Gravitatiegolf detector : een overmaatse rekstrook met gevoeligheid 10^{-23} m/m

Opto-mechatronic challenges for Big Science

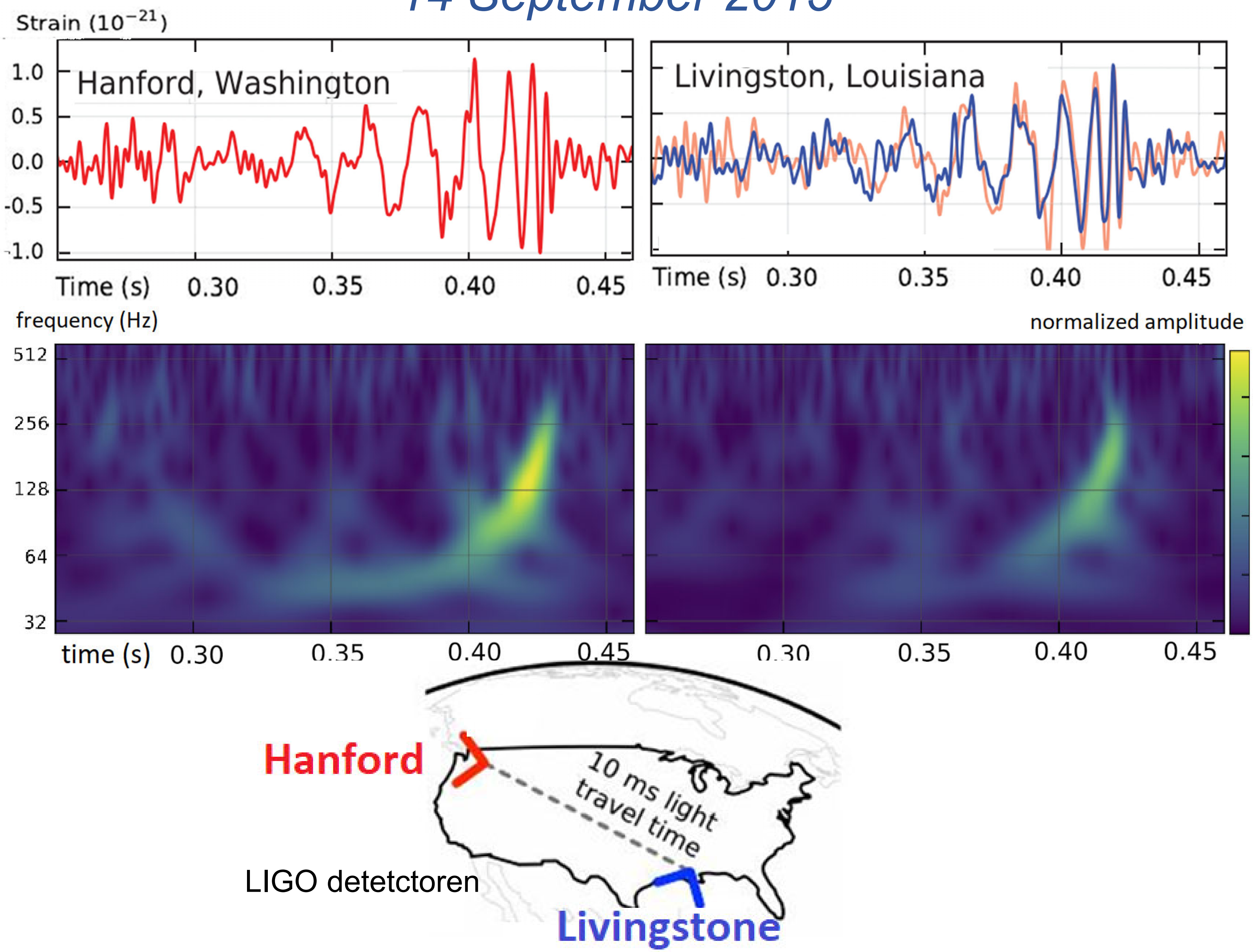
Mikrocentrum Veldhoven
18 Sept. 2019

Eric Hennes

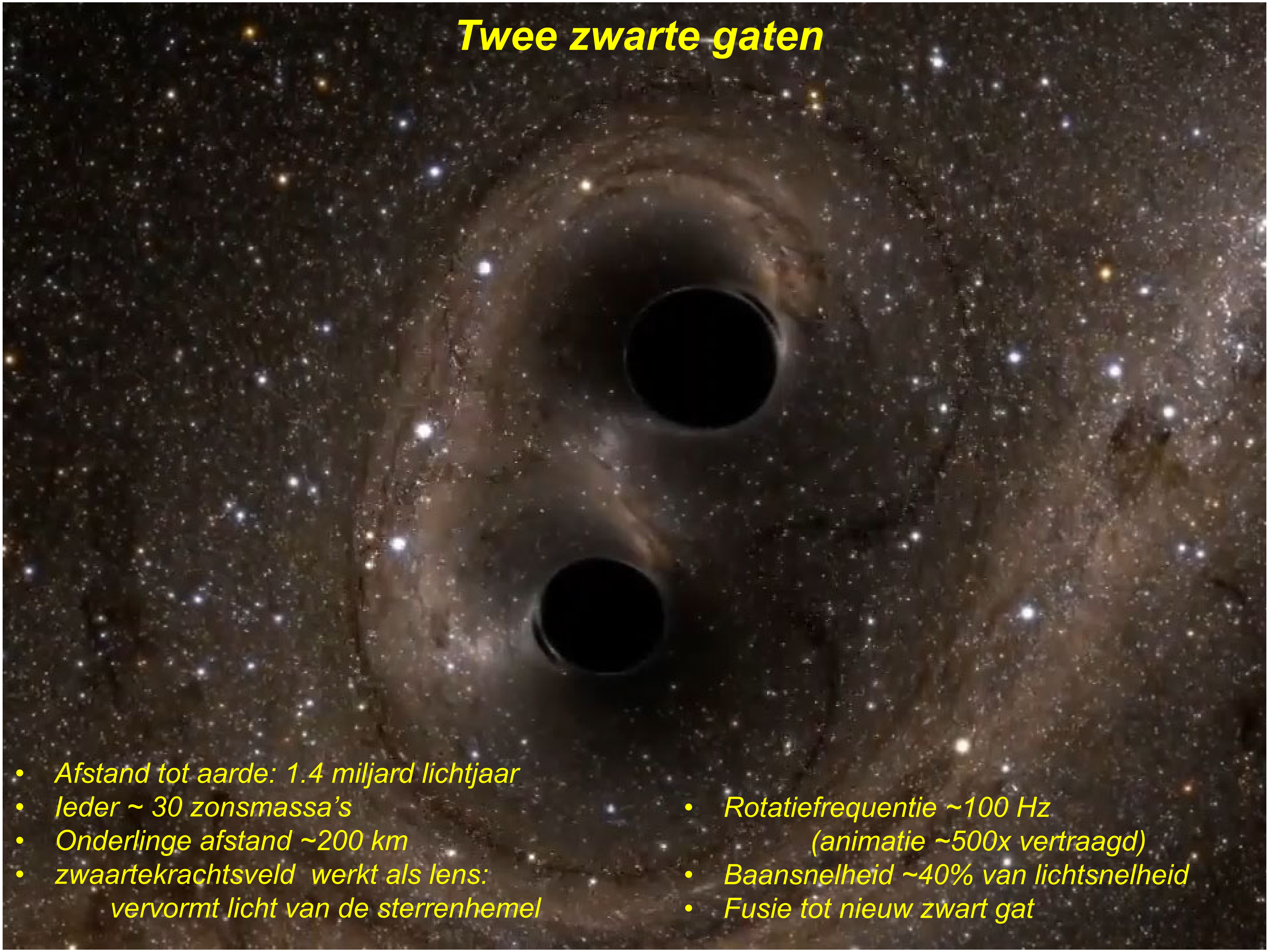
Nikhef

Nationaal Instituut voor deeltjes- en astrodeeltjesfysica

14 September 2015



Twee zwarte gaten



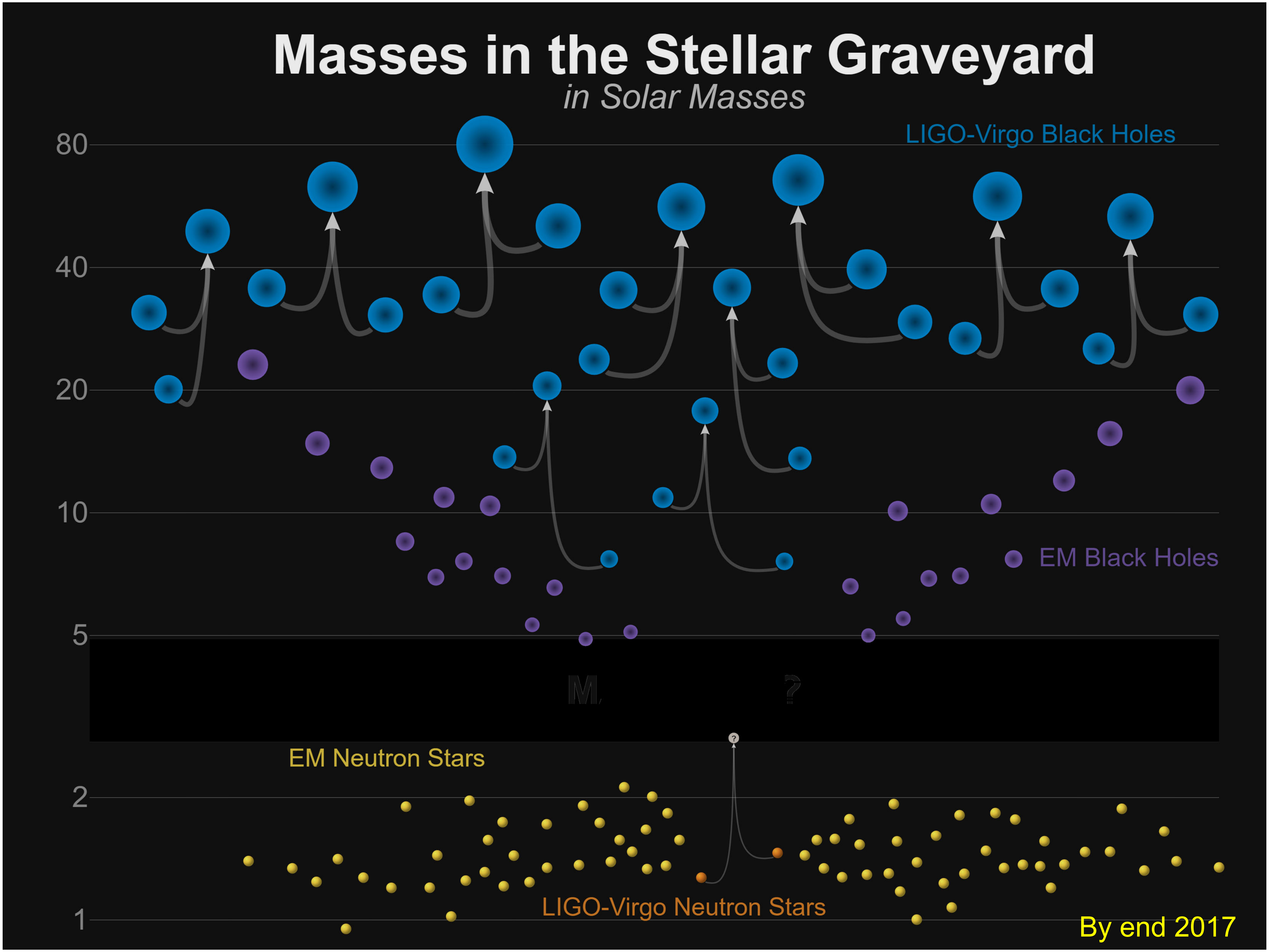
- *Afstand tot aarde: 1.4 miljard lichtjaar*
- *Ieder ~ 30 zonsmassa's*
- *Onderlinge afstand ~200 km*
- *zwaartekrachtsveld werkt als lens:*
  vervormt licht van de sterrenhemel

- *Rotatiefrequentie ~100 Hz*
  (animatie ~500x vertraagd)
- *Baansnelheid ~40% van lichtsnelheid*
- *Fusie tot nieuw zwart gat*

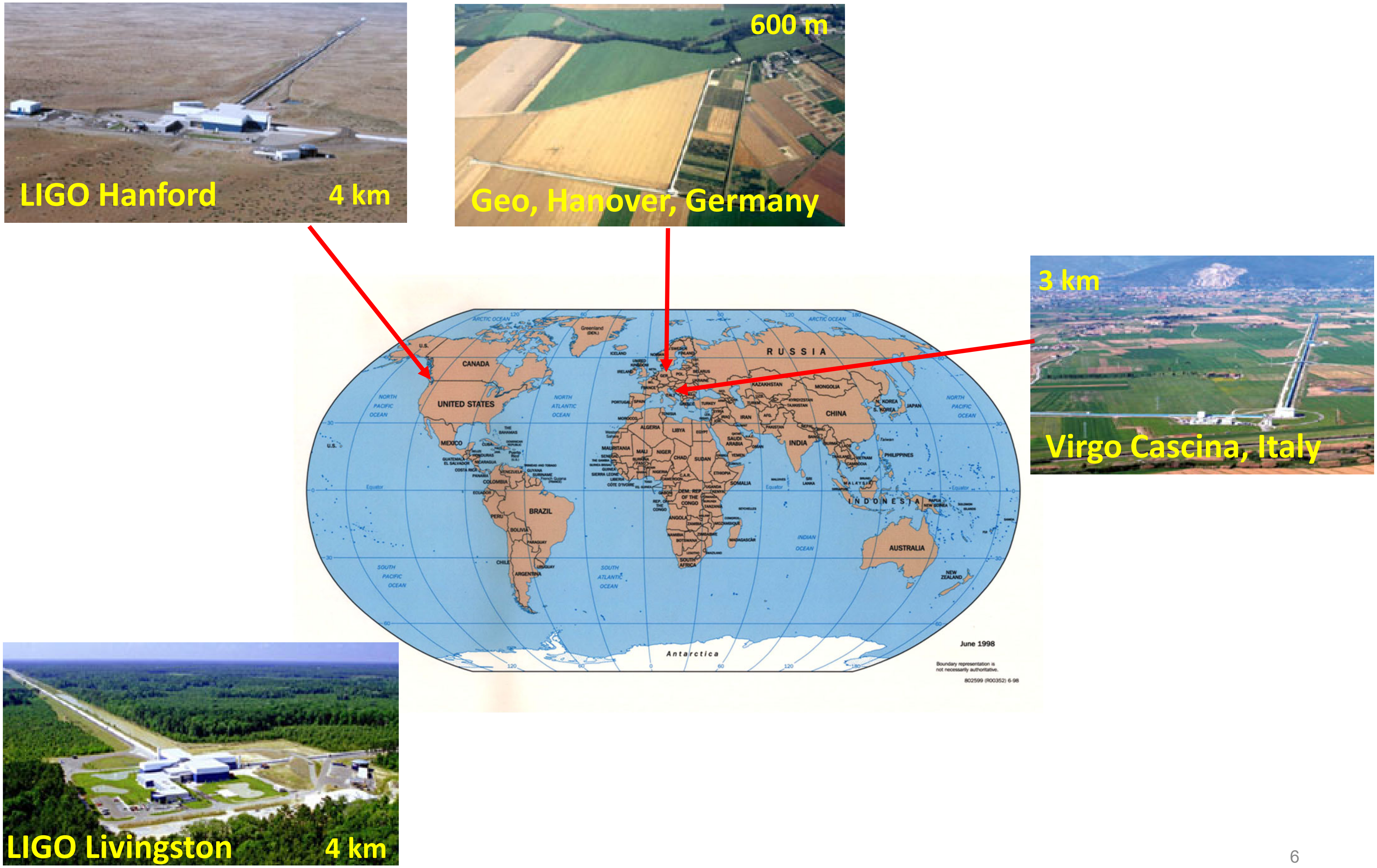
Twee zwarte gaten: *uitgezonden gravitatiegolf*

