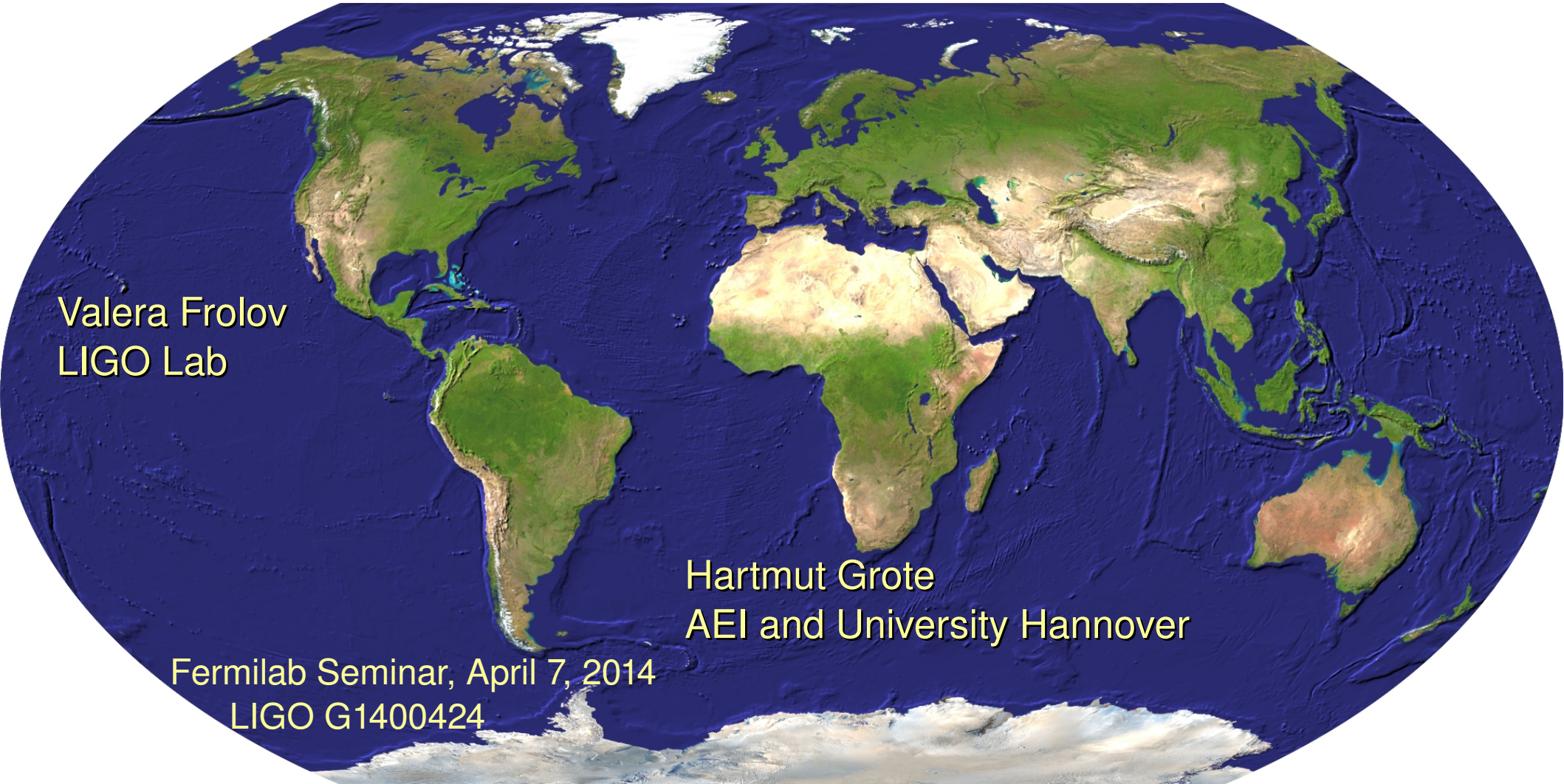
Gravitational-wave Detectors in Europe and the US

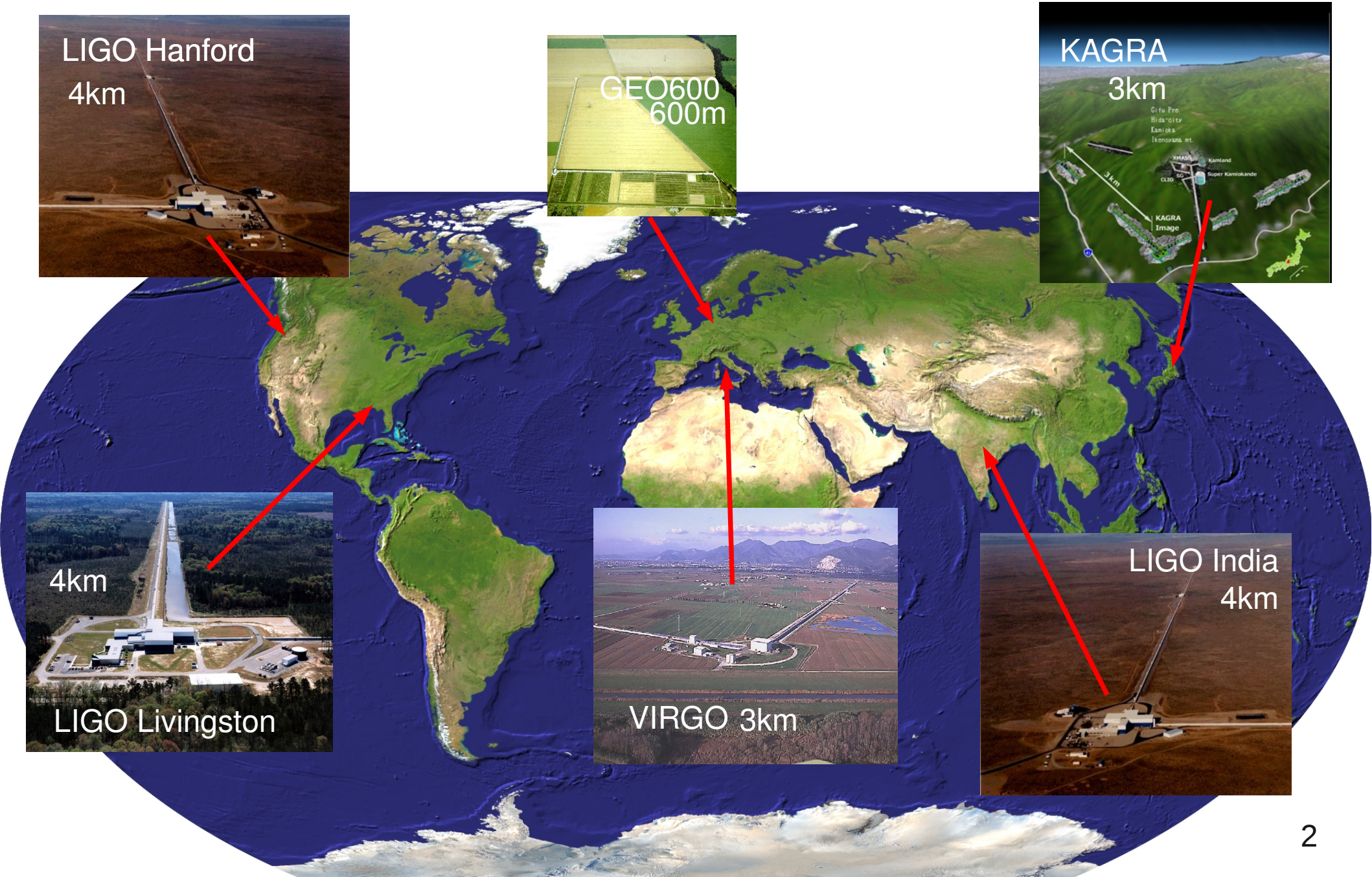


Valera Frolov
LIGO Lab

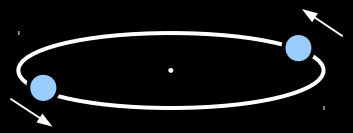
Hartmut Grote
AEI and University Hannover

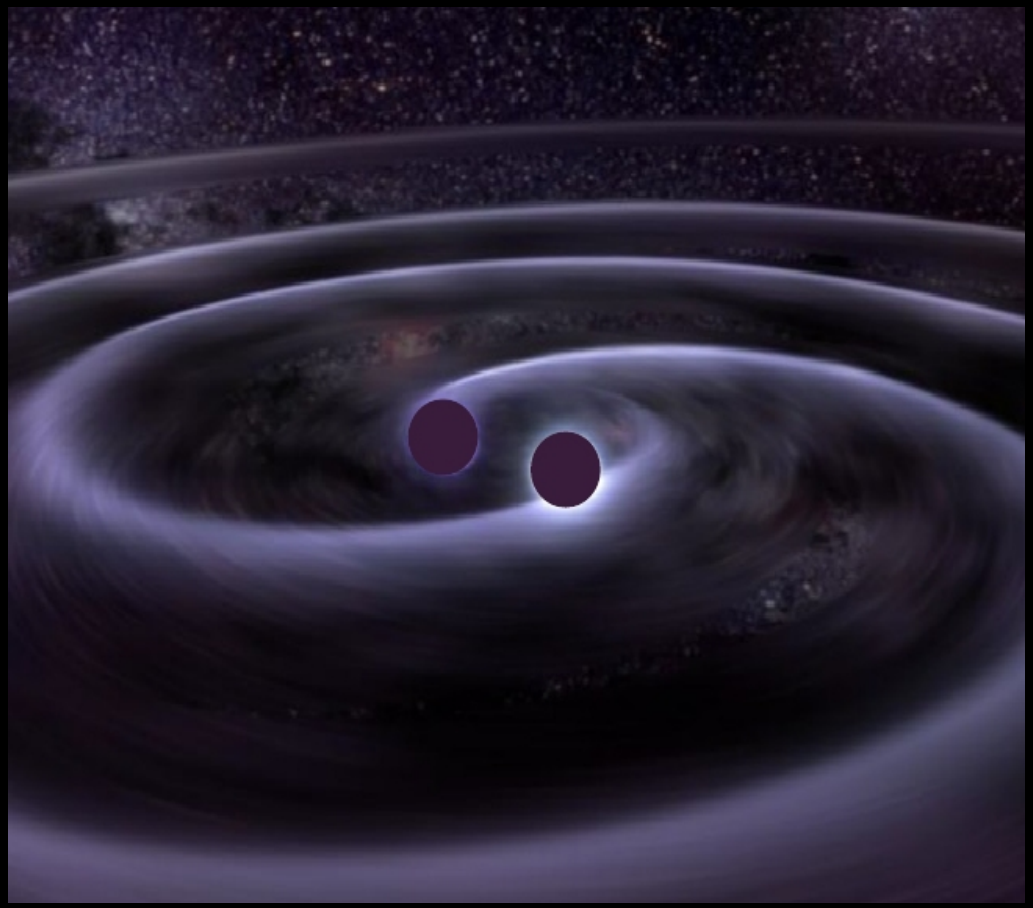
Fermilab Seminar, April 7, 2014
LIGO G1400424

Current GW – Interferometer Projects



Binary system radiating GWs



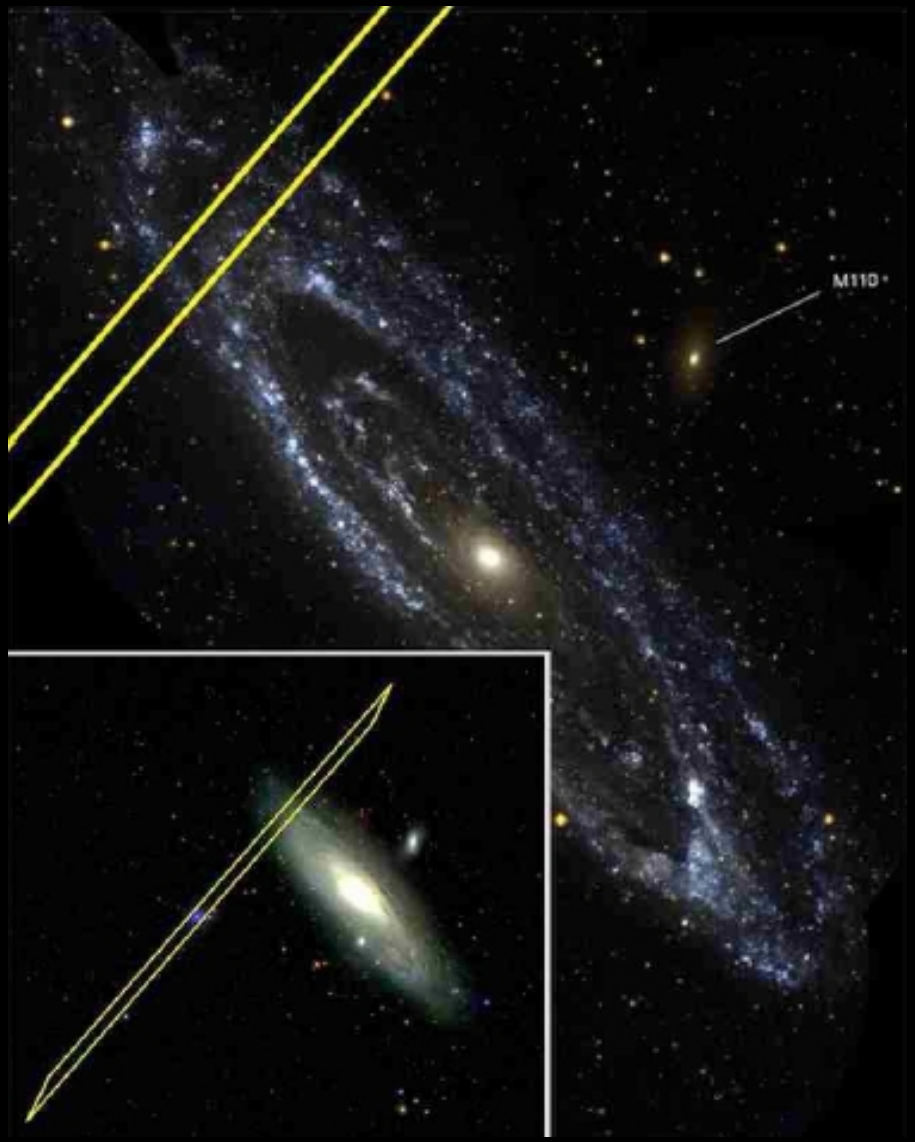


Late inspiral phase,
And possibly merger/ringdown

Result on GRB 070201

X-Ray sattelites determined sky patch of origin to be crossing Andromeda galaxy

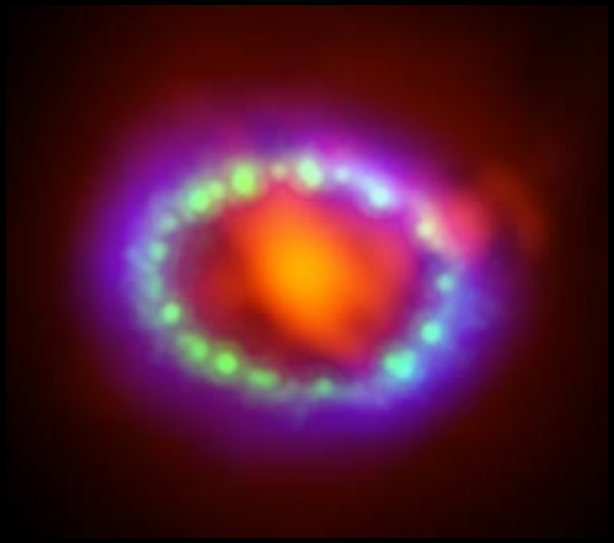
p>99% that GRB was not caused by inspiralling Compact objects in Andromeda



