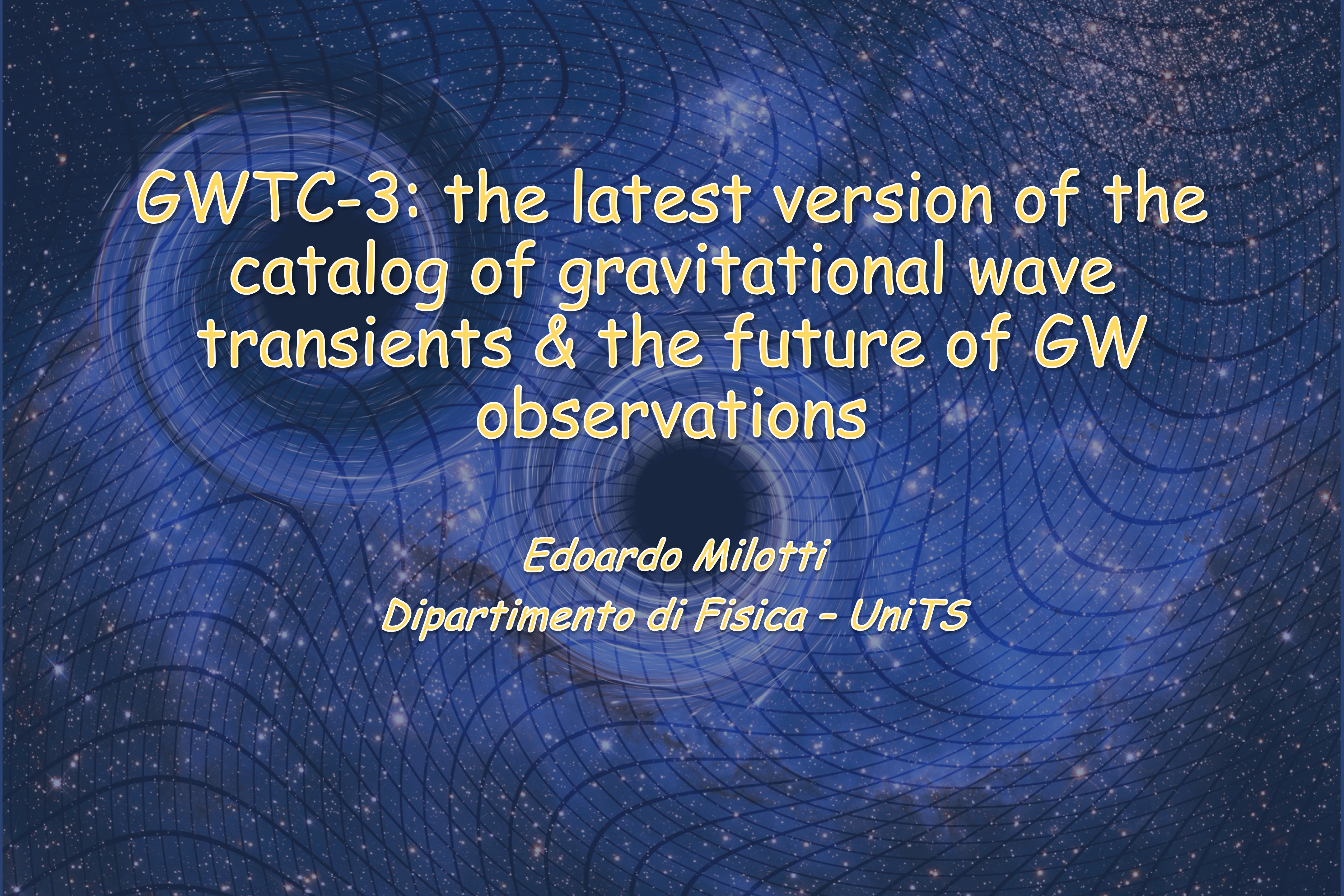


GWTC-3: the latest version of the catalog of gravitational wave transients & the future of GW observations

Edoardo Milotti

Dipartimento di Fisica - UniTS

The Gravitational Wave Transient Catalog (GWTC)

GWTC-3 is the third and latest update of the Gravitational-Wave Transient Catalog from LIGO, Virgo, and KAGRA.
GWTC-3 updates the previous catalogs with gravitational-wave observations from the second part of Observing Run 3, which lasted from November 2019 to March 2020. Collectively, GWTC-3 represents the largest number of gravitational-wave observations assembled to date.

So far, the following versions of GWTC have been released:

- **GWTC-1**, which contains a total of 11 events from the first and second observing runs (O1 and O2).
- **GWTC-2**, which added 39 events to GWTC-1, bringing the total number of events to 50 (from O1, O2, and O3a, the first part of O3).
- **GWTC-2.1** revisited the O3a analysis, finding an additional 8 candidates, but also reclassifying 3 of the original GWTC-2 candidates because their probability of being real astrophysical signals dropped to less than 50%. This brought the total to 55 events.
- **GWTC-3** adds a further 35 gravitational-wave events from O3b, bringing the total number of events observed to date to 90.

GWTC: Gravitational Waves Transient Catalog - 3

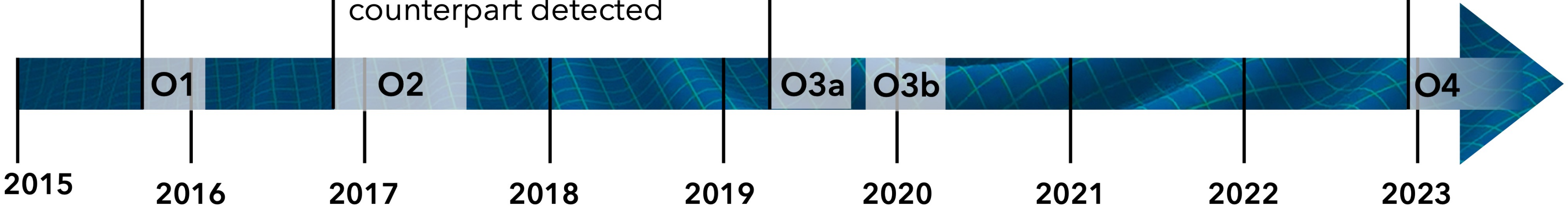
arXiv
1811.12907
2108.01045
2111.03606

3 GW detection during O1
- First direct detection of GW
- From coalescing binary systems of black holes

8 GW detection during O2
- 1 coalescing binary system of neutron stars: electromagnetic counterpart detected

79 GW detection during O3
- 44 during O3a, including 1 confirmed binary system of neutron stars
- 35 during O3b, including 2 confirmed systems of neutron stars - black holes
- No electromagnetic counterpart

O4 to start in ~~2022~~ 2023
- Planned for ~~December~~ March



90 GW detections reported

Coalescence of compact objects (black holes, neutron stars)

1 multimessenger event (GW + EM observation)

Mass range 1.2 → 107 M⊙ (stellar)

Distance range 40 Mpc → 6 Gpc (z → 0.45)

Leïla Haegel

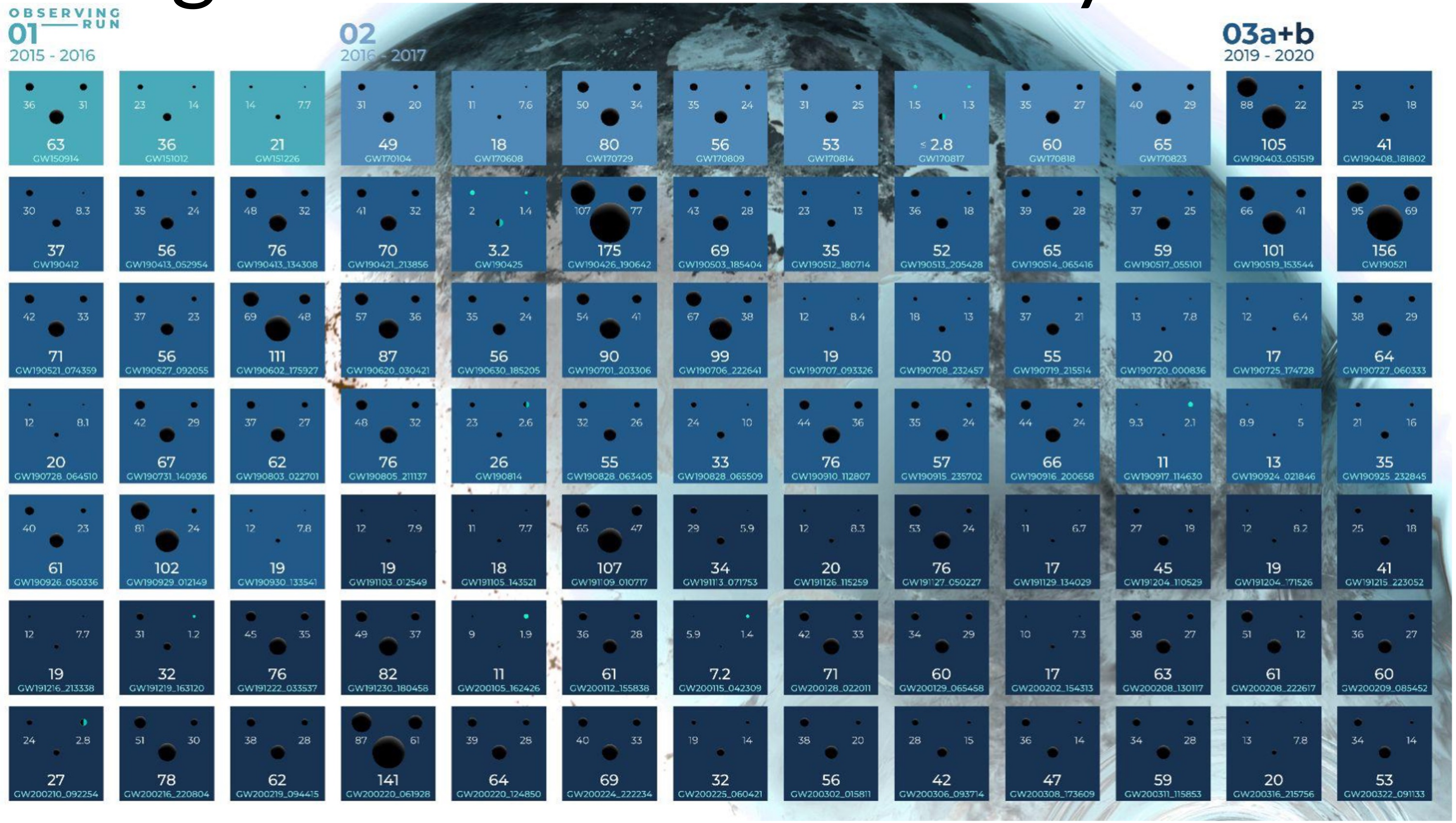
The gravitational-wave story

1916 Einstein predicts gravitational waves in general relativity

1974 First indirect evidence of gravitational waves from binary pulsars

2015 First observation of gravitational waves at the start of O1

Observing runs
O1: 2015–2016
O2: 2016–2017
O3: 2019–2020
O4: ~2022–2023



Instruments in O3b

Quantum squeezing
Vacuum state of light with phase fluctuations smaller than the normal vacuum to reduce phase noise at the expense of amplitude noise

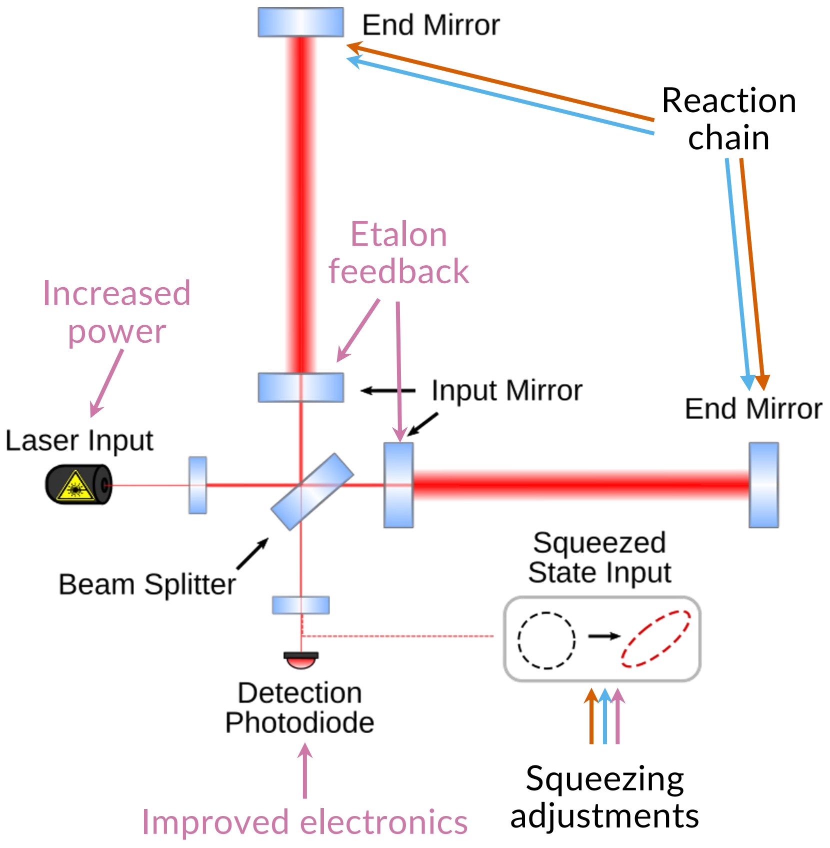
For more on squeezing:
Tse *et al.* (2019)
Phys. Rev. Lett. 123, 231107
Acernese *et al.* (2019)
Phys. Rev. Lett. 123, 23110

Similar to during O3a, where the main improvements were:

- adjustment of in-vacuum squeezing for LIGO Hanford and Livingston
- increase of laser power for Virgo

After October commissioning break:

- LIGO: Adjustments to the squeezing subsystem and reduction of scattered light noise; implementation of reaction-chain tracking
- Virgo: Increased laser power; improved electronics, alignment, etalon feedback system, squeezing and software



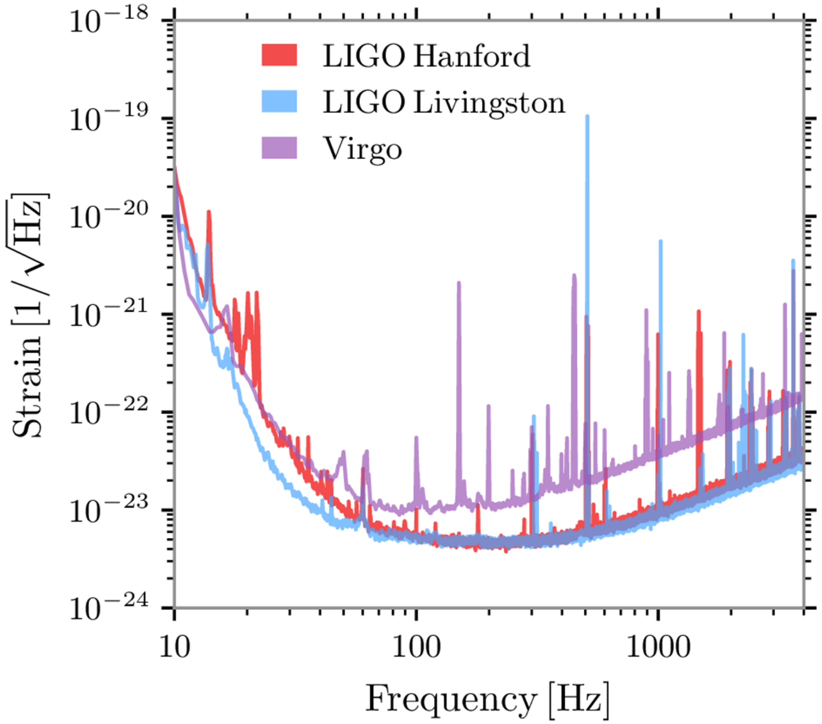
Detector sensitivity curves

Strain sensitivity can be characterized by the detector noise spectrum

A smaller value of the spectrum means lower noise at a given frequency and an increased sensitivity to signals

The previous upgrades led to a better **detector sensitivity** and also a high duty cycle, despite running through winter:

- 142.0 days with **at least one detector** observing
- 79%, 79% and 76% for Hanford, Livingston and Virgo
- Triple time 51.0%, double time 85.3% and single time 96.6%



Binary neutron star ranges

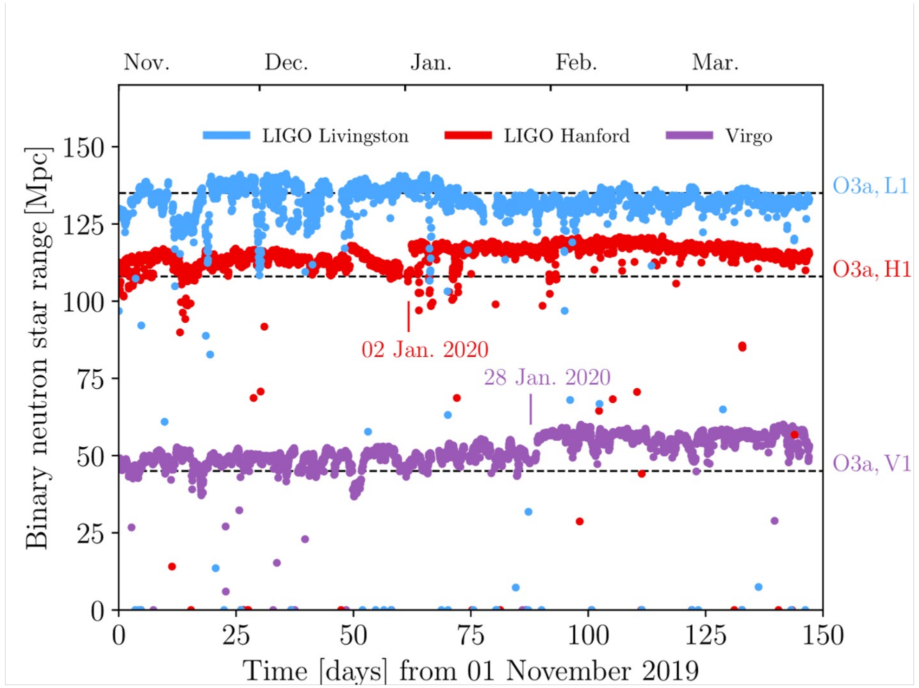
The **binary neutron star (BNS) range** is a standard measure of detector sensitivity. It distance a detector is able to detect a signal from a 1.4+1.4 solar mass binary

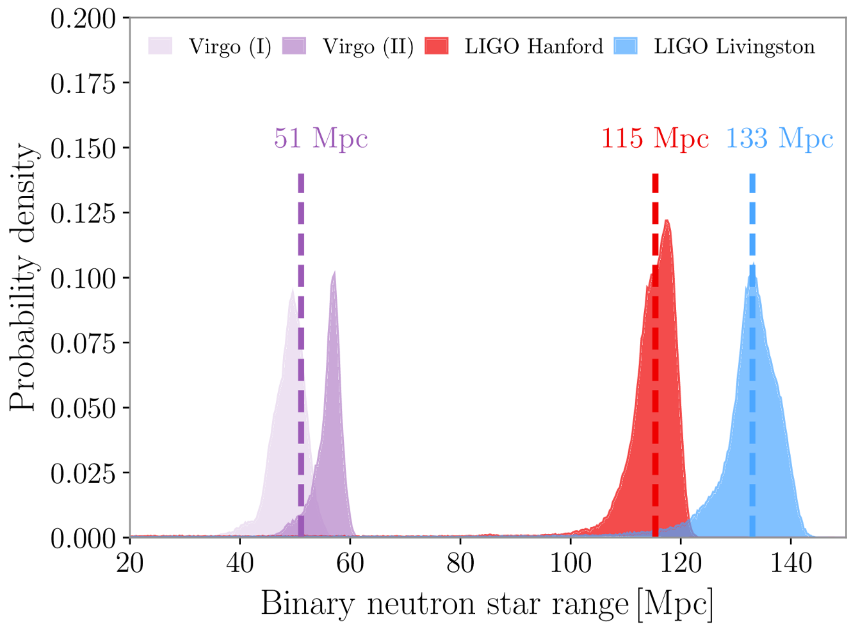
Higher mass sources are detected at greater distances

