VIRGO DAL PROGETTO EUROPEO PIONIERISTICO ALLA SCIENZA DELLE ONDE GRAVITAZIONALI

EGO EUROPEAN GRAVITATIONAL OBSERVATORY

sanoma

INFN CC3M

Istituto Nazionale di Fisica Nucleare
Comitato di Coordinamento Terza Missione

Gianluca Gemme

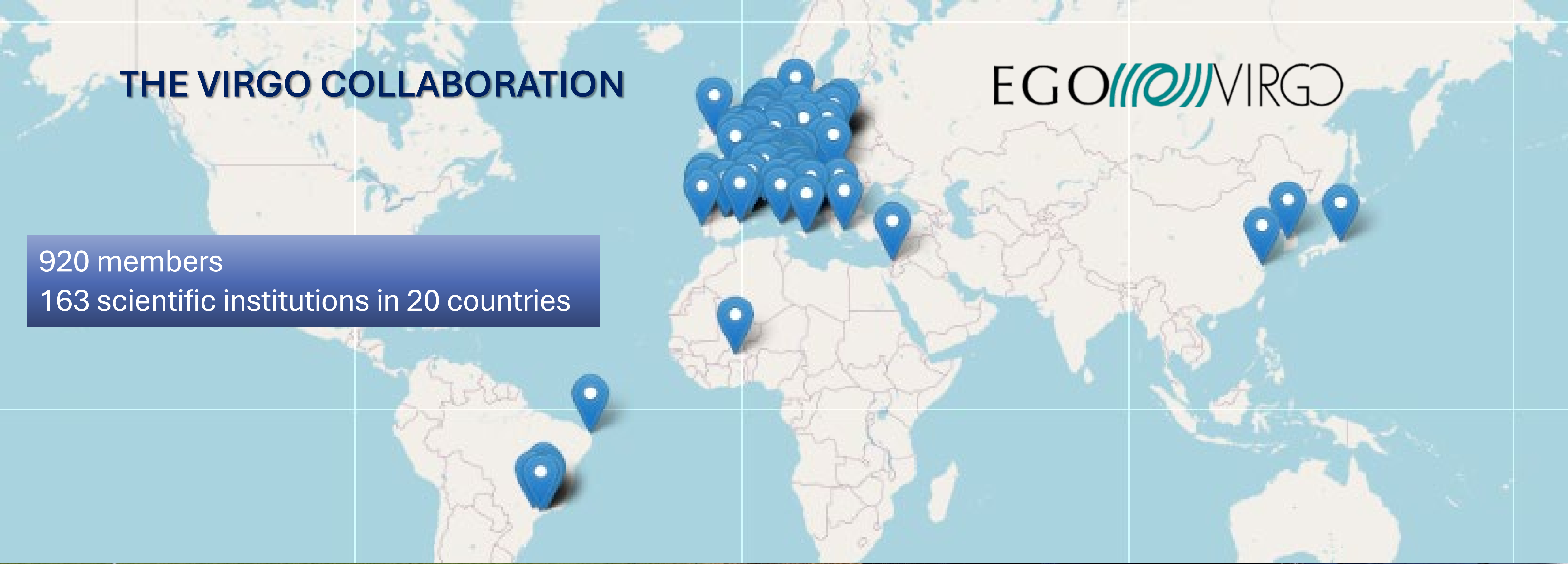
Istituto Nazionale di Fisica Nucleare

Spokesperson of the Virgo collaboration

THE EUROPEAN GRAVITATIONAL OBSERVATORY

THE VIRGO COLLABORATION

920 members
163 scientific institutions in 20 countries



INTERNATIONAL GRAVITATIONAL DETECTOR NETWORK

3000 members in four continents

AT THE SPEED OF THOUGHT

1916: prediction of the existence of gravitational waves ("GWs") by Albert Einstein

A direct consequence of its General Relativity theory, published the year before

→ Decades of discussion among scientists about the physical reality of GWs

"Gravitational waves propagate at the speed of thought" (A.S. Eddington, 1922)

1956 Breakthrough: the Chapel Hill conference

Theoretical consensus that GWs do exist and are worth being searched for

→ Experimental physicists start designing and building GW detectors

REVIEWS OF MODERN PHYSICS VOLUME 29, NUMBER 3 JULY, 1957

Summary of the Chapel Hill Conference*

PETER G. BERGMANN

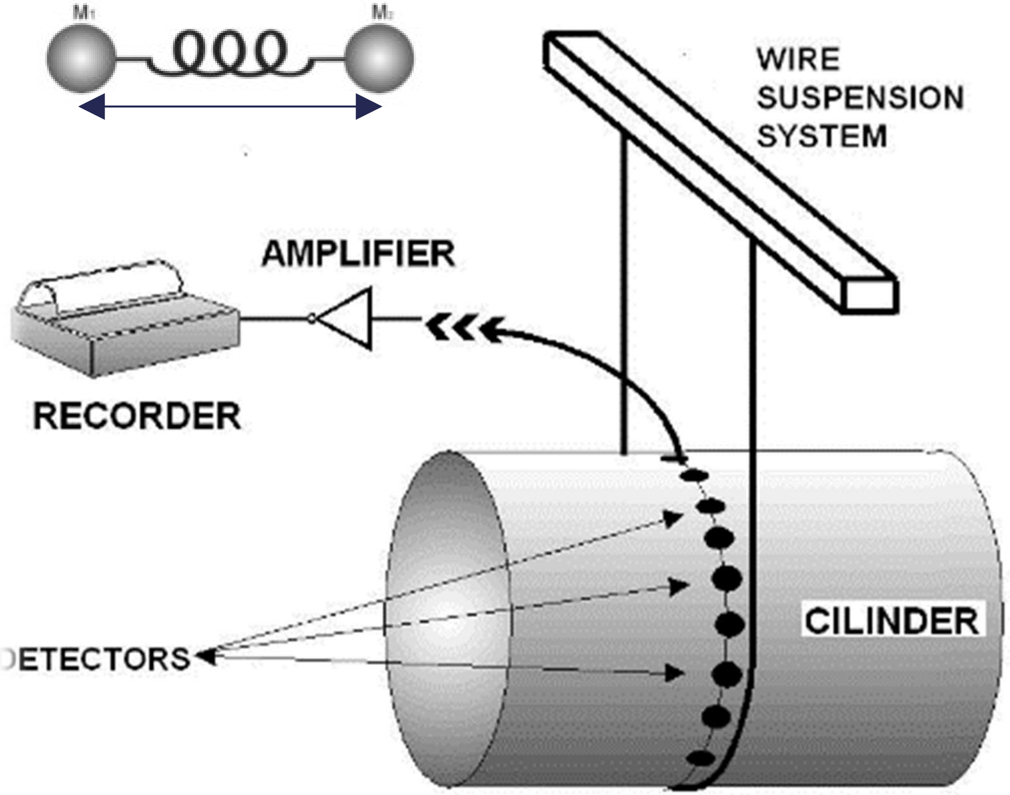
Department of Physics, Syracuse University, Syracuse 10, New York

In my opinion the most important nonquantum problem that has been discussed at this conference is the existence of gravitational waves. Actually there is a

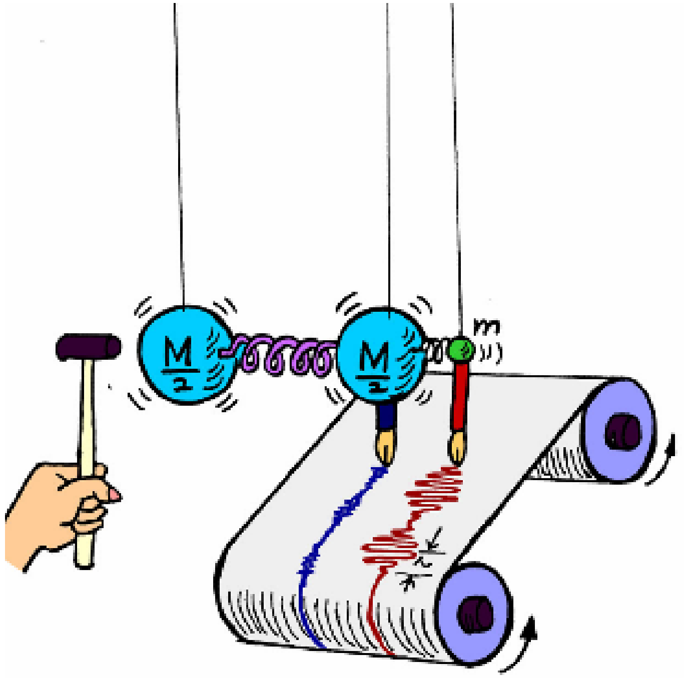
In summary then, I believe that in the time between this conference and the next relativity conference (planned in Europe for the summer of 1958) we have a good chance to make significant progress in the two classical problems concerning gravitational waves and true observables, and that thereby we may also contribute to the task of quantizing general-relativistic fields.

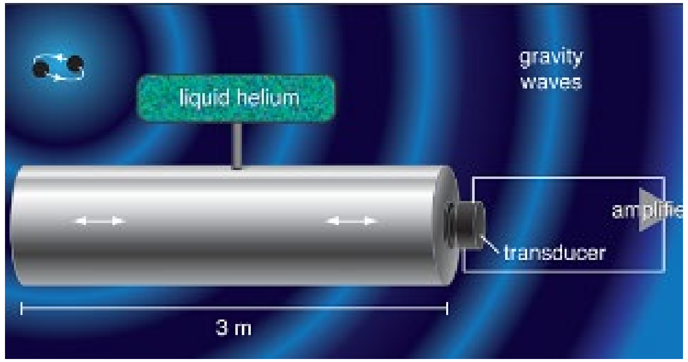
LA RICERCA SPERIMENTALE DELLE ONDE GRAVITAZIONALI

Verso la fine degli anni '50 Joe Weber realizza i primi strumenti per cercare di rivelare il Passaggio di un'onda gravitazionale in laboratorio:
le **ANTENNE RISONANTI**



