Gravitational Waves course: Introduction

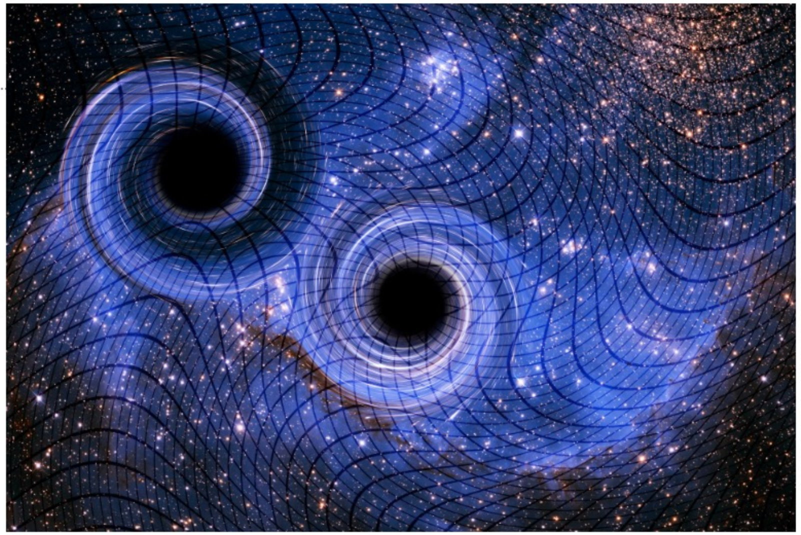
Edoardo Milotti
Dipartimento di Fisica – UniTS

https://wwwusers.ts.infn.it/~milotti/Didattica/GravitationalWaves/index.html

Gravitational waves

MSc Physics Course - University of Trieste, Italy
Prof. Edoardo Milotti

Course description



Introductory course in gravitational wave physics, which provides the basics needed to understand gravitational wave detections. After a general introduction which includes a terse introduction to General Relativity, the course discusses: astrophysical mechanisms of gravitational wave emission; astrophysical sources of gravitational waves; gravitational wave detectors; basics of gravitational-wave signal analysis; achievements and future of gravitational-wave physics and astrophysics.

Prerequisites:
Basic knowledge of ray and wave optics. Special relativity. Fourier series and Fourier transforms.

Timetable and course program

The 2023-24 course shall start on Tuesday, Sept. 26th, 2023

Place: Physics Department

Latest timetable:

- Tuesday, 9AM-11AM, room T19, Physics Department (Bld. F)
- Thursday, 11AM-1PM, room T19, Physics Department (Bld. F)

Prerequisites:

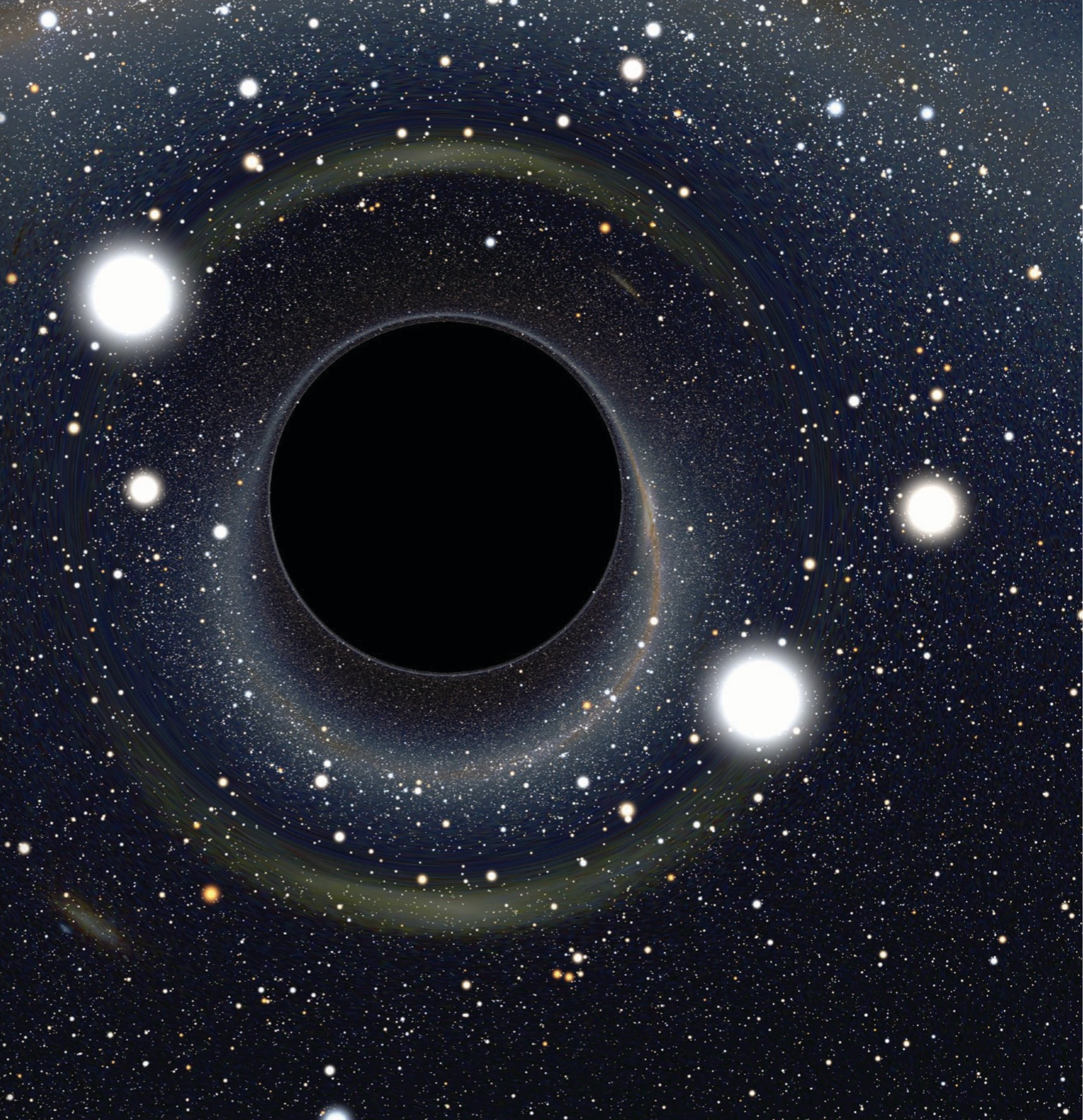
- *Basic elements of optics*
- *Familiarity with special relativity*
- *Familiarity with Fourier series and transforms*

Outline of the course:

- *Elements of General Relativity*
- *Generation, propagation and detection of gravitational waves*
- *Gravitational-wave interferometers*
- *Basics of GW signal analysis*
- *Overview of the main astrophysical sources of GWs*

Related courses

- *Nuclear and subnuclear astrophysics (Longo)*
- *Astrophysics of compact objects (Barausse)*



