

Gravitational Waves

A new window upon our Universe – Einstein Telescope



Typical effect on few kilometer scale:
0.000 000 000 000 000 000 1 meter

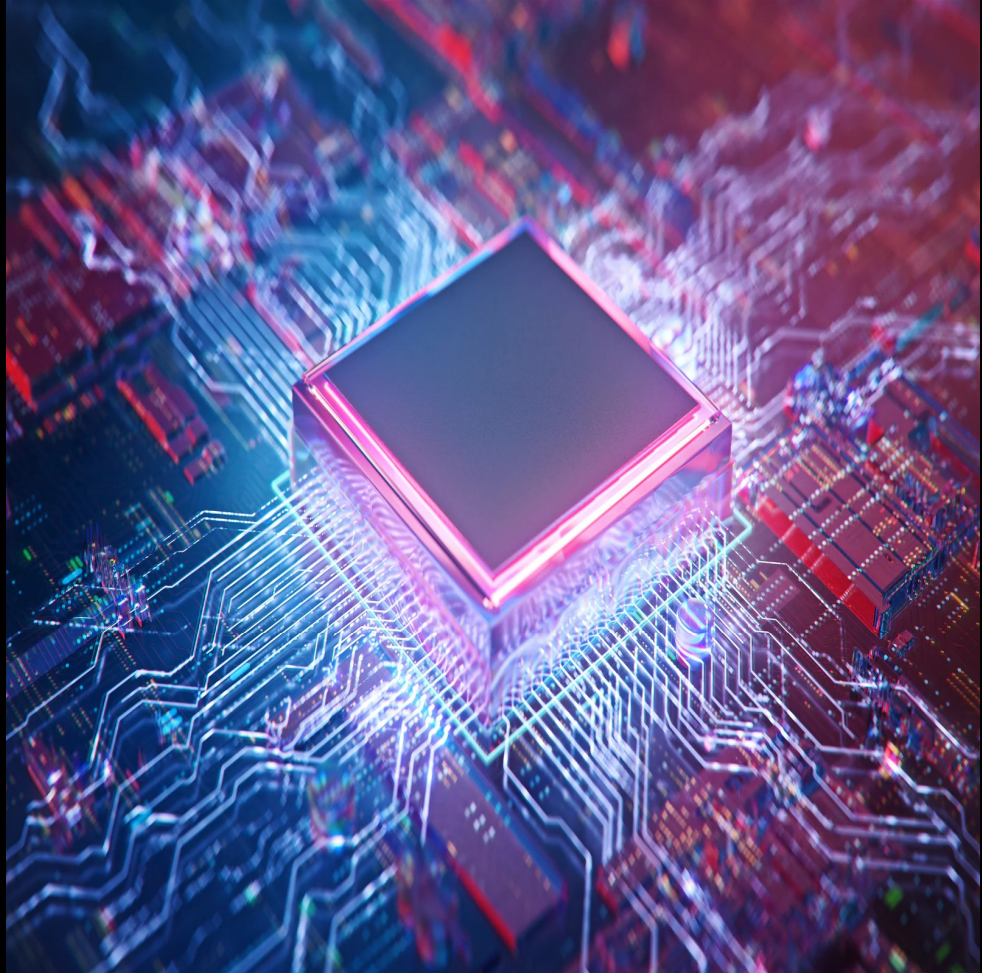
*ETpathfinder visit, Friday 25 November 2022, Frank Linde
KIVI (Koninklijk Instituut Van Ingenieurs)*

*Mindboggling
accuracy*

0.000 000 000 000 000 000 001 meter

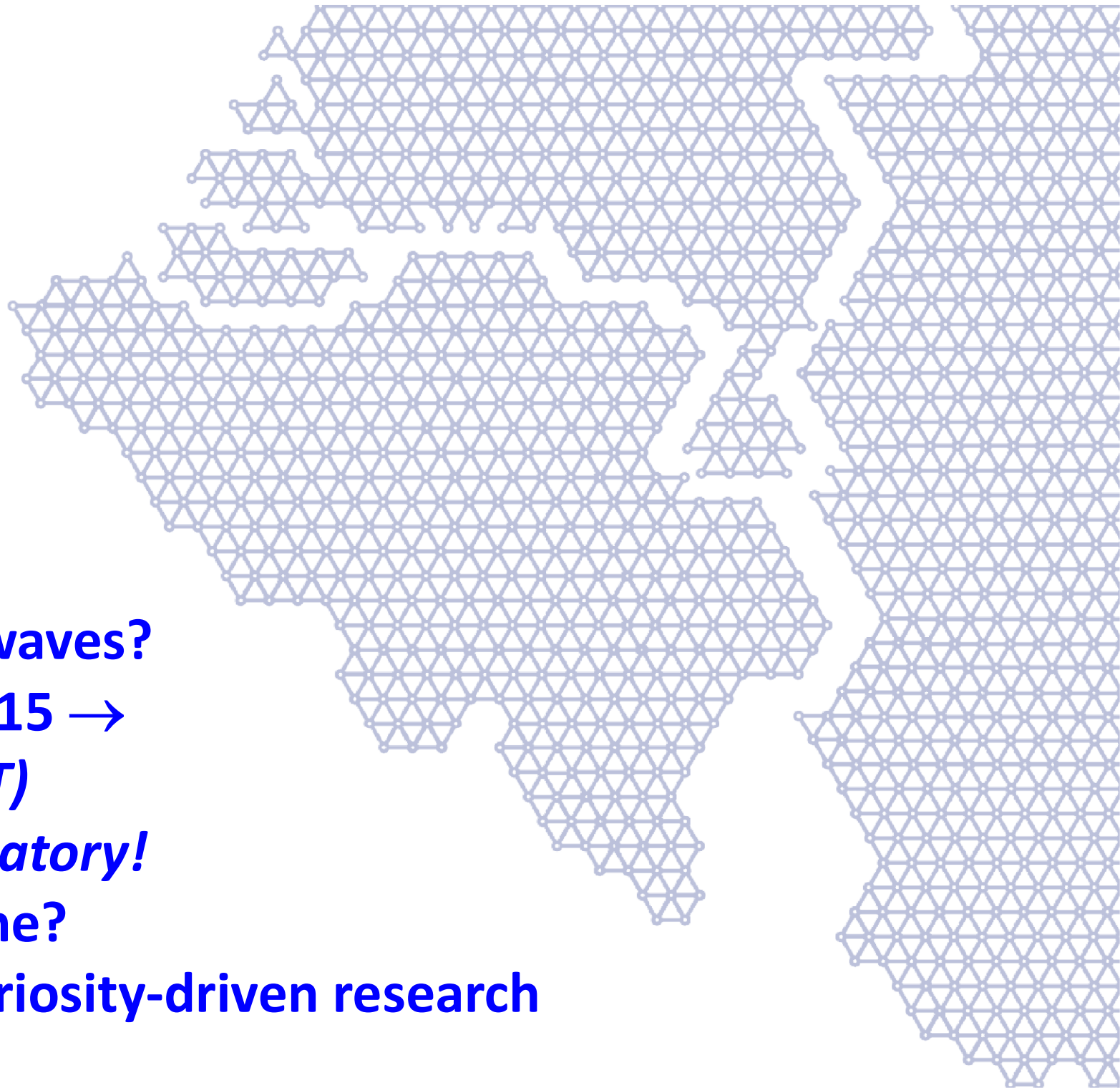


To put 0.000 000 000 000 000 000 001 m in context
nm-scale chip industry: 0.000 000 001 m



nm-scale i.e. single atomic layers is the magic word in the world of microelectronics

Overview

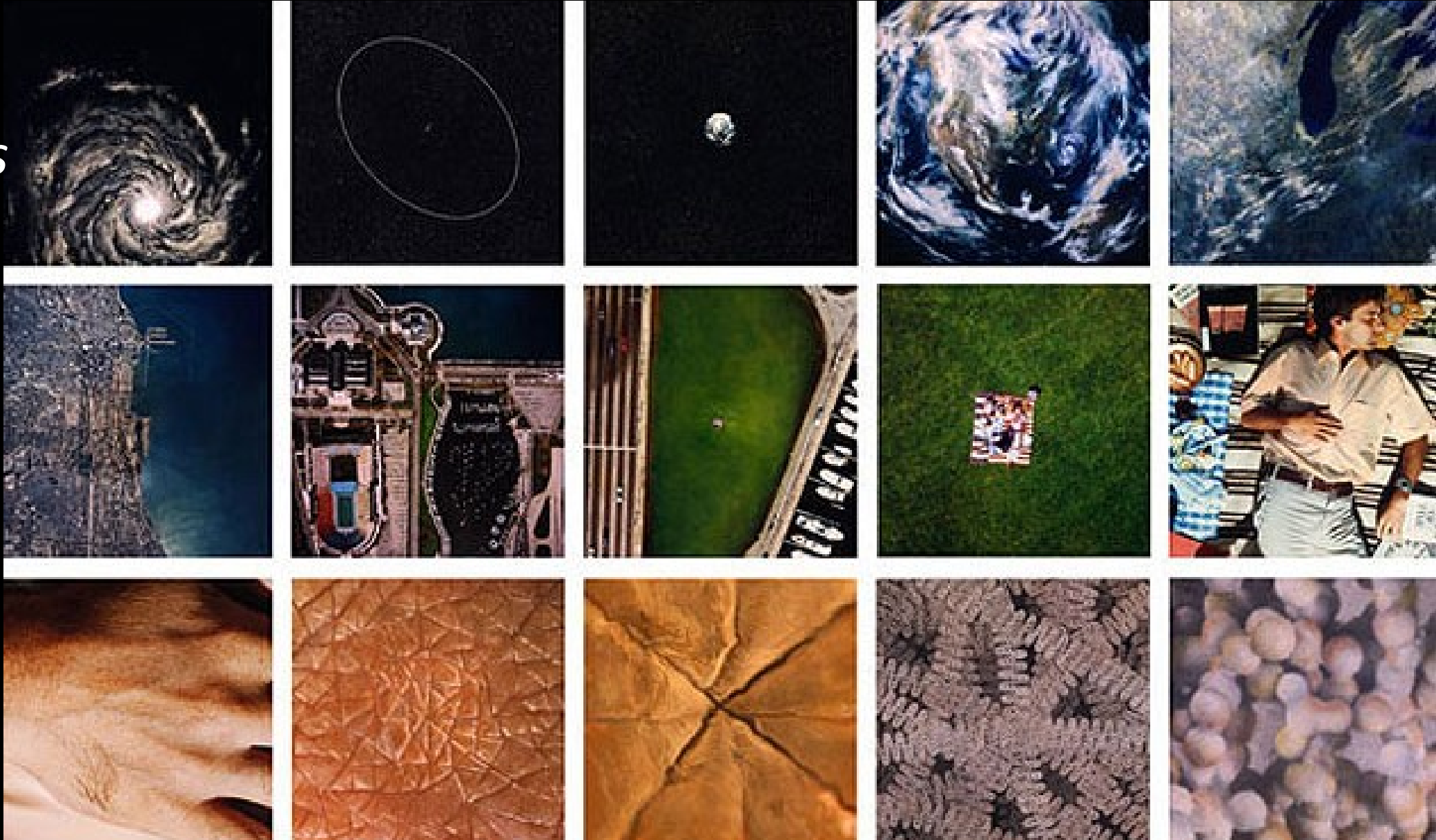


→ Curiosity-driven research

- How to detect gravitational waves?
- Revolutionary detections: 2015 →
- Future: *Einstein Telescope (ET)*
- ETpathfinder: *ET's R&D laboratory!*
- ET in the Euregio Meuse-Rhine?
- Socio-economic impact of curiosity-driven research

Curiosity-driven research

SRON
macro
cosmos



micro
cosmos
Nikhef

Forces of Nature

← compatible with relativity (Einstein) →

← compatible with quantummechanics (Bohr, ...) →

← verified to the extreme (CERN, Higgs, ...!) →



gravity



gravitational waves!

electro-magnetic force



↓
daily life!

radio, TV, mobile, computer,
Remote control, biology, etc.

strong nuclear force



weak nuclear force



How does it work?

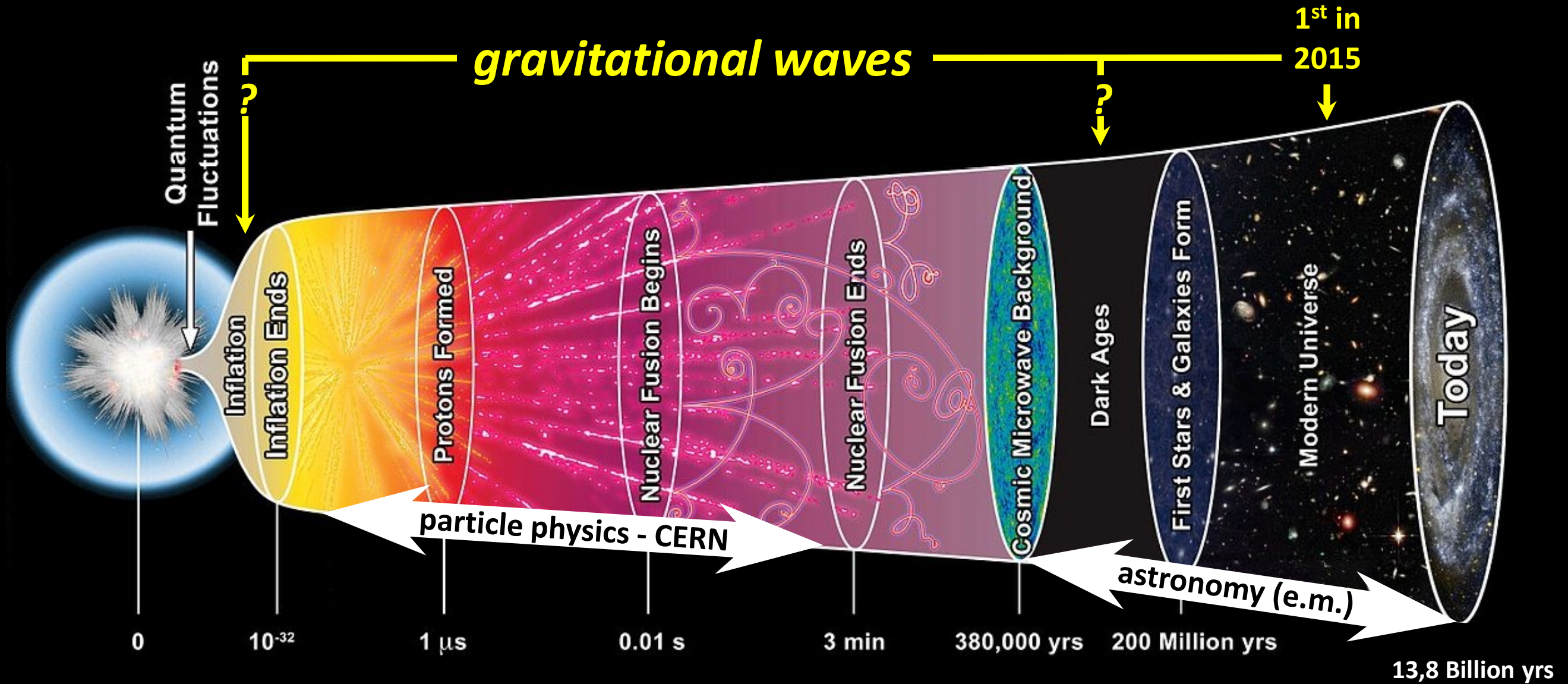
Forces of Nature

electro-magnetic force
strong nuclear force
weak nuclear force

$$\begin{aligned}
 \mathcal{L}_{SM} = & \underbrace{\frac{1}{4} W_{\mu\nu} \cdot W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} G_{\mu\nu}^{\alpha} G_{\alpha}^{\mu\nu}}_{\text{kinetic energies and self-interactions of the gauge bosons}} \\
 & + \underbrace{\bar{L} \gamma^{\mu} \left(i \partial_{\mu} - \frac{1}{2} g \tau \cdot W_{\mu} - \frac{1}{2} g' Y B_{\mu} \right) L + \bar{R} \gamma^{\mu} \left(i \partial_{\mu} - \frac{1}{2} g' Y B_{\mu} \right) R}_{\text{kinetic energies and electroweak interactions of fermions}} \\
 & + \underbrace{\frac{1}{2} \left| \left(i \partial_{\mu} - \frac{1}{2} g \tau \cdot W_{\mu} - \frac{1}{2} g' Y B_{\mu} \right) \phi \right|^2 - V(\phi)}_{W^{\pm}, Z, \gamma \text{ and Higgs masses and couplings}} \\
 & + \underbrace{g'' (\bar{q} \gamma^{\mu} T_a q) G_{\mu}^{\alpha}}_{\text{interactions between quarks and gluons}} + \underbrace{(G_1 \bar{L} \phi R + G_2 \bar{L} \phi_c R + h.c.)}_{\text{fermion masses and couplings to Higgs}}
 \end{aligned}$$

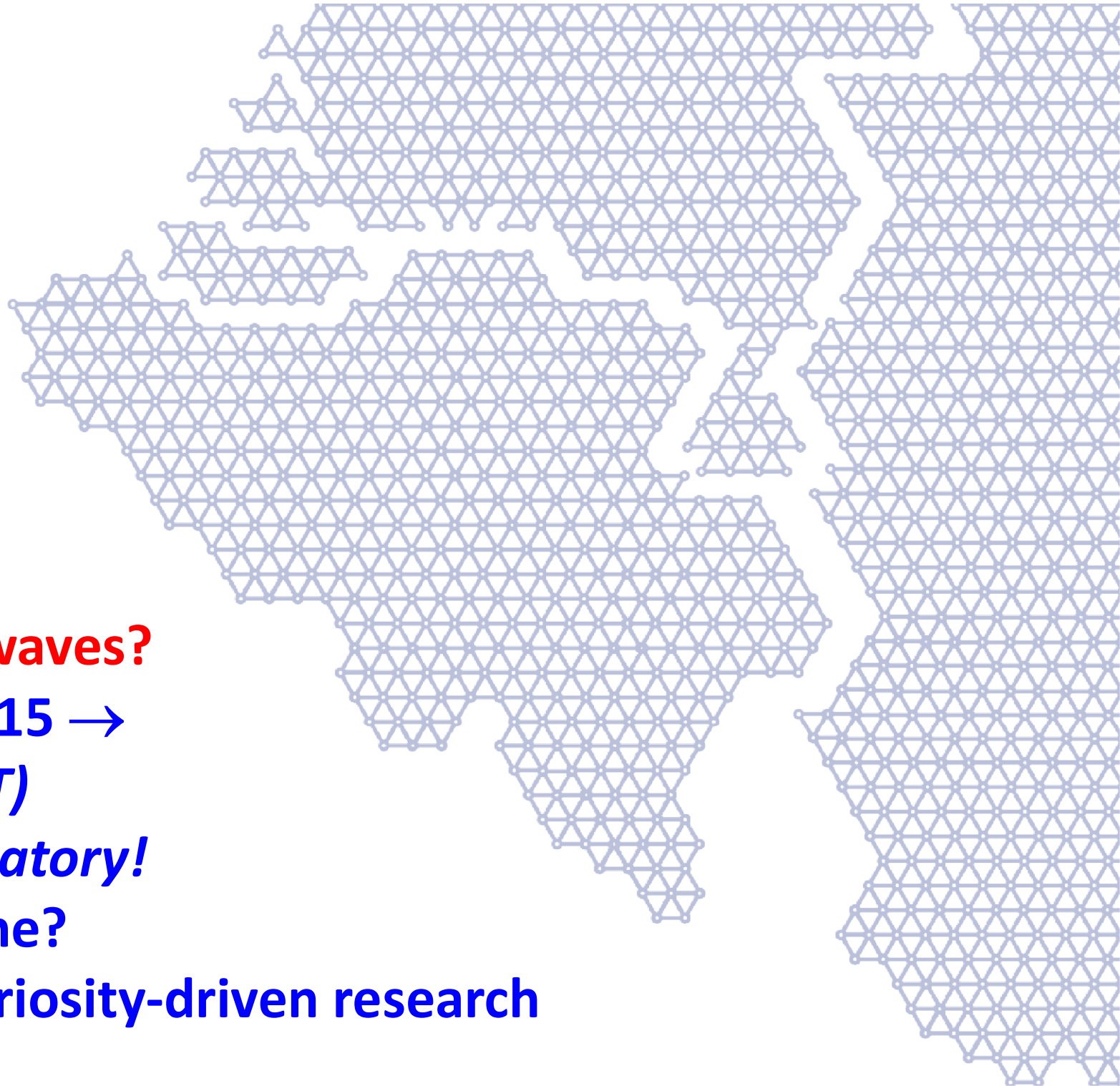
How does it work?

What did we learn?



Where do we come from? – Where are we headed for?