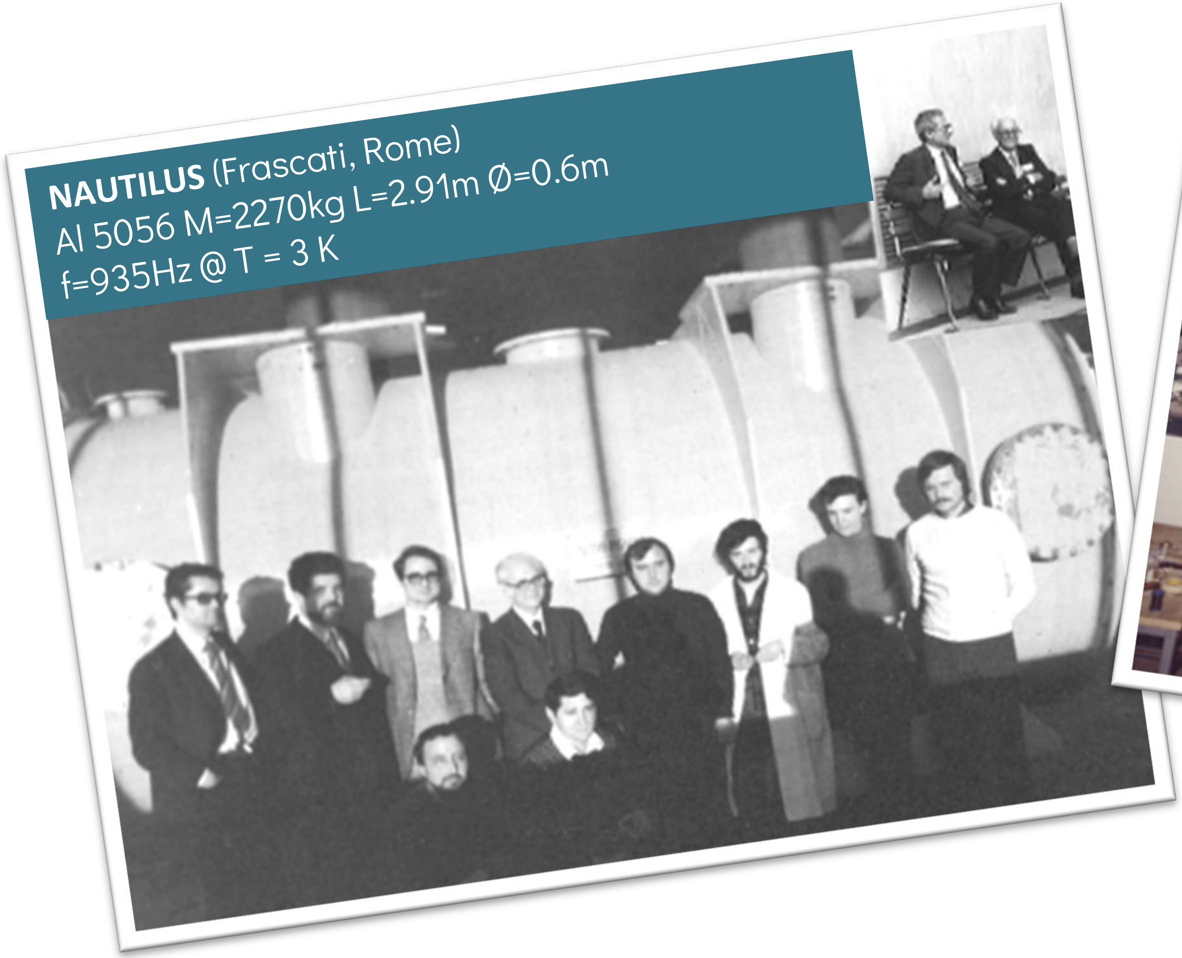
UN DIAPASON MOLTO SENSIBILE

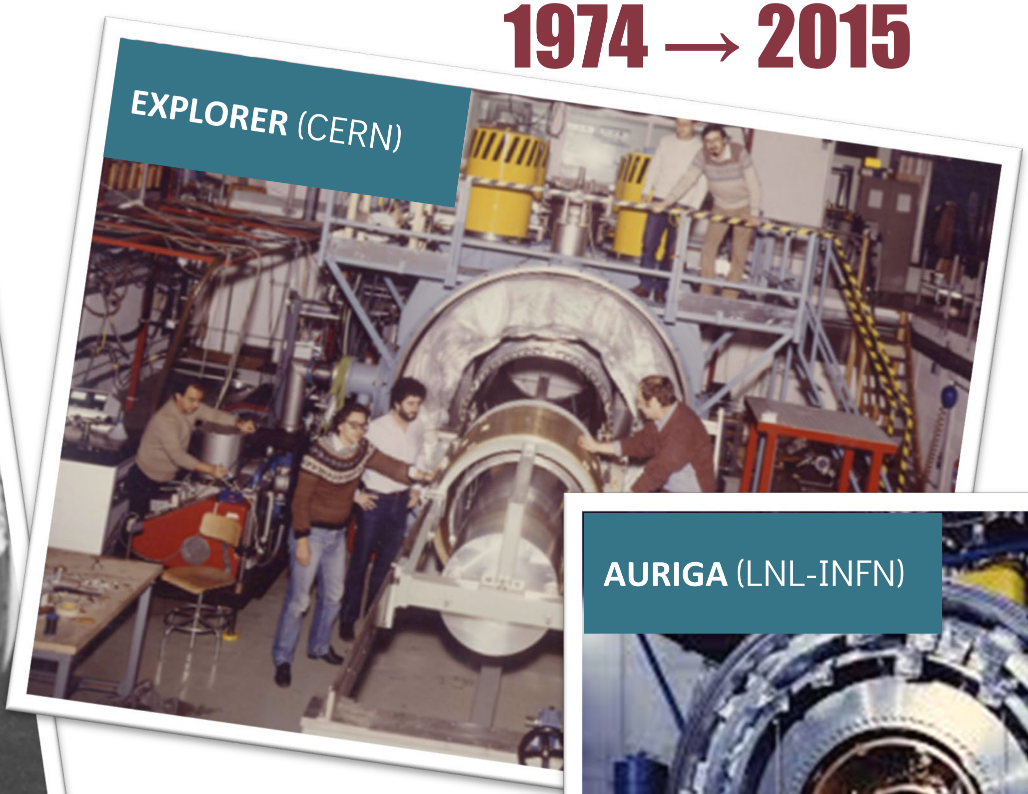




SCIENZIATI ITALIANI ALLA RICERCA DELLE ONDE GRAVITAZIONALI

1974 → 2015

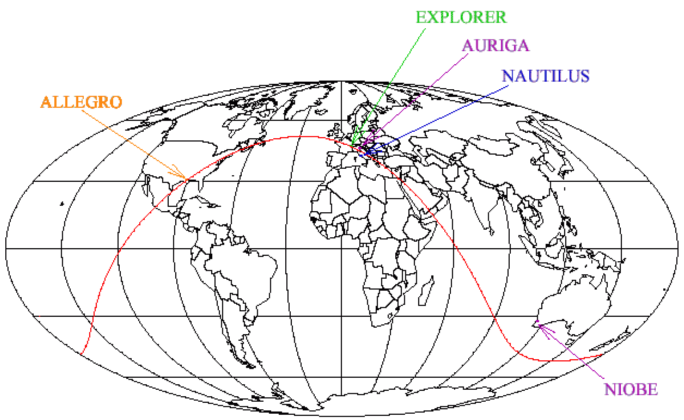




Guido Pizzella, Gianvittorio Pallottino, Ivo Modena, Umberto Giovanardi, Fulvio Ricci, Piero Rapagnani, Sergio Frasca, Massimo Bassan, Eugenio Coccia, Pia Astone, Viviana Fafone…

M Cerdonio, G. A. Prodi, S. Vitale, A. Ortolan, L. Taffarello, G. Vedovato, J.-P. Zendri, M. Bonaldi, P. Falferi…

History of E-N DATA TAKING



1990-2012

10 years of science run

NEL FRATTEMPO…

1962

I fisici russi **M. E. Gertsenshtein** e **V. I. Pustovoit** pubblicano il primo lavoro che descrive i principi generali per l'uso degli interferometri come rivelatori di onde gravitazionali. Il lavoro passò largamente inosservato…

1962-1970

Edoardo Amaldi stimolò la comunità scientifica italiana verso la ricerca sperimentale in nuovi campi

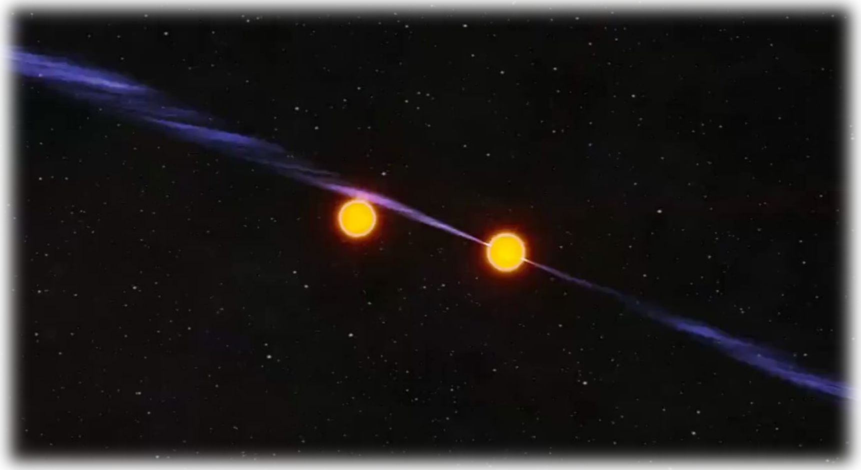
Guido Pizzella, l'assistente di Amaldi, cominciò a interessarsi della ricerca delle onde gravitazionali. Il suo interesse si rivolse alle 'antenne' di Weber

1972

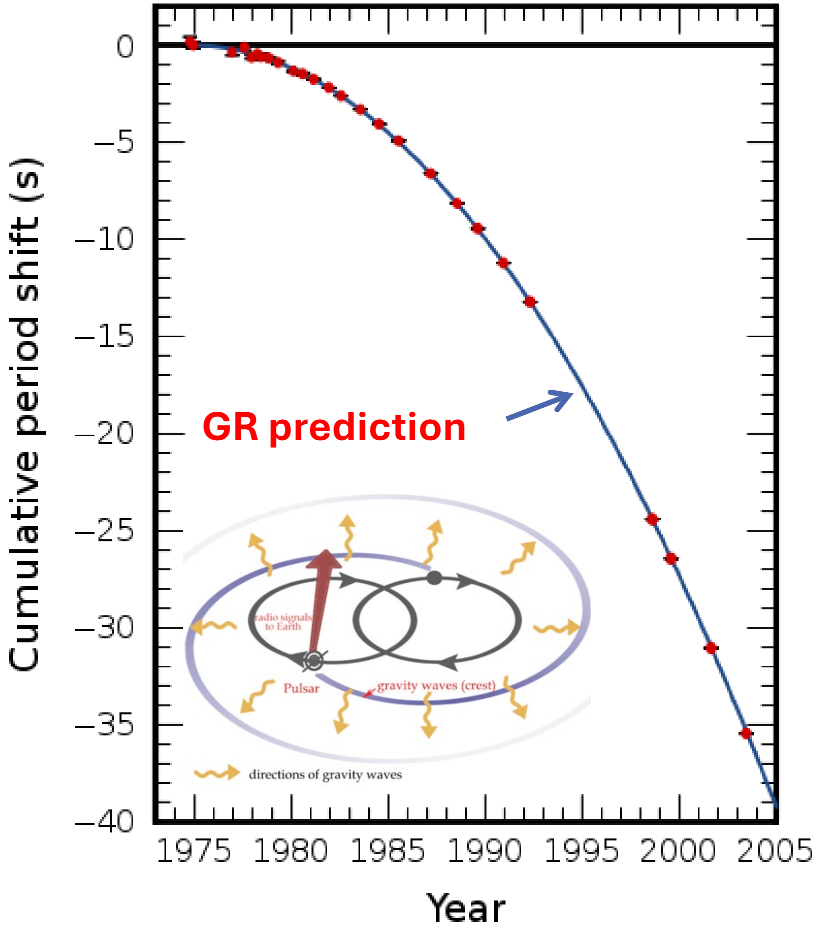
Rainer Weiss del Massachusetts Institute of Technology (MIT) in Cambridge (MA, USA) propose indipendentemente metodi ottici per rivelare le onde gravitazionali

SIAMO SICURI CHE ESISTANO?
UN'EVIDENZA INDIRETTA...

1974-1979



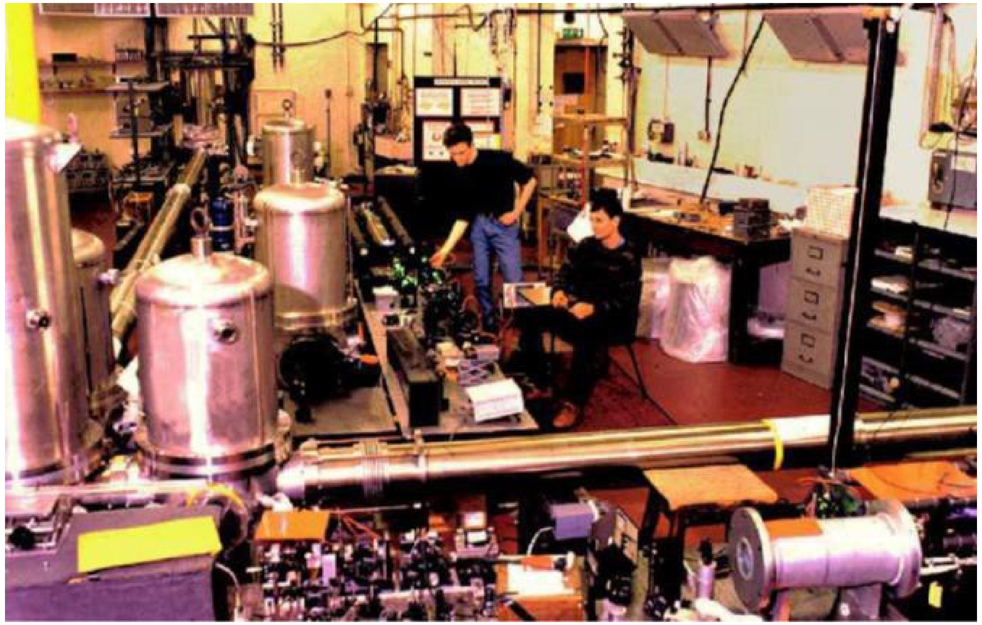
The Nobel Prize in Physics 1993
Russell A. Hulse, Joseph H. Taylor Jr.



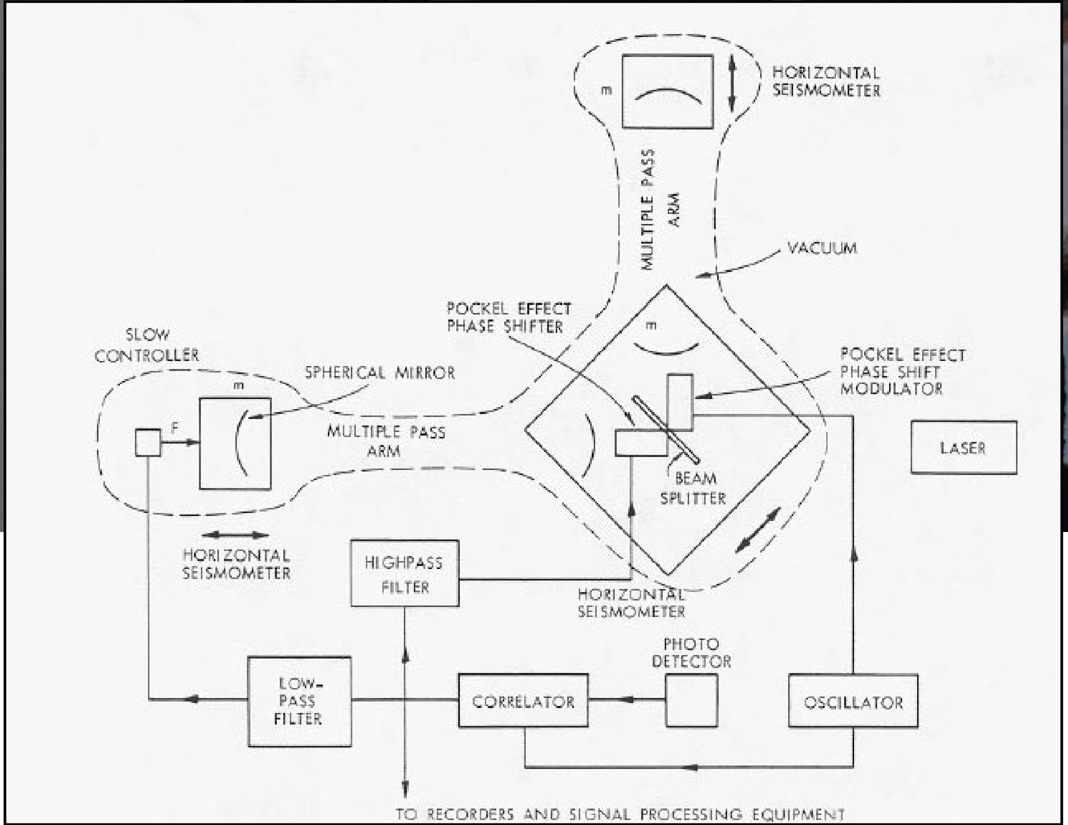
INTERFEROMETRIC DETECTORS: TIMELINE

- 1970: first IFO prototype (R. Forward, Hughes Research Laboratories)
- 1972: IFO design studies (Weiss)
- 1980's: ~10m-long IFO prototypes: Caltech, MIT, Garching, Glasgow, Orsay
- 1985: Marcel Grossman conference
  - Alain Brillet (CNRS) and Adalberto Giazotto (INFN) meet
- 1989: LIGO proposal (approved 1990, funded 1991)
- 1987-89: Virgo proposal (approved 1992)
  - Birth of what will become Virgo
  - Core: French-Italian collaboration

