Sites and infrastructures

Jo van den Brand
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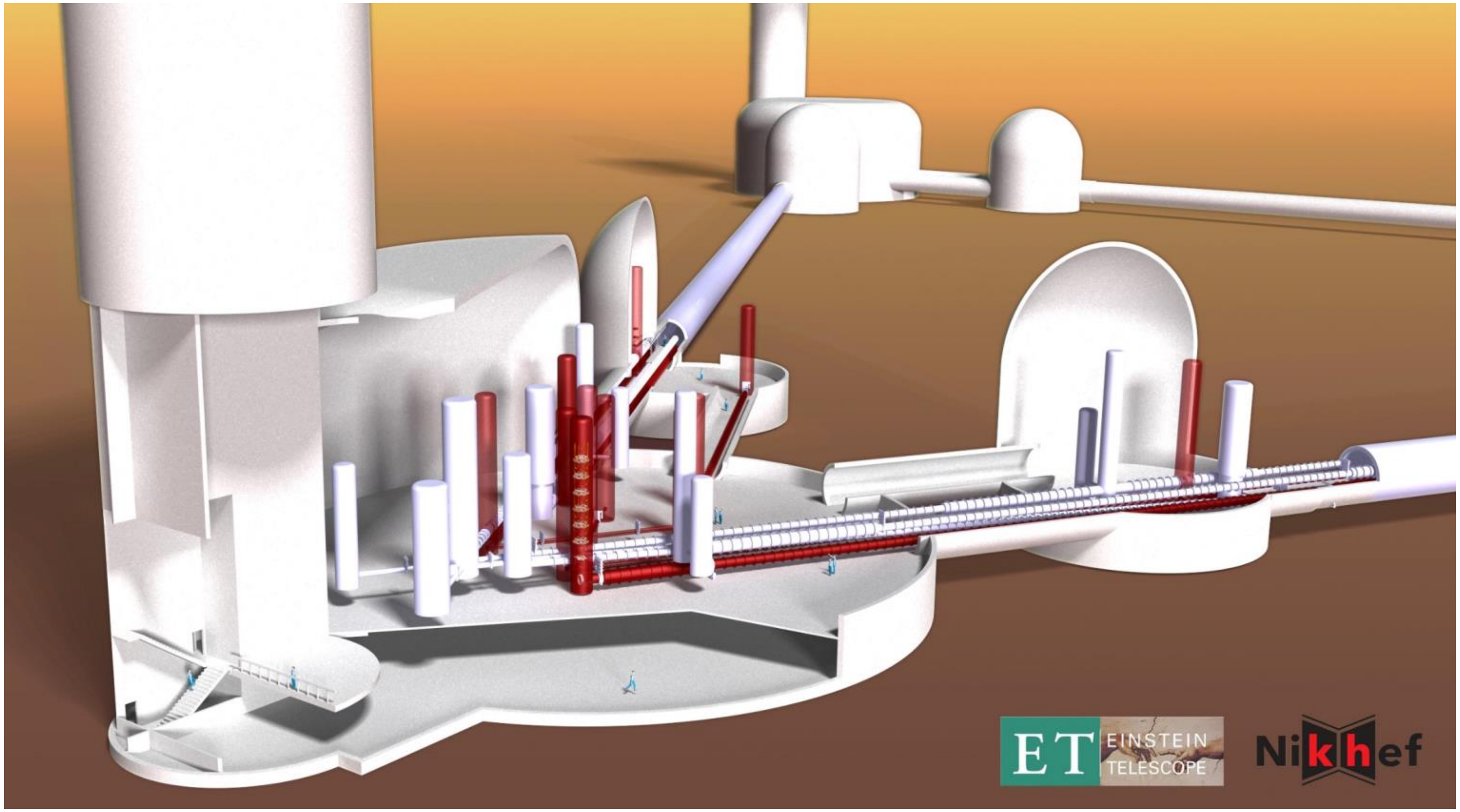
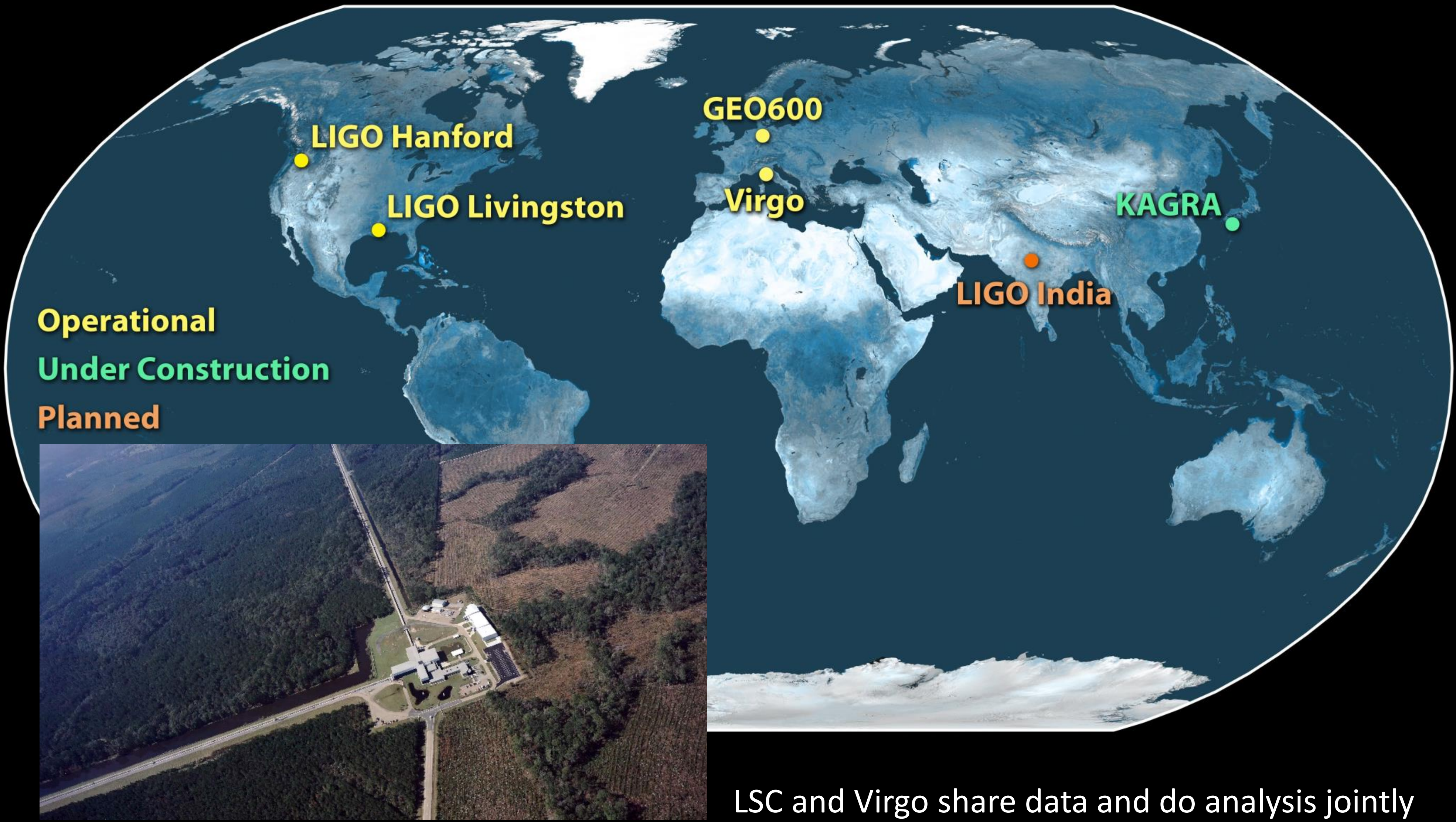


AEI, Hannover, June 19, 2018

Towards a global GW research infrastructure



LSC and Virgo share data and do analysis jointly

Towards a global GW research infrastructure

LSC and Virgo share data and do analysis jointly

Towards a global GW research infrastructure

LSC and Virgo share data and do analysis jointly

Scientific achievements: properties of black holes

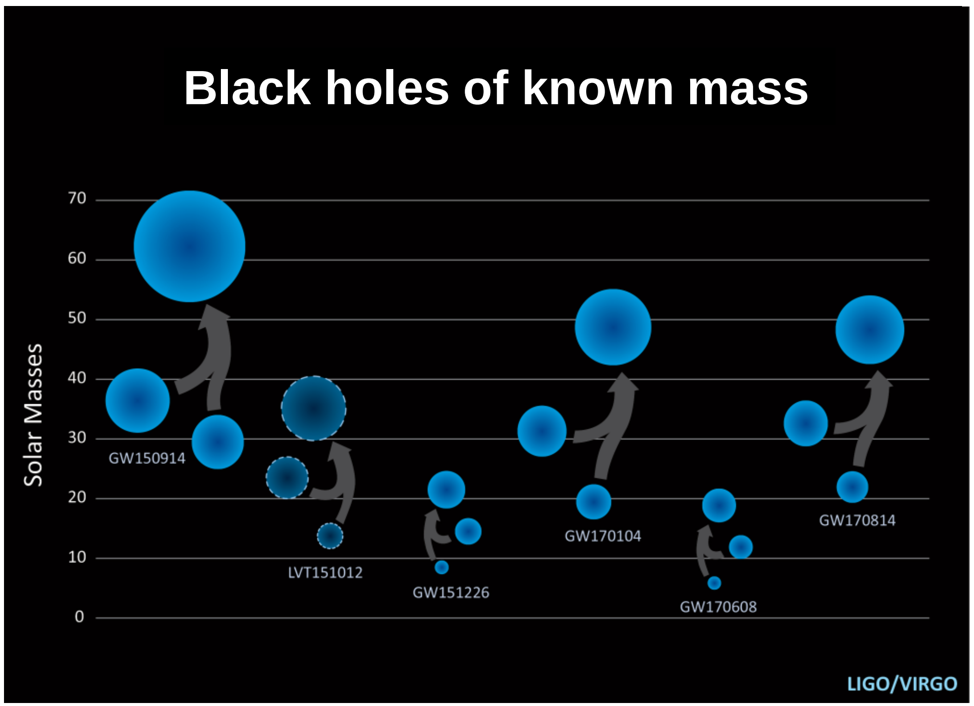
Extract information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distributions may shed light on formation mechanisms

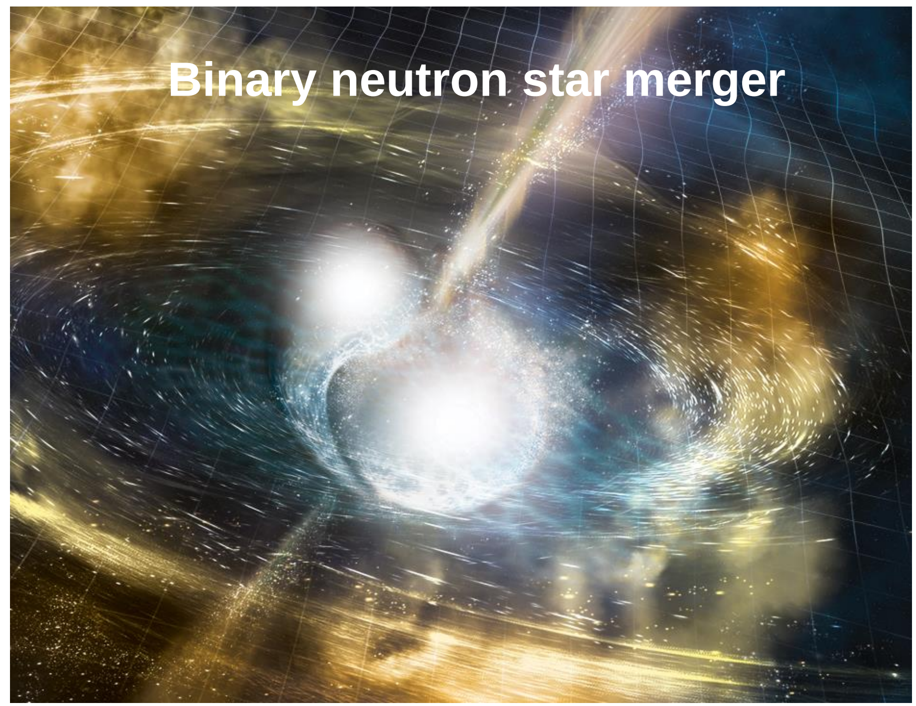
LVC reported on 6 BBH and 1 BNS mergers

Fundamental physics, astrophysics, astronomy, nuclear physics, and cosmology

Testing GR, waveforms (with matter)

A new field that is just getting started: black hole science and multi-messenger astronomy