- *Frequentie ~ 200 Hz*
- *Duur ~ 0.25 sec*
- *Energie: 3 zonsmassa's ($E=mc^2$)*

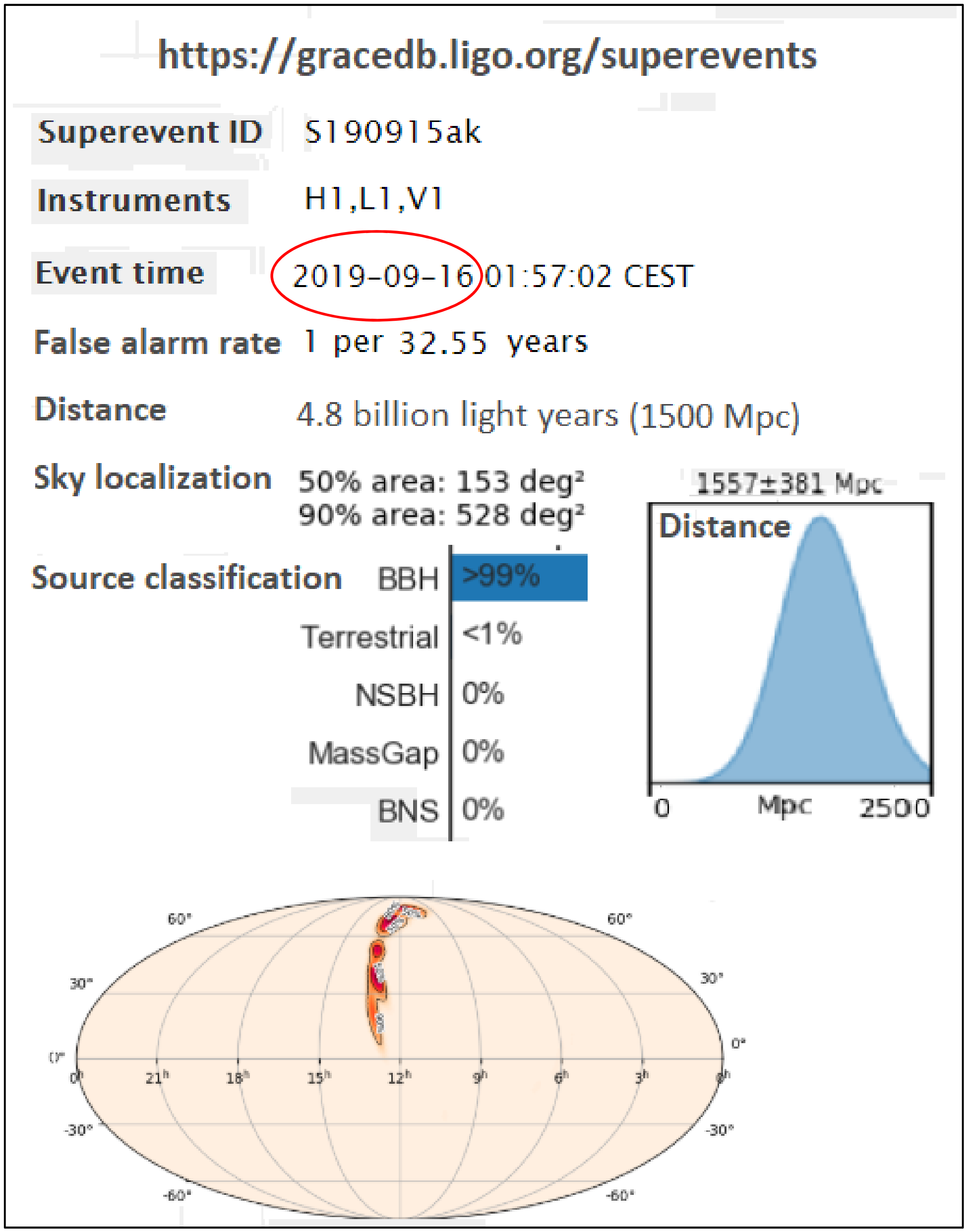
- *Bereikt aarde na 1.4 miljard jaar*
- *Max. ruimte-rek 10^{-21} m/m*
- *Detectie → Nobelprijs 2017*


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
[redacted]
EM Neutron Stars
LIGO-Virgo Neutron Stars
By end 2017

Present network of gravitational wave antennas



recent status of the GW network



36 “superevents” since April 1, 2019:

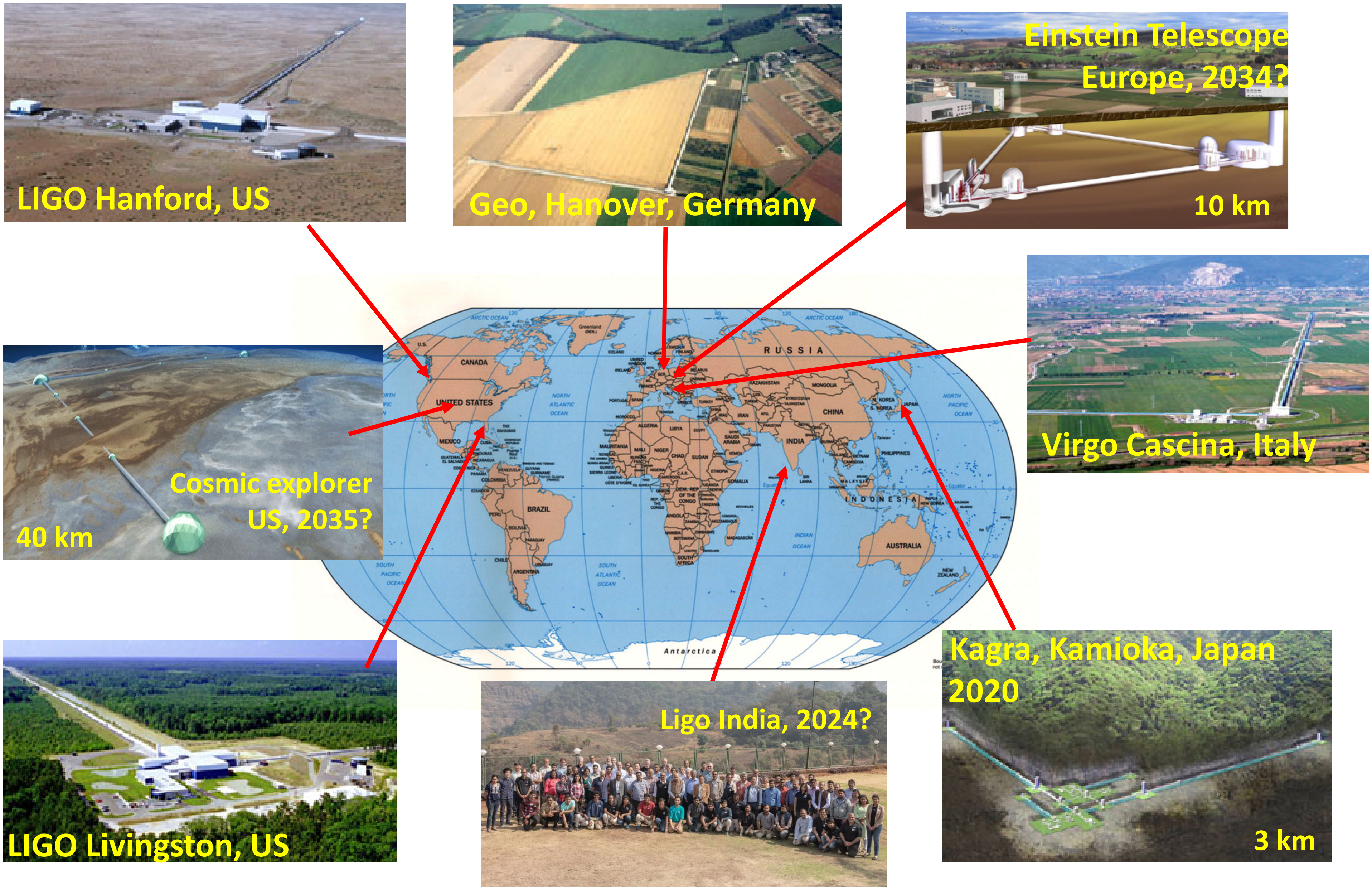
S190915ak	2019-09-15 23:57:25 UTC	S190630ag	2019-06-30 18:52:28 UTC
S190910h	2019-09-10 08:30:21 UTC	S190602aq	2019-06-02 17:59:51 UTC
S190910d	2019-09-10 01:26:35 UTC	S190524q	2019-05-24 04:52:30 UTC
S190901ap	2019-09-01 23:31:24 UTC	S190521r	2019-05-21 07:44:22 UTC
S190829u	2019-08-29 21:06:19 UTC	S190521g	2019-05-21 03:02:49 UTC
S190828l	2019-08-28 06:55:26 UTC	S190519bj	2019-05-19 15:36:04 UTC
S190828j	2019-08-28 06:34:21 UTC	S190518bb	2019-05-18 19:19:39 UTC
S190822c	2019-08-22 01:30:23 UTC	S190517h	2019-05-17 05:51:23 UTC
S190816i	2019-08-16 13:05:12 UTC	S190513bm	2019-05-13 20:54:48 UTC
S190814bv	2019-08-14 21:11:18 UTC	S190512at	2019-05-12 18:07:42 UTC
S190808ae	2019-08-08 22:21:45 UTC	S190510g	2019-05-10 03:00:03 UTC
S190728q	2019-07-28 06:45:27 UTC	S190503bf	2019-05-03 18:54:26 UTC
S190727h	2019-07-27 06:03:51 UTC	S190426c	2019-04-26 15:22:15 UTC
S190720a	2019-07-20 00:08:53 UTC	S190425z	2019-04-25 08:18:26 UTC
S190718y	2019-07-18 14:35:34 UTC	S190421ar	2019-04-21 21:39:16 UTC
S190707q	2019-07-07 09:33:44 UTC	S190412m	2019-04-12 05:31:03 UTC
S190706ai	2019-07-06 22:26:57 UTC	S190408an	2019-04-08 18:18:27 UTC
S190701ah	2019-07-01 20:33:24 UTC	S190405ar	2019-04-05 16:01:56 UTC

Gravitational Wave Detector Network

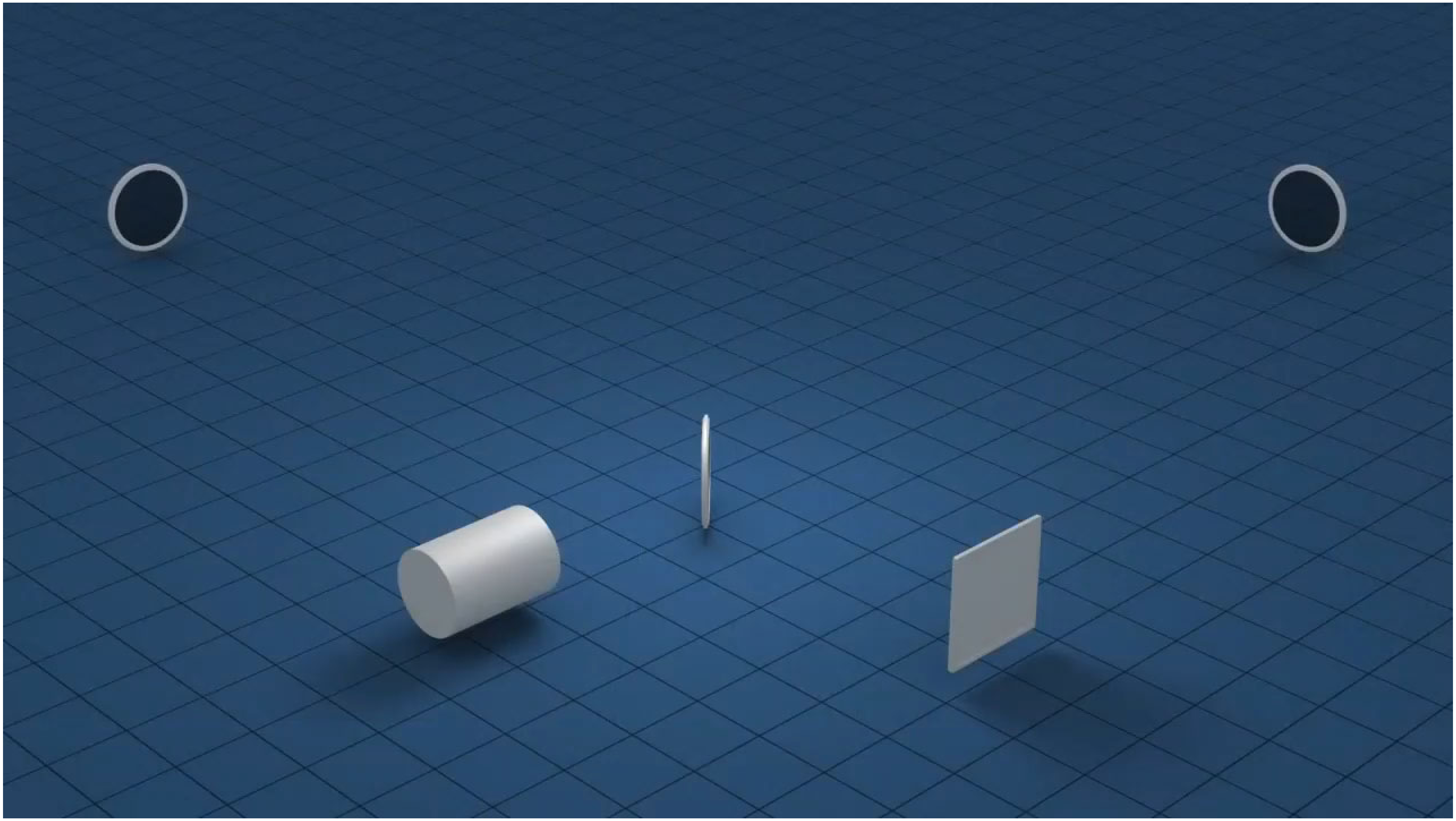
Operational Snapshot as of Sep 16, 20:01 UTC

Detector	Status	Duration
GEO 600	Observing	10:21
LIGO Hanford	Observing	8:10
LIGO Livingston	Observing	12:25
Virgo	Science	7:31
KAGRA	Future addition	

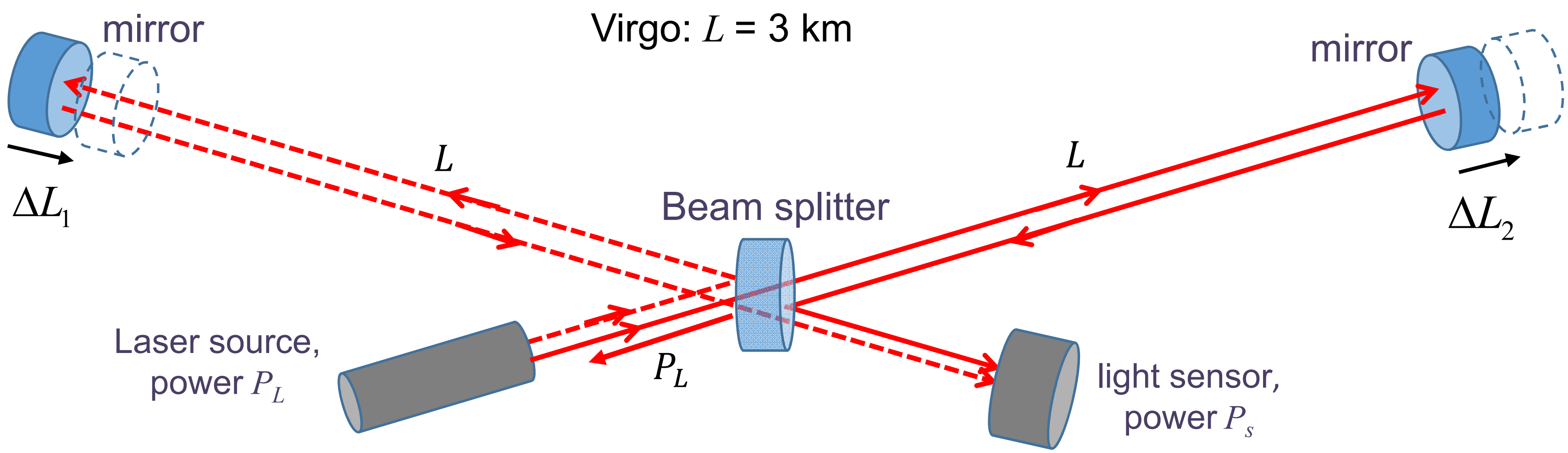
Present and future network of gravitational wave antennas