Robert Forward



THE BIRTH OF LIGO



QUARTERLY PROGRESS REPORT

No. 105

APRIL 15, 1972

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

RESEARCH LABORATORY OF ELECTRONICS

CAMBRIDGE, MASSACHUSETTS 02139

(V. GRAVITATION RESEARCH)

B. ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

1. Introduction

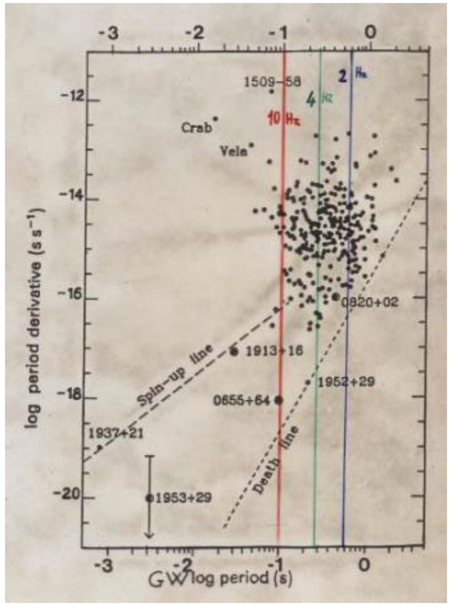
The prediction of gravitational radiation that travels at the speed of light has been

THE VIRGO PROJECT

A. Brillet and
A. Giazotto

Laser know-how
Precise measurements

Complementary expertises for a common goal → detect GWs



Seismic isolation for resonant bars
Going low in frequency to detect pulsars

SAN PIERO A GRADO, 1985

One-mile equivalent length interferometric pendulum for seismic noise reduction

A. Giazotto, D. Passuello, and A. Stefanini

I. N. F. N. Sezione di Pisa and Dipartimento di Fisica, Universitá di Pisa, Pisa, Italy

(Received 9 August 1985; accepted for publication 14 February 1986)

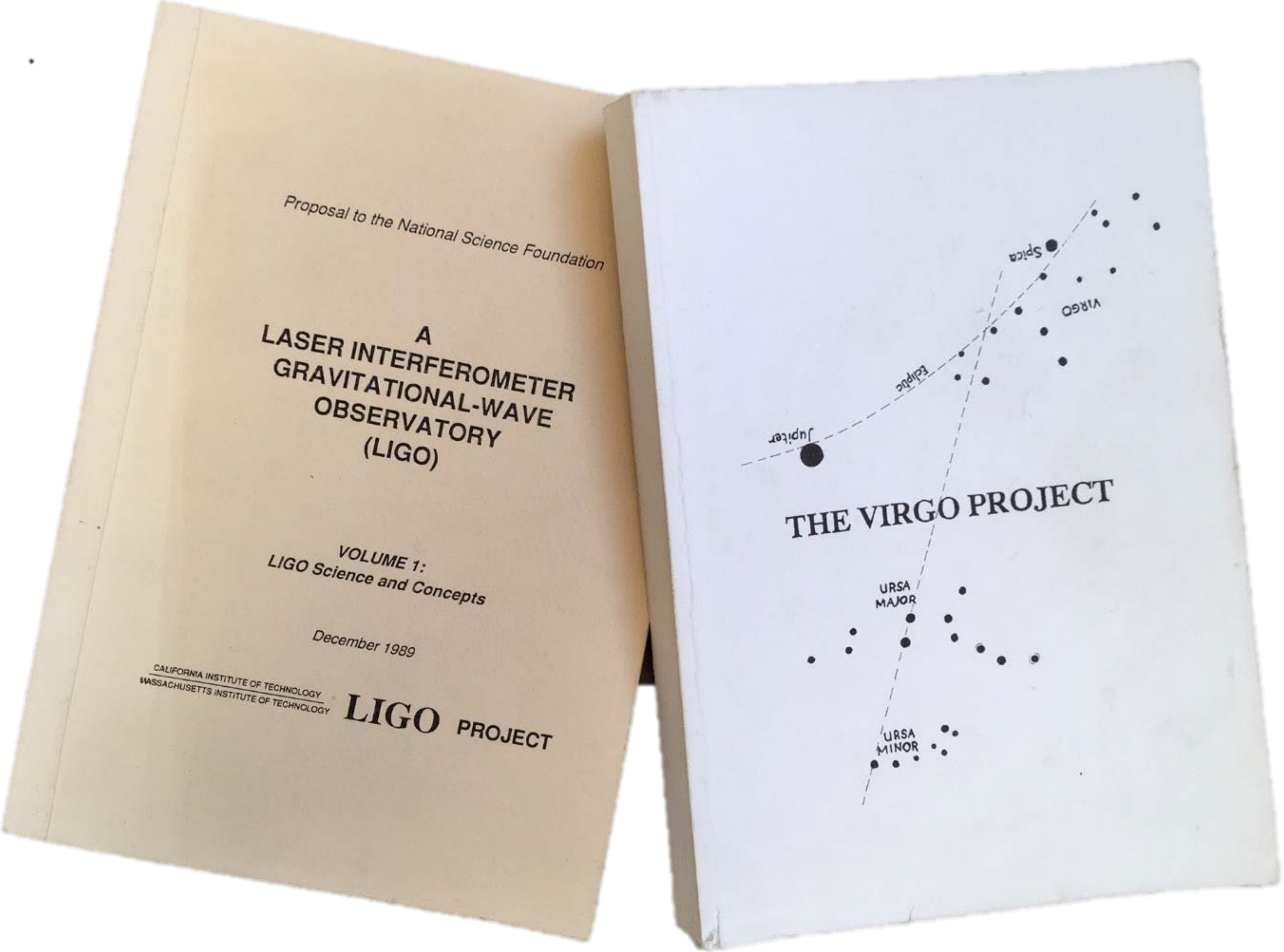
We describe the performances of a 100-kg, 1-m-long active pendulum provided with a reference arm to get rid of the effects of tilting of the ground. The pendulum displacement with respect to the suspension point is measured interferometrically. The phase signal, to be sent to the actuator which displaces the suspension point, is extracted from the interferometer using an analog phase follower. At 10 Hz we obtain a virtual pendulum length of 1.7 km with the reference arm locked and 1.2 km when the reference arm is free. This device can be used to reduce the seismic noise in an antenna for low-frequency gravitational wave detection.

INTRODUCTION

It is well known that the length of a pendulum can be electronically increased[1,2] with the purpose of reducing the seis-

$$\psi \simeq \phi[B/(1-B)] + 0(1/B),$$

i.e., the PZT2 driving voltage is proportional to ϕ and can be used to drive the actuator displacing the pendulum suspen-


Proposal to the National Science Foundation
A
LASER INTERFEROMETER
GRAVITATIONAL-WAVE
OBSERVATORY
(LIGO)
VOLUME 1:
LIGO Science and Concepts
December 1989
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LIGO PROJECT
THE VIRGO PROJECT
URSA MAJOR
URSA MINOR

May 1987: initial proposal

21

12 Maggio 1987
INFN PI/AE 87/1

Proposta di

Antenna interferometrica a grande base per la ricerca di Onde Gravitazionali

Laboratori INFN Pisa e Universita' di Pisa:

Carlo BRADASCHIA
Raffaele DEL FABBRO
Angela DI VIRGILIO
Adalberto GIAZOTTO
Hans KAUTZKY
Vinicio MONTELATICI
Diego PASSUELLO

Universita' di Napoli

Fabrizio BARONE
Riccardo BRUZZESE
Antonello CUTOLO
Luciano DI FIORE (INFN)
Massimo LANDINI
Maurizio LONGO
Leopoldo MILANO
Salvatore SOLIMENO

CNR Frascati

Franco BORDONI
Franco FULIGNI
Valerio IAFOLLA

Universita' di Salerno

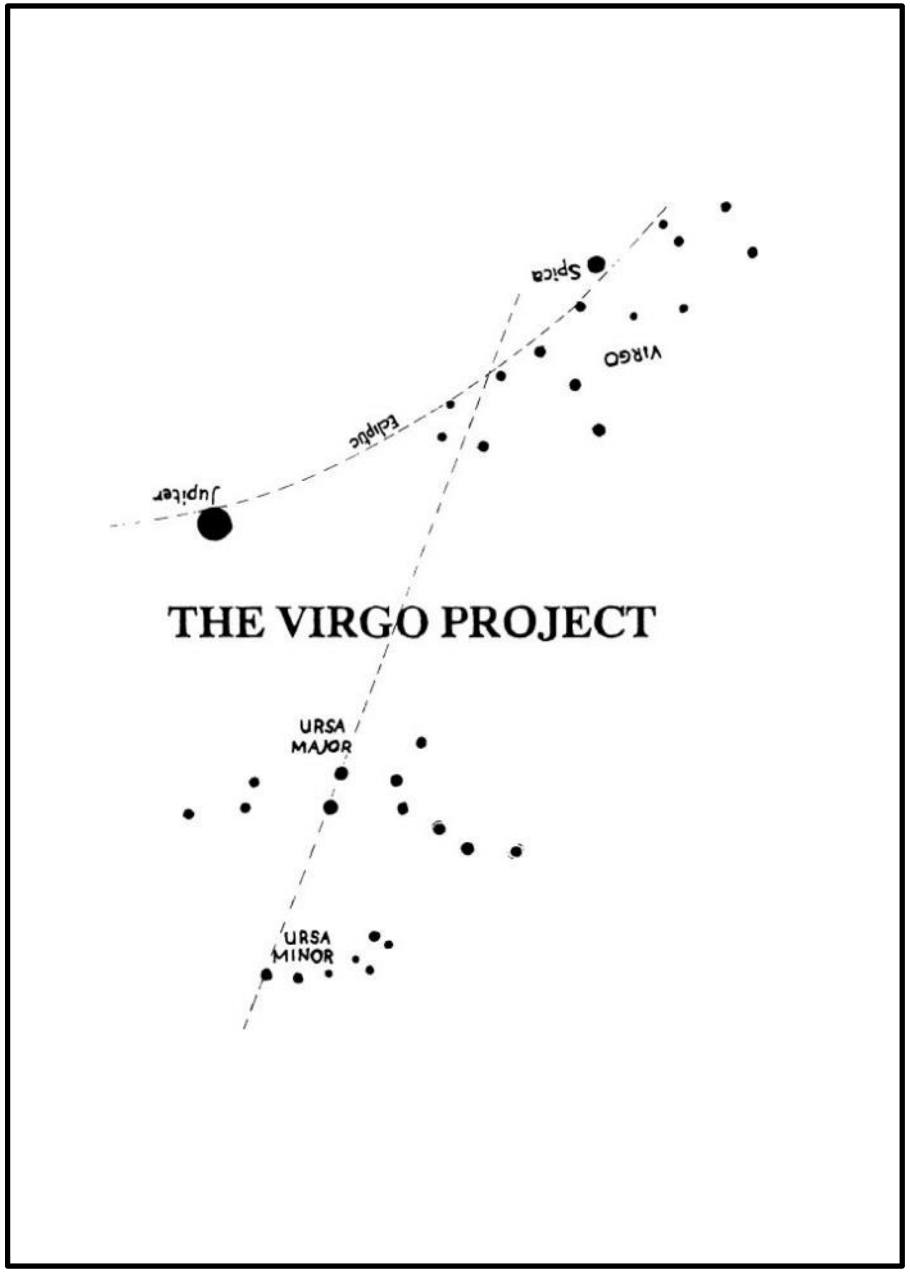
Innocenzo PINTO

Gravitation et cosmologie Relativiste (Orsay-Paris)
CNRS-Univ. Pierre et Marie Curie

J.L. BOULANGER
Alain BRILLET
Oliver CREGUT
C. Nary MAN
Alain MARRAUD
David SHOEMAKER
Philippe TOURRENC
Jean-Yves VINET

