A quick look at the future of Gravitational Wave Science

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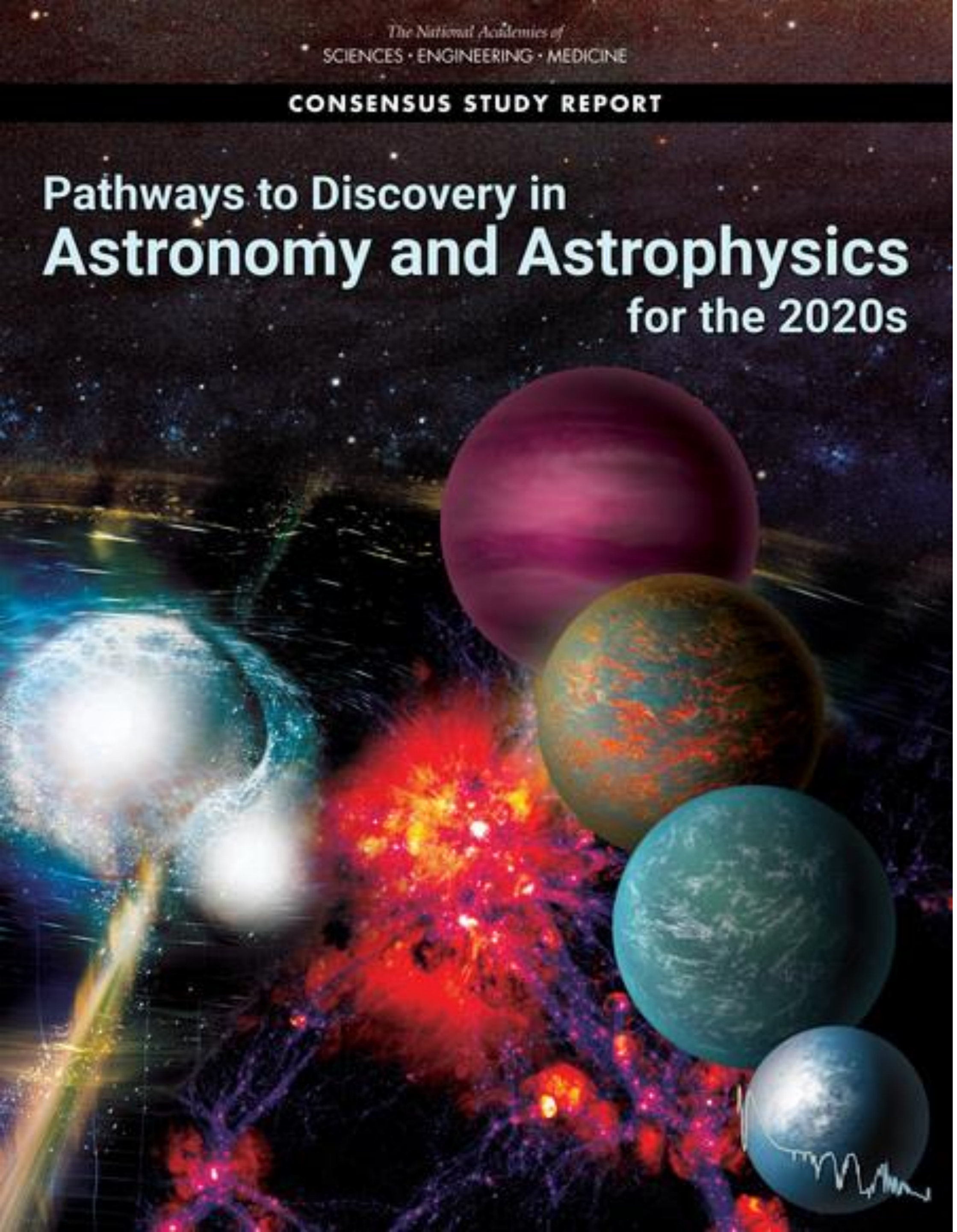
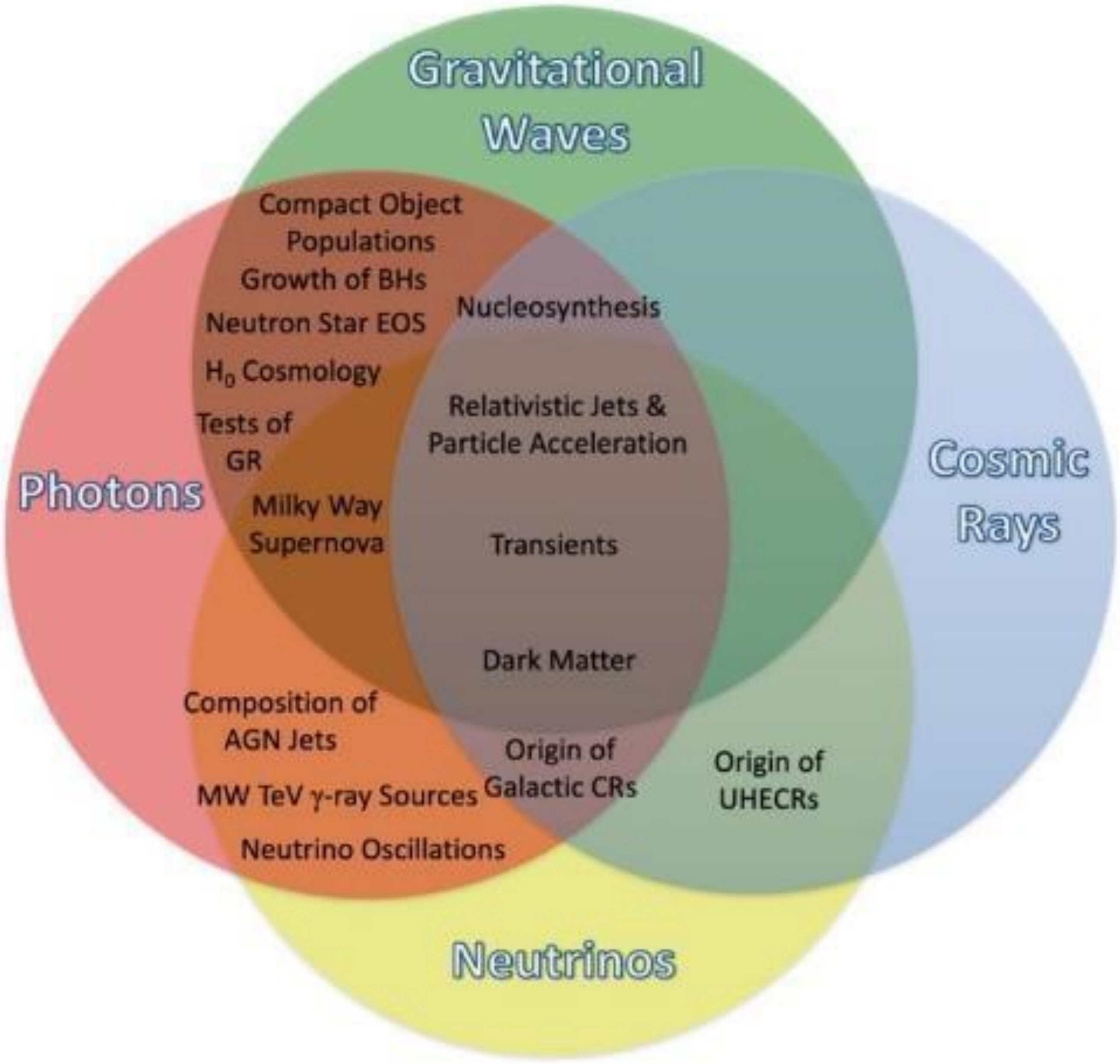

The National Academies of
SCIENCES · ENGINEERING · MEDICINE
CONSENSUS STUDY REPORT
Pathways to Discovery in
Astronomy and Astrophysics
for the 2020s

