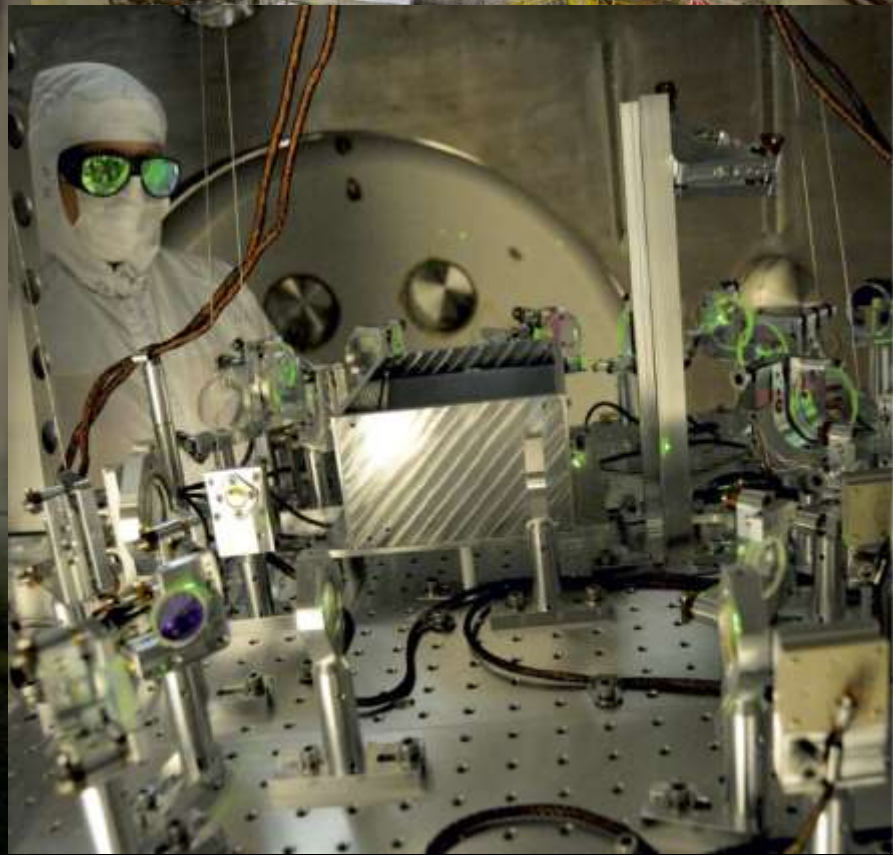
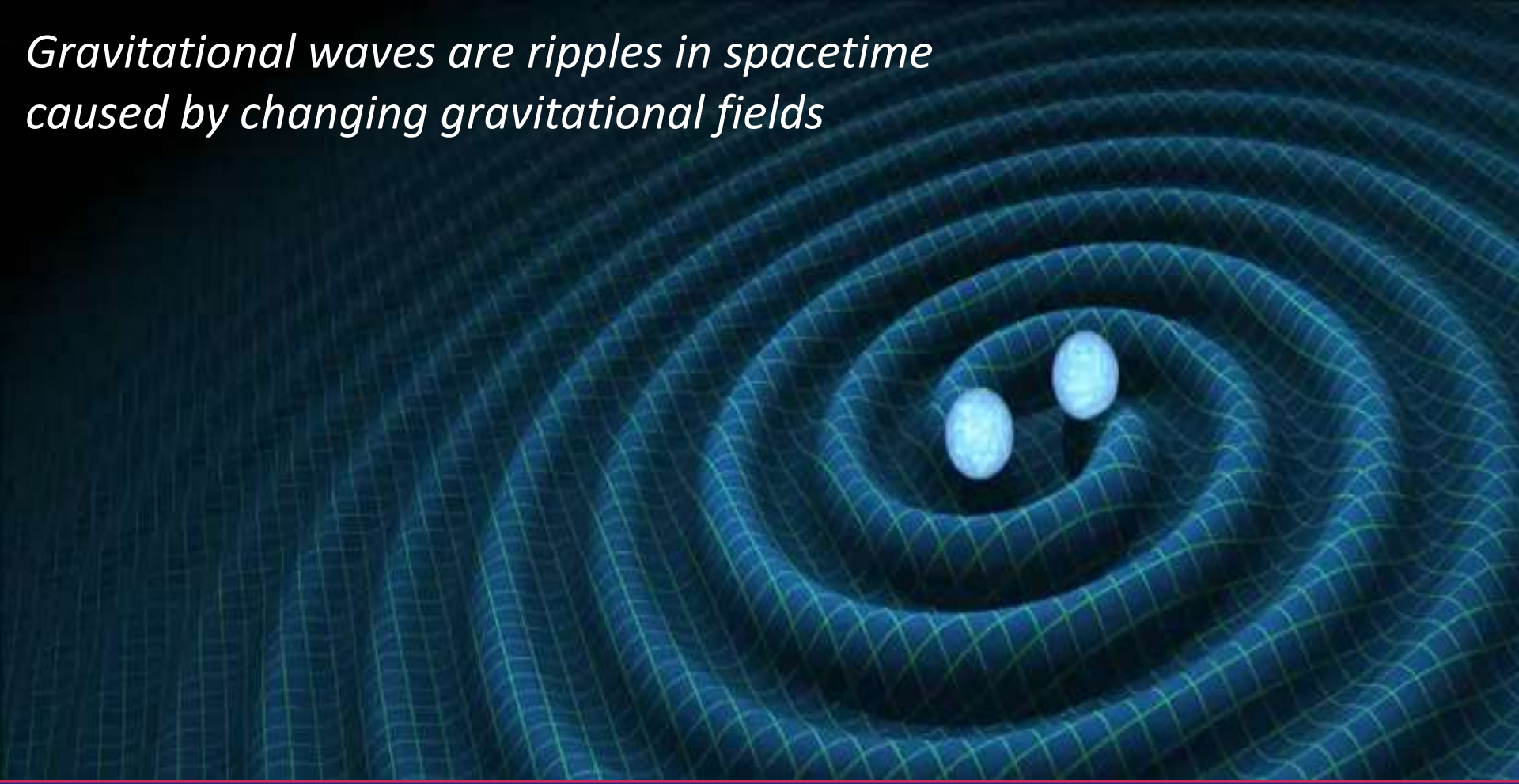
Gravitational Waves: A Dark Future

Conor Mow-Lowry

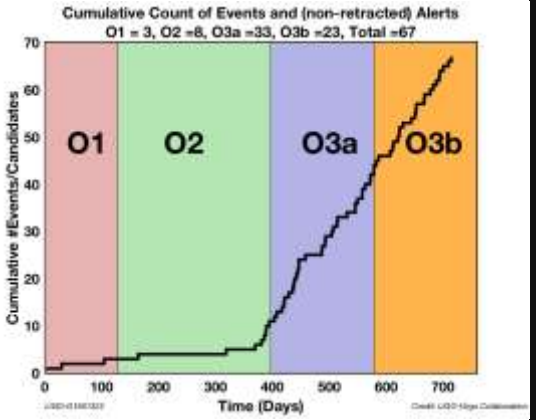
For the Dutch GW community



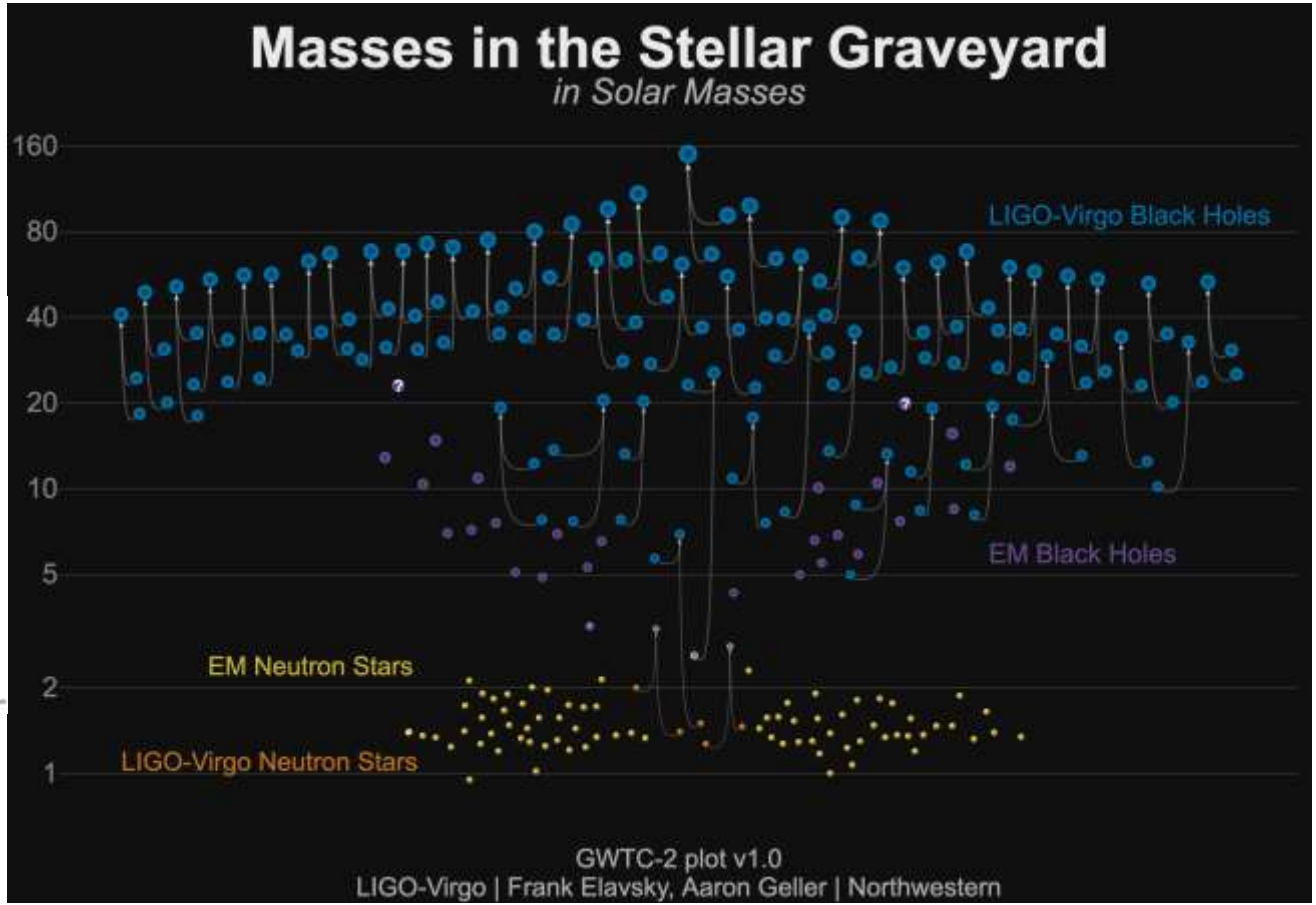
Gravitational waves are ripples in spacetime caused by changing gravitational fields



Frequent observation of binary coalescences

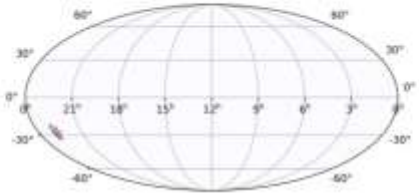


About one signal detected per week!