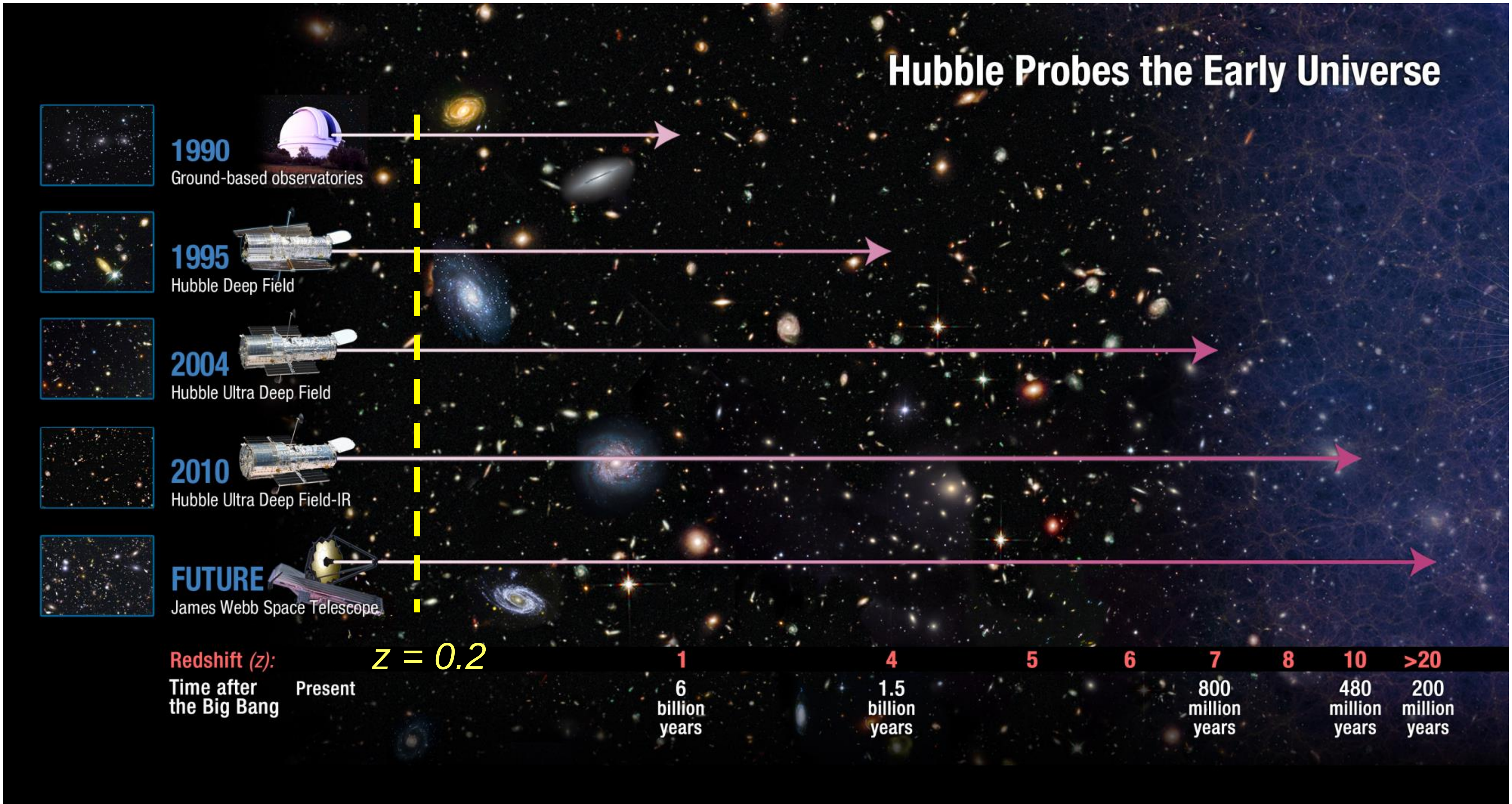


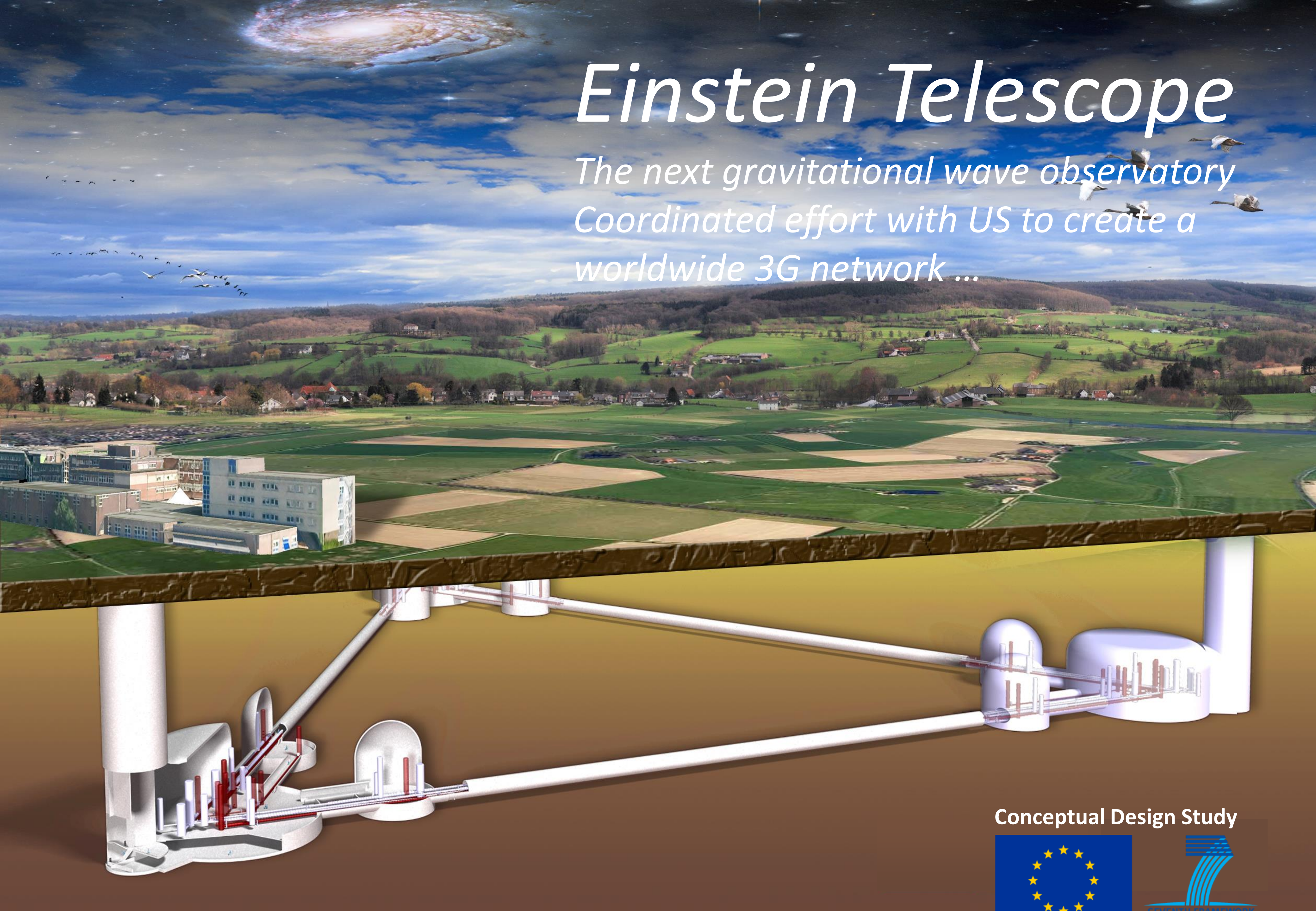
Einstein Telescope: observing all BBH mergers in Universe

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, …




Einstein Telescope
The next gravitational wave observatory
Coordinated effort with US to create a
worldwide 3G network ...
Conceptual Design Study

Studies of potential sites for Einstein Telescope

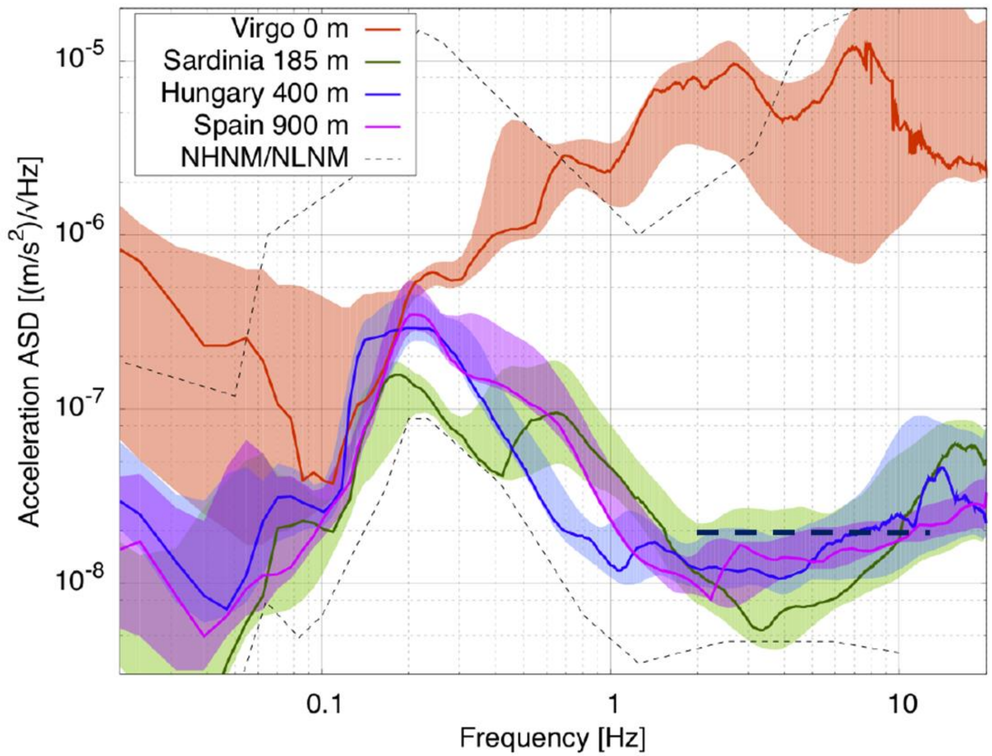
Canfranc underground laboratory in Spain features excellent site quality

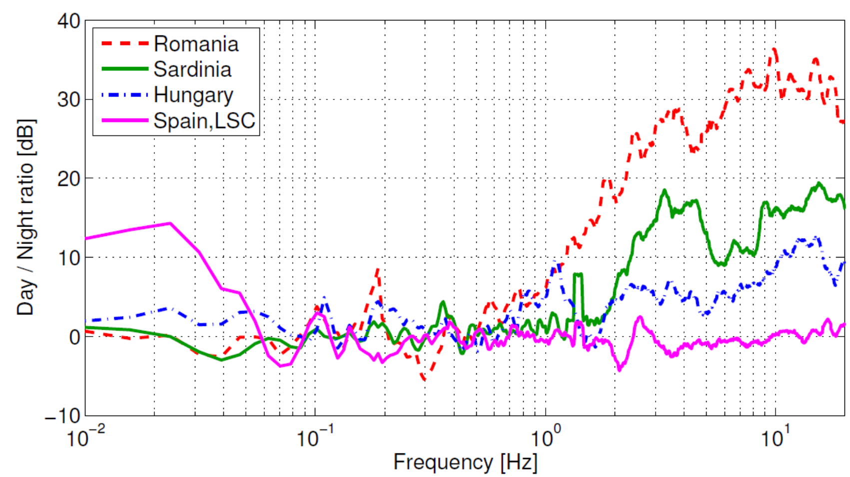
Lowest seismic noise level (complies with ET specs)

No diurnal dependence of seismic noise

Lowest population density (< 2 per km^2)

Large distance from ocean (120 km)