2 Jan: squeezing improvements
28 Jan: electronics, squeezing and alignment improvements

Median BNS ranges

LIGO Hanford: 115 Mpc, LIGO Livingston: 133 Mpc, Virgo: 51 Mpc





Glitch rate

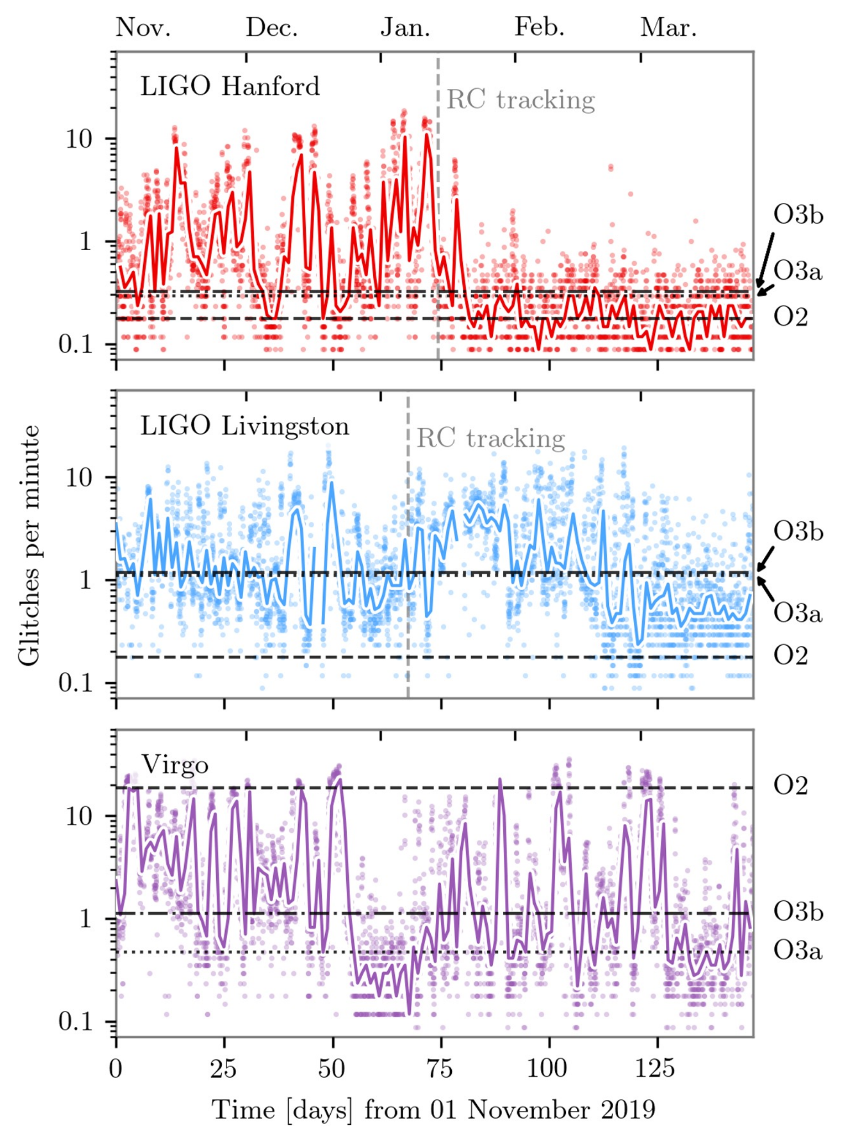
Glitches are transient non-Gaussian noise. New glitch types can arise from instrument changes or sensitivity increases

A high glitch rate can drive up noise background estimates for gravitational-wave searches

For more on glitches: Davis *et al.* (2021) Class. Quant. Grav. 38, 135014

Hanford sees a significant drop in glitch rate after reaction-chain tracking was implemented.

Virgo glitch rate contains peaks largely correlated to unstable weather conditions.

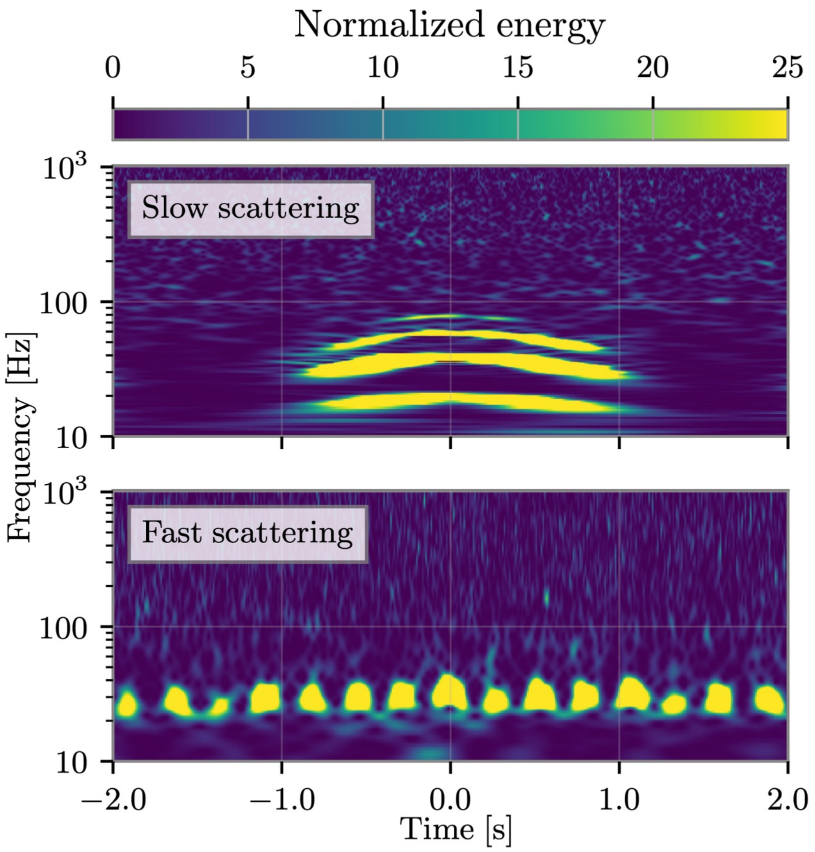


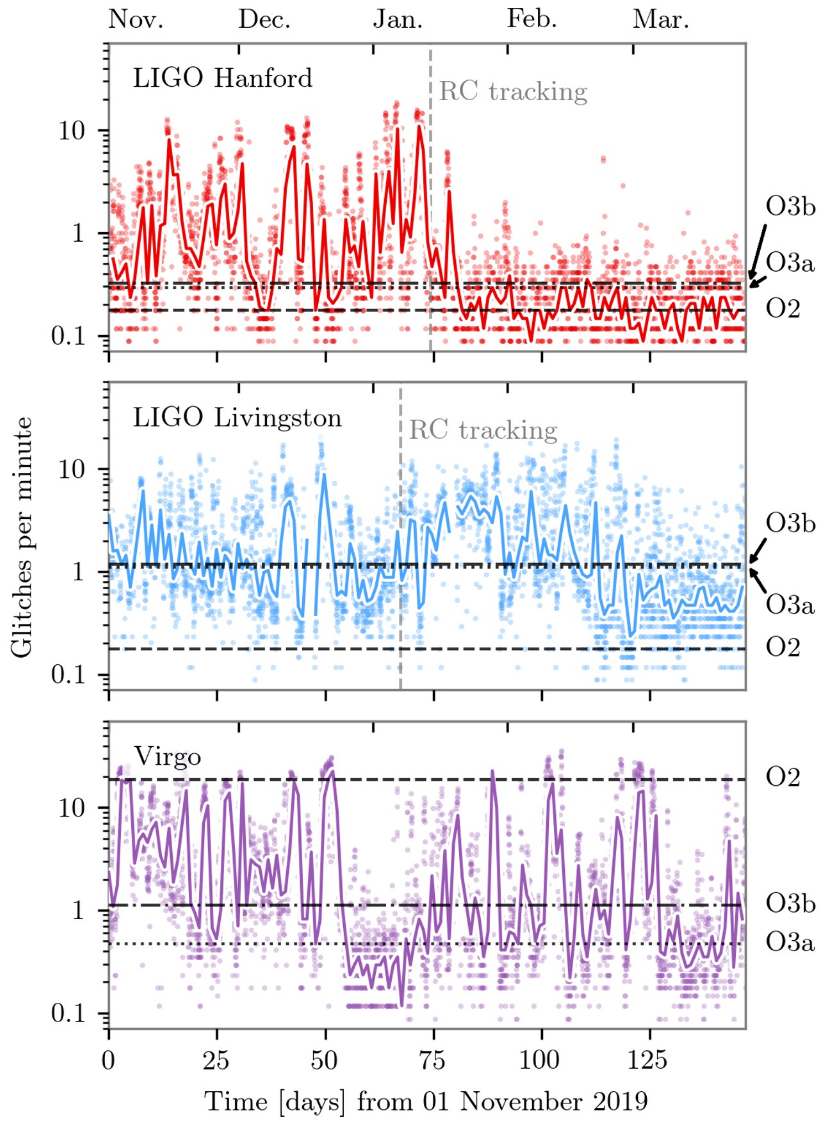
Glitch rate

Scattered light (of various forms) was a major driver of glitch rate at all three detectors

Scattered light tends to be driven by local **ground motion**, and correlated with **bad weather**

For more on O3 scattered light:
Soni *et al.* (2021)
Class. Quant. Grav. 38, 025016





Event validation

Same **event validation** procedures used as in O3a

Candidates in the main event list have a probability of astrophysical origin > 0.5

Noise mitigation includes subtraction of excess noise and glitches

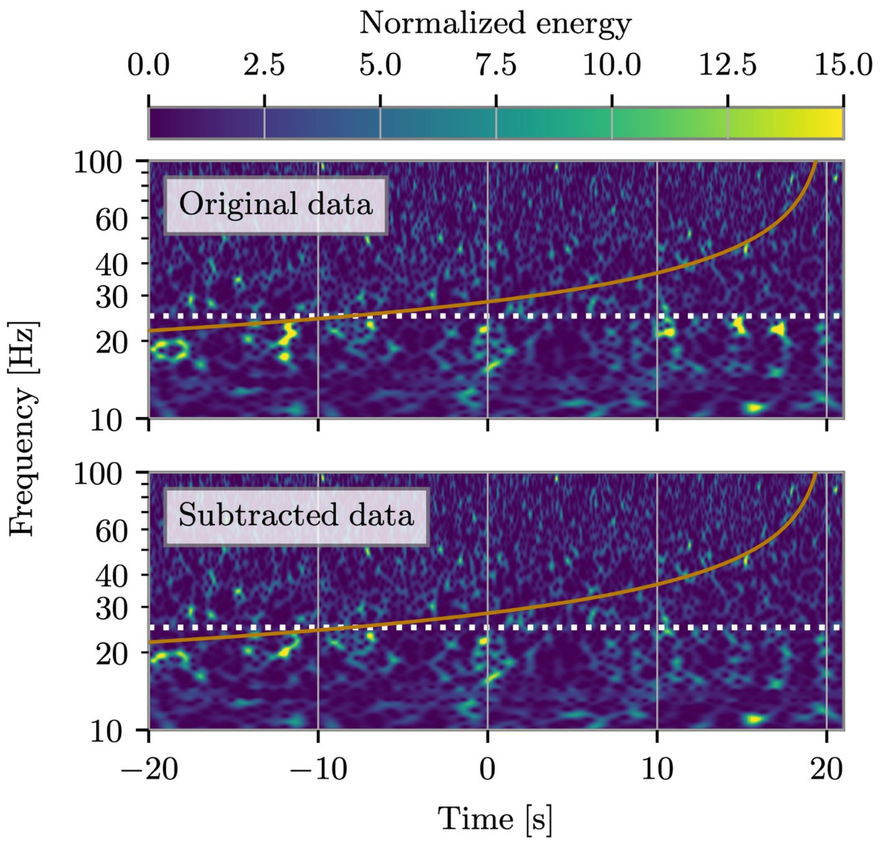
Glitches were modeled with the BayesWave algorithm

No candidates in the main event list were found to be likely instrumental artifacts by event validation procedures.

3 marginal candidates were found to be **likely instrument artifacts.**

Glitch subtraction applied to 8 events before source property analysis.

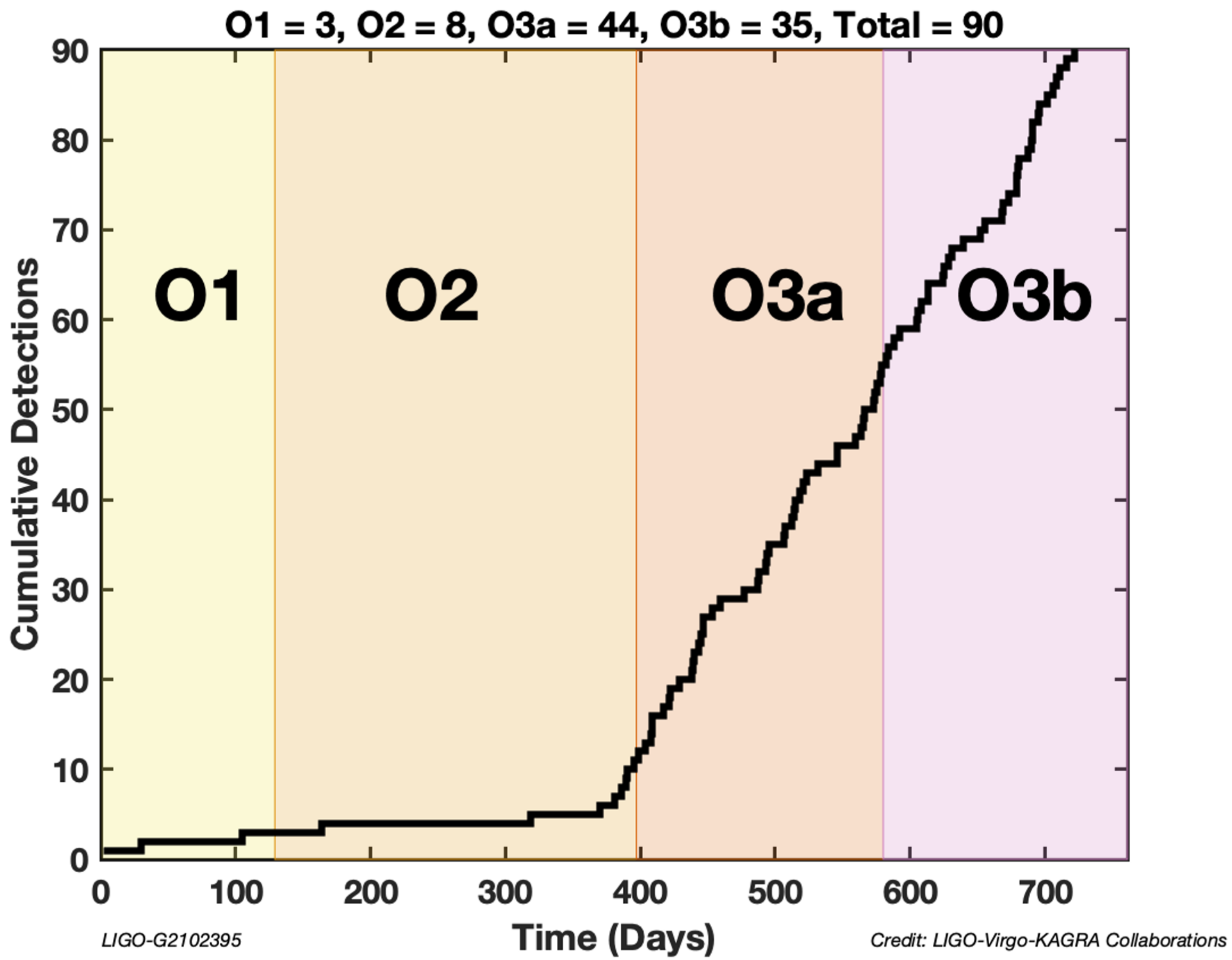
GW200115_042309



Detections across observing runs

The event rate in O3b is consistent with O3a and our expectations

Adding 35 new gravitational wave candidates brings our total to 90



Search methods

Same methods as GWTC-2.1 (GstLAL, MBTA, PyCBC) and GWTC-2 (cWB)

Searches are done on two timescales: low-latency and **offline re-analysis**

Modeled searches

- GstLAL, MBTA, PyCBC Broad, PyCBC BBH
- Assume the source is a compact binary coalescence (CBC)
- Uses matched filtering and banks of template waveforms with varying parameters to find signals in the data
- HL, HV, LV, HLV coincidences
- GstLAL allows for single-detector candidates

Minimally modeled search

- cWB
- Can potentially identify non-CBC sources
- Does **not** use matched filtering or waveforms
- Identifies excess power in coincident strain data to find signals
- HL, HV, LV coincidences

Estimating significance

Follow GWTC-1, GWTC-2.1 in using **p-astro > 0.5** threshold for inclusion in main event list (assuming CBC sources).

Follow GWTC-2.1 in using **FAR < 2 per year** threshold for inclusion in marginal event list.