Overview

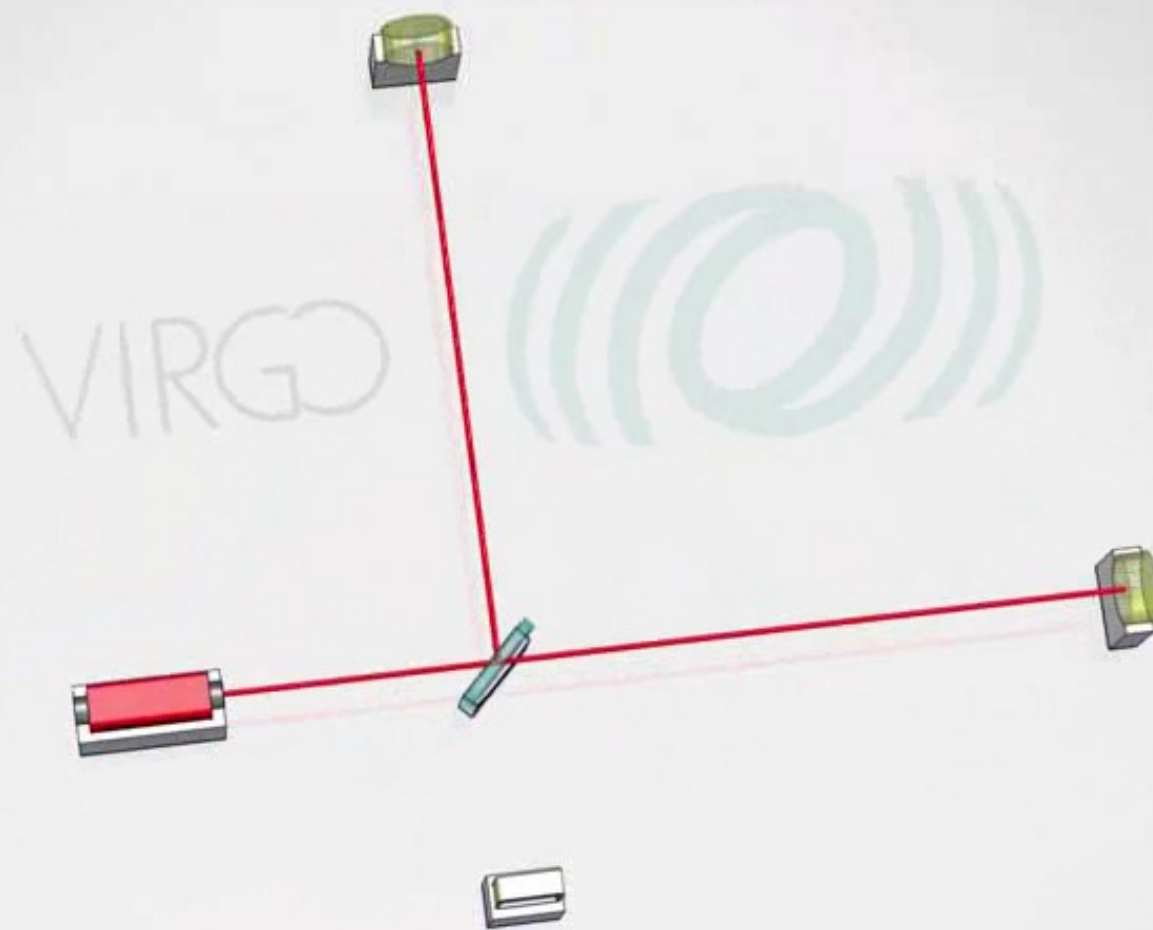


- **Curiosity-driven research**

→ **How to detect gravitational waves?**

- **Revolutionary detections: 2015 →**
- **Future: *Einstein Telescope (ET)***
- **ETpathfinder: *ET's R&D laboratory!***
- **ET in the Euregio Meuse-Rhine?**
- **Socio-economic impact of curiosity-driven research**

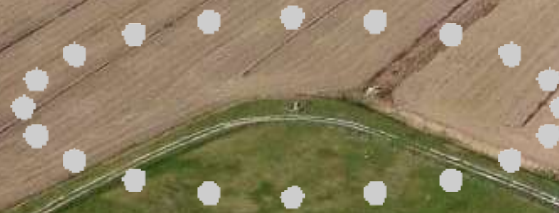
From the concept to reality



Today's facilities:

*started around 1990
few km long arms
on surface
at room temperature
in the USA, Europe & Japan*

0(100) detections/year



Virgo
near Pisa



LIGO - Hanford

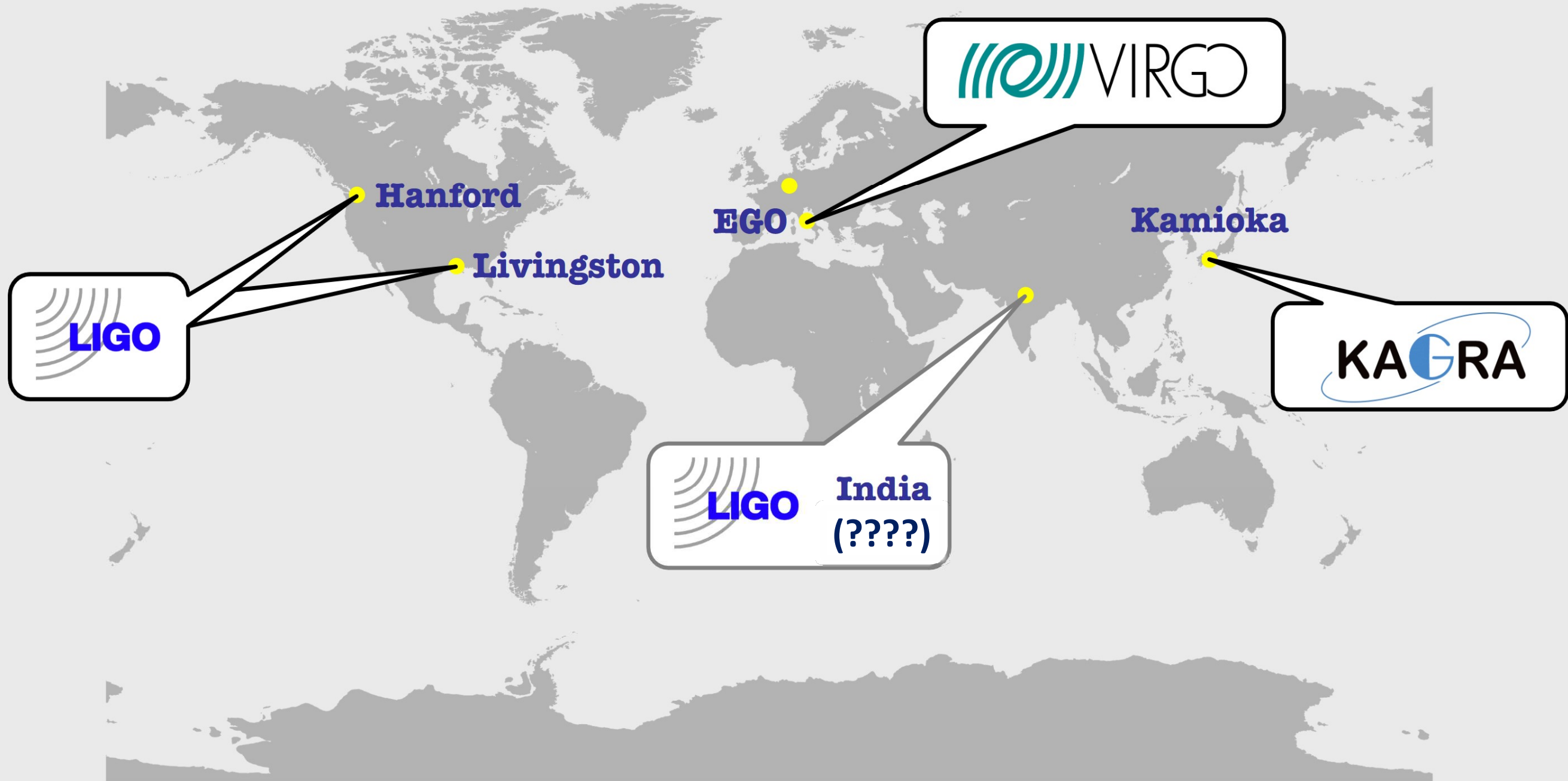
*4 km lange 'armen'
Hanford, WA
(VS)*



LIGO - Livingston

*4 km lange 'armen'
Livingston, LA
(VS)*

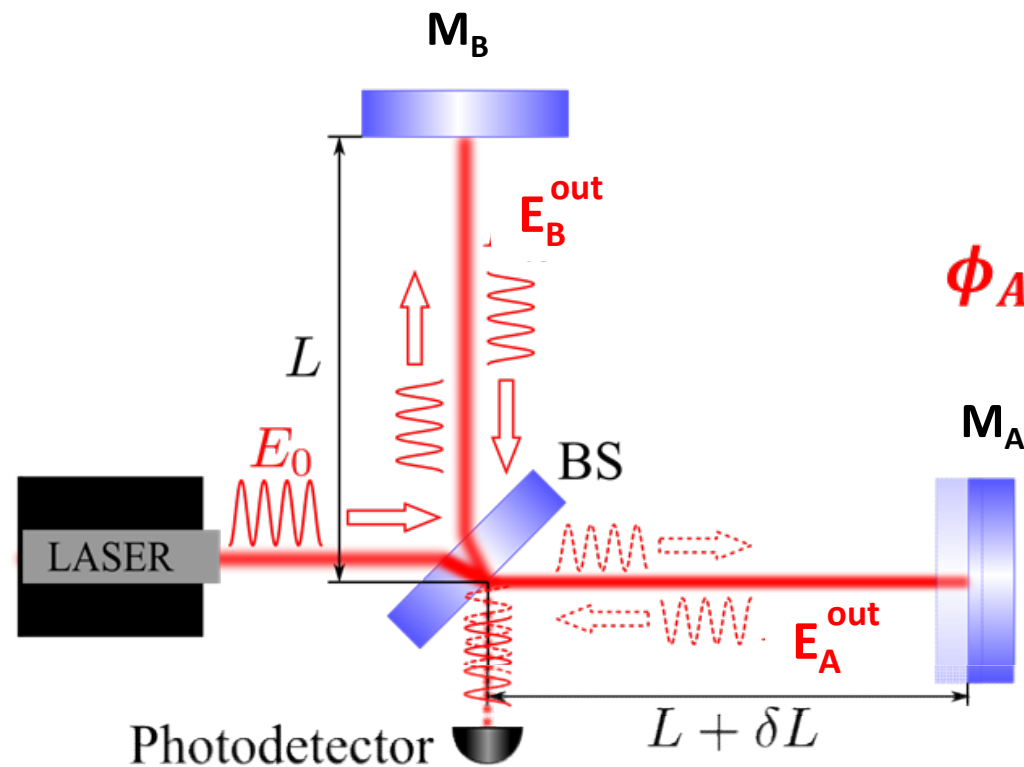
Worldwide network



How to reach down to 10^{-18} meters?

Michelson interferometer

For simplicity: assume laser light storage time $<$ GW period

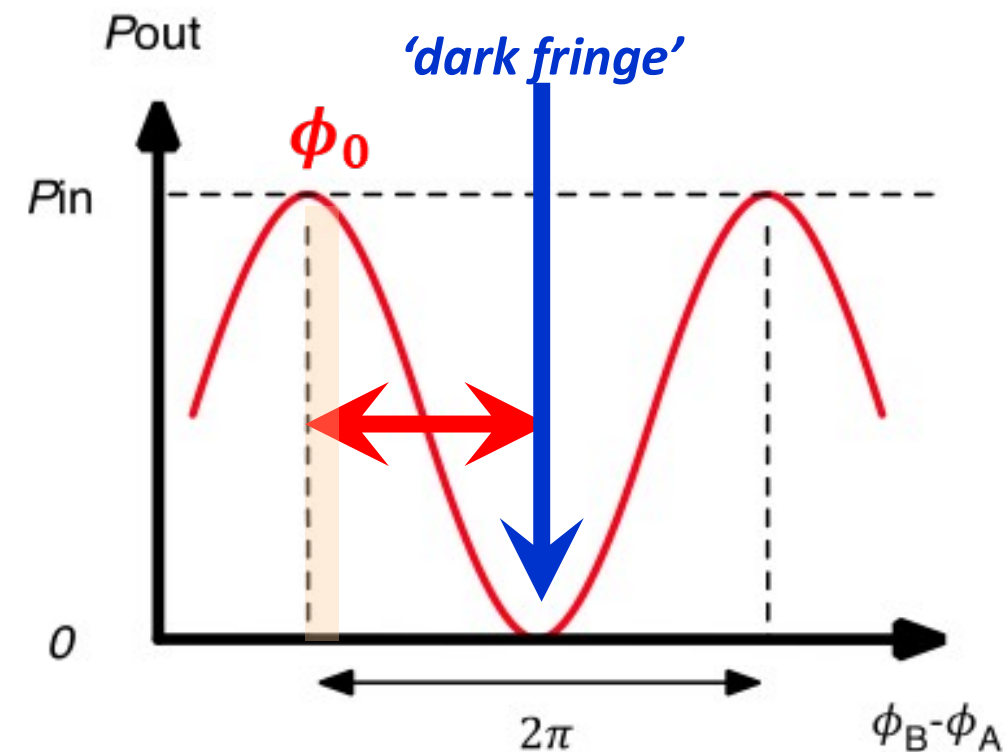


$$\phi = \frac{4\pi}{\lambda} (L \pm \Delta L)$$

$$\phi_A - \phi_B = \frac{8\pi}{\lambda} \Delta L$$

$$= \frac{8\pi L}{\lambda} h$$

$$h \equiv \frac{\Delta L}{L}$$



$$E_{out} = \frac{1}{2} \left(e^{-i\phi_A} - e^{-i\phi_B} \right) E_{in}$$

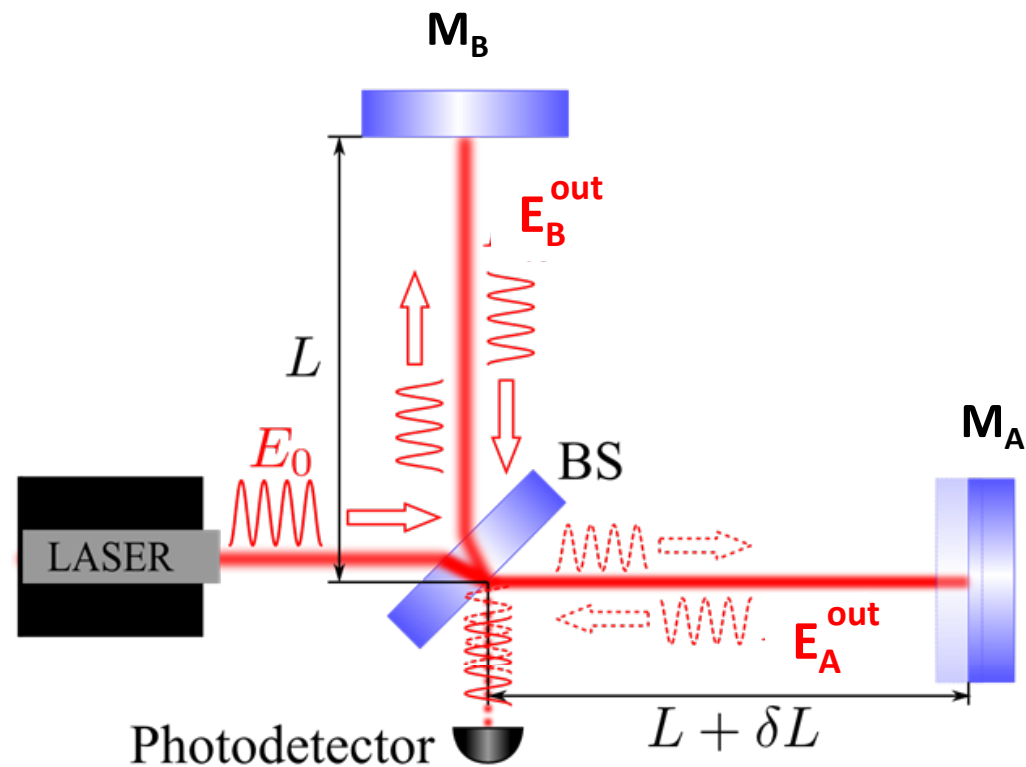
$$= \left[i e^{-i(\phi_A + \phi_B)/2} \sin \left(\frac{\phi_A - \phi_B}{2} \right) \right] E_{in}$$

$$P_{out} = E_{out} E_{out}^* = P_{in} \sin^2 \left(\frac{\phi_A - \phi_B}{2} \right)$$

$$= \left[1 - \cos(\phi_A - \phi_B) \right] \frac{P_{in}}{2}$$

How to reach down to 10^{-18} meters?

Michelson interferometer



Need: very stable laser (10^{-8})!

**Operate close to 'dark fringe'
(not @ 'dark fringe': no signal ...)**

$$P_{out} = \frac{P_{in}}{2} \left(1 - \cos\left(\phi_0 + \frac{8\pi L}{\lambda} h\right) \right)$$

$$\Rightarrow \left[\begin{array}{l} \text{laser power} \\ \text{strain } \Delta h \end{array} \right. \Delta P_{out} \sim \frac{\Delta P_{in}}{2} (1 - \cos \phi_0)$$

$$\frac{\Delta P_{out}}{\Delta h} \sim P_{in} \frac{4\pi L}{\lambda} \sin \phi_0$$

$$\Rightarrow \Delta h \sim \frac{\Delta P_{in}}{P_{in}} \times \frac{\lambda}{8\pi L} \times \frac{1 - \cos \phi_0}{\sin \phi_0}$$

$$\geq 10^{-19} \times \frac{1 - \cos \phi_0}{\sin \phi_0}$$

How to reach down to 10^{-18} meters?

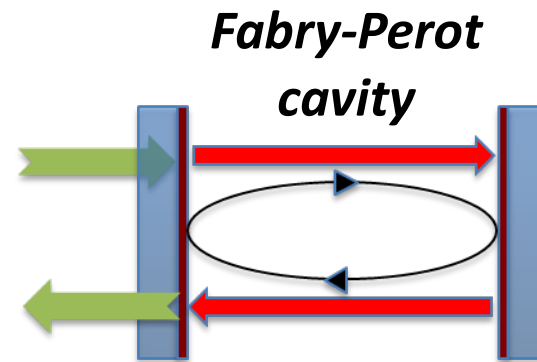
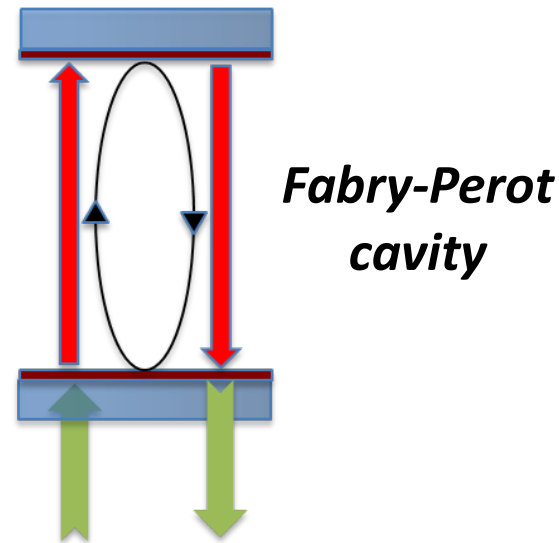
**Fabry-Perot
cavities**

power builds up by
large (few 100) factor;
effectively increasing
the arm lengths
correspondingly!

Laser

**power
recycling**

**signal
recycling**



$$L = n\lambda/2$$

$$\Delta h \geq 10^{-21-22} \times \frac{1 - \cos \phi_0}{\sin \phi_0}$$



How to reach down to 10^{-18} meters?

Fabry-Perot
cavities

power
recycling

signal
recycling

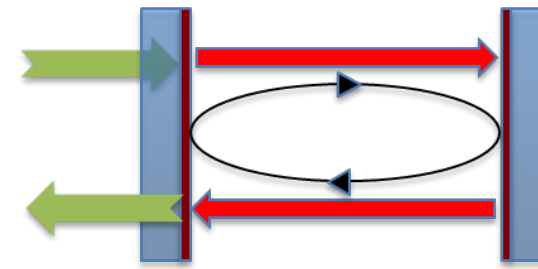
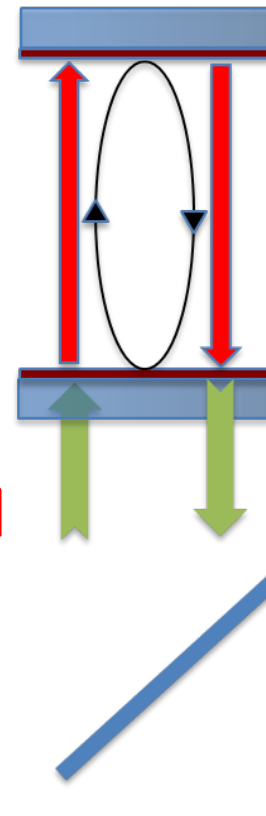
interferometer
operated very near
'dark fringe'
⇒ almost all power
exiting towards laser

Laser

reflect coherently with
fresh laser light into
the interferometer!

PRM

PRM = *Power Recycling Mirror*



How to reach down to 10^{-18} meters?