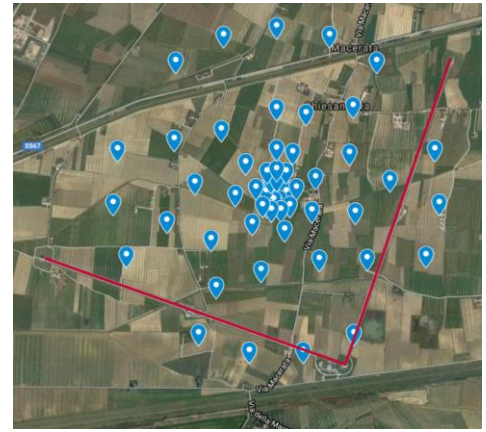




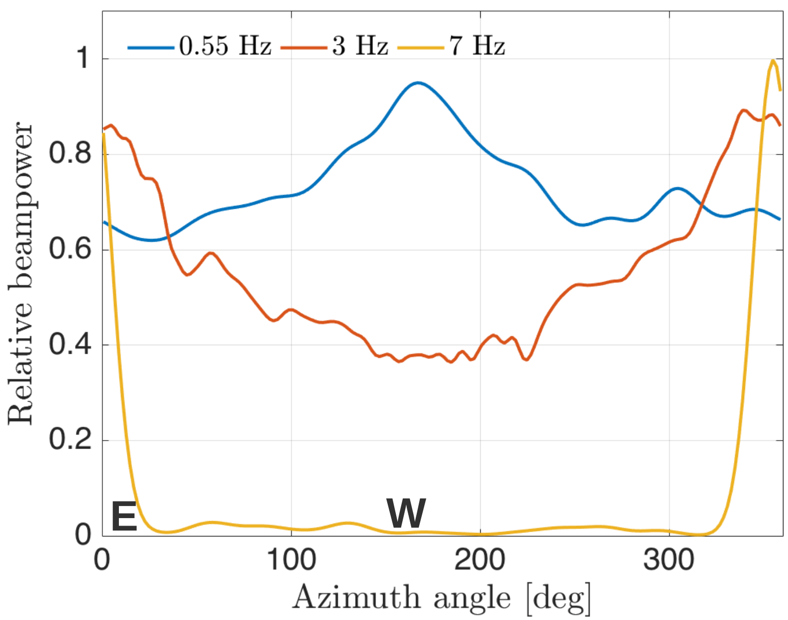
Virgo passive seismic array study

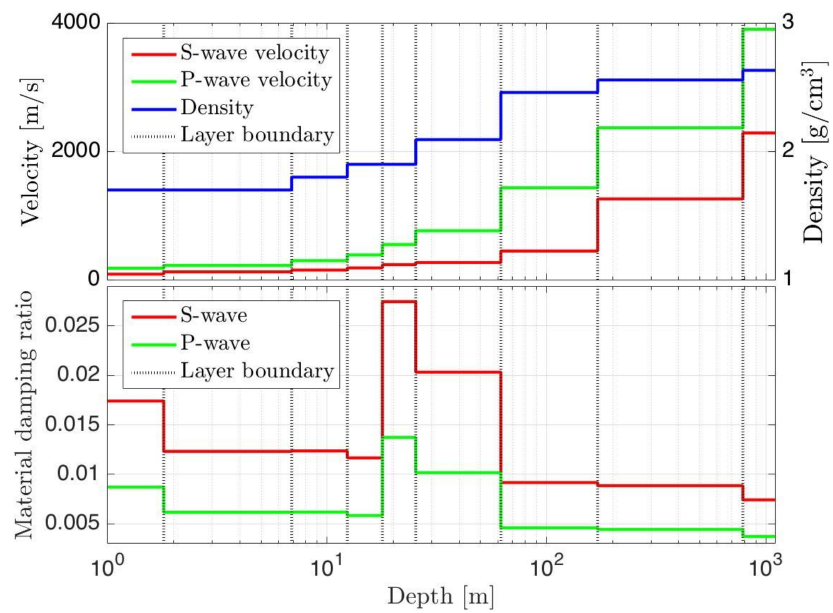
Sensor array study of August 2016 resulted in a 1D velocity and density model of the Virgo site with nine subsurface layers

- Sensor array study 13-29 August 2016 with 64 seismic sensors (geophone based)
- Array is designed to be sensitive in from 0.2-8 Hz
- Beamforming analysis: Main noise sources (microseism, road-bridges and local oscillations), phase velocity and dispersion curve
- Inversion method: based on 9-layer model from previous shallow borehole and gravimetric measurements [1]



Soumen Koley





Results published in*:* Koley S et al 2017 SEG Technical Program Expanded Abstracts 2017 pp. 2946-2950

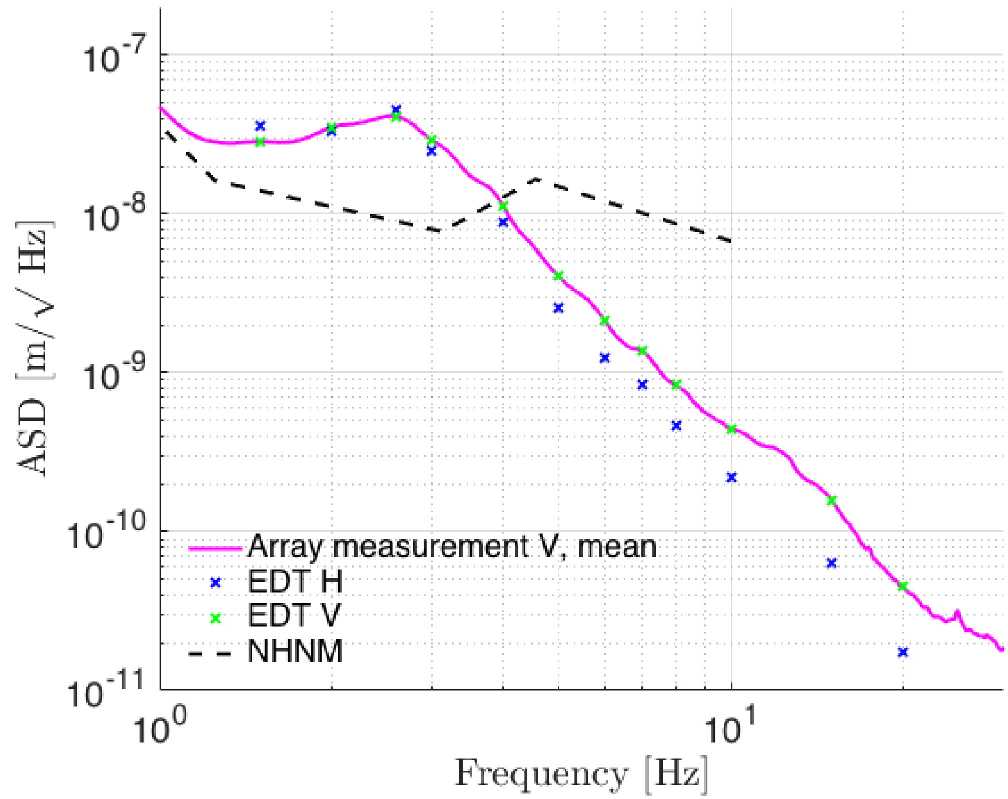
[1] Stefanelli S et al 2008 Annals of Geophysics 51, 5/6

Surface ASD of the modeled ambient seismic field

The surface PSD measured at the center of the array is representative for the seismic noise in the area

PSD measured by sensor array

- Vertical PSD measured by the central sensor of our sensor array in 2016 (magenta curve)
- Representative for the seismic noise of the area
- H/V ratio < 1 as expected for (nearly) homogeneous media. This ratio has been observed at the site before [1]
- Future seismic studies can profit from sensor arrays based on 3-channel sensors



[1] Punturo M et al (Virgo Collaboration) 2012 Advanced Virgo sensitivity curve study

Comparison to PSD measured at the Virgo central building

The PSD at high frequencies is significantly higher close to the central building due to higher anthropogenic activity

PSD measured by sensor array

- Vertical PSD measured by the central sensor of our sensor array in 2016 (magenta curve)
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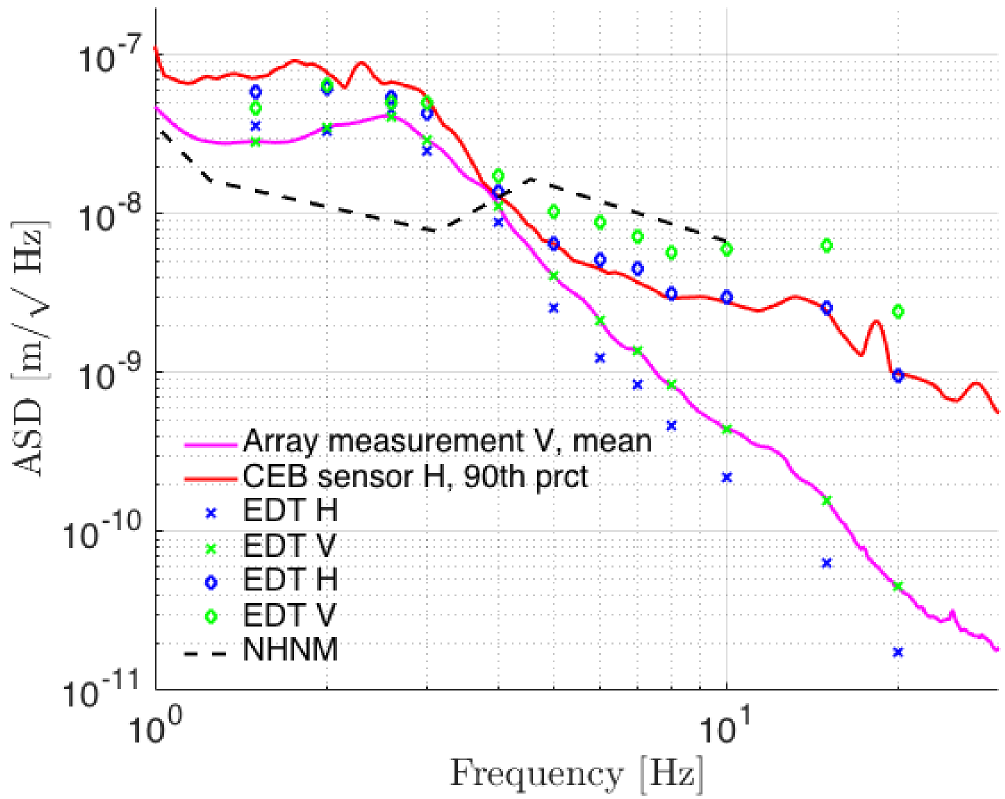


PSD in design sensitivity curve [2]

- 90th percentile of a horizontal PSD measured in 2014 (red curve) at the central building
- Significant higher anthropogenic noise at high frequencies
- Site optimizations in terms of anthropogenic noise could lead to a reduction of seismic noise

[1] Punturo M et al (Virgo Collaboration) 2012 Advanced Virgo sensitivity curve study
[2] Acernese F 2014 et al Classical and Quantum Gravity 32 2

Effects of seismic noise

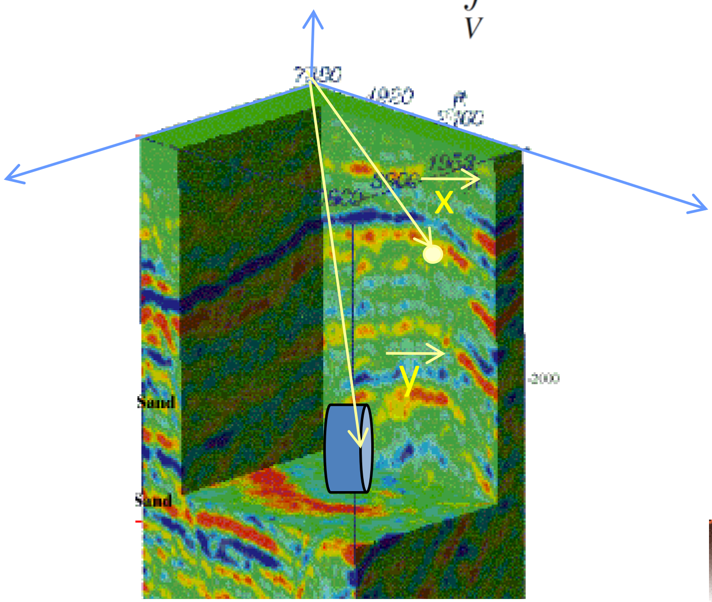
Active and passive vibration isolation systems are used to suppress seismic noise. Gravity gradient noise (also Newtonian noise) acts directly on test masses

GGN limits sensitivity at low frequencies

Important to estimate contribution

- Employ seismic sensor array
- Determine noise sources from beamforming
- Characterize subsurface
- Integrate

$$\mathbf{a}^{NN}(\mathbf{y},\omega) = -G \int_V \nabla \left[\rho_0(\mathbf{x})\, \boldsymbol{\xi}(\mathbf{x},\omega)\right] \mathbf{K}(\mathbf{x}-\mathbf{y})\, dV_x$$