UNIVERSITÀ DEGLI STUDI DI PISA
DIPARTIMENTO DI FISICA

Istituto Nazionale di Fisica Nucleare
Sezione di Pisa



1989: Virgo proposal

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THE VIRGO PROJECT

INFN Sez. di Pisa
Dipartimento di Fisica
dell'Università di Pisa

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A. MARRAUD
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F. BARONE
L. DI FIORE
L. MILANO
G. RUSSO
S. SOLIMENO

CNRS-Universitè Paris 6

J.M. AGUIRREGABIRIA
H. BEL
J-P. DURUISSEAU
G. LE DENMAT
Ph. TOURRENC

Dipartimento di Elettronica delle Università
di Salerno e di Napoli

M. CAPOZZI
M. LONGO
M. LOPS
I. PINTO
G. ROTOLI

Groupe d'Astrophysique Relativiste
Observatoire de Meudon

T. DAMOUR
S. BONAZZOLA
J.A. MARCK
Y. GOURGHOULON

CNR Frascati

F. FULIGNI
V. IAFOLLA
G. NATALE

University of Illinois
at Urbana, USA

L.E. HOLLOWAY

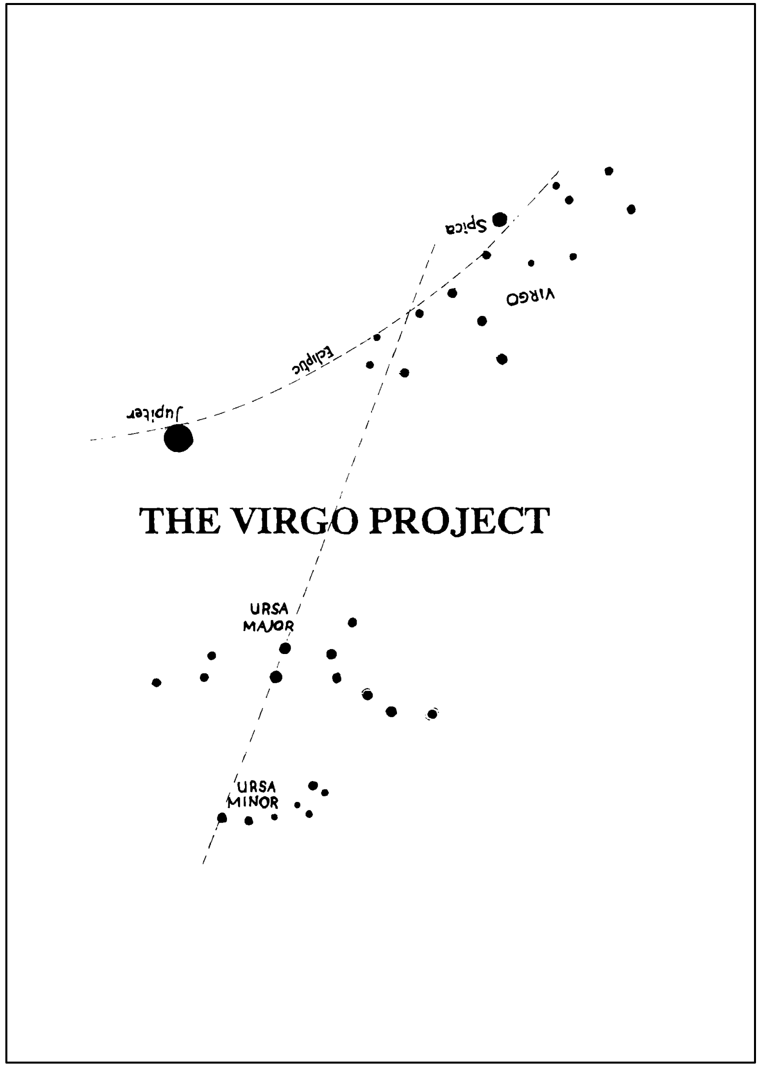
Instituto de Fisica [1] - USP, Instituto Astronomico e Geofisico[2] - USP, Centro Basileiro de Pesquisas Fisicas[3] - CNPQ, Observatorio Nacional- CNPQ[4], Instituto de Fisica GW- UniCAMP.[5]

M. S. D. CATTANI[1]
J. A. F. DE FREITAS PACHECO[2]
C. O. ESCOBAR[1]
C.A. GÃLVAO[3]
N.O. SANTOS[4]
A. TURTELLI JR[5]
W. VELLOSO[2,*]

* Present address: INFN laboratory, via vecchia livornese 582/a, Pisa, Italy

1989: Virgo proposal

1989



VIRGO must be considered both as an experiment and as a step towards a future observatory. The immediate goal of the VIRGO experiment is to realize, or to participate in, the first detection of gravitational radiation, but it also has the long term goal of being one component of the gravitational wave detectors network which will involve other detectors in other countries, and provide data of astrophysical interest. These goals imply a collaboration with the other groups having similar projects, without excluding some competition.
The group leaders from Italy, France, Germany, Scotland, and the USA have agreed to exchange all information and to collaborate on all the aspects of the construction of large interferometers in order to generate the international effort required by the birth of gravitational astronomy.

A BRILLET & A GIAZOTTO

THE VIRGO DETECTOR SITE: CASCINA

COPIA PER ESTRATTO

comune di cascina

deliberazione del consiglio comunale
n. 100 del 8 Maggio 1989

OGGETTO: Antenna interferometrica a grande base per la ricerca di onde gravidazionali.

IL CONSIGLIO COMUNALE

Premesso che l'Istituto Nazionale di Fisica Nucleare sezione di Pisa ha presentato un progetto di notevole interesse scientifico per la realizzazione di un'antenna interferometrica a grande base per la ricerca di onde gravitazionali da installare nel territorio del Comune di Cascina;

visto che a seguito degli incontri avuti col gruppo di ricercatori interessati, la scelta dell'area é caduta su una zona in località S.Stefano a Macerata;

che questa Amministrazione Comunale é interessata a che l'Istituto realizzi il progetto nel Comune di Cascina per la rilevanza scientifica dell'iniziativa;

dato atto che l'area interessata é prevista nel P.R.G. come zona agricola ai sensi art.81 D.P.R. N.616/1977;

a voti unanimi, resi palesemente dai n.28 Consiglieri presenti e votanti,

D E L I B E R A

- di esprimere parere favorevole di massima al progetto per la installazione dell'antenna interferometrica a grande base per la ricerca di onde gravitazionali, come da proposta dall'Istituto di Fisica Nucleare e dall'Università di Pisa qui allegata (N.1), da realizzare nell'are di cui alla planimetrica allegata (N.2);
- di dare atto che la presente deliberazione non é soggetta a controllo ai sensi dell'articolo unico L.R. n.44/84.

Some legal battles in the mid 90's to acquire the land for the Virgo detector

EGO: THE EUROPEAN GRAVITATIONAL OBSERVATORY

- Created on December 11th, 2000 by its two founding members
  - CNRS for France
  - INFN for Italy

- NWO-I, the Netherlands Scientific Research Institutes became EGO associate member in March 2022

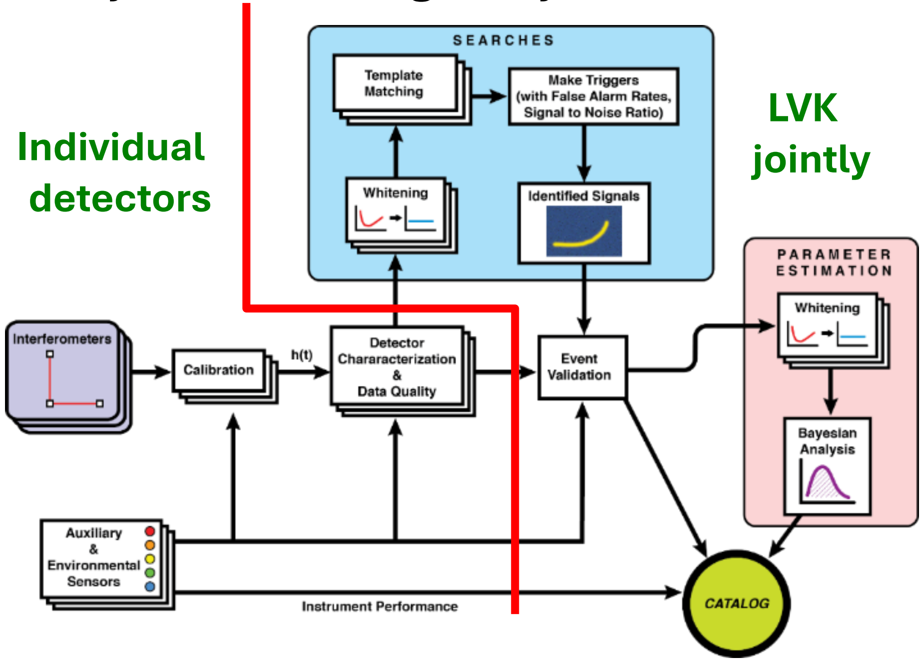
- August 2023: institutions from Belgium, Spain and Poland became Observers

LA PRIMA GENERAZIONE

2005-2011

THE LIGO-VIRGO-KAGRA MOU

Signed in May 2007 and regularly renewed since then



Agreement extended to KAGRA in October 2019

→ LIGO-Virgo-KAGRA (“LVK”) (meta)-Collaboration

Evolution foreseen from 2025 onwards

→ “IGWN”: The International Gravitational-Wave Observatory Network

Memorandum of Understanding

between

VIRGO

on one side

and the

Laser Interferometer Gravitational Wave Observatory (LIGO)

on the other side

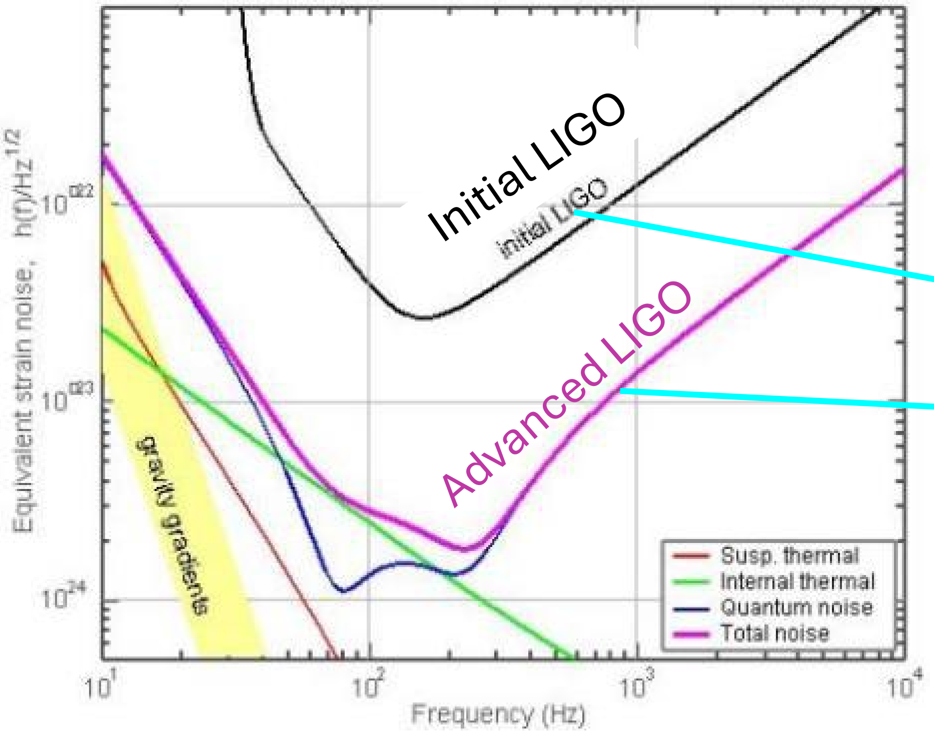
Purpose of agreement:

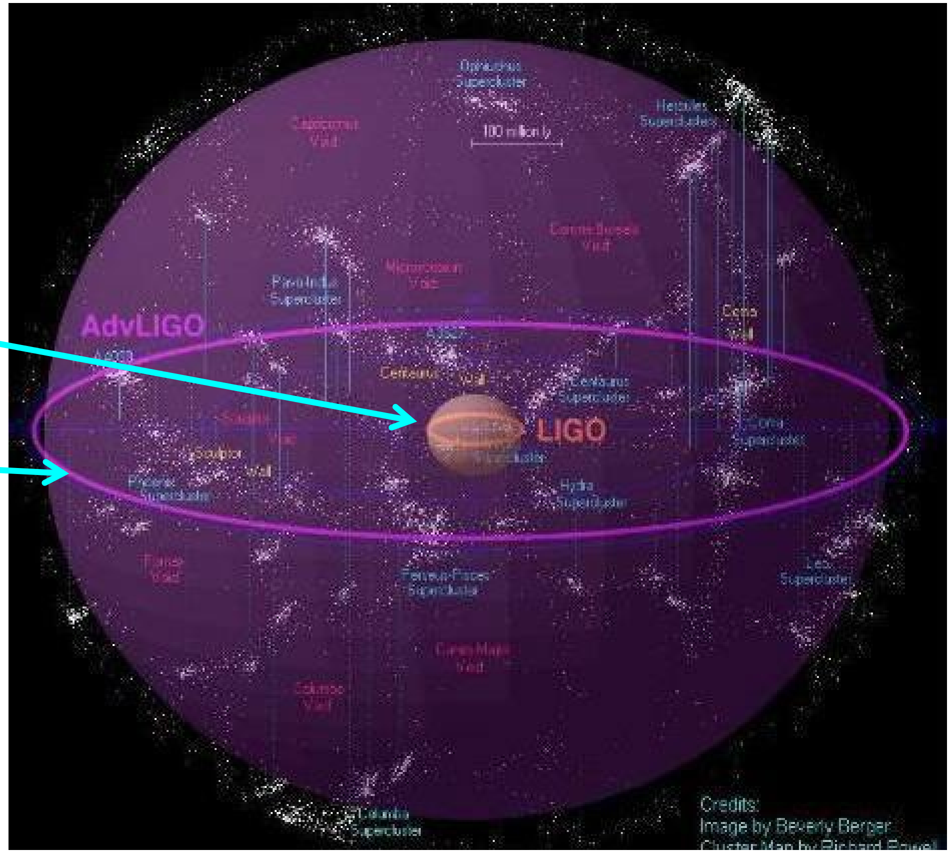
The purpose of this Memorandum of Understanding (MOU) is to establish and define a collaborative relationship between VIRGO on the one hand and the Laser Interferometer Gravitational Wave Observatory (LIGO) on the other hand in the use of the VIRGO, LIGO and GEO detectors based on laser interferometry to measure the distortions of the space between free masses induced by passing gravitational waves.