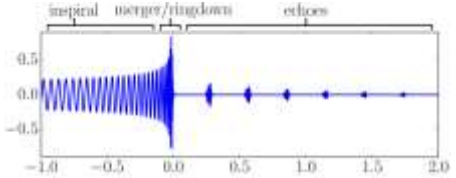


Gravitational wave data analysis: Highlights from the past year

- **Machine learning**
  - Towards detection of binary neutron star signals before merger
  - Characterizing and simulating transient noise, e.g. for Einstein Telescope Mock Data Challenges
  - High-quality sky localization of binary mergers in just a few minutes (down from a few hours!)

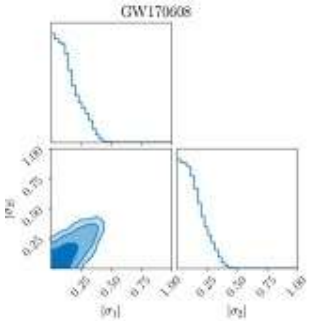


- **Testing general relativity in novel ways**
  - "Overtones" found in e.g. GW190412, GW190814: Are the overtones consistent with the basic signal?
  - Black holes, or black hole mimickers? Searching for gravitational wave echoes



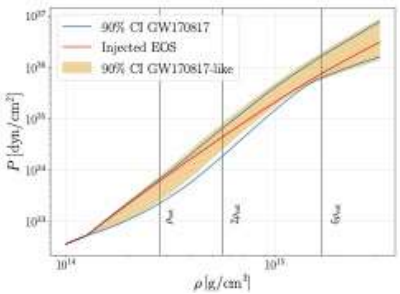
- **Lensing of gravitational waves**
  - *See talk by Justin Janquart tomorrow*

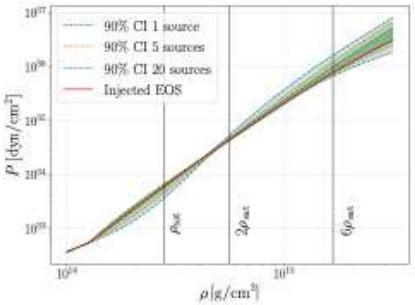
- **Gravitational waves and dark matter**
  - Bounding "dark charges" on binary black holes



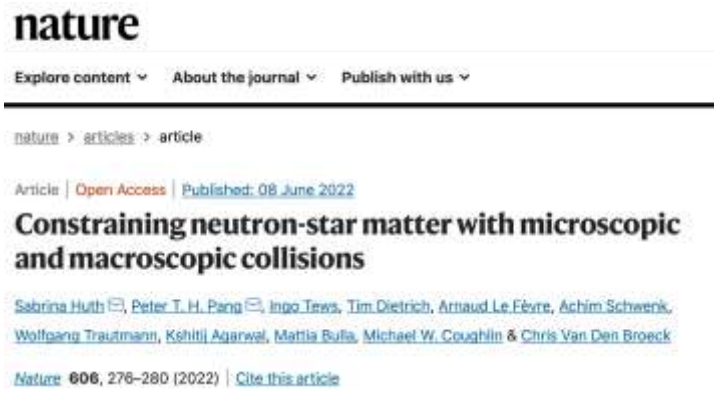
Gravitational wave data analysis: Highlights from the past year

- **Measuring the equation of state of neutron stars**
  - Looking ahead at how to exploit the full potential of Einstein Telescope





- **Studying dense nuclear matter using GW + EM + heavy ion collisions**



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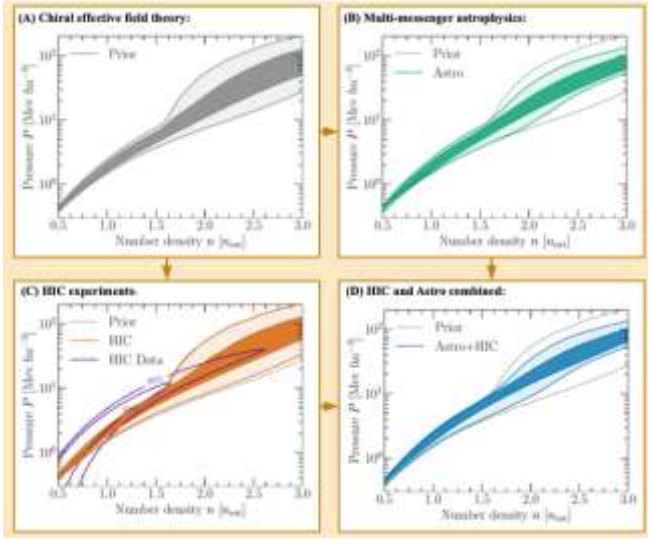
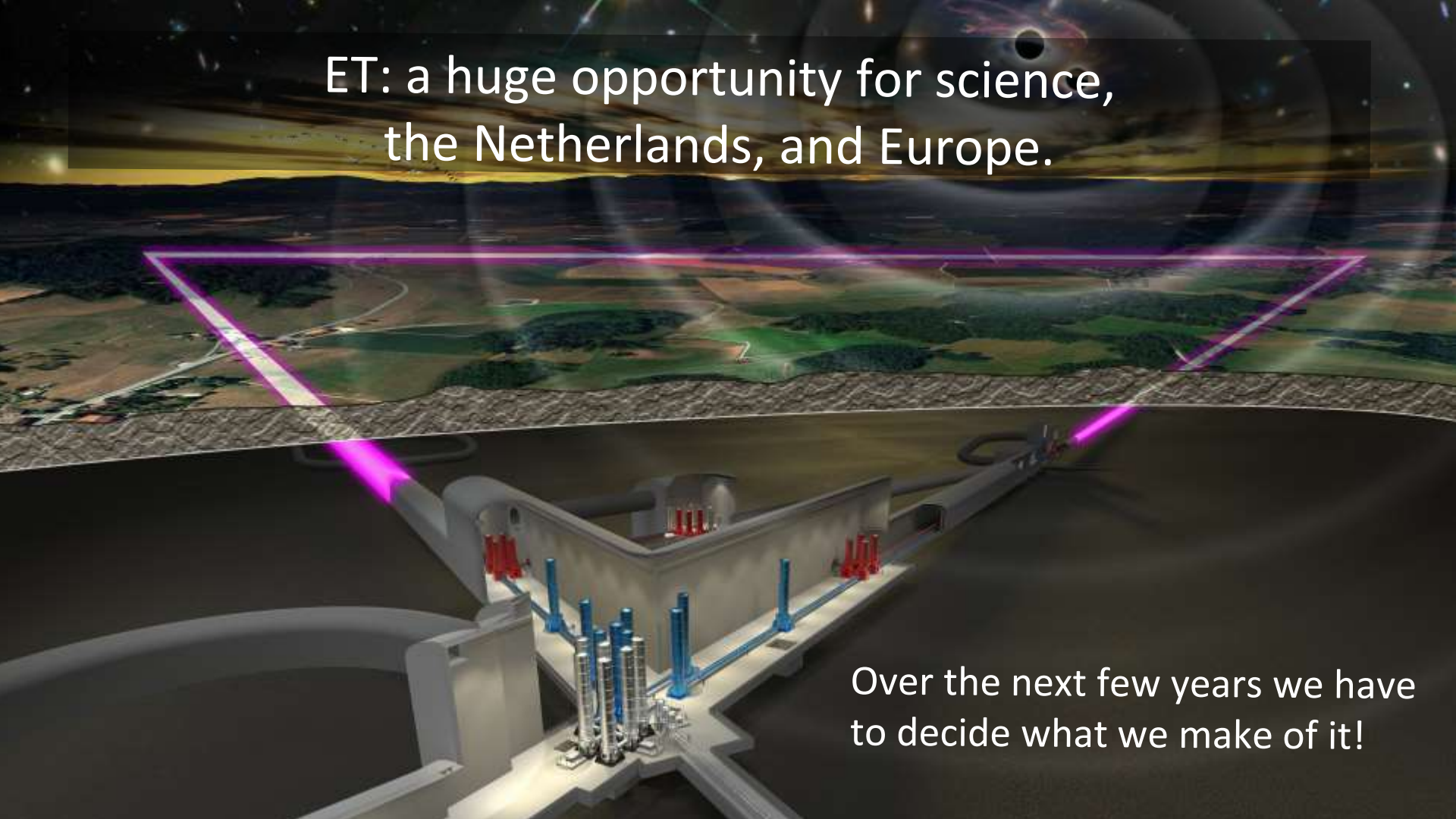
Constraining neutron-star matter with microscopic and macroscopic collisions