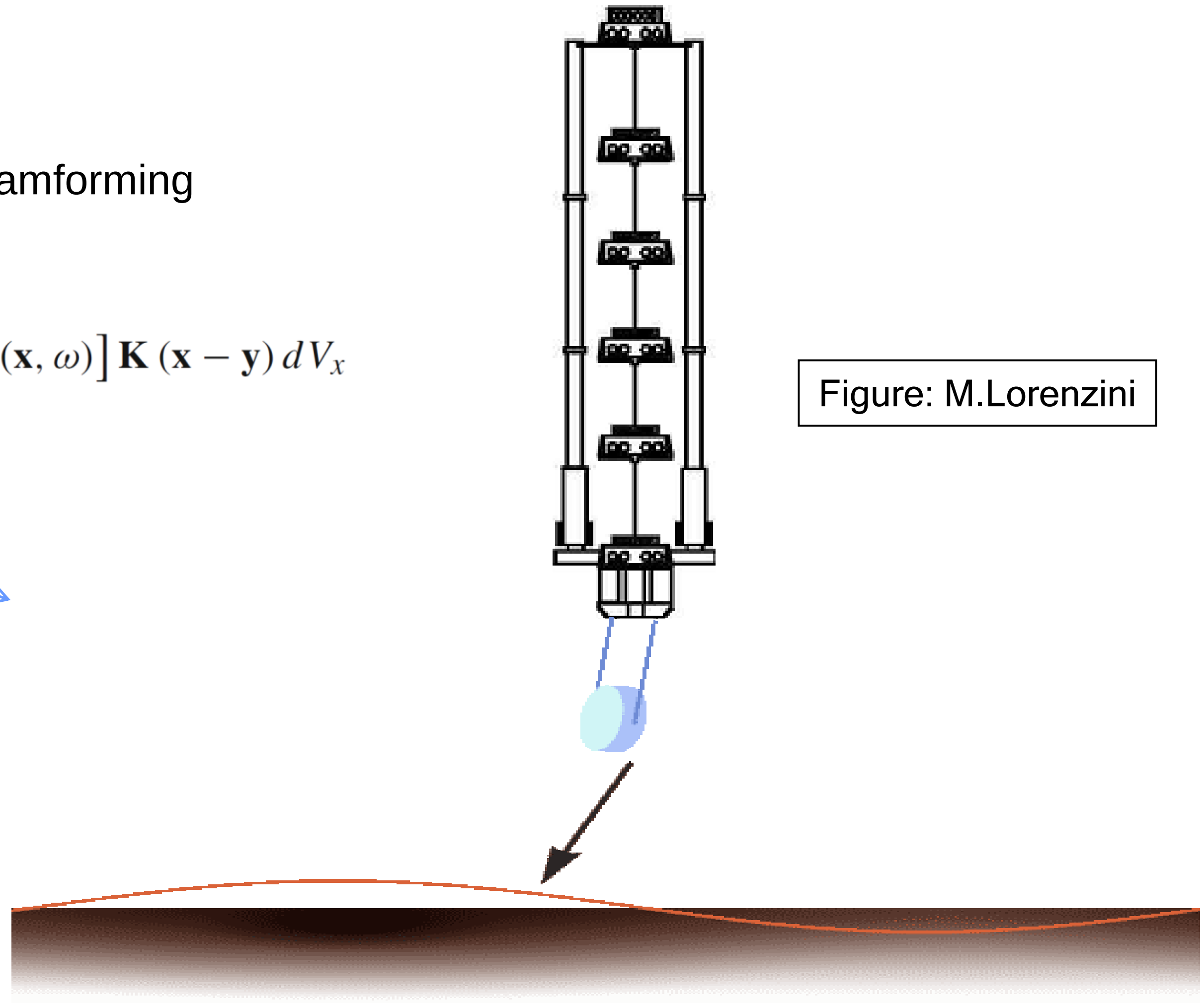
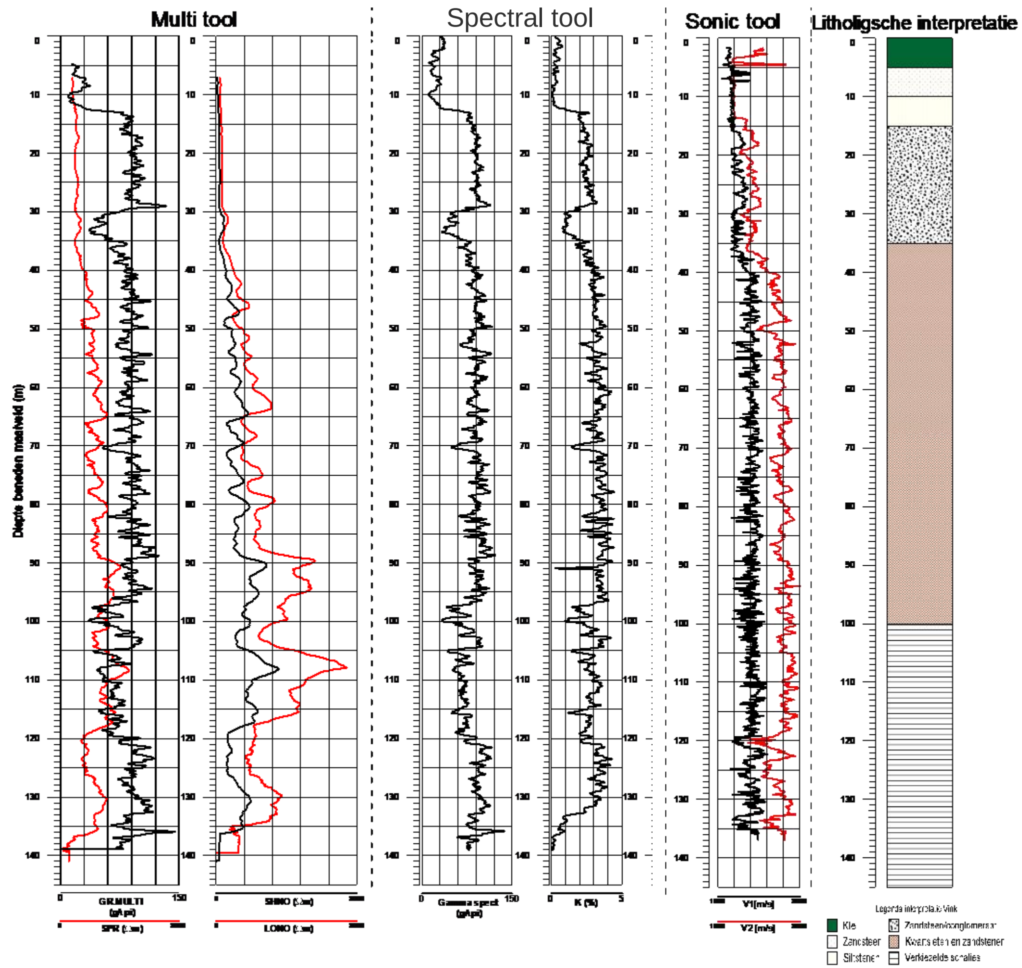


Figure: M.Lorenzini

B-G-NL candidate site for Einstein Telescope

We performed array and borehole studies at the ET candidate site in the Limburg are in the Netherlands to obtain detailed information about the underground composition



Borehole studies

- 175 m deep borehole (March 2017): Different subsurface measurements and confirmation of 'soft soil on hard rock'-geology
- In preparation: borehole to 300 m depth with seismic sensor installation (end 2018)

Seismic sensor array studies

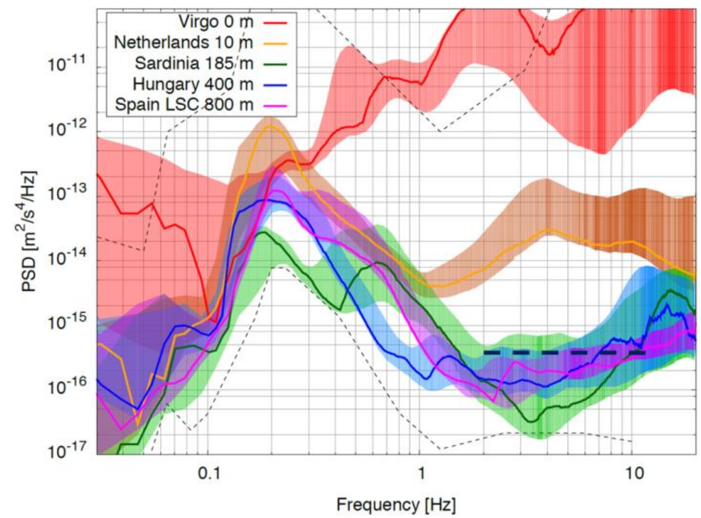
- Passive studies: 1D S-wave model (Nov and Dec 2017)
- Active array study: 2D P-wave and quality factor model (Feb 2018)

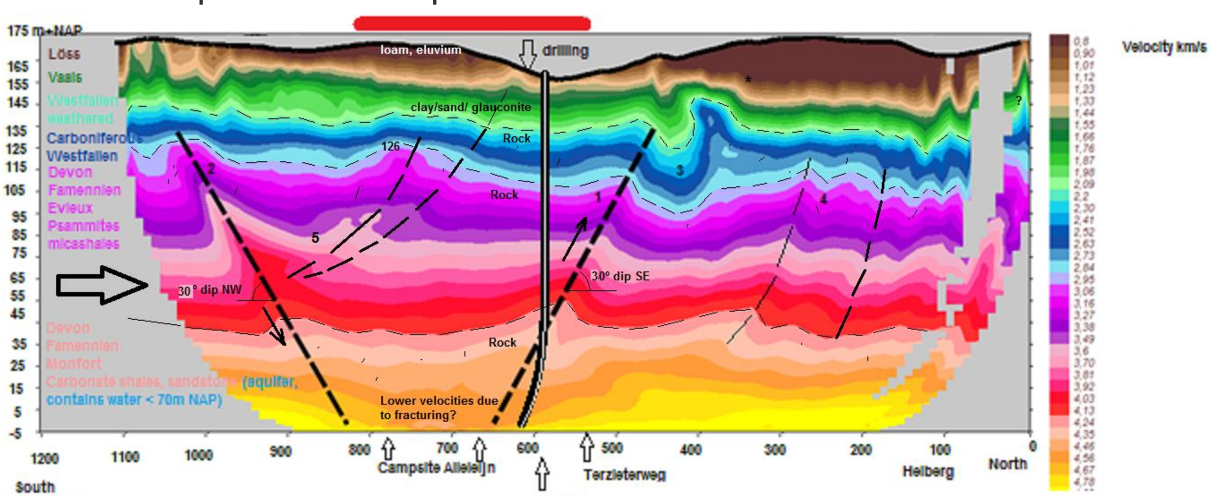
Newtonian noise at 100 m depth at the ET candidate site

While seismic noise at the surface is relatively high, Newtonian noise underground is expected to be strongly suppressed with respect to surface Newtonian noise due to the layered geology

PSD suppression in layered geology from seismic array studies

- Noise is mostly of anthropogenic origin and generated at the surface
- The soft soil surface layer features relatively low seismic wave velocity and short wavelengths
- This causes the surface contribution to largely average out at the mirror due to integration effects
- Waves are reflected at layer boundaries due to differences in seismic impedances
- Therefore only a relatively small amount of seismic energy enters the lower layers
- The lower layers feature high wave velocity and consequently small local displacement amplitudes

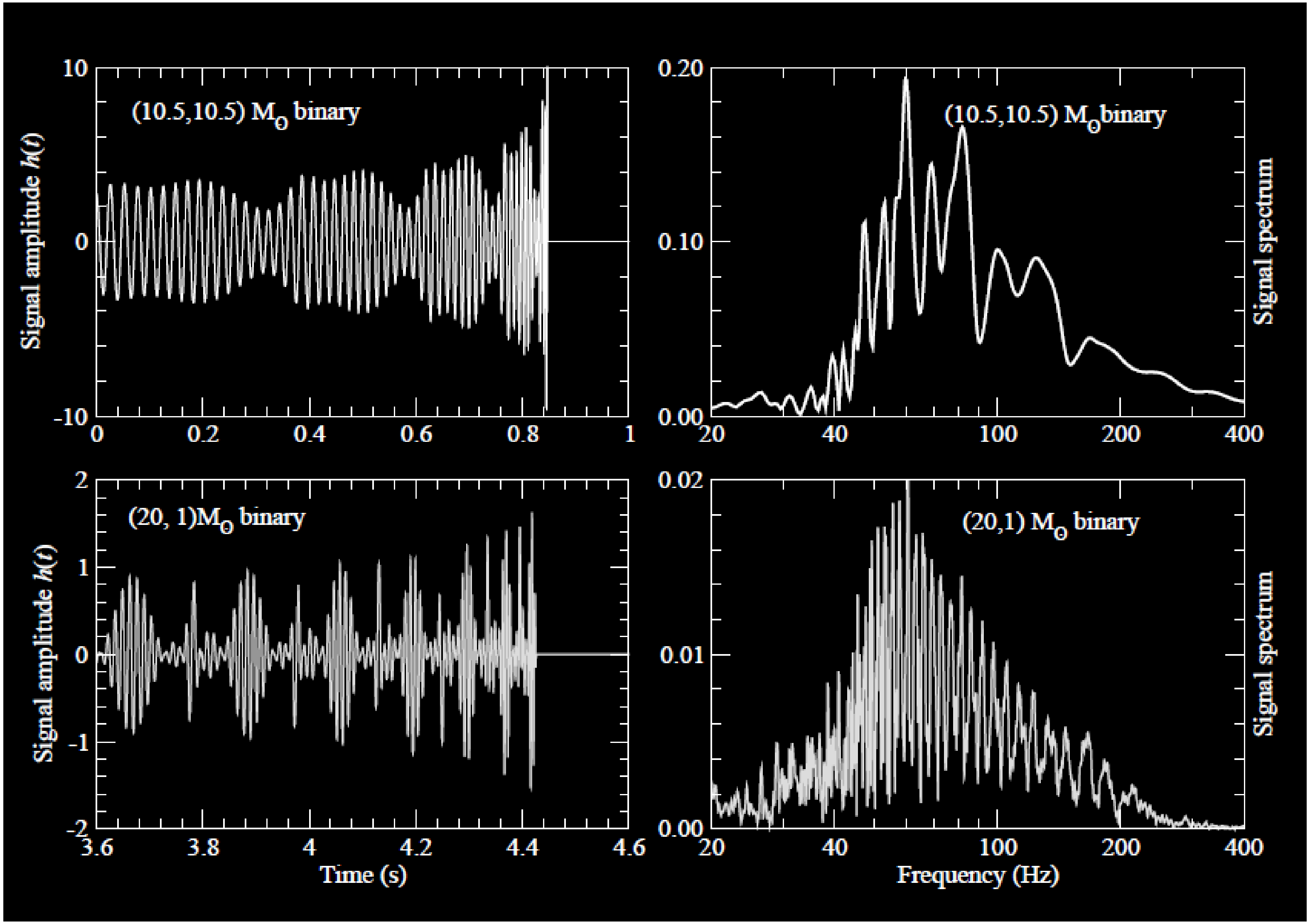




Why low-frequency sensitivity, and thus the need to go underground and feature cryogenic test masses?