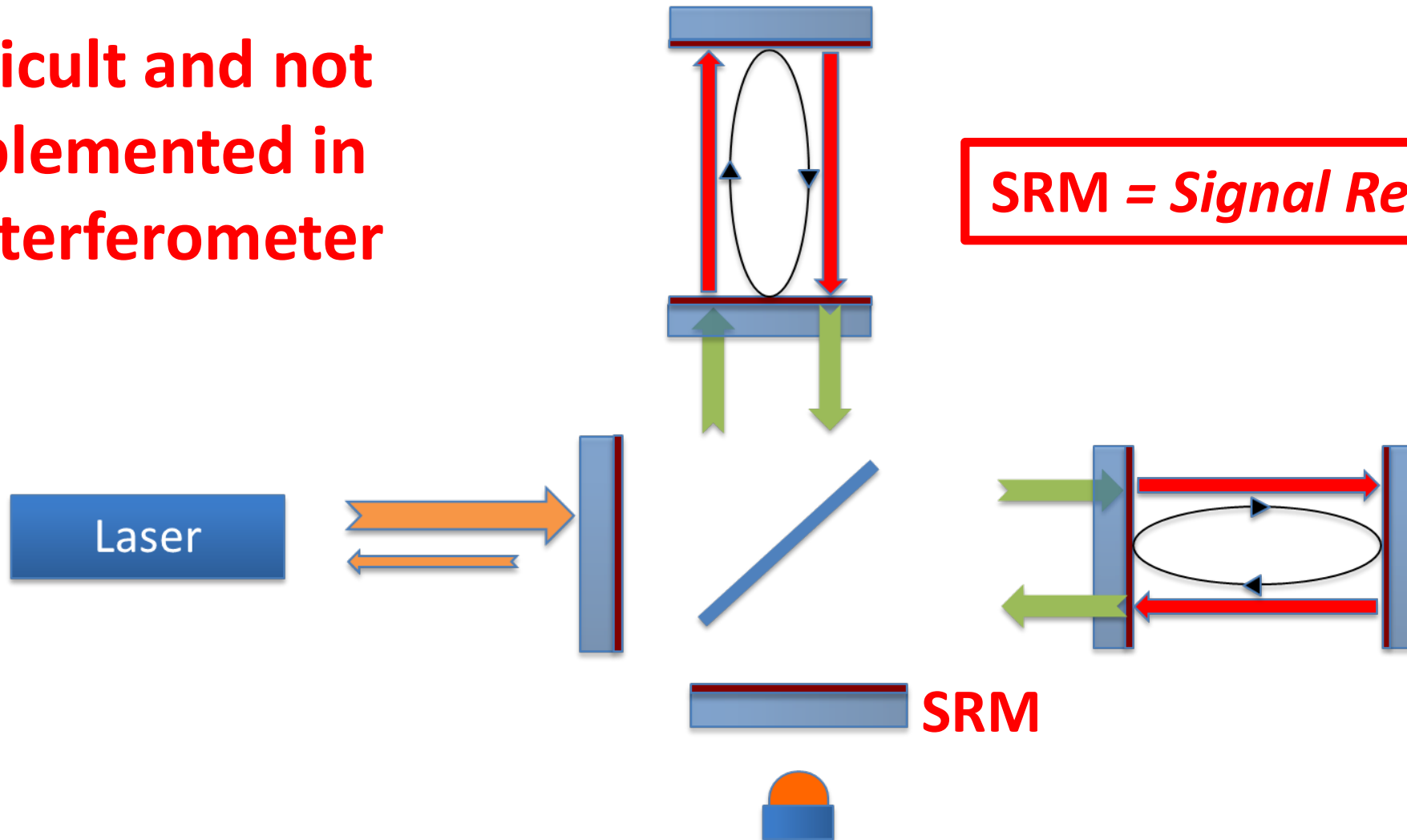
Fabry-Perot
cavities

power
recycling

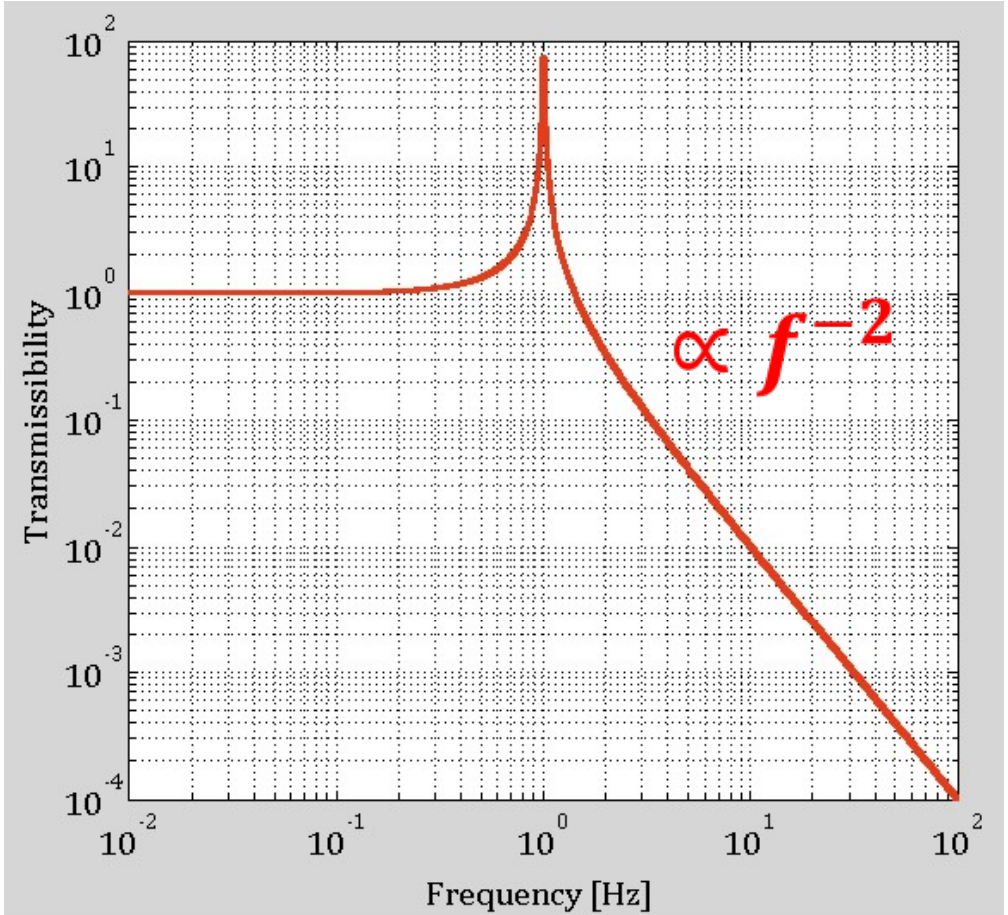
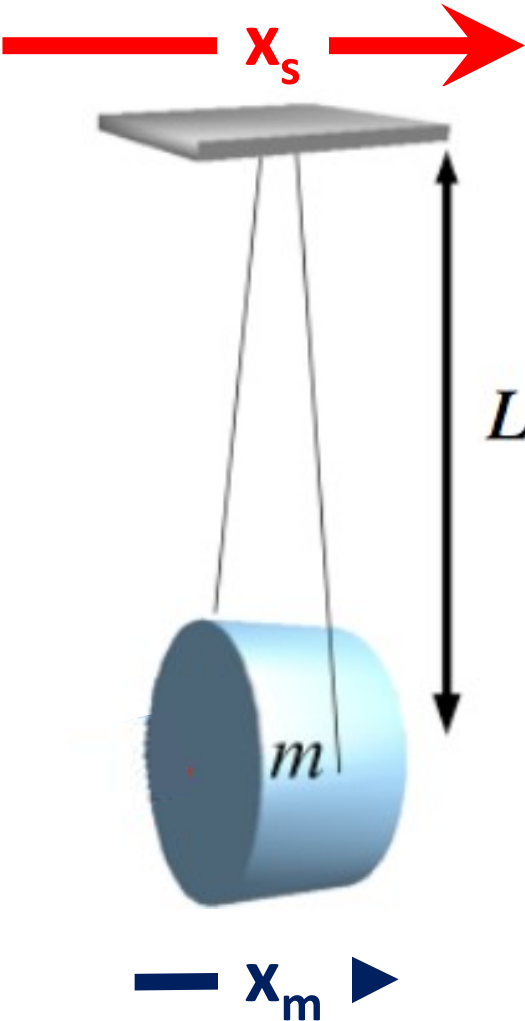
signal
recycling

too difficult and not
yet implemented in
Virgo interferometer

SRM = Signal Recycling Mirror

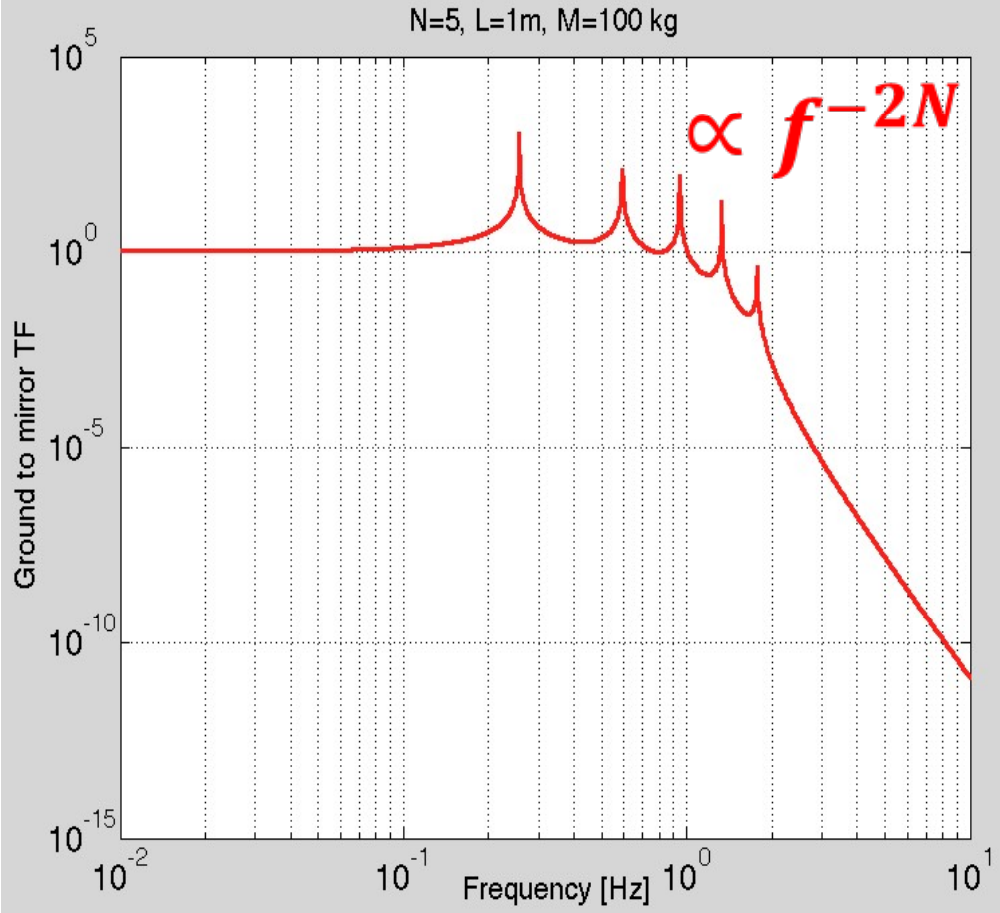
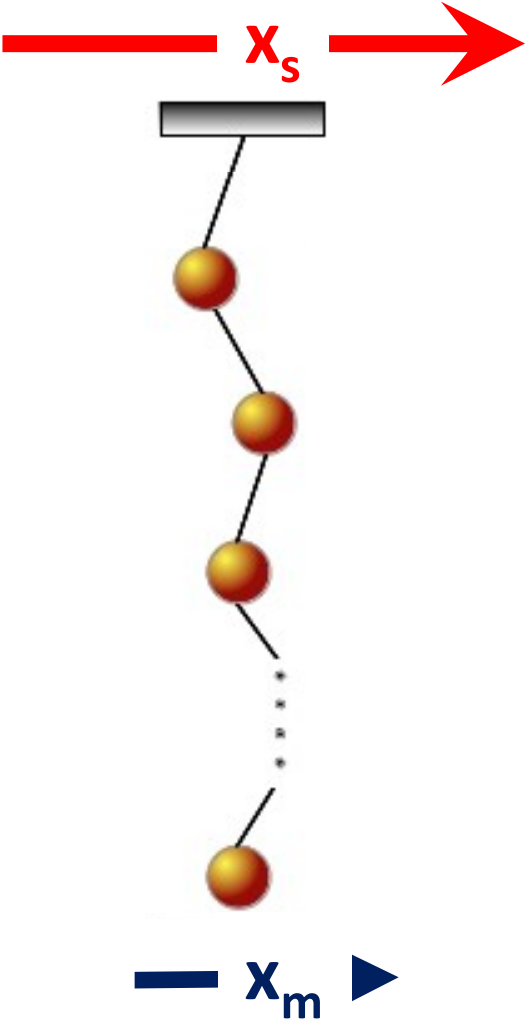


How to reduce noise? *E.g. (seismic) vibrations*

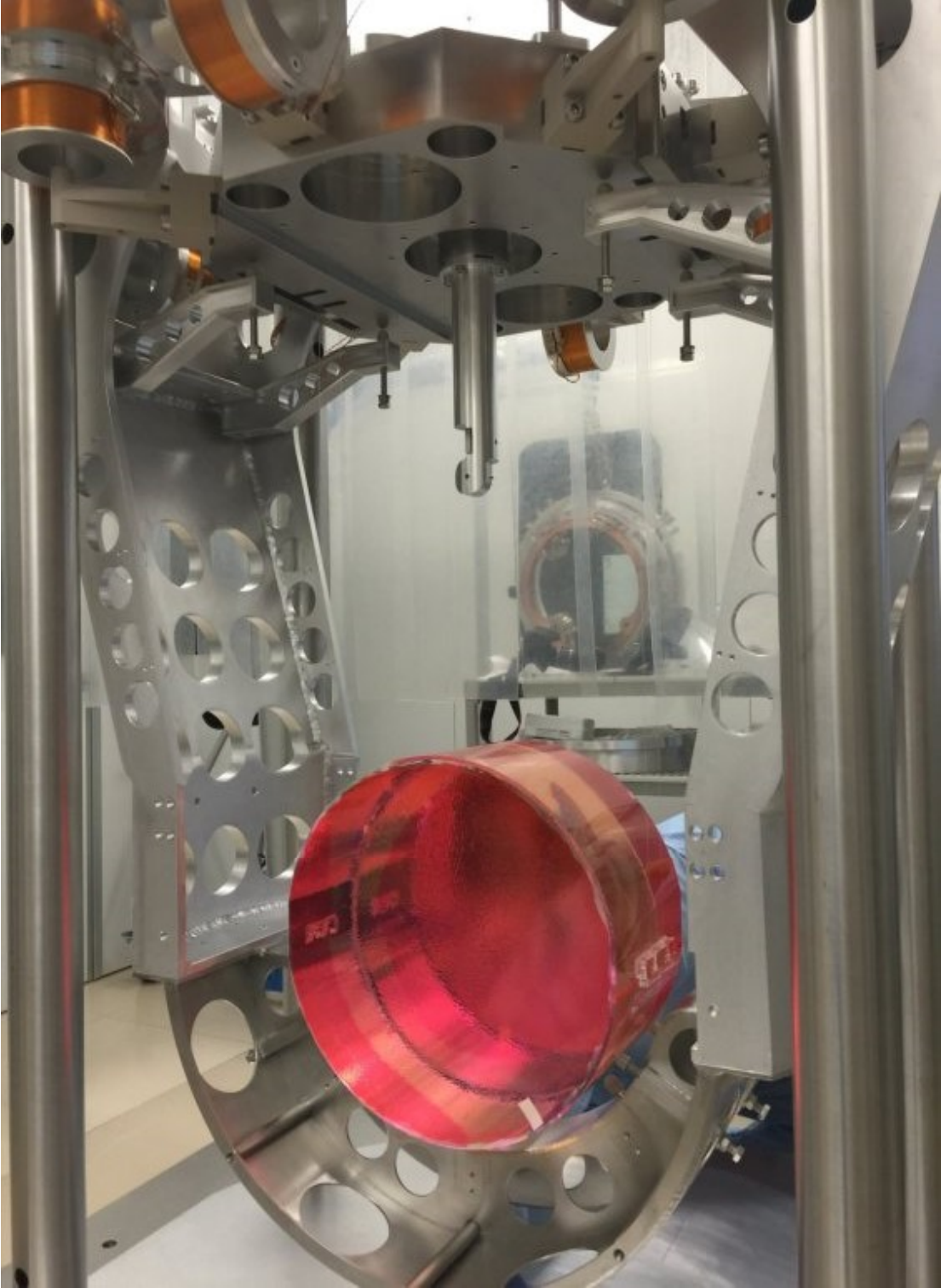


Elaborate multiple pendula attenuators

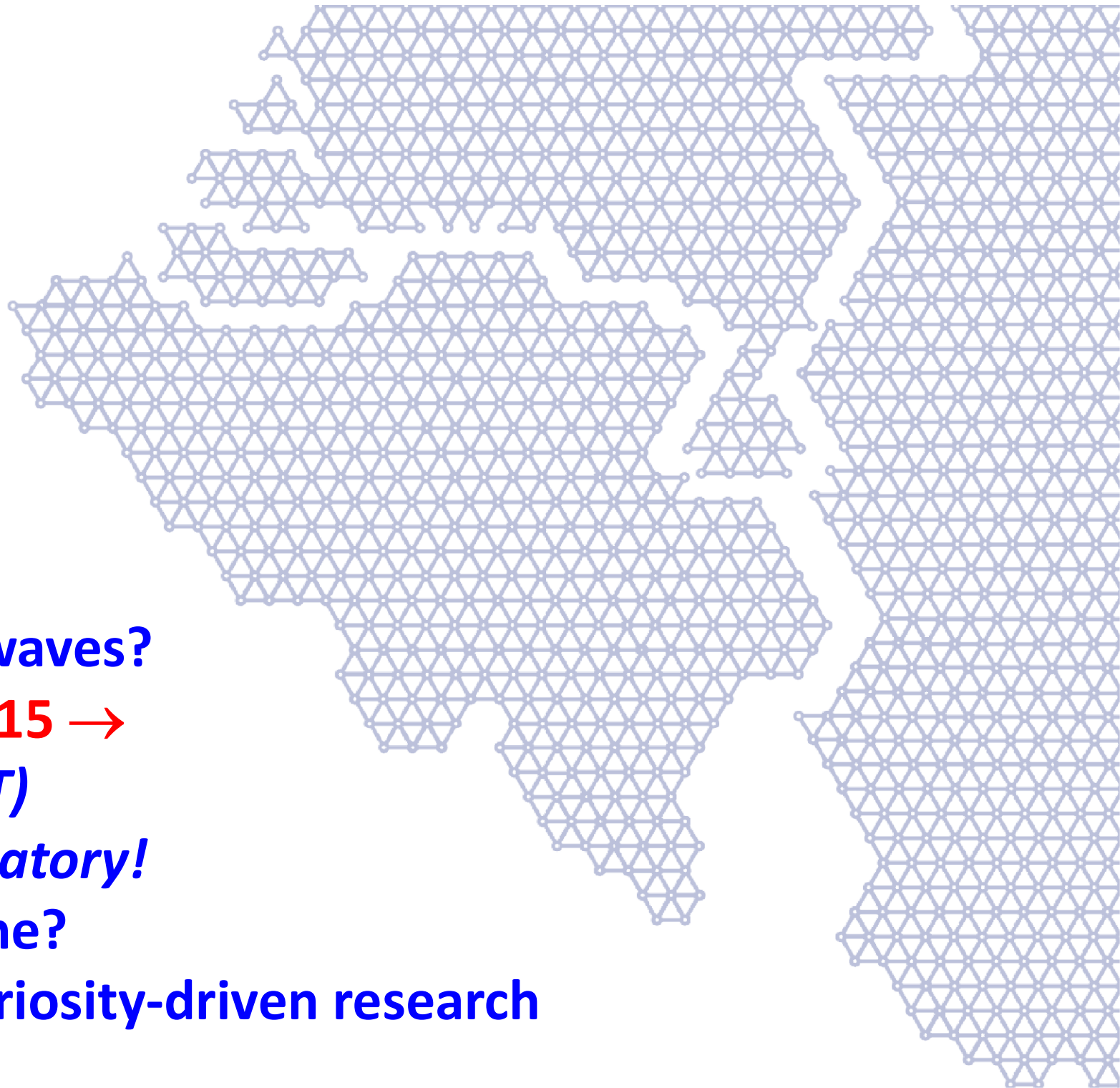
Just an example. Lots of other (quantum) tricks which I fail to explain i.e. very elaborate control systems!



Elaborate multiple pendula attenuators



Overview

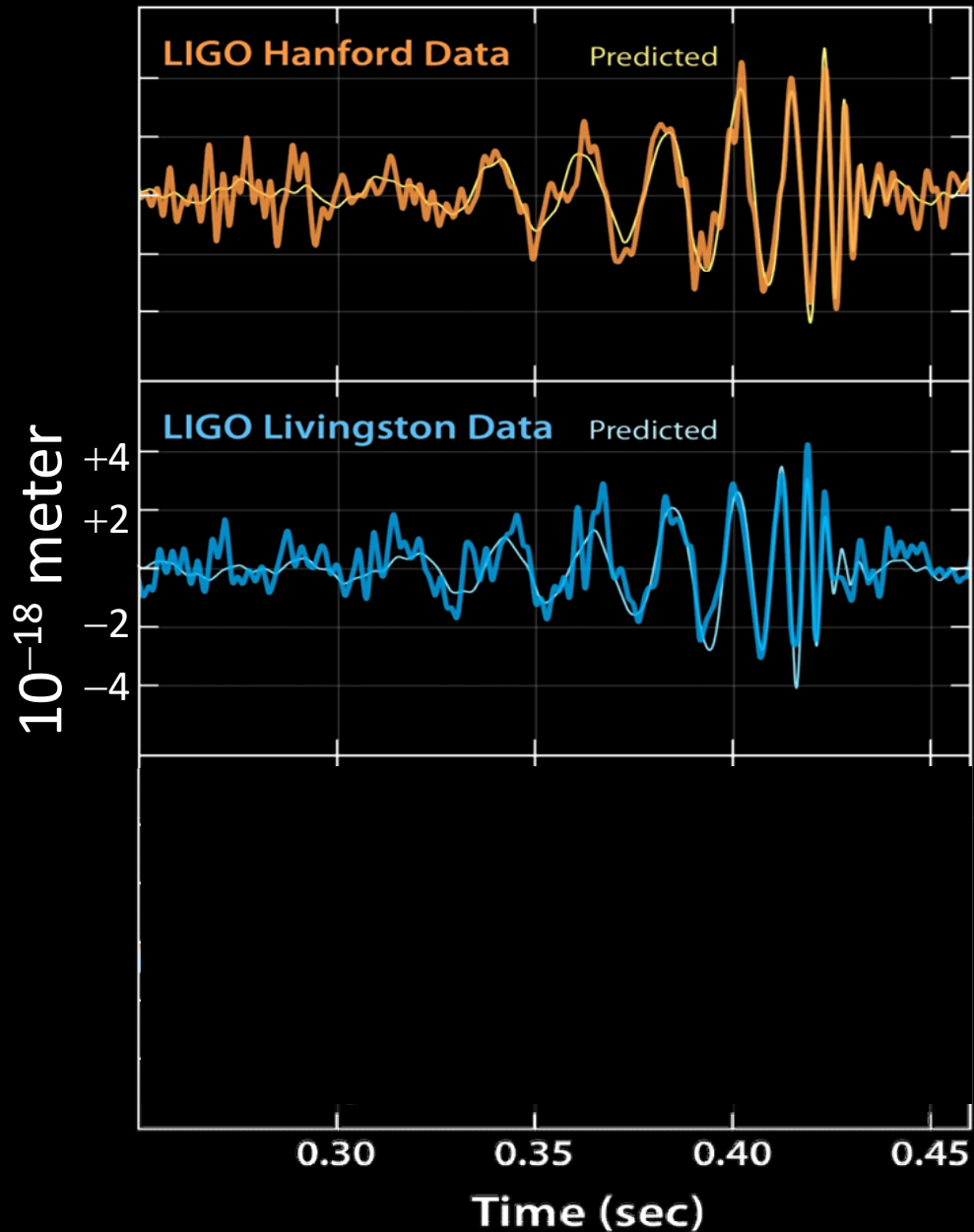


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1st detection SEP/2015: *black holes*

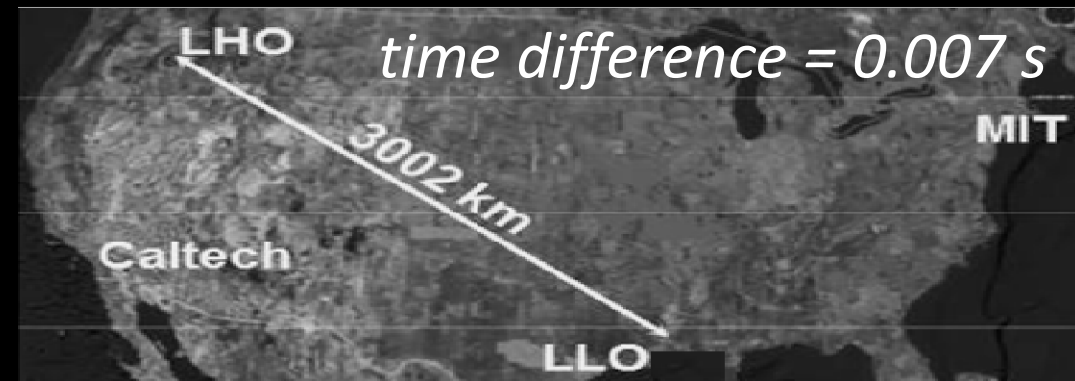


1st detection SEP/2015: black holes

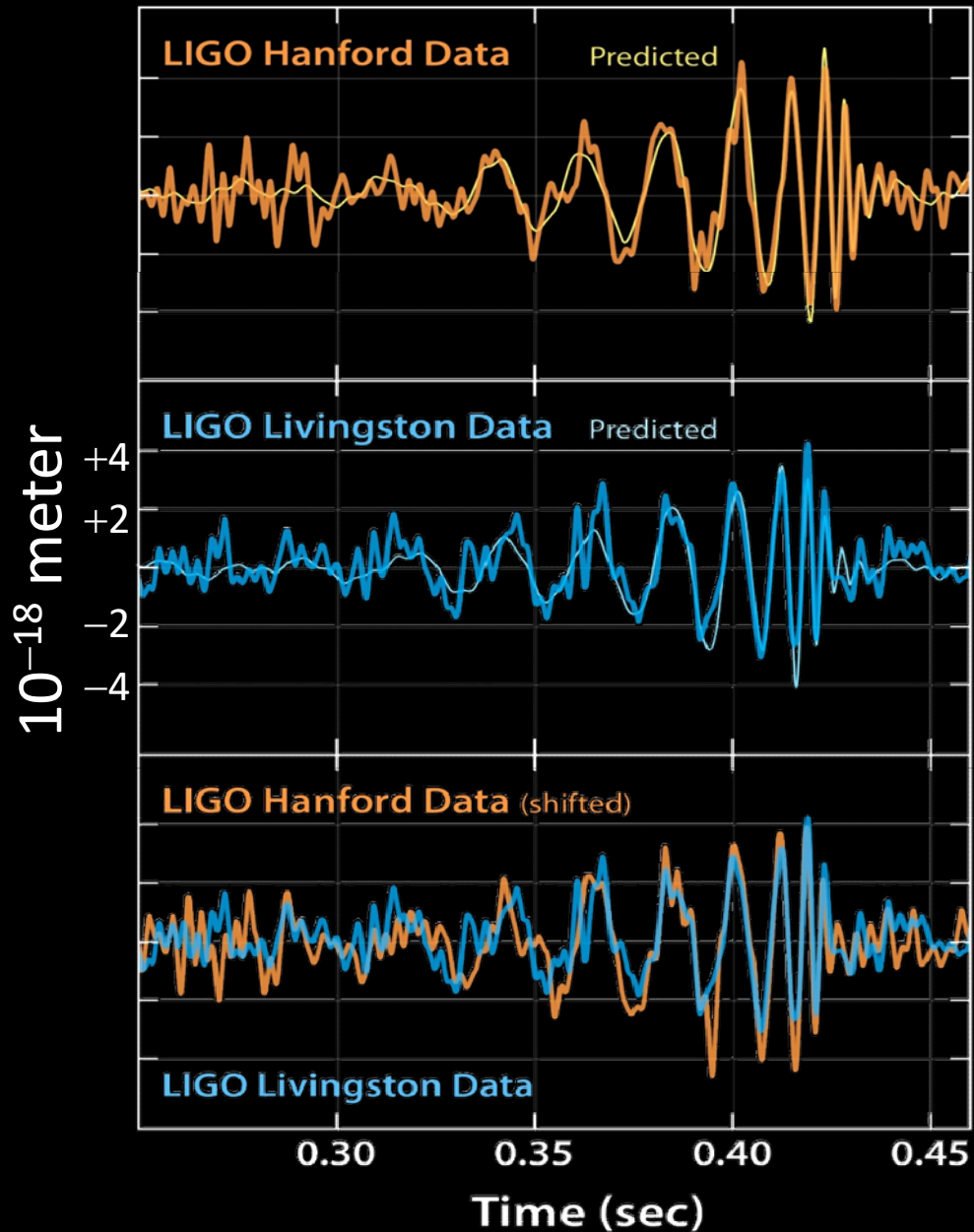


In a nutshell:

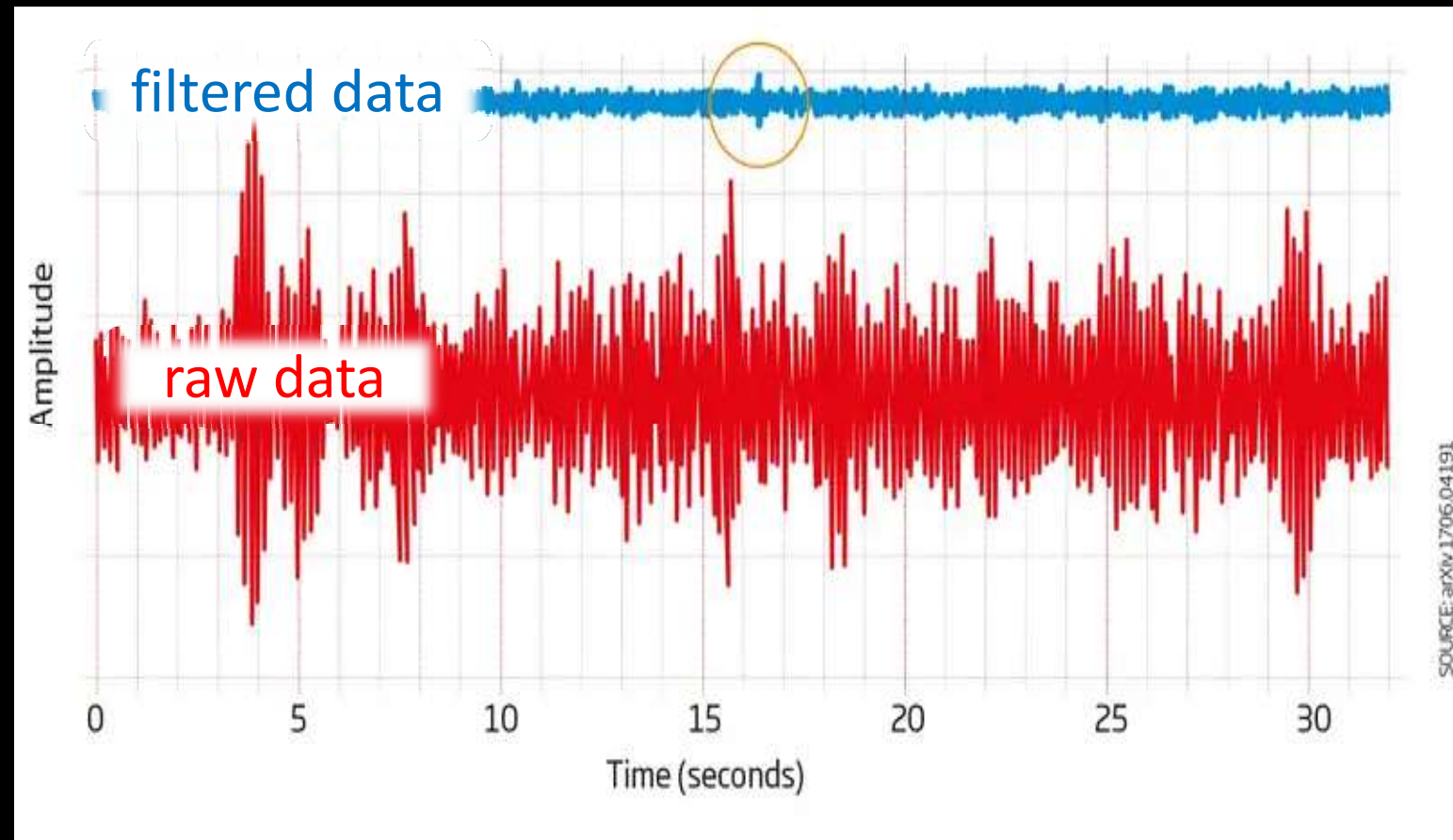
1.4 billion years ago two black holes ($29 \times M_{Sun}$ & $36 \times M_{Sun}$) merged into a single $62 \times M_{Sun}$ black hole



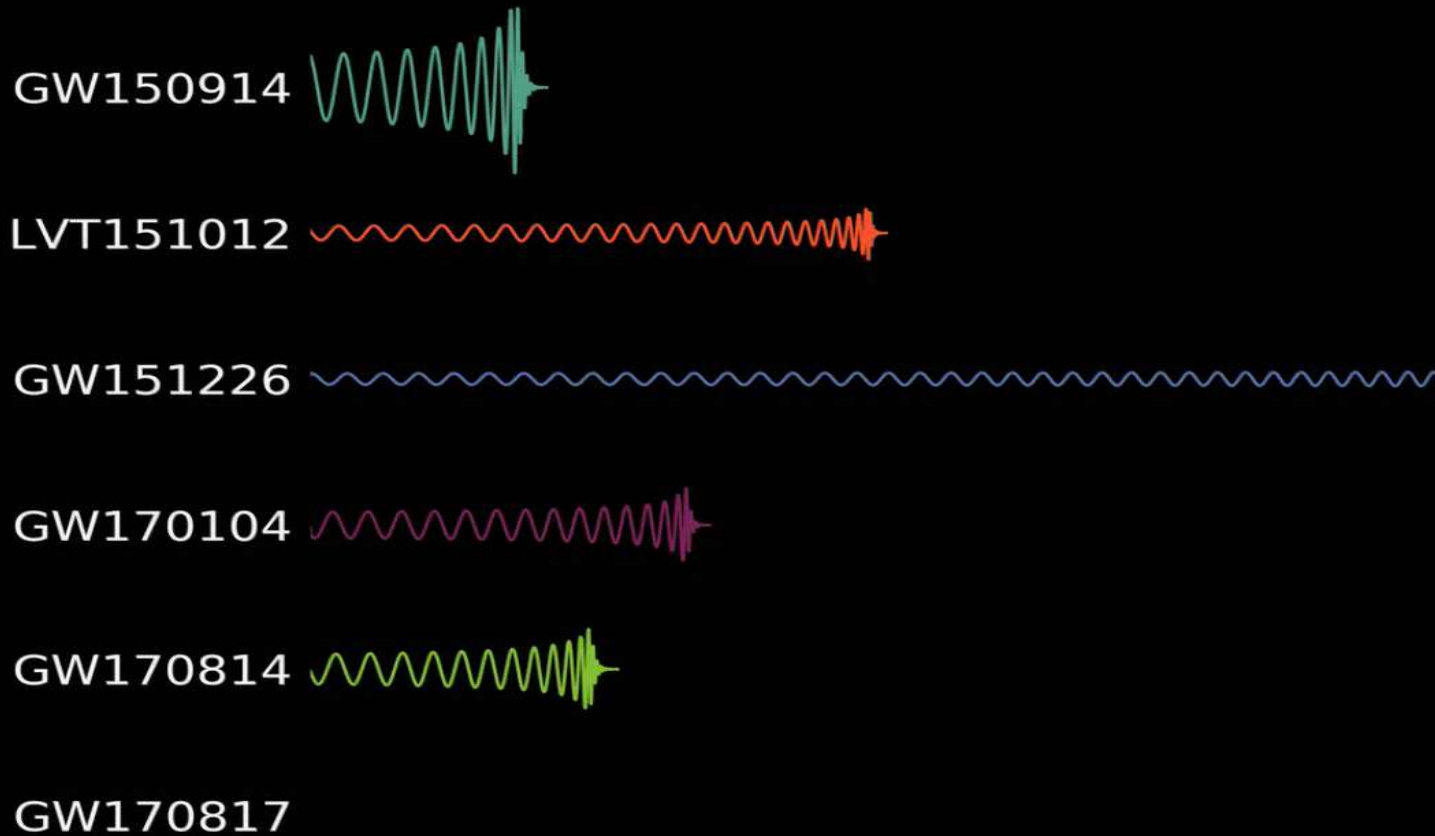
1st detection SEP/2015: black holes



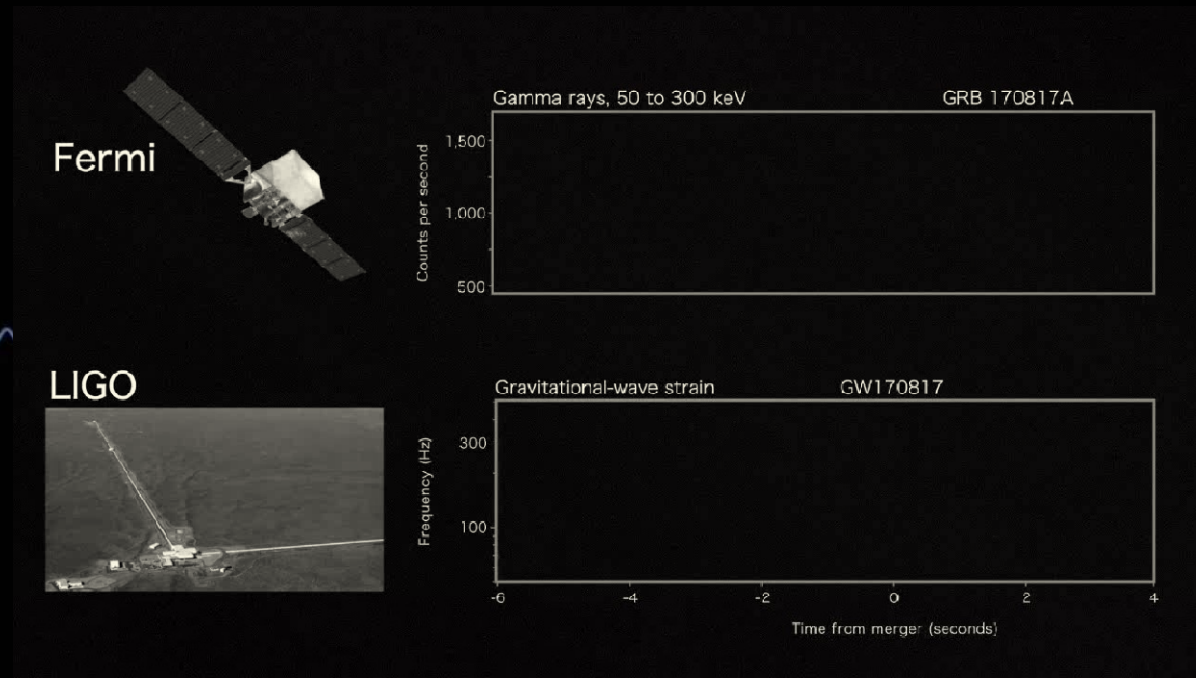
Reality: lots of data analysis to extract the minute imprint of a gravitational wave from the continuous data stream (and to guarantee it isn't an art-effect!)



Revolutionary one AUG/2017: neutron stars




time observable (seconds)



Revolutionary one AUG/2017: *neutron stars*

Revolutionary one AUG/2017: neutron stars

origin of chemical elements

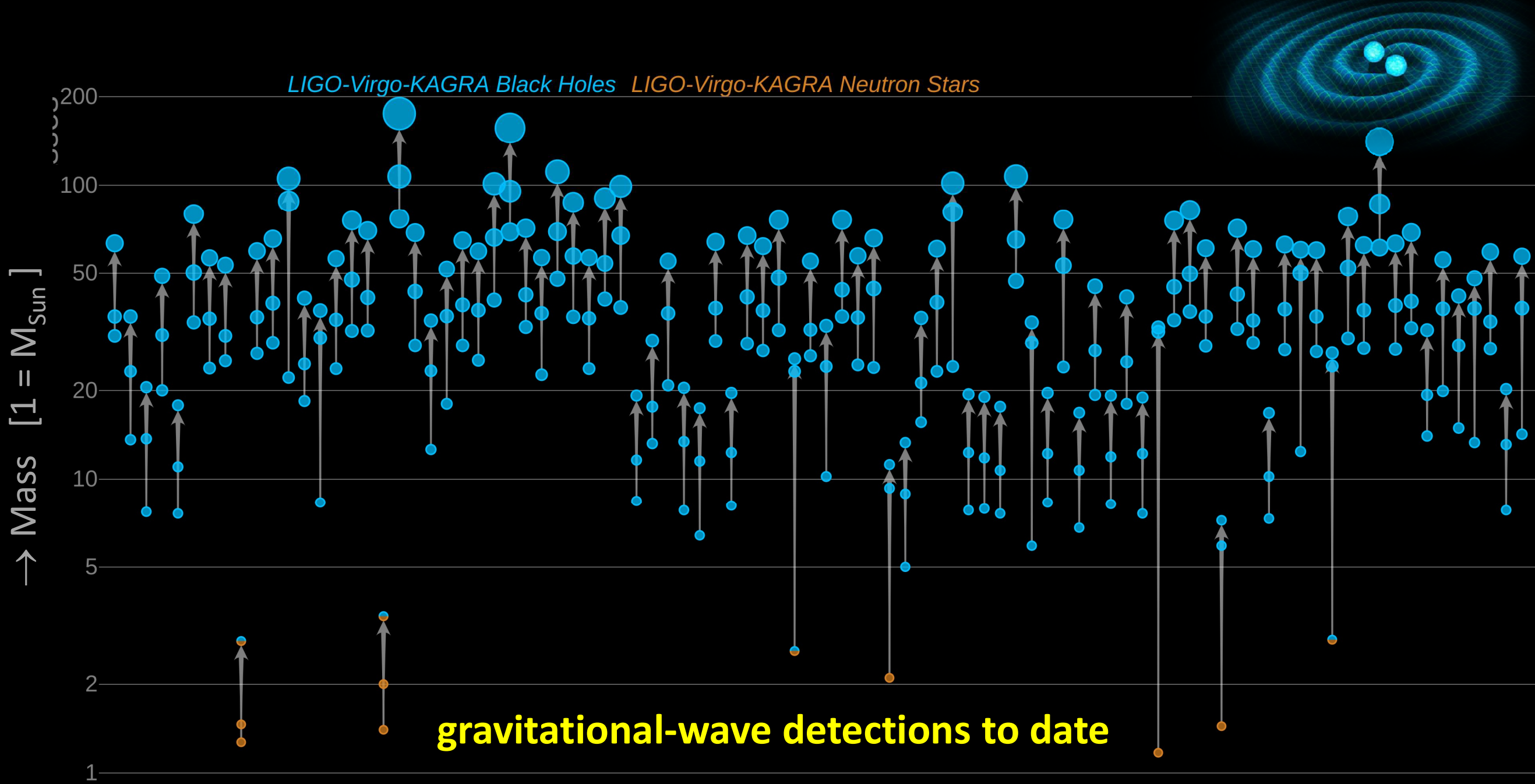
1 H																	2 He	
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt		80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																	
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
		89 Ac	90 Th	91 Pa	92 U													

Big Bang

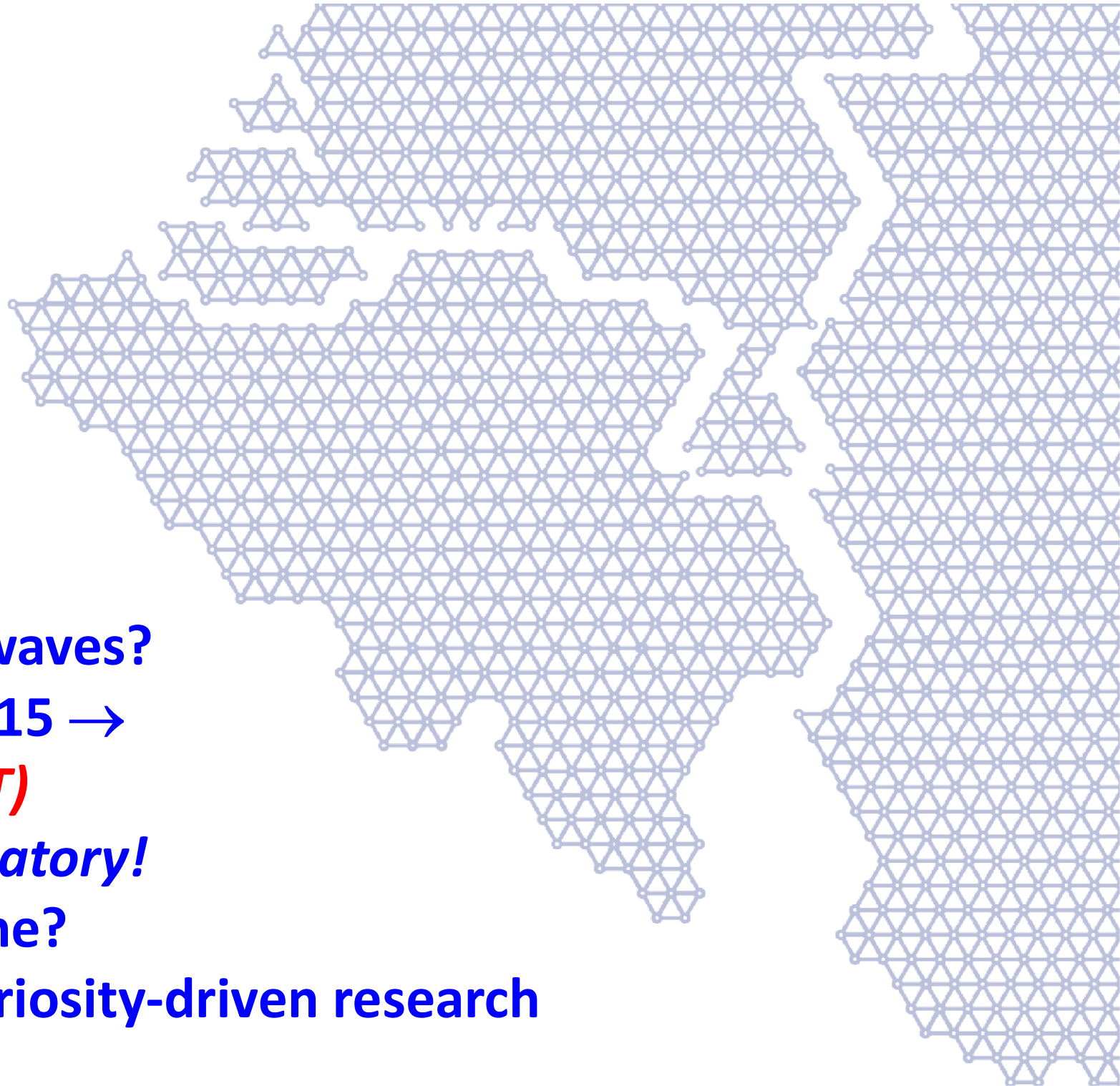
Supernovae

Neutron
star
mergers

predicted: 1916 ... 1st detection: 2015 ... Nobelprize: 2017 ... now: ~100 detections!

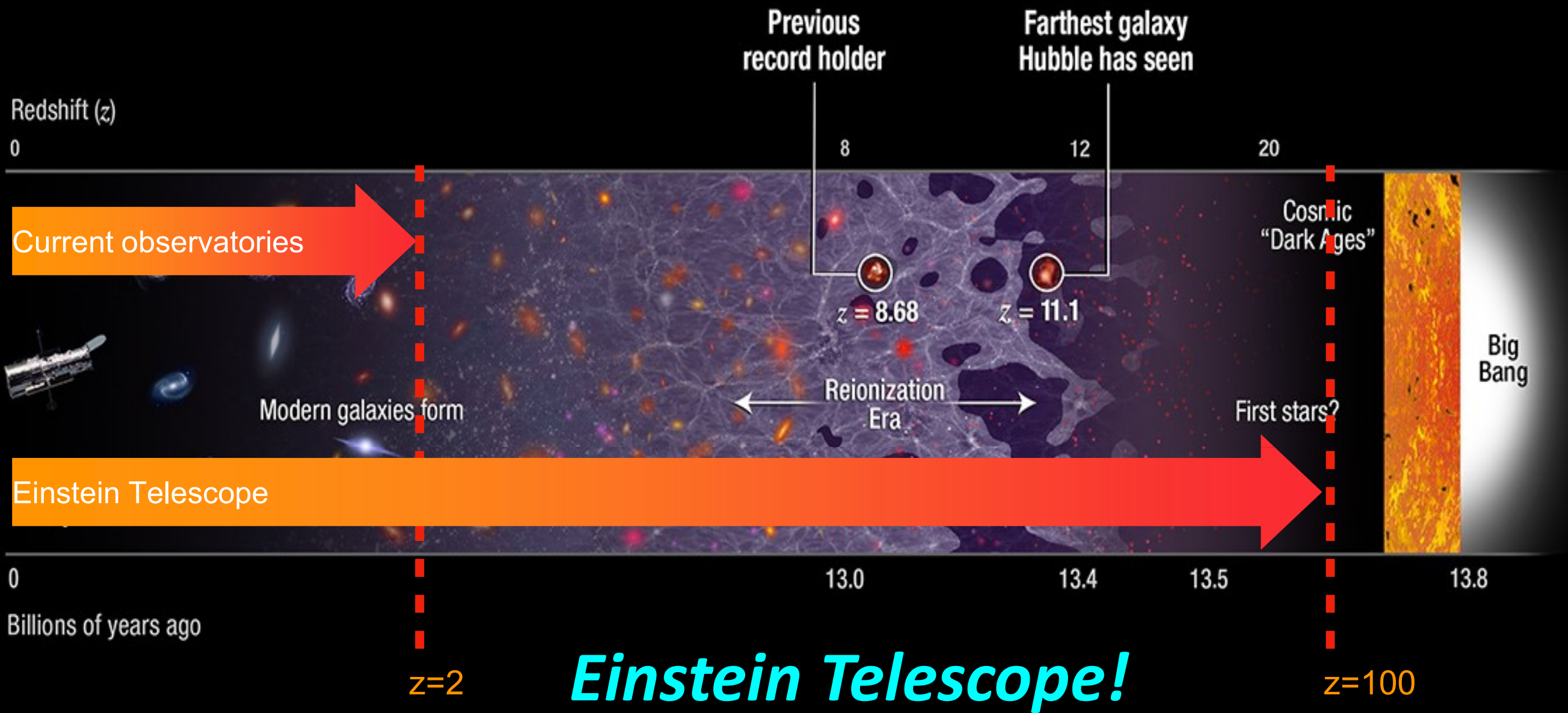


Overview



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Exploring our entire Universe?



