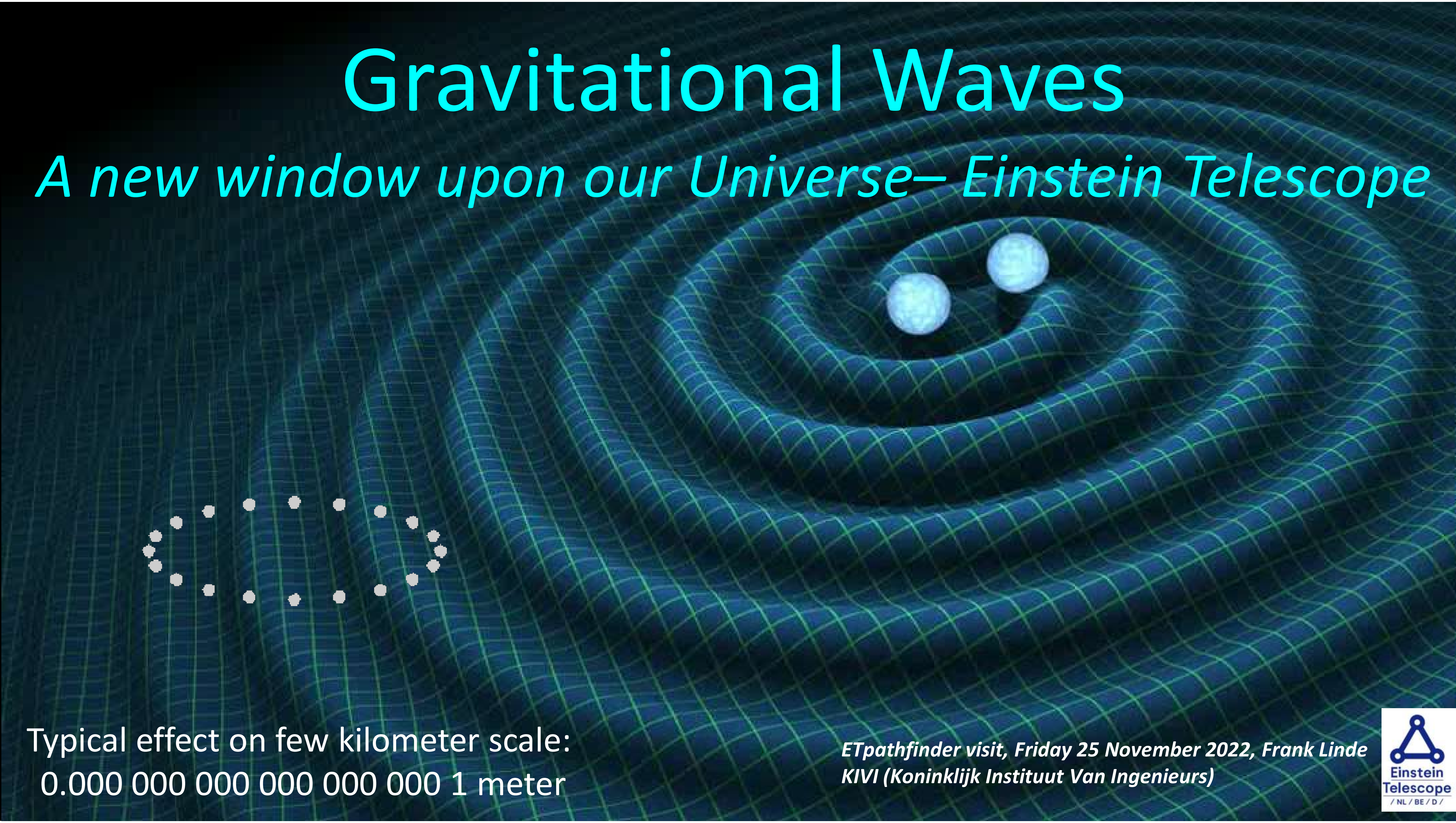
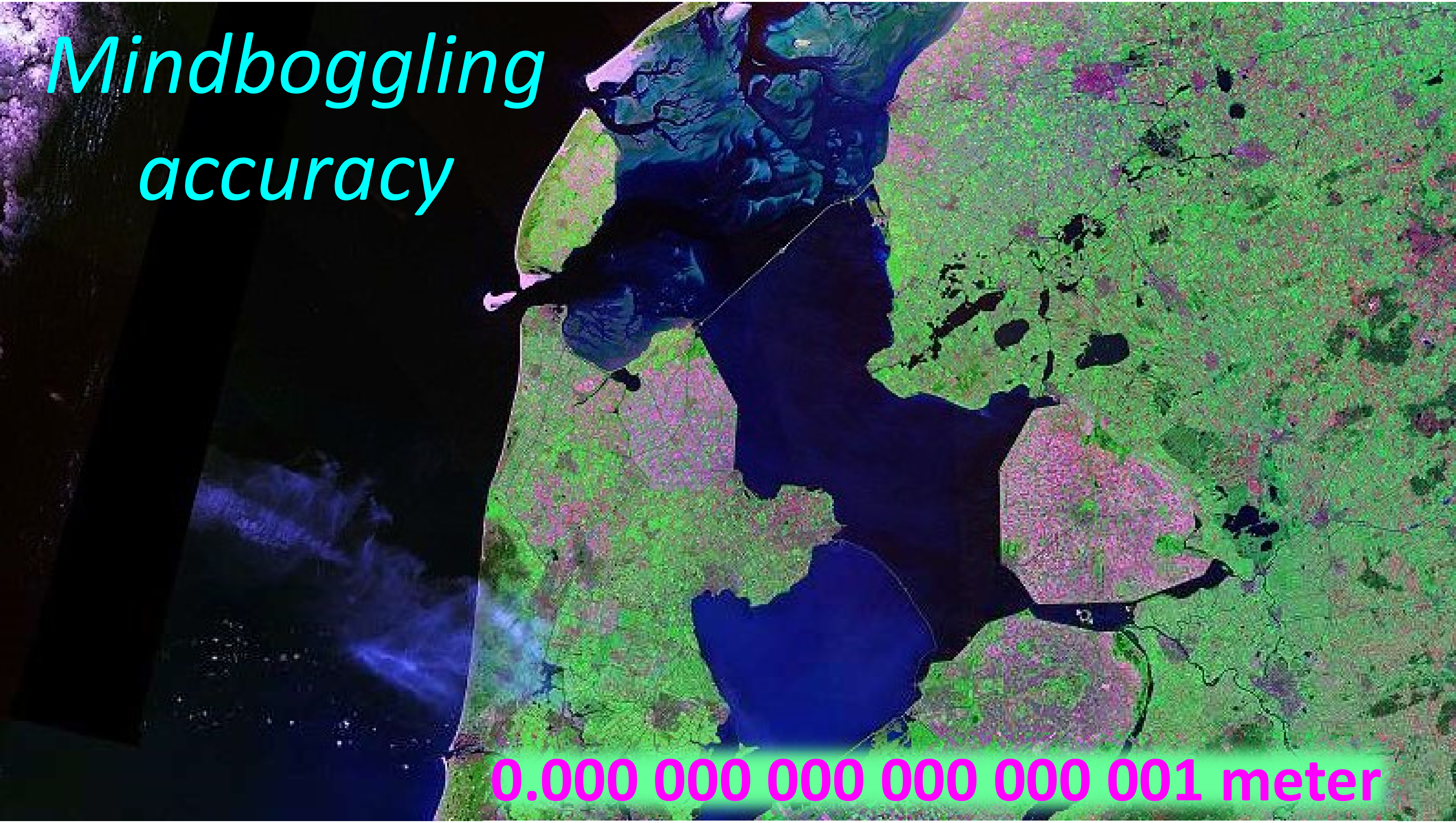
Gravitational Waves

A new window upon our Universe– Einstein Telescope



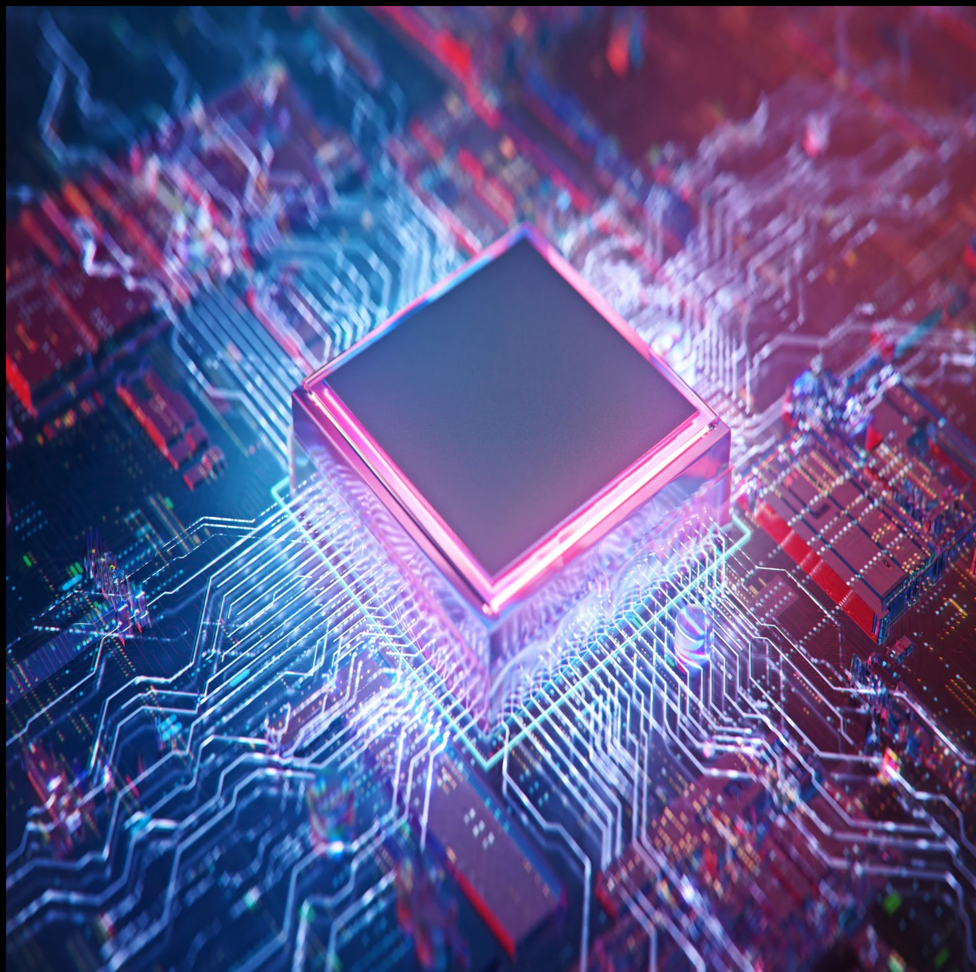
Typical effect on few kilometer scale:
0.000 000 000 000 000 000 1 meter

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


Mindboggling
accuracy
0.000 000 000 000 000 001 meter

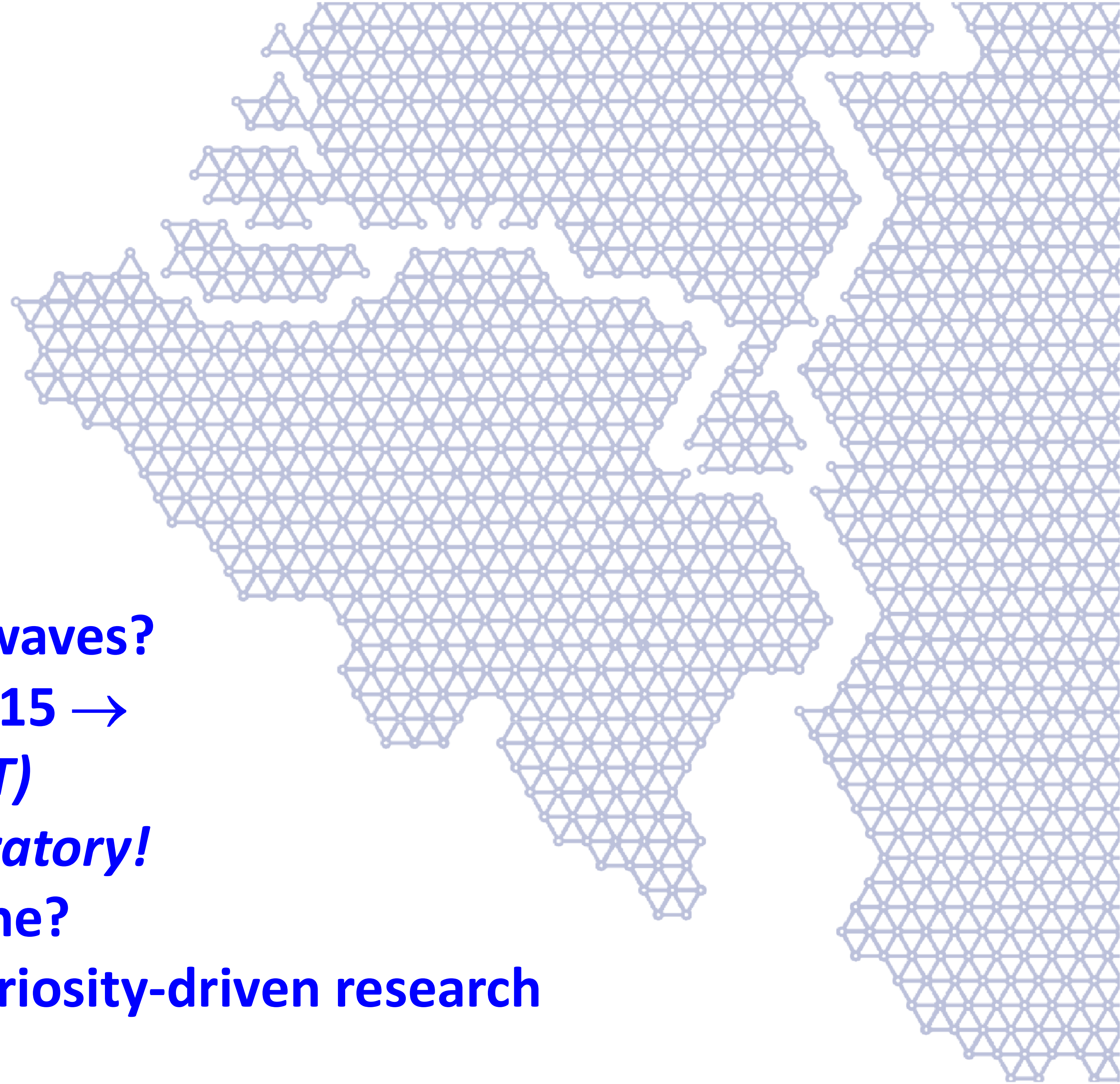
To put 0.000 000 000 000 000 001 m in context

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

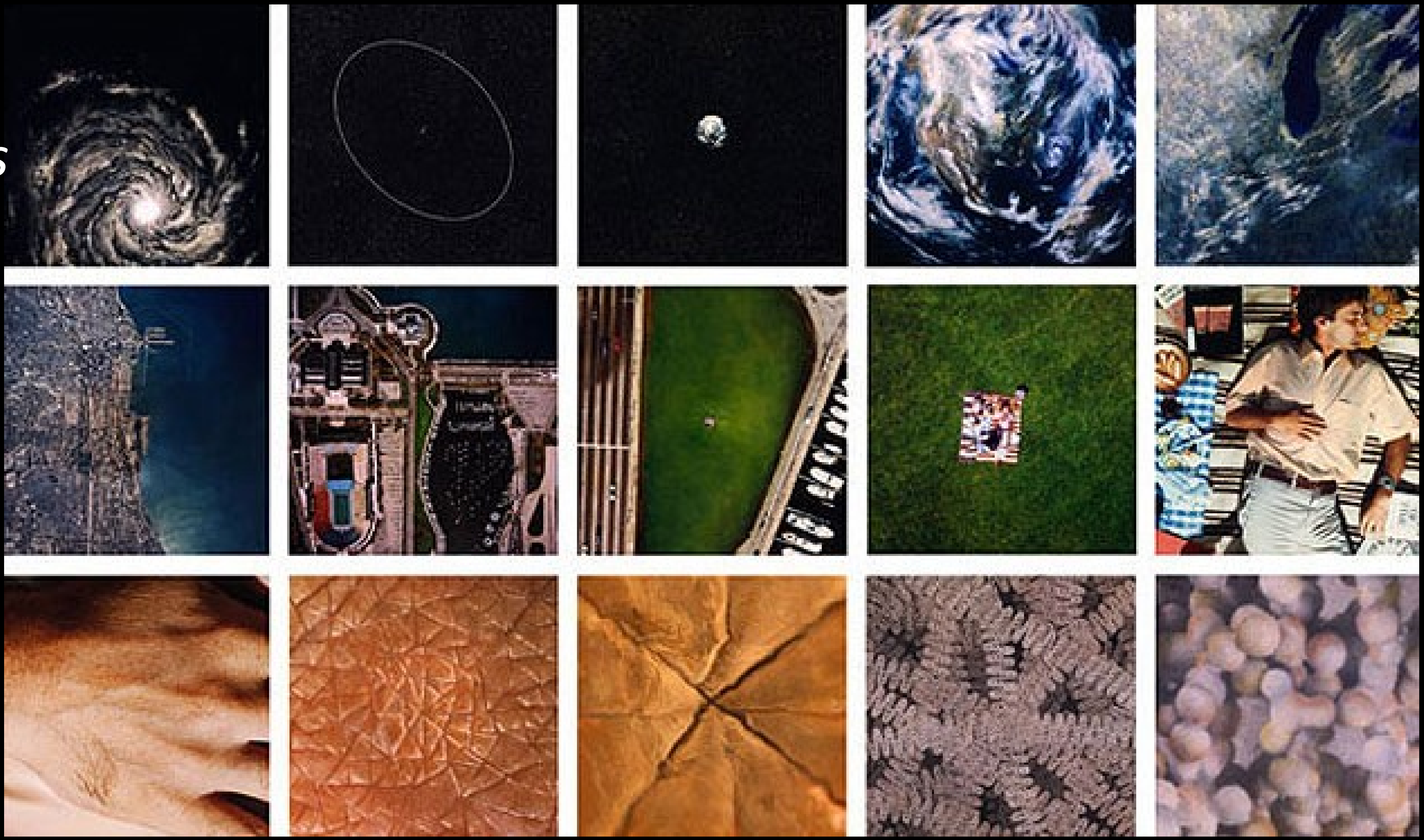


→ **Curiosity-driven research**

- **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

$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}W_{\mu\nu}\cdot W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^{\alpha}_{\mu\nu}G^{\mu\nu}_{\alpha}}_{\text{kinetic energies and self-interactions of the gauge bosons}}$$

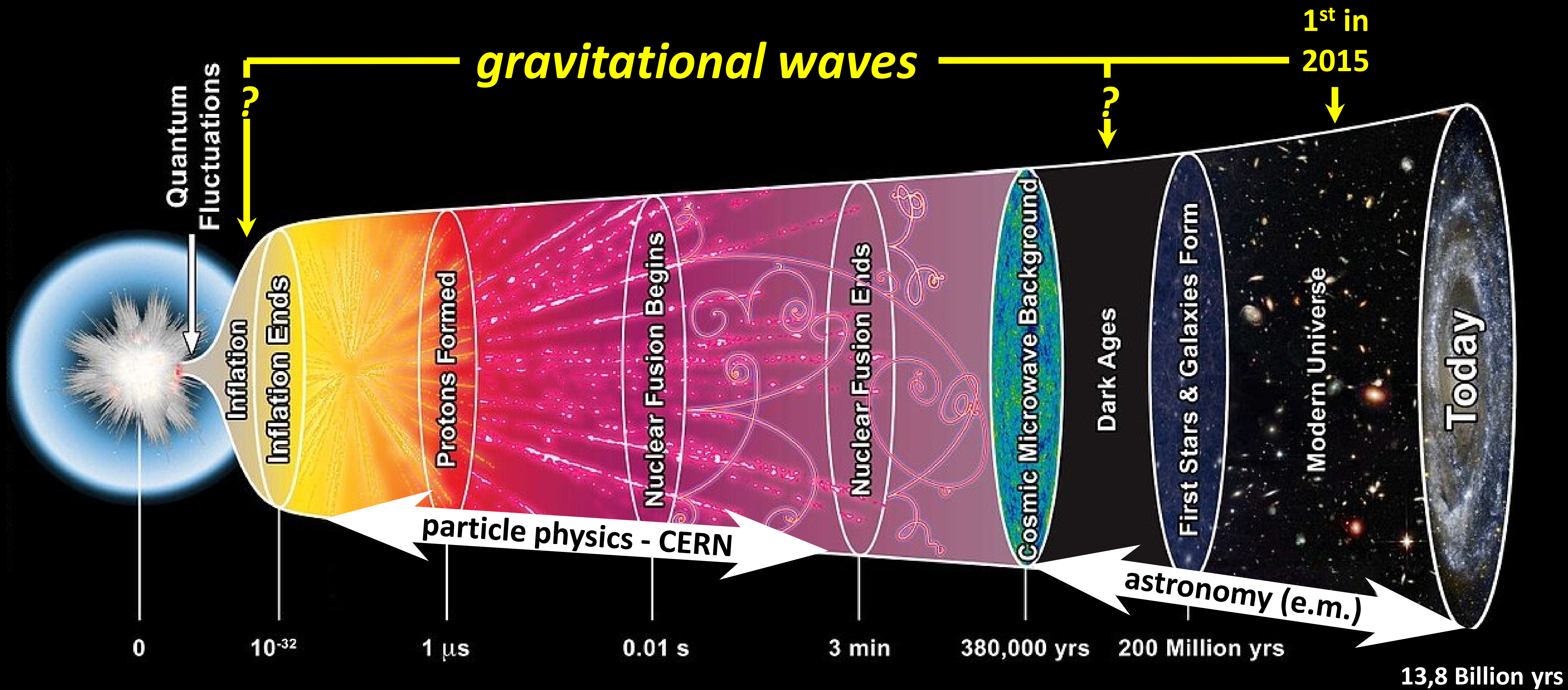
$$+ \underbrace{\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)L + \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g'YB_{\mu}\right)R}_{\text{kinetic energies and electroweak interactions of fermions}}$$

$$+ \underbrace{\frac{1}{2}\left|\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)\phi\right|^{2} - V(\phi)}_{W^{\pm},Z,\gamma \text{ and Higgs masses and couplings}}$$

$$+ \underbrace{g''\left(\bar{q}\gamma^{\mu}T_{a}q\right)G^{\alpha}_{\mu}}_{\text{interactions between quarks and gluons}} + \underbrace{\left(G_{1}\bar{L}\phi R + G_{2}\bar{L}\phi_{c}R + h.c.\right)}_{\text{fermion masses and couplings to Higgs}}$$

How does it work?

What did we learn?