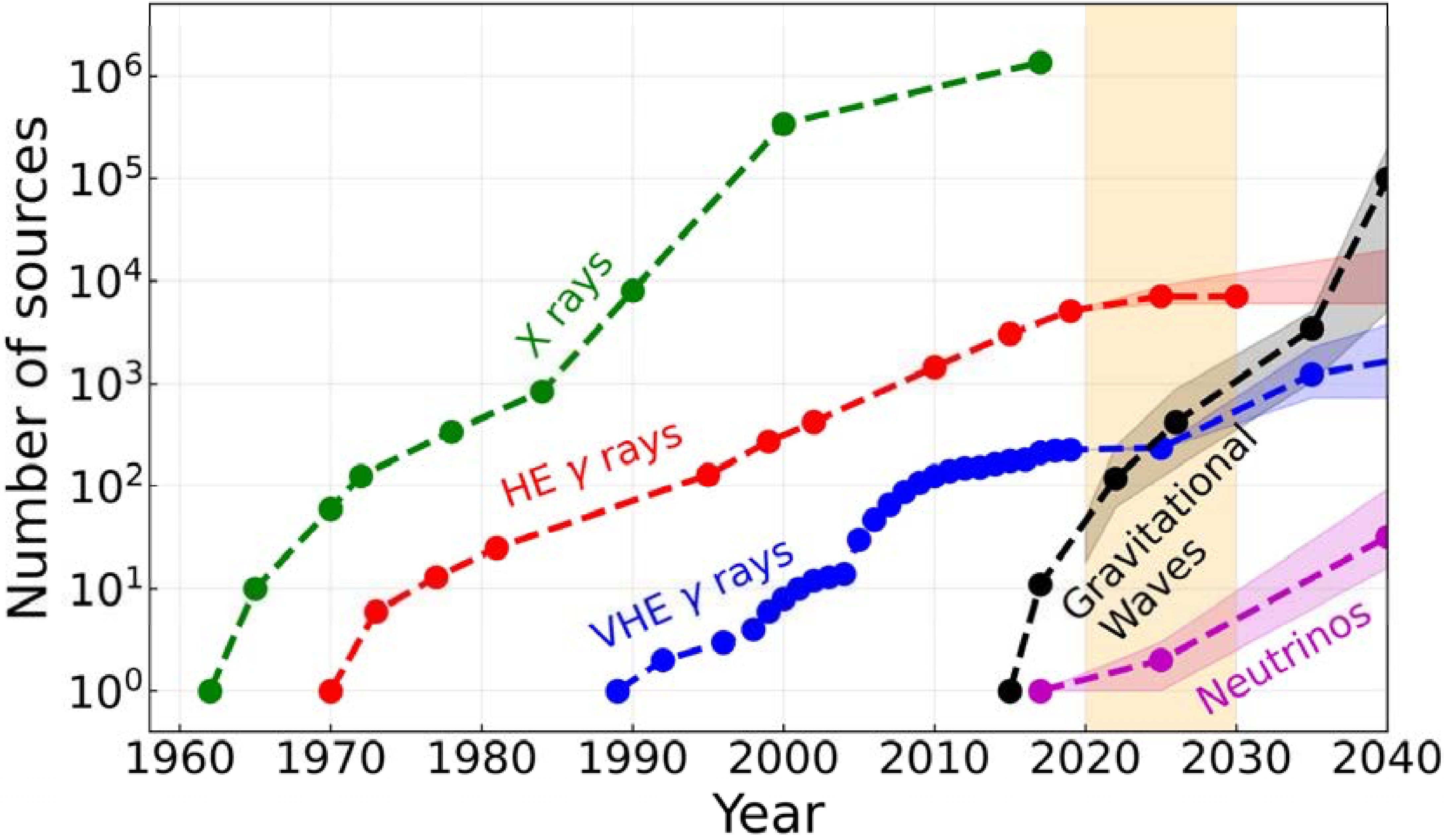

Gravitational Waves
Photons
Cosmic Rays
Neutrinos
Compact Object Populations
Growth of BHs
Neutron Star EOS
H_0 Cosmology
Tests of GR
Milky Way Supernova
Nucleosynthesis
Relativistic Jets & Particle Acceleration
Transients
Dark Matter
Composition of AGN Jets
MW TeV γ-ray Sources
Neutrino Oscillations
Origin of Galactic CRs
Origin of UHECRs

The panel sees a compelling opportunity to dramatically open the discovery space of astronomy through a bold, broad multi-messenger program, with three components:

• ***Neutrino program****:* A large-scale (MREFC) investment by the National Science Foundation (NSF) in IceCube-Gen2, to resolve the bright, hard-spectrum, TeV–PeV diffuse background discovered by IceCube into discrete sources and to make first detections at higher energies.

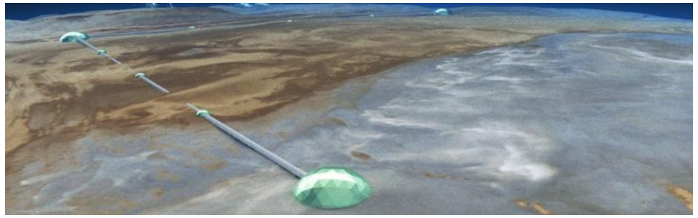
• ***Gravitational-wave program****:* Medium-scale investments in three bands (kHz, nHz, and mHz) to develop a rich observational program: **Cosmic Explorer, with NSF support for technology development to set the stage for large-scale investments and huge detection rates in the 2030s**; the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), with NSF support for expanded operations in the 2020s; and the Laser Interferometer Space Antenna (LISA), with National Aeronautics and Space Administration (NASA) support for a broad scope of activities to build a vibrant U.S. community for significant science contributions in the 2030s.

• ***Gamma-ray program****:* Medium-scale investments that support observations over a wide energy range, with two components. (In this report, for simplicity we use “gamma-ray” to mean photons at or above hard X-ray energies.) First, a NASA Probe-scale mission, targeted to multi-messenger astronomy, with sensitivity in the keV–MeV–GeV range and with capabilities for the identification, localization, and characterization of transients. This would be selected by competitive review; potential projects include the All-sky Medium Energy Gamma-ray Observatory (AMEGO), the Advanced Particle-astrophysics Telescope (APT), or the Transient Astrophysics Probe (TAP). Second, U.S. participation in TeV-range ground-based experiments for precision studies—for example, the Cherenkov Telescope Array (CTA) and the Southern Wide-Field Gamma-Ray Observatory (SWGO)—as NSF medium- scale projects. **All of these projects will be valuable themselves—gamma rays reveal processes that longer-wavelength photons cannot—and will greatly enhance the returns of neutrino and gravitational-wave observatories.**



Number of sources
10^6
10^5
10^4
10^3
10^2
10^1
10^0
1960
1970
1980
1990
2000
2010
2020
2030
2040
Year
X rays
HE γ rays
VHE γ rays
Gravitational Waves
Neutrinos

Technology Development for Future Ground-based Gravitational Wave Observatories



Gravitational wave detection is one of the most exciting and expanding scientific frontiers impacting central questions in astronomy

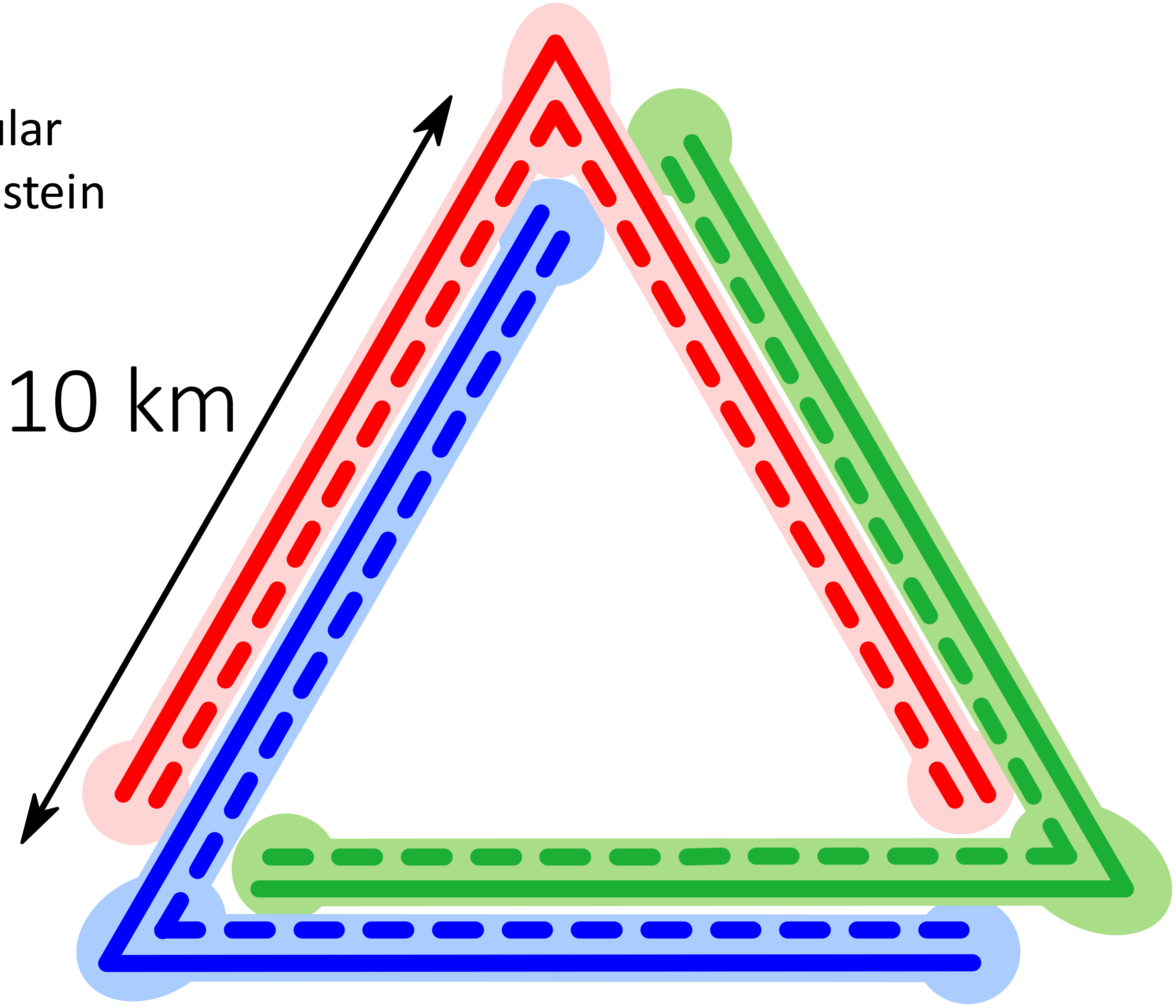
- Directly relevant to two Astro2020 priority areas: New Windows on the Dynamic Universe, Hidden Drivers of Galaxy Formation

More advanced detectors in the current LIGO facility (beyond A+) and planning for future generation facilities such as Cosmic Explorer are essential

Conclusion: … Continuous technology development will be needed this decade for next generation detectors like Cosmic Explorer. These developments will also be of benefit to the astrophysical reach of current facilities.

Einstein Telescope concept

Three nested detectors in a triangular arrangement will form the final Einstein Telescope geometry.



