fixed set of pulsars across the sky, these arrays should be able to detect gravitational waves in the nanohertz range.
- Such signals are expected to be emitted by pairs of merging supermassive black holes.

DECIGO

0.1 - 10 Hz

The DECI-Hertz Interferometer Gravitational wave Observatory (or DECIGO) is the proposed Japanese, space-based, gravitational wave observatory.



- **It is due for launch in 2027.**
- The primary objective of DECIGO is to directly observe the beginning of the universe (10^{-36}-10^{-34} sec after the beginning)
- To measure the acceleration of the expansion of the universe
- to further characterize the dark energy, and
- to observe the formation of giant black holes in the center of galaxies.