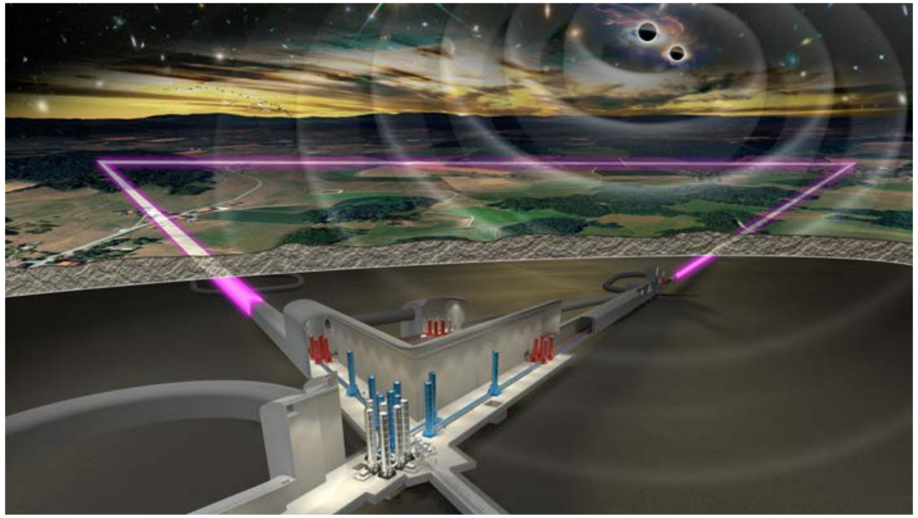


Einstein Telescope

and ETpathfinder

Stefan Hild, University of Maastricht & Nikhef

Courtesy to the LIGO, LSC, Virgo and Einstein Telescope teams

www.einsteintelescope.nl / www.etpathfinder.eu

Maastricht University Nikhef

DISCLAIMER

Everything around ET is currently very dynamic and many things are in flow:

- new and important developments,
- new research proposals granted,
- new organizational bodies formed

…. and this happens on many different levels, Europe-wide (ISB, OSB, SCB, IEB project directorate, project office), but also in various countries on national levels.

This talk cannot do justice to all of those!

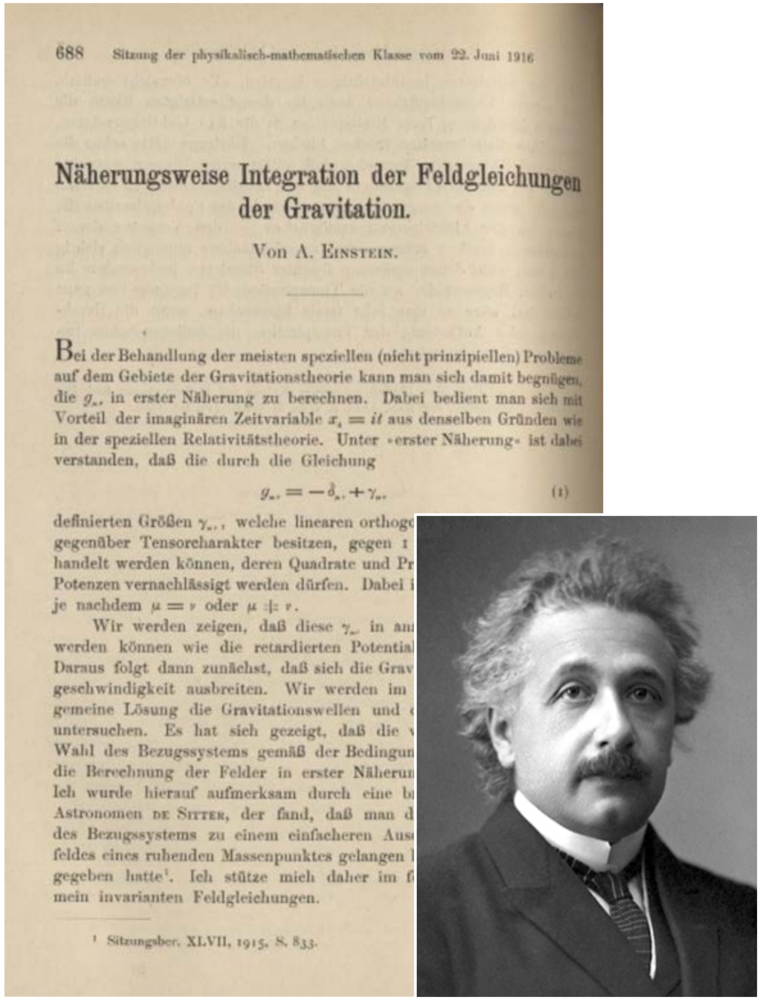
While I aimed to give a representative snapshot, in the time I have I can only present here a subjective selection.

For more details and updates please check: www.et-gw.eu, www.einsteintelescope.de, APPEC news etc

Outline

- What have we learned Gravitational Waves so far?
- How to measure Gravitational Waves
- Overview of Einstein Telescope
- ETpathfinder

We have come a long way ....



688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

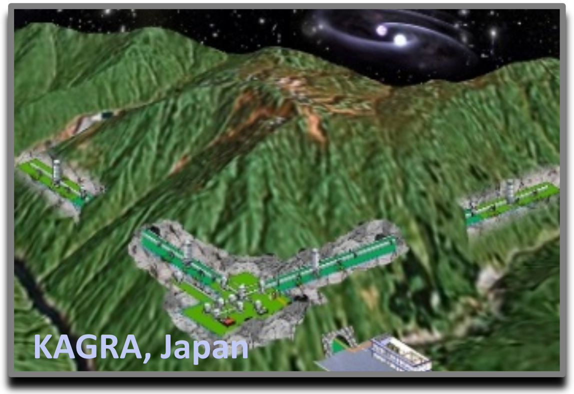
Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthog
gegenüber Tensorcharakter besitzen, gegen 1
handelt werden können, deren Quadrate und Pr
Potenzen vernachlässigt werden dürfen. Dabei i
je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in an
werden können wie die retardierten Potential
Daraus folgt dann zunächst, daß sich die Grav
geschwindigkeit ausbreiten. Wir werden im
gemeine Lösung die Gravitationswellen und
untersuchen. Es hat sich gezeigt, daß die
Wahl des Bezugssystems gemäß der Bedingun
die Berechnung der Felder in erster Näherun
Ich wurde hierauf aufmerksam durch eine b
Astronomen de Sitter, der fand, daß man d
des Bezugssystems zu einem einfacheren Aus
feldes eines ruhenden Massenpunktes gelangen
gegeben hatte[1]. Ich stütze mich daher im f
mein invarianten Feldgleichungen.

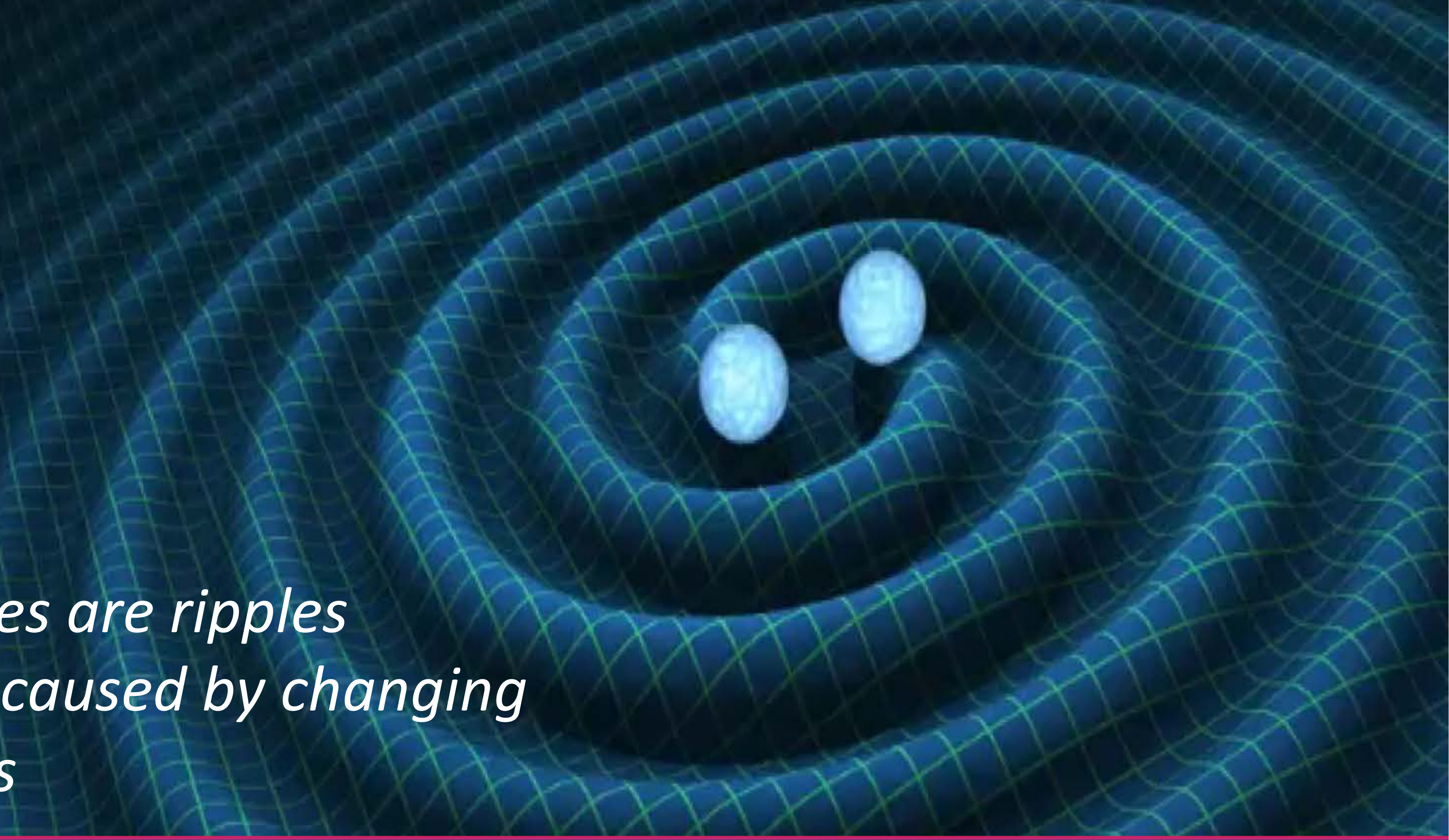
[1] Sitzungsber. XLVII, 1915, S. 833.



6th Anniversry of the discovery of GW

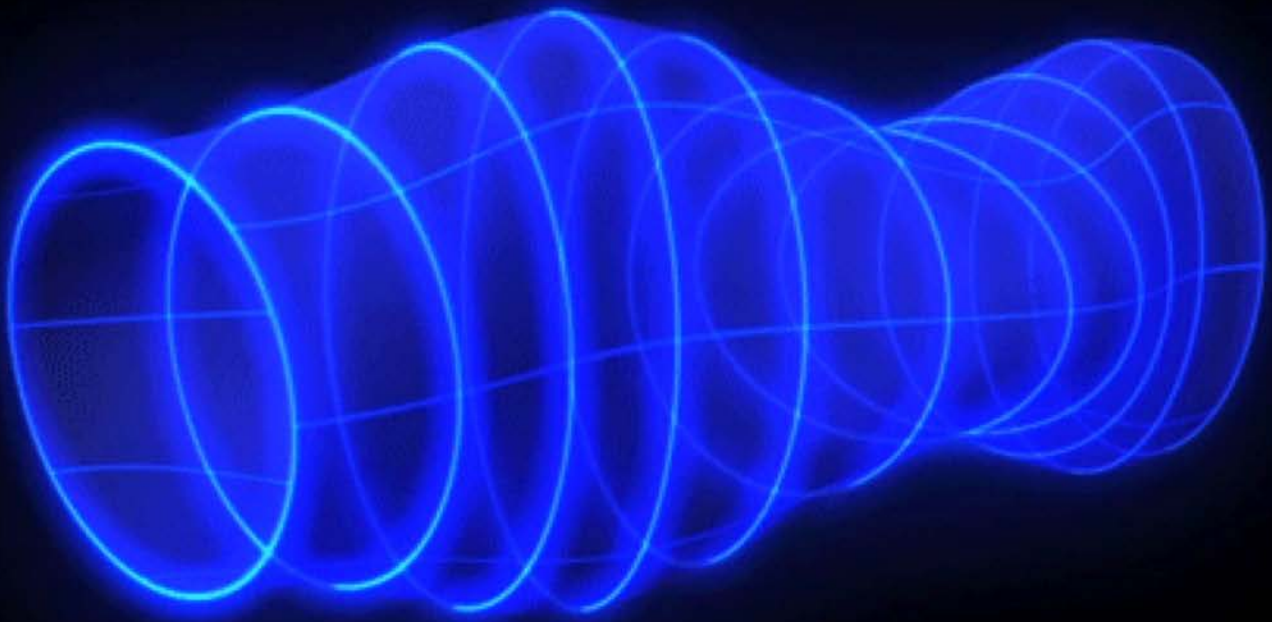
Many, many prizes including **2017 Nobel prize** + Science magazine awarded us with "Scientific Breakthrough of the year" two years in a row (2016+2017)

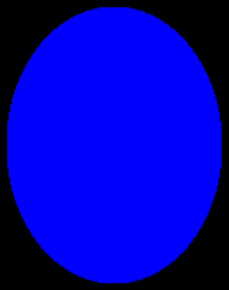
As a consequence of Theory of General Relativity Einstein predicted Gravitational Waves in 1916.



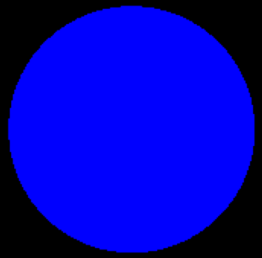
Gravitational waves are ripples in space and time caused by changing gravitational fields

[S.Hild]

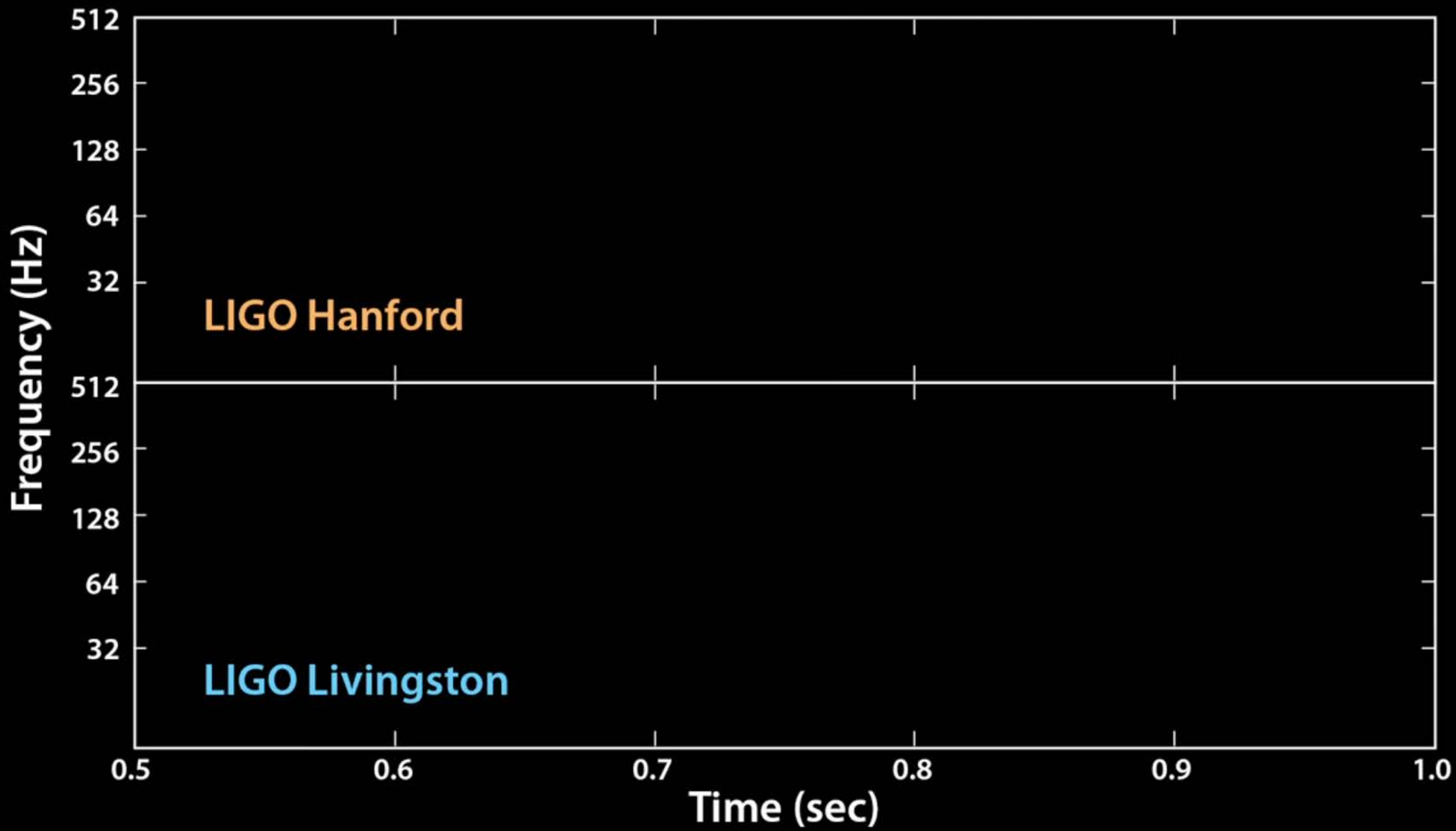




“Plus” polarization

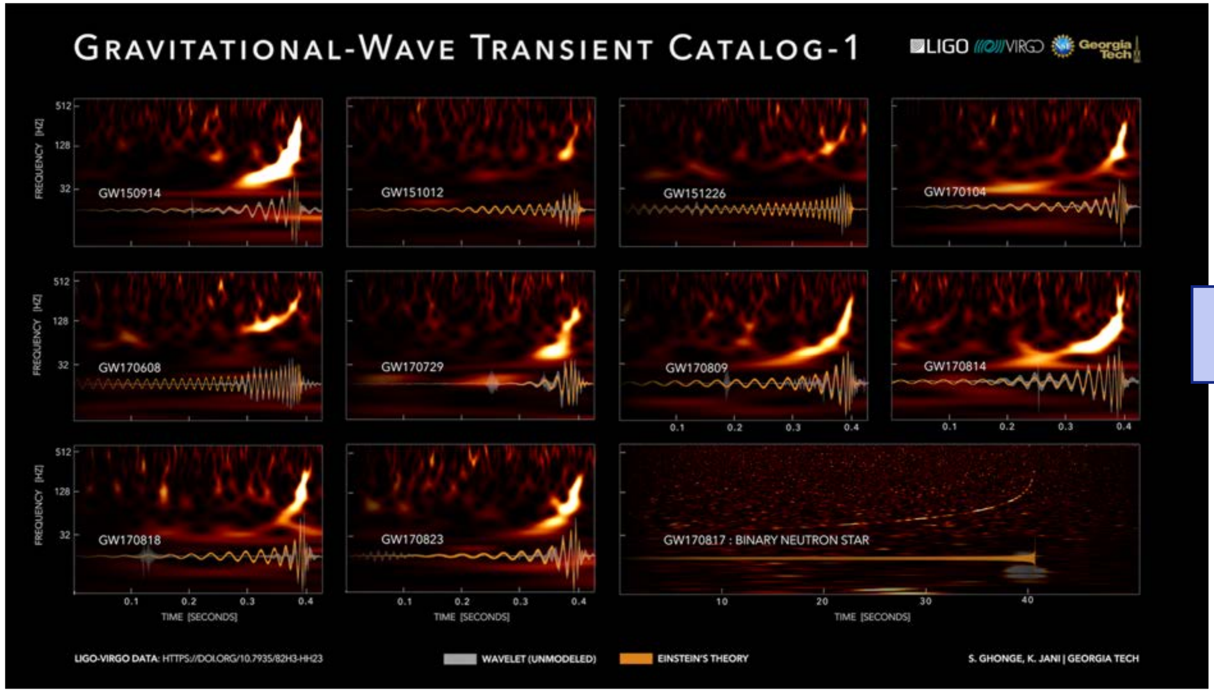


“Cross” polarization

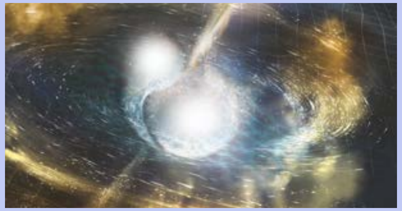

512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

From a few seconds of signals …

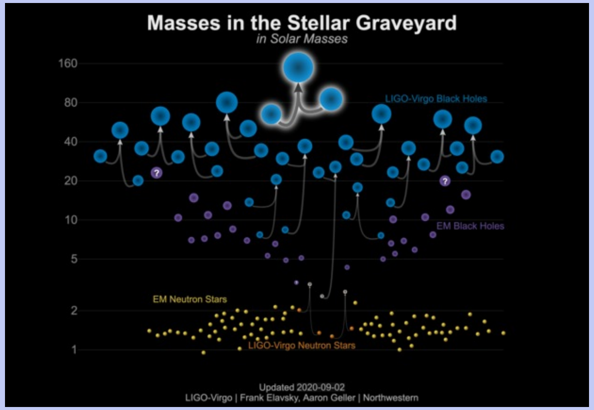
… detected with LIGO and Virgo …



… we learned a lot!

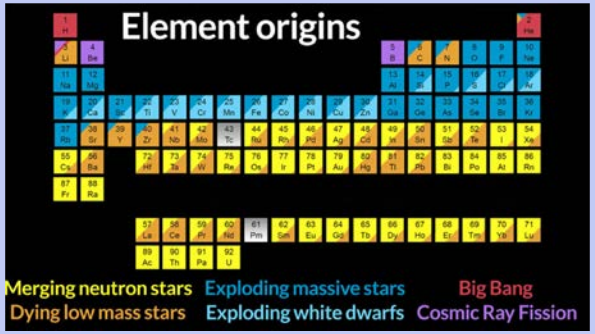


Confirmed BNS as origin for some GRBs

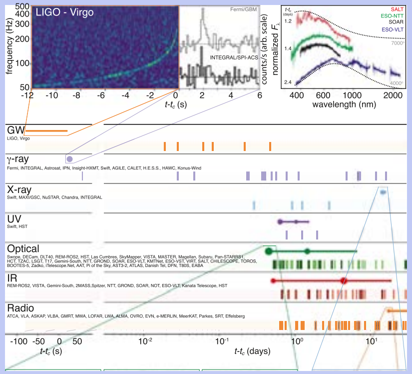


Found new class of heavy stellar mass BBH

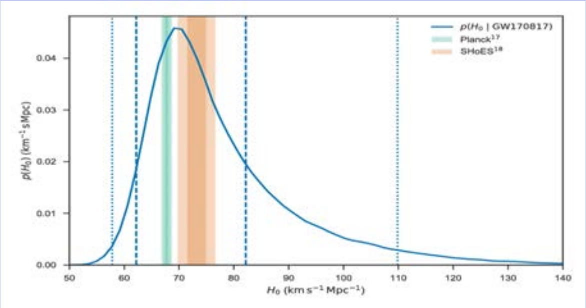
Ruled out some proposed EOS of neutron stars



Confirmed Kilonova and R-process

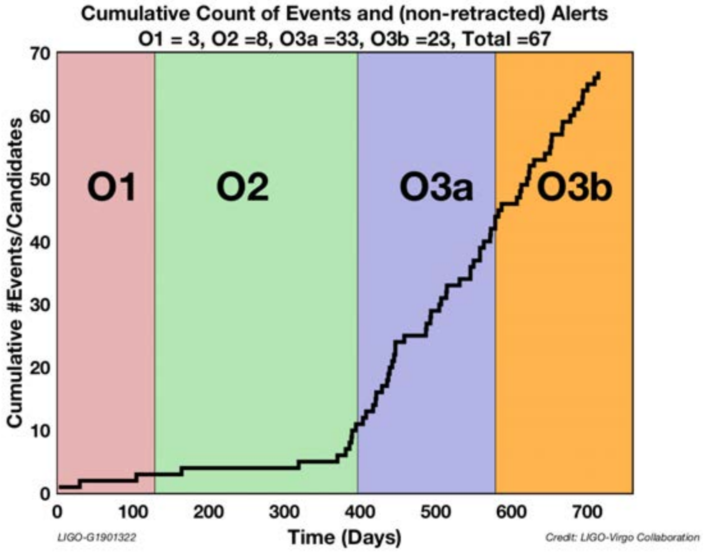


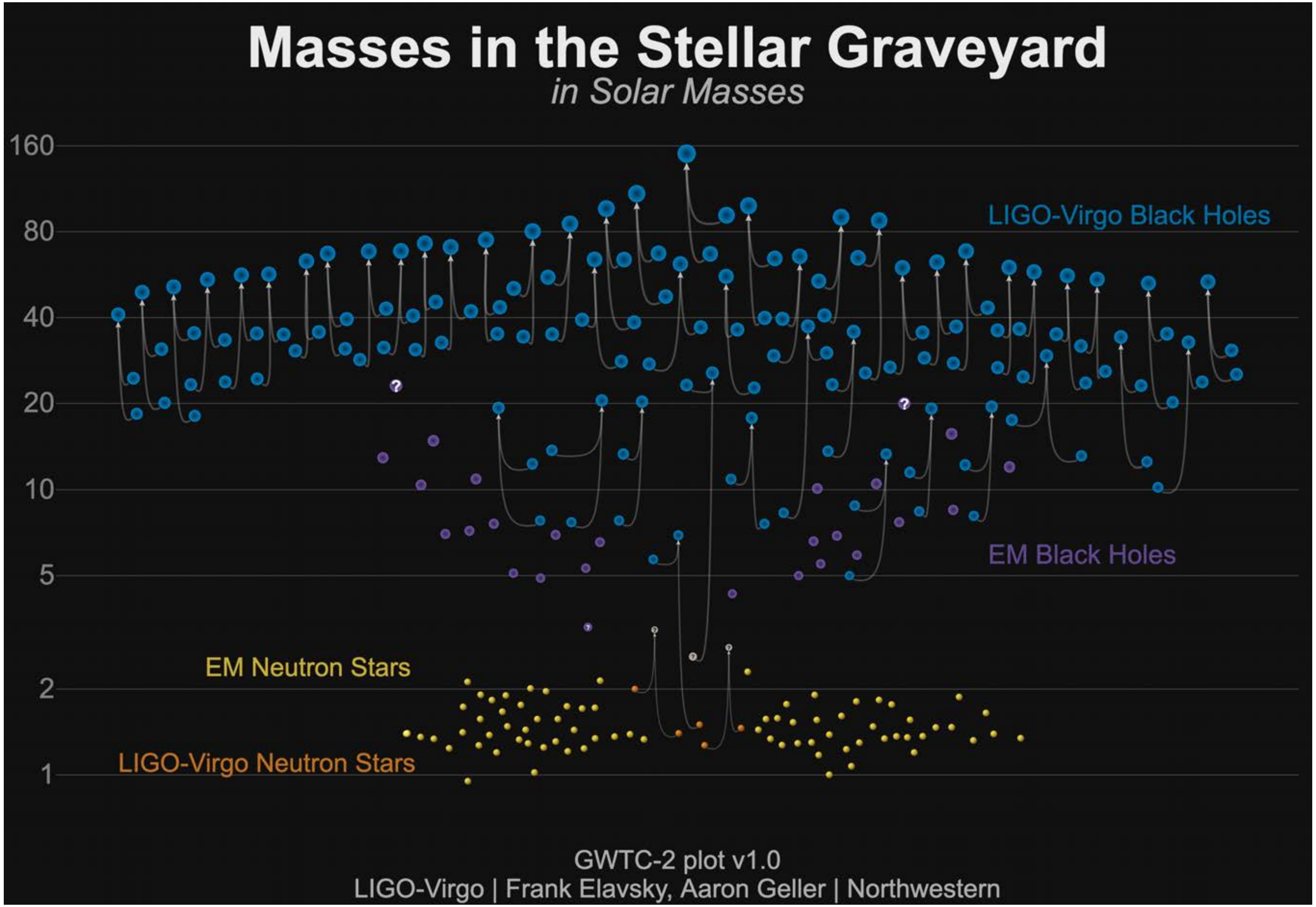
Start of GW multi-messenger astronomy



Cosmology independent of distance ladder

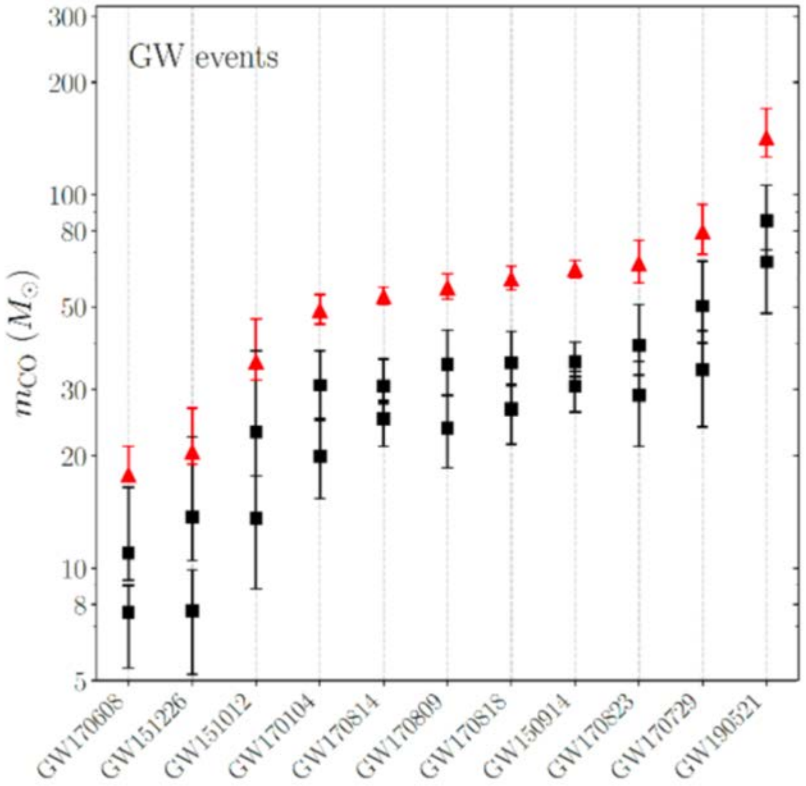
Routinely observing compact binary systems !

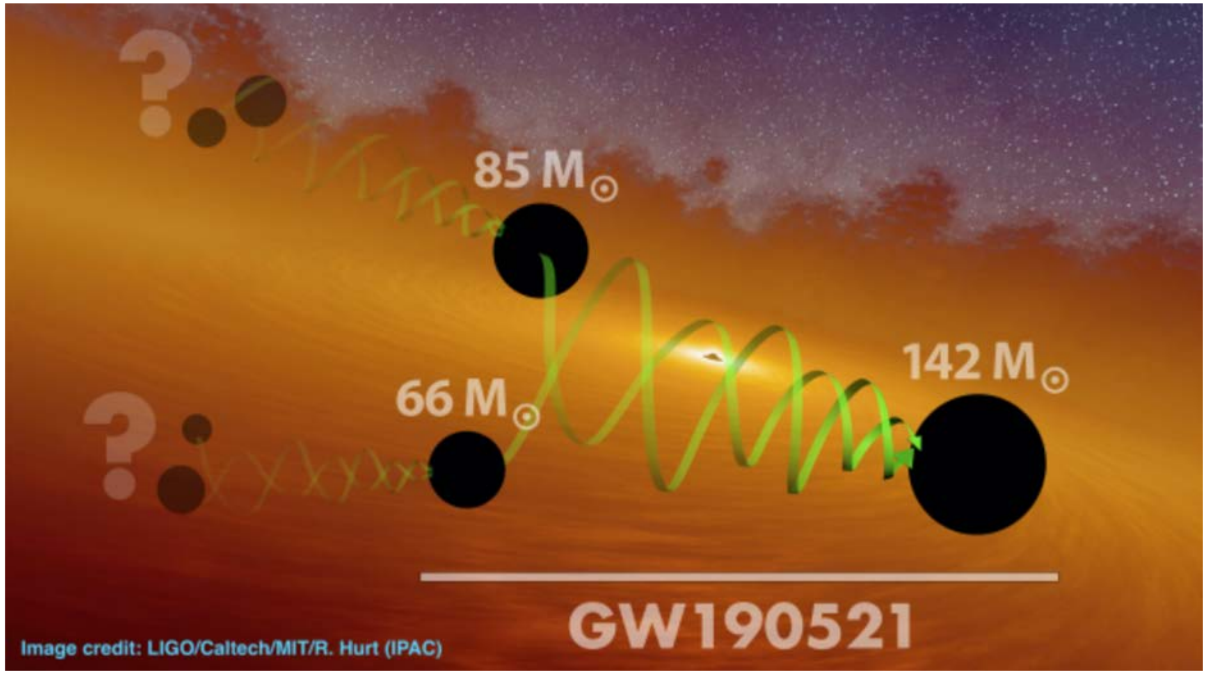




About one signal detected per week!

Discovery of an intermediate mass blach hole (IMBH)



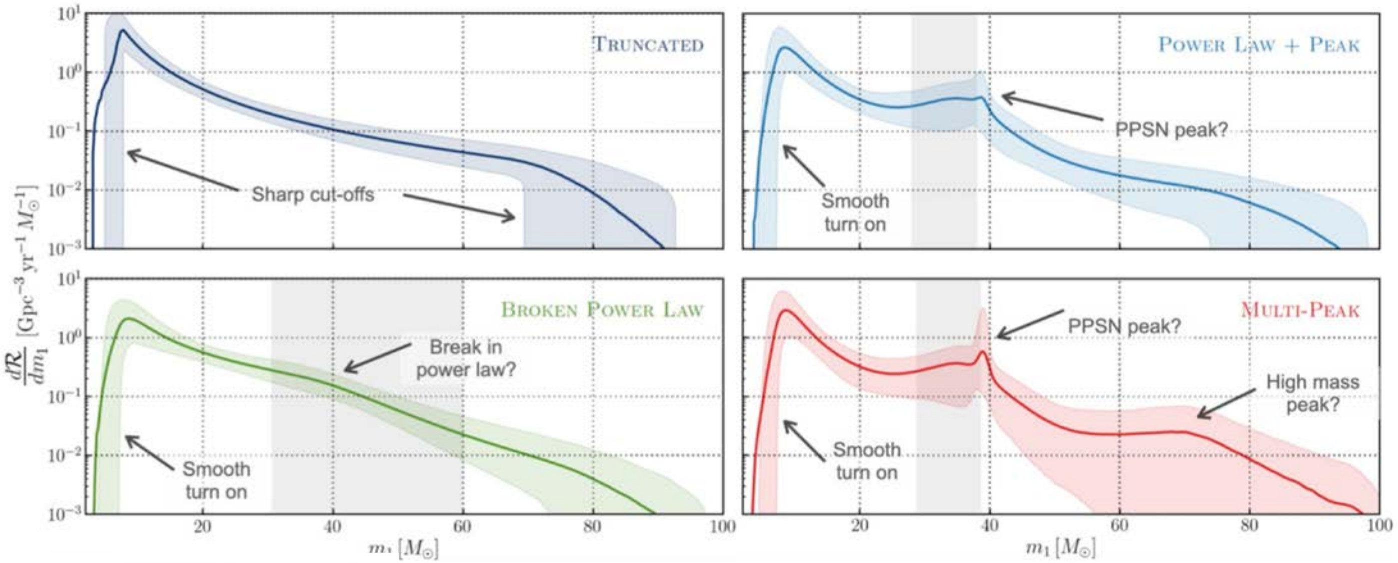


Featured in Physics | Editors' Suggestion | Open Access

GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_\odot$

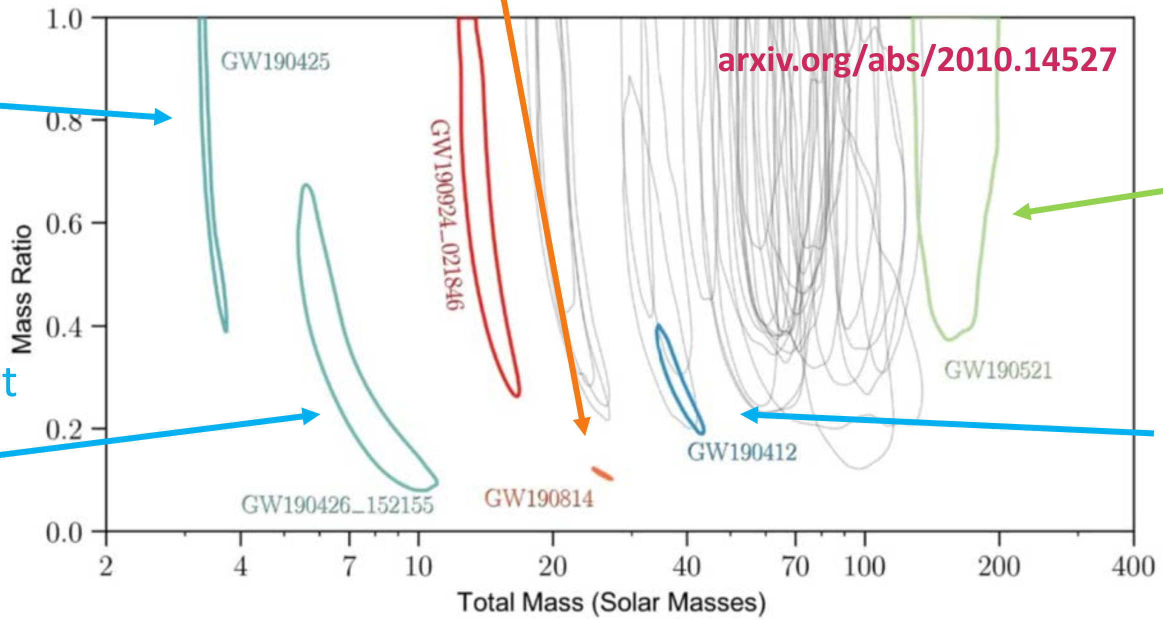
R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. **125**, 101102 – Published 2 September 2020

GWTC-2 and Black Hole Populations



arxiv.org/abs/2010.14533

a highly asymmetric system of ambiguous nature, corresponding to the merger of a 23 and a 2.6 solar mass compact object, the lightest black hole or heaviest neutron star observed in a compact binary



arxiv.org/abs/2010.14527

Another BNS

a low-mass event consistent with either an NSBH or BBH

IMBH: a BBH with total mass over 150 times the mass of the Sun

the first BBH with definitively asymmetric component masses

Many observations/discoveries

Select Language

LSC LIGO Scientific Collaboration

News | Detections | Our science explained | Multimedia | Educational resources | For researchers | About the LSC | LIGO Lab | Observing Plans

DETECTIONS

Information about gravitational-wave detections made by the LIGO-Virgo-KAGRA Collaborations to date.

