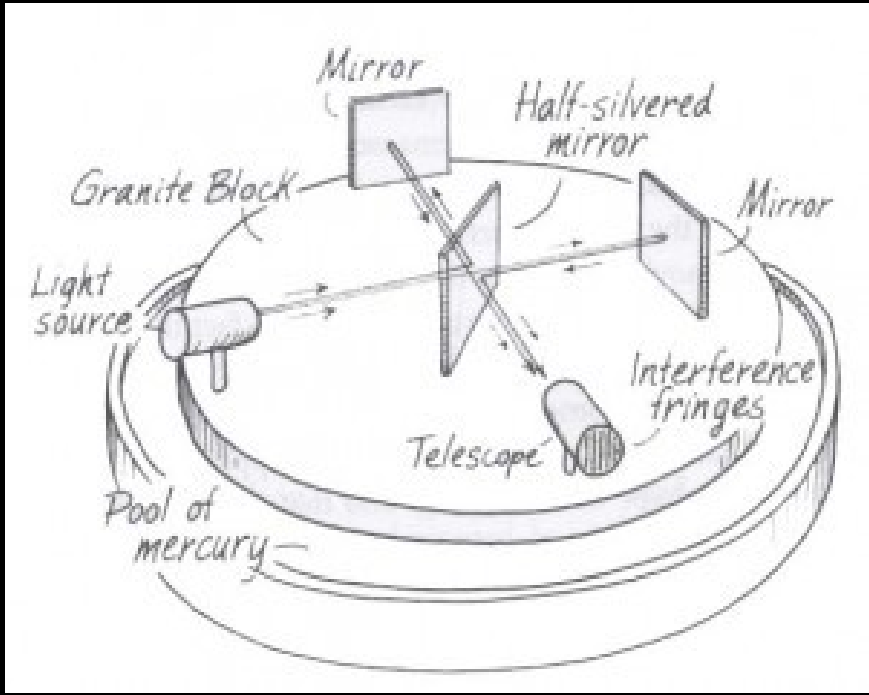
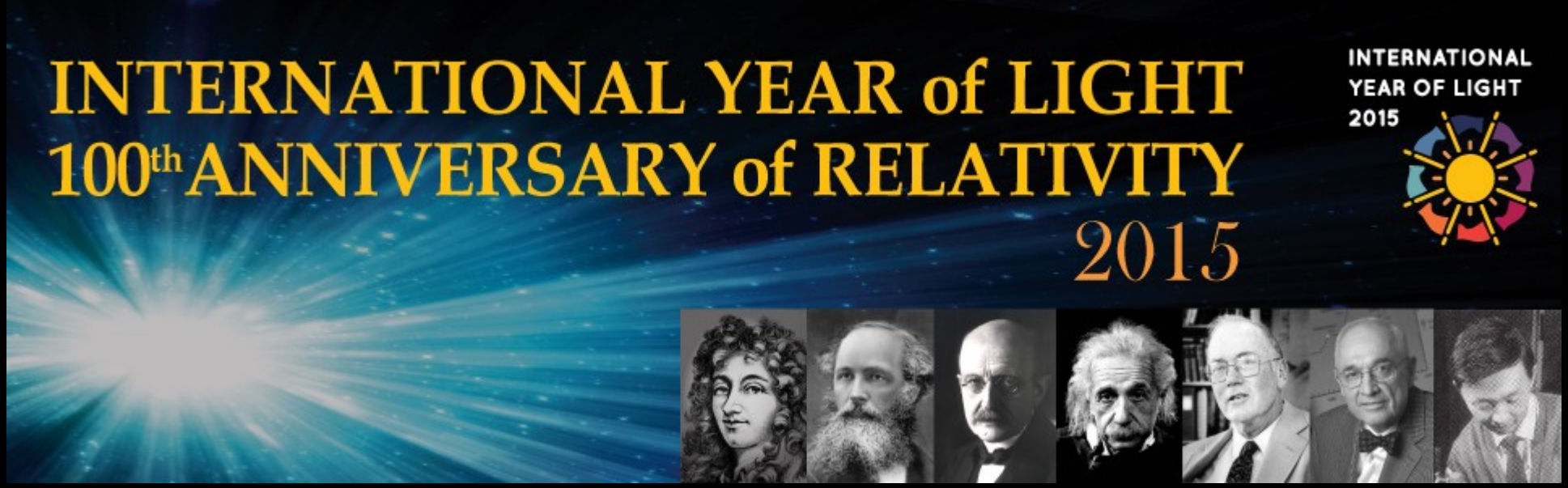
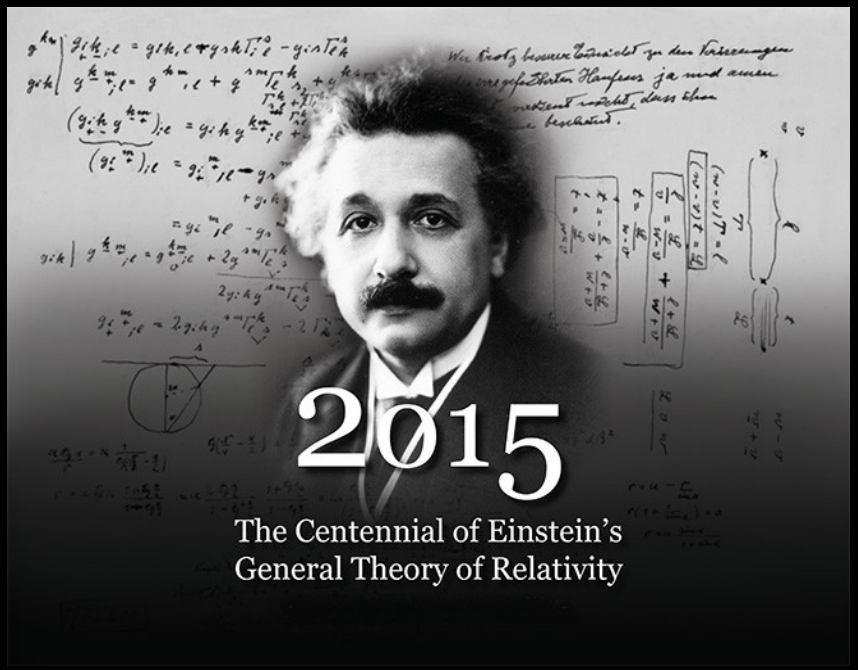
# Overview and Status of Advanced Interferometers

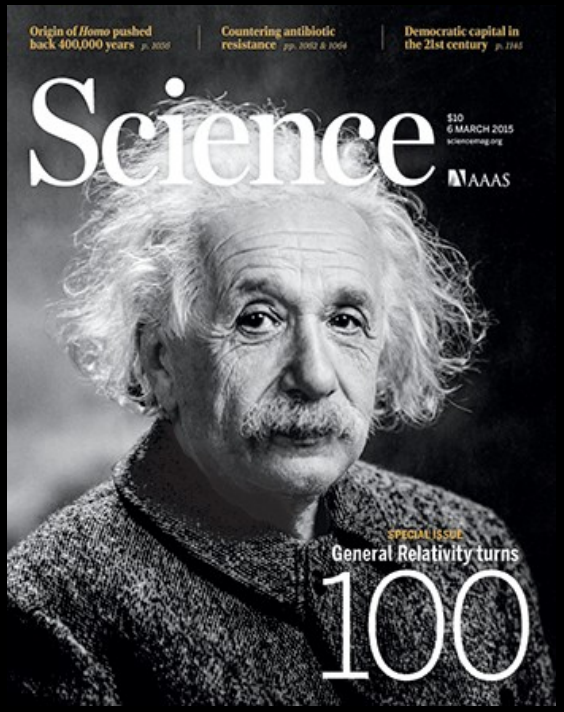



Hartmut Grote (AEI Hannover and LIGO Lab)
On behalf of the LIGO scientific collaboration
LIGO doc. Nr. G1501194

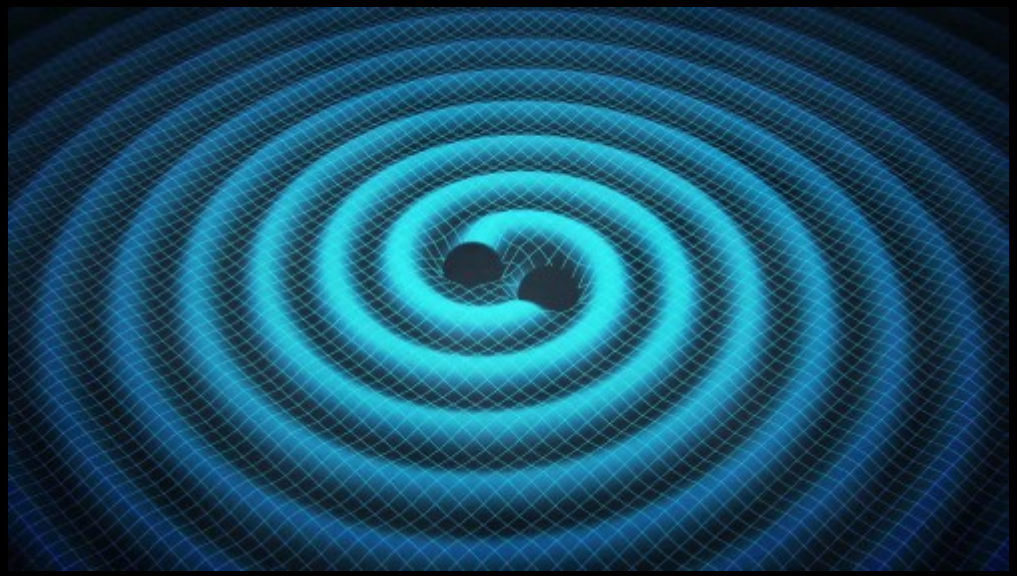
TAUP, Torino
11.Sept. 2015


INTERNATIONAL YEAR of LIGHT
100th ANNIVERSARY of RELATIVITY
2015
INTERNATIONAL
YEAR OF LIGHT
2015


2015
The Centennial of Einstein's
General Theory of Relativity

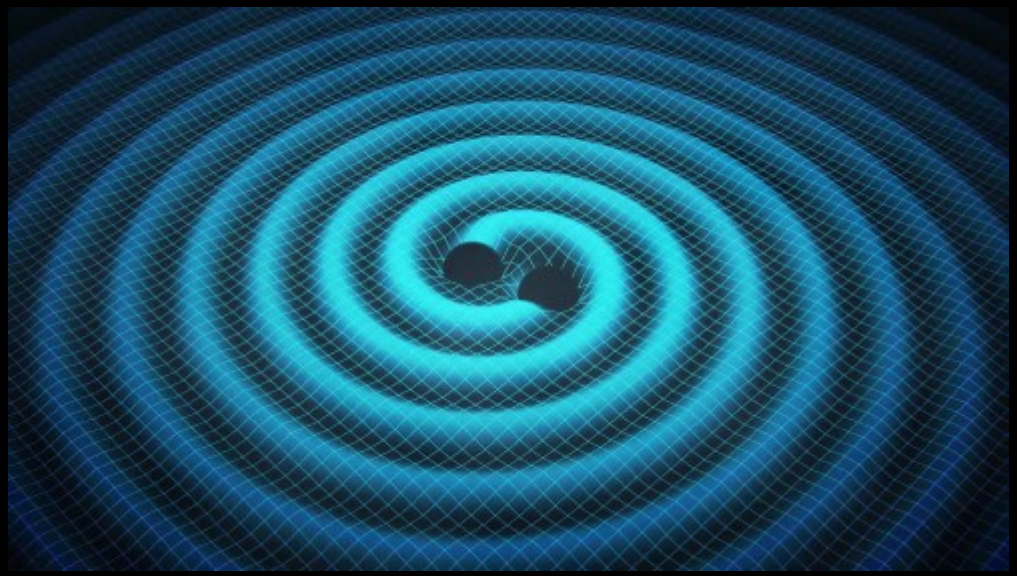

Origin of Homo pushed back 400,000 years
Countering antibiotic resistance
Democratic capital in the 21st century
Science
$10
6 MARCH 2015
AAAS
SPECIAL ISSUE
General Relativity turns
100

# Gravitational Waves



Distortion of space-time traveling at the speed of light

# Gravitational Waves



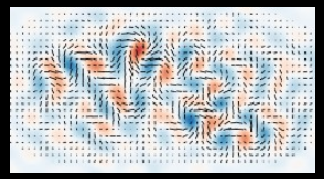
Distortion of space-time traveling at the speed of light

...traveling at the speed of thought !!