Supernovae

create strong gravitational-waves in an asymmetrical core-collapse

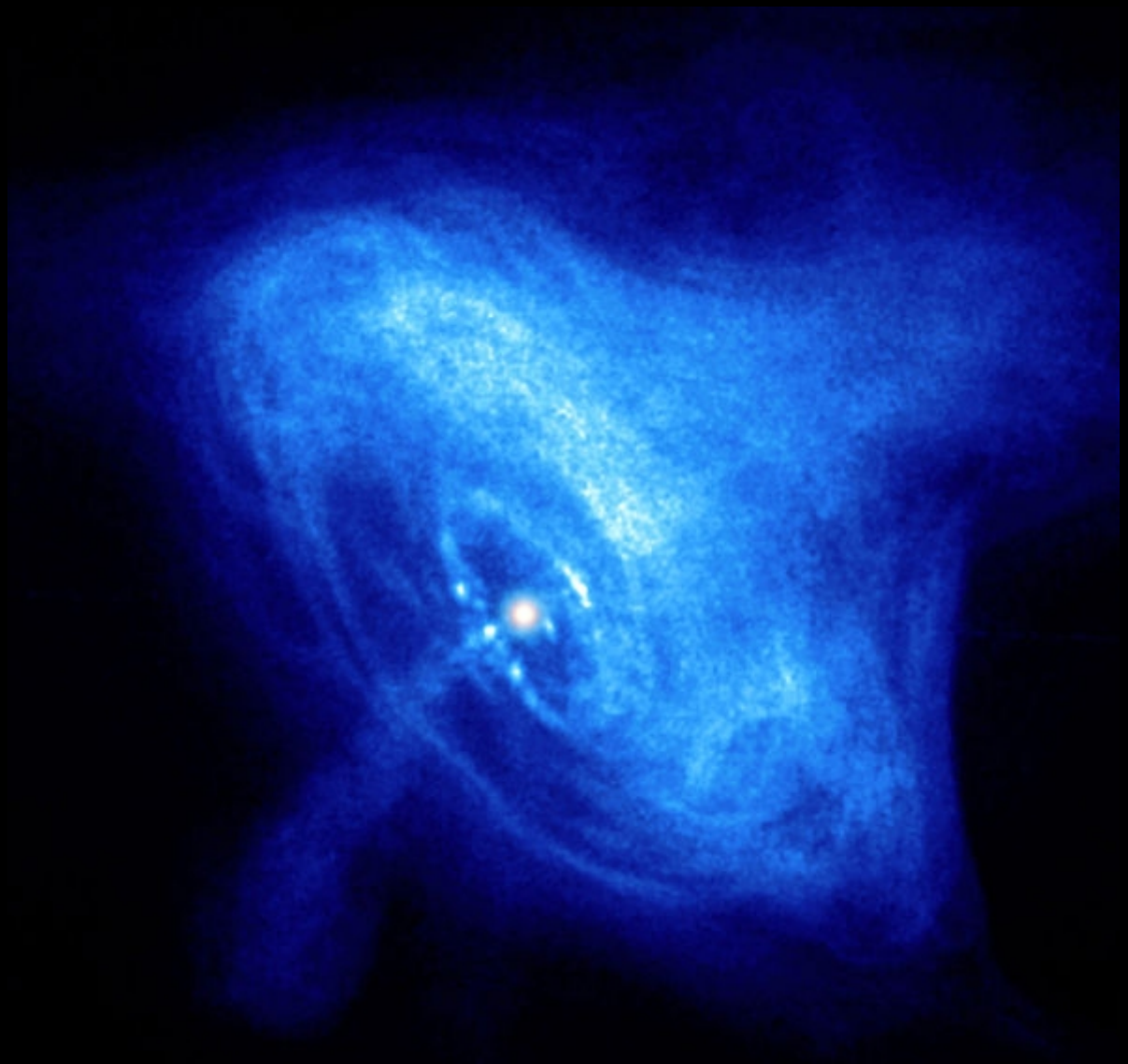
ESO, 1987



SN 1987a

Seen by
ALMA/Hubble/Chandra, 2014

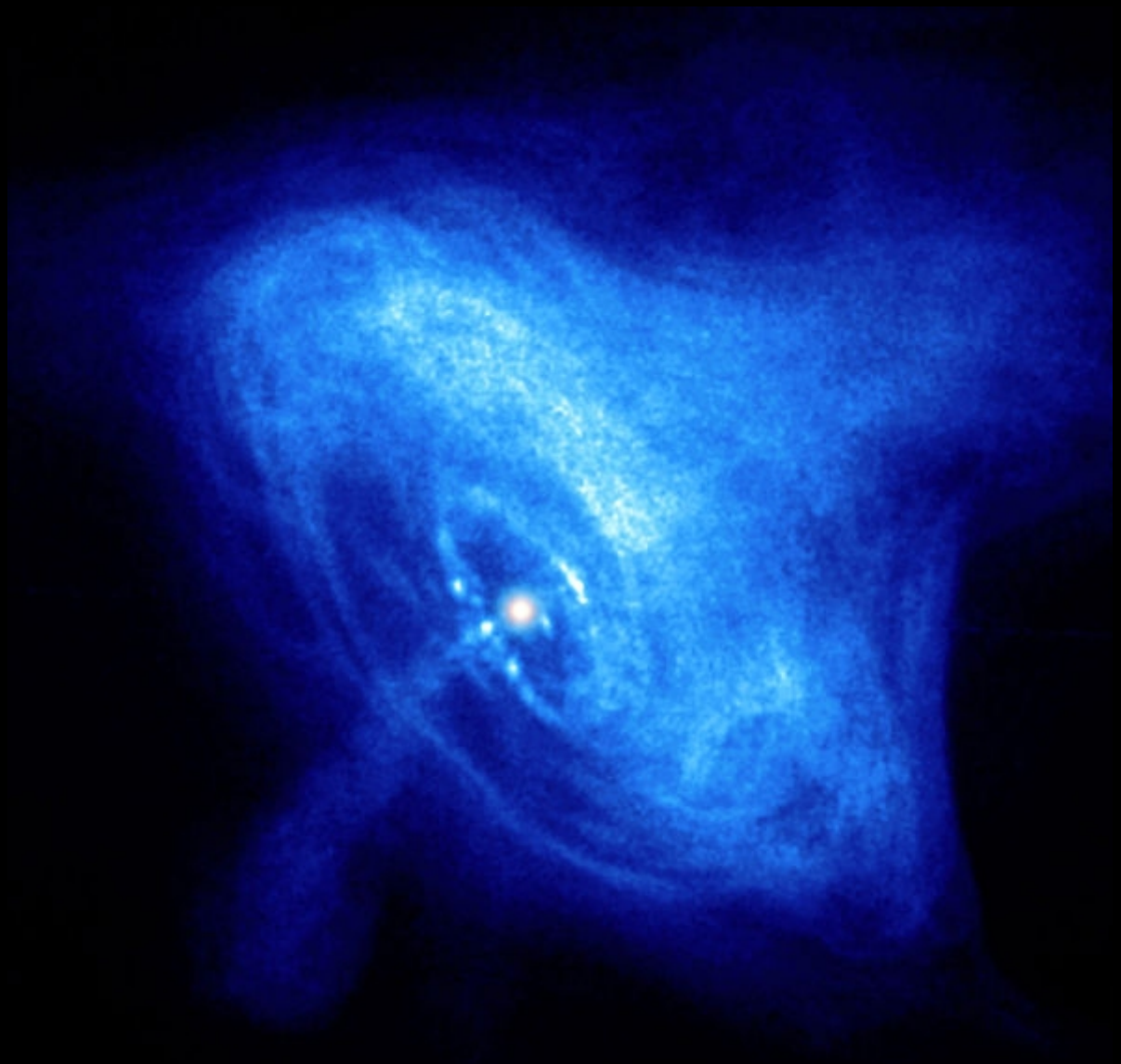
Fast rotating Neutron Stars with asymmetries



Remnant Neutron Star from

Supernova 1054 in crab nebular

Fast rotating Neutron Stars with asymmetries



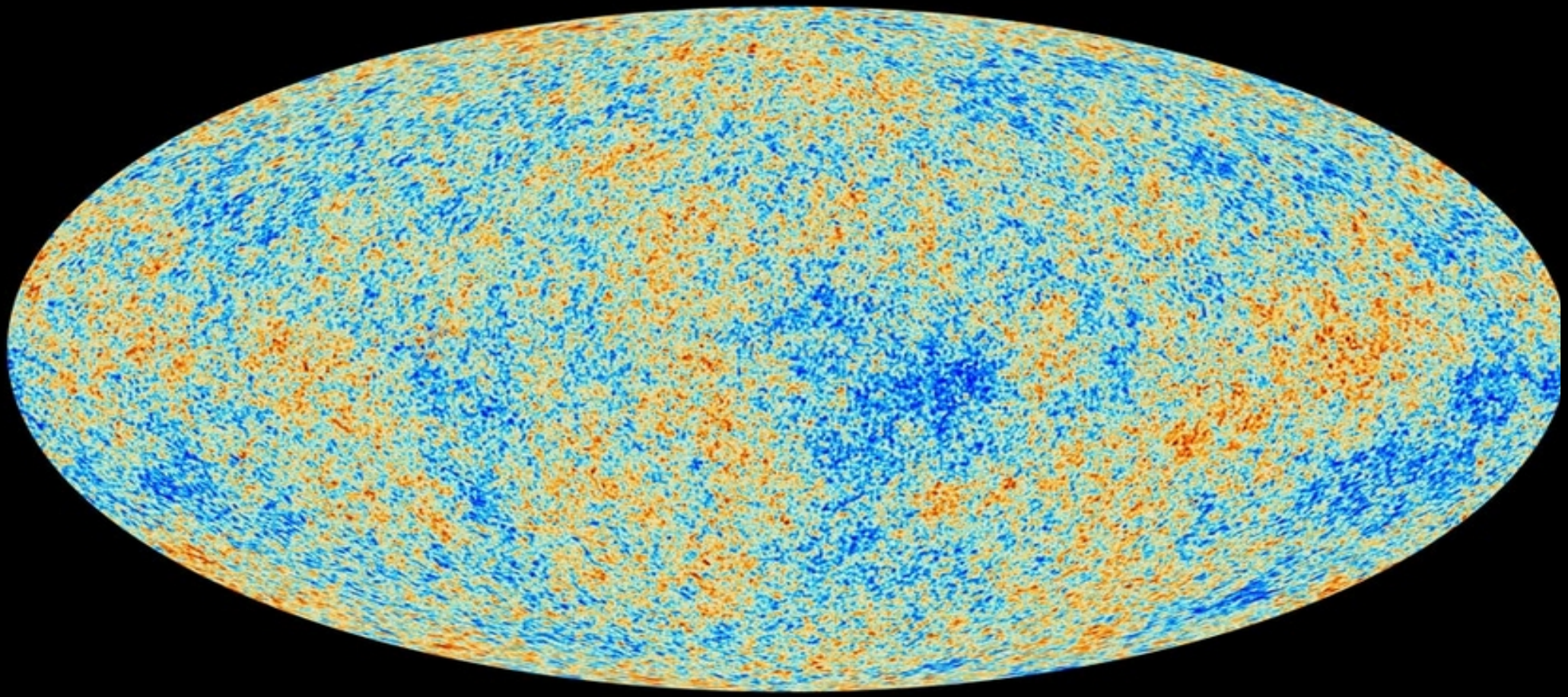
Remnant Neutron Star from

Supernova 1054 in crab nebular

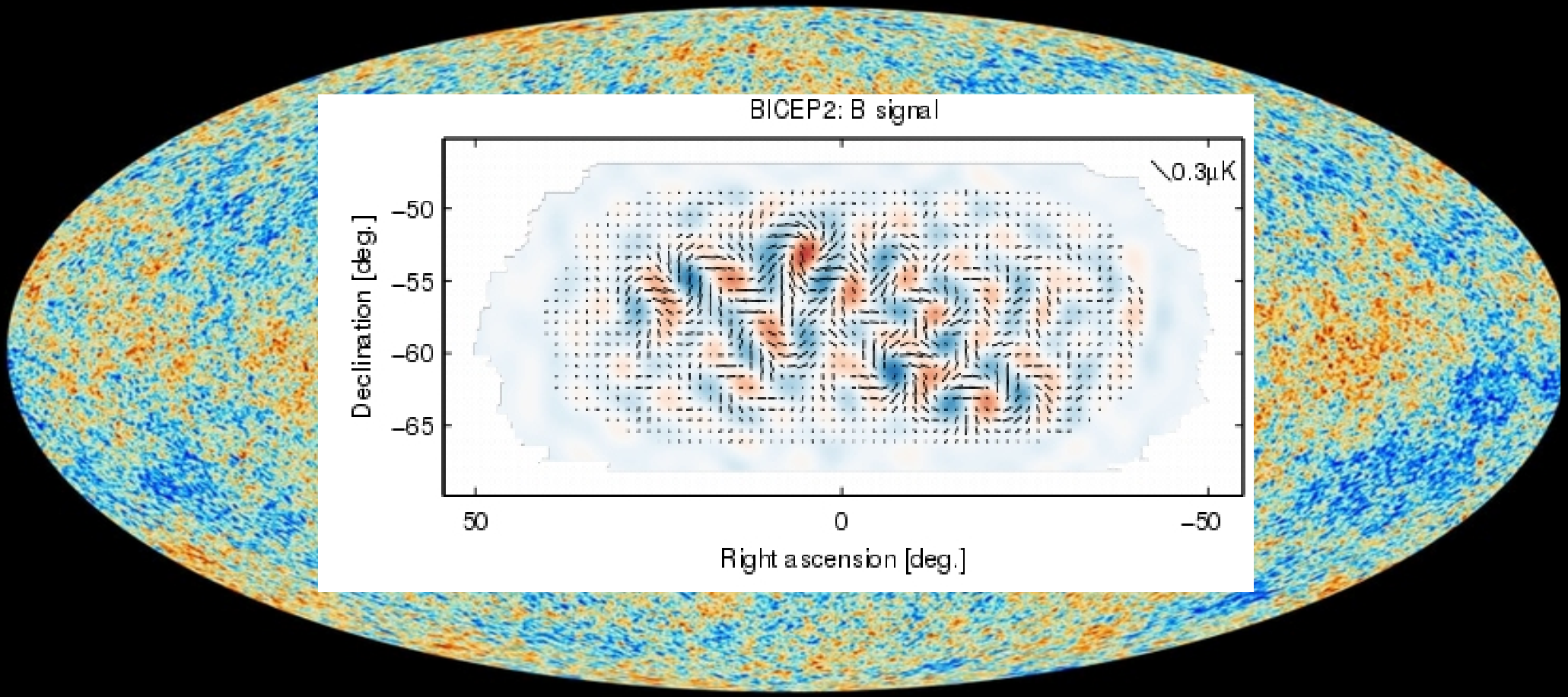
Result: Less than 1% of energy from spin-down-limit in Gravitational waves.