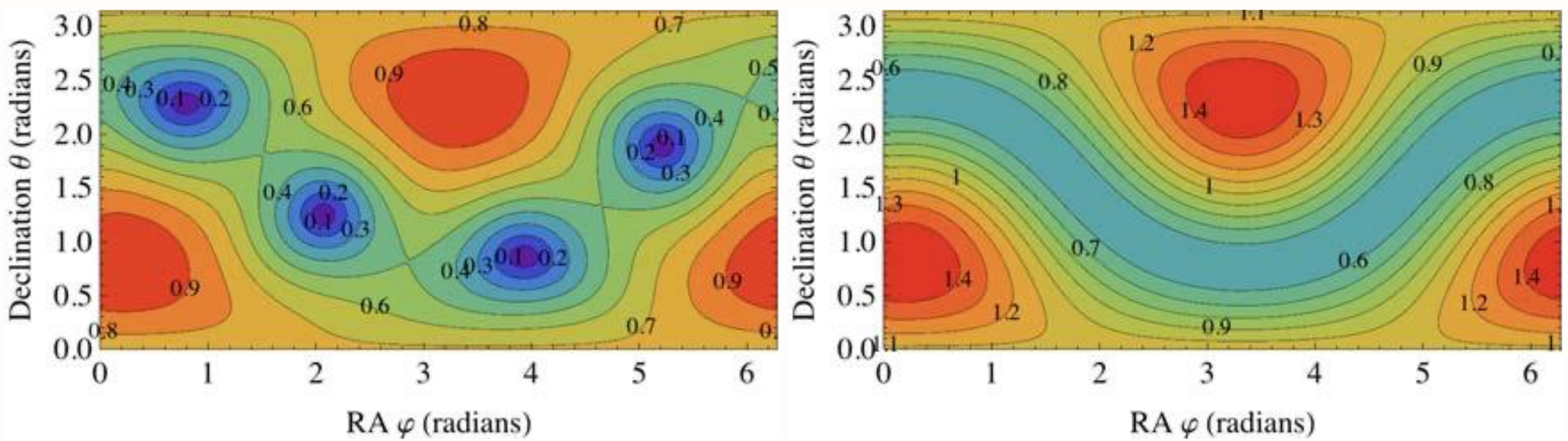
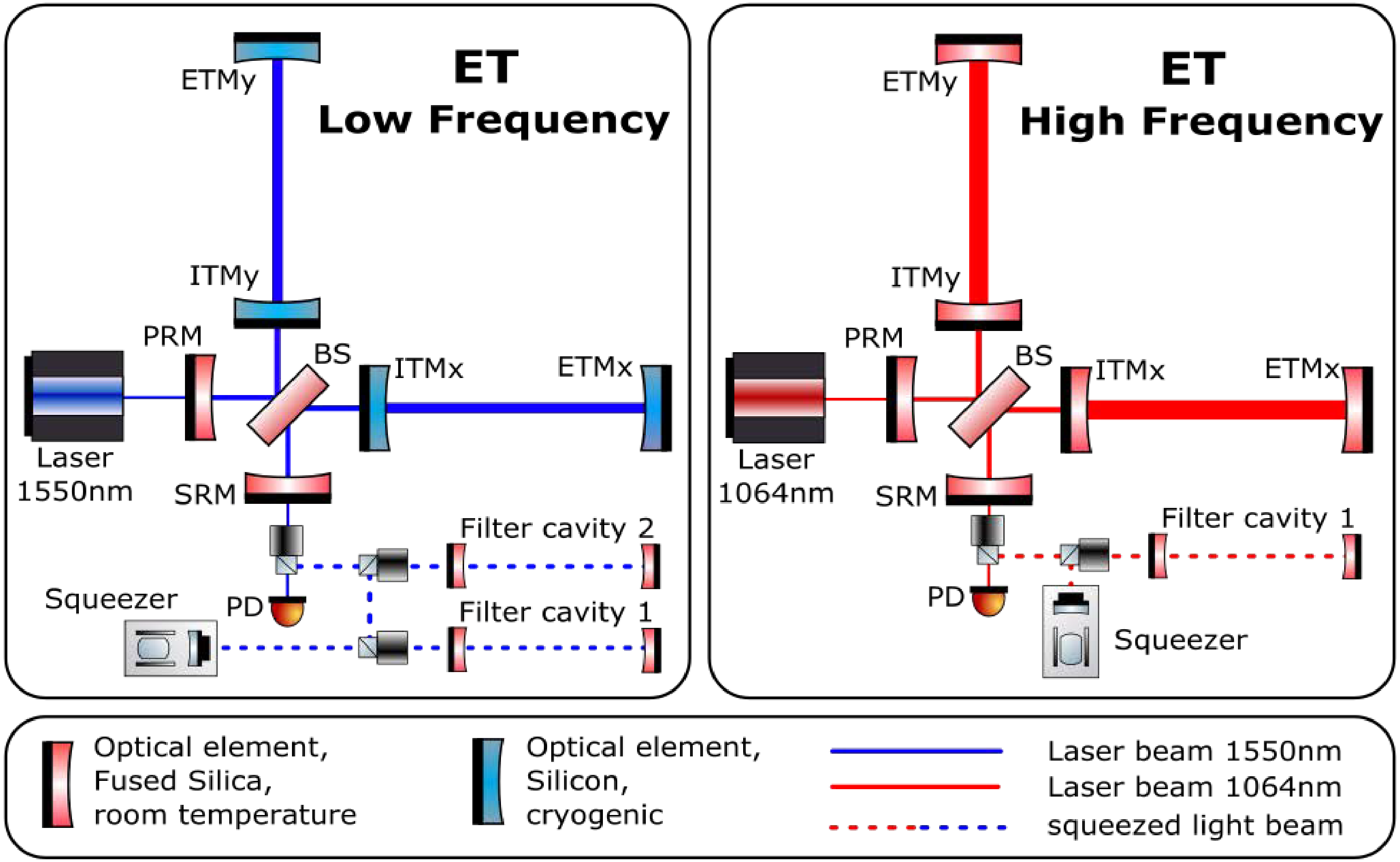


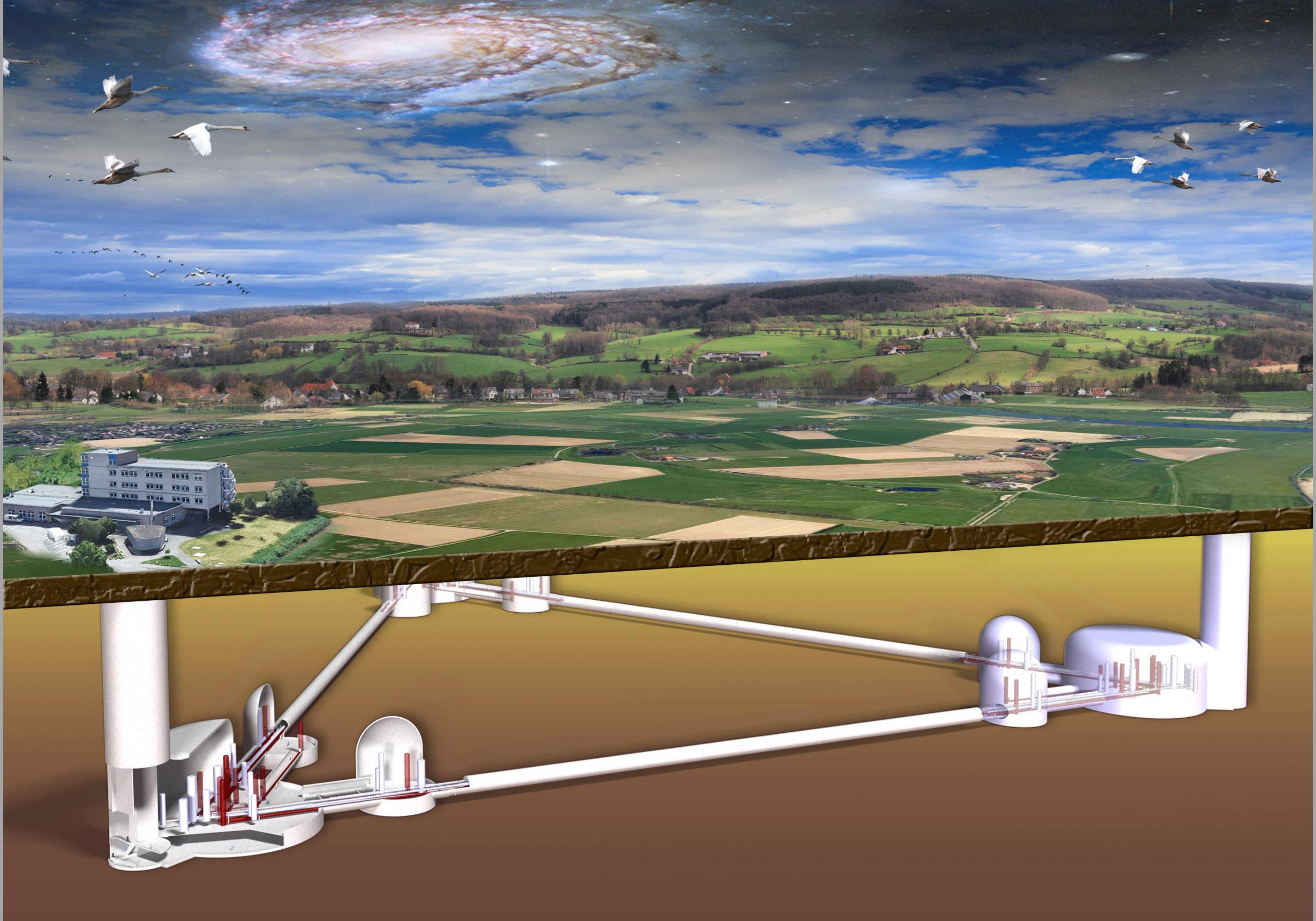
Figure 1.4: Antenna pattern of ET (right panel) compared to that of Virgo (left panel). ET is assumed to be at the same location as Virgo. Note that Virgo is a single L-shaped detector while ET consists of three V-shaped interferometers rotated relative to one other by 120 deg . The combined antenna pattern of the three detectors in ET (defined as $F^2 = \sum_{A=1}^{3} F_A^2$, where F_1, F_2, F_3 are the individual antenna pattern functions) makes the response the same for all sources whose sky location makes the same angle to the plane formed by ET (see *e.g.* contours marked 0.6).