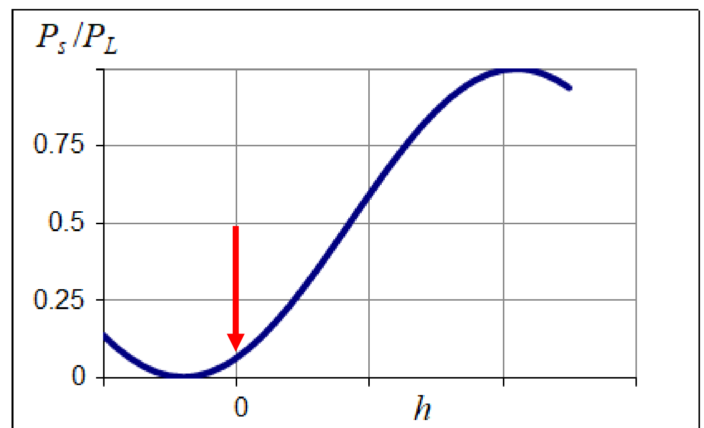
Michelson interferometer meet ruimte-rek



Michelson interferometer used as "rekstrookje"



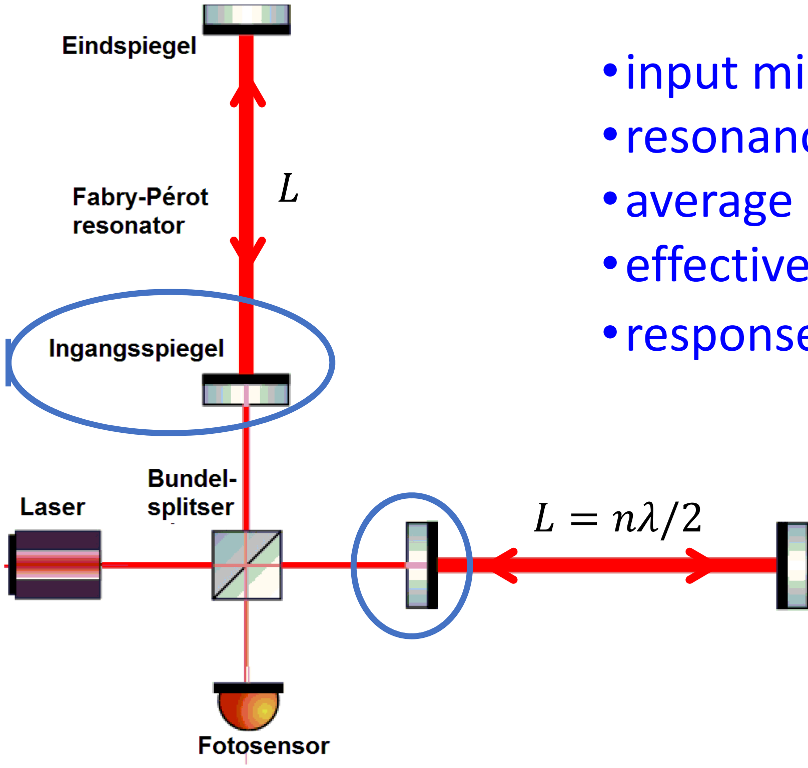
- Gravitational strain $h = \frac{\Delta L_2 - \Delta L_2}{L}$
- measured power $P_s(t) = \frac{P_L}{2}\left[1 + \cos\left(\varphi_0 + \frac{d\varphi}{dh} h(t)\right)\right]$
- phase shift per unit h $\frac{d\varphi}{dh} = \frac{4\pi L}{\lambda}$



- Choice: $\varphi_0 \cong \pi$ → sensor in "dark fringe".
- This reduces effect of laser intensity noise
- Injected power P_L returns back towards laser

Increase phase response: optical resonator

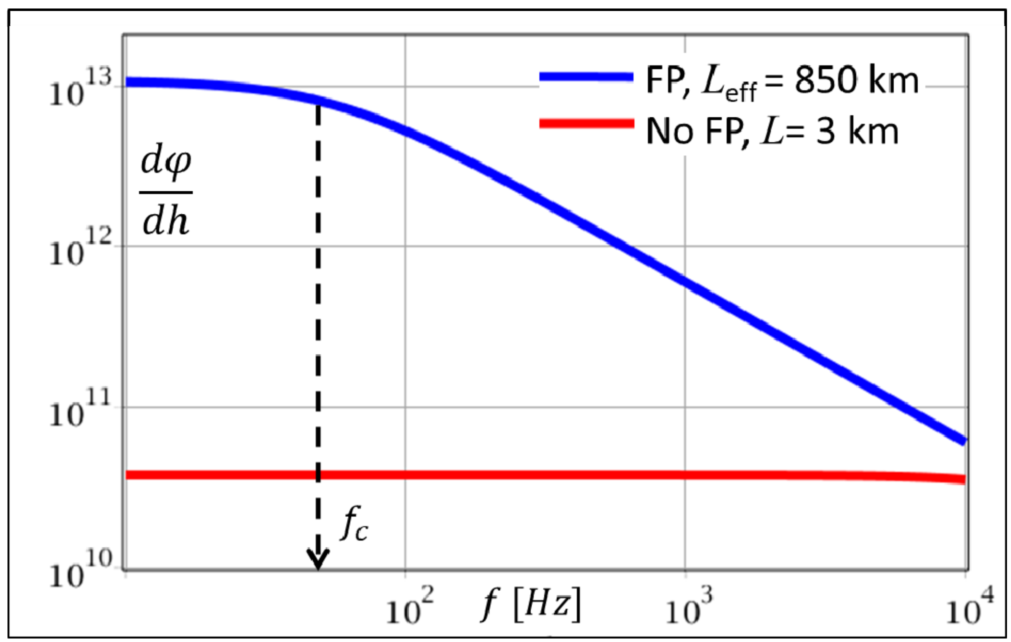
- input mirrors: transmissivity $T = 1 - R$ = 1.4%
- resonance condition : $L = n\lambda/2$
- average # of photon round trips: $4/T$ = 280
- effective length L_{eff} = 840 km
- response lower when $\lambda_{grav.golf} < L_{eff}$



$$\frac{d\varphi}{dh} = \frac{4\pi L}{\lambda} \frac{L_{eff}/L}{\sqrt{1 + (f/f_c)^2}}$$

$$f_c = c/2\pi L_{eff}$$

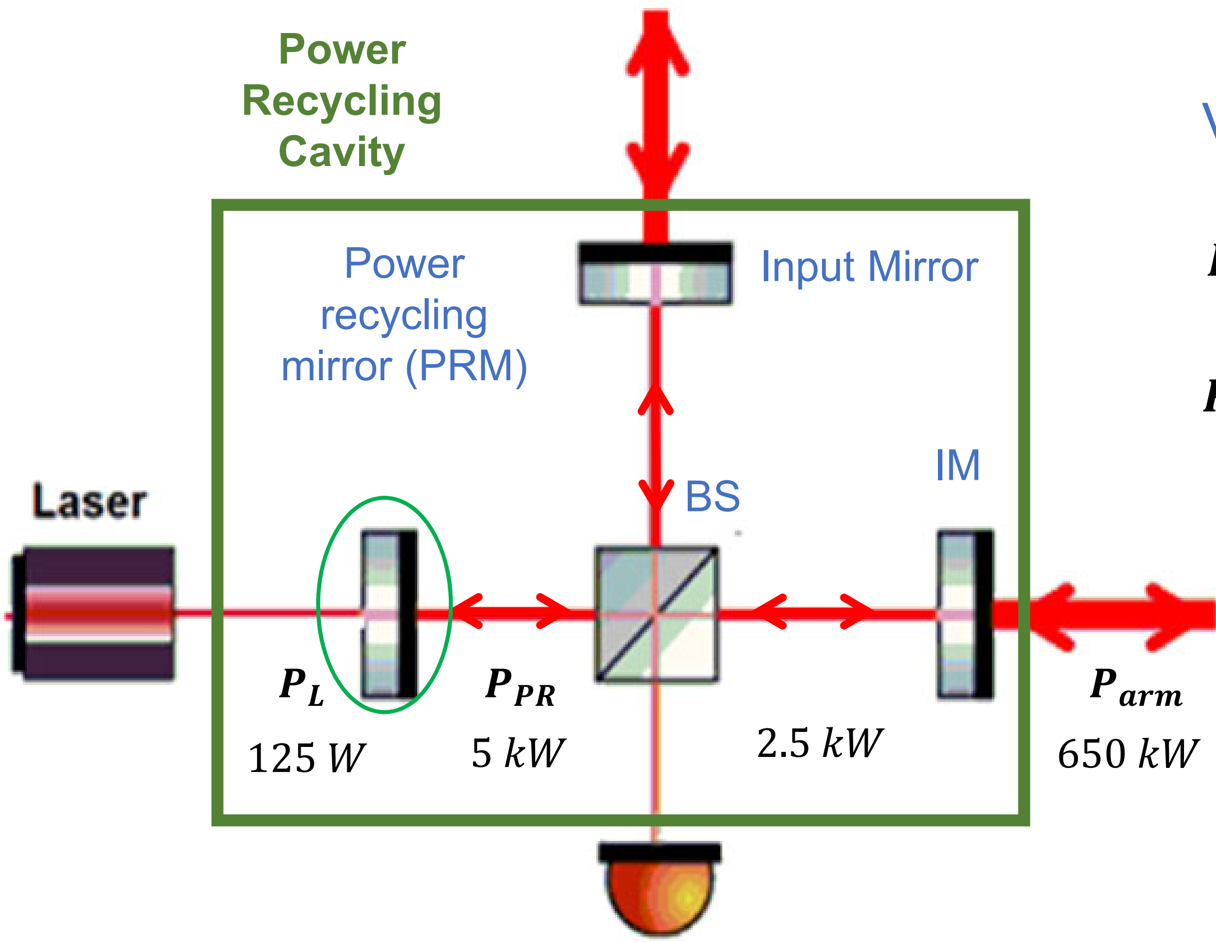
$$L_{eff} = 4L/T$$



Phase-response resonant arm cavity

increase beam power: Power recycling cavity

- Recycling mirror reflects power coming from the interferometer back to the beam splitter
- Choose position such that you get a **resonant cavity**

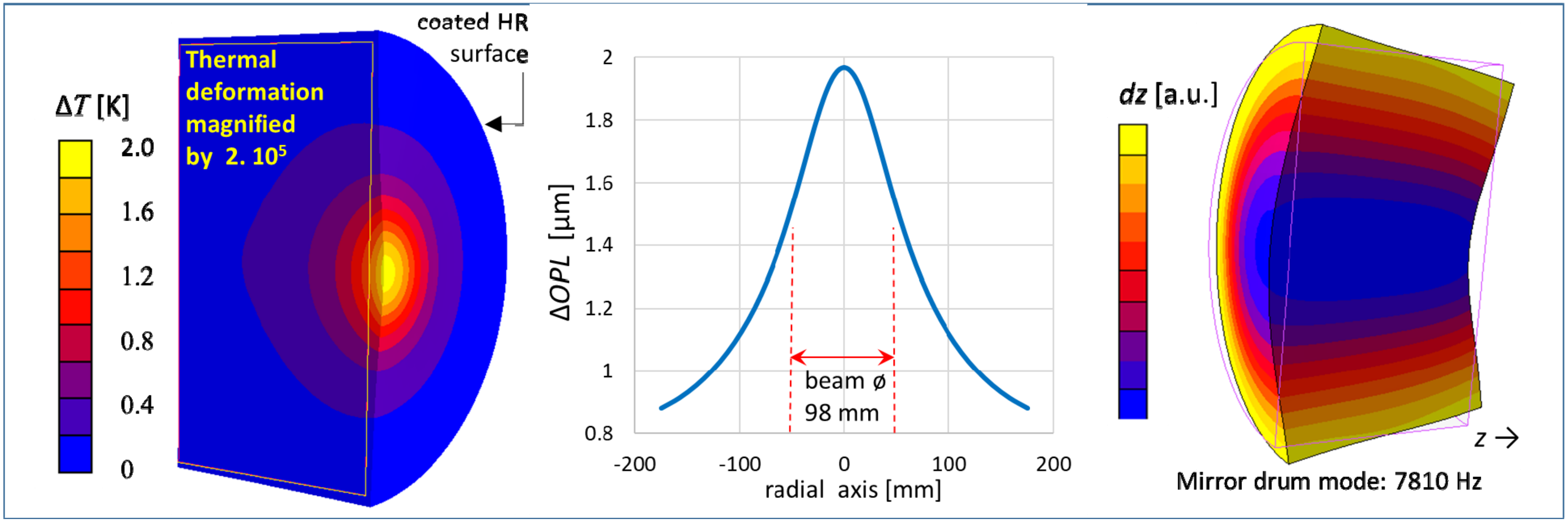


Virgo: gain $G = 37$

$$P_{PR} = G.P_L = 5\ kW$$

$$P_{arm} = \frac{P_{PR}}{2L} P_L = 650\ kW$$

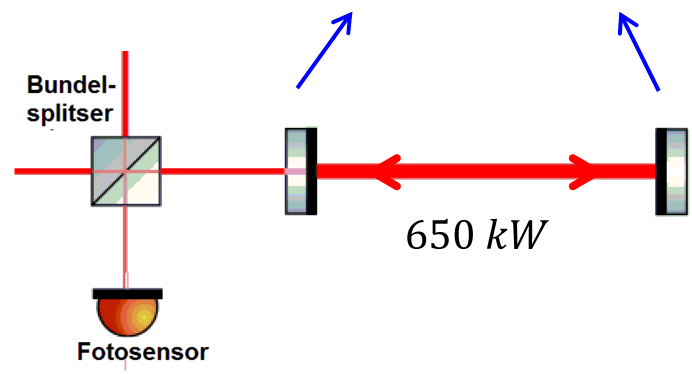
Effect of heat load on mirror : thermal lensing



- Arm cavities: optical power: 650 kW
- Absorption in mirror center: 1 ppm → ~ 1 W
- Average ΔT-increase changes drum mode
- Thermal gradients cause:
  - Surface deformation
  - Refractive index gradient in substrate