Jump to a separate page for a specific event (listed in reverse-chronological order of announcement date), or see the General Detection Resources section below for further information on LIGO detections.

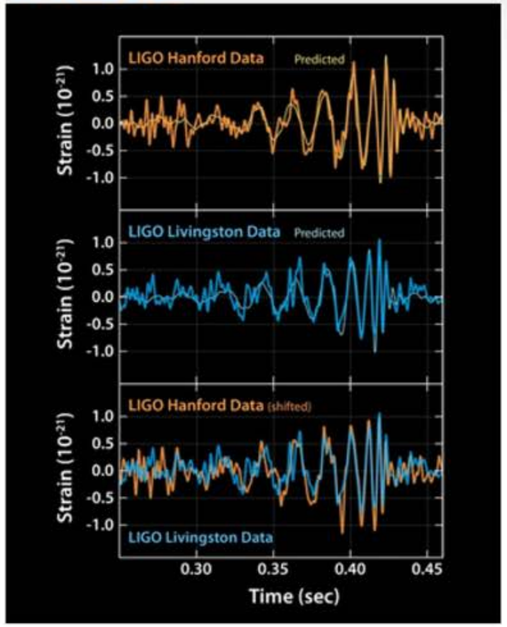
- GW200105 & GW200115 (First confirmed neutron star-black hole mergers.)
- O3a Catalog (GWTC-2: Summary of detections during the first half of the third observing run.)
- GW190521
- GW190814
- GW190412
- GW190425
- O1/O2 Catalog (Summary of detections during first and second observing runs.)
- GW170608
- GW170817 (First binary neutron star detection; first electromagnetic counterpart.)
- GW170814
- GW170104
- GW151226
- GW150914 (First detection.)

GENERAL DETECTION RESOURCES

DOCUMENTS, WEBSITES, & MULTIMEDIA

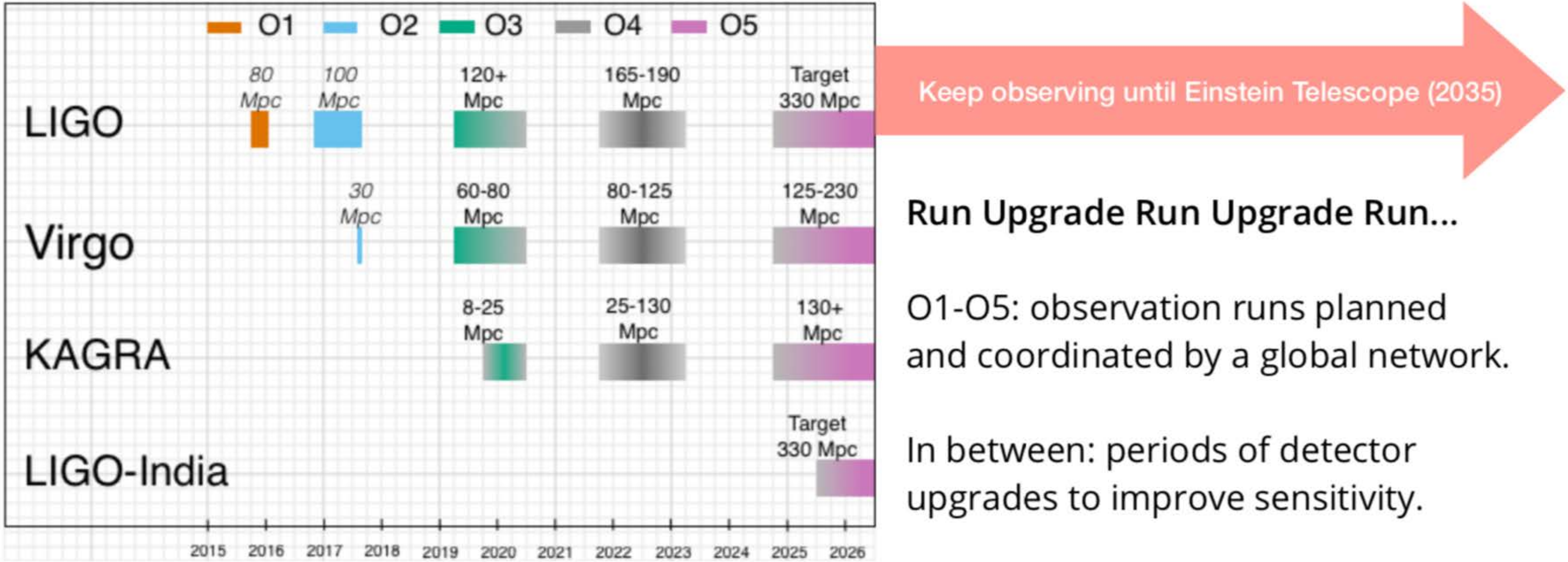
- Full list of LSC Publications. (See Runs O1 and higher for papers following the first detection.)
- Science Summaries
- Gravitational Wave Open Science Center (GWOSC): Download LIGO/Virgo data or explore tutorials on gravitational-wave data analysis. See also their data release page to download LIGO/Virgo data.

AT A GLANCE



GW150914 signal observed by the twin LIGO observatories at Livingston, Louisiana, and Hanford, Washington. The signals came from two merging black holes, each about 30 times the mass of our sun, lying 1.3 billion light-years away. The top two plots show data received at Livingston and Hanford, along with the predicted shapes for the waveform. These predicted waveforms show what two merging black holes should look like according to the equations of Albert Einstein's general theory of relativity, along with the instrument's ever-present noise. Time is plotted on the X-axis and strain on the Y-axis.

Timeline



Run Upgrade Run Upgrade Run...

O1-O5: observation runs planned and coordinated by a global network.

In between: periods of detector upgrades to improve sensitivity.

Outline

- What have we learned Gravitational Waves so far?
- How to measure Gravitational Waves
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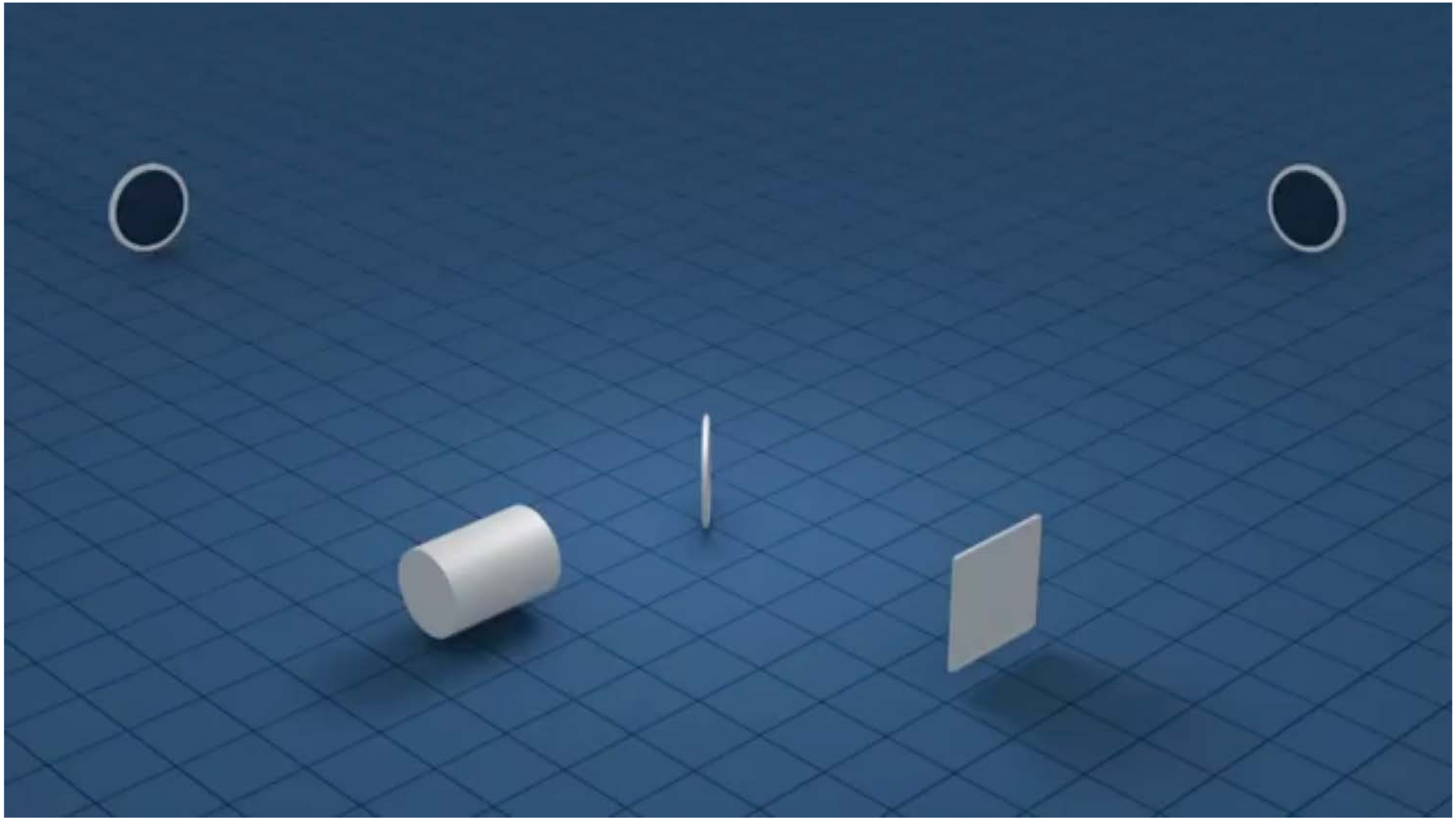
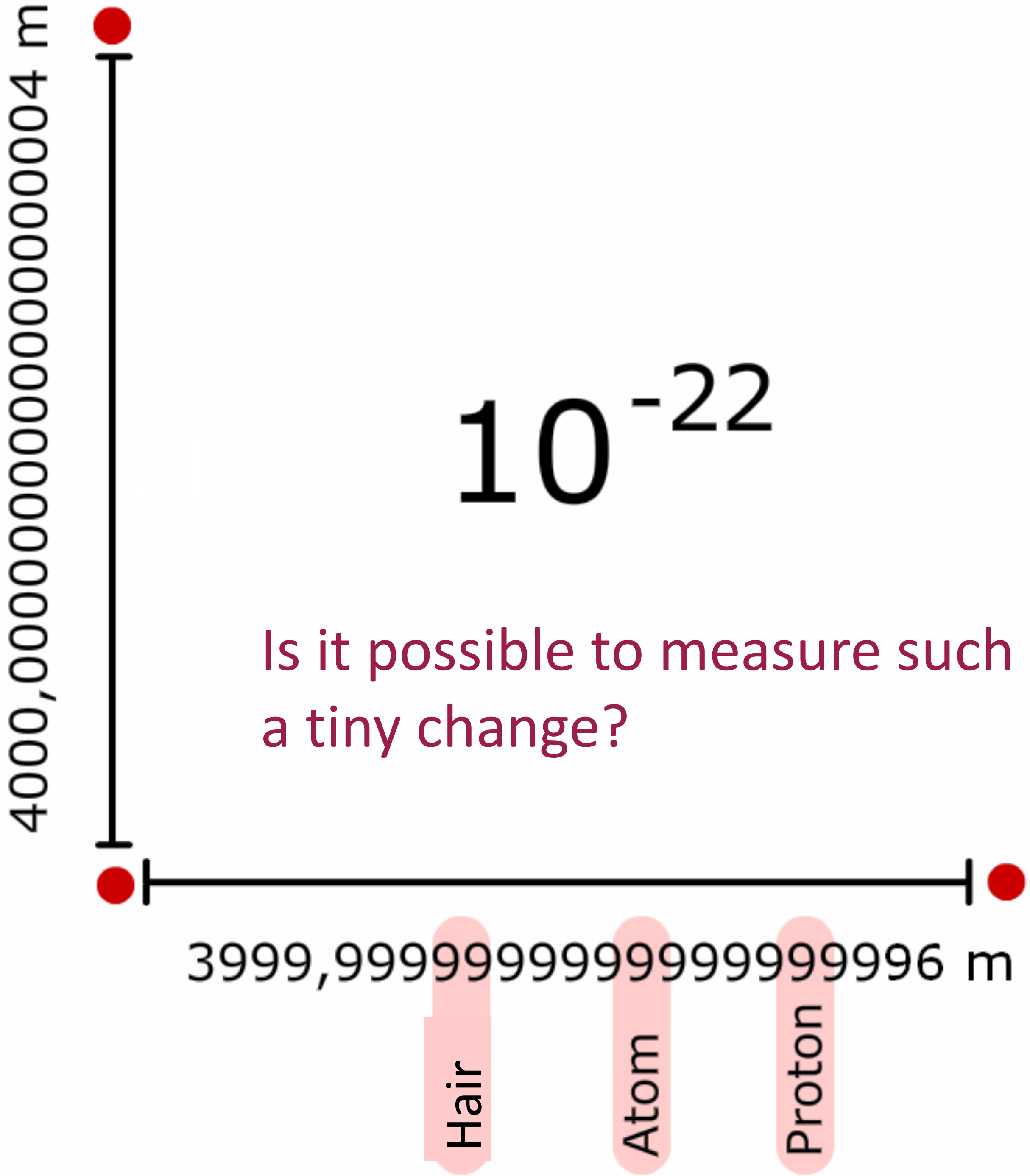
Need high-precision laser-interferometry



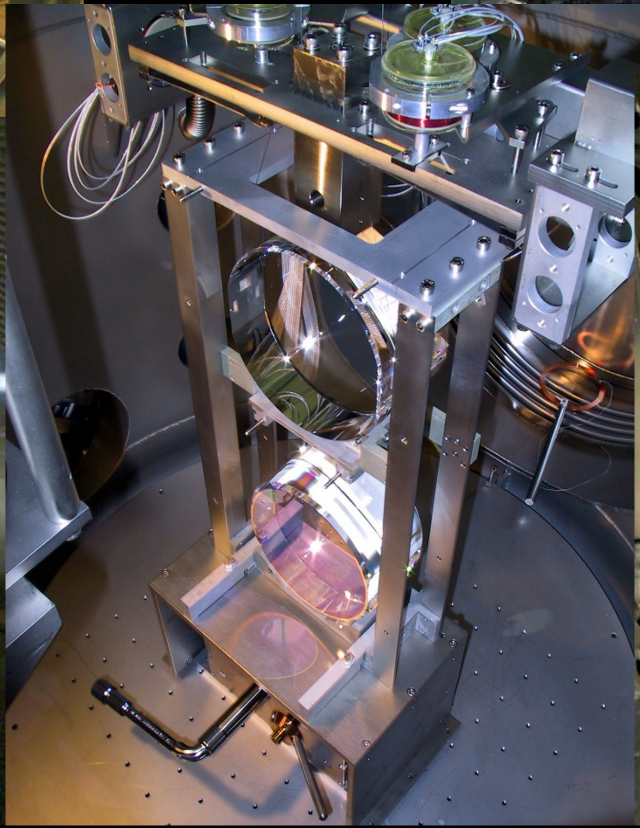
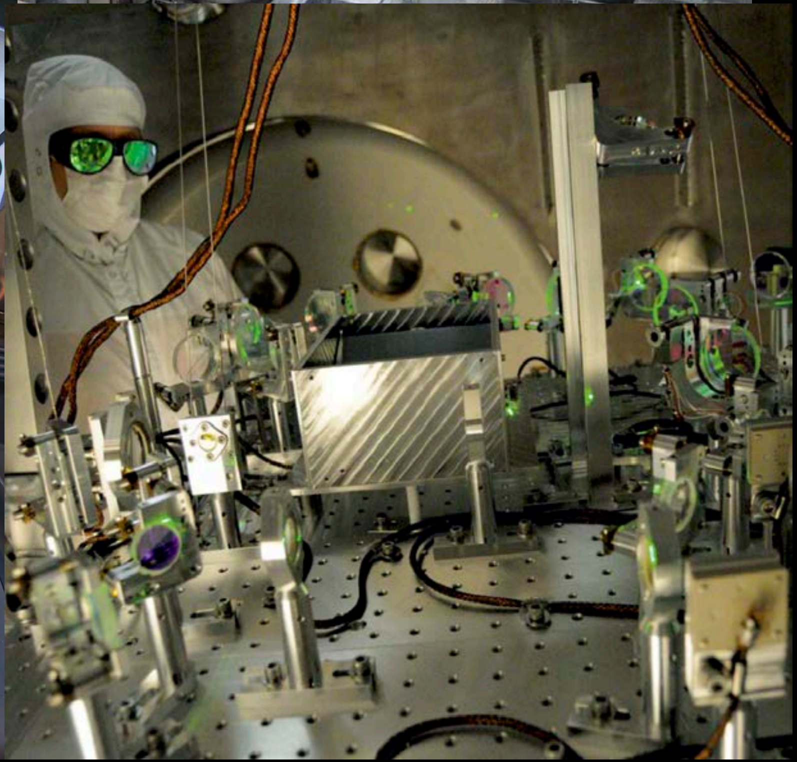


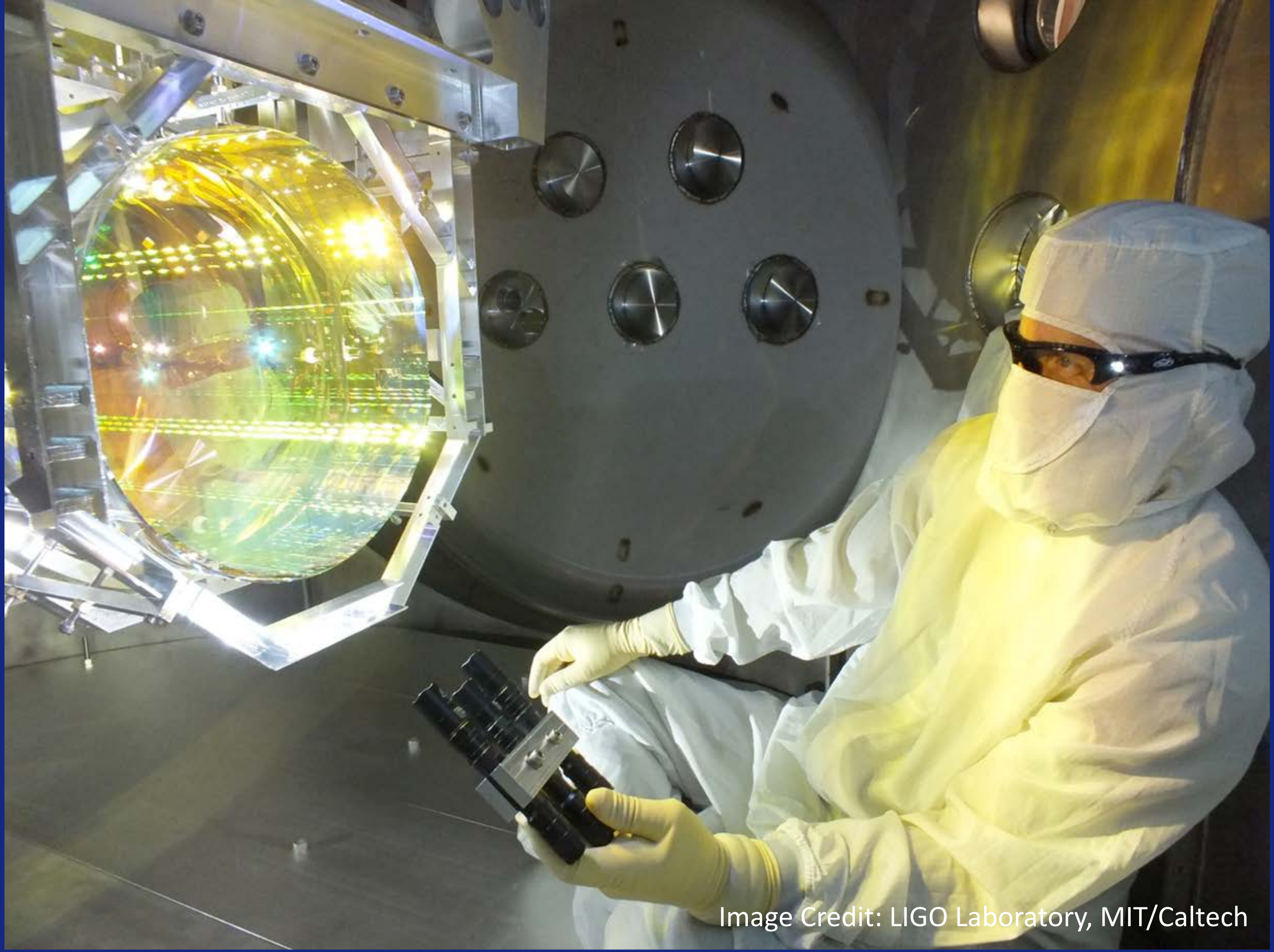
10^{-22}

Is it possible to measure such a tiny change?

Virgo is a 3km long Michelson



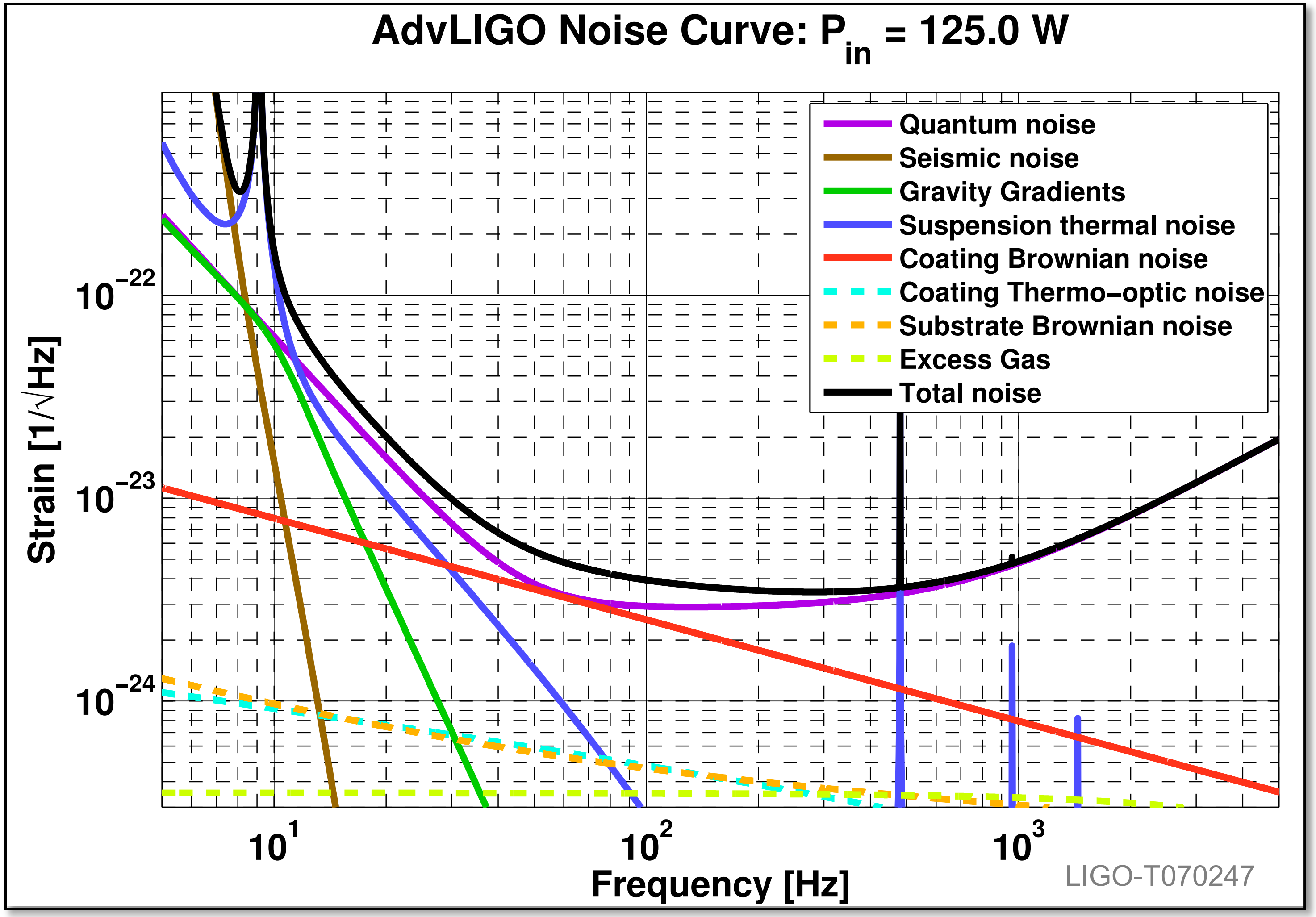


- Ultra-stable laser (1064nm, Linewidth <1Hz)
- High power optics: ~100kW CW
- Optical resonantors (km length, high finesse)
- **Mirrors polished to sub nm flatness and microroughness**
- **Special low Brownian noise coatings**
- **Low absorption (<0.5ppm per coating; <0.25ppm/cm in optics)**
- **Controlling positions of mirrors to pm accuracy**
- Modecleaning and mode healing using optical cavities

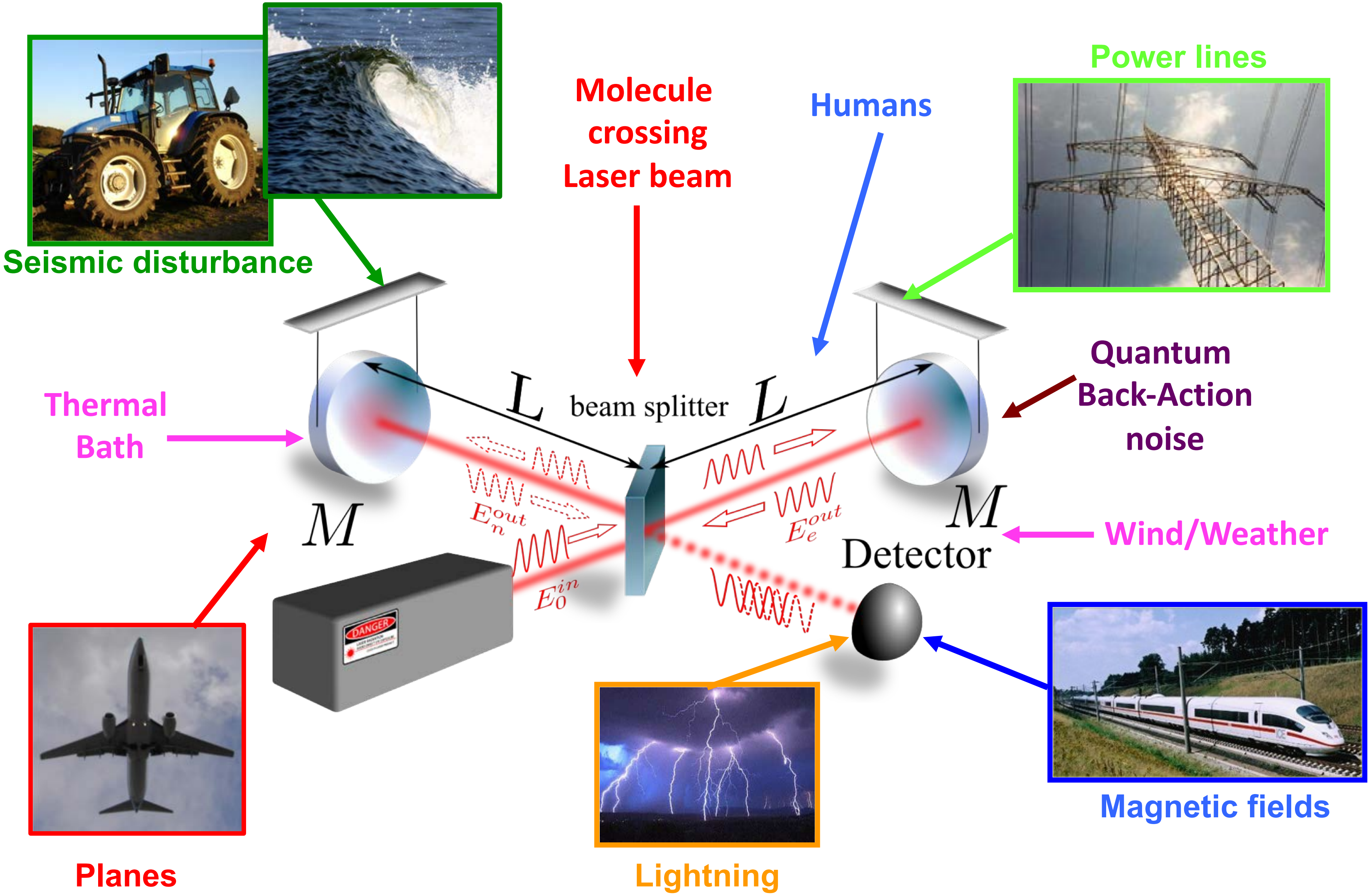
Pushing the boundaries on all fronts!

Noise Sources limiting the Advanced Detectors

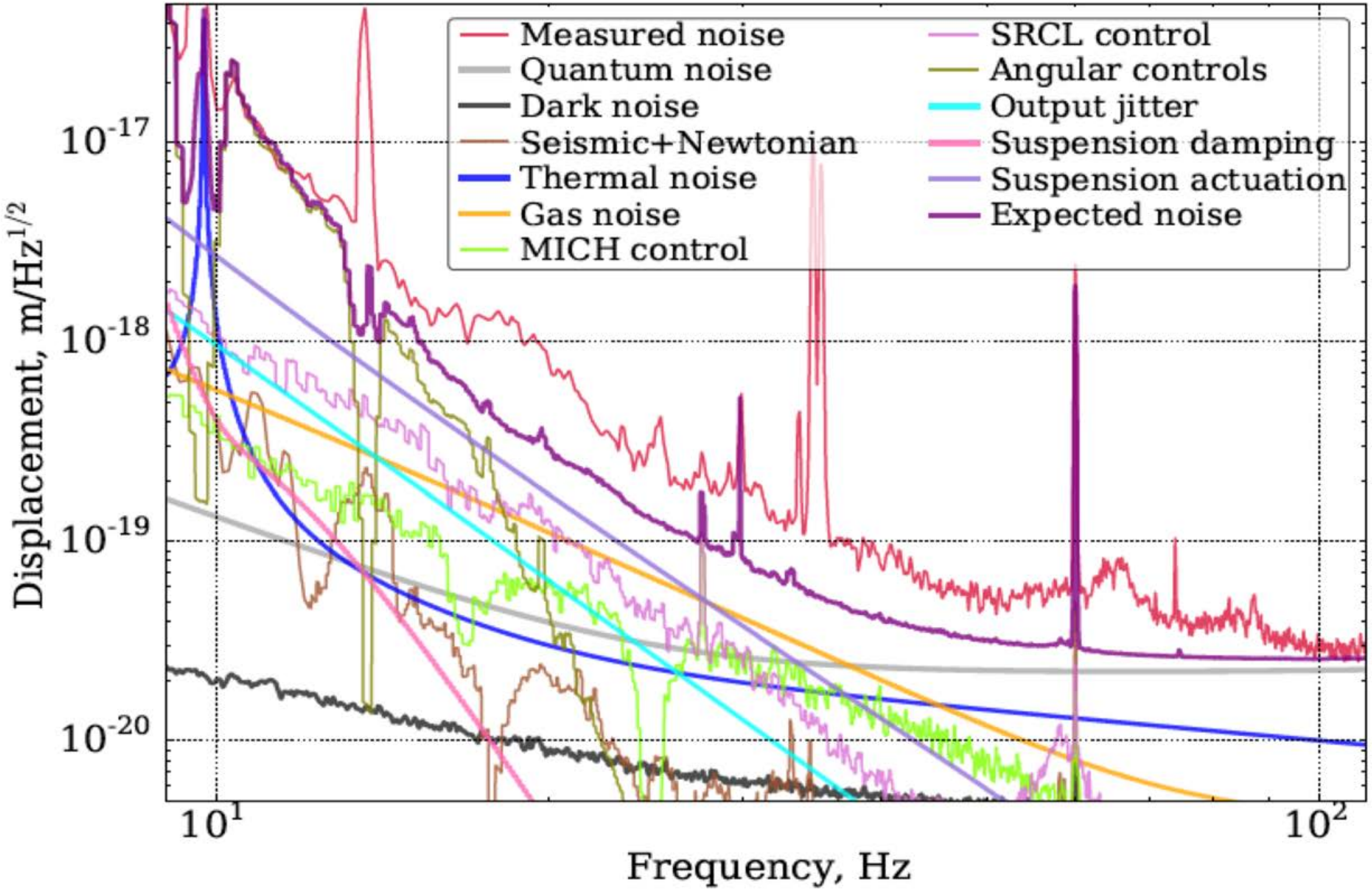
- **Quantum Noise** limits most of the frequency range.
- **Coating Brownian** limits in the range from 50 to 100Hz.
- Below ~15Hz we are limited by ‘walls’ made of **Suspension Thermal**, **Gravity Gradient** and **Seismic noise**.
- And then there are the, often not mentioned, ‘technical’ noise sources which trouble the commissioners so much.