False alarm rate (FAR)

- How often do we expect noise to produce a trigger with the same ranking statistic?
- Does not take into account any astrophysical information

Probability of astrophysical origin (p-astro)

- Assess significance by comparing the foreground and background ranking statistic distributions, informed by the estimated astrophysical rates

$$
\begin{aligned}
p_{\mathrm{astro}} &= p_{\mathrm{BNS}} + p_{\mathrm{NSBH}} + p_{\mathrm{BBH}} \\
&= 1 - p_{\mathrm{terr}}
\end{aligned}
$$

Candidate list

Same methods as GWTC-2.1 (GstLAL, MBTA, PyCBC) and GWTC-2 (cWB)

Main event lists: p-astro > 0.5 in at least one pipeline (for CBC sources)

Thresholds for inclusion

- Main event list (35 events)
  - p-astro > 0.5
  - ~10–15% contamination
- Marginal event list (7 events)
  - p-astro < 0.5 but FAR < 2 per year
- Deep sub-threshold list (1041 events)
  - FAR < 2 per day
  - ~2% purity

Low latency vs offline

- 39 events found in low latency
  - 16 retracted
  - 5 events not found offline
- 17 events found offline, not found in low-latency
- 35 events added to the catalog

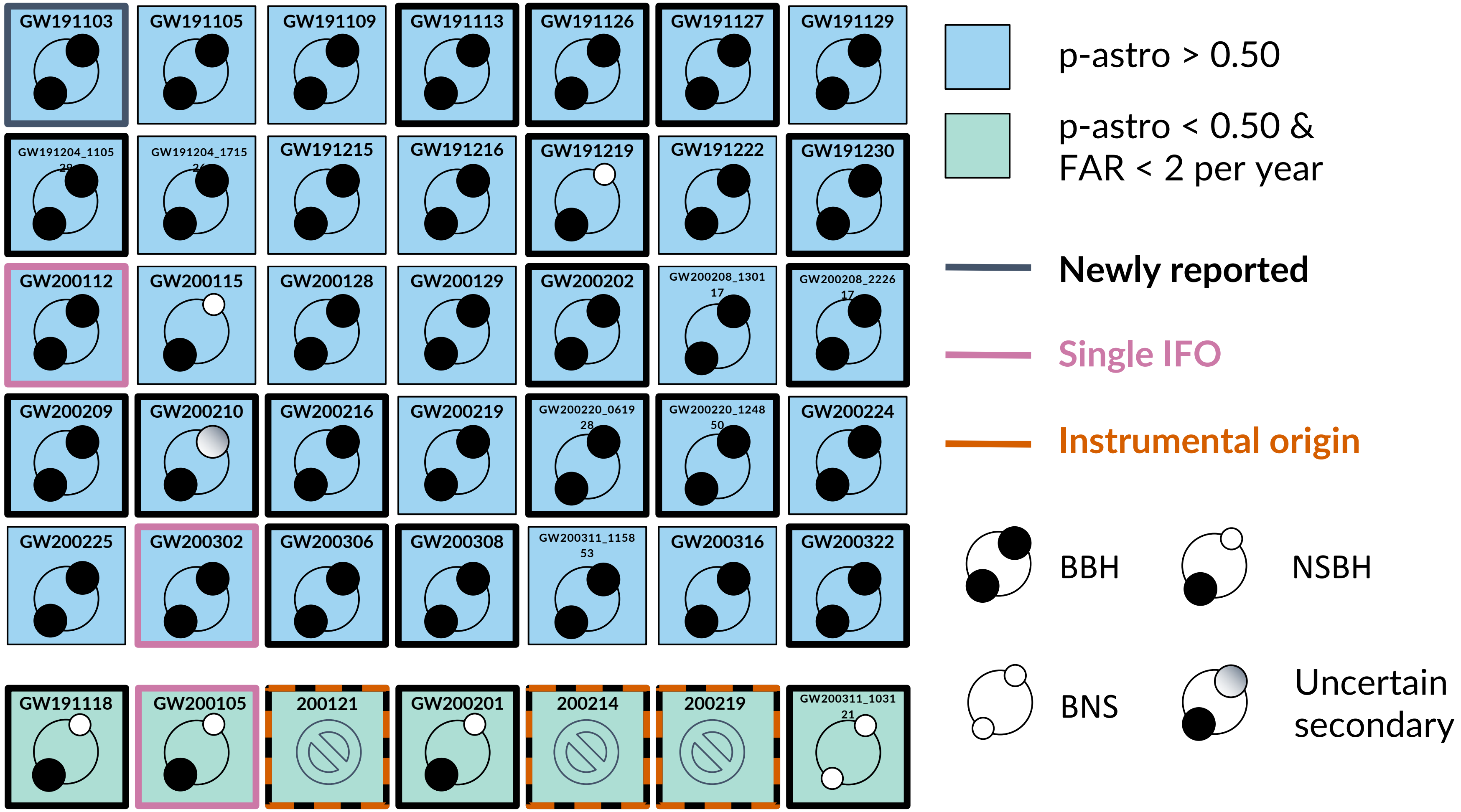
Candidate list

35 events with p-astro > 0.5

3 NSBH (or potential NSBH) + GW200105

3 marginal candidates with identified instrumental origin (including cWB only event 200214)

2 single detector candidates + GW200105



GW191103	GW191105	GW191109	GW191113	GW191126	GW191127	GW191129
GW191204_110529	GW191204_171526	GW191215	GW191216	GW191219	GW191222	GW191230
GW200112	GW200115	GW200128	GW200129	GW200202	GW200208_130117	GW200208_222617
GW200209	GW200210	GW200216	GW200219	GW200220_061928	GW200220_124850	GW200224
GW200225	GW200302	GW200306	GW200308	GW200311_115853	GW200316	GW200322
GW191118	GW200105	200121	GW200201	200214	200219	GW200311_103121

🟦 p-astro > 0.50

🟩 p-astro < 0.50 & FAR < 2 per year

Newly reported

Single IFO

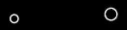
Instrumental origin

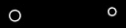
BBH

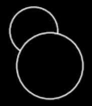
NSBH

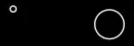
BNS

Uncertain secondary


GW191103_012549


GW191105_143521


GW191109_010717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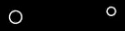
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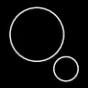
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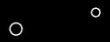
GW191129_134029


GW191204_110529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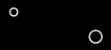
GW191215_223052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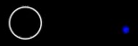

GW191219_163120


GW191222_033537


GW191230_180458

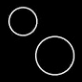

GW200112_155838


GW200115_042309


GW200128_022011


GW200129_065458

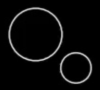

GW200202_154313


GW200208_130117

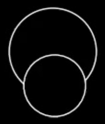

GW200208_222617


GW200209_085452


GW200210_092254


GW200216_220804


GW200219_094415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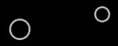
GW200220_124850


GW200224_222234


GW200225_060421

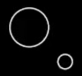

GW200302_015811


GW200306_093714


GW200308_173609


GW200311_115853


GW200316_215756


GW200322_091133

Zoheyr Doctor / CIERA / LIGO-Virgo Collaboration

Growing catalogue

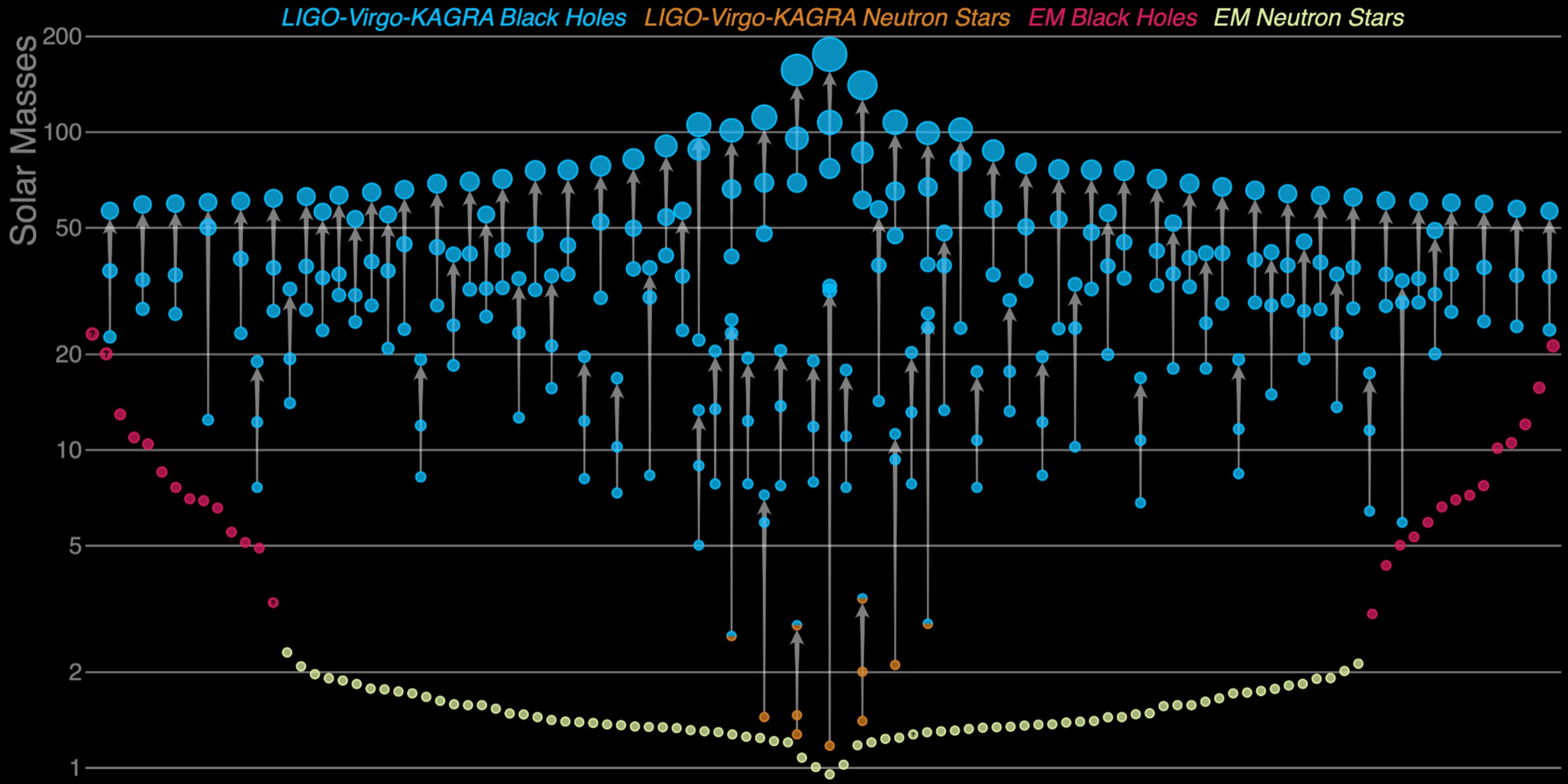
GWTC-3 adds **35** events with more than 50% probability of an **astrophysical** source

Total number of candidates is 90

Most are binary black holes **(BBHs)**

Some are neutron star–black hole binaries **(NSBHs)**

Two are binary neutron stars **(BNSs)**



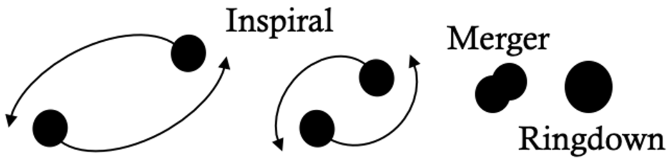
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

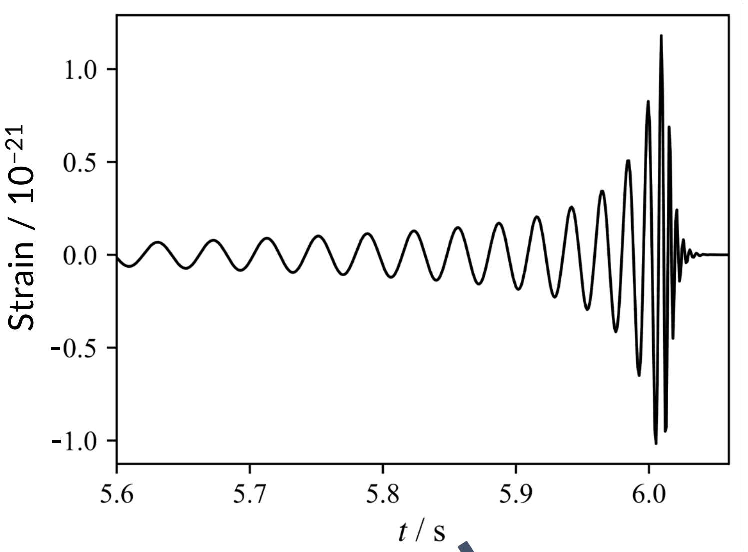
Sources

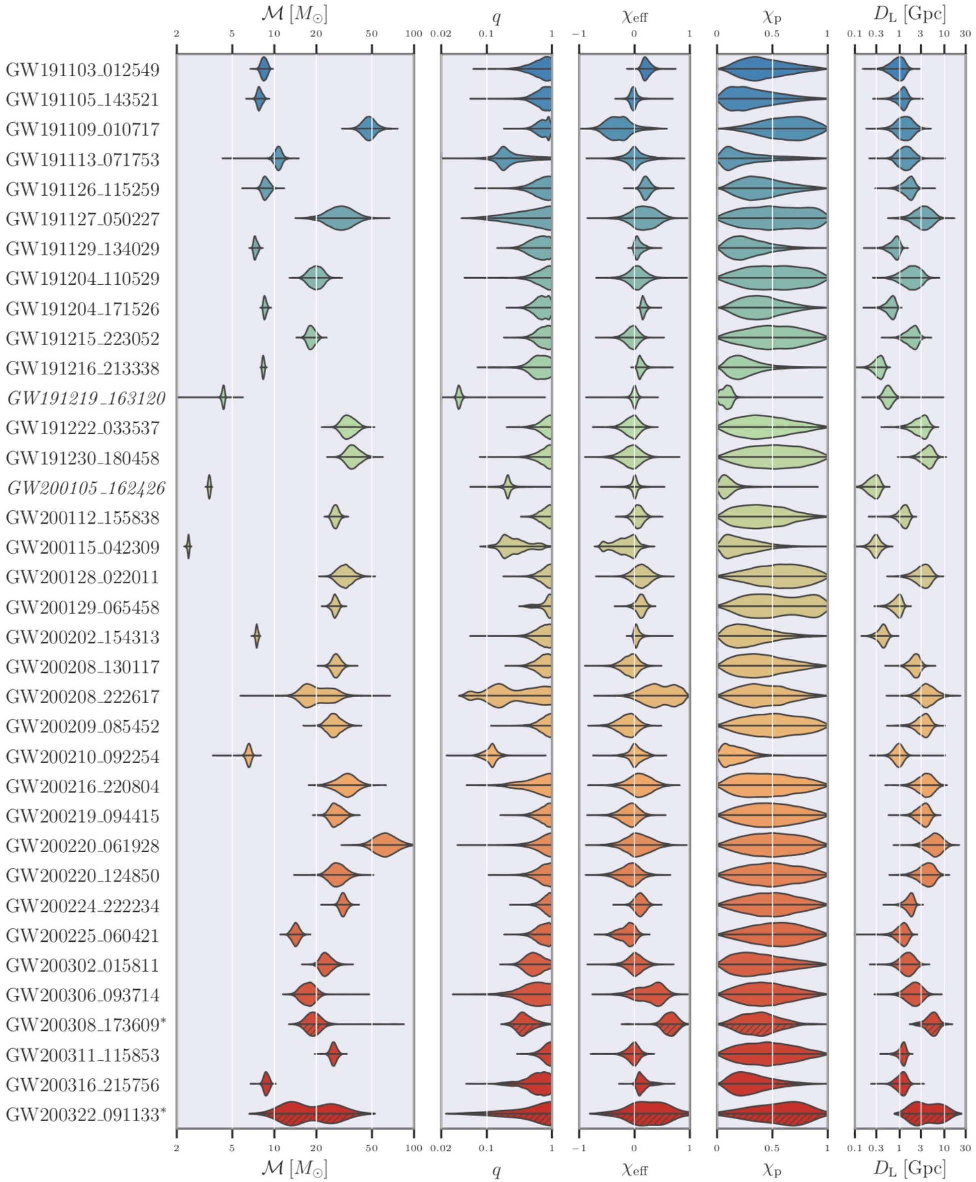
All signals so far have come from the merger of two compact objects: **neutron stars** and **black holes**

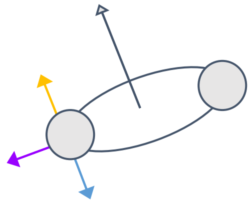
We analyse data to **infer source properties** like masses, spins, distance and sky location

We use the same **waveform models** as GWTC-2.1









Highlighted events

negative effective inspiral spin,
2nd most massive in O3b

least massive BBH in O3b

positive effective inspiral spin

NSBH, most extreme mass ratio

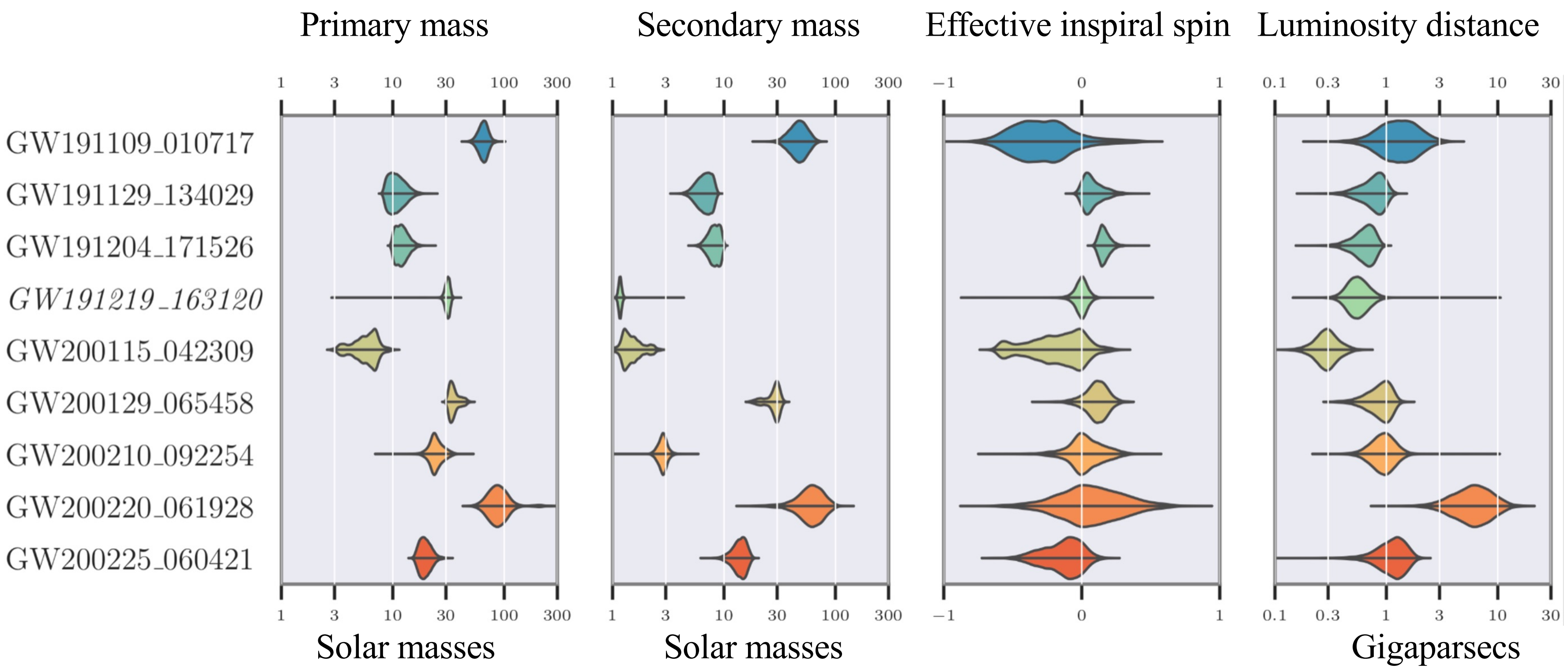
NSBH

misaligned spin

NSBH?

most massive in O3b

negative effective inspiral spin



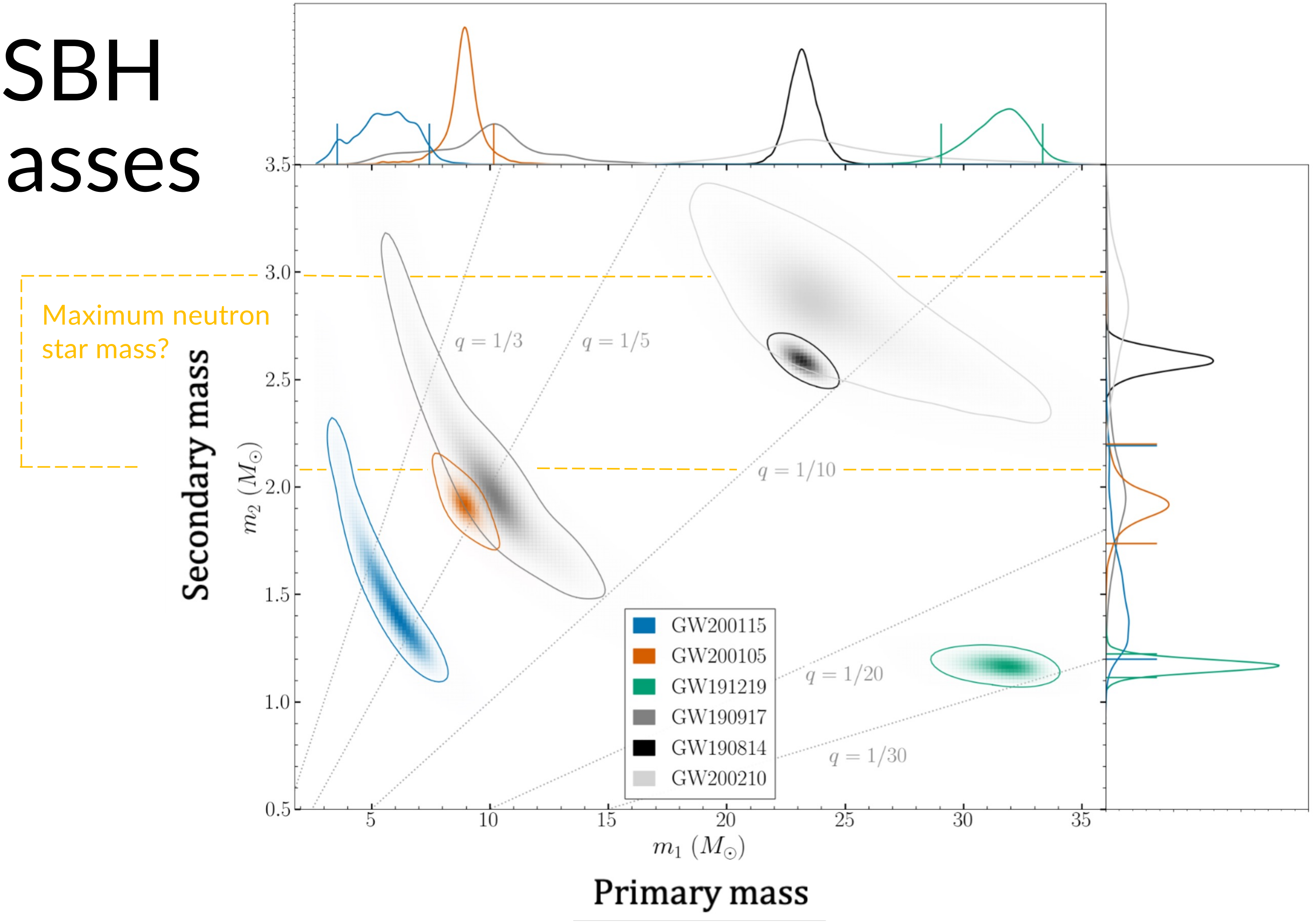
NSBH masses

Mass ratio q is **ratio** of **secondary** to **primary** mass:

$$q = \frac{m_2}{m_1}$$

Coloured contours in this plot are **confident** neutron star–black hole pairs

Grey contours in this plot are **ambiguous**, with secondary that may be a black hole or a neutron star