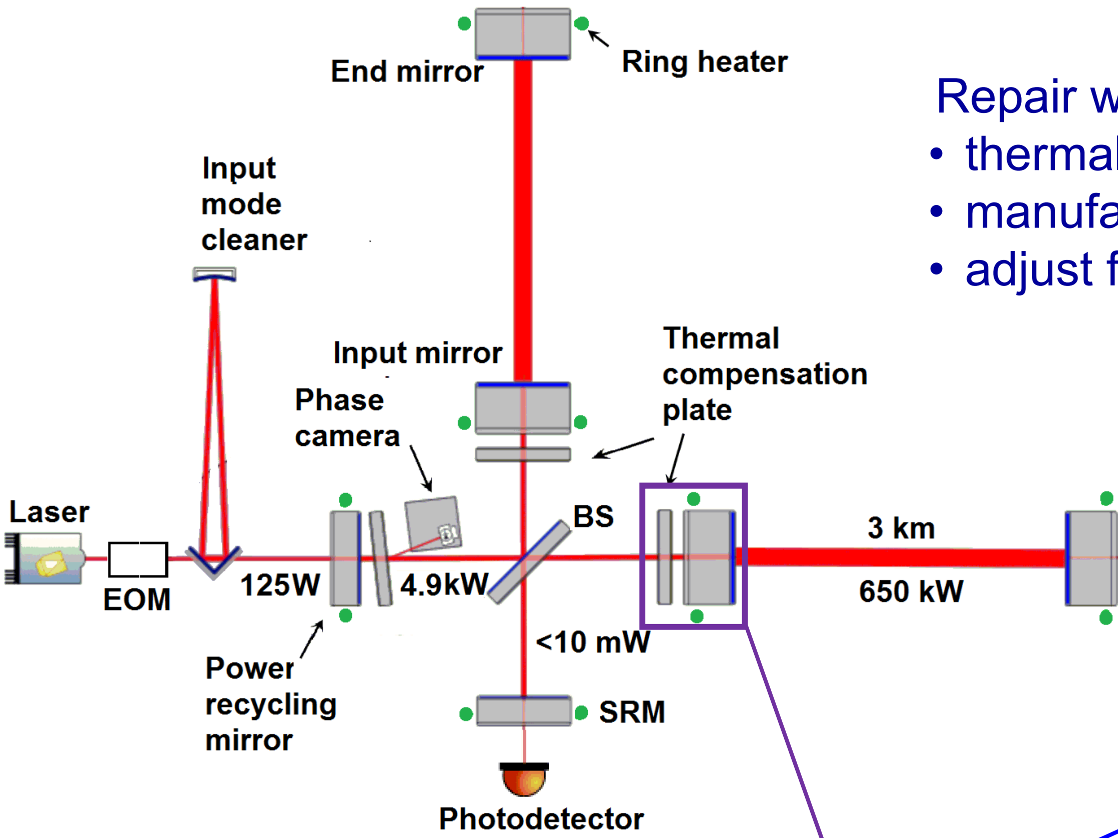
→Distortion of reflected and transmitted beams

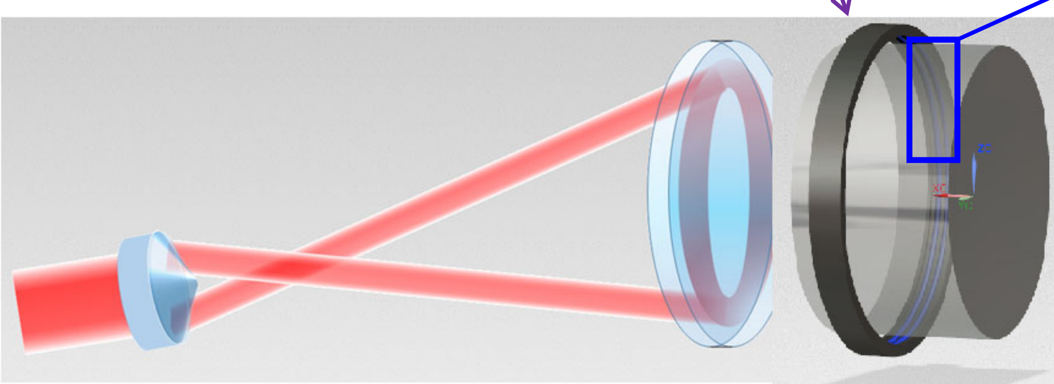
→Need for Thermal Compensation System



Thermal actuators

Repair wave front distortions due to:
- thermal lensing
- manufacturing defects
- adjust focal length

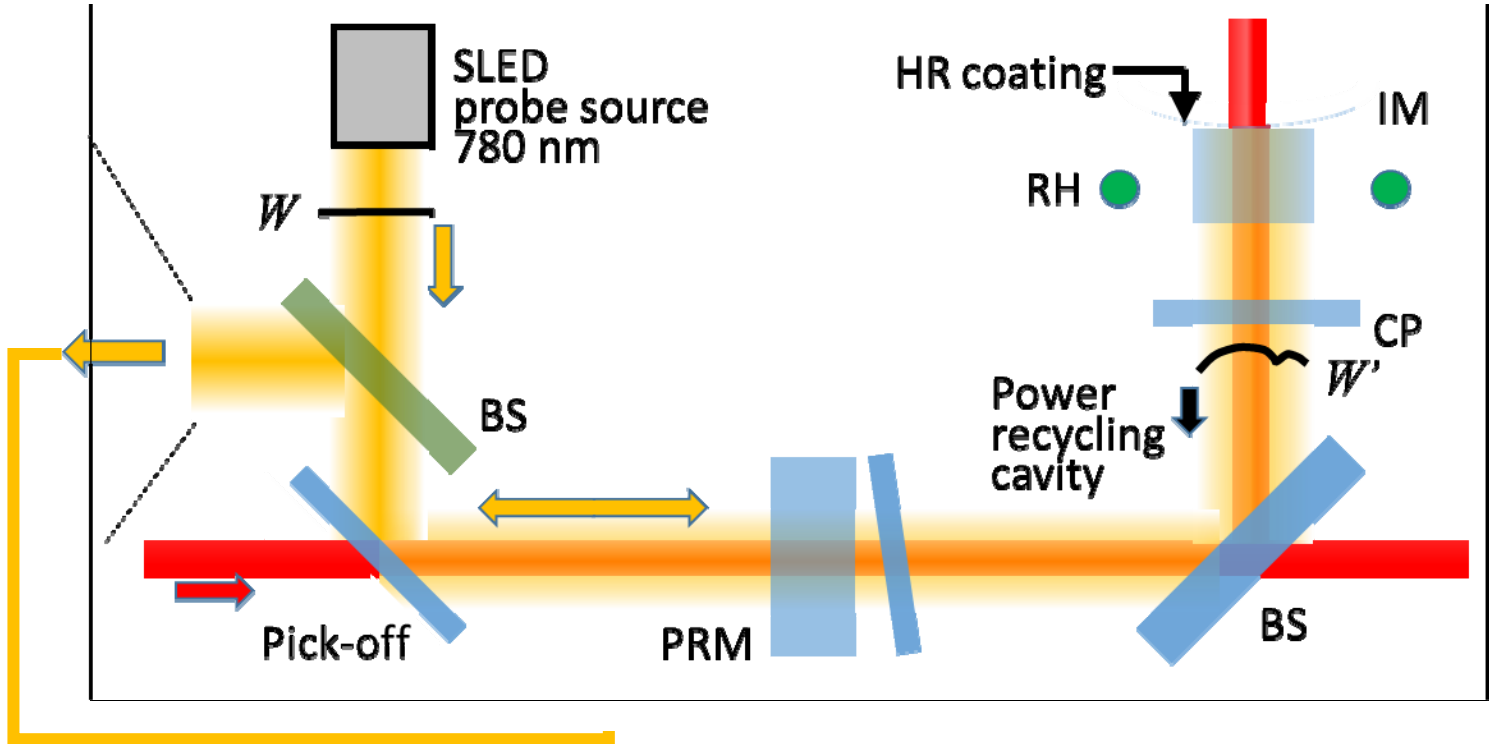


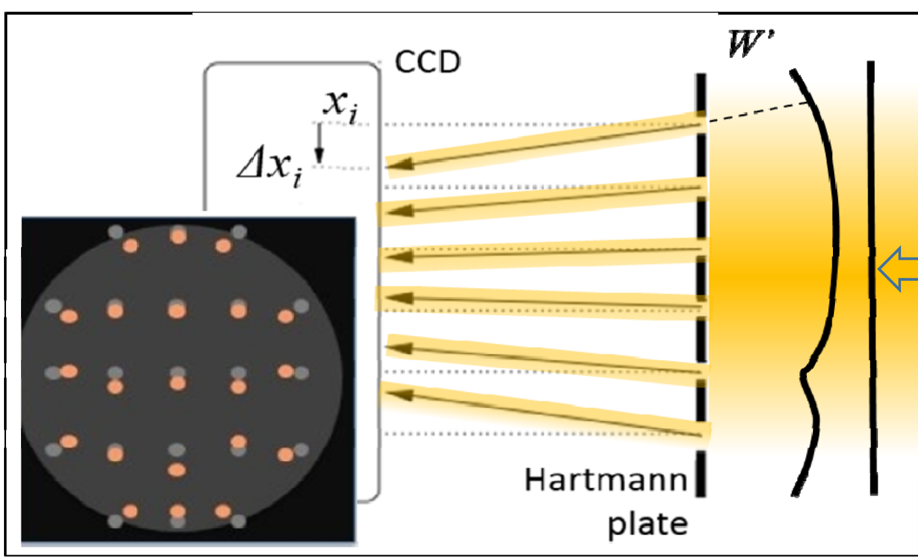


CO_2 annularly shaped or scanning laser beam (λ = 10 μm)

Ring heater,
copper shielded

Hartmann wave front sensor

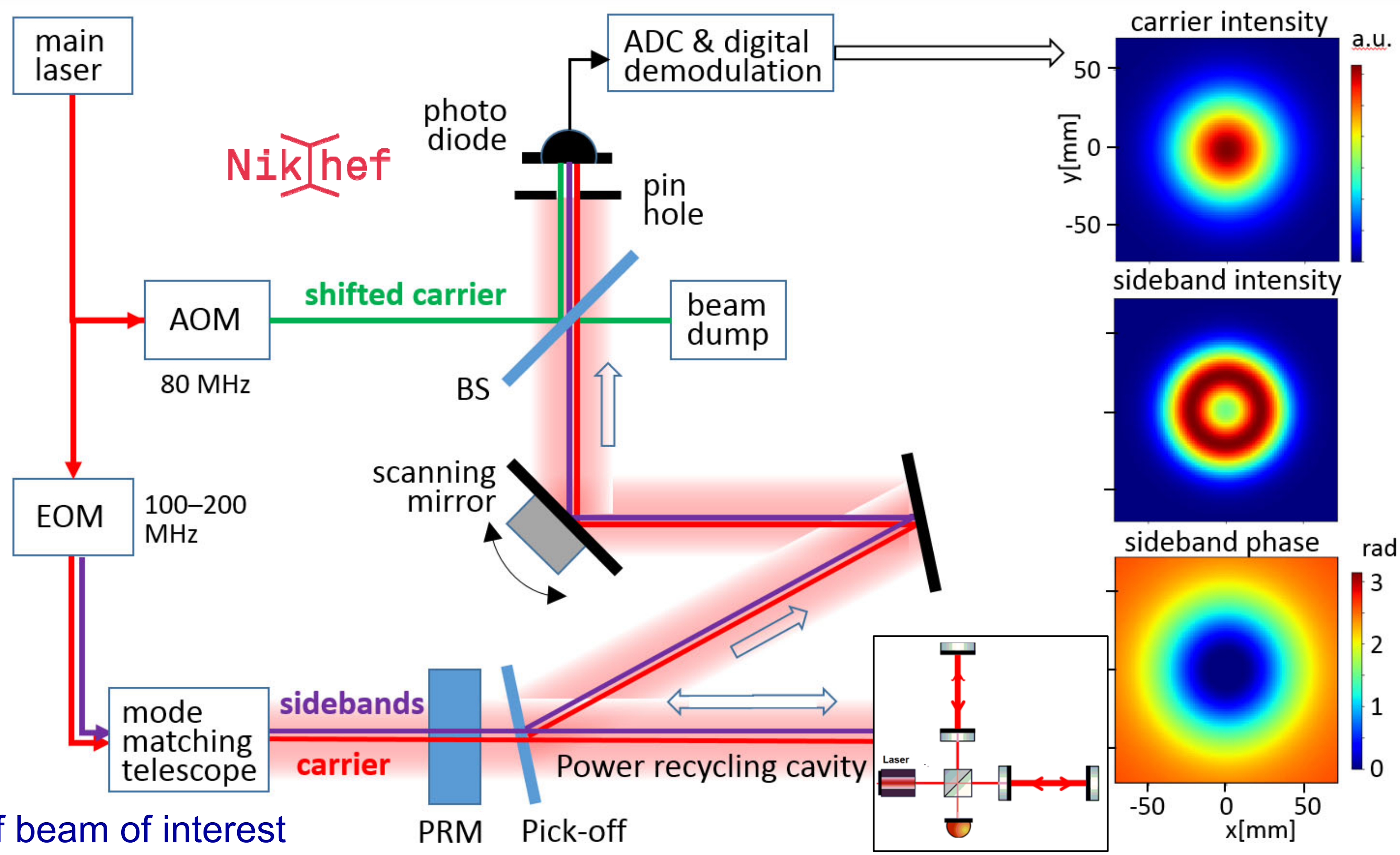




- inject plane probe beam into subsystem
- project reflected beam to plate with pin holes
- measure pin hole pattern shift on CCD camera

Phase camera: scanning wave front sensor

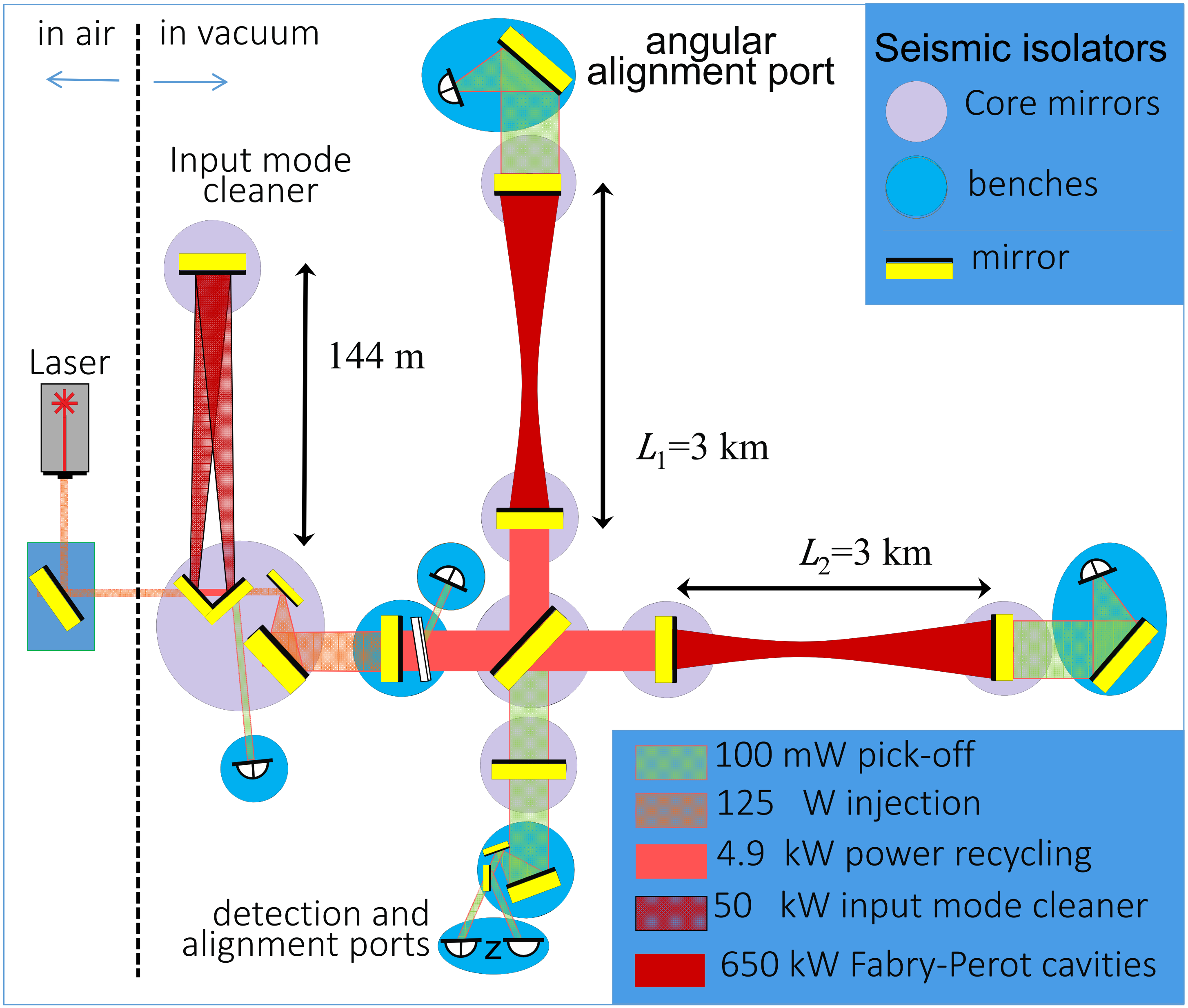
measure amplitude and phase of carrier and all side bands