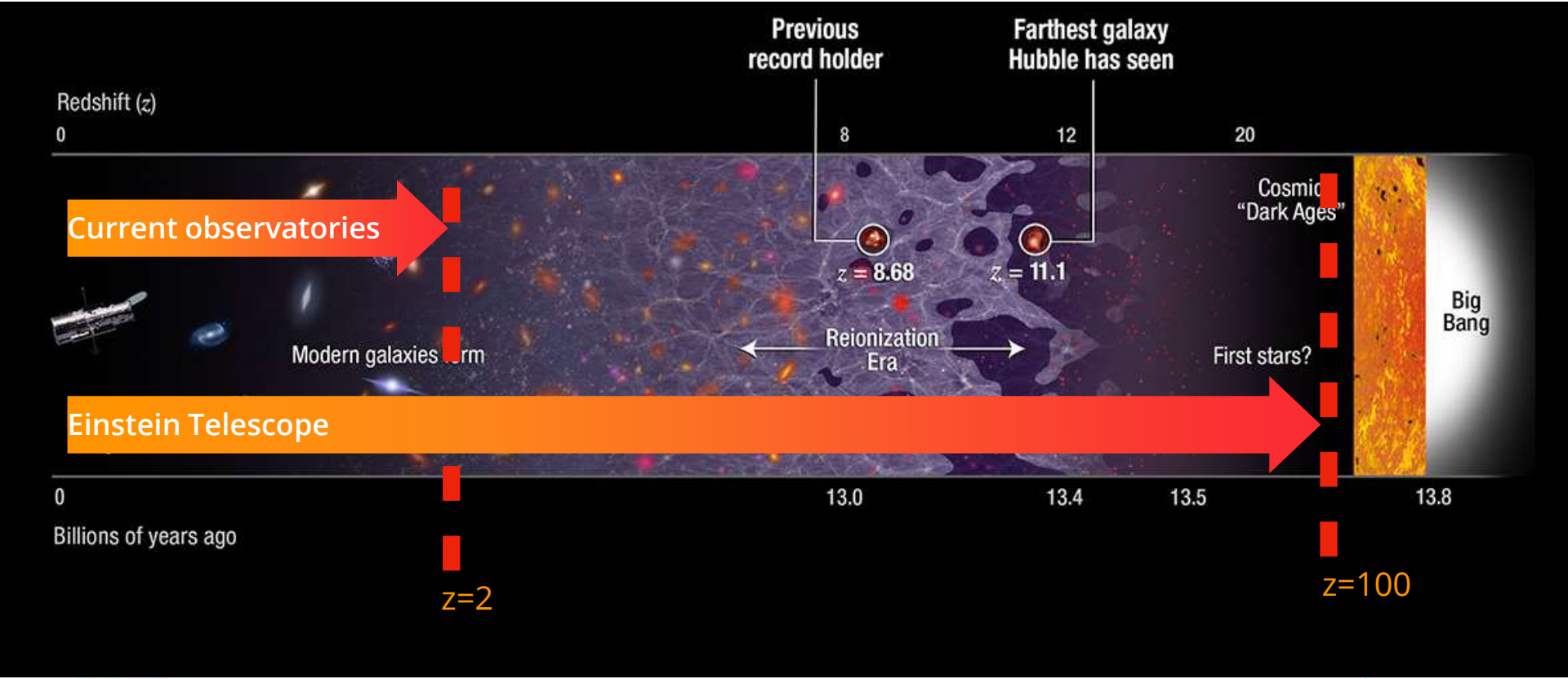
Sabrina Huth, Peter T. H. Pang, Ingo Tews, Tim Dietrich, Arnaud Le Fèvre, Achim Schwenk, Wolfgang Trautmann, Kshitij Agarwal, Mattia Bulla, Michael W. Coughlin & Chris Van Den Broeck

Nature **606**, 276–280 (2022) | Cite this article




ET: a huge opportunity for science,
the Netherlands, and Europe.
Over the next few years we have
to decide what we make of it!

From the science case for ET



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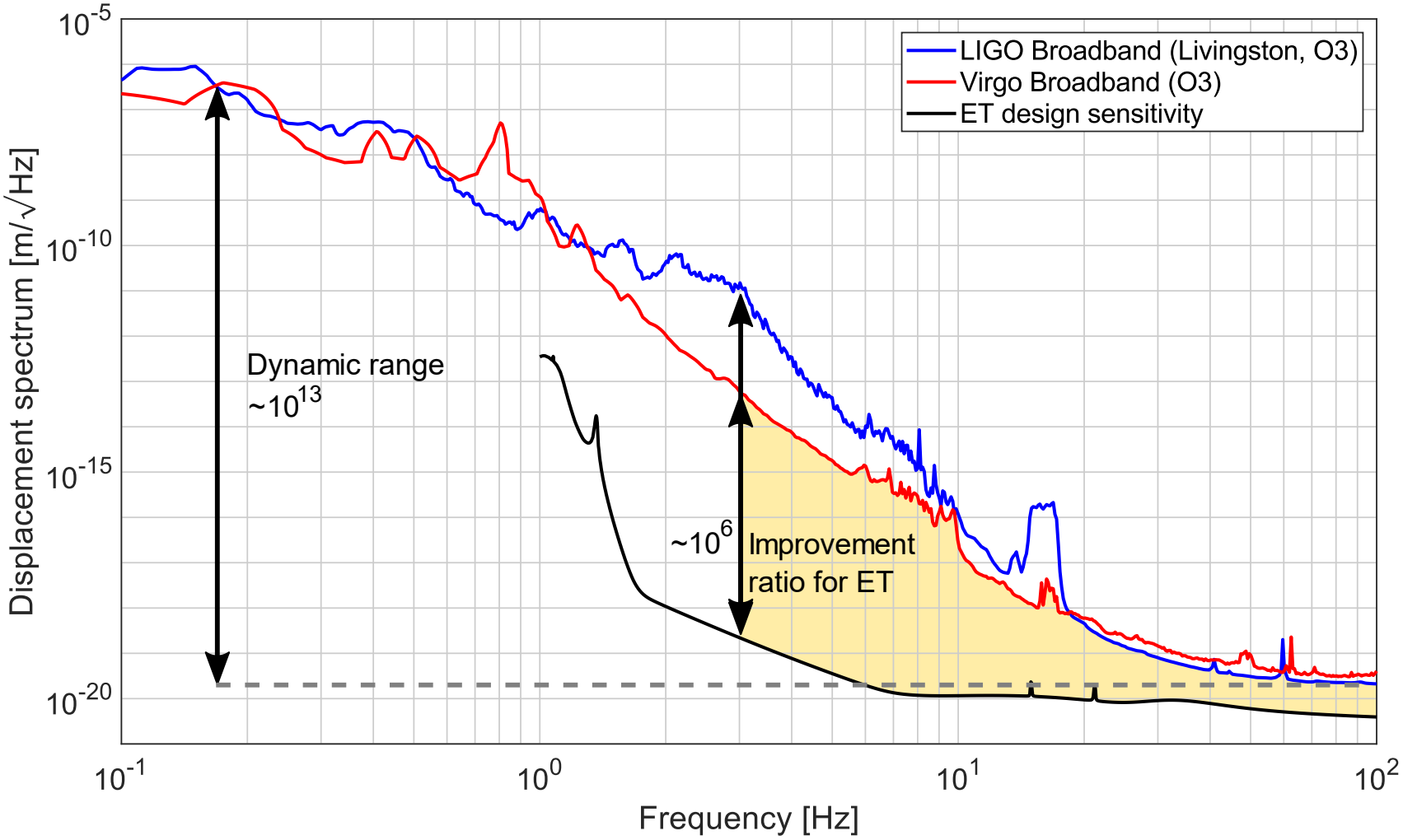
LIGO Broadband (Livingston, O3)
Virgo Broadband (O3)
ET design sensitivity
Dynamic range
~10^13
~10^6
Improvement
ratio for ET
Displacement spectrum [m/√Hz]
Frequency [Hz]
10^-5
10^-10
10^-15
10^-20
10^-1
10^0
10^1
10^2

The Einstein Telescope

- A **multi-billion Euro**, pan-European project involving thousands of people.
- There is a possibility of it “landing” in NL, and we are a major part of the ET project and collaboration leadership
- We must make **strategic decisions** – the project is too big to ‘fit’ in Nikhef as it stands.
- Groeifonds – **No direct funding for scientists**

Currently ongoing:
Site-studies, collaboration building, prototyping, research projects

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National growth-funds, funding for what?

- 42 M€ have been (conditionally) awarded now. Money can flow from 2023, and NWO can provide pre-financing fur urgent items. The money is dedicated to:

  - 19 M€ managed by LIOF (the Limburg Development and Investment Company): connections to industry for research and innovation: 'The aim of this programme is to **optimally position [...] in particular Dutch industry**, for R&D and orders relating to Einstein Telescope',

  - 23 M€ managed by Nikhef: '**for the preparation and realisation of the underground infrastructure** [...]', project organisation and management

- **870 M€ have been reserved** for the construction of the ET infrastructure, if the EMR site is selected as the location of ET.

- Organisational challenge for Nikhef: NGF (local project office, with regional partners and EZK, OCW, LIOF, industry, ...) need to align with ET EU project (int. project office, CERN, government representatives, ...) need to coordinate with the collaboration (spokesperson, scientists, working groups and boards, ...)