Observe GW signals over a long time

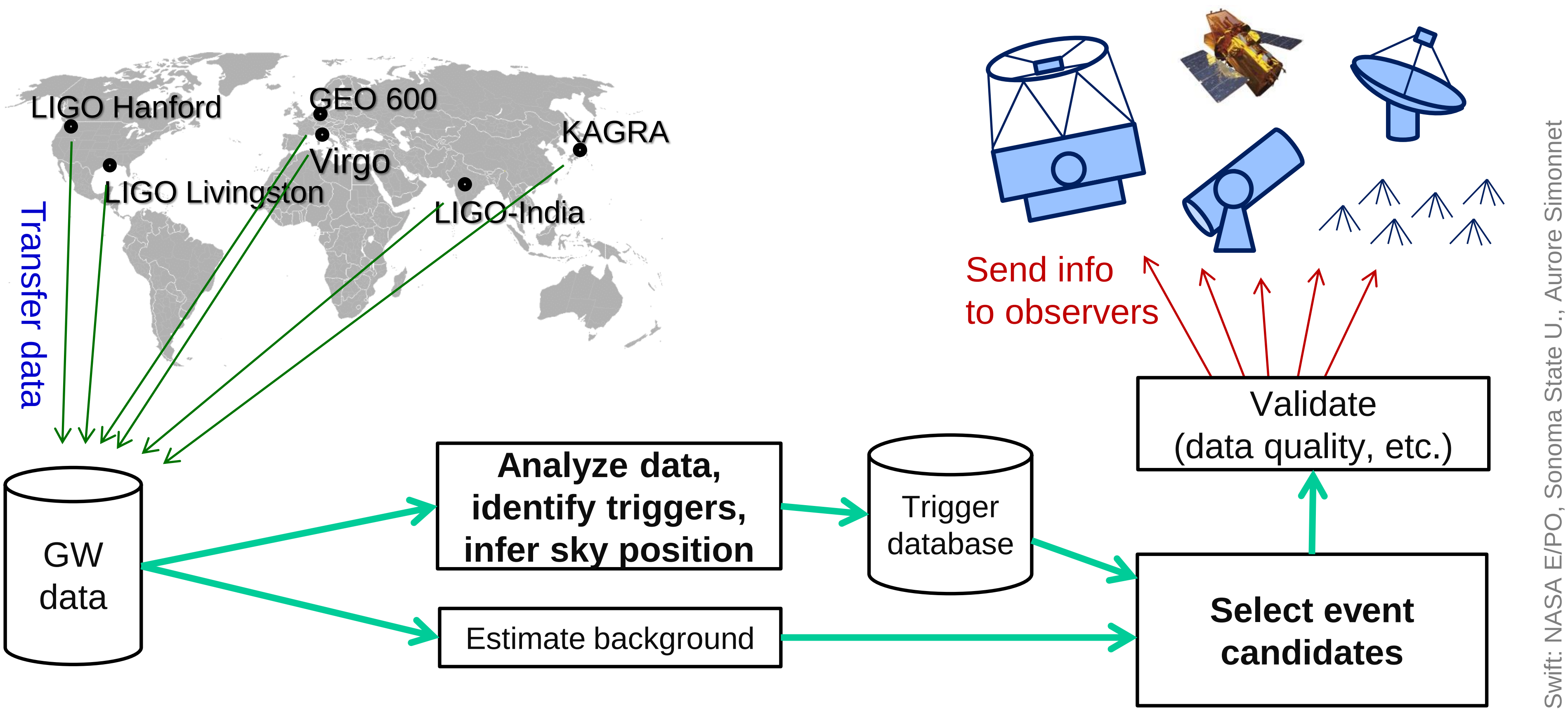
It is of great importance to study spin-precession effects. Modulations encode the parameters of sources (their masses, spins, inclination of the orbit, etc.



Provide alerts to enable multi-messenger astronomy

A BNS system will stay in ET's sensitivity band for nearly a week starting from 1 Hz, 20 hours starting from 2 Hz, and a little less than 2 hours starting from 5 Hz. For the same lower frequency limits the duration of a BBH signal from a pair of 10 M BHs is 2 days, 45 minutes and 4 minutes

LIGO & Virgo have signed MOUs with 95 groups for burst/EM/neutrino follow-up, in addition to a number of triggered / joint search MOUs



We want to observe intermediate-mass black holes

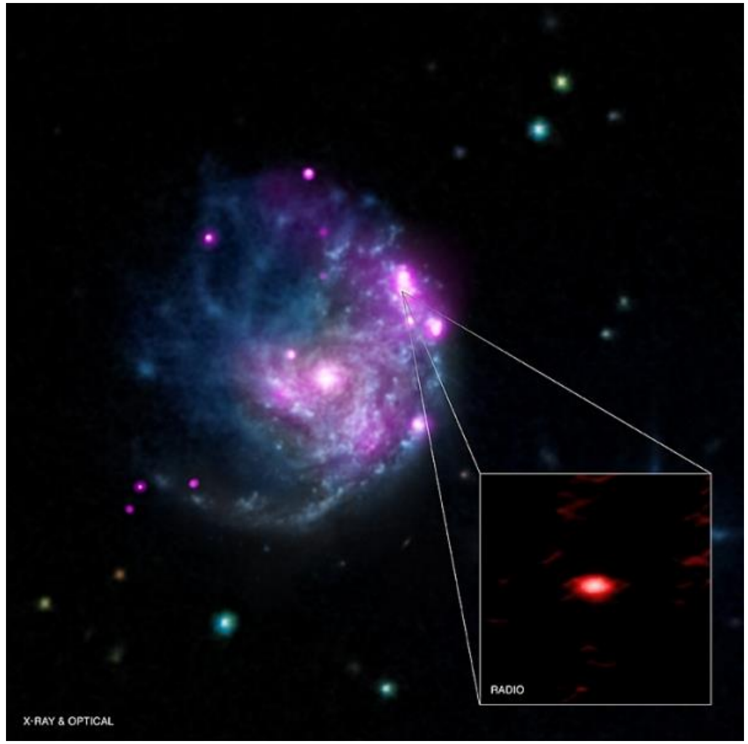
Globular clusters may host intermediate-mass black holes (IMBHs) with masses in the range 100 to 1000 solar masses

IMBH will be the most massive object in the cluster and will readily sink to the center

Binary with a compact-object companion will form. The binary will then harden through three-body interactions

Binary will eventually merge via an intermediate-mass-ratio inspiral (IMRI)

The number of detectable mergers depends on the unknown distribution of IMBH masses and their typical companions. Detect 300 events per year out to z = 1:5 for 100M (redshifted) primaries and 10M secondaries

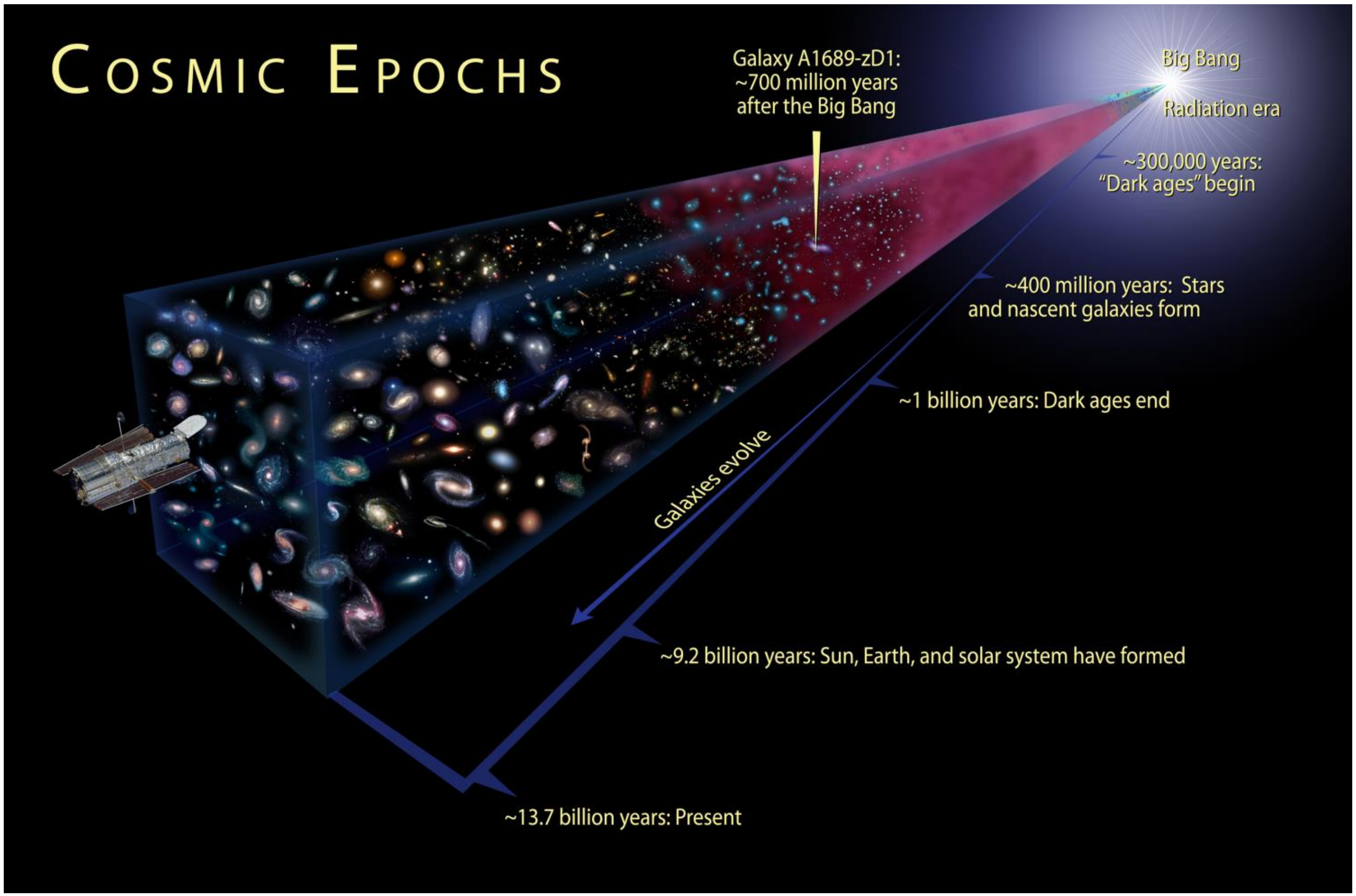


NGC 2276-3c: NASA's Chandra Finds Intriguing Member of Black Hole Family Tree
http://chandra.harvard.edu/photo/2015/ngc2276/

Study events from dark ages with large redshifts

We want sensitivity for high-z events. Einstein Telescope can measure up to $z \approx 20$ and gravitational waves will be redshifted

ET also needs sensitivity at low-frequency. For this we need to go underground to suppress seismic noise



Why does 3G need multiple ITFs?