Vela Pulsar: < 10%

Stochastic Gravitational-Wave Background



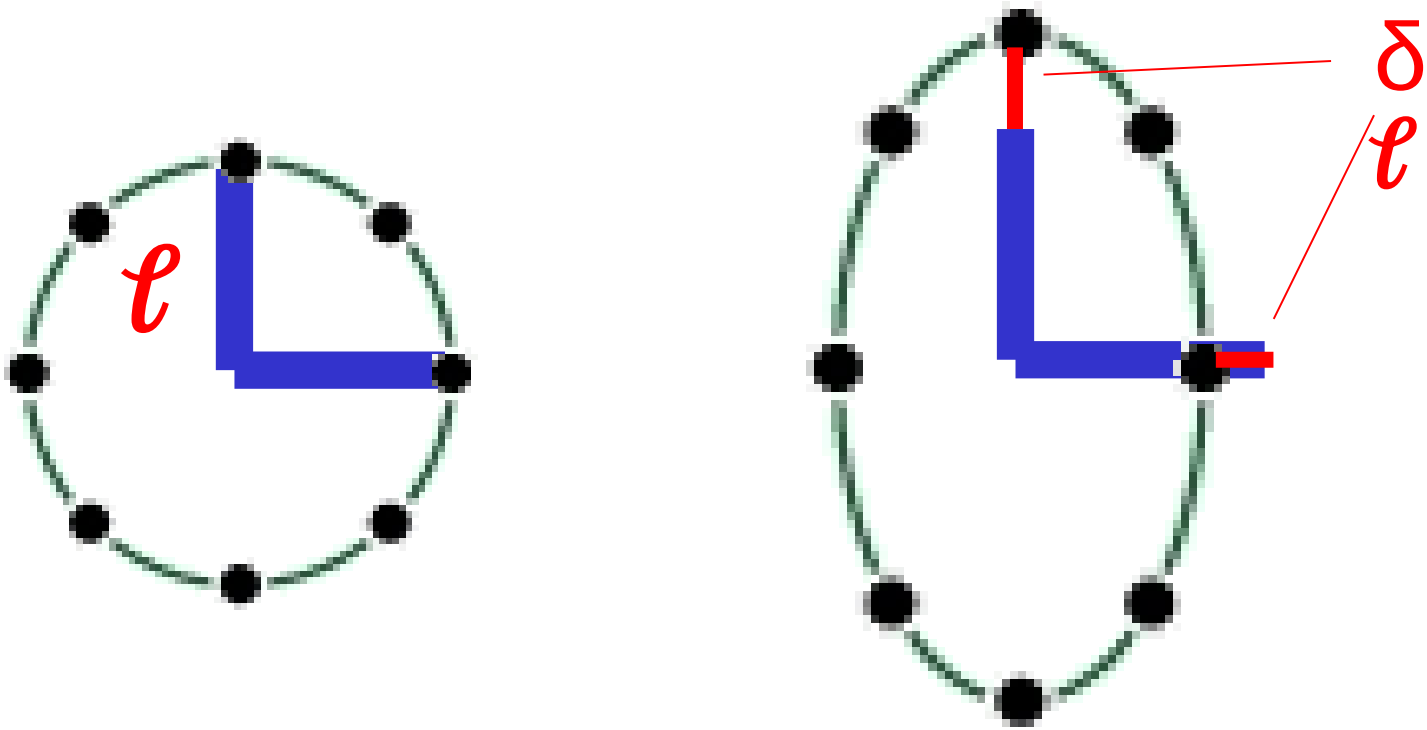
Stochastic Gravitational-Wave Background



Gravitational wave astronomy has long been a dream for cosmologists.
We now know these waves are out there, and encode priceless
cosmic information unavailable to optical,
radio or any other form of electromagnetic astronomy.
Expect a boost for the decades-old programme
of perfecting Earth-based gravitational wave detectors.

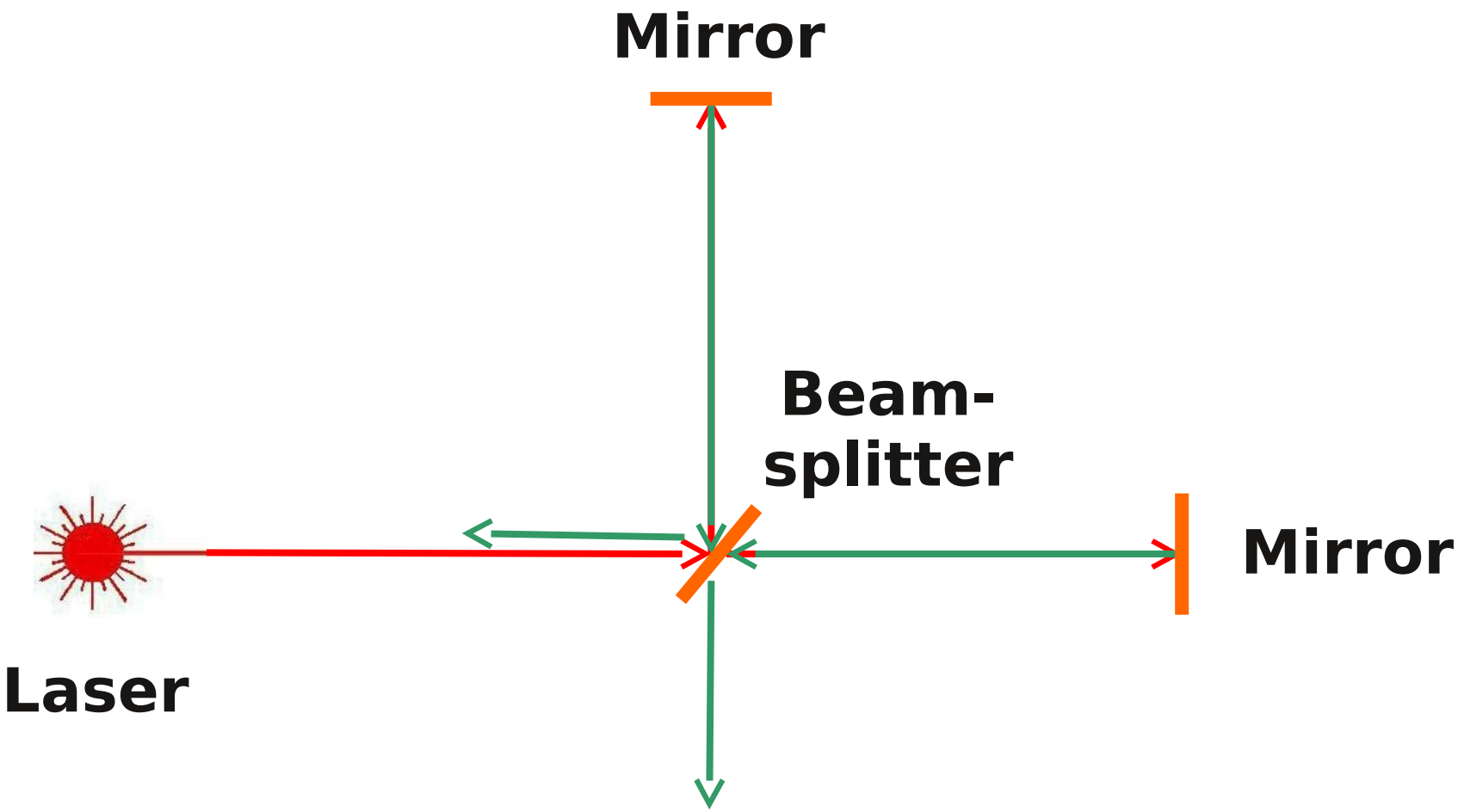
Paul Davies,
commenting BICEP2 results

The effect of a Gravitational Wave



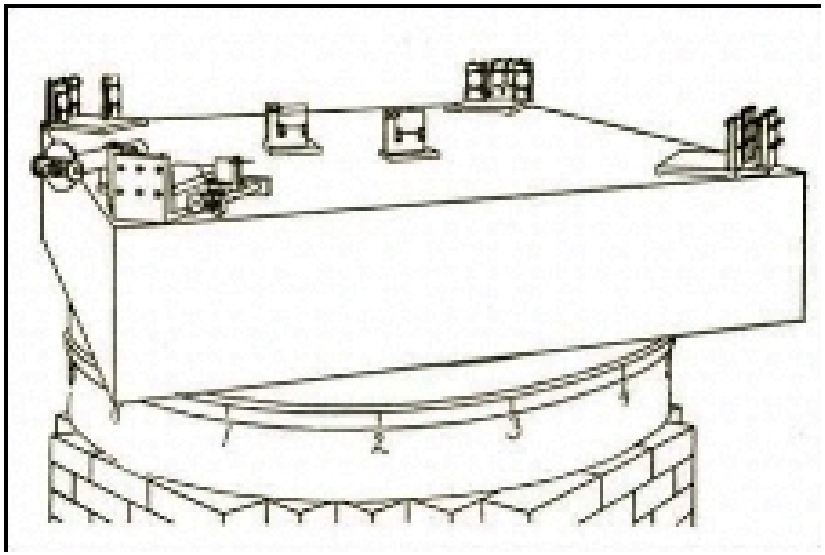
... is a differential length change $\delta\ell$ in the x- and y-direction, perpendicular to the direction of wave travel.