New positions listed in NGF:

Projectmanagement	1 fte
Projectondersteuning	2 fte
Secretariaat	1 fte
Technische staf (uit te besteden)	4 fte
Juridische staf (uit te besteden)	2 fte
Communicatie en outreach	2 fte

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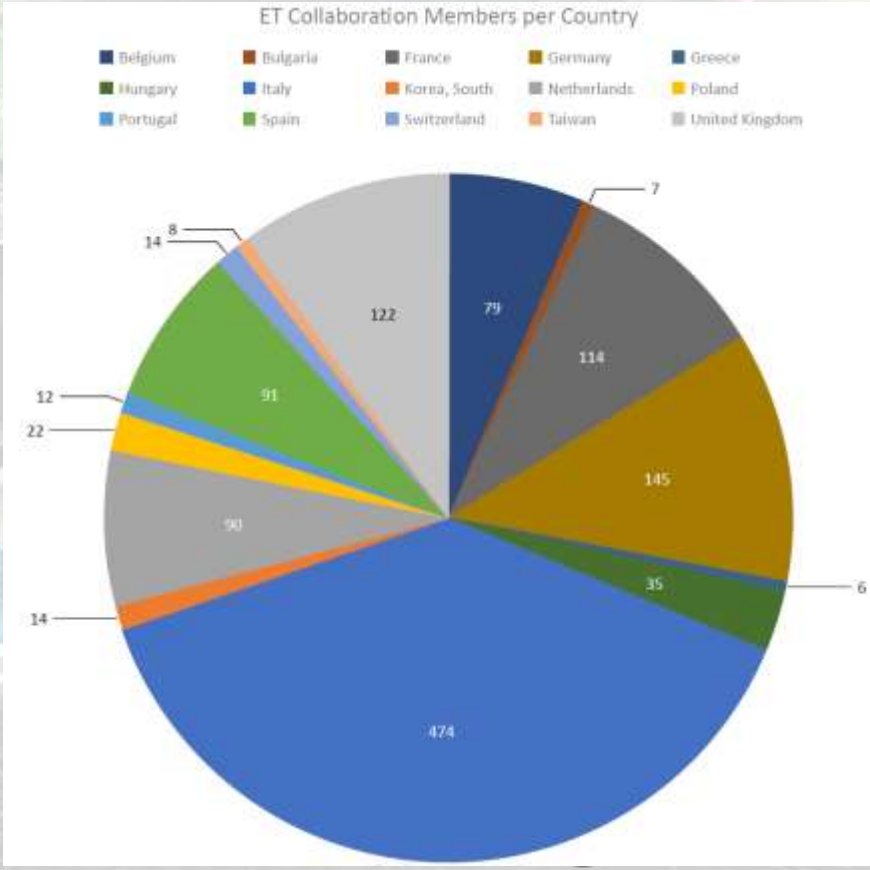
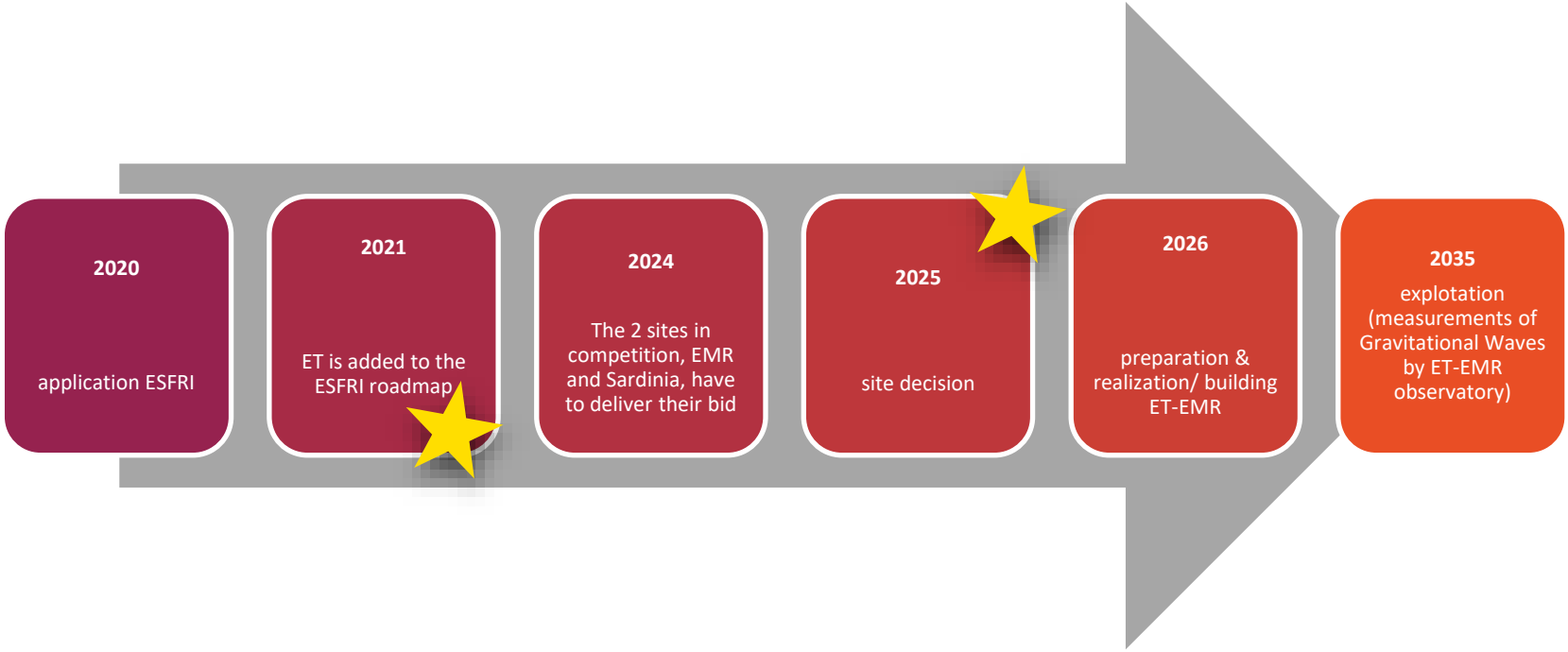
The ET Collaboration has begun

- 79 Intstitutions
- 1200+ Members
- 280 “Research” FTEs
- Relatively even split between instrument/experiment and astronomy/analysis



The Einstein Telescope, the EU project timeline



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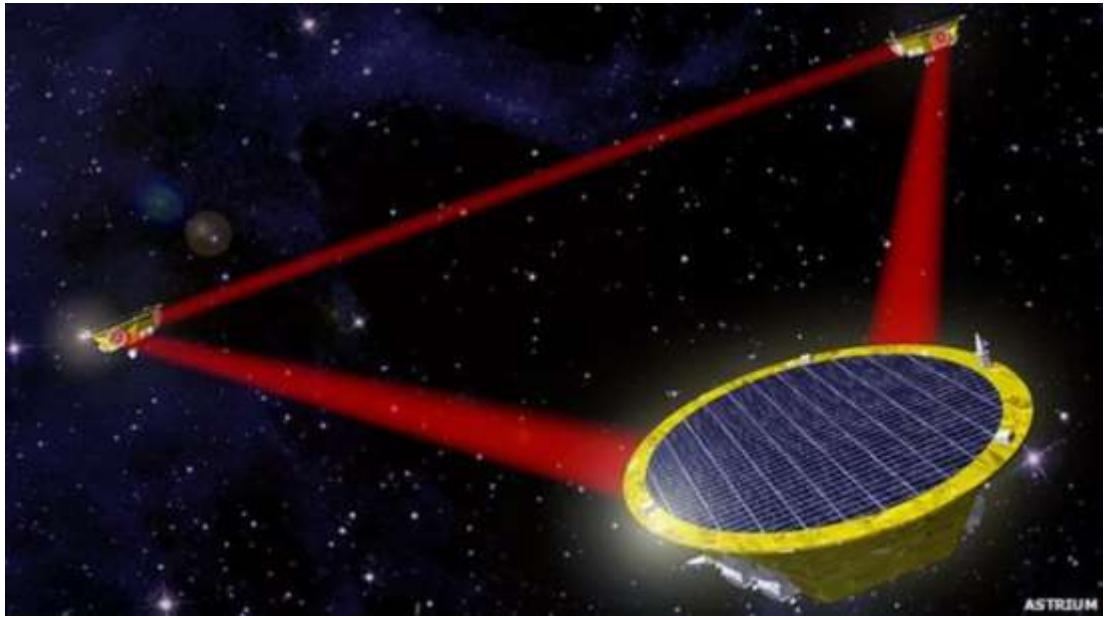
LISA – 2037 launch date

A Spaceborne observatory measuring supermassive black holes and cosmic history



Quadrant Photo-diodes

Not commercially available

- Large area
  - ➡ **2 mm diameter**, small gaps (10 - 20 µm) ⟹ High capacitance
- High responsivity
  - ➡ > 0.7 A/W at 1064 nm ⟹ **InGaAs**
- Commercially available InGaAs diodes
  - ➡ are thin ⟹ High capacitance

Nikhef

SRON Netherlands Institute for Space Research

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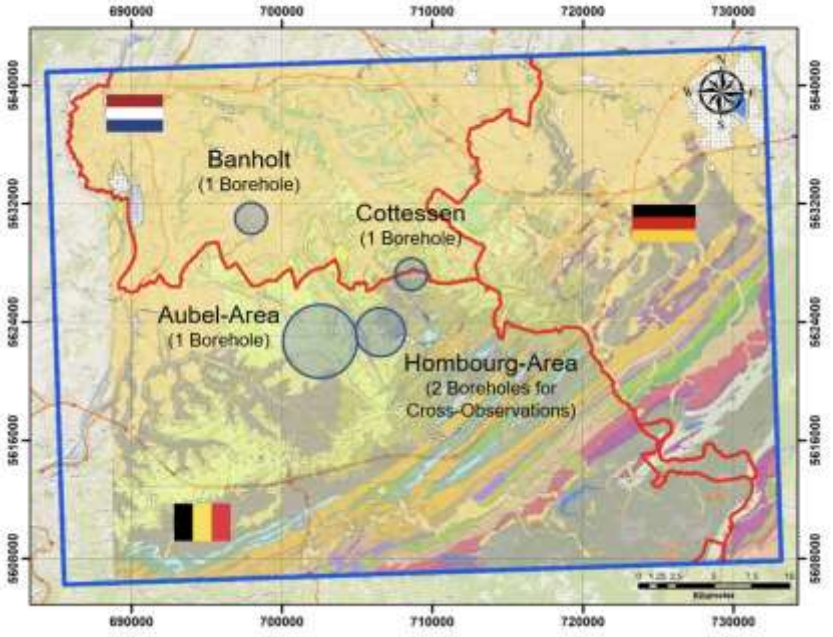
Towards the ET infrastructure