Observe the entire sky with high pointing precision

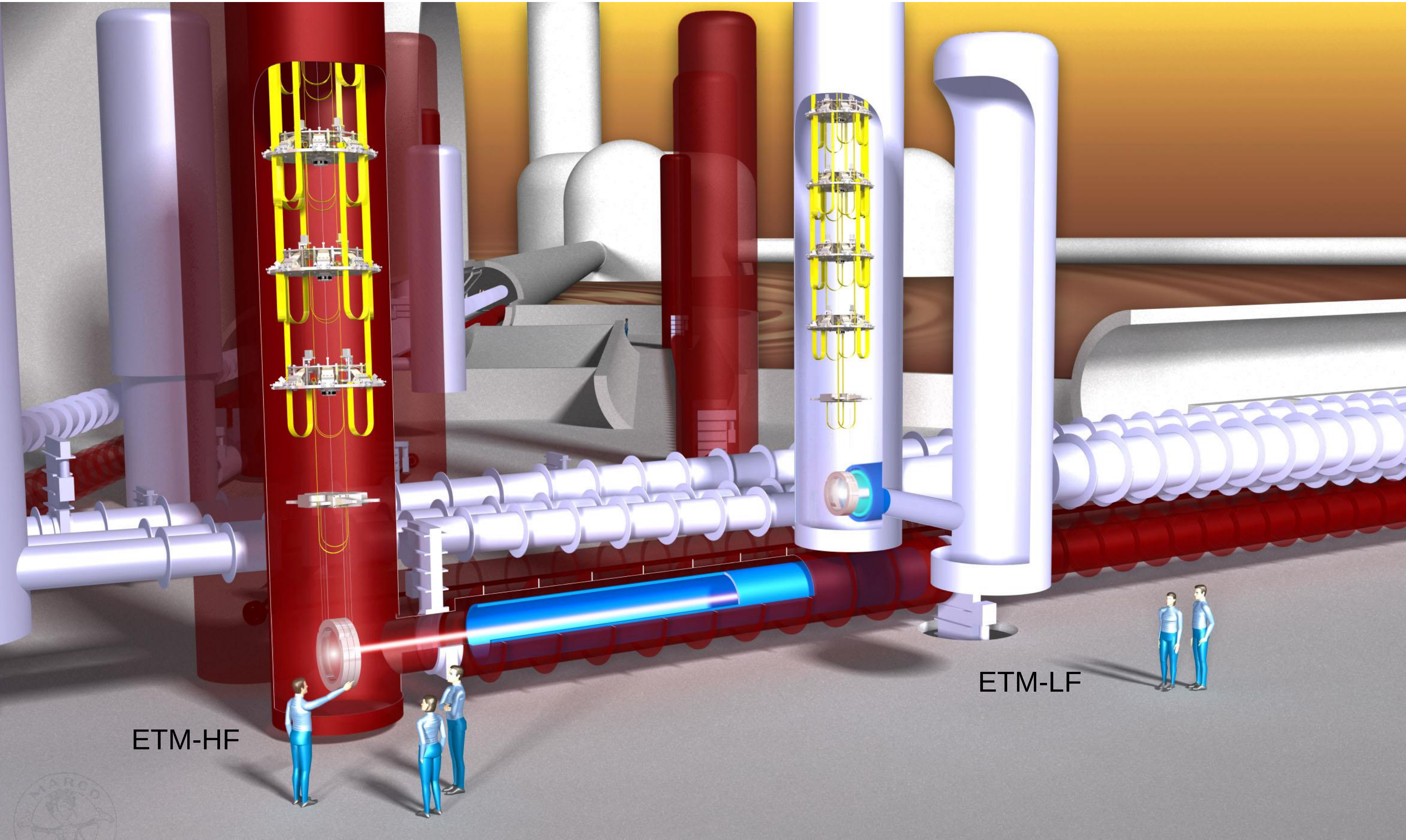
We want to constantly observe the entire sky and this requires multiple 3G observatories

We require a network of 3G detectors spread over the globe

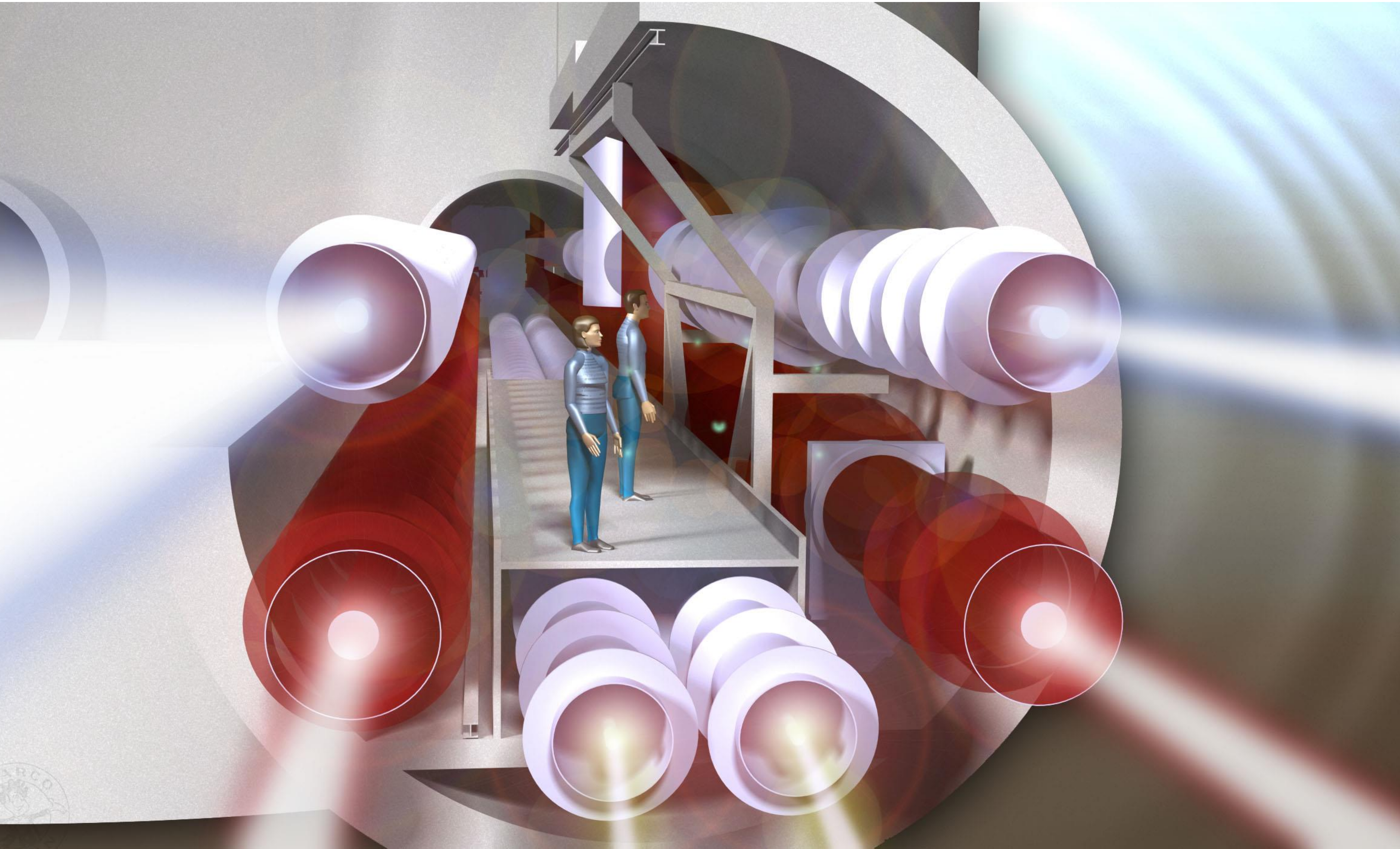
- Correlate high statistics GW data with other (e.g. EM) observations (SKA-II, LSST, Theseus, …)
- One L-shaped sensitive instrument, or one triangular detector? Or do we need a 3G network?

Einstein Telescope: infrastructure considerations

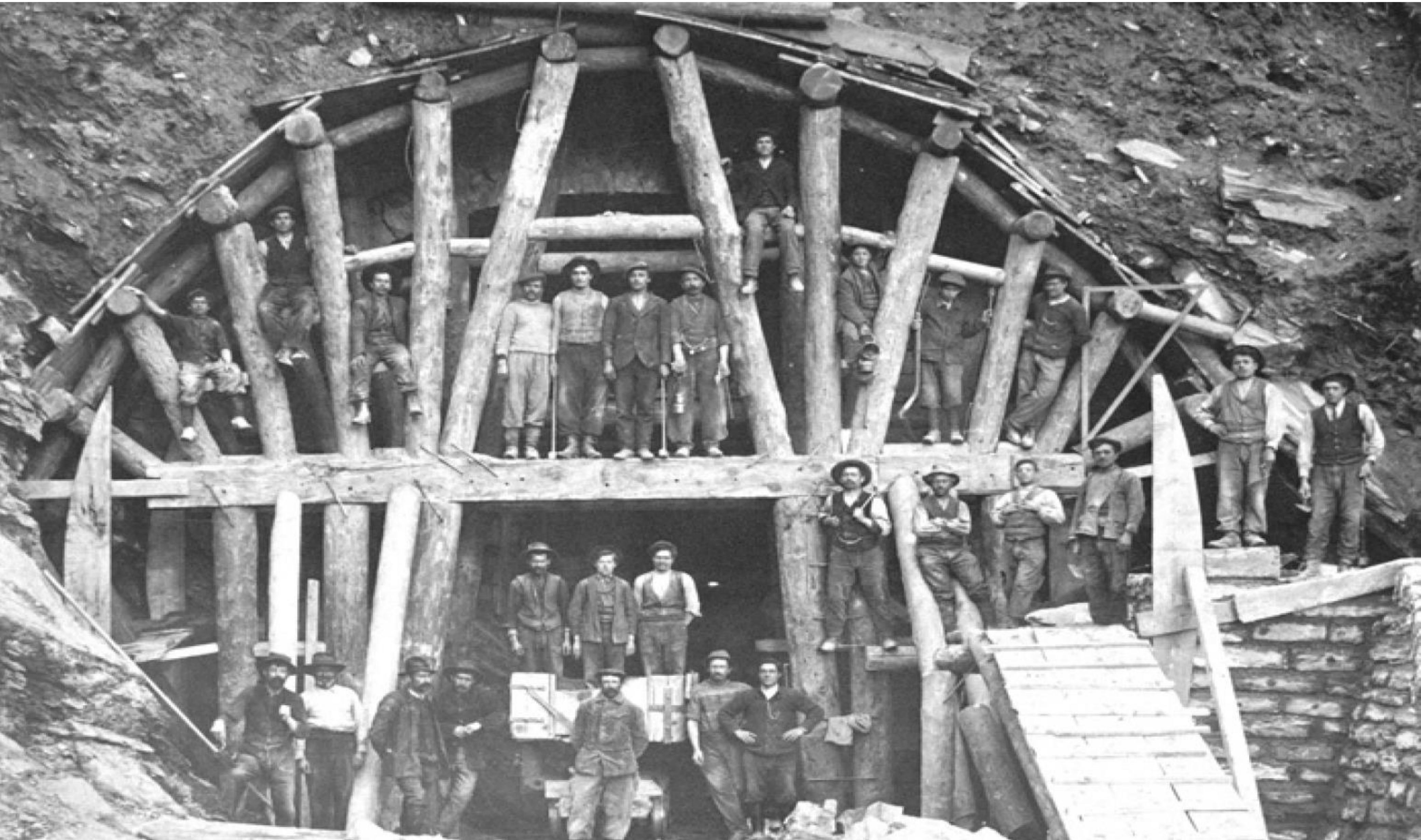
Einstein Telescope: infrastructure considerations



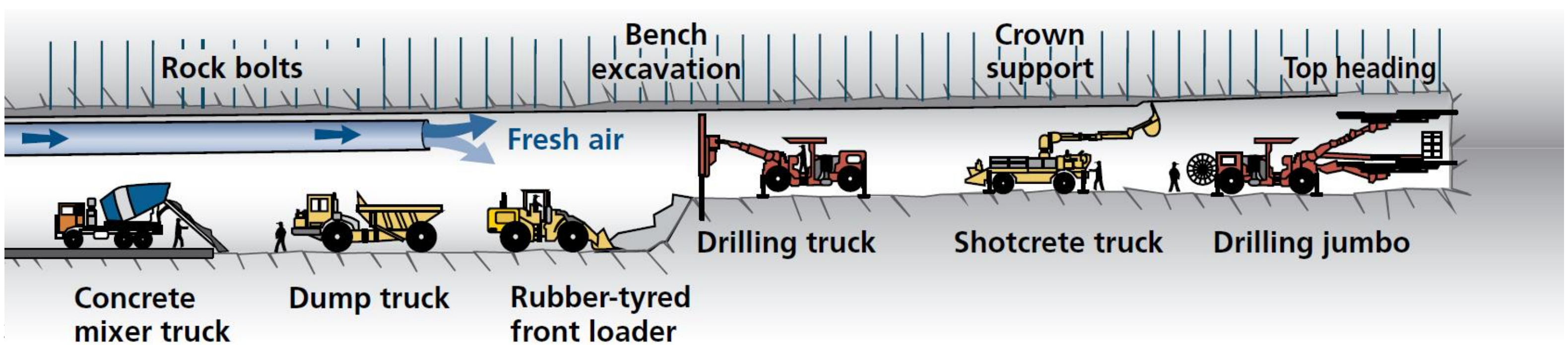
Einstein Telescope: infrastructure considerations



