Gravitational-wave detection with ground-based interferometers

M. Granata

Laboratoire des Matériaux Avancés – CNRS/IN2P3

outline

gravitational waves

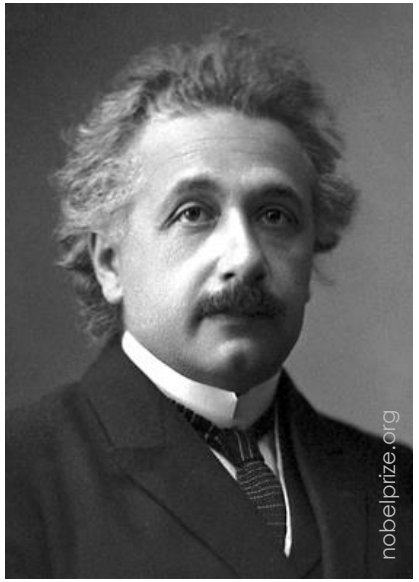
ground-based detectors

- history
- interferometers
  - layout
  - mirrors
  - suspensions
  - sensitivity
- observable sources

1st detection

outlook

1915 – General Relativity



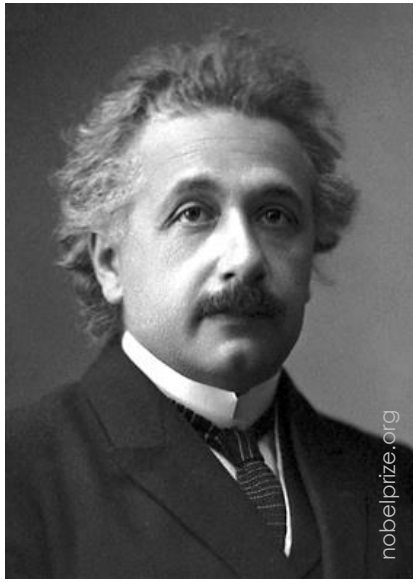
local space-time is dynamic

gravity is equivalent to space-time curvature

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

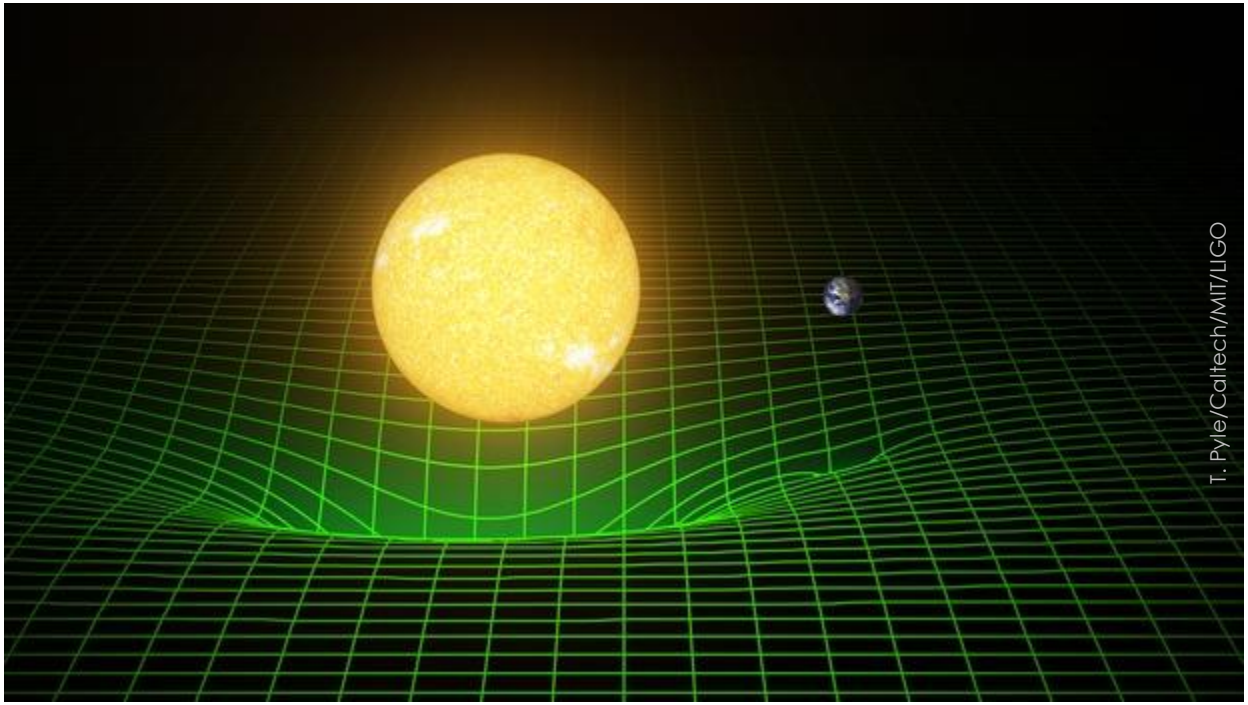
$$\underbrace{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R}_{\text{space-time geometry}} = \underbrace{\frac{8\pi G}{c^4} T_{\mu\nu}}_{\text{energy/matter}}$$

