# Virgo evolutions

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EGO, Cascina, April 19, 2018

# Advanced Virgo

Virgo is a European collaboration with about 280 members

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

Participation by scientists from France, Italy, The Netherlands, Poland, Hungary, Spain, Germany

- 20 laboratories, about 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 Trento-Padova
  - LAL Orsay – ESPCI Paris
  - LAPP Annecy
  - LKB Paris
  - LMA Lyon
  - Nikhef Amsterdam
  - POLGRAW(Poland)
  - RADBOUD Uni. Nijmegen
  - RMKI Budapest
  - Univ. of Valencia
  - University of Jena

Advanced Virgo project has been formally completed on July 31, 2017

Part of the international network of 2nd generation detectors

Joined the O2 run on August 1, 2017

7 European countries

# Towards a global GW research infrastructure


LSC and Virgo share data and do analysis jointly

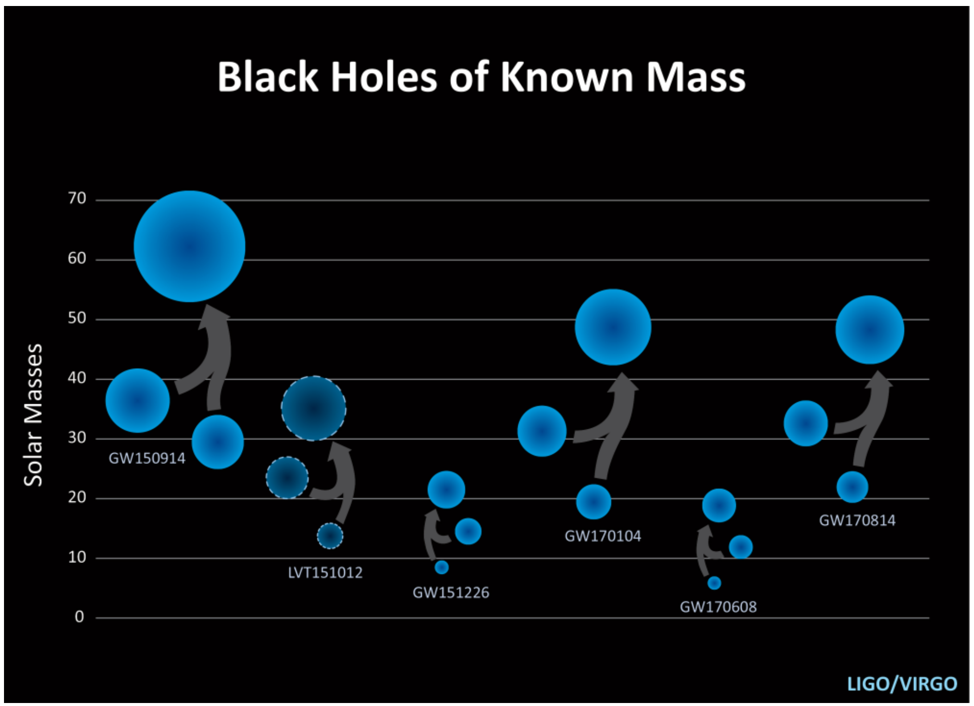
# Scientific achievements: properties of black holes

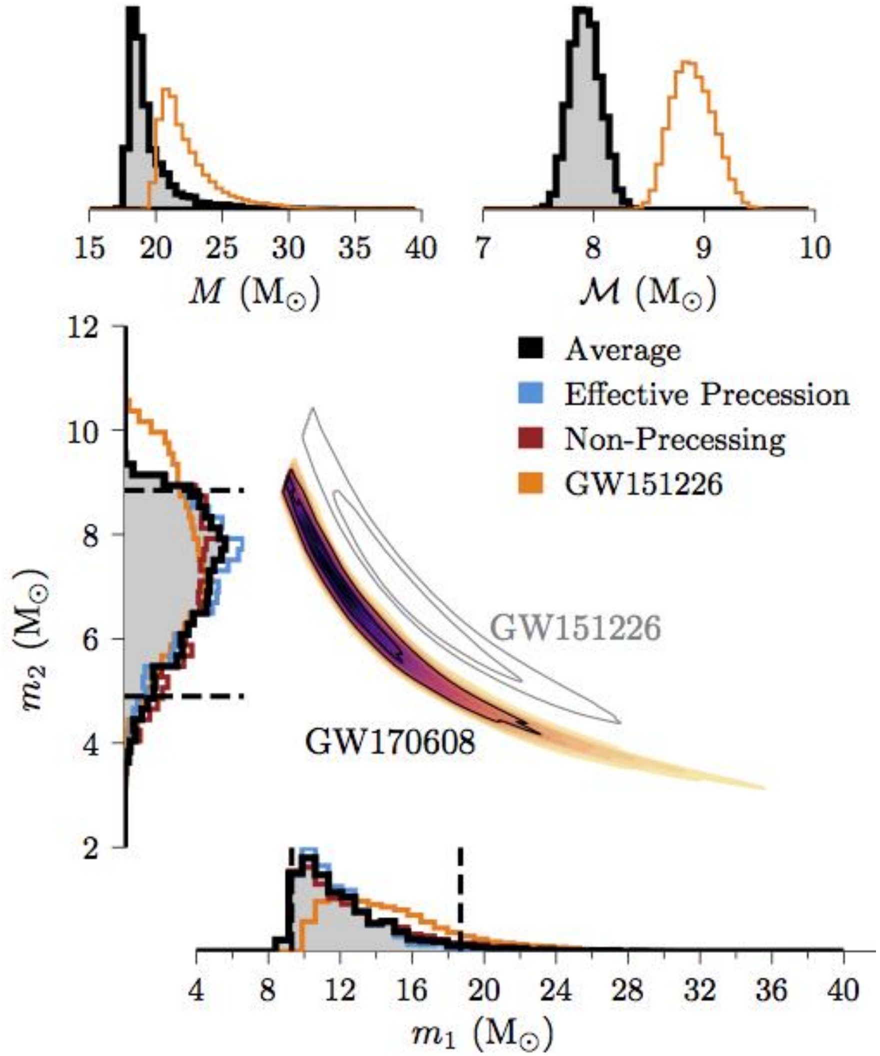
Extract information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms

LVC reported on 6 BBH mergers

Fundamental physics, astrophysics, astronomy, and cosmology

Testing GR, waveforms (with matter)



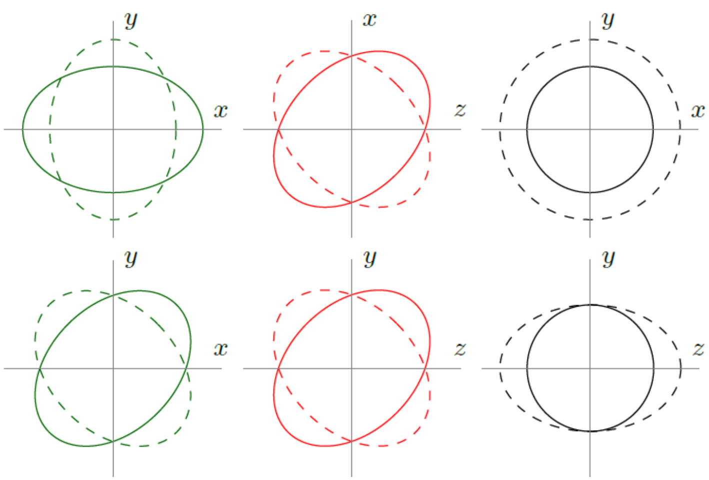
# Virgo joins LIGO in August 2017

# Polarization of gravitational waves

Polarization is a fundamental property of spacetime. It determined how spacetime can be deformed. General metric theories allow six polarizations. General Relativity allows two (tensor) polarizations

GR only allows (T) polarizations

General metric theories also know vector (V) and scalar (S) polarizations




| Theory | + | x | x | y | b | l |
|---|---|---|---|---|---|---|
| General Relativity | allowed | allowed | forbidden | forbidden | forbidden | forbidden |
| GR in noncompactified 4/6D Minkowski | allowed | allowed | allowed | allowed | allowed | allowed |
| Einstein-Æther | allowed | allowed | allowed | allowed | allowed | allowed |
| 5D Kaluza-Klein | allowed | allowed | allowed | allowed | allowed | forbidden |
| Randall-Sundrum braneworld | allowed | allowed | forbidden | forbidden | forbidden | forbidden |
| Dvali-Gabadadze-Porrati braneworld | allowed | allowed | depends | depends | depends | depends |
| Brans-Dicke | allowed | allowed | forbidden | forbidden | allowed | allowed |
| *f(R)* gravity | allowed | allowed | forbidden | forbidden | allowed | allowed |
| Bimetric theory | allowed | allowed | allowed | allowed | allowed | allowed |
| Four-Vector Gravity | forbidden | forbidden | allowed | allowed | forbidden | forbidden |