Einstein Telescope!

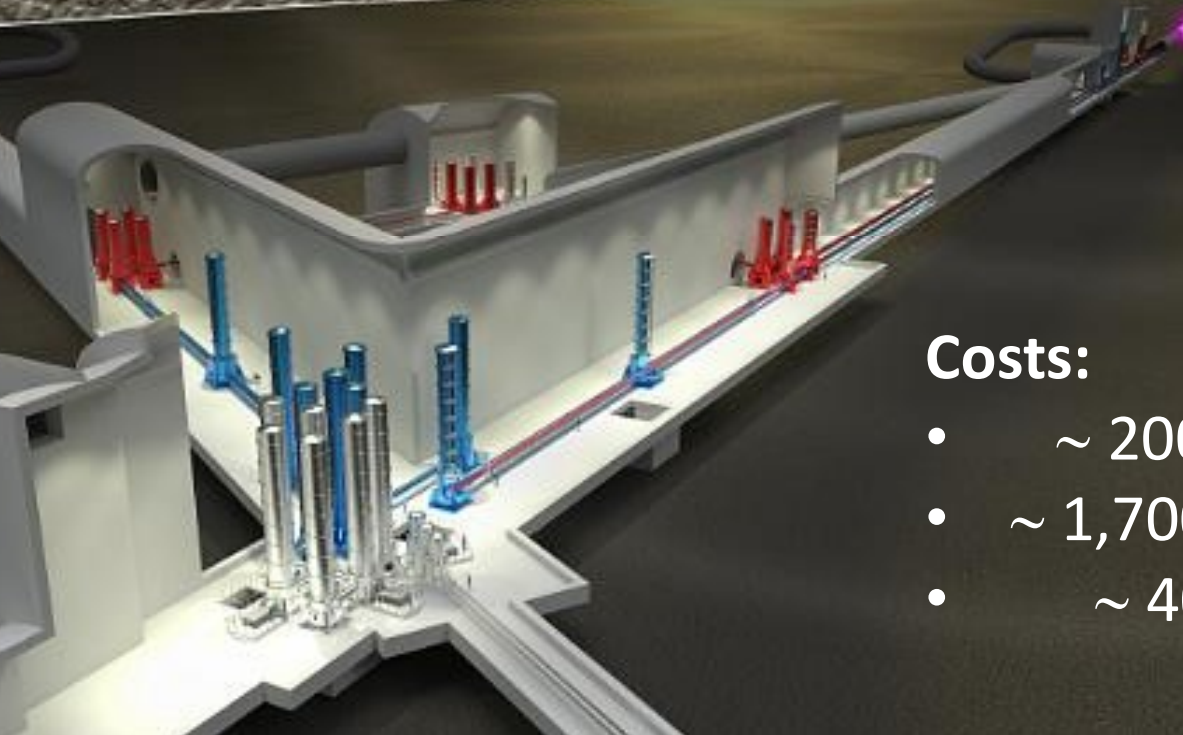
Einstein Telescope:

1st ideas in 2004
10 km long arms
@ 250 m deep
cold: 250 °C below zero
European

>100,000 detections/year
from entire Universe!



Start in 2035-2040?



Costs:

- ~ 200 M€ R&D/preparations
- ~ 1,700 M€ realisation
- ~ 40 M€/year exploitation
(plan: ~ 50 years)

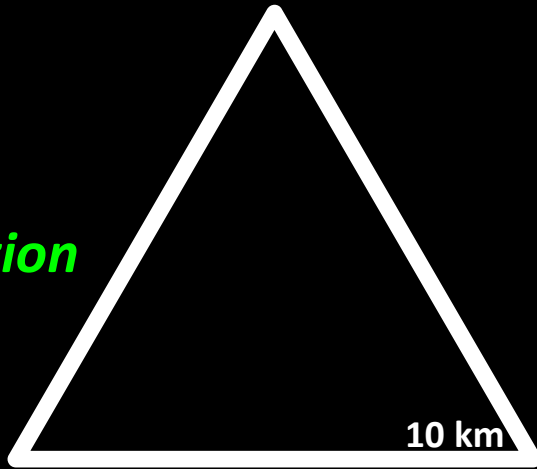
Higher sensitivity: *from 3-4 km to 10 km*

$$h \equiv \frac{\Delta L}{L}$$

easiest way to improve sensitivity: increase length (think about LISA)

'standalone'
capabilities:

- *polarisation*
- *sky localisation*



Hot issue:
L versus Δ

Cheaper:

- *Less caverns*
- *less large access shafts*
- *smaller \varnothing tunnel*
- *2 vs 6 interferometers*

Easier to commission
Easier to install

20 km

Einstein Telescope:

- 10 km (ET) instead of 3-4 km (Virgo/LIGO)
- 3×2 interferometers (3 LF, 3 HF)

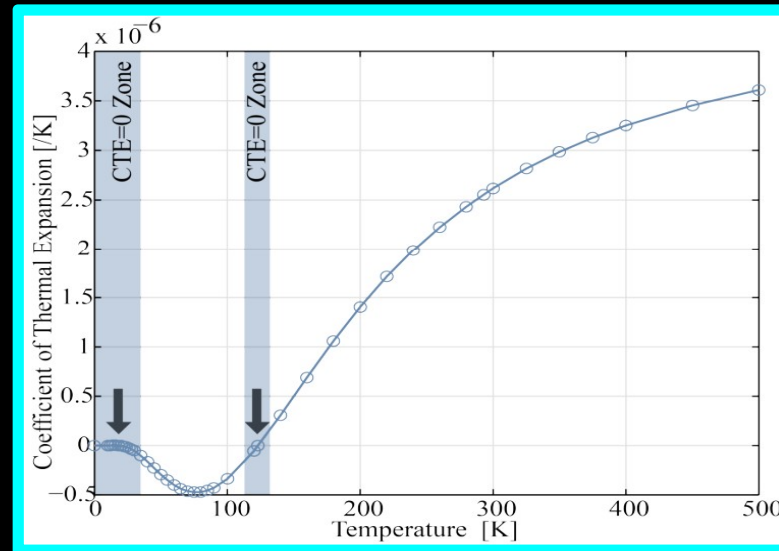
Cosmic Explorer (USA): 20-40 km L?

Do we want to repeat Virgo/LIGO experience?

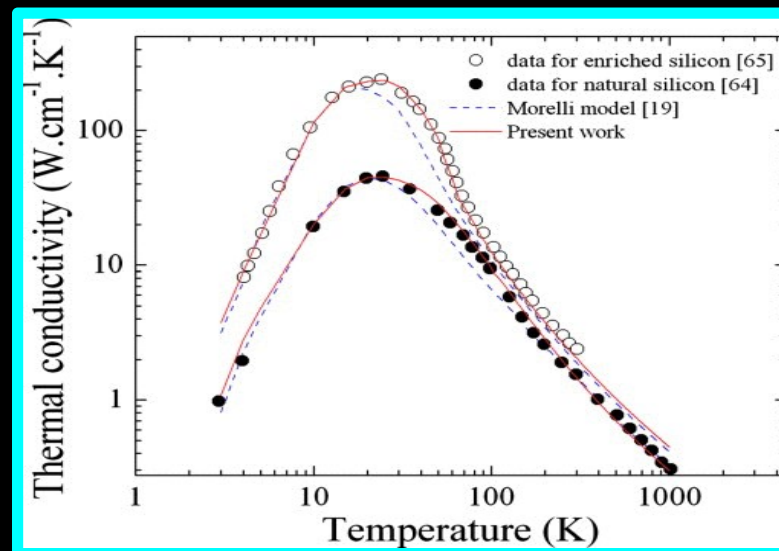
Higher sensitivity: *from 20 °C to -250 °C*



Cryogenic (Si) mirrors



(crystalline) silicon

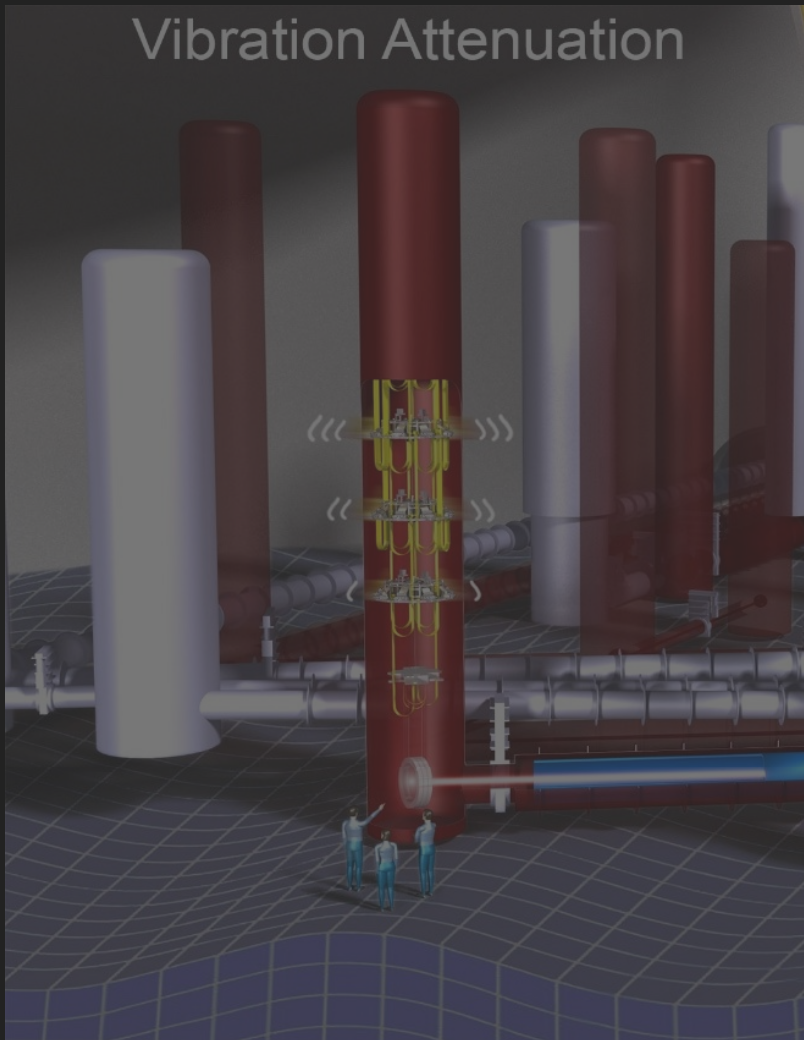


No thermal expansion
at very low temperatures
⇒ *Excellent in view of mirror deformations due to non-uniform heating by laser beams*

Very high thermal conductivity
at 10-80 K range temperatures
⇒ *Excellent in view of mirror deformations due to non-uniform heating by laser beams*

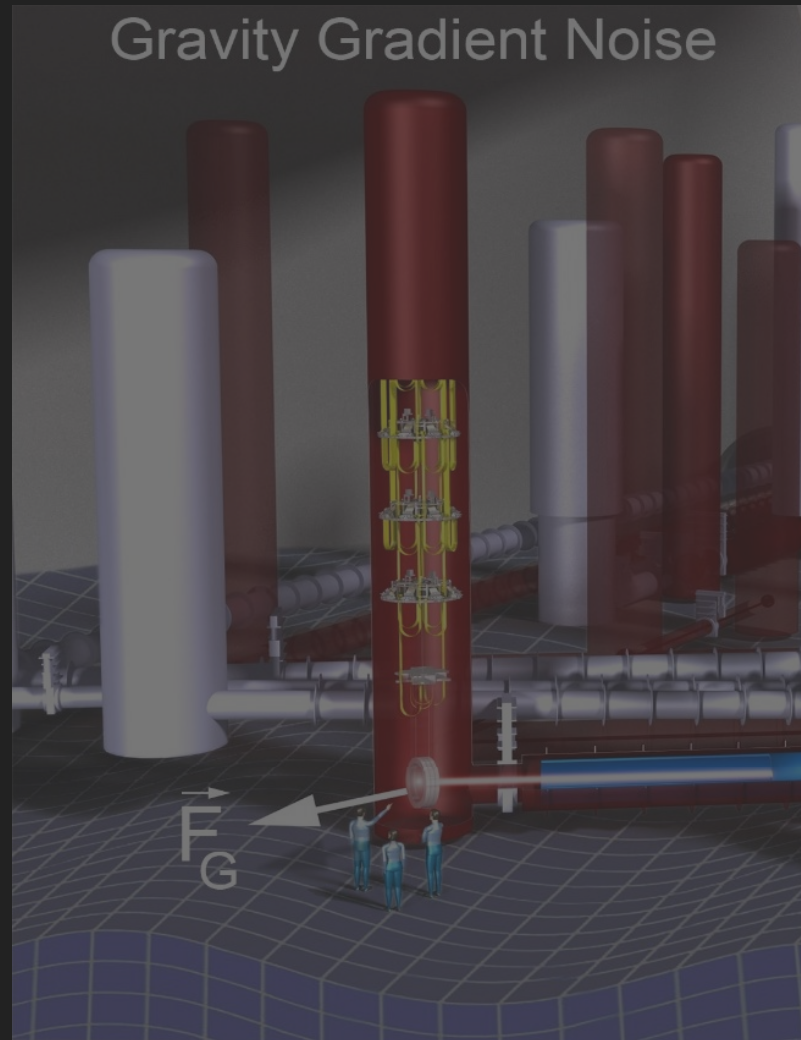
Higher sensitivity: *underground*

Vibration Attenuation



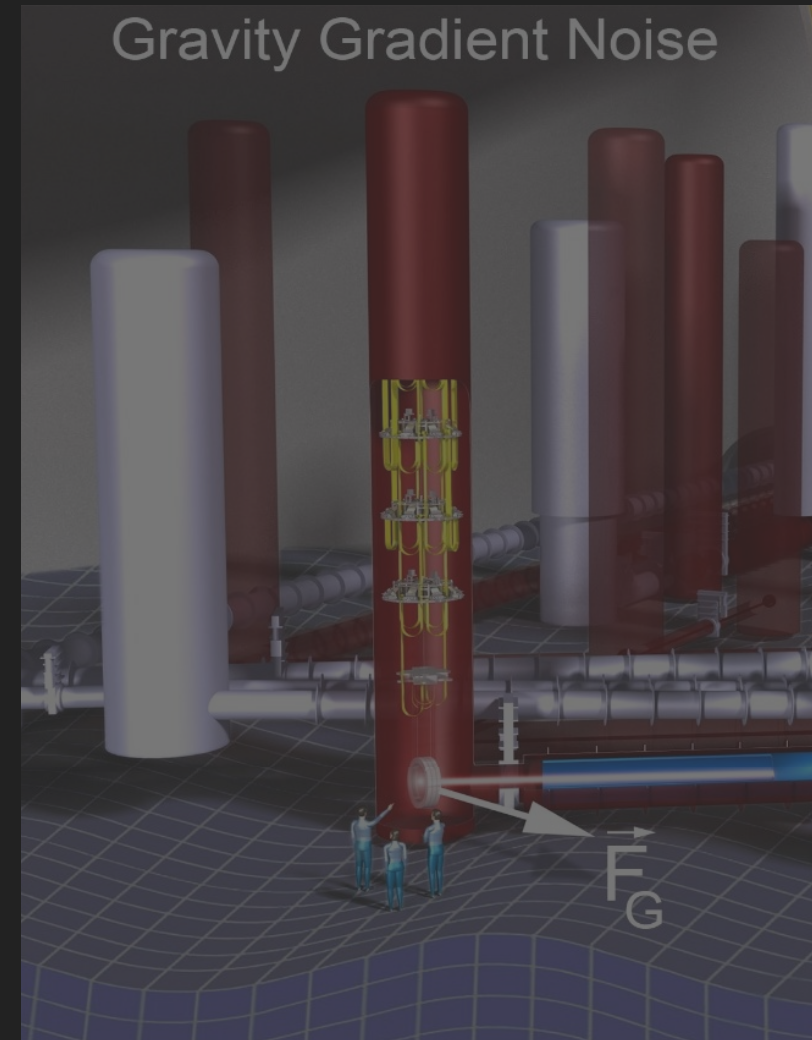
trillingen makkelijk
te dempen → no problem

Gravity Gradient Noise



zwaartekrachtfluctuaties: niet af te schermen=GGN
→ rustige omgeving en/of actieve GGN correctie

Gravity Gradient Noise



Higher sensitivity: *more things just 'better'*

Controls

Quantum tricks (like squeezing)

Lasers

Photodiodes

Attenuators (passive + active)

Actuators

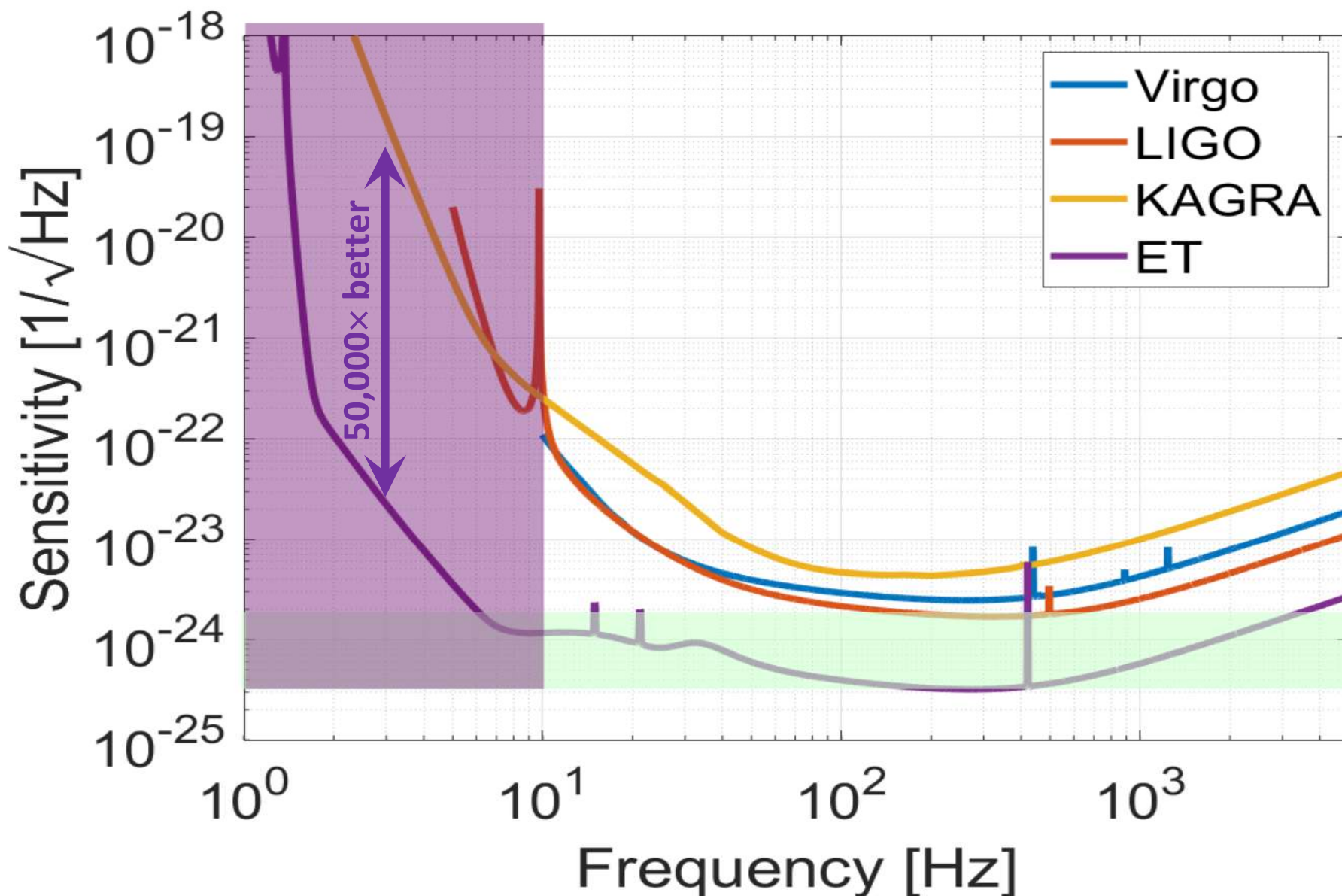
Vacuum

Etc.

The real issues to beat/control:

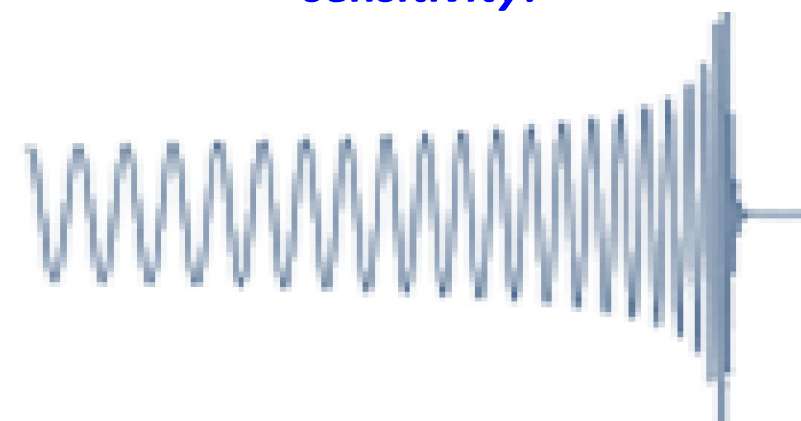
- *scattered light i.e. imperfections*
- *noise (pumps, ventilation, cryogenic coolers, etc.) we make!*

More detections: higher sensitivity & larger bandwidth



Why the push for lower frequencies?

Signals spend most time at low frequencies i.e. longer observation time with better low-frequency sensitivity!