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

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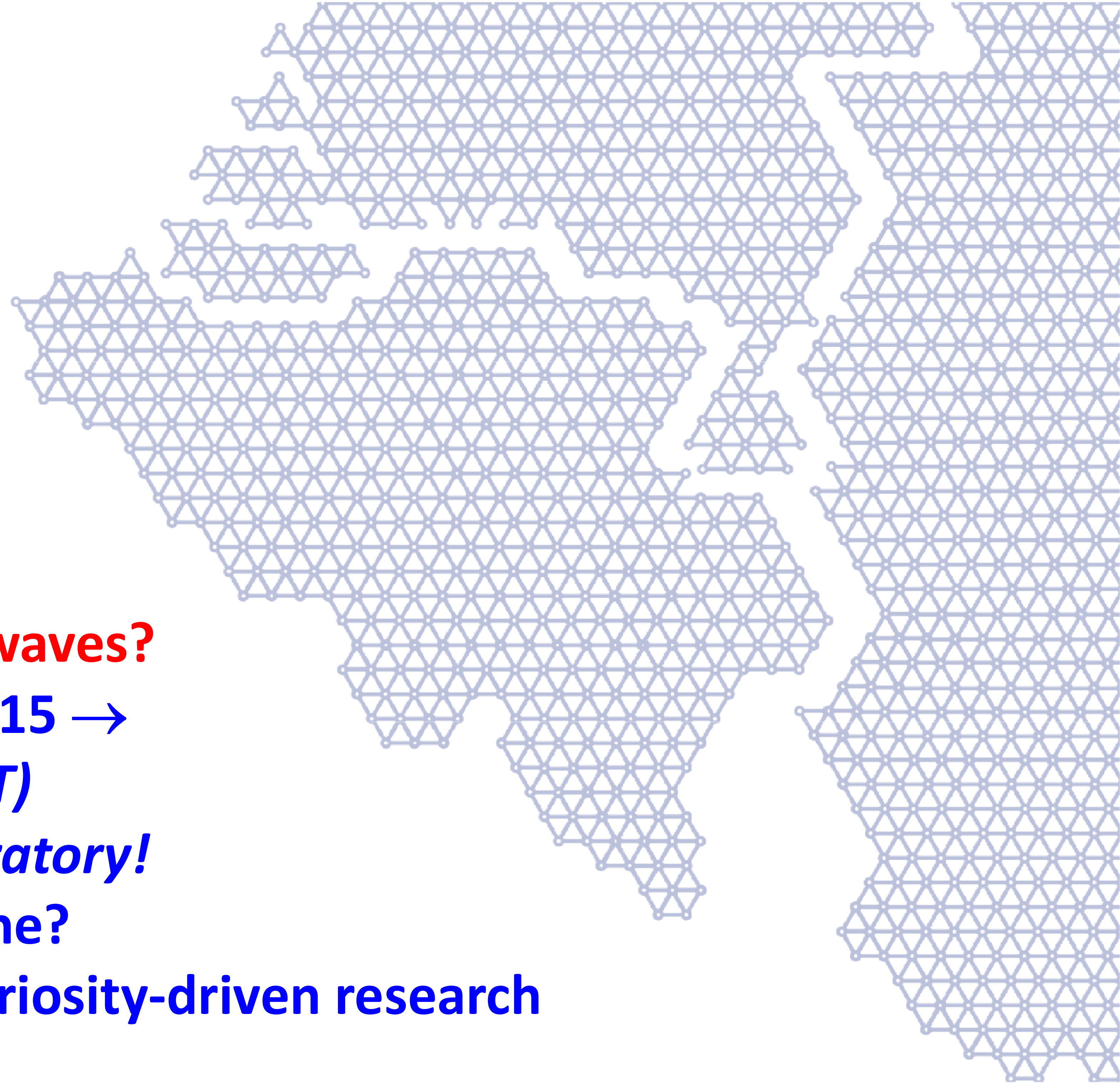
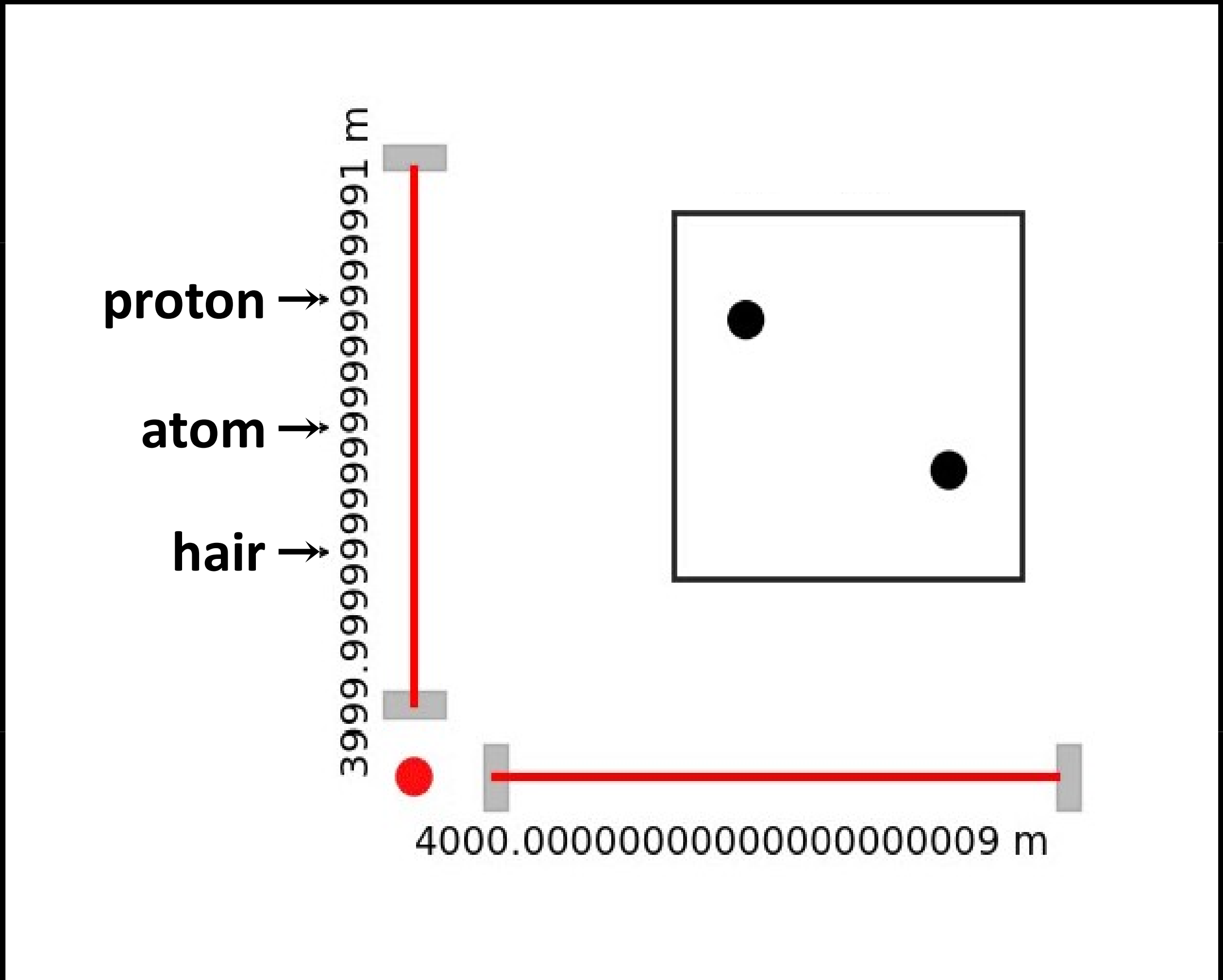
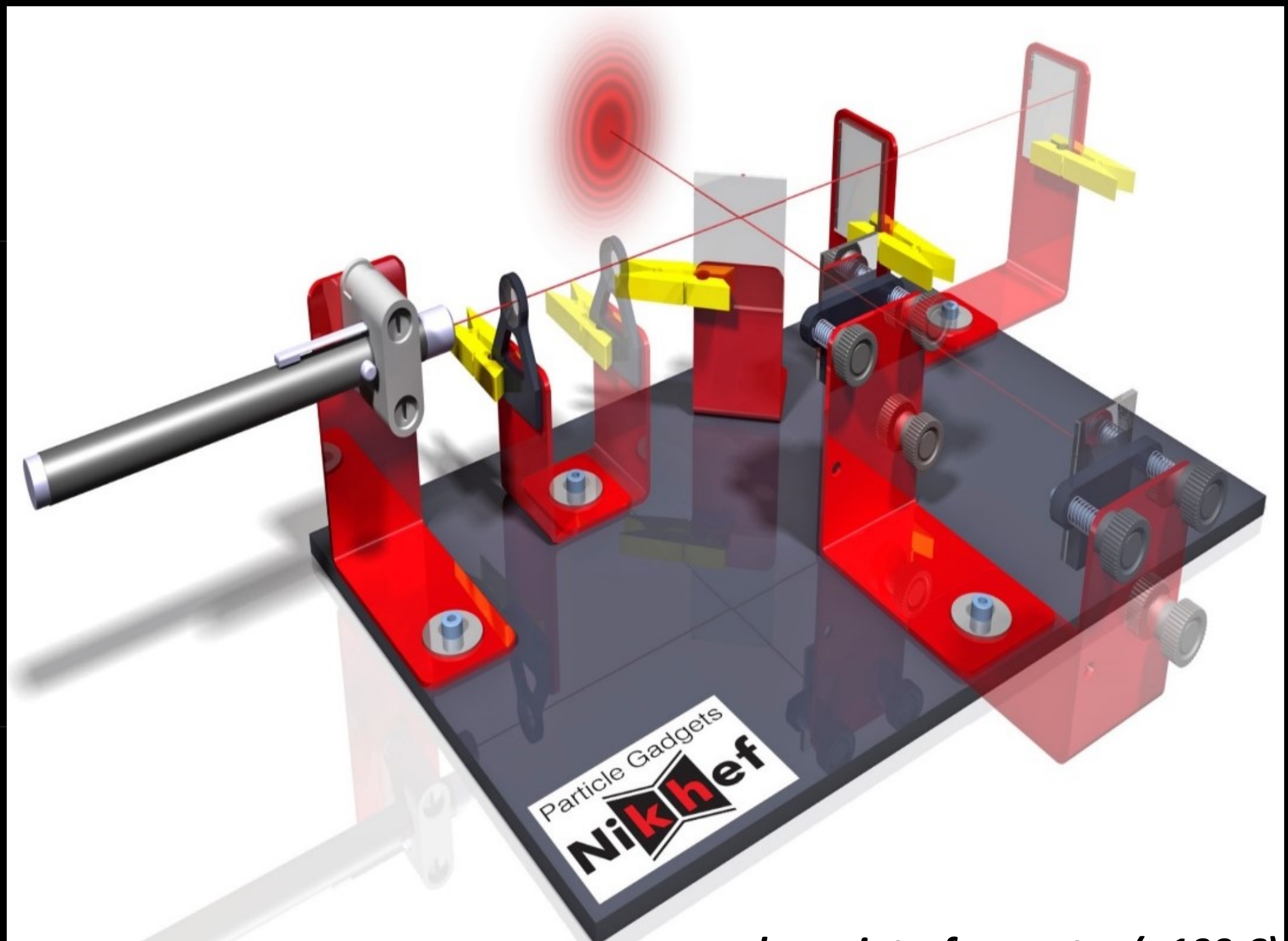


The concept: *laser-interferometer*



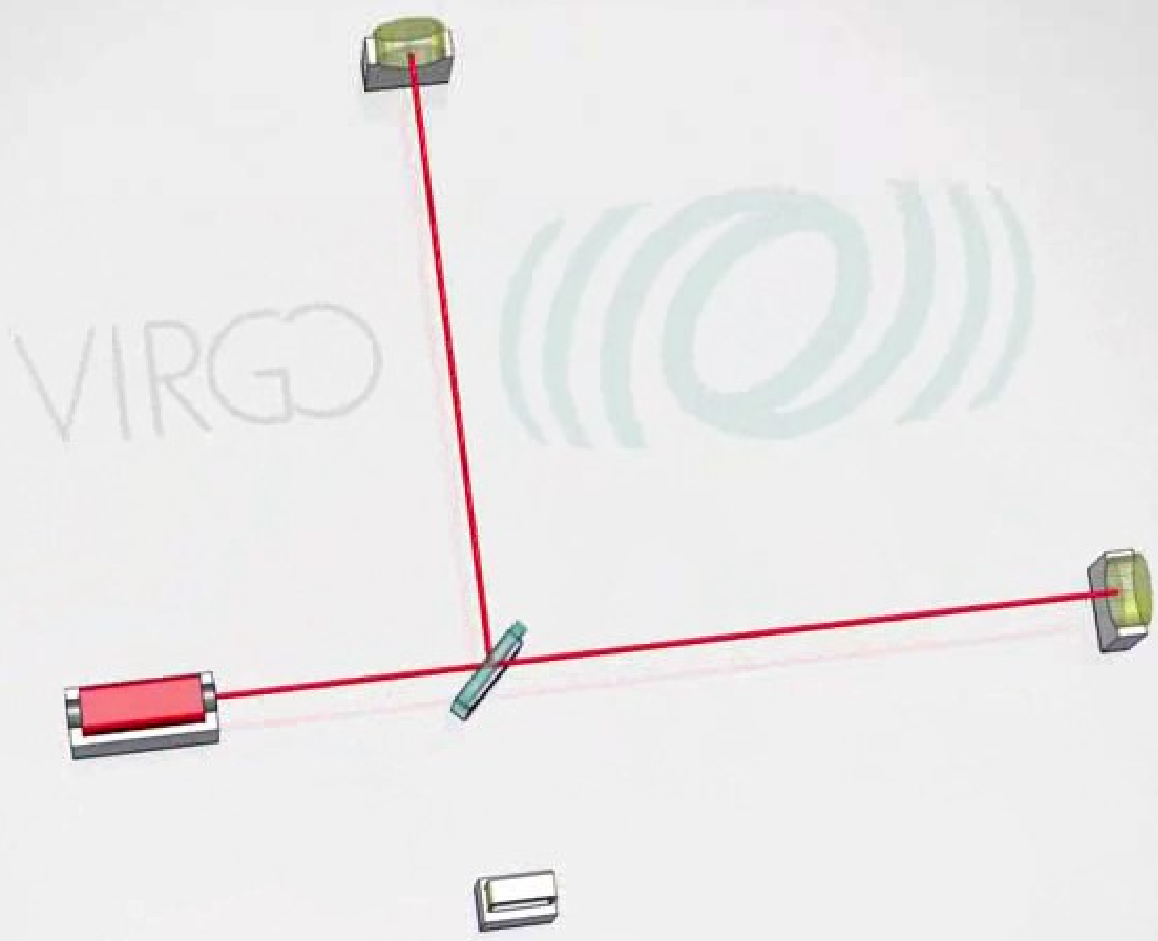


your own laser-interferometer (~100 €)

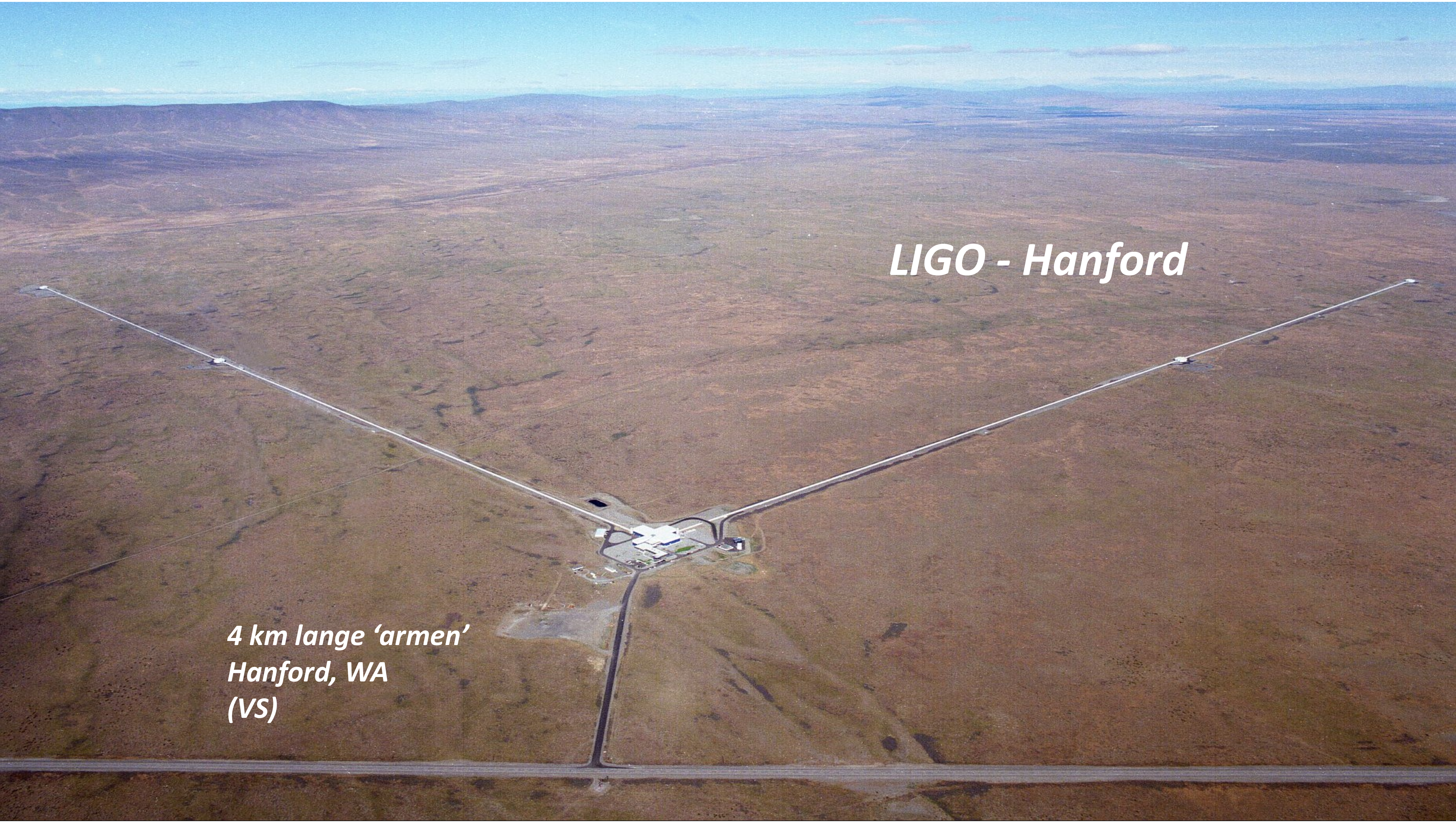
Real life: permanent struggle to fight disturbances:

Laser (in)stabilities, imperfect mirrors, (seismic, thermal, raindrops, tree-leaves, wind, …) vibrations, scattered light, imperfect vacuüm, imperfecte alignment, quantum noise, etc. etc.

From the concept to reality



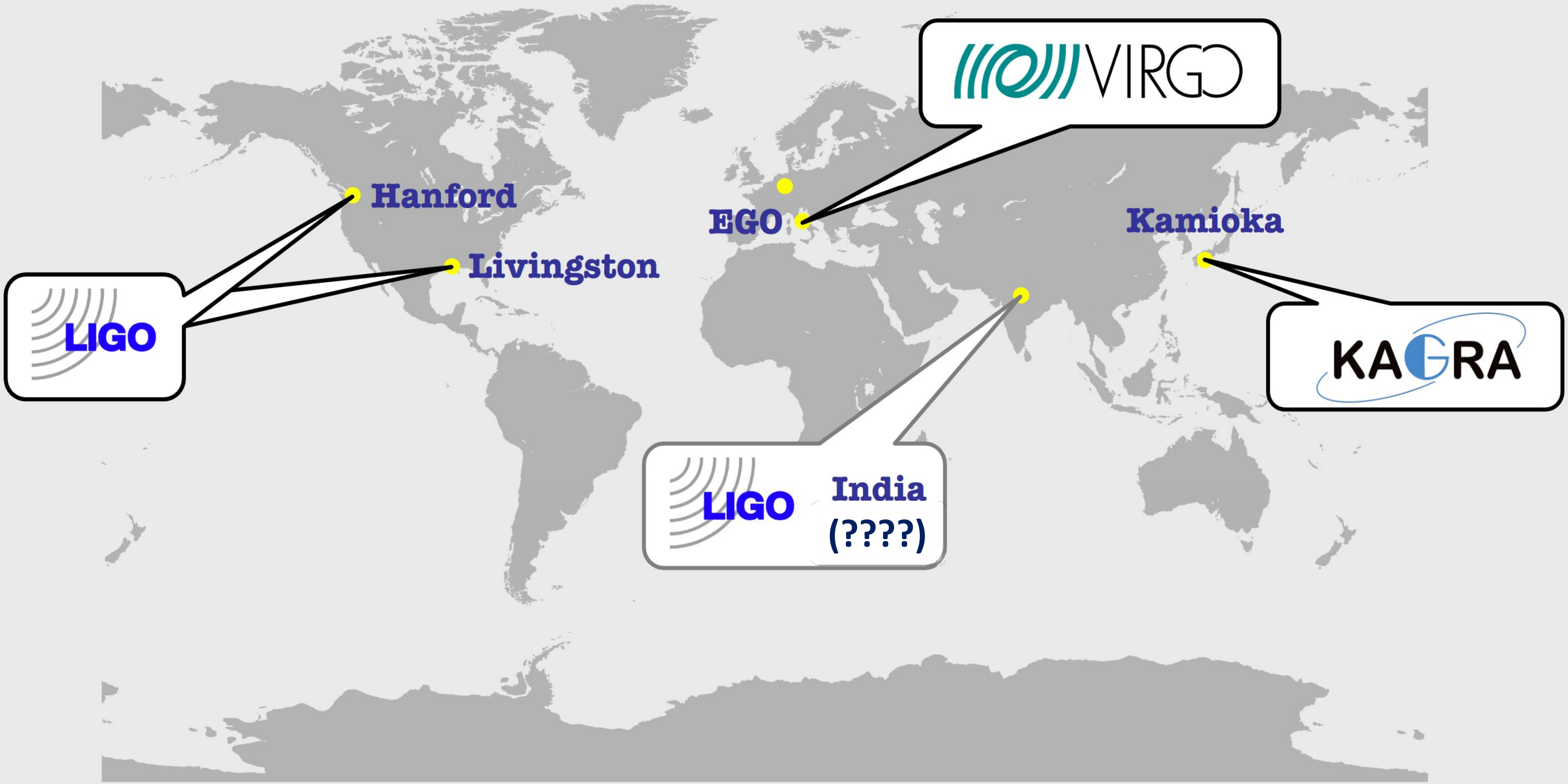

Today's facilities:
started around 1990
few km long arms
on surface
at room temperature
in the USA, Europe & Japan
$\mathcal{O}$(100) detections/year
Virgo
near Pisa



LIGO - Hanford
4 km lange ‘armen’
Hanford, WA
(VS)


LIGO - Livingston
4 km lange ‘armen’
Livingston, LA
(VS)

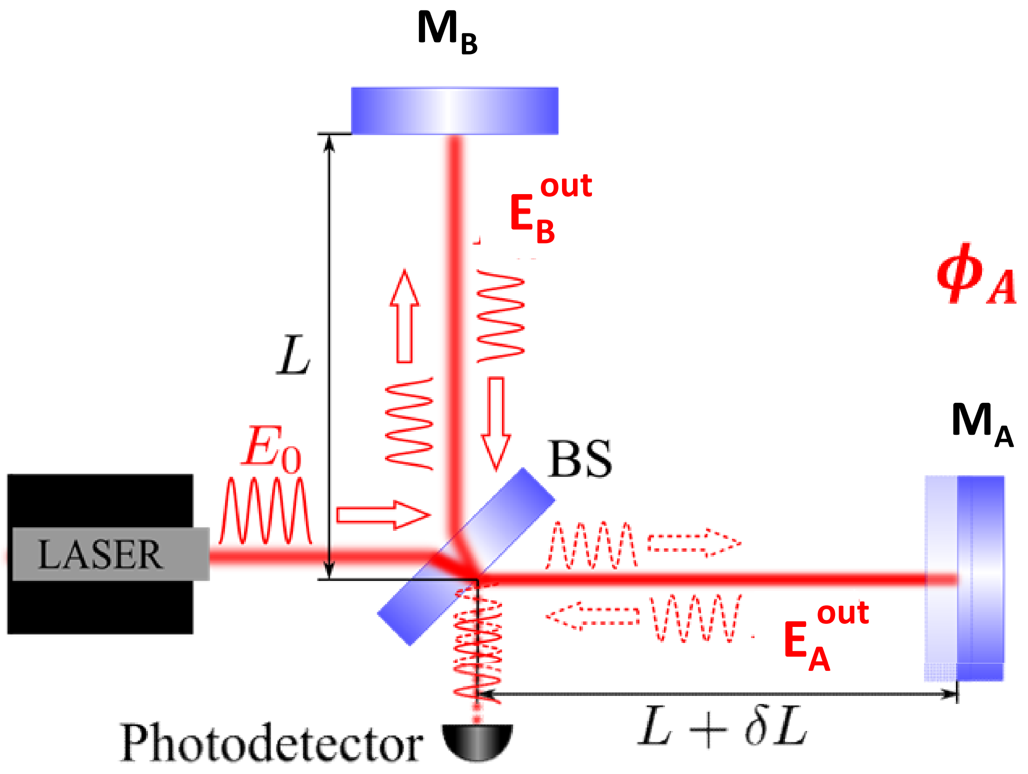
Worldwide network



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

Michelson interferometer

For simplicity: assume laser light storage time < GW period

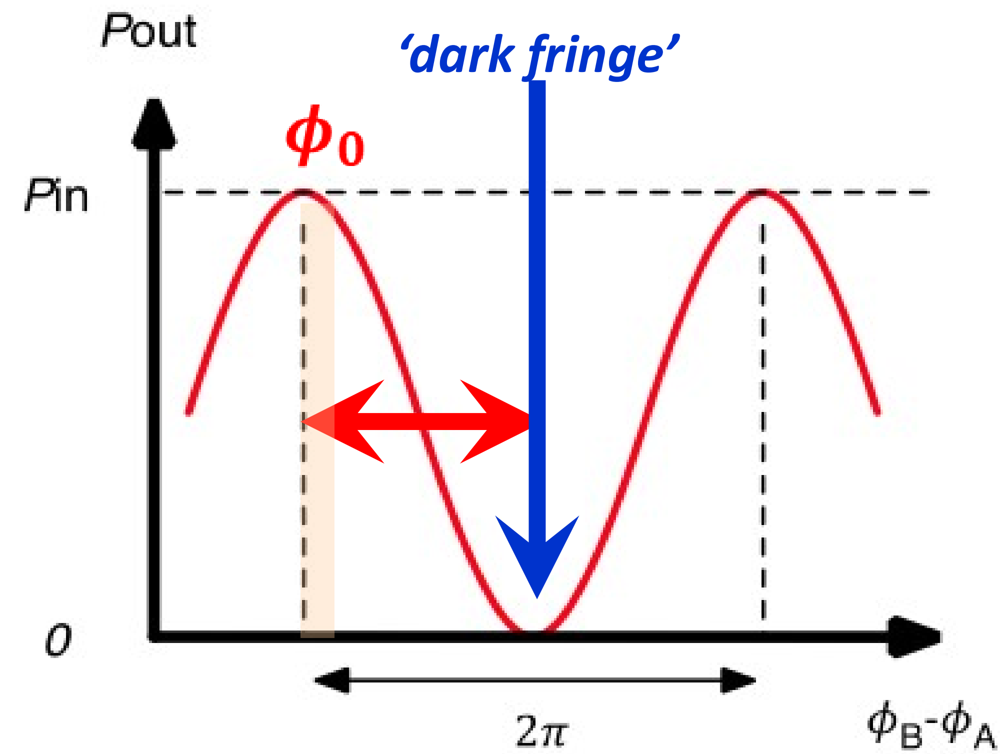


$$\phi = \frac{4\pi}{\lambda}(L \pm \Delta L)$$

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

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

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

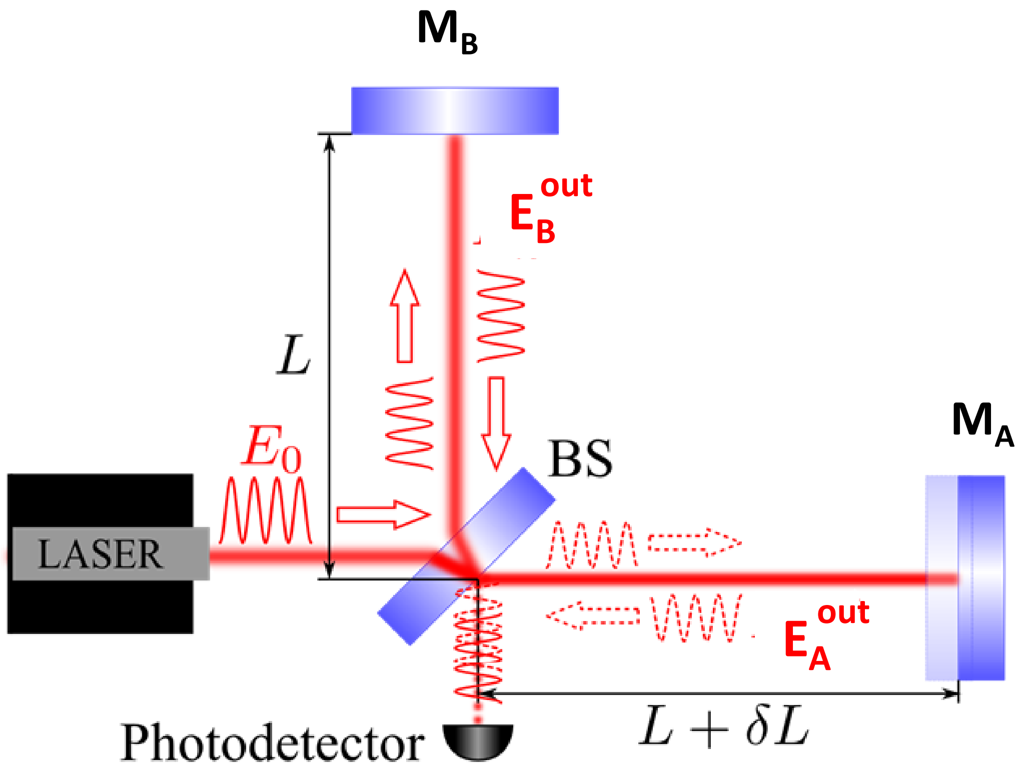


$$E_{out} = \frac{1}{2}\left(e^{-i\phi_A} - e^{-i\phi_B}\right)E_{in}$$
$$= \left[ie^{-i(\phi_A+\phi_B)/2}\sin\left(\frac{\phi_A - \phi_B}{2}\right)\right]E_{in}$$

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

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 • • •)

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

$\Rightarrow$ *laser power*: $$\Delta P_{out} \sim \frac{\Delta P_{in}}{2}(1 - \cos\phi_0)$$

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

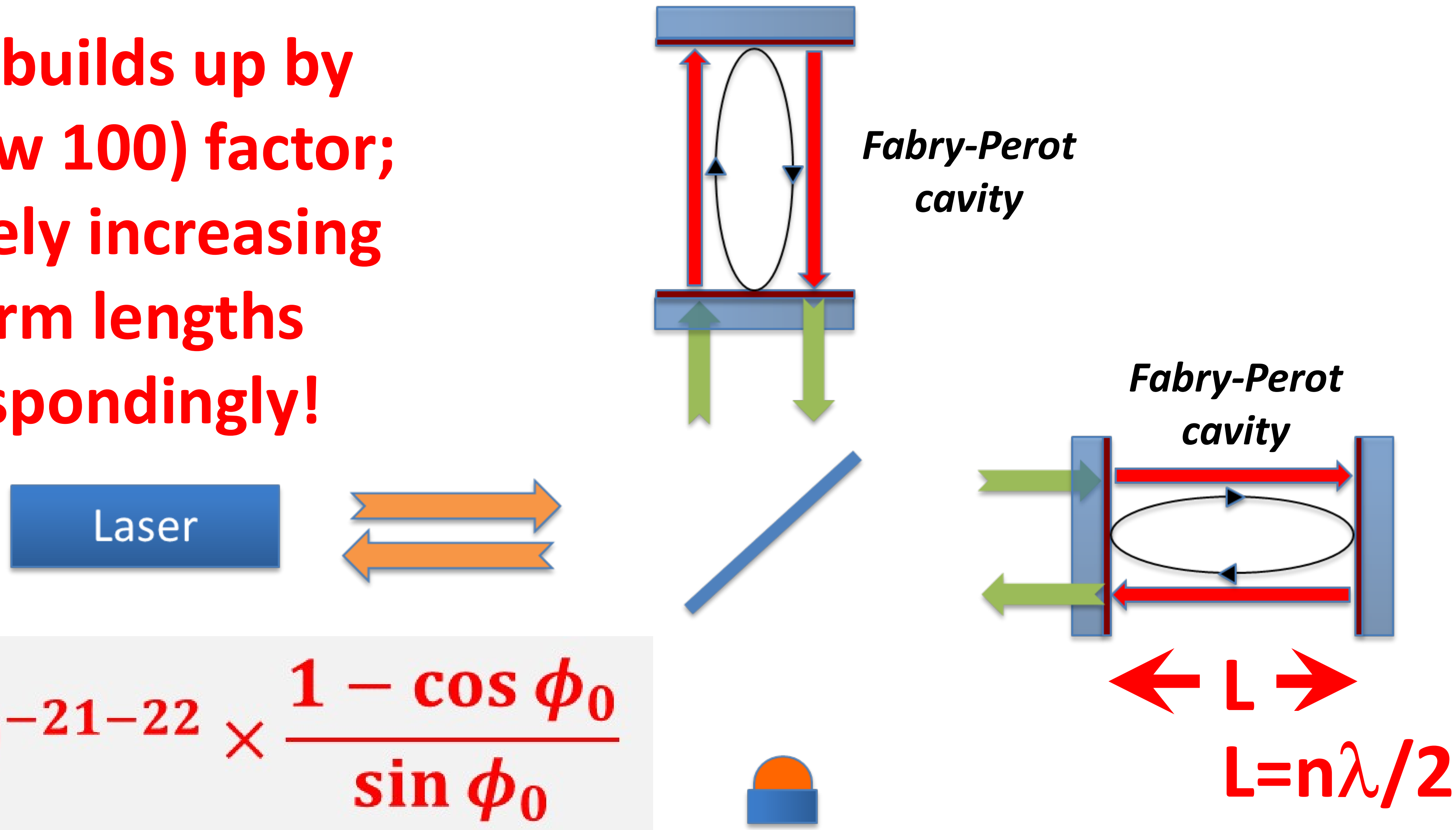
$$\Rightarrow \Delta h \sim \frac{\Delta P_{in}}{P_{in}} \times \frac{\lambda}{8\pi L} \times \frac{1 - \cos\phi_0}{\sin\phi_0}$$