Course topics

- Introduction to General Relativity
    - Riemann manifolds and curved spaces. Christoffel symbols, covariant derivative, parallel transport, geodesic equations. The Riemann curvature tensor, the Ricci tensor, the Ricci scalar. Symmetries of the Riemann and of the Ricci tensors
    - Key principles of GR: principle of general covariance; principle of consistency; equivalence principle; experimental tests of the weak equivalence principle.
    - Geodesic deviation. The stress-energy tensor. The Einstein equations. The Newtonian limit. Linearized gravity. The Lorentz gauge. Gravitational waves in GR.
- Basics of interferometric detection of gravitational waves.
    - Basic description of instrumental effects.
    - GWs at the Chapel Hill conference (1957). The tranverse-traceless gauge. Gravitational wave polarization.
    - Interferometric detection of gravitational waves, the Michelson interferometer as basic scheme; Schnupp asymmetry; laser beam modulation and sidebands. Overview of the Virgo optical technology; fundamentals of Fabry-Perot resonators; matrix optics. Optical stability of Fabry-Perot resonators; transfer function of the Michelson interferometer with FP arms; power recycling.
- Generation of gravitational waves.
    - Gravitational waves produced by simple configurations of moving masses. Heuristic considerations. Calculation of the Ricci tensor of GWs. The stress-energy tensor of GWs and the energy flux.
    - Total power emitted by a GW source. Power emitted by a binary system. Generic behavior of the emission during a compact binary coalescence.
    - The Newtonian approximation for compact binary systems.
    - The physics of the black hole merger GW150914.
- Noise sources and sensitivity of gravitational wave detectors.
    - Introduction to the theory of thermal noises.
    - Shot noise and radiation pressure noise. The Standard Quantum Limit. Squeezing of light to beat the SQL
- Introduction to the analysis of GW signals.
    - Description of the background noise of the GW IFOs. The False Alarm Rate (FAR).
    - Matched filters. Antenna patterns and detection volume. The CBC pipelines. Excess power methods.
    - Commentary of the GW150914 methods paper.
- Overview of GW sources.
    - The first BNS event: GW170817.
    - Multimessenger astronomy with gravitational waves. Cosmological observations.
    - The gravitational-wave transient catalog (GWTC). The near- and medium-term future of GW astrophysics.

Textbooks and course notes

Textbooks:

- ***General relativity***: T. A. Moore: "A General Relativity Workbook", University Science Books, 2013 (website)
- ... (more to come)

Useful study materials

- Kip Thorne: "Black Holes and Time Warps: Einstein's Outrageous Legacy", Norton, 1995 (Italian edition: "Buchi neri e salti temporali", Castelvecchi, 2019)
- J. Foster and J. D. Nightingale: "A Short Course in General Relativity", Springer, 2006, link

Exams

All students are expected to prepare a 20-minute-long presentation on a specific course topic, which is agreed in advance. The presentation can be delivered either in English or in Italian, and it should analyze the given topic in depth. The exam also includes additional questions on the other topics in the course program

Do not forget to sign up for the exam on the ESSE3 website. Also, do not forget to evaluate the course (you cannot sign up if you don't evaluate ...)

Scheduled exam dates:

Exam sessions usually take place in the Physics Dept., and start at 9.30 AM.

List of forthcoming sessions:

- **September 19th 2023**
- **January 30th 2024**

Perspectives:

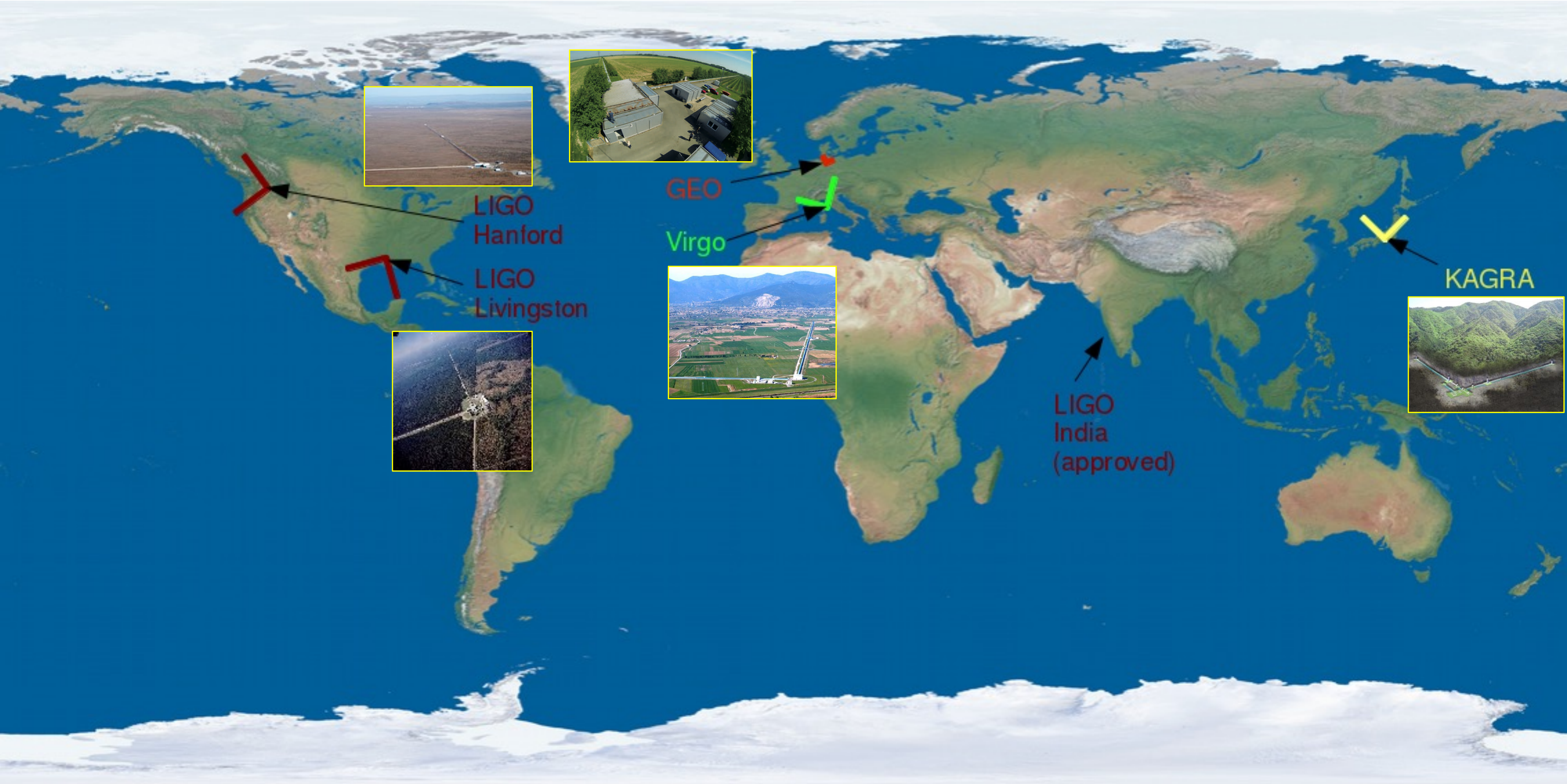
- *MSc theses on GW data analysis topics in the framework of the LIGO/Virgo/KAGRA Collaboration (E. Milotti, A. Trovato, G. Principe)*
- *MSc theses on experimental topics related to the Virgo interferometer (in collaboration with the Padova Virgo group)*
- *PhD positions both in Trieste and many other universities in Italy and abroad*
- *Participation to a large international scientific collaboration*