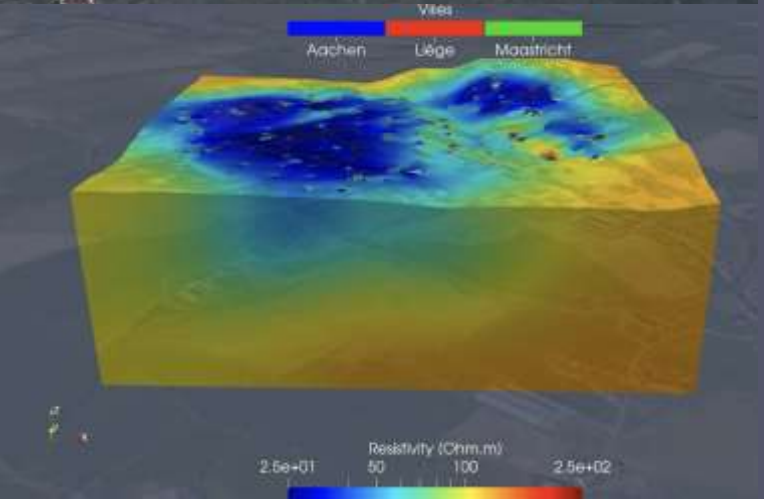
E-TEST Einstein Telescope EMR Site & Technology

Interreg Euregio Meuse-Rhine European Regional Development Fund

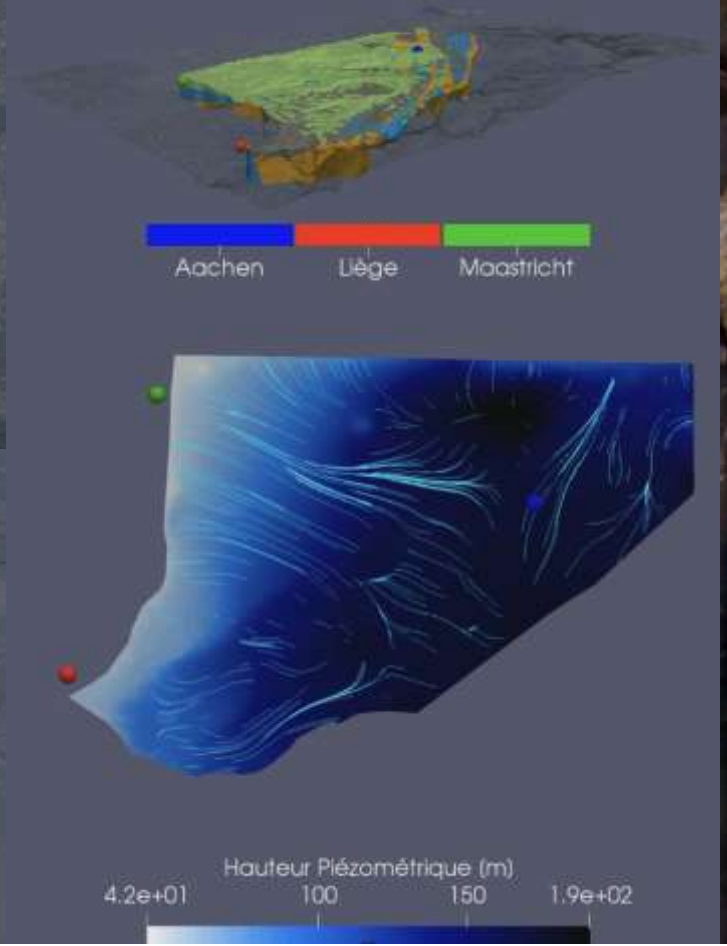
Royal Netherlands Meteorological Institute Ministry of Infrastructure and the Environment · Nikhef · LIÈGE université · UNIVERSITÄT BONN · RWTH AACHEN UNIVERSITY · TNO innovation for life

- Budget: 7 M€ (out of 15) for geology studies
- Timeline: 2020-2023
- Focus: exploration and geological analysis of EMR
- Goals:
  - producing a 3D geological and geotechnical model of the cross-borders region to inform civil engineering design: location, tunnel construction, cost estimate, etc.
  - assessing seismic noise characteristics (level, propagation, local sources, etc.)



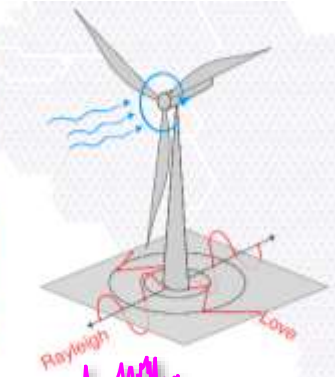


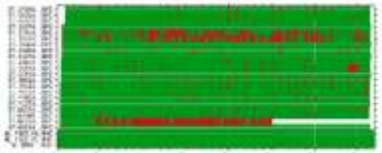
Hydrogeological surveys



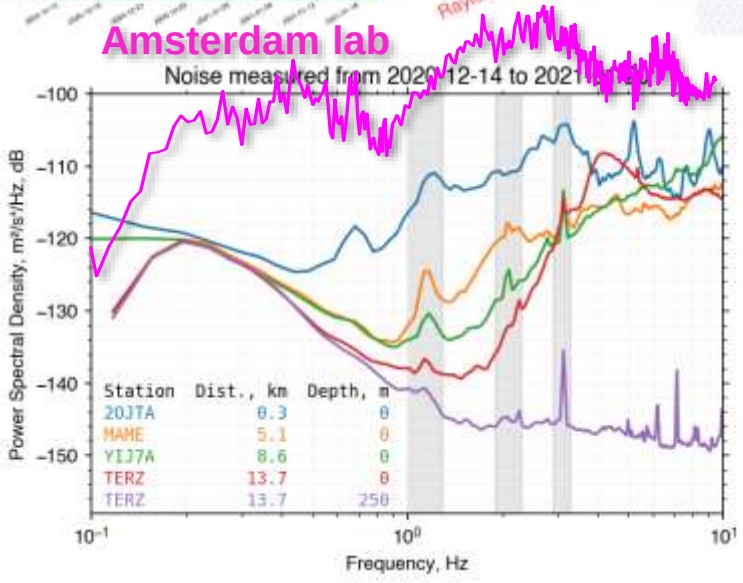
Groundwater flow models

Borehole core logging





Amsterdam lab



Seismic noise characterization

Active seismic campaign for subsurface imaging

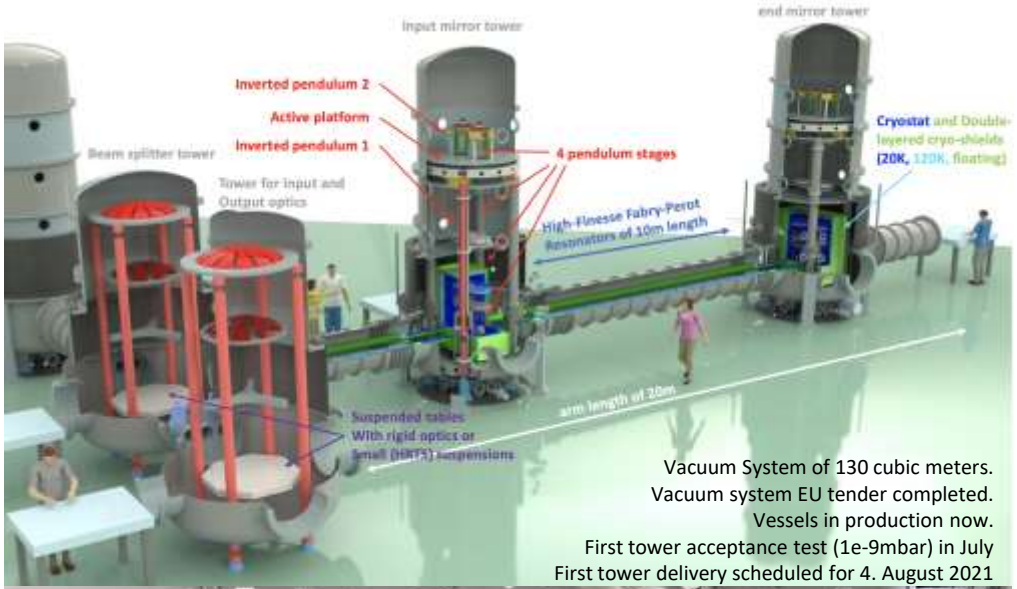
ET-pathfinder

New facility for testing ET technology in a low-noise, full-interferometer setup.