We enter into this agreement in order to lay the groundwork for decades of world-wide collaboration. We intend to carry out the search for gravitational waves in a spirit of teamwork, not competition. Furthermore, we remain open to participation of new partners, whenever additional data can add to the scientific value of the search for gravitational waves. All partners in the collaborative search should have a fair share in the scientific governance of the collaborative work.

Among the scientific benefits we hope to achieve from the collaborative search are: better confidence in detection of signals, better duty cycle and sky coverage for searches, and better source position localization and waveform reconstruction. In addition, we believe that the intensified sharing of ideas will also offer additional benefits.

LA SECONDA GENERAZIONE
'ADVANCED DETECTORS'





2015~2030+

ADVANCED VIRGO

Advanced Virgo (AdV): upgrade of the Virgo interferometric detector

Participated by France and Italy (former founders of Virgo), The Netherlands, Poland, Hungary, Spain

Funding approved in Dec 2009
(21.8 ME + Nikhef in kind contribution)

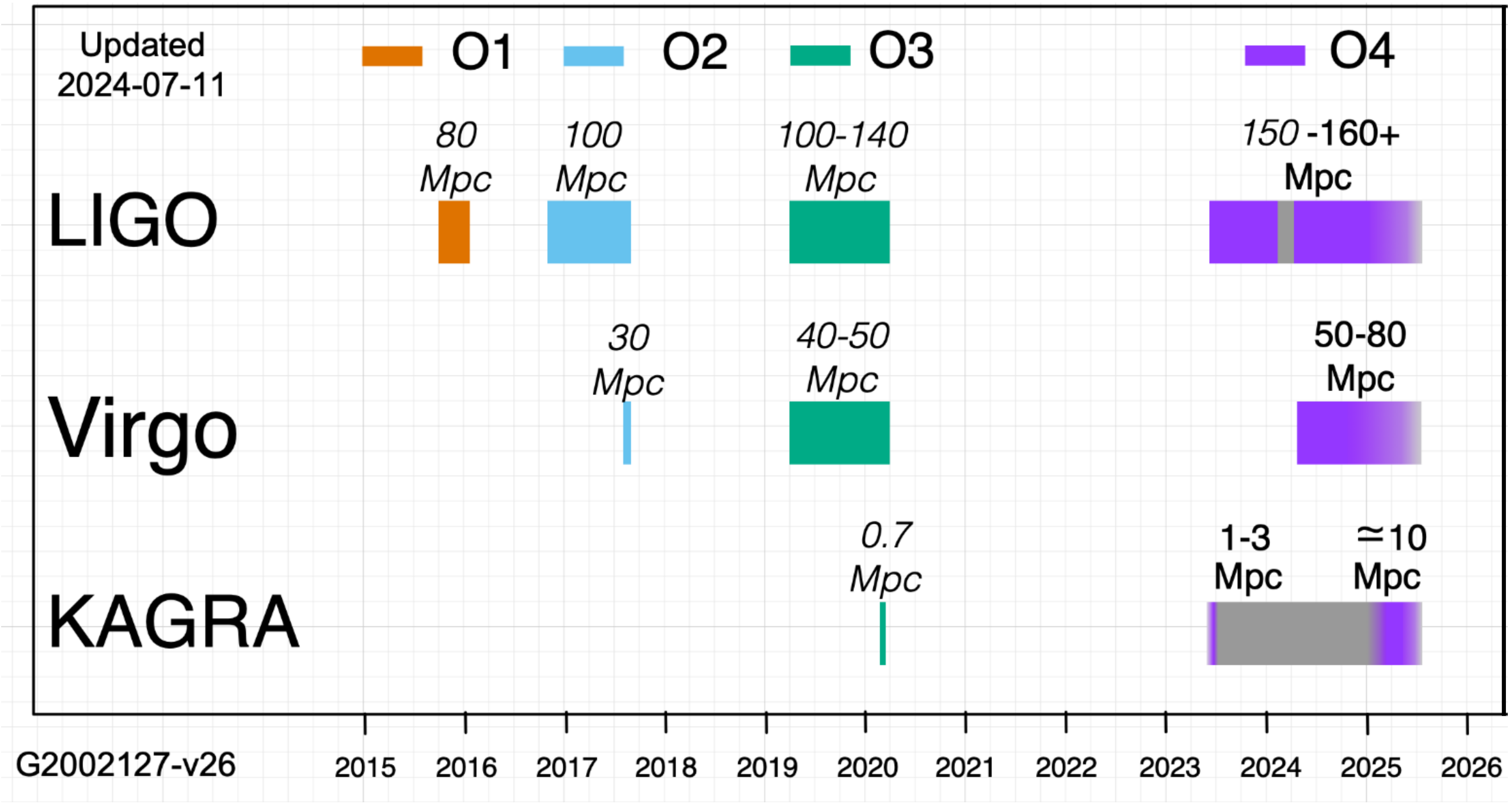
Project formally completed with the start of the O2 run (1 Aug 2017)

6 European countries
21 labs, ~280 authors

APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Padova
INFN TIFPA Trento
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW
RADBOUD Uni. Nijmegen
RMKI Budapest
University of Valencia

…and more have just joined:
GSSI, Milano Bicocca,
Torino, UniSalerno

OBSERVING RUNS AND UPGRADE PERIODS (AND A PANDEMIC…)



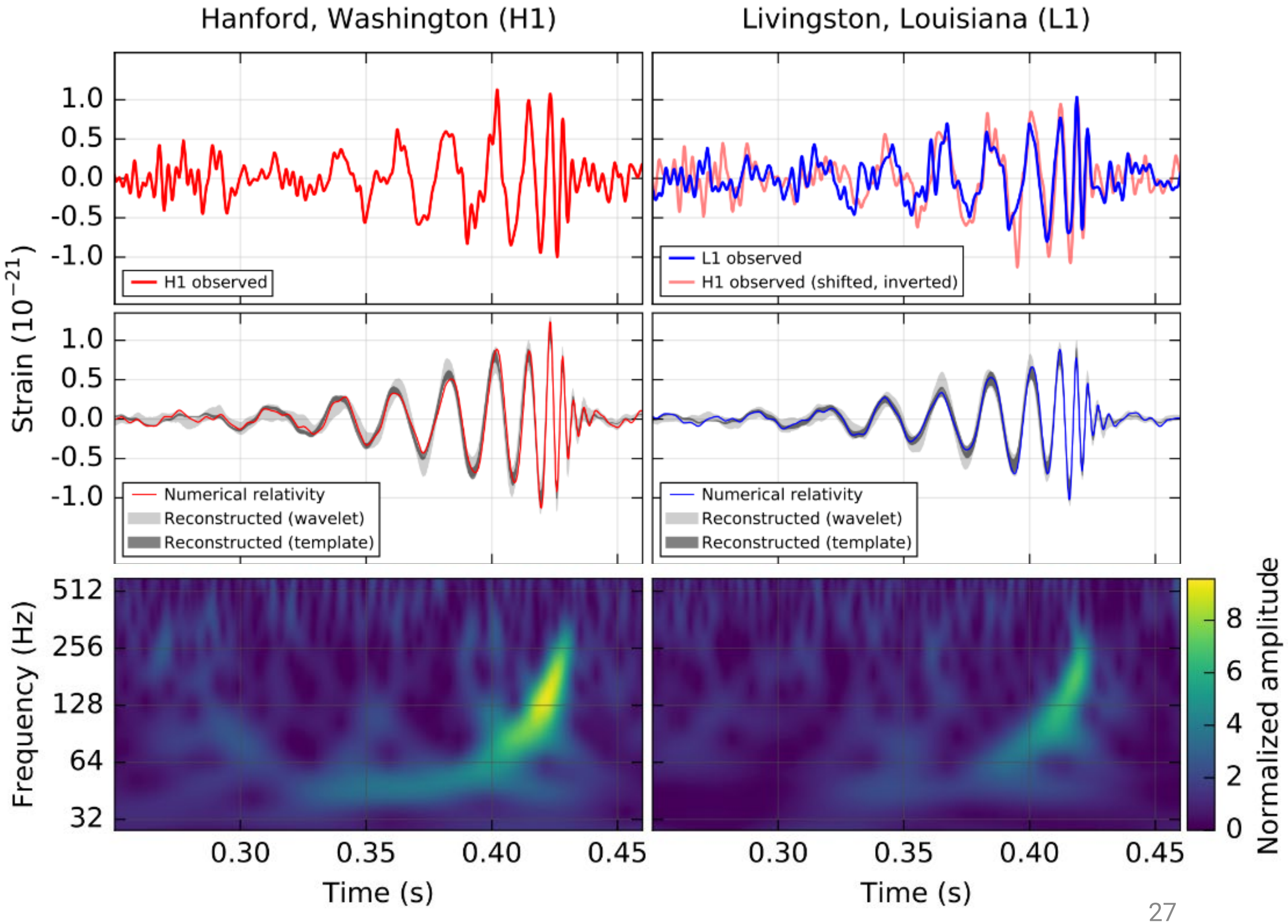
GW150914: THE FIRST DETECTION

- Detected on Sep 14, 2015
- Binary Black Hole (BBH) merger about 1.4 billion years ago

- BH masses:

$36M_\odot$ Primary → $62M_\odot$ Final

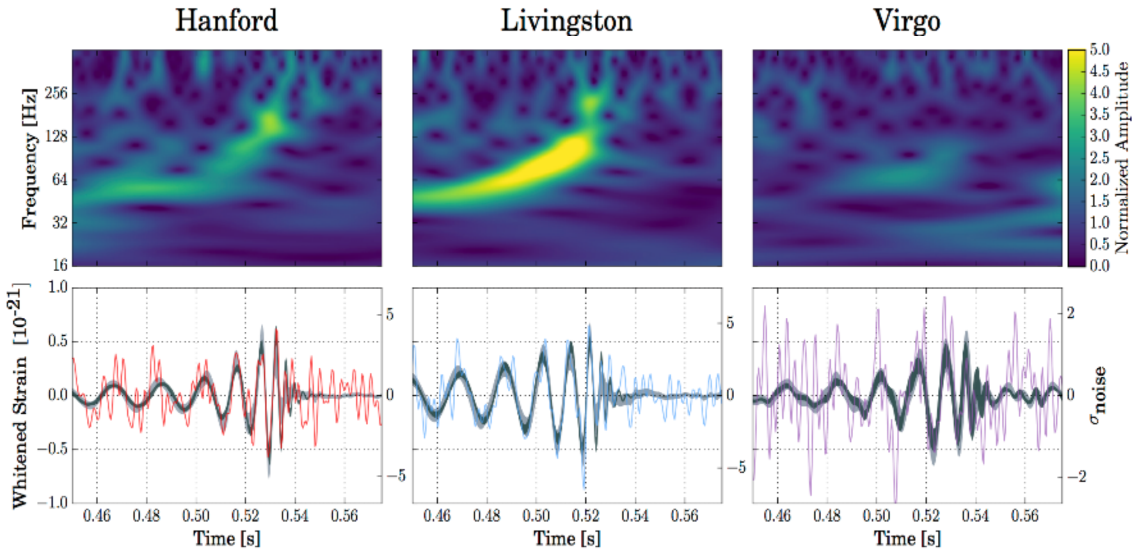
$29M_\odot$ Secondary → $62M_\odot$ Final



From Abbott et al. 2016, PRL 116, 061102

GW170814: FIRST VIRGO DETECTION

- The first event seen by Virgo.
- Sky localization improved by almost a factor of 10.