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

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

Fabry-Perot cavities | **power recycling** | **signal recycling**

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

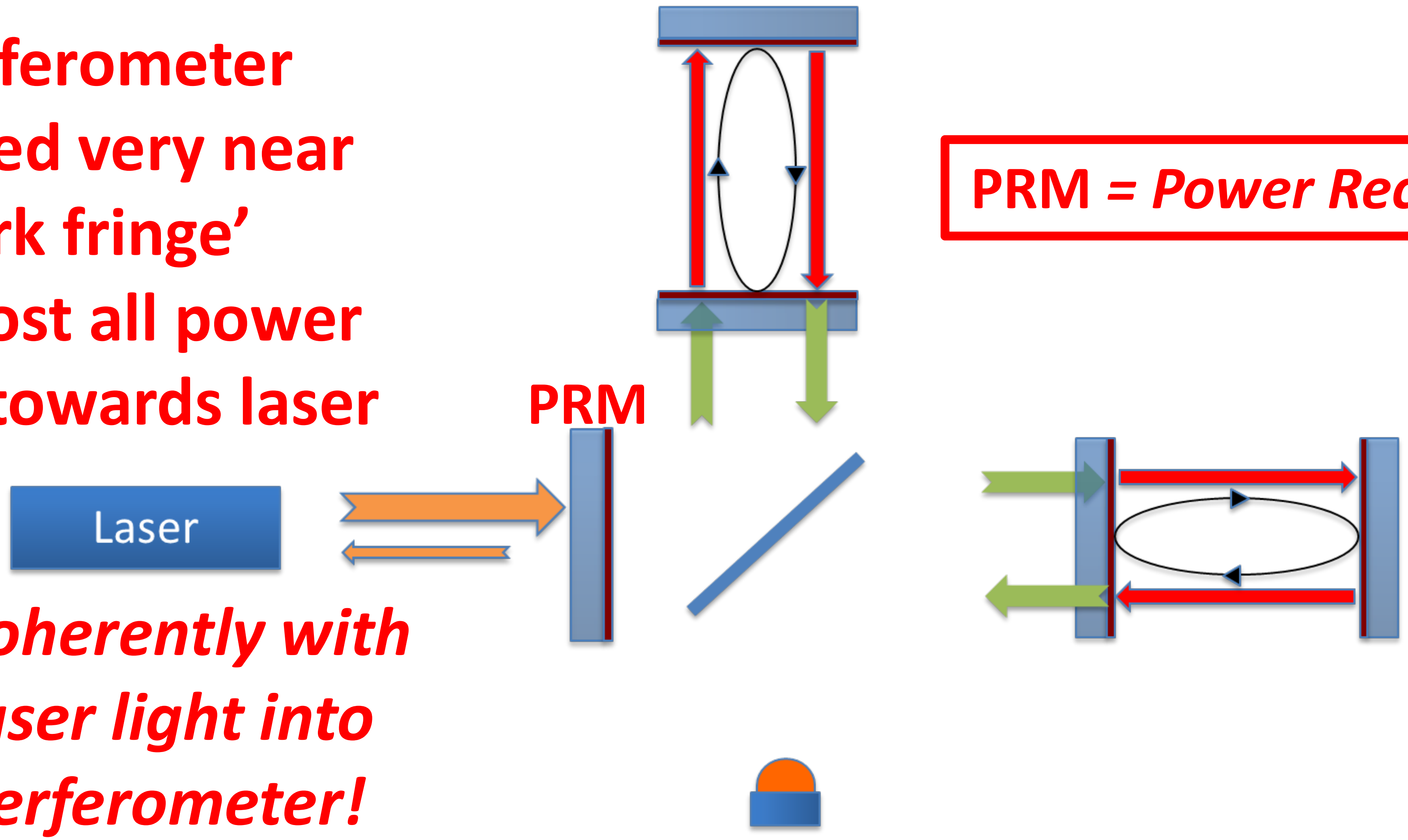


$$\Delta h \geq 10^{-21-22} \times \frac{1-\cos\phi_0}{\sin\phi_0}$$

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

Fabry-Perot cavities	**power recycling**	signal recycling

interferometer operated very near 'dark fringe'
$\Rightarrow$ almost all power exiting towards laser



PRM = *Power Recycling Mirror*

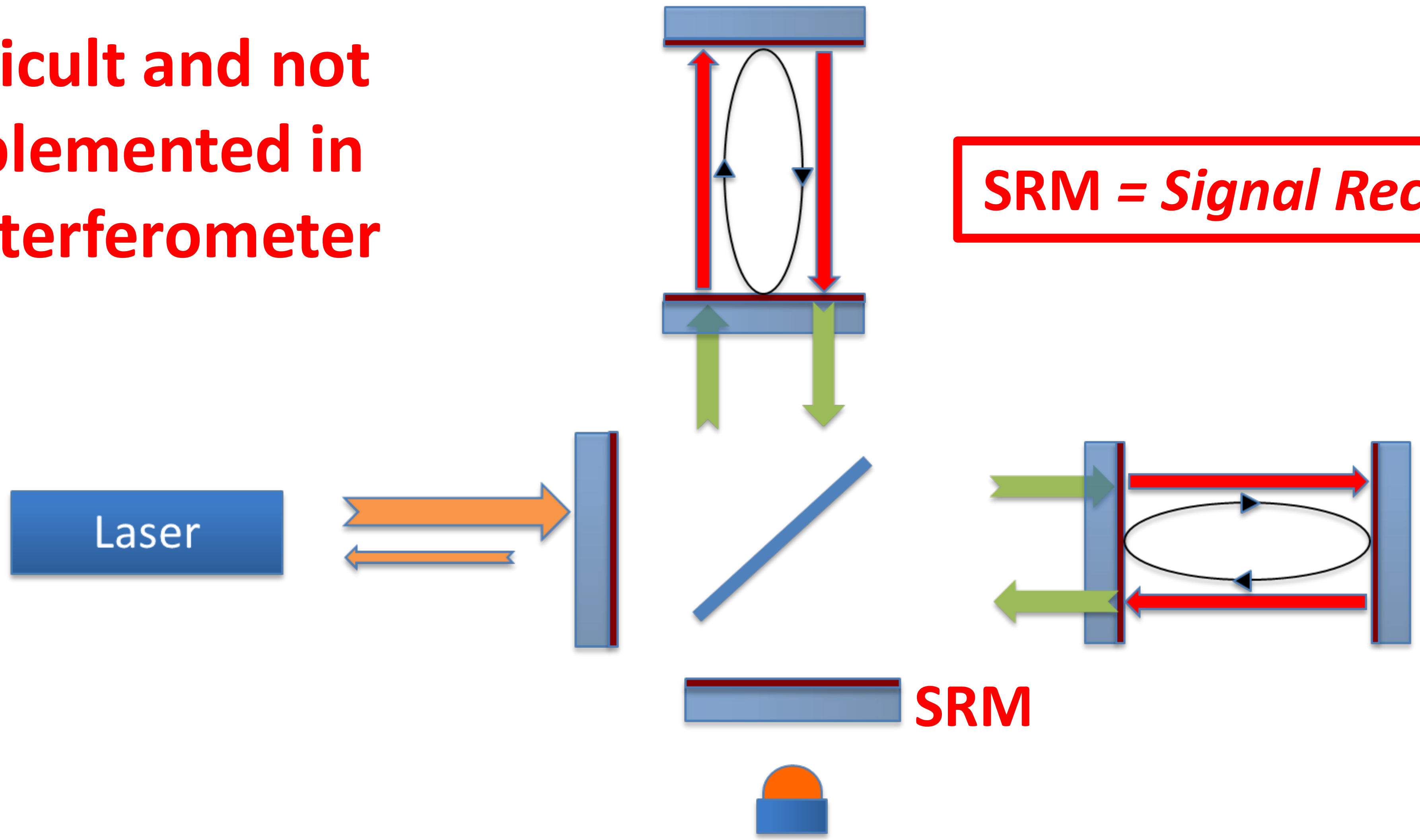
reflect coherently with fresh laser light into the interferometer!

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

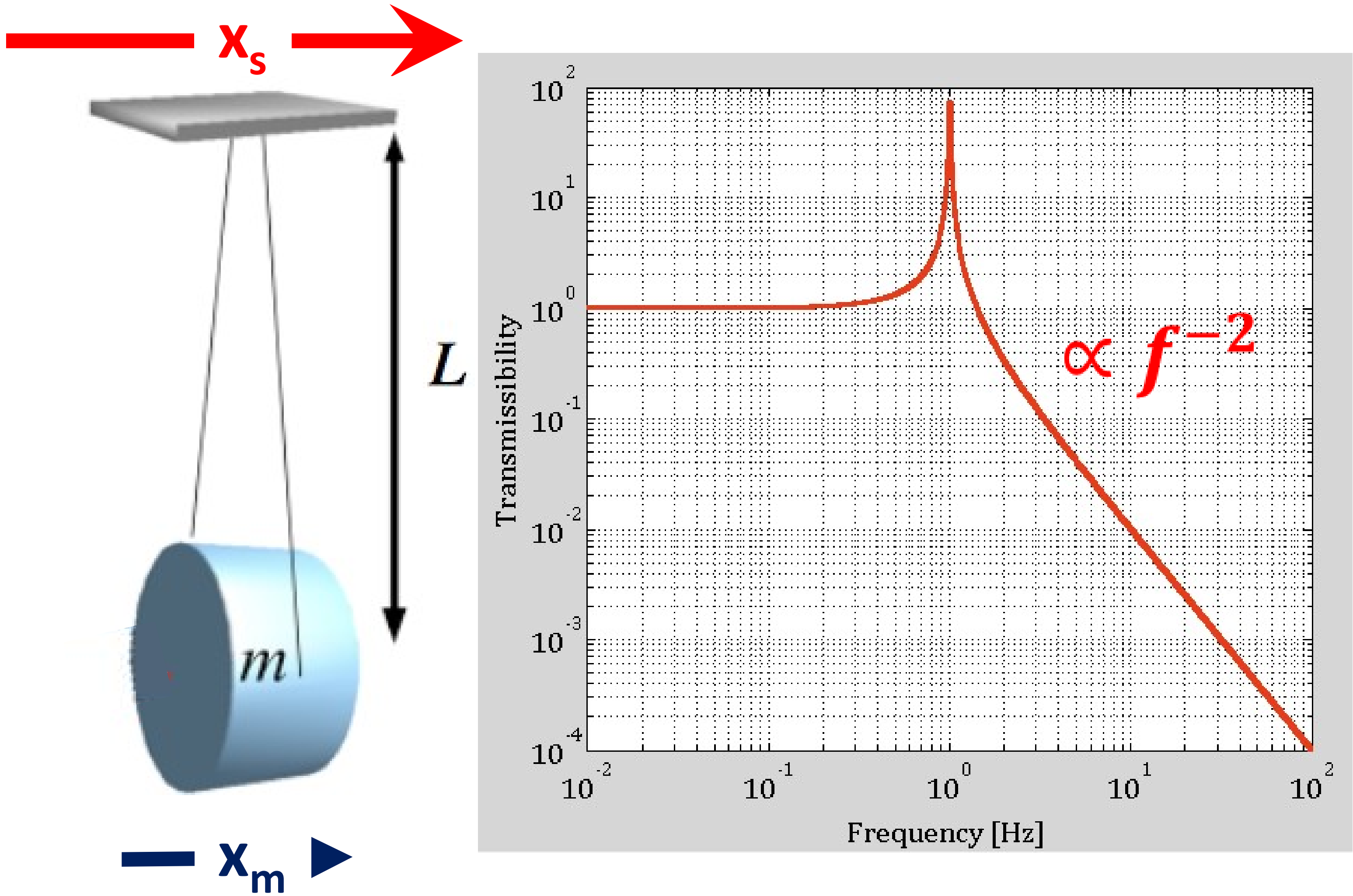
Fabry-Perot cavities	power recycling	signal recycling

too difficult and not yet implemented in Virgo interferometer

SRM = *Signal Recycling Mirror*

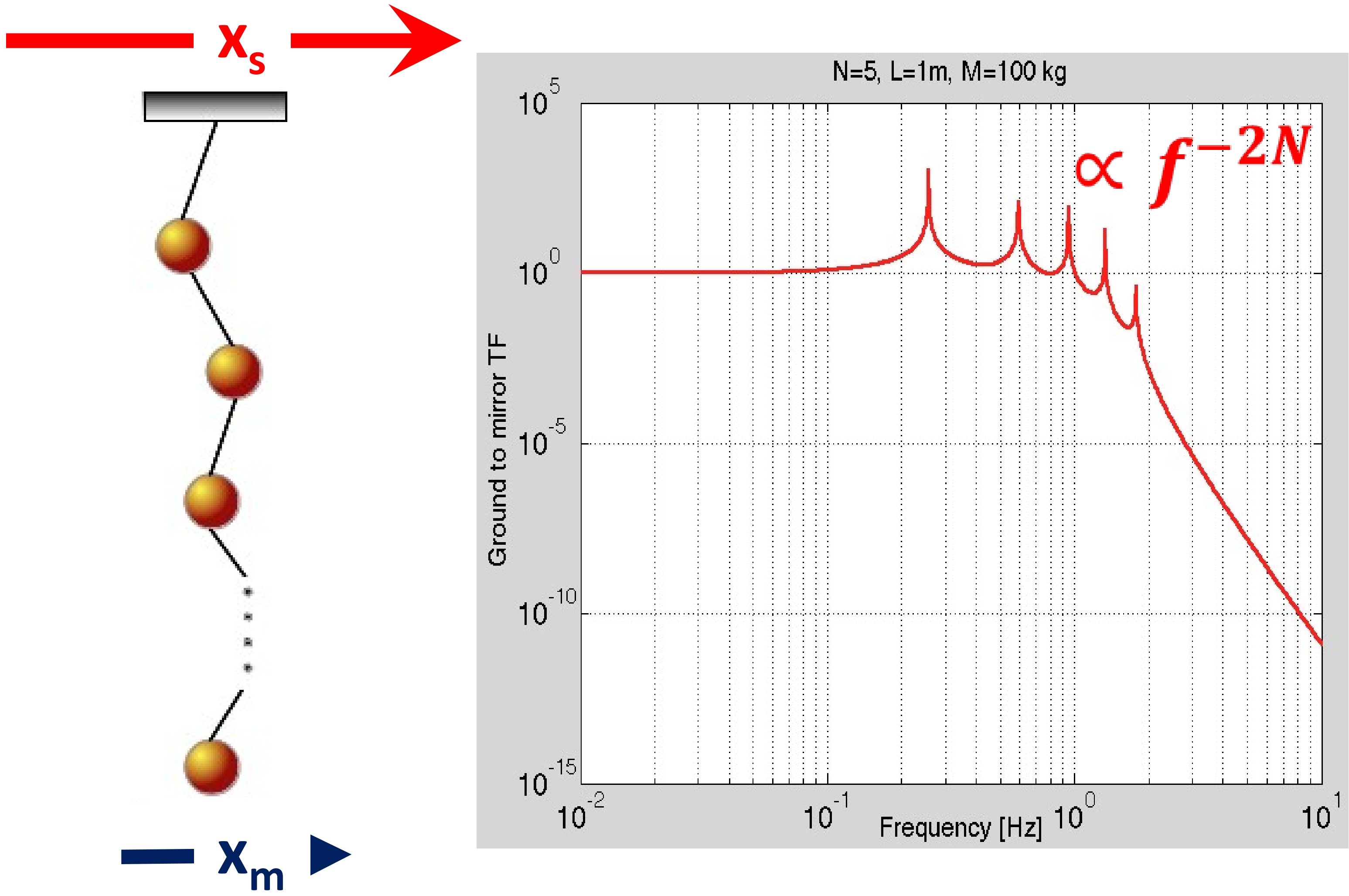


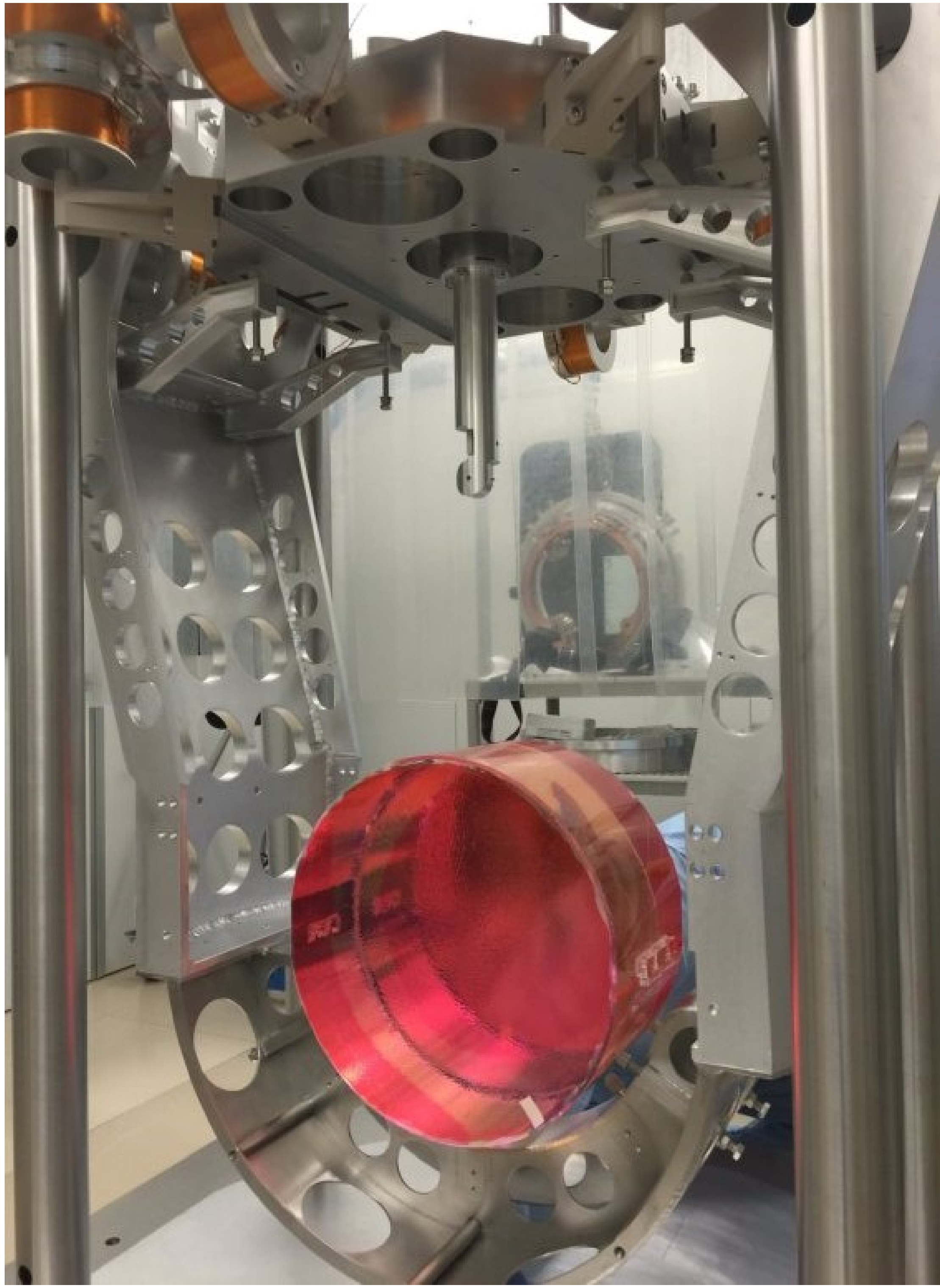
How to reduce noise? *E.g. (seismic) vibrations*



Elaborate multiple pendula attenuators

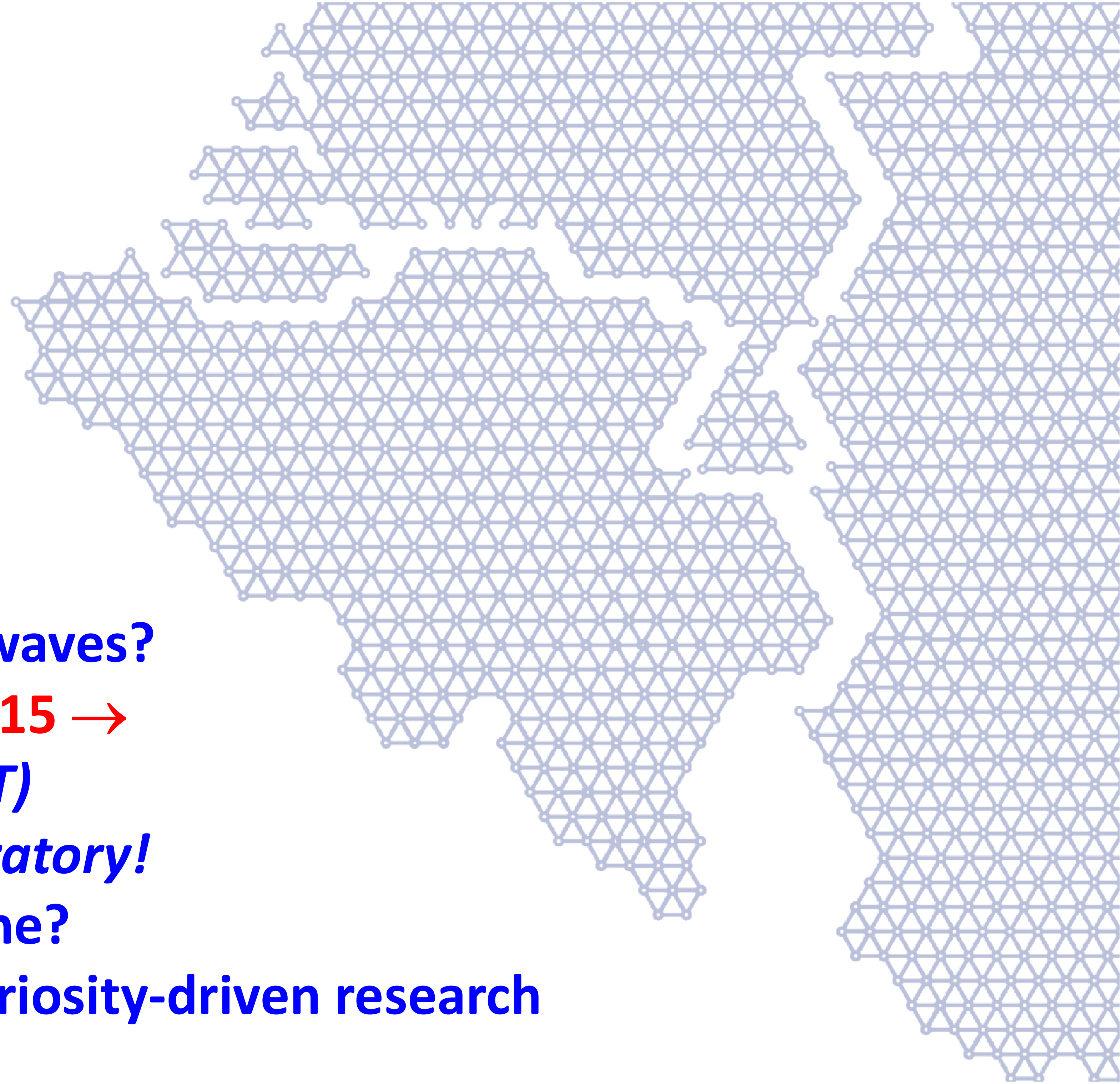
Just an example. Lots of other (quantum) tricks which I fail to explain i.e. very elaborate control systems!