1915 – General Relativity

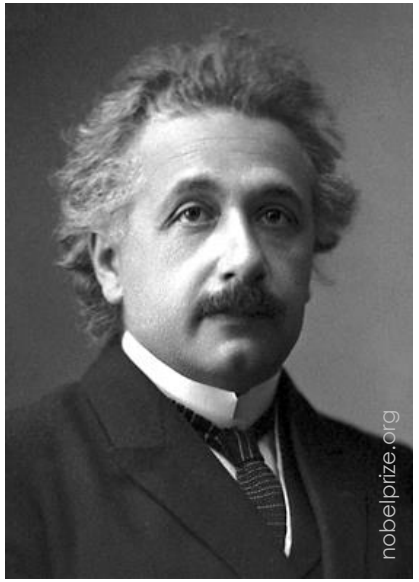


local space-time is dynamic

gravity is equivalent to space-time curvature



1916 – gravitational waves (GWs)



perturbative approach

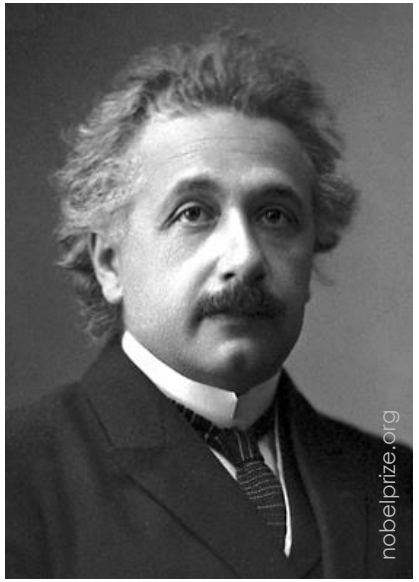
→ linearized field equations

→ wave solution

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad |h_{\mu\nu}| \ll 1$$

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) \overline{h}_{\mu\nu} = 0$$

1916 – gravitational waves (GWs)