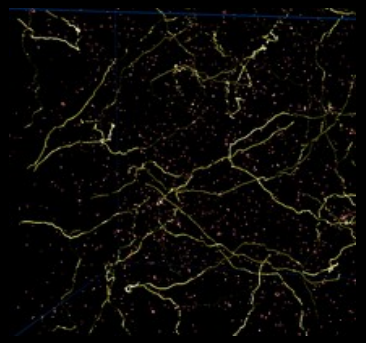
A.S.Eddington

# The Gravitational-wave Spectrum

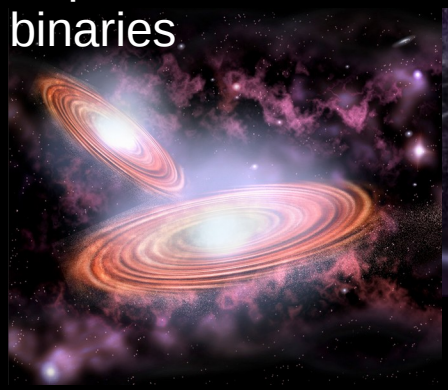
Primordial GWs



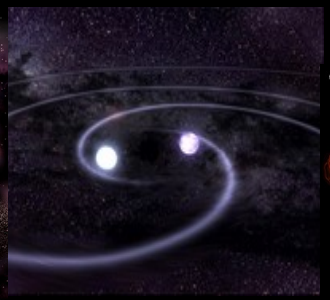
Cosmic strings



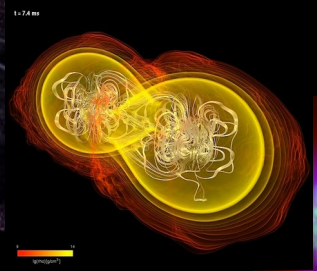
Supermassive BH binaries



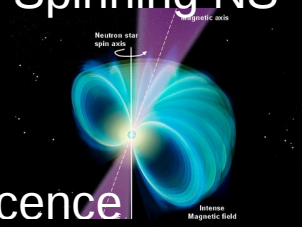
BH and NS binaries



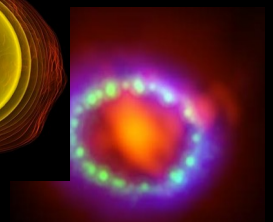
Binary coalescence



Spinning NS



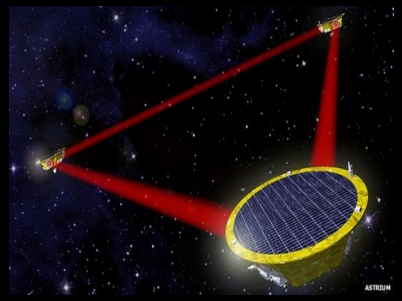

Supernovae



$10^{-16}$ $10^{-8}$ $10^{-3}$ $10^{0}$ $10^{3}$ Hz

Inflation probe

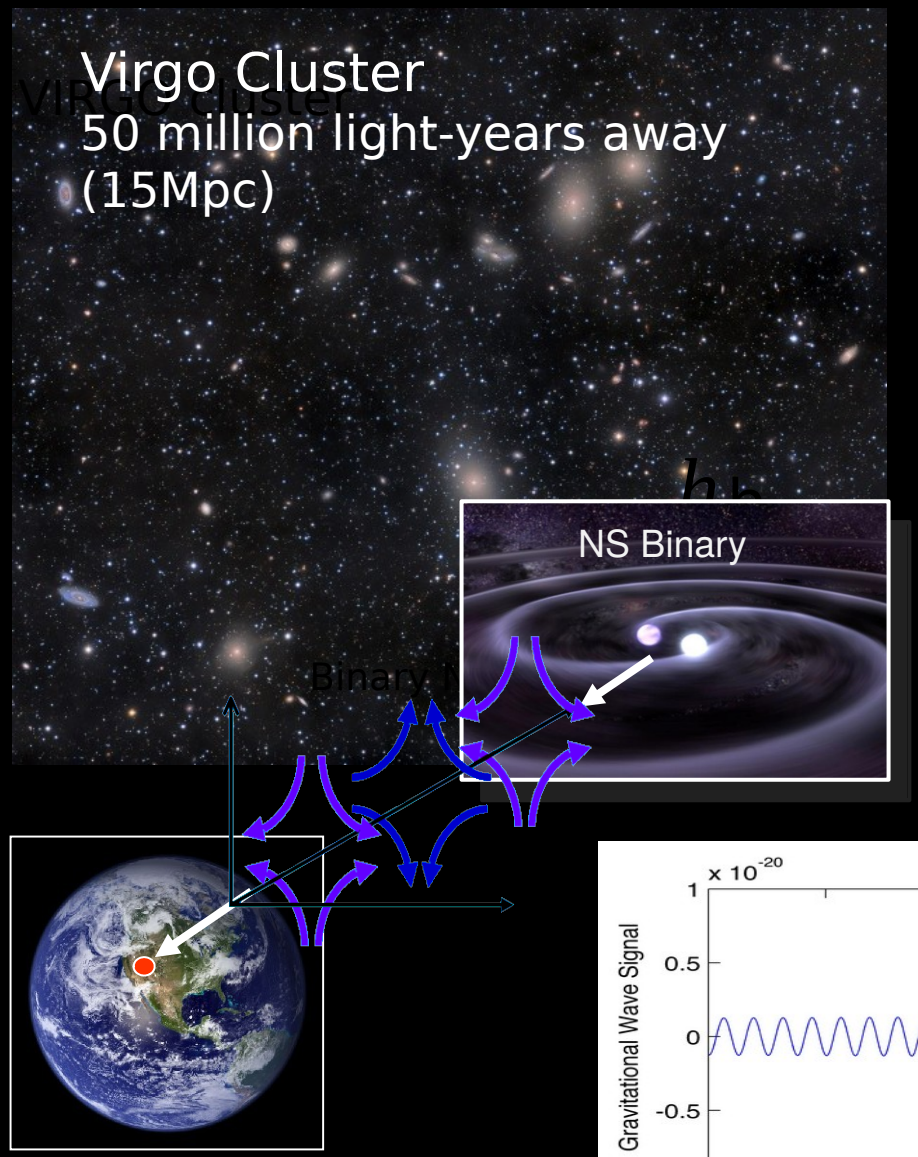
Pulsar timing



Interferometers In space

Ground-based interferometers

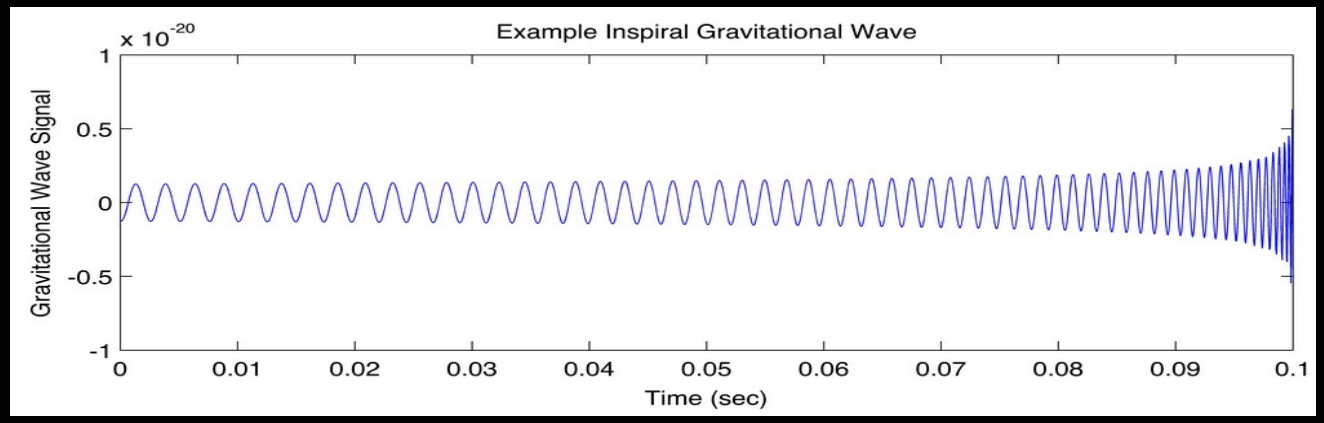
# Gravitational waves are hard to measure, they are small...




strain $h = \Delta L / L$

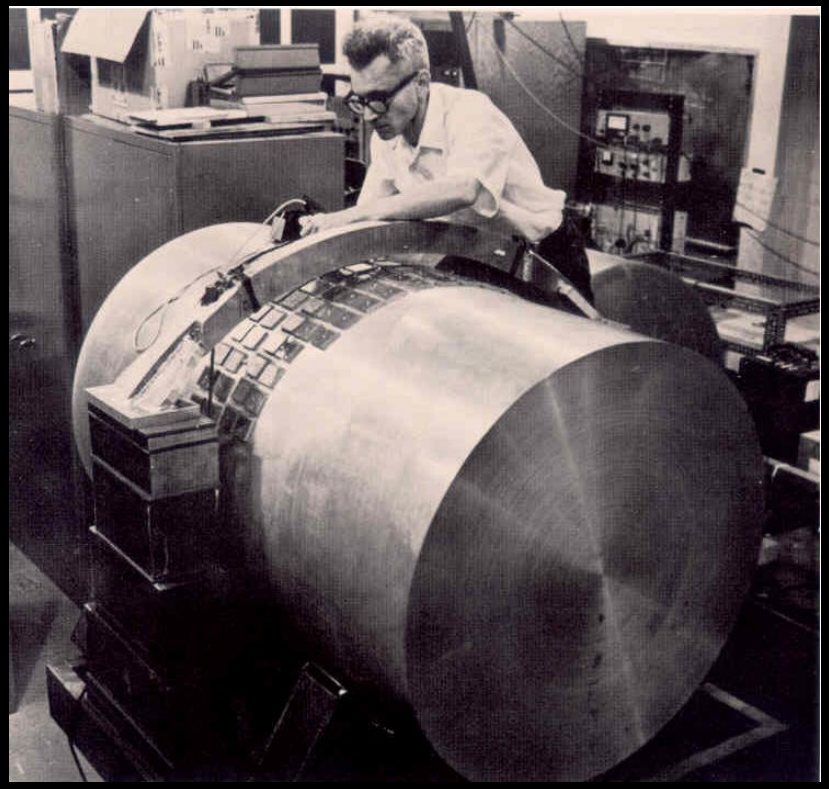
Inspiral signal from NS binary in Virgo cluster

$h_{NS} \sim 10^{-22}$



# Joseph Weber (1919 – 2000)

The pioneer of the GW-detection research:

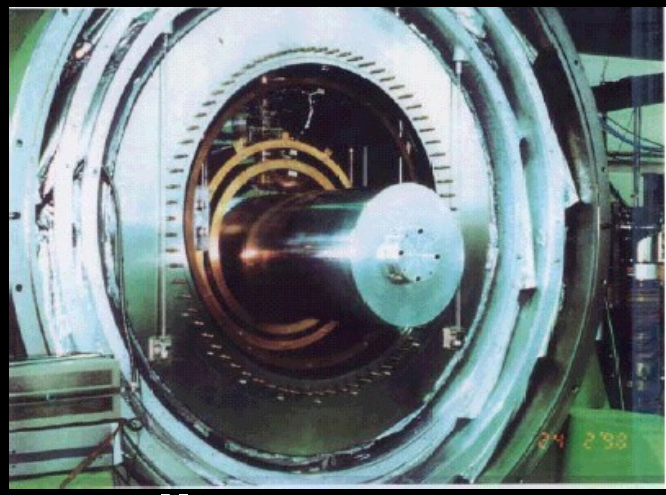


Resonant antennas: bars („Weber-bars“)

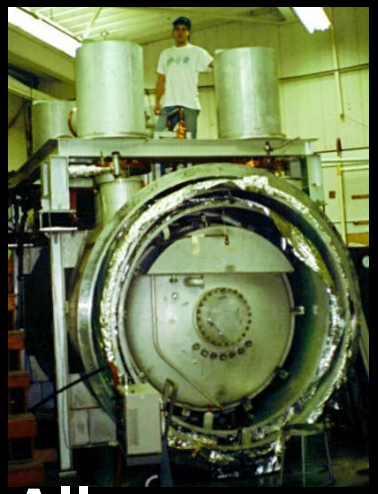
# Resonant Bar Detectors

**Auriga**
Legnaro, INFN
(Italy)

**M ~ a few tons**
**L ~ 3 m**
**F ~ 900 Hz**



**Nautilus**
Frascati, INFN
(Italy)



**Allegro**
Baton Rouge,
LSU (USA)

**Explorer**
Geneva, CERN, INFN
(Switzerland)

**Niobe**
Perth, UWA
(Australia)

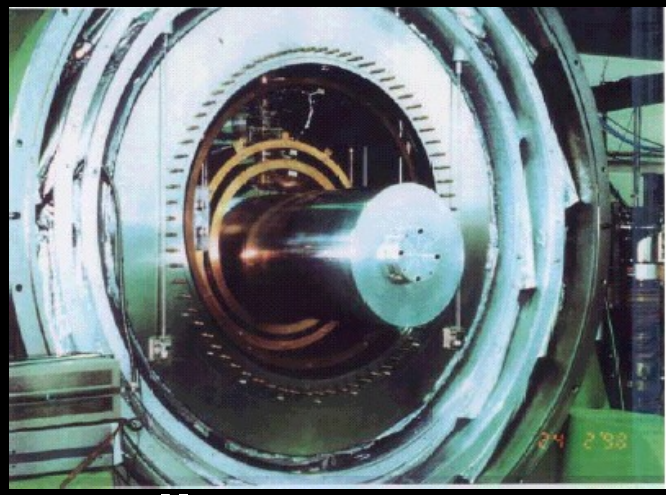
# Resonant Bar Detectors

**Auriga**
Legnaro, INFN
(Italy)

**M ~ a few tons**
**L ~ 3 m**
**F ~ 900 Hz**

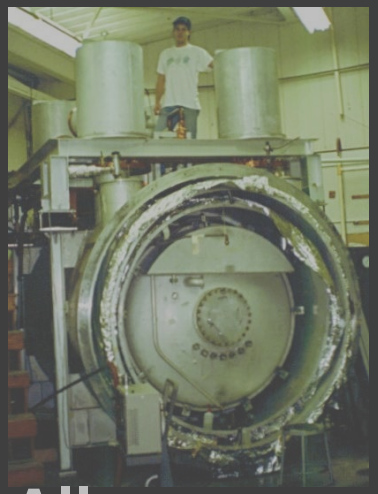
**h ~ $10^{-21}$ @ ~900 Hz**

**STILL RUNNING !**



**Nautilus**
Frascati, INFN
(Italy)

**RETIRED**

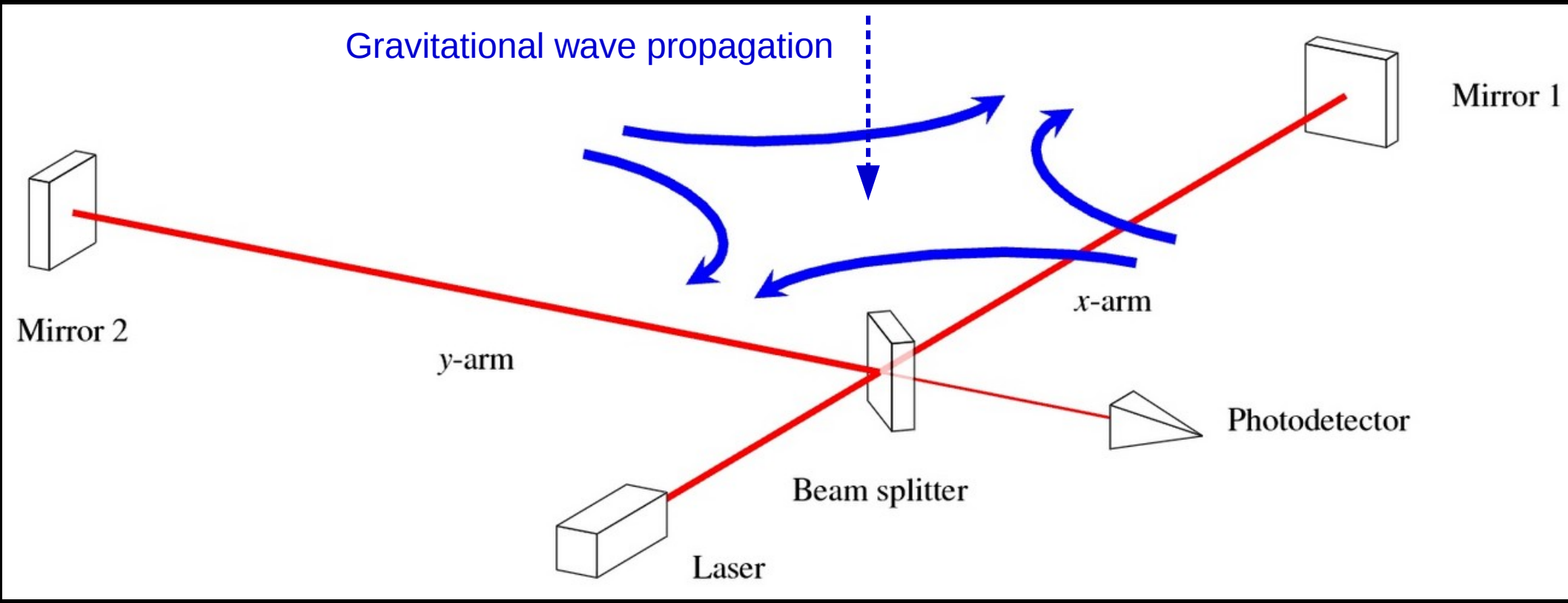


**Allegro**
Baton Rouge,
LSU (USA)

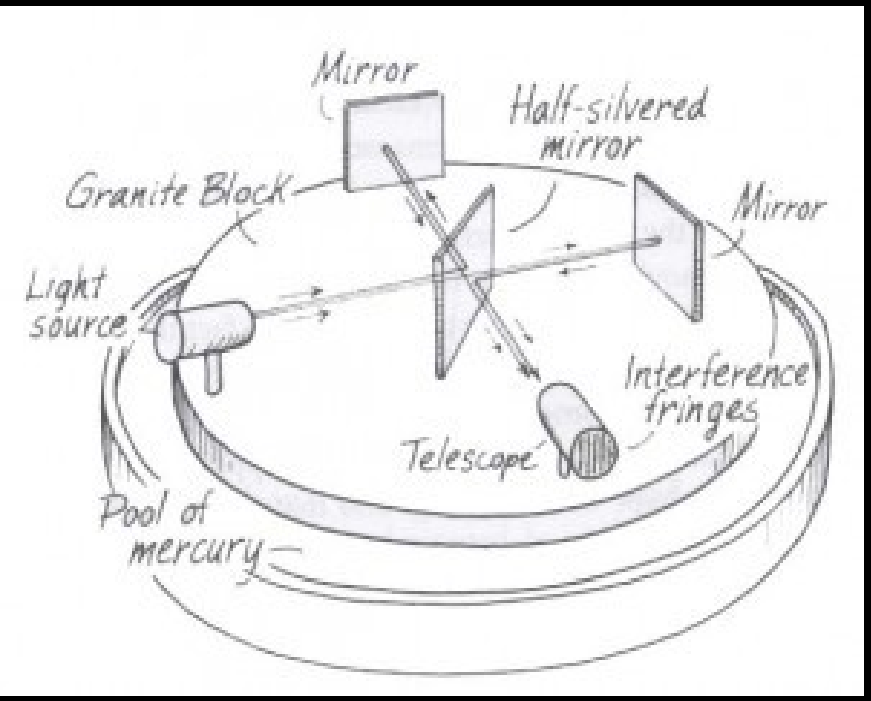
**Explorer**
Geneva, CERN, INFN
(Switzerland)

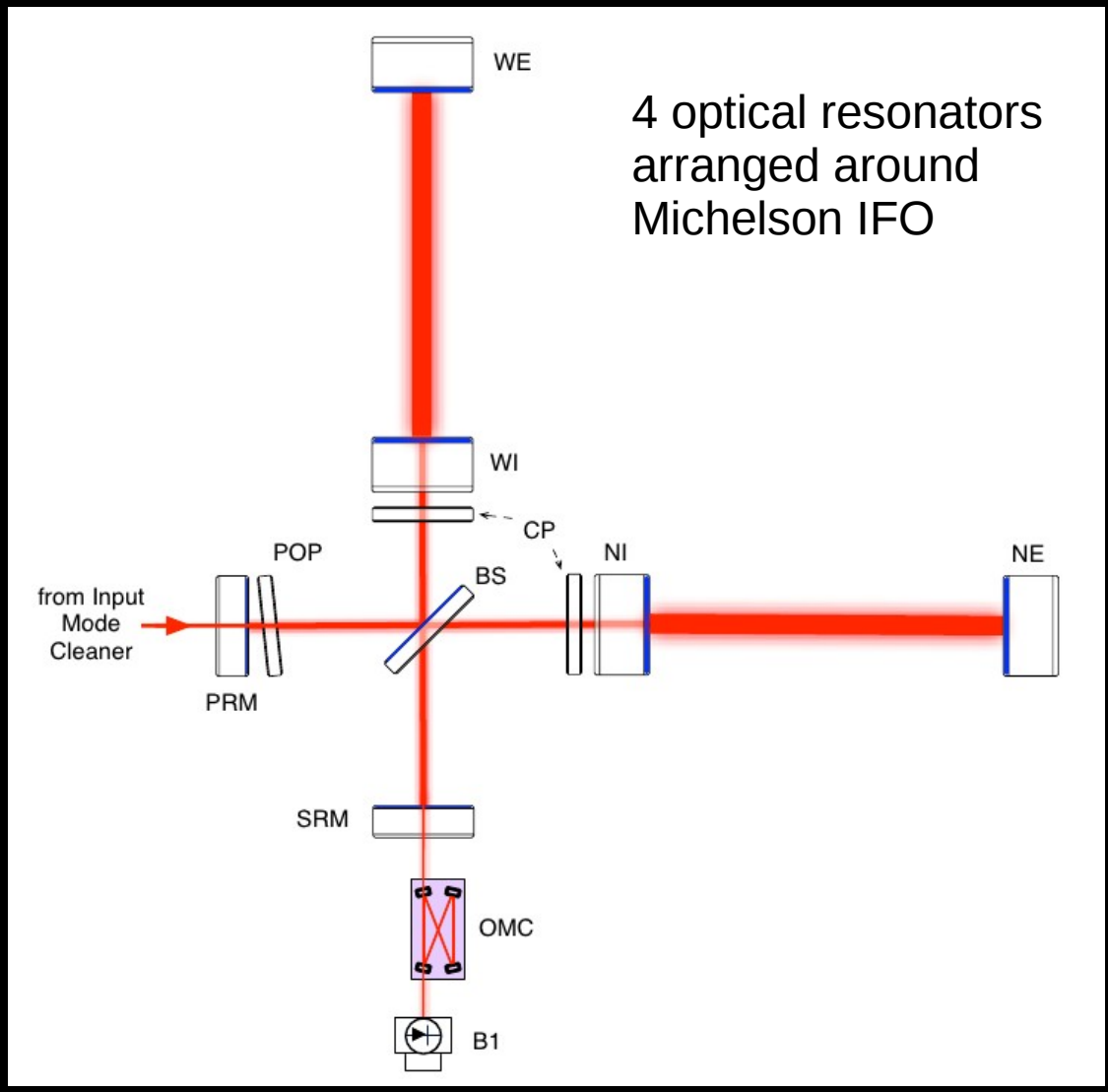
**Niobe**
Perth, UWA
(Australia)