Elaborate multiple pendula attenuators

Overview



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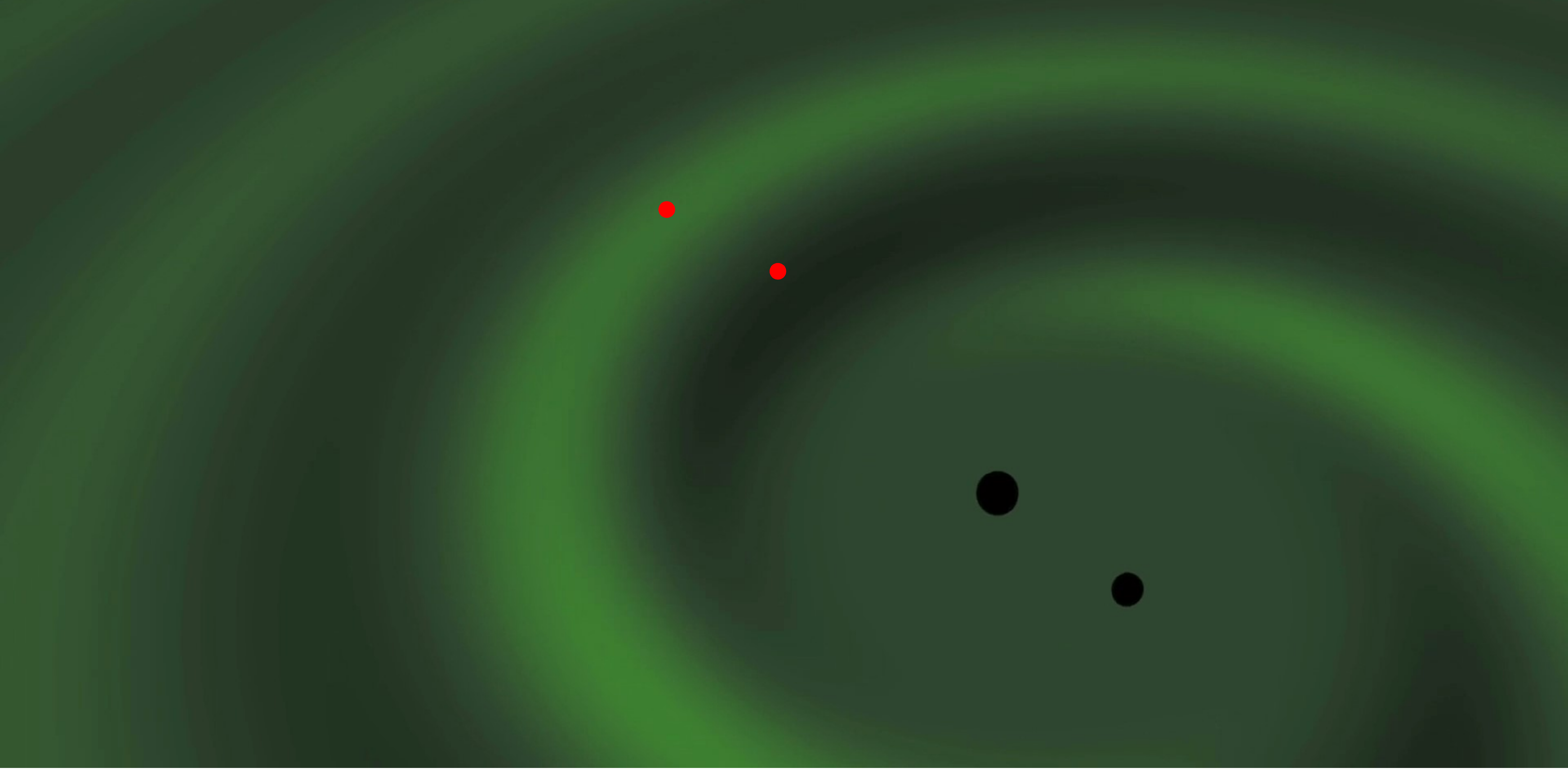
1st detection SEP/2015: *black holes*



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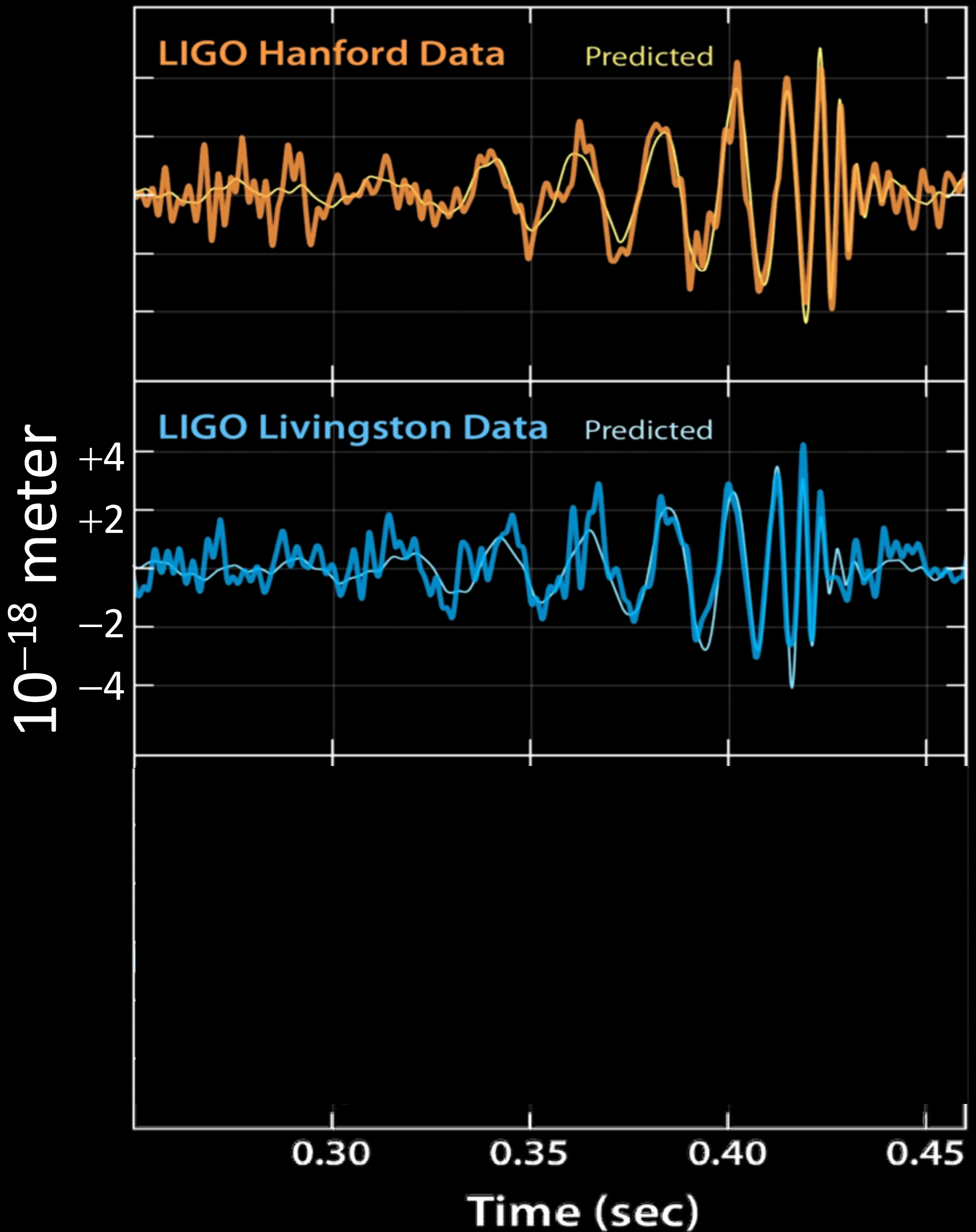
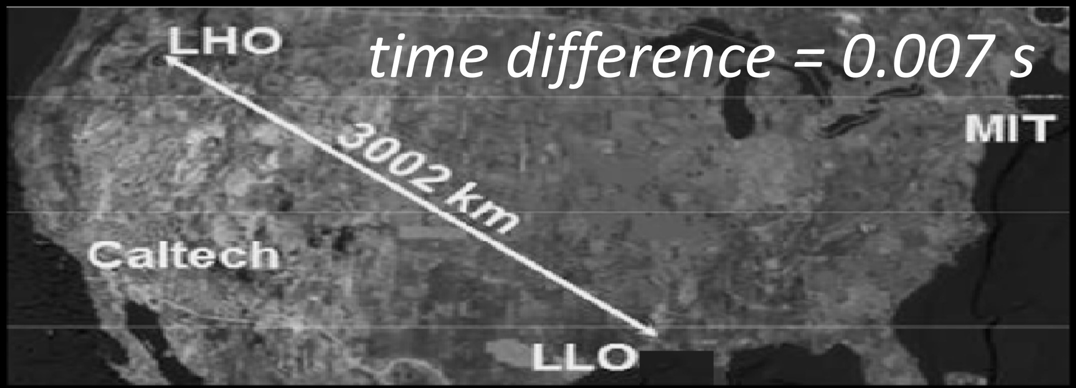


In a nutshell:

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



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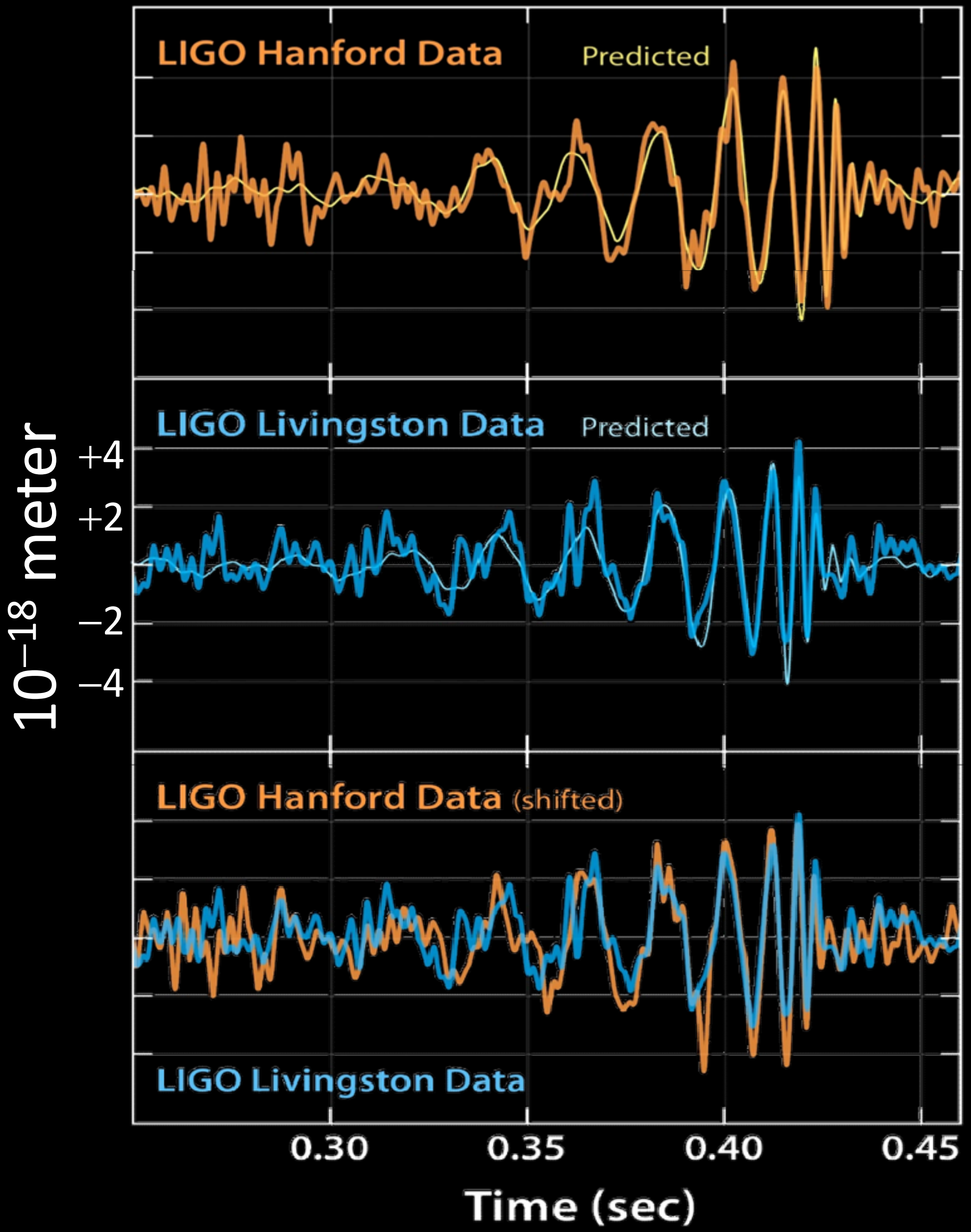
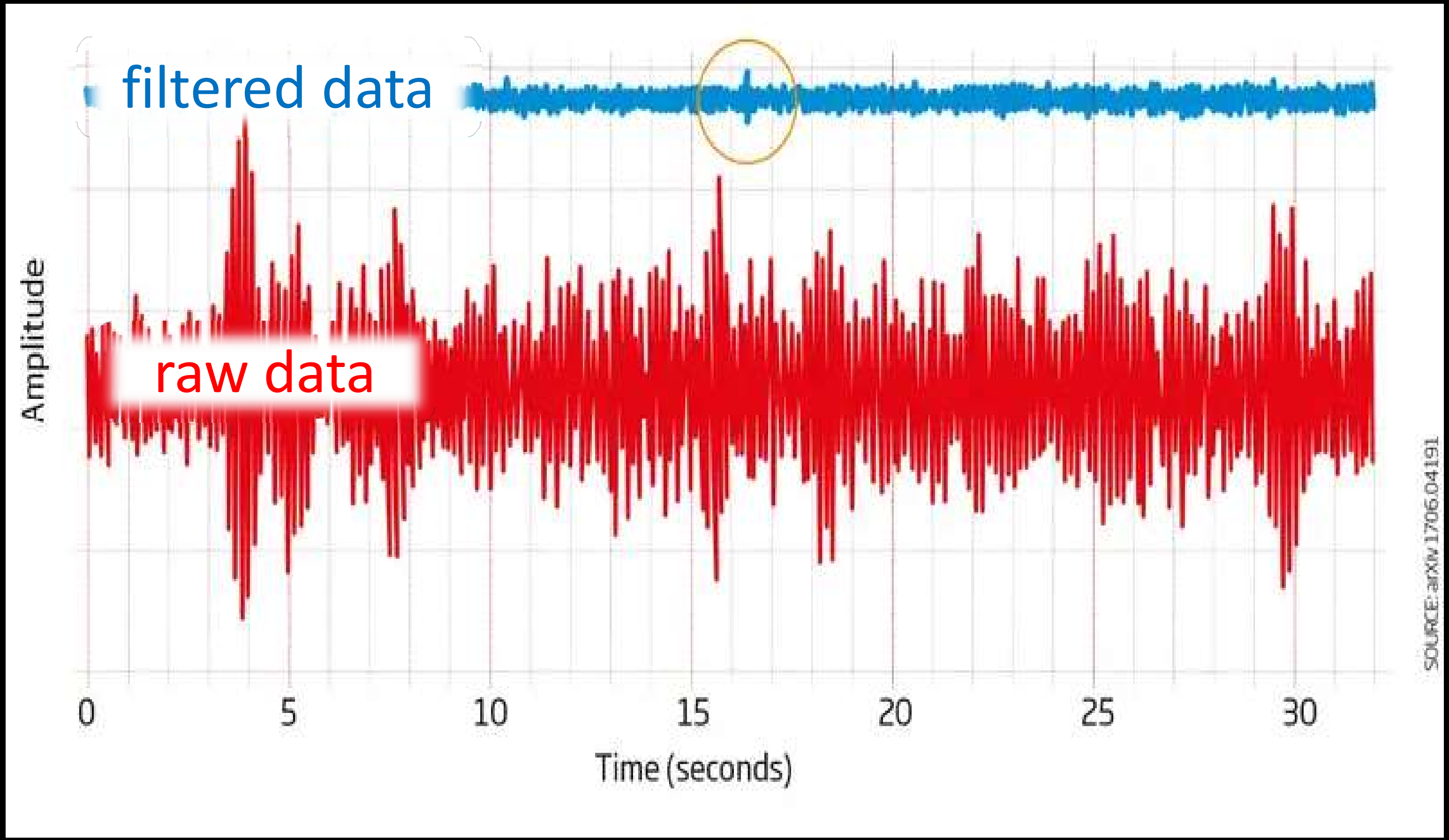
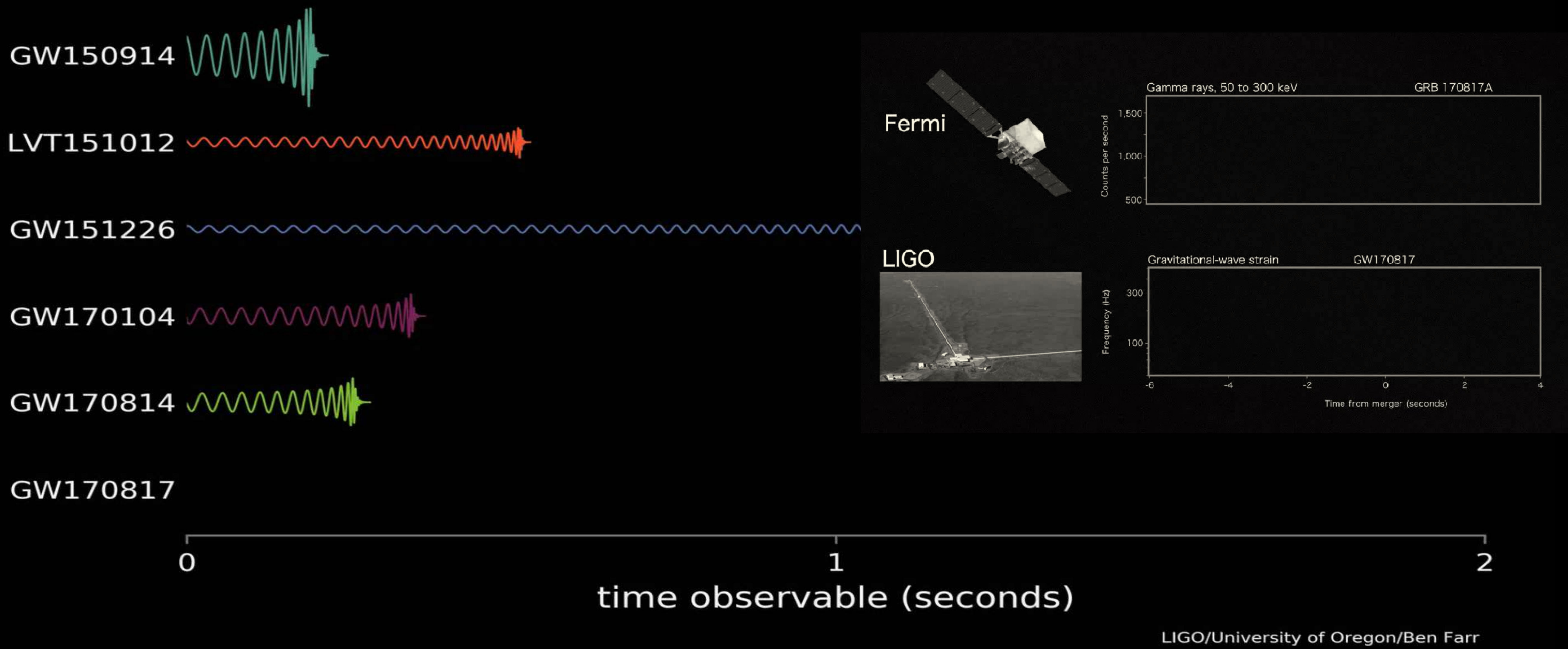


***Reality:* lots of data analysis to extract the minute imprint of a gravitational wave from thd continuous data stream (and to guarantee it isn't an art-effect!)**



Revolutionary one AUG/2017: *neutron stars*



Revolutionary one AUG/2017: *neutron stars*

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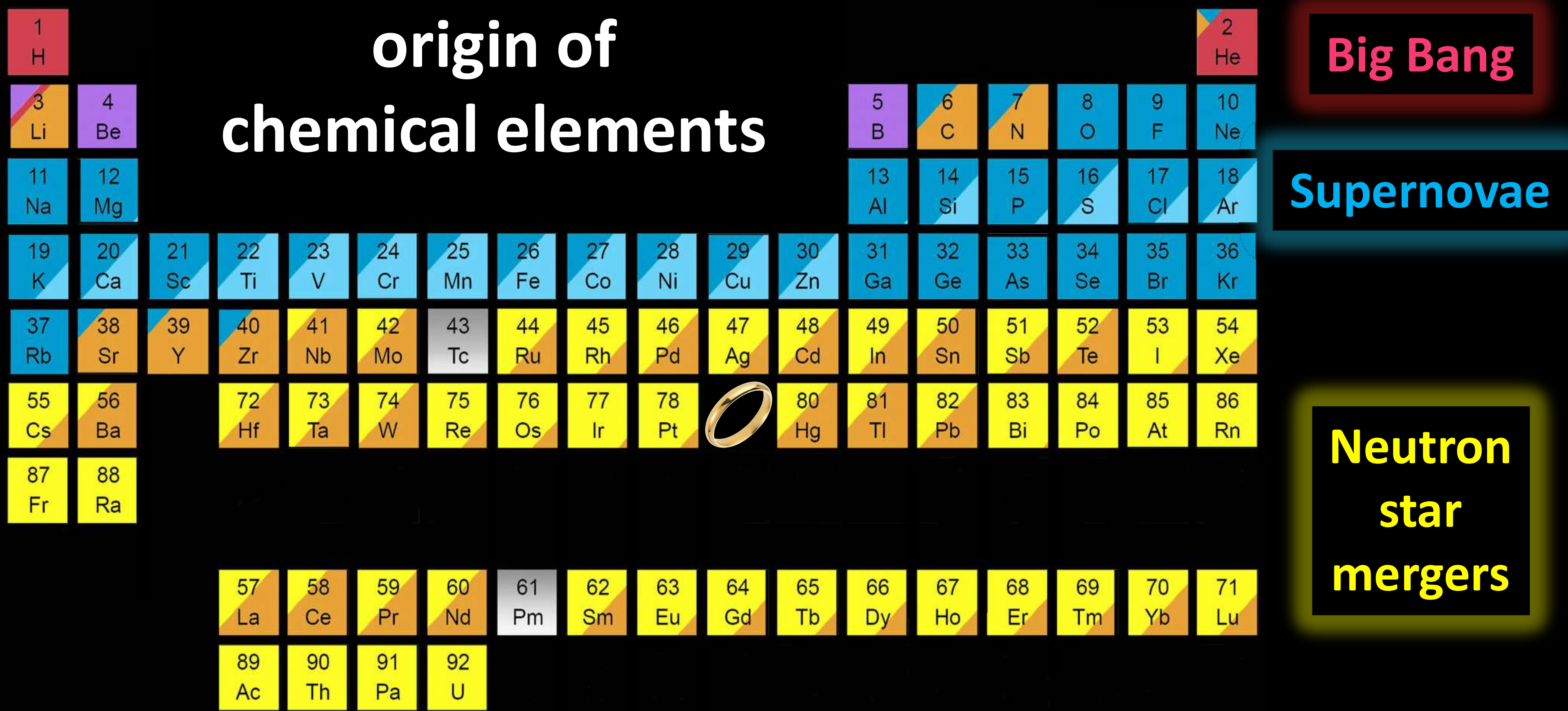
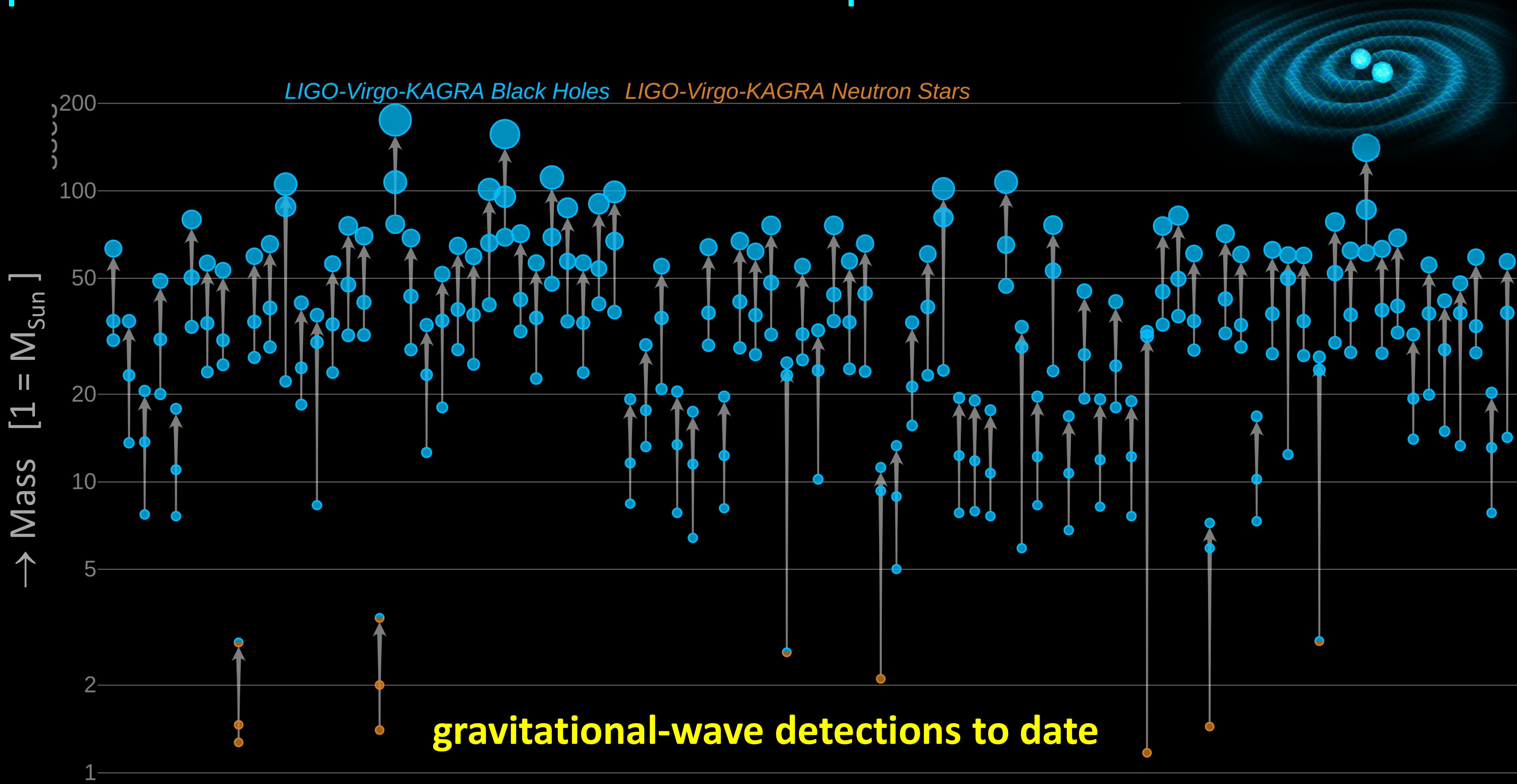


predicted: *1916* ··· 1st detection: *2015* ··· Nobelprize: *2017* ··· now: *~100 detections!*