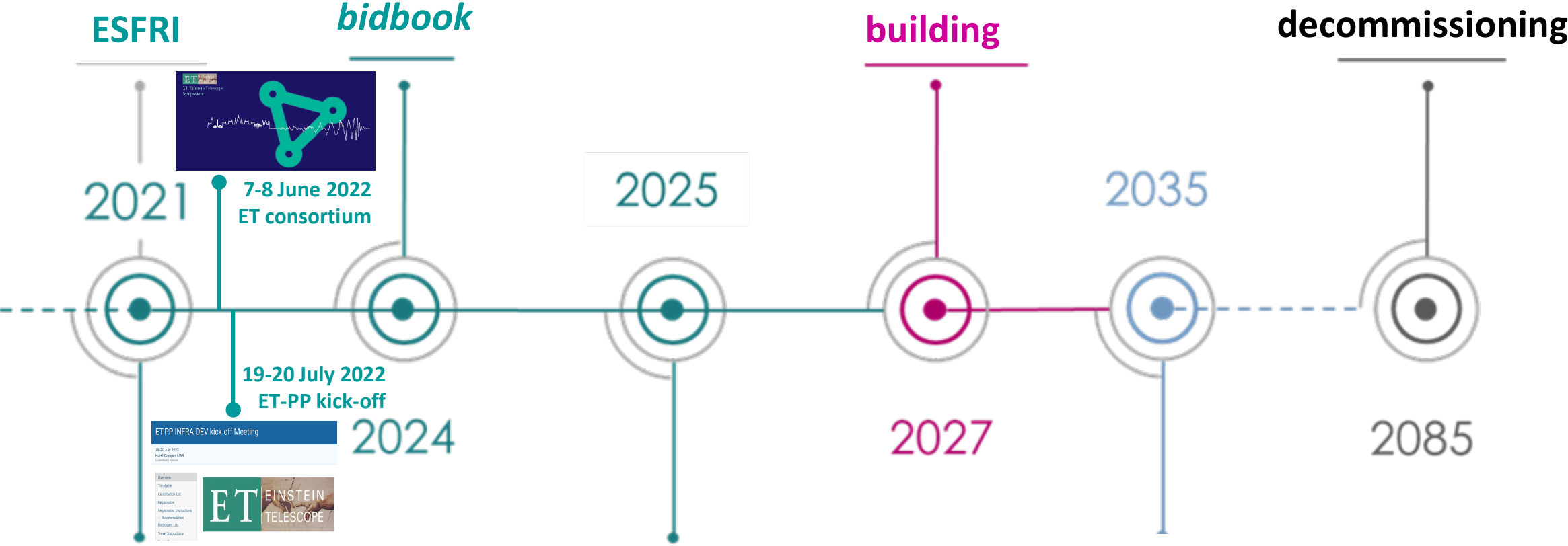


ET can observe signals for 24 hours!



Einstein
Telescope

Einstein Telescope planning



ESFRI

bidbook

building

decommissioning

2021

7-8 June 2022
ET consortium

2025

2035

19-20 July 2022
ET-PP kick-off

ETPP INFRA-DEV kick-off Meeting

18-20 July 2022
Held Campus UvA
Hilversum

- Overview
- Tentative
- Contributors List
- Registration
- Registration Instructions
- Accommodation
- Participant List
- Travel Instructions

ET EINSTEIN TELESCOPE

2024

2027

2085

NGF proposal

EU € negotiations

opening

- Locatiekeuze
- Financiering
- Governance

preparation phase

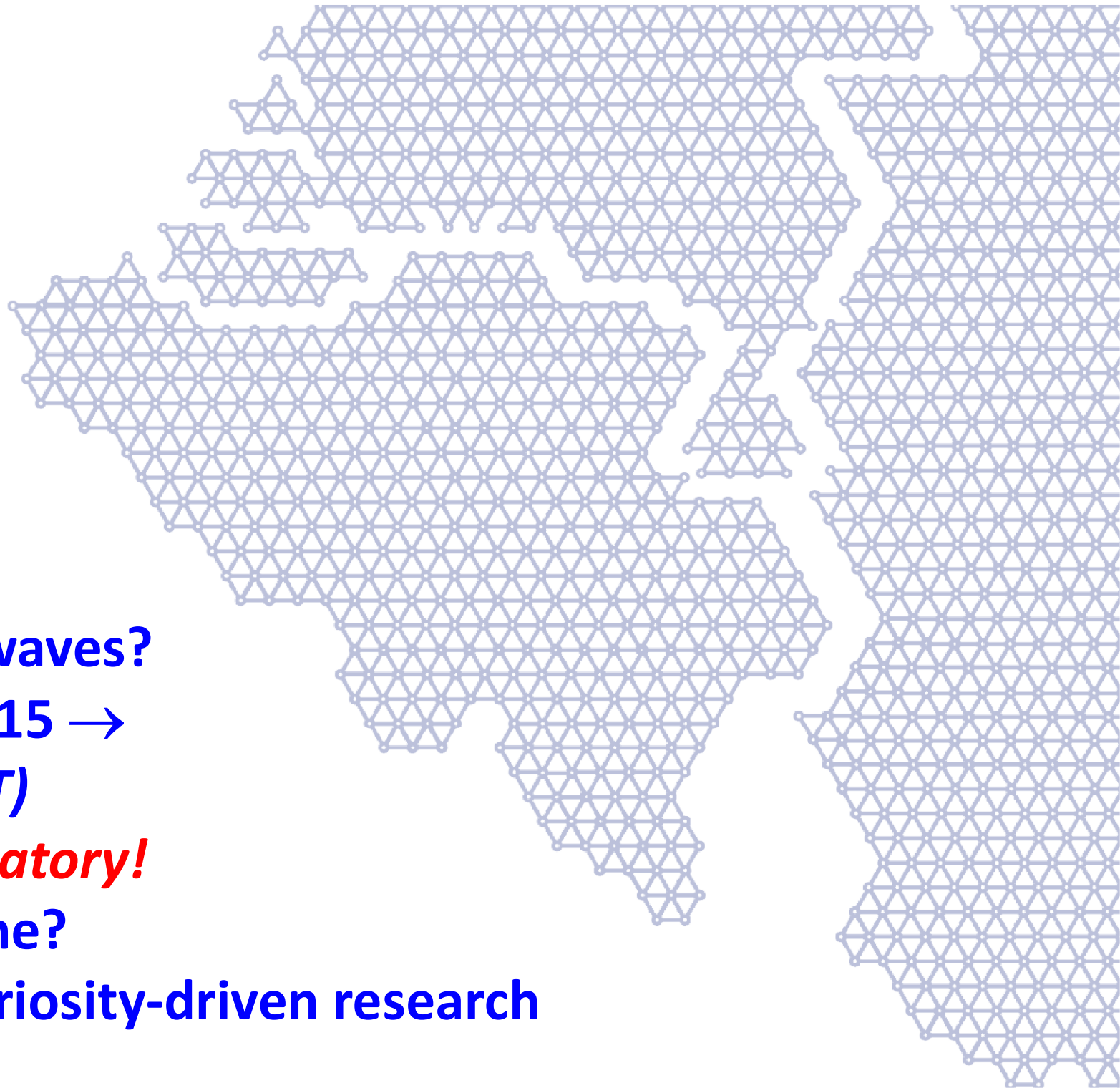
building phase

exploitation phase

Huge boost for EMR/NL: Dutch Nationaal Groeifonds

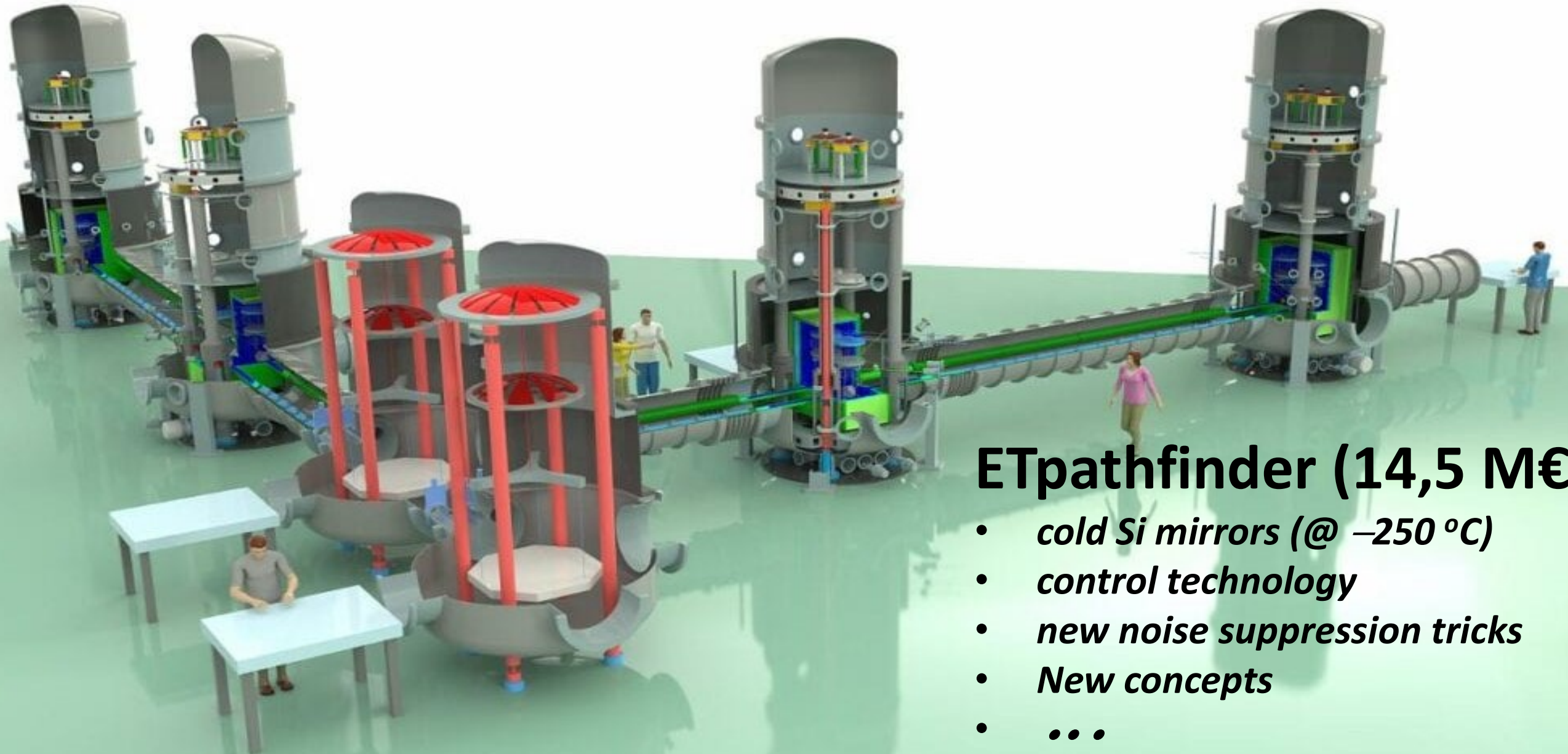


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To develop ET's innovations: R&D laboratory



ETpathfinder (14,5 M€)

- *cold Si mirrors (@ $-250\text{ }^{\circ}\text{C}$)*
- *control technology*
- *new noise suppression tricks*
- *New concepts*
- ...

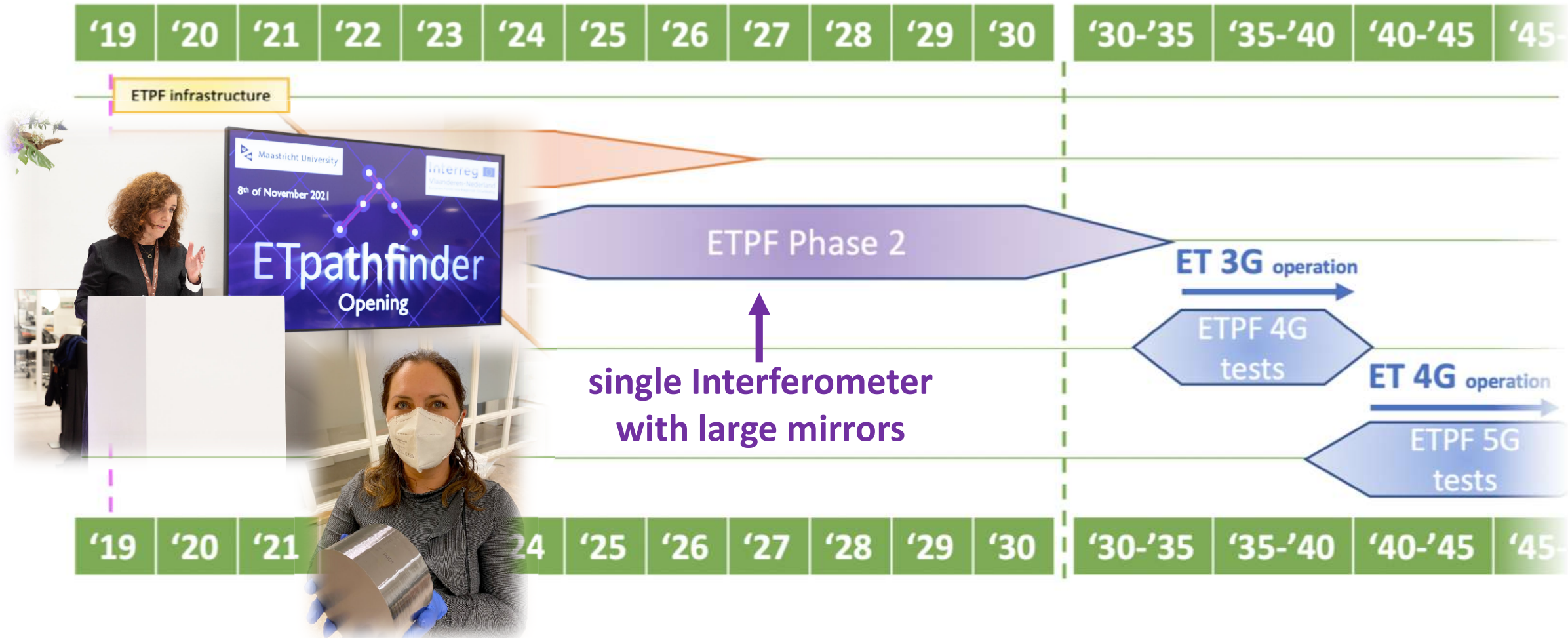
In ≤ 3 years (2019-2022):
~ 14 M€ spent
huge cleanroom built
vacuum installed
lots of optics
lots of computing
lots of design work
attenuators in progress
...



ETpathfinder: *always 'one step beyond'*

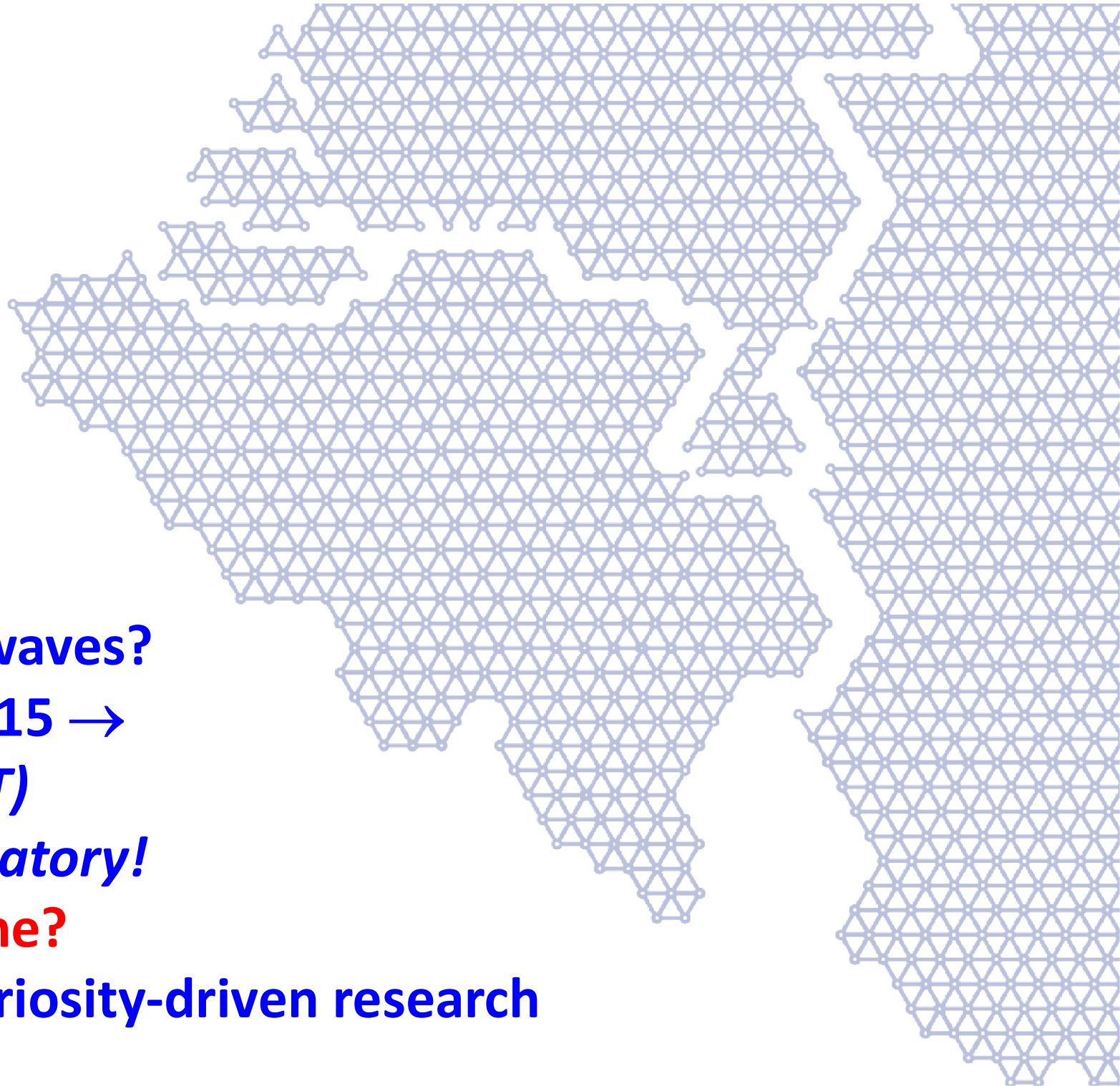


ONE STEP BEYOND...



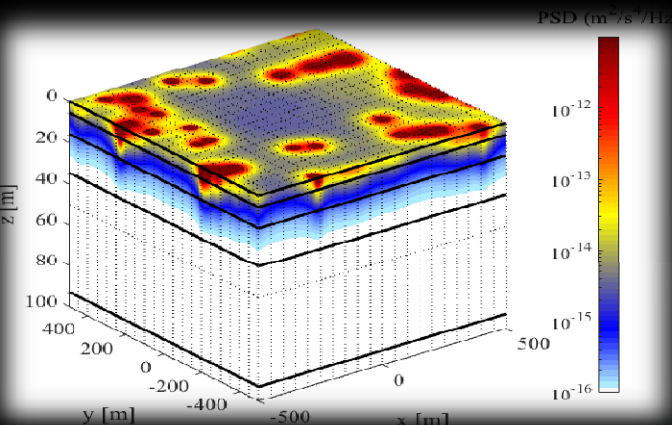
ETpathfinder: started as B-D-NL project → worldwide R&D laboratory

Overview

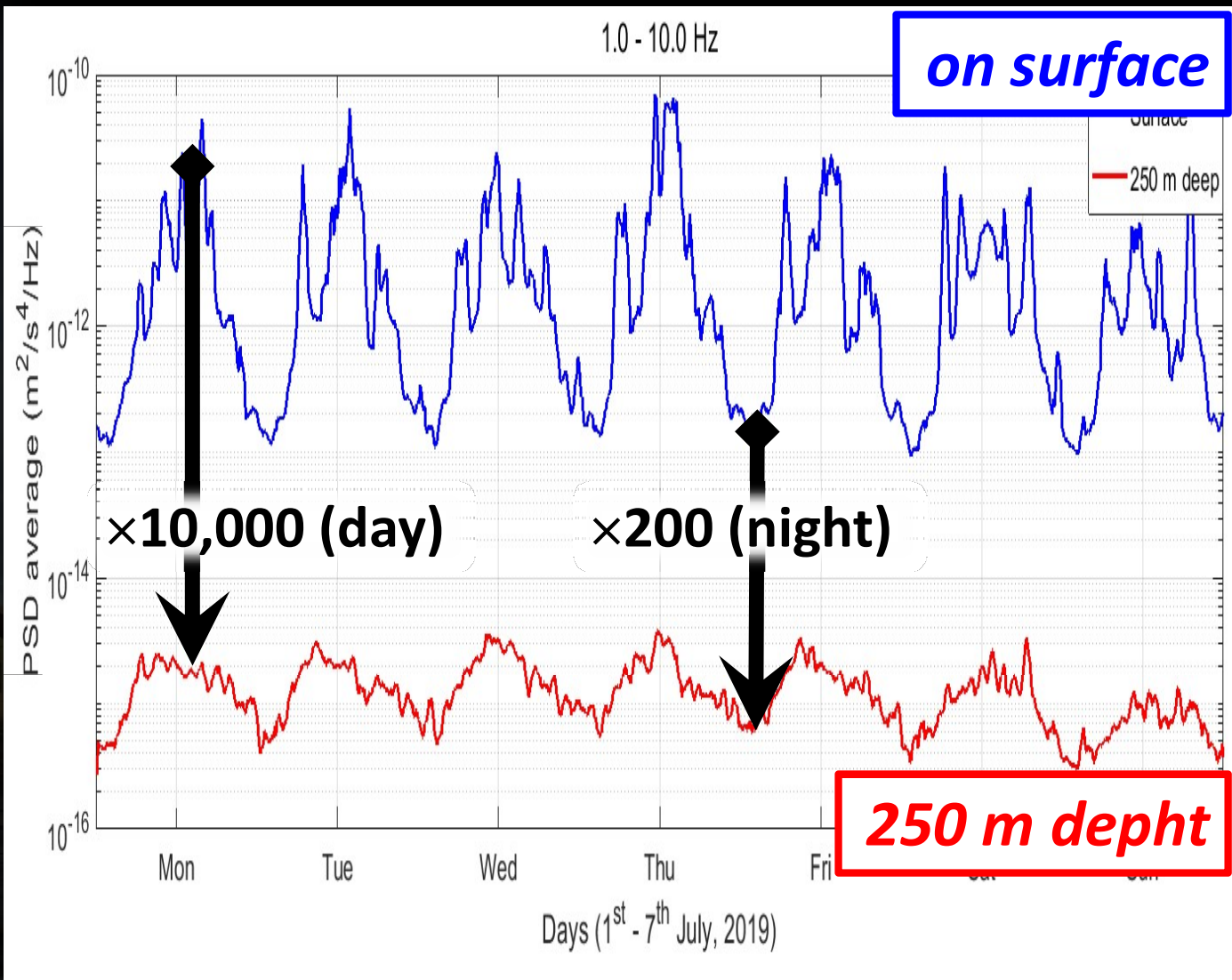


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ET key requirement: low-noise environment

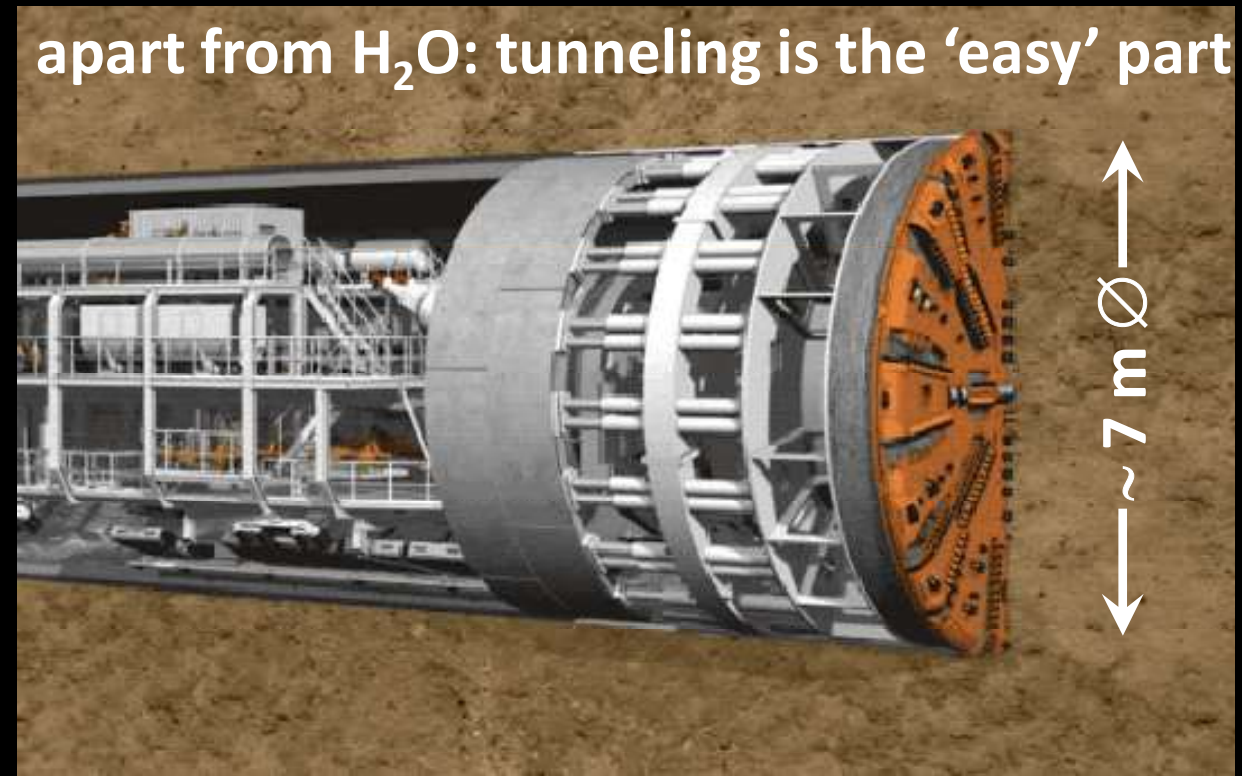


Seismic vibrations



noise measurements confirm simulations

The challenge: build ET cost-efficiently!