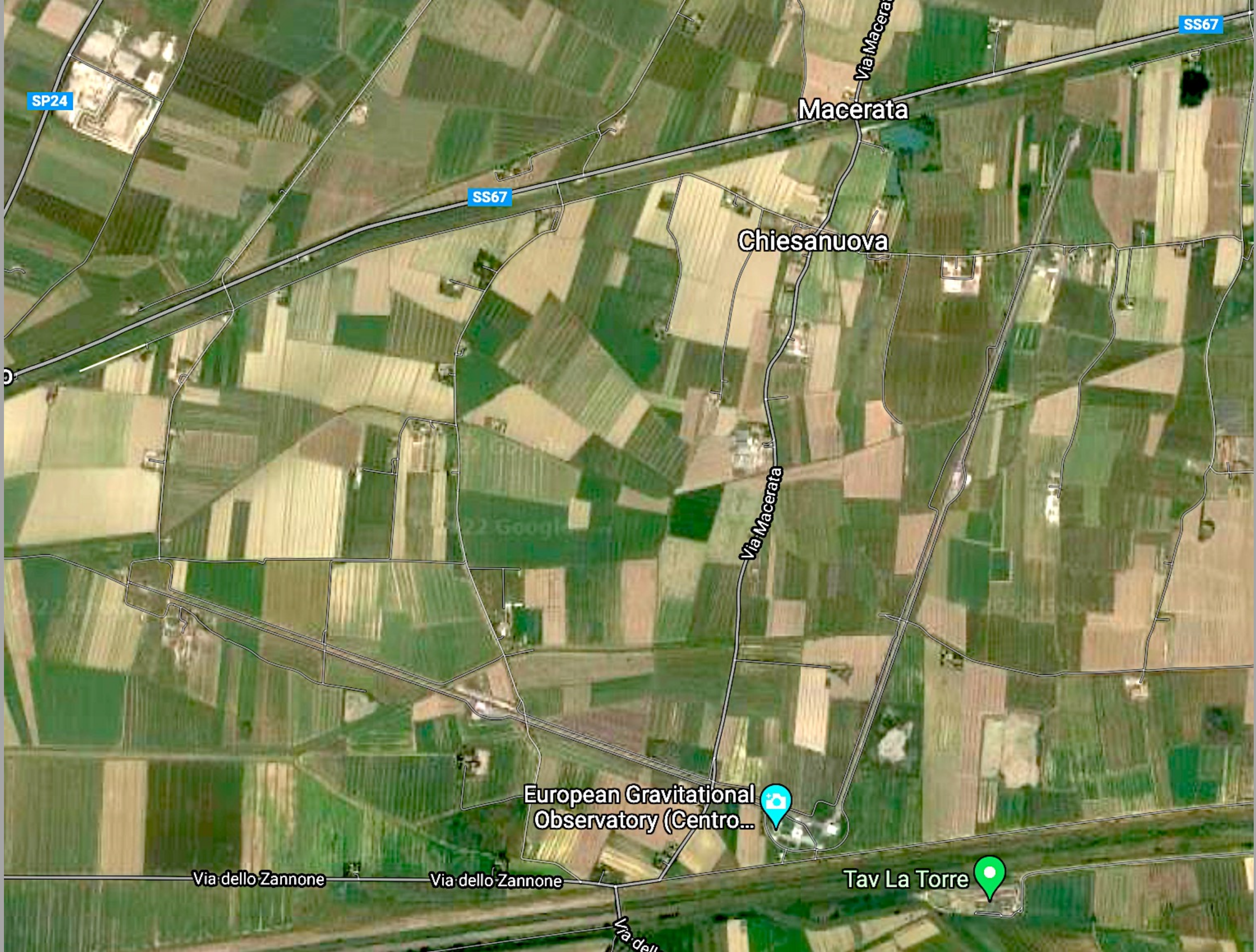
Skills associated with the research field:

- *(astro)physics of compact and exotic objects*
- *advanced programming skills*
- *statistical signal analysis*
- *applied machine learning*
- *advanced optics*

Find out more :
https://www.virgo-gw.eu
https://www.ligo.org
https://gwcenter.icrr.u-tokyo.ac.jp/en/

La rete mondiale di osservatori gravitazionali (2020)




SS67
SP24
Macerata
SS67
Chiesanuova
Via Macerata
European Gravitational Observatory (Centro...
Via dello Zannone
Via dello Zannone
Tav La Torre


European Gravitational Observatory (Centro...
Via Eduardo Amaldi
Via E Amaldi
Via E Amaldi
Via E Amaldi
Via E Amaldi
Via E Amaldi
Via E Amaldi


Le 23 Juillet 2003
Il 23 luglio 2003
CLAUDIE HAIGNERÉ,
Ministre déléguée à la Recherche et aux Nouvelles Technologies
LETIZIA MORATTI
Ministro dell'Istruzione, dell'Università e della Ricerca
Ont inauguré le détecteur d'ondes gravitationnelles
VIRGO
réalisé conjointement par
LE CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE
et
L'ISTITUTO NAZIONALE DI FISICA NUCLEARE
sur le site de
hanno inaugurato il rivelatore di onde gravitazionali
VIRGO
realizzato congiuntamente da
L'ISTITUTO NAZIONALE DI FISICA NUCLEARE
e
LE CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE
sul sito di
European Gravitational Observatory
Les laboratoires suivants ont collaboré à la réalisation de Virgo
I seguenti laboratori hanno collaborato alla realizzazione di Virgo
INFN - Sezione di Firenze
CNRS - Ecole Supérieure de Physique et de Chimie industrielle
INFN - Sezione di Napoli
CNRS-IN2P3 - Laboratoire d'Annecy-le-Vieux de Physique des Particules
INFN - Sezione di Roma 1
CNRS-IN2P3 - Laboratoire de l'accélérateur linéaire - Orsay
INFN - Sezione di Perugia
CNRS-IN2P3 - Institut de Physique Nucléaire de Lyon
INFN - Sezione di Pisa
CNRS - Observatoire de la Côte d'Azur - Département Fresnel
INFN - Laboratorio Nazionale di Frascati