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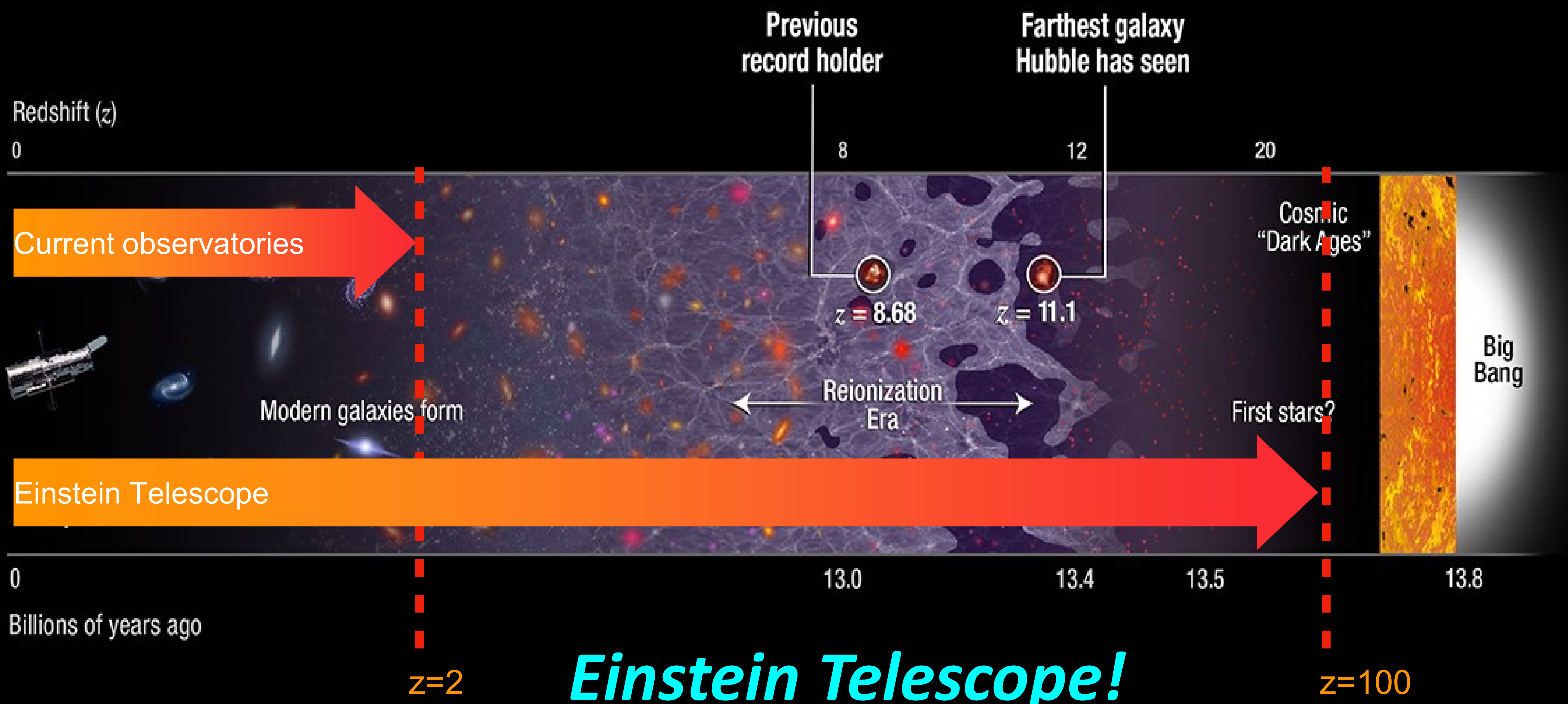
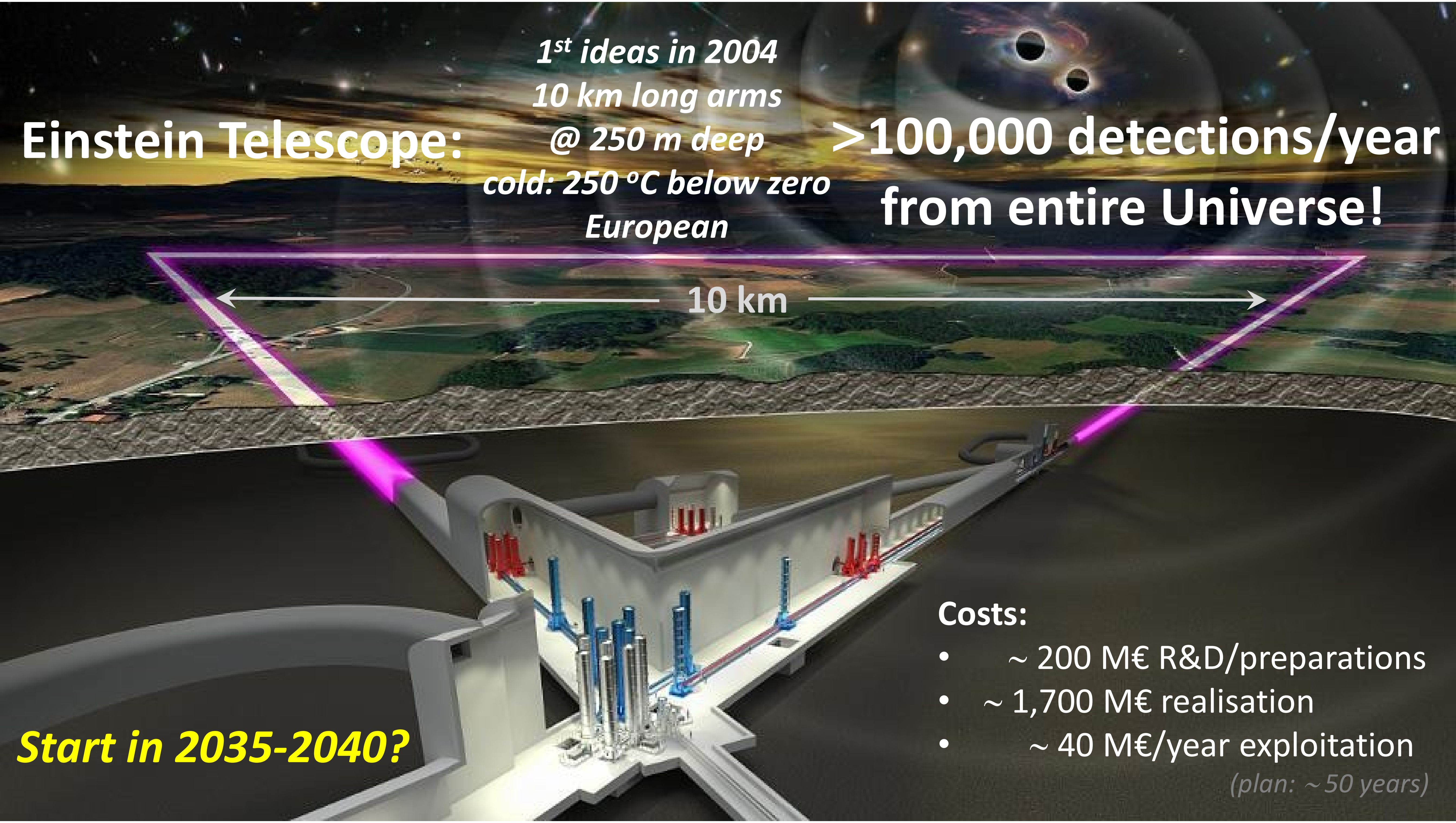
Exploring our *entire* Universe?



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!
10 km
Costs:
• ~ 200 M€ R&D/preparations
• ~ 1,700 M€ realisation
• ~ 40 M€/year exploitation
(plan: ~ 50 years)
Start in 2035-2040?

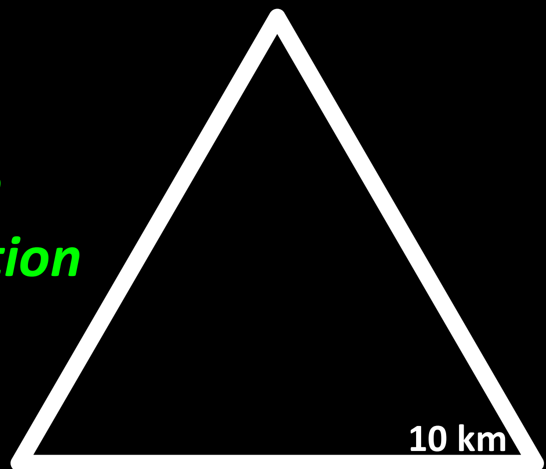
Higher sensitivity: *from 3-4 km to 10 km*

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

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

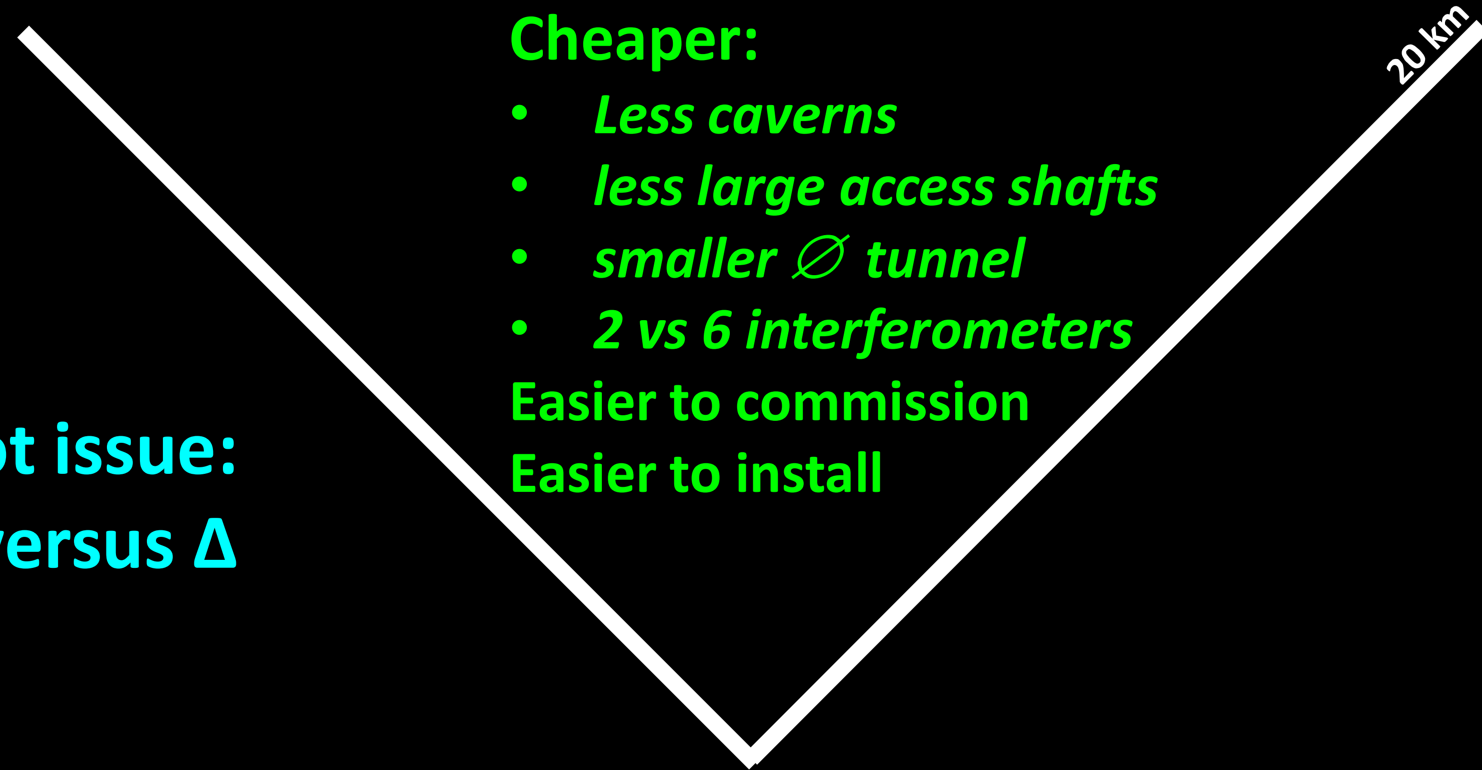
‘standalone’ capabilities:

- *polarisation*
- *sky localisation*



Hot issue:

L versus Δ



Cheaper:

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

Easier to commission

Easier to install

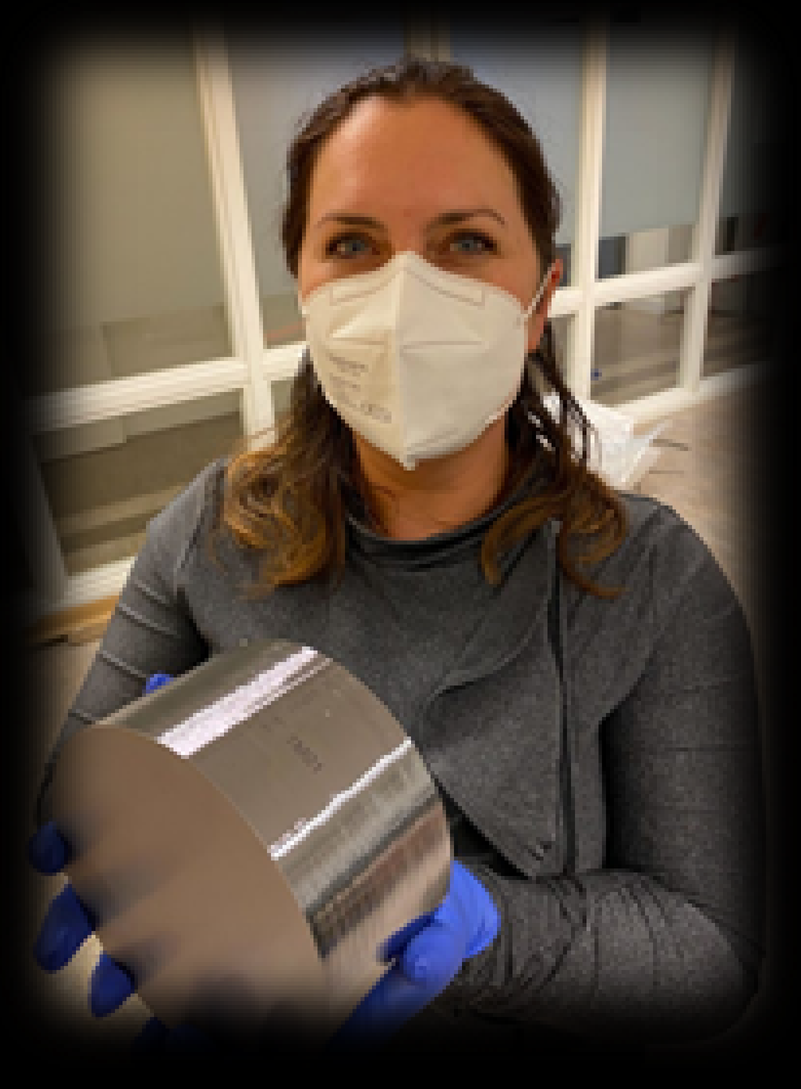
Einstein Telescope:

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

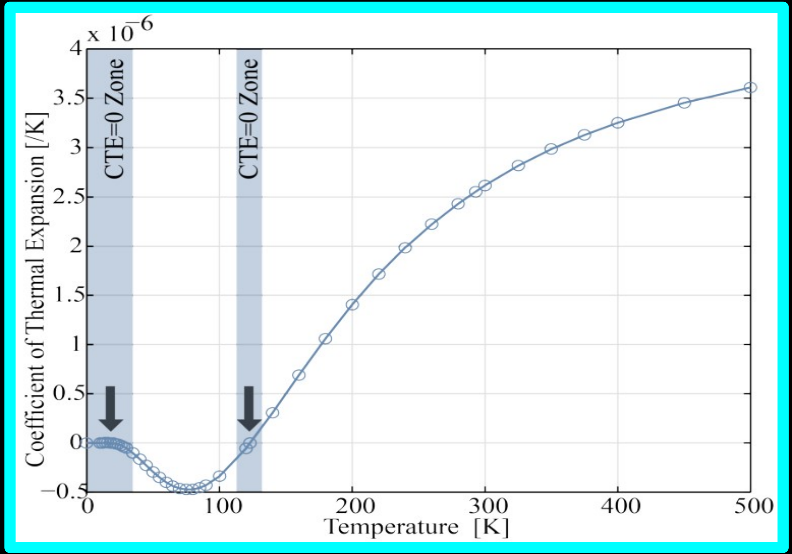
Cosmic Explorer (USA): 20-40 km L?

Do we want to repeat Virgo/LIGO experience?

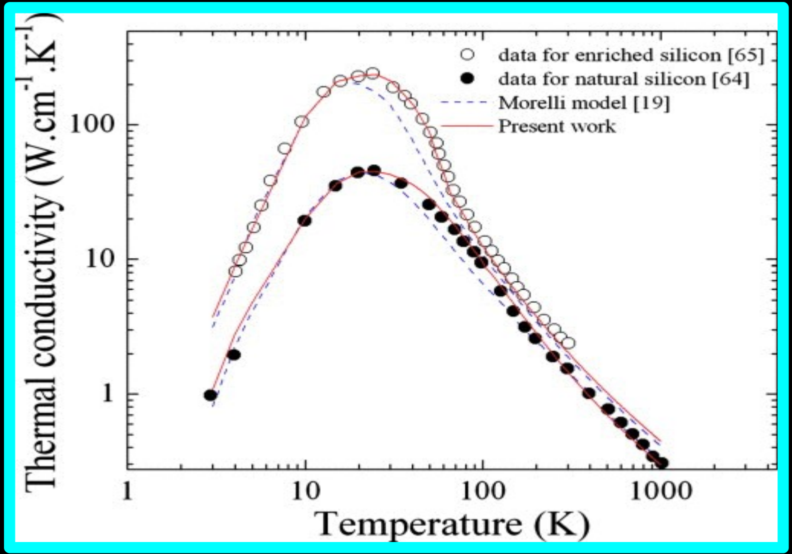
Higher sensitivity: *from 20 °C to –250 °C*



Cryogenic (Si) mirrors



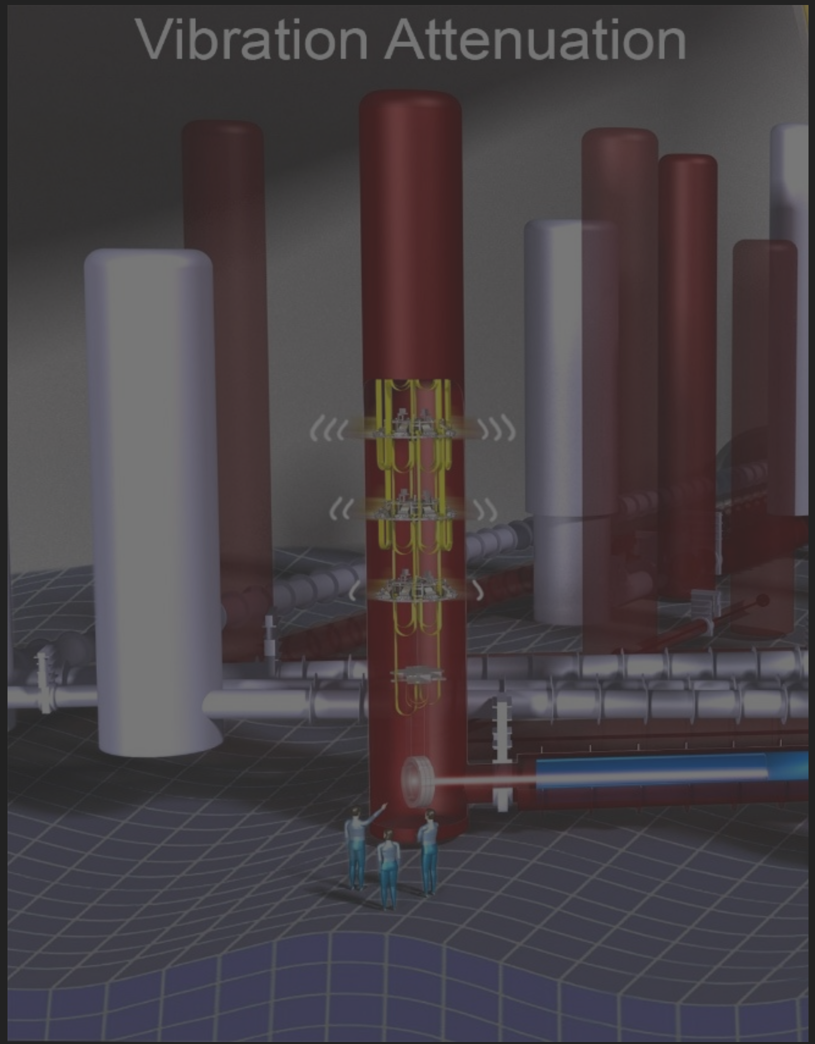
(crystalline) silicon

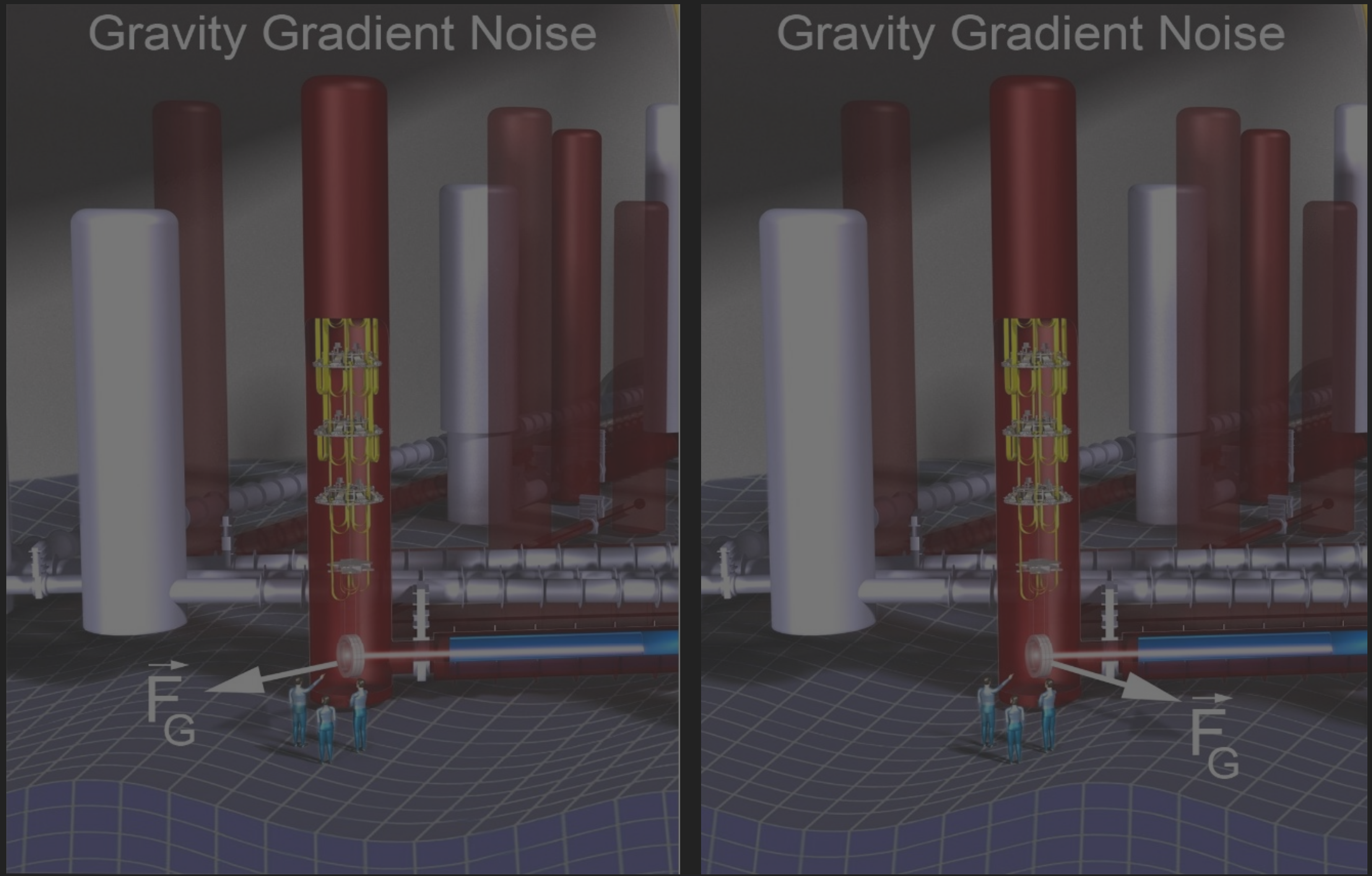


No thermal expansion
at very low temperatures
⇒ *Excellent in view of mirror deformations due to non-uniform heating by laser beams*

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*





trillingen makkelijk te dempen → no problem

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

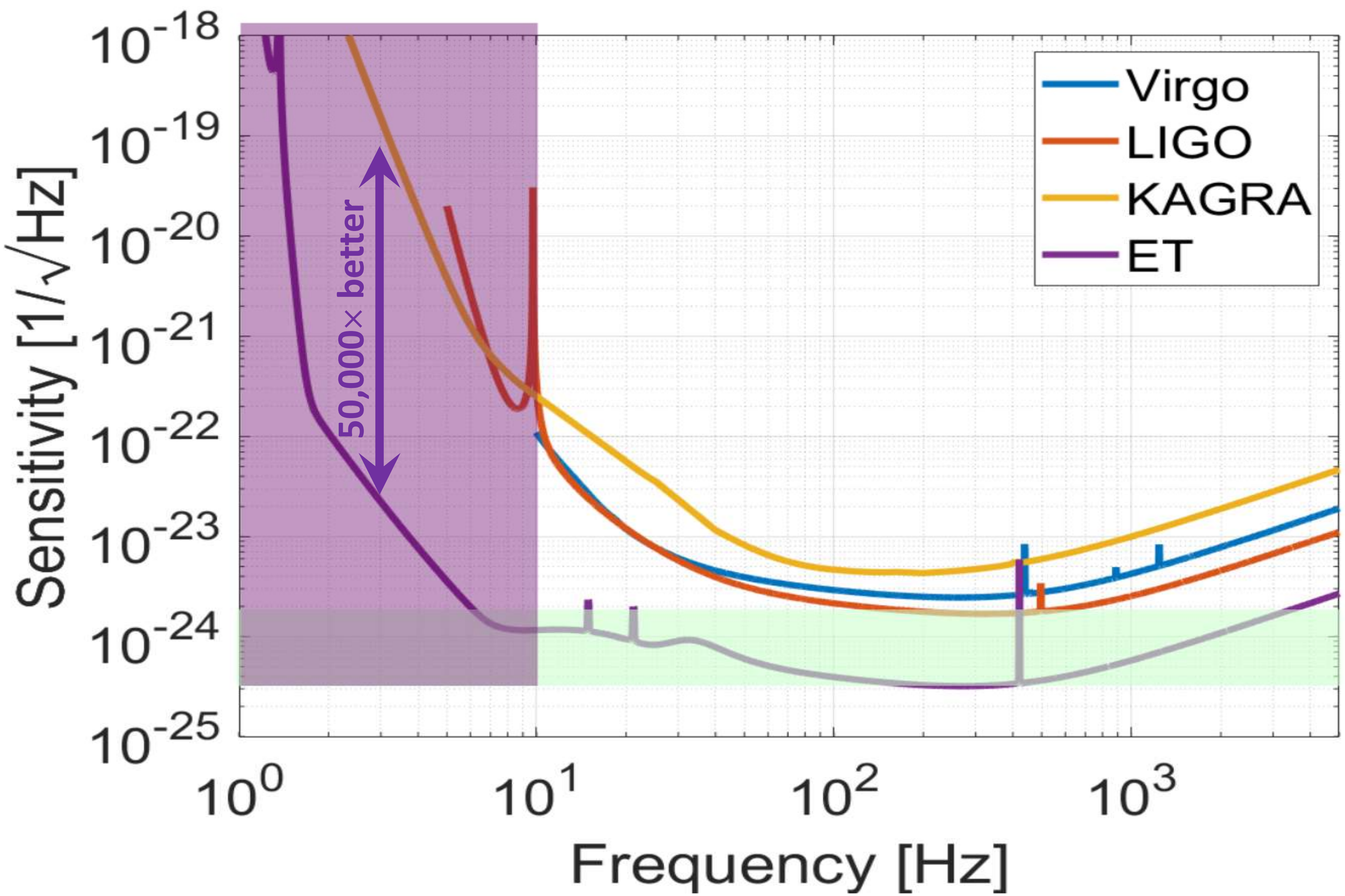
Higher sensitivity: *more things just ‘better’*

Controls
Quantum tricks (like squeezing)
Lasers
Photodiodes
Attenuators (passive + active)
Actuators
Vacuum
Etc.

The real issues to beat/control:

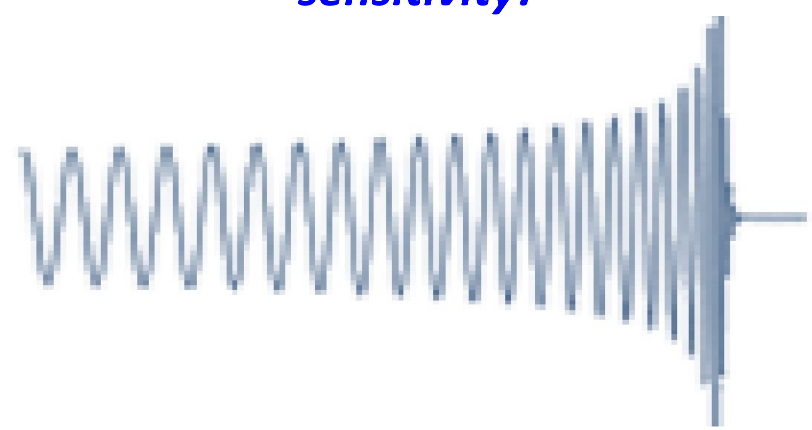
- ***scattered light i.e. imperfections***
- ***noise (pumps, ventilation, cryogenic coolers, etc.) we make!***

More detections: ***higher sensitivity & larger bandwidth***



Why the push for lower frequencies?