perturbative approach

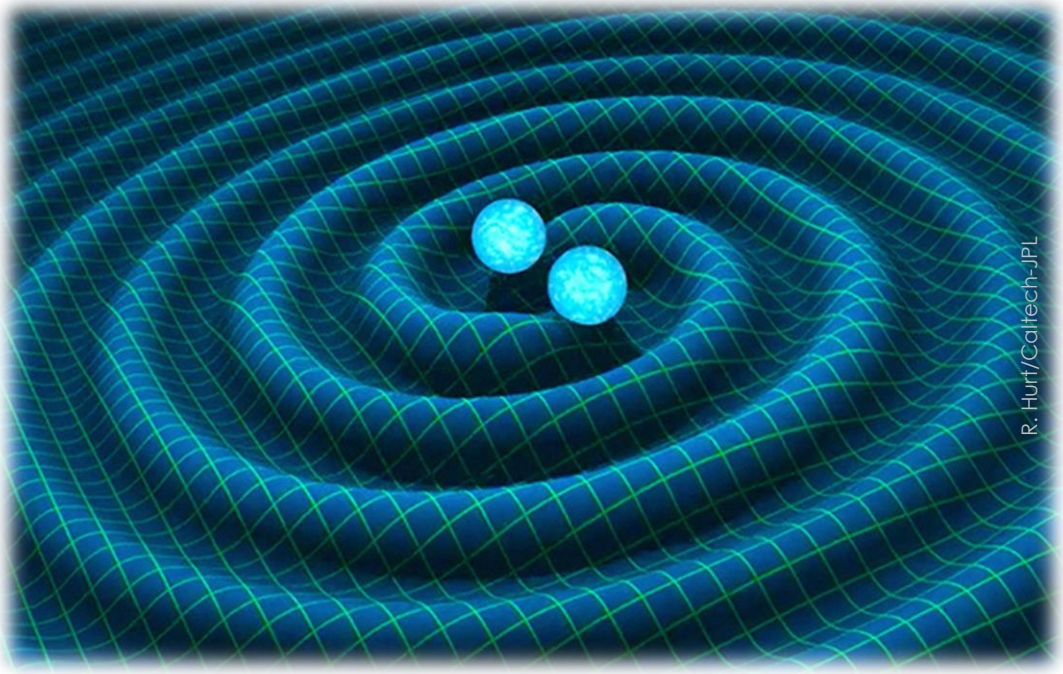
→ linearized field equations

→ wave solution

ripples in space-time fabric

propagating at light speed

plane and transverse



strain waves

relative distance variations

$$\frac{\Delta l}{l} \propto h$$

strain waves

relative distance variations

$$\frac{\Delta l}{l} \propto h$$

$$h = \frac{2G}{c^4}\frac{1}{r}\ddot{Q}$$

mass quadrupole moment

dimensionless amplitude

propagation distance

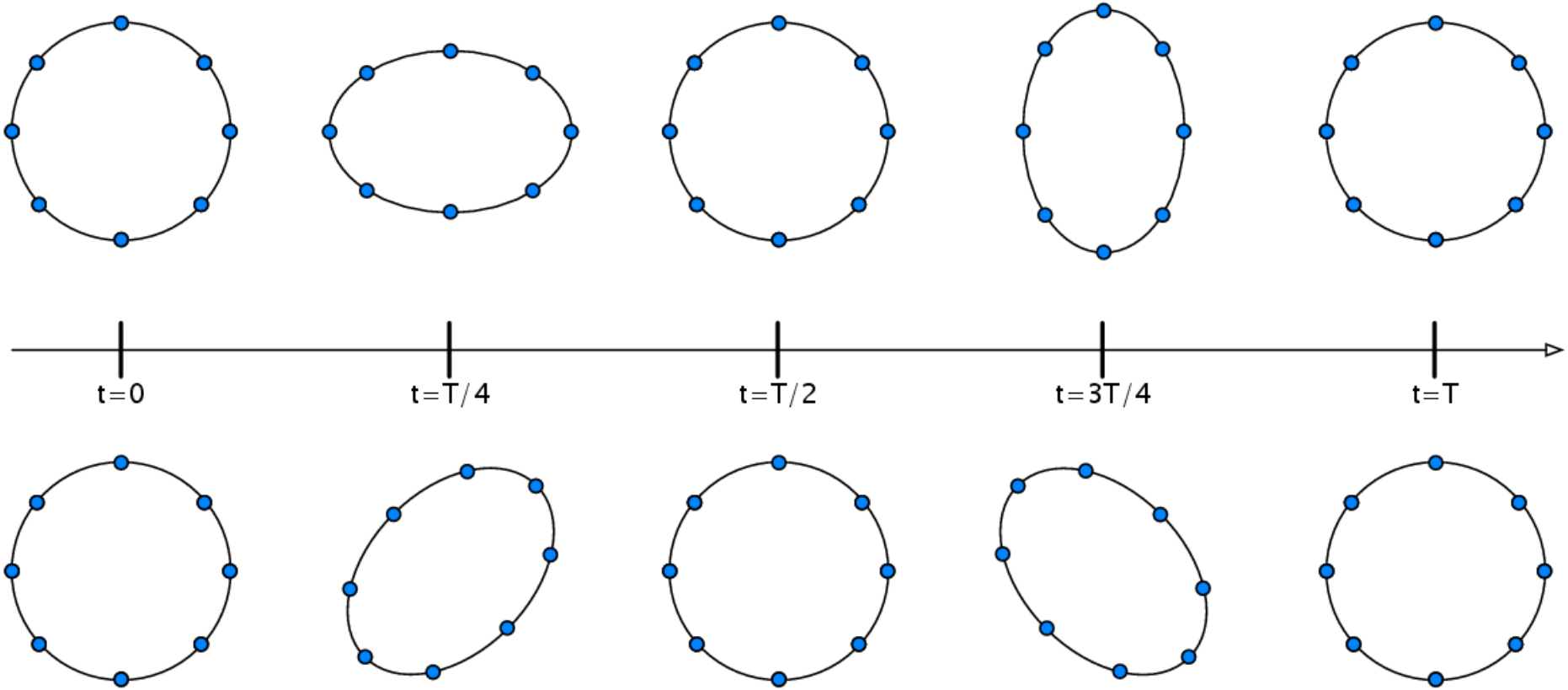
emitted by accelerated masses

strain waves

relative distance variations

$$\frac{\Delta l}{l} \propto h$$

quadrupole effect – 2 orthogonal polarizations:



scale of effect vastely exaggerated

tiny strain waves

relative distance variations

$$\frac{\Delta l}{l} \propto h$$

$$h = \frac{2G}{c^4}\frac{1}{r}\ddot{Q}$$

$$G/c^4 \sim 10^{-43}\ \mathrm{N}^{-1}$$

extremely weak emission efficiency

tiny strain waves

relative distance variations

$$\frac{\Delta l}{l} \propto h$$

$$h = \frac{2G}{c^4}\frac{1}{r}\ddot{Q}$$

astrophysical sources: *large, highly accelerated* masses

R = 200 km
m = 35 M_{sun}
f_{orb} = 75 Hz
r = 400 Mpc

$$h \propto mR^2\omega_{\mathrm{orb}}^2/r \lesssim 10^{-21}$$

40 years of skepticism

debate: a mathematical strangeness?

1957: Chapel Hill conference

GWs are a physical reality

dawn of the detection quest

resonant bars

- ’60s-’70s: 1st experiments

resonant bars

- '60s-'70s: 1st experiments

  detections claimed

  no believable evidence

- > '70s: Institute for Gravitational Research (IGR), Max Planck Institute (MPA), Allegro, Niobe AURIGA, Explorer, Nautilus, […]

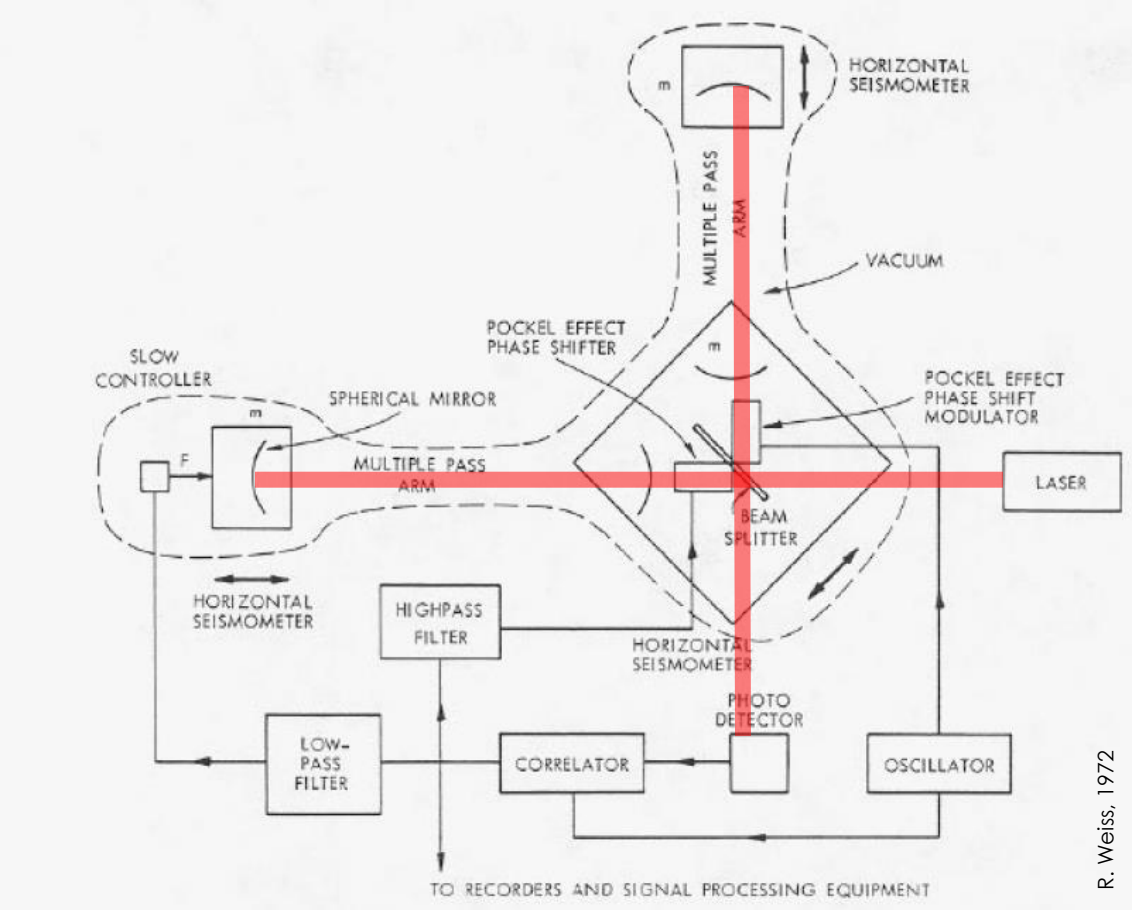
  1st international network (IGEC)