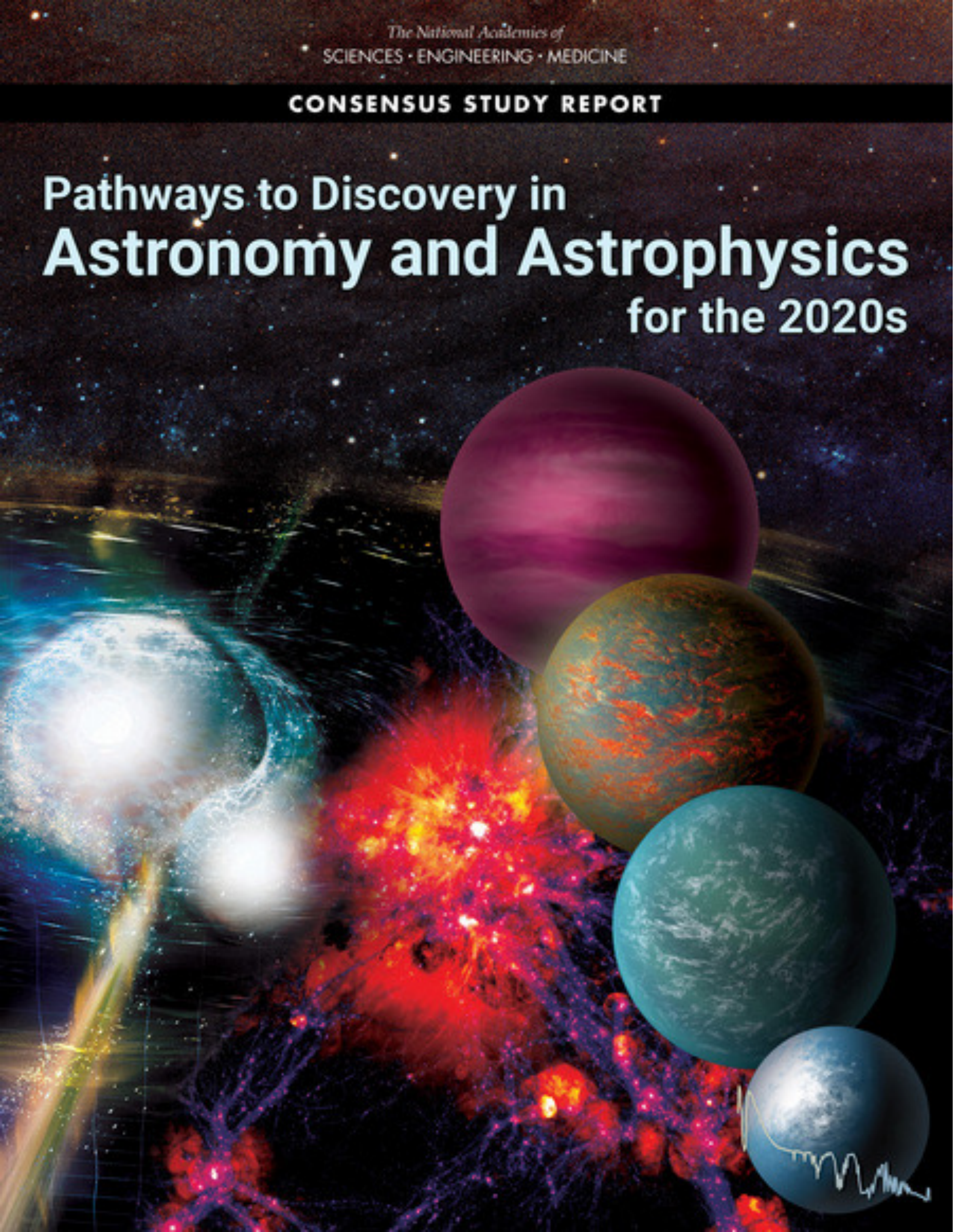
IEEE MILESTONE

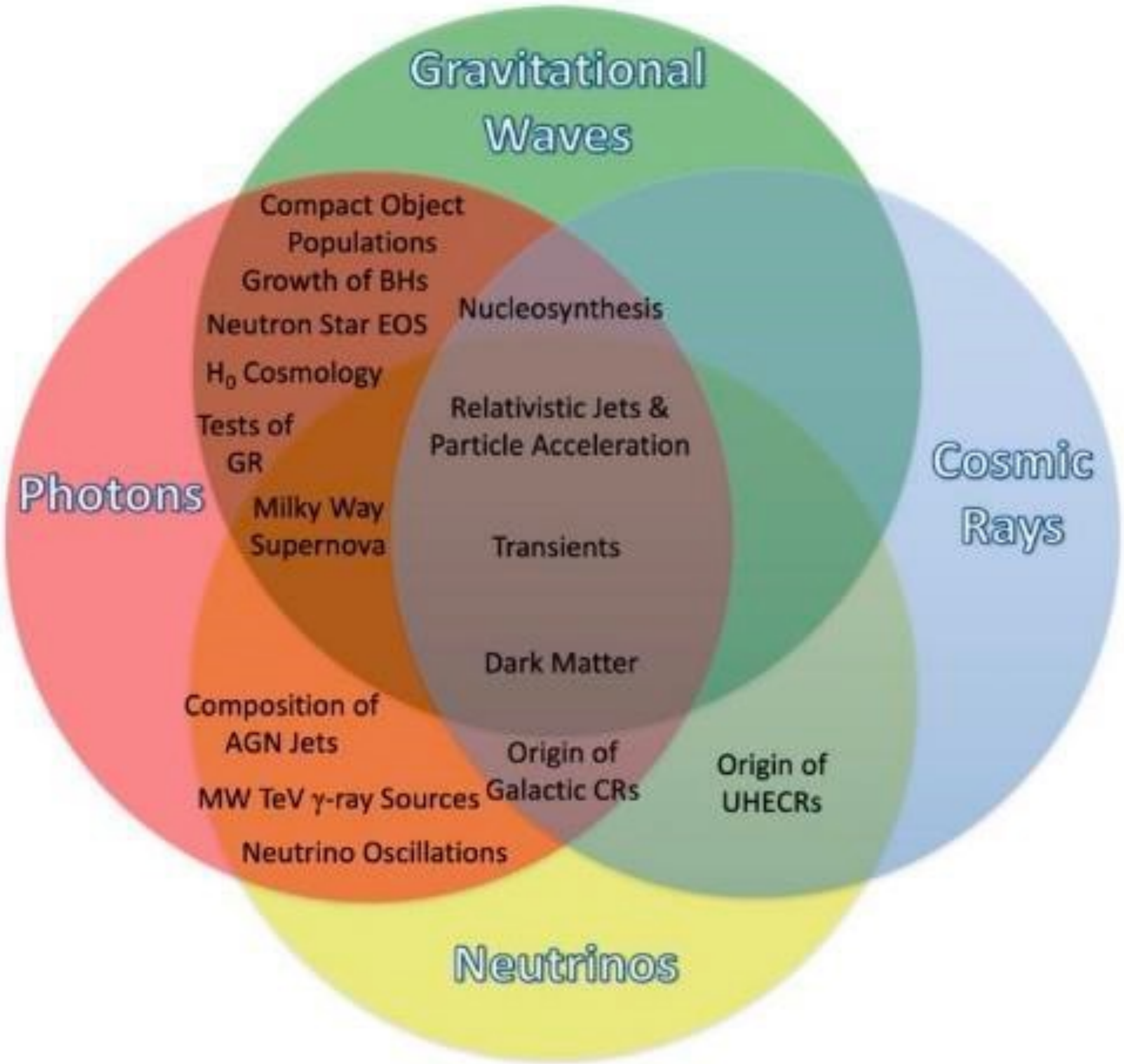
Gravitational-Wave Antenna, 1972-1989

Initially developed from 1972 to 1989, the Gravitational-Wave Antenna enabled detection of ripples in spacetime propagating at the speed of light, as predicted by Albert Einstein's 1916 Theory of General Relativity. Construction of the Virgo Gravitational-Wave Observatory commenced in 1997. In 2017, Virgo and two antennas located in the U.S.A. launched the era of Multi-Messenger Astronomy with the coordinated detection of gravitational waves from a binary neutron star merger.