# Michelson Interferometers



# Michelson (with additions)



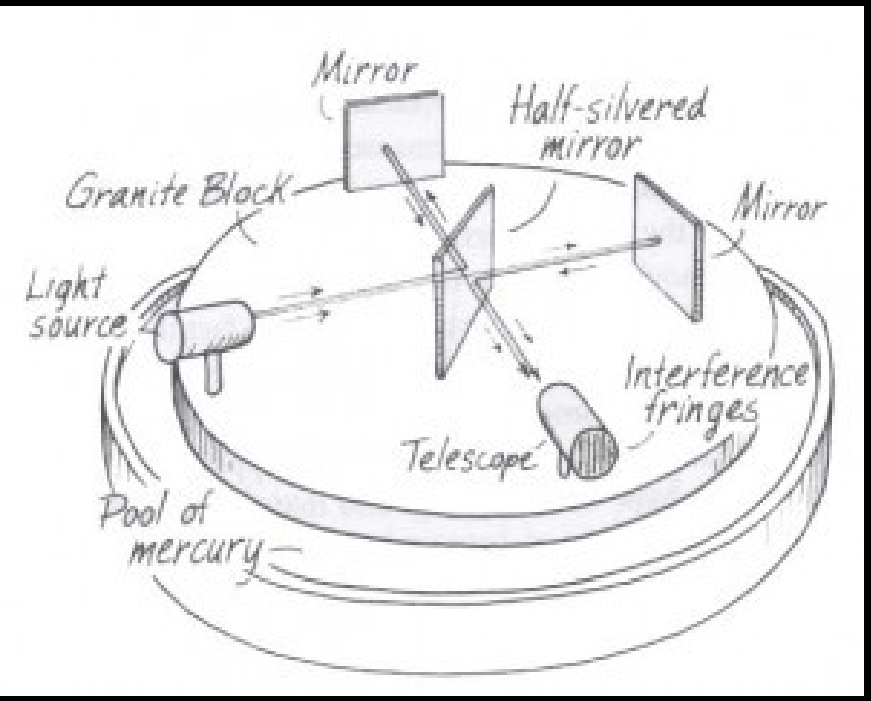

Michelson-Morley experiment:
Accuracy: 10^-8 m (10^-9 relative)

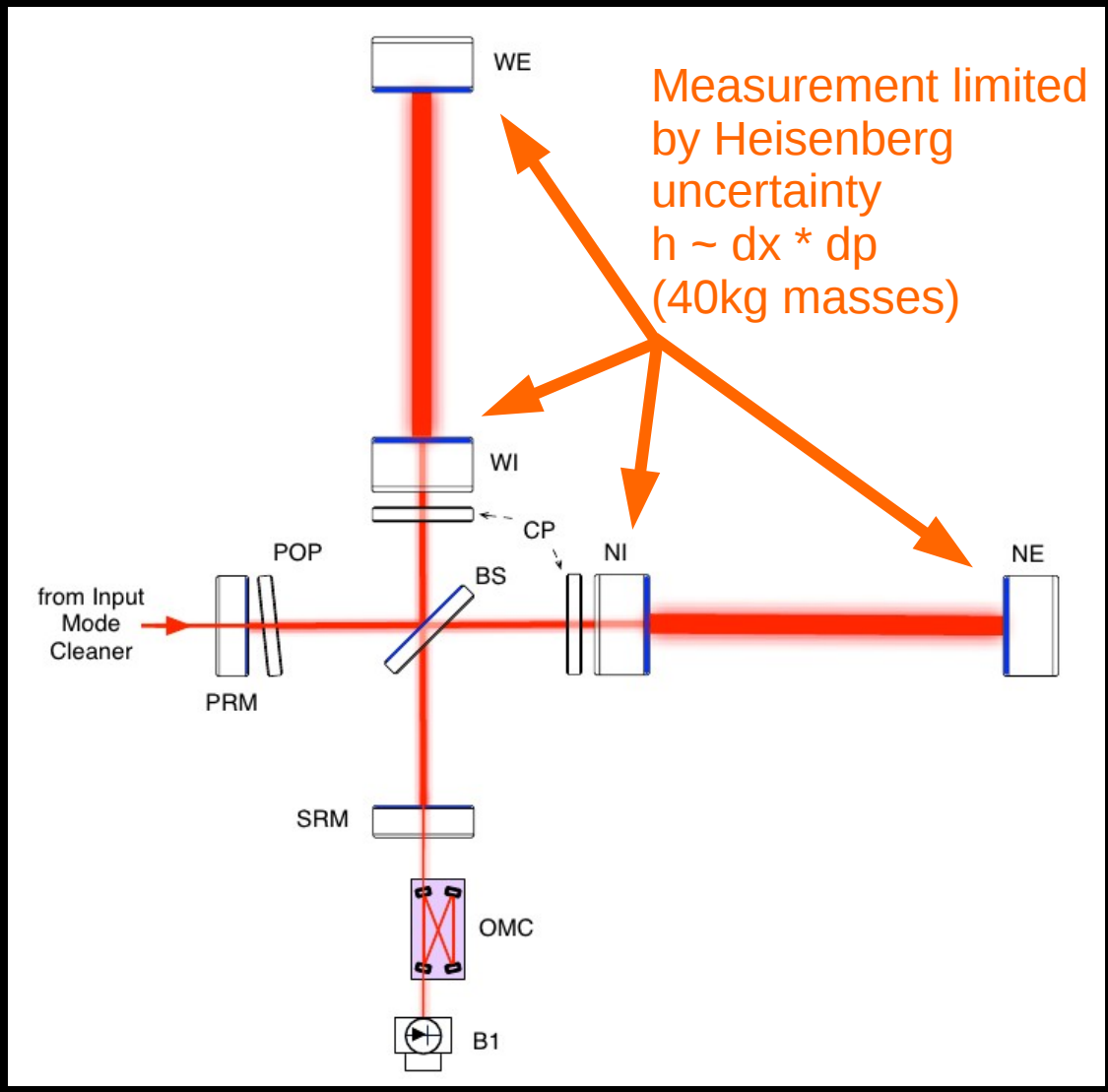
10m arm-length

Advanced Interferometer:
Accuracy: 10^-19 m (3 x 10^-23 relative), 100Hz BW

3-4 km arm-length

# Michelson (with additions)




Michelson-Morley experiment:
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Advanced Interferometer:
Accuracy: 10^-19 m (3 x 10^-23 relative), 100Hz BW

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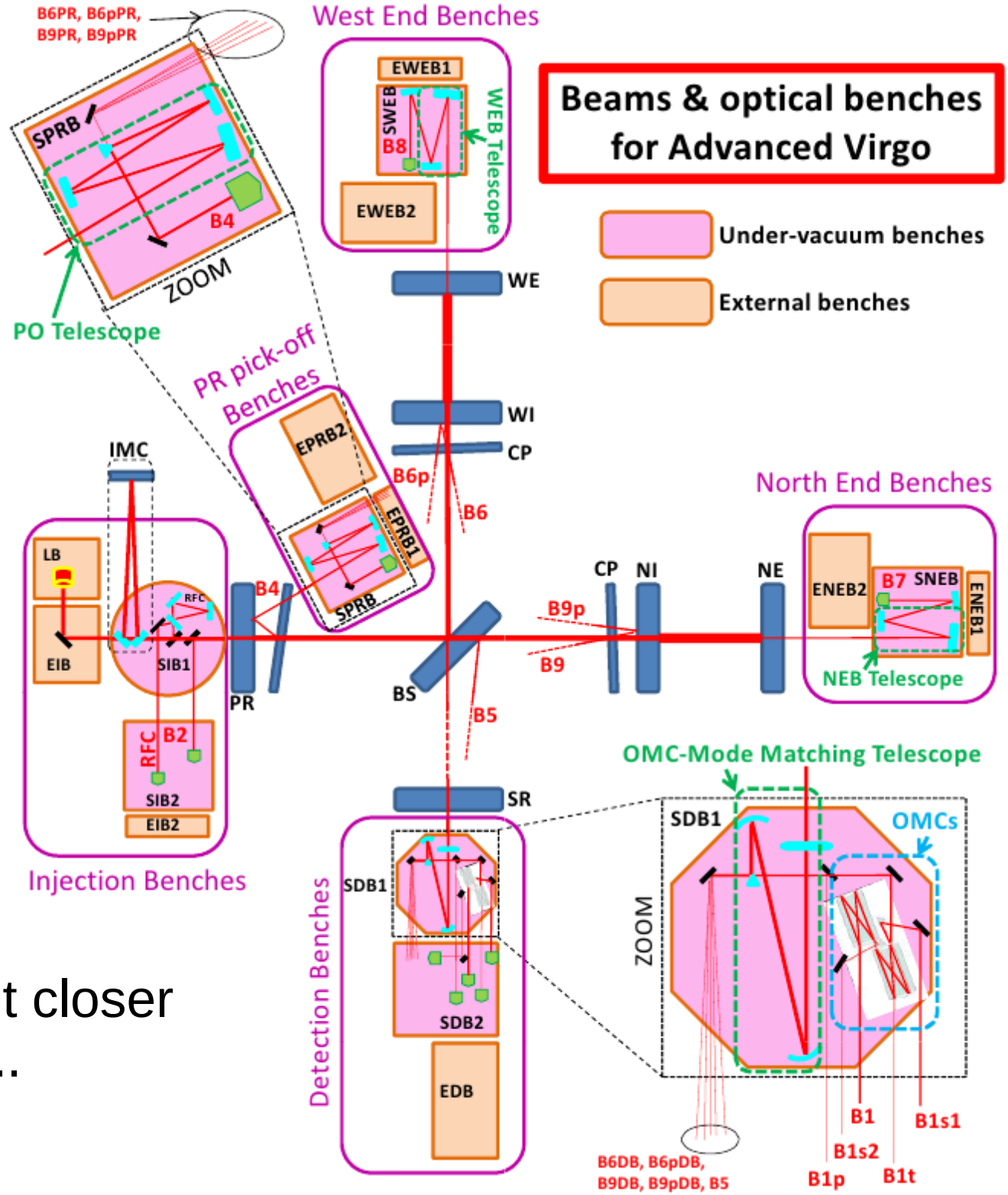
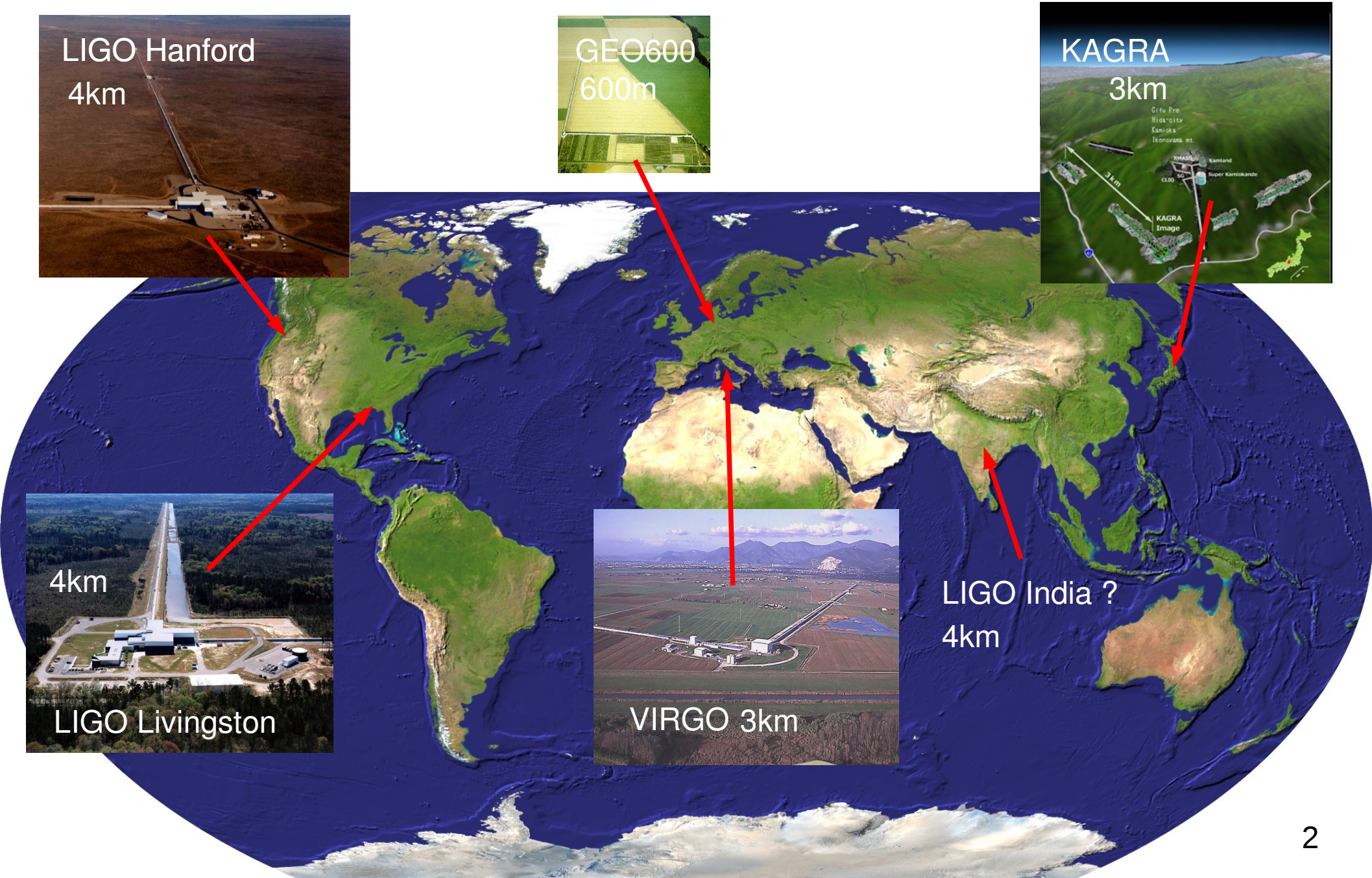
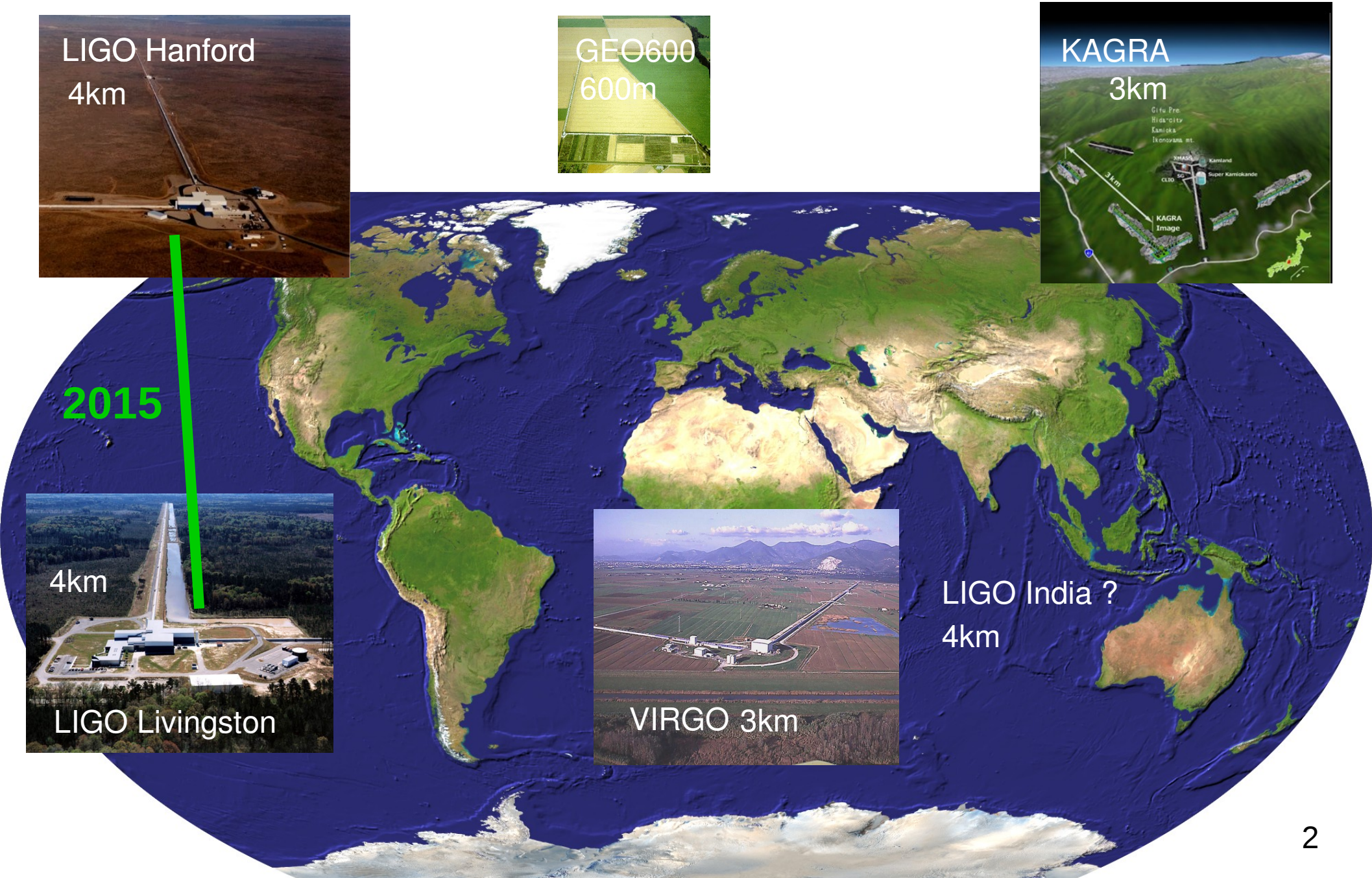



...and a bit closer
To reality...