Masses & spins

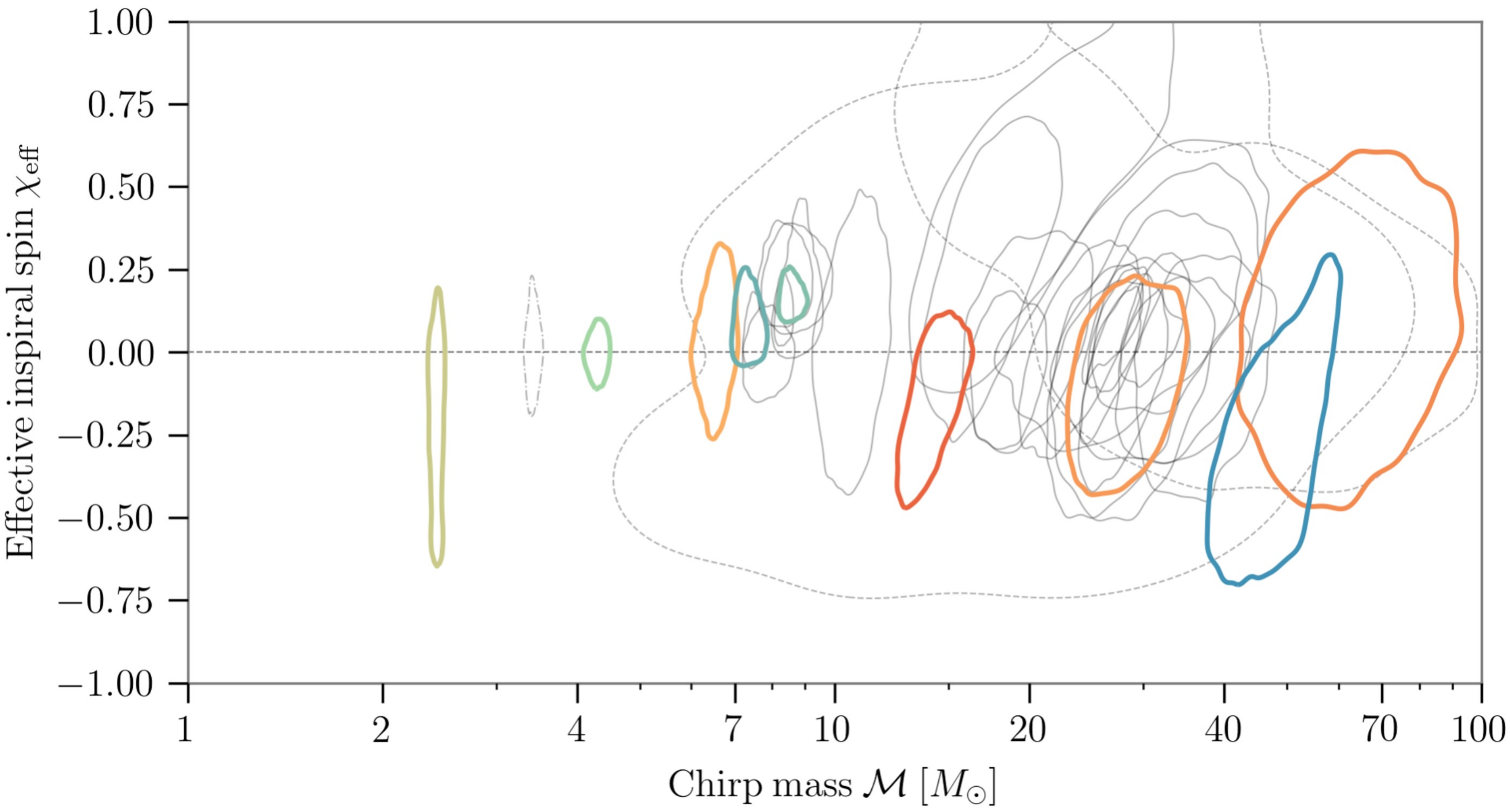
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \quad \chi_{\mathrm{eff}} = \frac{(m_1 \vec{\chi}_1 + m_2 \vec{\chi}_2) \cdot \vec{L}_{\mathrm{N}}}{(m_1 + m_2)}$$

Most effective inspiral spins **consistent with zero**

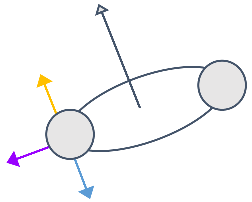
Some events with significant support for negative effective inspiral spins

More events have significant support for positive effective inspiral spins

Consistent with GWTC-2.1



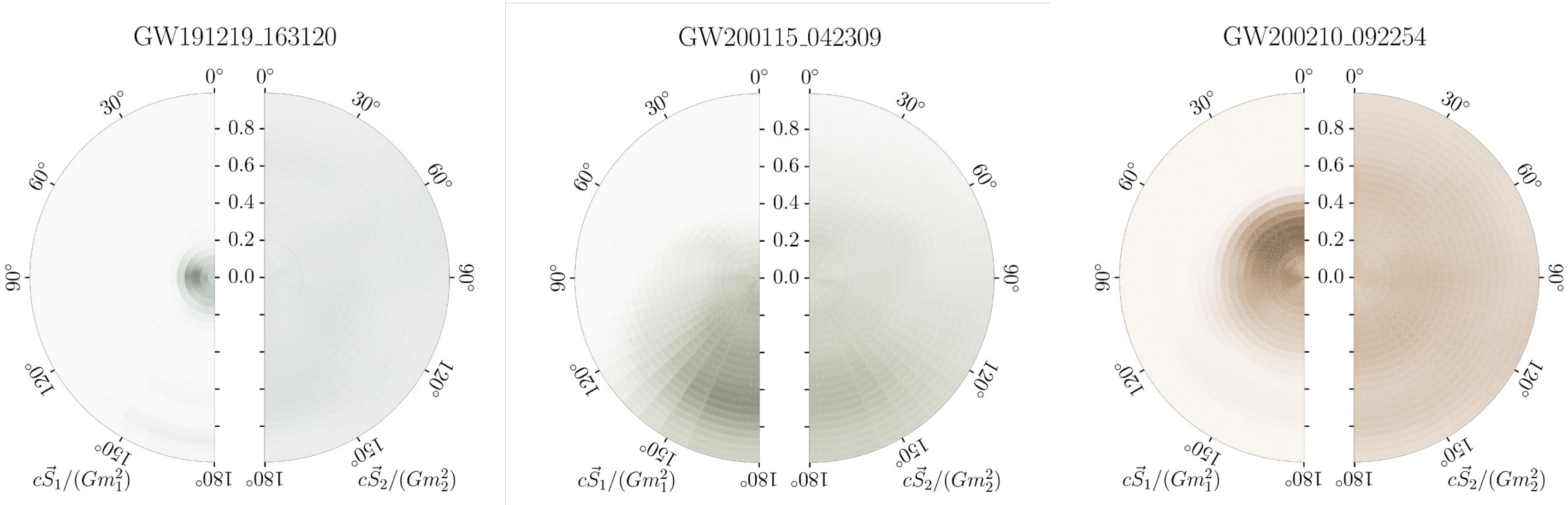
NSBH spins

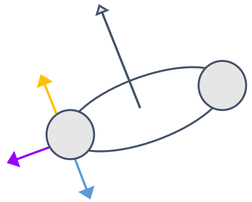


Primary spin better measured as more important for dynamics

Spin components in the orbital plane better measured for more extreme mass ratios

Spins **approximately aligned** with orbital angular momentum expected for binaries formed in isolation

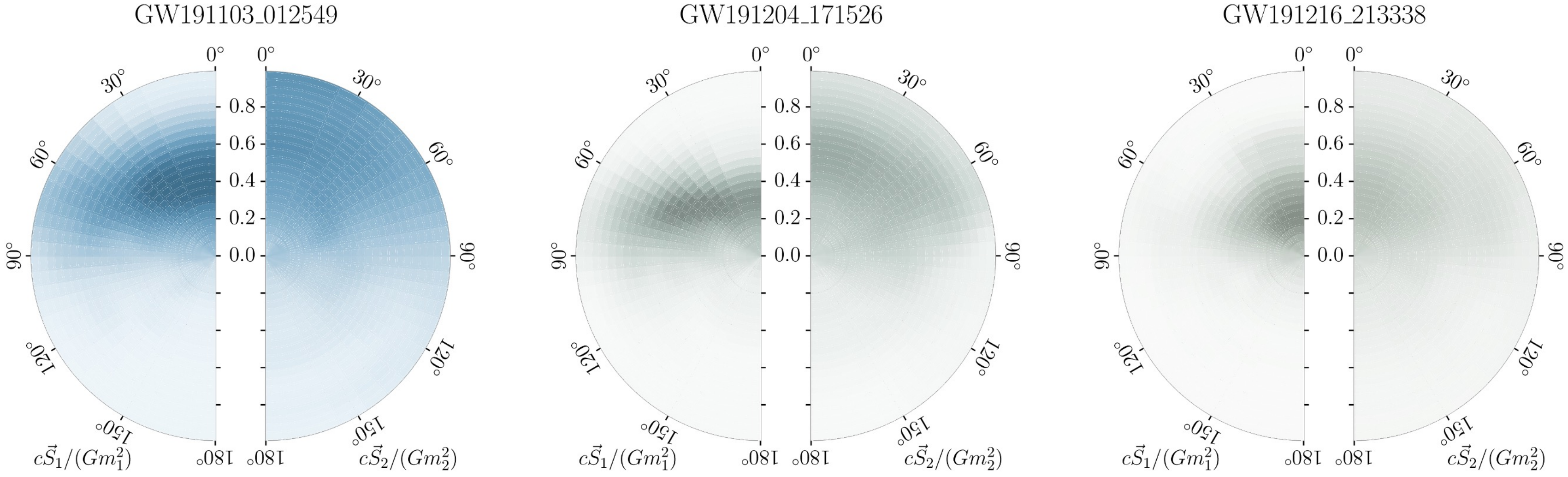


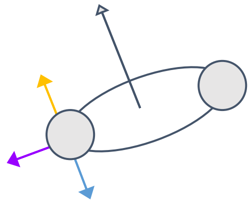


BBH spins: small and positive

Spins expected to be small if angular moment transfer is efficient in stars

Spins in X-ray binaries extend close to the Kerr limit of 1



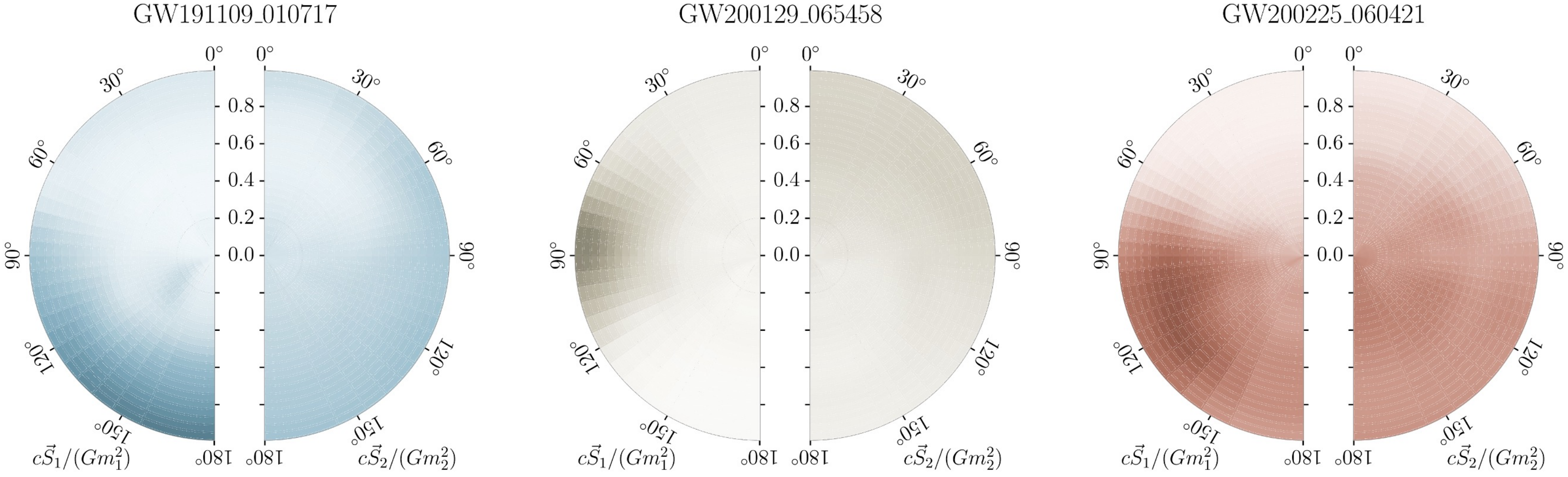


BBH spins: misaligned or negative

Misaligned spins expected for binaries formed dynamically

Equal-mass mergers produce spins around 0.7

GW200129 shows best evidence for **misaligned spins**



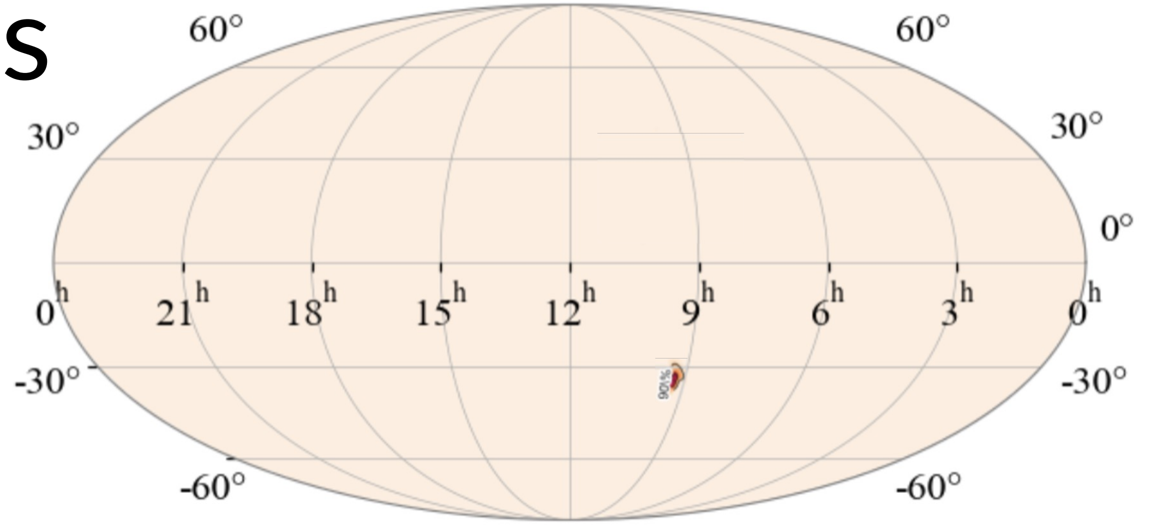
Locations

Localisation strongly depends on number of detectors observing a signal

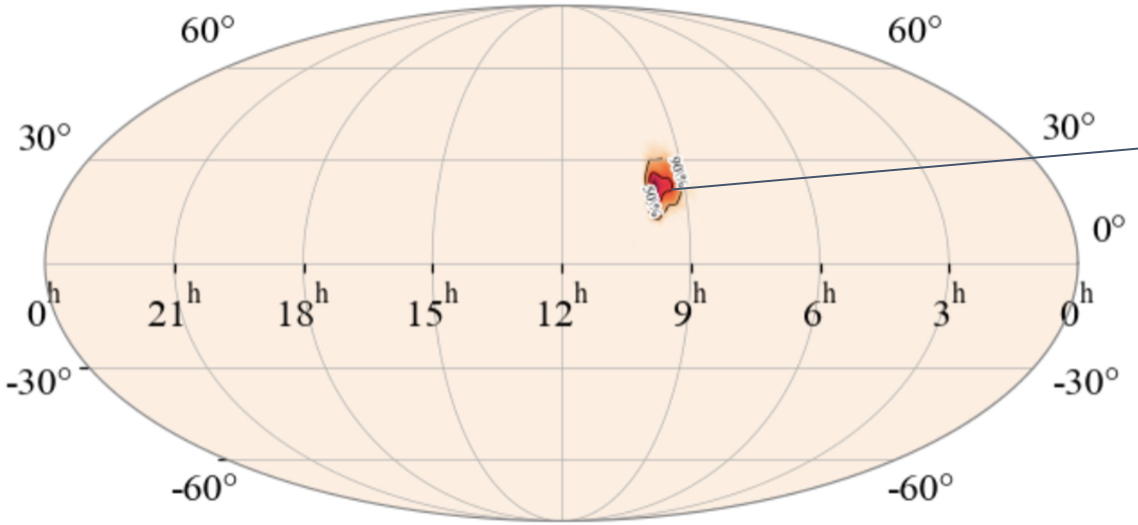
Smallest 90% credible **sky area** is GW200208_130117 with **30 deg^2** (compare to Moon's area of 0.2 deg^2!)