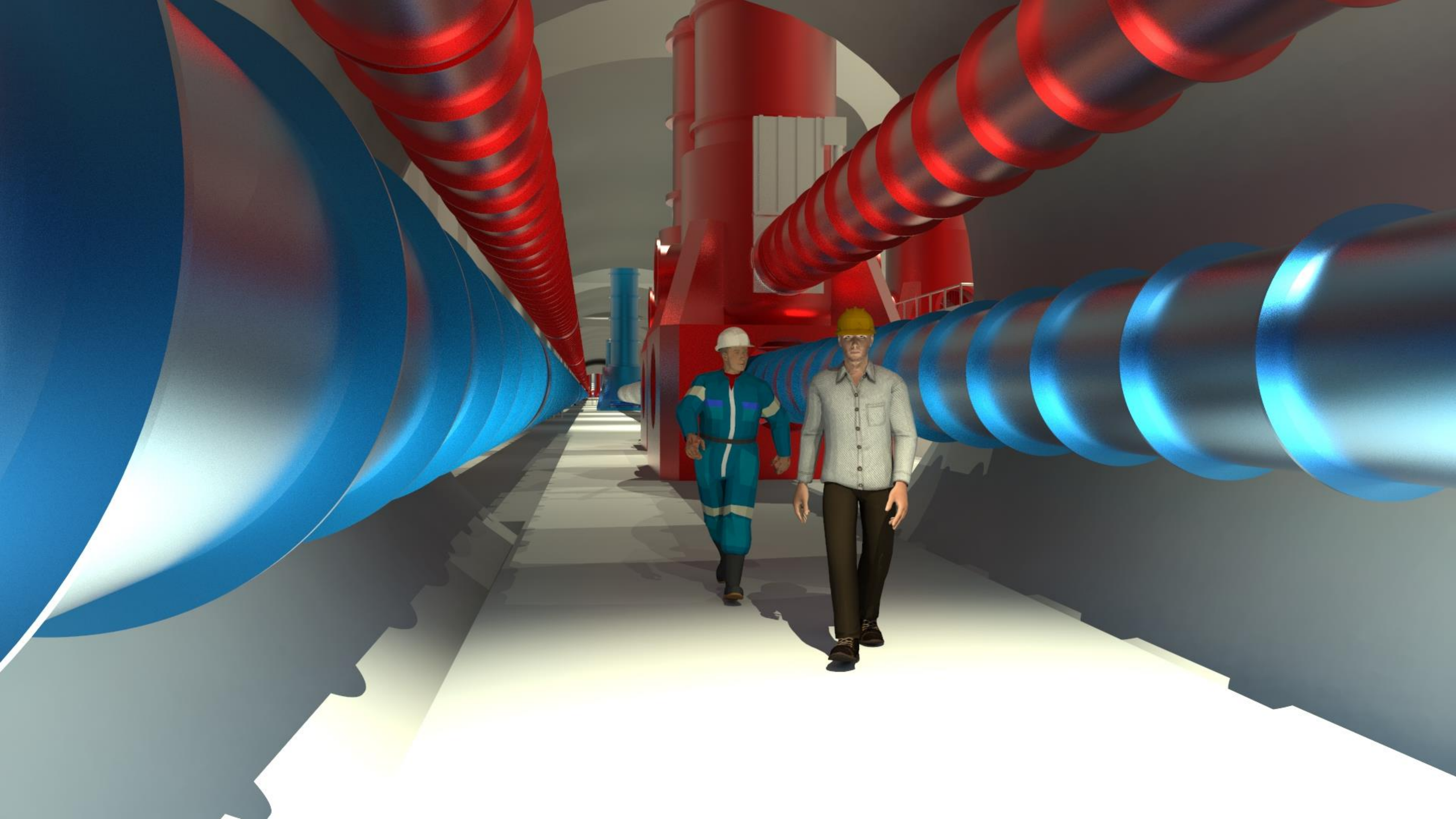
- *The baseline for ET is a 2-band xylophone detector configuration, composed of a low-frequency (ETLF) and a high-frequency (ET-HF) interferometer.*

- *Both interferometers are Michelson interferometers featuring 10 km arm length with an opening angle of 60 degrees.*

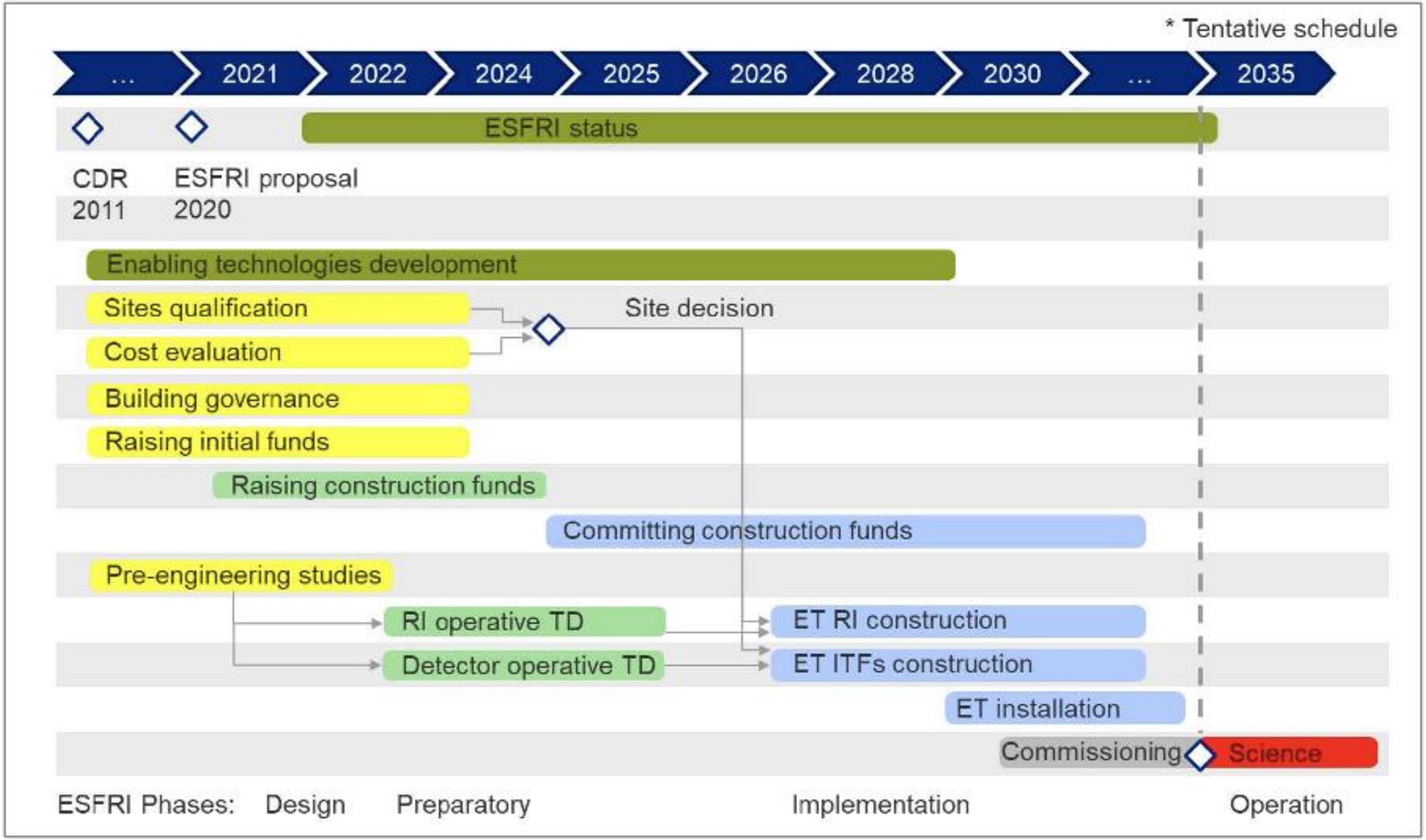
- *Due to their similar geometry both detectors will share common tunnels.*