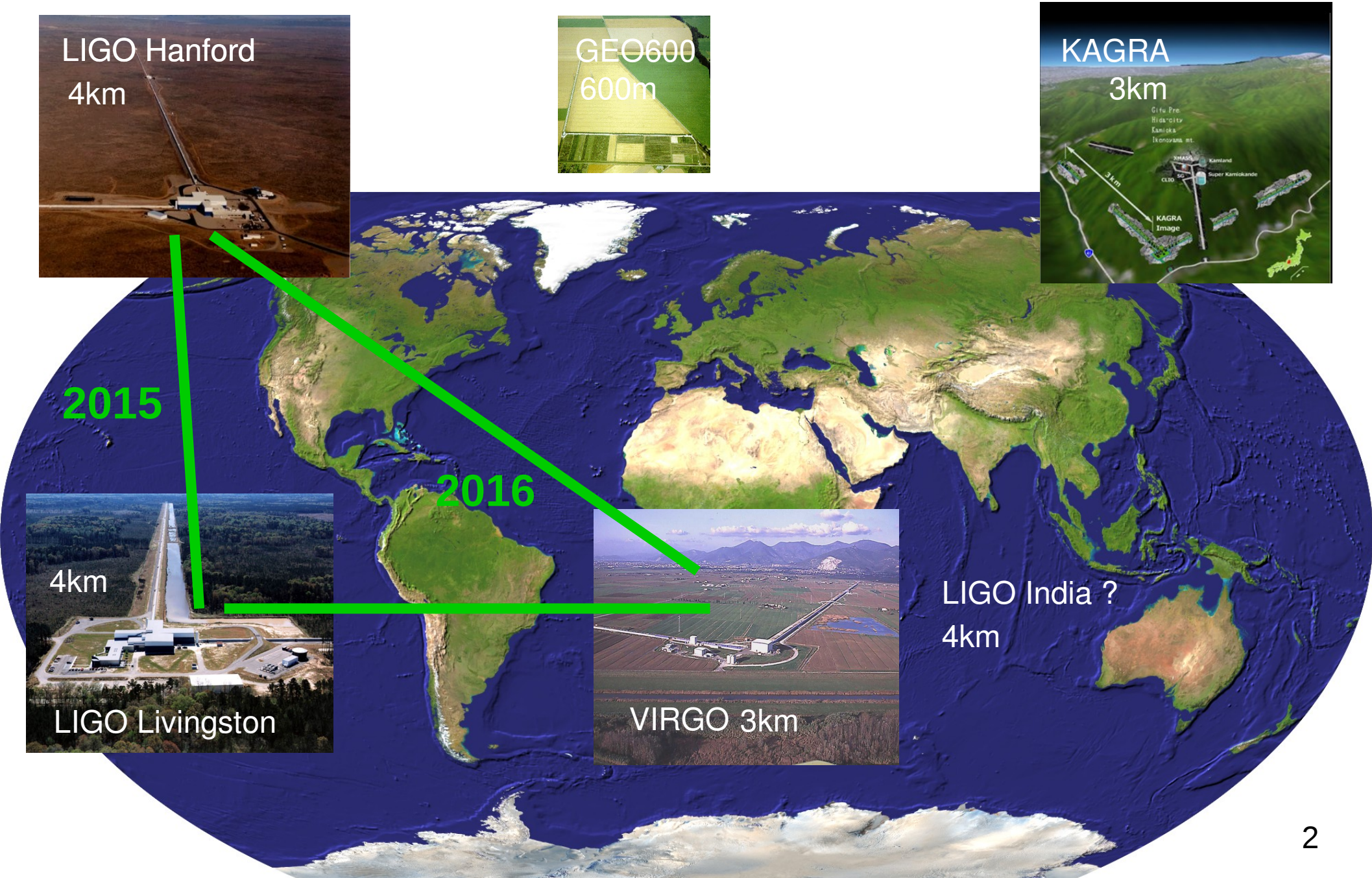
# Current GW – Interferometer Projects



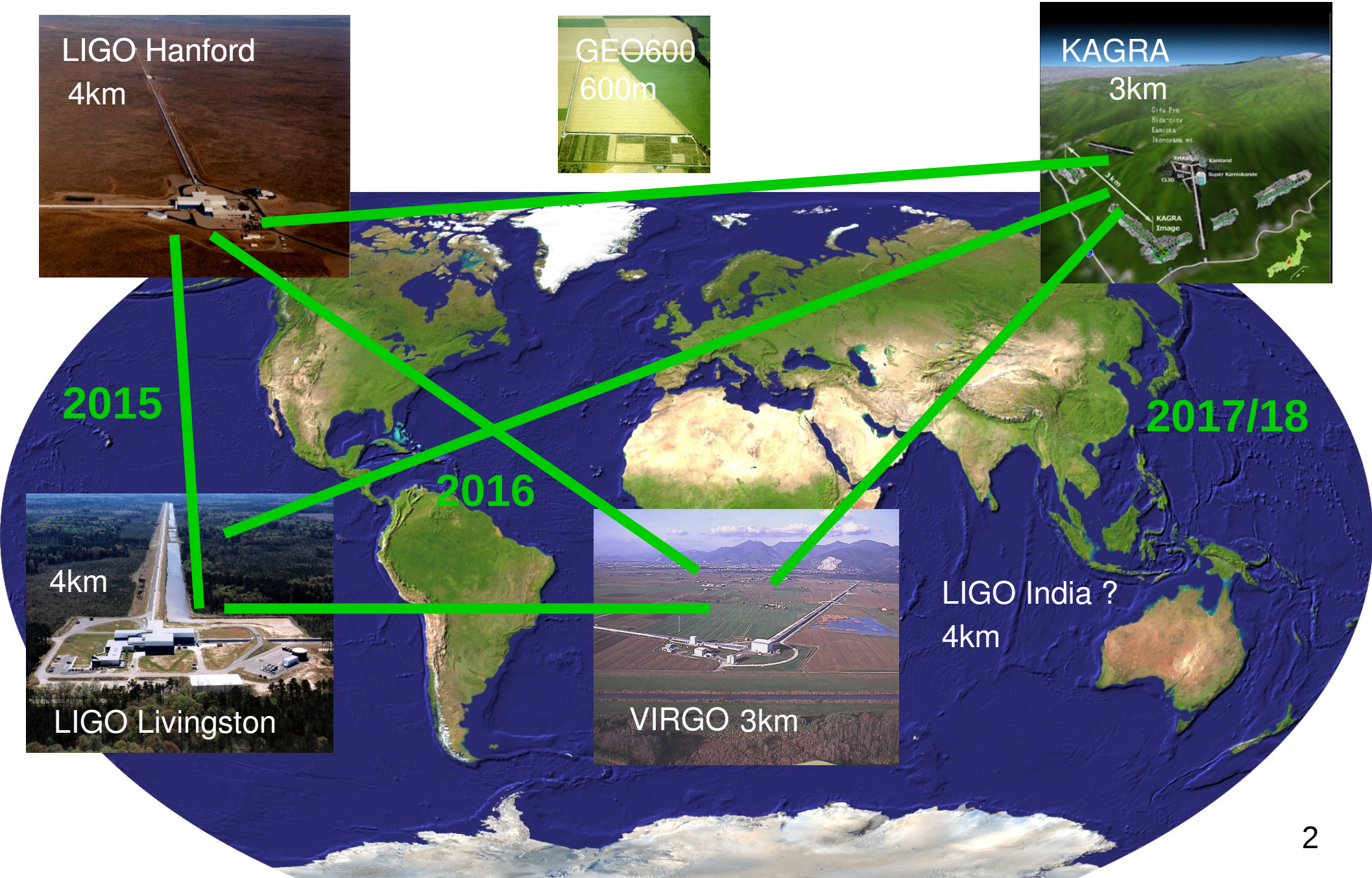
# Current GW – Interferometer Projects



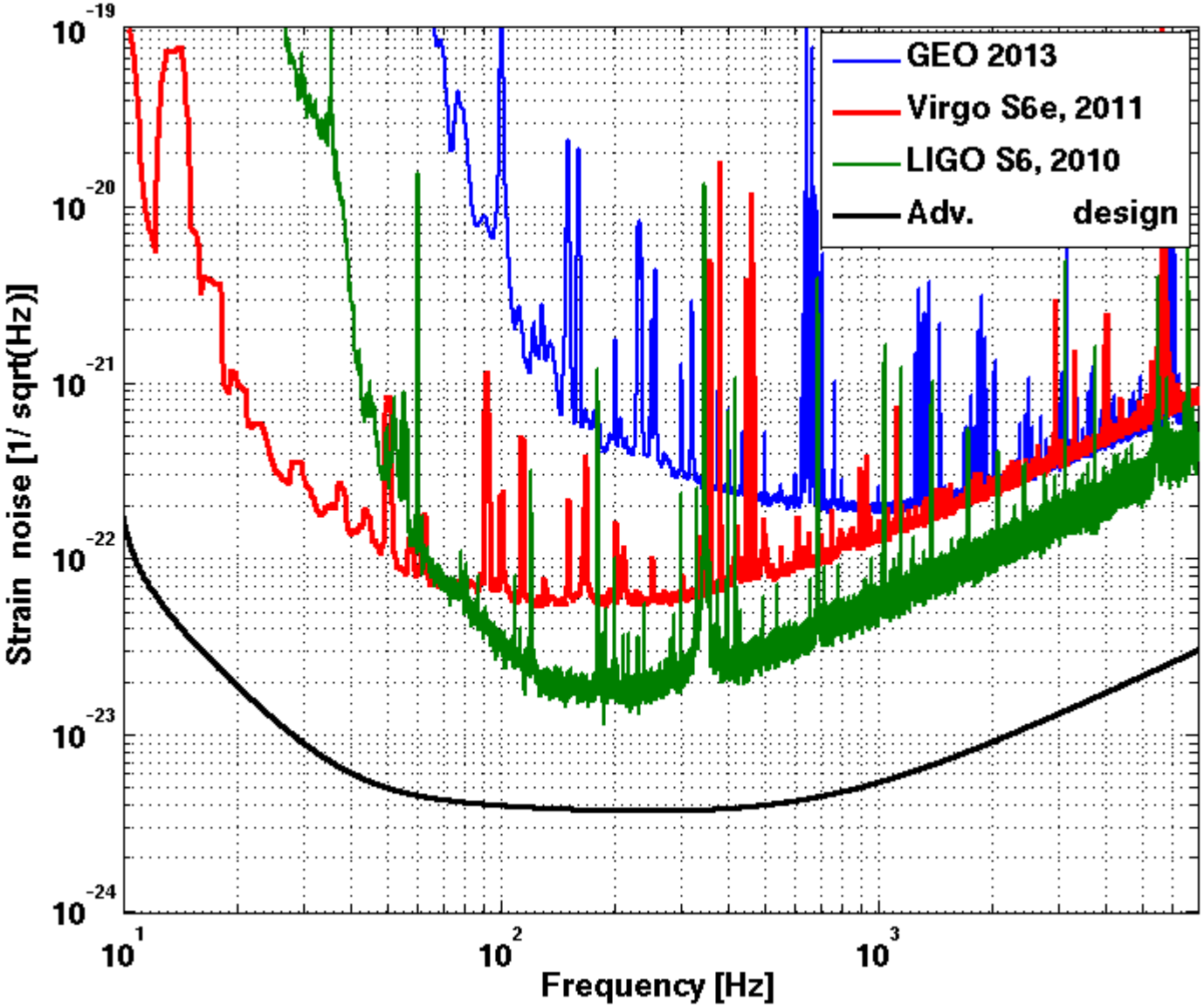
# Current GW – Interferometer Projects



# Current GW – Interferometer Projects

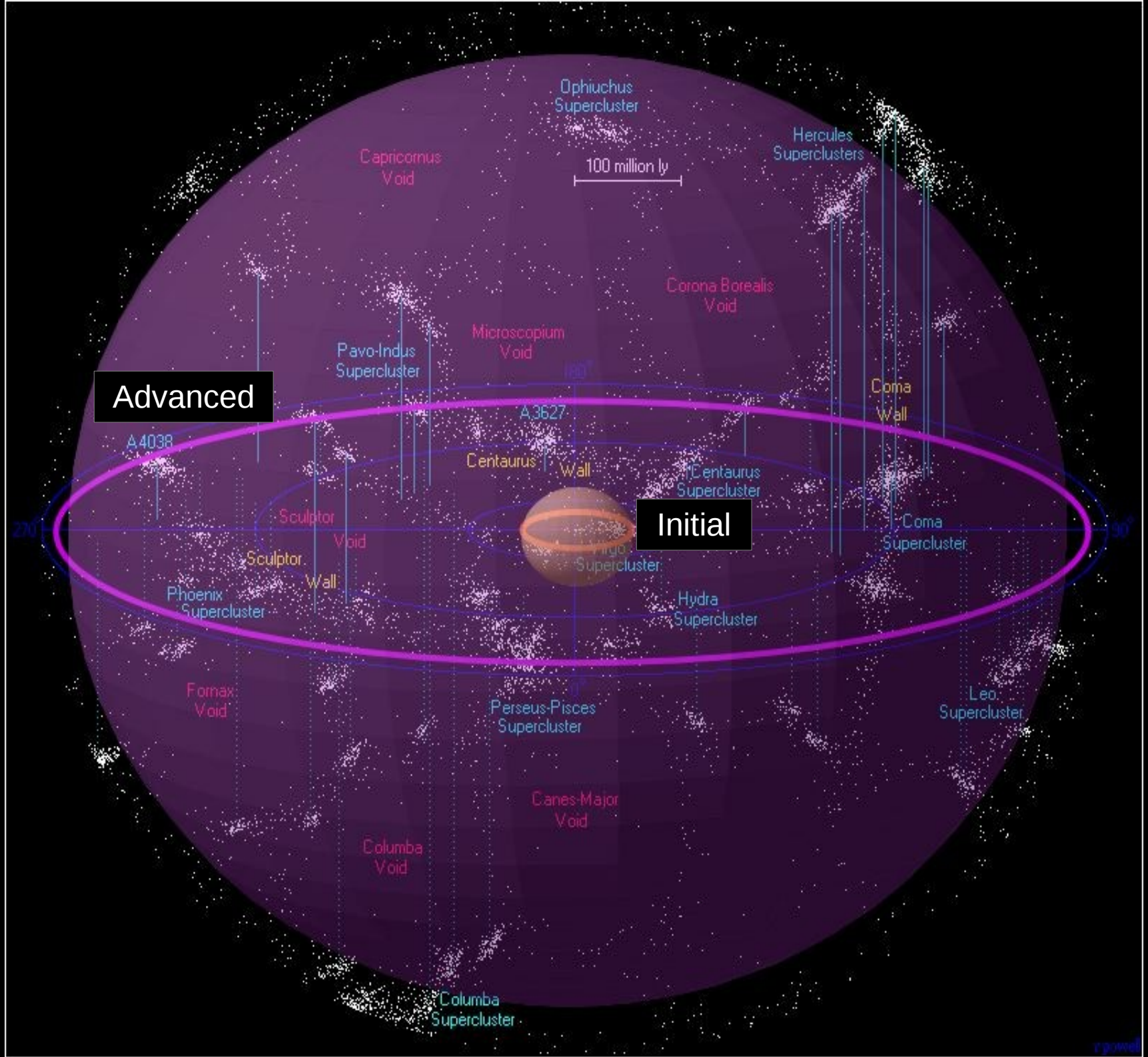


# Improving Sensitivity in Advanced Detectors




Initial

Advanced




Detection range for average oriented BNS inspiral (SNR=8):