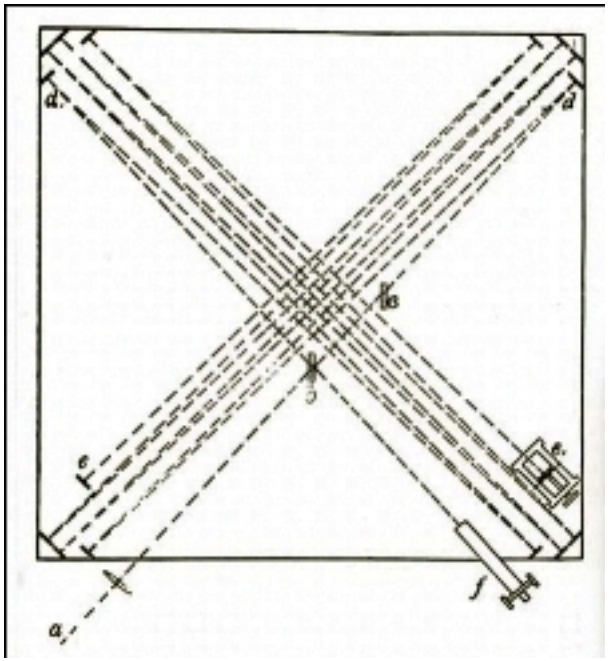
Michelson Interferometer



Albert Michelson

1852 - 1931

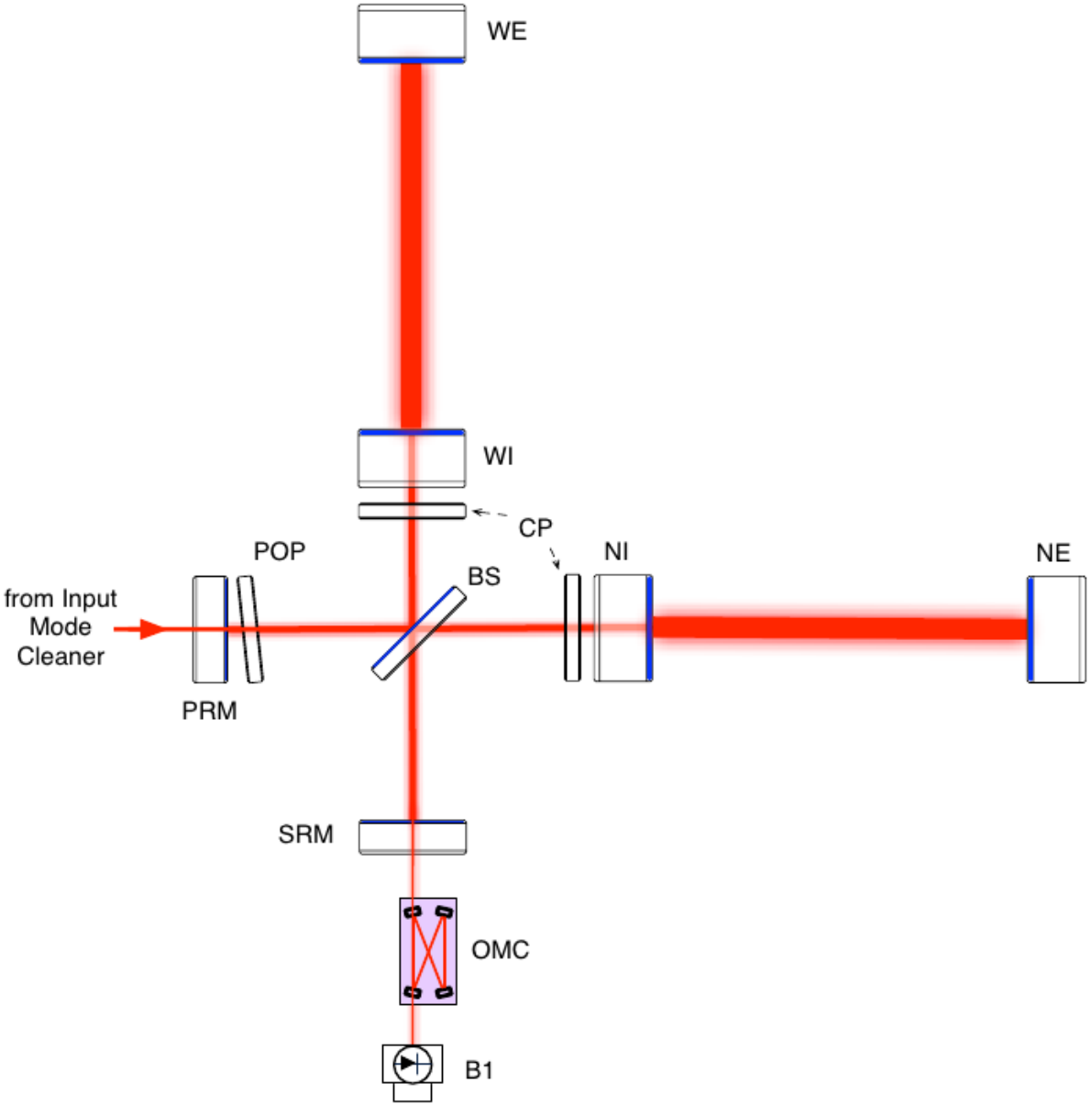


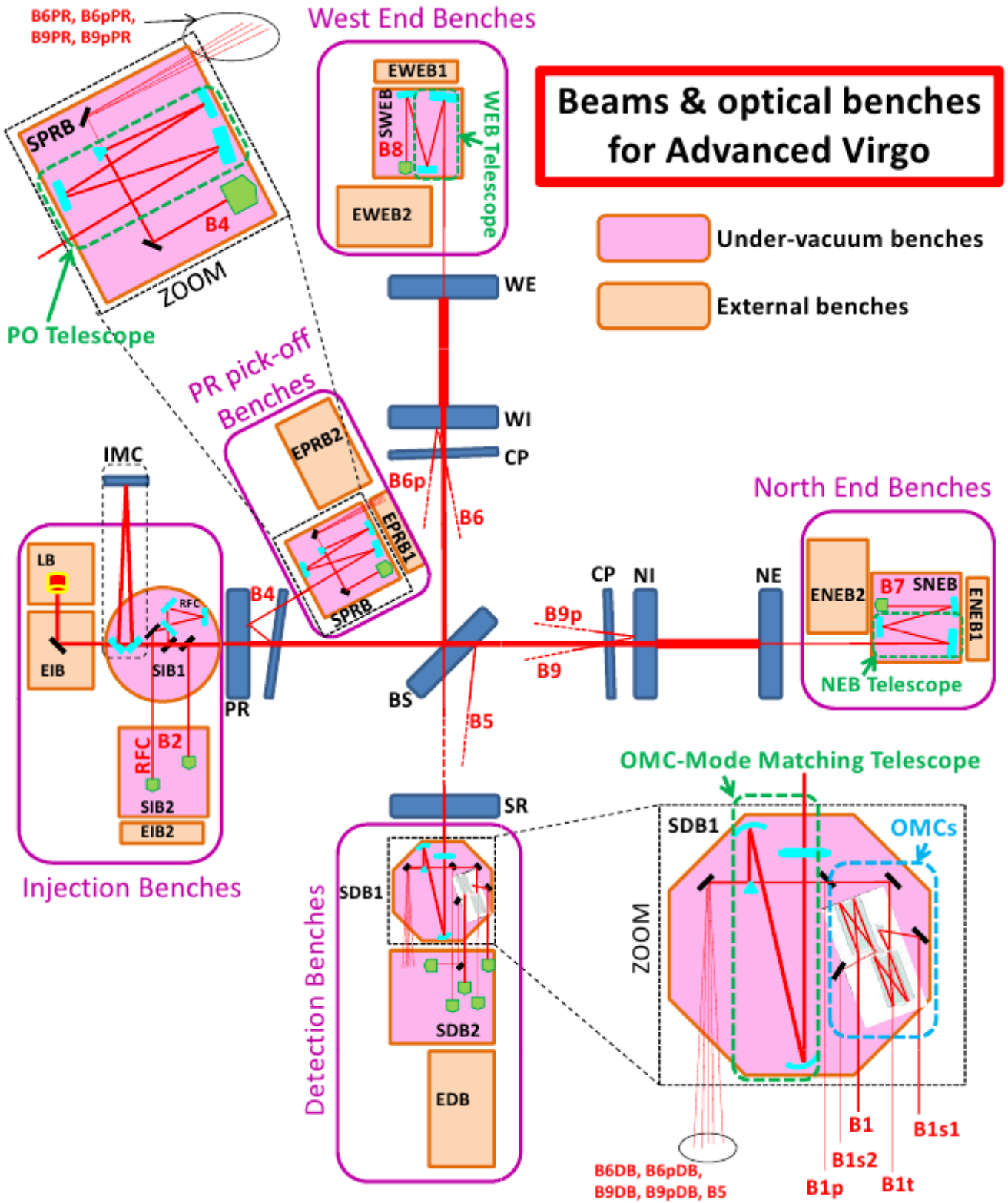


Michelson – Morley experiment

Accuracy: 10 nm (10^{-9} relative)

Advanced Detector with Power- and Signal Recycling and Arm Cavities (Virgo,LIGO,KAGRA)



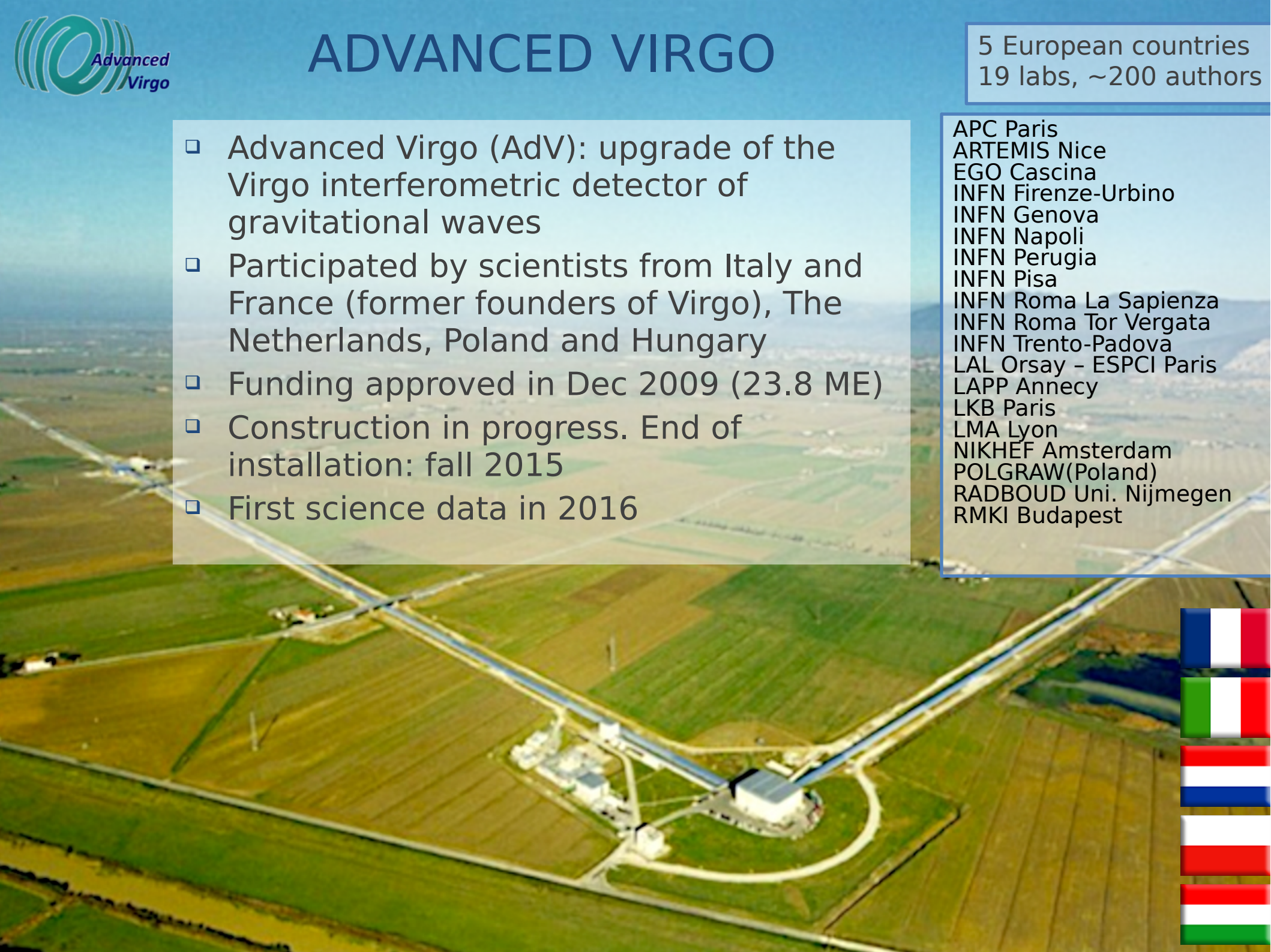

Beams & optical benches for Advanced Virgo
Under-vacuum benches
External benches
B6PR, B6pPR, B9PR, B9pPR
West End Benches
EWEB1
SWEB
B8
WEB Telescope
EWEB2
SPRB
B4
ZOOM
PO Telescope
WE
PR pick-off Benches
WI
CP
EPRB2
EPRB1
SPRB
B6p
B6
IMC
LB
EIB
RFC
SIB1
B4
PR
BS
B5
B9p
B9
CP
NI
NE
North End Benches
ENEB2
B7
SNEB
ENEB1
NEB Telescope
RFC
B2
SIB2
EIB2
Injection Benches
SR
OMC-Mode Matching Telescope
SDB1
OMCs
ZOOM
SDB1
SDB2
EDB
Detection Benches
B6DB, B6pDB, B9DB, B9pDB, B5
B1
B1s1
B1s2
B1p
B1t

ADVANCED VIRGO

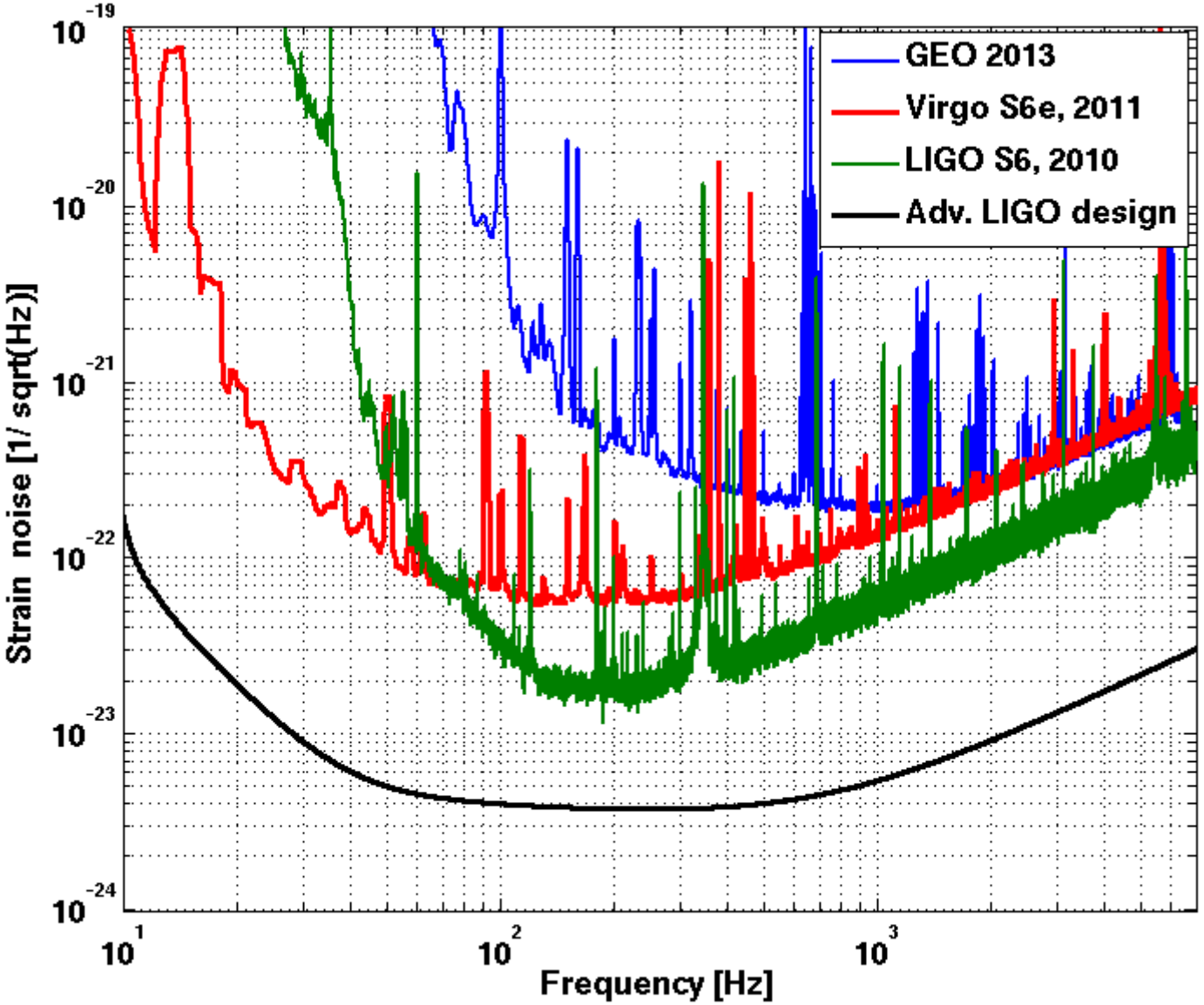
5 European countries
19 labs, ~200 authors

- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector of gravitational waves
- Participated by scientists from Italy and France (former founders of Virgo), The Netherlands, Poland and Hungary
- Funding approved in Dec 2009 (23.8 ME)
- Construction in progress. End of installation: fall 2015
- First science data in 2016

APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest



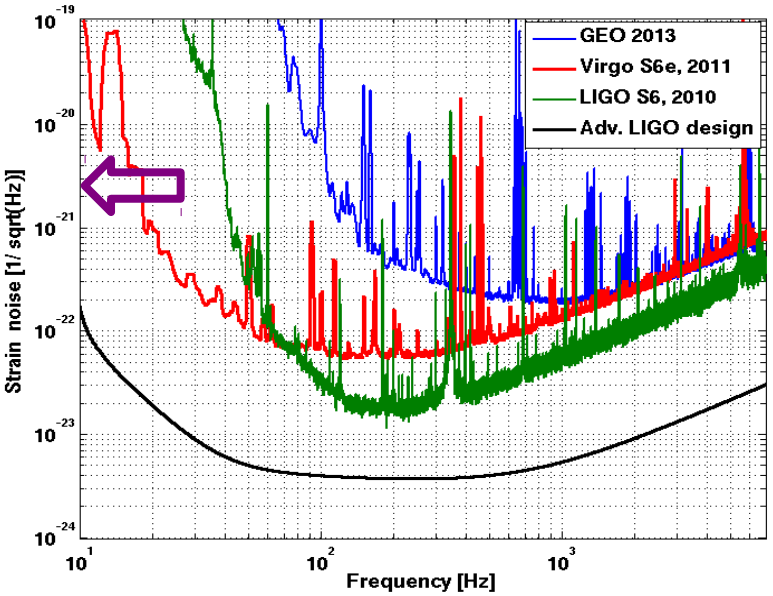
Improving Sensitivity in Advanced Detectors