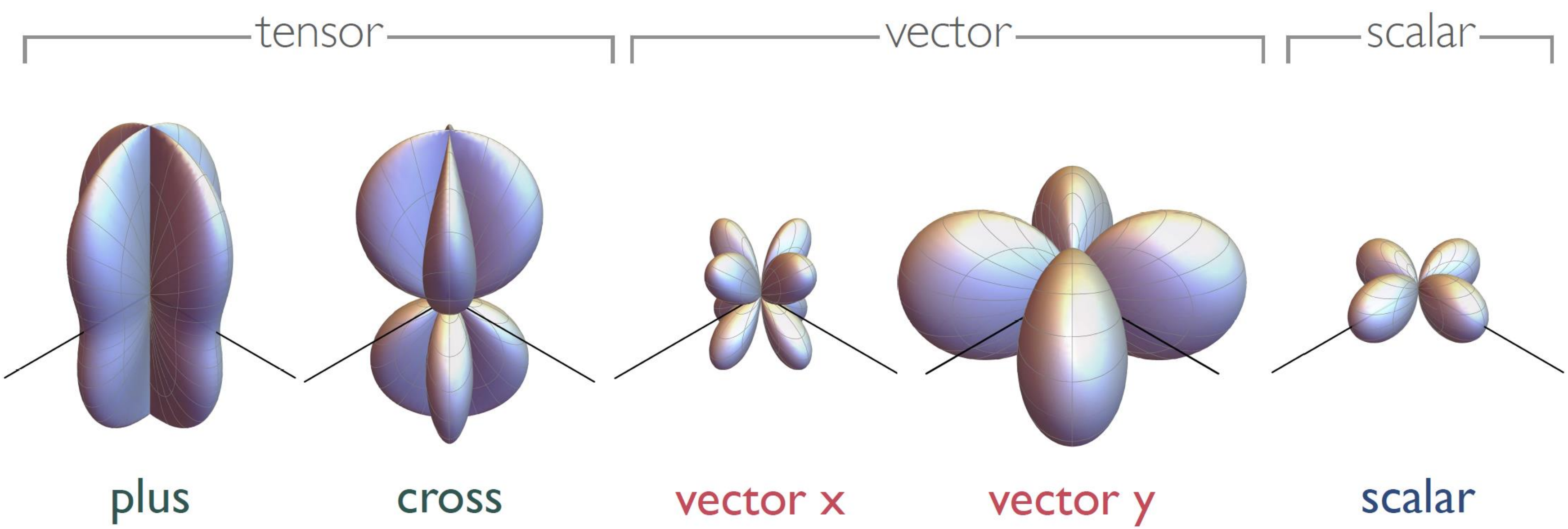
Nishizawa et al., Phys. Rev. D 79, 082002 (2009) [except G4v & Einstein-Æther]. allowed / depends / forbidden

# First test of polarizations of gravitational waves

According to Einstein’s General Relativity there exist only two polarizations. General metric theories of gravity allow six polarizations. GW170814 confirms Einstein’s prediction

Angular dependence (antenna-pattern) differs for T, V, S

LIGO and Virgo have different antenna-patterns
This allows for a fundamental of the polarizations of spacetime



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tensor — vector — scalar

**Our analysis favors tensor polarizations in support of General Relativity**

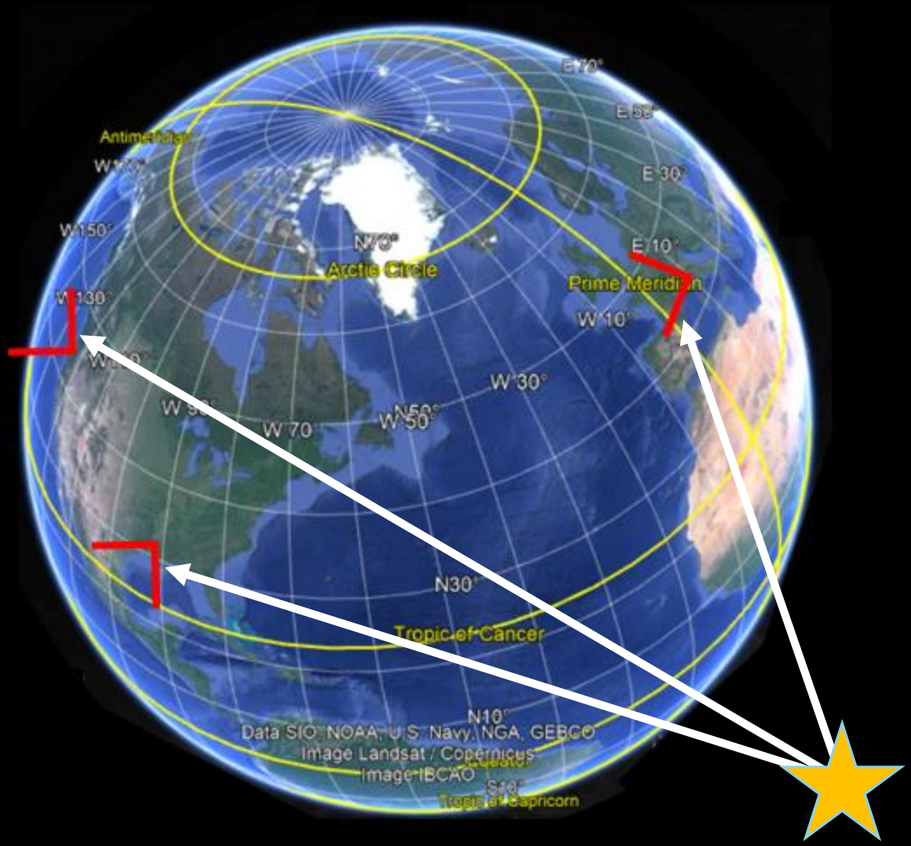
**Our data favor tensor structure over vector by about a (Bayes) factor 200**
**And tensor over scalar by about a factor 1000**

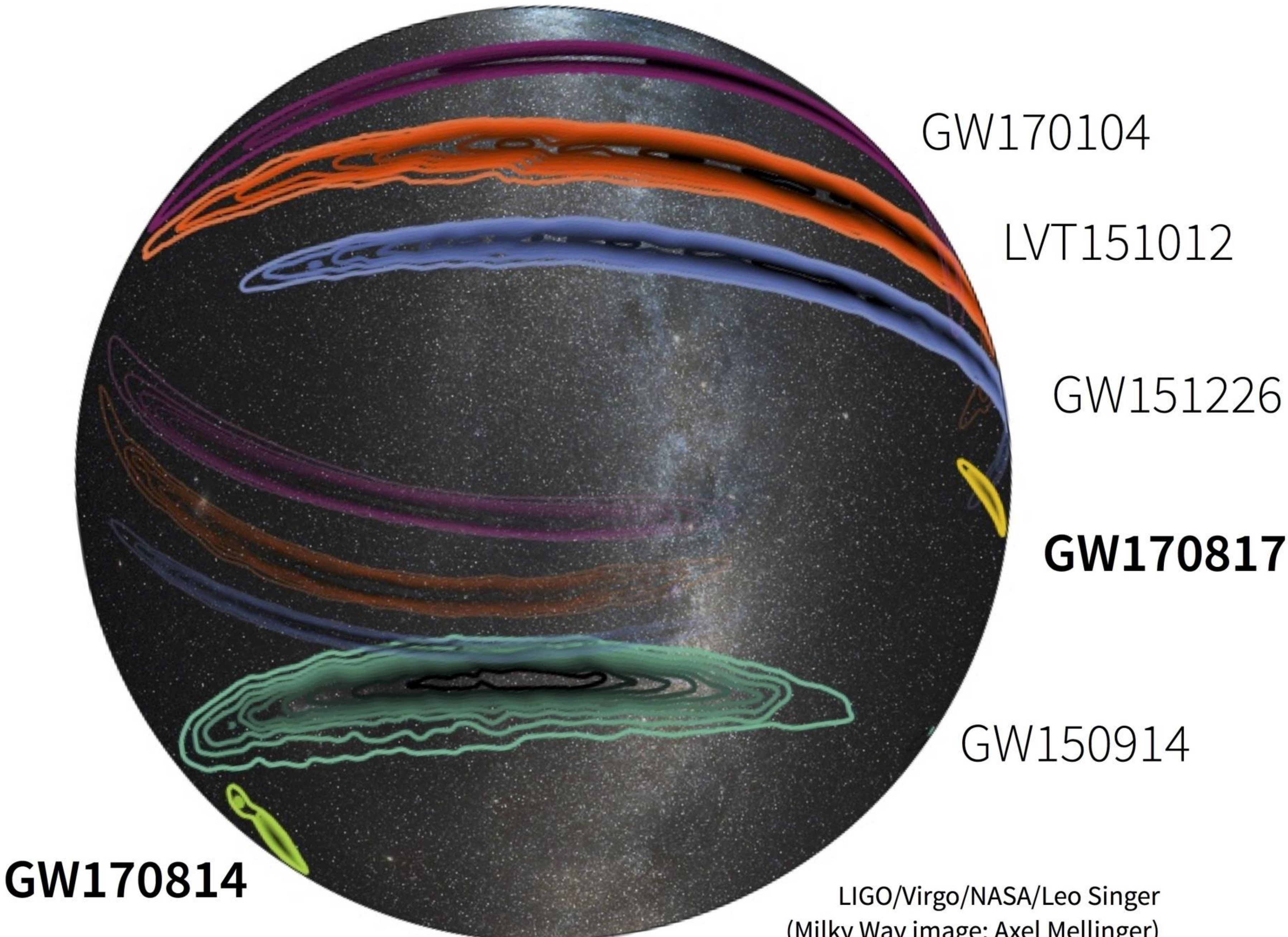
**This is a first test, and for BBH we do not know the source position very well**