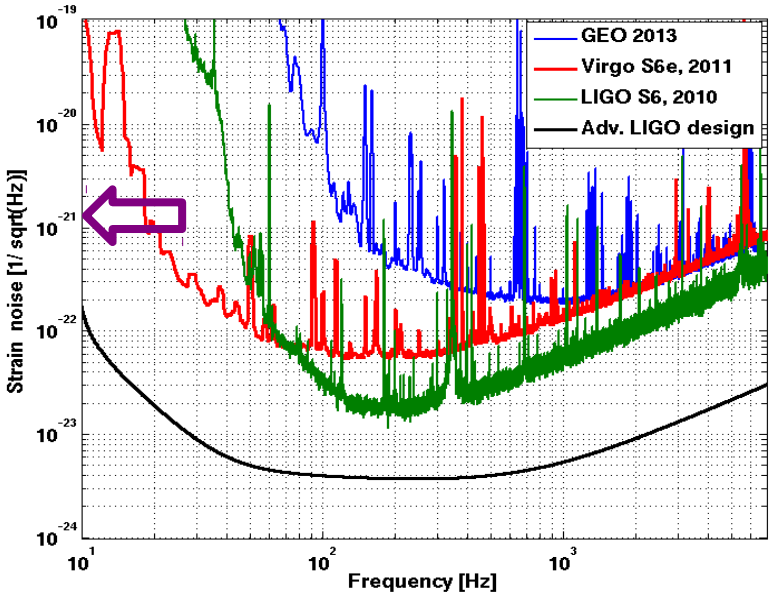
Initial: ~20Mpsec

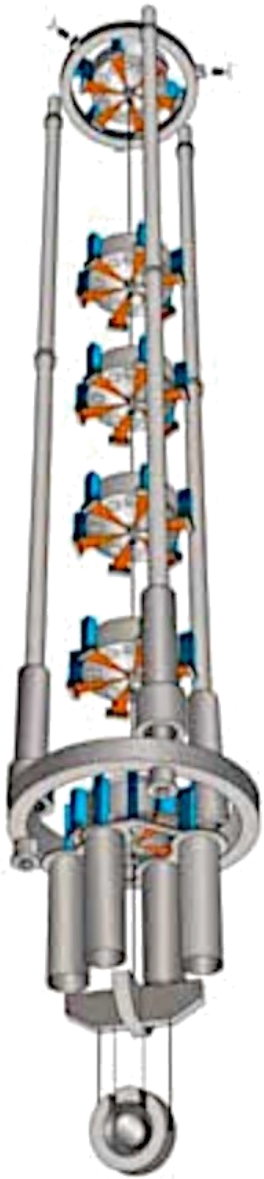
Advanced: ~200Mpsec

# TECHNOLOGIES

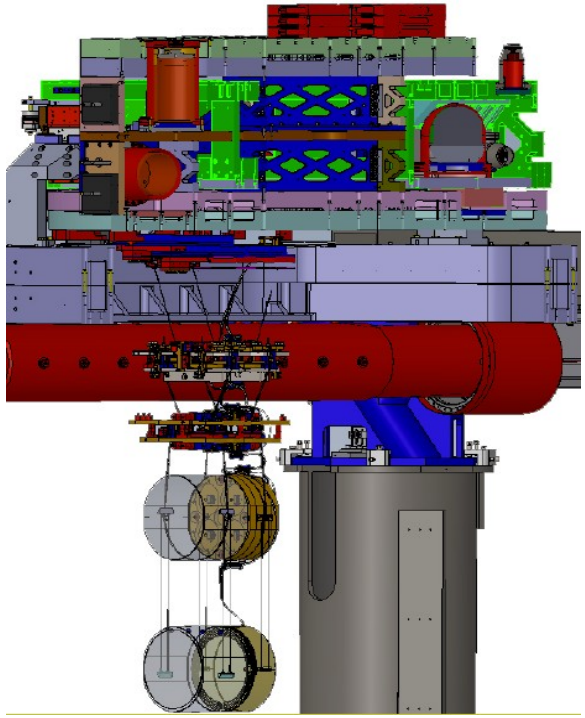
LOW FREQUENCY RANGE

- 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



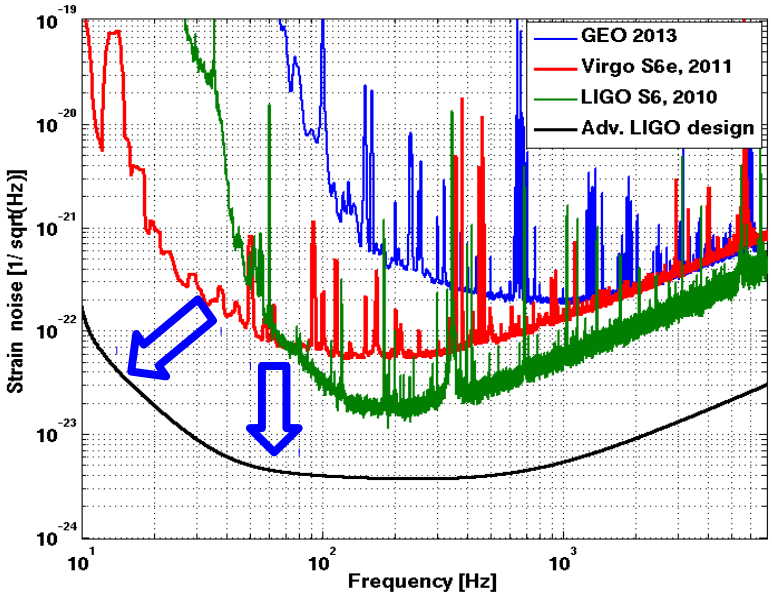
Adv. Virgo



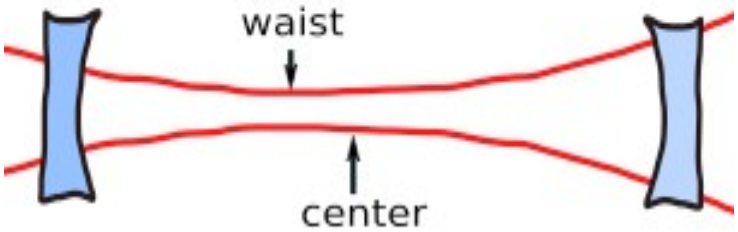
Adv. LIGO

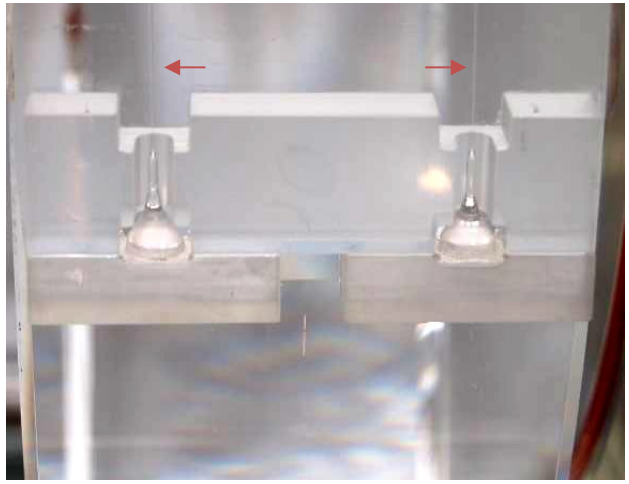
# TECHNOLOGIES

MID FREQUENCY RANGE



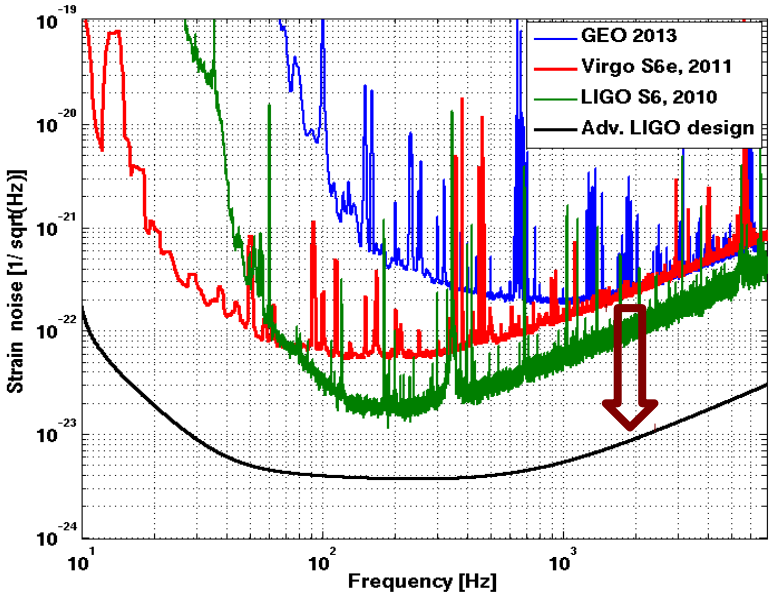

- Dominated by thermal noise of
  - Mirror coatings
  - Suspensions
- Reduced by:
  - Improved optical configuration: larger beam spot
  - Mirror coatings engineered for low losses
  - Test masses suspended by fused silica fibers (low mechanical losses)