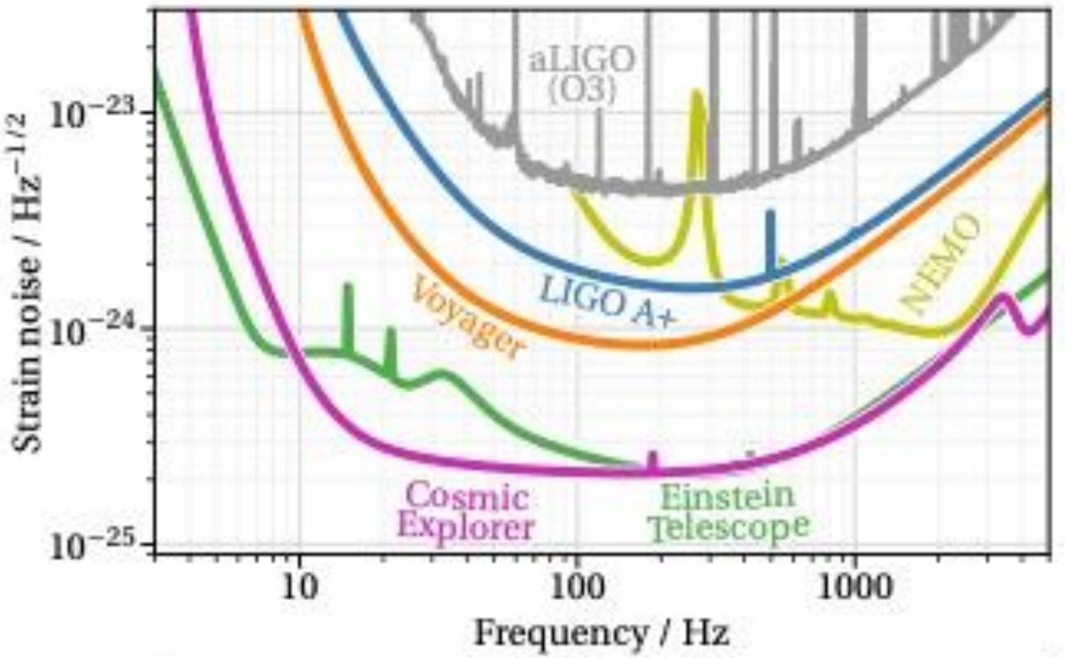


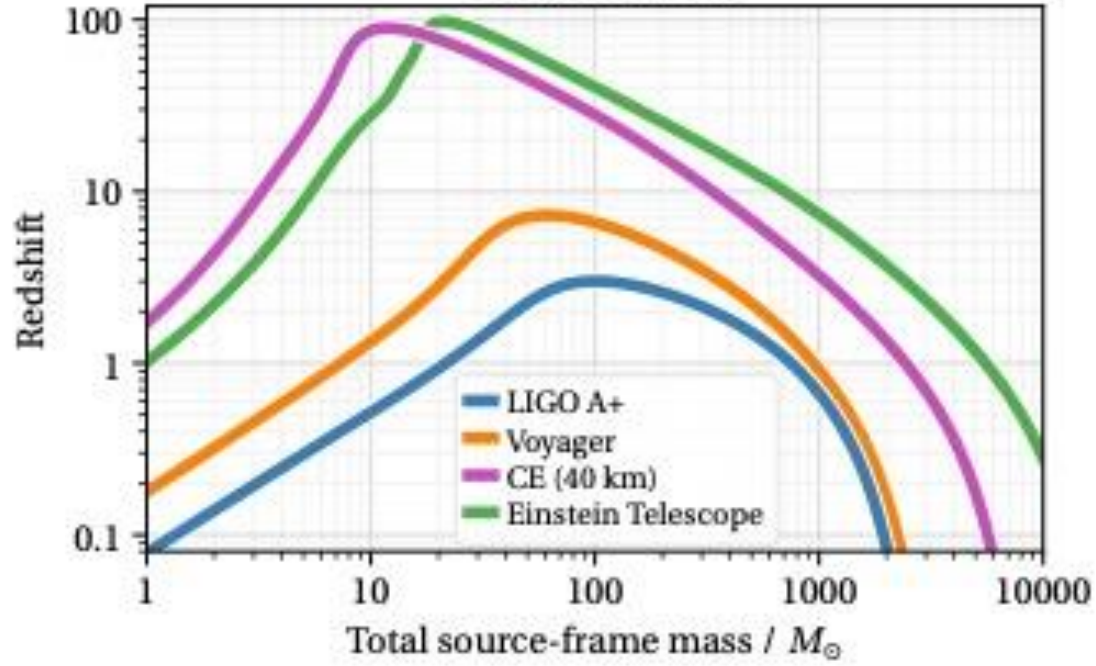




Einstein Telescope timeline





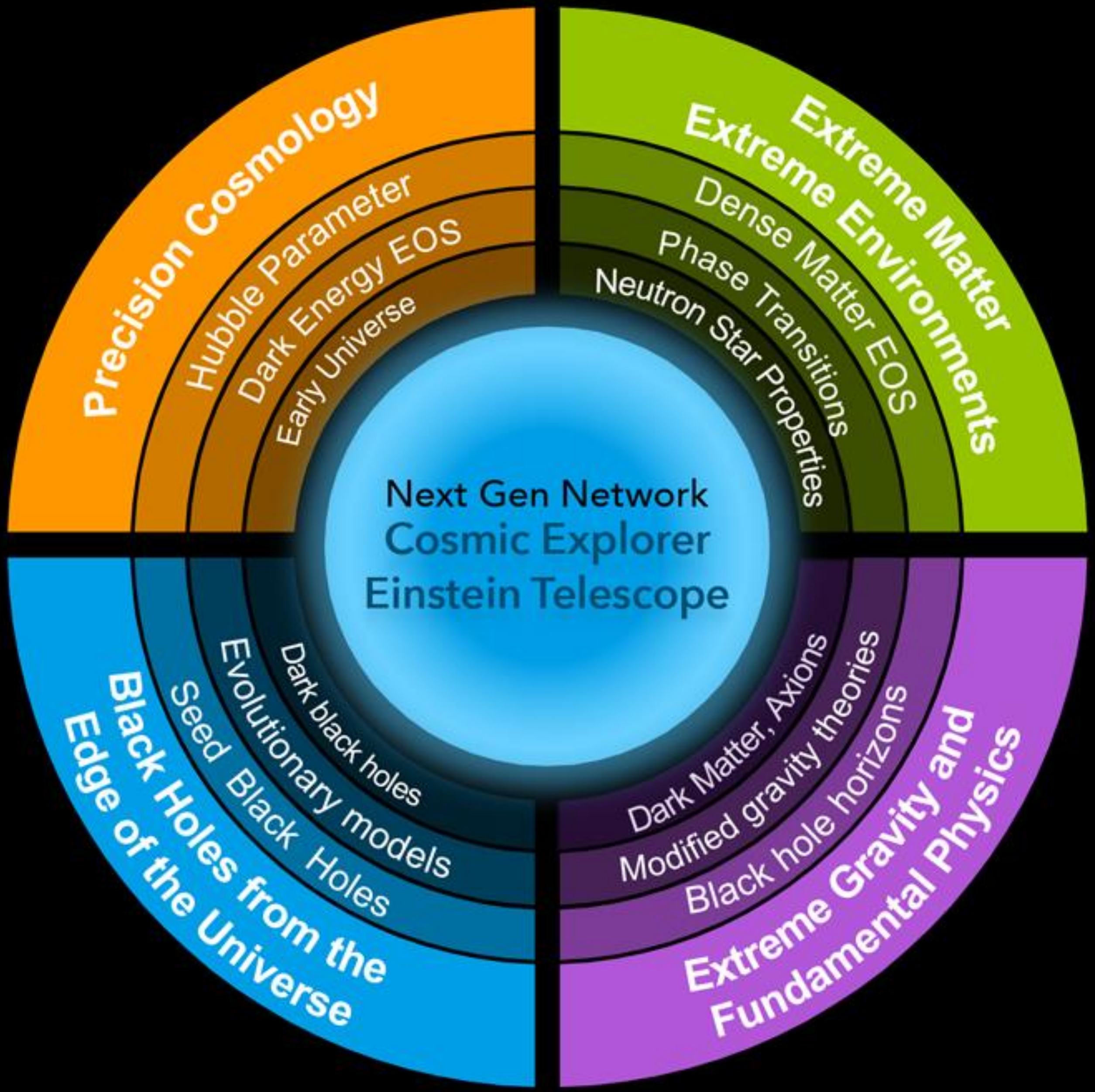


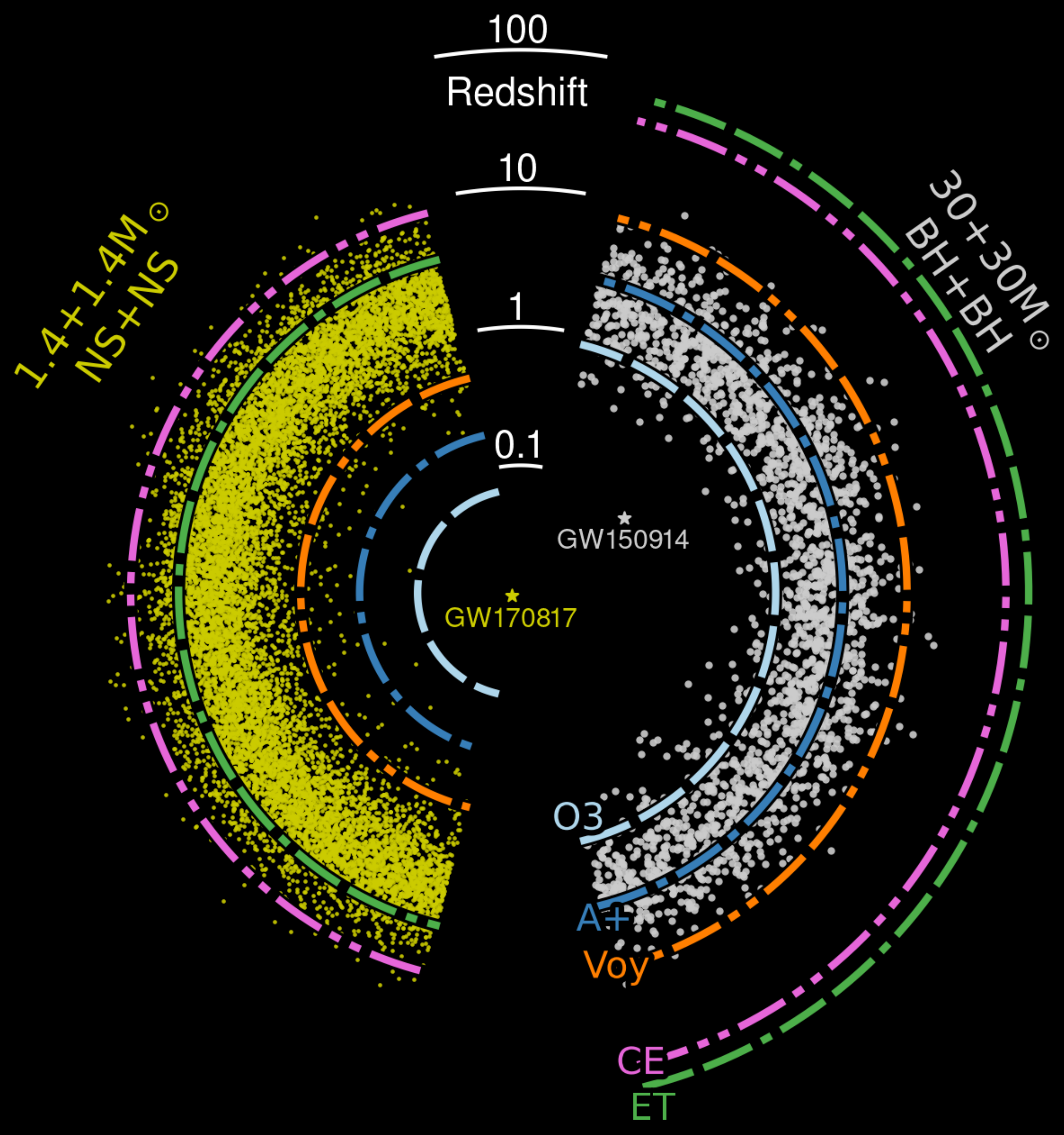
***Top*: Amplitude spectral densities of detector noise** for Cosmic Explorer (CE), the current (O3) and upgraded (A+) sensitivities of Advanced LIGO, LIGO Voyager, NEMO, and the three paired detectors of the triangular Einstein Telescope.

***Bottom*: Maximum redshift** (vertical axis) at which an equal-mass binary of given source-frame total mass (horizontal axis) can be observed with a signal-to-noise ratio of 8. Different curves represent different detectors.

For binary neutron stars (total mass ~$3M_\odot$), ET and CE will give access to redshifts larger than 1, where most of the mergers are expected to happen.

For binary black holes, they will enable the exploration of redshifts of 10 and above, where mergers of black holes formed by either the first stellar population in the universe (Pop III stars) or by quantum fluctuations shortly after the Big Bang (primordial black holes) might be found.