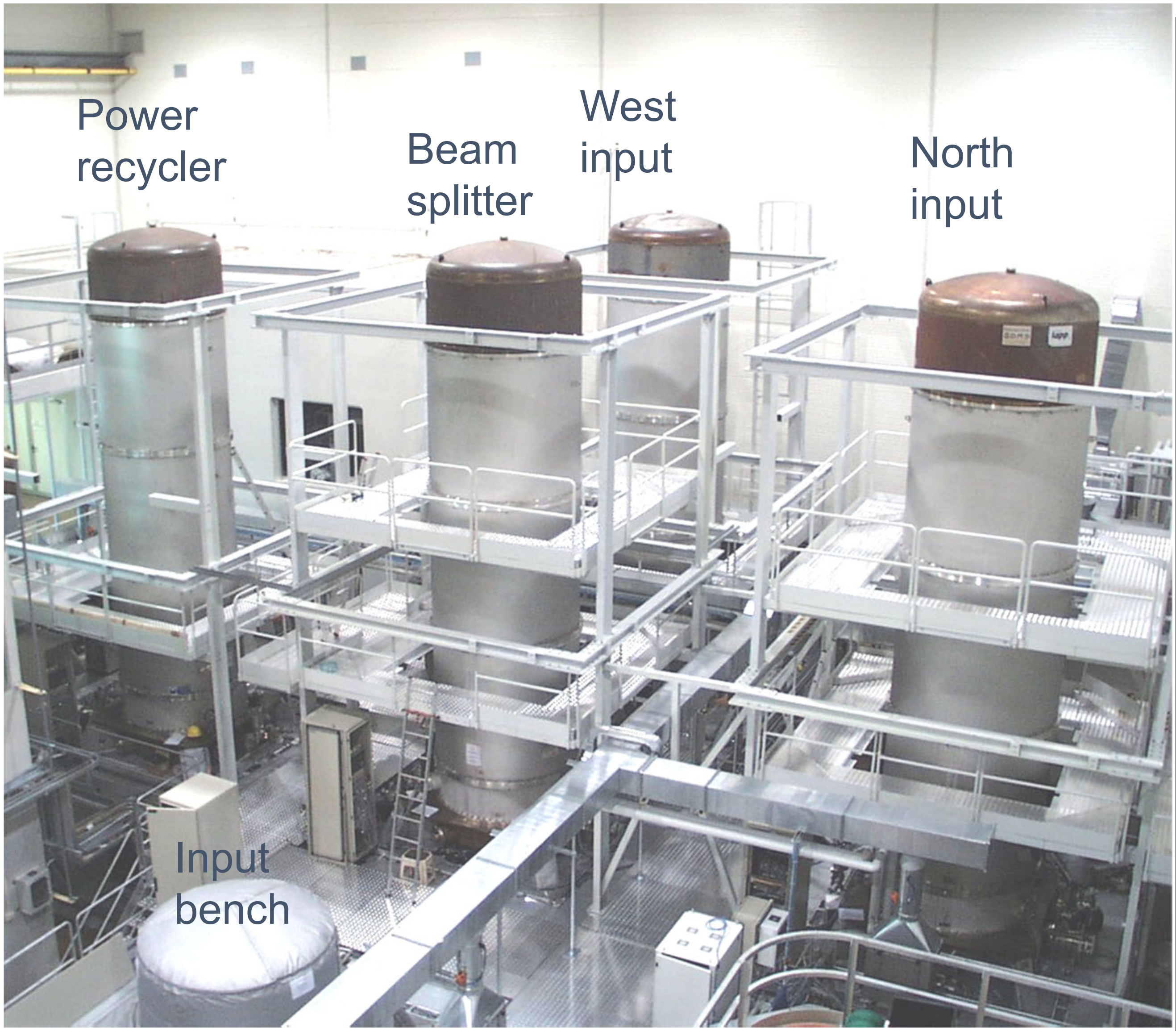
1. Pick-off beam of interest
2. Send it to 2D scanning mirror
3. Mix it with (shifted) laser beam
4. Send it to photo diode
5. Digitize and demodulate
6. Reconstruct amplitude and phase components

interferometer

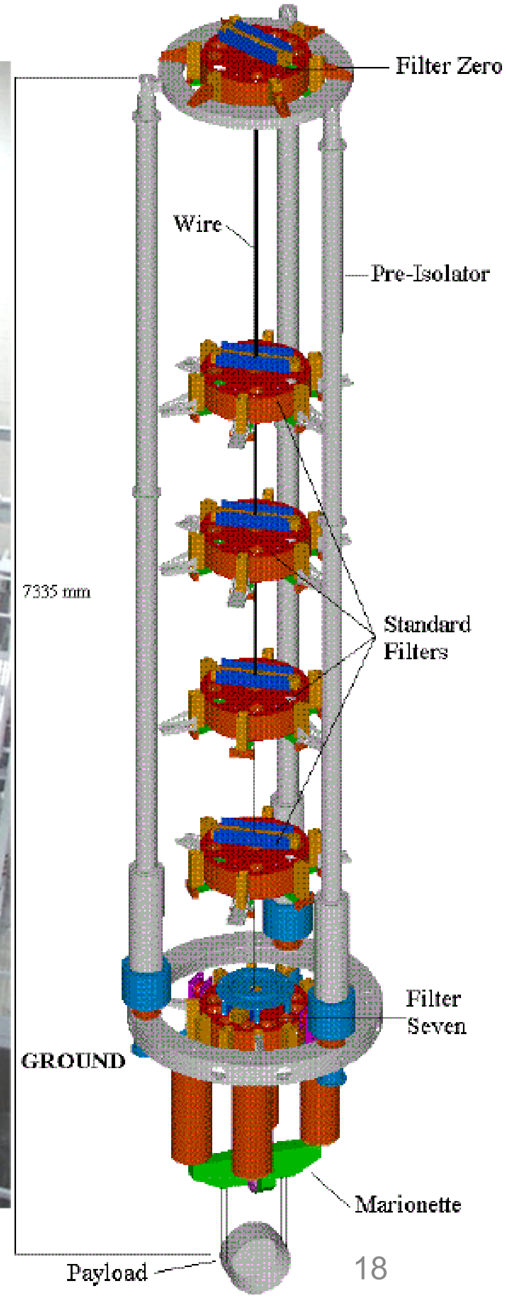
Advanced Virgo optical layout



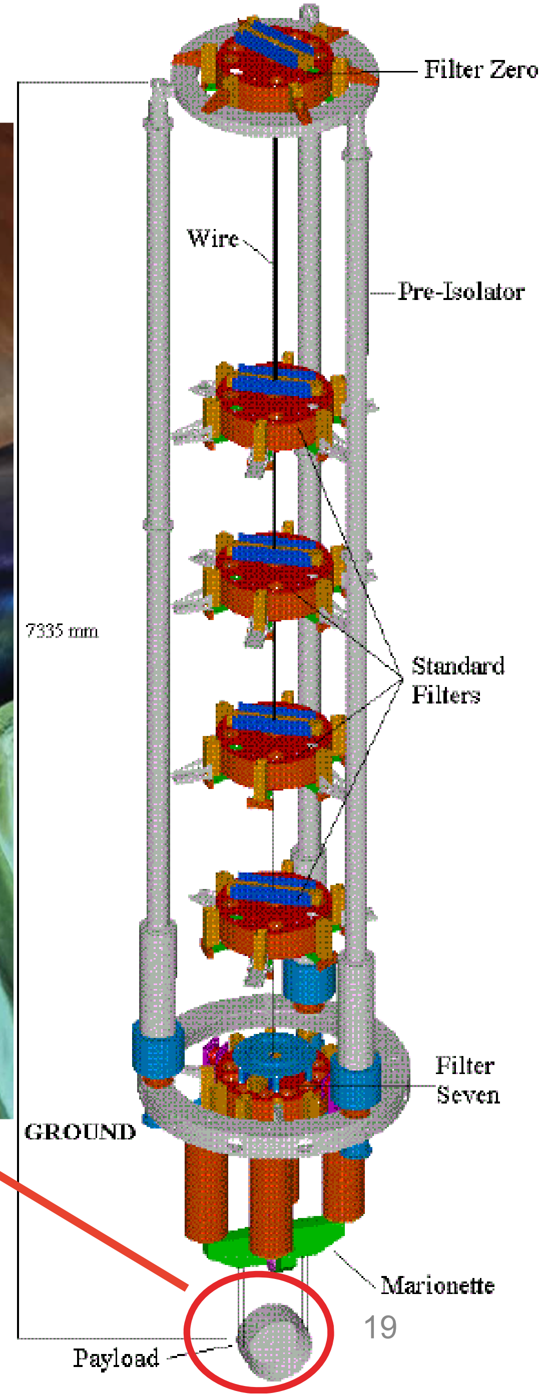
Virgo: central building



Super attenuator



Virgo mirror (42 kg) suspension

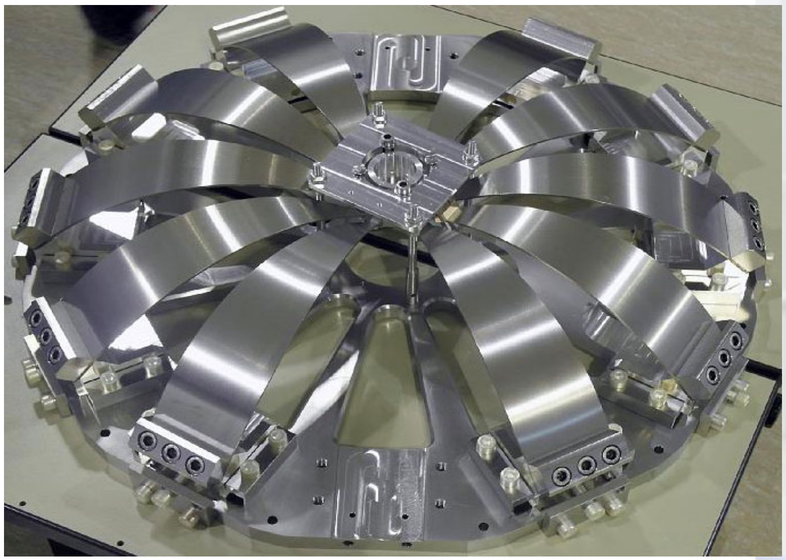


Diameter 35 cm
Thickness 20 cm

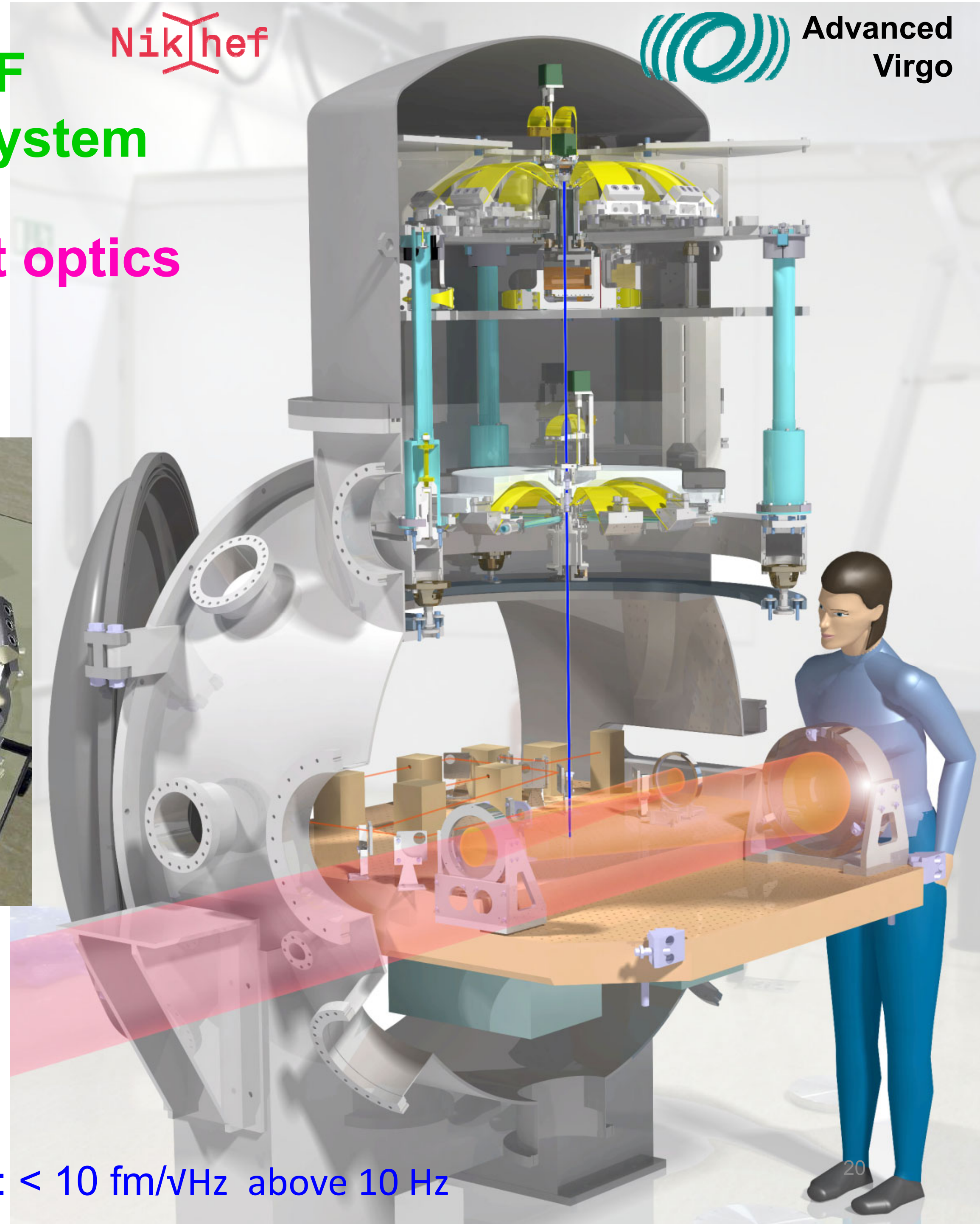
Multi-stage 6-DOF seismic attenuation system

for

alignment and read-out optics



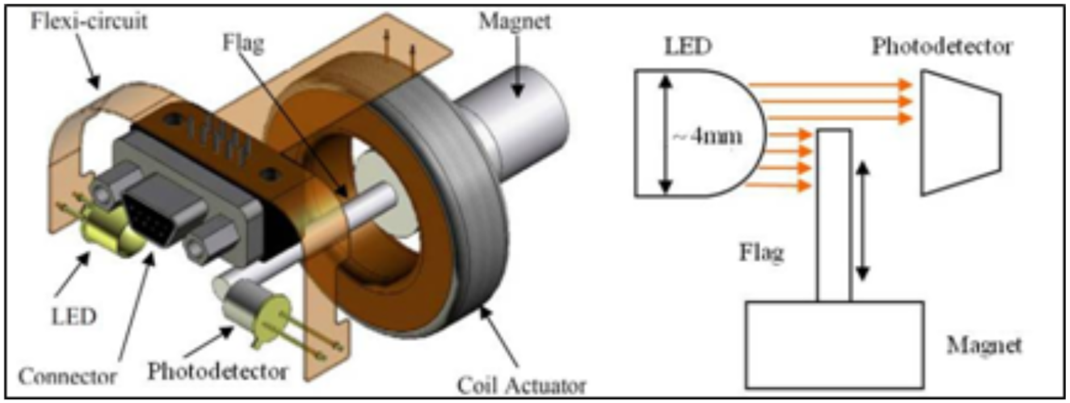
GAS spring
Load 420 kg
Frequency 200 mHz