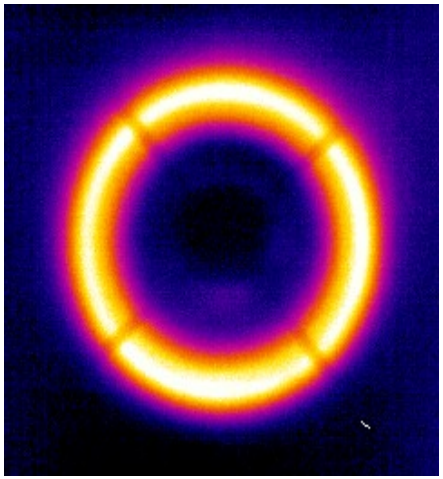



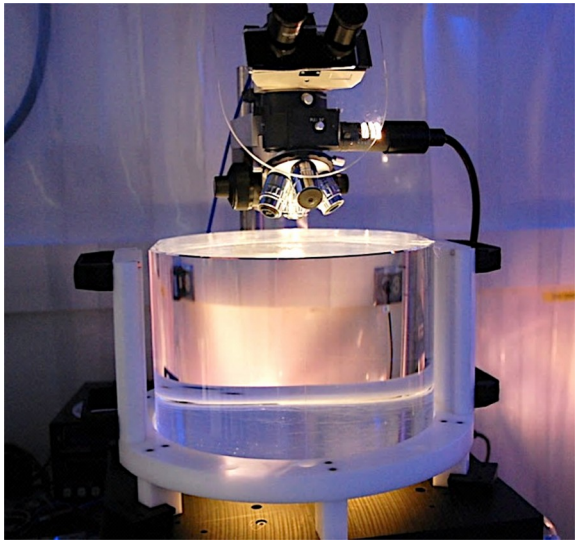
# TECHNOLOGIES

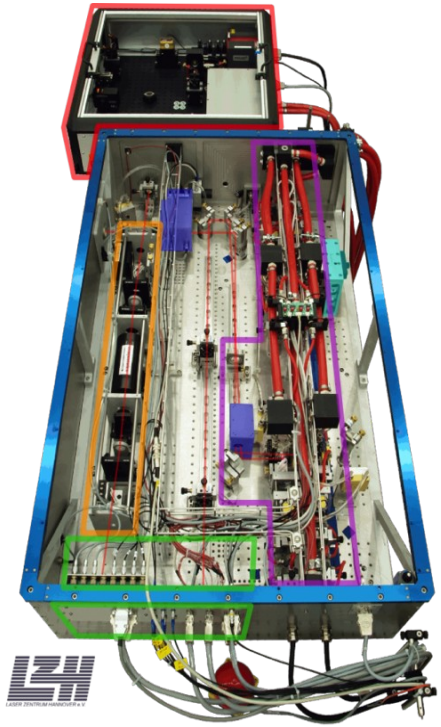
HIGH FREQUENCY RANGE




- 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





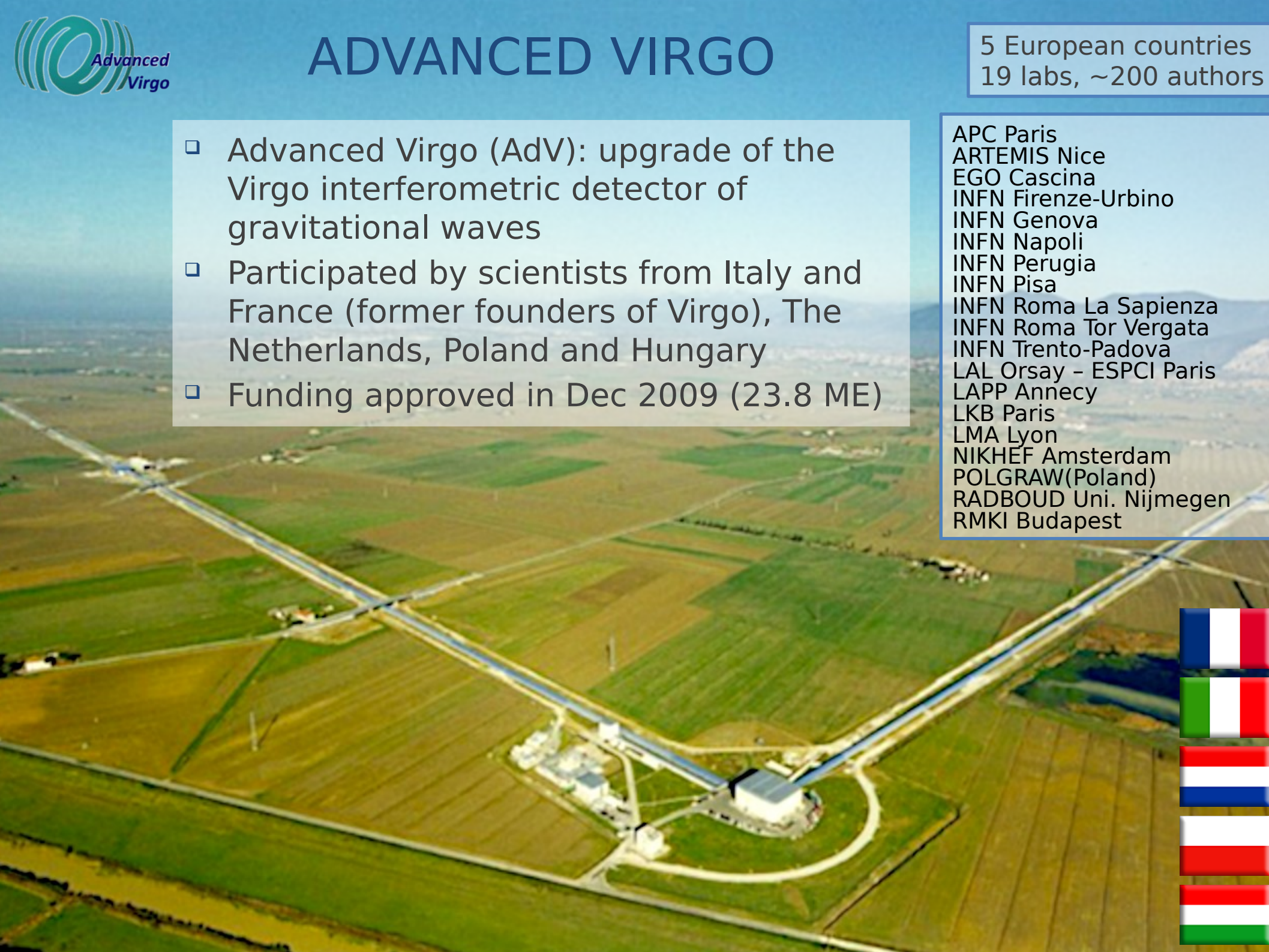


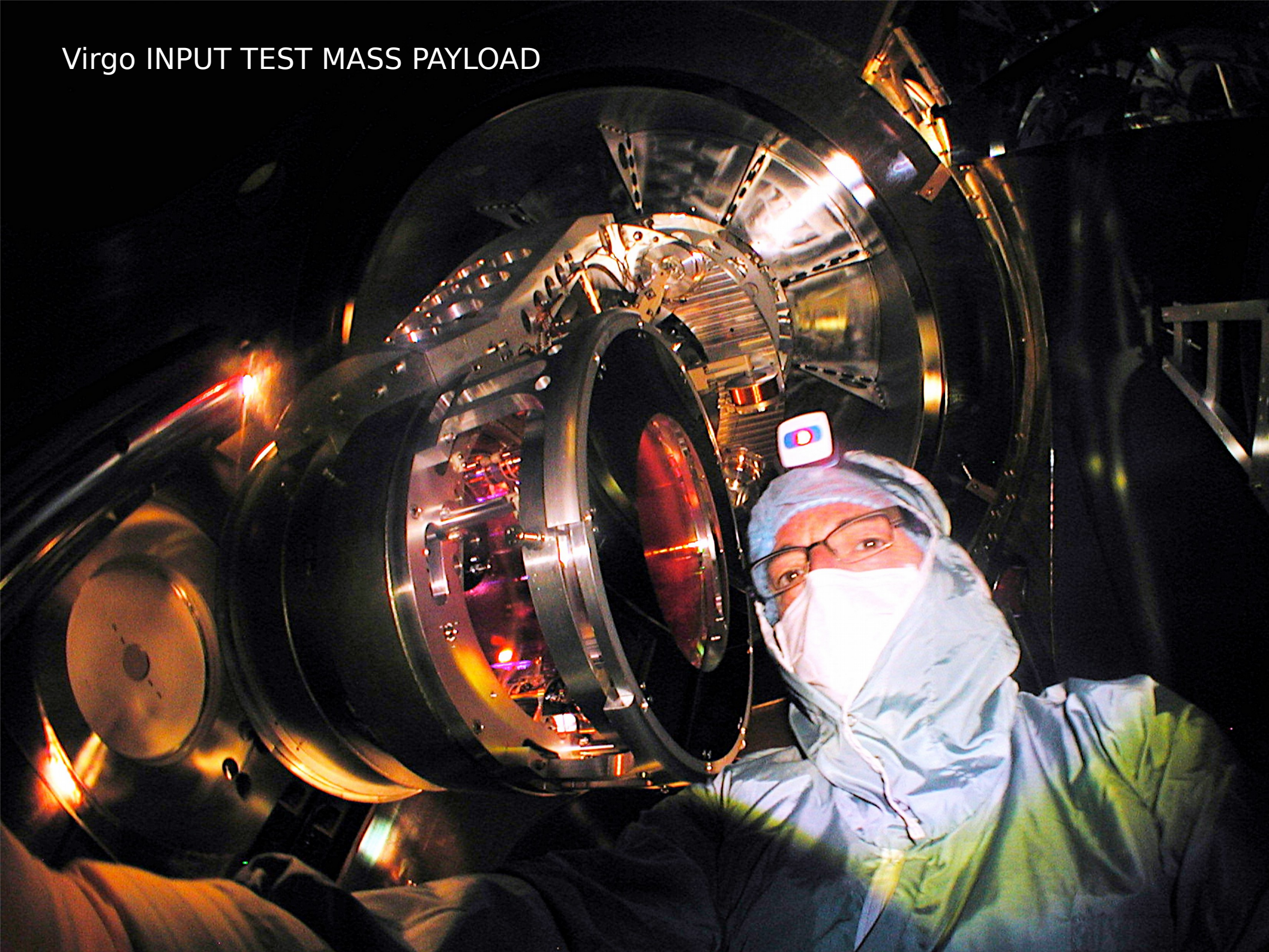
# ADVANCED VIRGO

5 European countries
19 labs, ~200 authors

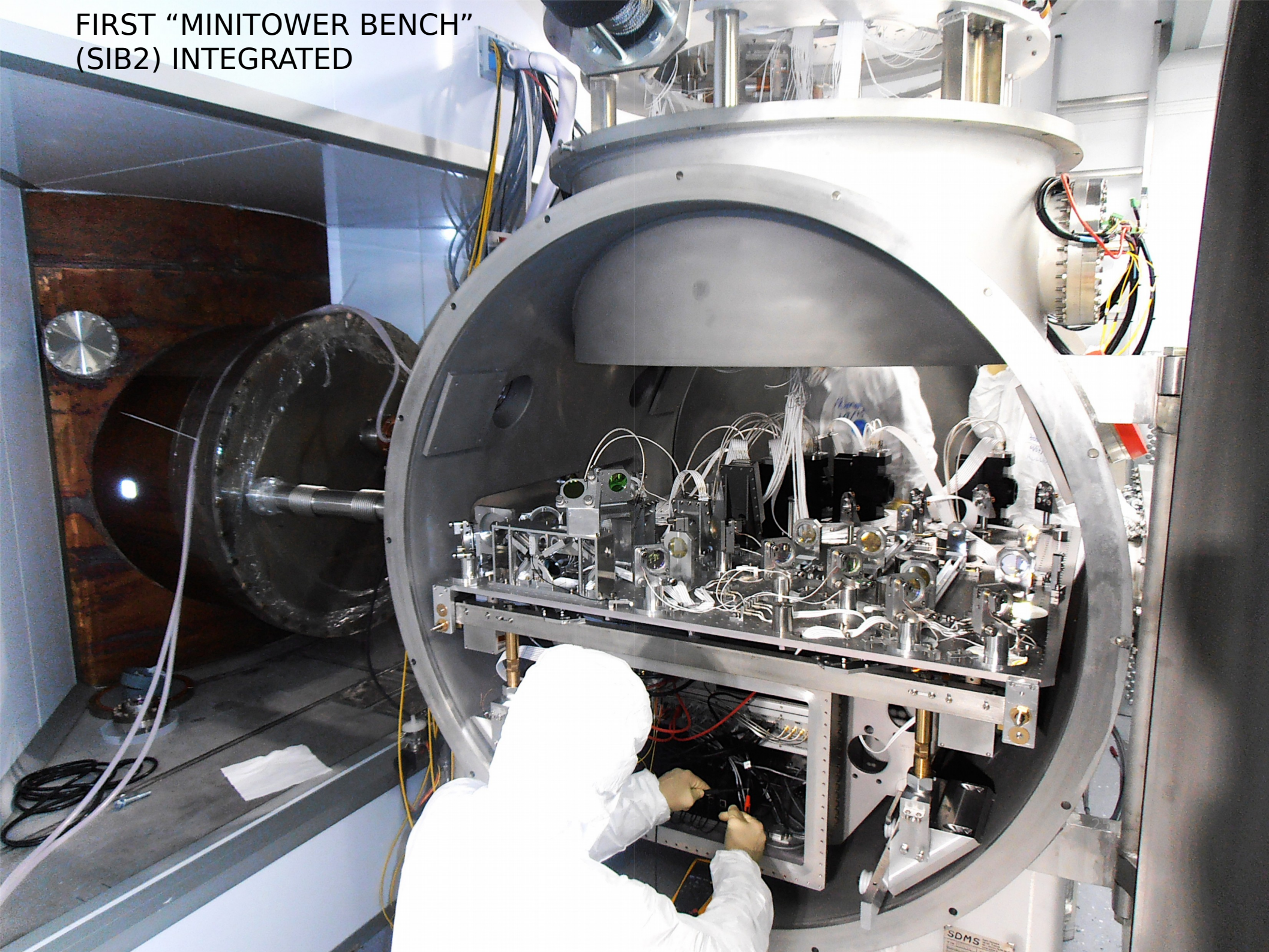
- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector of gravitational waves
- Participated by scientists from Italy and France (former founders of Virgo), The Netherlands, Poland and Hungary
- Funding approved in Dec 2009 (23.8 ME)

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




Virgo INPUT TEST MASS PAYLOAD

FIRST “MINITOWER BENCH”
(SIB2) INTEGRATED



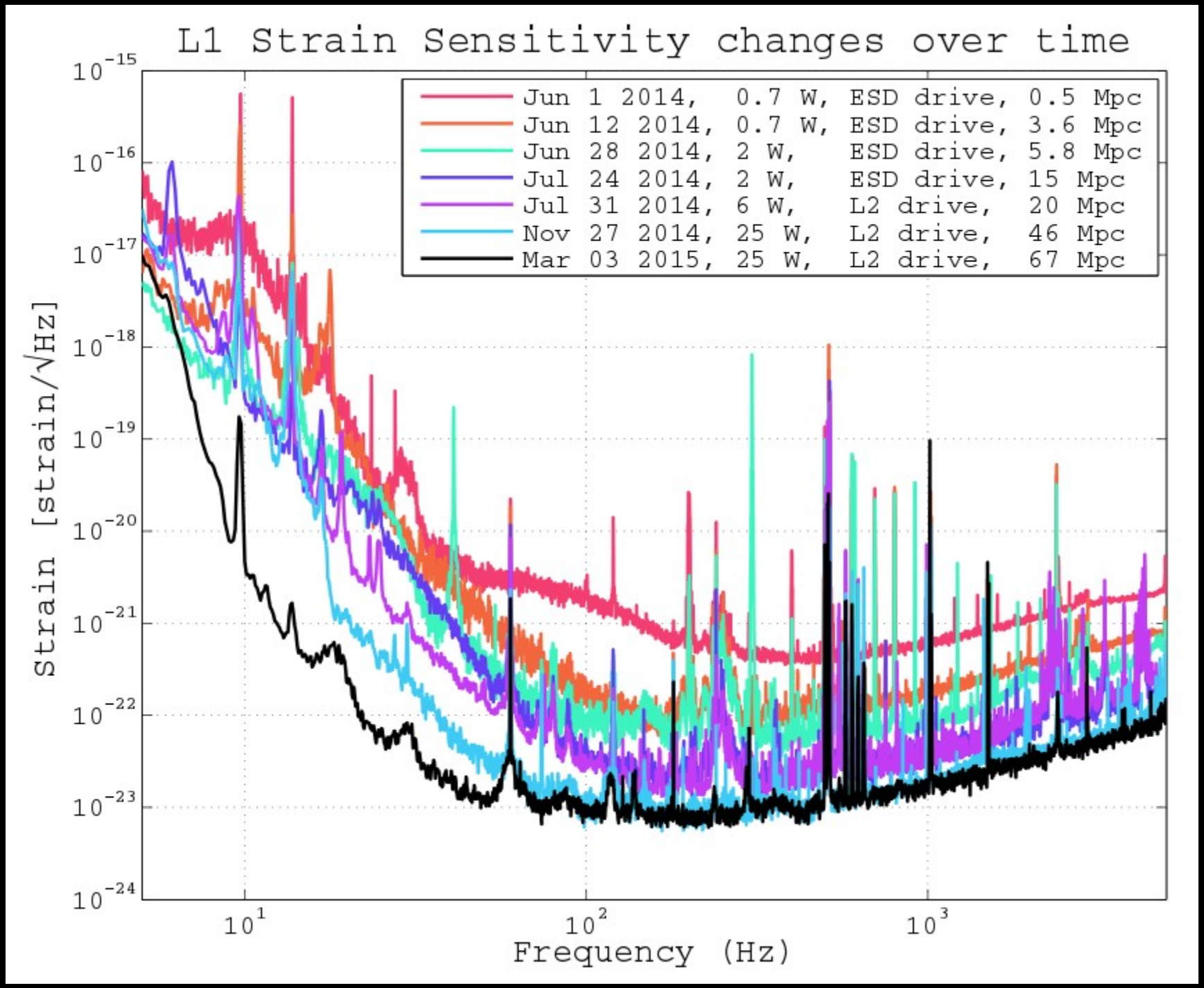
# Status of Advanced Virgo

- Installation in progress, to be completed end of 2015
- Plan to take observational data together with LIGO in 2016!

# Advanced LIGO

**LIGO scientific collaboration:**

**17 countries,**
**80+ institutions**
**900+ members**


L1 Strain Sensitivity changes over time
Jun 1 2014, 0.7 W, ESD drive, 0.5 Mpc
Jun 12 2014, 0.7 W, ESD drive, 3.6 Mpc
Jun 28 2014, 2 W, ESD drive, 5.8 Mpc
Jul 24 2014, 2 W, ESD drive, 15 Mpc
Jul 31 2014, 6 W, L2 drive, 20 Mpc
Nov 27 2014, 25 W, L2 drive, 46 Mpc
Mar 03 2015, 25 W, L2 drive, 67 Mpc
Strain [strain/√Hz]
Frequency (Hz)

# Status of Advanced LIGO

- Installation (project) completed in March 2015
- Both interferometers reached first stage sensitivity (~60Mpsec)
- First observational run (O1) of advanced detector era to start Monday (14.Sept.2015) !

# Can we expect GW detections ?

**Table 5.** Detection rates for compact binary coalescence sources.

| IFO | Source[a] | $\dot{N}_{low}$ yr$^{-1}$ | $\dot{N}_{re}$ yr$^{-1}$ | $\dot{N}_{high}$ yr$^{-1}$ | $\dot{N}_{max}$ yr$^{-1}$ |
|---|---|---|---|---|---|
| | NS–NS | $2 \times 10^{-4}$ | 0.02 | 0.2 | 0.6 |
| | NS–BH | $7 \times 10^{-5}$ | 0.004 | 0.1 | |
| Initial | BH–BH | $2 \times 10^{-4}$ | 0.007 | 0.5 | |
| | IMRI into IMBH | | | <0.001[b] | 0.01[c] |
| | IMBH-IMBH | | | $10^{-4}$[d] | $10^{-3}$[e] |
| | NS–NS | 0.4 | 40 | 400 | 1000 |
| | NS–BH | 0.2 | 10 | 300 | |
| Advanced | BH–BH | 0.4 | 20 | 1000 | |
| | IMRI into IMBH | | | 10[b] | 300[c] |
| | IMBH-IMBH | | | 0.1[d] | 1[e] |

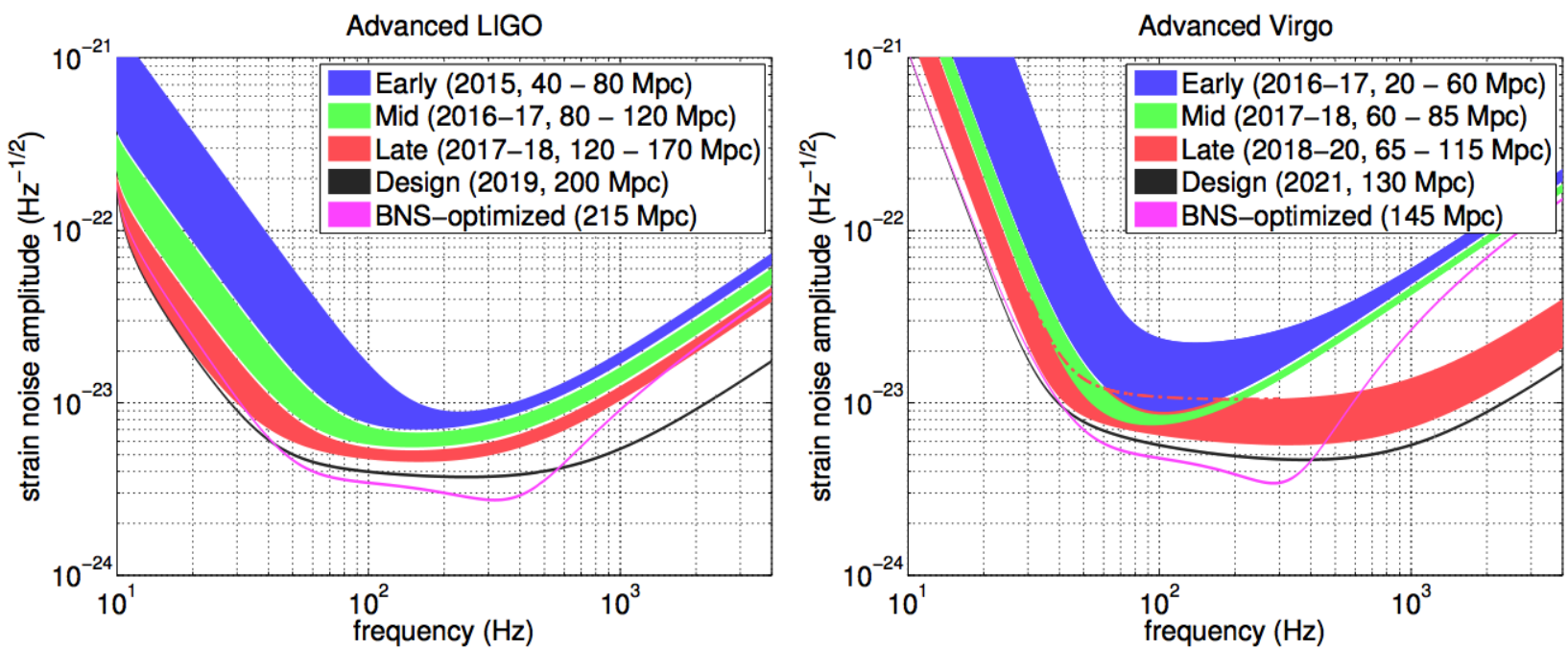
Class. Quant. Grav., **27** (2010) 173001