# Virgo allowed source location via triangulation

GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it

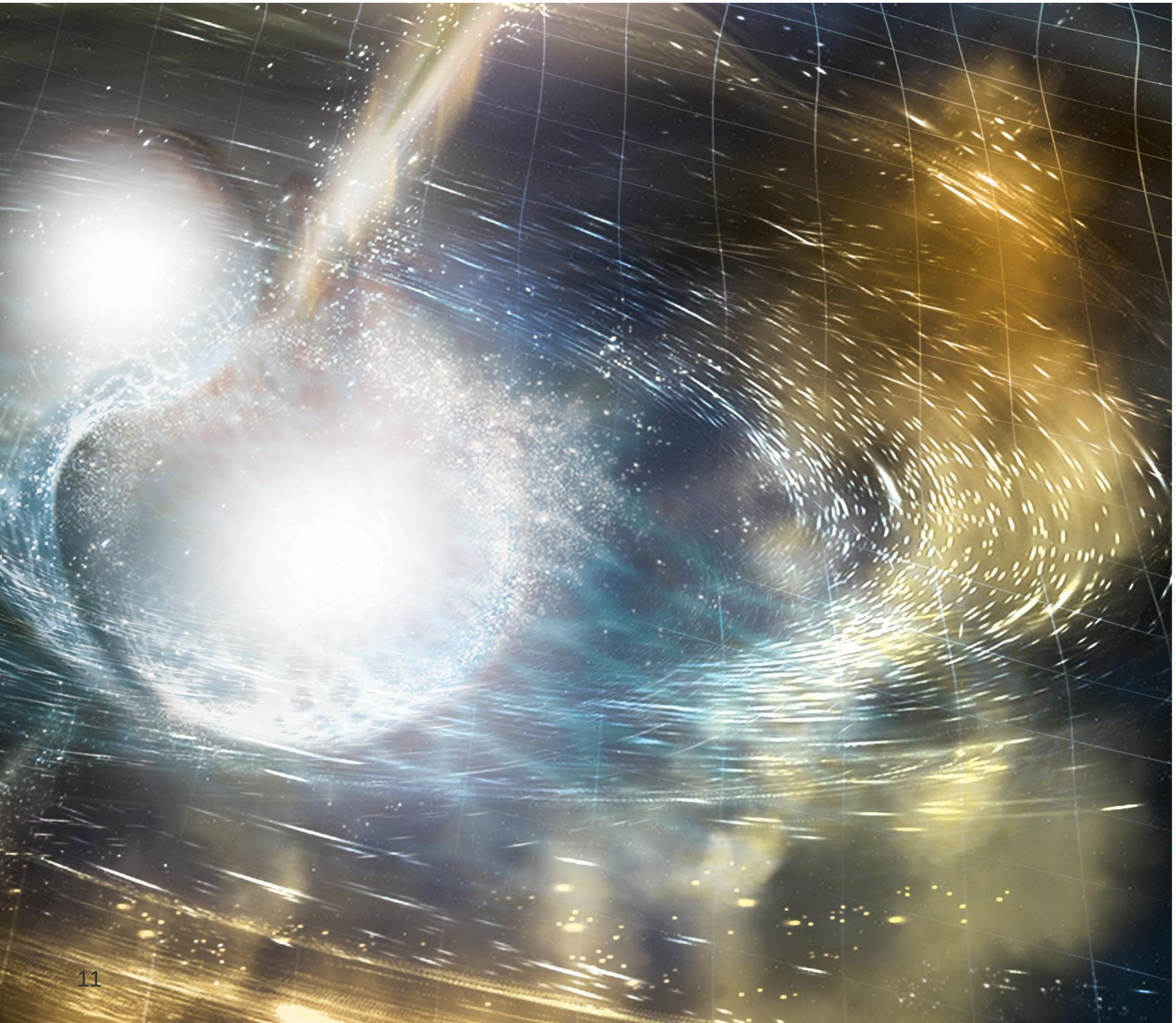


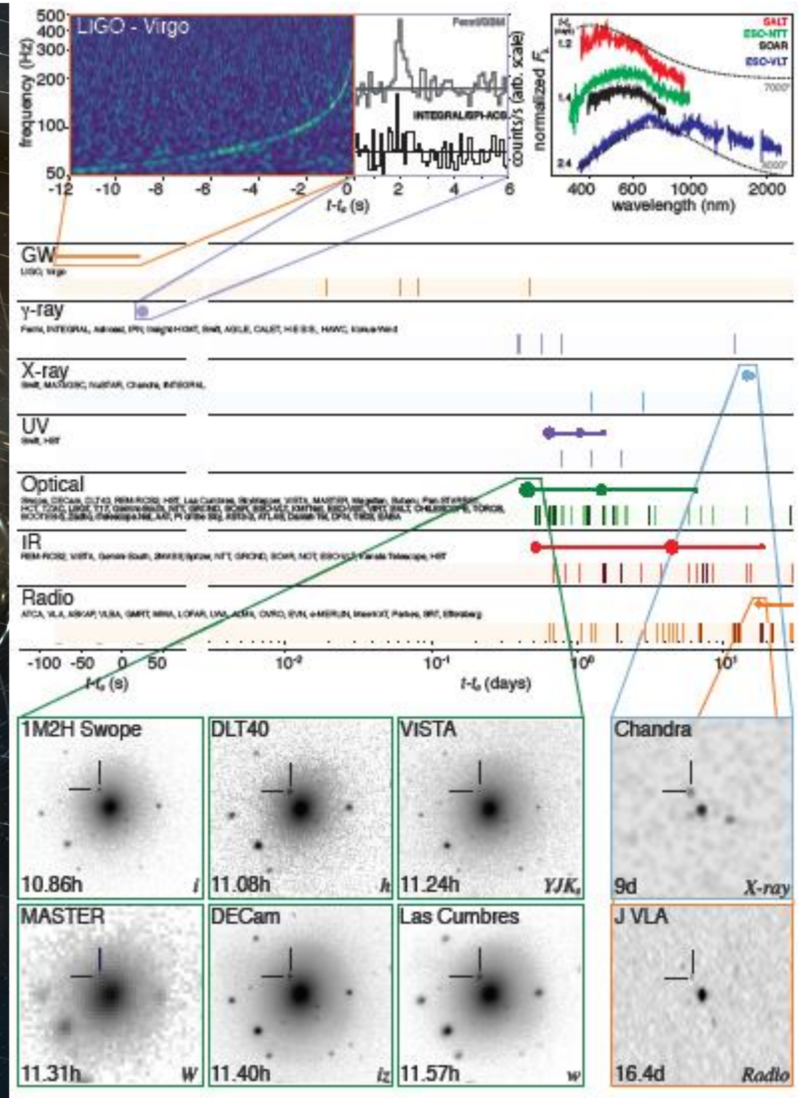




GW170104
LVT151012
GW151226
GW170817
GW150914
GW170814
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

# GW170817: start of multi-messenger astronomy with GW

Many compact merger sources emit, besides gravitational waves, also light, gamma- and X-rays, and UV, optical, IR, and radio waves, as well as neutrino’s or other subatomic particles. Our three-detector global network allows identifying these counterparts





# Our science is limited by the sensitivity of our instruments

# Precision tests of GR with BBH mergers

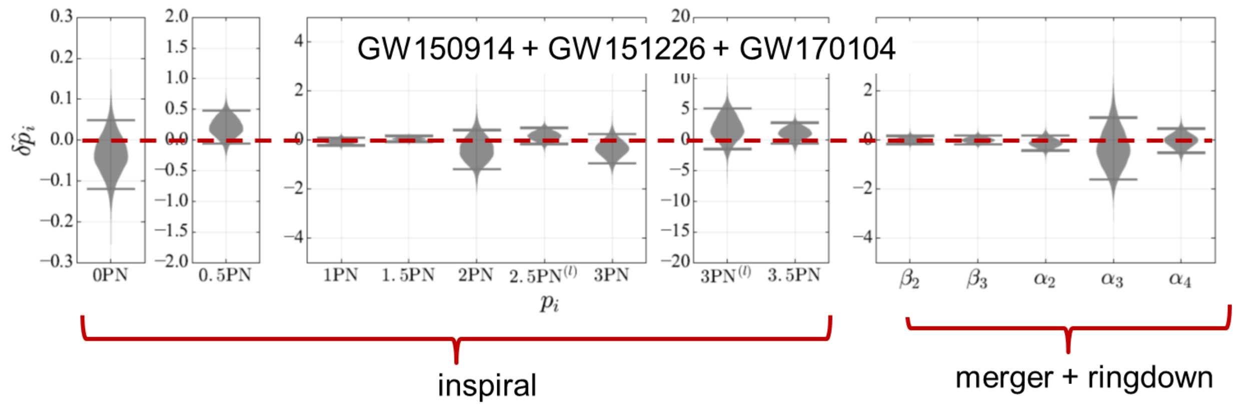
Bayesian analysis increases accuracy on parameters by combining information from multiple events

**Inspiral and PN expansion**

Inspiral PN and logarithmic terms: Sensitive to GW back-reaction, spin-orbit, spin-spin couplings, …

Merger terms: numerical GR

Ringdown terms: quasi-normal modes; do we see Kerr black holes?