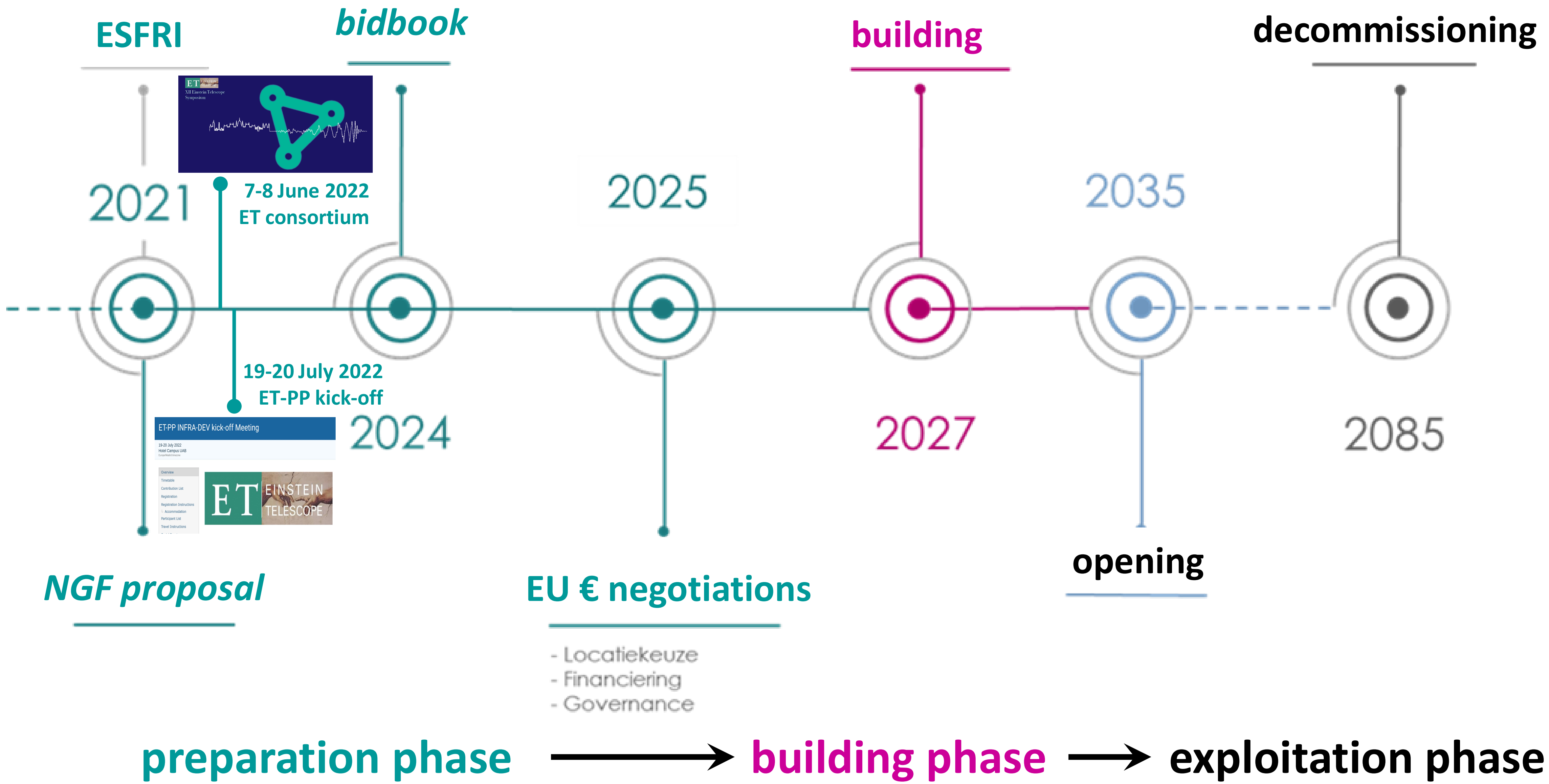
Signals spend most time at low frequencies i.e. longer observation time with better low-frequency sensitivity!



ET can observe signals for 24 hours!

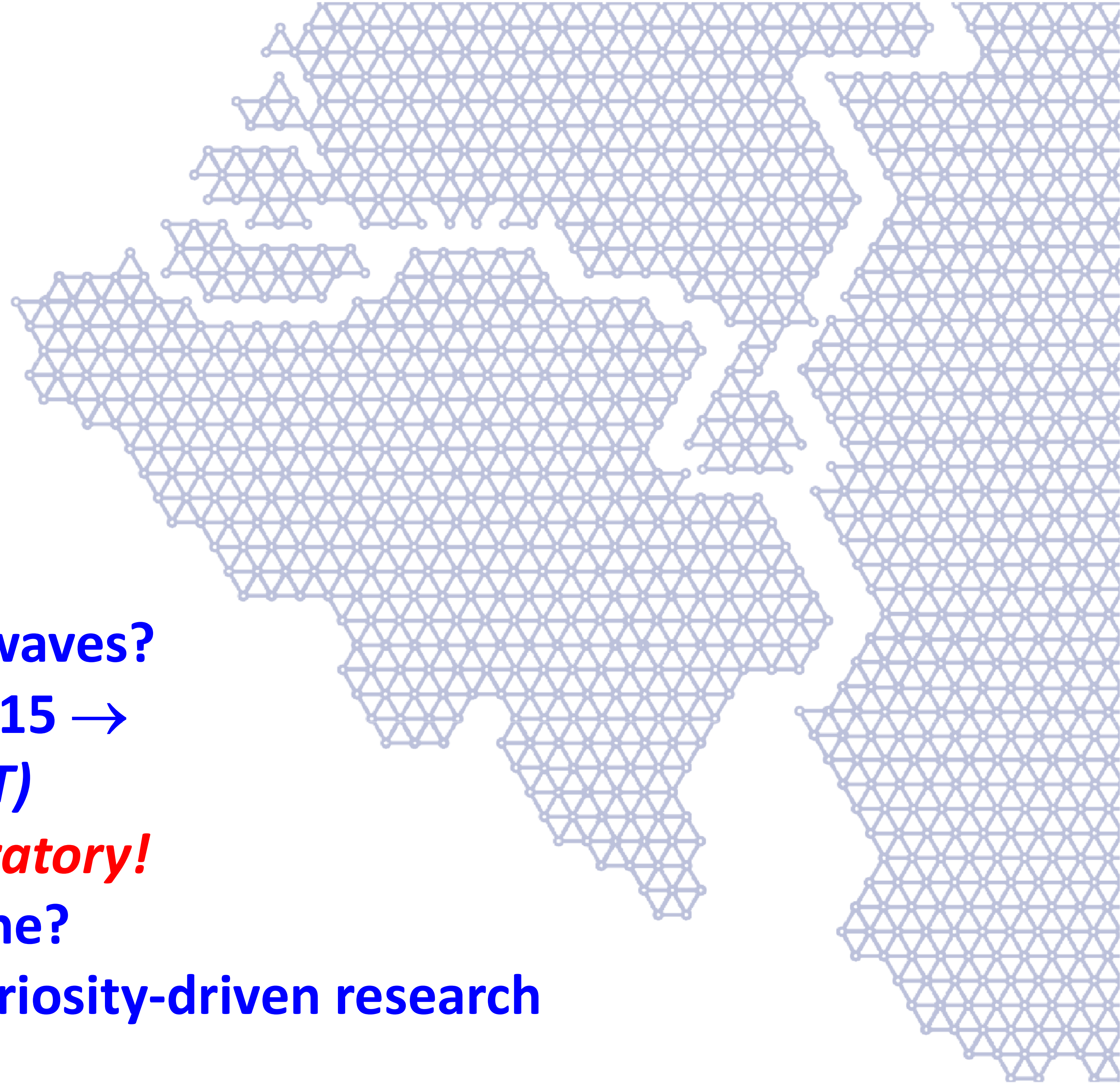

Einstein
Telescope

Einstein Telescope planning



Huge boost for EMR/NL: Dutch Nationaal Groeifonds

Overview



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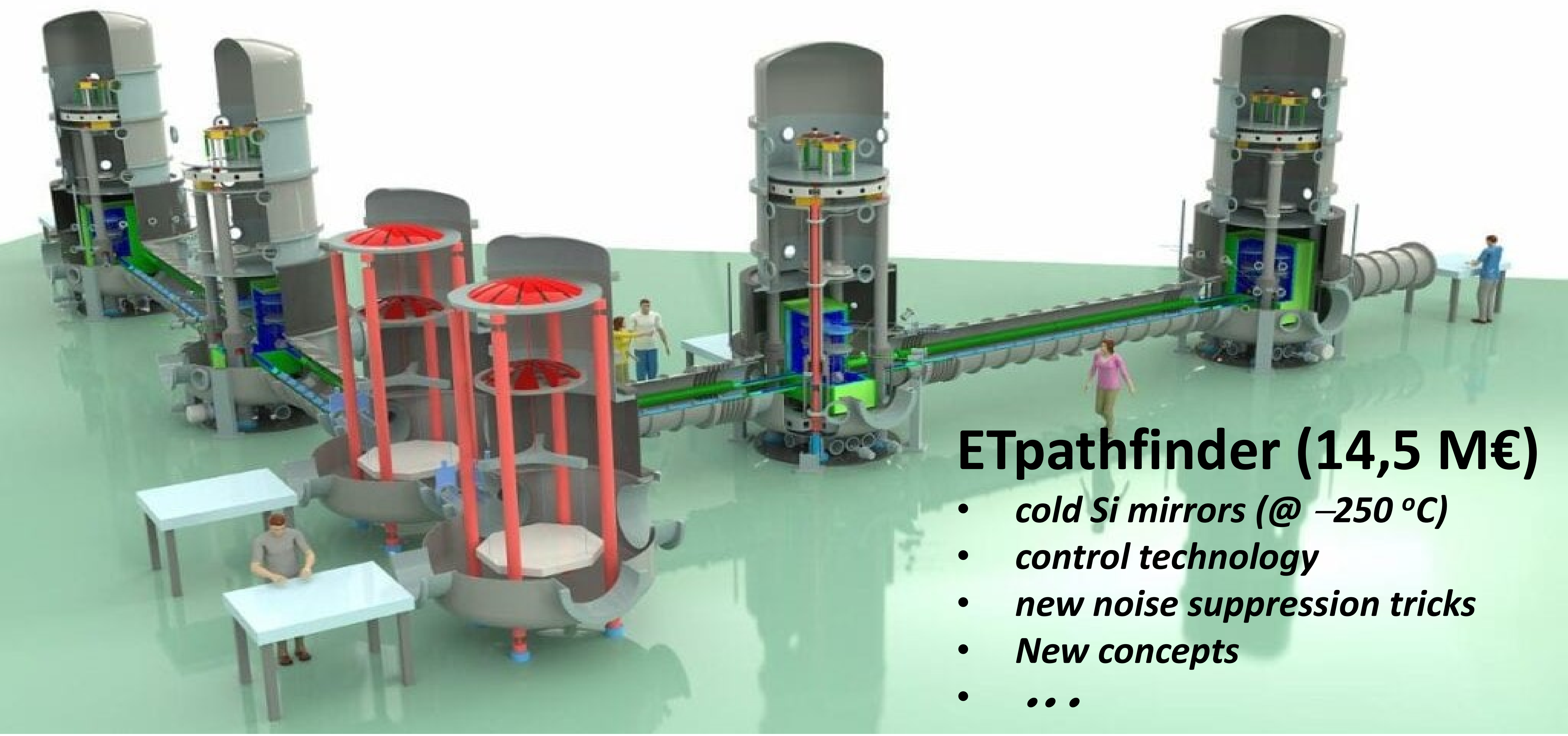
To develop ET’s innovations: *R&D laboratory*



ETpathfinder (14,5 M€)

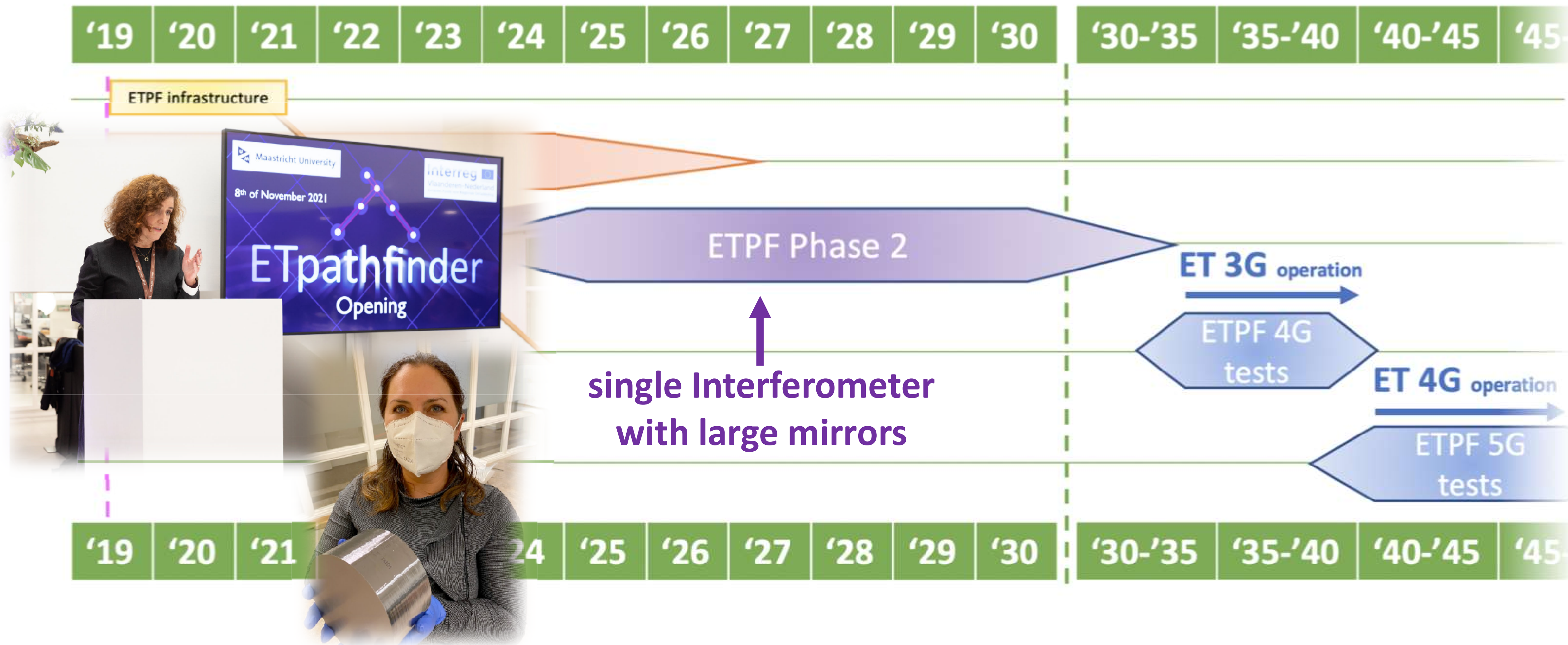
- ***cold Si mirrors (@ –250 °C)***
- ***control technology***
- ***new noise suppression tricks***
- ***New concepts***
- ***…***

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 <u>'one step beyond'</u>*

ONE STEP BEYOND...



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

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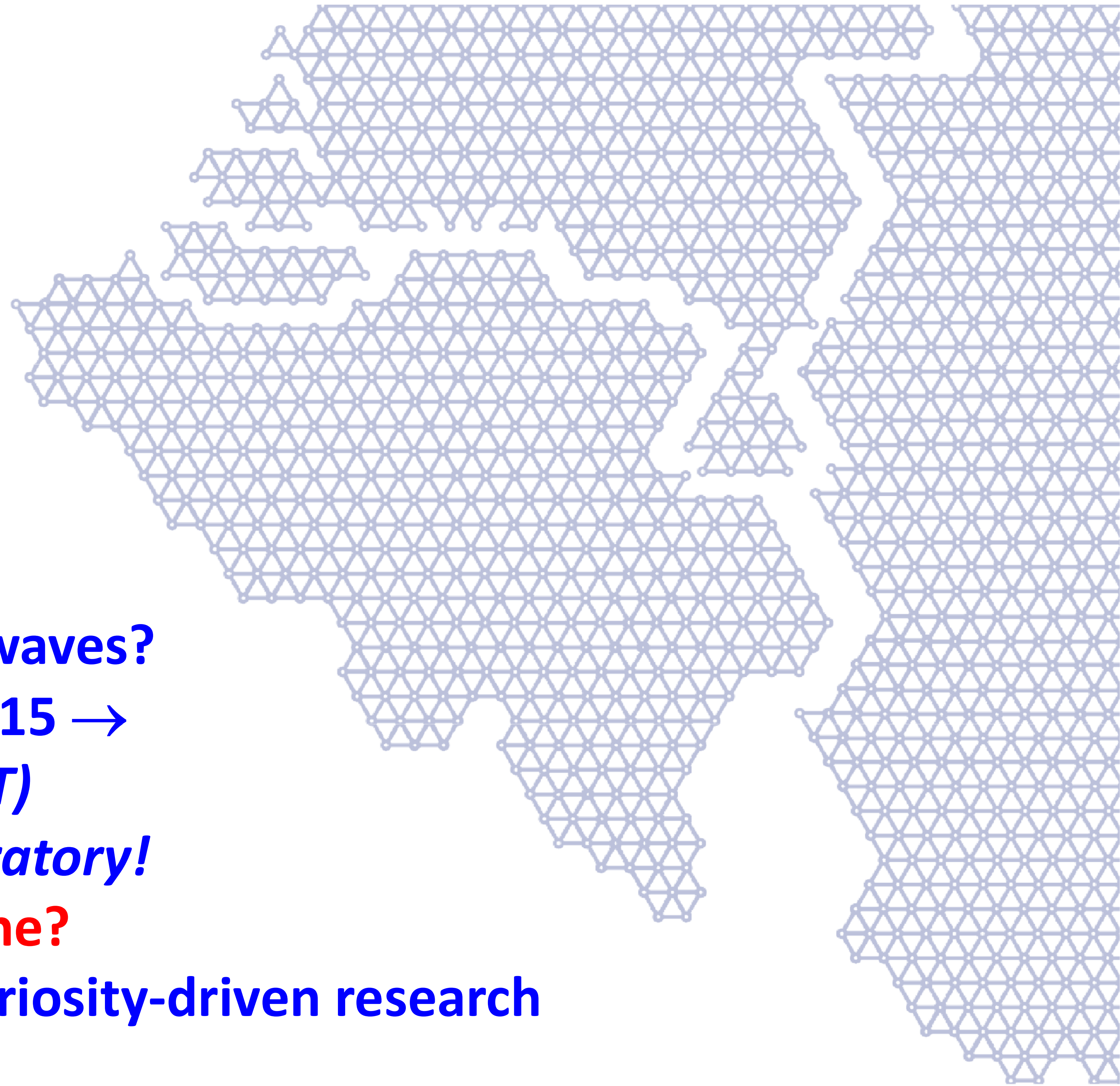

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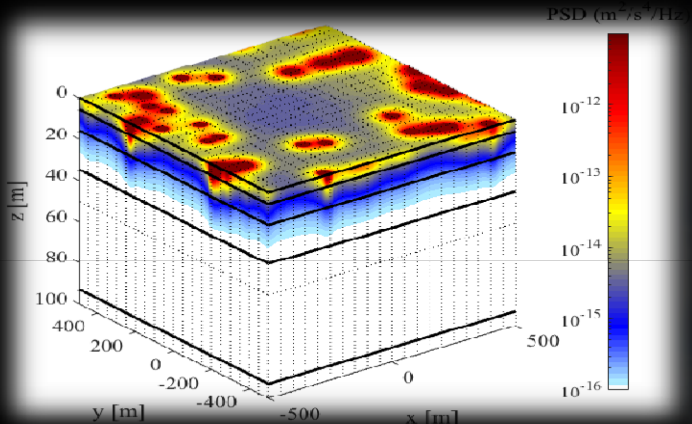
- **ETpathfinder: *ET's R&D laboratory!***

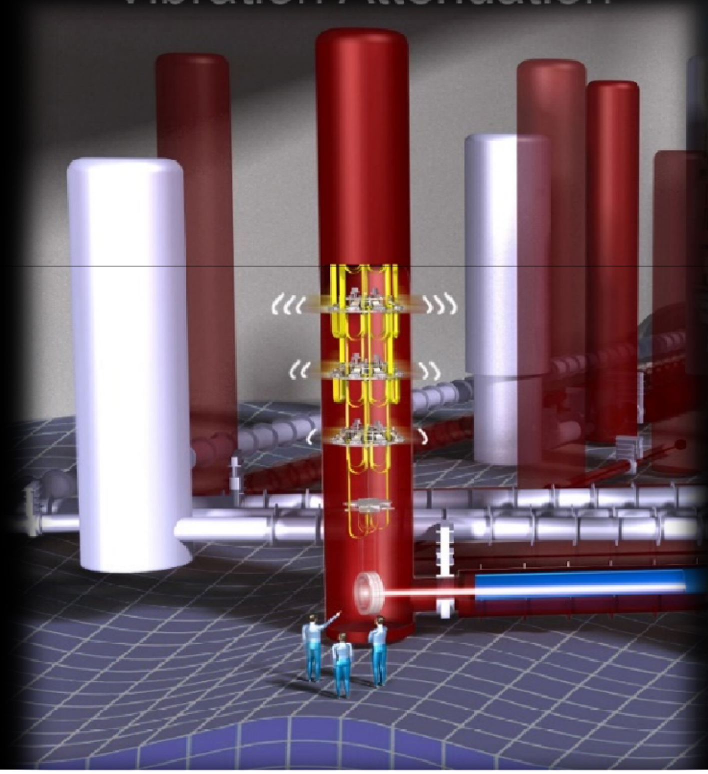
→ **ET in the Euregio Meuse-Rhine?**

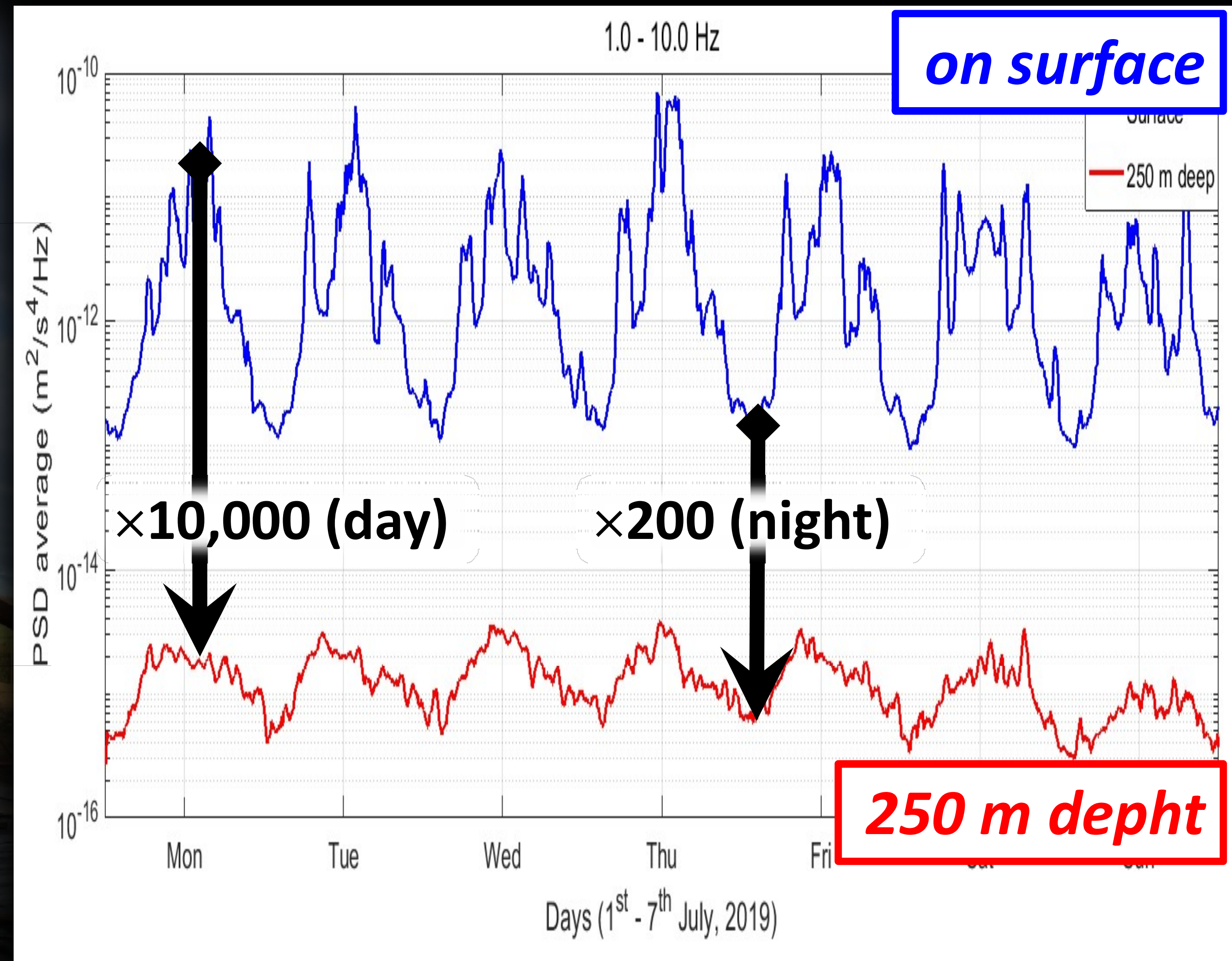
- **Socio-economic impact of curiosity-driven research**