In addition …



Seismic disturbance
Molecule crossing Laser beam
Humans
Power lines
Thermal Bath
L
beam splitter
L
Quantum Back-Action noise
M
M
E_n^{out}
E_e^{out}
E_0^{in}
Wind/Weather
Detector
DANGER
Planes
Lightning
Magnetic fields



(a) LIGO Livingston Observatory

Outline

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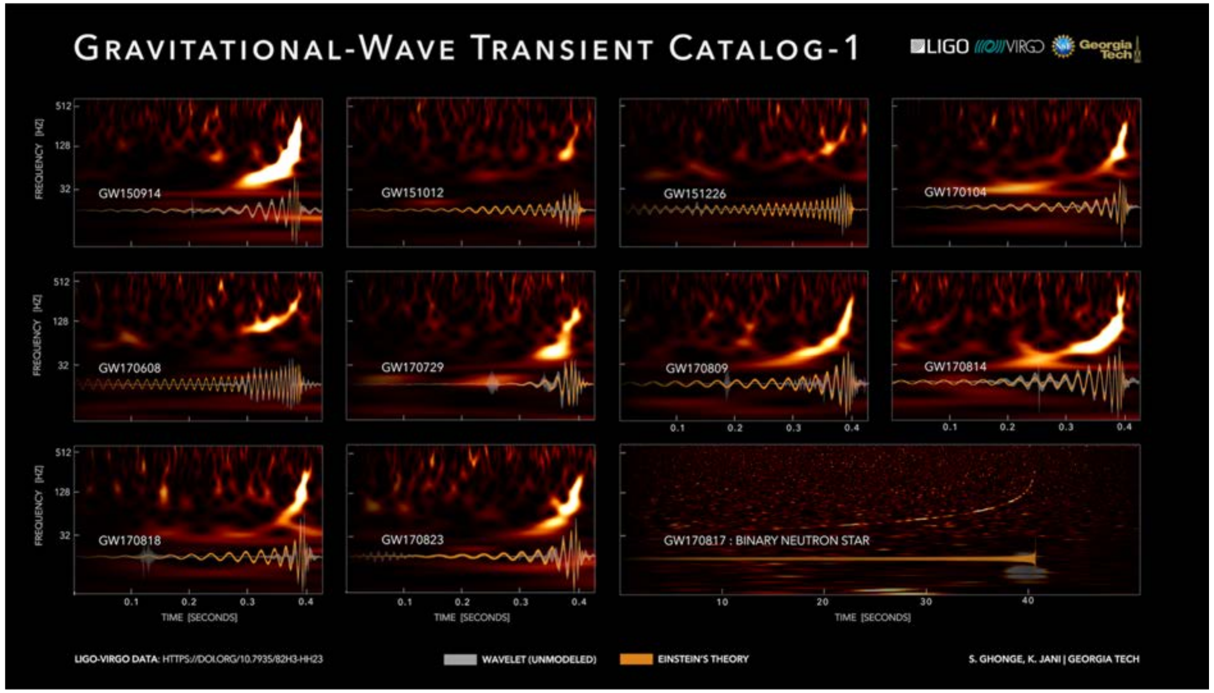
From a few seconds of signals …

… detected with LIGO and Virgo …



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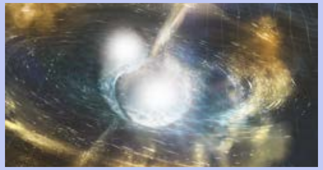
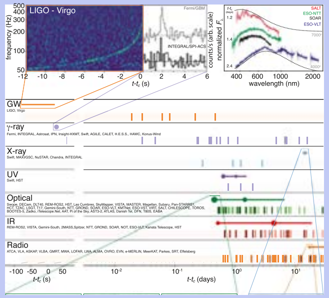


Confirmed BNS as origin for some GRBs

Ruled out some proposed EOS of neutron stars



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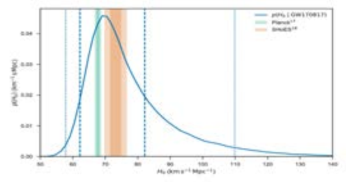
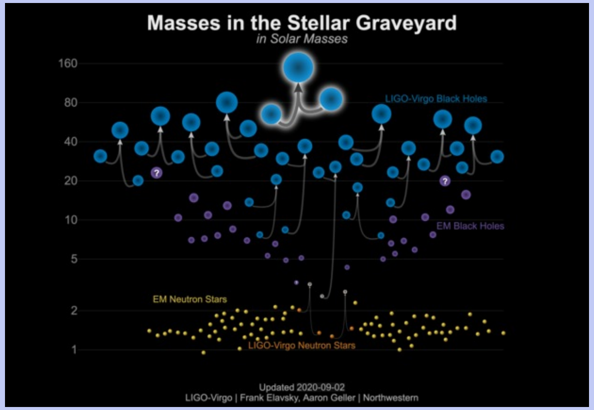


Cosmology independent of distance ladder



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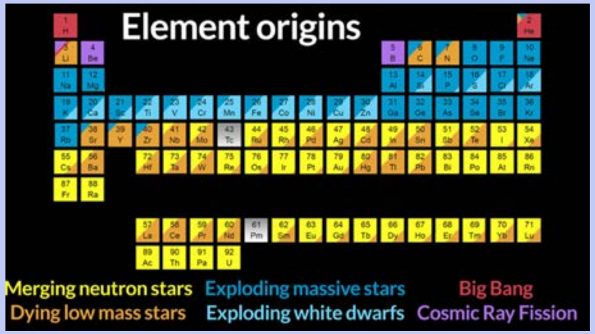
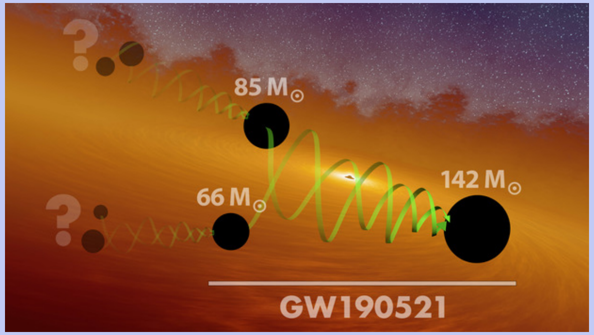
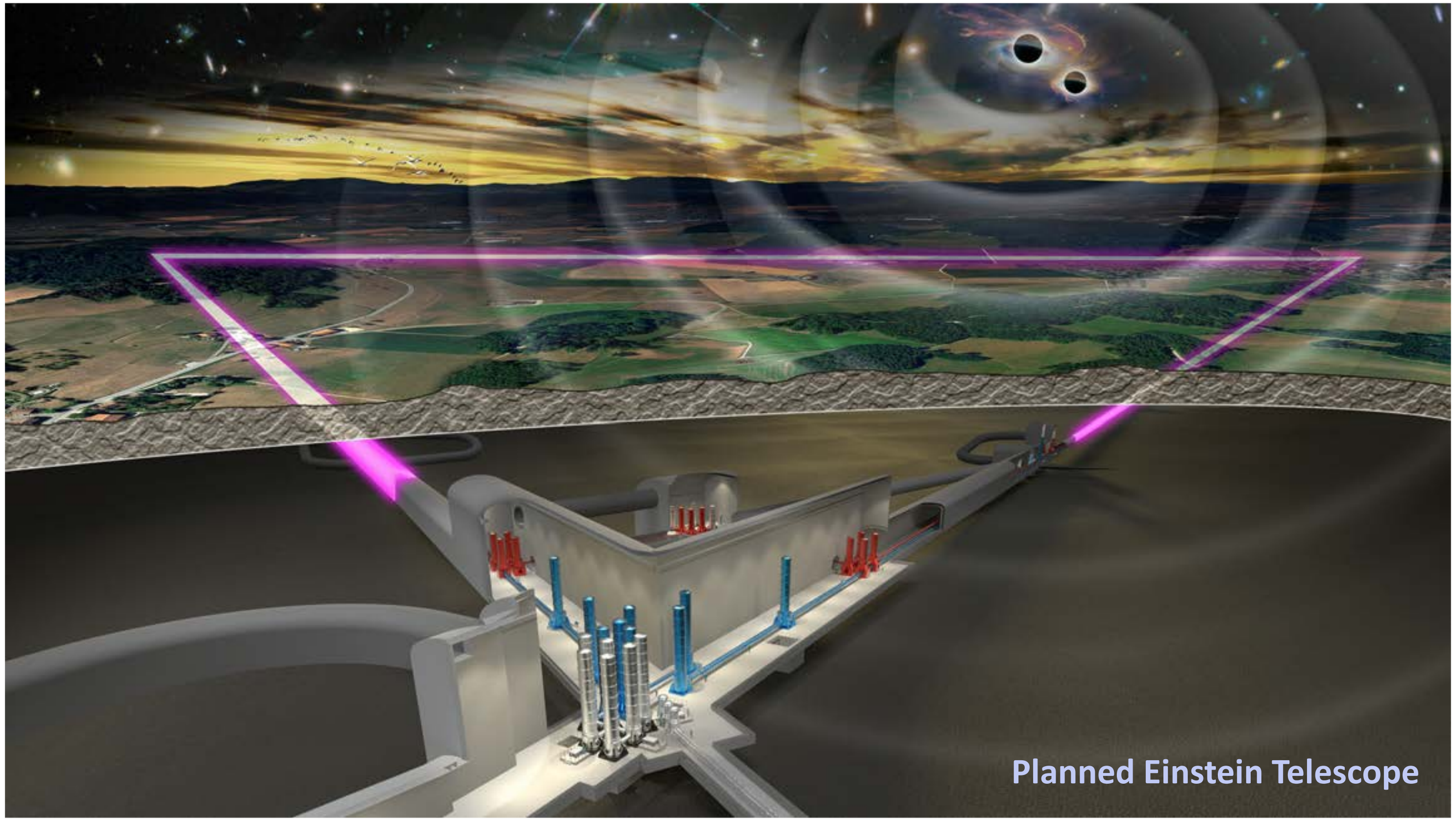


Confirmed Kilonova and R-process



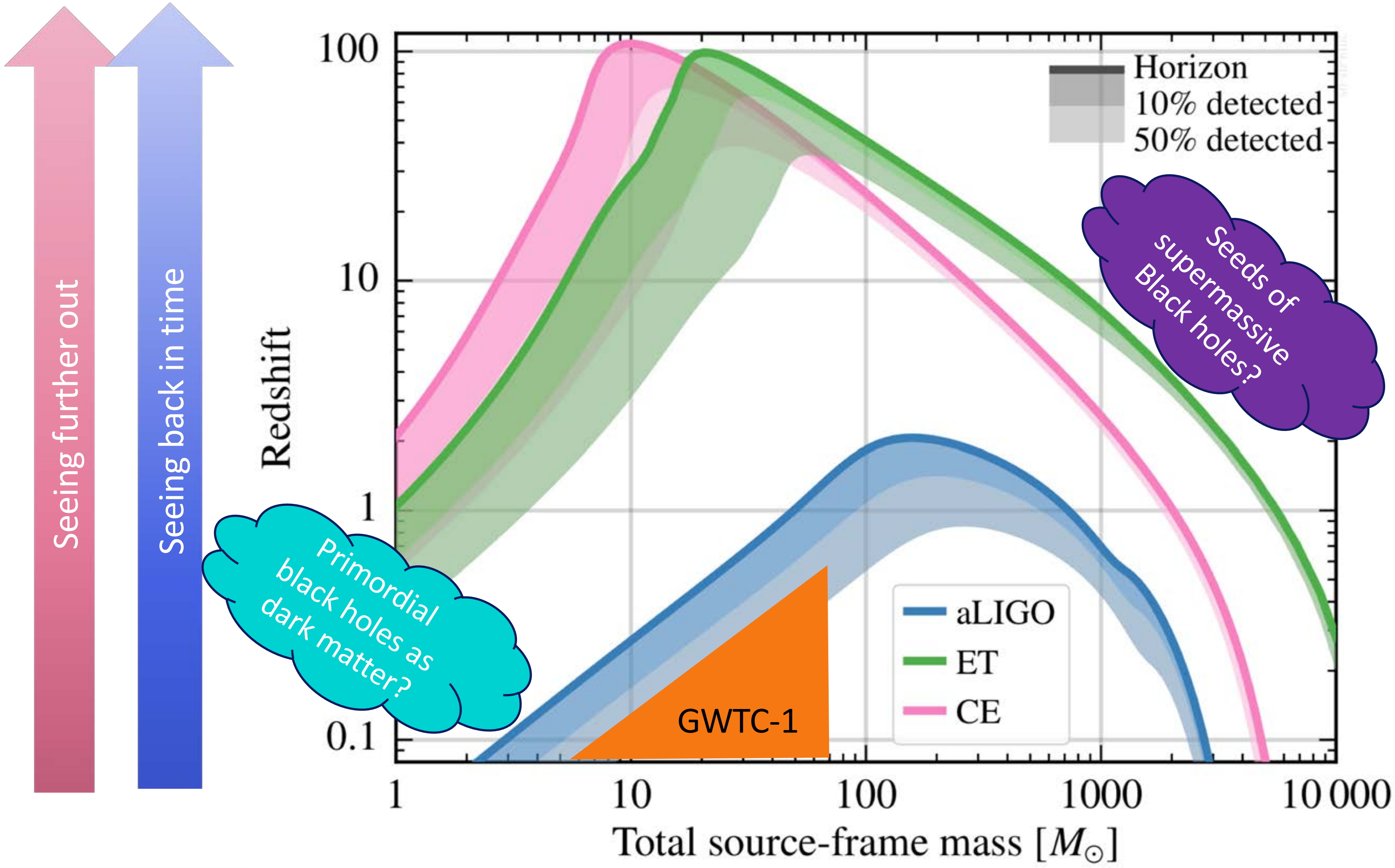
Proved existence of intermediate-mass black holes

From current detectors to ET



- Current detectors observe about one signal per week.
- ET will observe about 100.000 to 1.000.000 binary black holes mergers per year! And many other new sources => discovery space!

Reaching for the full cosmos!

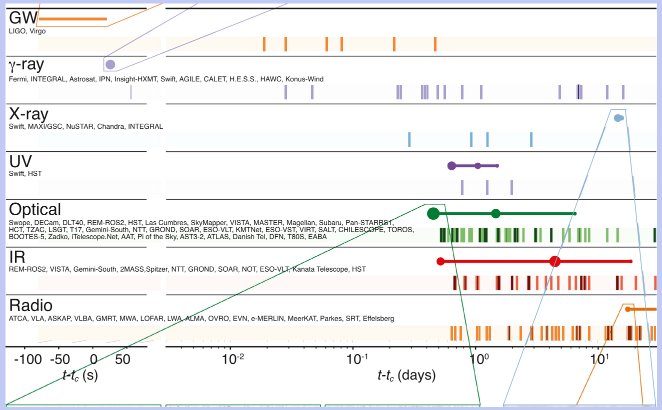


Binary Coalescences Overview:

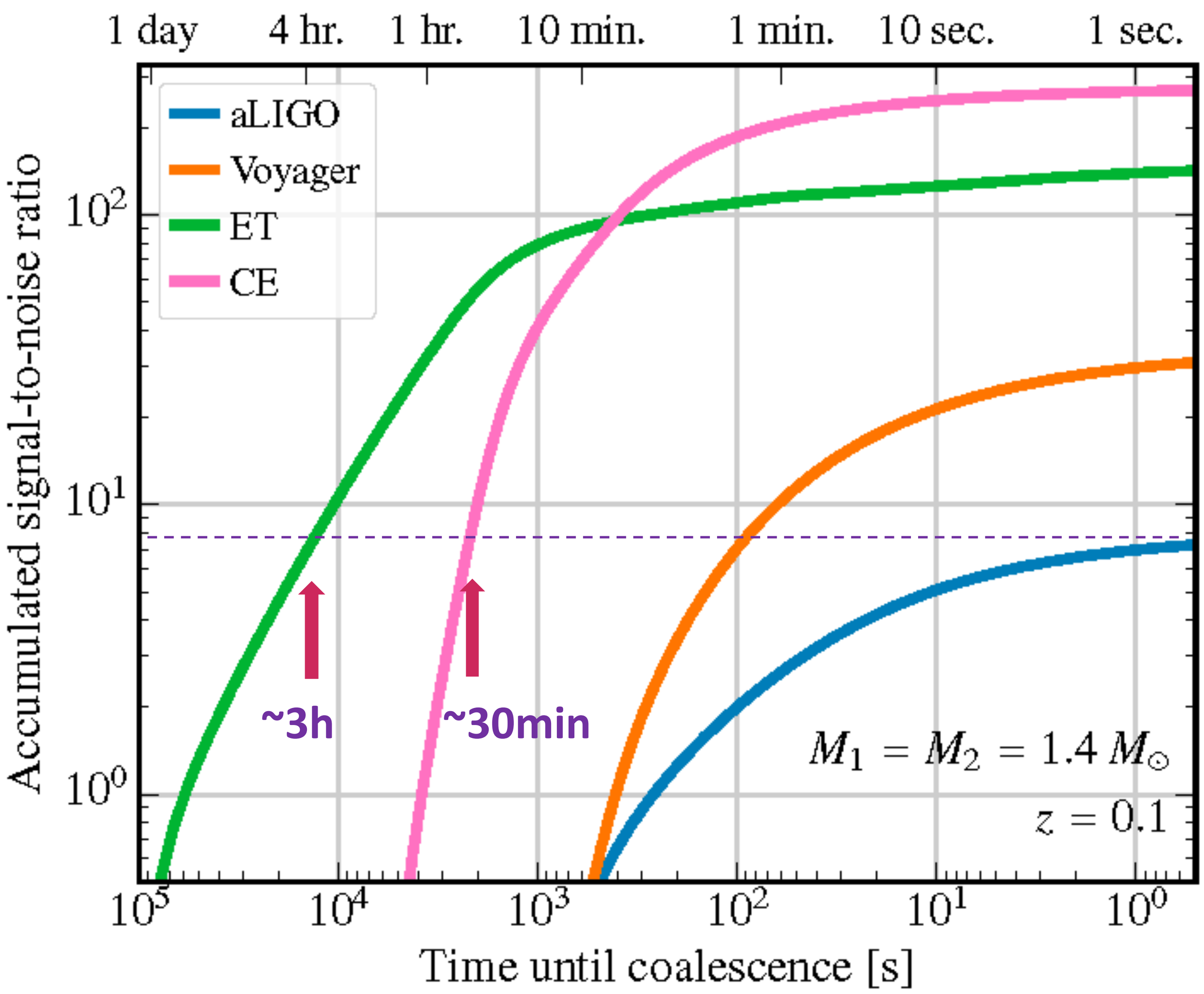
- Census of stellar and intermediate-mass BBH population over full Universe, 10^5-10^6 events per year;
- High SNR events will provide excellent precision to do accurate test of GR, nature of the BH, strong-field dynamics, black hole no-hair theorem etc;
- Extend the range of observed BBH masses towards >1,000M_{sol} and <1$M_{sol;}$
- Observe several 10,000 binary neutron star mergers per year.
- ET will determine NS EOS.

Seeing BNS with GWs before merger!

GW170817: Optical counterpart located ~6 hours after merger.



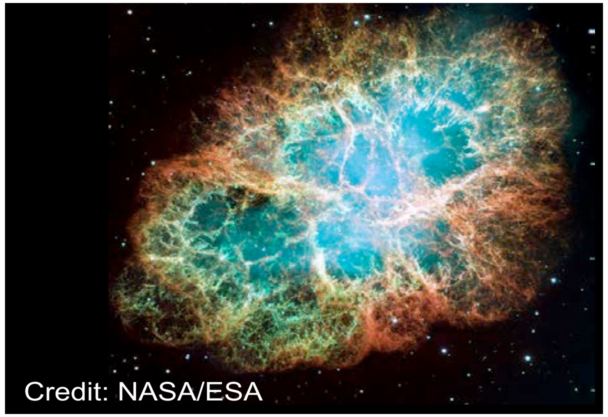
With ET we have a chance to observe the kilonova right from the beginning, observe fast radio emission and pin down the engine of short GRBs.

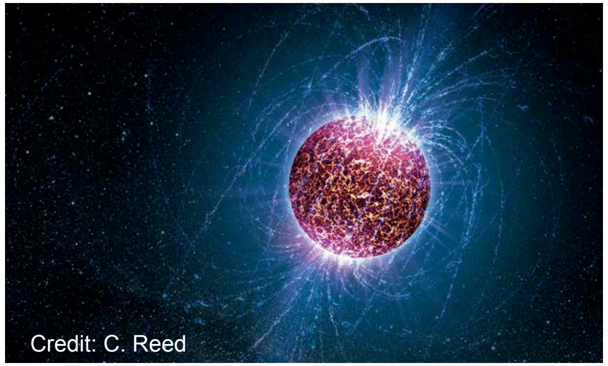


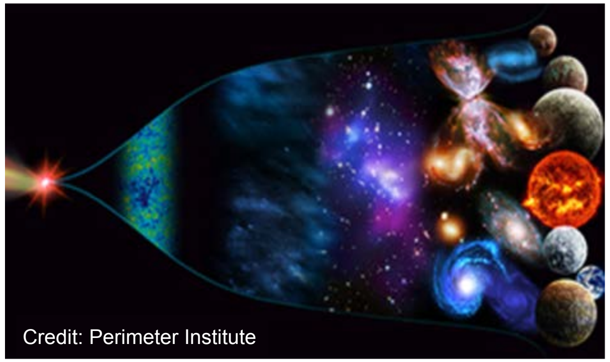
Credit: Evan Hall

More Science!

- Supernovae
- Isolated rotating neutron stars
- Testing of a variety of dark matter candidates
- Exploring the nature of dark energy
- Stochastic background of GWs, back to shortly after Big Bang
- What else might be out there what do we not think/know about yet?


Credit: NASA/ESA


Credit: C. Reed

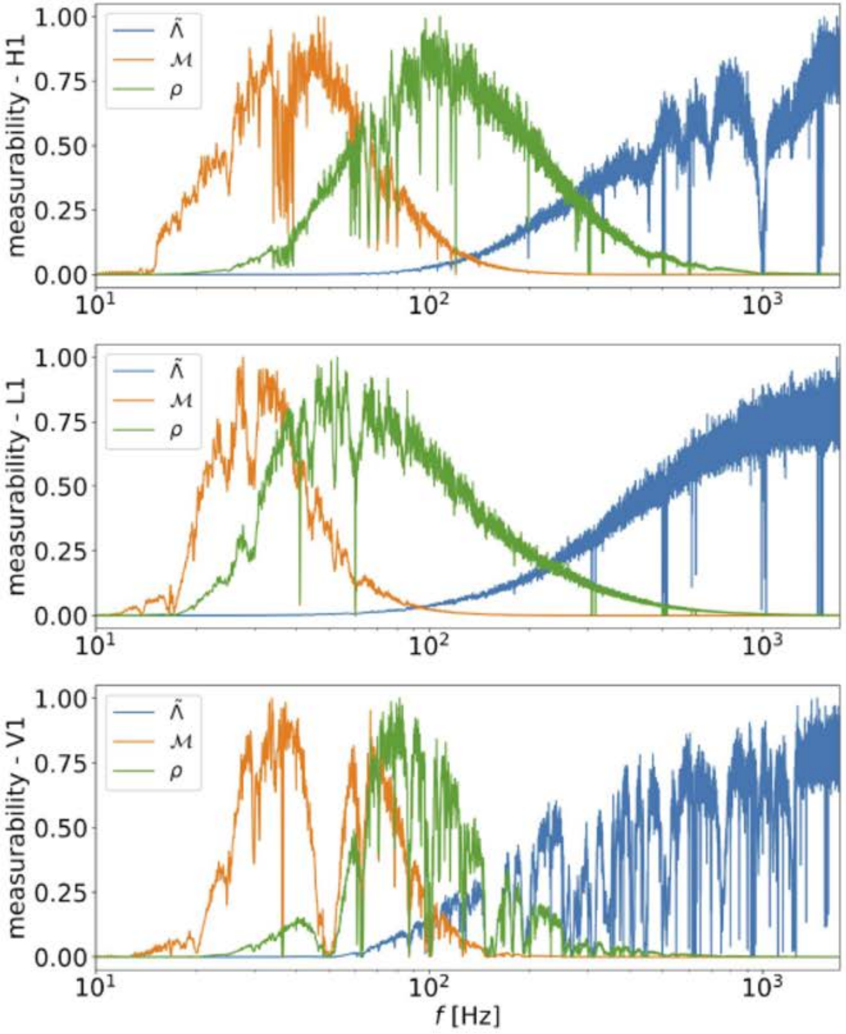

Credit: Perimeter Institute

Spectral contribution to science

Useful exercise: In which frequency band is information about certain source parameter accumulated?

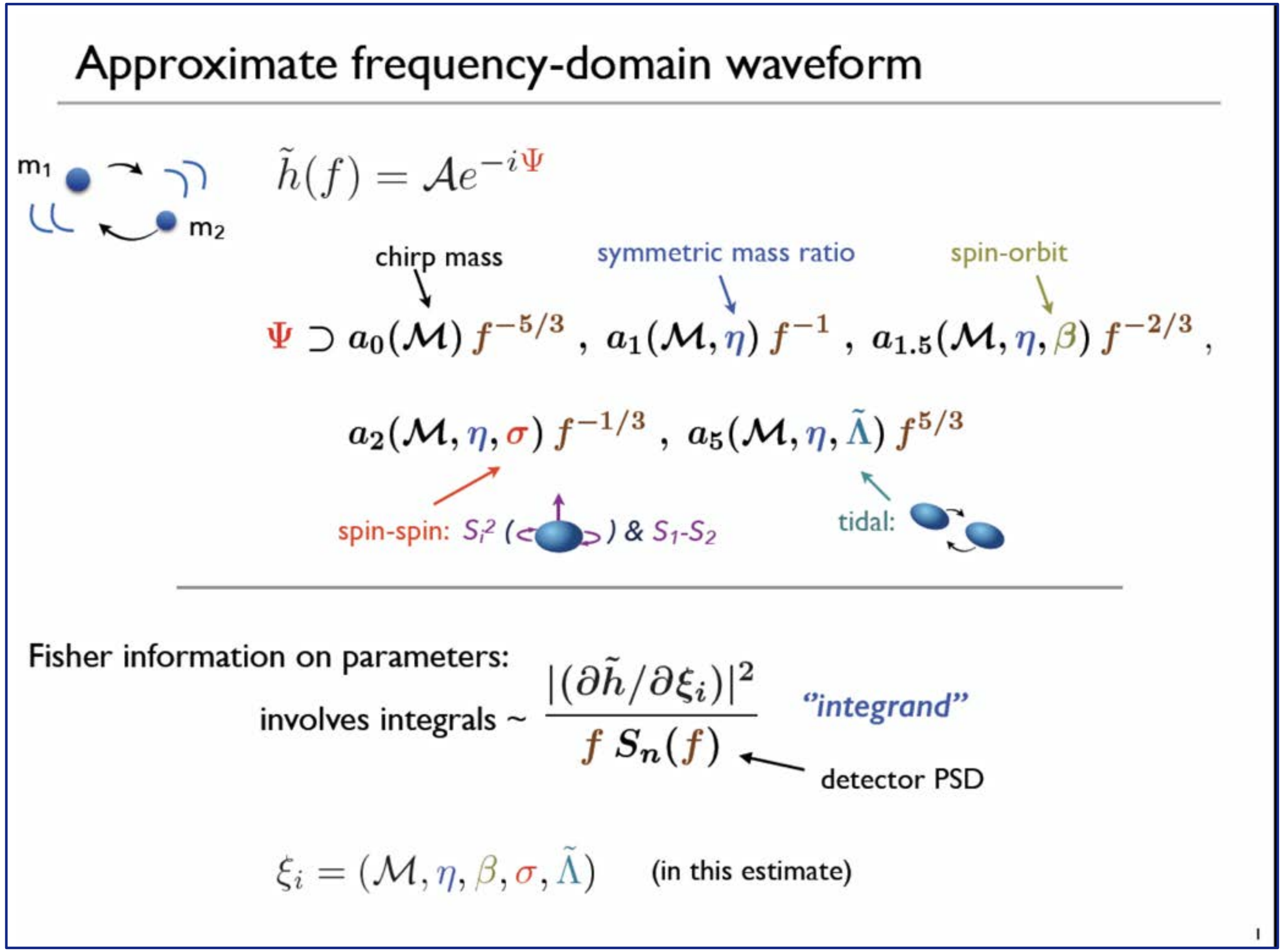
Example: GW170817

- Mid frequencies = SNR
- Low frequencies = Chirp Mass
- High frequencies = deformability



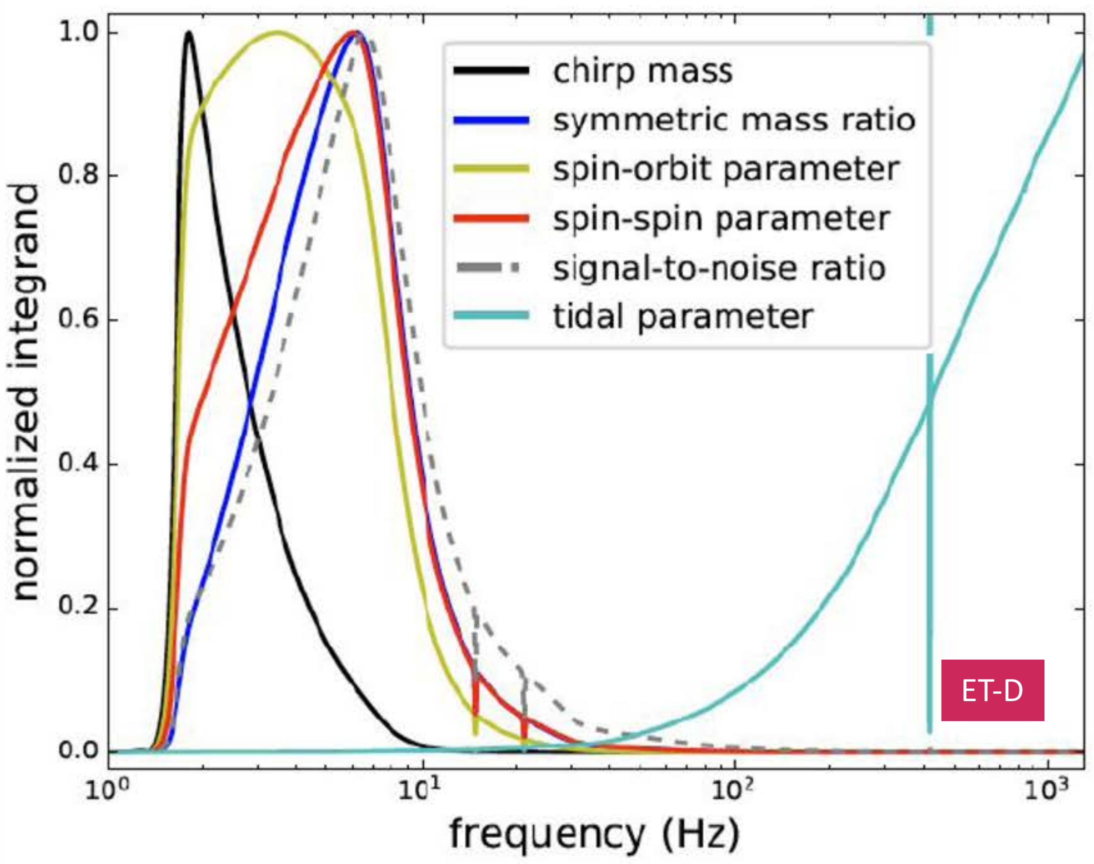
Credit: arXiv:1804.08583

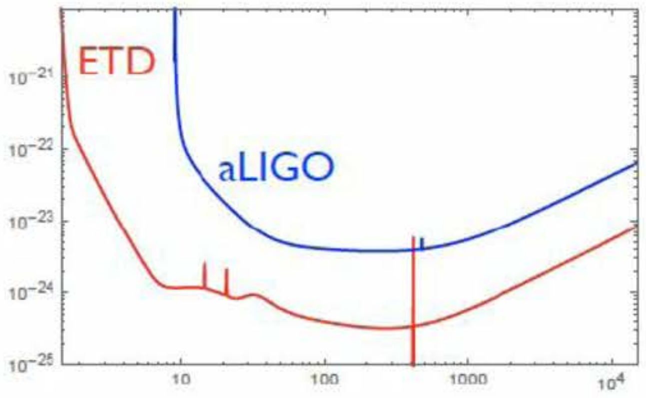
Spectral contribution to science



Slide credit: T. Hinderer

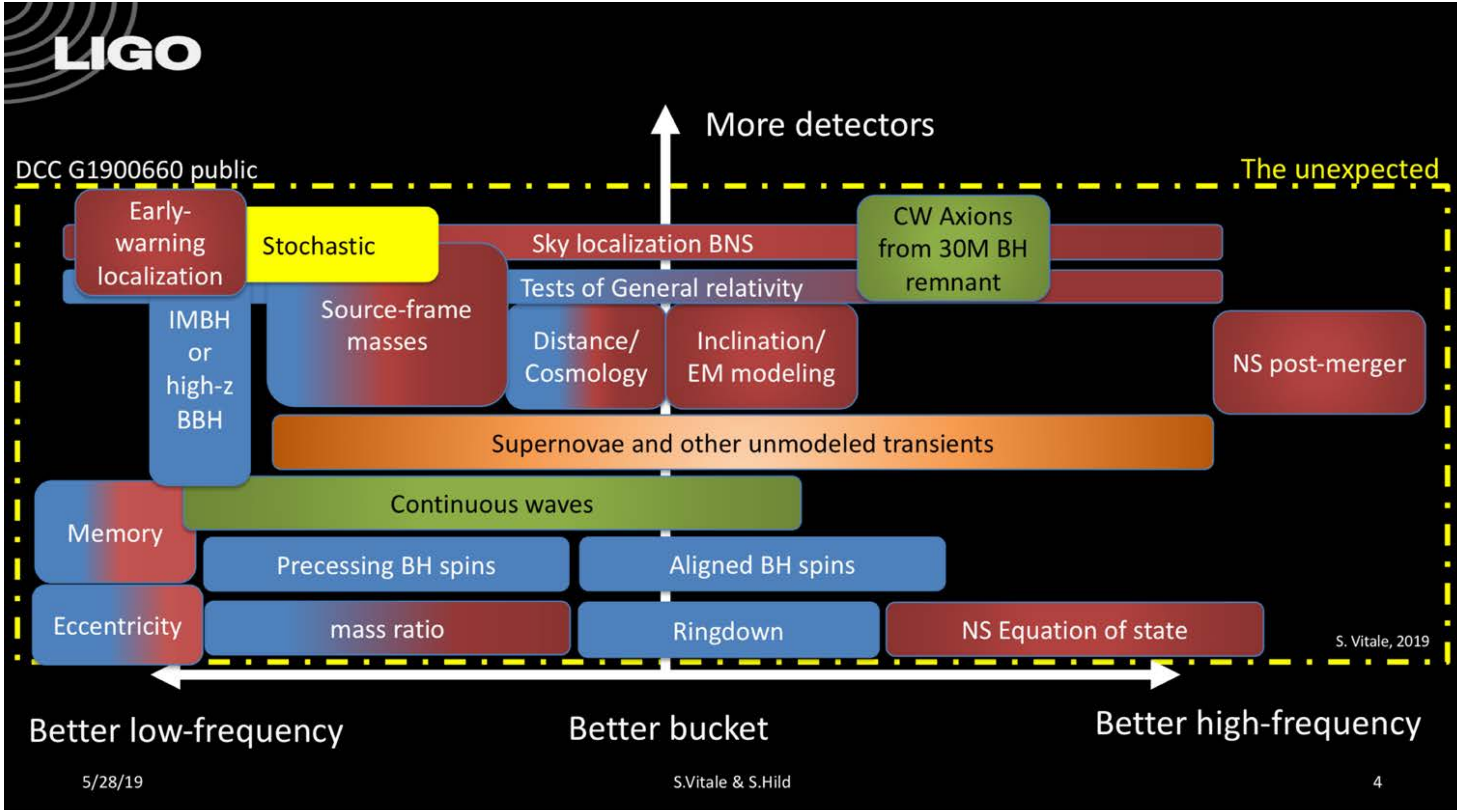
Spectral contribution to PE for ET

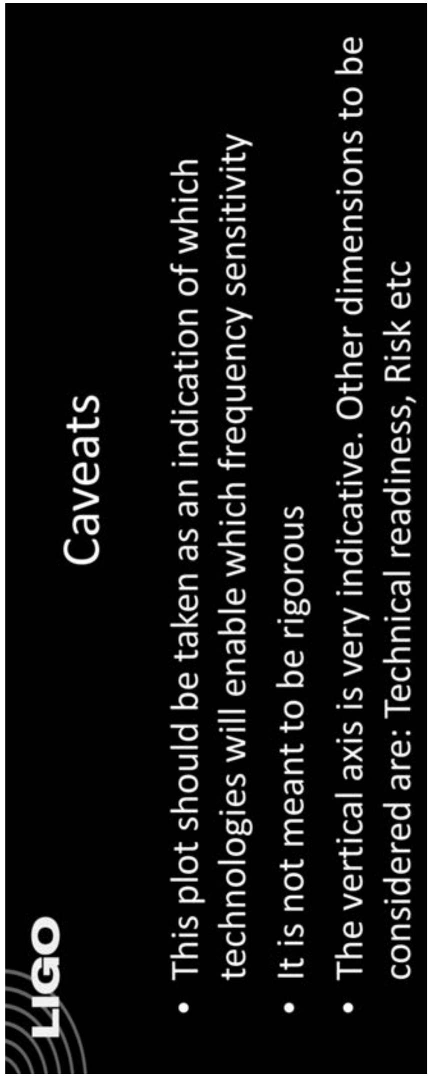




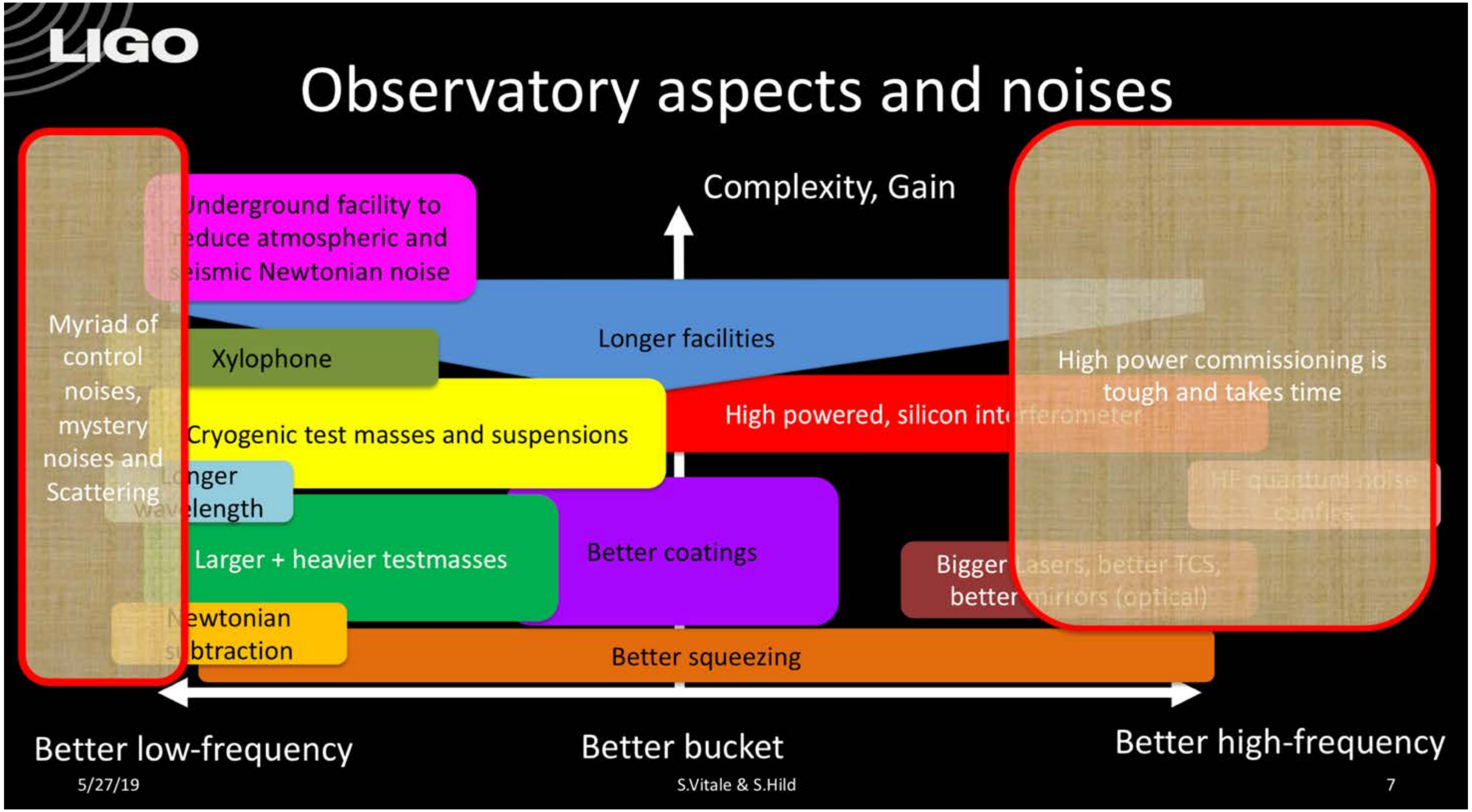
Credit: I. Harry, T. Hinderer, private communication

Continue with bucket approach?