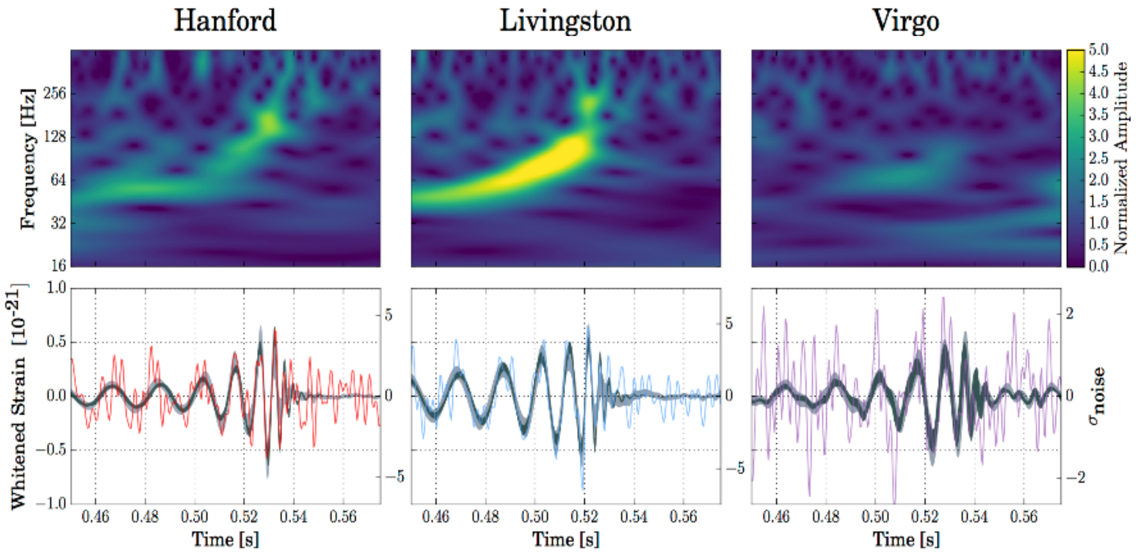


From Abbott et al. 2017, PRL 116, 061102

http://www.virgo-gw.eu/skymap.html

GW170814: ANOTHER BBH

- The first event seen by Virgo.
- Sky localization improved by almost a factor of 10.

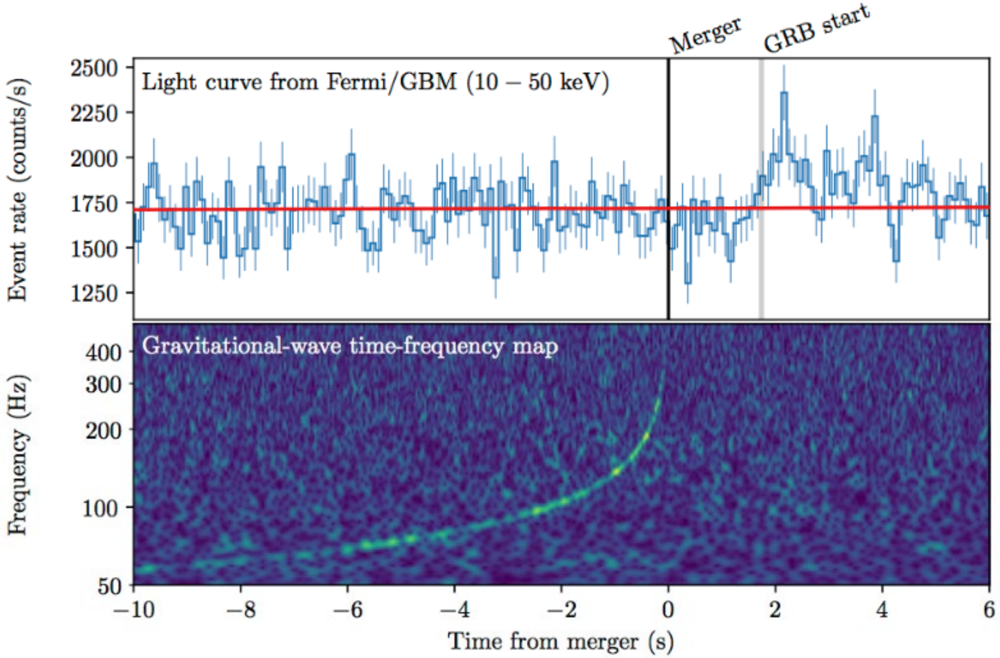


From Abbott et al. 2017, PRL 116, 061102

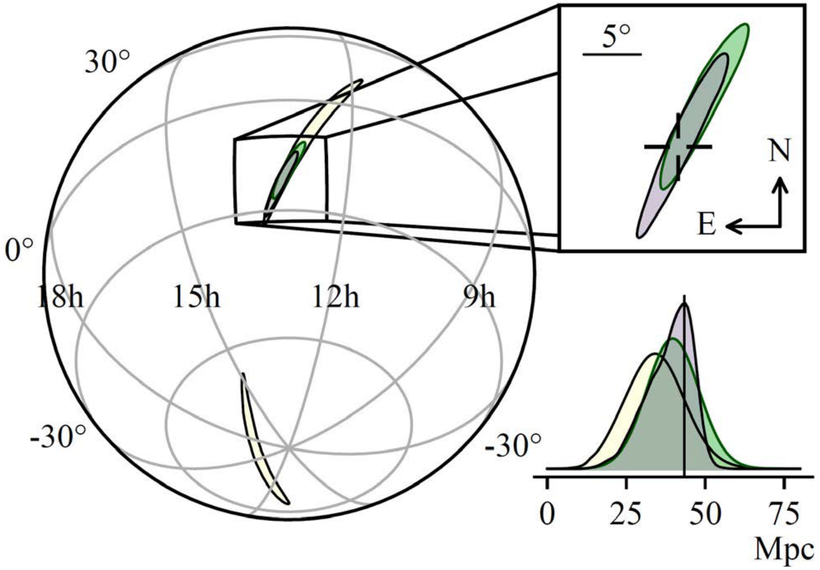
http://www.virgo-gw.eu/skymap.html

GW170817: BINARY NEUTRON STAR INSPIRAL

- ➢ Associated with gamma-ray burst detected by GRB satellites ~2 seconds after the merger

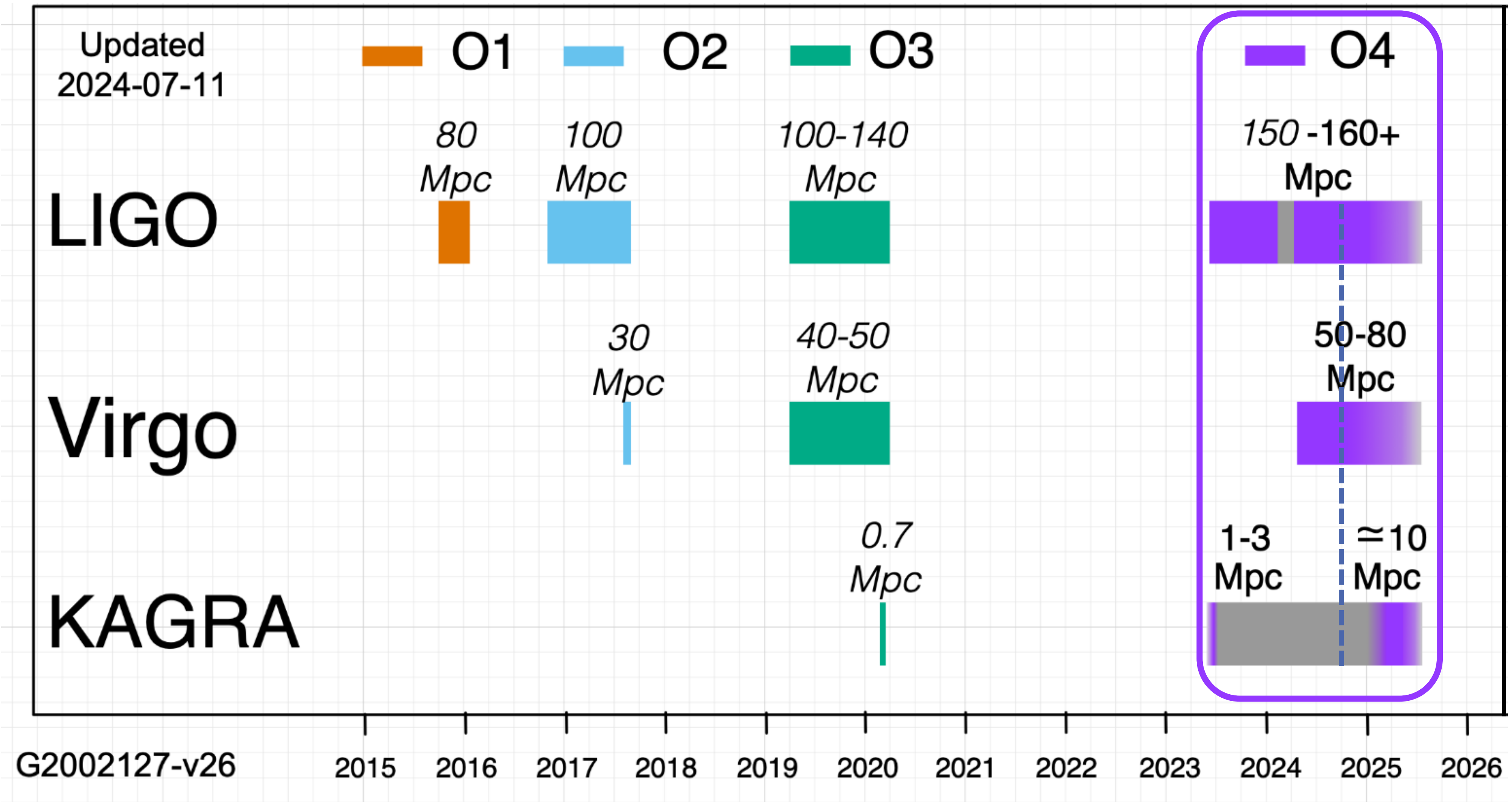


From Abbott et al. 2017, ApJL

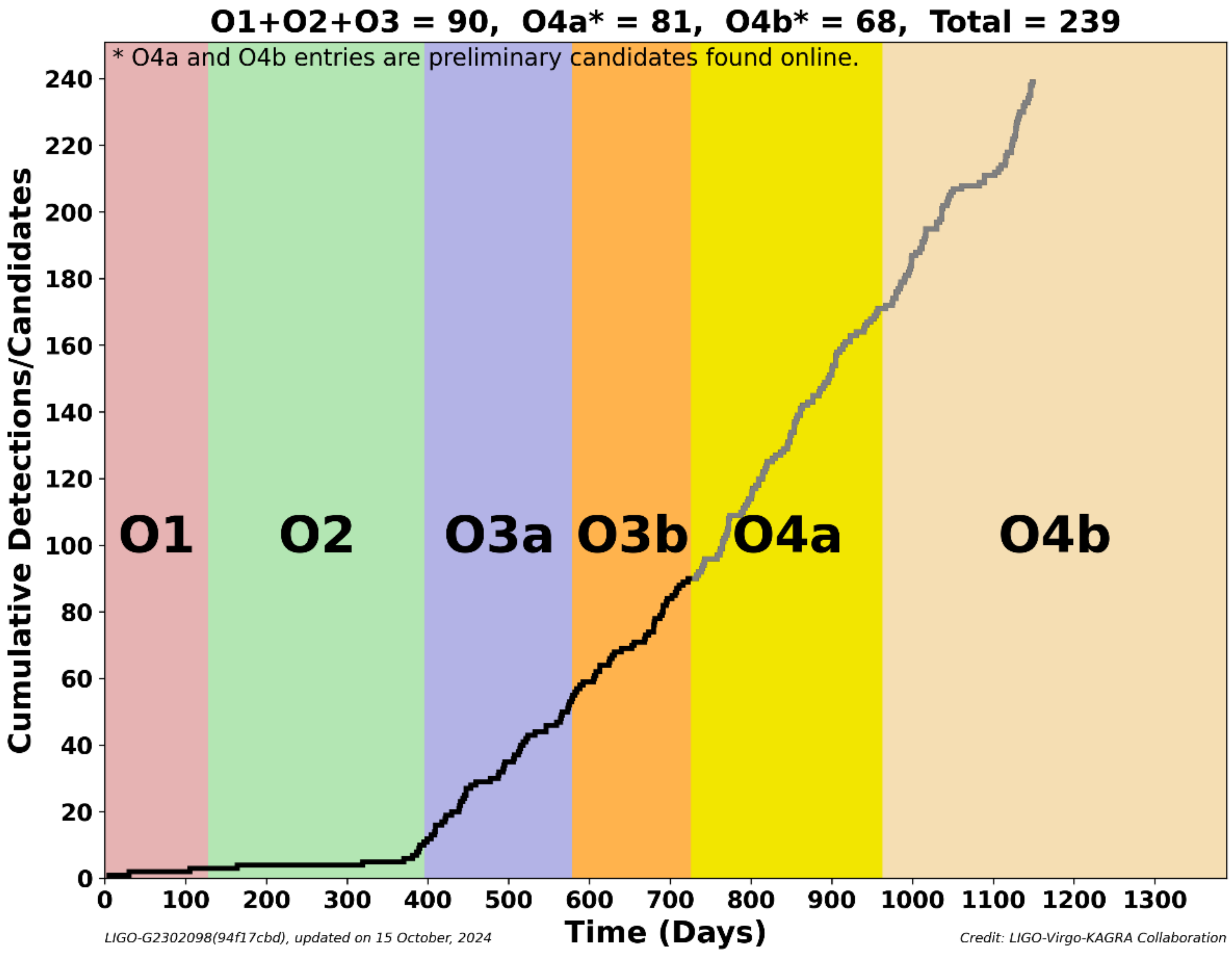


- ➢ Localization 30 deg^2
- ➢ Optical counterpart was seen around 11 hours later
- ➢ Fractional difference in speed of gravity and the speed of light is between -3×10^{-15} and 7×10^{-16}
- ➢ Binary neutron star mergers produce kilonova explosions that generate heavy elements
- ➢ Different measurement of Hubble Constant