Key aspects:

- Silicon mirrors (3 to 100+kg)
- cryogenics (and water/ice management)
- “New” wavelengths (1550 and 2090nm)

- Initial funding 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



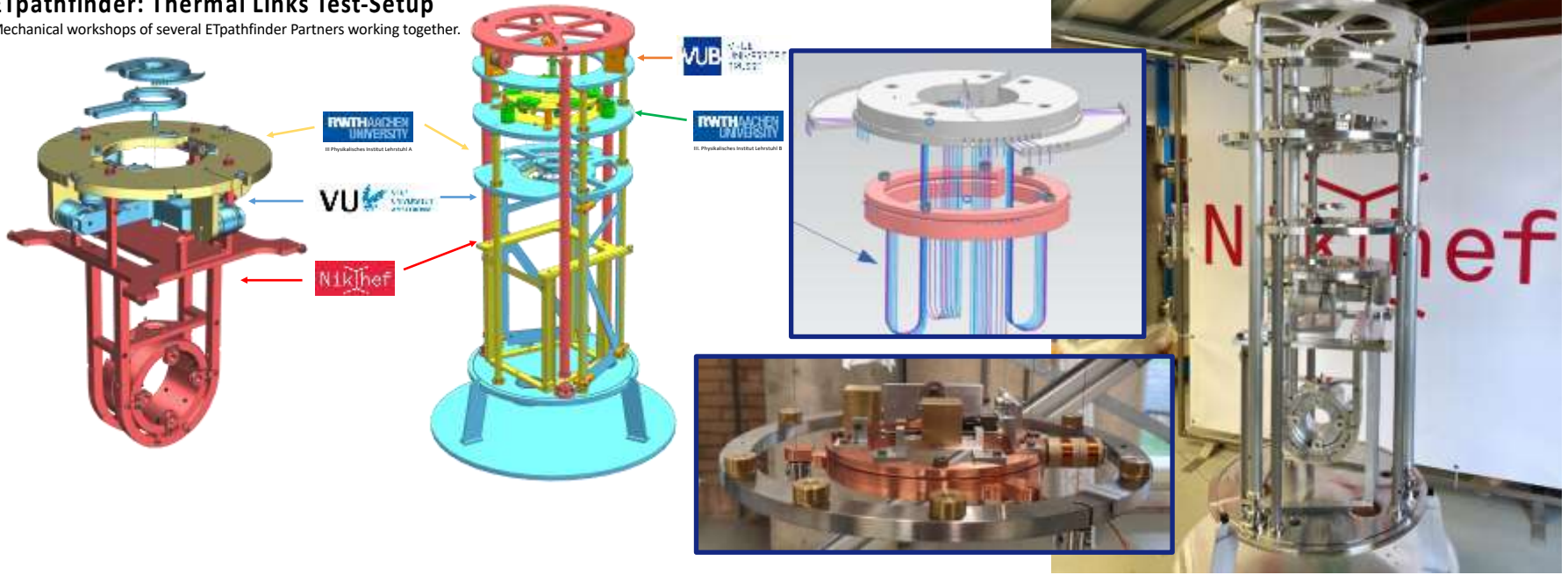
Vacuum System of 130 cubic meters.
Vacuum system EU tender completed.
Vessels in production now.
First tower acceptance test (1e-9mbar) in July
First tower delivery scheduled for 4. August 2021

ETpathfinder Partners

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

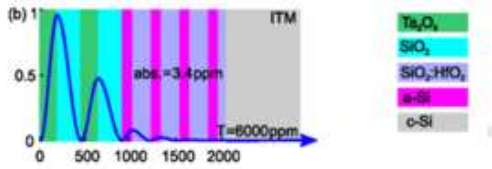
ETpathfinder: Thermal Links Test-Setup

Mechanical workshops of several ETpathfinder Partners working together.



Research example: **Mirror coatings**

- Brownian motion of the highly-reflective coated detector mirrors generates ‘surface ‘vibration’. Conventional coatings: made of stacks of two alternating amorphous materials (with different refractive indices to create high reflectivity).
  Challenge: We cannot meet all coating requirements with the materials we know!
- Two projects in Maastricht by Jessica Steinlechner to reduce coating Brownian noise:



Vidi project - started in Dec 2021

The short-term, ‘safe’ approach which will
(1) Combine more than two materials to optimize coating performance in
(2) an amorphous and crystalline hybrid coating

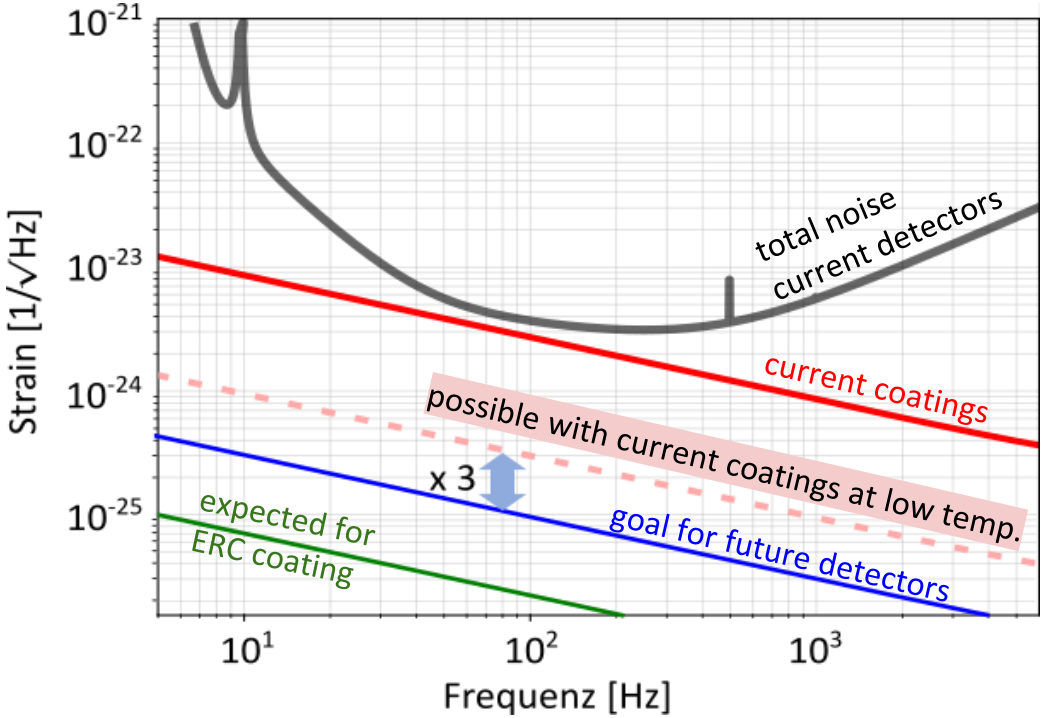
- Can meet Einstein Telescope goals
- 5 years, 1 postdoc (Alex Amato) and 1 PhD student (Diksha)

ERC starting grant - starting in Nov 2022

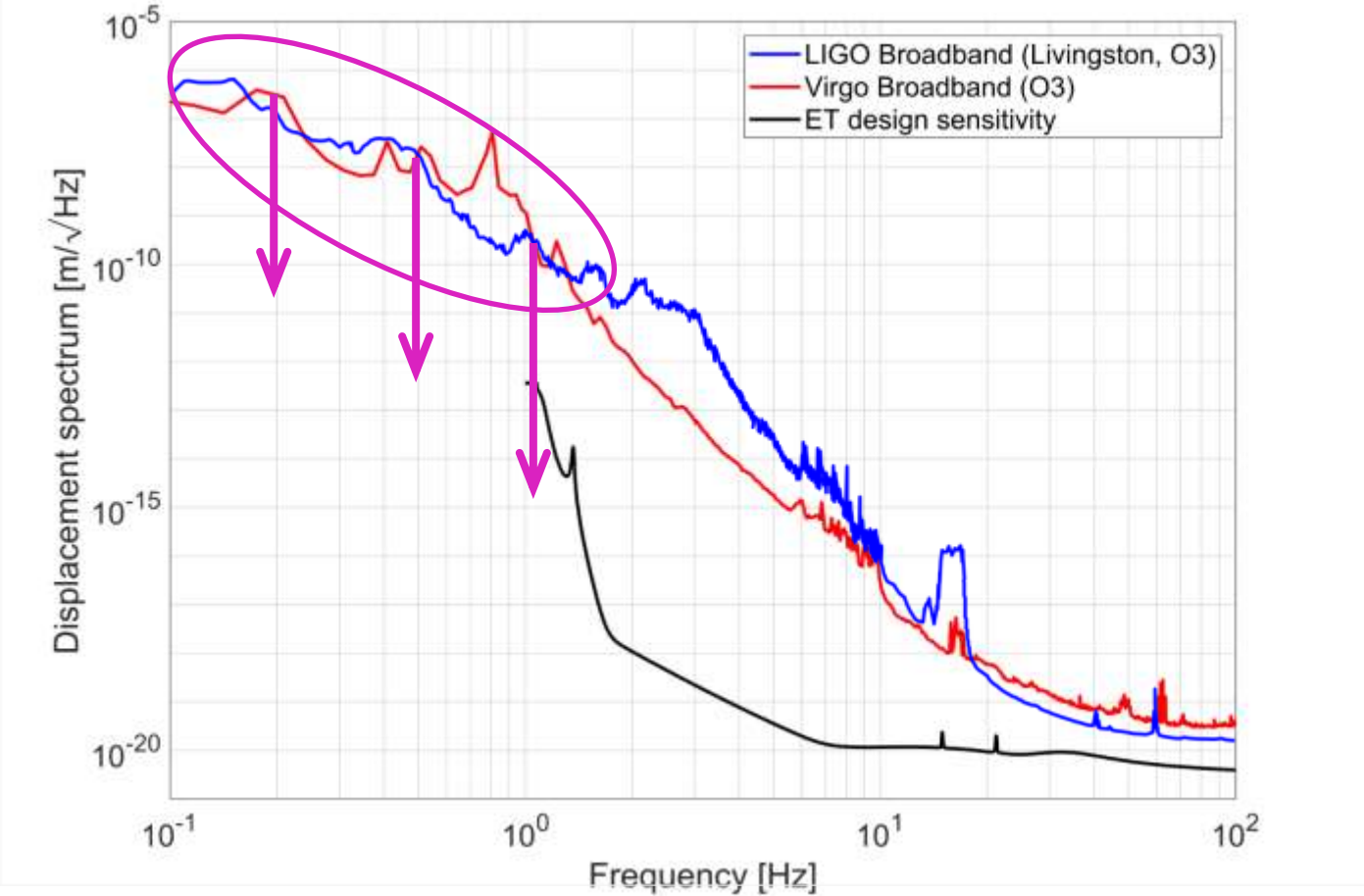
The longer-term, ‘high risk, high gain’ approach