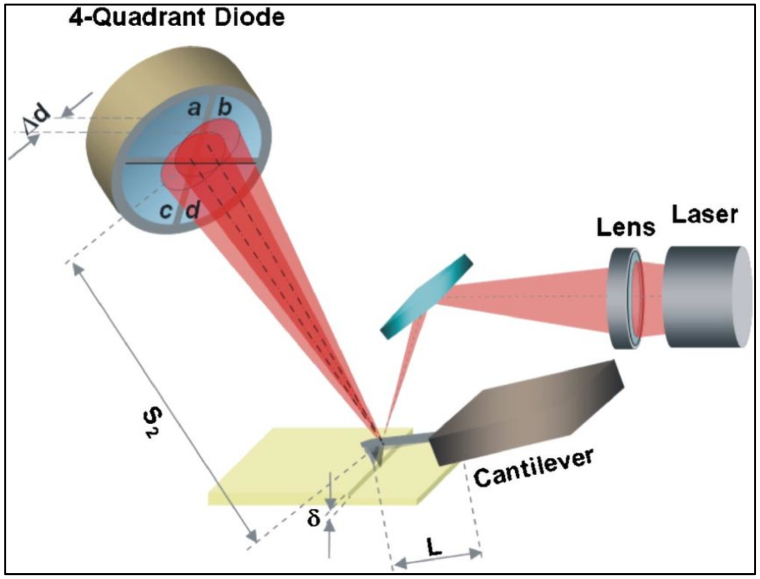


Residual horizontal bench motion: < 10 fm/√Hz above 10 Hz

Contactless motion sensing applied in alignment and vibration control

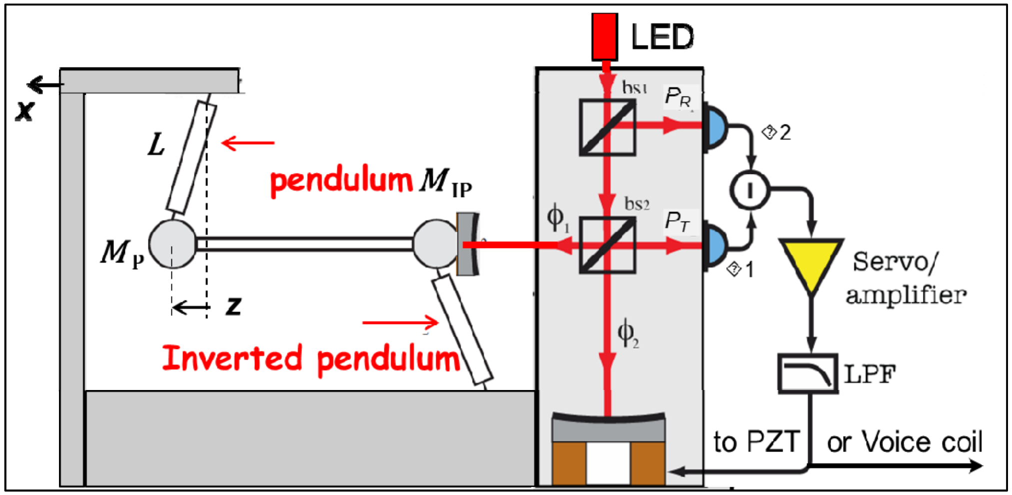
Shadow (flag) sensor, integrated in OSEM:
Optical Sensor & Electro-Magnetic actuator

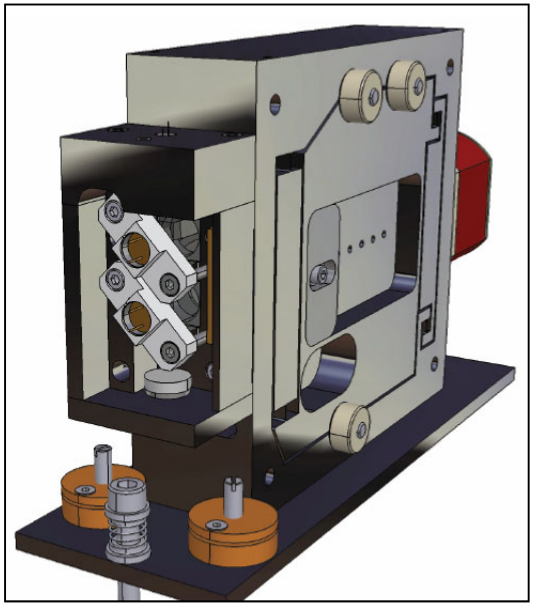




Optical lever: tilt and translation sensor

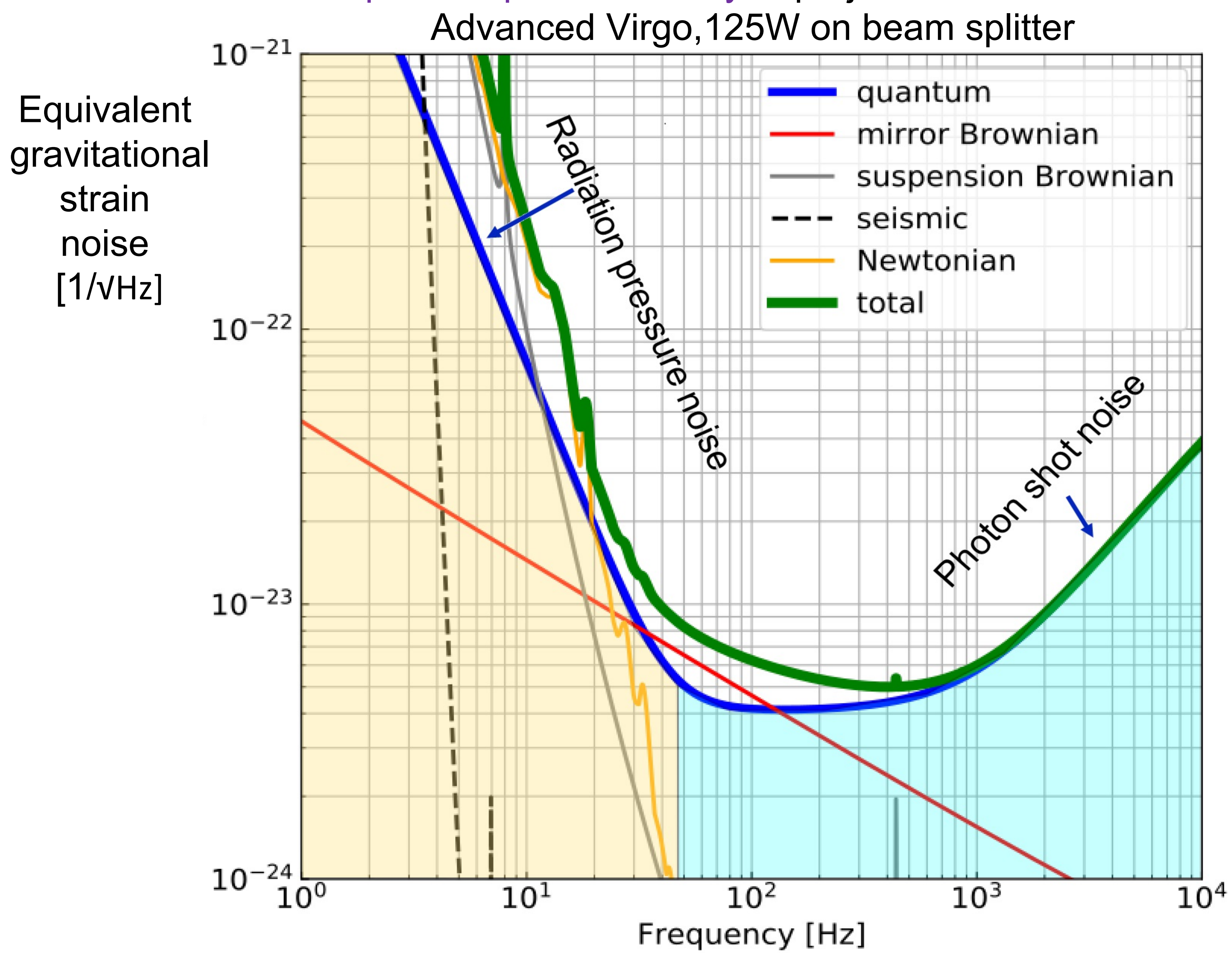
interferometric read-out of inertial sensor (accelerometer)





Detector noise budget

Amplitude spectral density of projected noise sources



Detector noise budget

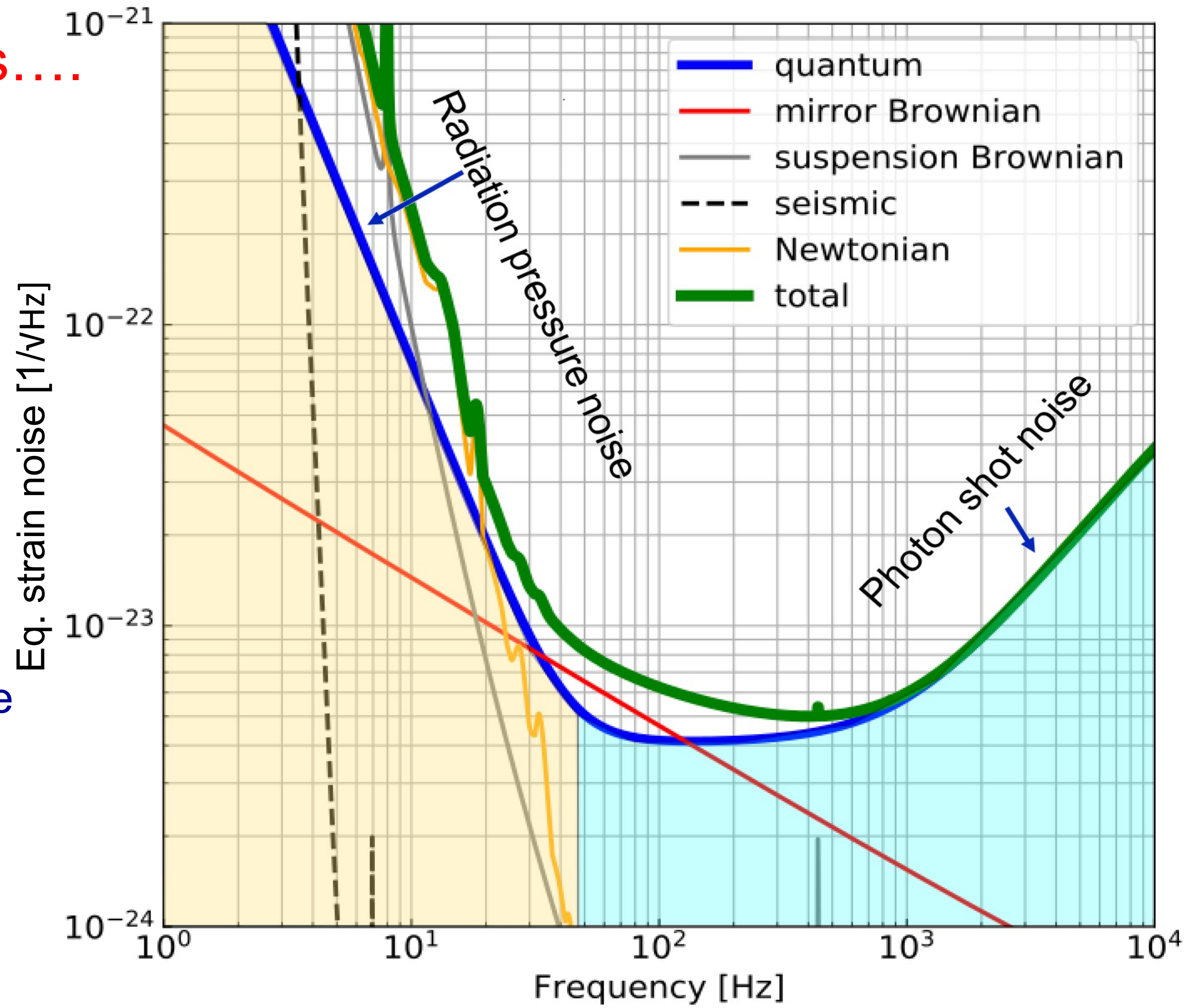
How to shift the walls….

at high frequencies:
- increase laser power

at mid frequencies:
- decrease temperature
- decrease dissipation

at low frequencies:
- increase mirror mass
- decrease laser power
- subtract Newtonian noise
- go underground
- go to space

at all frequencies:
- increase arm length
- inject squeezed light



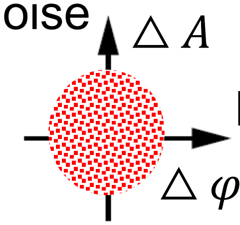
Amplitude spectral density of projected noise sources
Advanced Virgo,125W on beam splitter

play with Heisenberg...inject squeezed light

amplitude and phase of light wave cannot be both "certain"

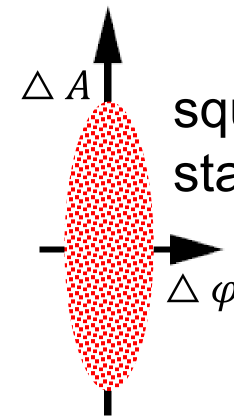
$$E(t) = (\bar{A} + \triangle A)e^{i(\omega t + \triangle\varphi)}$$