Smallest 90% credible **sky volume** localised is GW200202 with **0.0024 Gpc^3**

GW200208_130117



GW200202_154313



Data

Data products mirror the release for GWTC-2.1

Notebooks and example **scripts** included with data products

Gravitational Wave Open Data Workshops provide more resources to understand data analysis

Strain data

Bulk data release available from www.gw-openscience.org/O3/O3b/

Data products

Analysis results available from www.gw-openscience.org/GWTC-3/

- Data-quality files
- Glitch-subtracted data
- Candidate list
- Search sensitivity (O3, and O1+O2+O3)
- Parameter-estimation results
- Data behind the figures

Summary

A total of **90** candidates with p-astro > 0.5 plus many more lower probability candidates

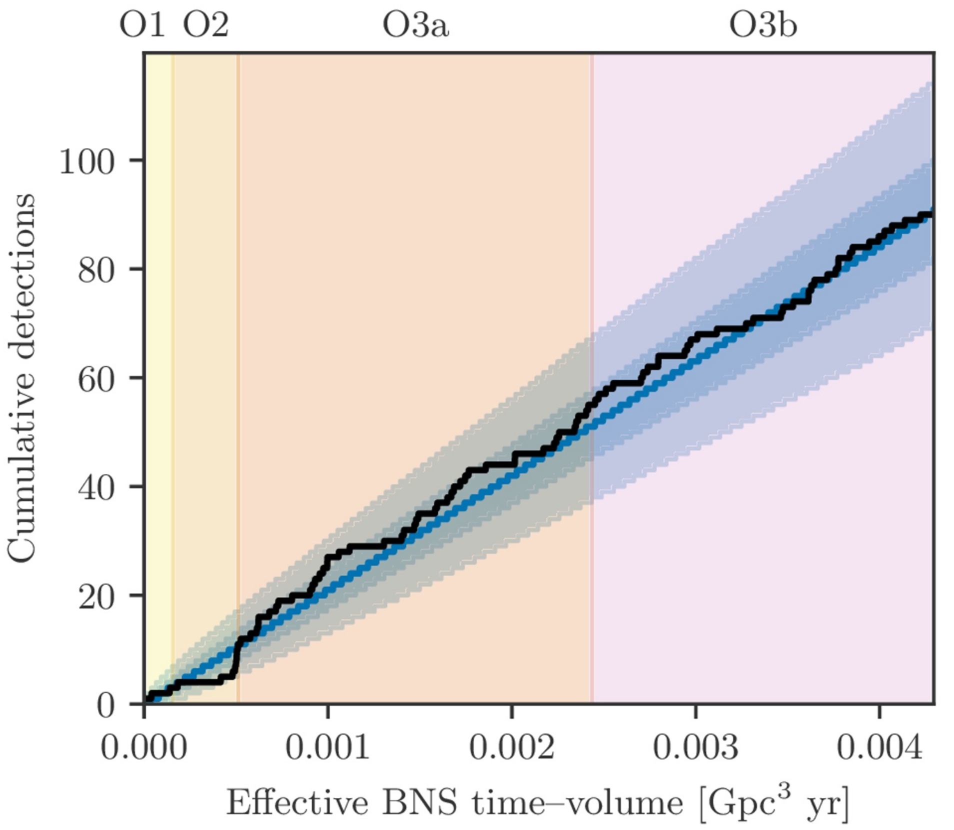
Applications to **cosmology** (9 Dec), **astrophysics** (10 Dec) and **tests of general relativity** (20 Jan)

O3 saw the detector network reach its greatest performance to date

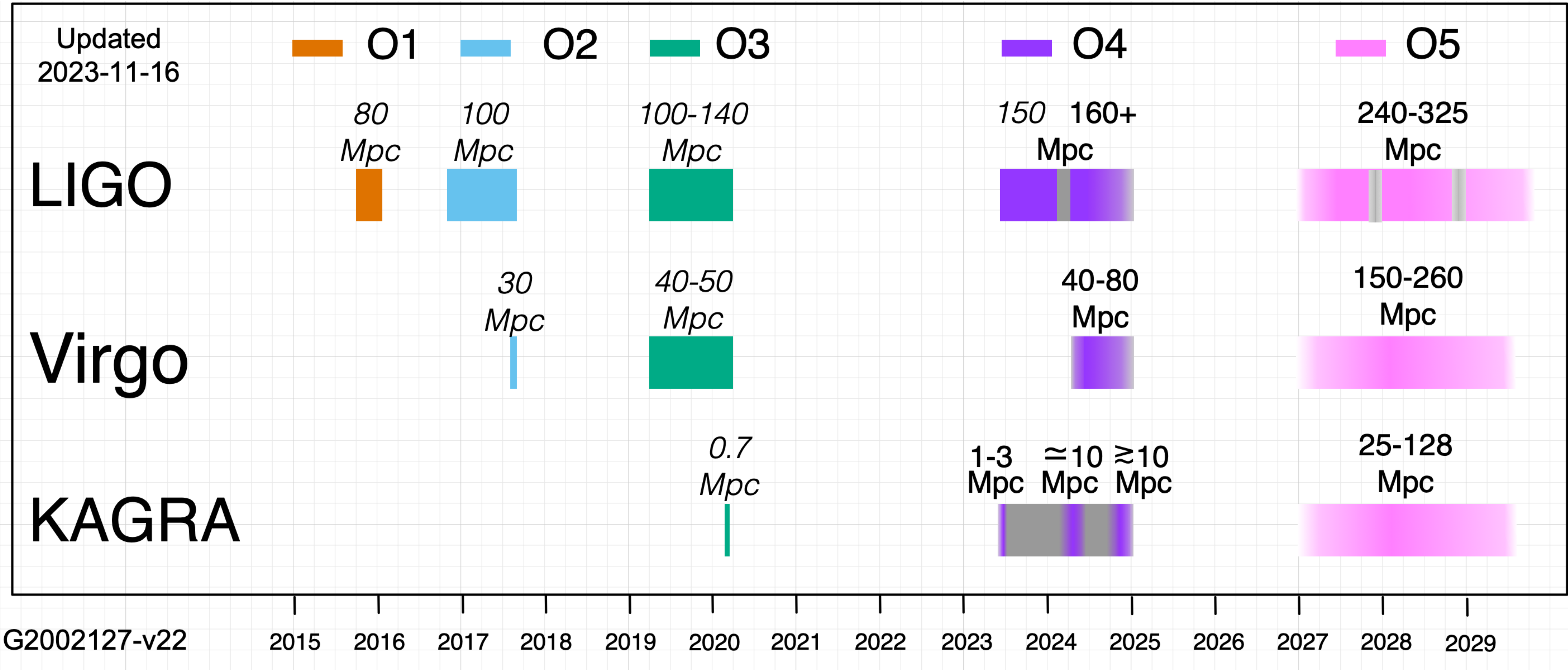
35 O3b candidates with p-astro > 0.5

O3b candidates have a diverse range of masses and spins, and include confident neutron star–black holes

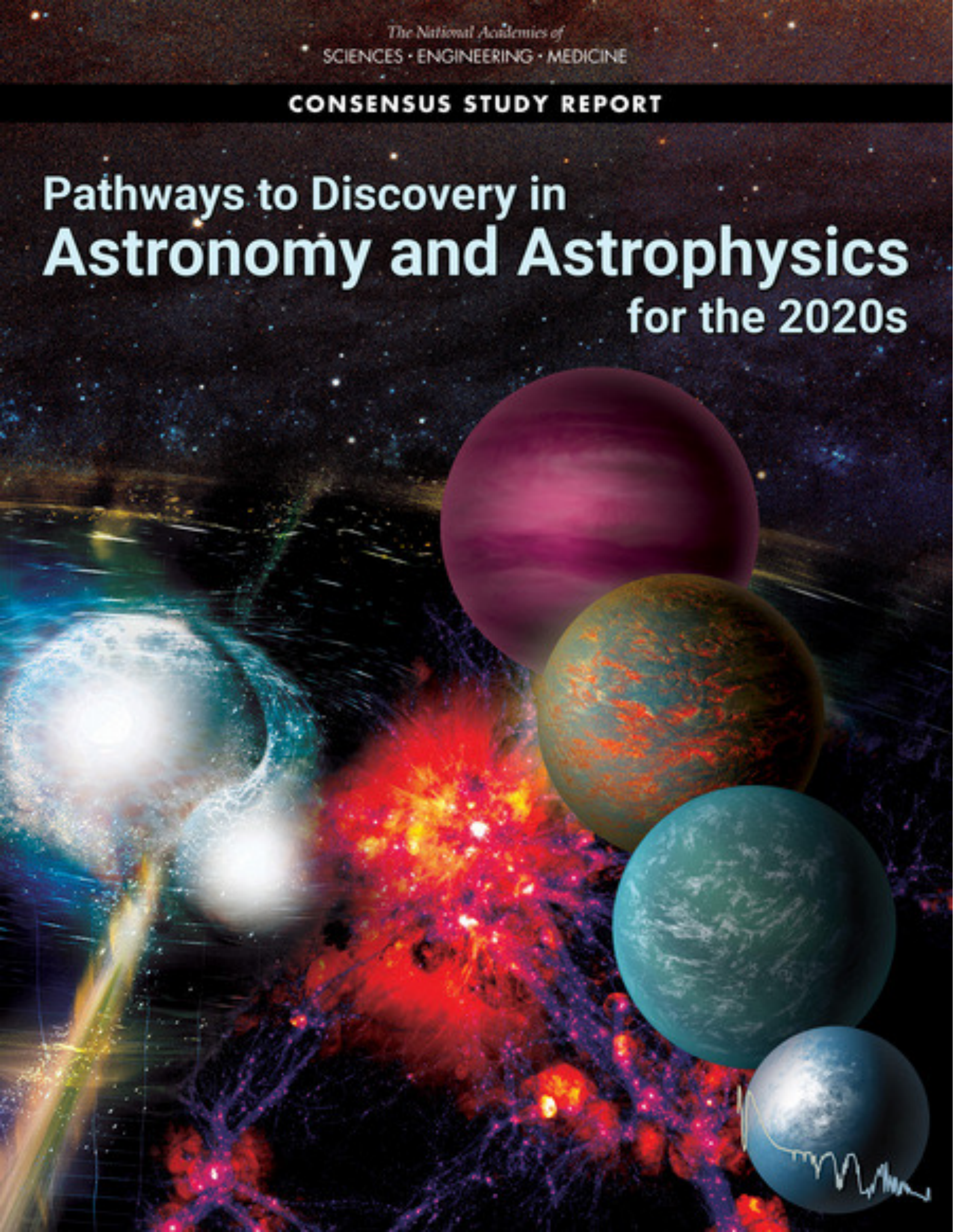
Interactive catalog
https://catalog.cardiffgravity.org/



LIGO, VIRGO AND KAGRA OBSERVING RUN PLANS



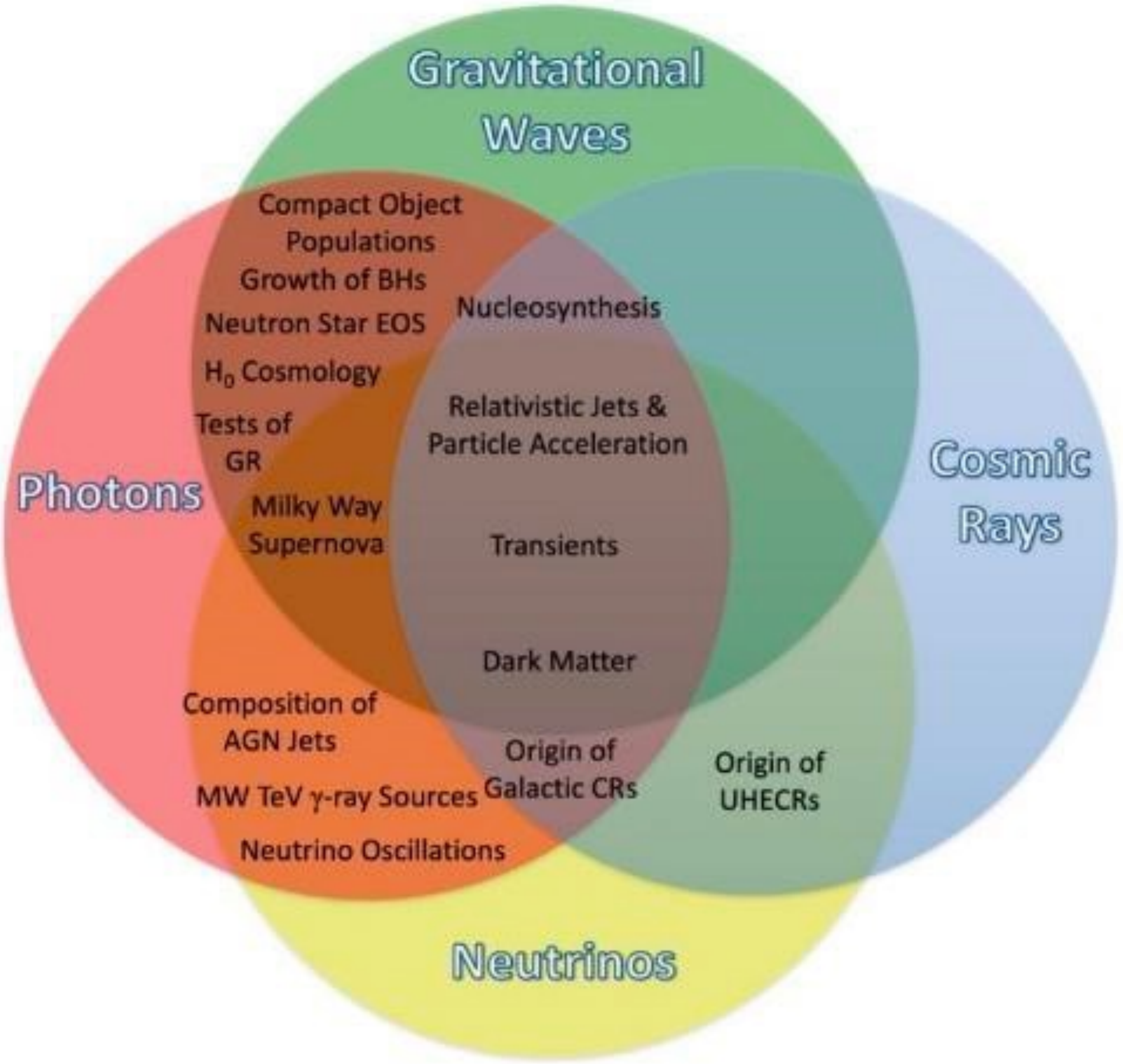
https://observing.docs.ligo.org/plan/



The National Academies of
SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

Pathways to Discovery in
Astronomy and Astrophysics
for the 2020s

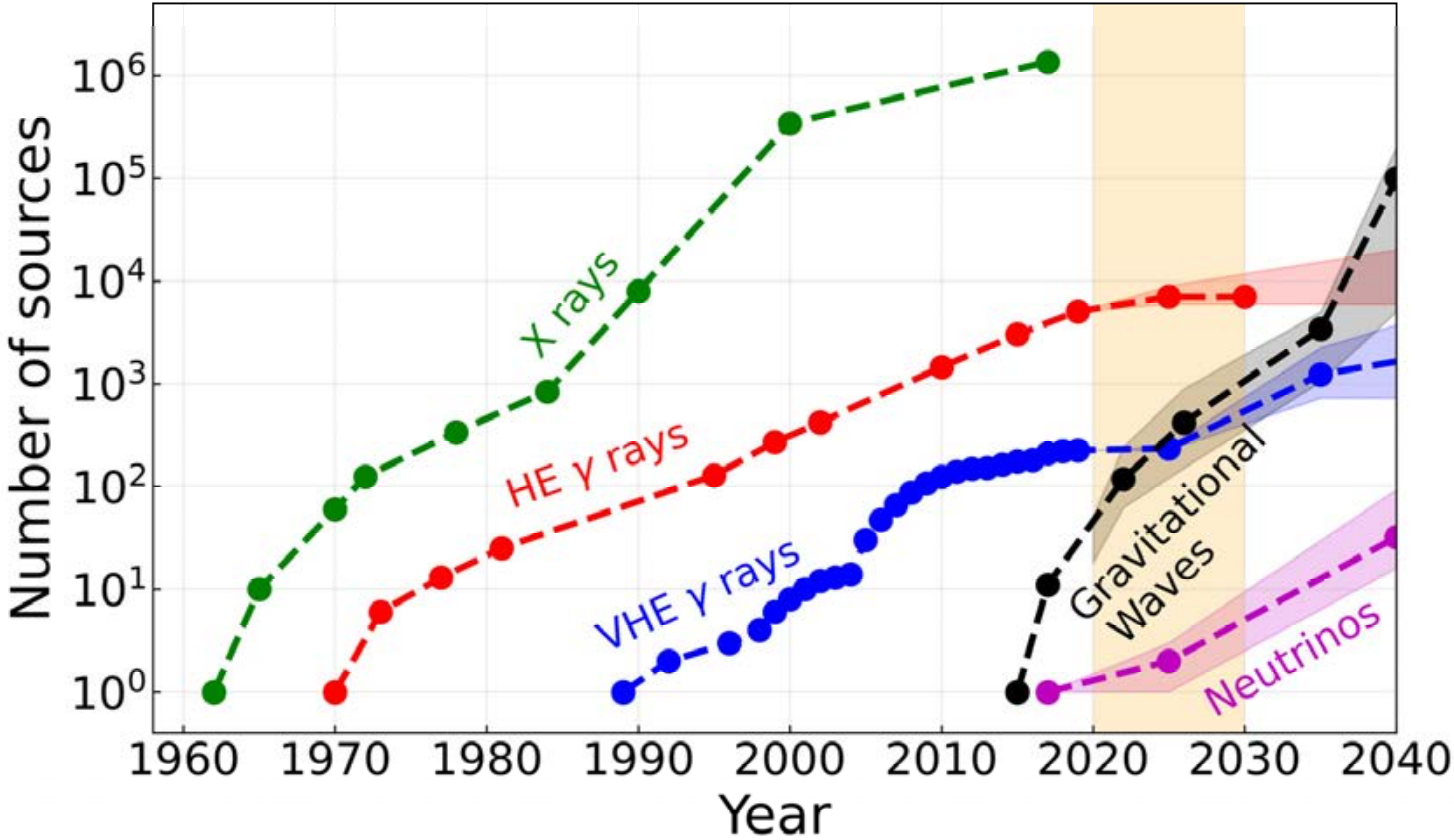


The panel sees a compelling opportunity to dramatically open the discovery space of astronomy through a bold, broad multi-messenger program, with three components:

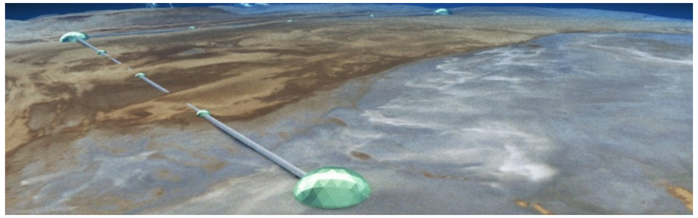
- ***Neutrino program**:* A large-scale (MREFC) investment by the National Science Foundation (NSF) in IceCube-Gen2, to resolve the bright, hard-spectrum, TeV–PeV diffuse background discovered by IceCube into discrete sources and to make first detections at higher energies.