**Towards high precision tests of gravity**

Combining information from multiple events and having high-SNR events will allow unprecedented tests of GR and other theories of gravity

**Our collaborations set ambitious goals for the future**

We need to improve:

- sensitivity of our instruments over the entire frequency range
- improve of data exchange with the global community (e.g. Open Public Alerts)
- optimize our computing and analysis
- improve our source modeling (NR)

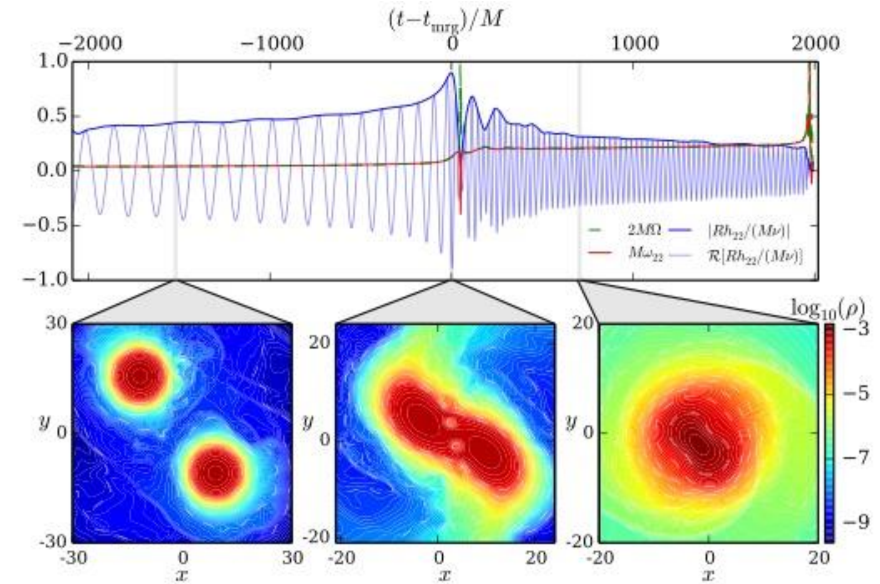
**We are not done yet!**

# Probing the structure of neutron stars

Tidal effects leave their imprint on the gravitational wave signal from binary neutron stars. This provides information about their deformability. There is a strong need for more sensitive detectors

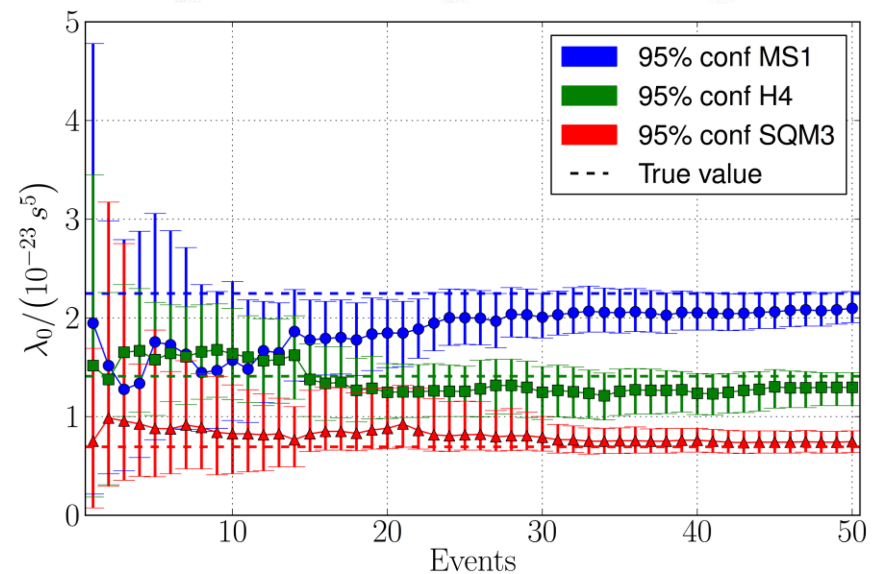
### Gravitational waves from inspiraling binary neutron stars

- When close, the stars induce tidal deformations in each other
- These affect orbital motion
- Tidal effects imprinted upon gravitational wave signal
- Tidal deformability maps directly to neutron star equation of state




### Measurement of tidal deformations on GW170817

- More compact neutron stars favored
- “Soft” equation of state

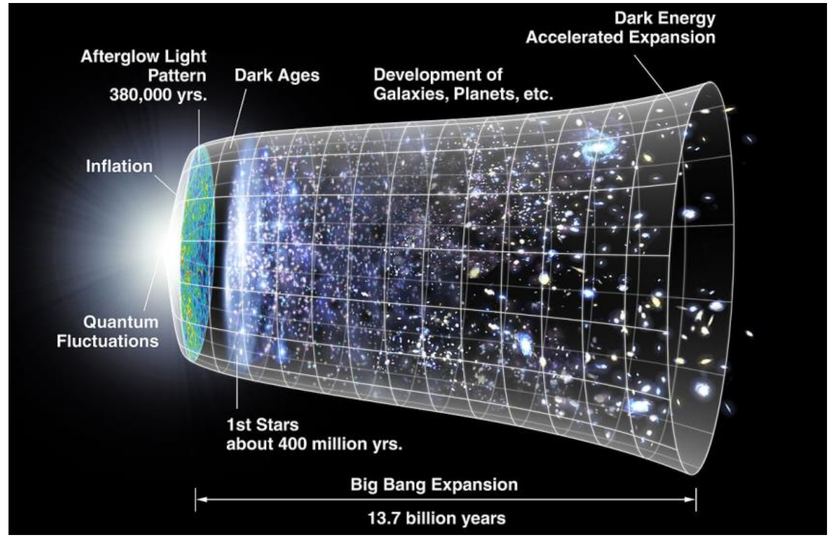



LIGO + Virgo, PRL 119, 161101 (2017)

Bernuzzi, Nagar, Font, …

# A new cosmic distance marker

A few tens of detections of binary neutron star mergers allow determining the Hubble parameters to about 1% accuracy




## Measurement of the local expansion of the Universe

The Hubble constant

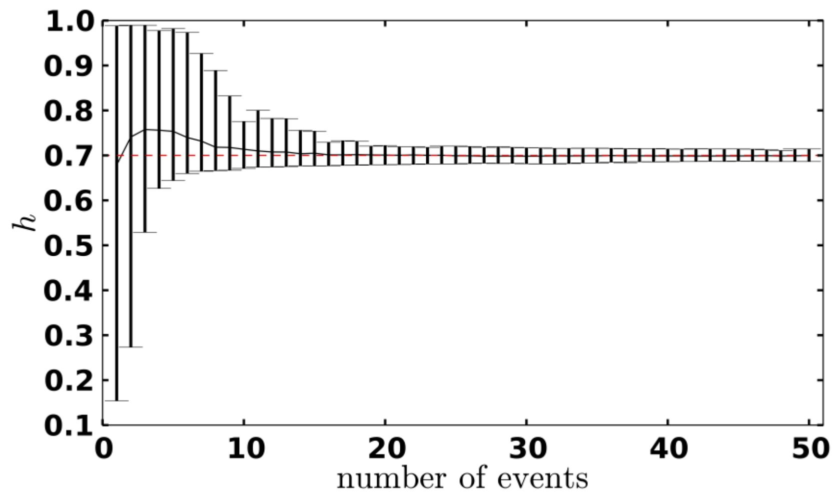
- Distance from GW signal
- Redshift from EM counterpart (galaxy NGC 4993)

LIGO+Virgo *et al*., Nature 551, 85 (2017)

## GW170817

- One detection: limited accuracy
- Few tens of detections with LIGO/Virgo will be needed to obtain O(1%) accuracy

Del Pozzo, PRD 86, 043011 (2012)




## Third generation observatories allow studies of the Dark Energy equation of state parameter

# Scientific impact of gravitational wave science

Multi-messenger astronomy started: a broad community is relying of detection of gravitational waves

**Fundamental physics**

Access to dynamic strong field regime, new tests of General Relativity
Black hole science: inspiral, merger, ringdown, quasi-normal modes, echo's
Lorentz-invariance, equivalence principle, polarization, parity violation, axions

**Astrophysics**

First observation for binary neutron star merger, relation to sGRB
Evidence for a kilonova, explanation for creation of elements heavier than iron

**Astronomy**

Start of gravitational wave astronomy, population studies, formation of progenitors, remnant studies