Huge volume (few million m³) to be excavated. Requires detailed knowledge of (hydro)geology.

- 30-50 km length of tunnels
- 10-24 (large) caverns
- 1-3 large access shafts

Issues: water, rock quality, costs, sustainability, permitting, nuisance during construction, . . .

Civil engineering: the challenges

Water:

- During construction
 - Risk
- In operation
 - Noise
 - Costs



Scope of work for the Civil Engineering Scan for Einstein Telescope

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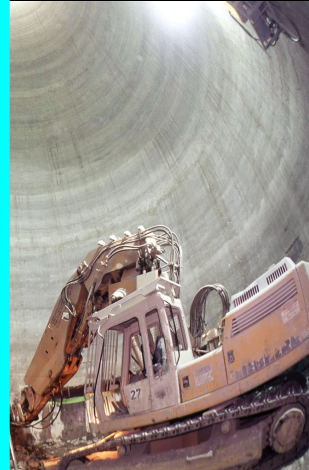
Civil Engineering Scan for Einstein Telescope: Operational, Time and Cost Assessment

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Implenia Österreich GmbH
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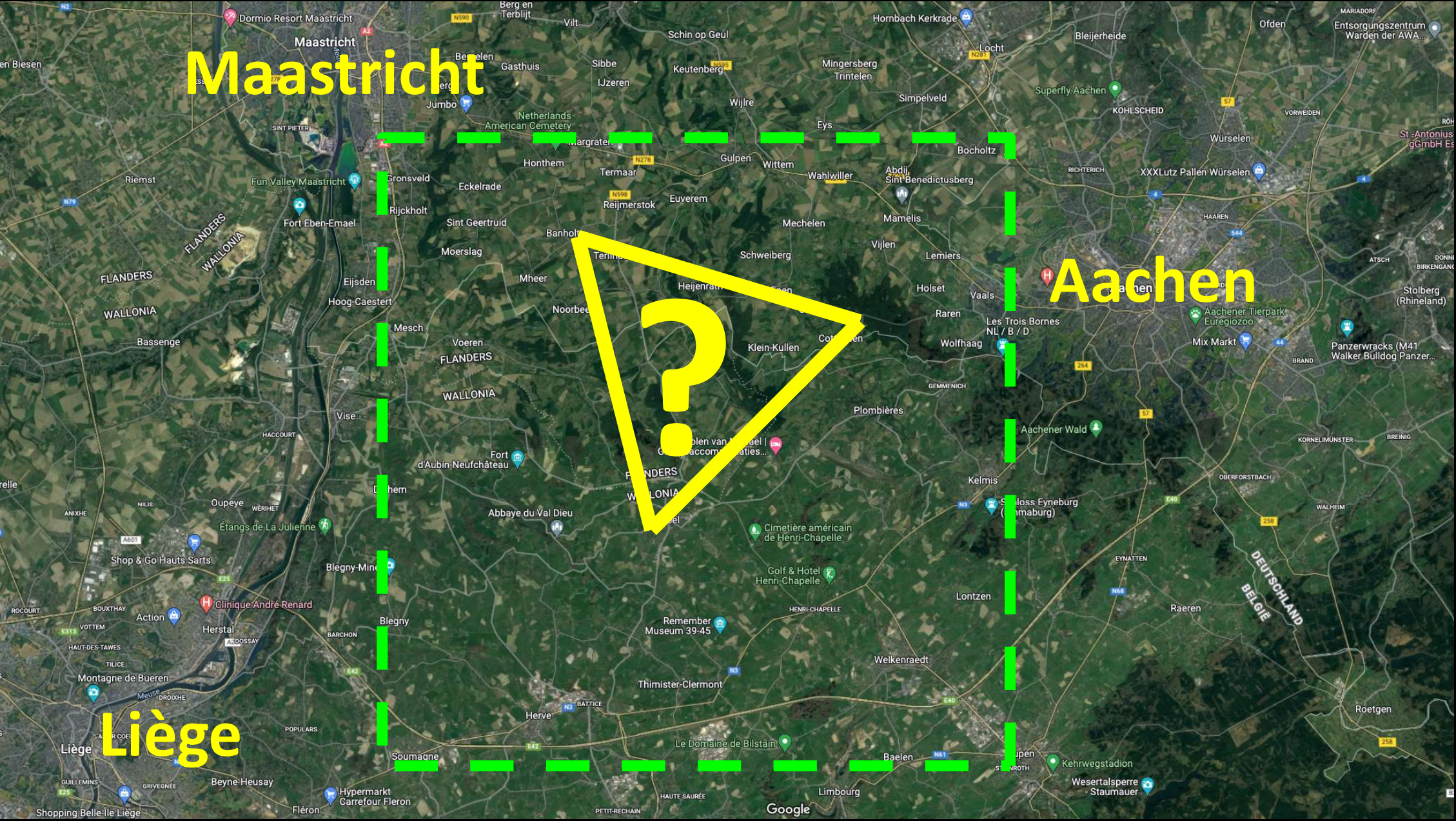
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Caverns:

- Rock quality
- Costs
- Less!
- Less wide
- Less high
- (L ↔ Δ)

Siting ET in the Euregio Meuse-Rhine



1st subsidy: Interreg EMR 'E-TEST'

Interreg
Euregio Meuse-Rhine

EUROPEAN UNION
European Regional Development Fund

E-TEST Einstein Telescope
Earth's Surface & Technology

E-TEST

The Einstein Telescope will open a new window on the Universe through the observation of gravitational waves. Its infrastructure will be buried 300 meter below the surface to reduce human-, wind- and ground-induced vibrations and movements. The Interreg project E-TEST is a very important step of the Einstein Telescope, as it will be a proof of concept, both on the prototype side and on the geological side. E-TEST will build a prototype – a large suspended mirror at cryogenic temperature (10 Kelvin) – to validate the telescope's technology. E-TEST will also run an underground study to map and model the geology of the Euregio Meuse-Rhine. This will allow to define the optimal design and location of the future Einstein Telescope. This project is a major scientific breakthrough but will also have a significant economic impact on SMEs in the Euregio Meuse-Rhine.

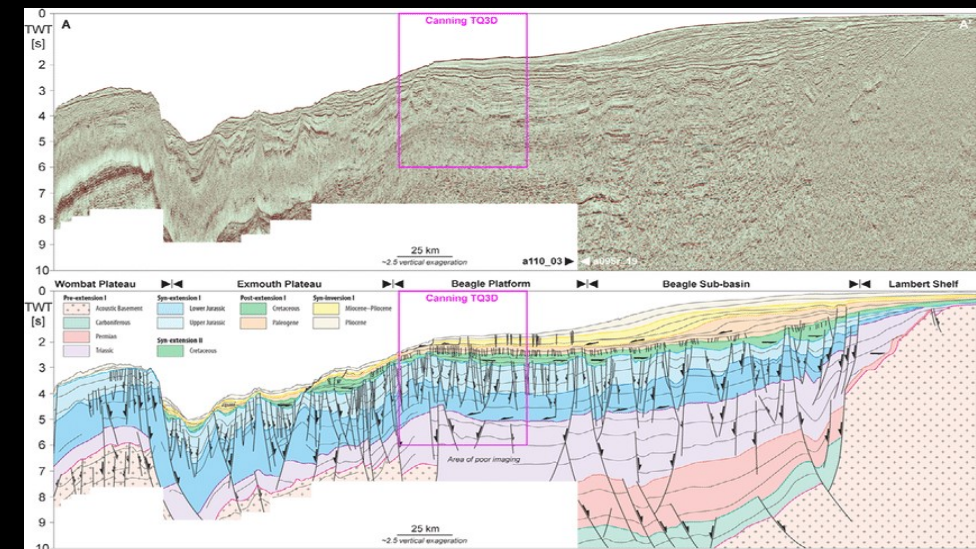
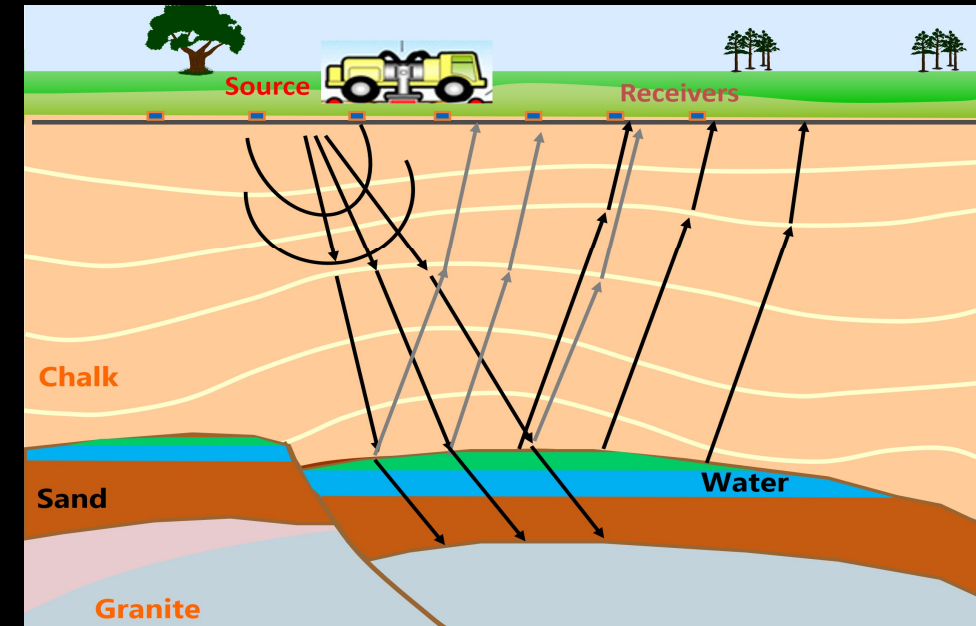
www.interregemr.eu

At Interreg Euregio Meuse-Rhine, we fund projects where partners work together across borders. In 2014-2020, we invest EUR 96 million from the European Regional Development Fund in our region.

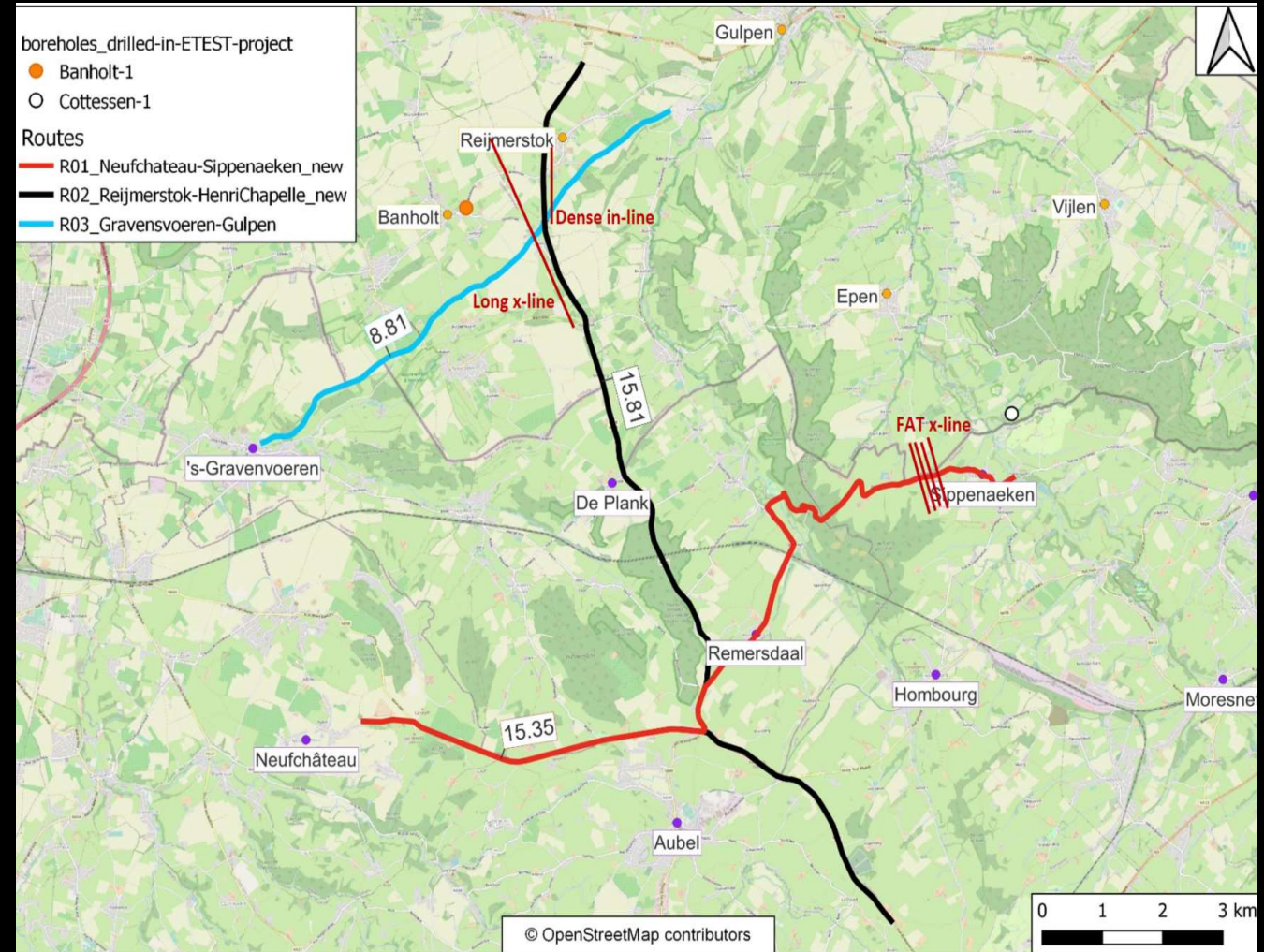
We are a collaboration between 13 regions from Belgium, Germany and The Netherlands. Together, we develop shared solutions to common challenges. This gives Interreg its own, distinct spirit of cooperation: across regions and across borders.

To map the EMR geology

- Hydrology
- Boreholes
- Seismic
- ERT
- EM
- gravimetric
- ...



40 km stretch active seismic campaign – Sep/22



40 km stretch active seismic campaign – Sep/22

Strong community - political support NL, B & D



Lots of institutes involved already

A screenshot of the Einstein Telescope website. The page features a blue header with the logo and navigation links (NL, DE, FR, EN, Open menu). The main content area has a white background with a blue geometric pattern on the right. The title "The Einstein Telescope?" is prominently displayed. Below it, there is a paragraph of text and a question. At the bottom, there is a red banner with a blue geometric pattern and a white text box containing a sub-header and a paragraph of text.

Einstein Telescope

NL DE FR EN Open menu

The Einstein Telescope?

The Einstein Telescope is an advanced gravitational-wave observatory, currently in the planning stage. The border region between the Netherlands, Belgium and Germany is being considered as a possible location. This is because of its tranquillity, stable ground and strong ecosystem of scientific institutions and high-tech companies.

Will this new centre for research into the distant universe be located in the region? Scientists, companies and governments in all three countries are exploring the possibilities together.

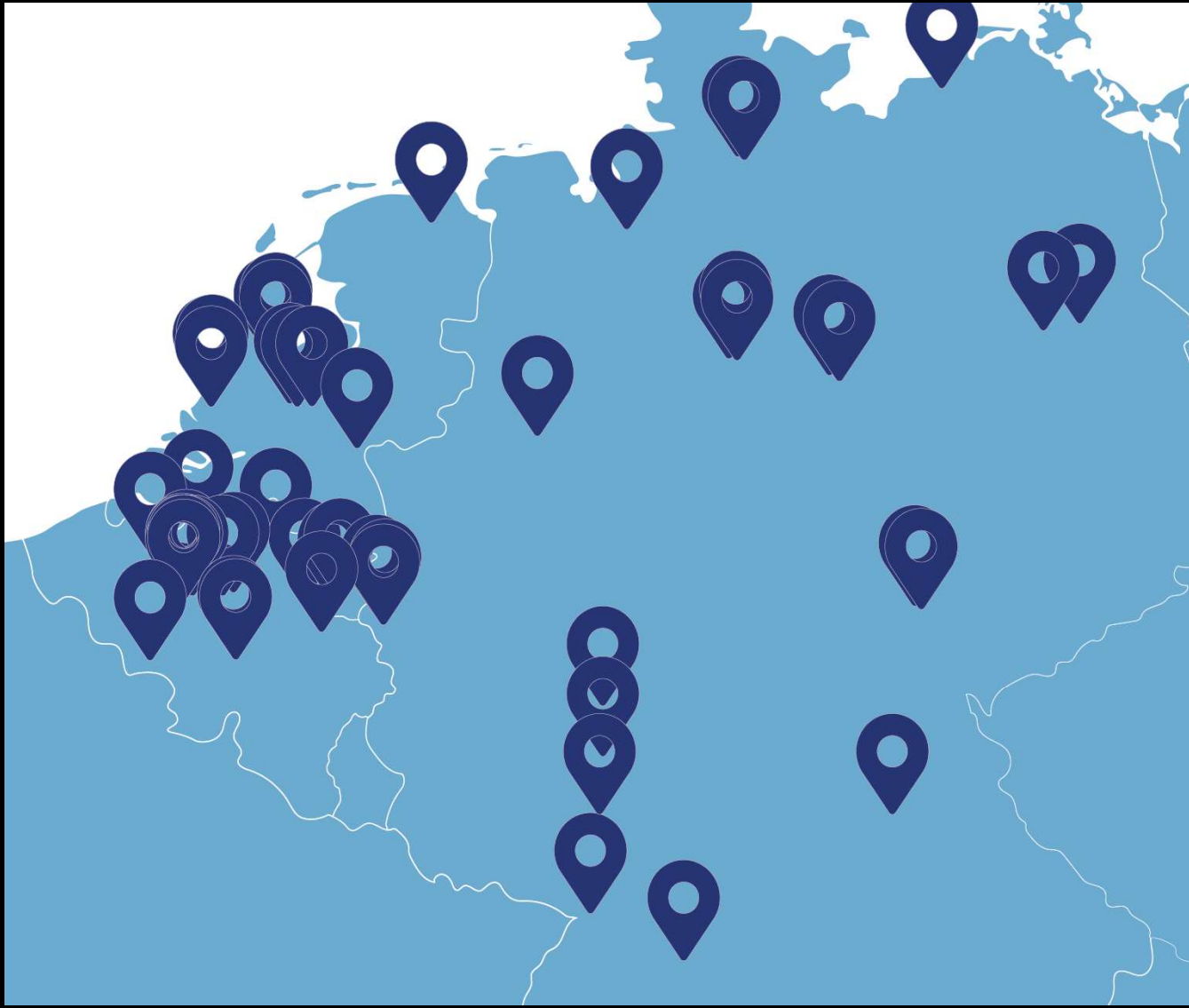
When stars collide or black holes form, space vibrates

Gravitational waves contain information about the most extreme events in the universe, from the nature of black holes and neutron stars to the first moments after the Big Bang. Thanks to these waves, we can study the cosmos as never before.