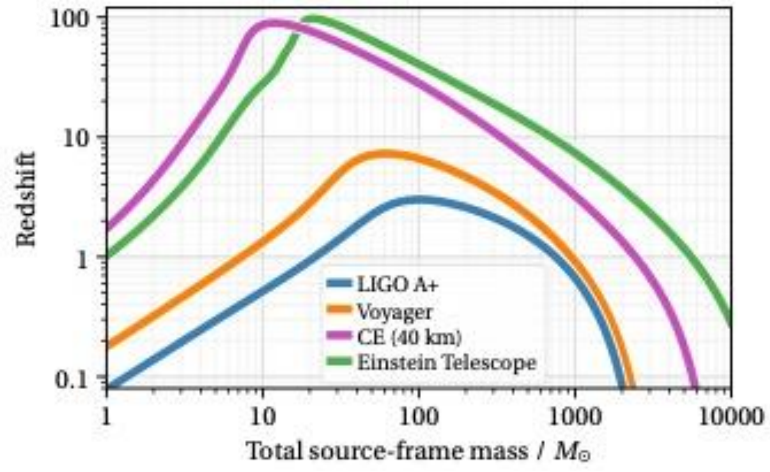

Precision Cosmology
Hubble Parameter
Dark Energy EOS
Early Universe
Extreme Matter
Extreme Environments
Dense Matter EOS
Phase Transitions
Neutron Star Properties
Next Gen Network
Cosmic Explorer
Einstein Telescope
Black Holes from the
Edge of the Universe
Seed Black Holes
Evolutionary models
Dark black holes
Extreme Gravity and
Fundamental Physics
Black hole horizons
Modified gravity theories
Dark Matter, Axions



Astrophysical horizon of current and proposed future detectors for compact binary systems.

The lines indicate the maximum redshift at which a detection with signal-to- noise ratio 8 could be made. The detectors shown here are Advanced LIGO during its third observing run (“O3”), Advanced LIGO at its anticipated sensitivity for the fifth observing run (“A+”), a possible cryogenic upgrade of LIGO called Voyager (“Voy”), the Einstein Telescope (“ET”), and Cosmic Explorer (“CE”).

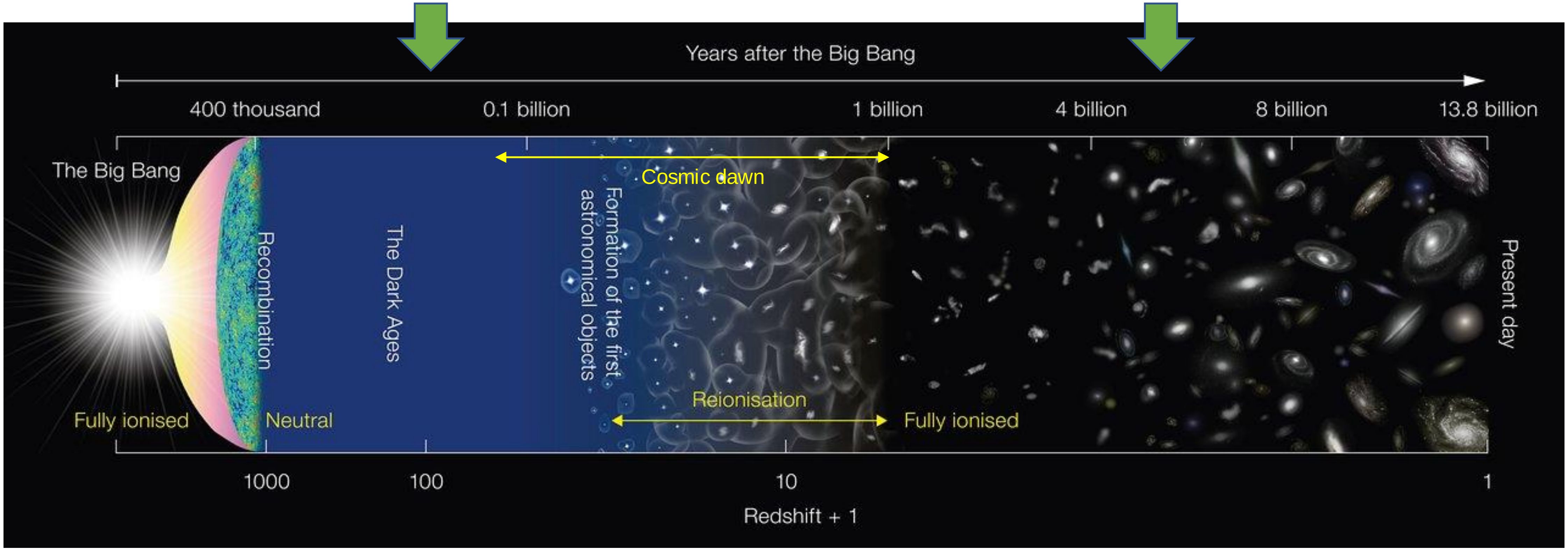
The yellow and white dots are for a simulated population of binary neutron star mergers and binary black hole mergers, respectively, following the Madau and Dickinson stellar formation rate.



The 3G detectors shall look deep into the *Dark Ages* of the Universe, down to times before the start of the *Cosmic Dawn* – the period from about 50 million years to one billion years after the Big Bang when the first stars, black holes, and galaxies in the Universe formed – and thus may be able to get a glimpse of the history of Population III stars.

ET horizon

current detectors' horizon



• COSMIC DAWN

The *cosmic dawn* is the epoch extending from redshift z ~ 20 when the universe was only a few hundred million years old to redshift z ~ 6, corresponding to about one billion year. During that epoch, dark mater haloes begin to collapse and the first stars, the first black holes and galactic discs start to form and grow, lightening up the universe. Around z ~ 11 - 6 the universe completed the phase of cosmic *re-ionization* of gas turning neutral hydrogen and helium, into a hot tenuous intergalactic plasma. The farthest QSO ULAS J1120+0641, Gamma Ray Burst GRB 090423 and galaxy MACS0647-JD, detected at the limits of current capabilities, were in place when the universe was less than one billion years old, at redshift ~ 7, 8, 9, respectively. They are the brightest sources probing the tip of an underlying distribution of fainter early objects, the less luminous pre-galactic structures and black holes for which little is known. Even the brightest QSOs fade away in the optical due to the Gunn-Peterson trough* and the search for the deepest sources may be hindered by confusion due to crowding and the unresolved background light.

• COSMIC HIGH NOON

The cosmic high noon is an epoch of critical transformations for galaxies, extending from z ~ 6 to 2. Around redshift 3, the luminous QSOs and the star formation rate (SFR) have their *peak*. Galactic discs had much higher surface densities and gas fractions than now, and the nature of gravitational instabilities seeded in their amorphous structures and the physics of star's formation may have been different or more extreme than today. The cosmic-integrated star formation rate and the accretion rate of gas feeding black holes and their powerful outflows were probably at maximum strength around z ~ 2. Galaxy mergers during cosmic high noon were likely to be the force driving the process of galaxy assembly, star formation and black hole growth. The role of mergers is still a matter of dispute but it is at the base of our current paradigm of galaxy formation.