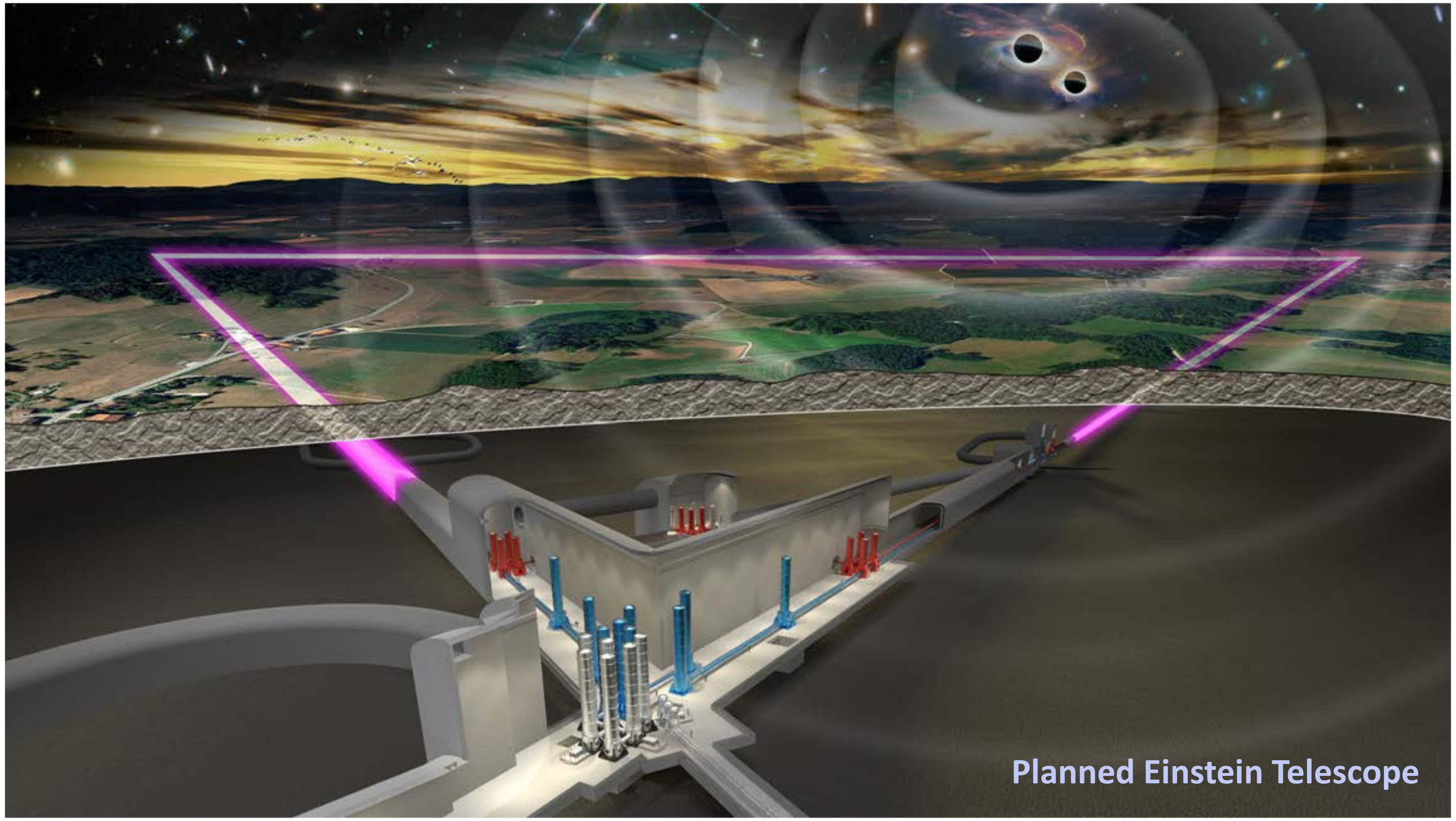


Continue with bucket approach?



From current detectors to ET

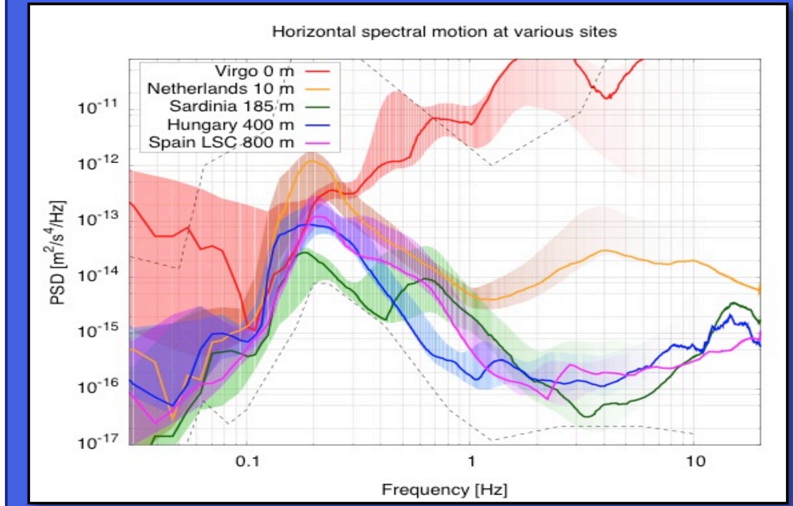
Current detectors started ~1990s



ET will be an infrastructure to provide observing power for half of the 21st century, i.e. from about 2035-2085!

Why does ET look so different compared to current interferometers?

Key concepts of ET in a single slide



Underground location for Reduction of seismic and atmospheric GGN
+ long baseline

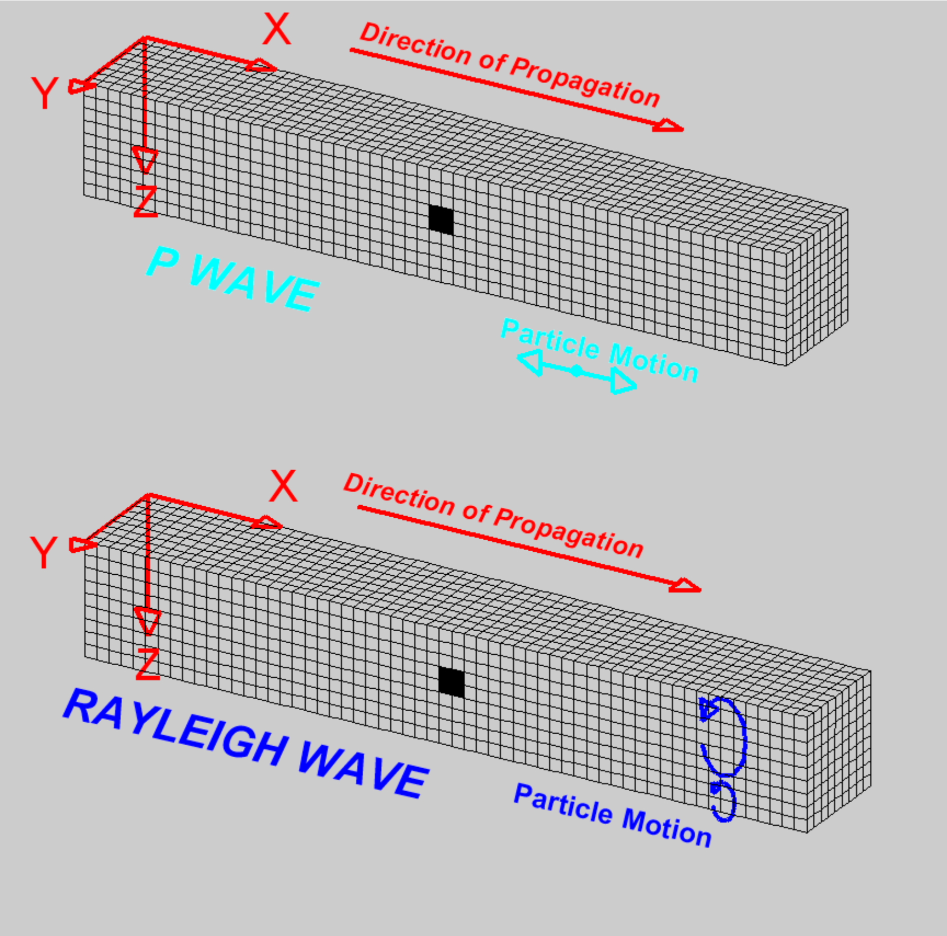
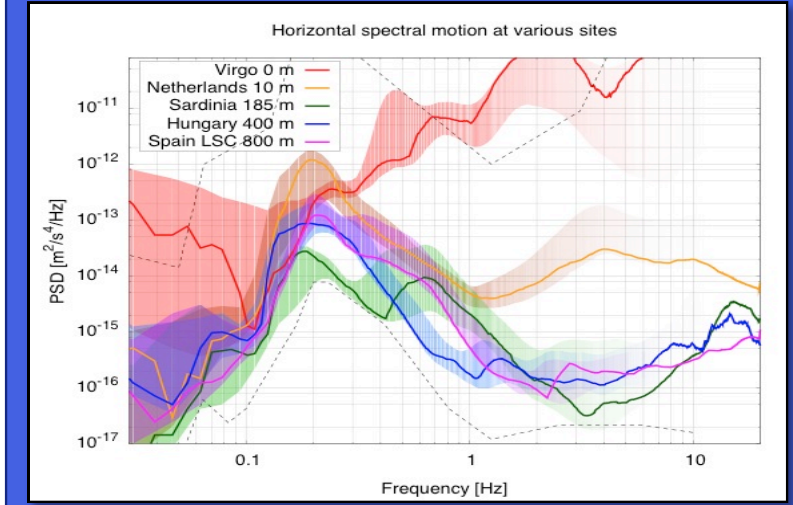


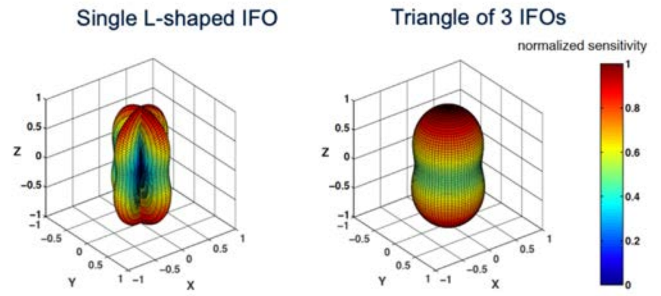
Image credits: http://www.geometrics.com/what-are-the-different-types-of-seismic-waves/

Key concepts of ET in a single slide

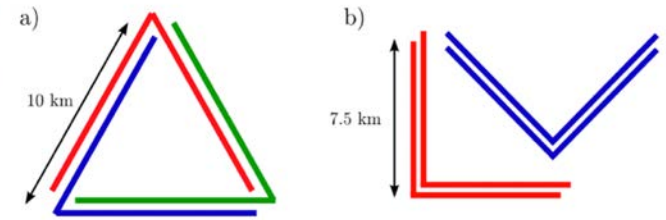


Underground location for Reduction of seismic and atmospheric GGN
+ long baseline

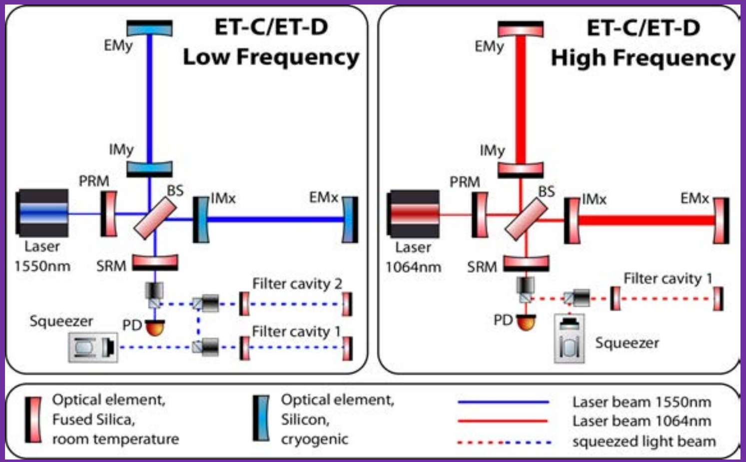
Triangular for full sky coverage and redundancy



Freise, A.; Chelkowski, S.; Hild, S.; Pozzo, W. D.; Perreca, A. & Vecchio, A. *CQG*, **2009**, *26*, 085012 (14pp)



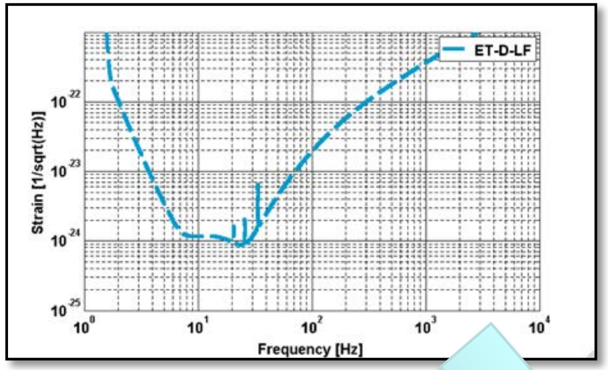
Triangle first proposed:1985, MPQ-101. W.Winkler, K.Maischberger, A.Rüdiger, R.Schilling, L.Schnupp, D.Shoemaker,: Plans for a Large Gravitational Wave Antenna in Germany

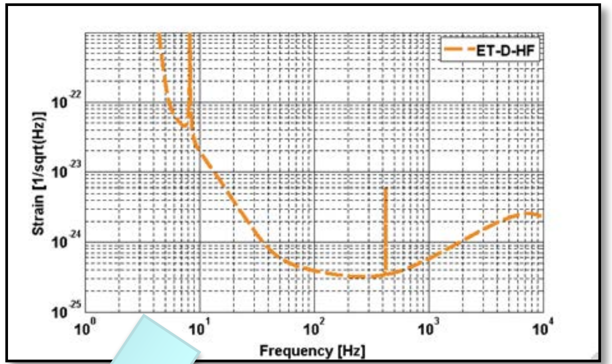


Xylophone concept

Many new technologies, like for instance cryogenic silicon mirrors

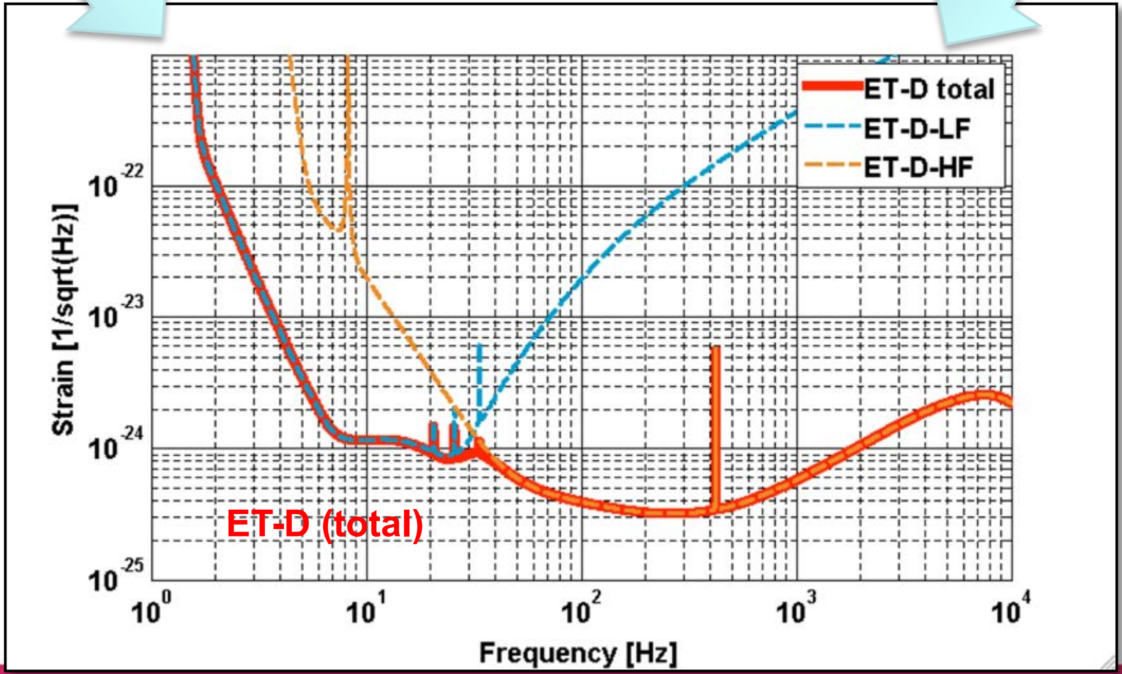
Combining 2 IFOs





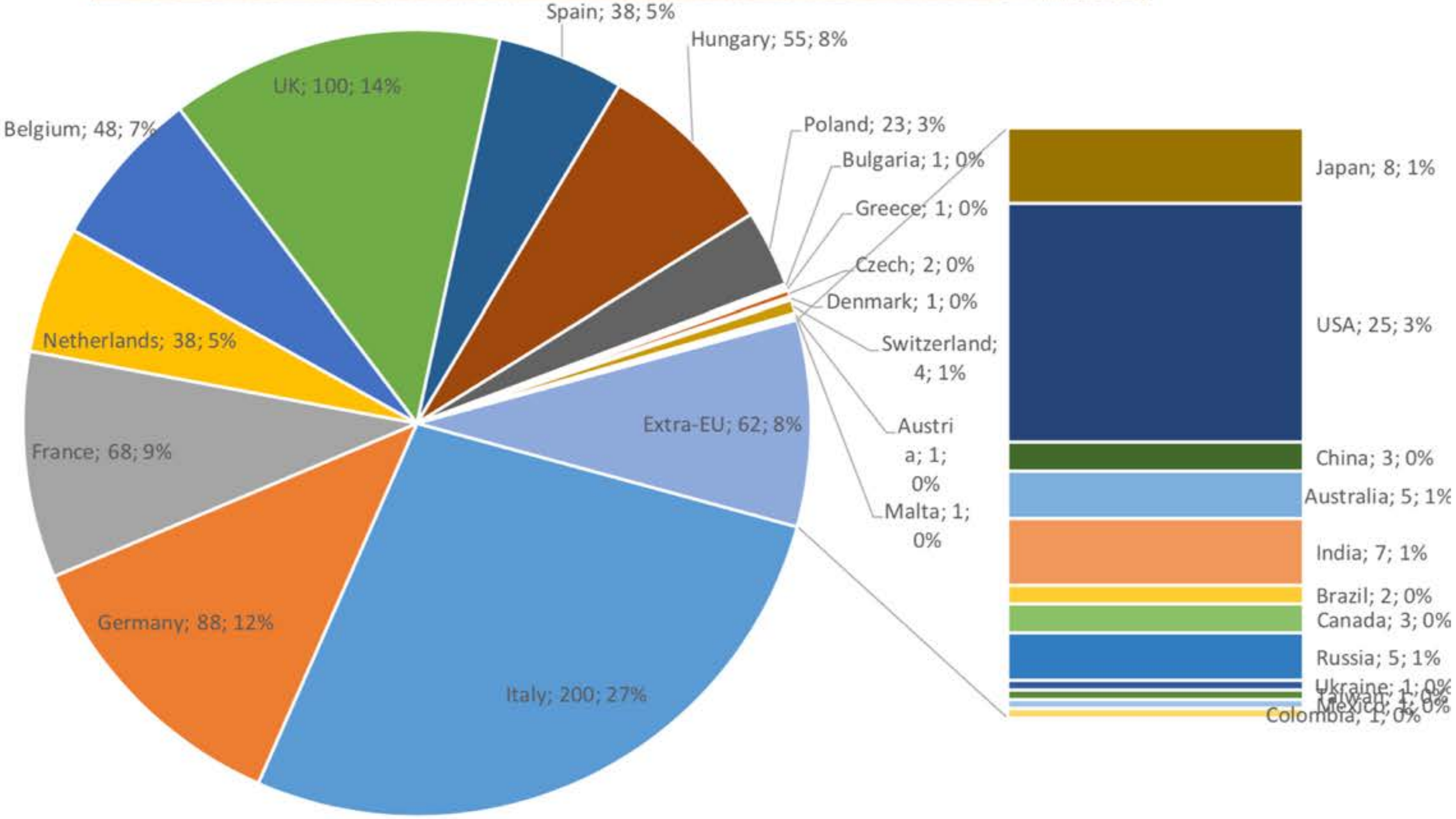
ET-D-LF

ET-D-HF



ET collaboration

- Launched the ET letter of intent @ the 9th ET symposium (April 2018)
- At the 10th ET symposium, April 2019, we collected more than 730 signatories



http://www.et-gw.eu/index.php/letter-of-intent

LVC week – Warsaw 2019 3

12th ET symposium
7th-8th June 2022 in Budapest

https://indico.ego-gw.it/event/411/

From the ET-costbook and socio-economic studies

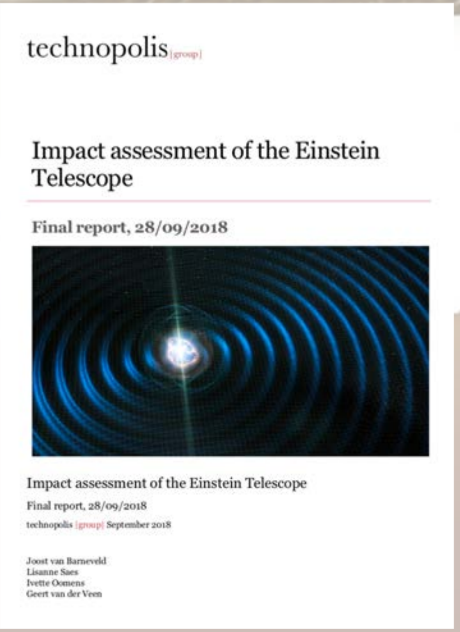
Site infrastructure	**ca 900**
Vacuum	**ca 550**
Seismic isolation	**ca 50**
Cryogenics	**ca 50**
Optics	**ca 125**
Design and Prepaprtion	**ca 200**
Total	**ca 1900**

Estimated budget in Mega-Euro (excl Personnel)

Note: Largest cost items have big overlap with CERN, i.e. underground and civil construction, vacuum systems, cryogenics etc. Also note there is an exciting MOU between CERN, INFN and Nikhef covering those items.

1 Euro invested in ET generates **3.6 Euro of Total Output*** or between **1.4 and 1.55 Euro of Value Added****. **Estimated overall employment effect of about 34000 py during construction**.

*TO measures the increase of the volume of economic activity induced by the project.
**VA measures the new value generated by the project, i.e. its contribution to the GDP, net of the duplication effects due to the production of intermediate goods and services along the supply chain.


technopolis |group|

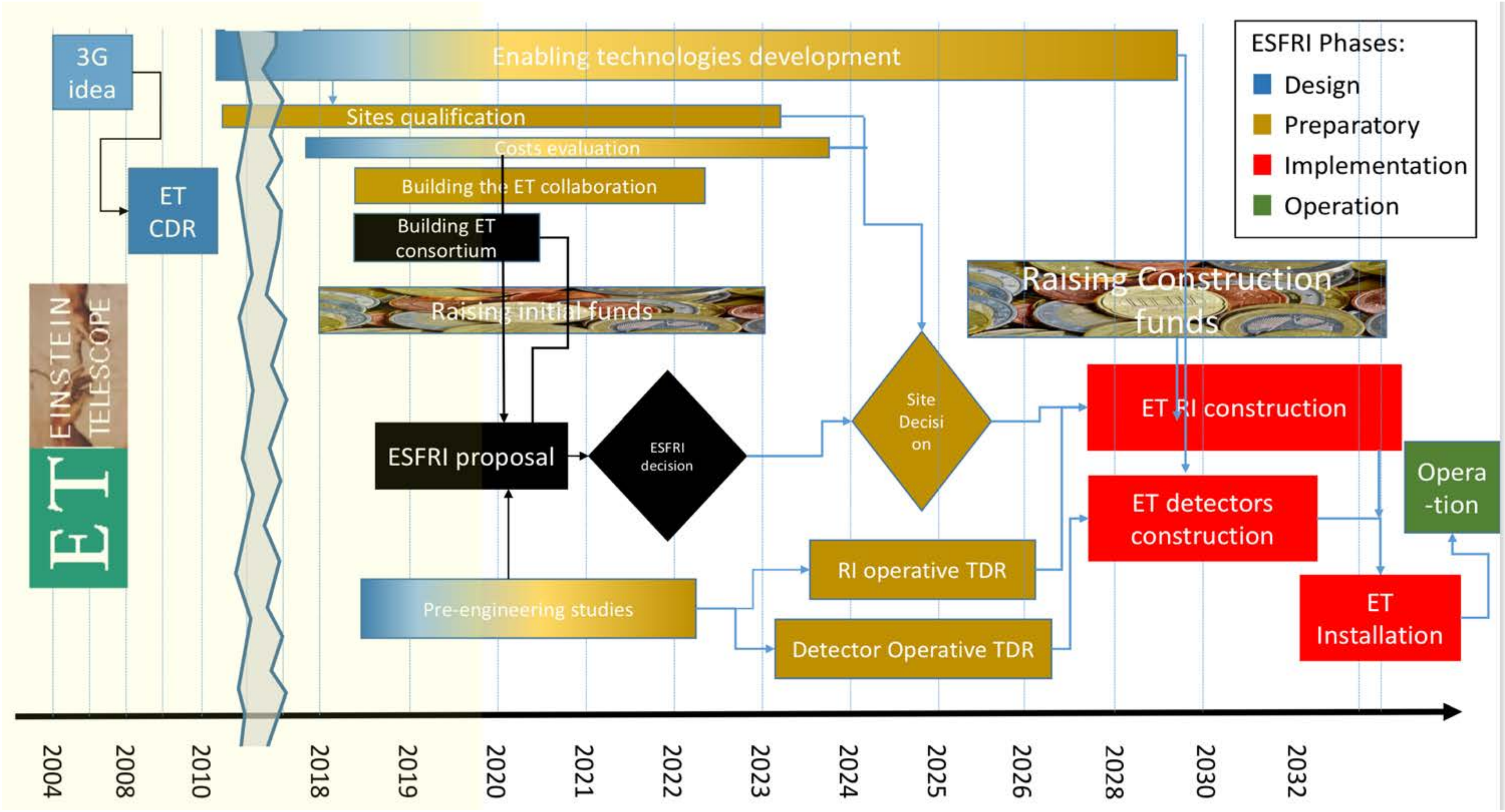
Impact assessment of the Einstein Telescope

Final report, 28/09/2018

Impact assessment of the Einstein Telescope
Final report, 28/09/2018
technopolis |group| September 2018

Joost van Barneveld
Lisanne Saes
Ivette Oomens
Geert van der Veen

ET timeline



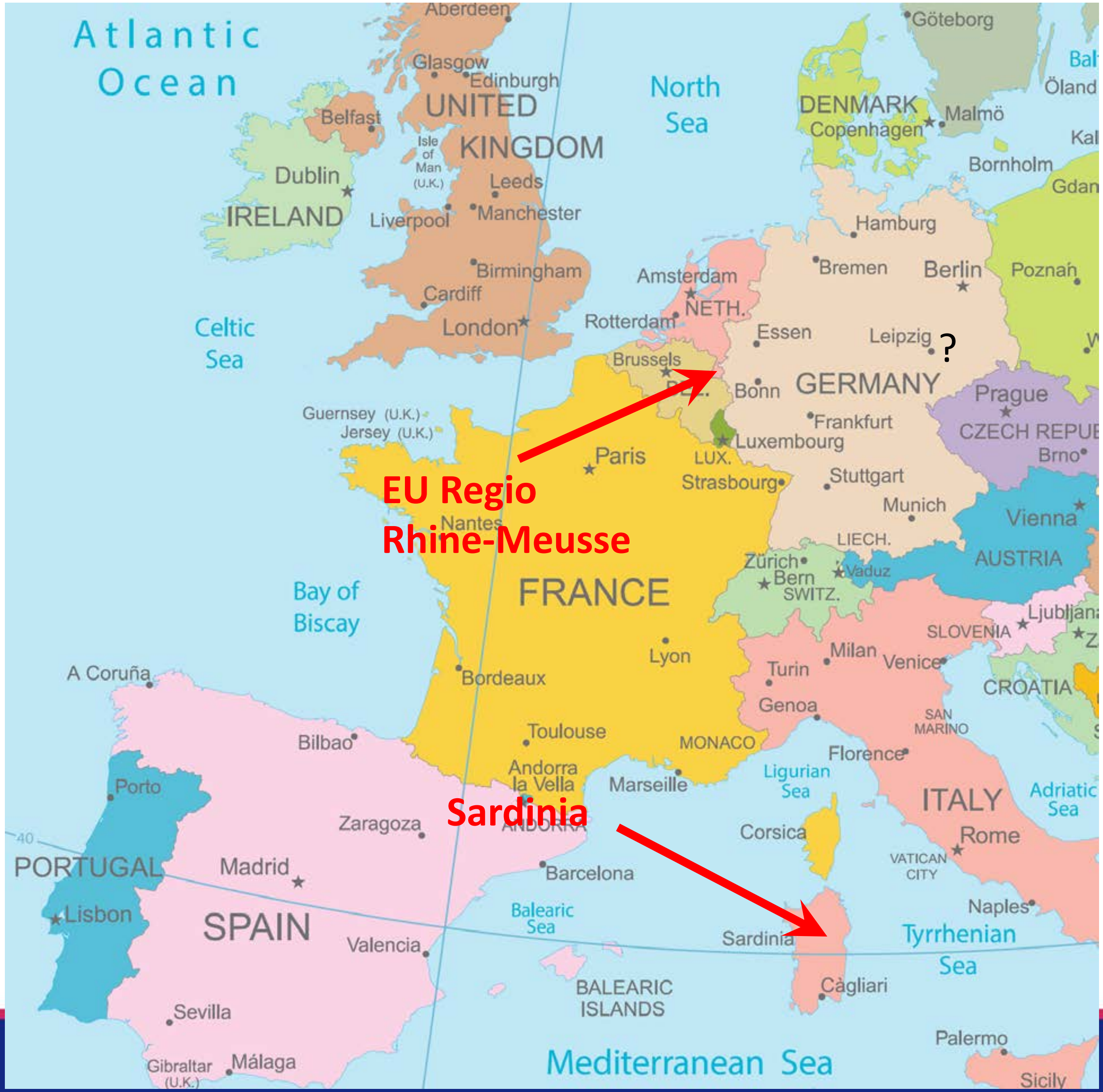
- Idea for ET like-observatory is from 2004
- CDR was finished in 2011
- Discovery of GWs in 2015/16 brought ET really to life

Site Candidates

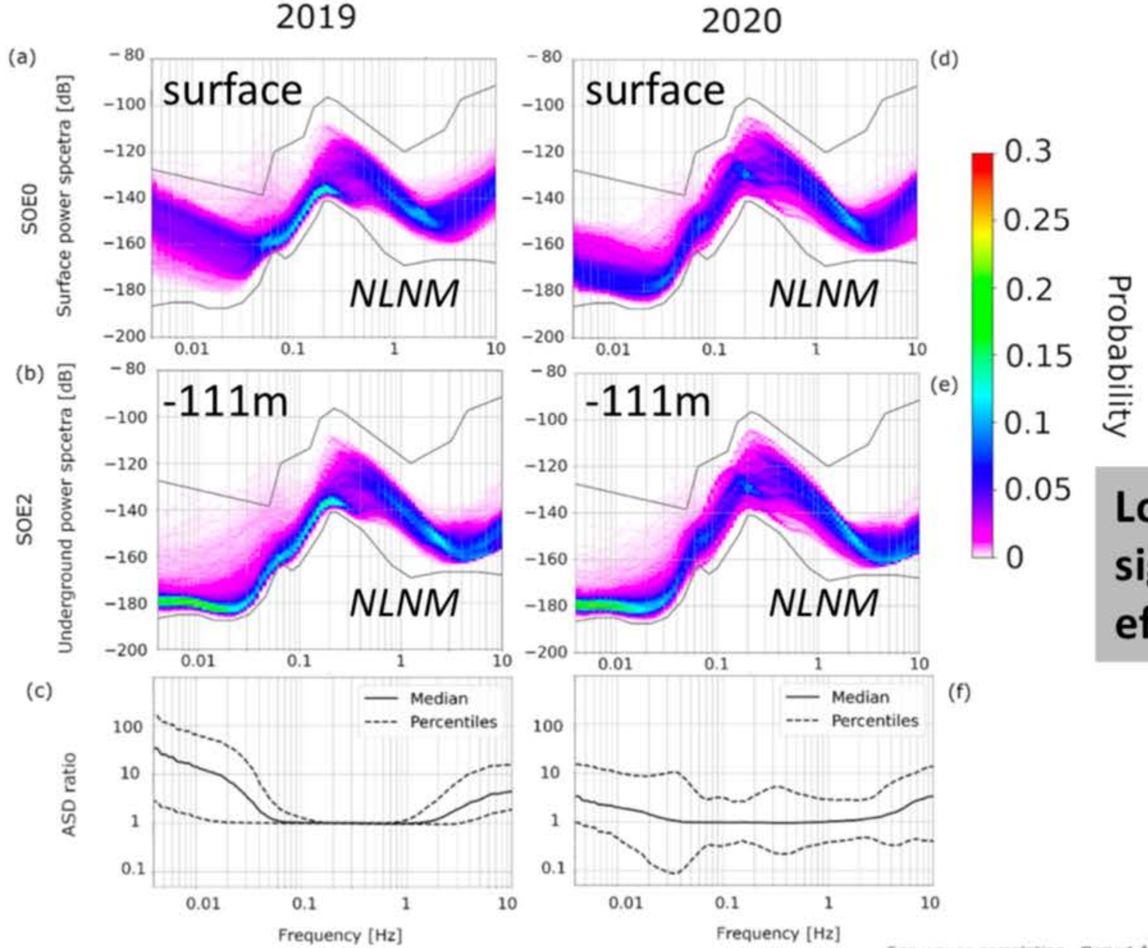
Currently **two site candidates**:

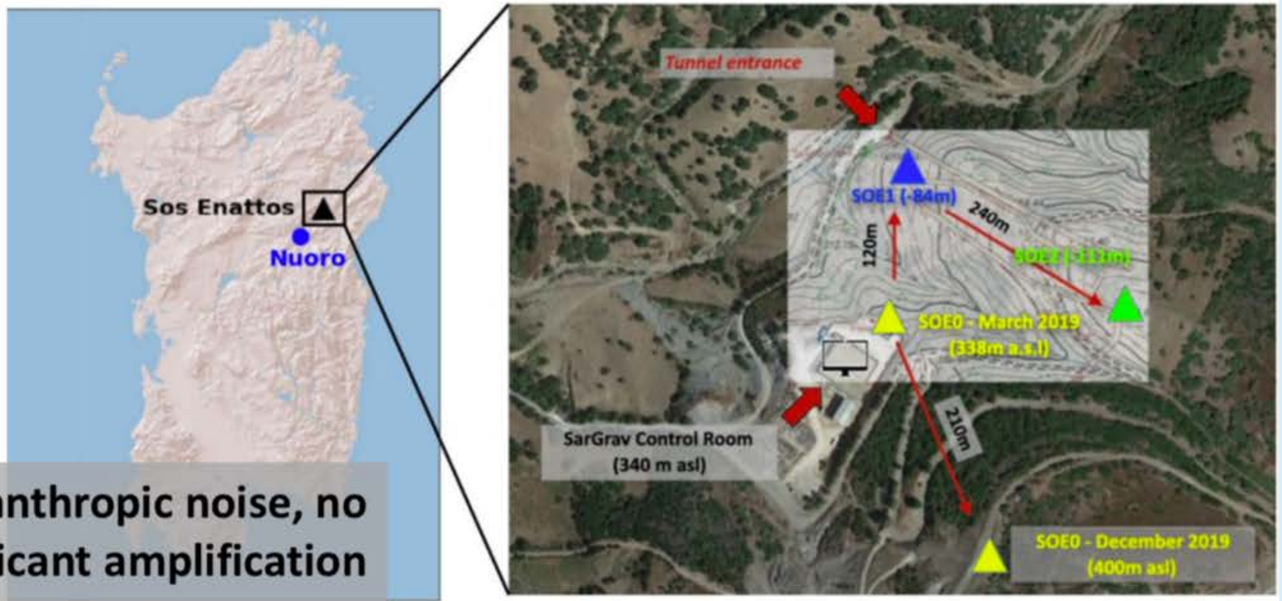
- **Sardinia**
- **EU Regio Meuse-Rhine / Limburg**