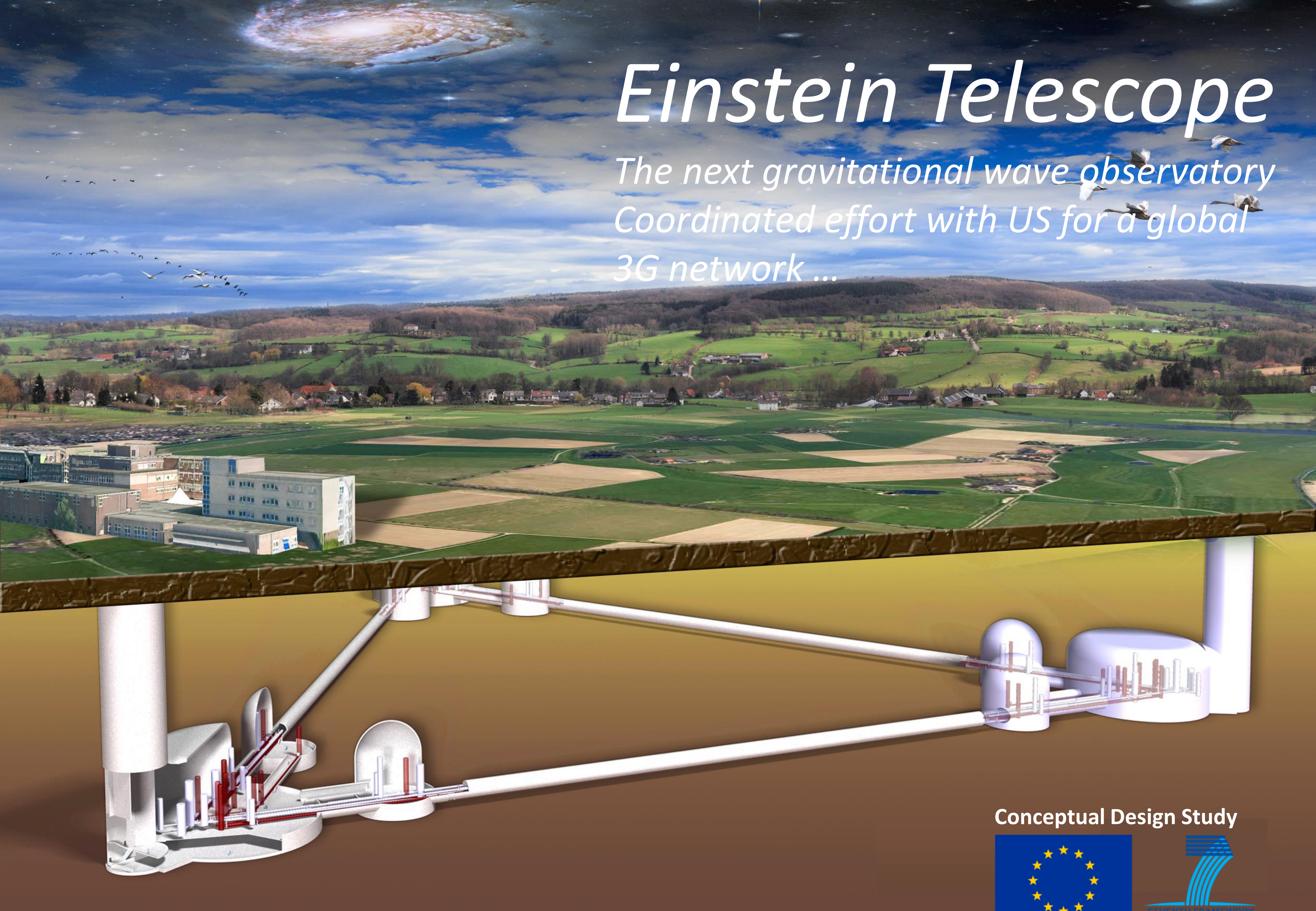
**Cosmology**

Binary neutron stars can be used as standard “sirens”
Dark Matter and Dark Energy

**Nuclear physics**

Tidal interactions between neutron stars get imprinted on gravitational waves
Access to equation of state

LVC will be back with improved instruments to start the next observation run (O3)

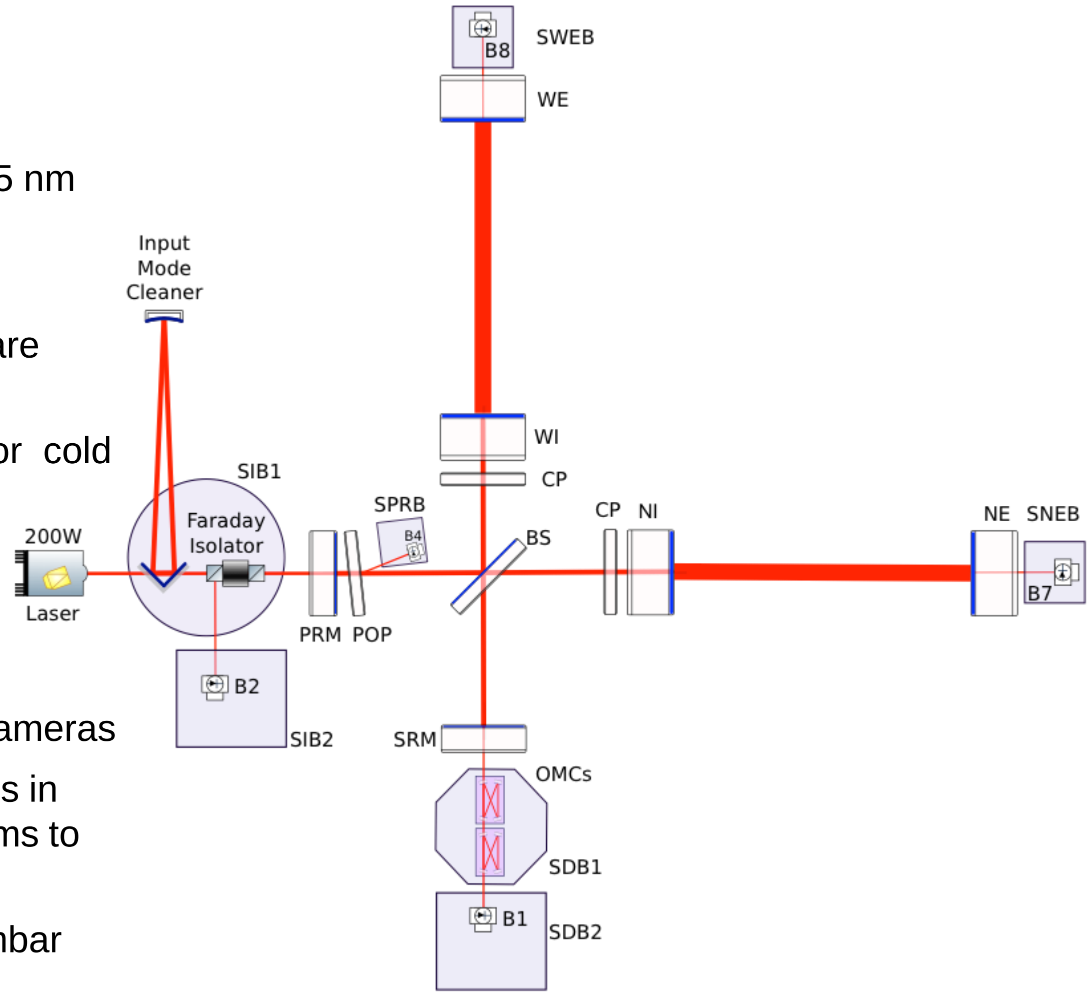

Einstein Telescope
The next gravitational wave observatory
Coordinated effort with US for a global
3G network …
Conceptual Design Study

# Advanced Virgo design

Advanced Virgo started operation on August 1, 2017. It features many improvements with respect to Virgo and Virgo+

For 2017 and 2018

- Larger beam: 2.5x larger at ITMs
- Heavier mirrors: 2x heavier
- Higher quality optics: residual roughness < 0.5 nm
- Improved coatings for lower losses: absorption < 0.5 ppm, scattering < 10 ppm
- Reducing shot noise: arm finesse of cavities are 3 x larger than in Virgo+
- Thermal control of aberrations: compensate for cold and hot defects on the core optics:
  - ring heaters
  - double axicon $CO_2$ actuators
  - $CO_2$ central heating
  - diagnostics: Hartmann sensors & phase cameras
- Stray light control: suspended optical benches in vacuum, and new set of baffles and diaphragms to catch diffuse light
- Improved vacuum: $10^{-9}$ mbar instead of $10^{-7}$ mbar

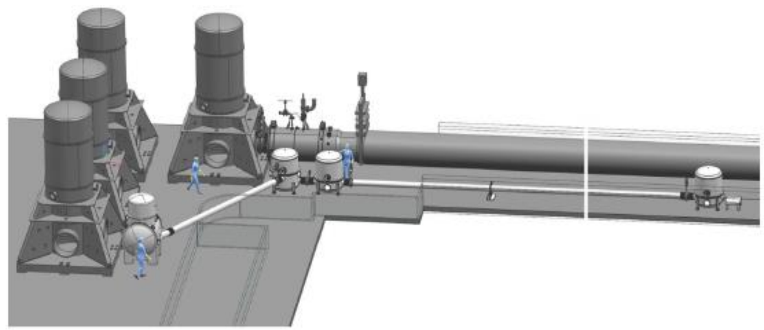


# AdV+ as the next incremental step forward in sensitivity

AdV+ is the European plan to maximize Virgo's sensitivity within the constrains of the EGO site. It has the potential to increase Virgo's detection rate by up to an order of magnitude