THE FOURTH OBSERVING RUN



A SIGNIFICANT GW EVENT CANDIDATE EVERY ~3 DAYS



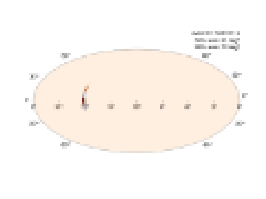
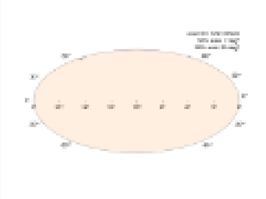
https://gracedb.ligo.org/superevents/public/O4/

LIGO/Virgo/KAGRA Public Alerts

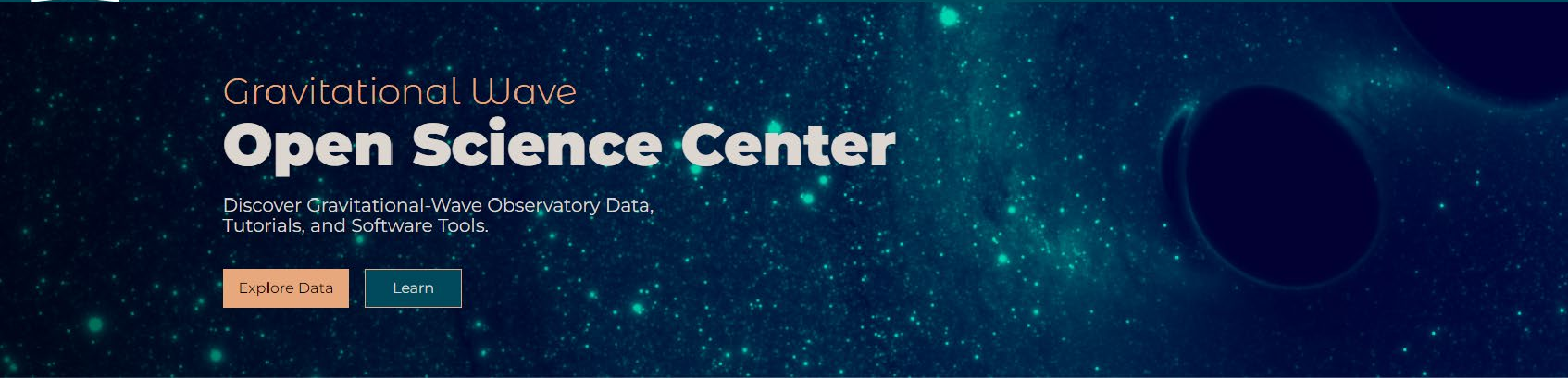
- More details about public alerts are provided in the LIGO/Virgo/KAGRA Alerts User Guide.
- Retractions are marked in red. Retraction means that the candidate was manually vetted and is no longer considered a candidate of interest.
- Less-significant events are marked in grey, and are not manually vetted. Consult the LVK Alerts User Guide for more information on significance in O4b.
- Less-significant events are not shown by default. Press "**Show All Public Events**" to show significant and less-significant events.

O4b Significant Detection Candidates: **68** (74 Total - 6 Retracted)

O4b Low Significance Detection Candidates: **944** (Total)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S241011k	BBH (>99%)	Yes	Oct. 11, 2024 23:38:34 UTC	GCN Circular Query Notices | VOE		1 per 1.252e+26 years	
S241009em	BBH (>99%)	Yes	Oct. 9, 2024 22:04:55 UTC	GCN Circular Query Notices | VOE		1 per 11.246 years	

https://gwosc.org/

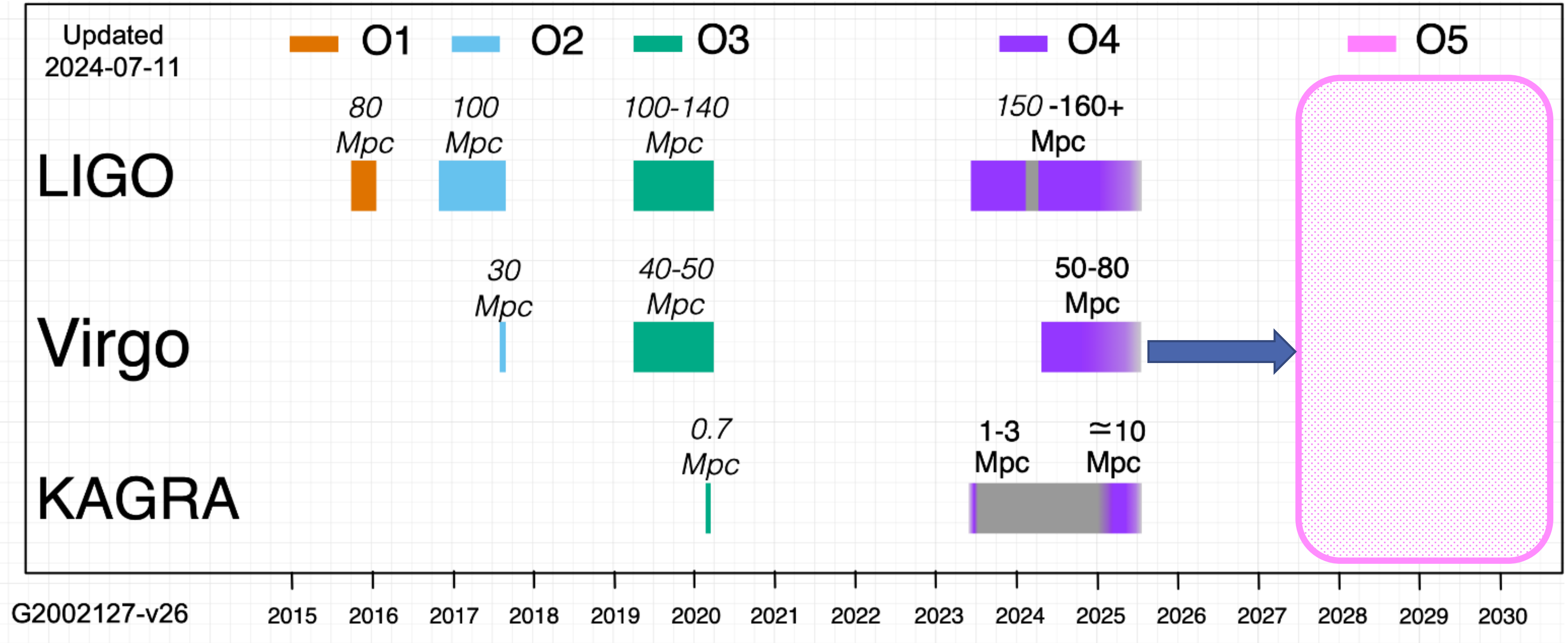


The LIGO–Virgo–KAGRA Collaboration is committed to the principles of open science

The GW Open Science Center

- Releases gravitational-wave data Offers event catalogs
- Provides documentation and tools

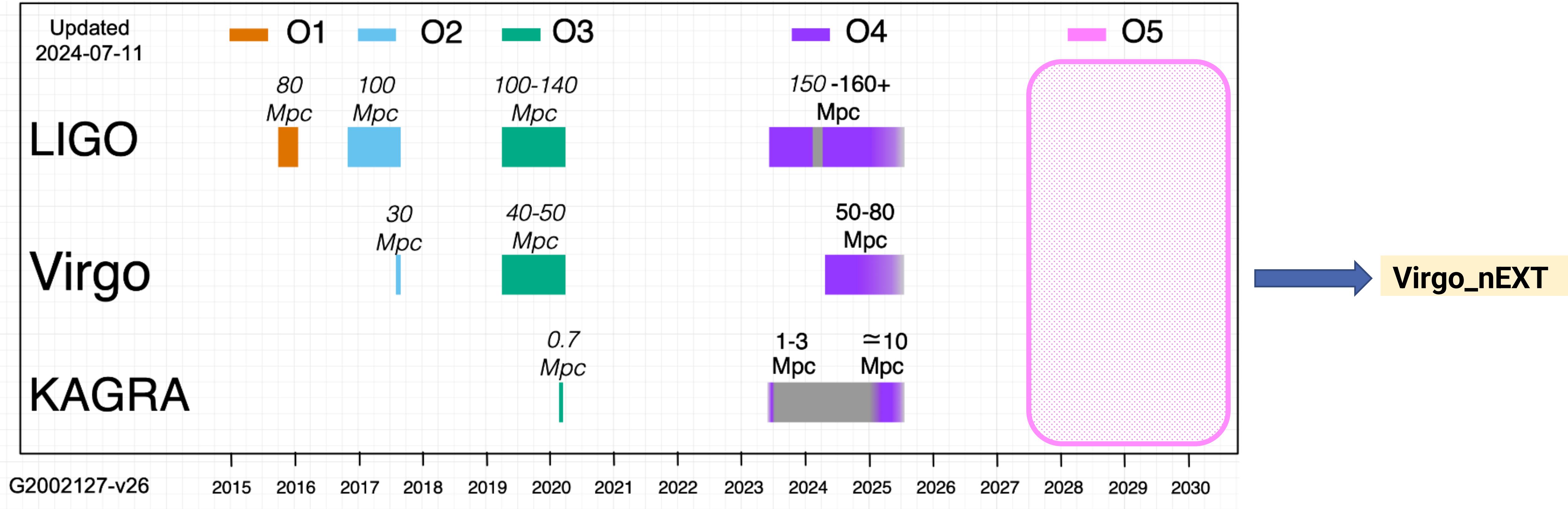
WHAT'S NEXT?



Plans for O5

- Goal: ×1.5 astrophysical range
- Better mirrors coatings, increase laser power, more robust optical layout…

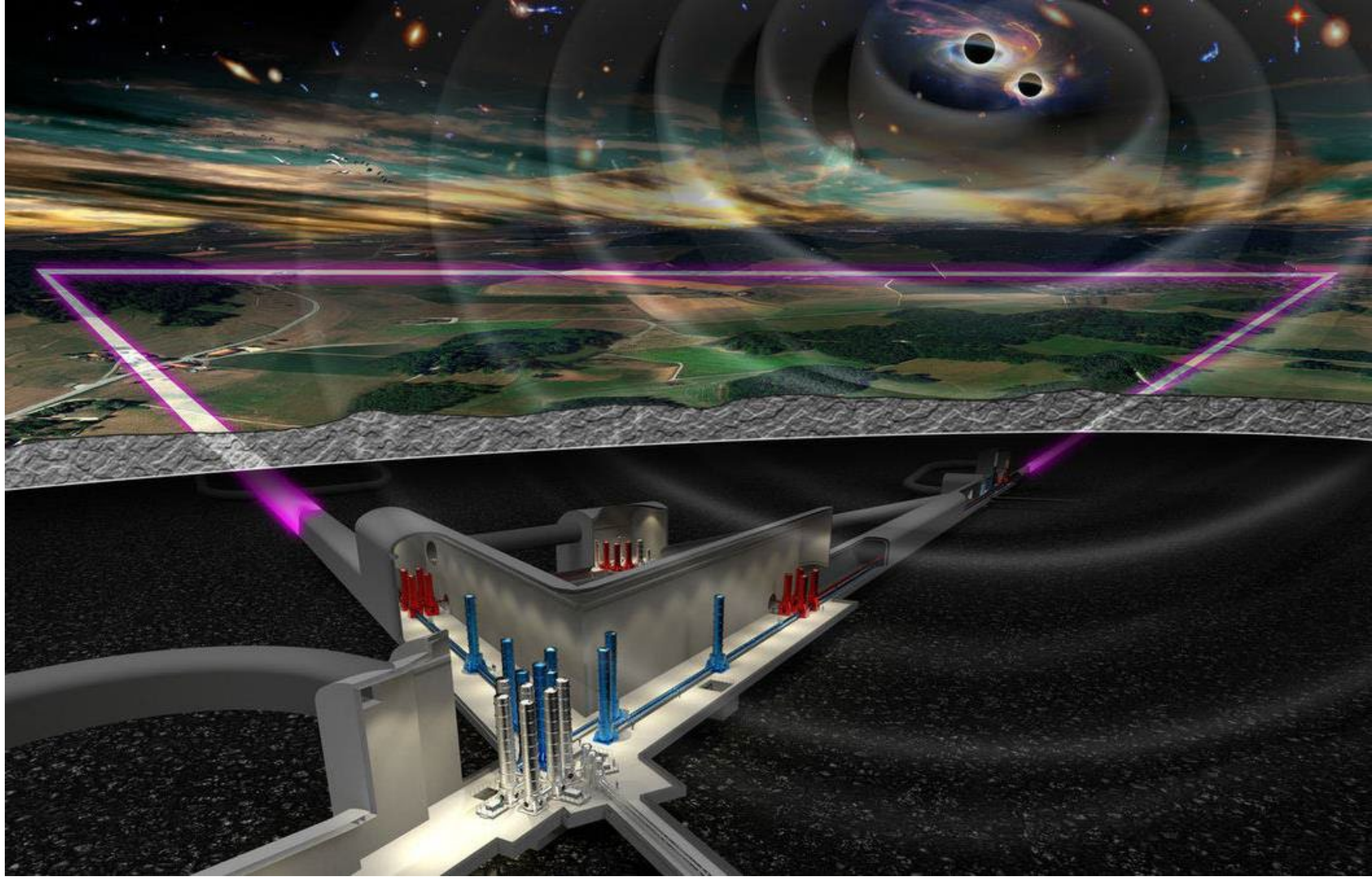
WHAT'S NEXT?