  few detectors still operational

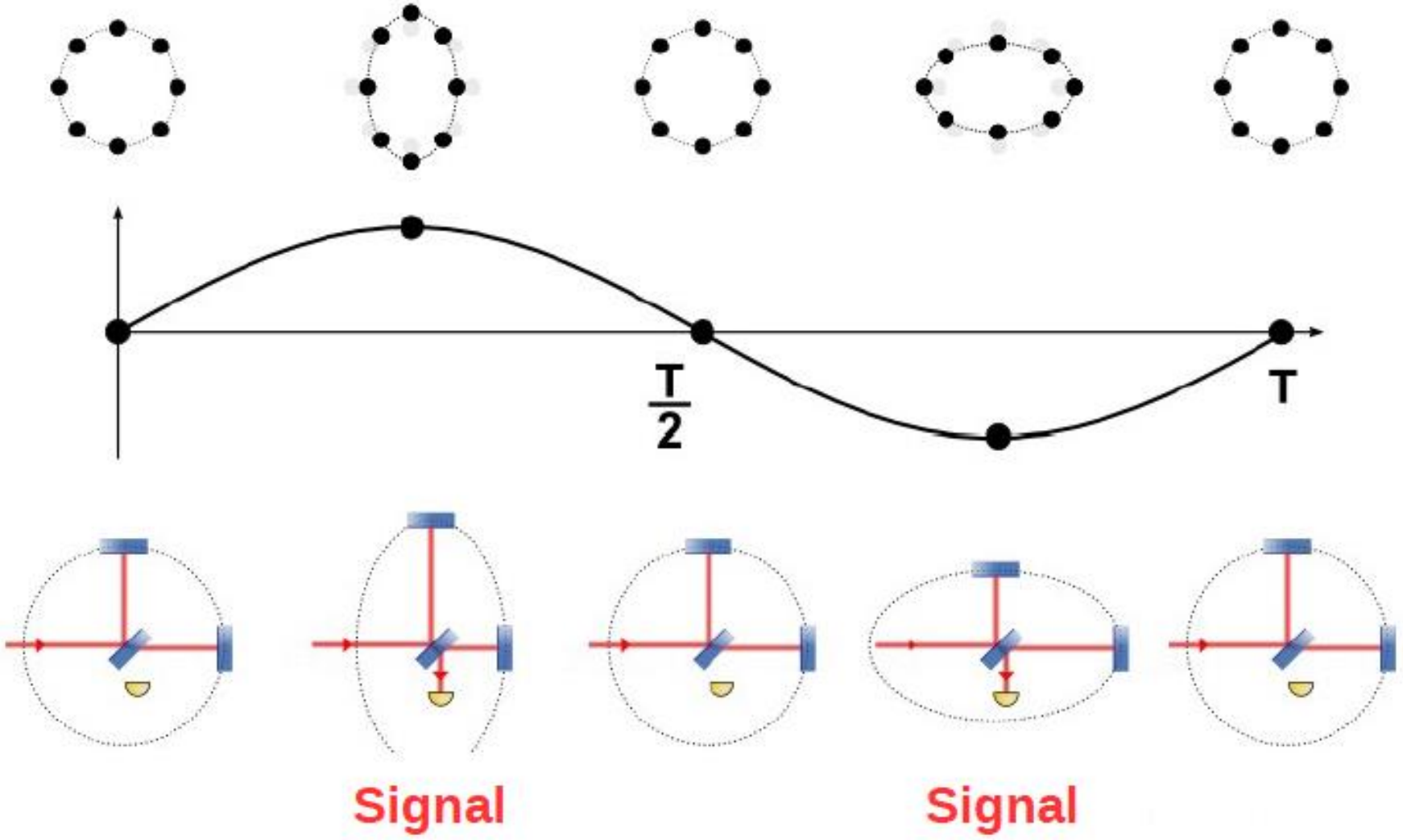
interferometers

optical transducers

- Michelson configuration – differential output
- suspended mirrors = free-falling test masses
- laser position readout



interferometers