- ***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
10⁶
10⁵
10⁴
10³
10²
10¹
10⁰
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

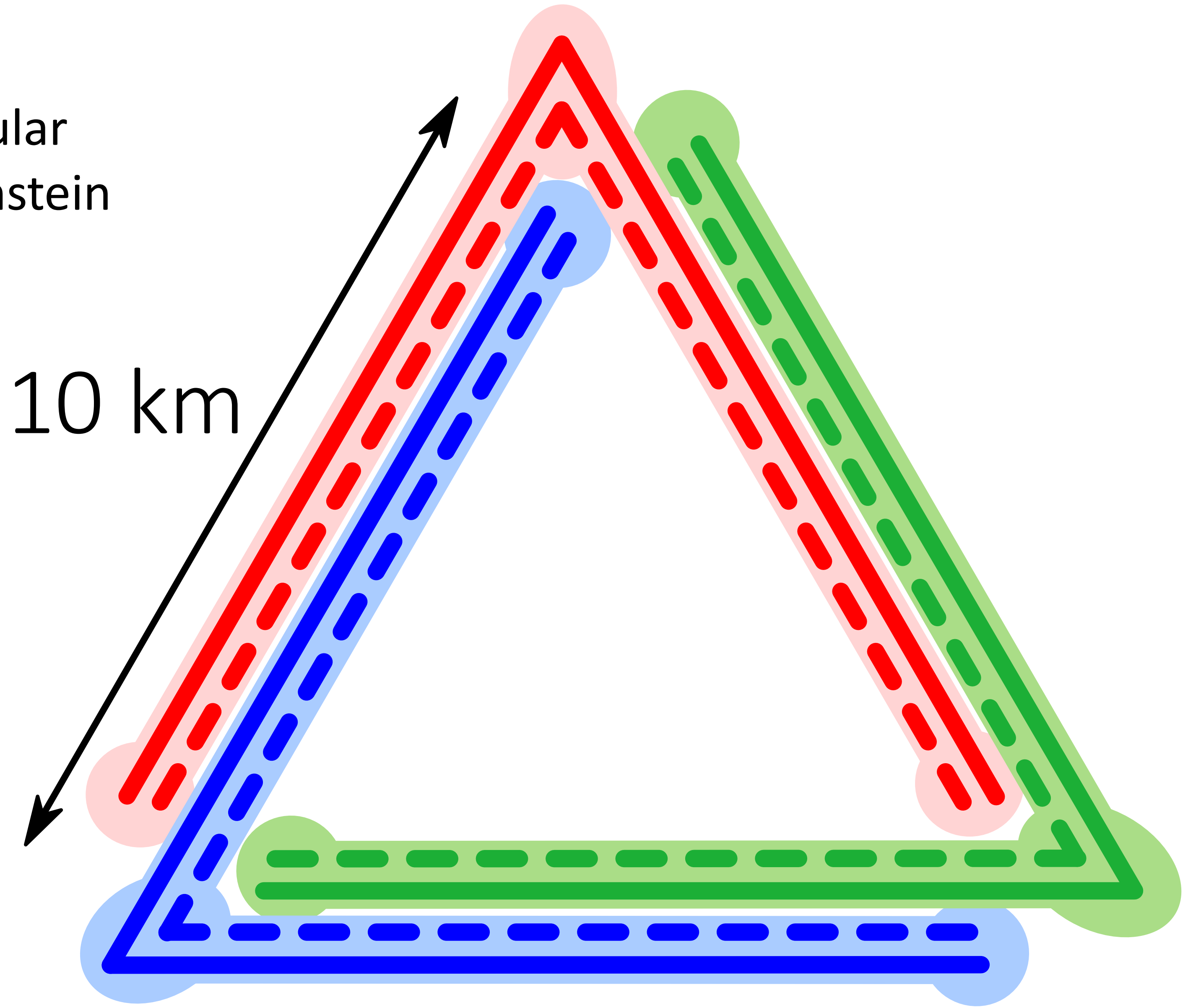
- Directly relevant to two Astro2020 priority areas: New Windows on the Dynamic Universe, Hidden Drivers of Galaxy Formation

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.



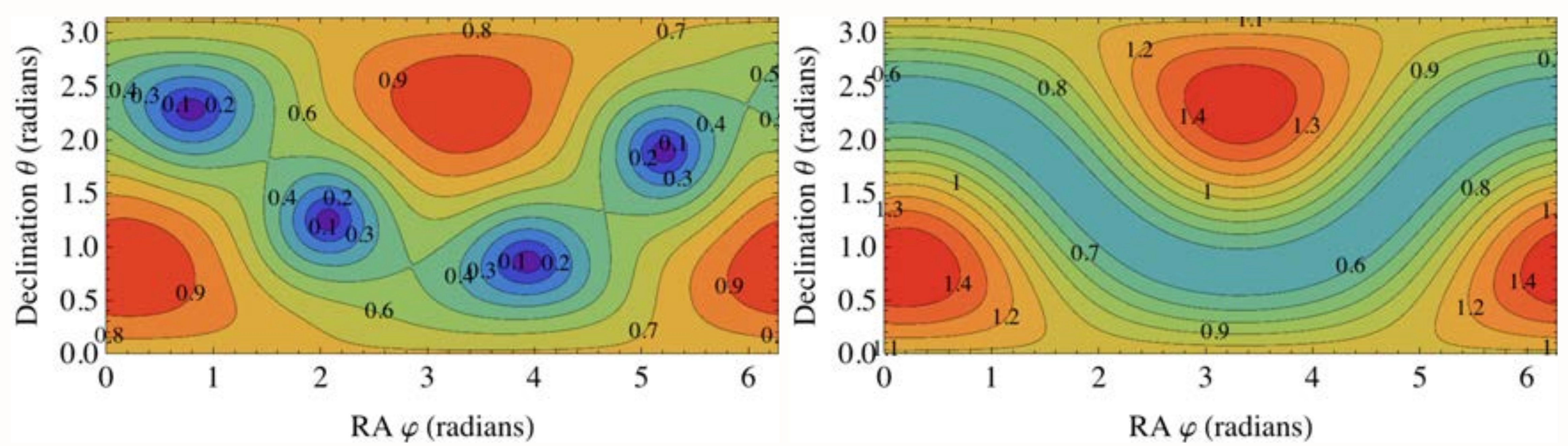
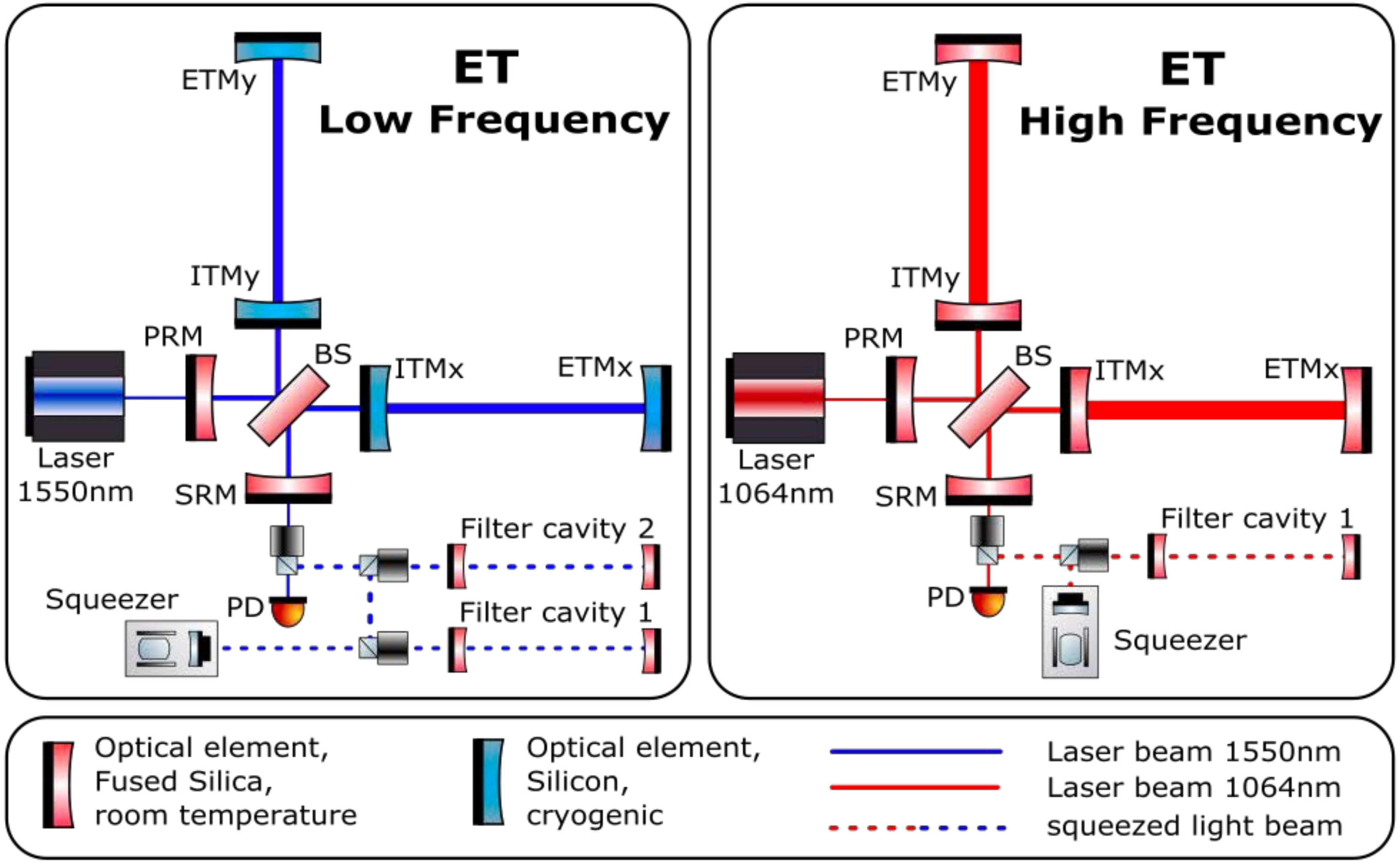


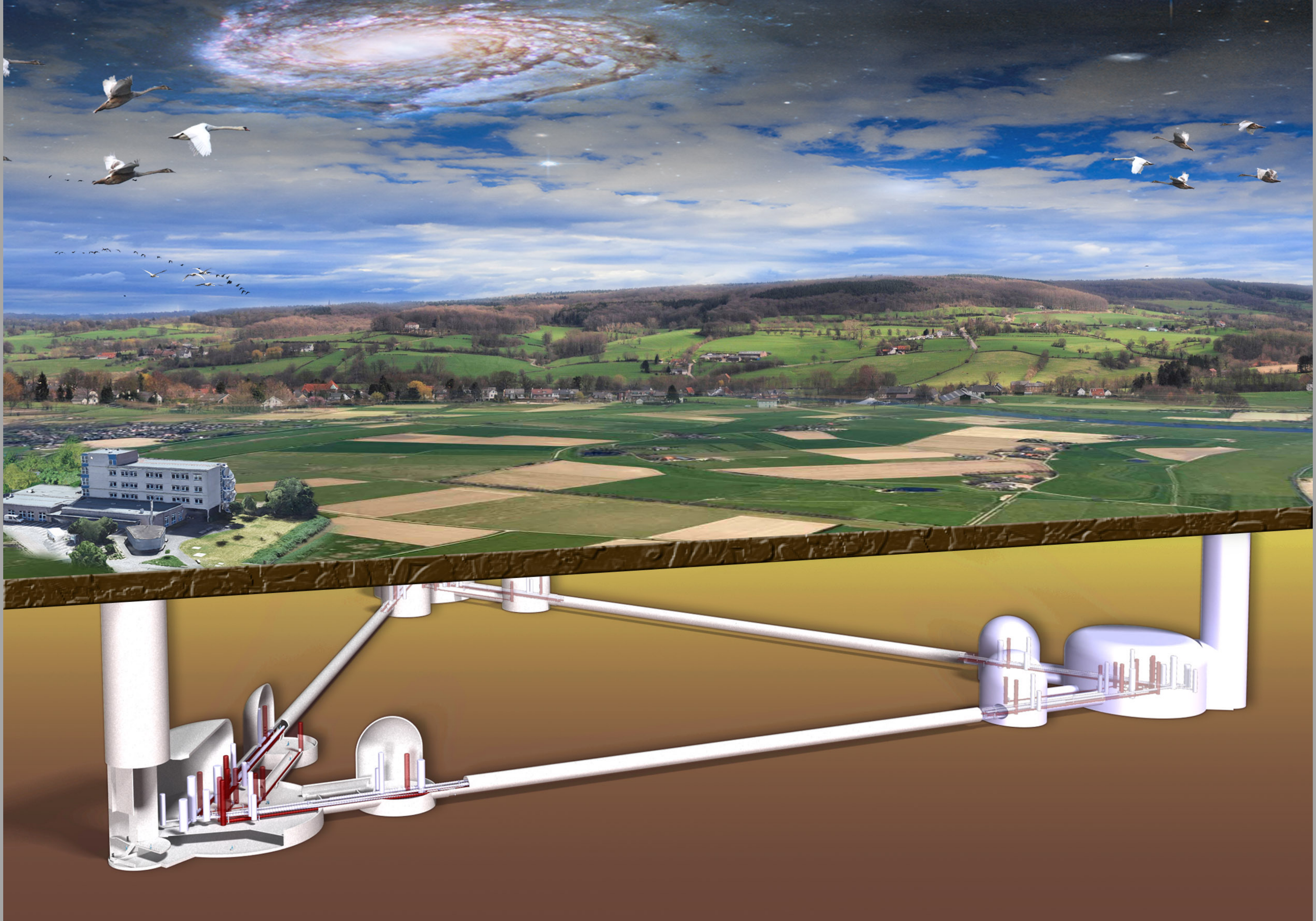
Figure 1.4: Antenna pattern of ET (right panel) compared to that of Virgo (left panel). ET is assumed to be at the same location as Virgo. Note that Virgo is a *single* L-shaped detector while ET consists of *three* V-shaped interferometers rotated relative to one other by 120 deg . The combined antenna 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).

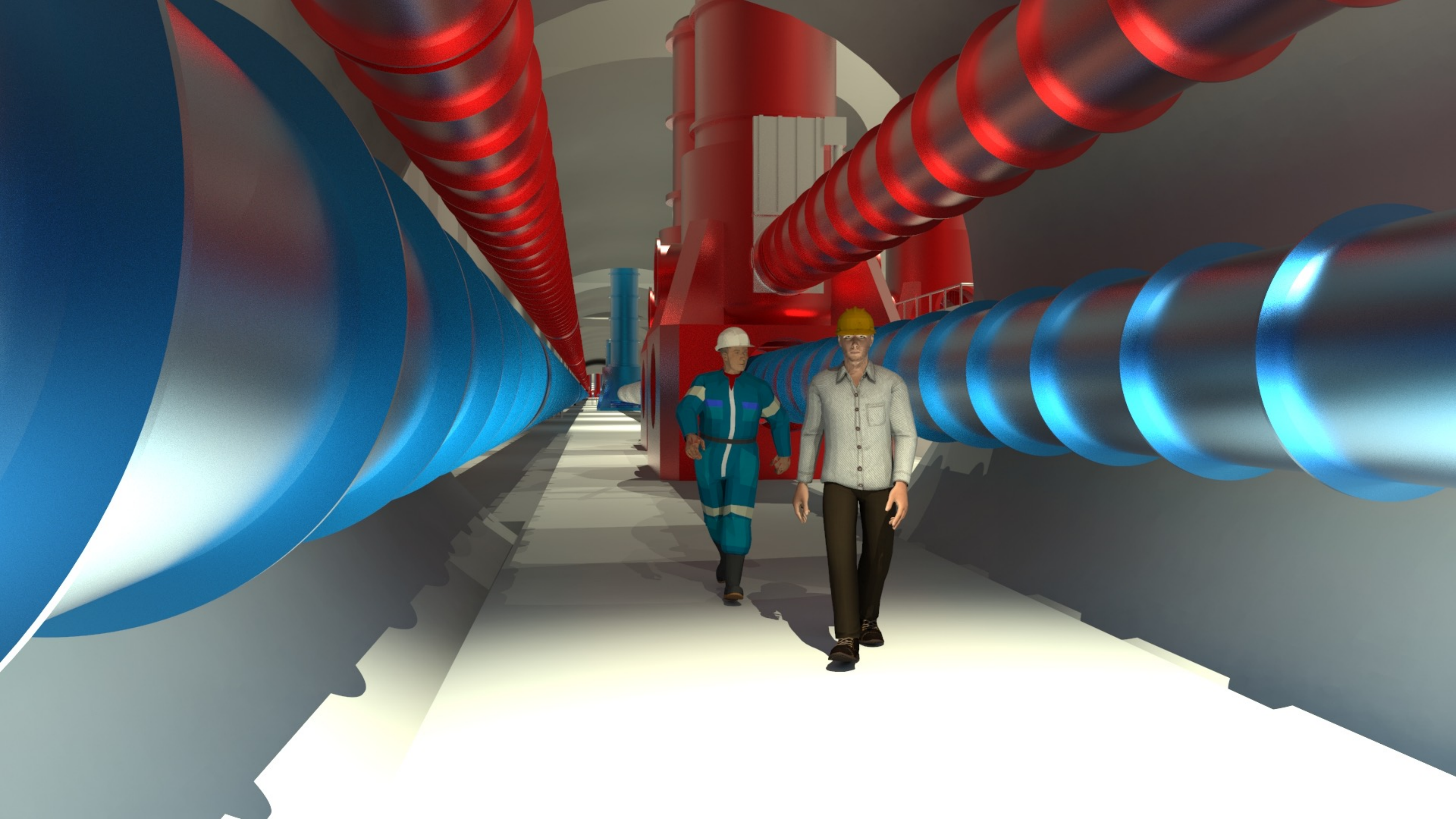
- *The baseline for ET is a 2-band xylophone detector configuration, composed of a low-frequency (ETLF) and a high-frequency (ET-HF) interferometer.*

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

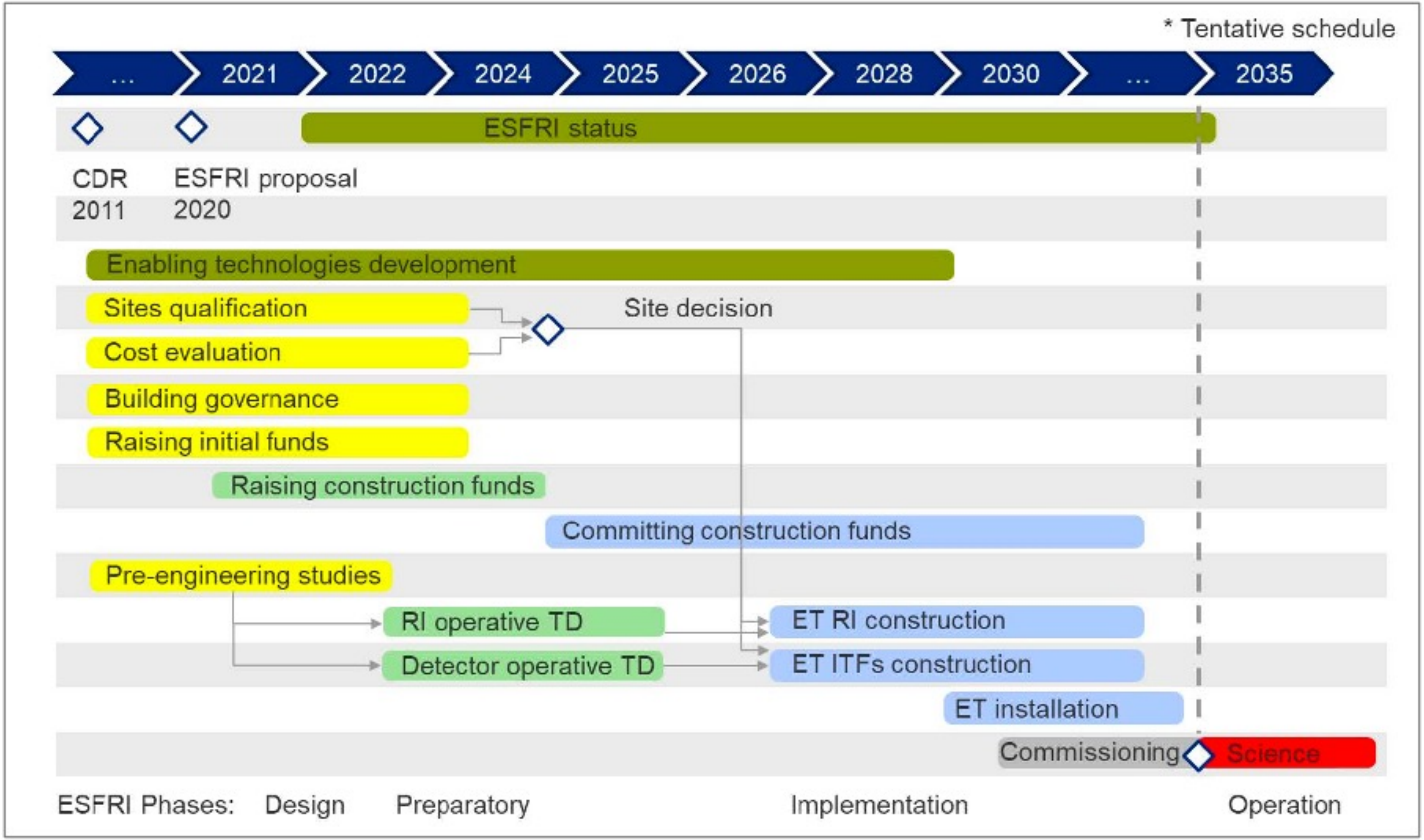
- *Due to their similar geometry both detectors will share common tunnels.*