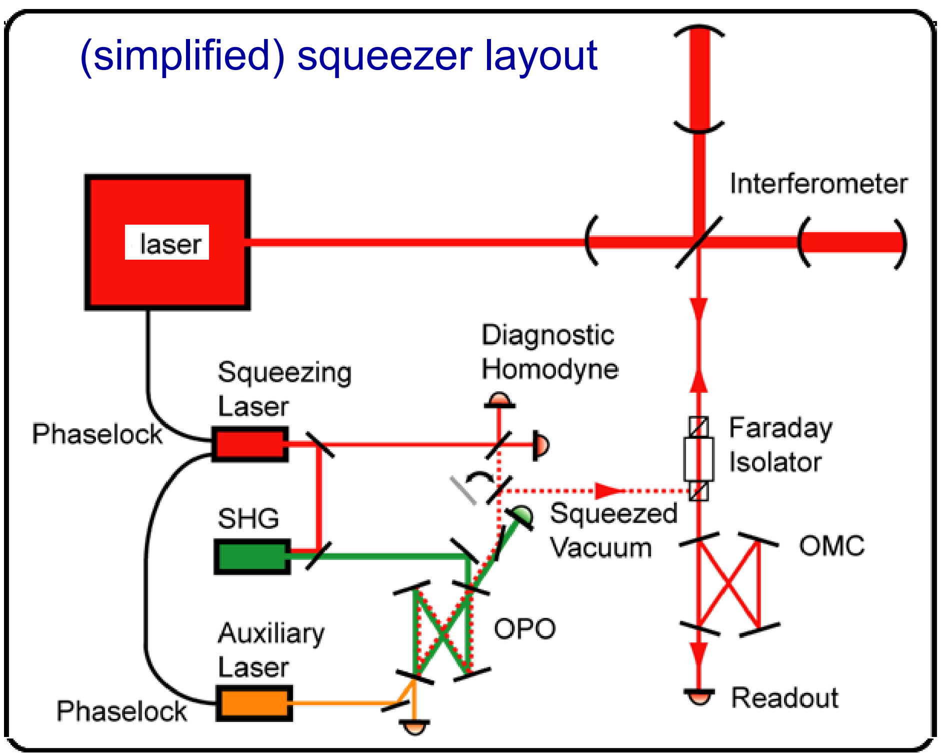
amplitude noise → radiation pressure noise



phase noise → detector shot noise

reduce one at the cost of the other

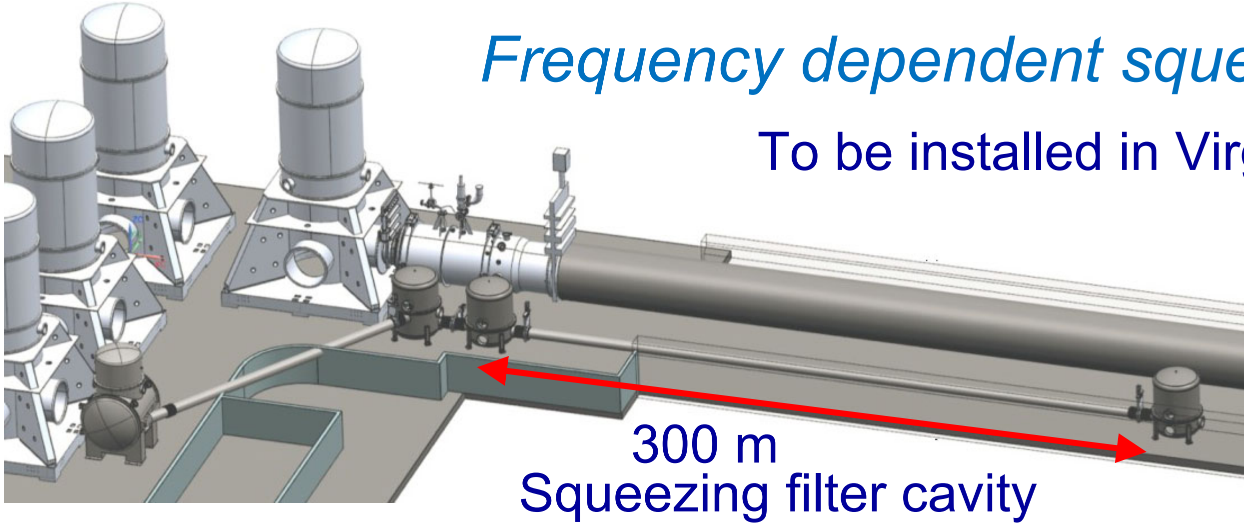


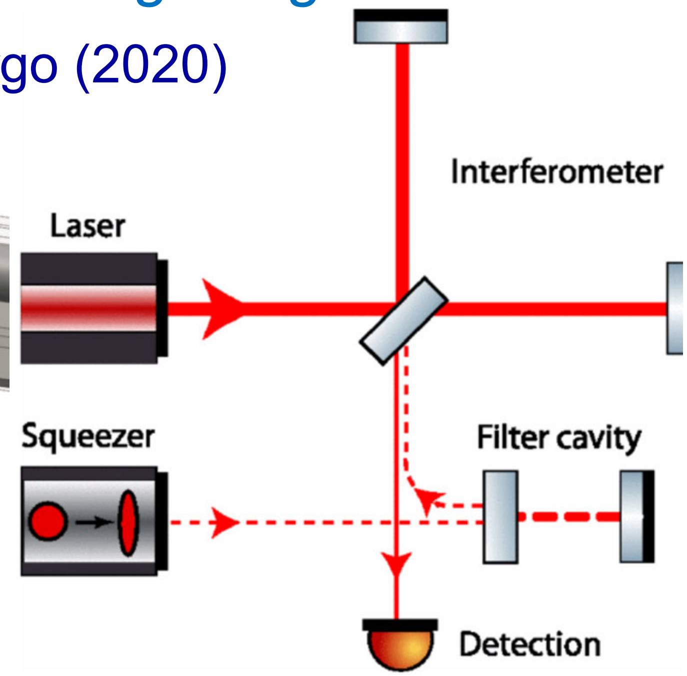


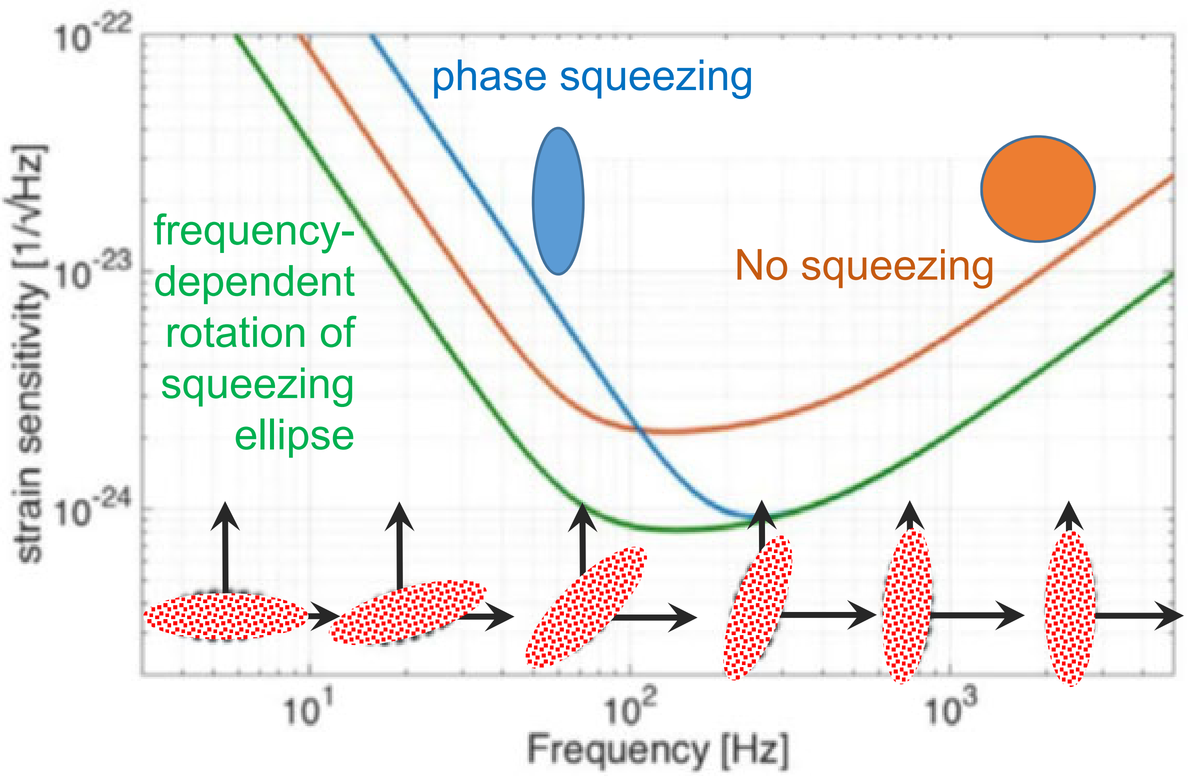
Virgo's squeezer (made by AEI Hanover)

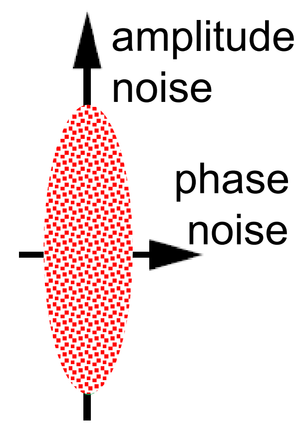
Frequency dependent squeezing of light

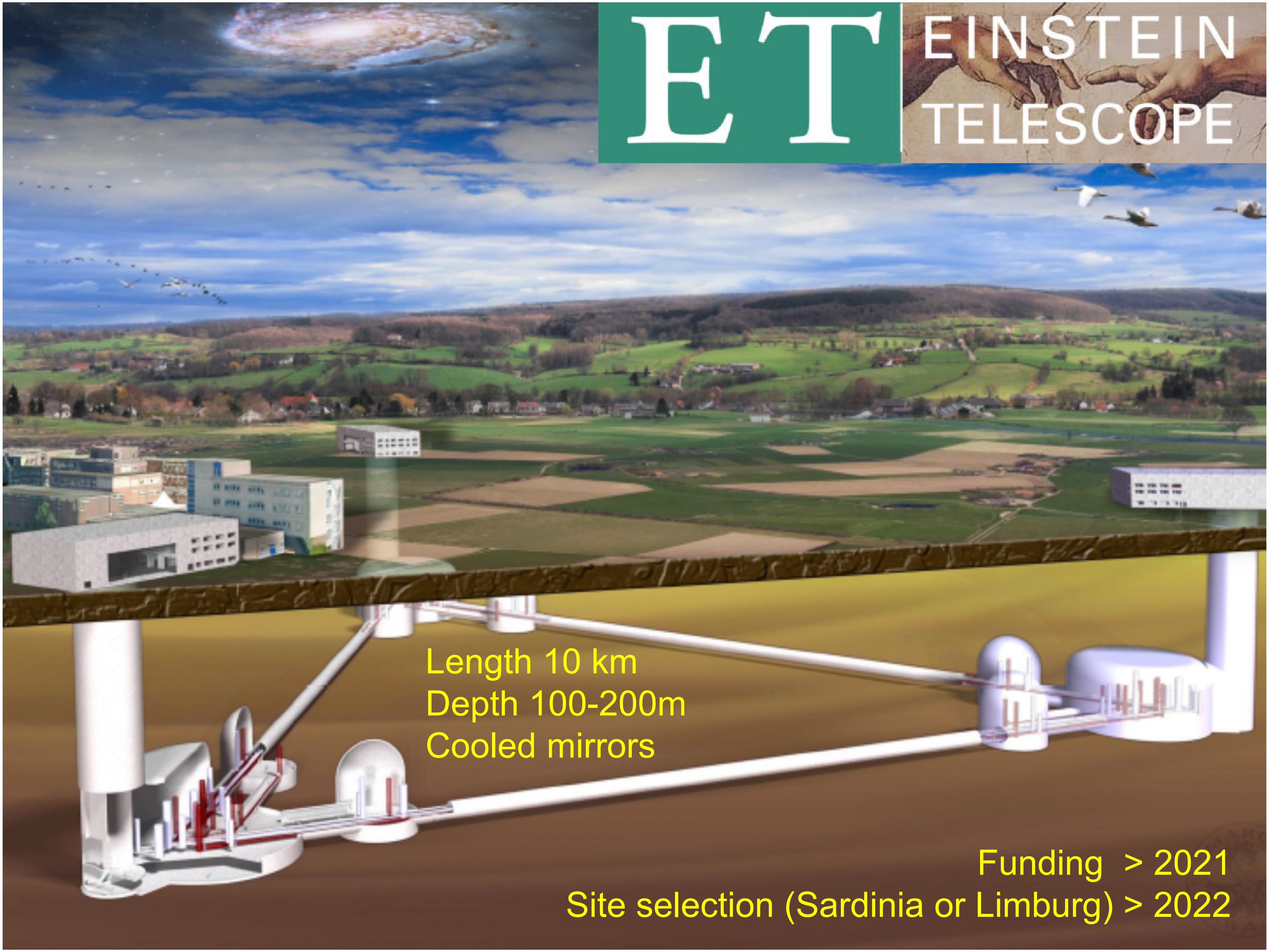
To be installed in Virgo (2020)

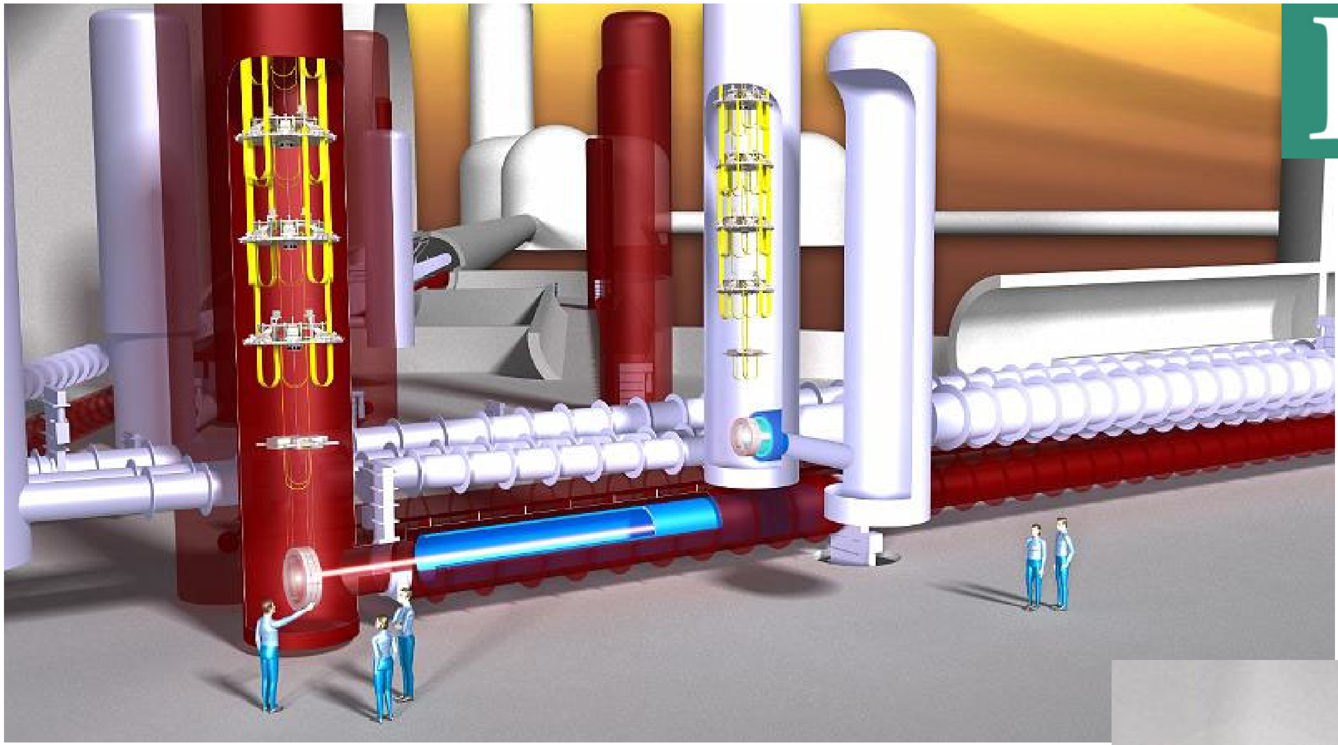


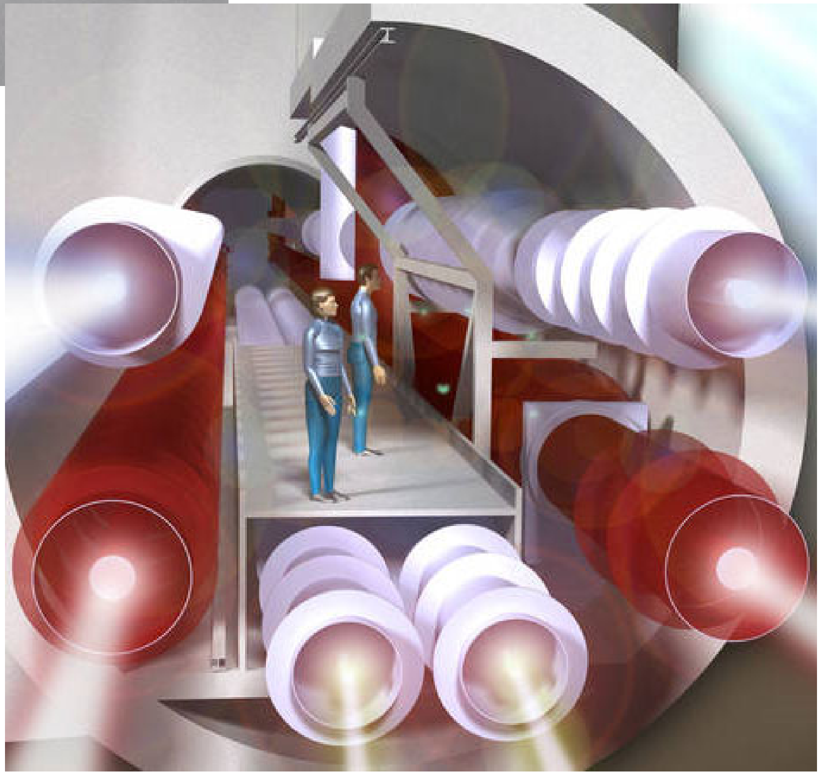







ET
EINSTEIN
TELESCOPE
Length 10 km
Depth 100-200m
Cooled mirrors
Funding > 2021
Site selection (Sardinia or Limburg) > 2022