February 2021

IEEE


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

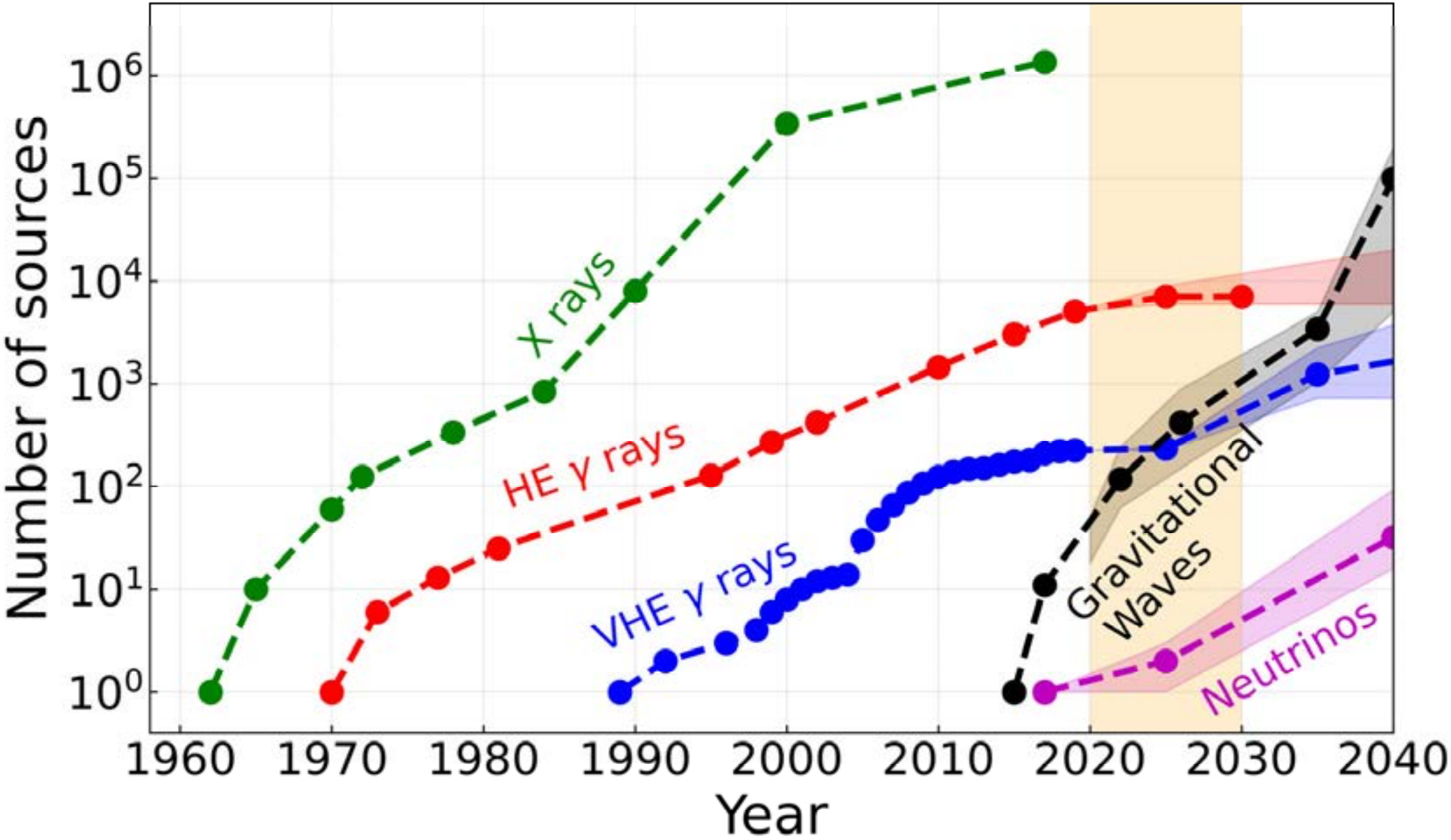

Gravitational Waves
Photons
Cosmic Rays
Neutrinos
Compact Object Populations
Growth of BHs
Neutron Star EOS
H_0 Cosmology
Tests of GR
Milky Way Supernova
Nucleosynthesis
Relativistic Jets & Particle Acceleration
Transients
Dark Matter
Composition of AGN Jets
MW TeV γ-ray Sources
Neutrino Oscillations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

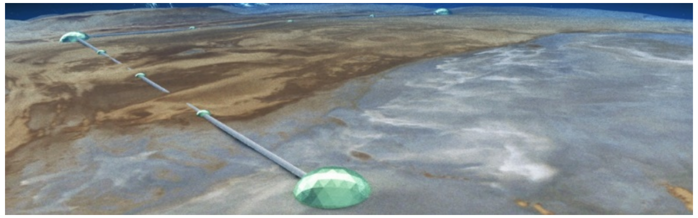
• ***Gravitational-wave program***: Medium-scale investments in three bands (kHz, nHz, and mHz) to develop a rich observational program: **Cosmic Explorer, with NSF support for technology development to set the stage for large-scale investments and huge detection rates in the 2030s**; the North American 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



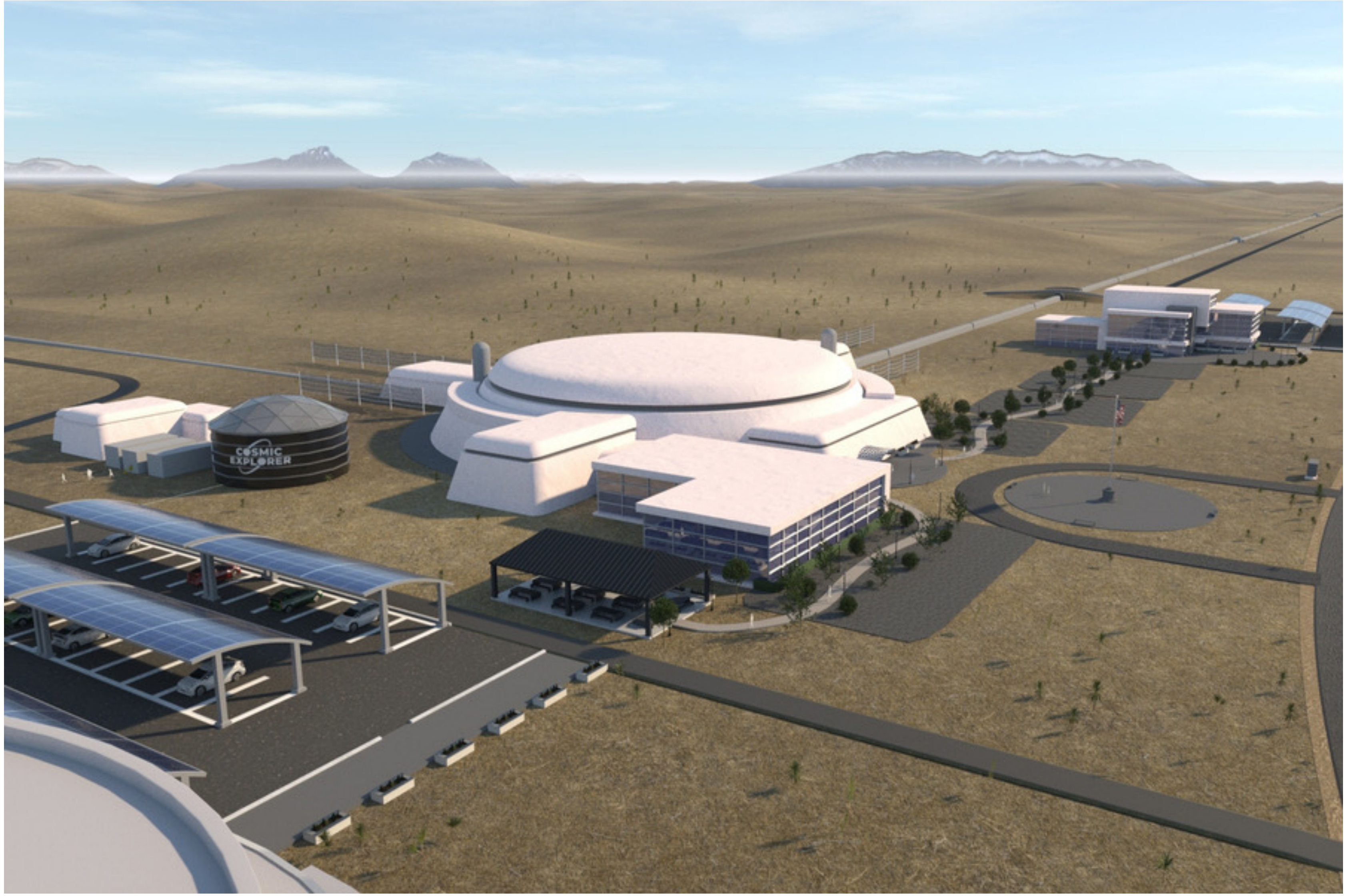
Gravitational wave detection is one of the most exciting and expanding scientific frontiers impacting central questions in astronomy