Geological properties and underground seismic being investigated



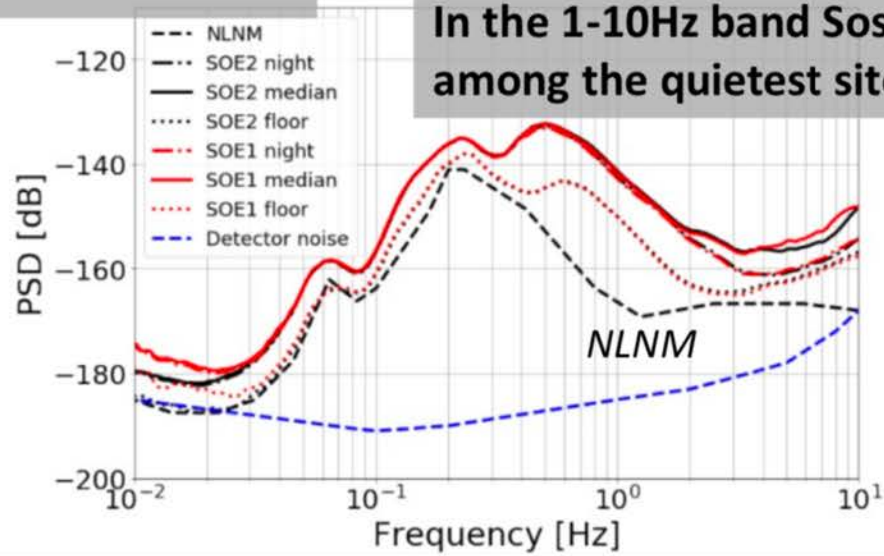
Sardinia: Seismic & environmental studies

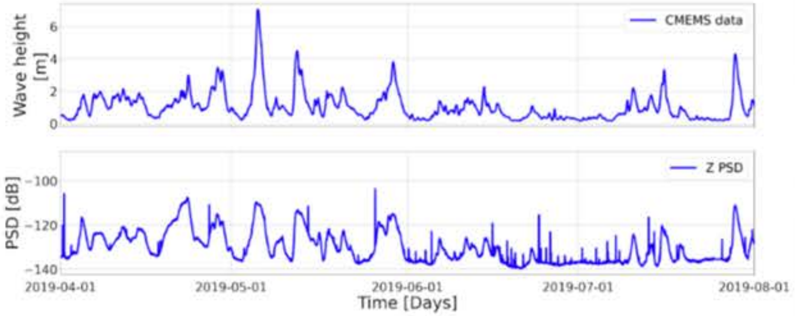


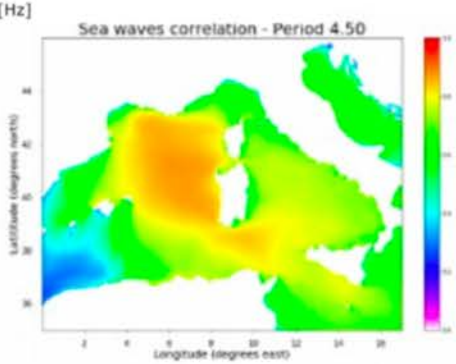


Low anthropic noise, no significant amplification effects

In the 1-10Hz band Sos Enattos is among the quietest sites in the world



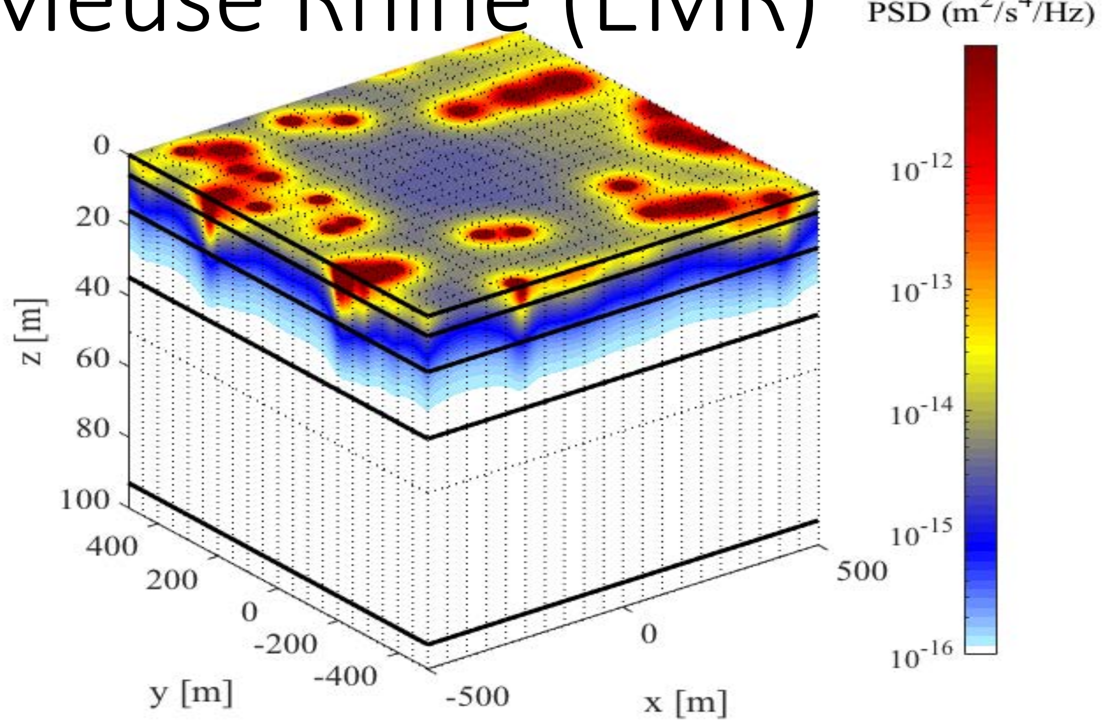




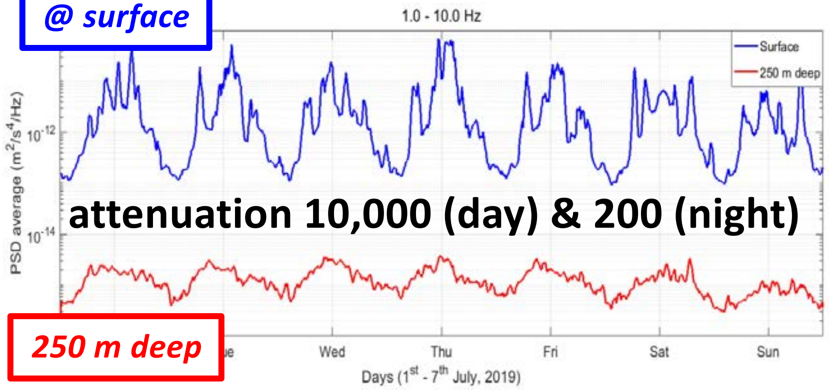
Microseisms correlation with NW 4.5s Med Sea waves

Credit: M. Punturo

Euregio Meuse Rhine (EMR)



@ surface



attenuation 10,000 (day) & 200 (night)

250 m deep

SEISMIC CHARACTERIZATION OF THE EUREGIO MEUSE-RHINE IN VIEW OF EINSTEIN TELESCOPE

13 September 2019

First results of seismic studies of the Belgian-Dutch-German site for Einstein Telescope

Soumen Koley[1], Maria Bader[1],
Alessandro Bertolini[1], Jo van den Brand[1,2], Henk Jan Bulten[1,3],
Stefan Hild[1,2], Frank Linde[1,4], Bas Swinkels[1], Bjorn Vink[5]

1. Nikhef, National Institute for Subatomic Physics, Amsterdam, The Netherlands
2. Maastricht University, Maastricht, The Netherlands
3. VU University Amsterdam, Amsterdam, The Netherlands
4. University of Amsterdam, Amsterdam, The Netherlands
5. Antea Group, Maastricht, The Netherlands

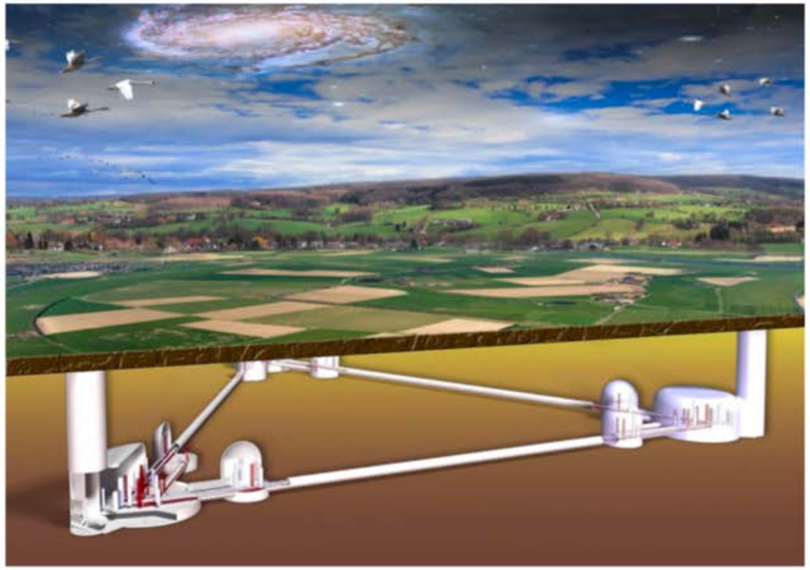


Figure 1: Artist impression of the Einstein Telescope gravitational wave observatory situated at a depth of 200-300 meters in the Euregio Meuse-Rhine landscape. The triangular topology with 10 kilometers long arms allows for the installation of multiple so-called laser interferometers. Each of which can detect ripples in the fabric of space-time – the unique signature of a gravitational wave – as minute relative movements of the mirrors hanging at the bottom of the red and white towers indicated in the illustration at the corners of the triangle.

Recent news: Dutch national Growth funds

Nikhef Menu Search

Dutch government embraces plans for Einstein Telescope in Limburg region

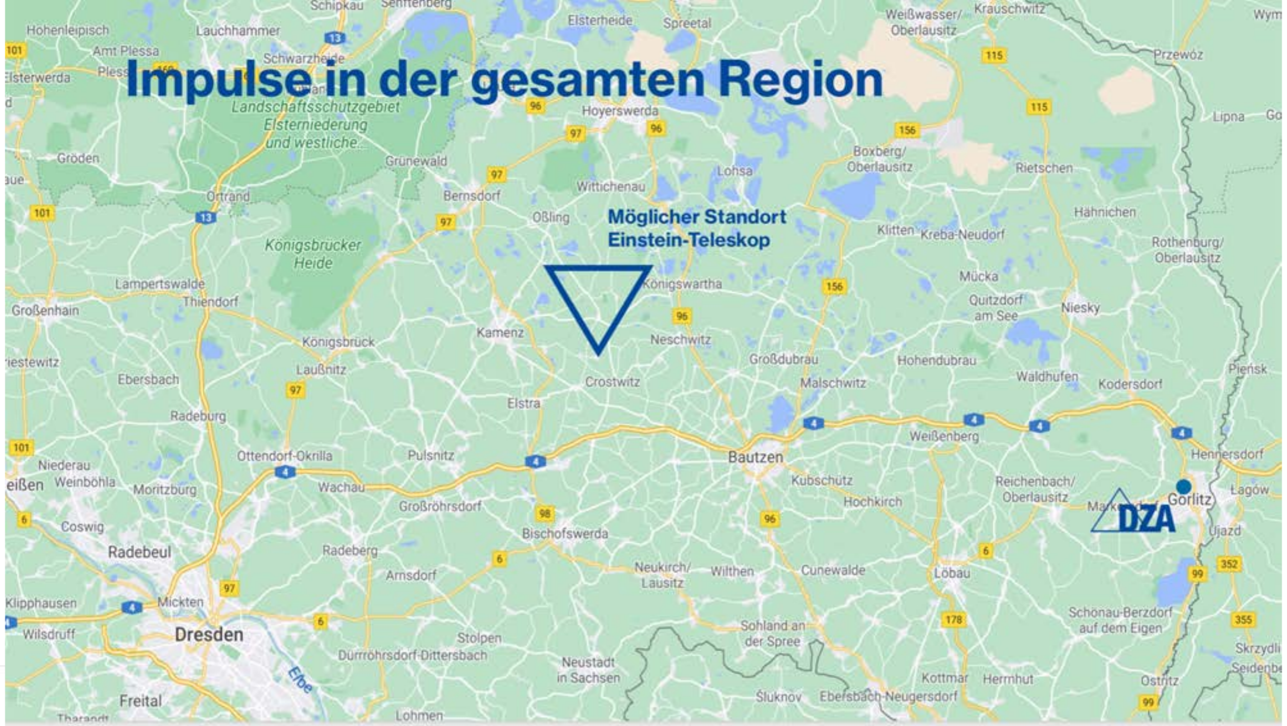
HOME →

14 April 2022

The Dutch government intends to conditionally allocate 42 million euros from the Dutch National Growth Fund to the Einstein Telescope, and is also reserving 870 million euros for a future Dutch contribution to the construction. This decision was taken by the Cabinet based on the advice of the Advisory Committee of the National Growth Fund. With this decision, the Cabinet gives an enormous boost to Dutch science and to the broad development of the South Limburg border region.

The intended investment of 42 million euros will go towards preparatory work such as innovation of the necessary technology, location research, building up a high-tech ecosystem and organisation. With the reservation of the 870 million, the Netherlands has an excellent basis to apply in the future, together with Belgium and Germany, for the realisation of the Einstein Telescope in the border region of South Limburg.

Das Deutsche Zentrum für Astrophysik



Spitzenforschung in der Lausitz

© knssr – stock.adobe.com

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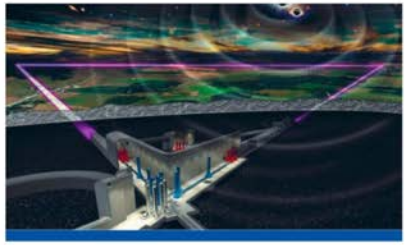

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Daten aus der ganzen Welt

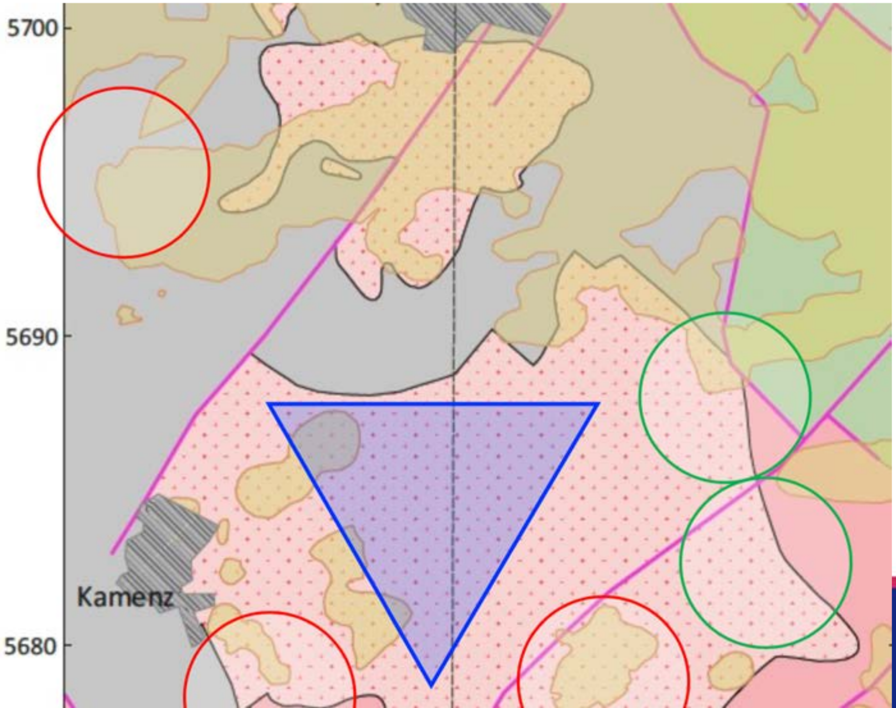
Datenströme verschiedener astronomischer Observatorien aus der ganzen Welt werden in Sachsen zusammenlaufen. Diese Datenmengen machen ein Mehrfaches des heutigen Internets aus und erfordern neue Technologien. Wir bändigen den Daten-Tsunami und beschleunigen die Digitalisierung.

Motor für Innovation

Wir bauen ein Technologiezentrum, in dem unter anderem neue Halbleiter-Sensoren, Silizium-Optiken und Regelungstechniken für Observatorien entwickelt werden. Dabei bauen wir auf die Erfahrung und das moderne Umfeld der Industrie in Sachsen auf, sorgen für die Ausgründung neuer Firmen und schaffen so Arbeitsplätze.

Astronomie von Weltrang

Neue Technologien öffnen zuvor unbekannte Fenster zum Universum – wir wollen diese im DZA verbinden. Ein Beispiel sind Gravitationswellen. Dafür untersuchen wir die Installation des geplanten europäischen Einstein-Teleskops im Granit-Stock der Oberlausitz. Dessen Bau würde an die Bergbau-Tradition der Region anknüpfen und wäre ein internationales Leuchtturm-Projekt.



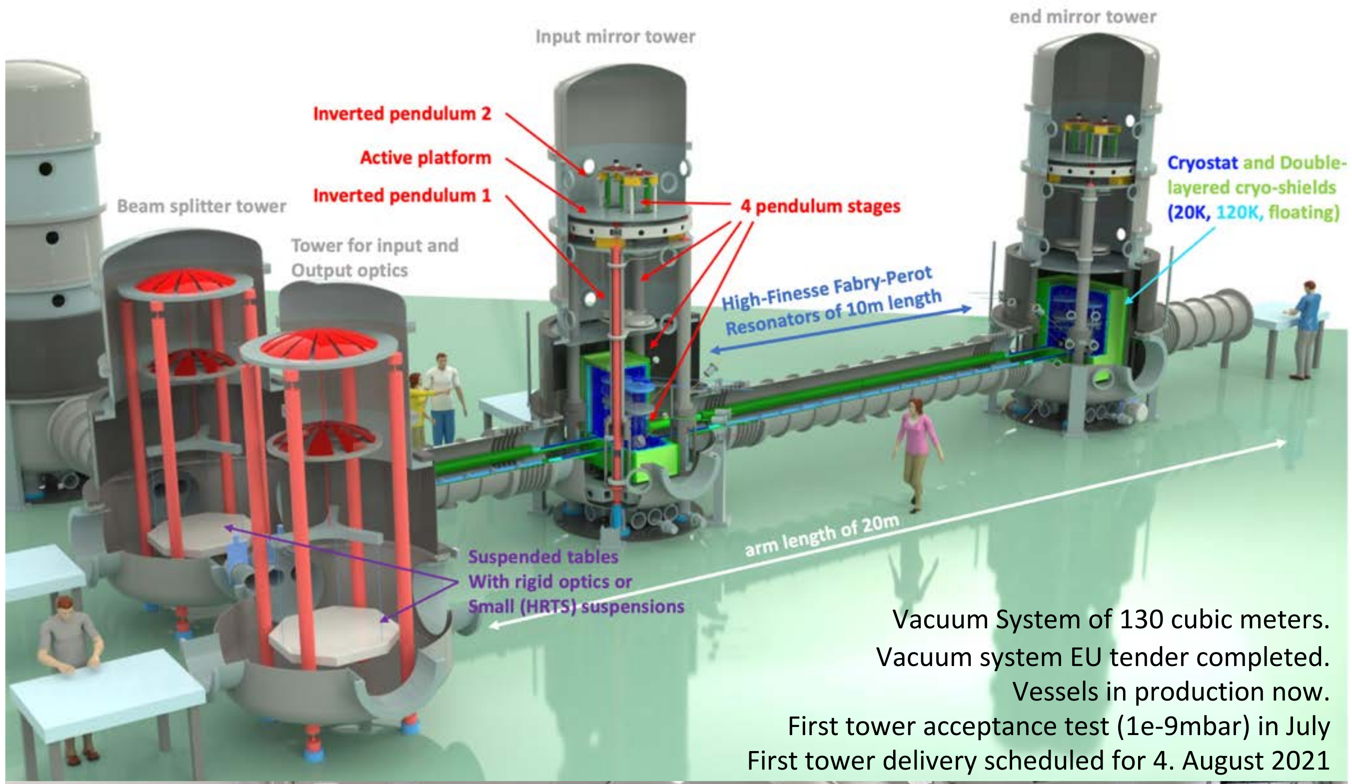
Slides credit: Günther Hasinger (ESA)

Outline

- What have we learned Gravitational Waves so far?
- How to measure Gravitational Waves
- Overview of Einstein Telescope
- Hosting ET in the Euregio Meuse Rhine?

ETpathfinder Overview

- New facility for testing ET technology in a low-noise, full-interferometer setup.
- Key aspects: Silicon mirrors (3 to 100+kg), cryogenics cryogenic liquids and sorption coolers, water/ice management), “new” wavelengths (1550 and 2090nm), coatings
- Start with 2 FPMI, one initially at 120K and one 15K (2022+).
- 20 partners from NL/B/G/FR/SP/UK
- Initial capital funding of 14.5 MEuro.
- Detailed Design Report available at apps.et-gw.eu/tds/?content=3&r=17177
- Open for everyone interested to join.
- www.etpathfinder.eu

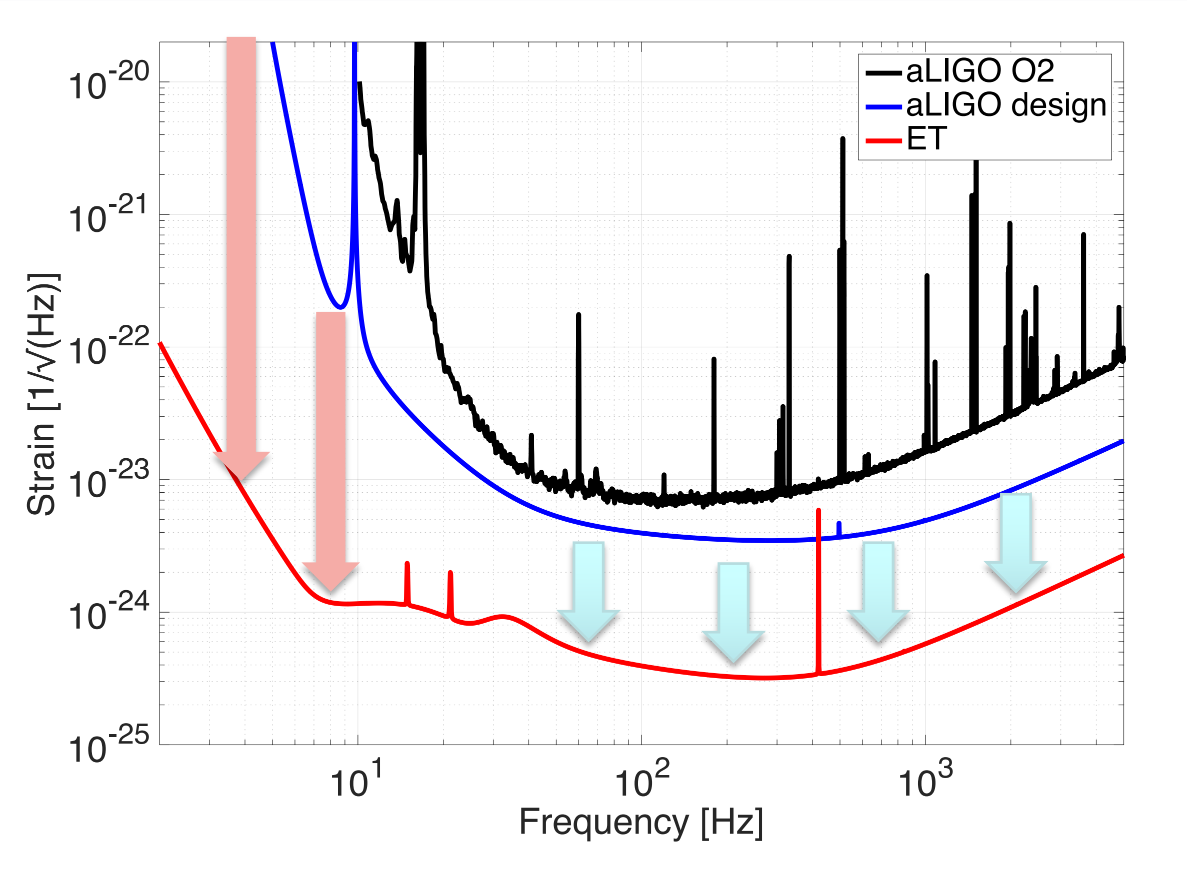


Vacuum System of 130 cubic meters.
Vacuum system EU tender completed.
Vessels in production now.
First tower acceptance test (1e-9mbar) in July
First tower delivery scheduled for 4. August 2021

Why ETpathfinder needed?

The Low-Frequency Challenge:

- At mid and high frequency we aim for factor ~10 improvement.
- At low frequency we are aiming for factors 100, 1000 and more improvement.
- **Needs fundamental changes in technology and concepts, that need testing and prototyping.**



New Technologies

Nikhef

ET requires technological advances on all fronts:

- New mirror material => Silicon
- New temperature => 10-20K
- New laser wavelength => 1.5-2.1 microns
- Advanced quantum-noise-reduction schemes

ETpathfinder Partners

Interreg
EUROPESE UNIE
Vlaanderen-Nederland
Europees Fonds voor Regionale Ontwikkeling

provincie limburg

Ministerie van Onderwijs, Cultuur en Wetenschap

Provincie Noord-Brabant

SMART HUB

Vlaamse Regering

VLAAMS-BRABANT

Provincie Antwerpen

Ministerie van Economische Zaken

GHENT UNIVERSIT

Universiteit Antwerpen

VUB VRIJE UNIVERSITEIT BRUSSEL

Nikhef

KU LEUVEN

Maastricht University

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

UNIVERSITY OF TWENTE.

LIÈGE université

vito

TNO

UHASSELT

LAPP
Laboratoire d'Annecy de Physique des Particules

UNIVERSITY OF BIRMINGHAM

IFAE
EXCELENCIA SEVERO OCHOA
Institut de Física d'Altes Energies

Max-Planck-Institut für Gravitationsphysik
ALBERT-EINSTEIN-INSTITUT

UCLouvain

Fraunhofer
ILT

RWTH AACHEN UNIVERSITY

From ETpathfinder Advisory Board (STAC) report

- […] Overall, the ETPF-STAC was very impressed with the vision for the facility, the technical capability of the leader and team, and the scope of the effort. It will be transformative for the field to have a facility and a research program covering the foreseen capabilities of the installation, and it can become a very natural center for technical innovation and scientific breakthroughs in precision measurement, interferometry, cryogeny for gravitational-wave detectors, and for the formation of a next generation of gravitational-wave scientists (to handle the next generation of gravitational-wave detectors). The growth of the team (and of the institutions interested in participating) is an exciting development and speaks to the timeliness and centrality of this infrastructure. […]
- The ETPF-STAC is very excited to be part of the establishment and exploitation of this unique facility and this dynamic team.


Start Construction: April 2020


Drilling 170 pillars


July: ~1000 t of concrete poured


Oct : First cleanroom walls being installed.
Cleanroom in operation ~ March 2021

Ca. 1980s

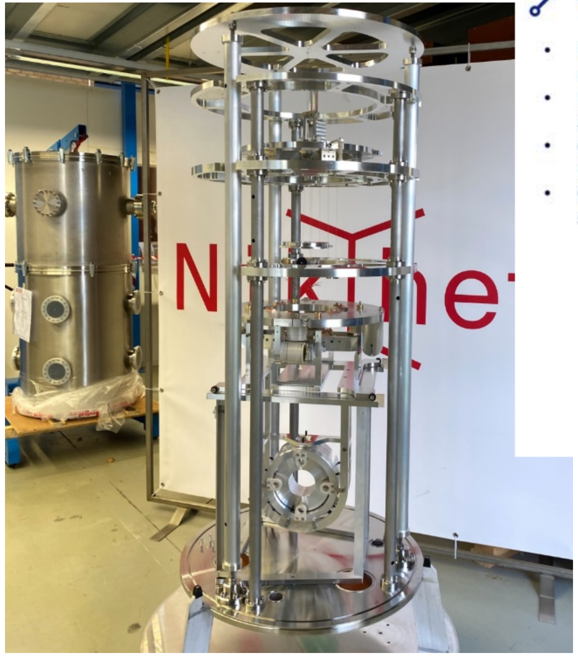

January 2020

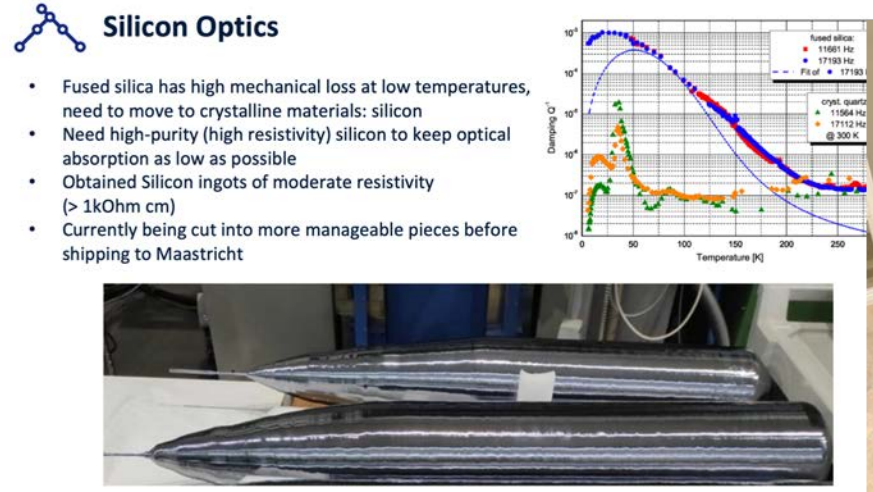

ALTMANN - 2 x 2 to
Summer 2021

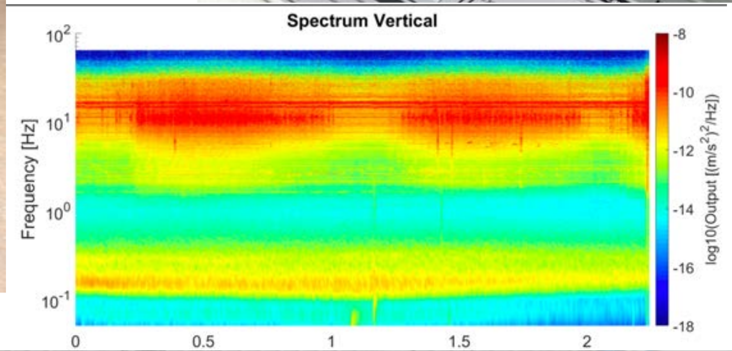

Now

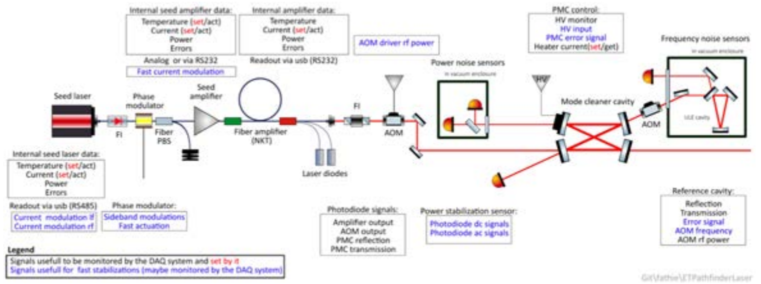
Official Opening in Nov 2021
by Ingrid van Engelshoven

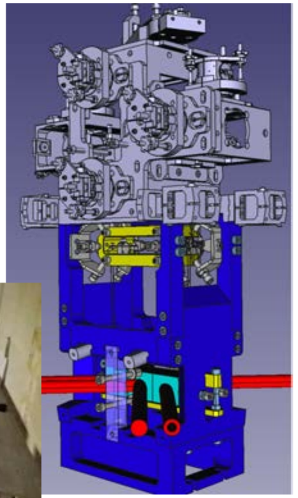
Some Highlights of recent ETpathfinder Activities

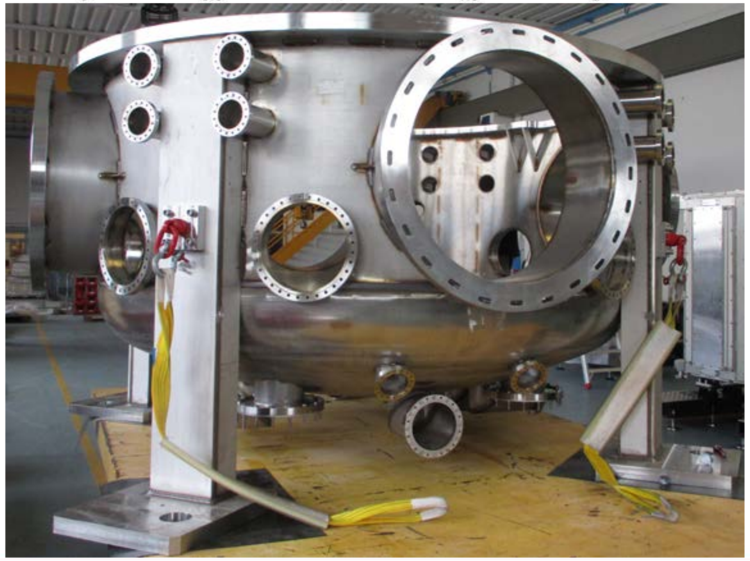


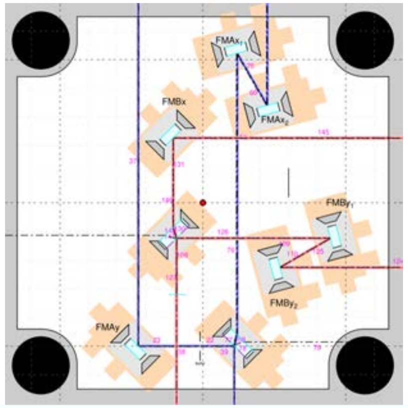






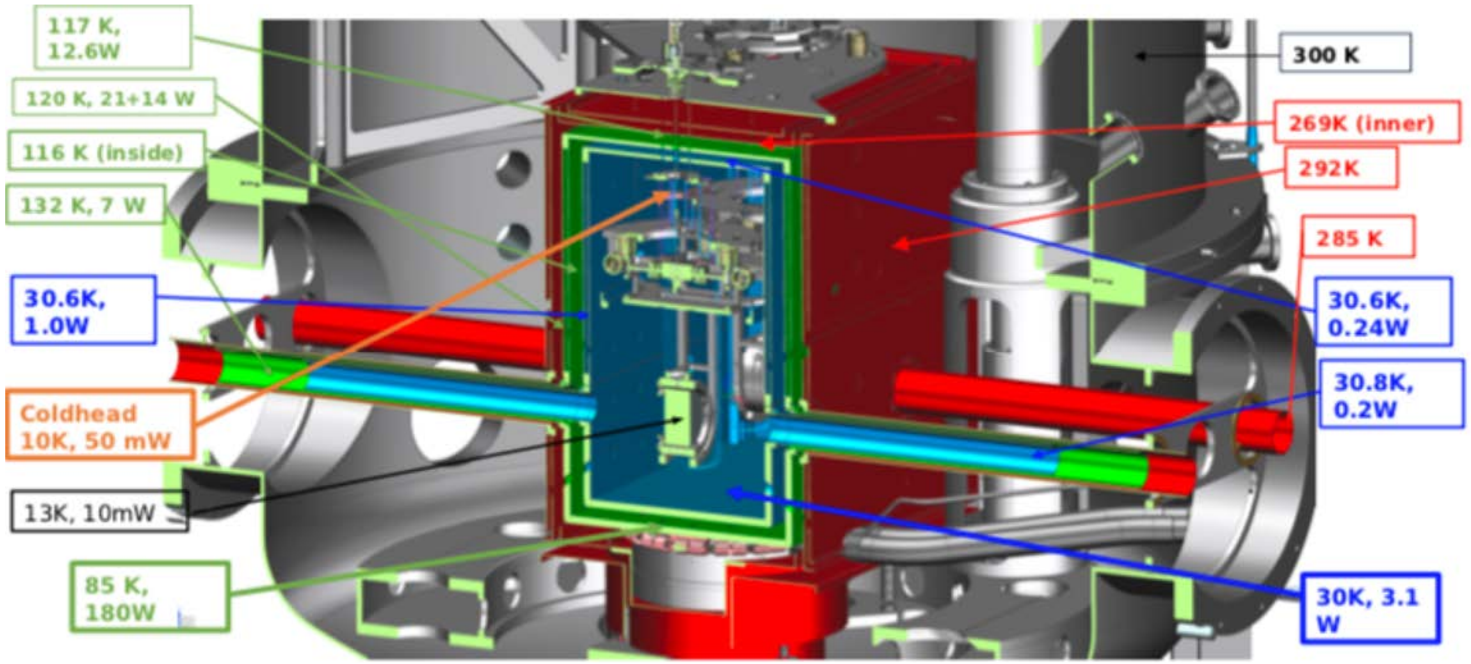




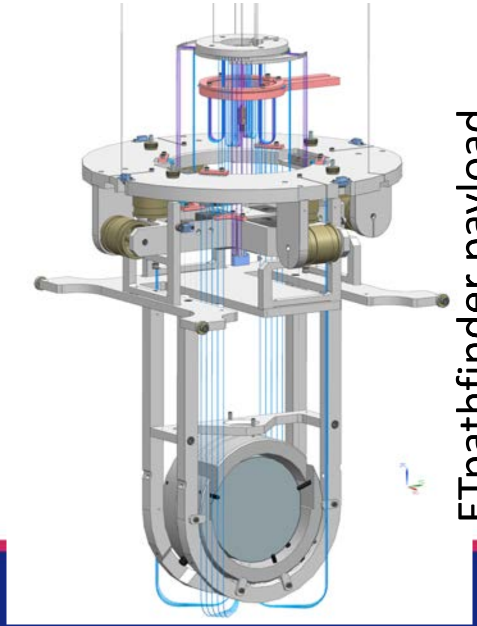


Cryogenics

- Mirrors need to be cooled to cryogenic temperatures (~15K, 123K), without introducing noise, i.e. cooling only possible via thin suspension wires.
- General approaches:
  - Dry system: pulse-tubes. Challenge = reduce and isolate vibrational noise.
  - **Sorption coolers (base line in ETpathfider) = more quite, less cooling power.**
  - Cryogenic Liquids: LN2, He, HeII. Challenge = avoid bubbling; transfer liquids from surface 300m above the caverns …



ETpathfinder cooling budget

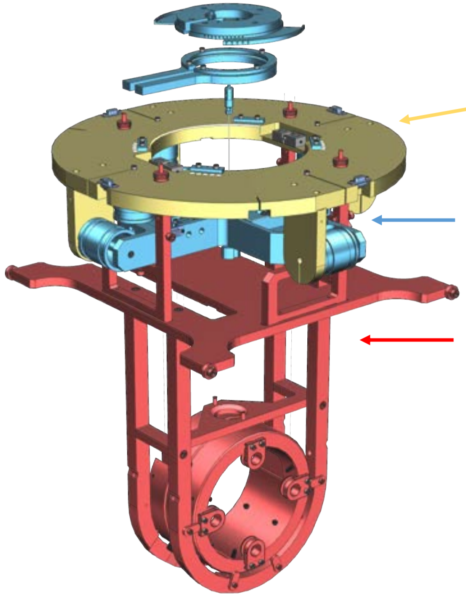


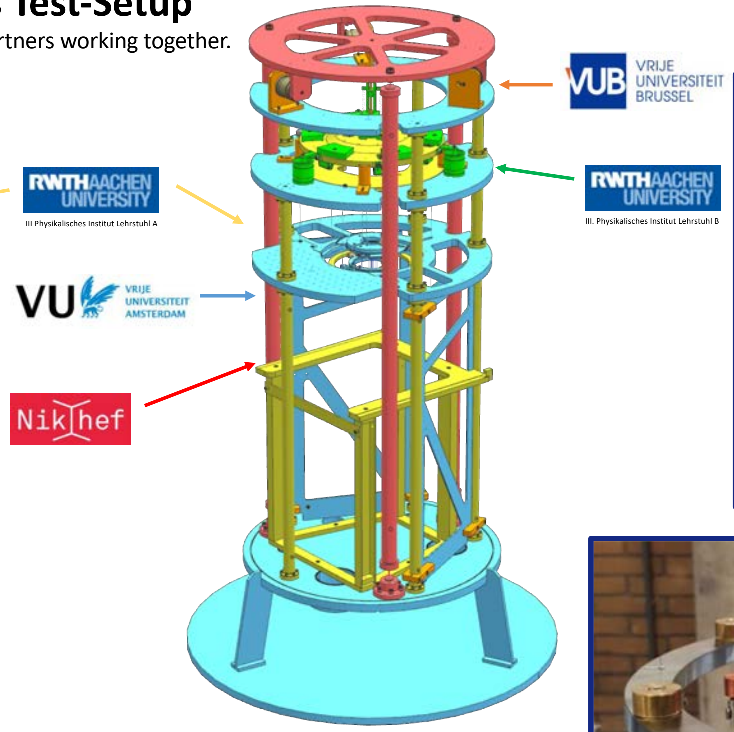
ETpathfinder payload

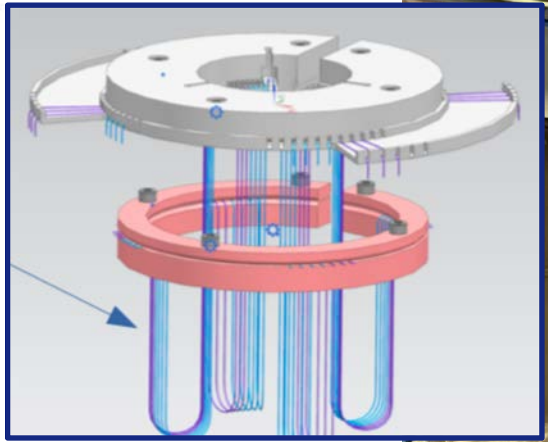
R&D example: How to cool a mirror without vibrations?