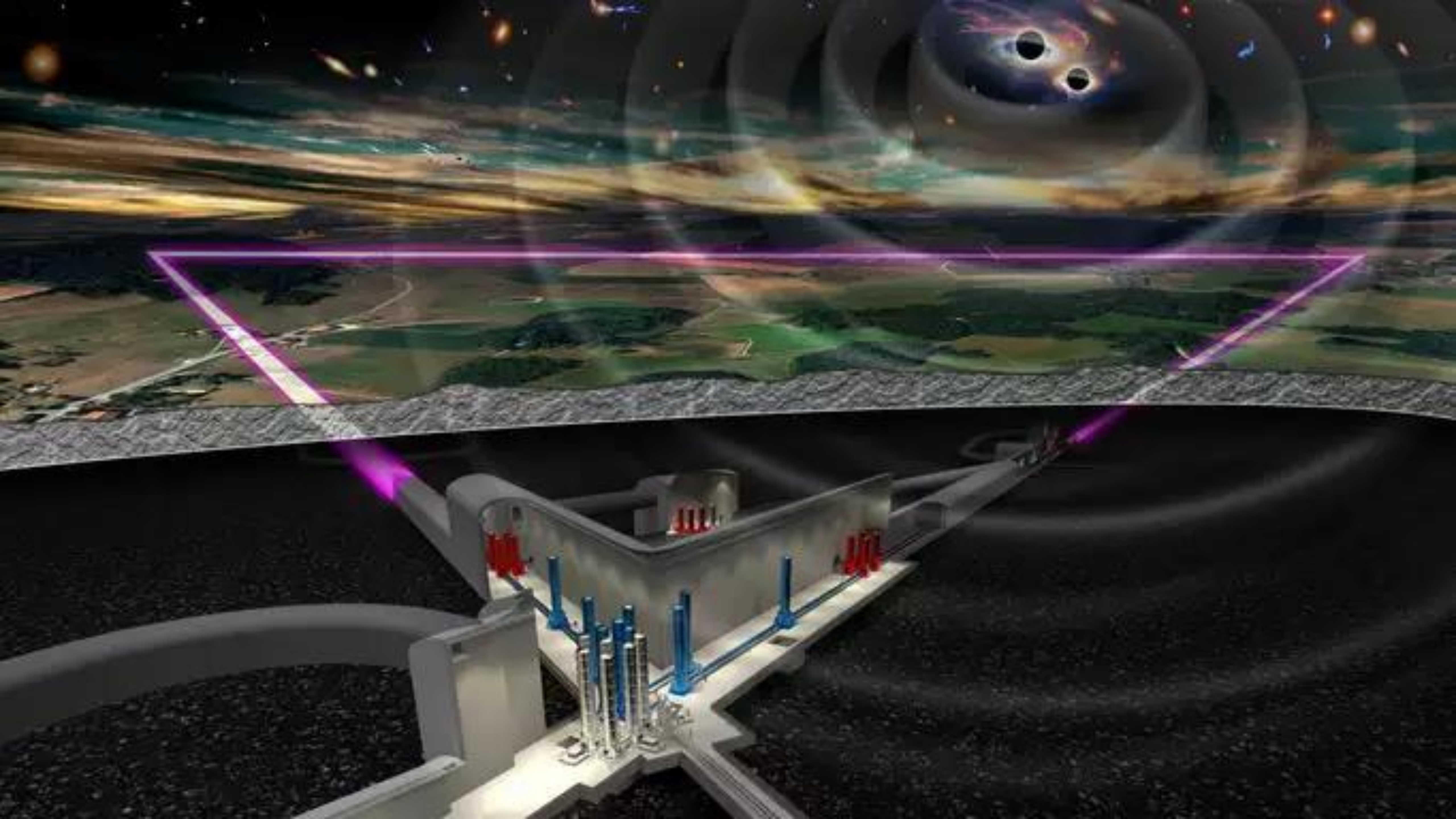
• COSMIC AFTERNOON

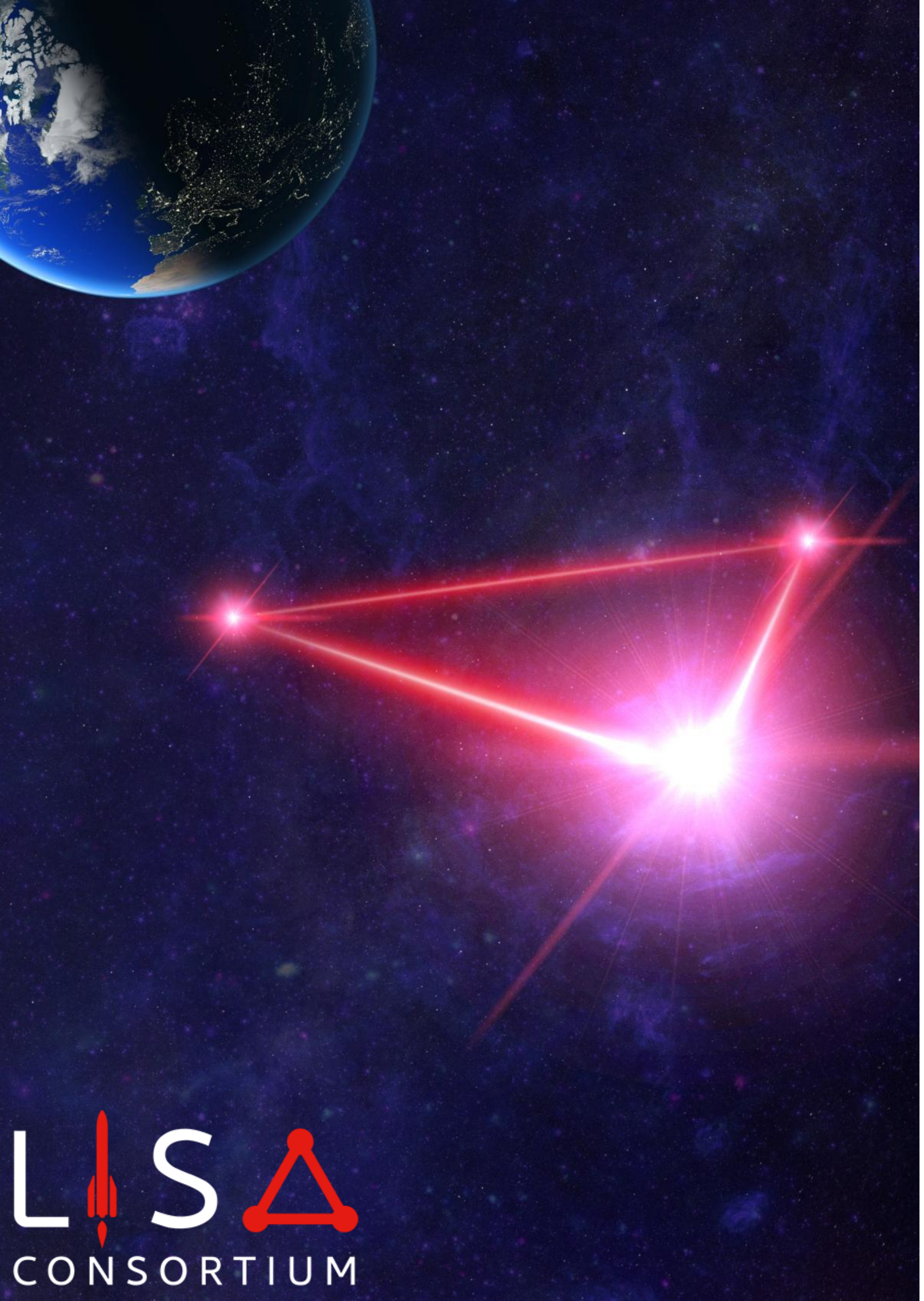
The *cosmic afternoon* corresponds to the epoch of decline of both the star formation and QSO's activity. It is a phase of relented evolution extending from z ~ 1 to the present. Observations of galaxies and of the less luminous active galactic nuclei (AGN) give a description of this quieter universe. Dormant black holes, as dark massive objects, are now found in near galaxies. Their mass correlates tightly with the mass of the stars in the host galaxy revealing the occurrence of a joint, symbiotic evolution that likely established during cosmic high noon and dawn. Among the galaxies, the Milky Way, our closest environment, is the perfect habitat for exploring the nature of all stellar populations, and in particular of compact objects, the white dwarfs, neutron stars and stellar black holes that we observe isolated or in binaries. Over the years the study of these sources allowed to unravel key processes of stellar evolution indicating, e.g. pathways for the formation of type Ia supernovae – standard candles for exploring the geometry of cosmic expansion – and evolution tracks for forming neutron star binary systems. Neutron star binaries have been the first cosmic laboratories to test General Relativity, giving unambiguous proof, albeit indirect, that gravitational waves exist in nature.

Surprisingly the Milky Way offers also the closest example of an imminent merger in our Local Group: Andromeda along with a handful of lesser galaxies is falling toward us, and Andromeda and the Milky Way house central black holes that will pair to form an binary before the Sun will expand into a red-giant.

* In astronomical spectroscopy, the Gunn–Peterson trough is a feature of the spectra of quasars due to the presence of neutral hydrogen in the Intergalactic medium (IGM). The trough is characterized by suppression of electromagnetic emission from the quasar at wavelengths less than that of the Lyman-alpha line at the redshift of the emitted light.

ETIC – Einstein Telescope Infrastructure Consortium

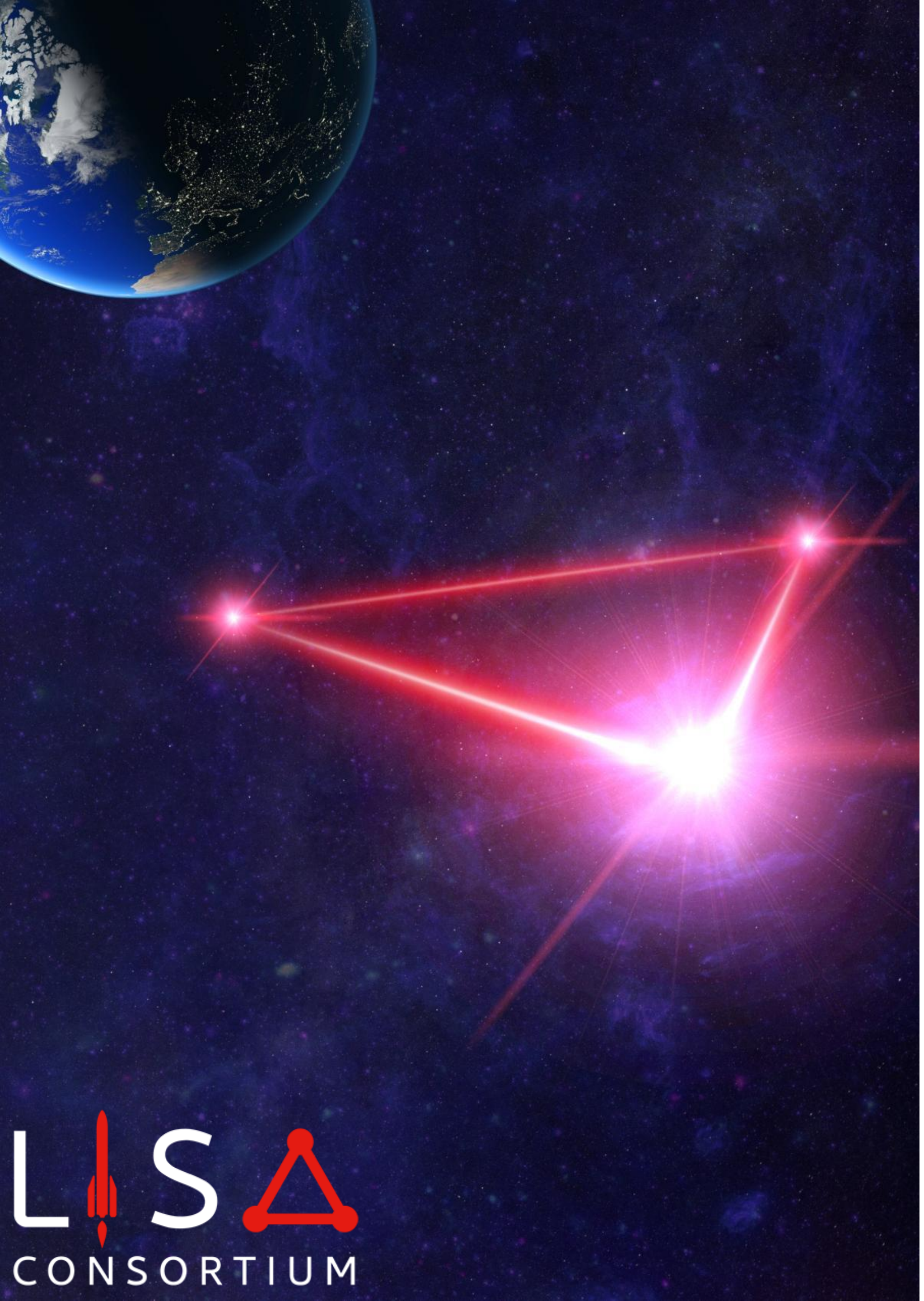




LISA is a space-borne Gravitational Wave Observatory with an arm-length of 2.5 million km, compared to the few km's of the ground-based observatories.