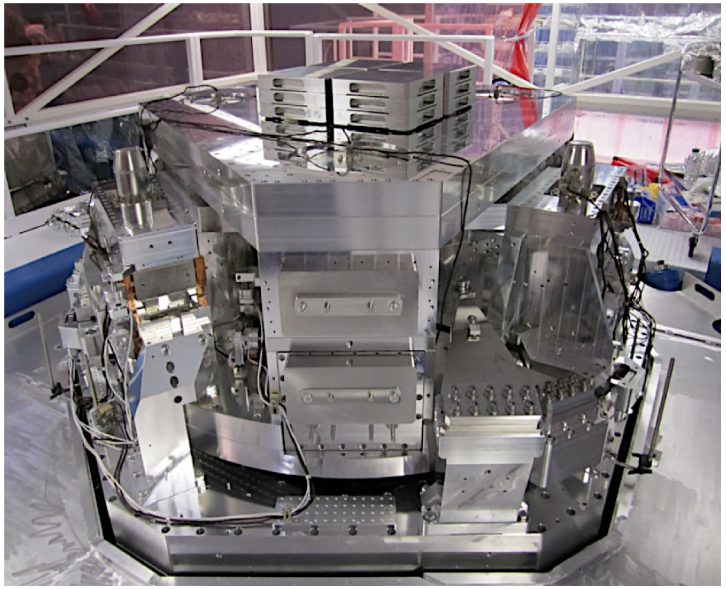


TECHNOLOGIES

LOW FREQUENCY RANGE

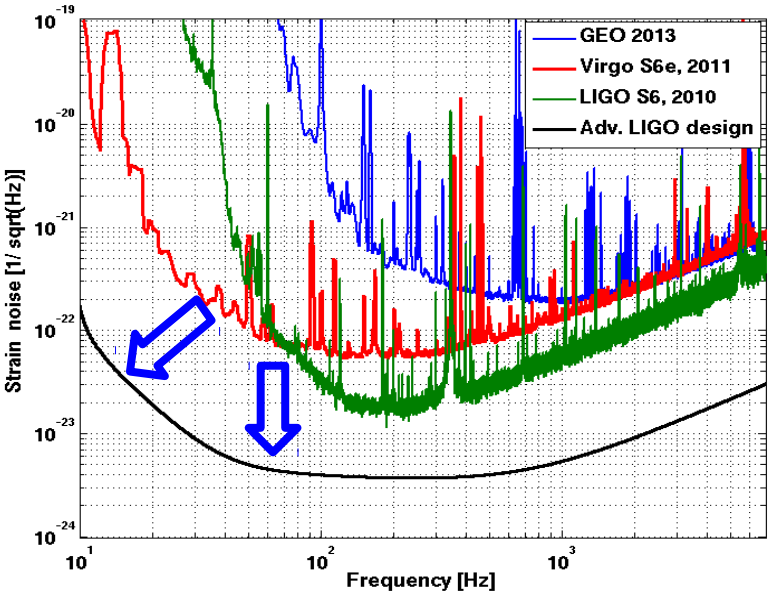
- Dominated by seismic noise
- Managed by suspending the mirrors from extreme vibration isolators
  - Virgo Superattenuator (from 1st generation) / 8 stages
  - LIGO active system + 4 stages
- Technical noises of different nature are the real challenge in this range
- Ultimate limit for ground based detectors: gravity gradient noise



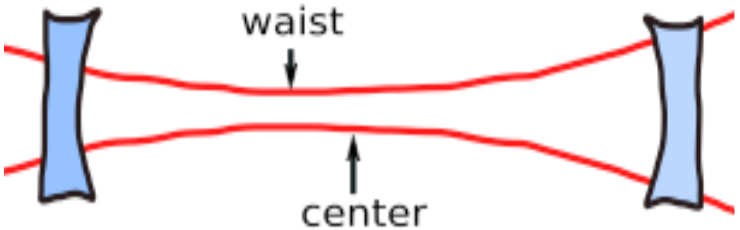


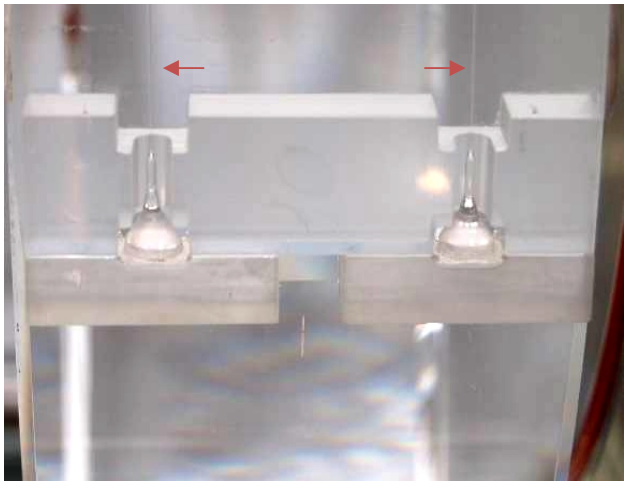
TECHNOLOGIES

MID FREQUENCY RANGE



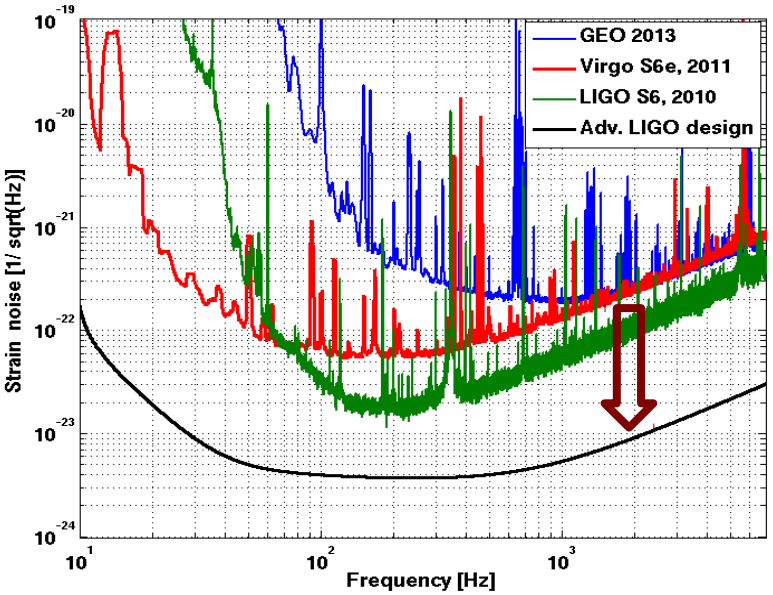
- Dominated by thermal noise of
  - Mirror coatings
  - Suspensions
- Reduced by:
  - Improved optical configuration: larger beam spot
  - Mirror coatings engineered for low losses
  - Test masses suspended by fused silica fibers (low mechanical losses)



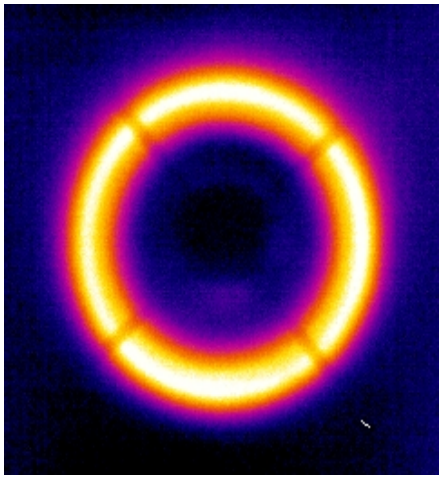


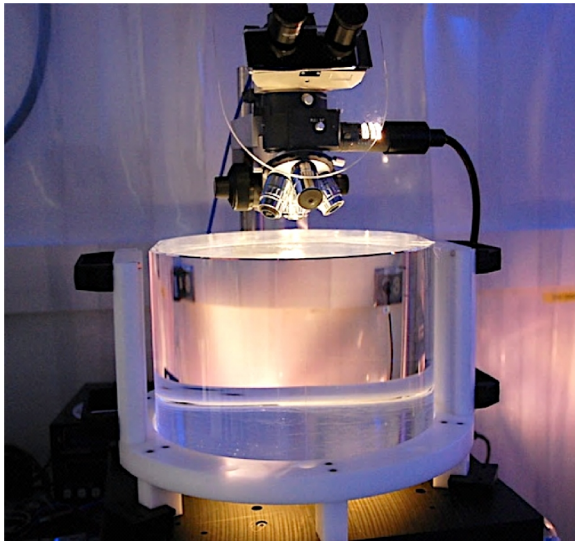
TECHNOLOGIES

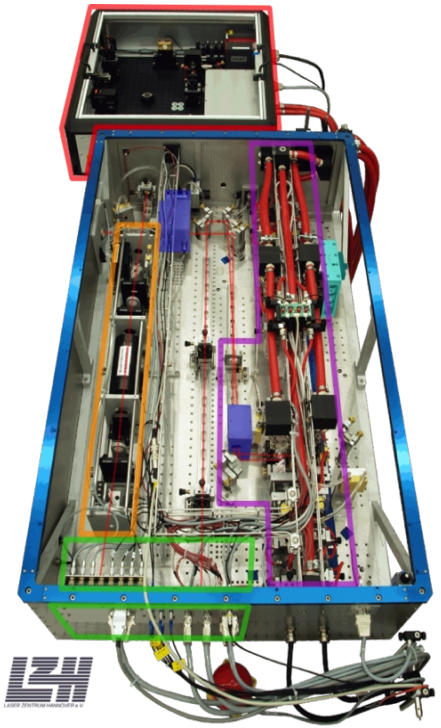
HIGH FREQUENCY RANGE



- Dominated by laser shot noise
- Improved by increasing the power: >100W input, ~1 MW in the cavities
- REQUIRES:
  - New laser amplifiers (solid state, fiber)
  - Heavy, low absorption optics (substrates, coatings)
  - Smart systems to correct for thermal aberrations: Ring heaters, heat projectors, scanning CO2 lasers

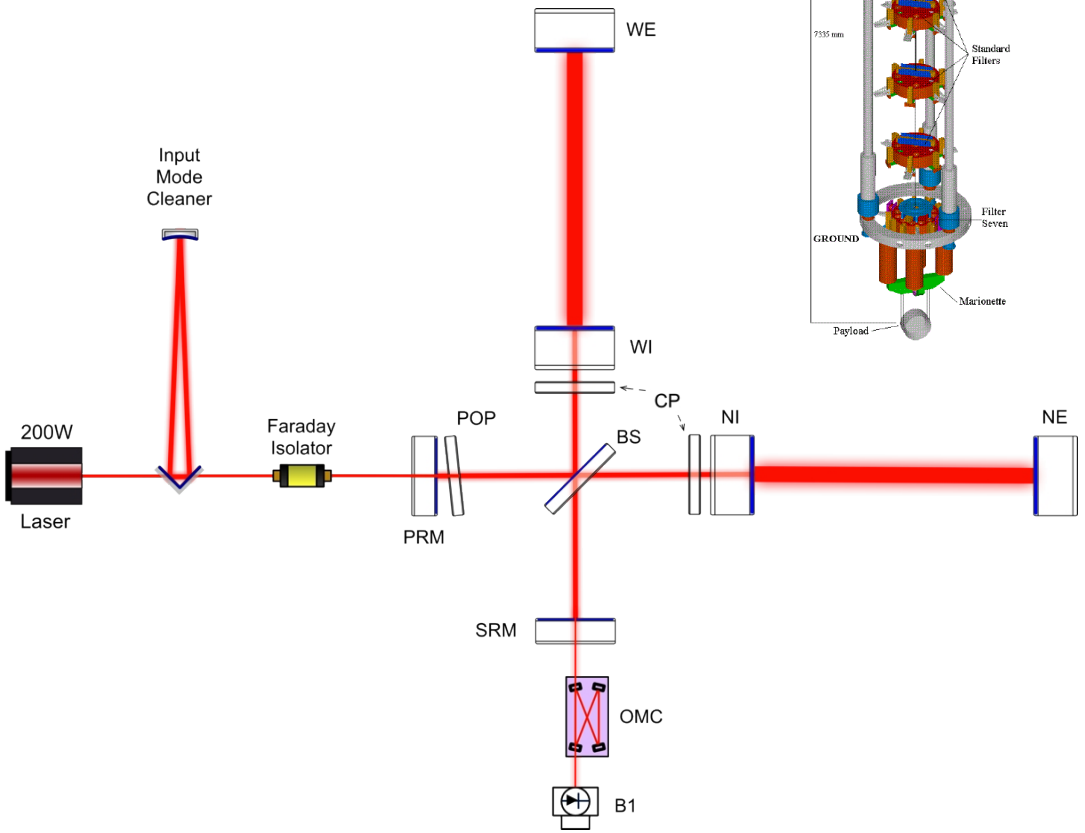


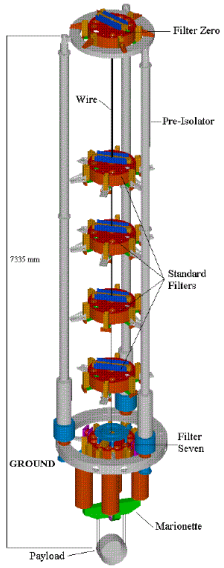




DETECTOR DESIGN

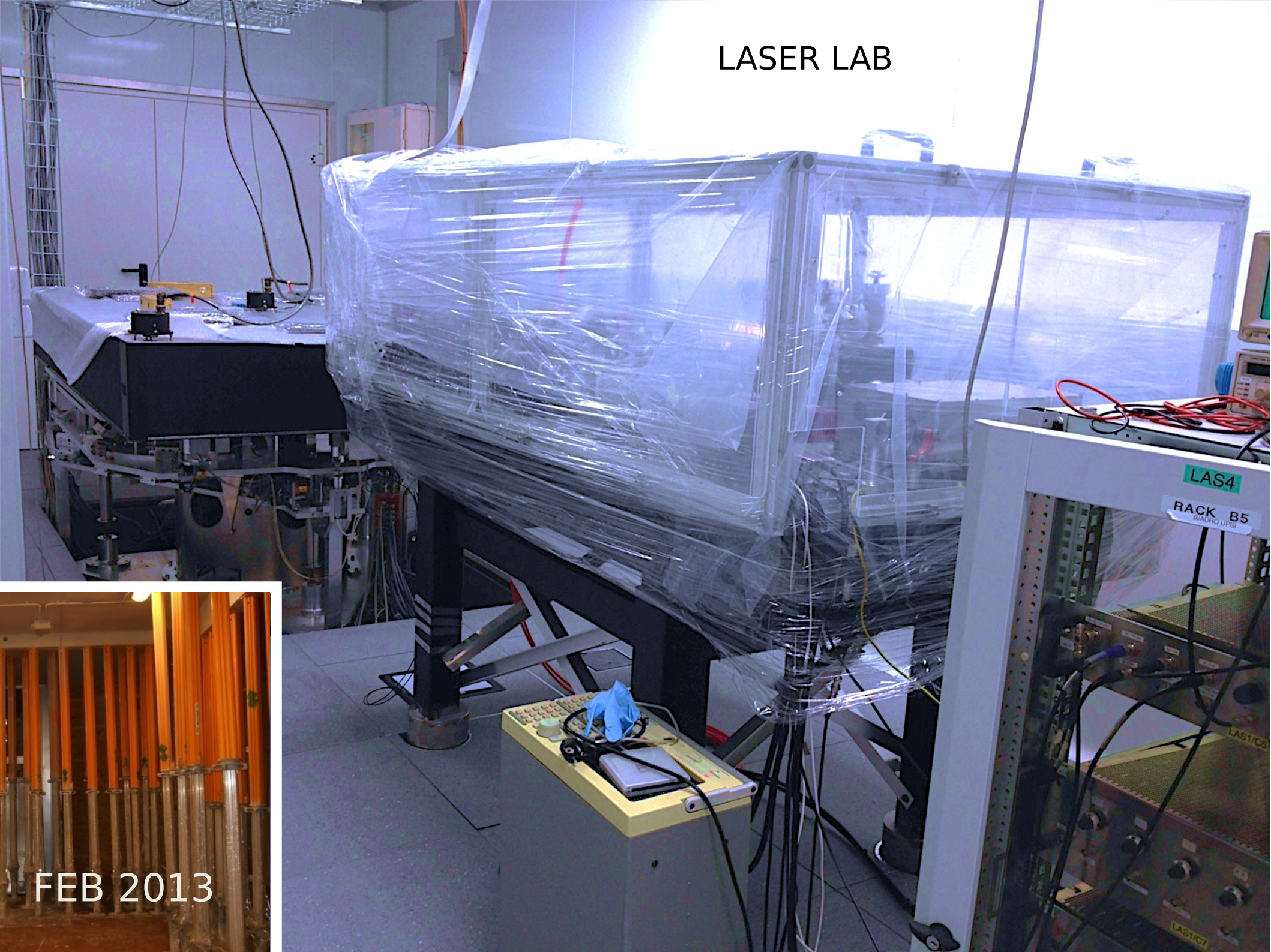
- MAIN CHANGES wrt Virgo
  - larger beam
  - heavier mirrors
  - higher quality optics
  - thermal control of aberrations
  - *200W fiber laser*
  - *signal recycling*
- Vibration isolation by Virgo superattenuators
  - performance demonstrated
  - large experience gained with commissioning at low frequency





2015 CHALLENGE

- Start in 2015 with a simplified configuration: likely to reduce commissioning time
  - No signal recycling (reduce locking complexity)
  - Virgo+ laser (up to 60W)
  - Low power (reduce risks with thermal effects and high power laser)
- Target BNS inspiral range: >100 Mpc
- Configuration upgrade schedule to be discussed with the partners
- First mirror just suspended in input modecleaner...