ETpathfinder: Thermal Links Test-Setup

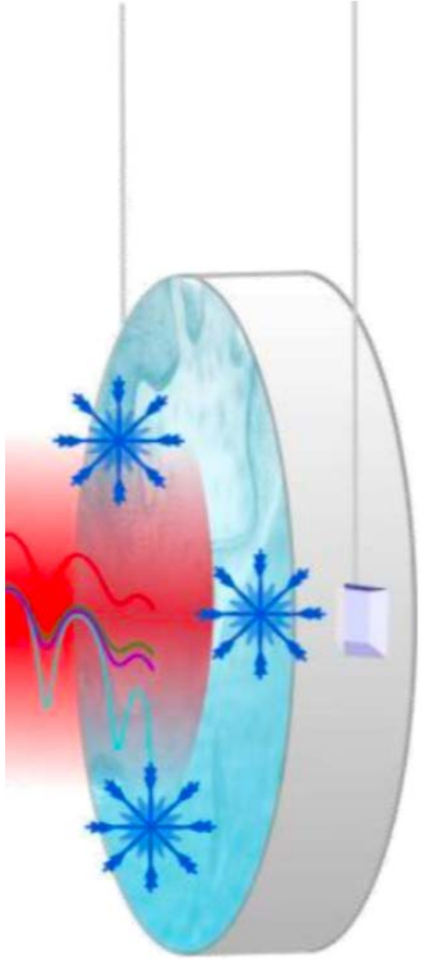
Mechanical workshops of several ETpathfinder Partners working together.

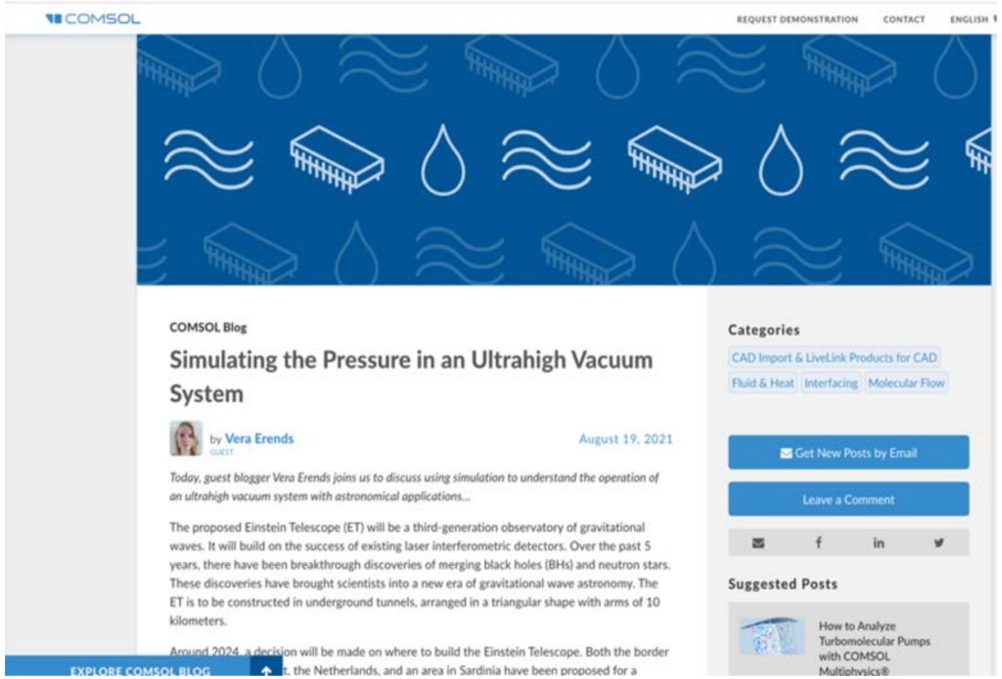






R&D example: How to avoid Ice on a mirror?

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COMSOL Blog

Simulating the Pressure in an Ultrahigh Vacuum System

by Vera Erends
GUEST

August 19, 2021

Today, guest blogger Vera Erends joins us to discuss using simulation to understand the operation of an ultrahigh vacuum system with astronomical applications...

The proposed Einstein Telescope (ET) will be a third-generation observatory of gravitational waves. It will build on the success of existing laser interferometric detectors. Over the past 5 years, there have been breakthrough discoveries of merging black holes (BHs) and neutron stars. These discoveries have brought scientists into a new era of gravitational wave astronomy. The ET is to be constructed in underground tunnels, arranged in a triangular shape with arms of 10 kilometers.

Around 2024, a decision will be made on where to build the Einstein Telescope. Both the border ...t, the Netherlands, and an area in Sardinia have been proposed for a

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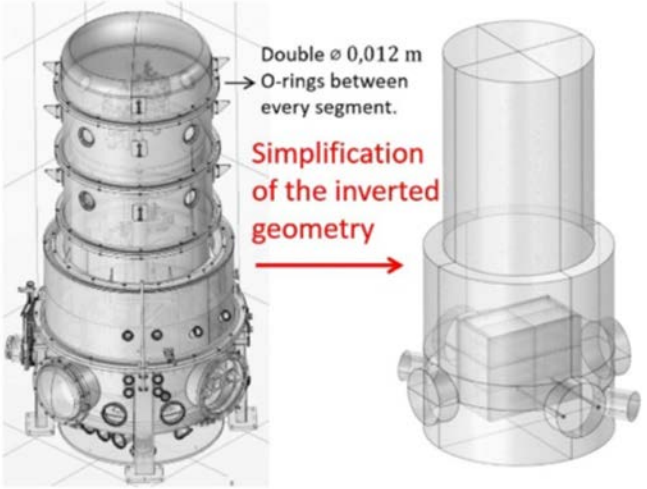
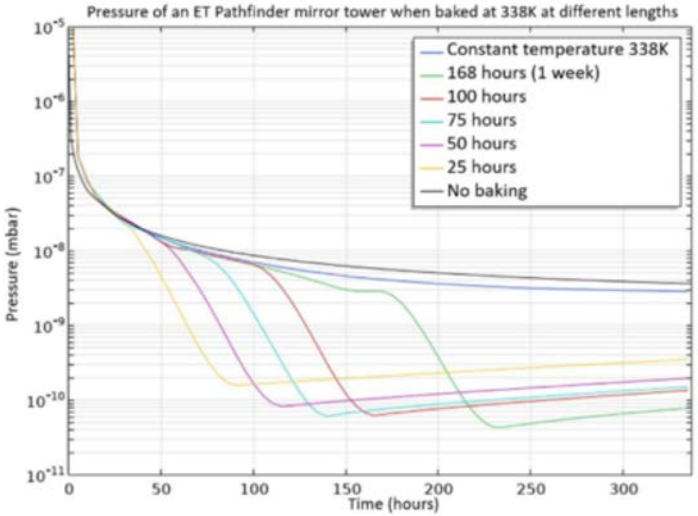


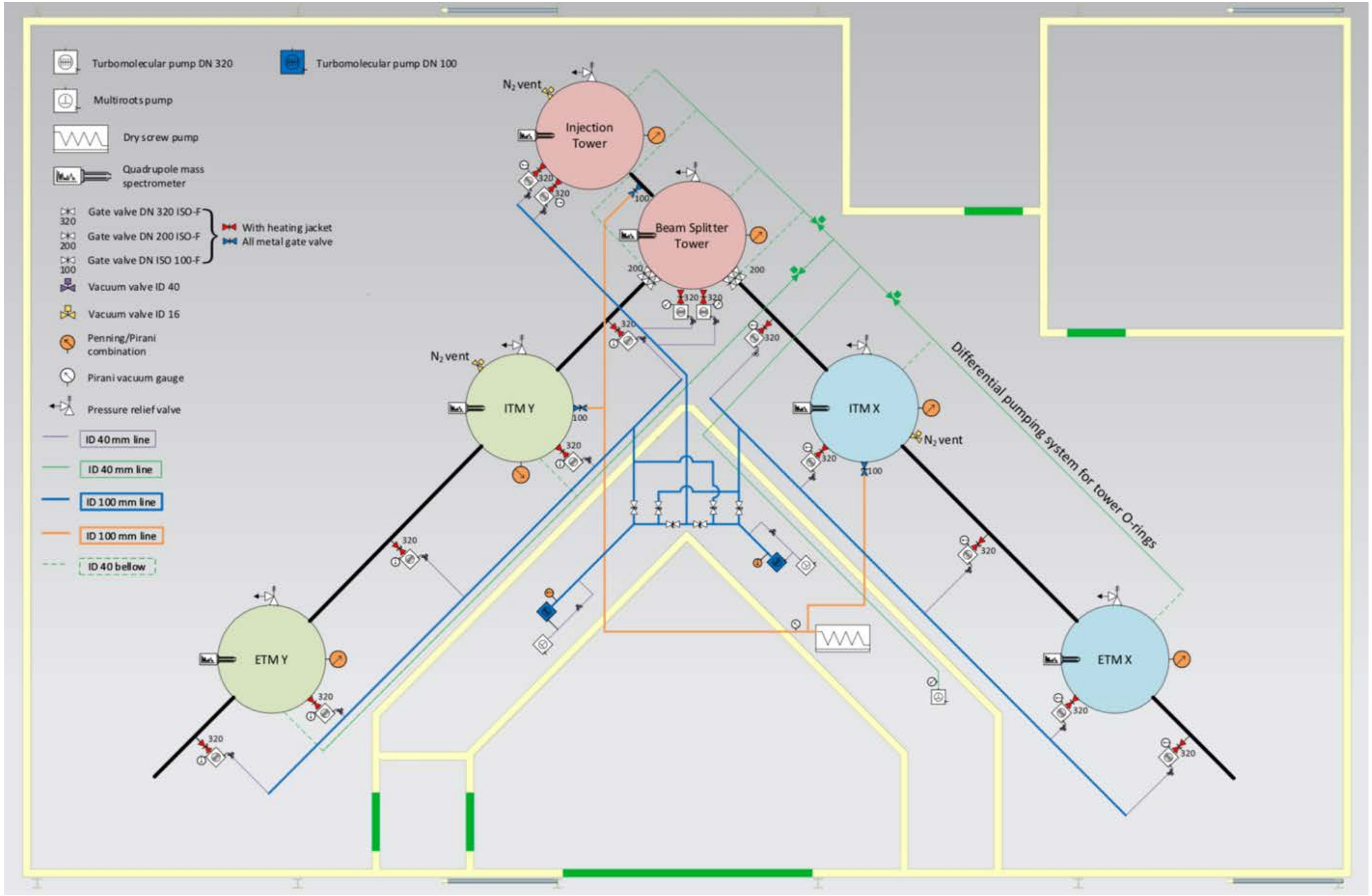


[S.Hild]

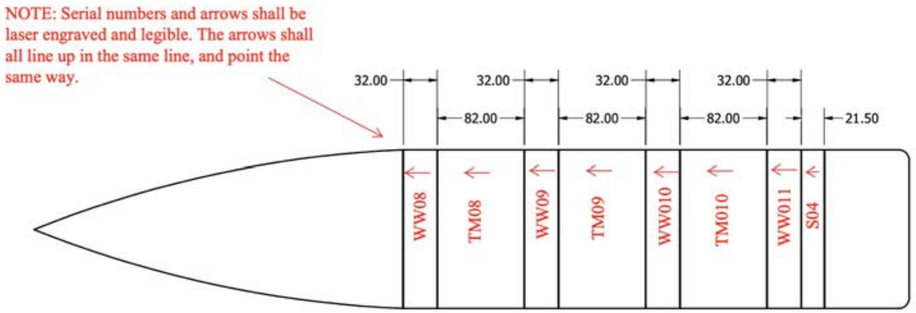
Vacuum P&I

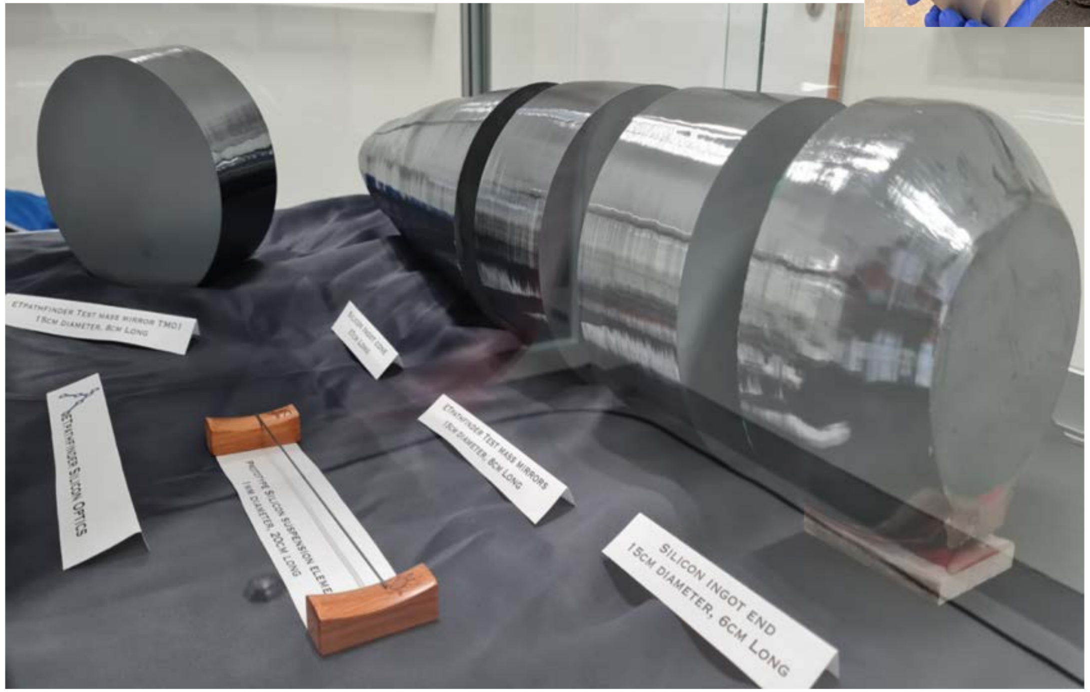
Looking for a team to help with the vacuum control system design:

- 20 pumps
- 42 valves
- 6 RGAs
- 24 penning/piranies



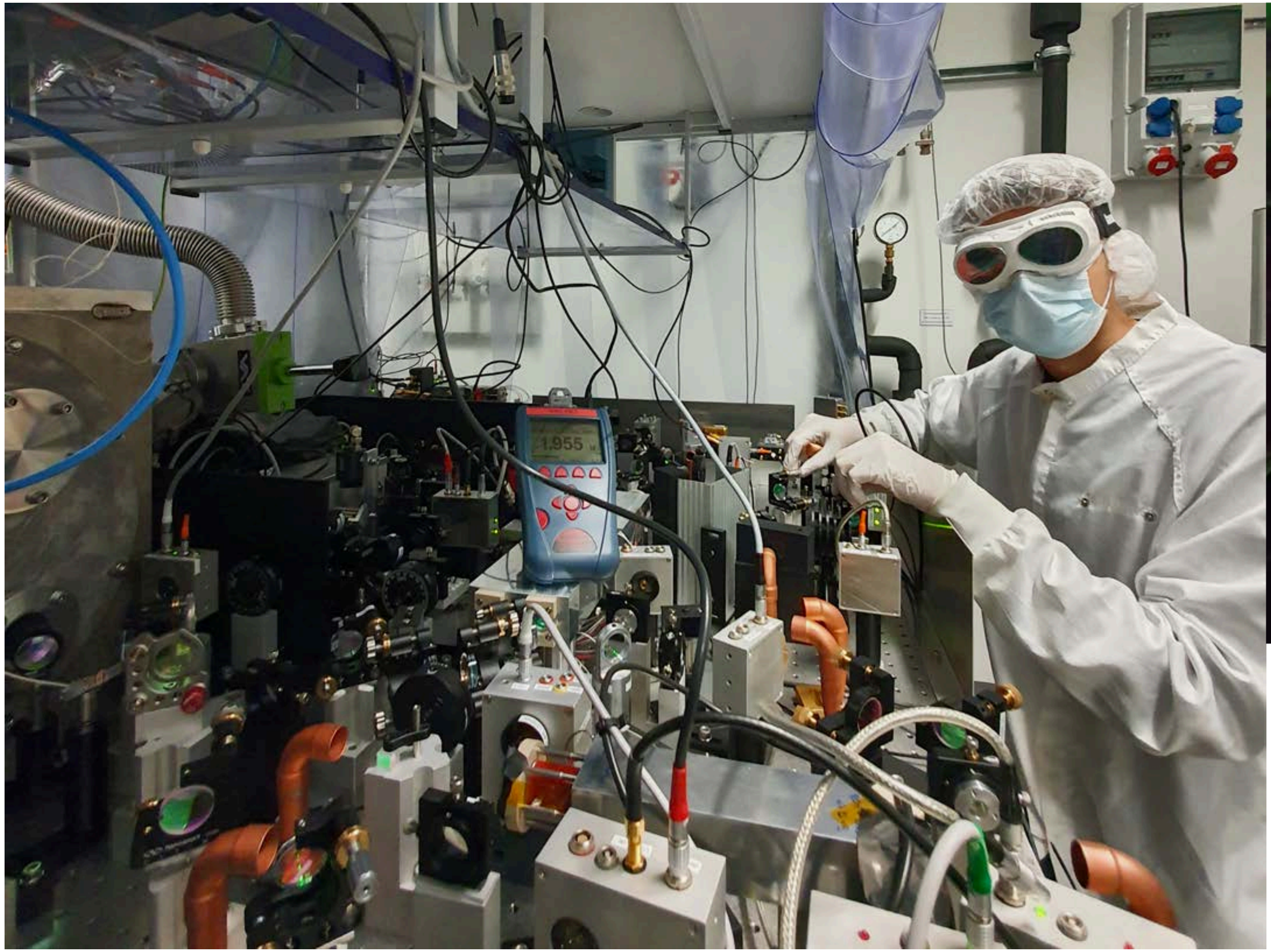
R&D example:
new mirror material = silicon





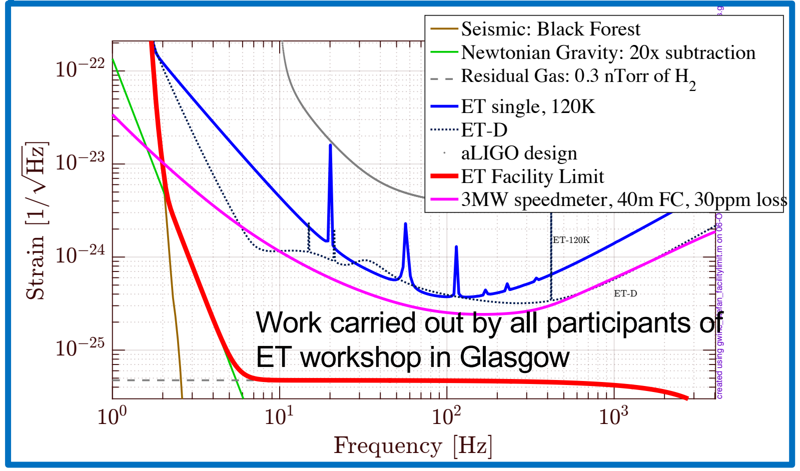
R&D example: New lasers and Quantum tricks

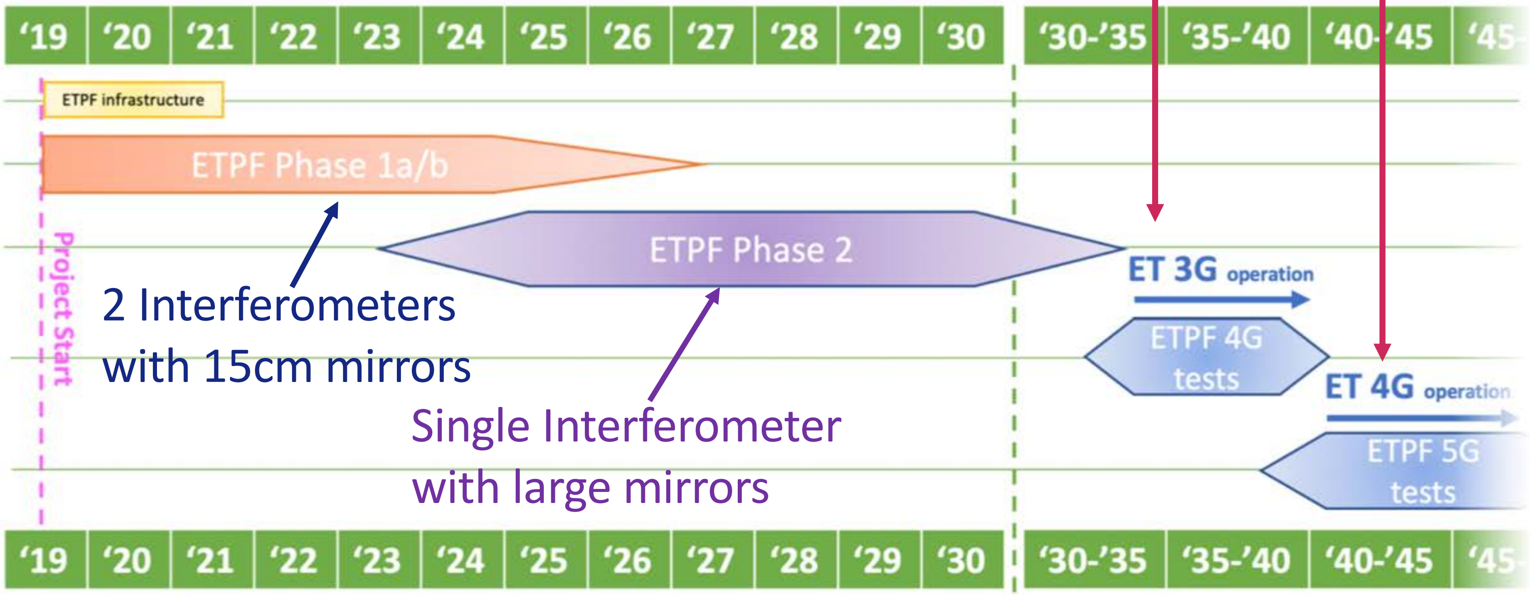
European Research Council
Established by the European Commission



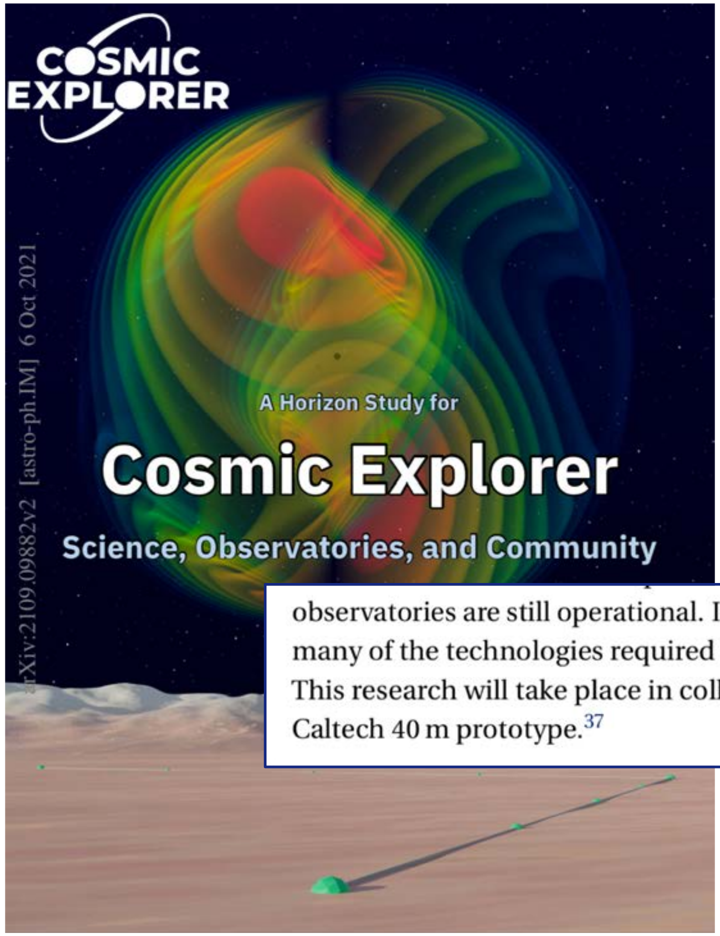
ETpathfinder is a longterm acitivity (and independ of ET site decision)

- ESFRI application states ET will be operational from 2035 to 2085.
- Expect many ET detector upgrades over the 50 years.
- While ET operates and observes in "generation X technology" ETpathfinder can do R&D for "generation X+1 technology"





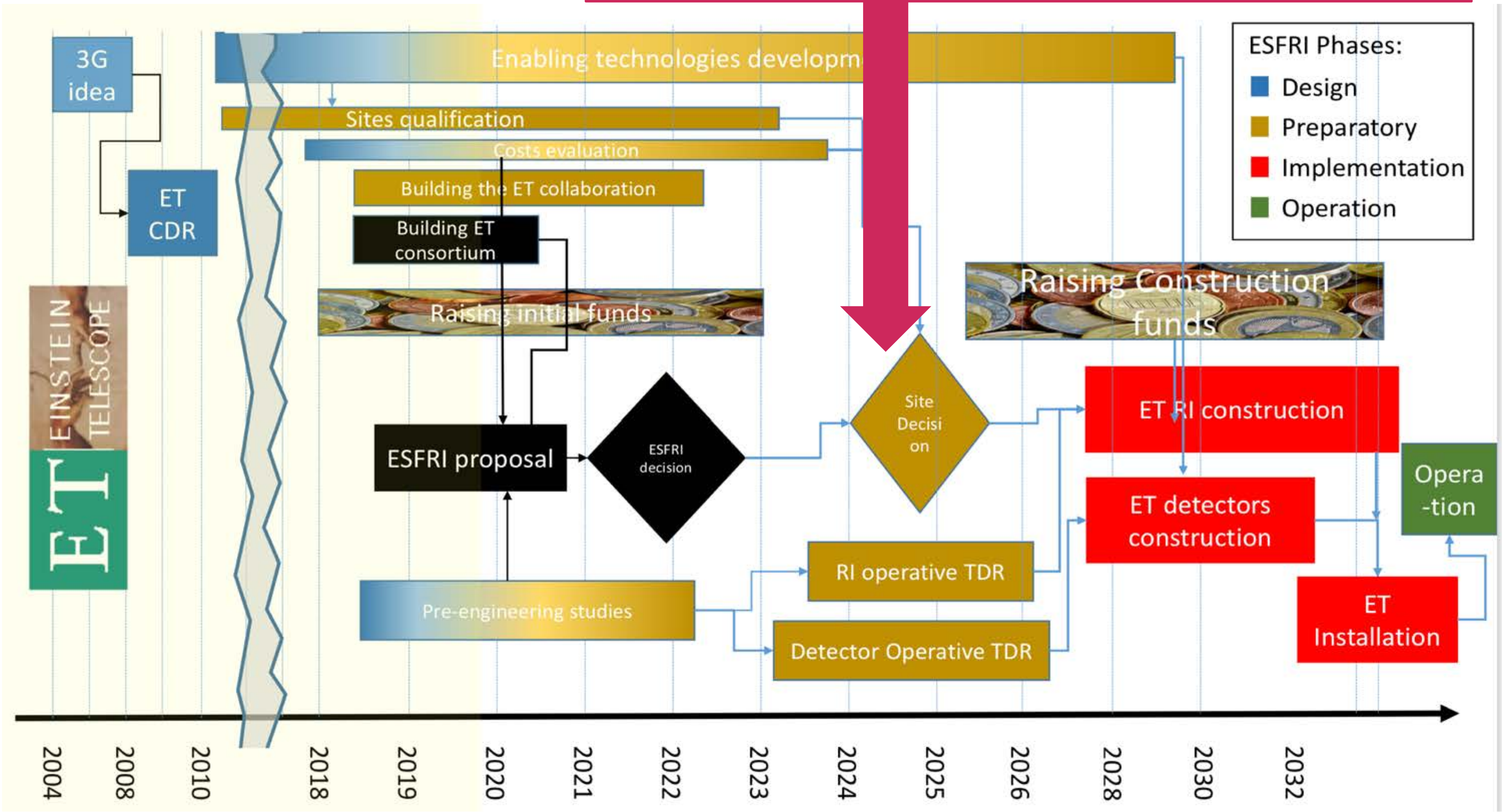
Beyond ET …



observatories are still operational. In addition to ensuring that CE will achieve its full potential, many of the technologies required for CE may also be used to enhance existing observatories. This research will take place in collaboration with other projects like ETpathfinder[38] and the Caltech 40 m prototype.[37]

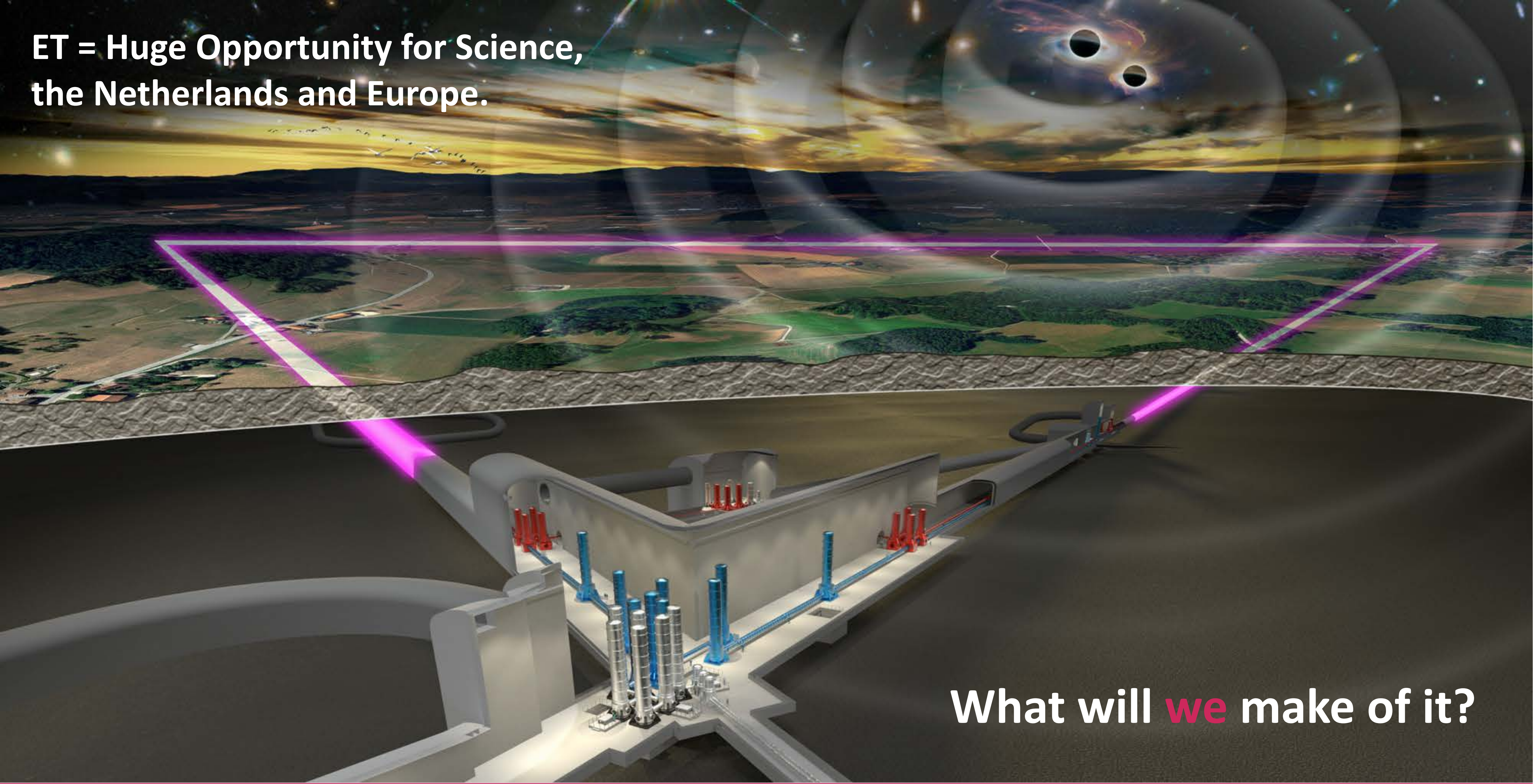
ET timeline

By 2024 the governments of host countries (N/B/G) need to have decided whether to support or not.



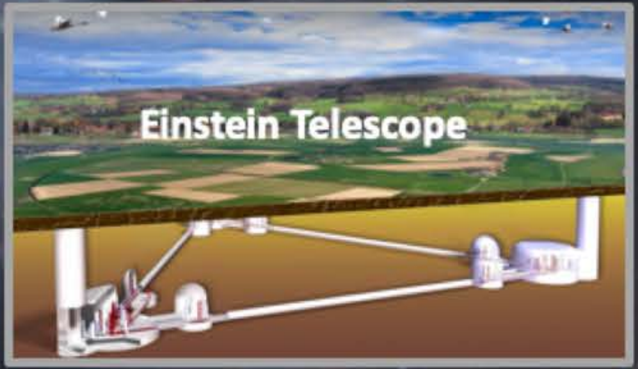
- Idea for ET like-observatory is from 2004
- CDR was finished in 2011
- Discovery of GWs in 2015/16 brought ET really to life

ET = Huge Opportunity for Science, the Netherlands and Europe.