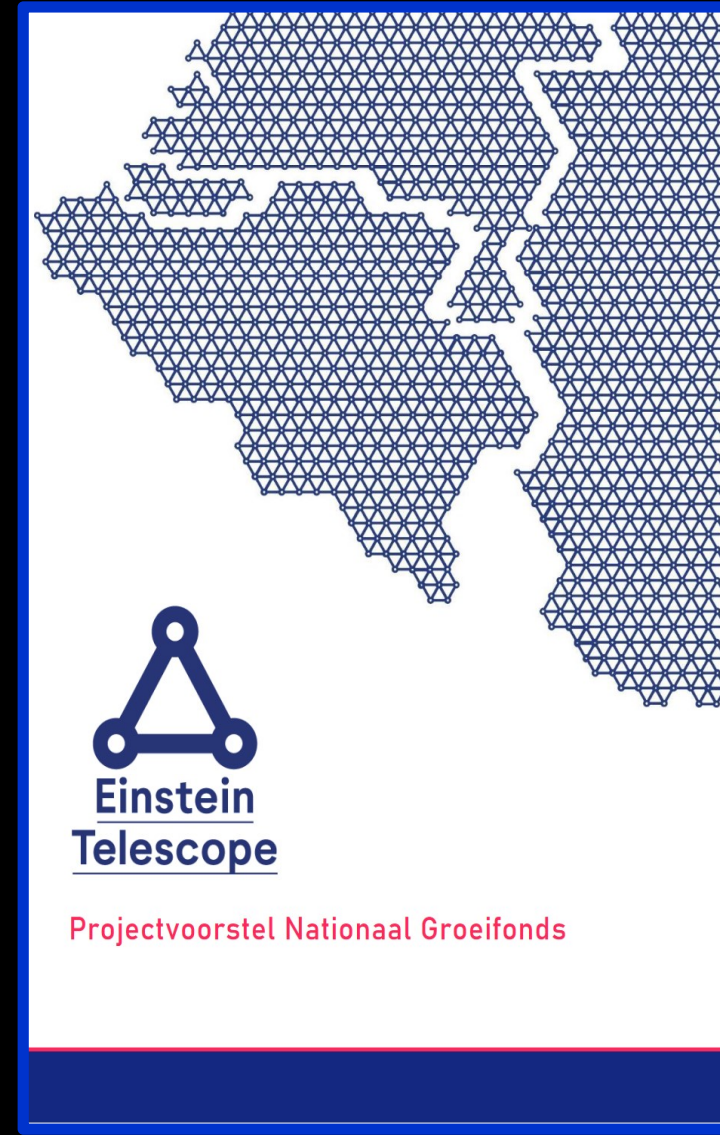
Highlights: NL/'Groeifonds' & D/'DZA'

<https://www.einsteintelelescope.nl/de/nachrichten/>

Strong community - political support NL, B & D



Lots of institutes involved already



Highlights: NL/'Groeifonds' & D/'DZA'

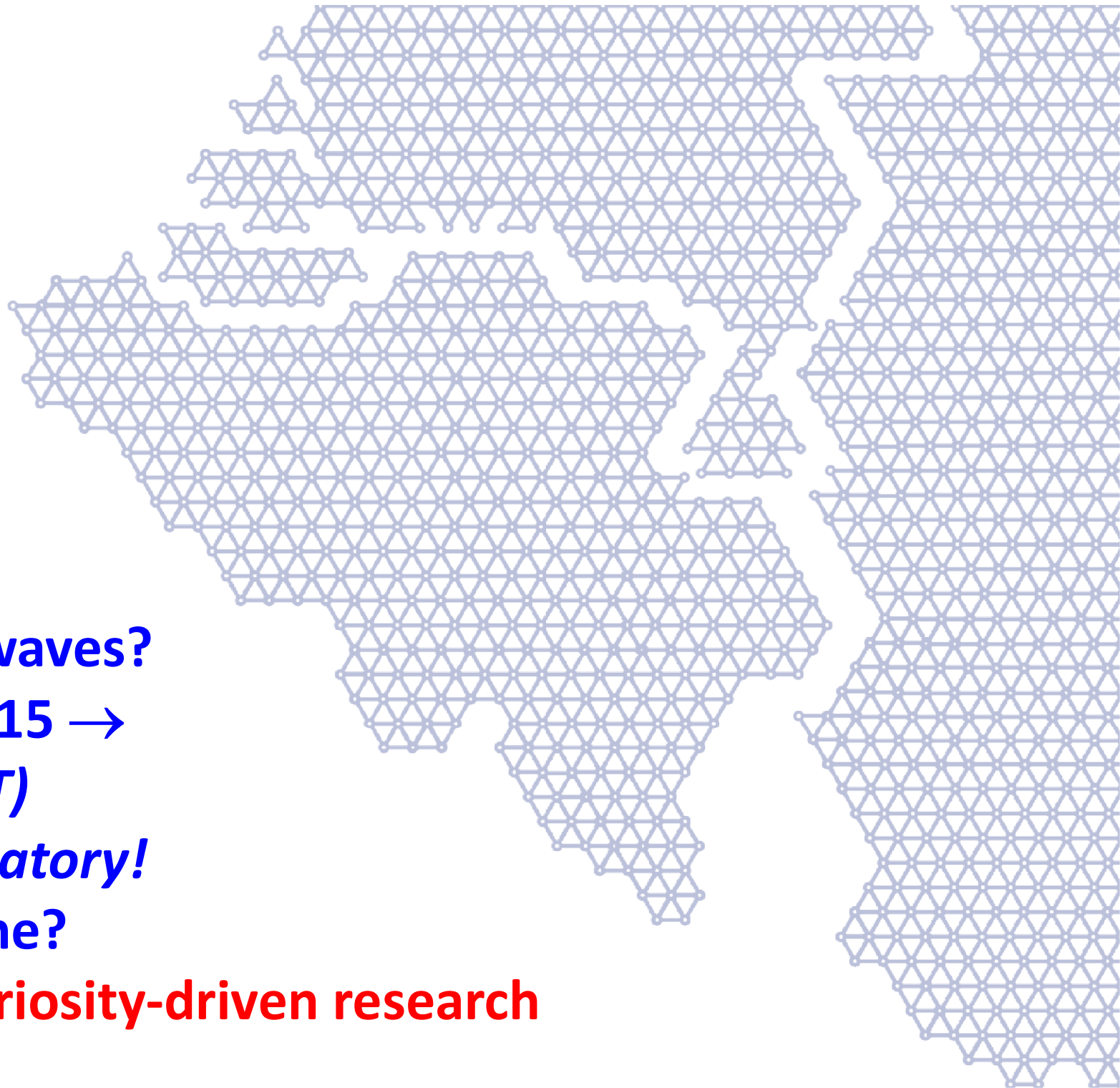
NL:

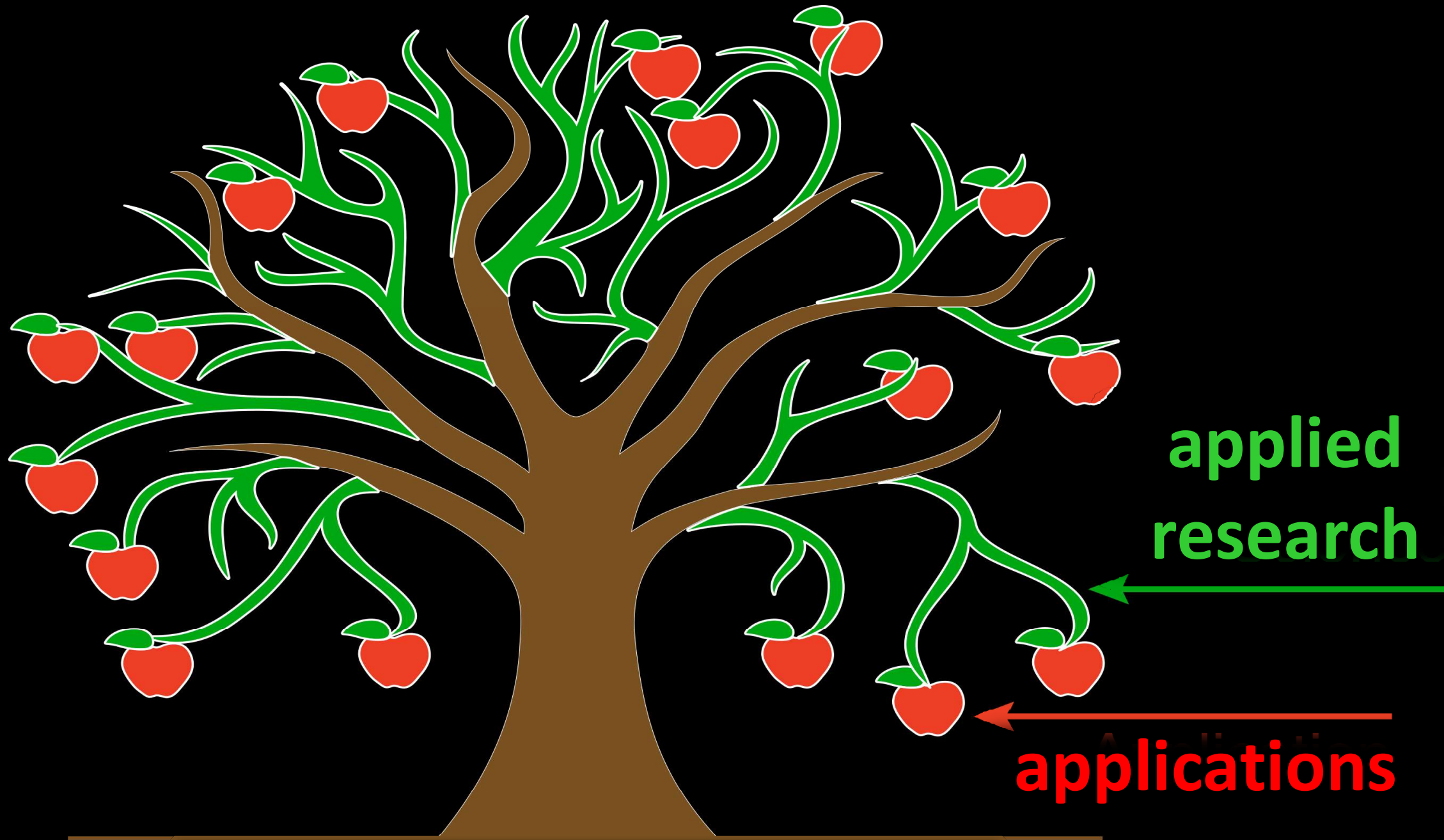
**42 M€ to
prepare bid
to host ET in
the EMR**

**870 M€ if ET
will be build
in the EMR**

Overview

- Curiosity-driven research
 - How to detect gravitational waves?
 - Revolutionary detections: 2015 →
 - Future: *Einstein Telescope (ET)*
 - ETpathfinder: *ET's R&D laboratory!*
 - ET in the Euregio Meuse-Rhine?
- **Socio-economic impact of curiosity-driven research**





curiosity-driven research

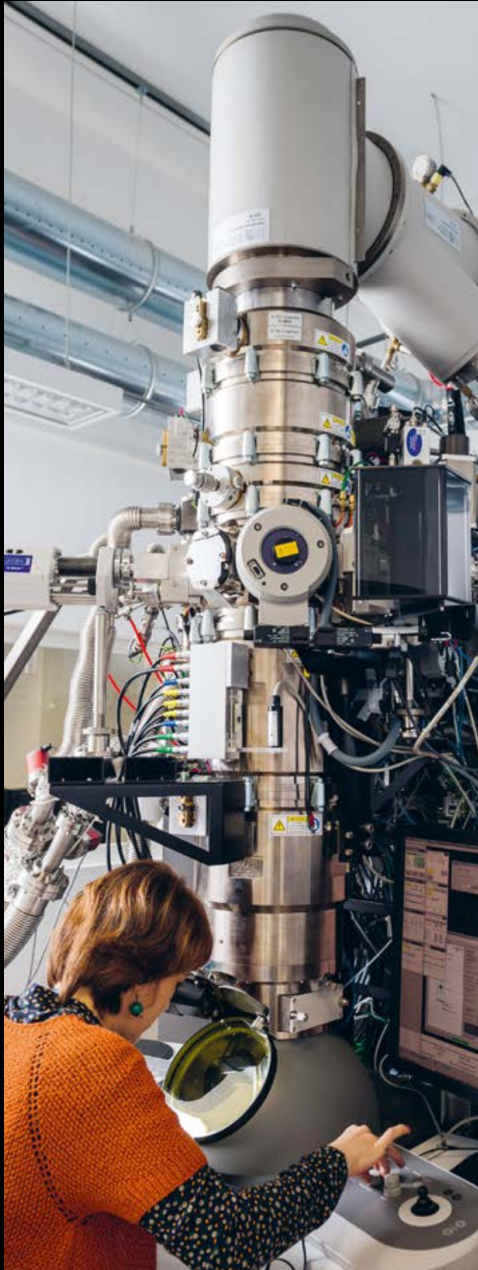
**applied
research**

applications

Past achievements: future's best guarantee!

$\partial_\nu F^{\mu\nu} = \mu_0 J^\mu$	1865: Maxwell	<i>Radio, TV, radar, mobile phone, microwave, remote control, etc. = most of your life!</i>
$E = h\nu$	1900: Planck	<i>Quantum mechanics i.e. chips, computers, LEDs, lasers, etc. Quantum computing?</i>
$E = mc^2$	1905: Einstein	<i>Nuclear power, nuclear medicine, etc.</i>
$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$	1915: Einstein	<i>GPS!</i>
$i\hbar\gamma^\mu\partial_\mu\psi = mc\psi$	1928: Dirac	<i>Antimatter. Science fiction? PET scanner!</i>
WWW	1989: Berners-Lee	<i>Can you imagine life without it?</i>

Physics-based industry in Europe



€4.40 TRILLION

Revenue of the physics-based industries within Europe has exceeded €4.40 trillion in every year of the period 2011-2016

€1.45 TRILLION

The GVA of the physics-based sector within Europe has exceeded €1.45 trillion in each year of the period 2011-2016

16%

The physics-based industries typically accounts for 16% of the total turnover of the EU28 business economy

Physics-based industries contributes significantly to the economies of European countries and to the European economy as a whole

of the EU28 business economy, which is more than the gross turnover contribution of the entire retail sector. [Figure 2a] shows the percentage distribution of physics-based industries turnover between the different countries of Europe for the year 2016. The major economies of Western Europe clearly dominate. Similar geographical distributions are observed for all other years in the period of study.

% SHARE OF TOTAL PB TURNOVER

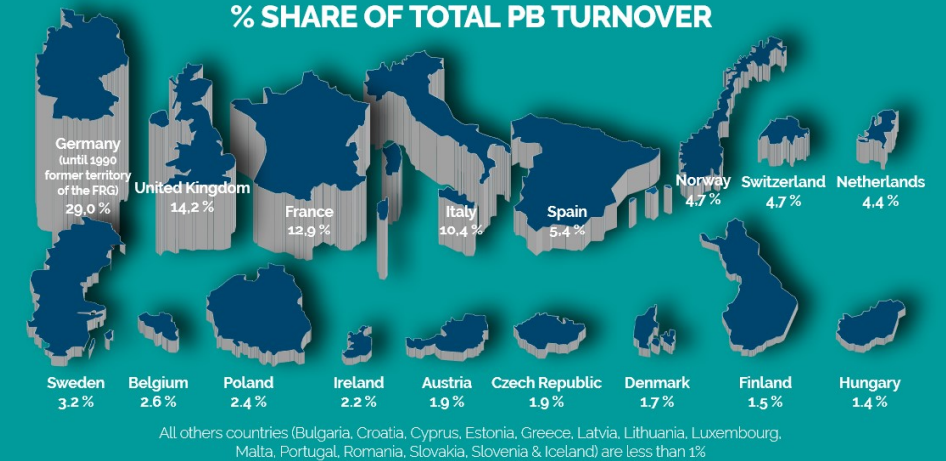


Figure 2a: percentage distribution of physics-based industries turnover in different countries of Europe (2016)

TURNOVER BY COUNTRY, MILLIONS € SINCE 2011 AVERAGE (2011-16)

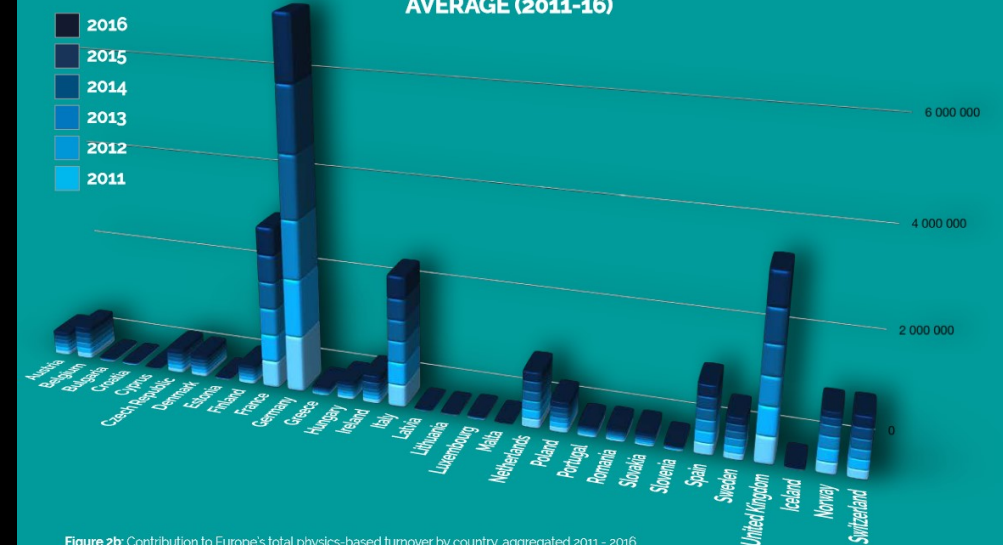
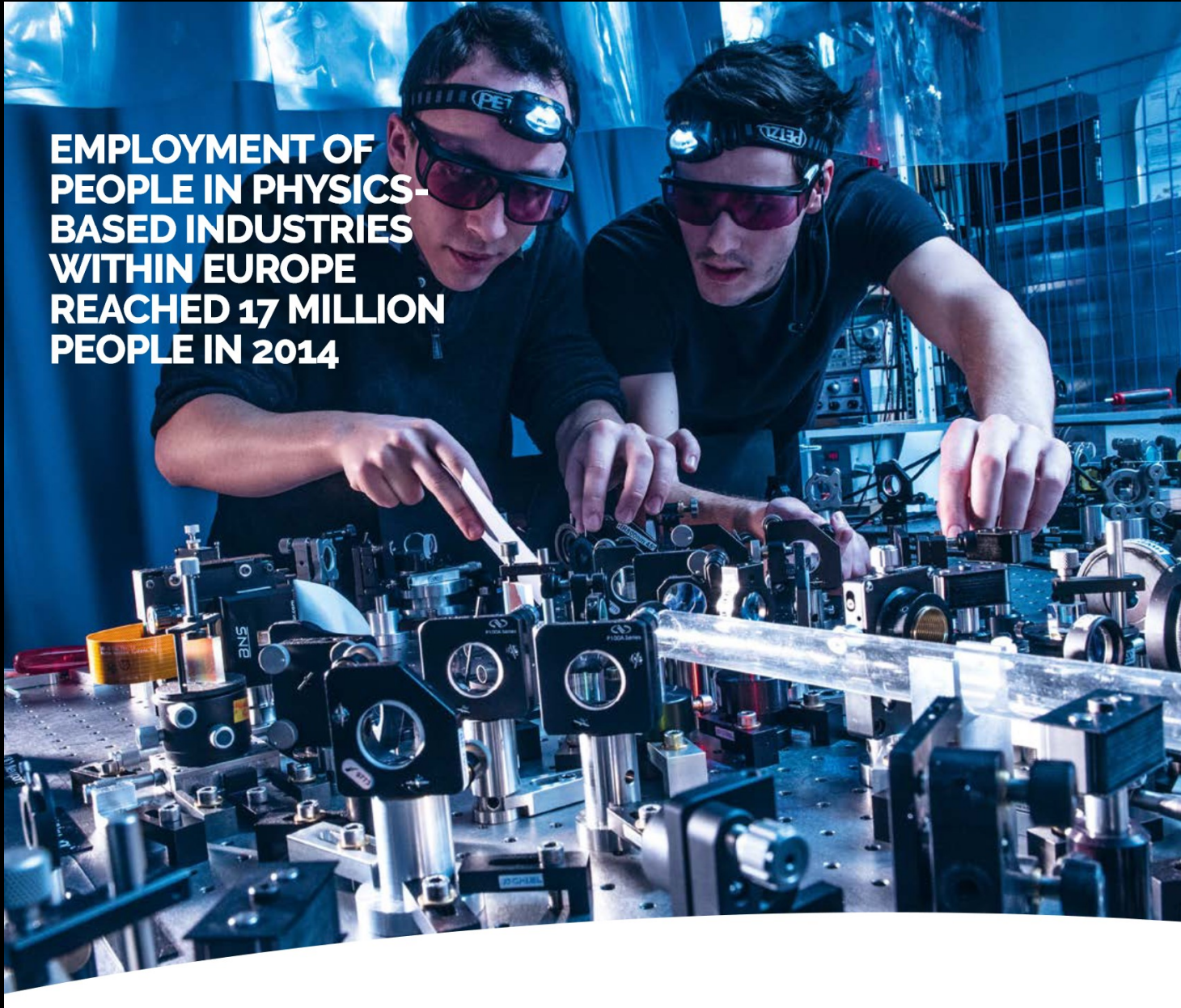


Figure 2b: Contribution to Europe's total physics-based turnover by country, aggregated 2011 - 2016

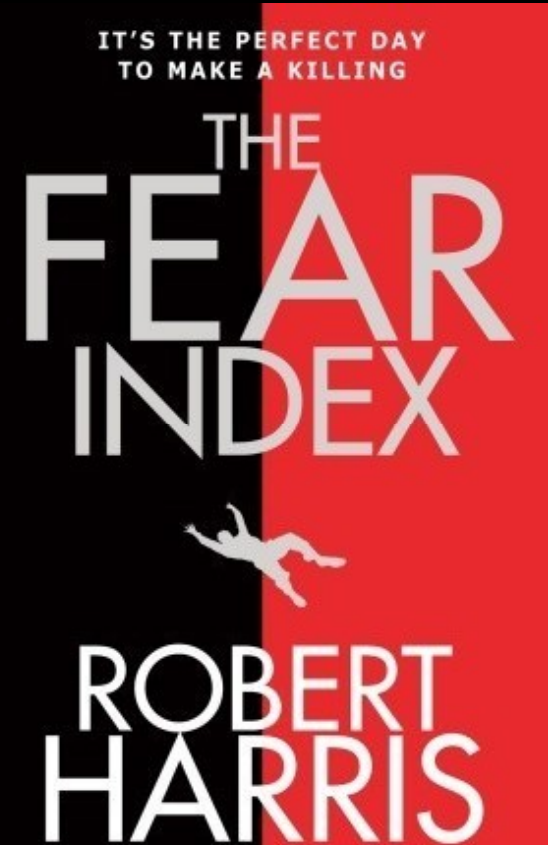
Real impact: *next generation!* 17 million jobs in 2014

EMPLOYMENT OF
PEOPLE IN PHYSICS-
BASED INDUSTRIES
WITHIN EUROPE
REACHED 17 MILLION
PEOPLE IN 2014



And they go anywhere:

- *Academia*
- *Industry*
- *Consulting*
- *Journalism*
- *Finance*
- *Politics*
- ...



Thank you!



ET specifications

	ET-HF	ET-LF
Approximate frequency range	10–10 ⁴ Hz	1–250 Hz
Detection scheme	DC readout	DC readout
Input power (after IMC)	500 W	3 W
Laser wavelength	1064 nm	1550 nm
Beam shape	LG ₃₃	TEM ₀₀
<i>ARM CAVITIES</i>		
Arm length	10 km	10 km
Opening angle	60°	60°
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	fused silica	silicon
Mirror diameter	62 cm	>45 cm
Mirror thickness	30 cm	about 50 cm
Mirror mass	200 kg	211 kg
Beam radius (at mirror)	7.2 cm	9.0 cm
Beam waist (symmetric cavity)	2.51 cm	2.9 cm
RoC (symmetric cavity)	5690 m	5580 m
Scatter loss per surface	37.5 ppm	37.5 ppm
Finesse	880	880
Reflective coating ITM	tantala/silica 8 $\lambda/4$ doublets	tantala/silica 9 $\lambda/4$ doublets
Reflective coating ETM	tantala/silica 17 $\lambda/4$ doublets	tantala/silica 18 $\lambda/4$ doublets
Transmission ITM	7000 ppm	7000 ppm
Transmission ETM	6 ppm	6 ppm

	ET-HF	ET-LF
<i>CENTRAL INTERFEROMETER</i>		
SR-phase	tuned (0.0)	detuned (0.6)
Focussing element	in or near the ITM focal length = 303 m	in or near the ITM focal length = 303 m
Distance ITM–BS	300 m	300 m
Distance BS–MPR	10 m	10 m
Recycling cavity length	310 m	310 m
Beam size on BS	4.7 mm	6 mm
Beam size on MPR	2.7 mm	3.4 mm
Recycling gain	21.6	21.6
Recycling cavity free spectral range	484 kHz	484 kHz
Round-trip Guoy phase	10.5°	9.6°
mode separation frequency	28 kHz	26 kHz
Recycling cavity temperature	room temperature	room temperature
Beam splitter material	fused silica	fused silica
Transmission PRM	4.6 %	4.6 %
Transmission SRM	10 %	20 %
<i>FILTER CAVITIES</i>		
Quantum noise suppression	frequency-dependent squeezing	frequency-dependent squeezing
Filter cavities	1 \times 300 m	2 \times 10 km
Half-bandwidth	5.7 Hz	5.7 Hz and 1.5 Hz
Detuning	25.4 Hz	25.4 Hz and 6.6 Hz
Round-trip loss	75 ppm	75 ppm