Electromagnetic observations of the universe, plus theoretical modeling, suggest that the richest part of the gravitational wave spectrum falls into the frequency range accessible to a space interferometer, from about 10^{-4}Hz to 10^{-1} Hz.

In this band, **important first-hand information** can be gathered to test the history of the universe out to redshifts of order 20, gravity in the dynamical strong field regime and the TeV scale energy of the early universe.

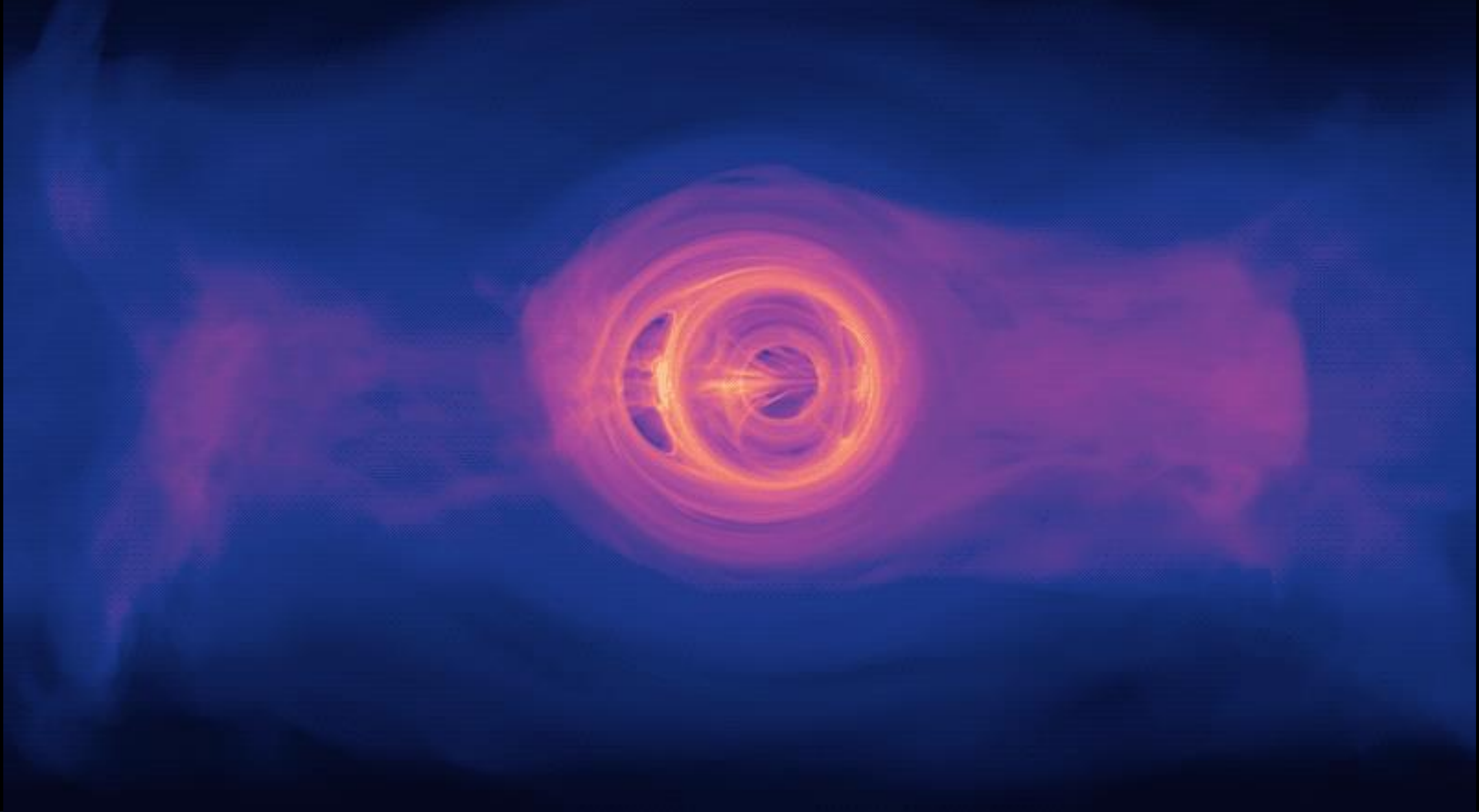


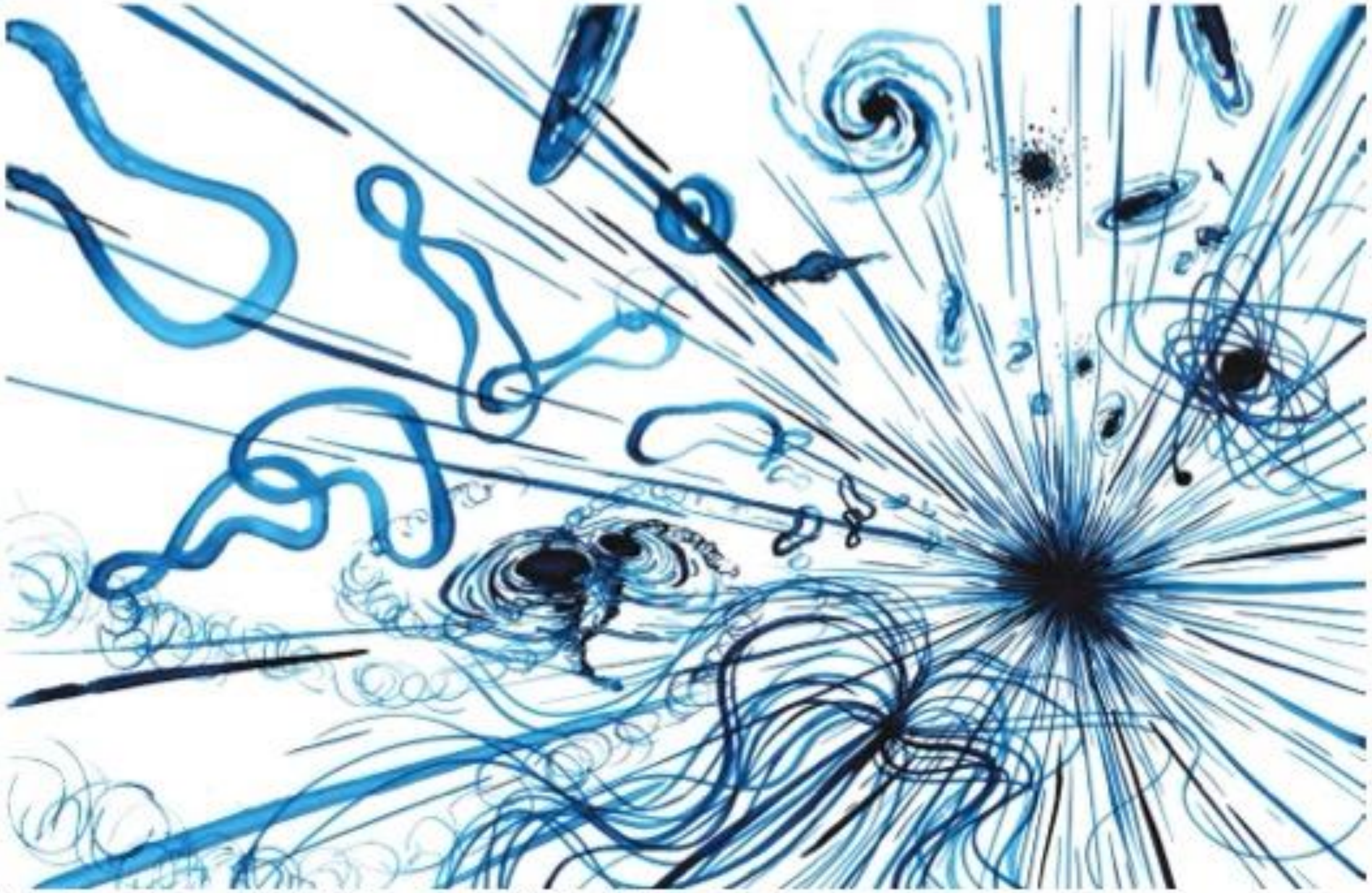
Mission objectives: As part of its core science objectives, LISA will:

- Study the formation and evolution of tens of thousands of compact binary star systems within the Milky Way;
- Trace the origin, growth and mergers of massive black holes across cosmic ages;
- Probe the dynamics of incredibly massive and dense star clusters found near the centres of most galaxies, using decaying orbits known as ‘extreme mass-ratio inspirals’, or EMRIs;
- Understand the astrophysics of stellar-origin black holes;
- Explore the fundamental nature of gravity and black holes;
- Probe the rate of expansion of the Universe;
- Understand the relic gravitational waves from the early evolution of the Universe (‘stochastic’ waves, which arise from many random independent events and combine to form a ‘cosmic gravitational wave background’) and their wider implications;
- Search for gravitational wave bursts and unforeseen sources.

Planned launch: 2037

https://www.esa.int/Science_Exploration/Space_Science/LISA_factsheet https://www.youtube.com/watch?v=x-k112InxfY https://svs.gsfc.nasa.gov/13043





Warped space-time around a black hole, as portrayed by artist Lia Halloran.

Kip Thorne and Lia Halloran on black holes

The mechanics of space-time storms, wormholes and time machines – told through poetry and paintings.

https://www.nature.com/articles/d41586-023-04023-0

And what do you think will happen in gravitational-wave research over the next decade?

Thorne: This year, the European Pulsar Timing Array and other observatories reported detecting a background of gravitational waves from colliding supermassive black holes, and perhaps from the birth of the Universe. Future discoveries, with LIGO and its successors on the ground as well as gravitational observatories in space, will deepen our understanding of warped space-time. Today, we're in the same situation we were in four centuries ago, when Galileo built the first optical telescope. He and other astronomers discovered a new world—the richness of the Solar System. Now, we're poised to discover the richness of the cosmos.