LASER LAB
LAS4
RACK B5
FEB 2013

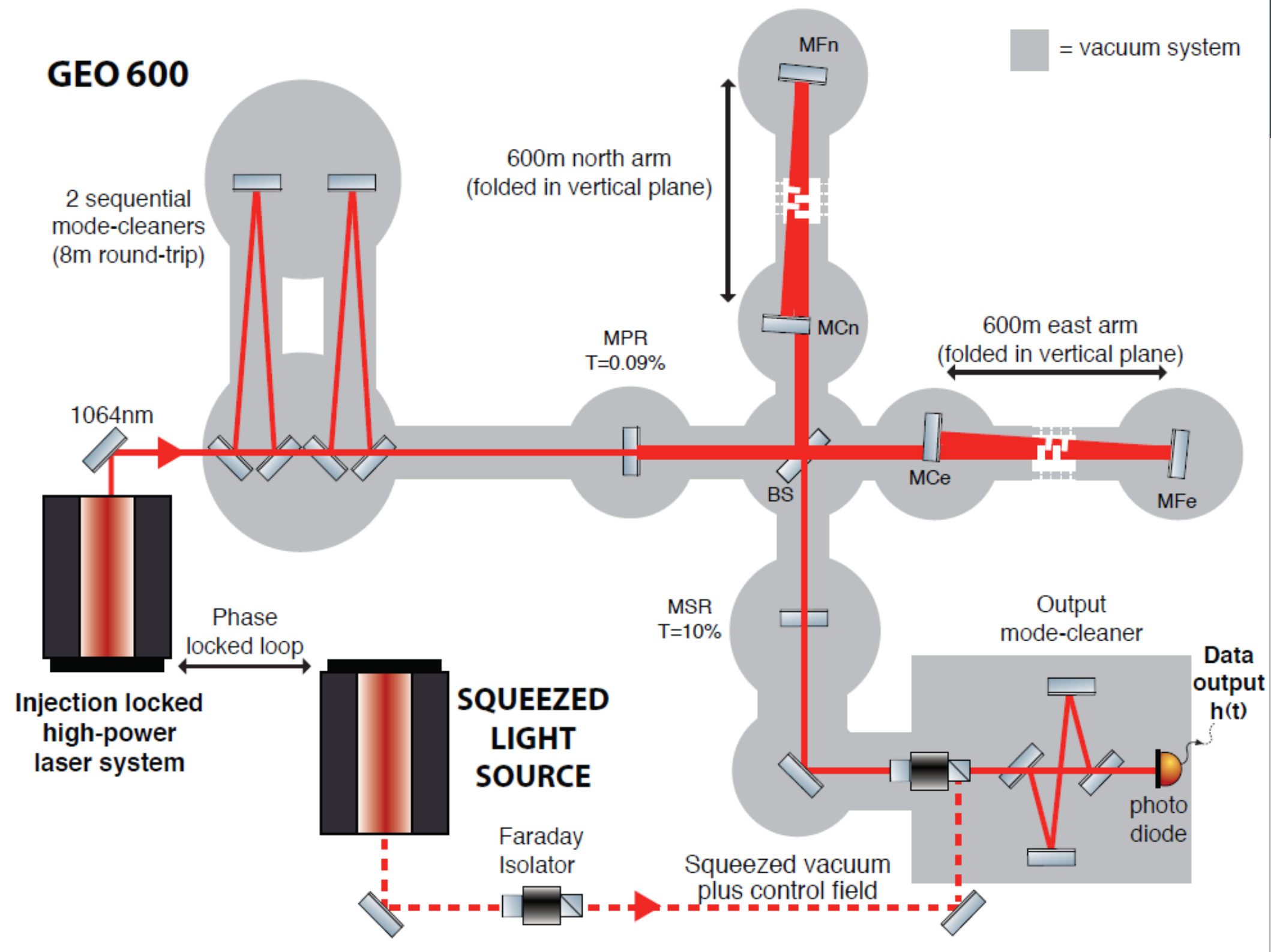
ASSEMBLY OF
THE INPUT OPTICS
BENCH

GEO600

Leibniz Universität Hannover

CARDIFF UNIVERSITY

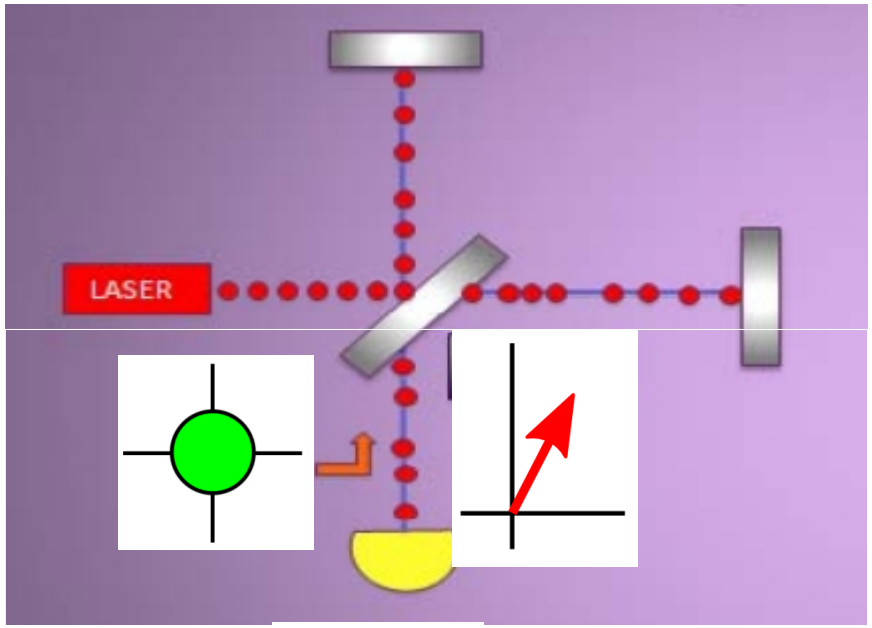
Universitat de les Illes Balears

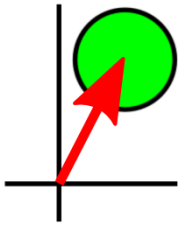

GEO 600
= vacuum system
MFn
600m north arm
(folded in vertical plane)
2 sequential
mode-cleaners
(8m round-trip)
MCn
MPR
T=0.09%
600m east arm
(folded in vertical plane)
1064nm
BS
MCe
MFe
MSR
T=10%
Output
mode-cleaner
Data
output
h(t)
Phase
locked loop
Injection locked
high-power
laser system
SQUEEZED
LIGHT
SOURCE
photo
diode
Faraday
Isolator
Squeezed vacuum
plus control field

GEO600 topics (2009 - 2016+)

- GEO-HF upgrade program
  - DC readout, OMC, SR change, Squeezing, Power increase (Laser upgrade, IO upgrade)
- 'Astrowatch'
  - Taking data 2/3 of time since 2011
- Instrument Research
  - Output mode-cleaner control
  - Thermal compensation
  - Squeezing
  - ...