ET key requirement: *low-noise environment*



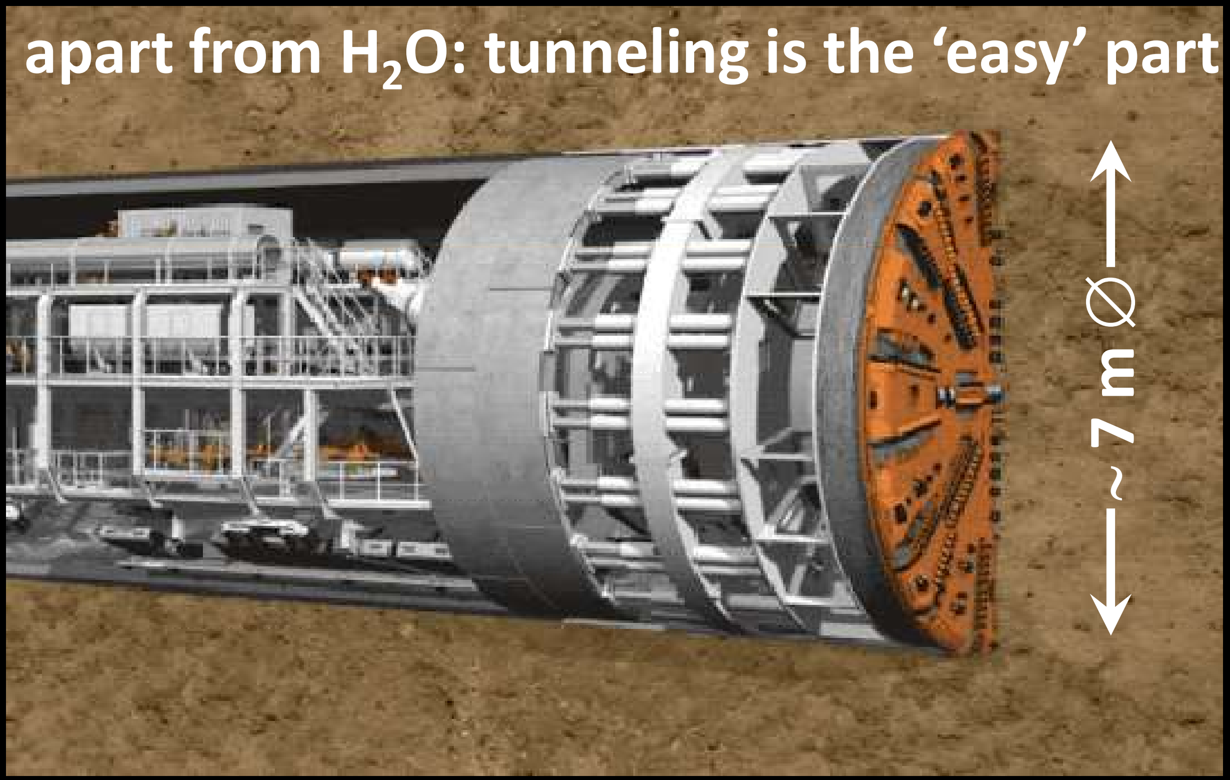
Seismic vibrations





noise measurements confirm simulations

The challenge: ***build ET cost-efficiently!***



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

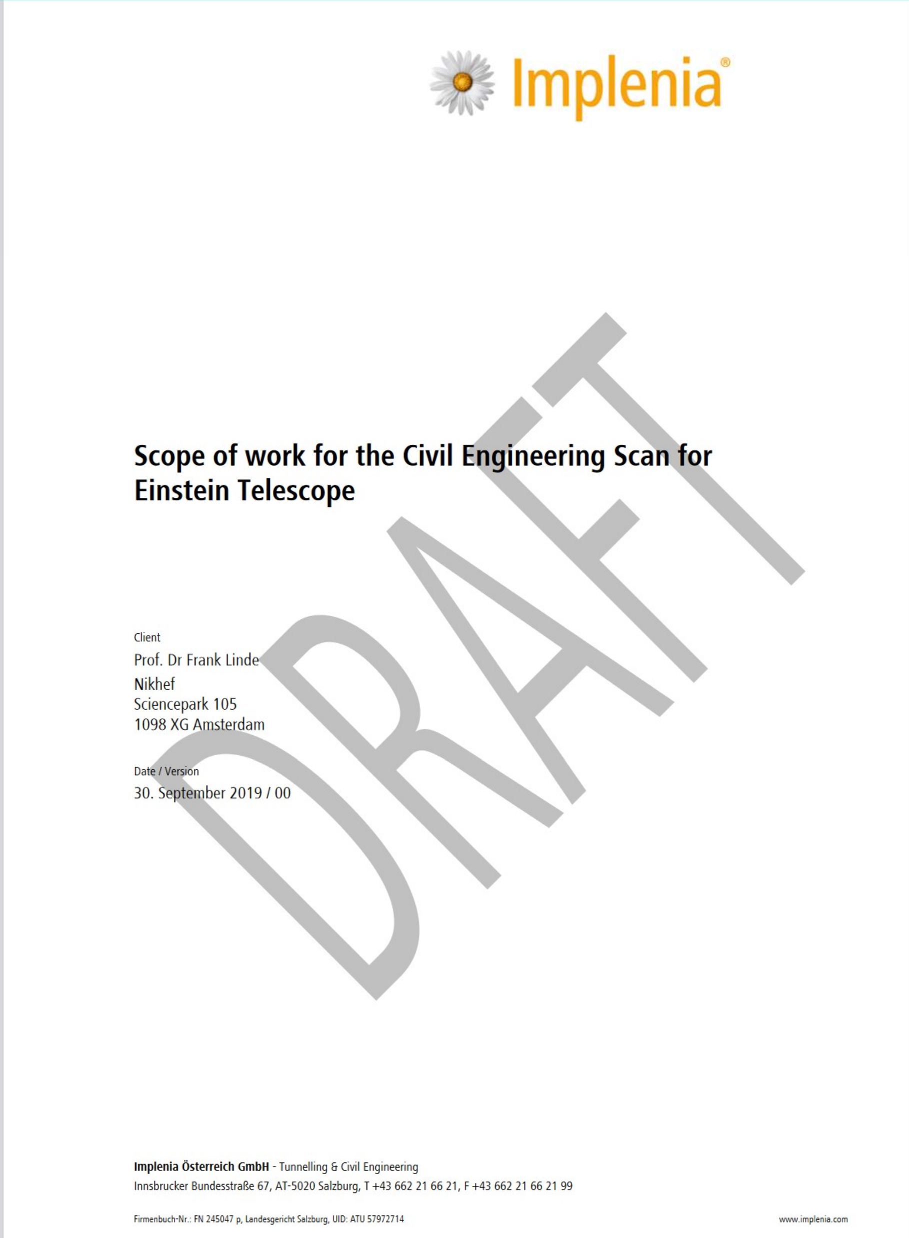
- *30-50 km length of tunnels*
- *10-24 (large) caverns*
- *1-3 large access shafts*

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

Civil engineering: the challenges

Water:
- During co
  - Risk
- In operat
  - Noi
  - Cos

Caverns:
- Rock qu
  - Co
- Less!
- Less wid
- Less hig
- (L ↔ Δ)


Implenia®

Scope of work for the Civil Engineering Scan for Einstein Telescope

Client
Prof. Dr Frank Linde
Nikhef
Sciencepark 105
1098 XG Amsterdam

Date / Version
30. September 2019 / 00

DRAFT

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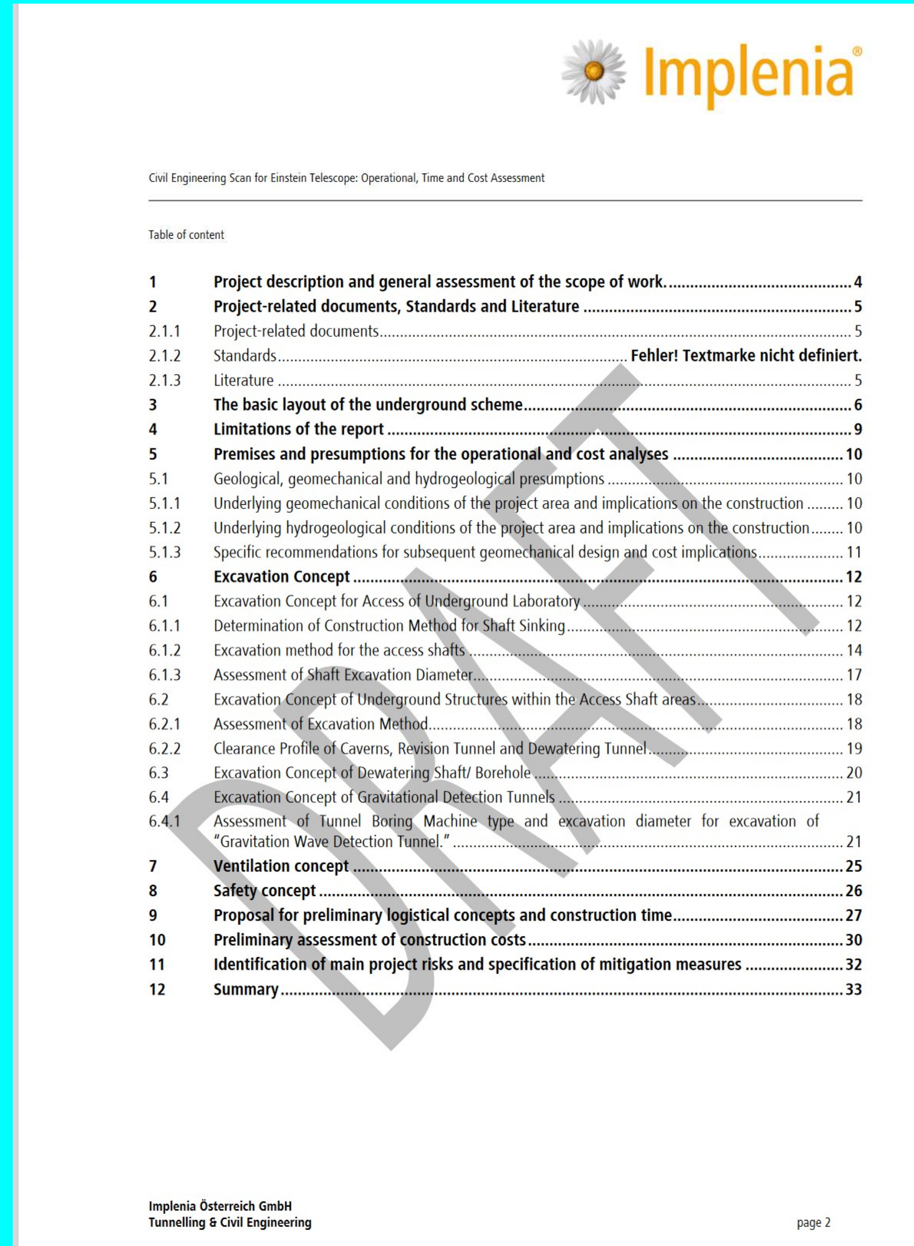
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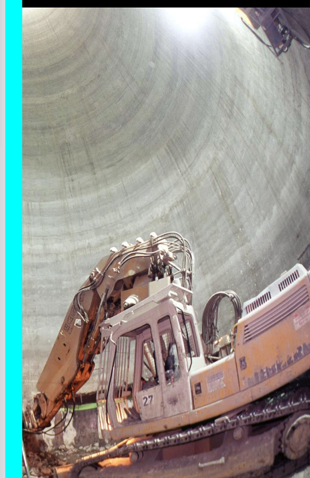
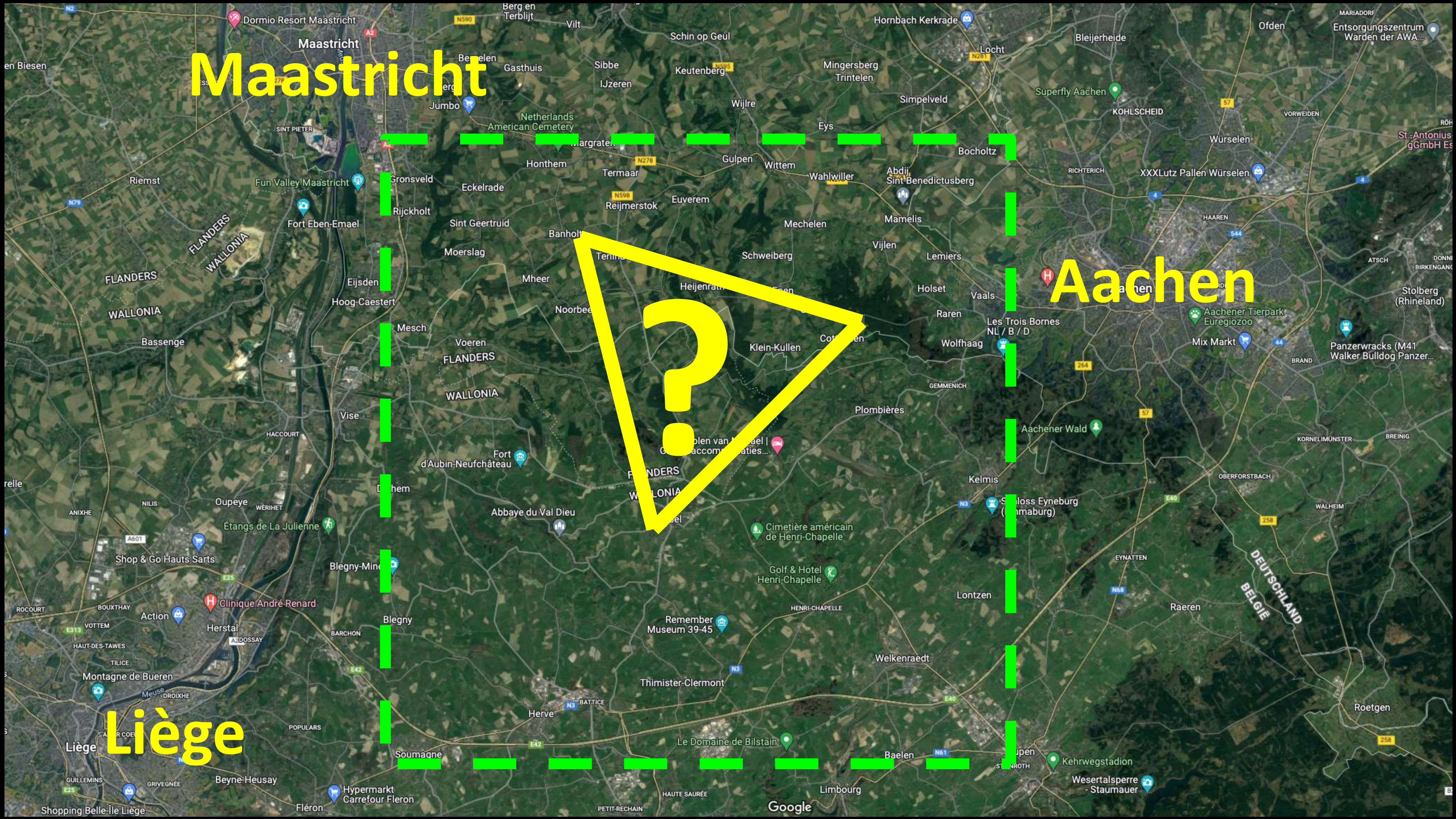
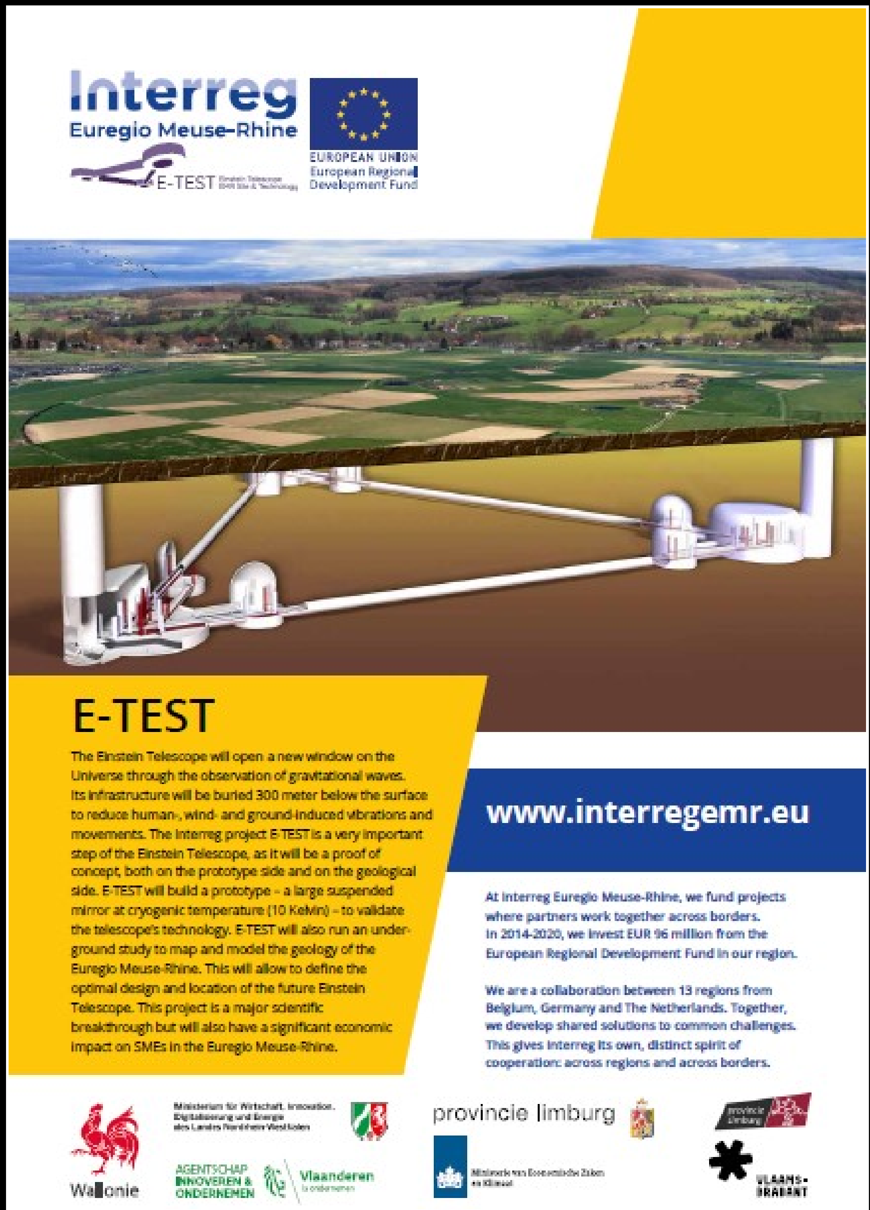


Siting ET in the Euregio Meuse-Rhine

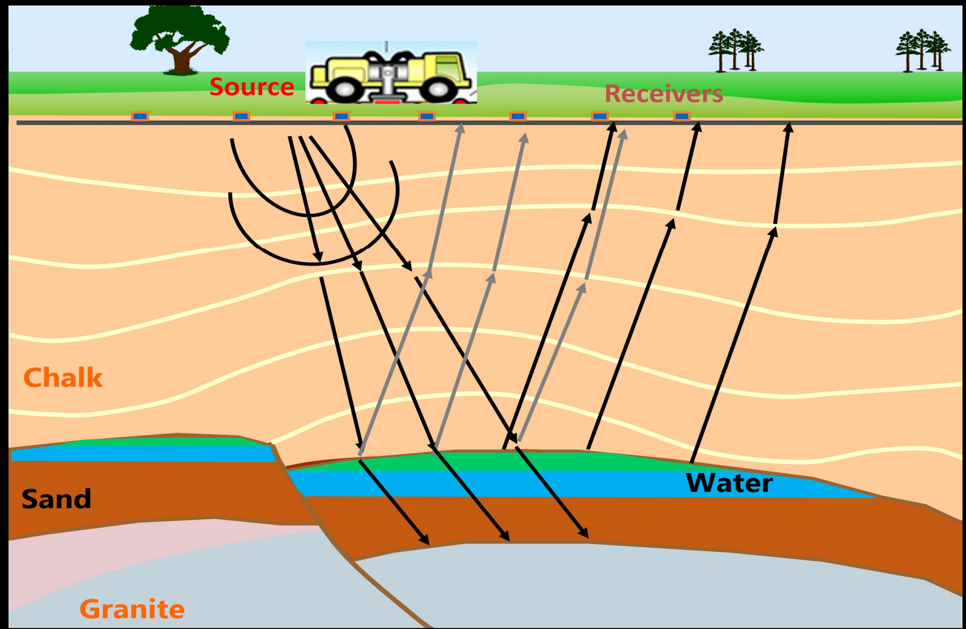


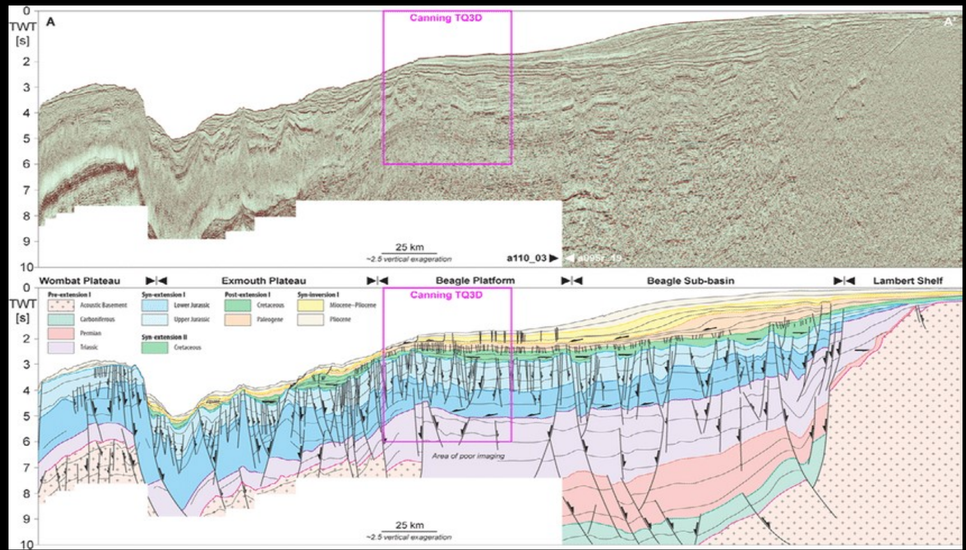
1st subsidy: Interreg EMR ‘E-TEST’



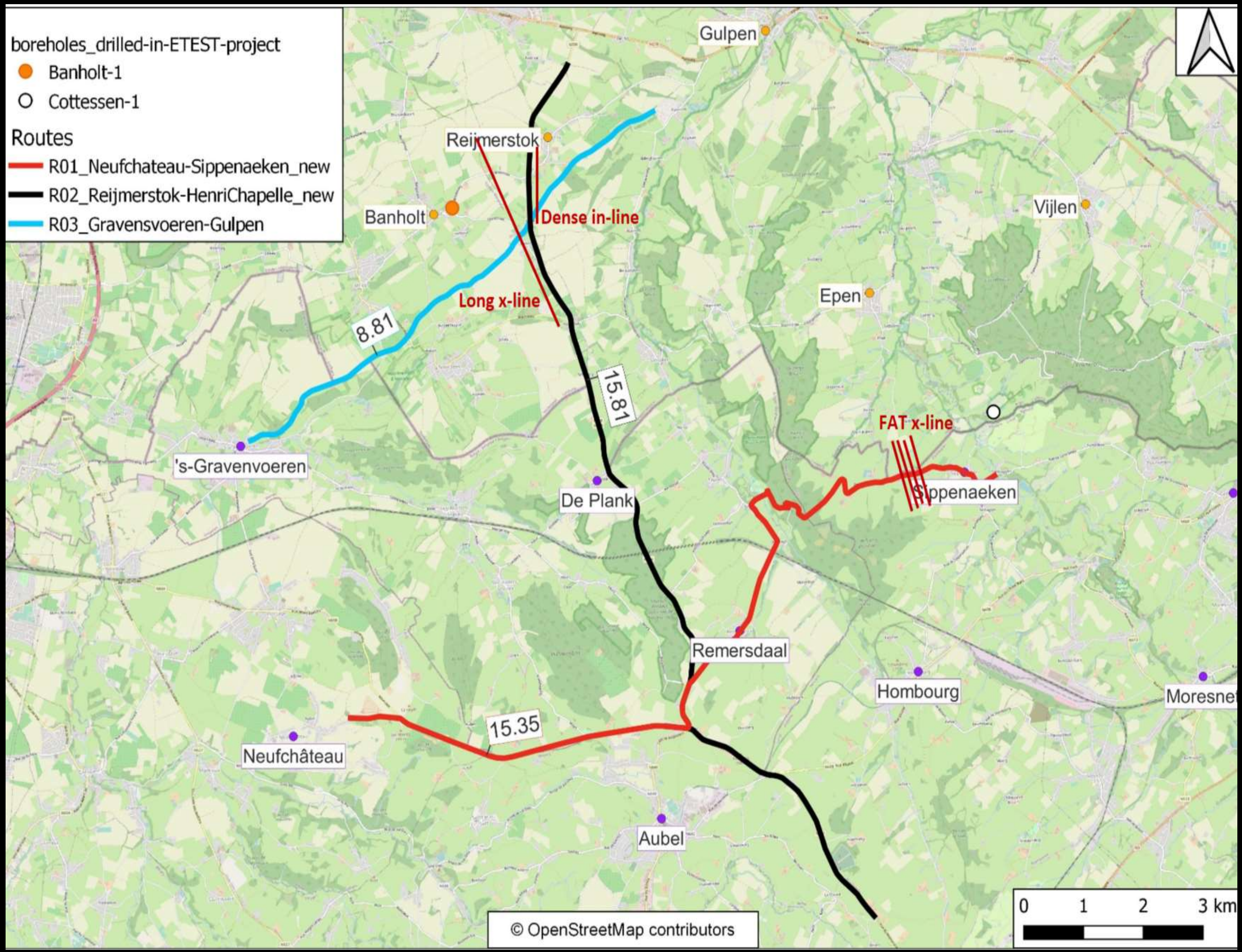
To map the EMR geology

- *Hydrology*
- *Boreholes*
- *Seismic*
- *ERT*
- *EM*
- *gravimetric*
- *…*



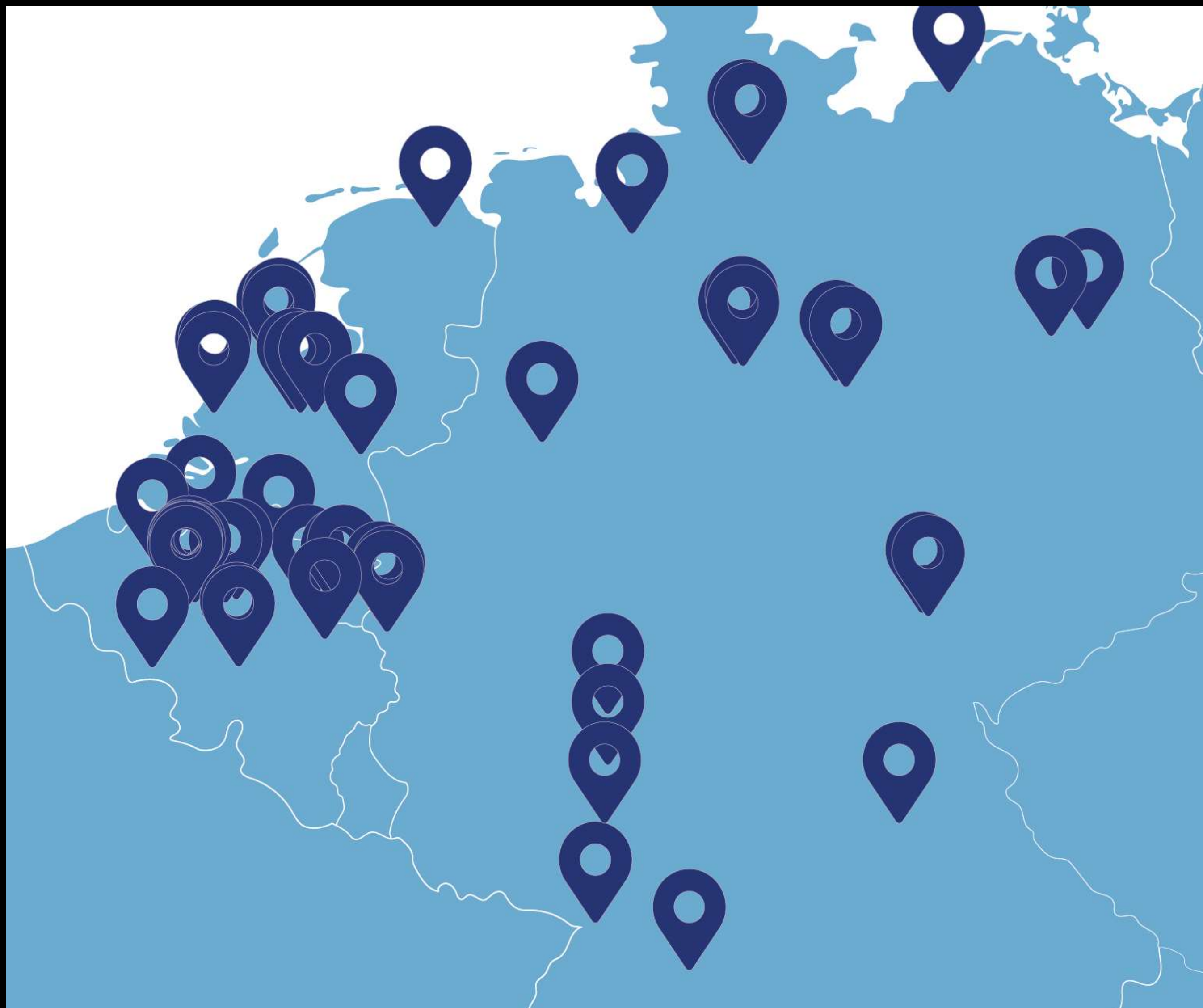


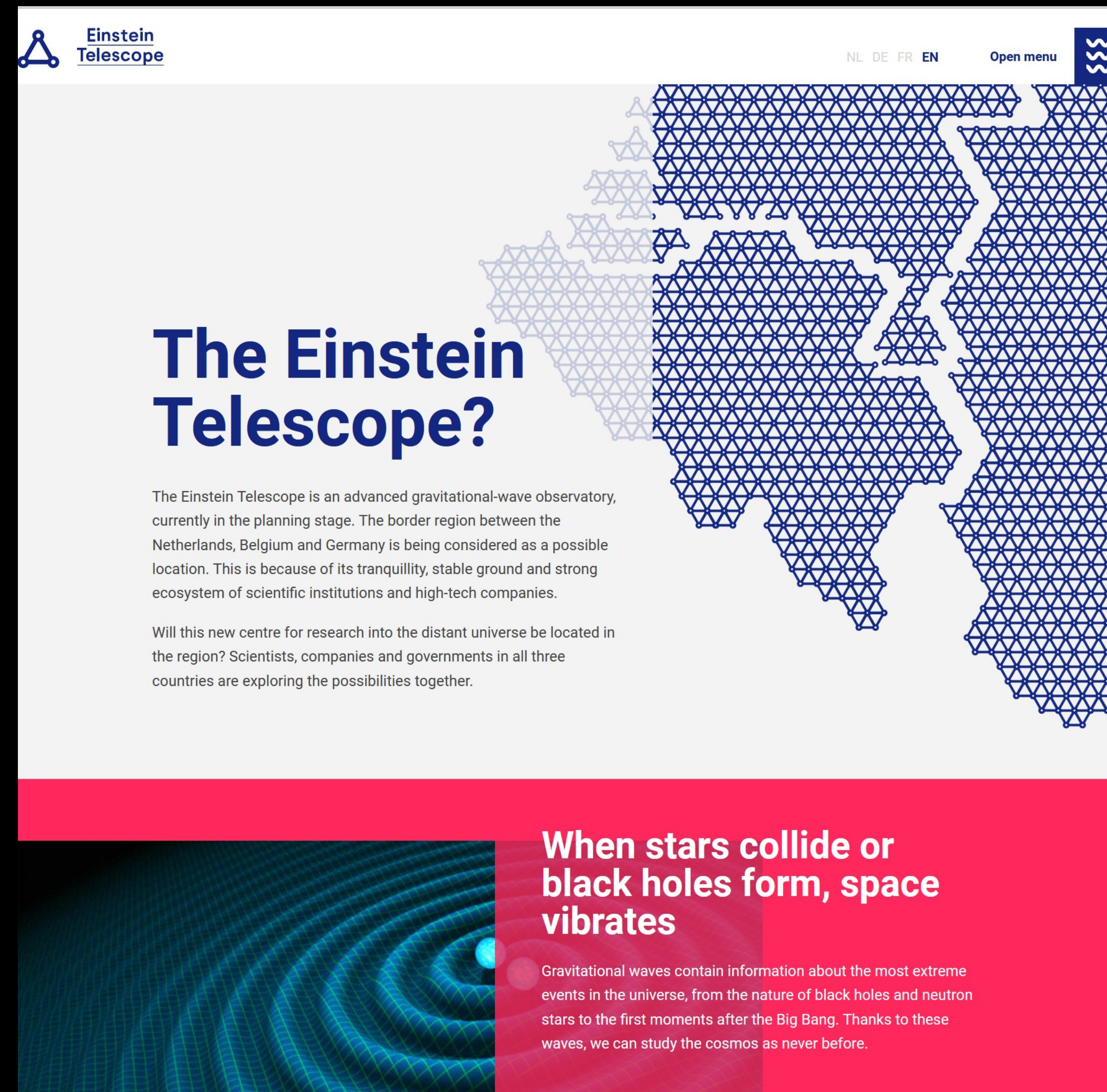
40 km stretch active seismic campaign – Sep/22