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

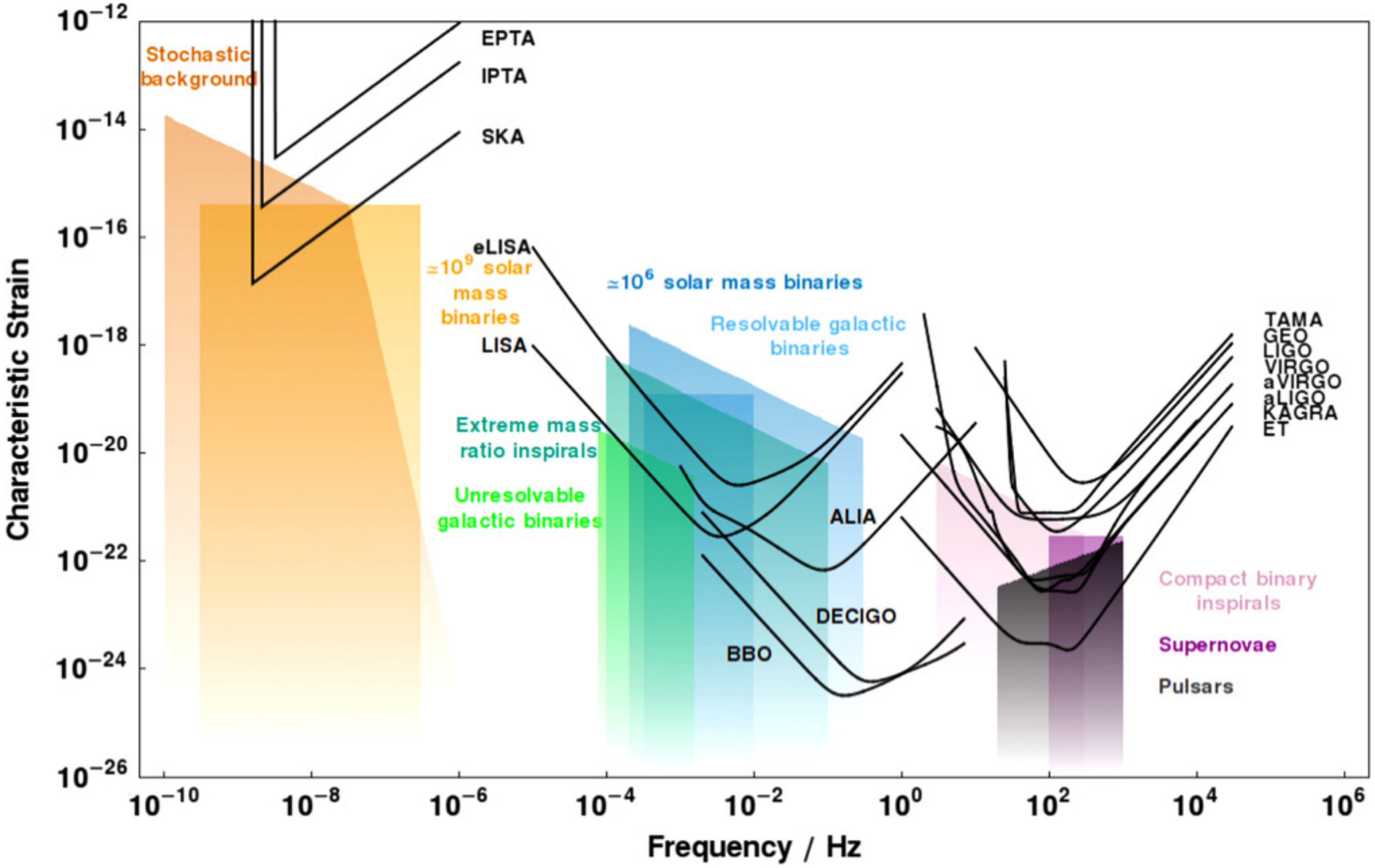
More advanced detectors in the current LIGO facility (beyond A+) and planning for future generation facilities such as Cosmic Explorer are essential

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.

Looking into the future: a wider GW network, the 3G detectors and LISA



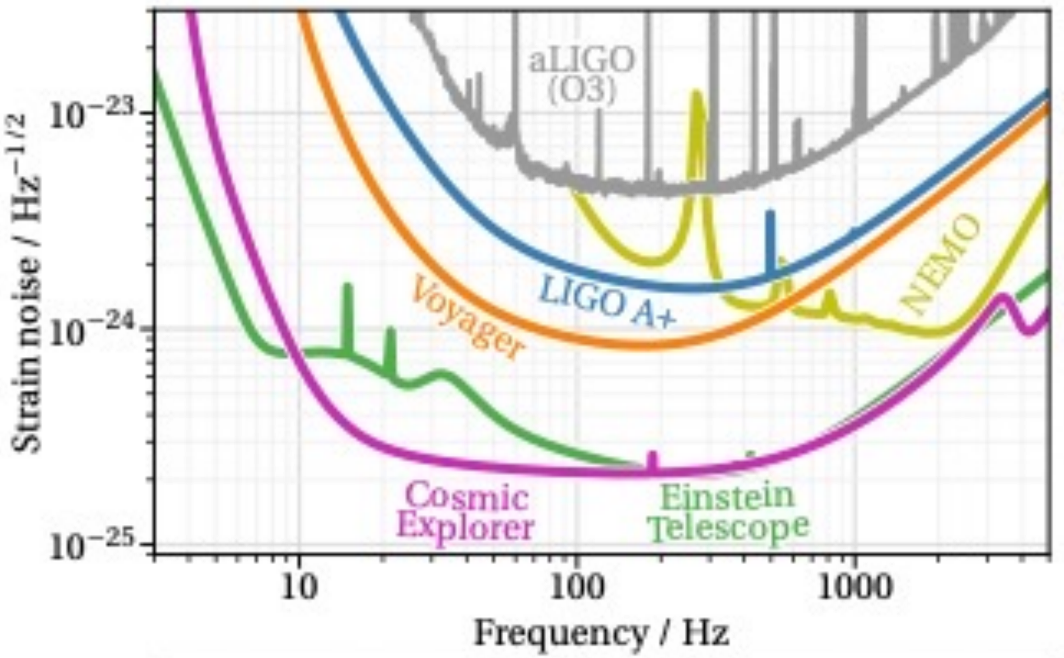
Looking into the future: a wider GW network, the 3G detectors and LISA