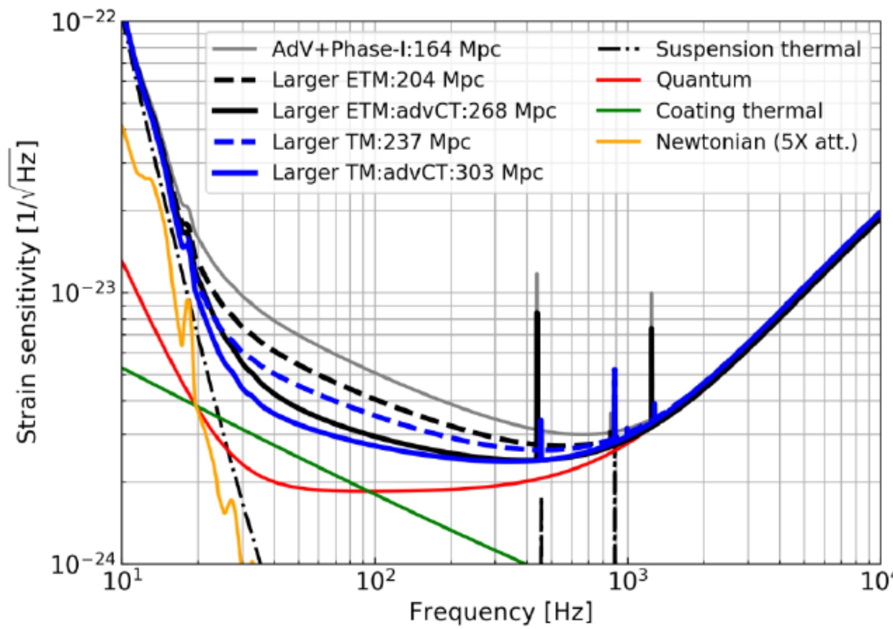
## AdV+ features

- Maximize science
- Secure Virgo's scientific relevance
- Safeguard investments by scientists and funding agencies
- Implement new innovative technologies
- De-risk technologies needed for third generation observatories
- Attract new groups wanting to enter the field



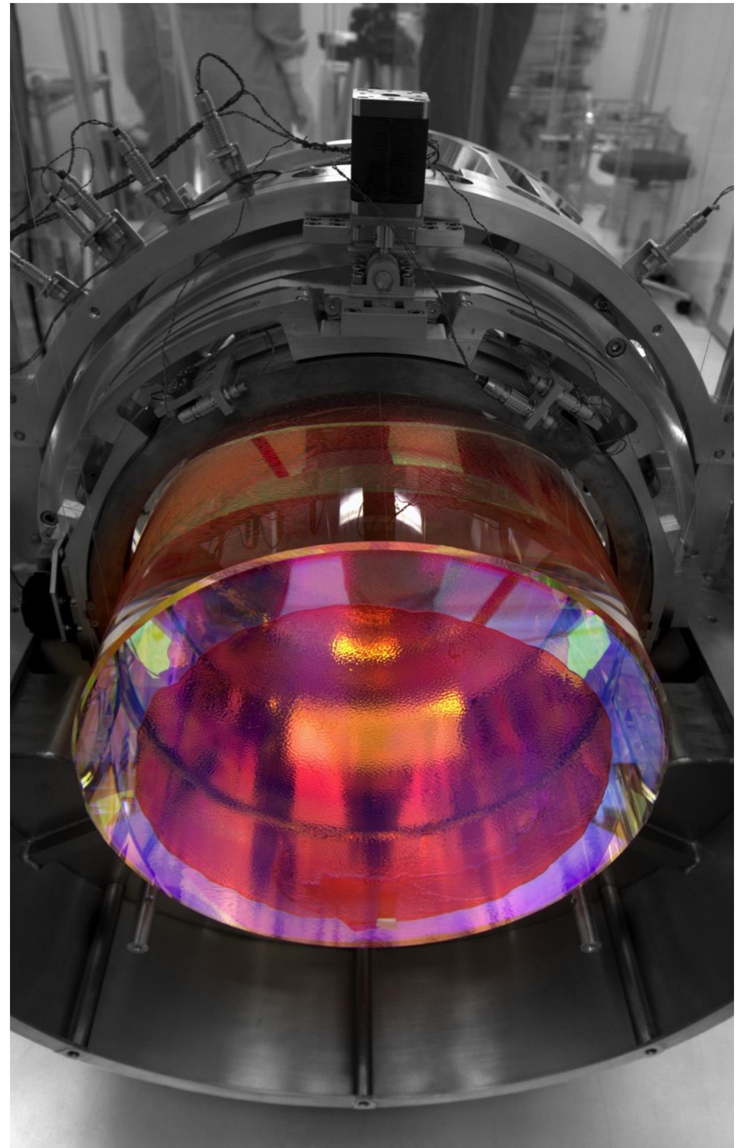
## Upgrade activities

- Tuned signal recycling and HPL: 120 Mpc
- Frequency dependent squeezing: 150 Mpc
- Newtonian noise cancellation: 160 Mpc
- Larger mirrors (105 kg): 200-230 Mpc
- Improved coatings: 260-300 Mpc



# AdV+ upgrade and extreme mirror technology

Laboratoire des Matériaux Avancés LMA at Lyon produced the coatings used on the main mirrors of the two working gravitational wave detectors: Advanced LIGO and Virgo. These coatings feature low losses, low absorption, and low scattering properties



## Features

- Flatness < 0.5 nm rms over central 160 mm of mirrors by using ion beam polishing (robotic silica deposition was investigated)
- Ti:$Ta_2O_5$ and $SiO_2$ stacks with optical absorption about 0.3 ppm

## Expand LMA capabilities for next generation

LMA is the only coating group known to be capable of scaling up

# Phase I

Quantum noise will be tackled after the O3 science run in Phase I: laser power will be increased to 200 W, and frequency dependent squeezing installed. Also tuned signal recycling and NN subtraction

**Power increase**

All in-fiber 200 W laser system for 125 W after the IMC

Foreseen as part of AdV

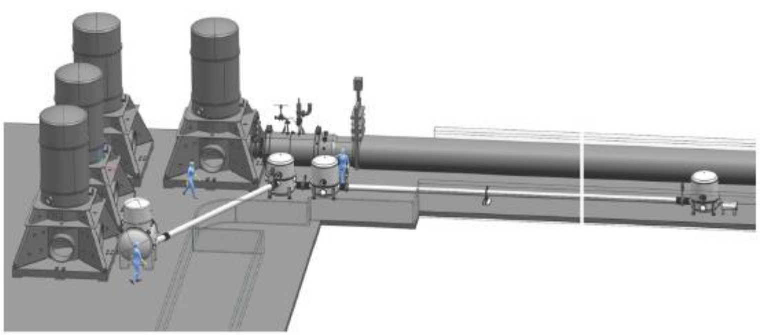
**Tuned signal recycling: 120 Mpc**

Install SR mirror

Control addition DOF (auxiliary lasers?)

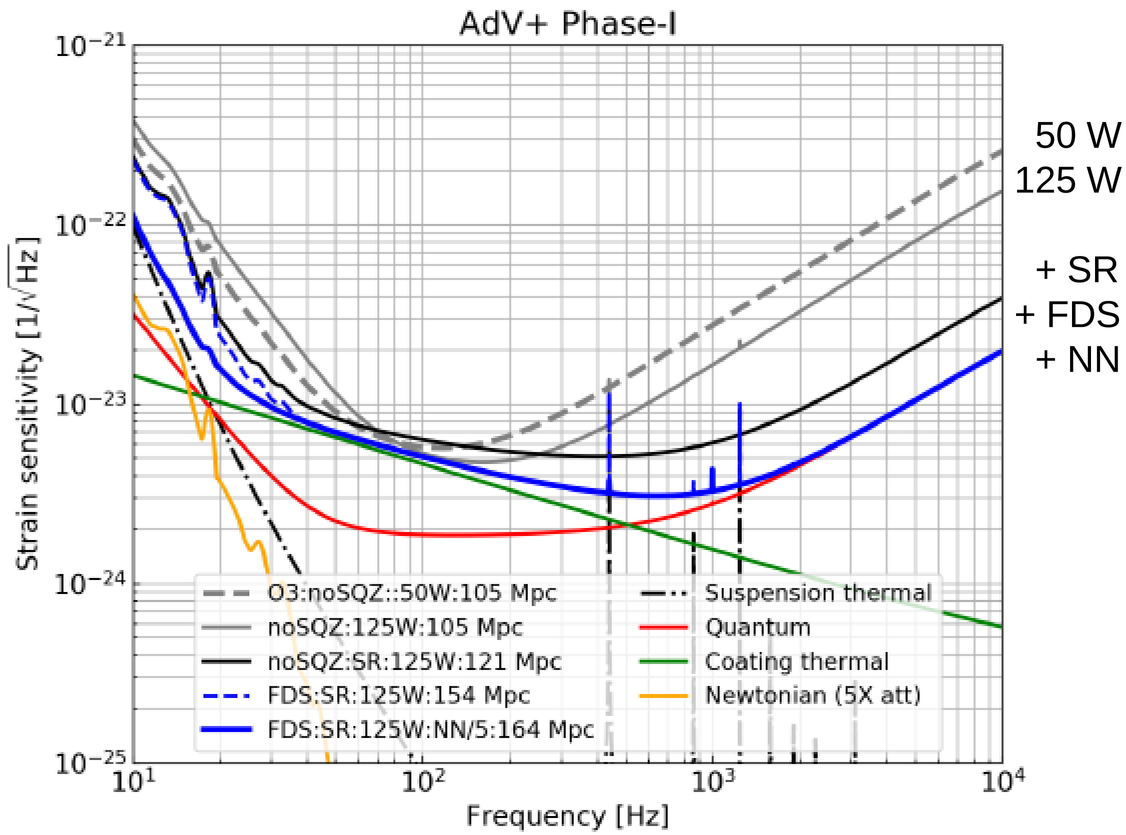
**Frequency dependent squeezing: 150 Mpc**