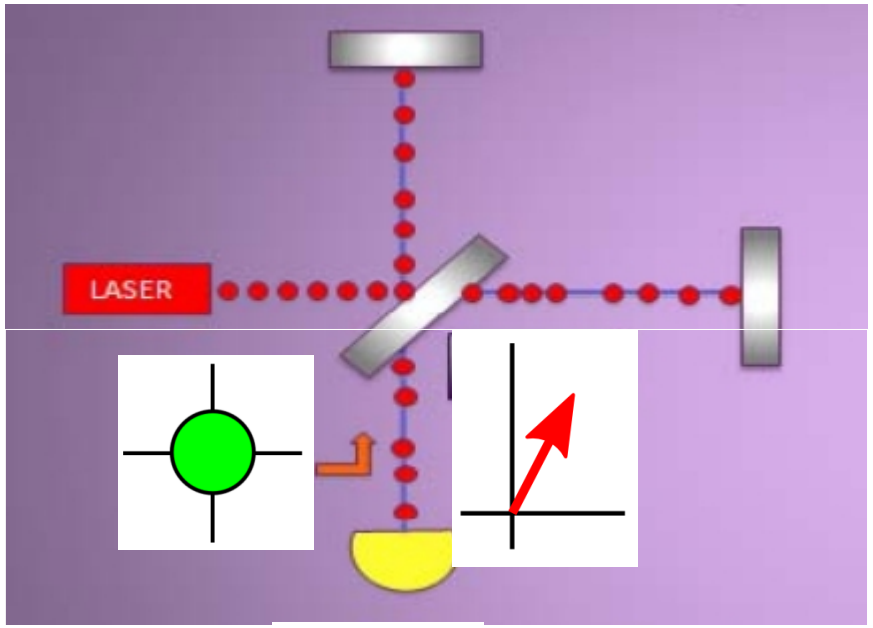
Vacuum fluctuations in interferometers

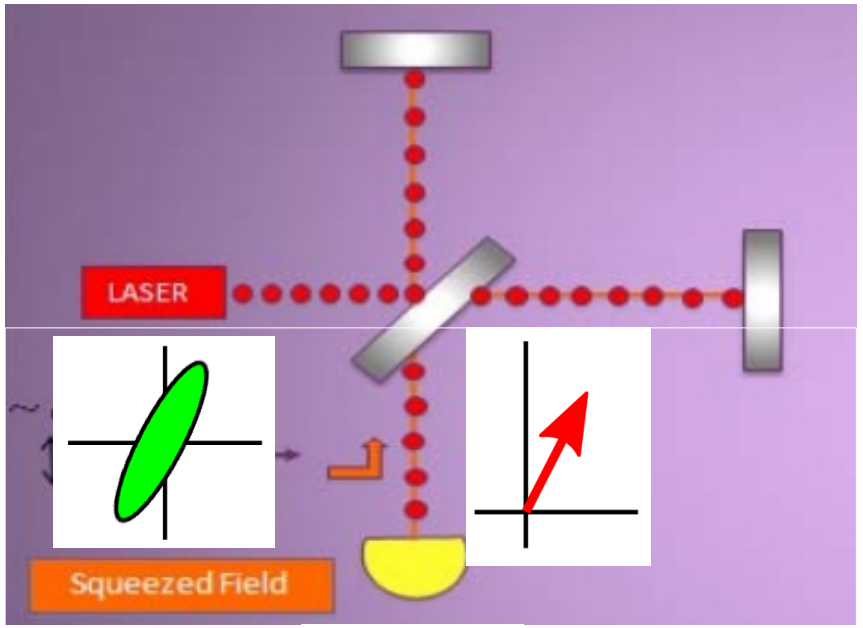


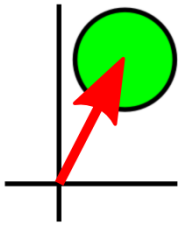


Diagrams credit: L. Barsotti, K. Dooley

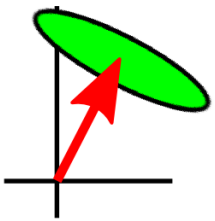
Vacuum fluctuations in interferometers





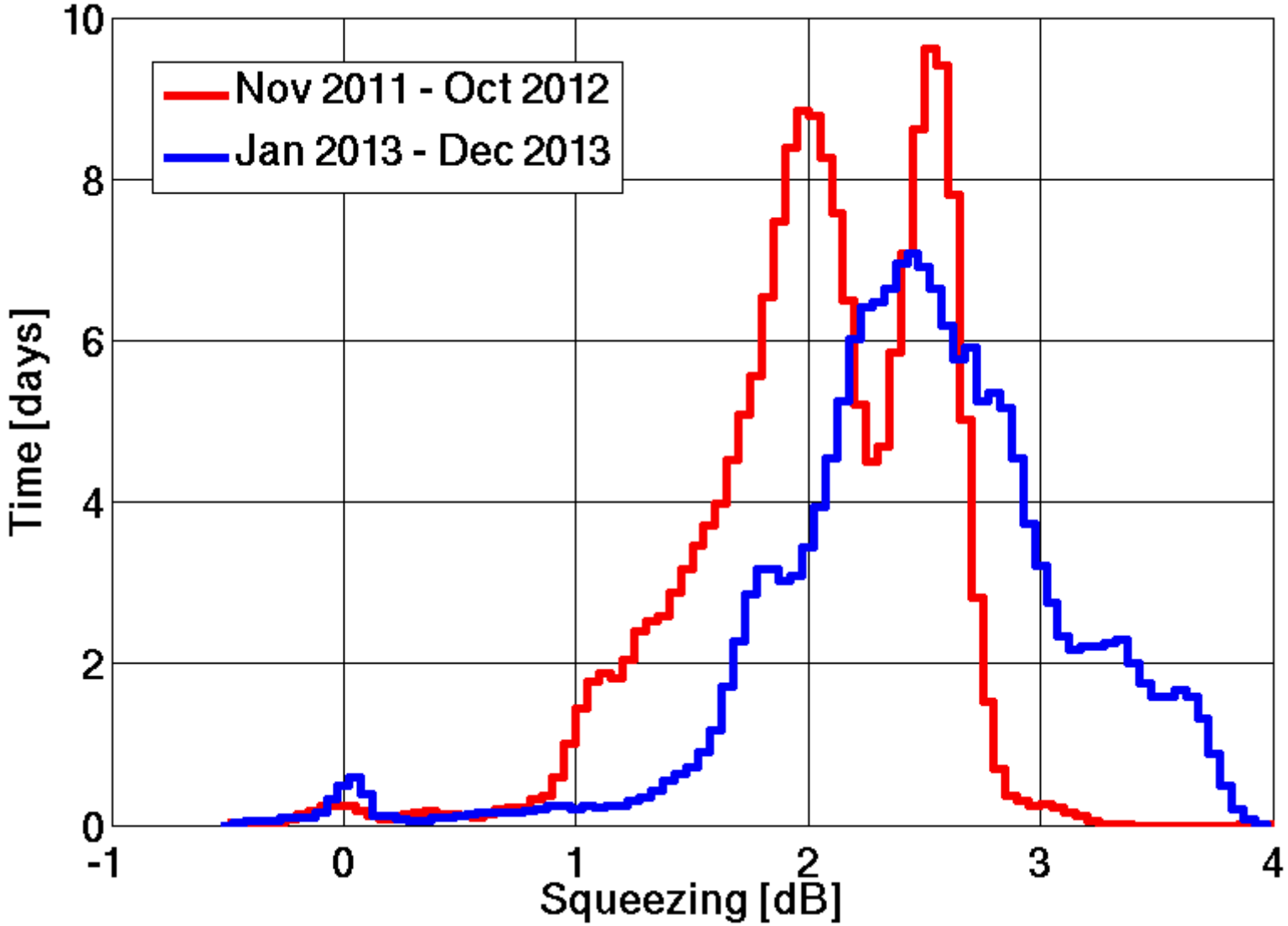


Diagrams credit: L. Barsotti, K. Dooley



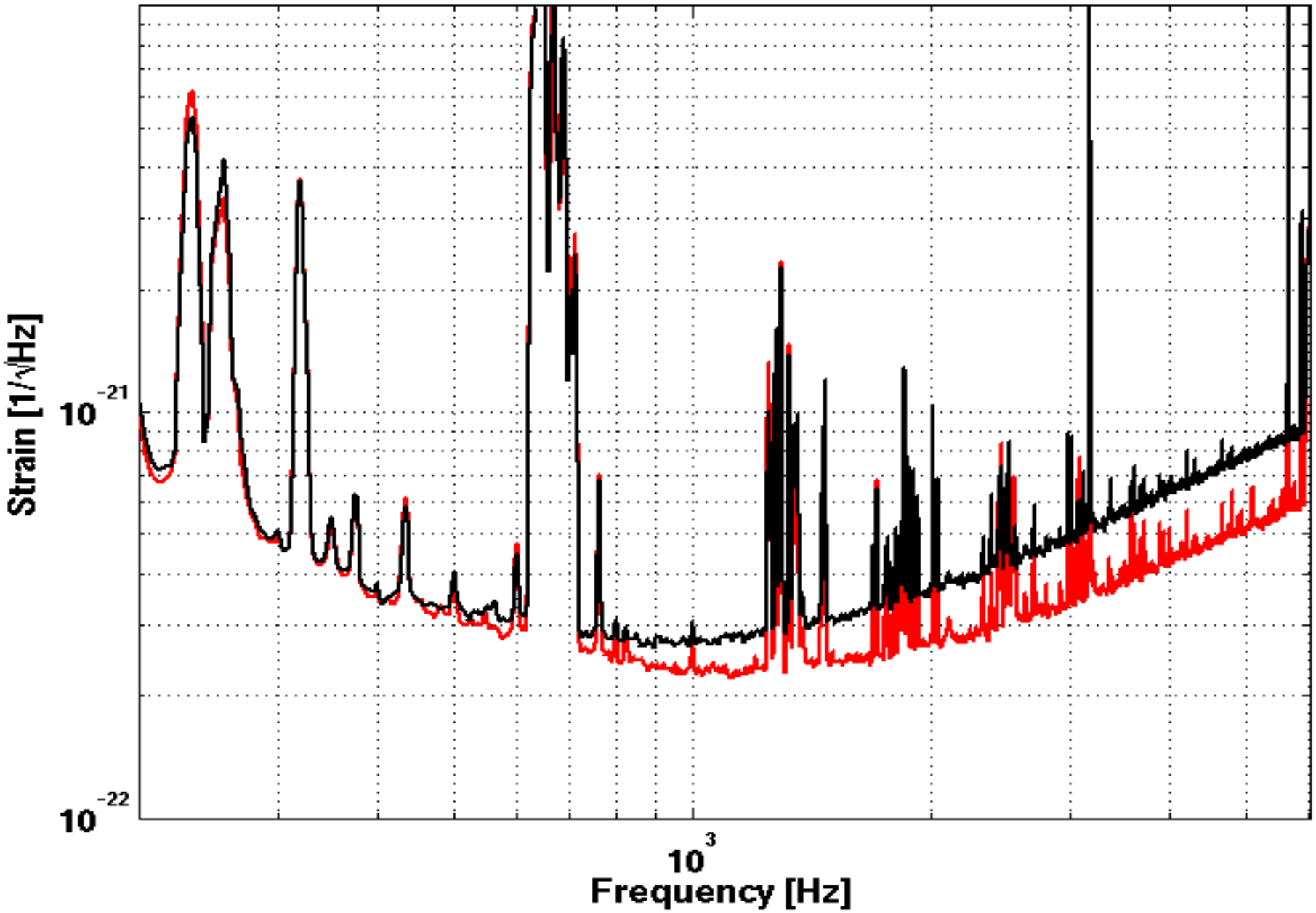
Squeezing the phase quadrature of the vacuum field entering the anti-symmetric port reduces the readout noise.

SQZ long-term performance 2012, 2013

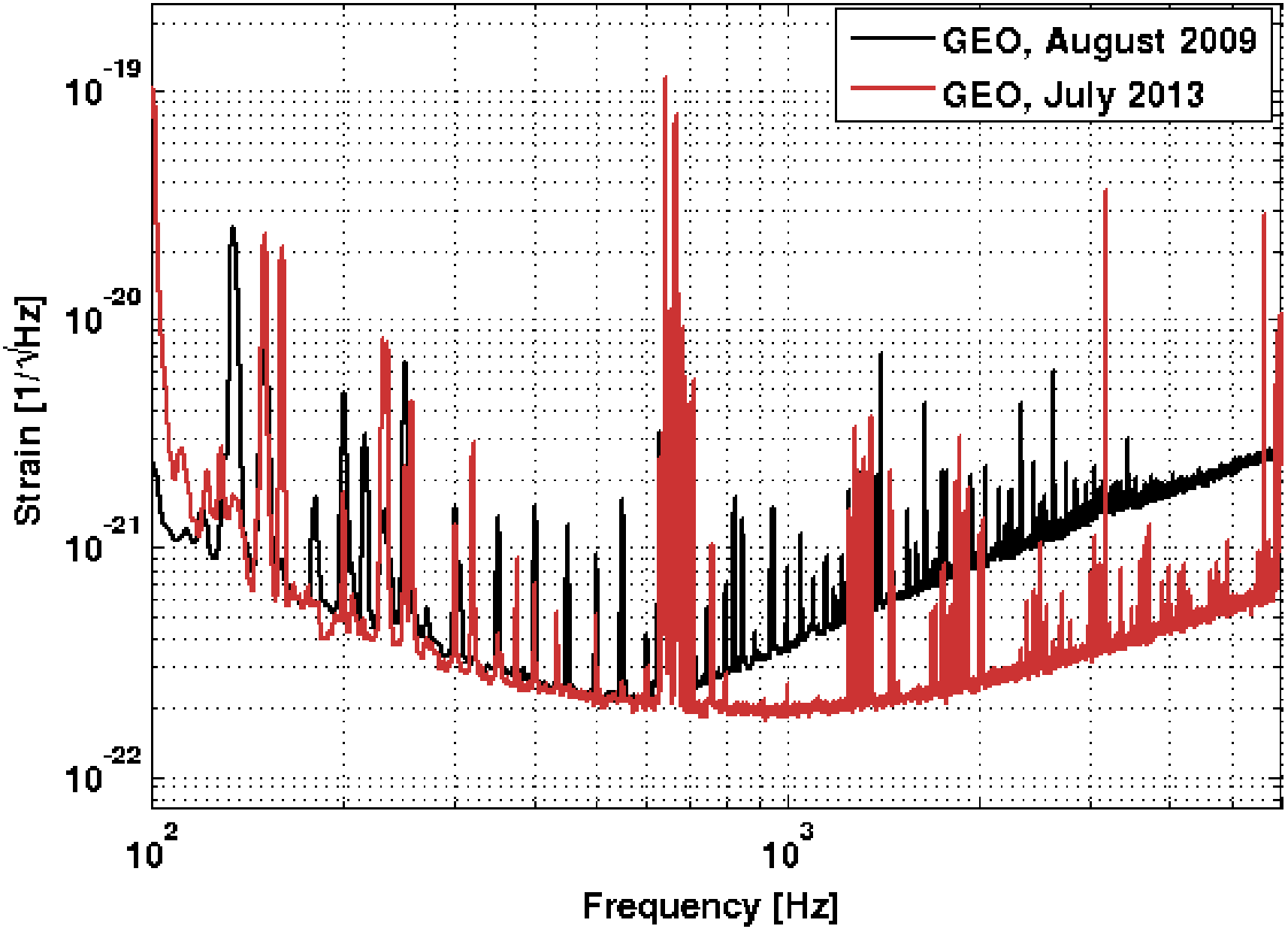


80-90% of science time is squeezing-enhanced

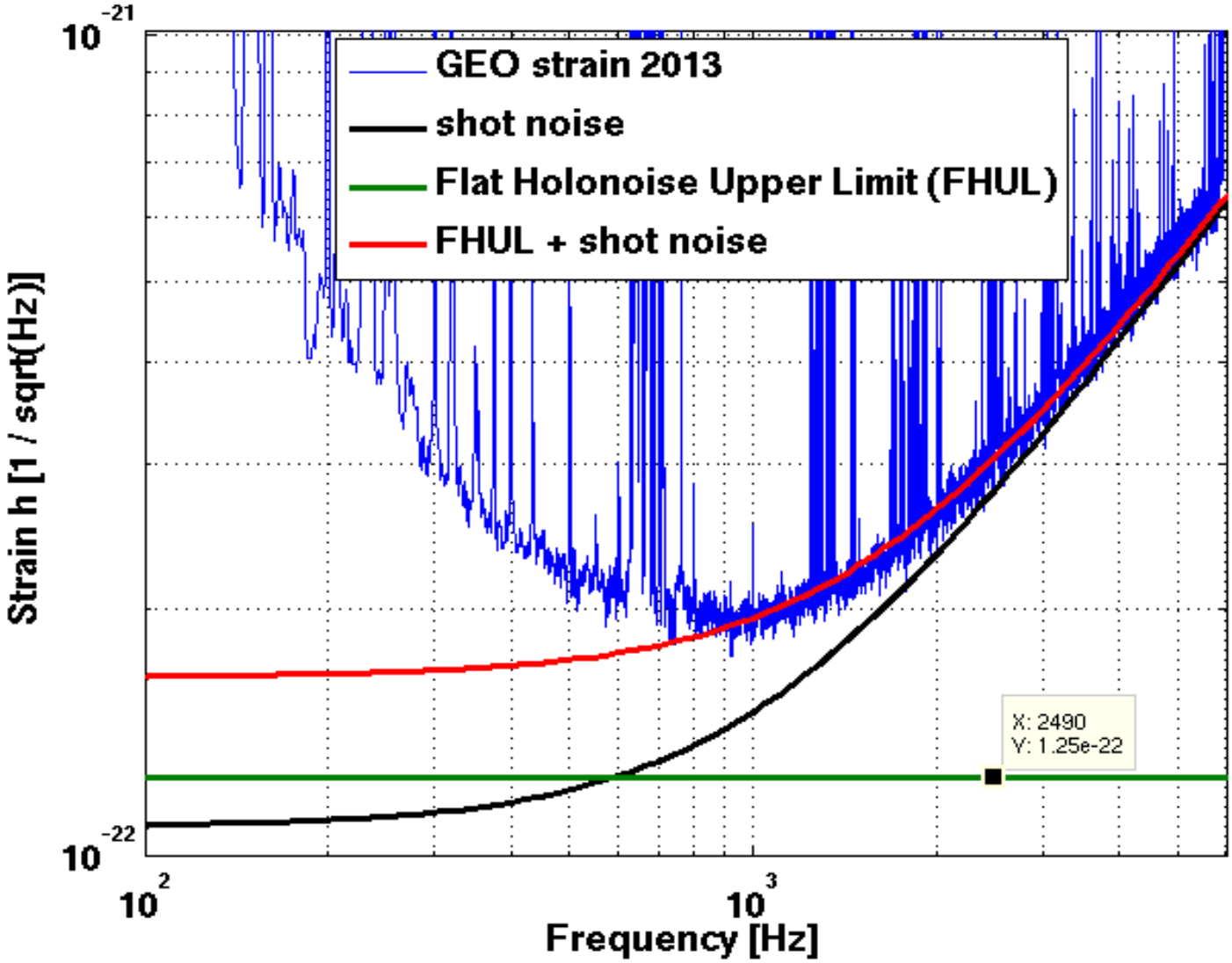
Recent squeezing at GEO: 3.7 dB



GEO sensitivity 2009 / 2013



Upper limit on flat unexplained strain noise

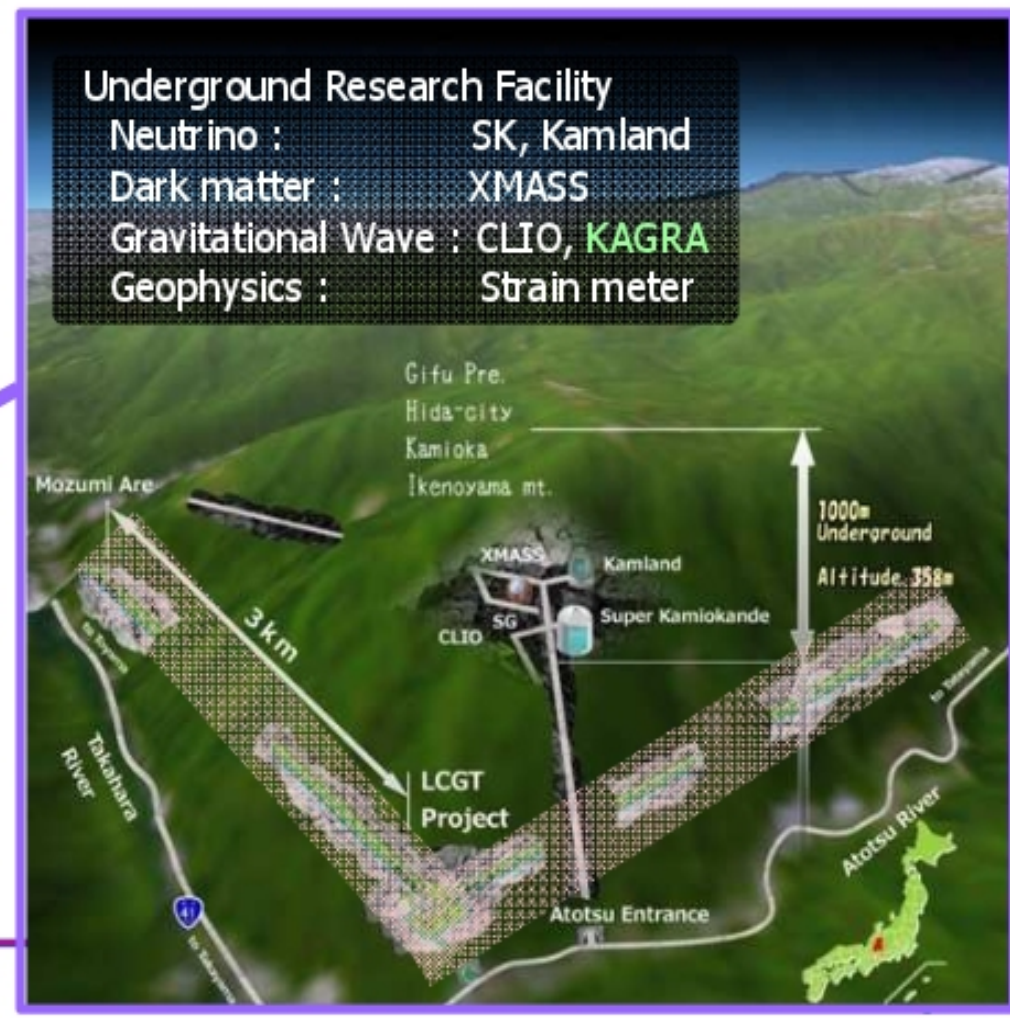


Phys. Rev. D 78, 2008: $h_H(f_0) = \sqrt{t_P/2} = 1.6 \times 10^{-22}\ \mathrm{Hz}^{-1/2}$