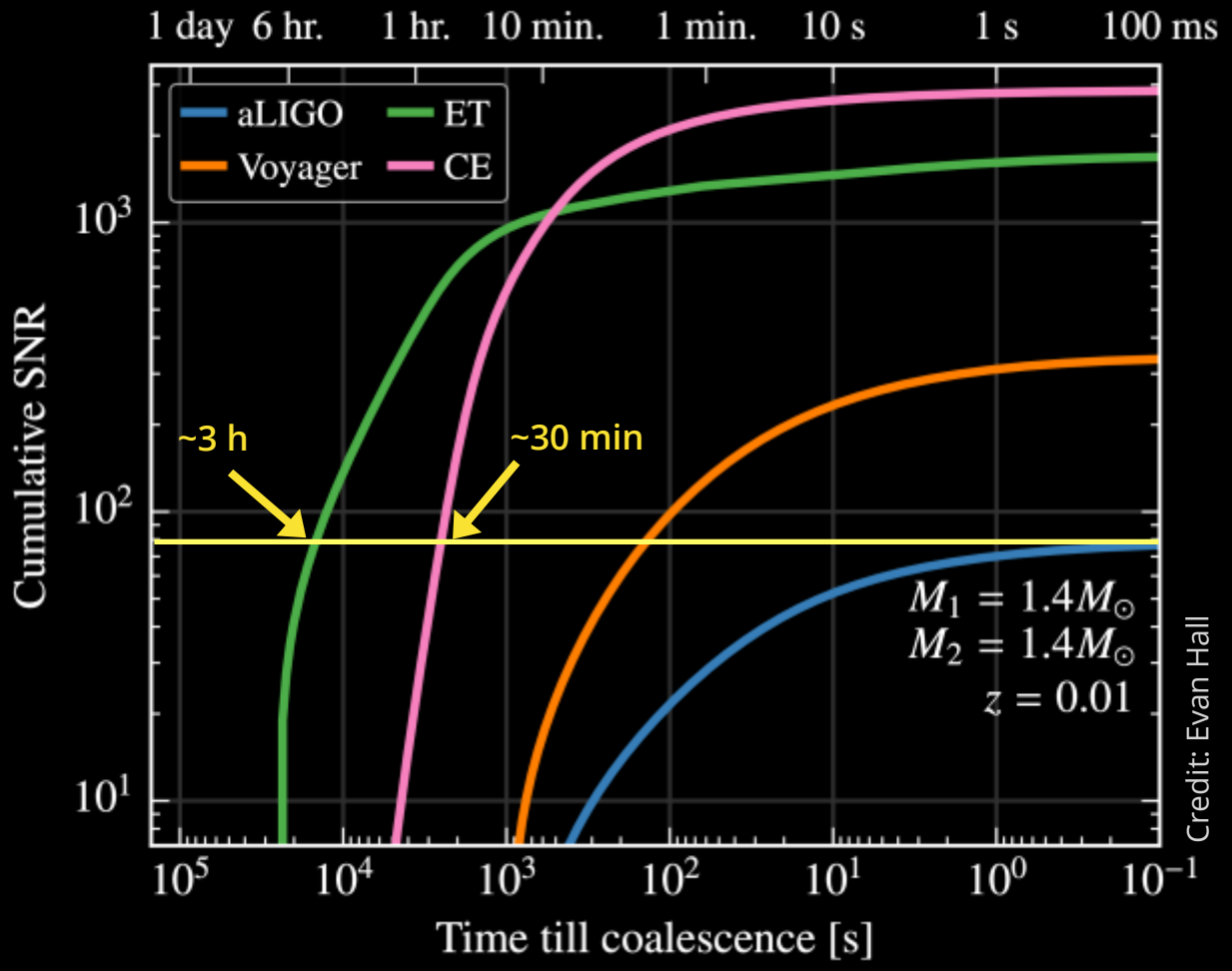
- Use ion implantation to create layers of different refractive index, e.g. SiO_2 or SiN_x, directly inside our crystalline silicon mirrors
- Exceed Einstein Telescope goals – ready for future upgrades?
- 5 years, 1 postdoc and 2 PhD students (all tbd)

Coating thermal noise reduction visualised



Research example: **Detecting low-frequency signals**

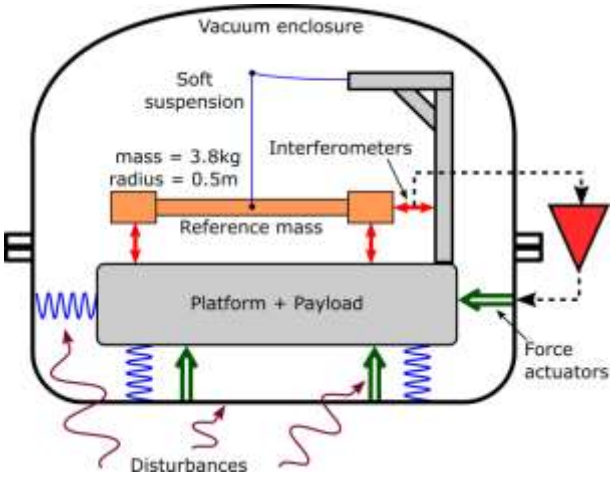



1 day 6 hr.
1 hr.
10 min.
1 min.
10 s
1 s
100 ms
aLIGO
ET
Voyager
CE
~3 h
~30 min
$M_1 = 1.4M_\odot$
$M_2 = 1.4M_\odot$
$z = 0.01$
Cumulative SNR
10^3
10^2
10^1
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
Time till coalescence [s]
Credit: Evan Hall

The ‘OmniSens’ project

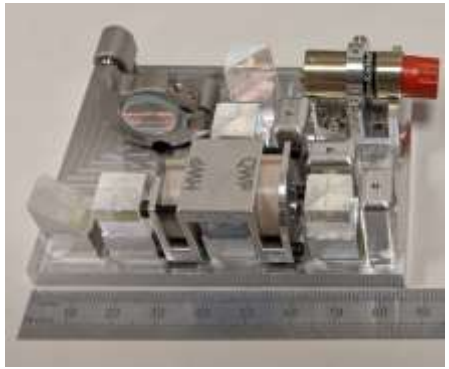
How can we ‘Break the Seismic Wall’ and get to the juicy low-frequency GW signals?

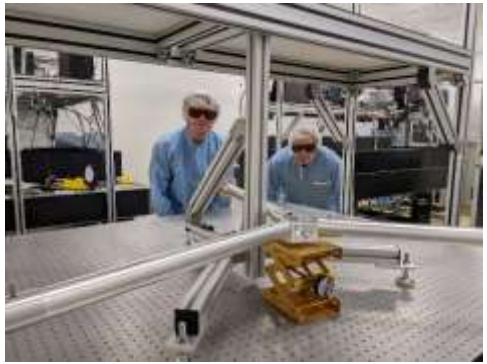
Use 6 laser interferometers to actively isolate all 6 Degrees of Freedom!

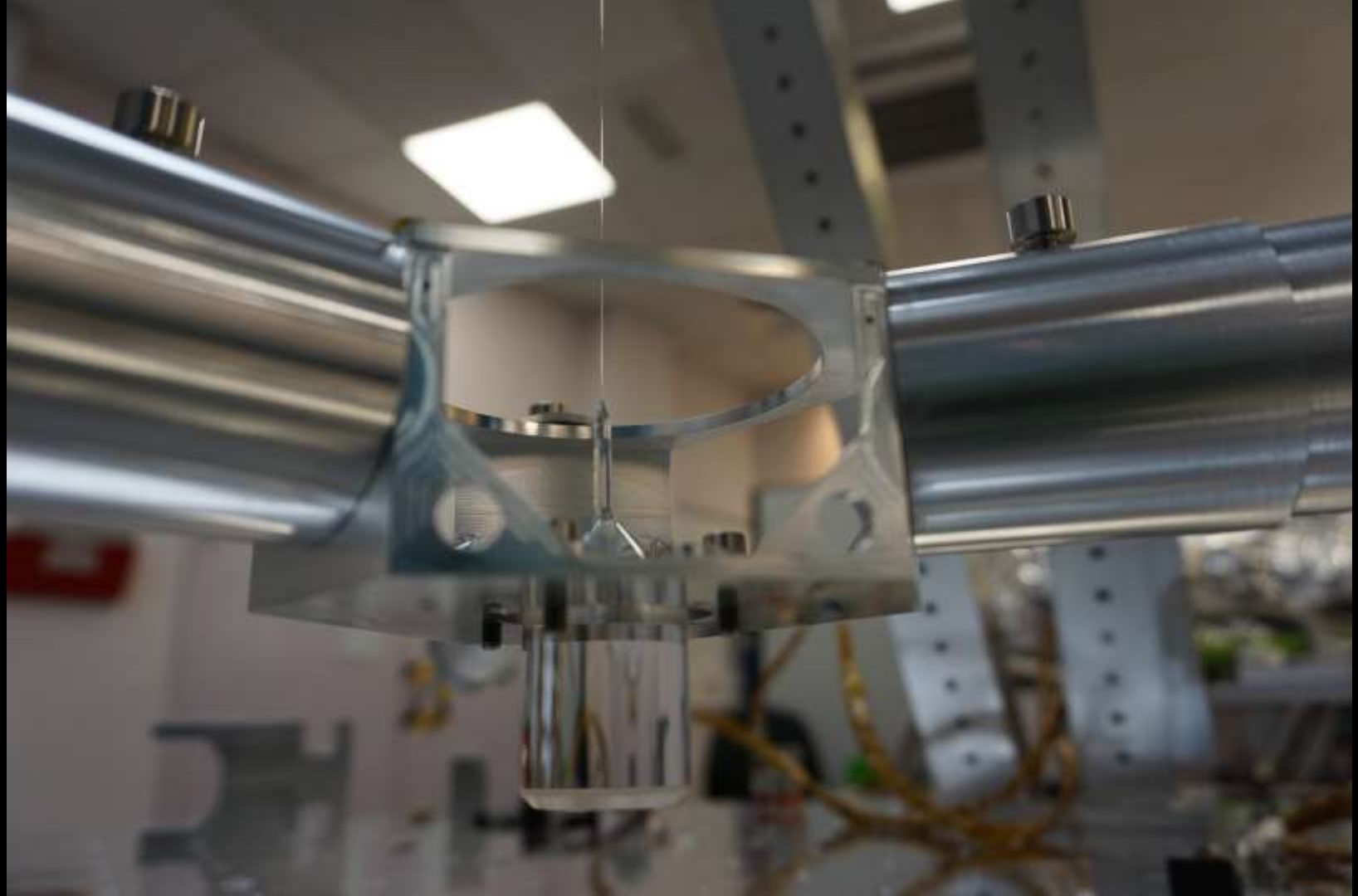


The **inertial stability** of the reference mass **is transferred** to the payload.