What will we make of it?

Actually, really exciting times ahead on all gravitational wave fronts!



+ LIGO India

+ Pulsar Timing Array

+ many other future projects

Thank you for your attention.

Questions?

EXTRA SLIDES

WP5 - Status of design and production

Tenders awarded

- Large GAS filters for suspended benches
- Benchtop suspensions

Tenders in preparation

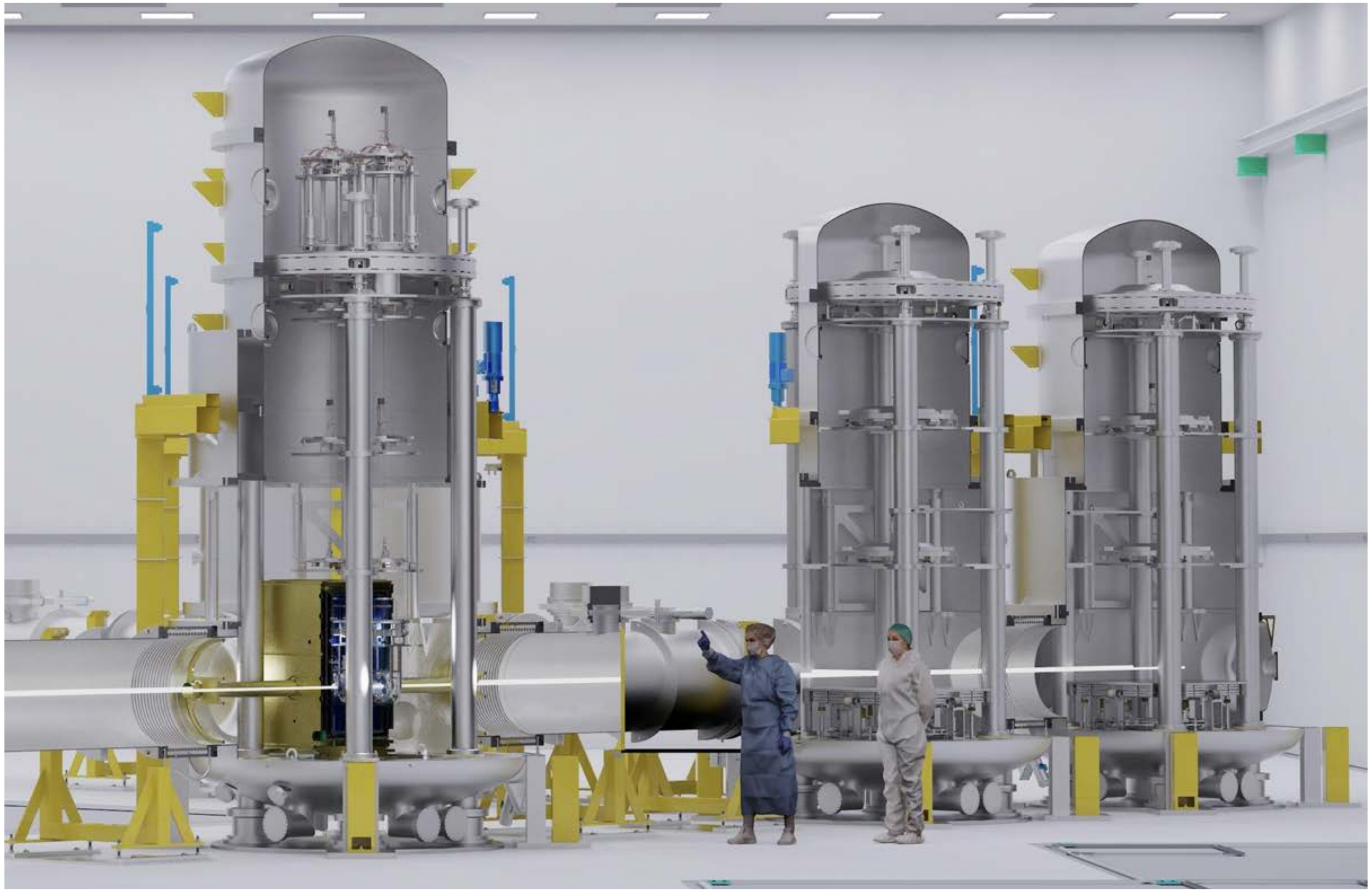
- Pre-isolation platforms for all towers

Tenders to be published

- 123K payloads: design under review
- Mirror isolation chains: design reviewed, production drawings in preparation

Short term objectives

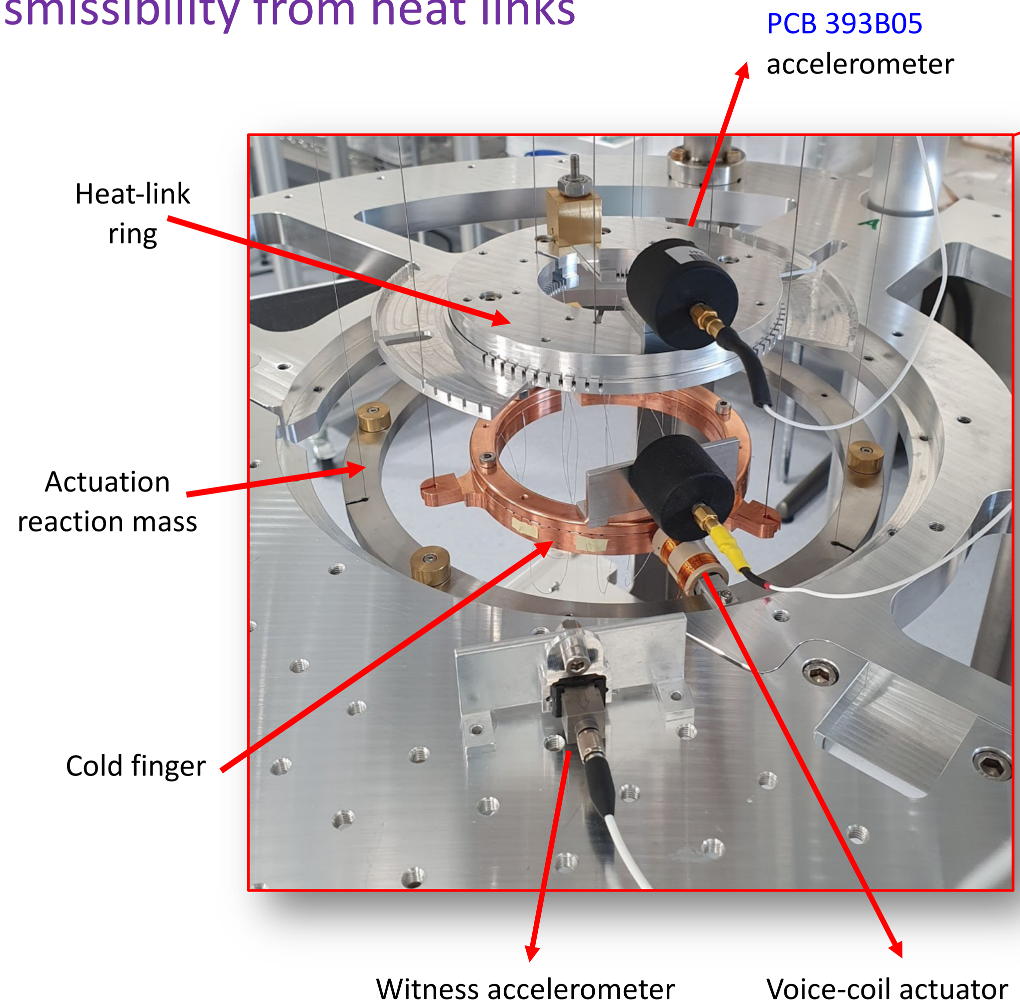
- Complete tendering by end of April
- Start pre-assembly end of summer

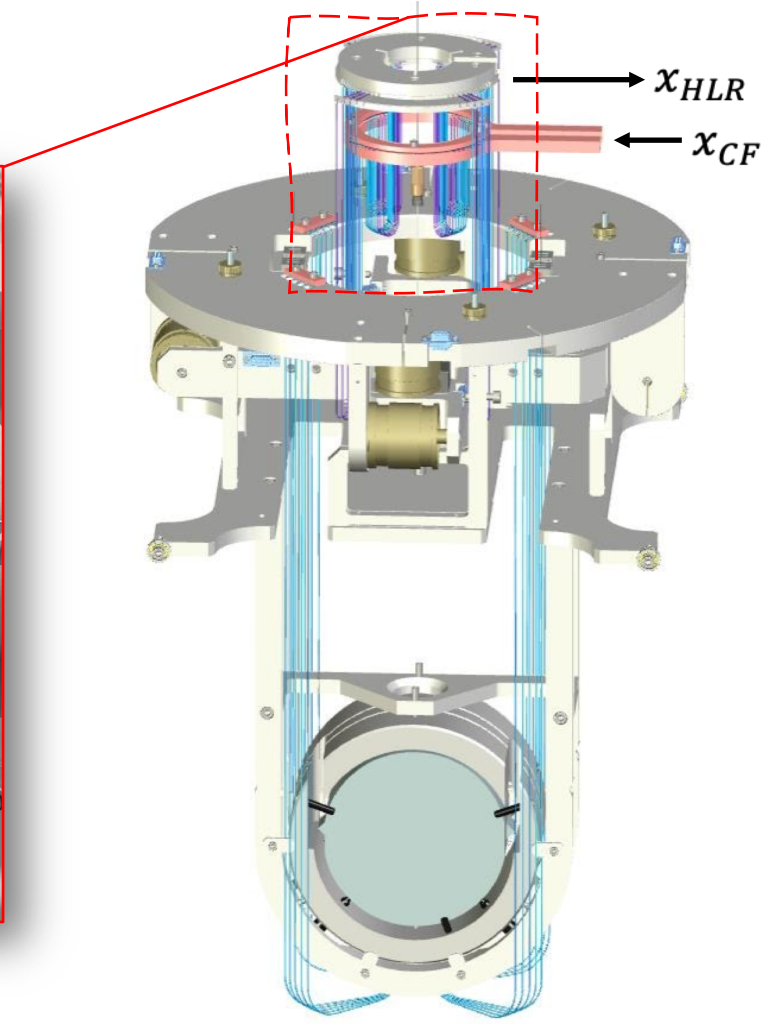


WP5 - Testing prototypes

Modeling and measuring transmissibility from heat links

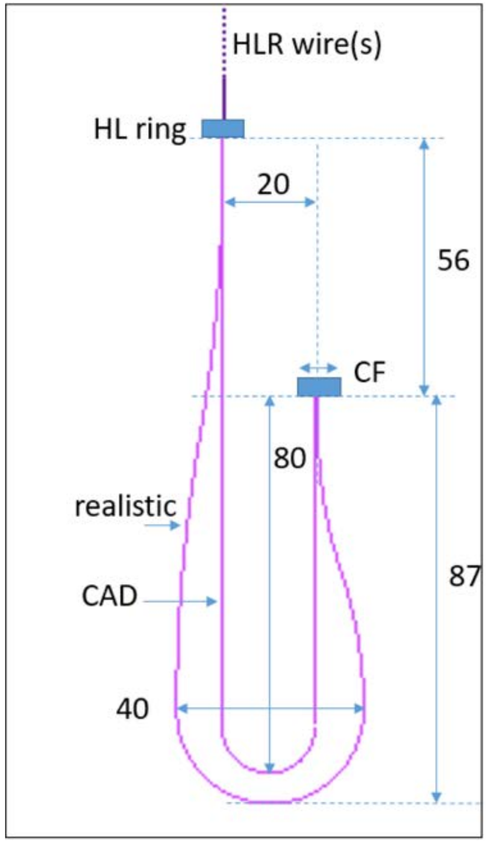
Payload test setup @ Nikhef





WP5 - Testing prototypes

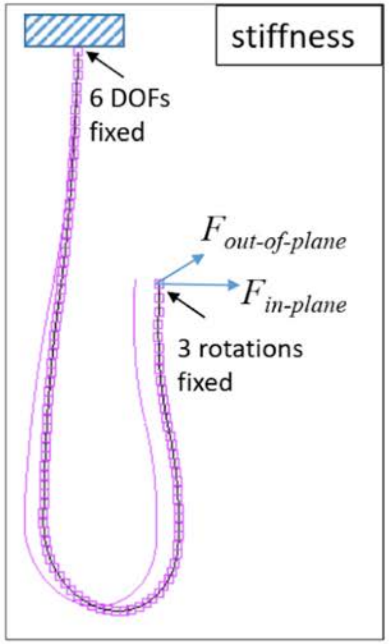
Modeling and measuring transmissibility from heat links

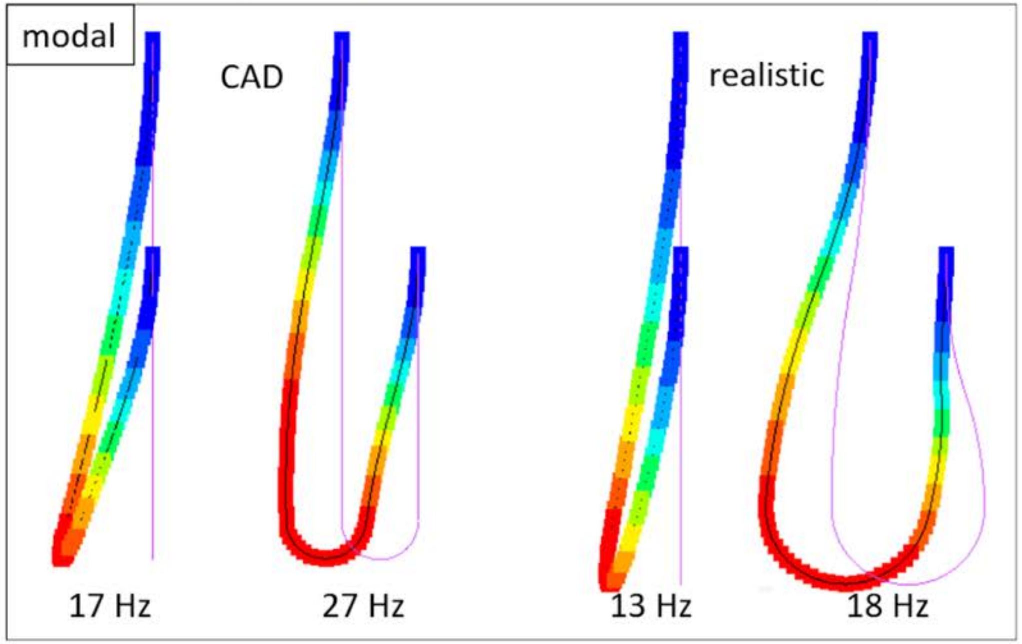


0.25-mm diameter, 22-cm long Al-5083 wire

HL wire stiffness and modal shapes (FEM)

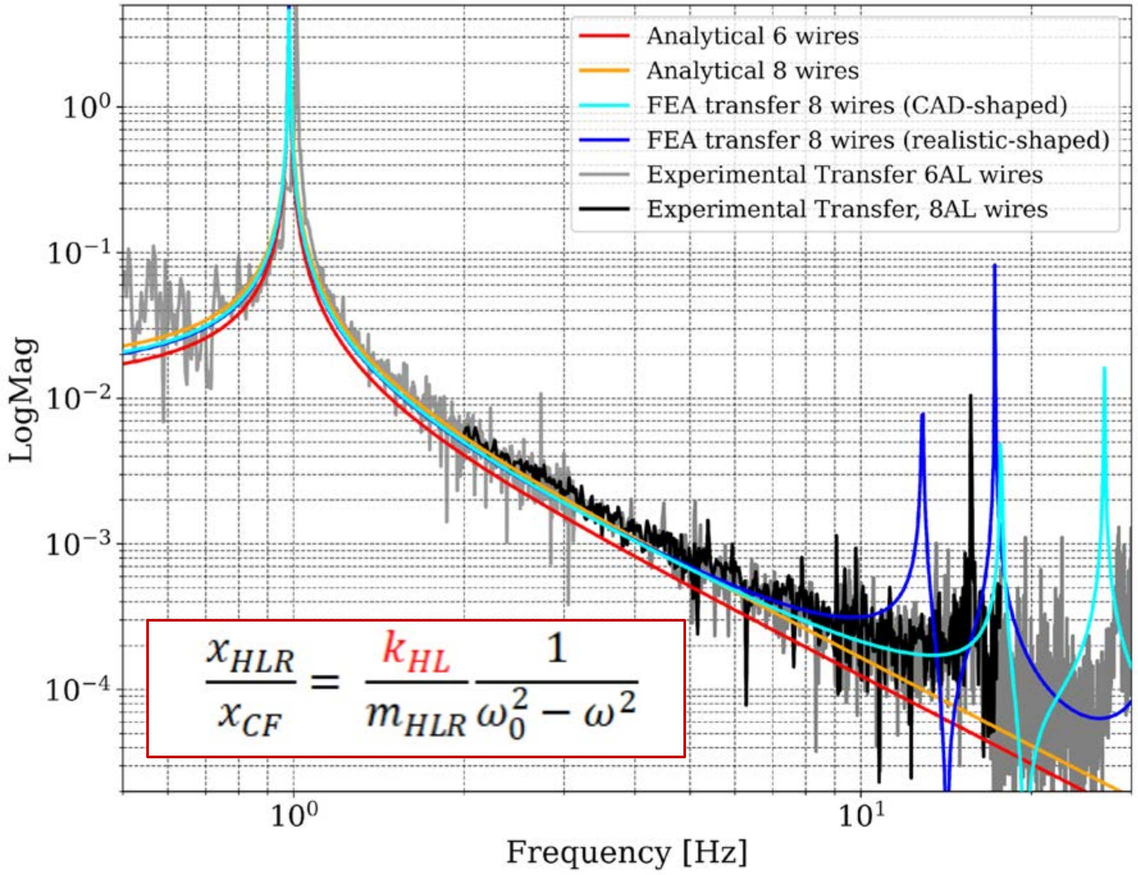
description		*symbol*	*value*		*unit*	*comment/formula*
	model:		*CAD*	*realistic*		
HL wires (FEM)	single wire stiffnesses	$k_{wire,in\text{-}plane}$	0.049	0.047	N/m	*from static FEM*
		$k_{wire,out\text{-}of\text{-}plane}$	0.037	0.035		
	total jellyfish stiffness	k_{Nwires}	0.345	0.326		$N_{HLwire}(k_{wire,in\text{-}plane}+k_{wire,out\text{-}of\text{-}plane})/2$
	1st in-plane mode	$f_{wire,in\text{-}plane}$	27	17	Hz	*from modal FEM*
	1st out-of-plane mode	$f_{wire,out\text{-}of\text{-}plane}$	18	13		



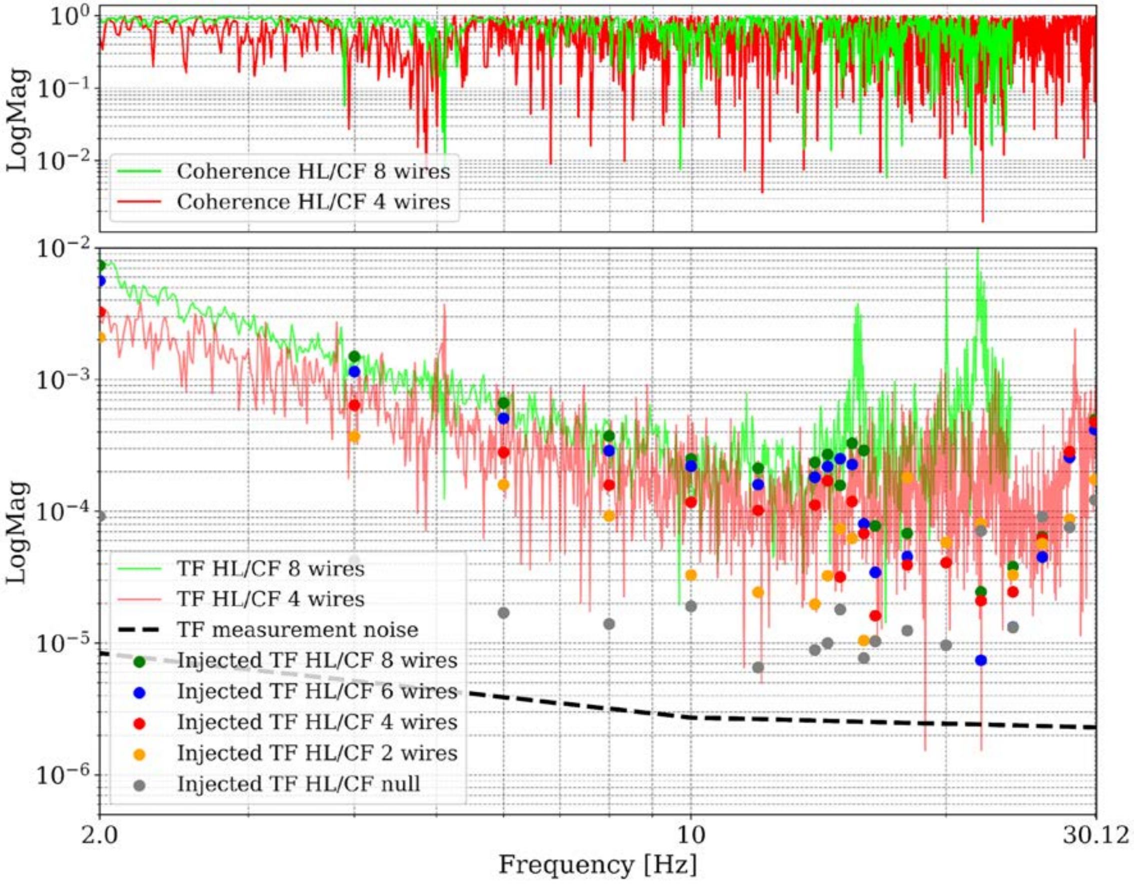


WP5 - Testing prototypes

Modeling and measuring transmissibility from heat links



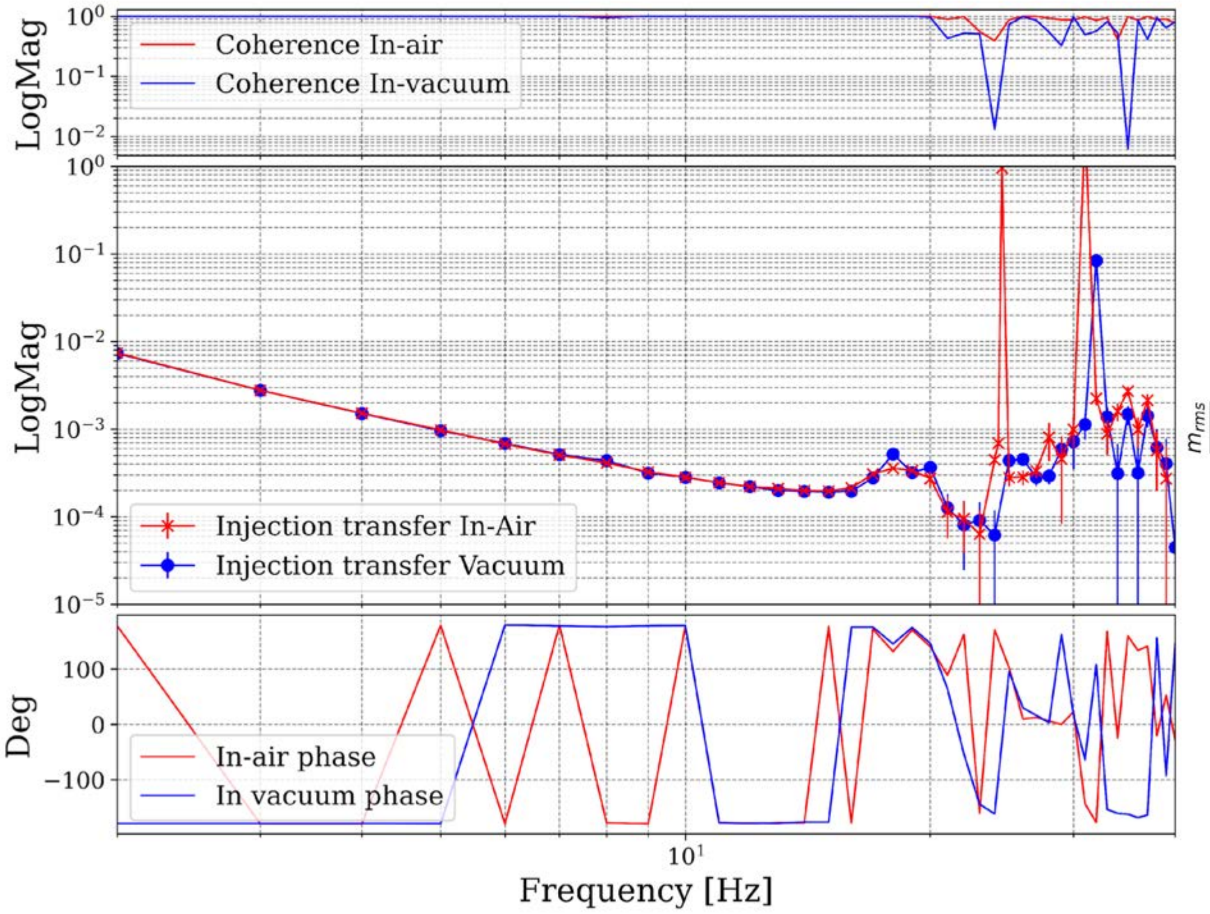
$$\frac{x_{HLR}}{x_{CF}} = \frac{k_{HL}}{m_{HLR}} \frac{1}{\omega_0^2 - \omega^2}$$

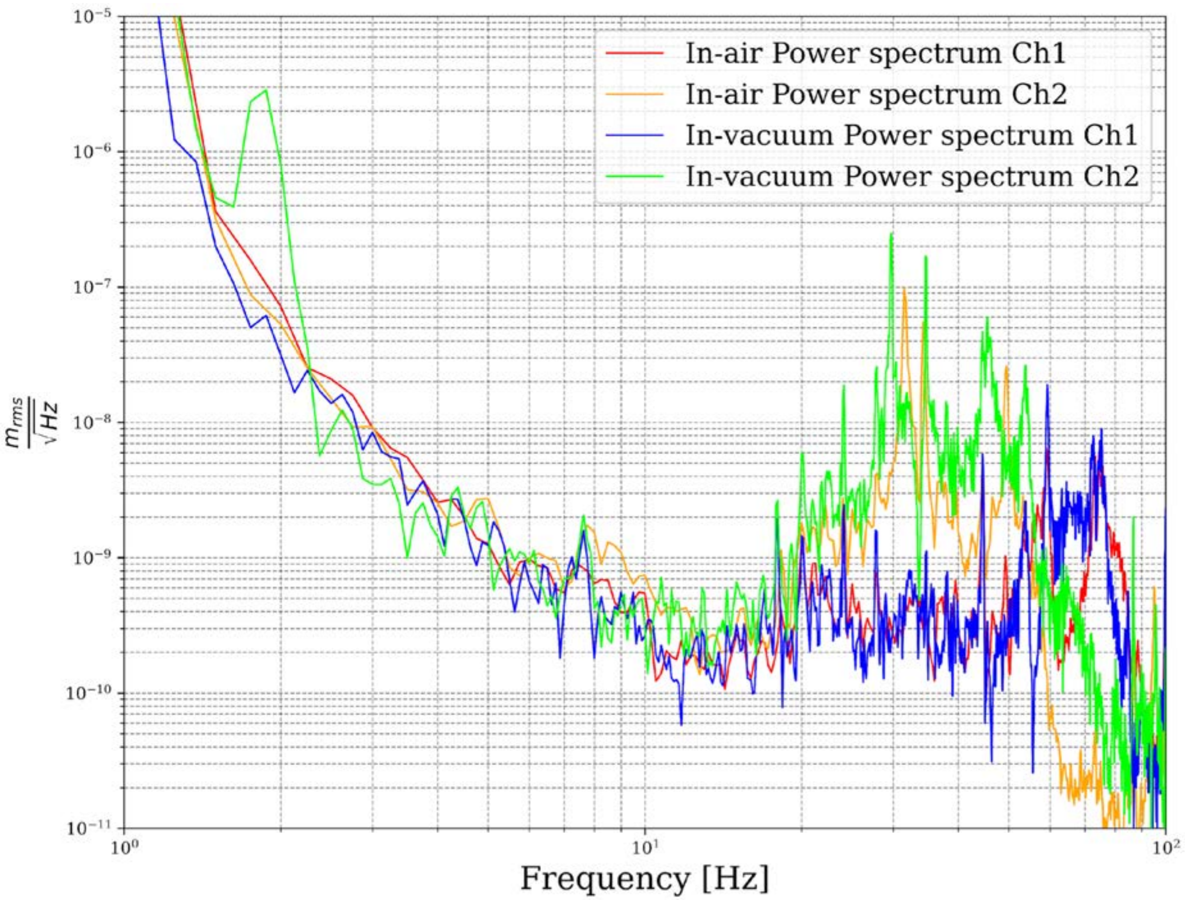


- Modeling the heat-link as a spring with stiffness k_{HL} estimated from the FEM gives a fair agreement with the measurements
- TF attenuation vs number of links qualitatively as expected; shape and arrangement of the wires also plays a role

WP5 - Testing prototypes

Modeling and measuring transmissibility from heat links





- No significant improvement by measuring in vacuum; structure observed around 18Hz compatible with the FEM
- Outcome: modeling tools have been validated and can be used for design of the 20K payload

WP5 - Testing prototypes

Pre-isolation platform prototype @ Nikhef

Pre-isolation platform

- Assembly and yaw centering procedure validated

- Weight balancing mechanism works !! Accurate (within +/-2.5%) weight balance over the four legs has been achieved

- Loading curve measured: 1002kg measured vs 1112kg modelled @50mHz. The system appears to be slightly more compliant than calculated. Design of flexures will be updated accordingly.

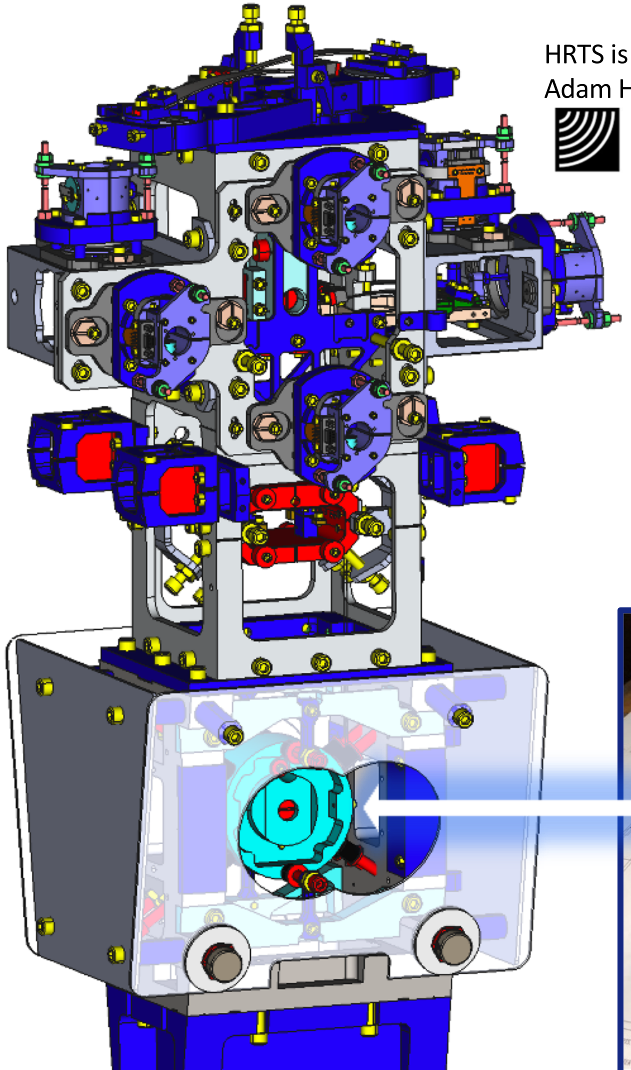
50-mHz natural frequency, 3.5-m high inverted pendulum with four legs

IP leg prototype in action

Timelapse video at 10x speed

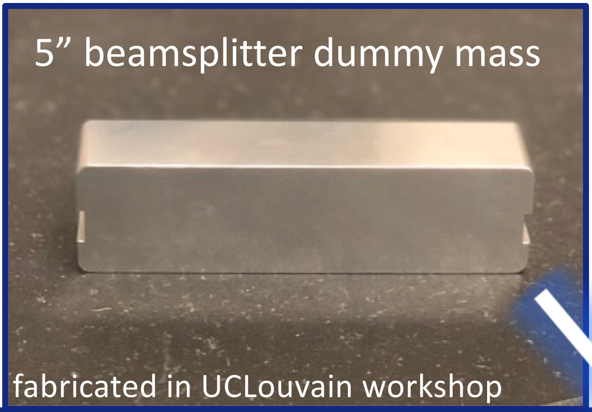
WP5 - Benchtop suspensions

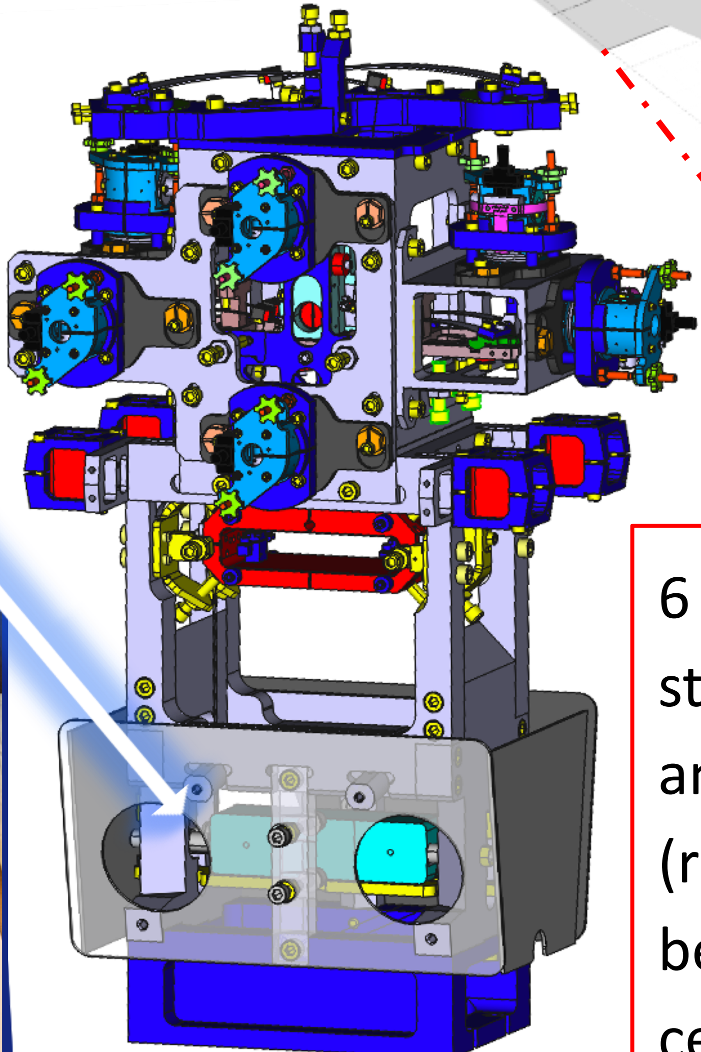
Tender published Dec 2021 and we have one offer at < 50% of expected cost

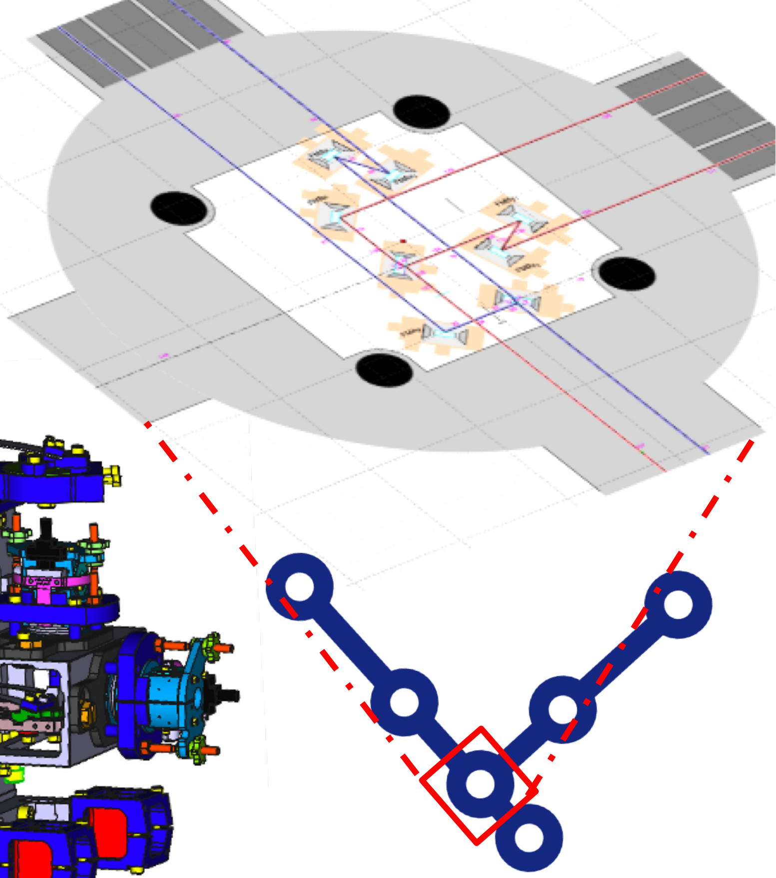


HRTS is a LIGO A+ design by
Adam Huddart et al. (STFC)