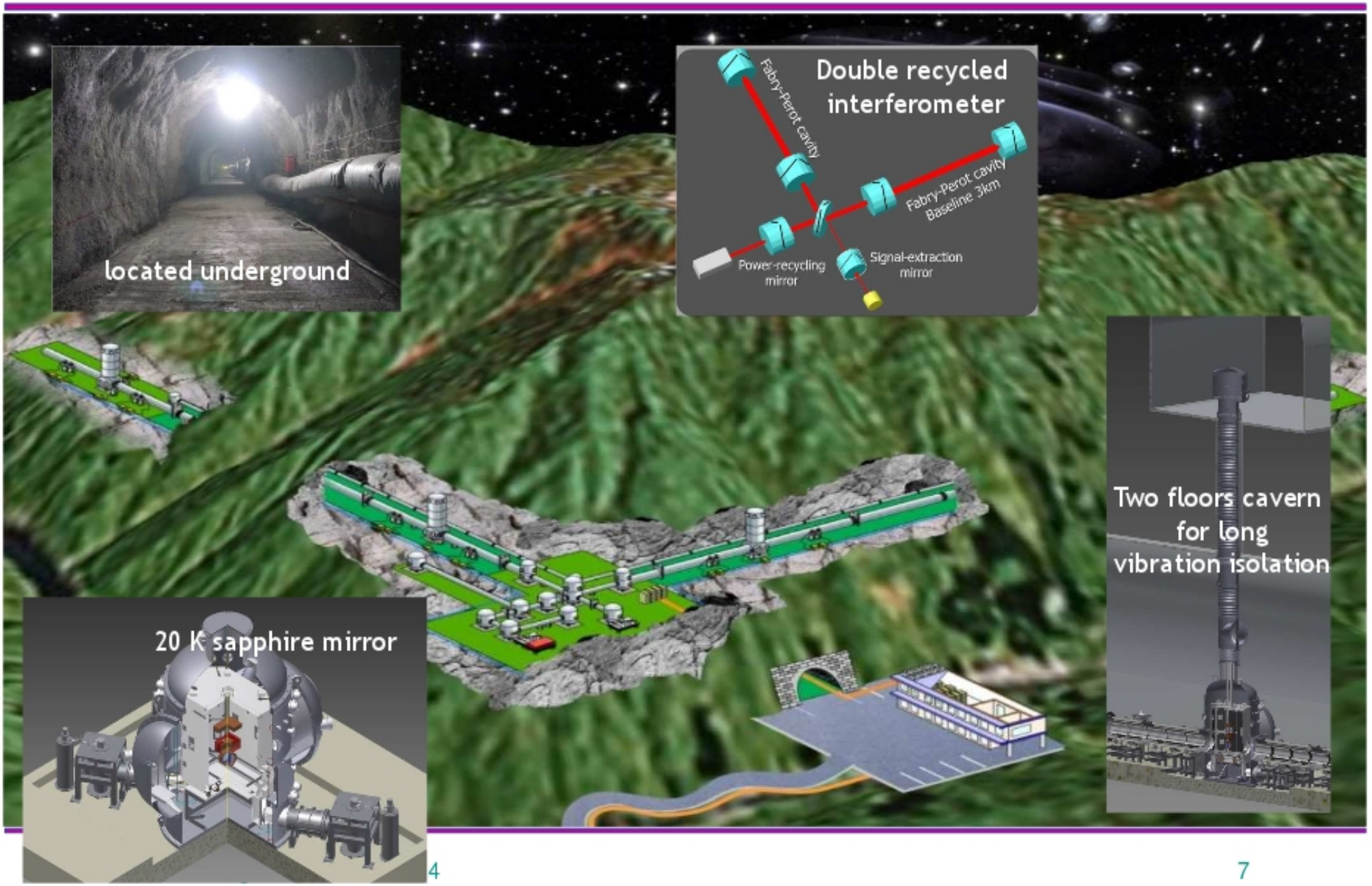
ArXiv: 1204.5948v19. 2014: $h^2 \approx \frac{\langle \hat{x}_\perp^2 \rangle}{cL_a} = t_P/\sqrt{4\pi} = (1.23 \times 10^{-22}\mathrm{Hz}^{-1/2})^2$

The KAGRA project

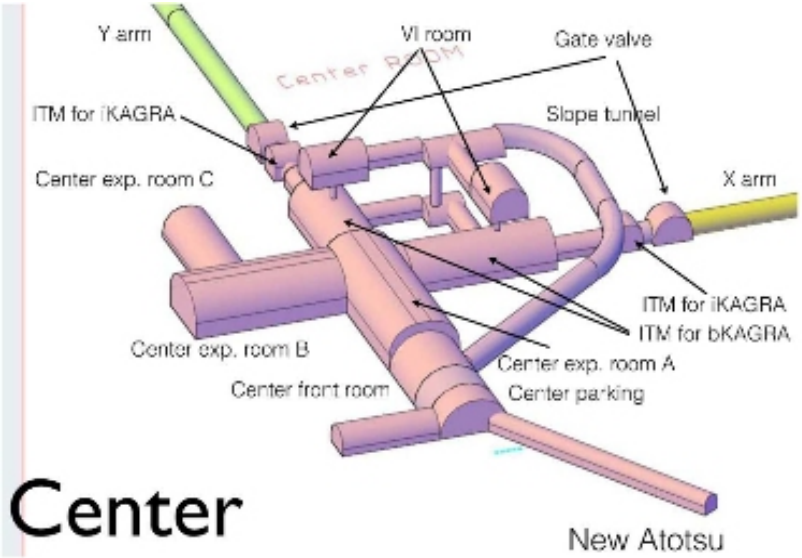
- Gravitational wave detector (3 km long laser interferometer)
- Currently under construction near Kamioka, Gifu
- Financed by MEXT (~ 156 M$)

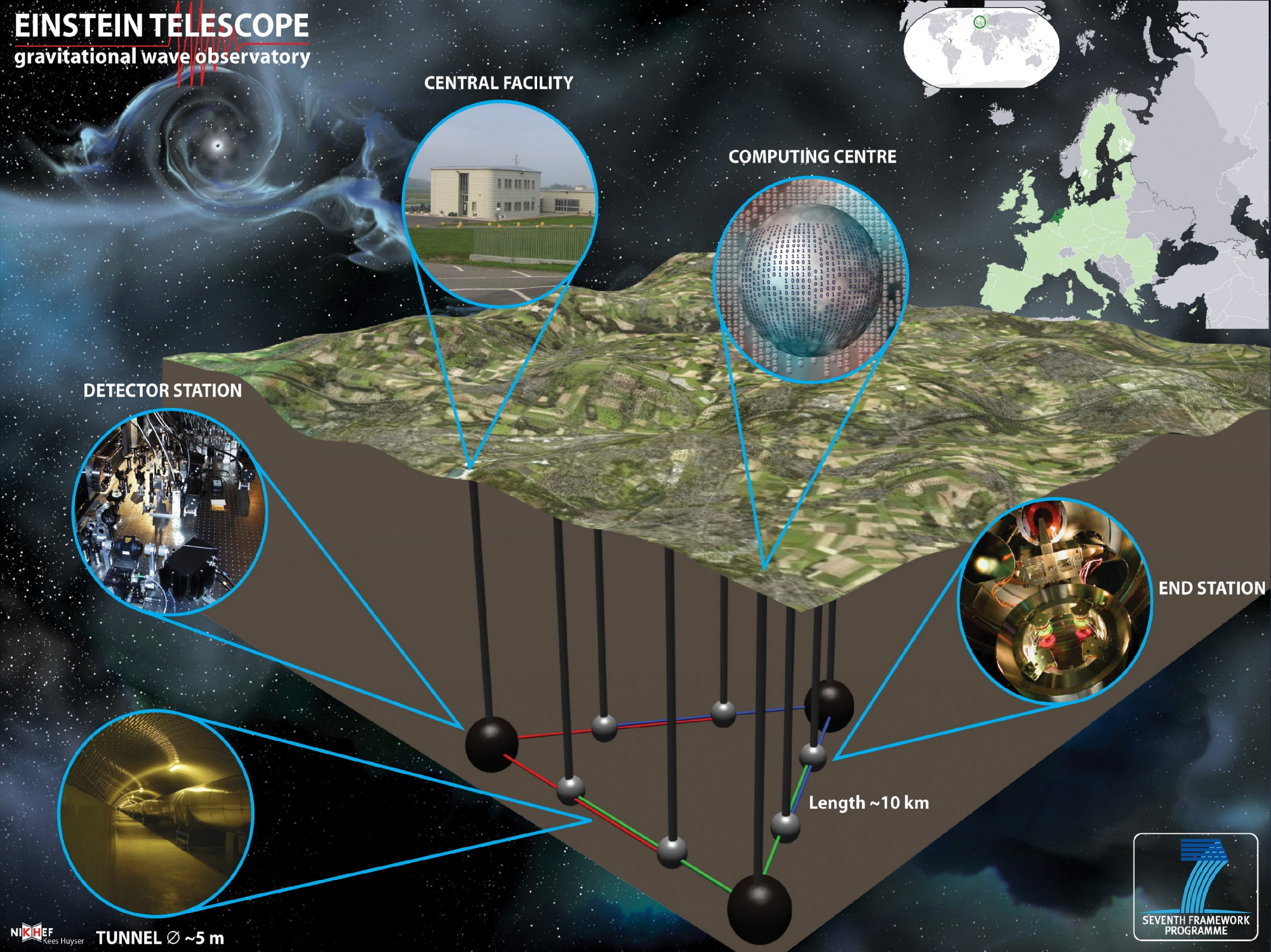
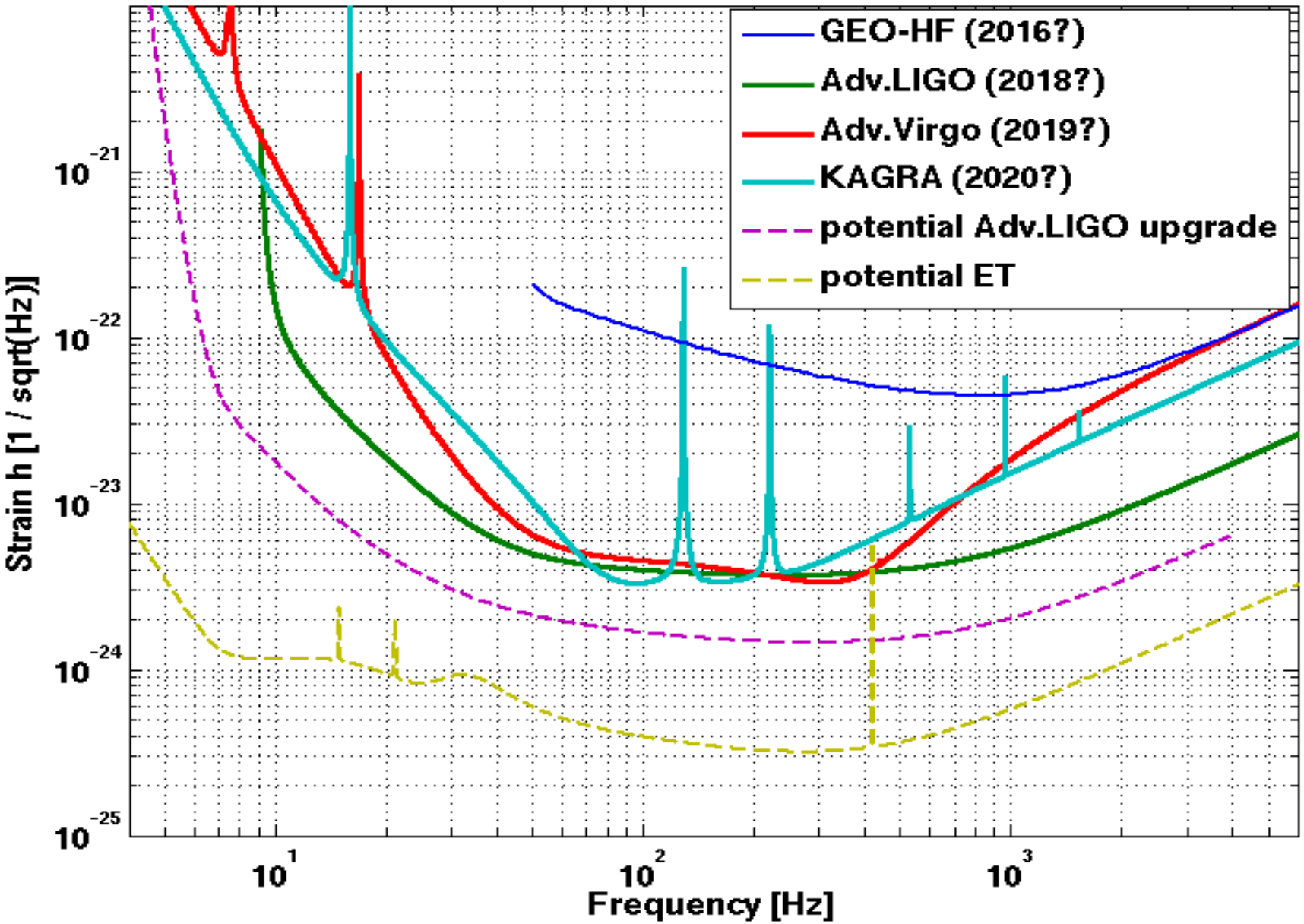


Main features of KAGRA



Excavation of the 3km-arms completed on 31. March 2014




EINSTEIN TELESCOPE
gravitational wave observatory
CENTRAL FACILITY
COMPUTING CENTRE
DETECTOR STATION
END STATION
Length ~10 km
TUNNEL ∅ ~5 m
NIKHEF
Kees Huyser
SEVENTH FRAMEWORK PROGRAMME

Strain Sensitivities