Squeezed light source and filter cavity



**Newtonian noise cancellation: 160 Mpc**

Seismic sensor networks



# Phase II

Reduce thermal noise: modify optical design of the Fabry-Perot arms to accommodate larger beams and heavier test masses

**Larger mirrors**

Diameter: 550 mm, thickness: 200 mm, mass: 105 kg

Scenario 1: ETM-only → 200 Mpc

Scenario 2: full upgrade → 230 Mpc

**Coating research**

**Factor three reduction in CTN**

Scenario 1: ETM-only → 260 Mpc

Scenario 2: full upgrade → 300 Mpc

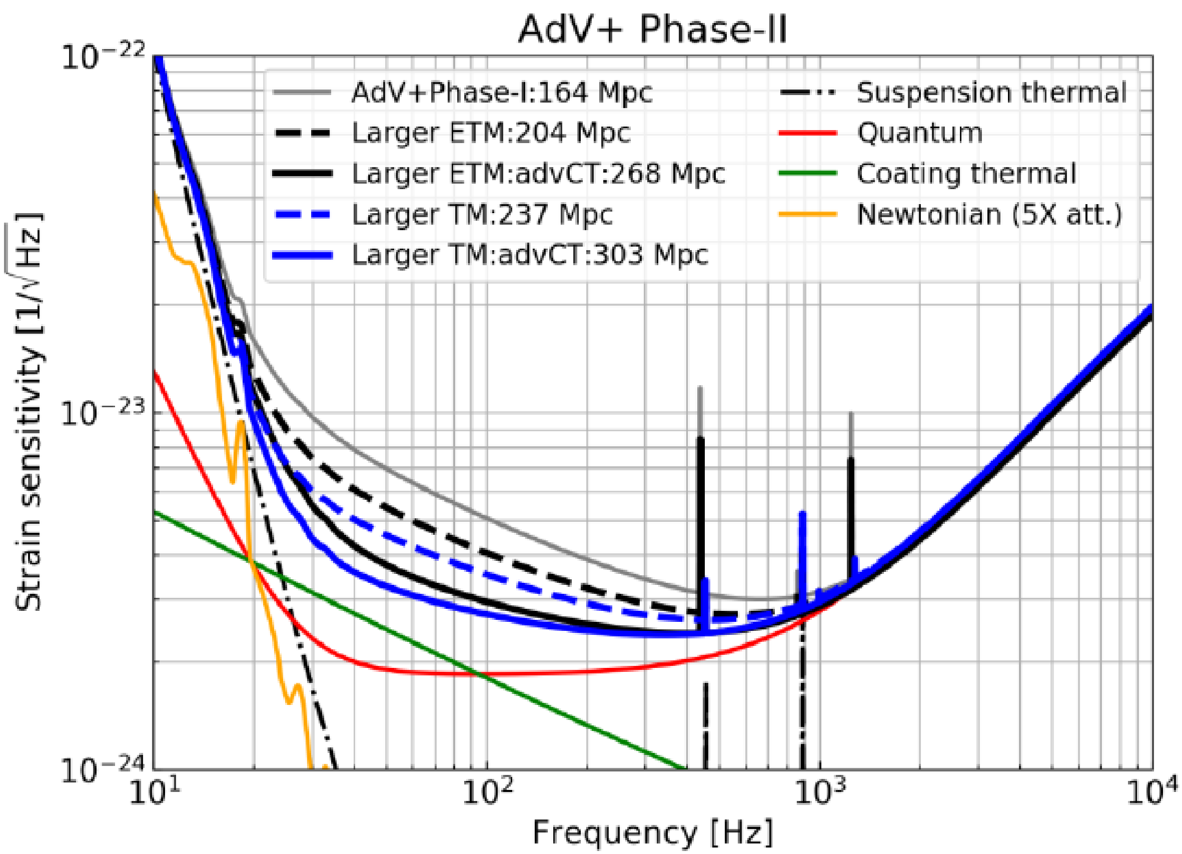
**Grand Coater upgrade**

**Many activities**

Vacuum, infrastructure

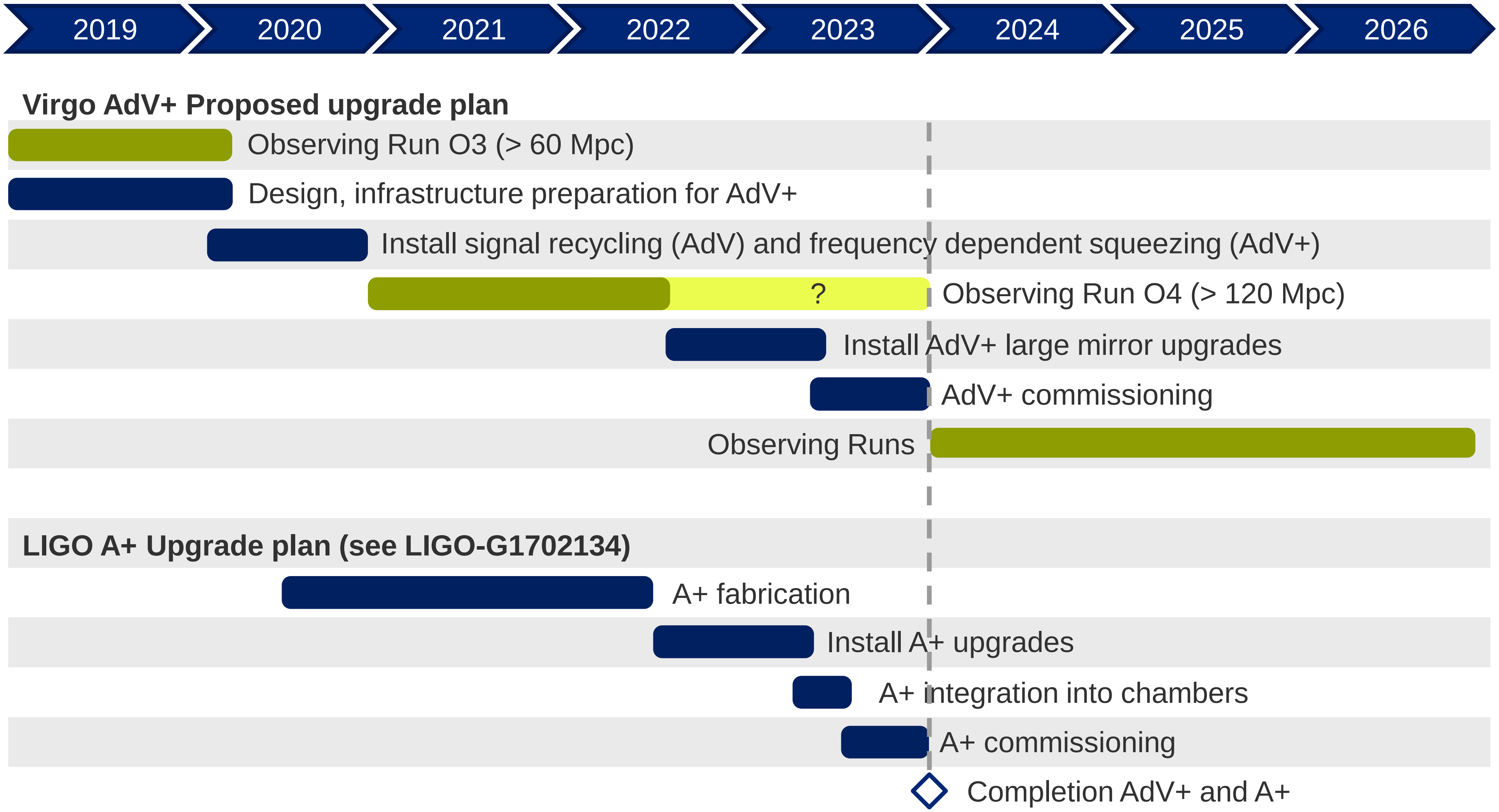
Payloads and superattenuators

Aberration control



# AdV+ to be carried out in parallel with LIGO's A+ upgrade

Five year plan for observational runs, commissioning and upgrades




**Note: duration of O4 has not been decided at this moment**
**AdV+ is part of a strategy to go from 2nd generation to Einstein Telescope**