What?	ERC Consolidator project (~2.5M€, 2 PhDs, 2 post-docs, 7 Eng. FTEs)
How?	Employ precision laser readout, active control, and glass suspensions
Where?	Primary grant holder is the VU, Lab located at Nikhef in Science Park





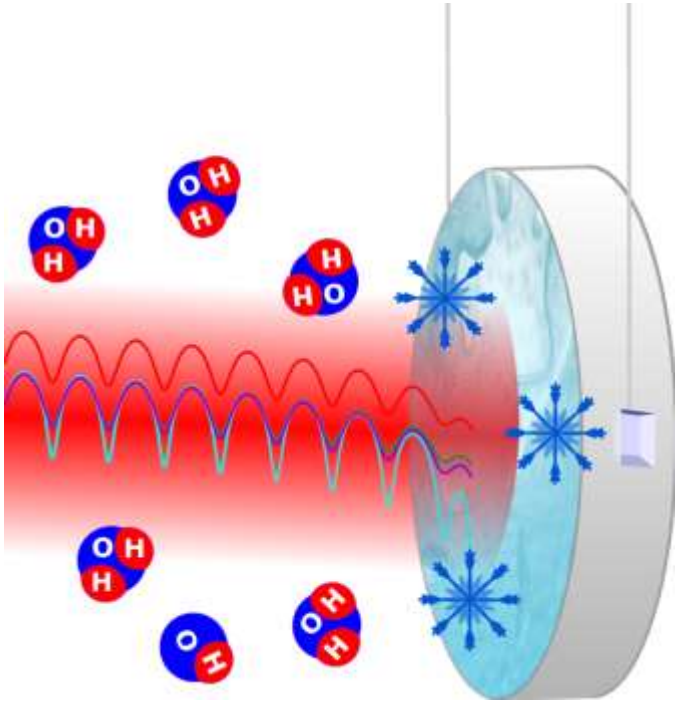


Ice: A cryogenic coating issue

- Observed at KAGRA (Japan) :
  - Ice growth due to a non-perfect vacuum
  - grows by tens of nanometres per day, continuously

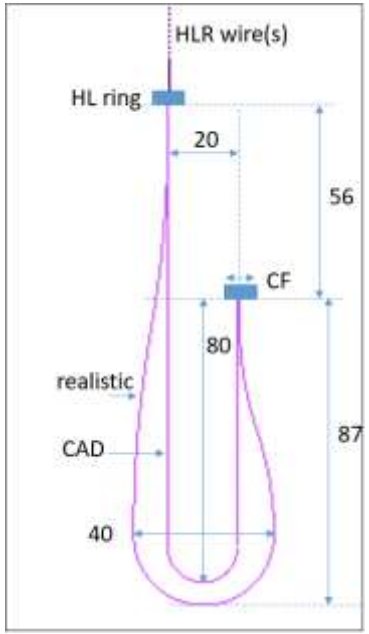
- Acts like an additional coating layer
  - increase in absorption
  - periodic change in reflectivity
  - increase in thermal noise – possibly the dominat effect after a few weeks!

- NWO-Klein project in Maastricht
  - simulate growth conditions
  - characterizing ice properties
  - developing mitigation procedures
    → currently: designing cryostat (Guido Iandolo & Alex Amato)



WP5 - Testing prototypes

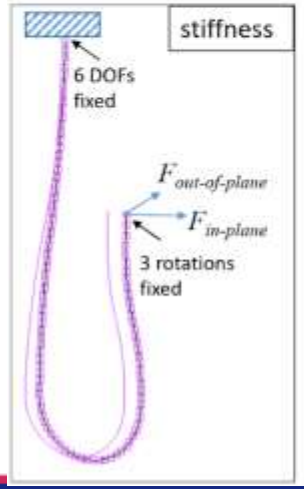
Modeling and measuring transmissibility from heat links

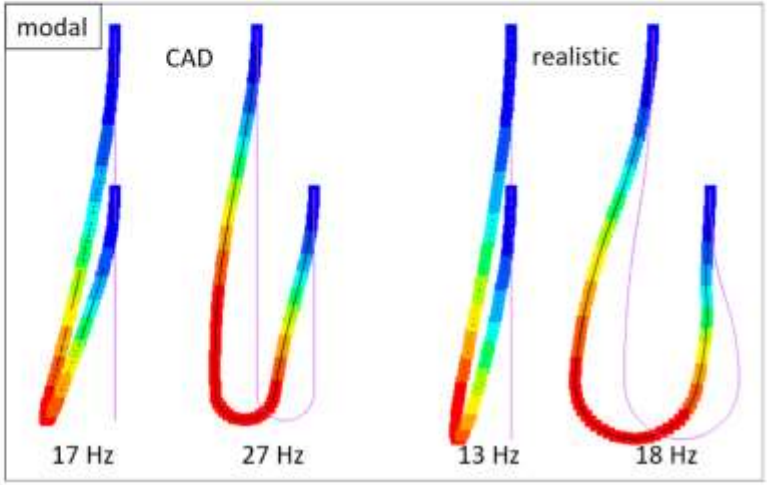


0.25-mm diameter, 22-cm long Al-5083 wire

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_{Hwires}	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		





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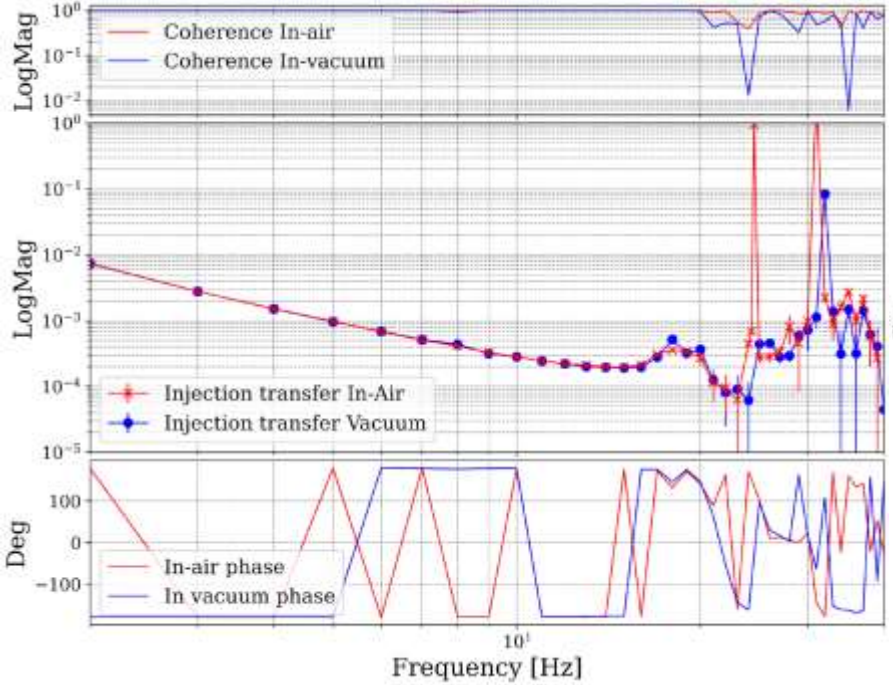

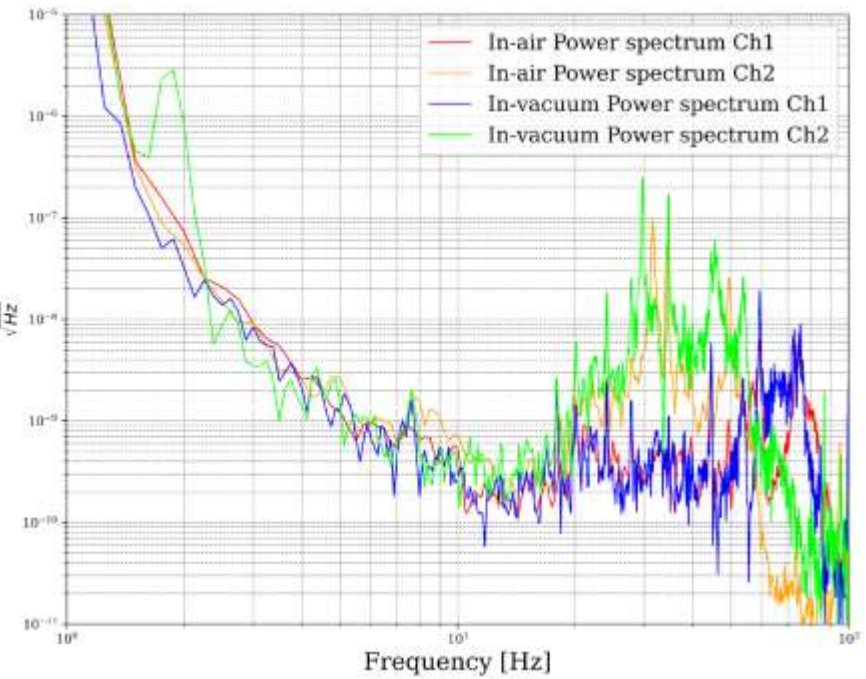

- No significant improvement by measuring in vacuum; structure observed around 18Hz compatible with the FEM
- Outcome: modeling tools have been validated and can be used for design of the 20K payload