LIGO





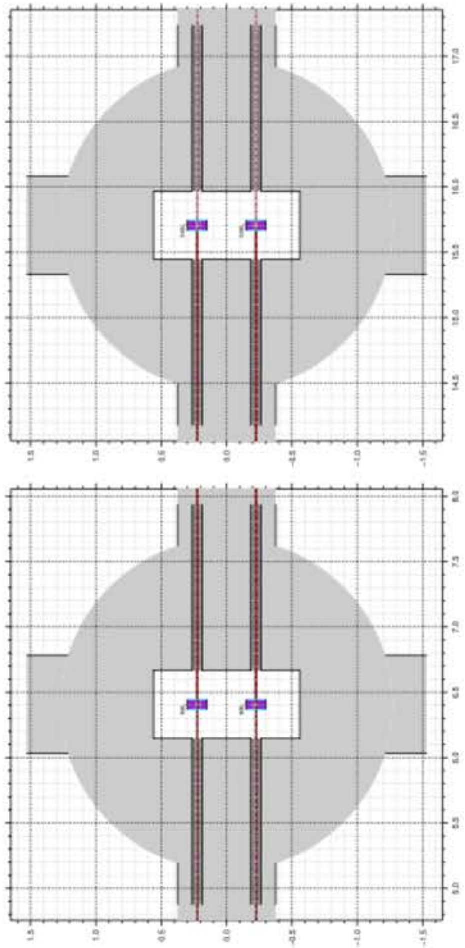


6 HRTS (left) for steering mirrors and 2 HRTS-BS (right) for beamsplitters on central bench

WP6 - Optics: Optical Layout

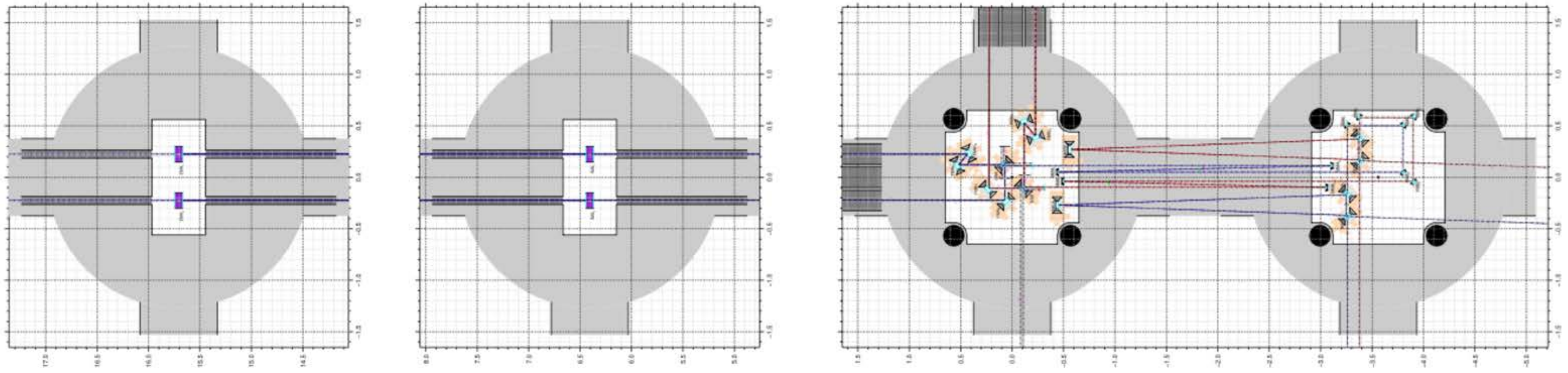
Two co-located interferometers

- *ETpathfinderA*: 1550nm, 123K -> 20K
- *ETpathfinderB*: 2090nm, 123K

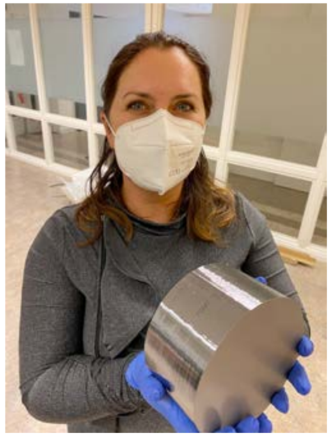


2090nm IFO

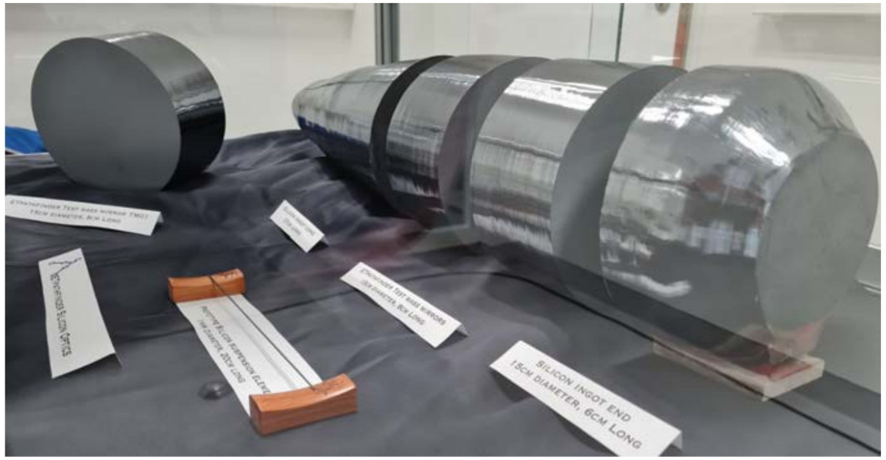
1550nm IFO

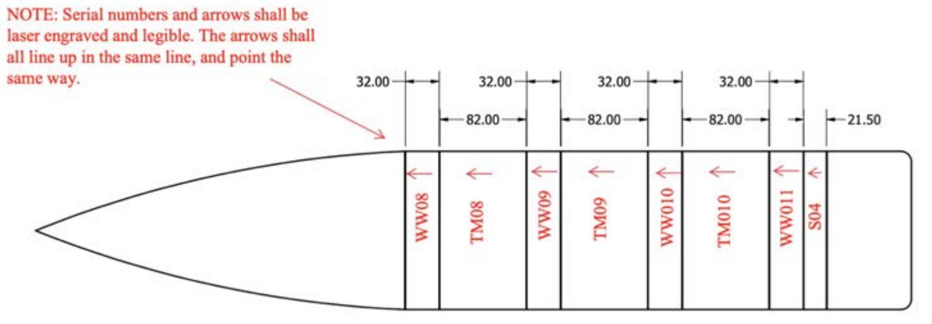


WP6 - Optics: Main test masses

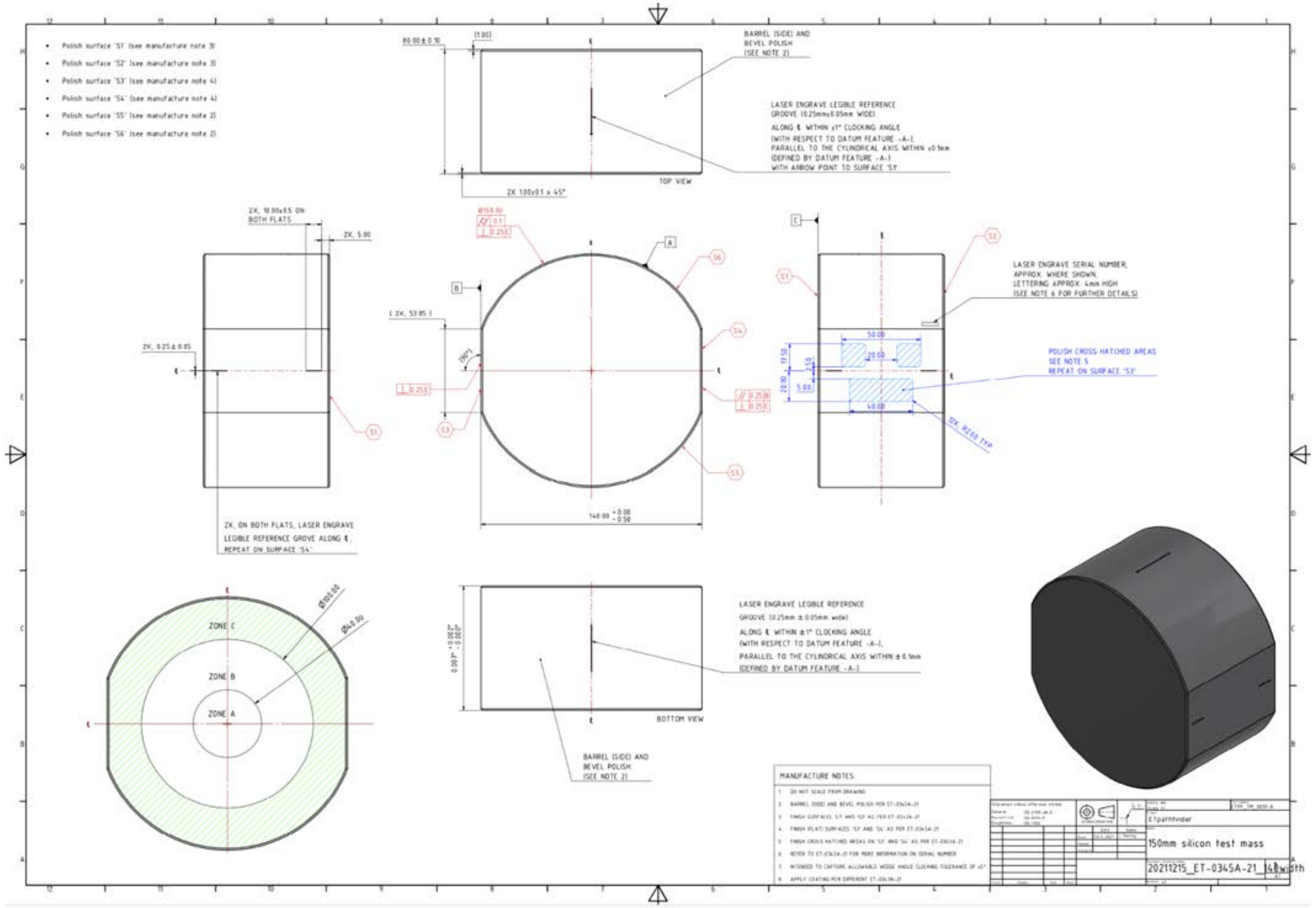


- Previously: purchased two silicon ingots, moderate resistivity
- New, higher resistivity (value TBD) ingot now purchased (VUB/UM) and currently out for cutting
- Will have material for 10 test masses (7 low resistivity, 3 high resistivity) plus plenty of witness samples
- Polishing:
  - Fruitful discussions with Zeiss, very promising but ultimately will not fit our schedule
  - Now preparing European Tender, to be published very soon
  - VUB now starting own silicon polishing tests after successful precursors
- Started discussions for coating, e.g. LMA availability and scheduling
  - Baseline is silica/tantala, but would like to try multimaterial coating with aSi or SiN if realisable in available coating chambers





Main mirror requiremen

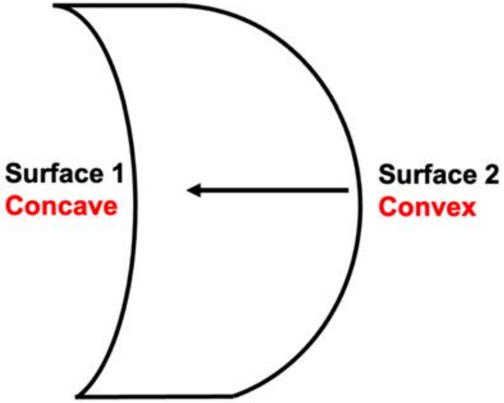


12 Radius of curvature

Refer to the sketch in Figure 1 below for an exaggerated visual representation of S1 and S2 ROC.

Surface 1: The ROC of S1 shall be spherical, concave. ROC: 14.5 m ±0.1 m.

Surface 2: The ROC of S2 shall be spherical, convex. ROC: 9 m ± 0.1 m.



13 Surface figure

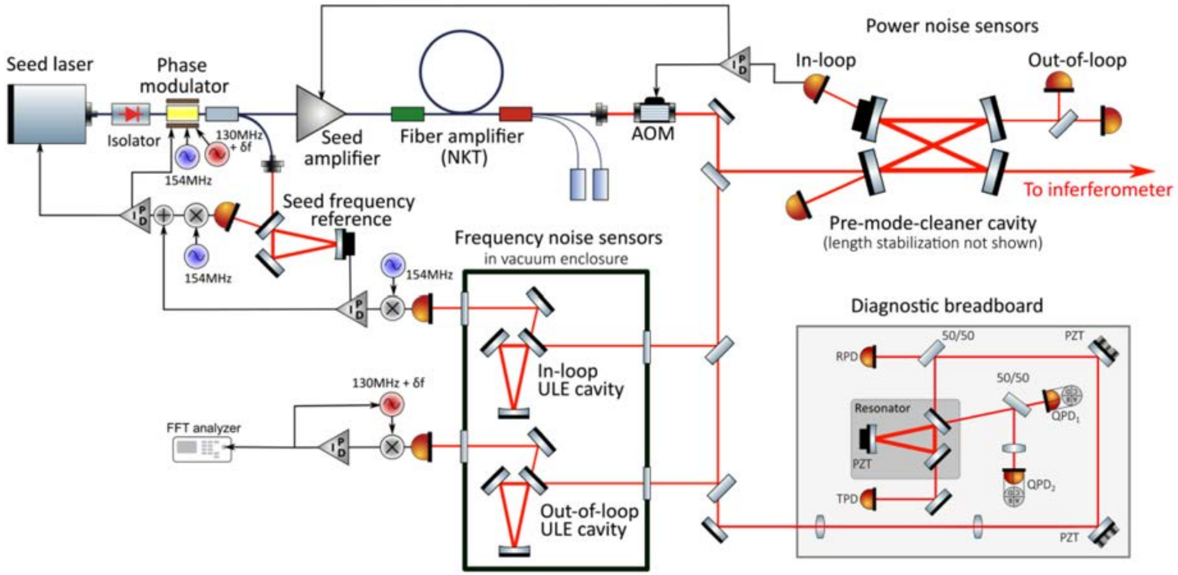
Surface 1:

- Zone A: Surface error shall be < 1 nm RMS measured over the totality of Zone A; Micro-roughness shall be < 0.1 nm over the same area (super polish).
- Zone B: Micro-roughness shall be < 5 nm over Zone B, no surface error requirement.
- Zone C: No surface error or microroughness requirement.

Surface 2:

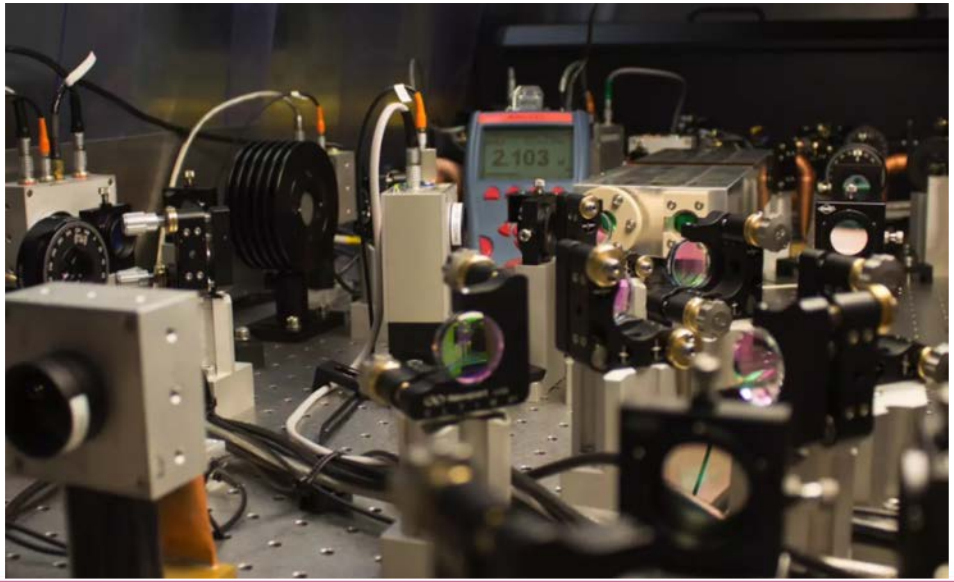
- Zone A: Surface error shall be < 2 nm RMS measured over the totality of Zone A; Micro-roughness shall be < 0.1 nm over the same area (super polish).
- Zone B: Micro-roughness shall be < 5 nm over Zone B, no surface error requirement.
- Zone C: No surface error or microroughness requirement.

WP6 - Optics: Lasers

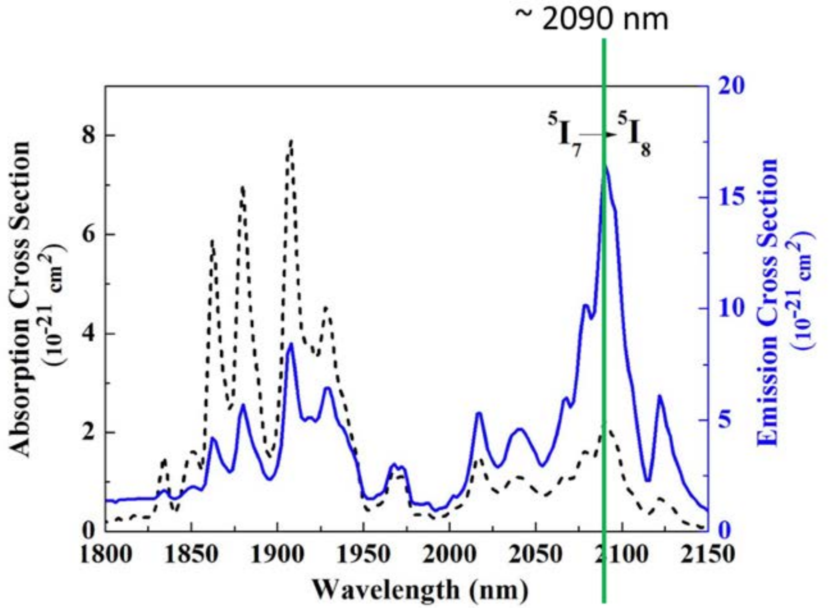


Main laser: 1550nm

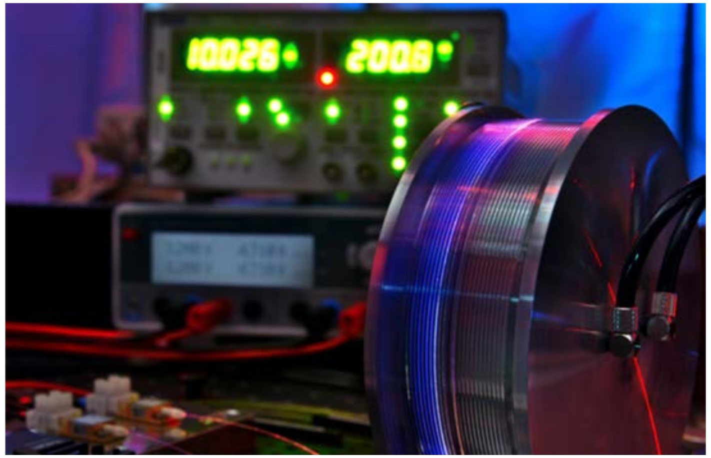
- pre-stabilised laser system contributed by AEI, see recent LVK publication LIGO-P2100463
- Optics lab at UM (outside of cleanroom) now available with commercial 5W laser, first tests of auxiliary optics have started
- Visit by Andrew Spencer (UofG) for a few months to work on integration of laser system with controls

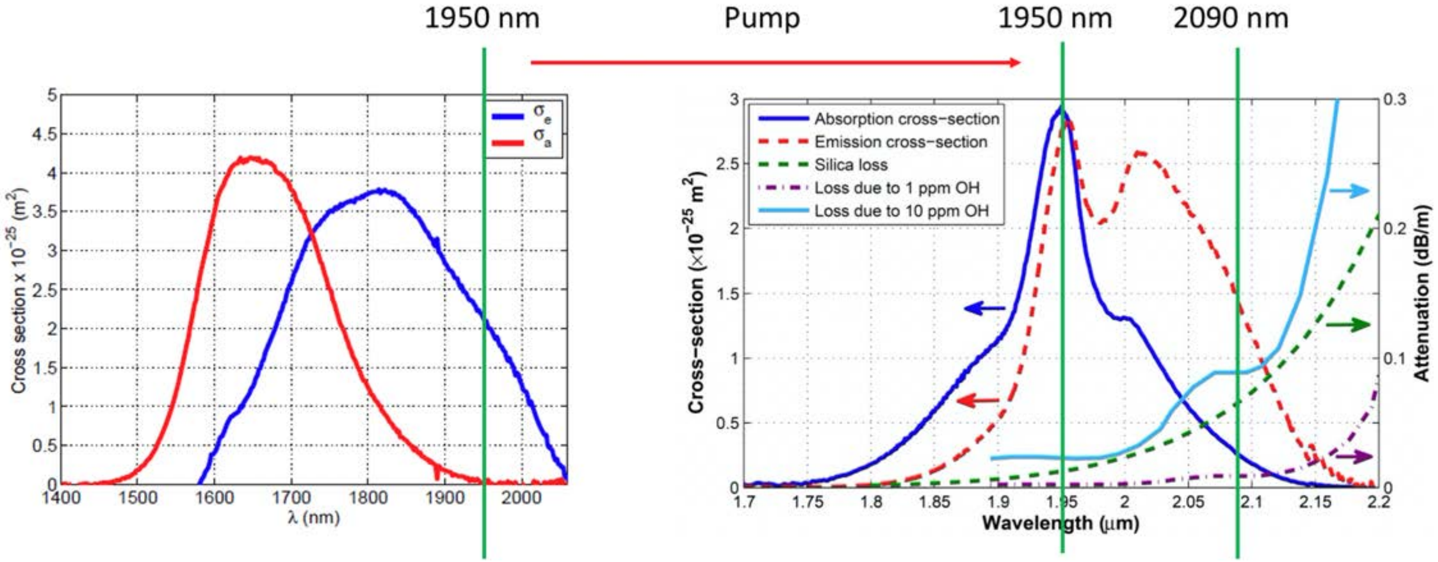


WP6 - Optics: 2µm laser



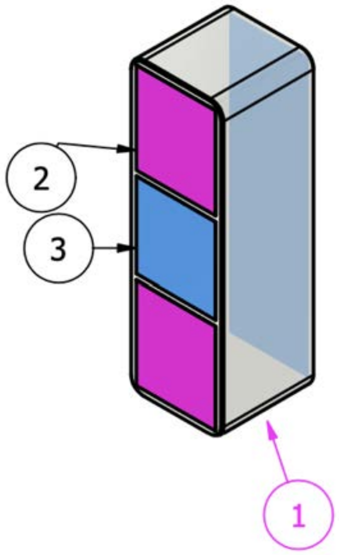
- Procurement of 2090nm laser system this year, can profit from Fraunhofer ILT work for E-TEST laser system
  - Very few commercial, narrow-linewidth sources available
  - Thulium fibre amplifier system seeded by laser diode, broad linewidth so far, will be open system to exchange seed later
  - ILT to work on Ho:YAG NPRO seed
- Amplifier:
  - Holmium fibre
  - Pumped by
    Holium fiber laser/amplifier



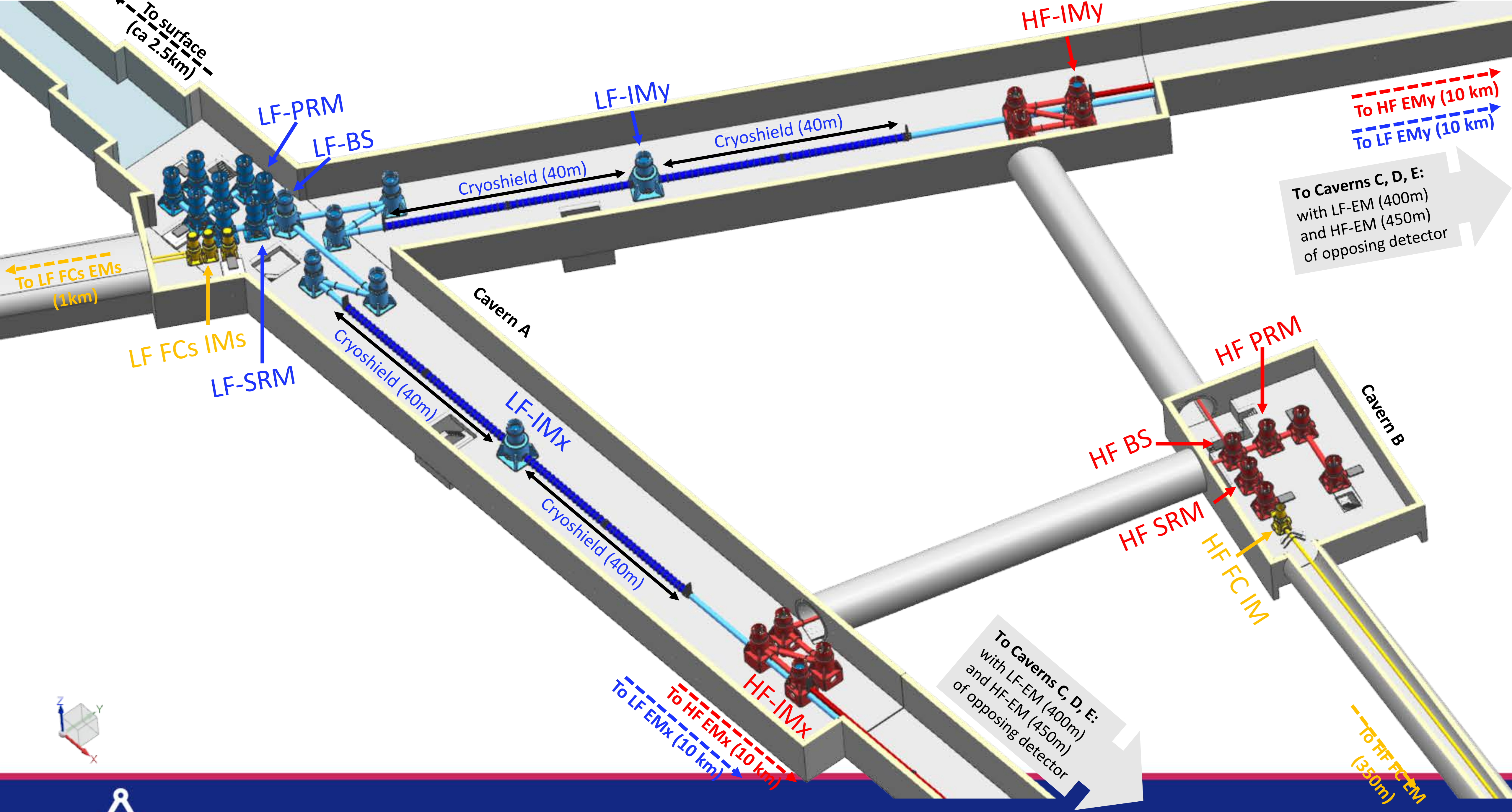


WP6 - Optics: other optics

- Design sketch for beam splitters, with split-coating on front, sent out for quotation
- Design of mode-matching telescopes ongoing; project by Maud Slangen finished in autumn, now taken over by Aaron Jones for finalisation
- General purpose optics for 1550nm have been purchased and arrived during 2021
- Now asking for quotations for general purpose optics for 2090nm
- Further setups become available at UM, e.g. a PCI absorption measurement setup, as well as a photodiode testing setup



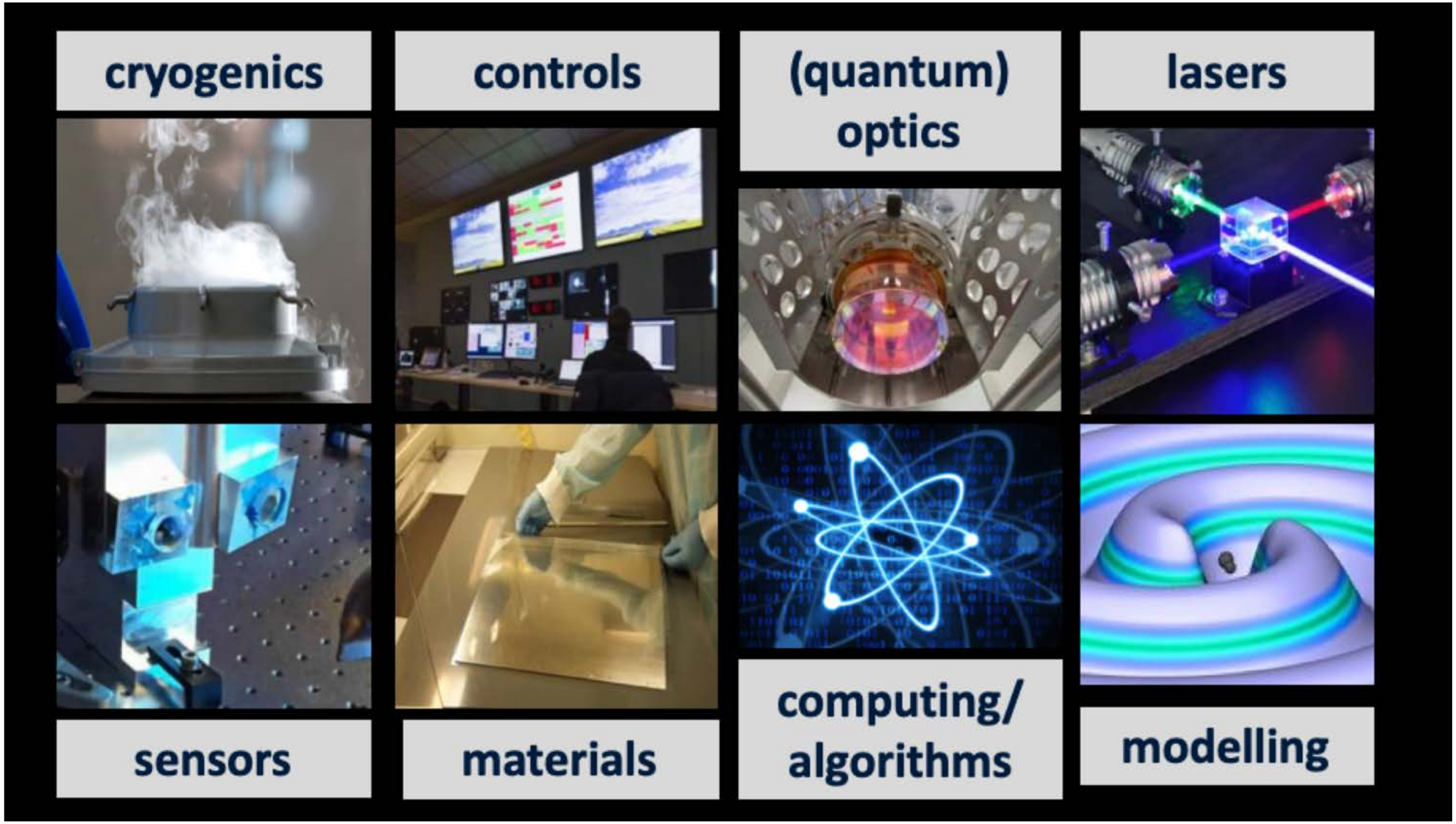
Item	Type	Description	Amount	Substrate	CA size	Polish S1	Coating S1	Polish S2	Coating S2	Additional spec
1a	Mirror	Steering mirrors	50	Suprasil3001	D 25.4 mm	λ/10 plano	Hrs,p>99.9% at 45°	λ/4 plano	AR<0.2% at 45°	
1b		- alternative material to item 1a	50	Infrasil301						
1c		- alternative material to item 1a	50	Corning7979						
2a	Lens	Plano/Convex lenses f200mm	20	Infrasil301	D 25.4 mm	λ/10 plano	AR<0.1%	λ/10	AR<0.1%	
2b		- alternative material to item 2a	20	Corning7979						
3a	Lens	Plano/Convex lenses f100mm	20	Infrasil301	D 25.4 mm	λ/10 plano	AR<0.1%	λ/10	AR<0.1%	
3b		- alternative material to item 2a	20	Corning7979						
4a	Lens	Plano/Convex lenses f50mm	20	Infrasil301	D 25.4 mm	λ/10 plano	AR<0.1%	λ/10	AR<0.1%	
4b		- alternative material to item 2a	20	Corning7979						
5	Beamsplitter	Polarizing beamsplitter	20	*	D 25.4 mm		AR<0.15%		AR<0.15%	E.R.>1000:1
6	Beamsplitter	Non-polarizing beamsplitter	20	*	D 25.4 mm		AR<0.15%		AR<0.15%	50/50 split
7	Beamsplitter	Non-polarizing beamsplitter	20	*	D 25.4 mm		AR<0.15%		AR<0.15%	66/33 split
8	Beamsplitter	Non-polarizing beamsplitter	20	*	D 25.4 mm		AR<0.15%		AR<0.15%	90/10 split
9	Beamsplitter	Non-polarizing beamsplitter	20	*	D 25.4 mm		AR<0.15%		AR<0.15%	99/1 split
10	Waveplate λ/2	Half-wave plate	20	*	D 25.4 mm					
11	Waveplate λ/2	Half-wave plate	20	*	D 25.4 mm					
12	Waveplate λ/4	Quarter-wave plate	20	*	D 25.4 mm					
13	Waveplate λ/4	Quarter-wave plate	20	*	D 25.4 mm					
14	Isolator	Free-space optical isolator	1		D 4 mm					



To surface (ca 2.5km)
LF-PRM
LF-BS
LF-IMy
HF-IMy
Cryoshield (40m)
Cryoshield (40m)
To HF EMy (10 km)
To LF EMy (10 km)
To Caverns C, D, E: with LF-EM (400m) and HF-EM (450m) of opposing detector
To LF FCs EMs (1km)
LF FCs IMs
LF-SRM
Cavern A
Cryoshield (40m)
LF-IMx
Cryoshield (40m)
HF PRM
Cavern B
HF BS
HF SRM
HF FC IM
HF-IMx
To HF EMx (10 km)
To LF EMx (10 km)
To Caverns C, D, E: with LF-EM (400m) and HF-EM (450m) of opposing detector
To HF FC EM (350m)


LIEBE GRÜSSE VOM SEMMERING-BASISTUNNEL!

Deleoping new Technologies and Fostering Economic Impact:



LIGO

LIGO Scientific Collaboration

LSC

Caltech
Max-Planck-Institut für Gravitationsphysik Albert-Einstein-Institut
American University Washington, DC
Andrews University
Bar-Ilan University
Bard College
Bellevue College
California State University Fullerton
Carleton College
MIT
Christopher Newport University
Colorado State University
Columbia University in the City of New York
Concordia University Wisconsin
Embry-Riddle Aeronautical University
Georgia Tech
NASA Goddard Space Flight Center
INPE
Haverford College
Hillsdale College
Hobart & William Smith Colleges
International Institute of Physics
LSU Louisiana State University
Maastricht University
Marquette University
NASA Marshall Space Flight Center
Missouri S&T
Montana State University
Montclair State University
Lomonosov Moscow State University
NCSA
Northwestern
PennState
RIT
Sonoma State University
University of Portsmouth
Science & Technology Facilities Council Rutherford Appleton Laboratory
King's College London
Australian National University
Charles Sturt University
Monash University
Southern University and A&M College
Stanford University
Stony Brook University
Flatiron Institute Center for Computational Astrophysics
University of Birmingham
Cardiff University Prifysgol Caerdydd
OzGrav
Swinburne University of Technology
Syracuse University
Texas Tech University
Tsinghua University
Polytechnique Montréal
University of the West of Scotland UWS
University of Zurich
University of Glasgow
GEO 600
The University of Adelaide
The University of Melbourne
The University of Western Australia
The University of Arizona
Berkeley University of California
The University of Chicago
The University of Sheffield
UF University of Florida
University of Maryland
University of Michigan
University of Minnesota
University of Oregon
The University of Rhode Island
USC Universidade de Santiago de Compostela
Leibniz Universität Hannover
University of Strathclyde Glasgow
Texas The University of Texas at Austin
UTRGV
UIB Universitat de les Illes Balears
東京大学 The University of Tokyo
The University of Utah
University of Washington
W Bothell
University of Cambridge
IISER Kolkata
tifr
ICTS International Centre for Theoretical Sciences
UWM University of Wisconsin Milwaukee
Villanova University
West Virginia University
Universität Hamburg
University of Southampton
CMI Chennai Mathematical Institute
DCSEM
RRCAT
NIMS National Institute for Mathematical Sciences | South Korea
서울대학교
UNIST
인제대학교 Inje University
KISTI 한국과학기술정보연구원 Korea Institute of Science and Technology Information
한양대학교 Hanyang University
LISC LIGO-India Scientific Collaboration
IISER Pune
IIT Hyderabad
IUCAA
KASI Korea Astronomy and Space Science Institute
Pusan National University
Korean Gravitational Wave Group