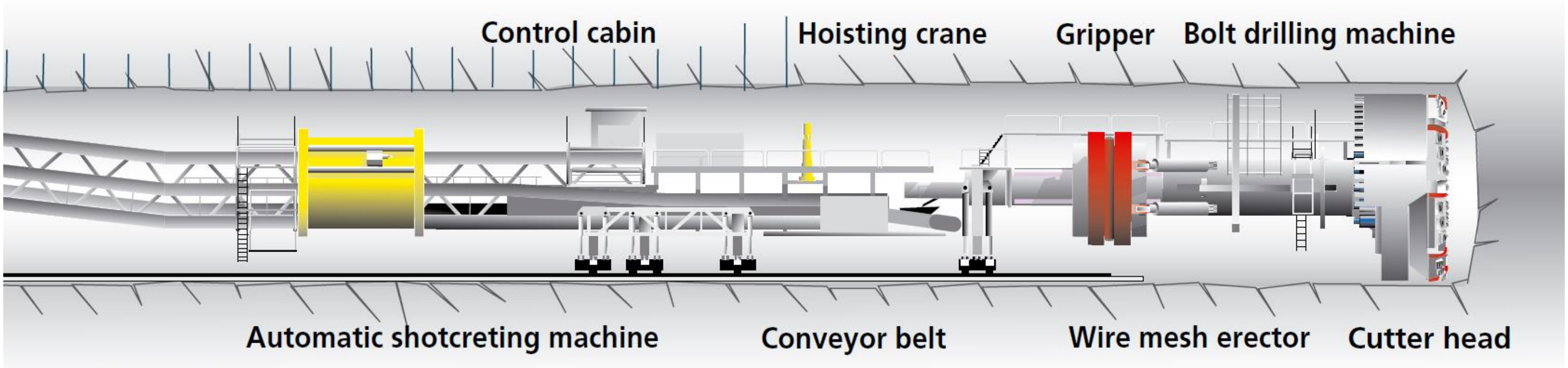
Einstein Telescope: how to construct?



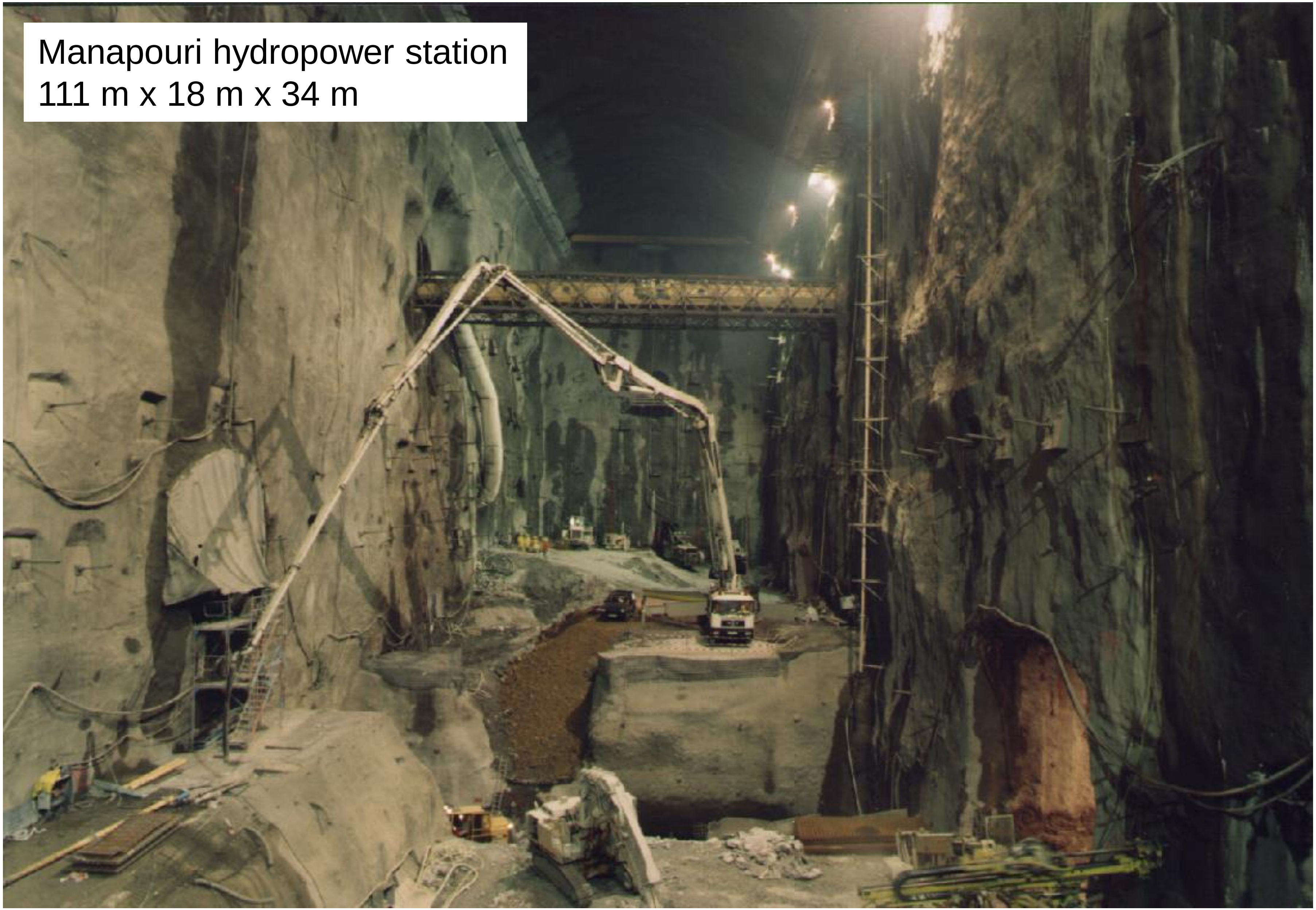
KAGRA: drill and blast



Einstein Telescope: Tunnel boring machines



Large underground caverns



LHC underground caverns and vertical shafts

How to transition from 2G to Einstein Telescope and CE?

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

AdV+ and A+ as the next steps forward in sensitivity

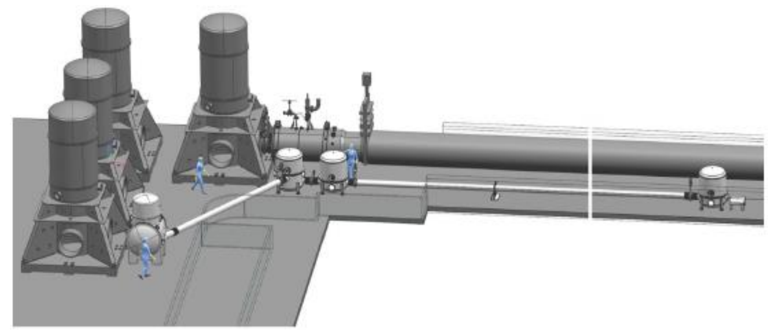
AdV+ is the European plan to maximize Virgo's sensitivity within the constrains of the EGO site. It will be carried out in parallel with the LIGO A+ upgrade

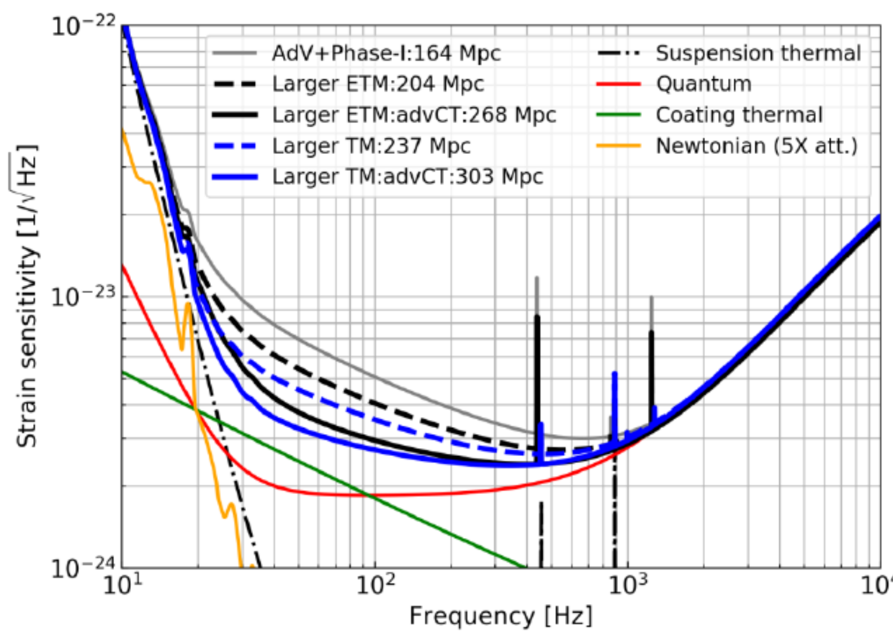
AdV+ features

- 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

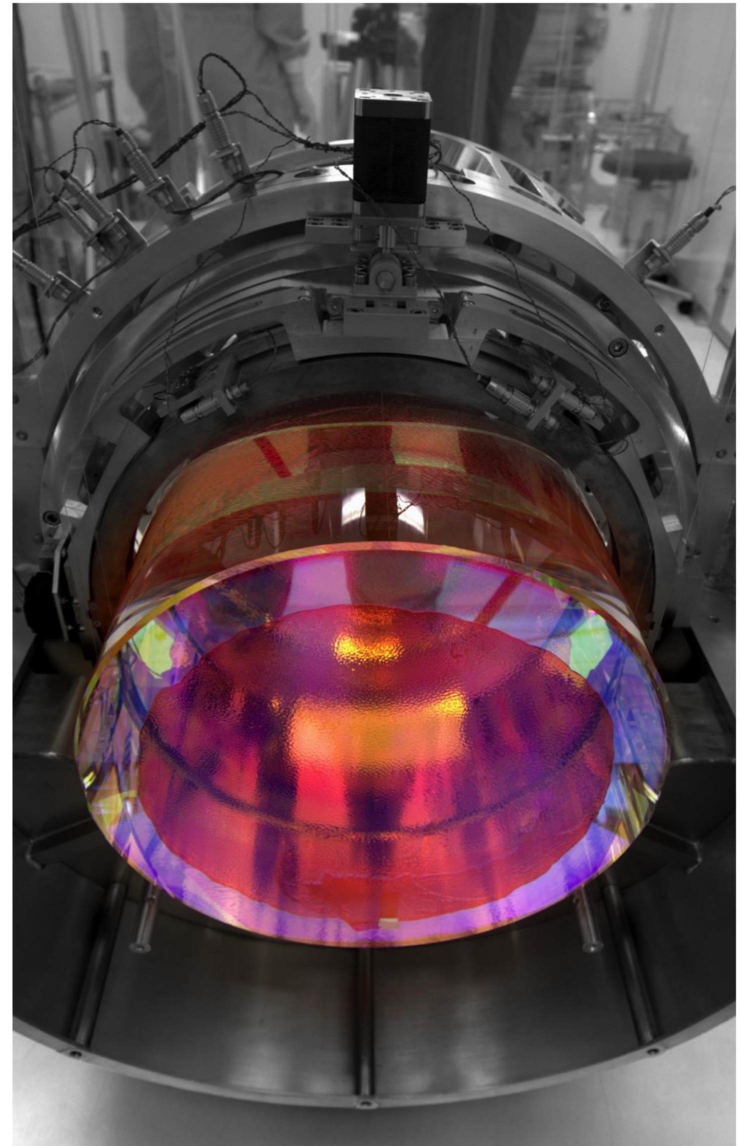
- Tuned signal recycling and HPL: 120 Mpc
- Frequency dependent squeezing: 150 Mpc
- Newtonian noise cancellation: 160 Mpc
- Larger mirrors (105 kg): 200-230 Mpc
- Improved coatings: 260-300 Mpc