Post-O5

- Goal: another ×2 astrophysical range
- Target: early 2030's

VIRGO_NEXT:
A STEP TOWARDS ET



ET pioneered the idea of a 3rd generation GW observatory:

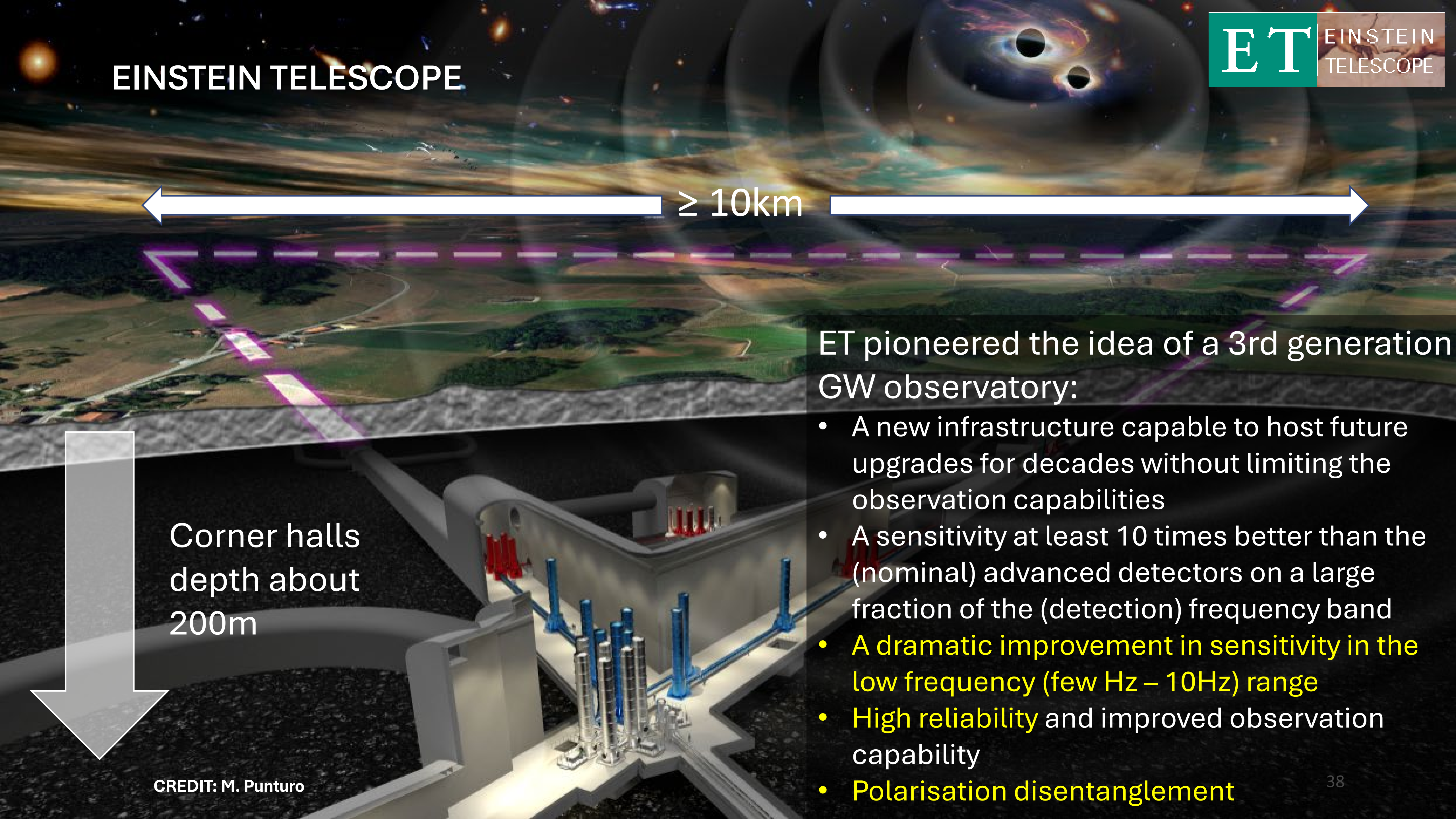
- longer baseline, flexibility due to new facility and innovative technologies

V_nEXT core technology is essentially ET-HF technology

- Higher arm power, improved squeezing, fused silica heavy masses and 1064nm wavelength

From ET perspective, V_nEXT is a pathfinder for ET(-HF) technology, greatly reducing risks of not achieving design parameters

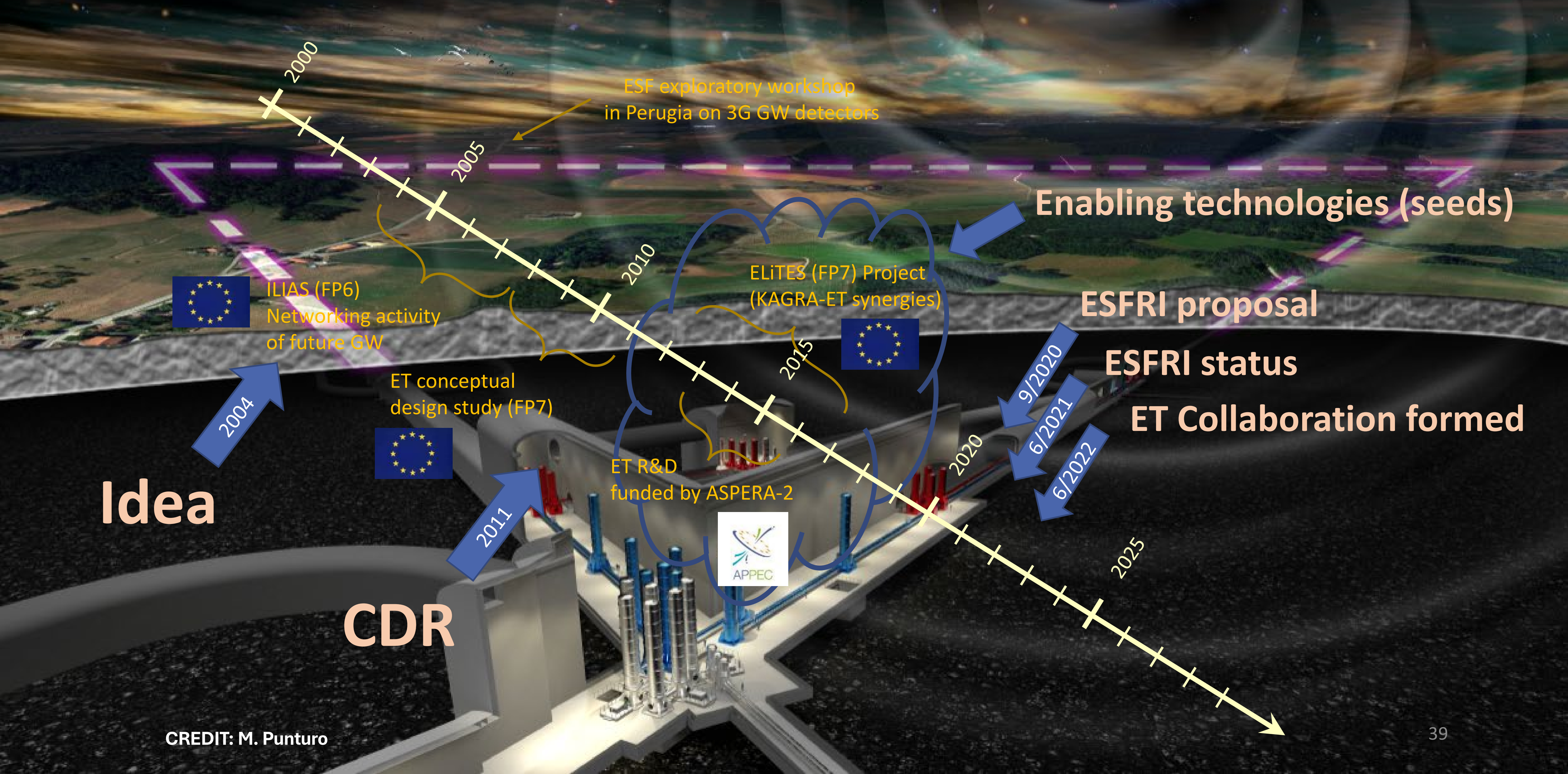
EINSTEIN TELESCOPE



ET pioneered the idea of a 3rd generation GW observatory:

- A new infrastructure capable to host future upgrades for decades without limiting the observation capabilities
- A sensitivity at least 10 times better than the (nominal) advanced detectors on a large fraction of the (detection) frequency band
- A dramatic improvement in sensitivity in the low frequency (few Hz – 10Hz) range
- High reliability and improved observation capability
- Polarisation disentanglement

ET: A LONG PATH



CREDIT: M. Punturo

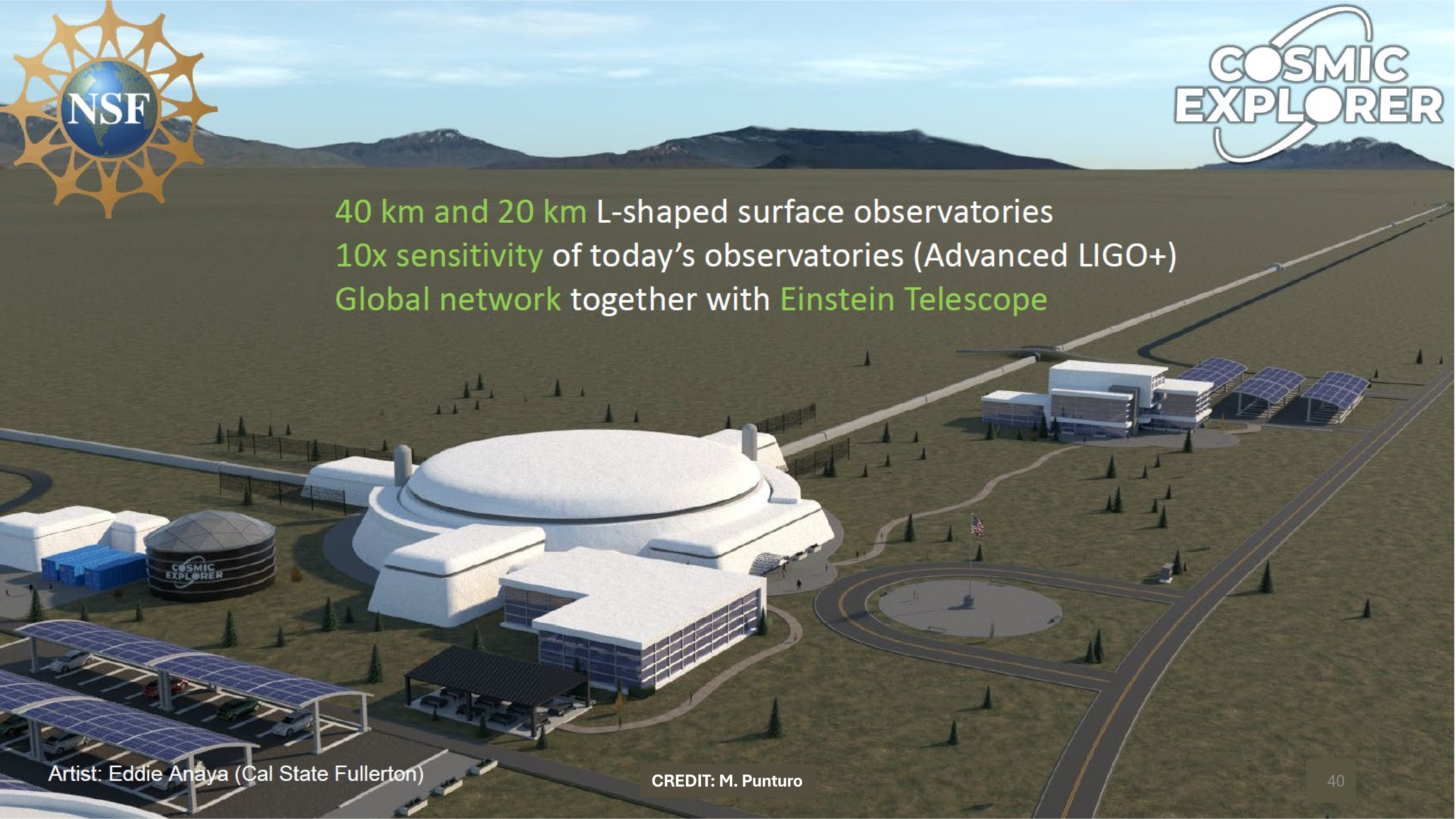
NSF

COSMIC EXPLORER

40 km and 20 km L-shaped surface observatories

10x sensitivity of today's observatories (Advanced LIGO+)

Global network together with Einstein Telescope



Artist: Eddie Anaya (Cal State Fullerton)

CREDIT: M. Punturo

Experimental research in Gravitational Wave is just started with the monumental successes of Advanced LIGO and Advanced Virgo

It has a bright future thanks to the huge science potential of this field

A new generation of GW observatories is under preparation covering a wider frequency range

3rd generation GW interferometric terrestrial detectors are in preparation

- In particular, Einstein Telescope is now an ESFRI project strongly supported by several European government and agencies and funded by some of them

The next decades in GW research will be rich in expected and unexpected surprises