10 x more sensitive
10 x times deeper sight
1000 x larger sensing "volume"
1000 x more events
from 1.4 billion light year(2015) → 14 billion light year

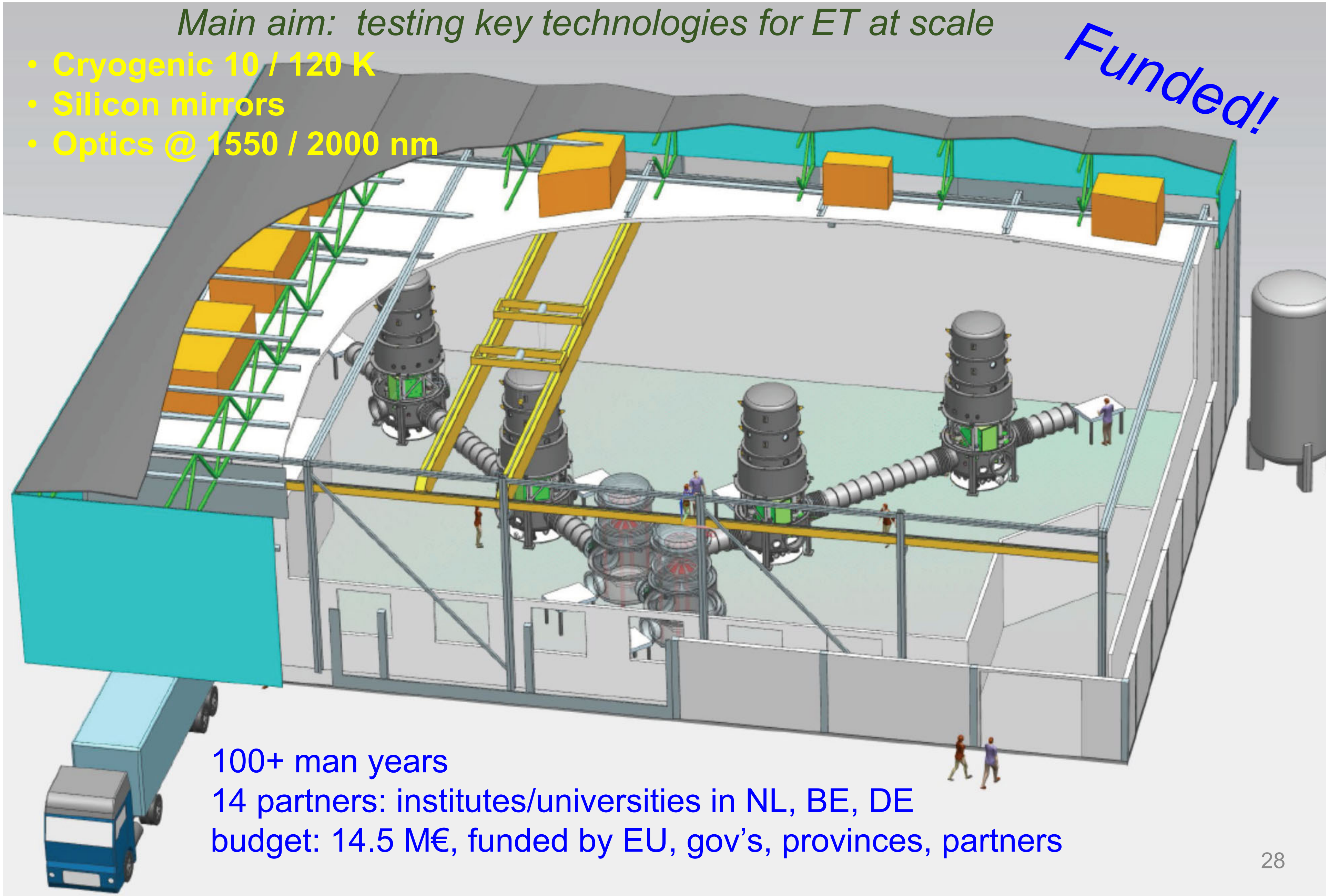
→ **Listening to the heart beat of the big bang!**

Maastricht 3G Prototype, alias ETpathfinder

Main aim: testing key technologies for ET at scale

- **Cryogenic 10 / 120 K**
- **Silicon mirrors**
- **Optics @ 1550 / 2000 nm**

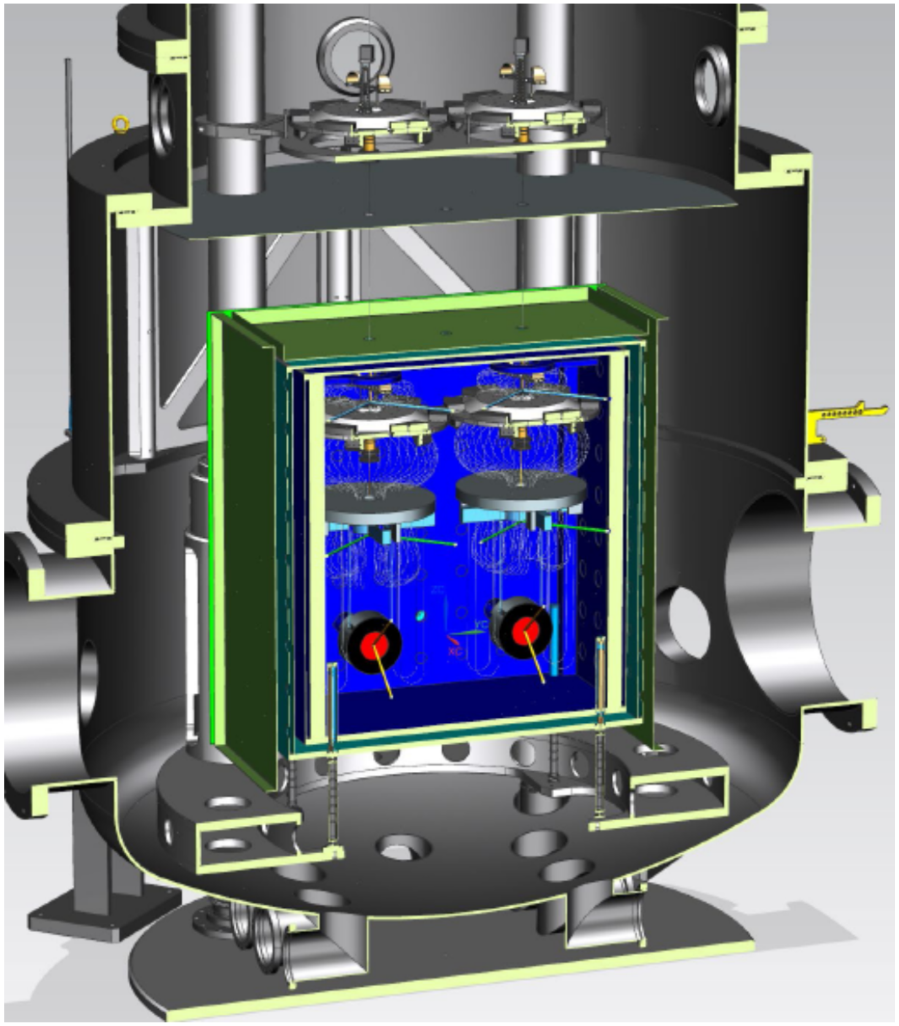
Funded!

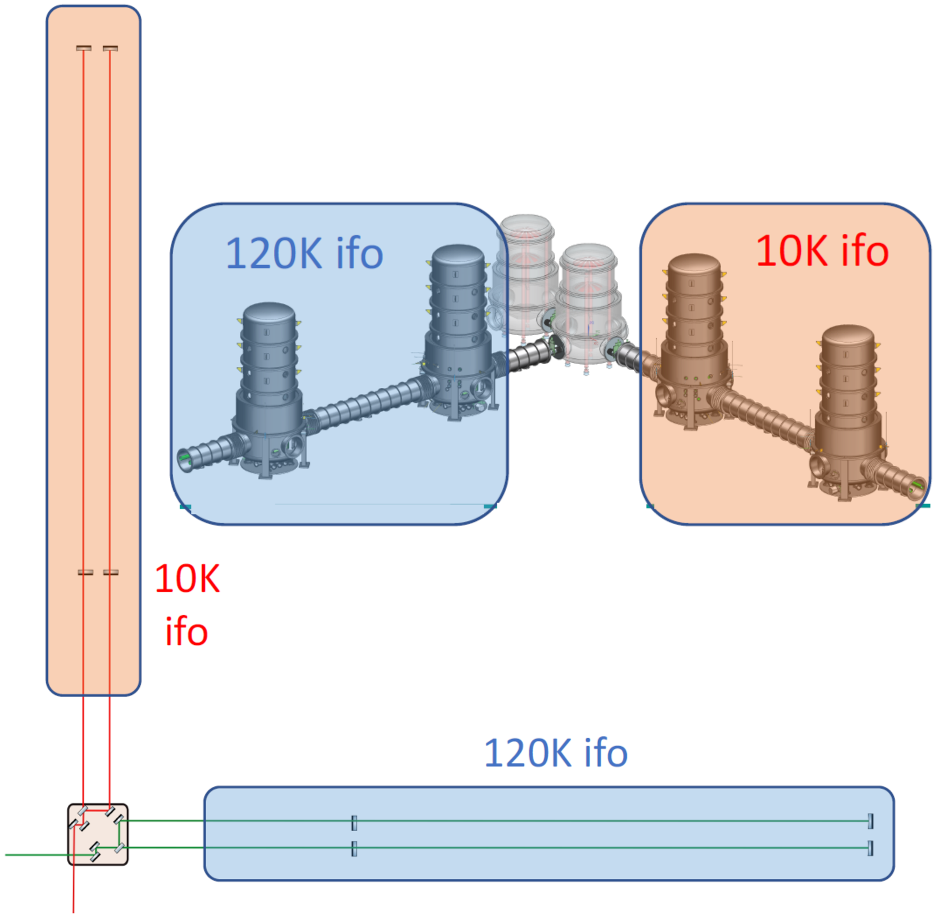


100+ man years
14 partners: institutes/universities in NL, BE, DE
budget: 14.5 M€, funded by EU, gov’s, provinces, partners

ETpathfinder phase 1

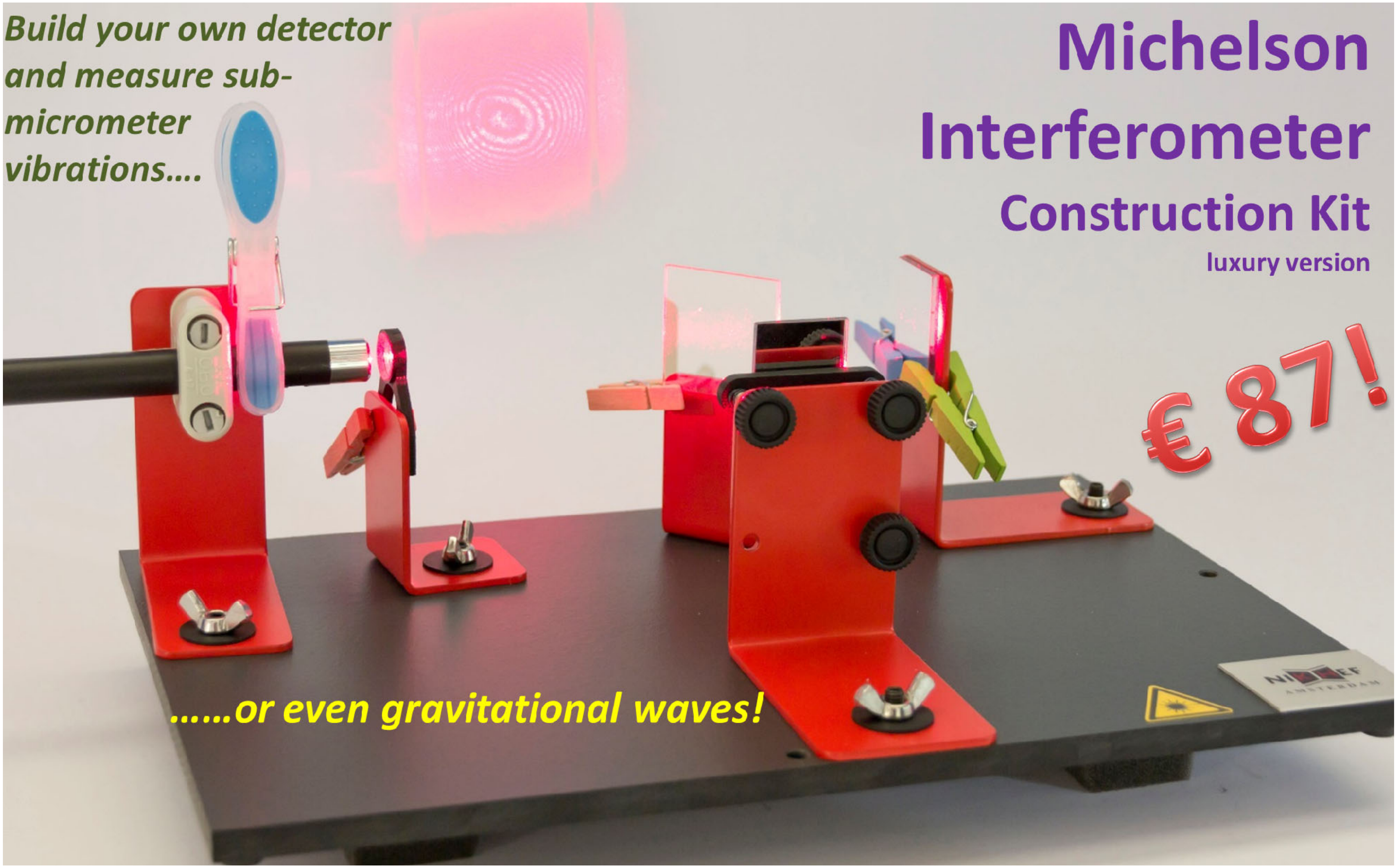
- 2 small mirrors in each cryostat
- 2 independent 10 m interferometers
- one @120K, one @10K





Challenges include :

- vibration-free cooling (sorption cooling?)
- Reduce vibration transfer via cold finger
- mirror cooling via silicon suspension wires
- Keep UHV without heat leaking in
- …..



Nikhef Particle Toys Contact: www.nikhef.nl, E.Hennes@nikhef.nl

Dank U wel!