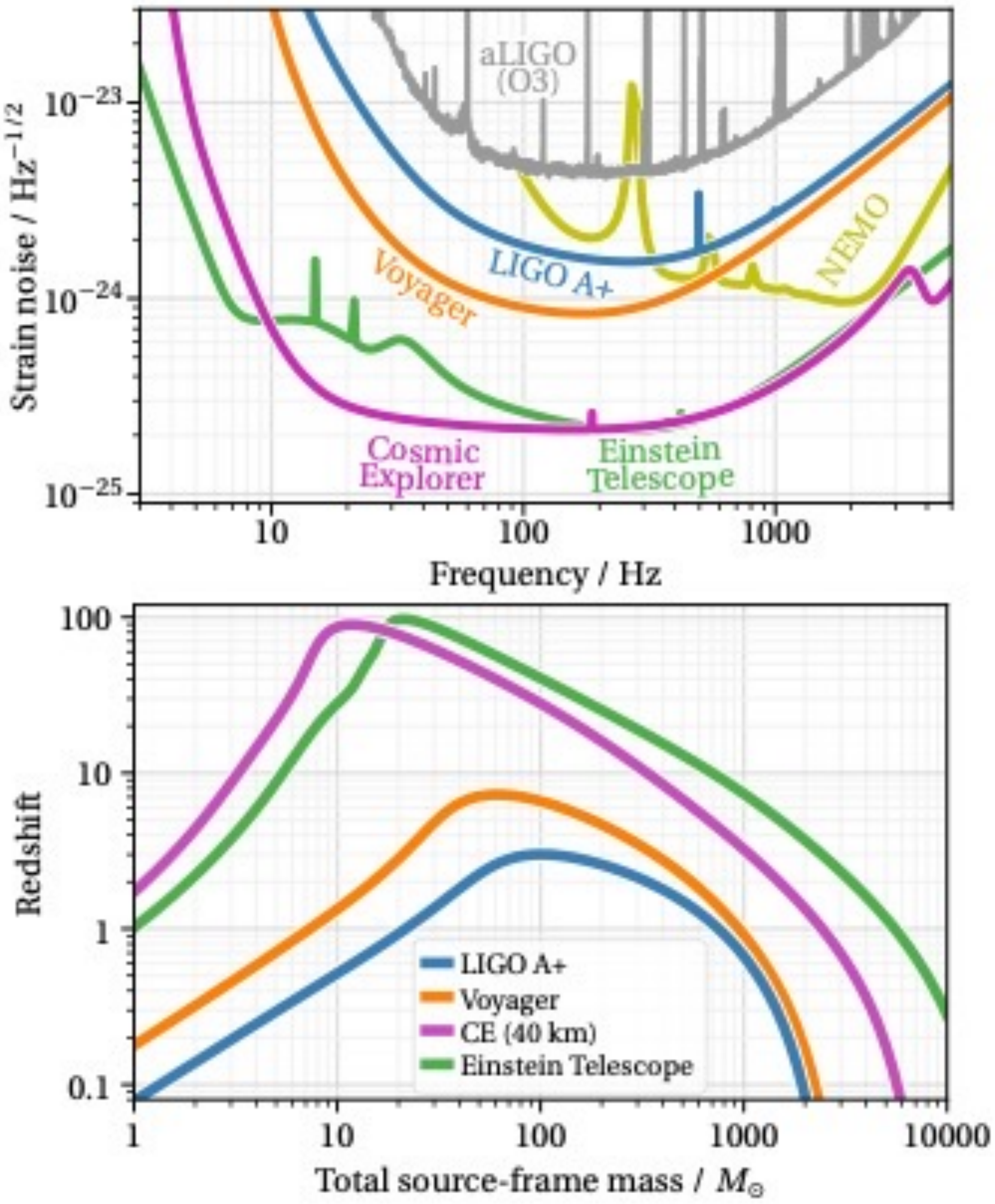






Einstein Telescope timeline



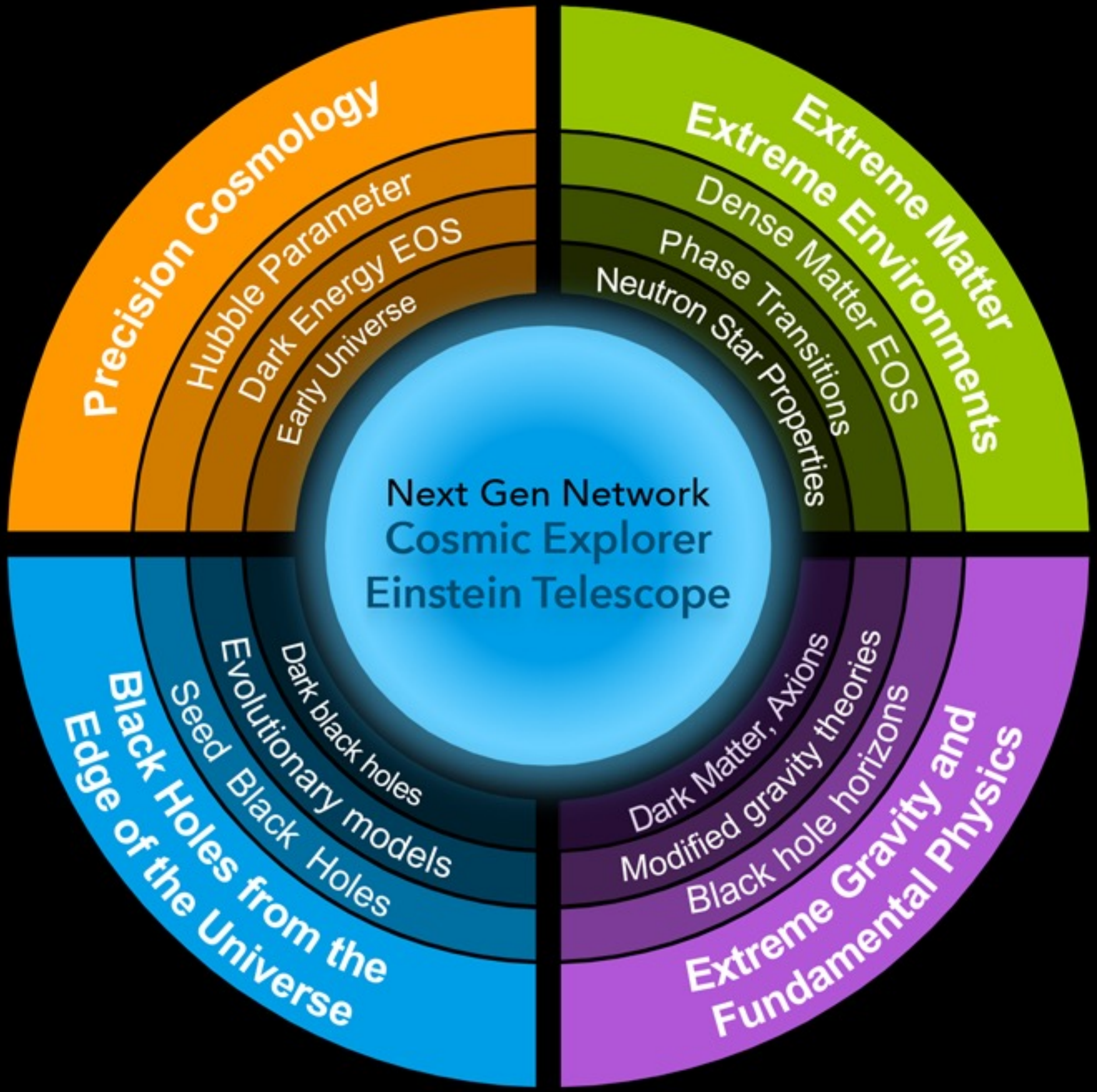


Top: **Amplitude spectral densities of detector noise** for Cosmic Explorer (CE), the current (O3) and upgraded (A+) sensitivities of Advanced LIGO, LIGO Voyager, NEMO, and the three paired detectors of the triangular Einstein Telescope.

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.



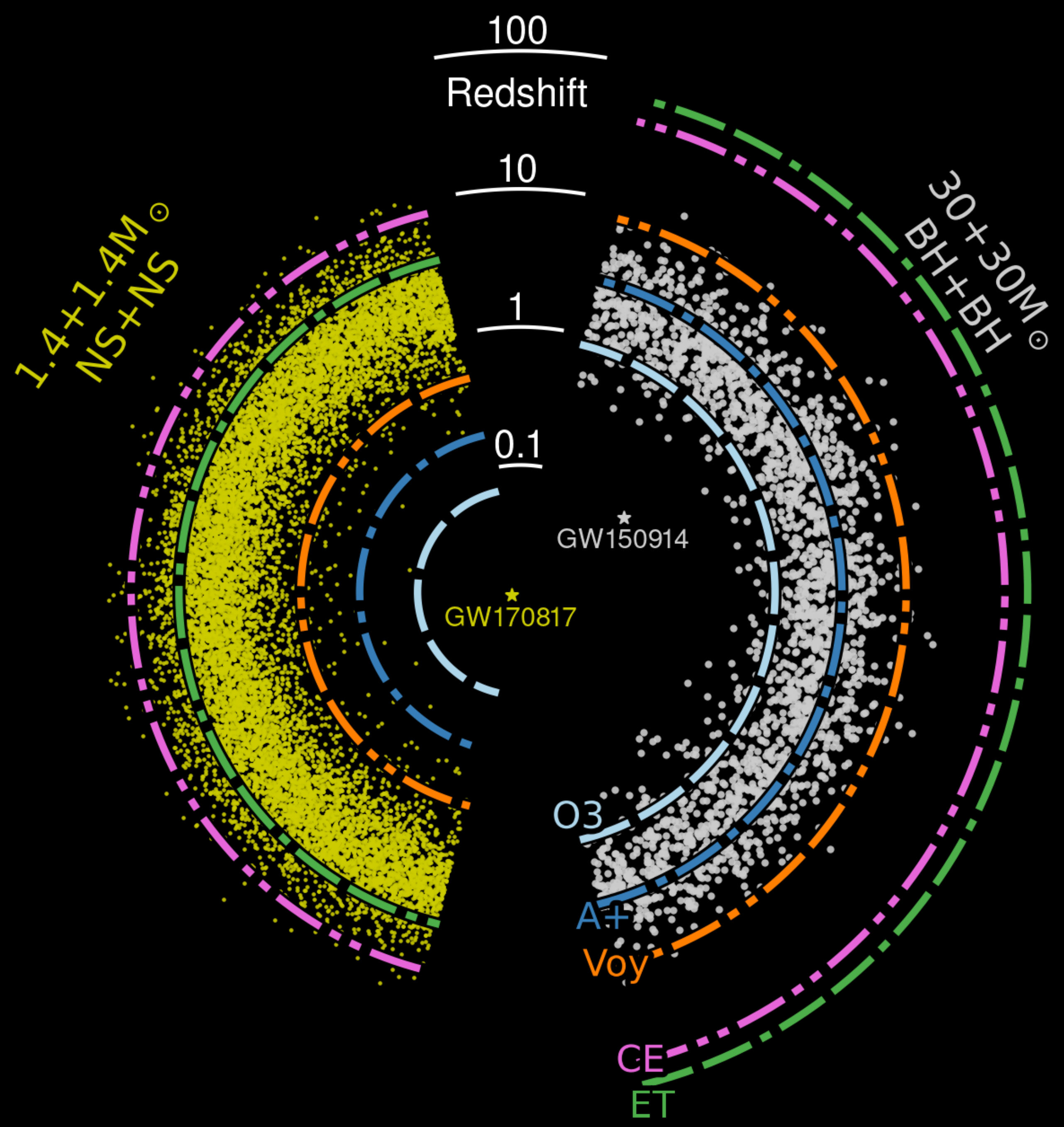
Next Gen Network
Cosmic Explorer
Einstein Telescope

Precision Cosmology
Hubble Parameter
Dark Energy EOS
Early Universe

Extreme Matter
Extreme Environments
Dense Matter EOS
Phase Transitions
Neutron Star Properties

Black Holes from the
Edge of the Universe
Seed Black Holes
Evolutionary models
Dark black holes

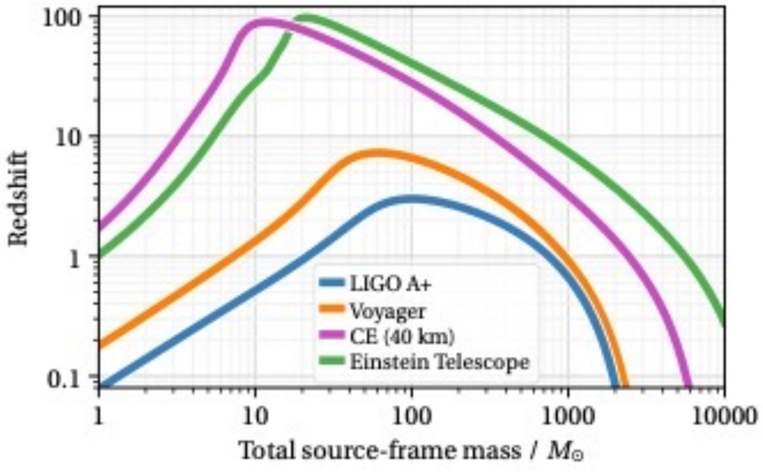
Extreme Gravity and
Fundamental Physics
Black hole horizons
Modified gravity theories
Dark Matter, Axions



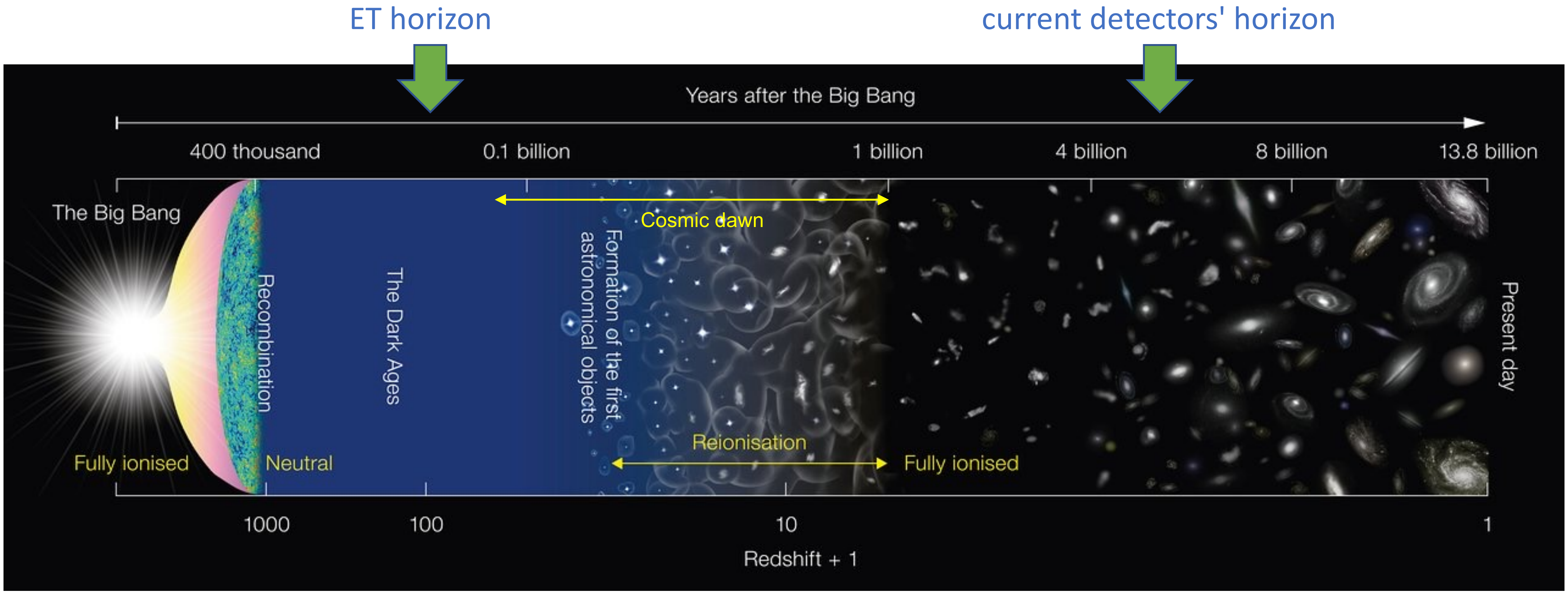
Astrophysical horizon of current and proposed future detectors for compact binary systems.

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.



• 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.