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

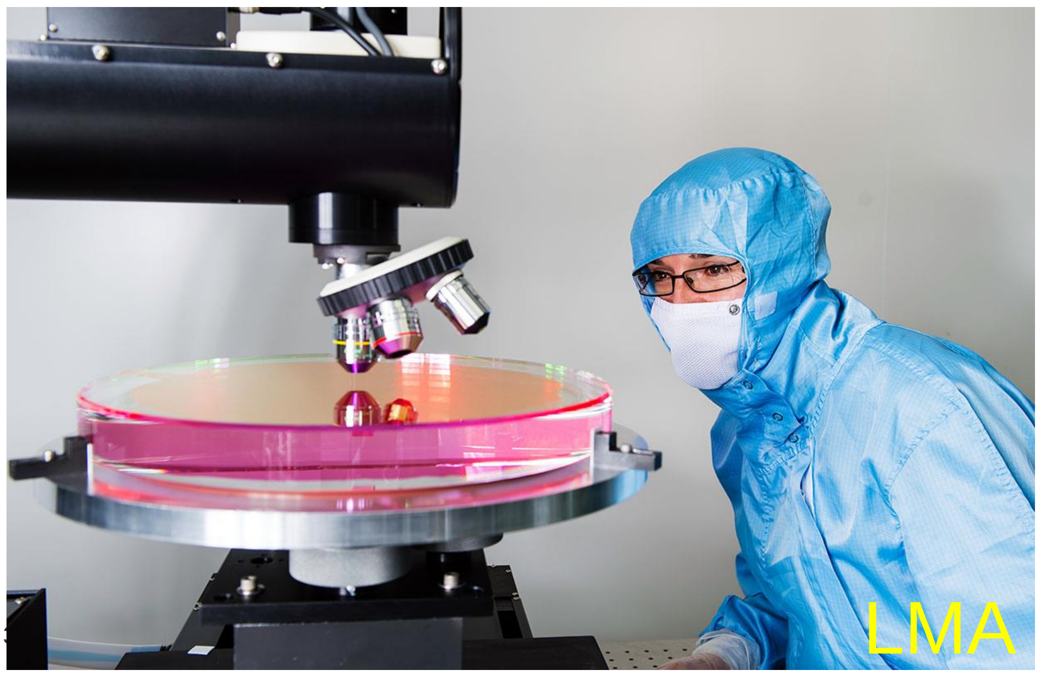


Features

- 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

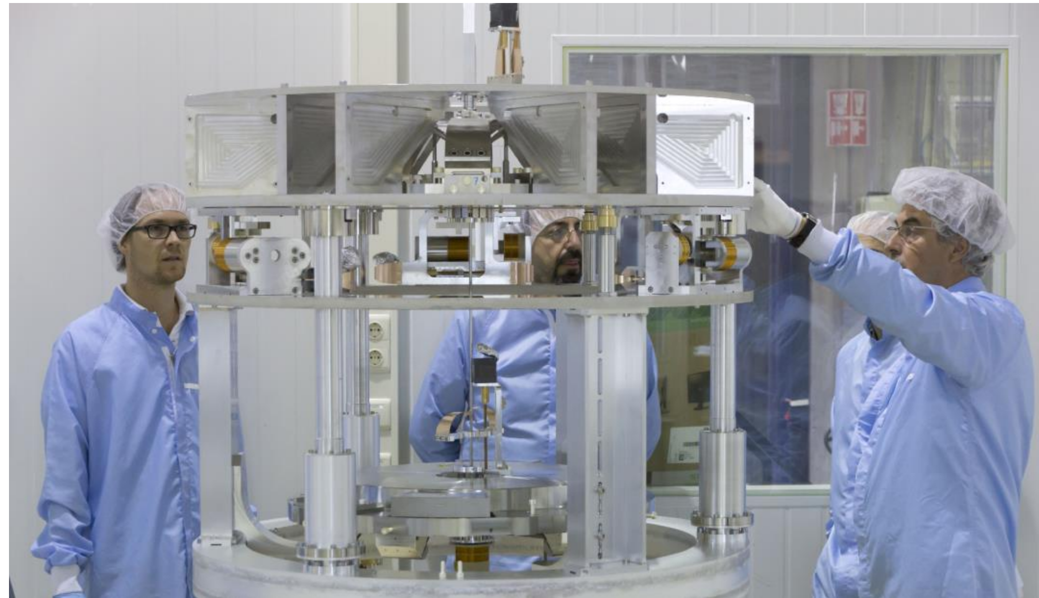
Expand LMA capabilities for next generation

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



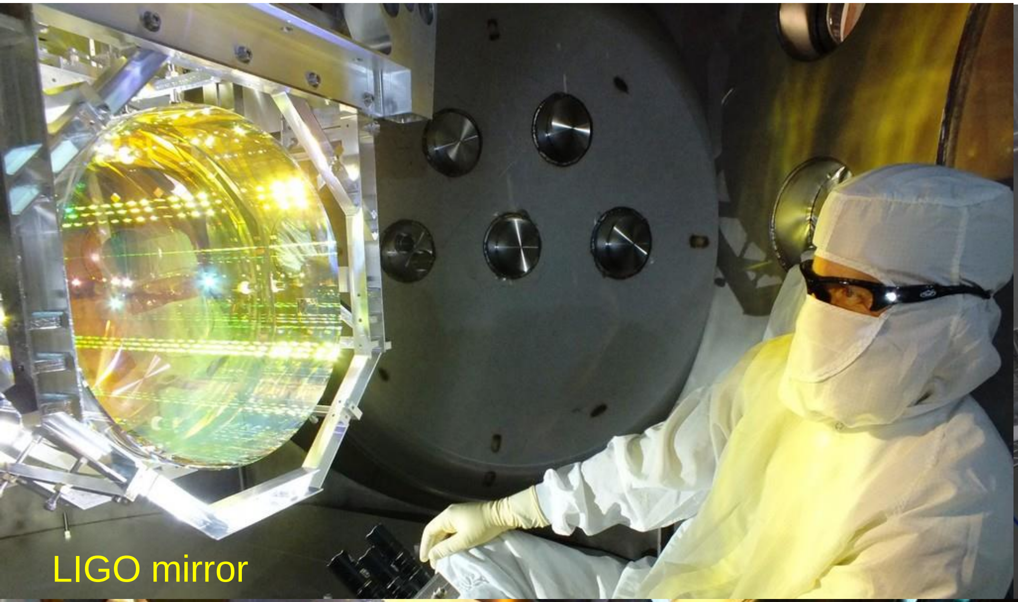
Vibration isolation systems

Optical systems for linear alignment, vibration isolation, PDs, QPDs, and phase camera’s, etc.



Advanced optical systems

Mirrors as test masses, beamsplitters, coating materials, suspended mode cleaners, …



LIGO mirror

Virgo beamsplitter

Virgo suspended injection bench

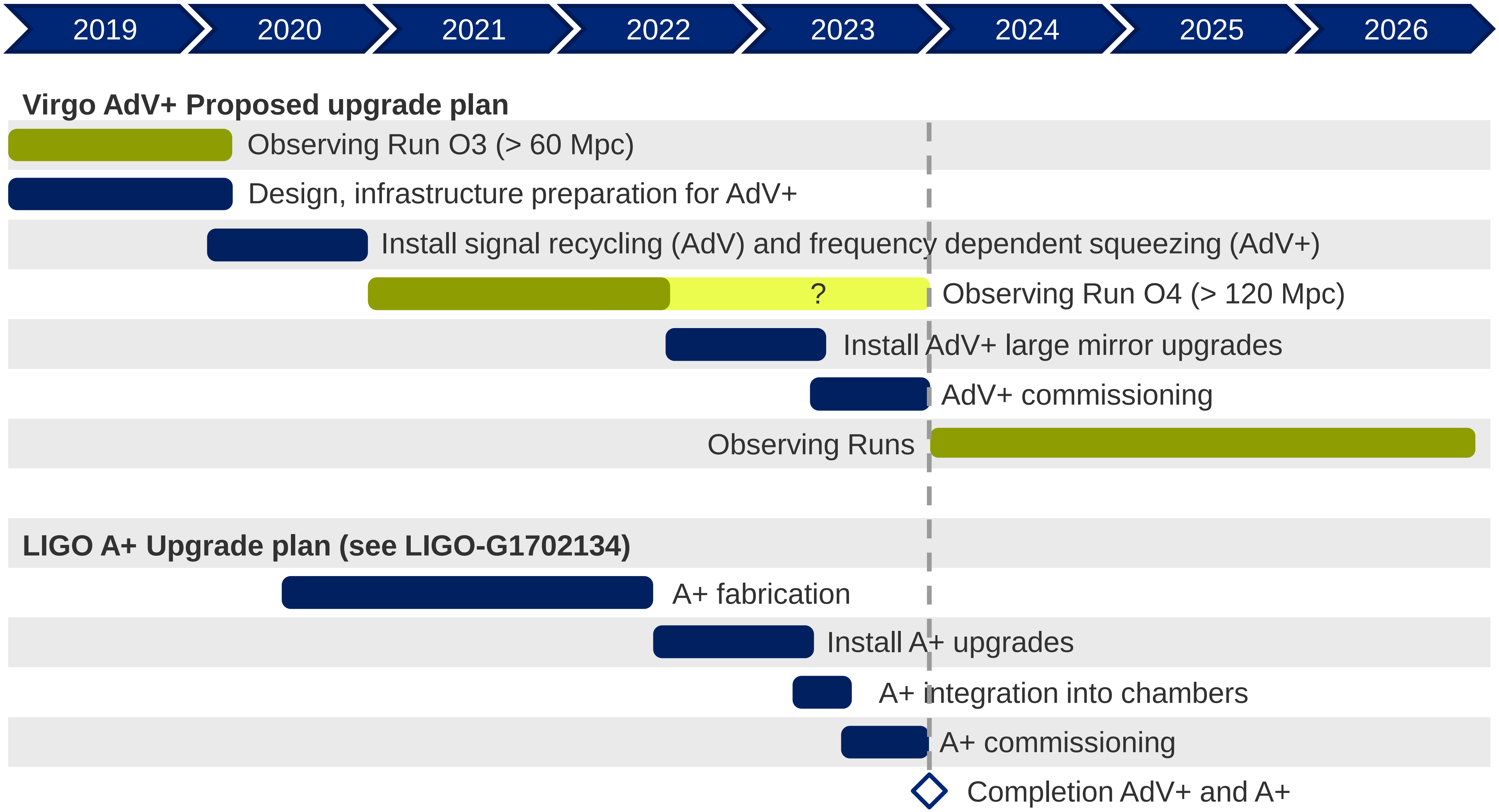
Lasers, quantum optics. Also controls: ML and deep learning

Ultra-stable laser systems. Not only 1 um, but also 1.55 and 2 um under investigation

Virgo squeezer from AEI

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

Bright future for gravitational wave research

Many exciting opportunities to enter the field, both in instrumentation upgrades such as AdV+ and in data analysis. The next LIGO Virgo observation run (O3) will start in early 2019

Gravitational wave research

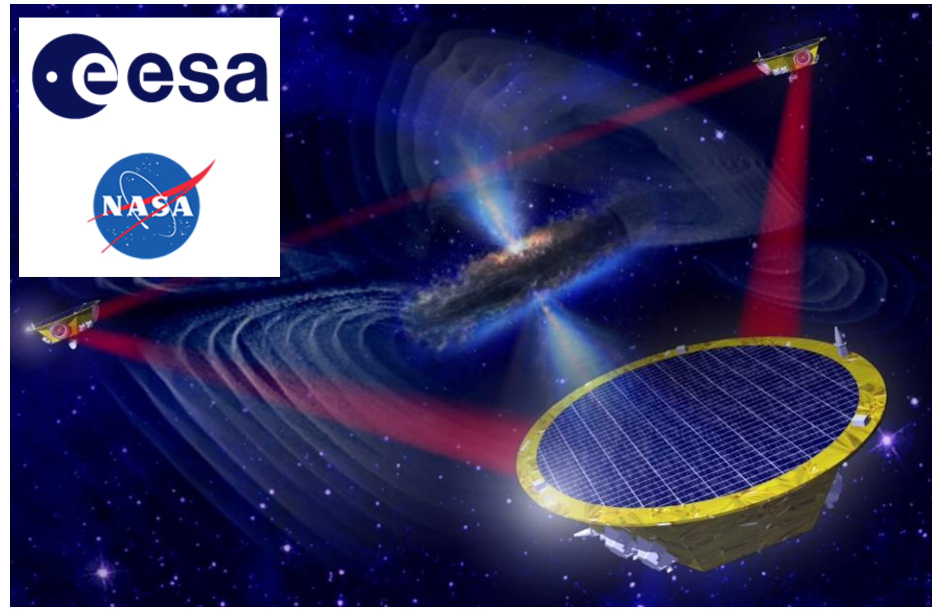
- LIGO and Virgo operational
- LIGO-India and KAGRA under construction
- ESA and NASA select LISA
- Pulsar Timing Arrays, such as EPTA and SKA
- Cosmic Microwave Background radiation

Einstein Telescope

- Design financed by EU in FP7
- APPEC gives GW a prominent place in the new Roadmap and especially the realization of ET

Next steps

- Organize the community and prepare a credible plan for EU funding agencies
- ESFRI Roadmap (2019)



Thank you for your attention!