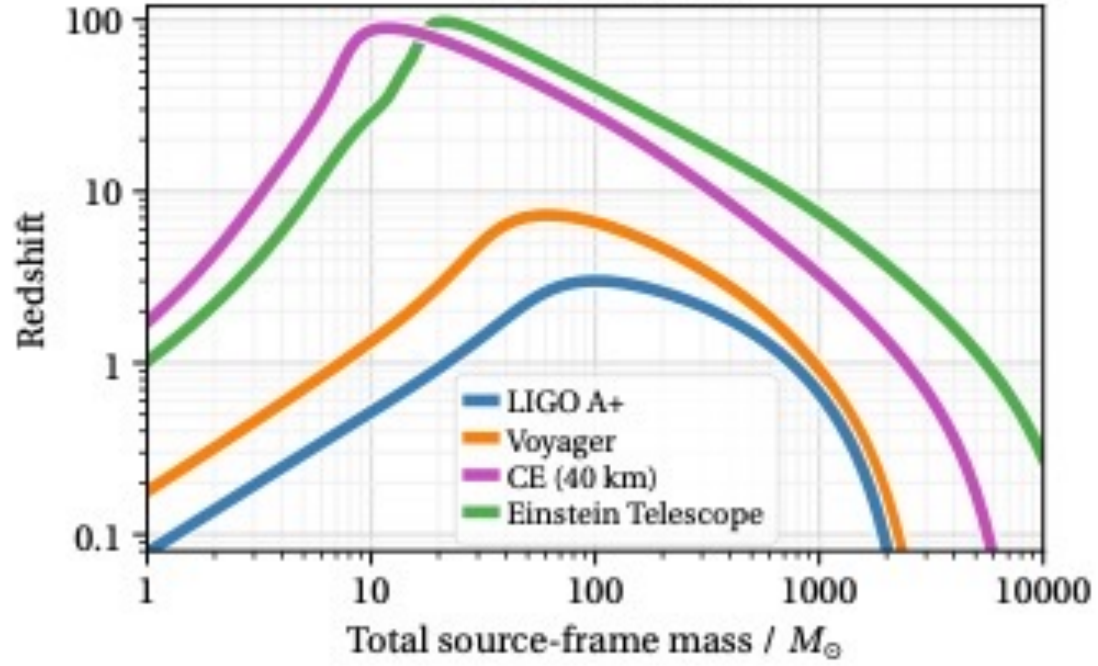


$$\Delta L = h \times L$$

$$\tau > \delta / c$$

$$f = \frac{1}{\tau} < \frac{c}{\delta}$$



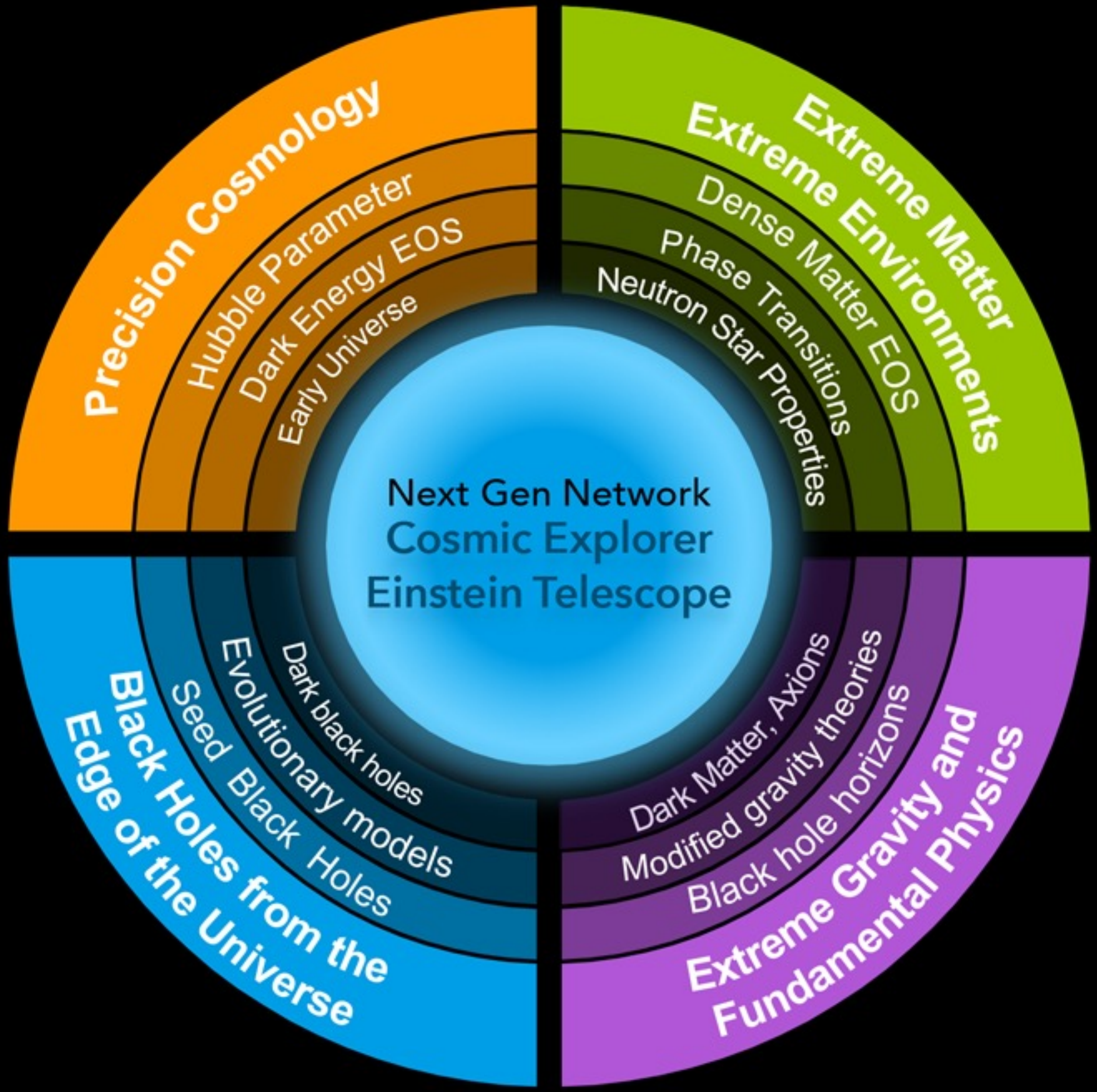


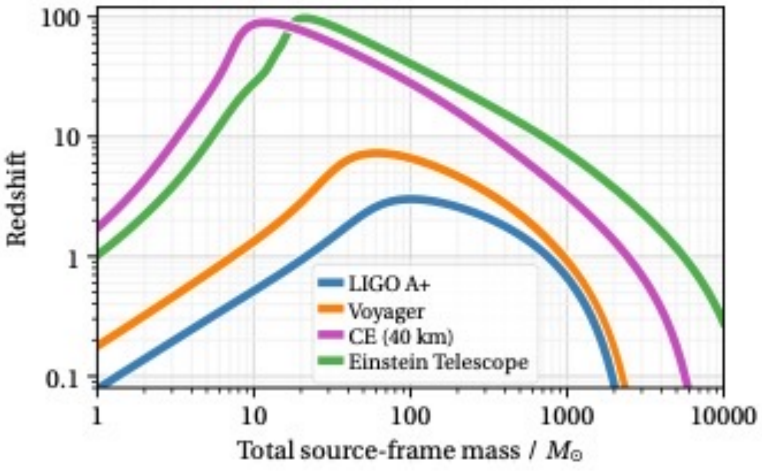
Top: **Amplitude spectral densities of detector noise** for Cosmic Explorer (CE), the current (O3) and upgraded (A+) sensitivities of Advanced LIGO, LIGO Voyager, NEMO, and the three paired detectors of the triangular Einstein Telescope.

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.

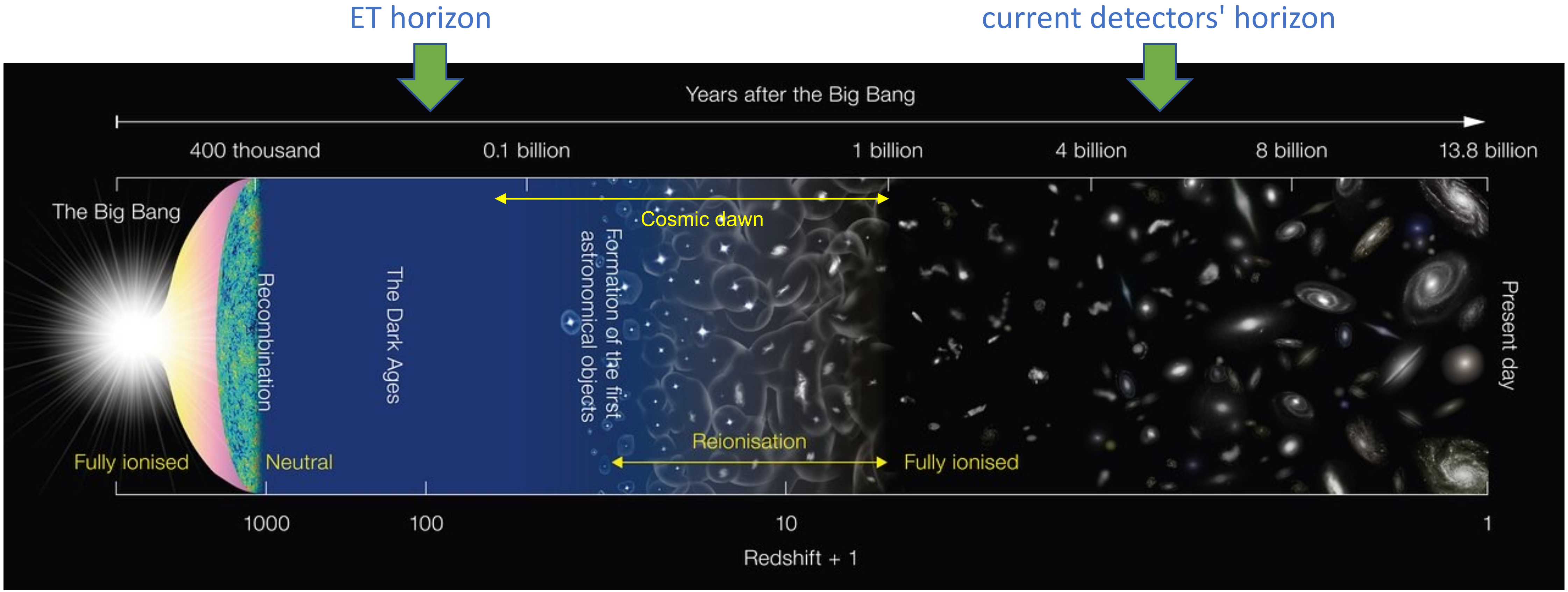
For binary neutron stars (total mass ~$3M_\odot$), ET and CE will give access to redshifts larger than 1, where most of the mergers are expected to happen.