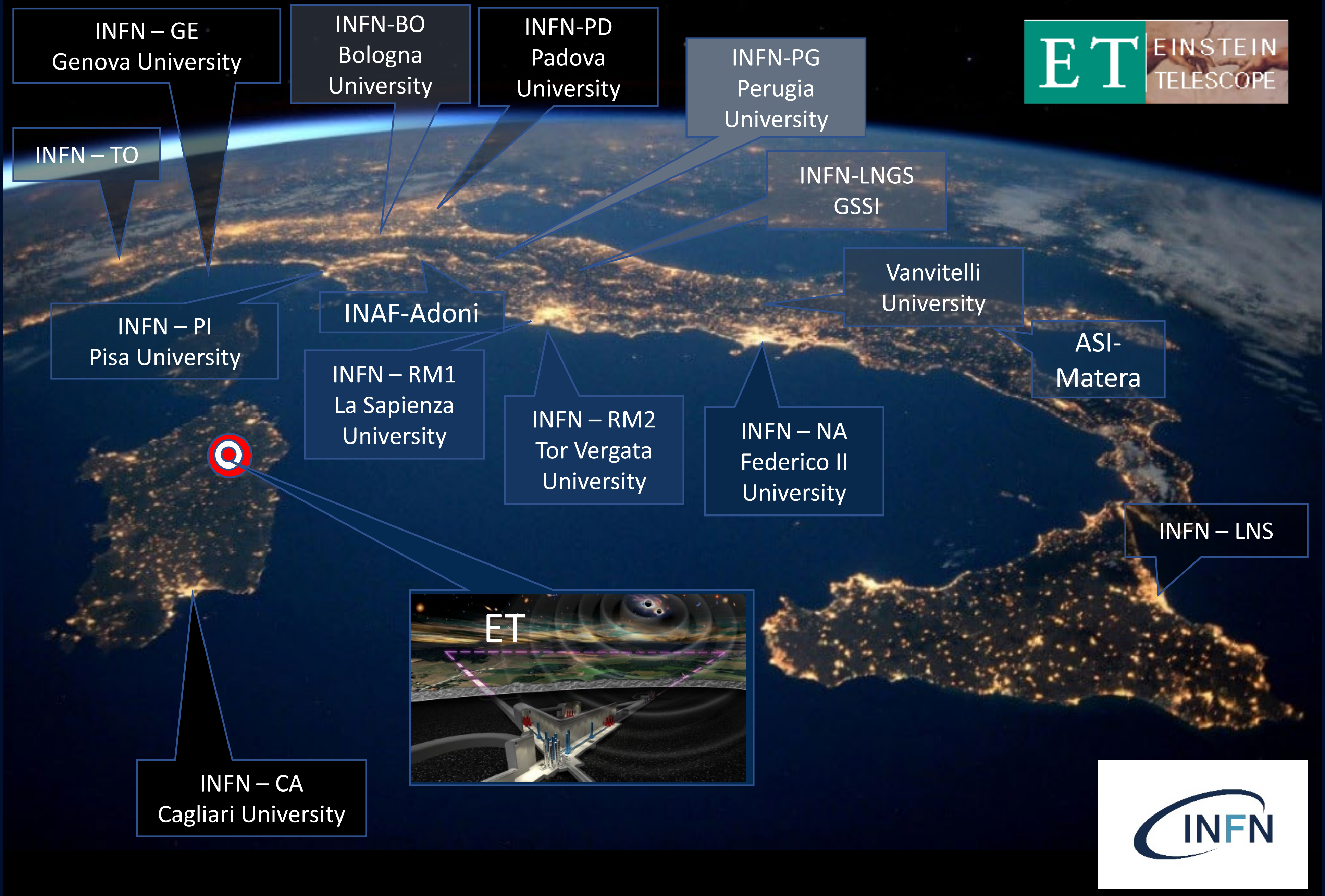
• COSMIC AFTERNOON

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



INFN – GE
Genova University

INFN-BO
Bologna
University

INFN-PD
Padova
University

INFN-PG
Perugia
University

INFN – TO

INFN-LNGS
GSSI

Vanvitelli
University

INFN – PI
Pisa University

INAF-Adoni

ASI-
Matera

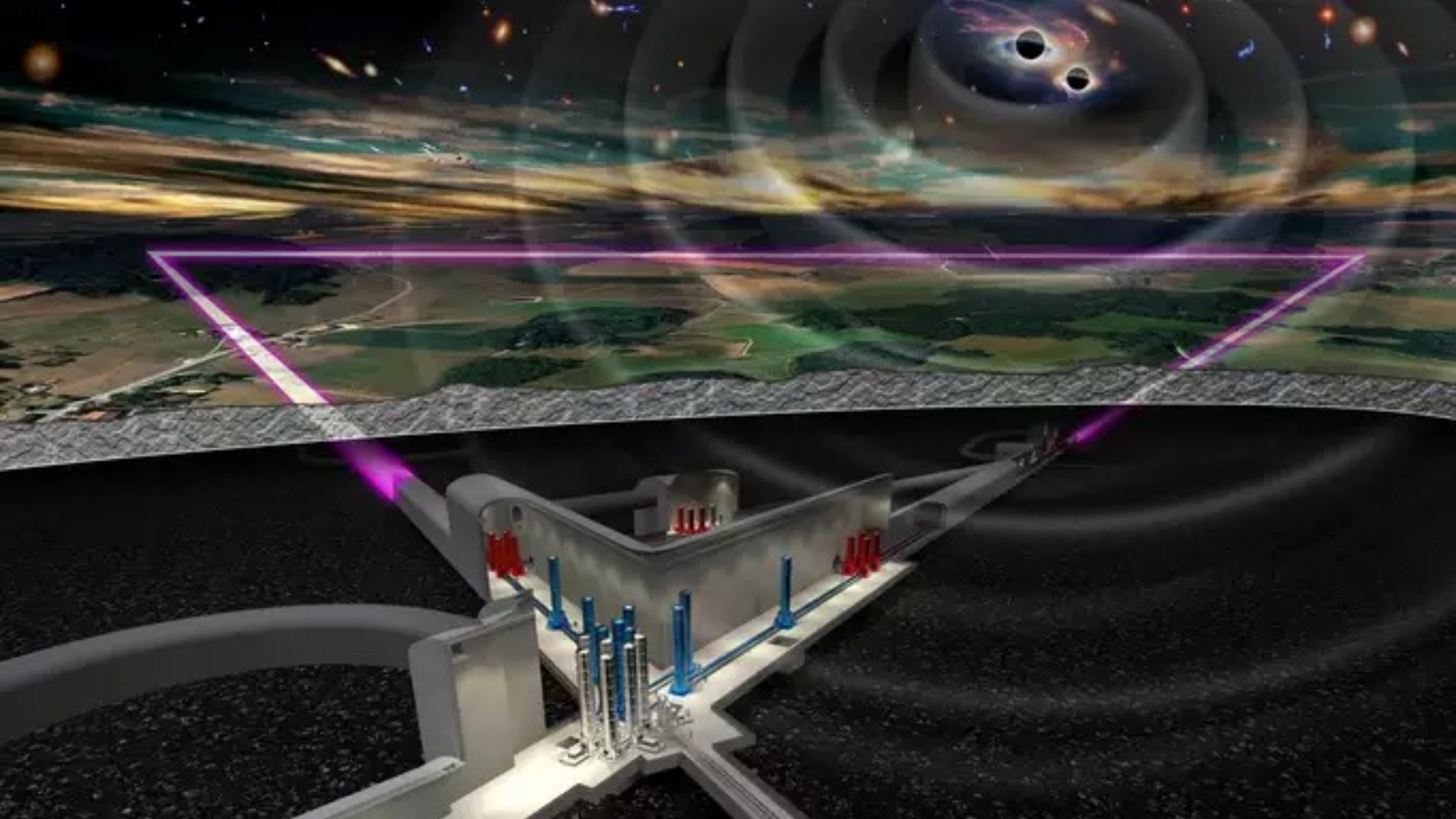
INFN – RM1
La Sapienza
University

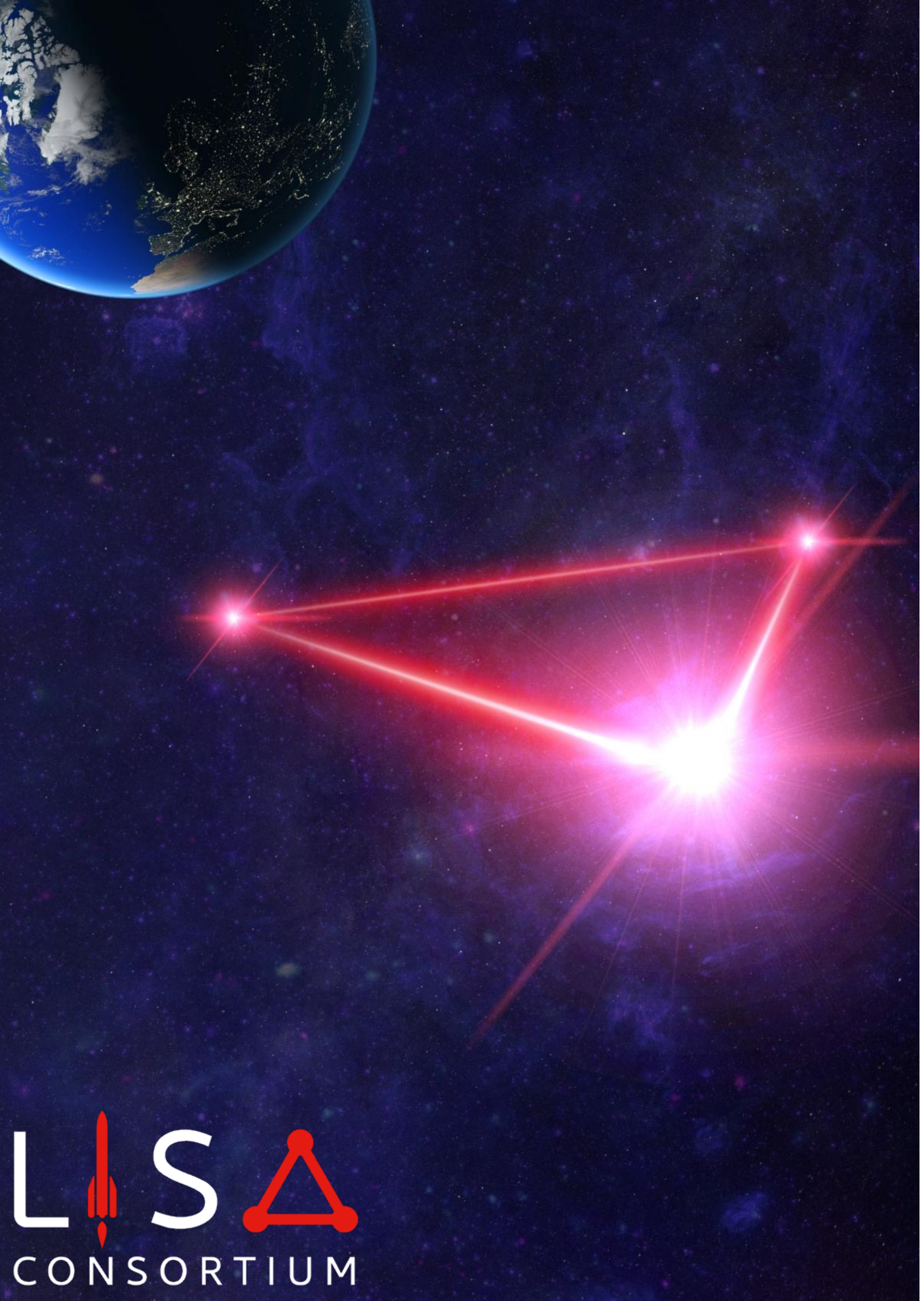
INFN – RM2
Tor Vergata
University

INFN – NA
Federico II
University

INFN – LNS

INFN – CA
Cagliari University

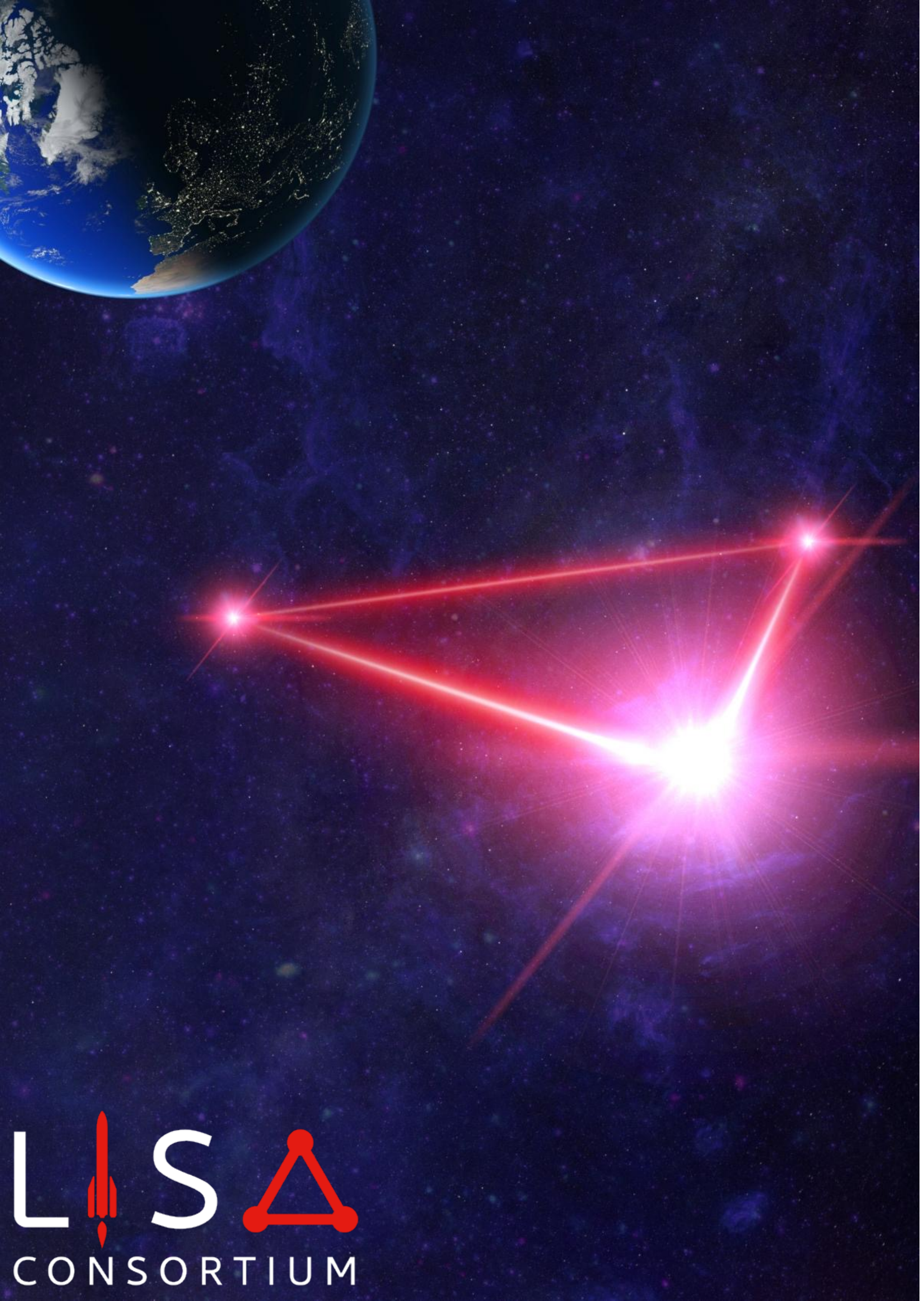




LISA is a space-borne Gravitational Wave Observatory with an arm-length of 2.5 million km, compared to the few km's of the ground-based observatories.

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.

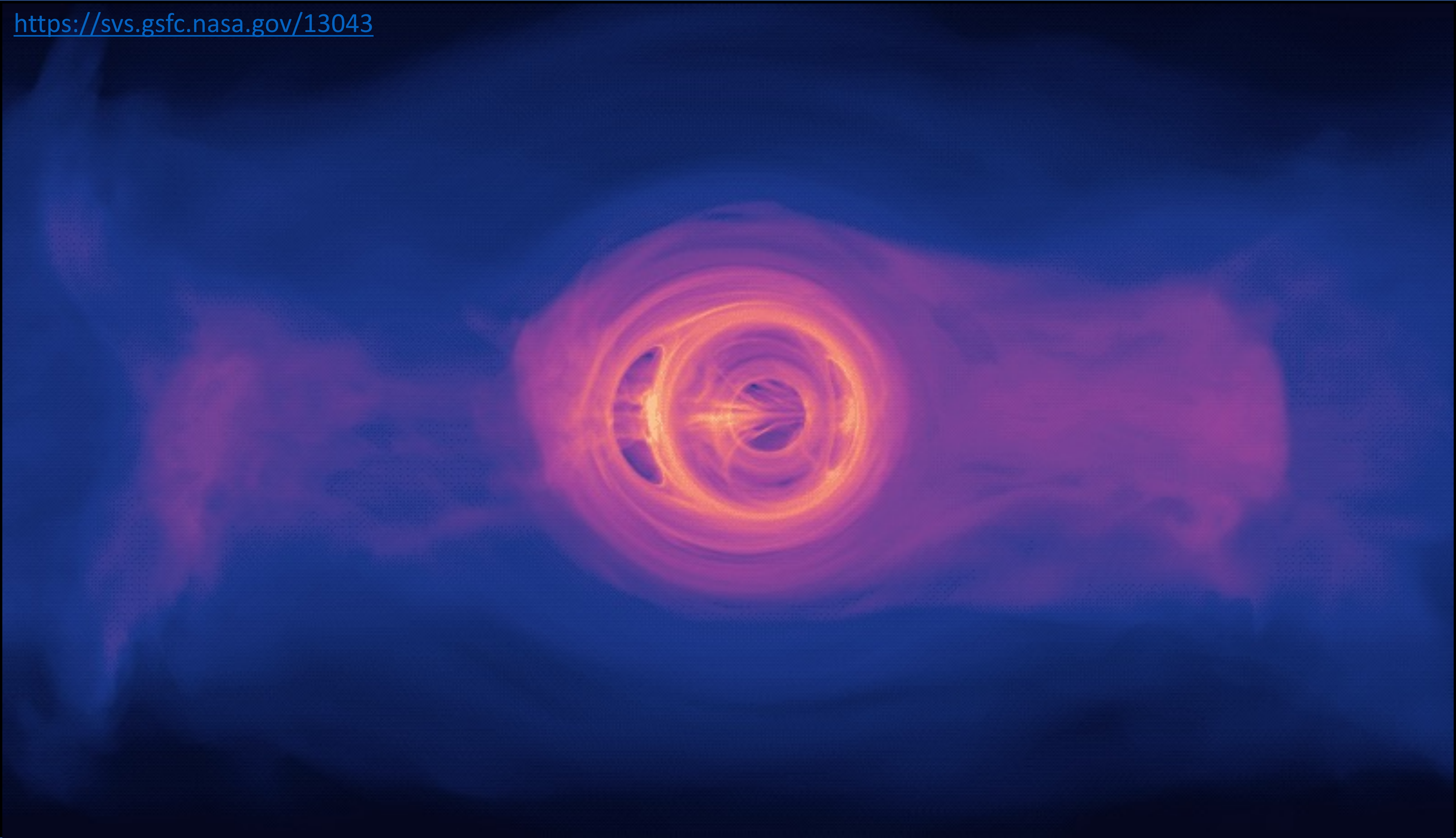


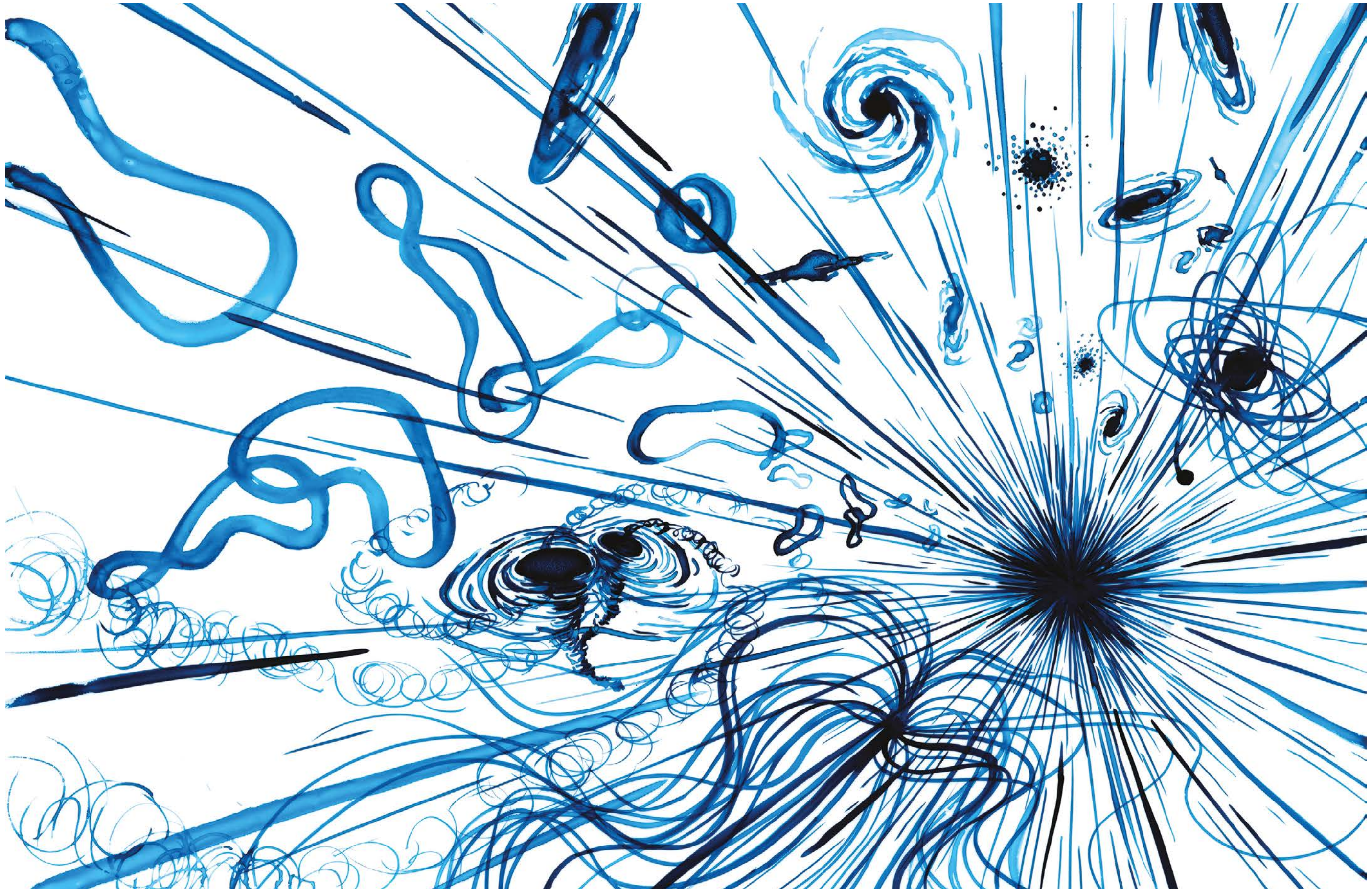
Mission objectives: As part of its core science objectives, LISA will:

- 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.