40 km stretch active seismic campaign – Sep/22

Strong community - political support NL, B & D



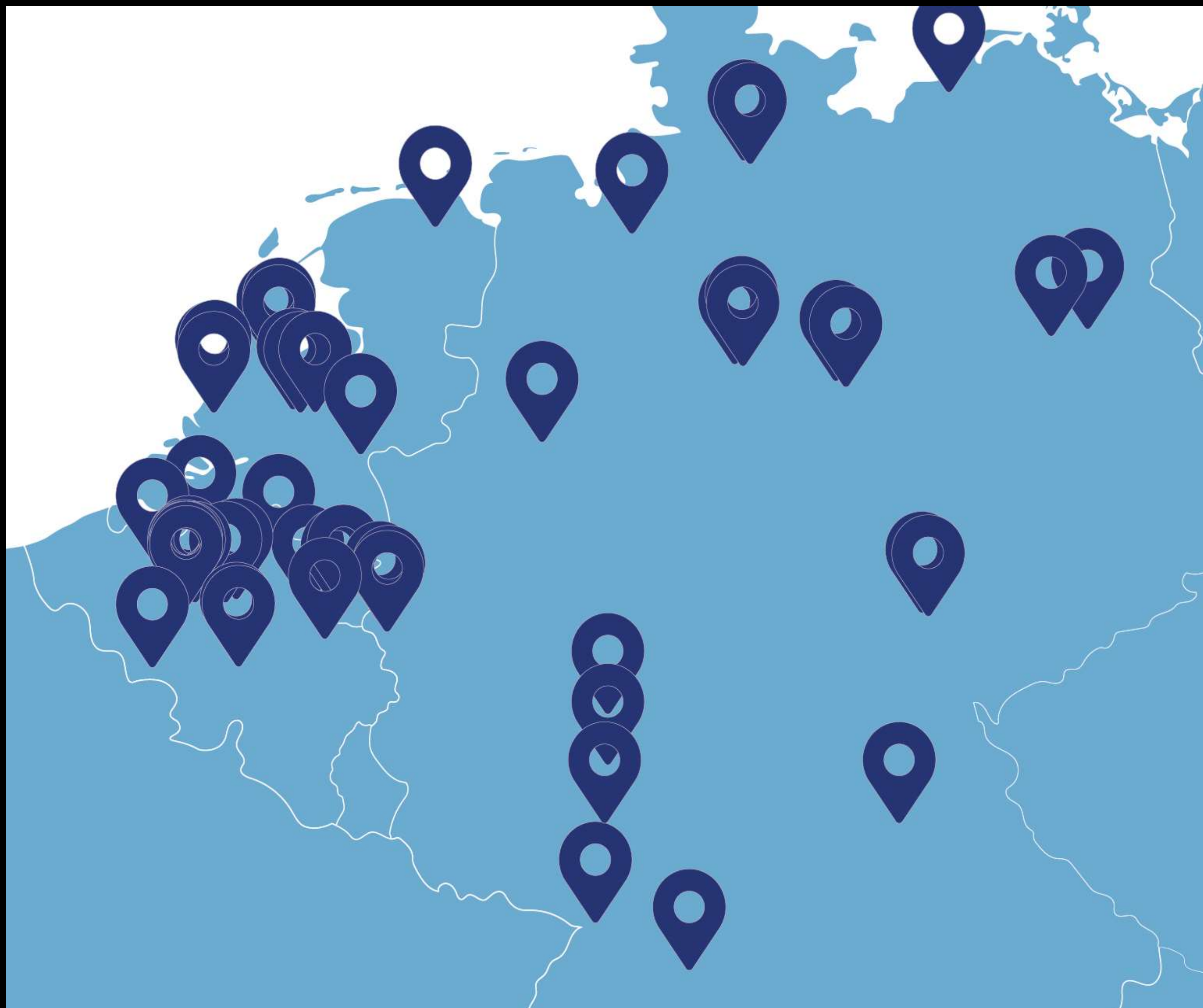


https://www.einsteintelescope.nl/de/nachrichten/

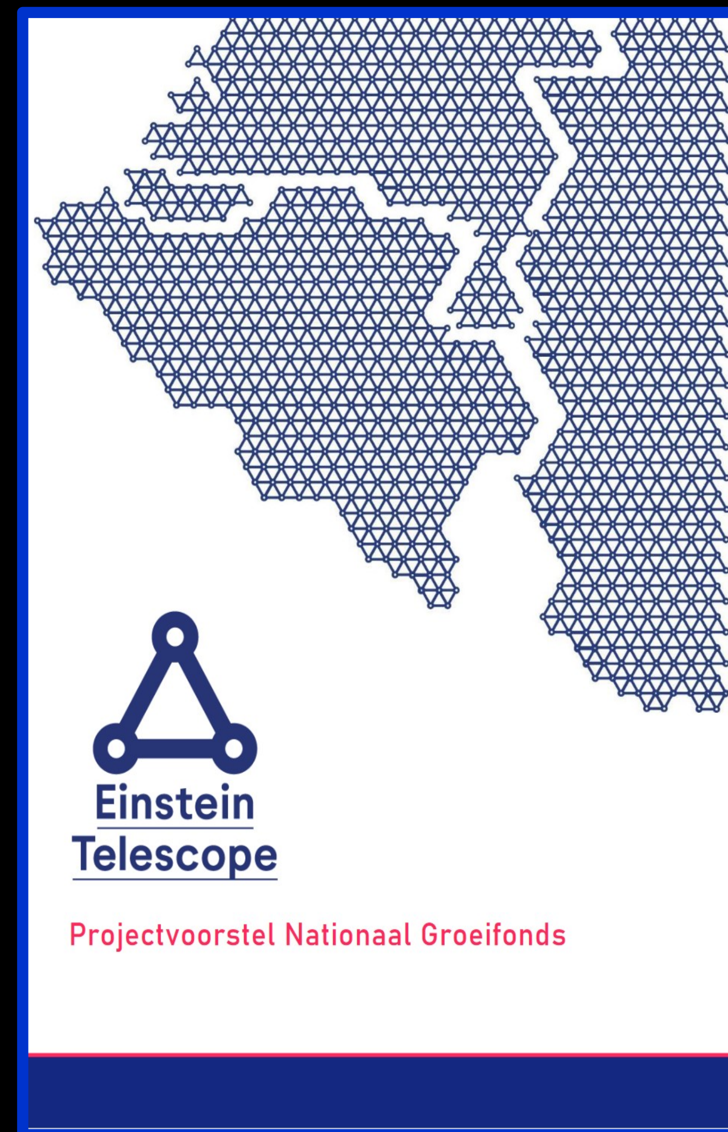
Lots of institutes involved already

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

Strong community - political support NL, B & D



Lots of institutes involved already



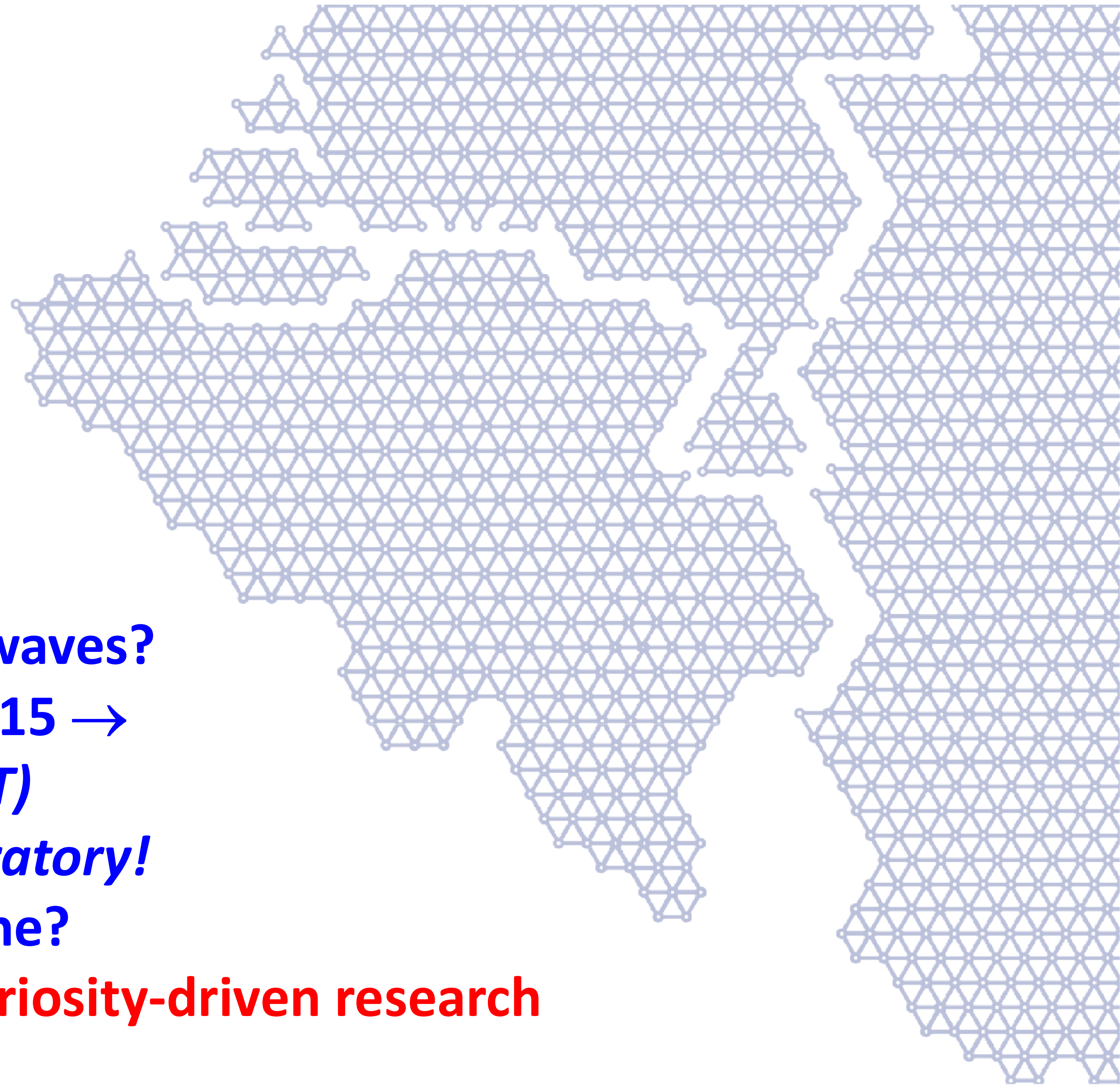
Highlights: NL/'Groeifonds' & D/'DZA'

NL:

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

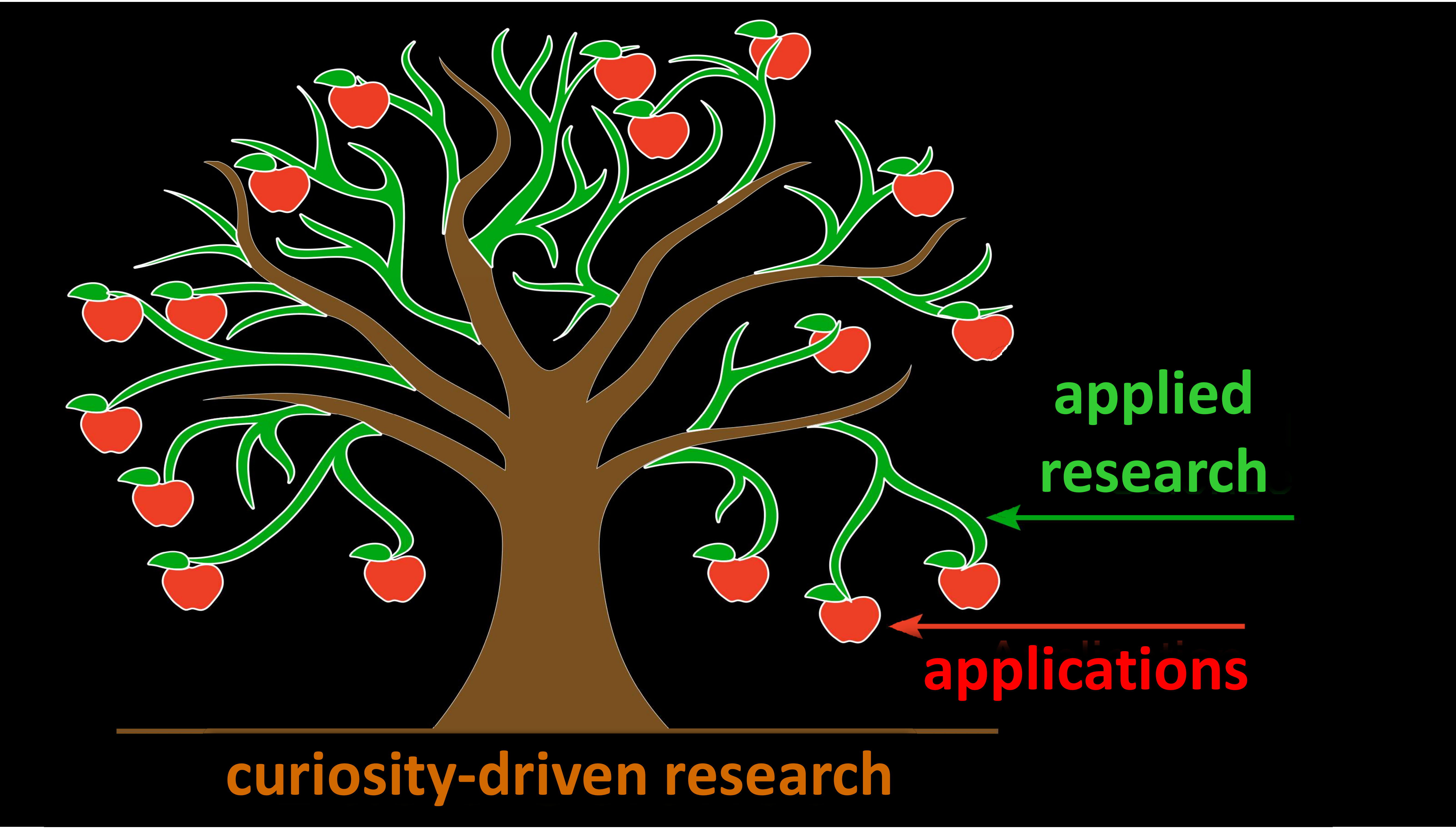
870 M€ if ET will be build in the EMR

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?**

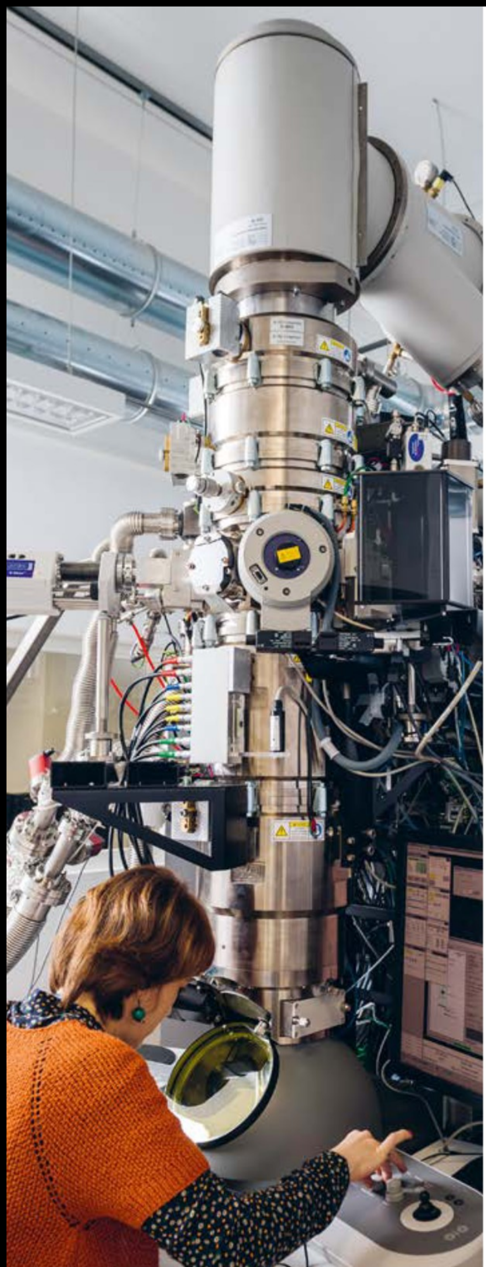
→ Socio-economic impact of curiosity-driven research


applied
research
applications
curiosity-driven research

Past achievements: *future's best guarantee!*

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

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

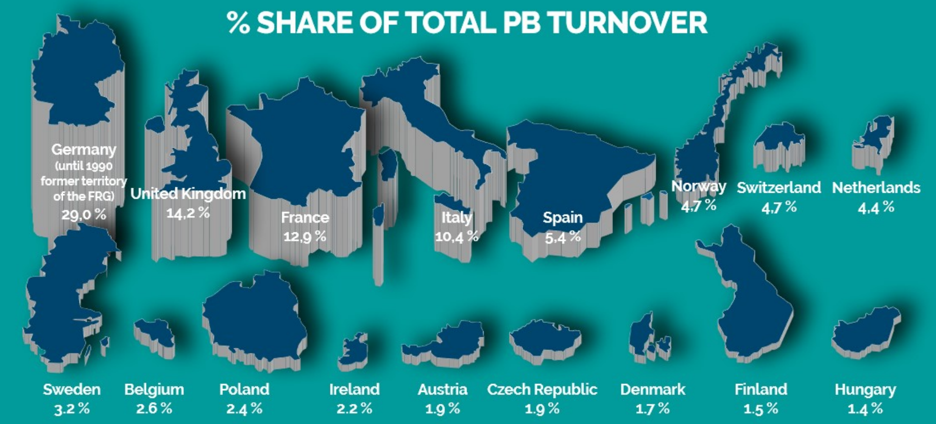
16%

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



All others countries (Bulgaria, Croatia, Cyprus, Estonia, Greece, Latvia, Lithuania, Luxembourg, Malta, Portugal, Romania, Slovakia, Slovenia & Iceland) are less than 1%

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

TURNOVER BY COUNTRY, MILLIONS € SINCE 2011

AVERAGE (2011-16)

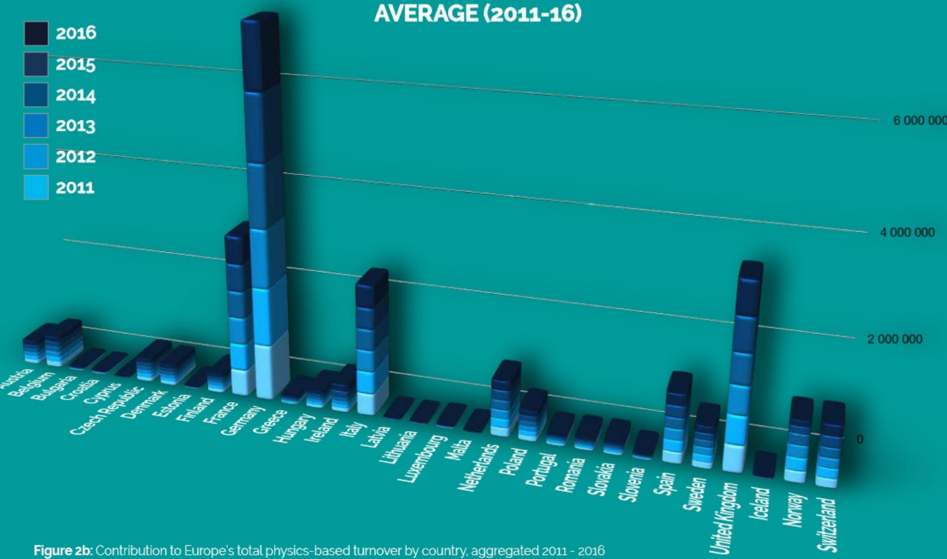
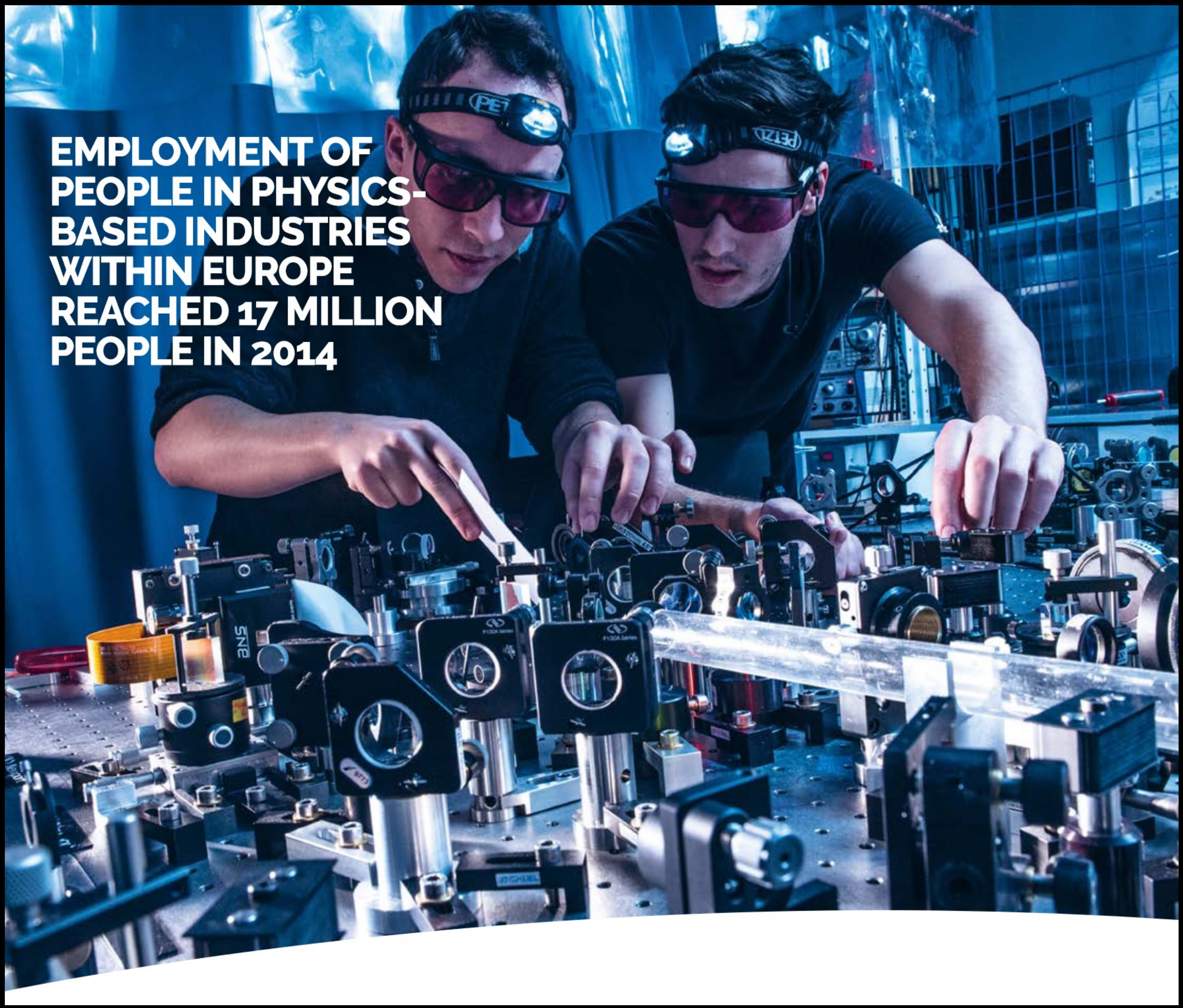


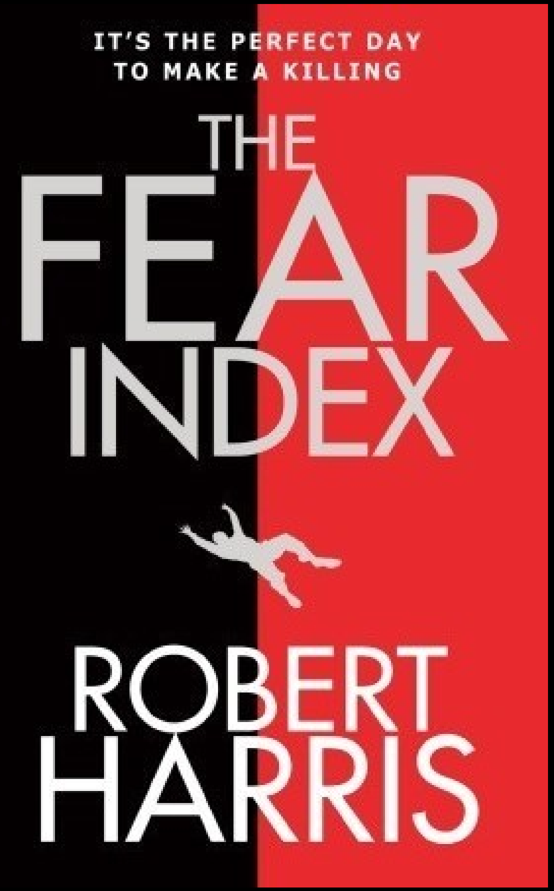
Figure 2b: Contribution to Europe's total physics-based turnover by country, aggregated 2011 - 2016

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



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}
ARM CAVITIES		
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
CENTRAL INTERFEROMETER		
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 %
FILTER CAVITIES		
Quantum noise suppression	frequency-dependent squeezing	frequency-dependent squeezing
Filter cavities	1 × 300 m	2 × 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