# Summary and outlook

AdV+ is part of our strategy towards 3G and optimizes Europe's transition from 2nd generation to Einstein Telescope. In parallel R&D calls should be issued

**Virgo exploitation**

- Do the best possible science with the global LVC network: improve our instruments

**AdV+**

- Secure Virgo's scientific relevance
- Safeguard investments by scientists and funding agencies
- Implement new innovative technologies
- De-risk technologies needed for third generation observatories
- Virgo as gateway to 3G: attract new groups wanting to enter the field

**Vigorous R&D program to develop key technologies**

- Allow our scientists to work towards improved low-frequency sensitivity; open R&D calls

**Foster our ties with Astronomy and HEP community**

- Facilitate open public alerts to optimize multi-messenger astronomy
- Gravity is a fundamental interaction with most important open scientific issues
- Involve Virgo scientists in upcoming EU HEP Strategy discussion

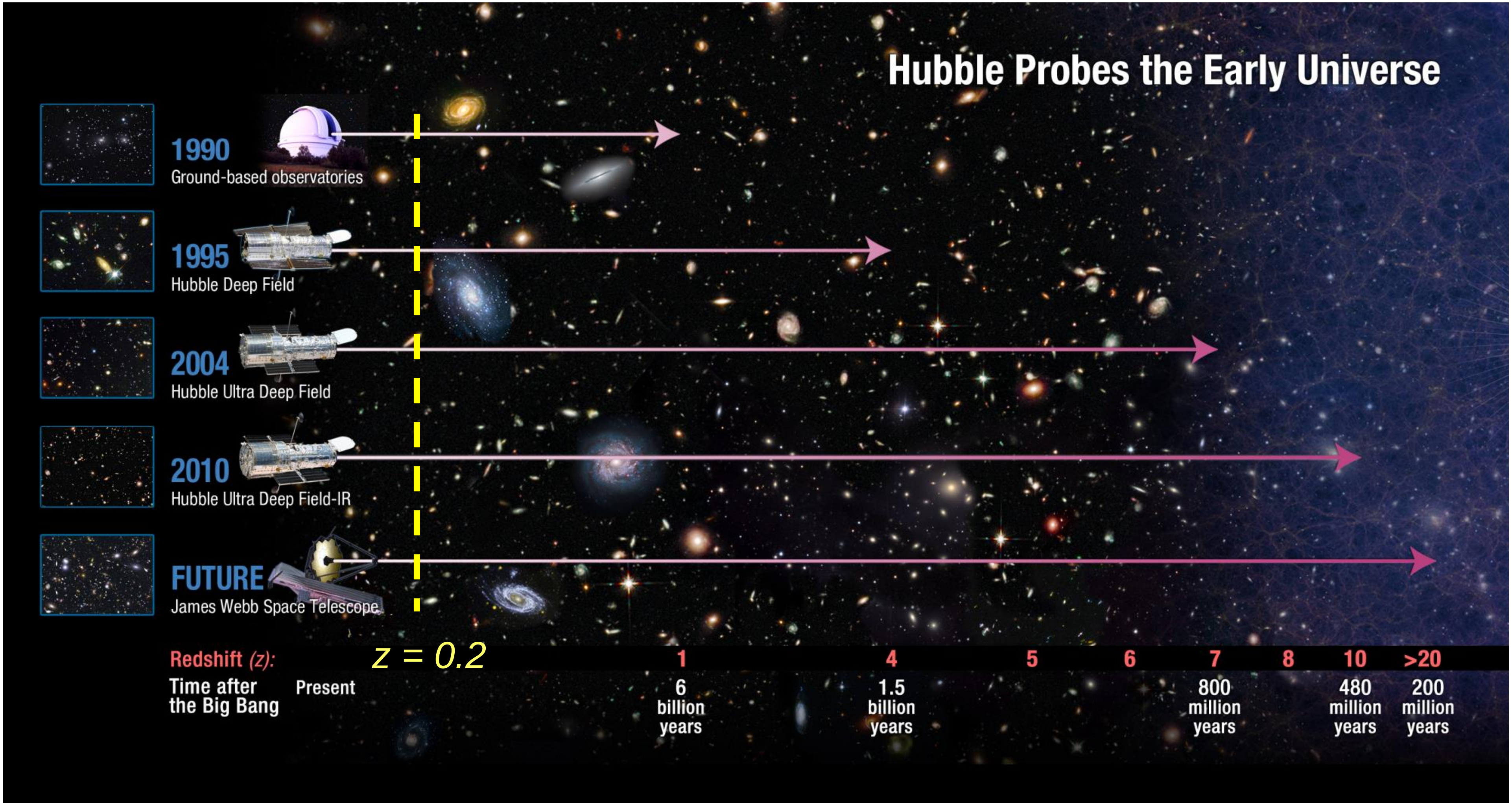
# Back-up slides

# Einstein Telescope: observing all BBH mergers in Universe

This cannot be achieved with existing facilities and requires a new generation of GW observatories

We want to collect high statistics (*e.g.* millions of BBH events), high SNR, distributed over a large z-range (*z* < *20*)

This allows sorting data versus redshift, mass distributions, *etc*. Early warning, IMBH, early Universe, CW, …



# Adequate exploitation funds are required

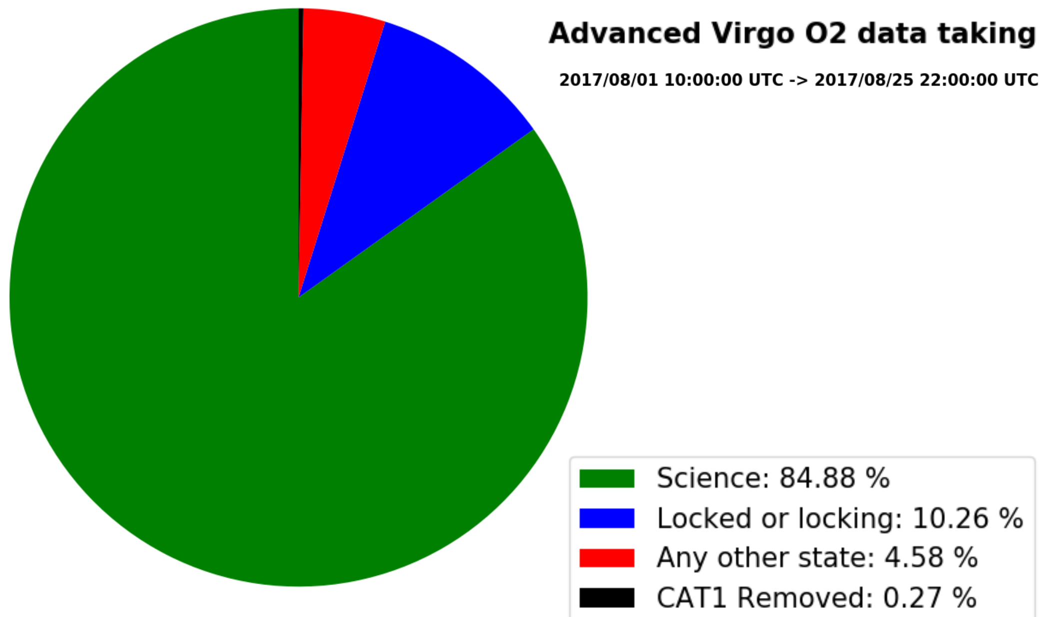
The global LIGO-Virgo network is our detector. The European Virgo detector has an obligation to carry its weight in the network of gravitational wave detectors

## Virgo highlights of O2 run

- Longest stable lock stretch (# 39064) was 69 hours
- BNS range up to 28.2 Mpc
- Virgo science duty cycle was about 85%


## Added scientific value of Virgo in the network

- Increased data set LH → LH **+ LV + HV + LHV**
- Increase of sky coverage
- Improvement of sky location of sources
- Measurement of GW polarization
- Improvement in distance measurement
- Three-fold coincidence for increased robustness
- Improvement in parameter estimation




## Resources needed to enable

- Commissioning Virgo to design sensitivity
- Running EGO as a professional GW observatory
- Future perspective for our young and promising scientists

Advanced Virgo

# Resources should be dedicated to allow MMA computing

The LIGO-Virgo Collaboration has MOUs with 95 collaborations in astronomy and astro-particle physics. Multi-messenger astronomy requires rapid follow-up of interesting triggers and fast distribution of science data between partners distributed over the globe

**Computing will become increasingly important as experiments mature**

- GW event rate rapidly increases as sensitivity improves (note that GW-amplitude is measured; $\mathrm{Rate} \sim S_{GW}^{3}$)
- Also computing needs grow as templates get longer

Moreover there is a strong push towards open data and an EU open science cloud