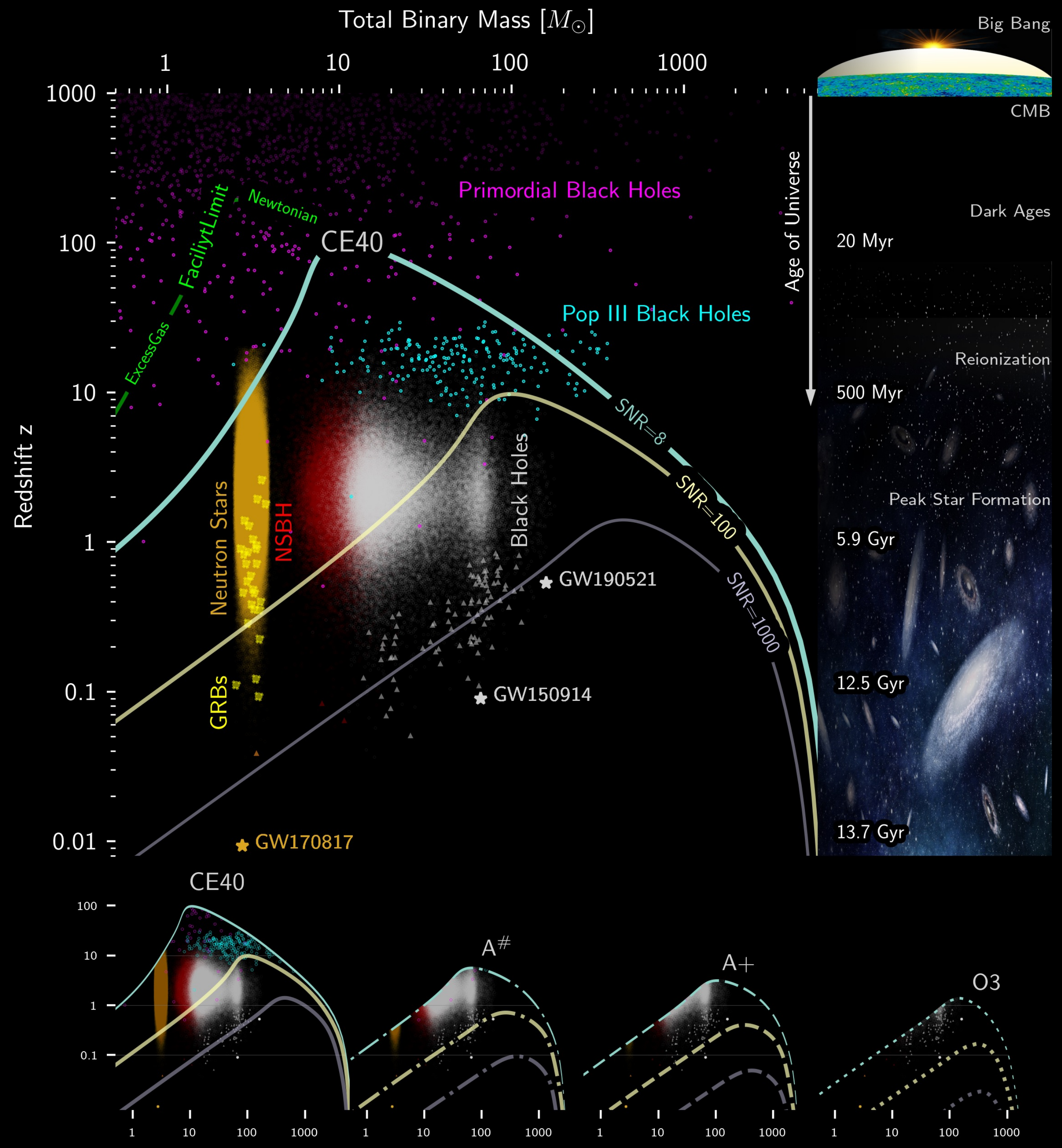
For binary black holes, they will enable the exploration of redshifts of 10 and above, where mergers of black holes formed by either the first stellar population in the universe (Pop III stars) or by quantum fluctuations shortly after the Big Bang (primordial black holes) might be found.


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



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.





Total Binary Mass $[M_\odot]$
Redshift z
Big Bang
CMB
Dark Ages
20 Myr
Reionization
500 Myr
Peak Star Formation
5.9 Gyr
12.5 Gyr
13.7 Gyr
Age of Universe
Primordial Black Holes
Pop III Black Holes
CE40
Newtonian
FacilitytLimit
ExcessGas
Neutron Stars
NSBH
Black Holes
GRBs
SNR=8
SNR=100
SNR=1000
GW190521
GW150914
GW170817
A#
A+
O3

The LISA GW detector in space

https://www.youtube.com/watch?v=h_ApNry_jN0
https://www.youtube.com/watch?v=aTPkoZxyovo&t=13s

Next:

- Special Relativity and notation
- An application of SR: the GZK cutoff
- The Cosmic Microwave Background

The Nobel Prize in Physics 2006

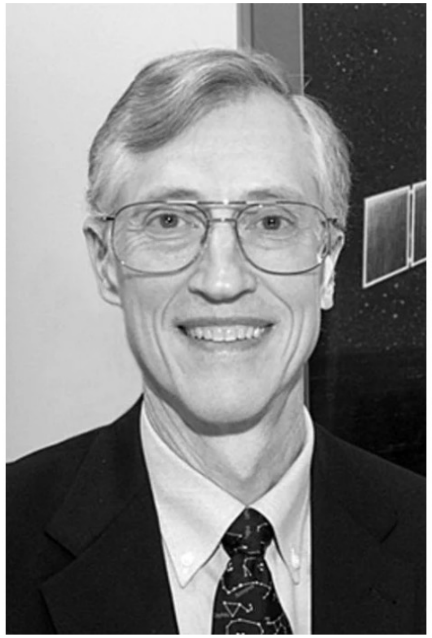


Photo: P. Izzo

John C. Mather

Prize share: 1/2

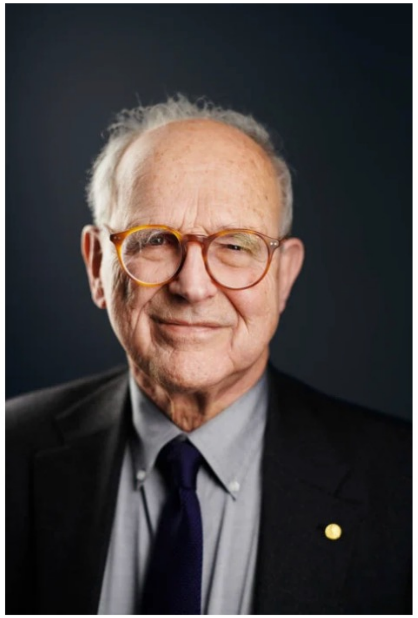
Photo: J. Bauer

George F. Smoot

Prize share: 1/2

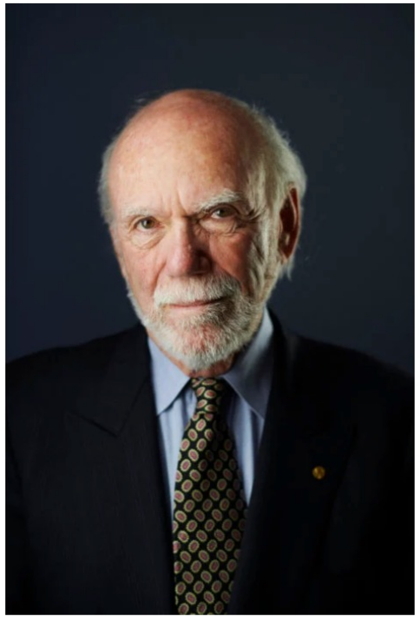
The Nobel Prize in Physics 2006 was awarded jointly to John C. Mather and George F. Smoot "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

The Nobel Prize in Physics 2017



Rainer Weiss

Prize share: 1/2



Barry C. Barish

Prize share: 1/4

Kip S. Thorne

Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne "for decisive contributions to the LIGO detector and the observation of gravitational waves"

The Sound of Gravity

https://www.youtube.com/watch?v=UMP3ZSVclmg&t=17s

The OMG particle

https://www.youtube.com/watch?v=osvOr5wbkUw&t=620s