# Observing prospects

Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories

J. Aasi[1], J. Abadie[1], B. P. Abbott[1], R. Abbott[1], T. D. Abbott[2], M. Abernathy[3], T. Accadia[4], F. Acernese[5ac], C. Adams[6], T. Adams[7], P. Addesso[8], R. X. Adhikari[1], C. Affeldt[9,10], M. Agathos[11a], O. D. Aguiar[12], P. Ajith[1], B. Allen[9,13,10], A. Allocca[14ac], E. Amador Ceron[13], D. Amariutei[15],
S. B. Anderson
P. Astone[17a],
P. Baker[21], G. I
L. Barsotti[24],
J. Batch[18], J. Ba
A. S. Bell[3], C.
P. T. Beyersdor
M. A. Bizoua
O. Bock[9,10],
R. Bork[1], M. E
P. R. Bra
D. O. Brid
D. A. Br
A. Buon
G. Cagnoli
C. D. Ca
M. Cavaglià[16], F
S. Chao[101], P. C
H. S. Cho[53],
F. Clara[18], D. E
A. Colla[17ab], M.
N. Cornis
P. Couva
T. D. Crei
S. L. Danil
M. Davier[31a], C
W. Del Pozz
S. Dhurandhar[60],
F. Donovan[24], K. L. Dooley[9,10], S. Doravari[1], M. Drago[61ab], S. Drasco[20], R. W. P. Drever[62],
J. C. Driggers[1], Z. Du[46], J.-C. Dumas[33], S. Dwyer[24], T. Eberle[9,10], M. Edwards[7], A. Effler[2], P. Ehrens[1],

arXiv:1304.0670v1 [gr-qc] 2 Apr 2013



# KAGRA Project

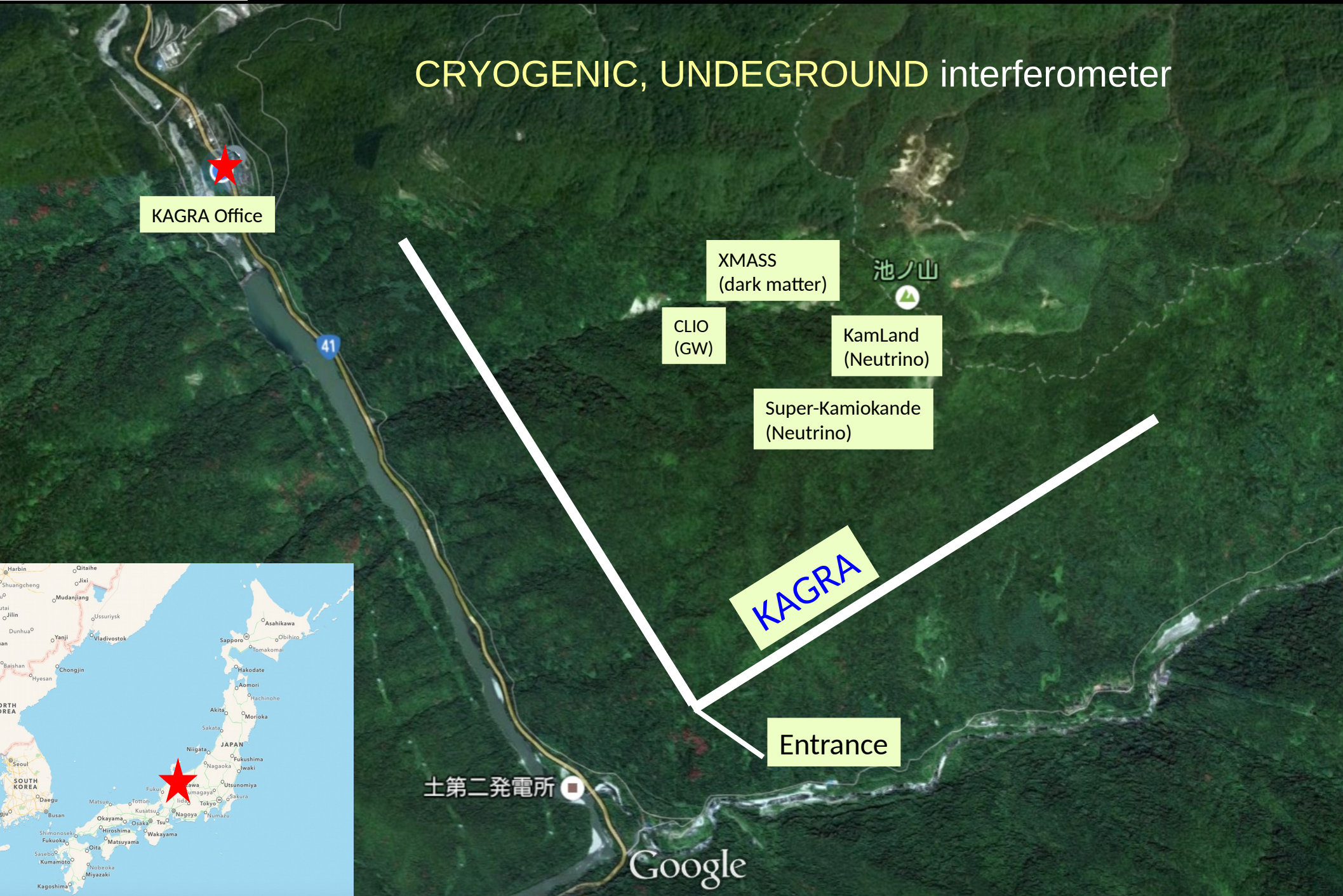
Cryogenic and Underground Gravitational-wave detector

Host: U of Tokyo ICRR

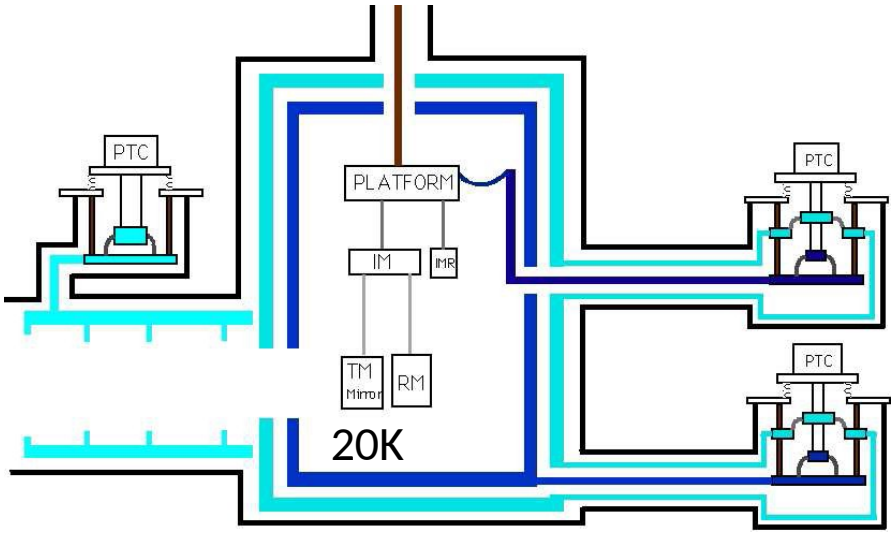
Co-host: NAOJ, KEK

~230 collaborators from ~60 universities

# Kamioka site

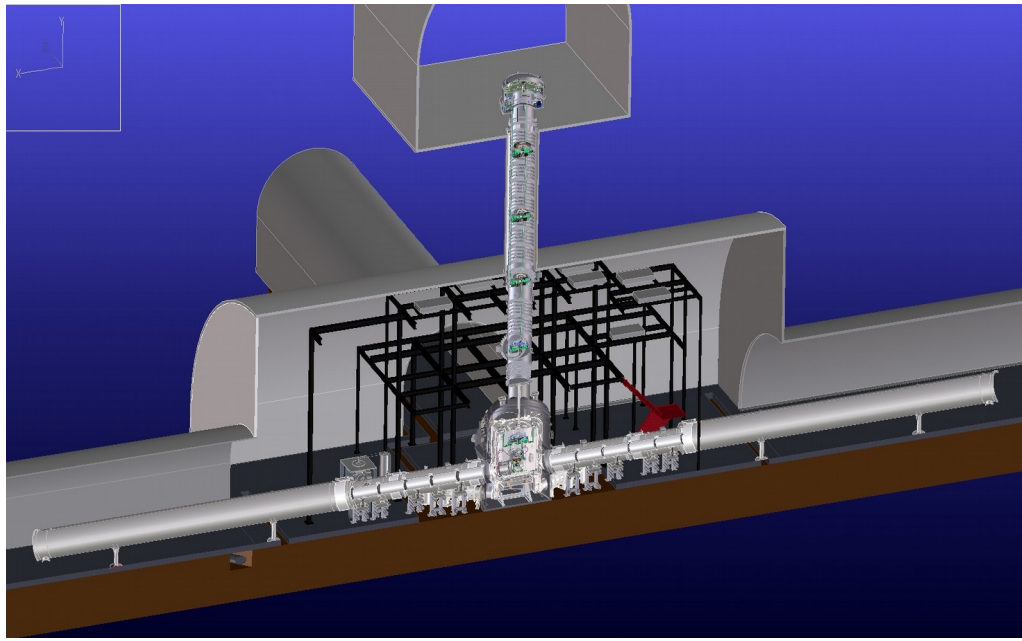


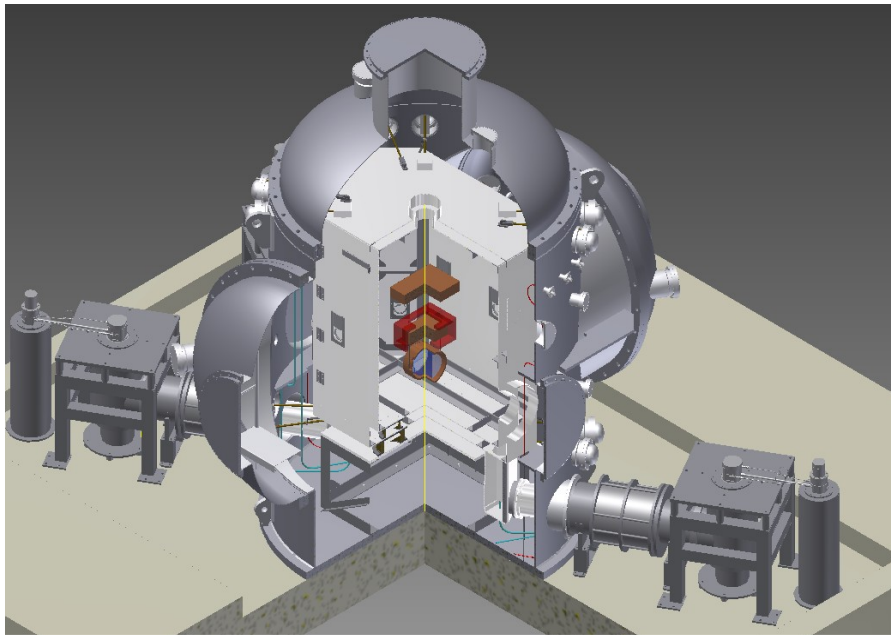
# Cryostat Design




8K

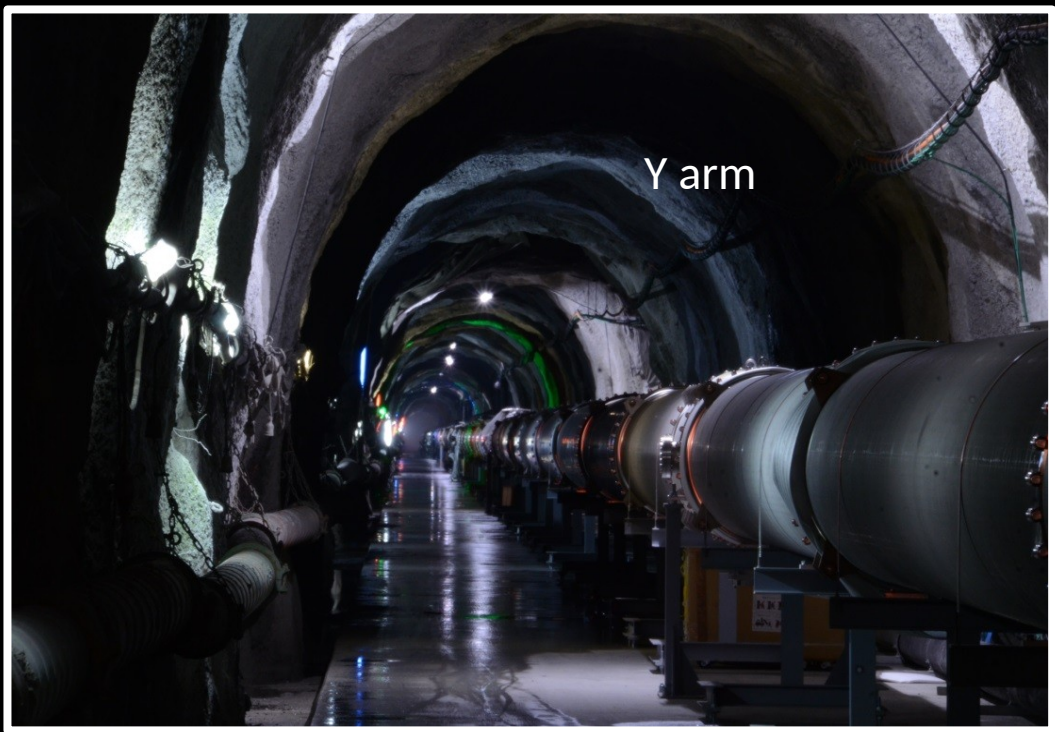
80K

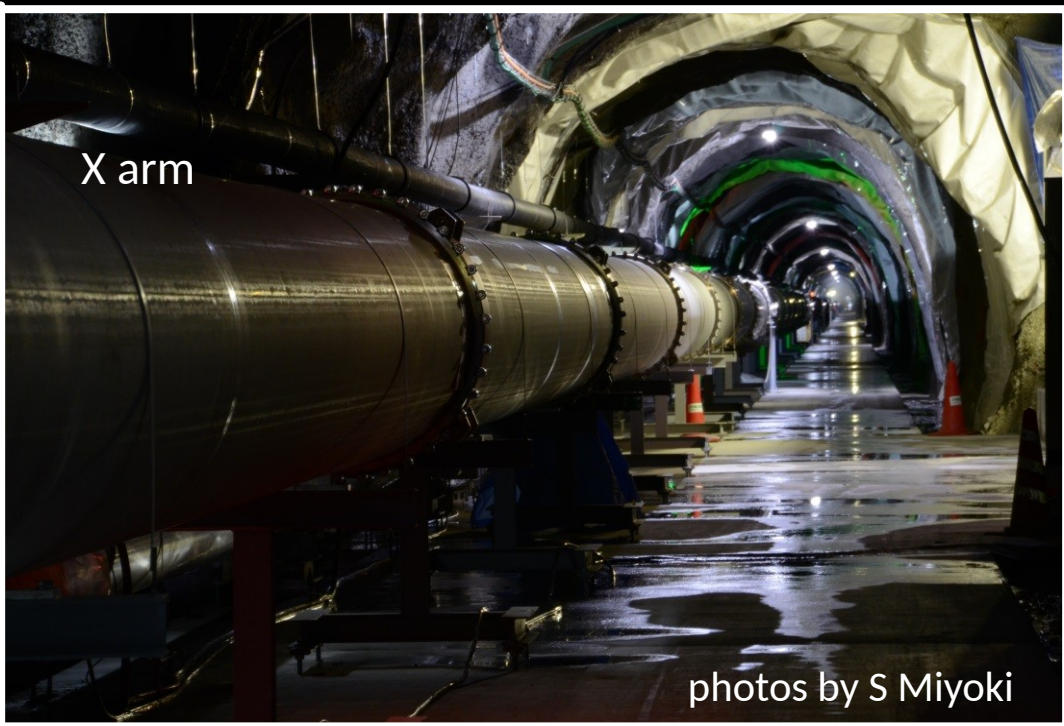




- 2.6 diameter, 3.6m high, 10 ton
- 8K an 80K
- 4 pulse tube cryo-coolers for each cryostat

# Vacuum system



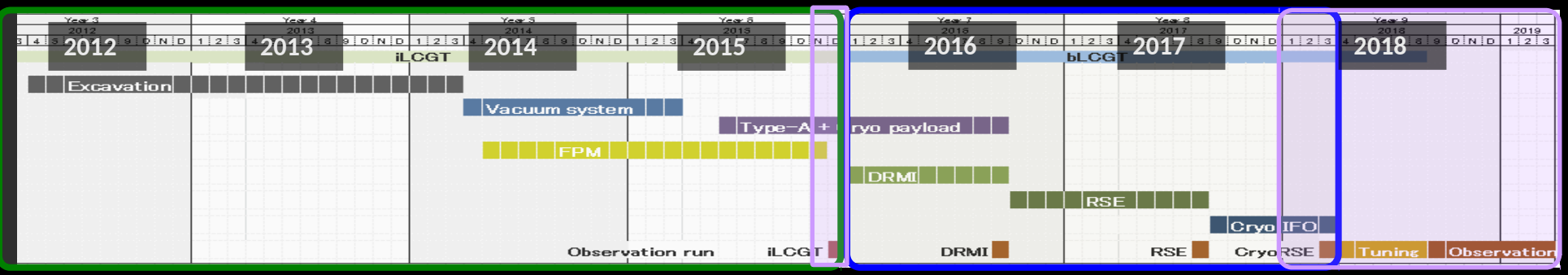

- Both 3 km arm vacuum tubes (800mm d) and 125 baffles were jointed and leak tested → no leak!
- Cryostats installed

# KAGRA timeline

Project Started in 2010
1 yr delay due to
the earthquake

Engineering
Observation

First
Observation




## iKAGRA

- Simple 3-km Michelson ifo
- Room temperature
- Simplified suspensions

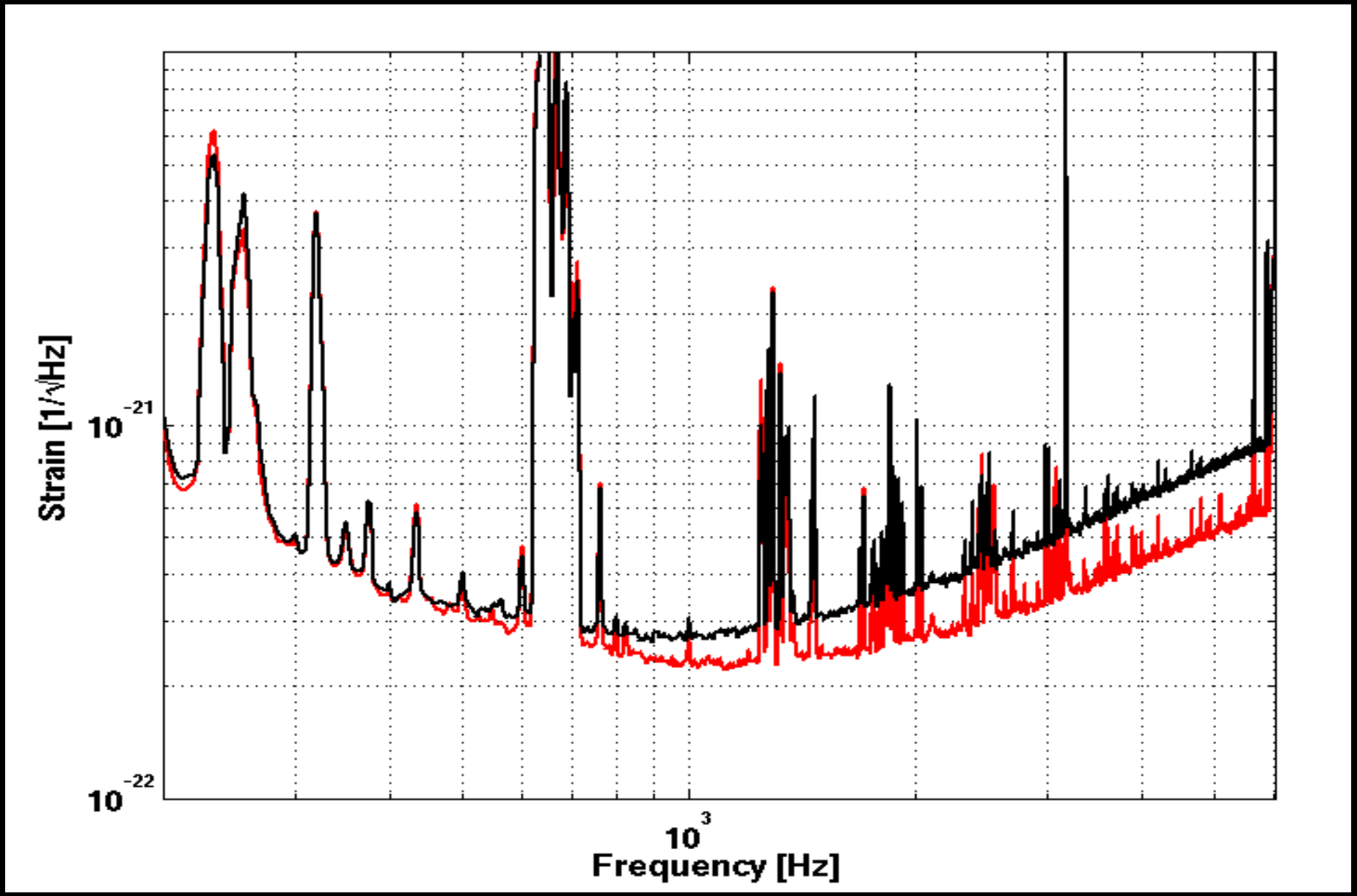
## bKAGRA

- Dual-recycled FP MI ifo
- Cryogenic temperature
- VIRGO-type big suspensions

# GEO600

**Smaller-scale detector run as prototype observatory.**
**Development and test of new technologies.**
**Example: Control and long-term application of squeezed light.**

# Squeezed light at GEO: 3.7 dB reduction of read-out noise

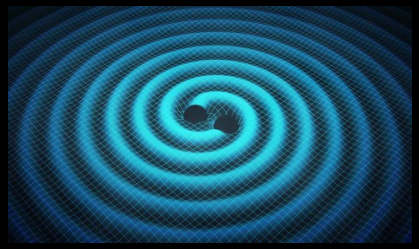


# Beyond Advanced Interferometers

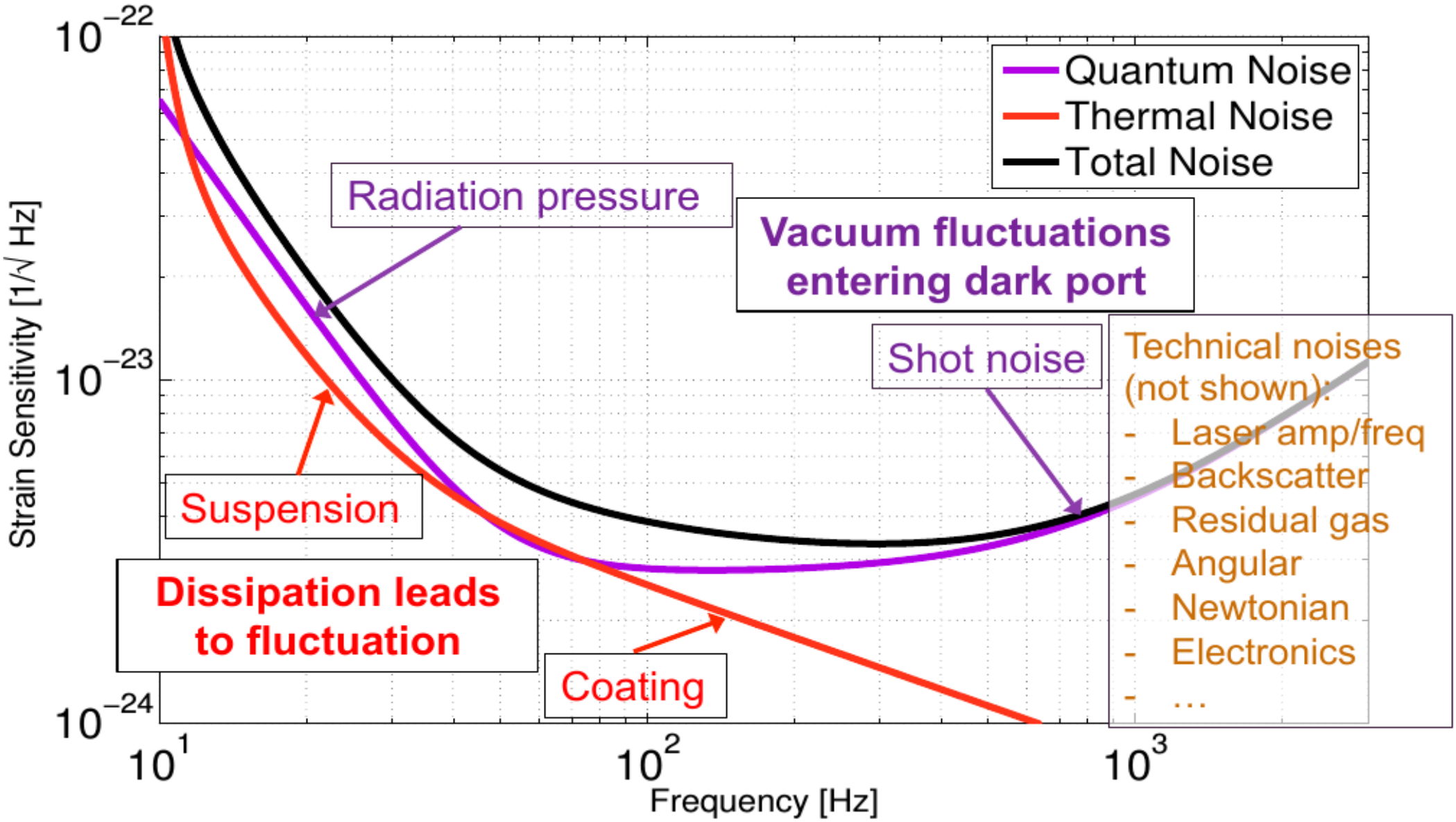
- Upgrades with squeezed light planned for LIGO and Virgo
- LIGO: likely suspension/mirror upgrade, perhaps new detector in same facility on intermediate timescale (10y).
  Perhaps new facility
- ET (europe): New facility, 10x more sensitive than advanced IFOs (design study completed)

# Summary

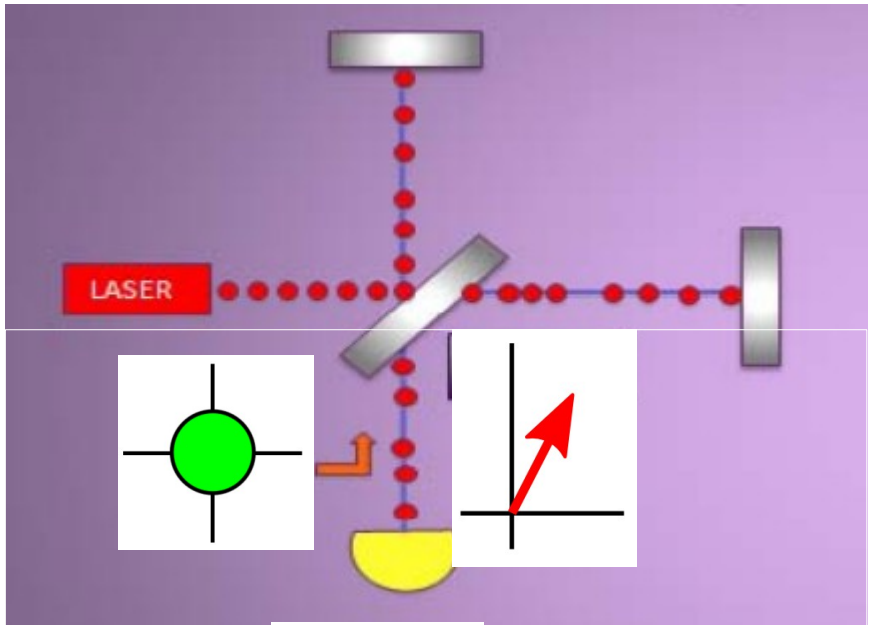
- Gravitational waves as new tool for astronomy, just around the corner...
- Advanced Interferometers (Virgo, LIGO, KAGRA) progressing nicely, on schedule
- LIGO starting 1st observational run (O1) next week, Virgo to join O2 in 2016, KAGRA 2017/18
- Expect 1st detections within few years...

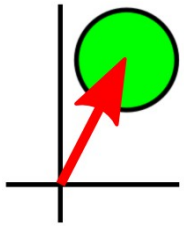


# Limiting Noise



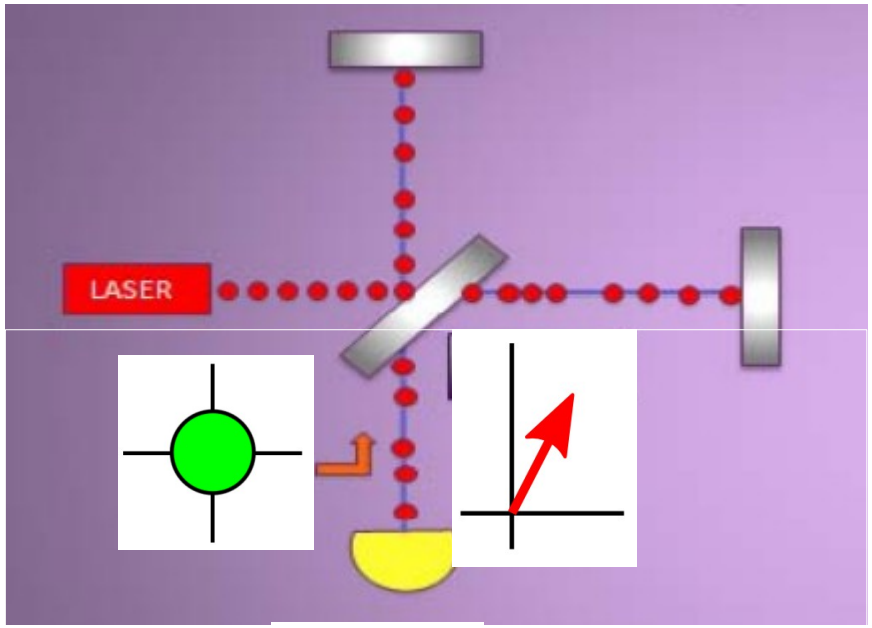
# Vacuum fluctuations in interferometers

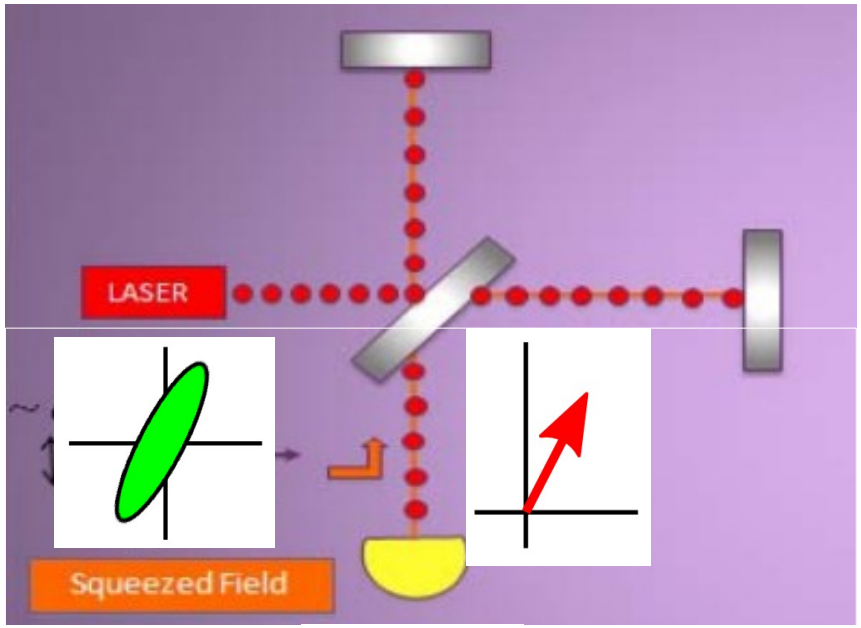


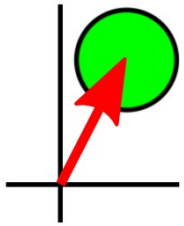



Diagrams credit: L. Barsotti, K. Dooley

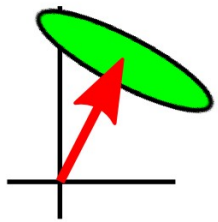
# Vacuum fluctuations in interferometers



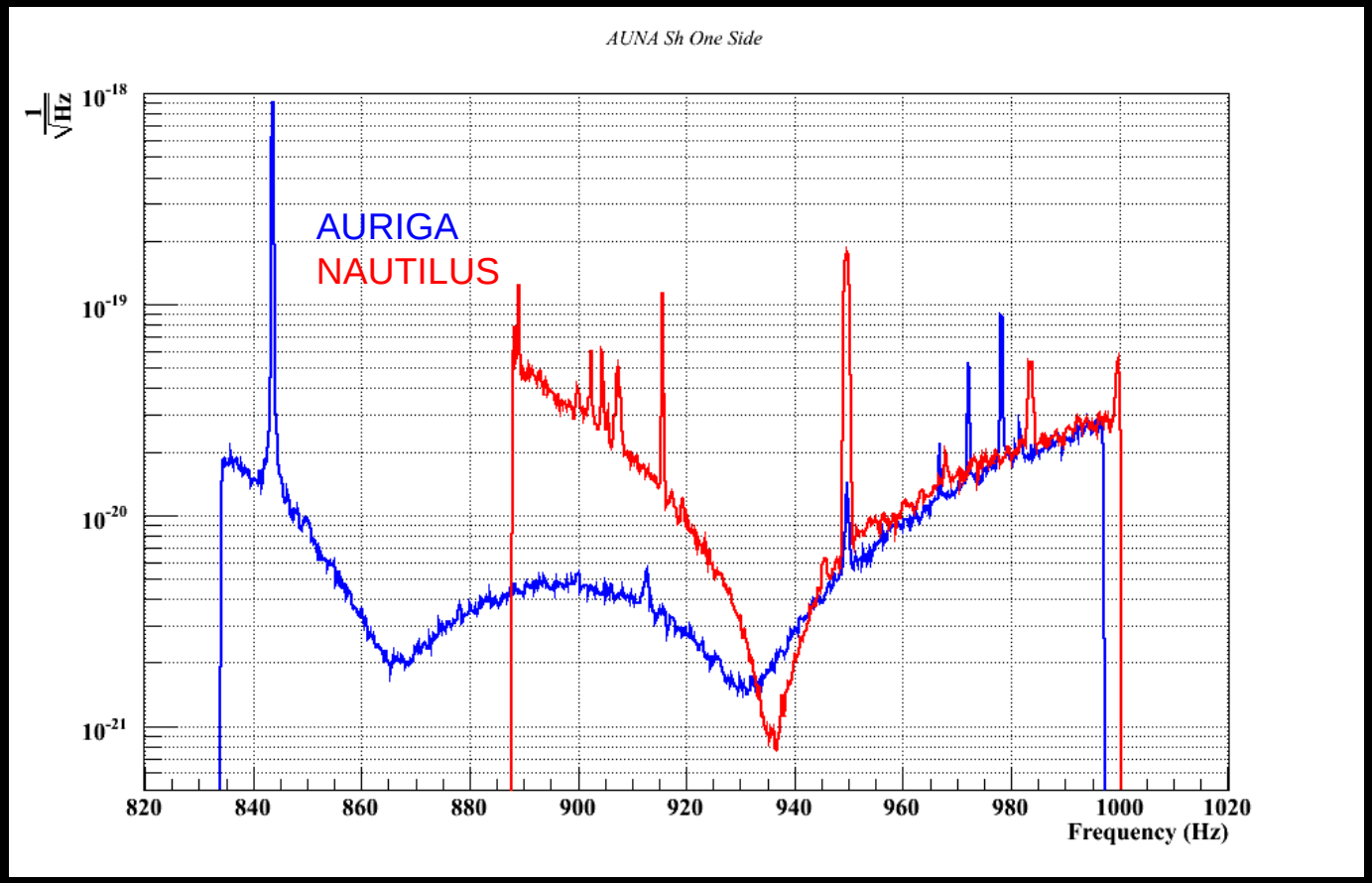



Diagrams credit: L. Barsotti, K. Dooley



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

**AURIGA & NAUTILUS continously on the air ~ 90% (combined)**
**with noise close to Gaussian (~ 20 outliers/day at SNR>6)**
**until LIGO/Virgo resume operation**




**AUNA**: “astrowatch” of AURIGA & NAUTILUS under triggers from SN neutrinos, giant X-rays flares, etc