J. Degallaix

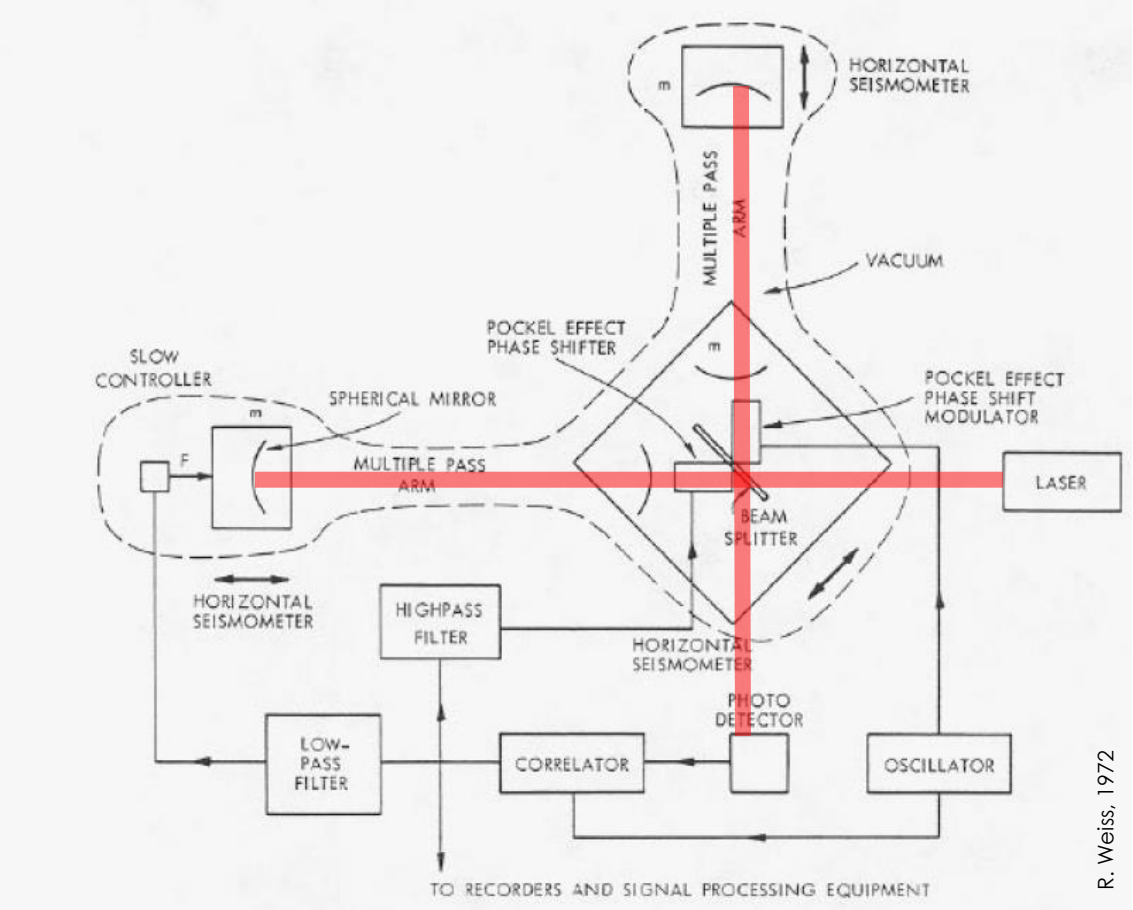
interferometers

optical transducers

- Michelson configuration – differential output
- suspended mirrors = free-falling test masses
- laser position readout

km-scale arms

$$\delta L \propto hL \sim 10^{-18}$$

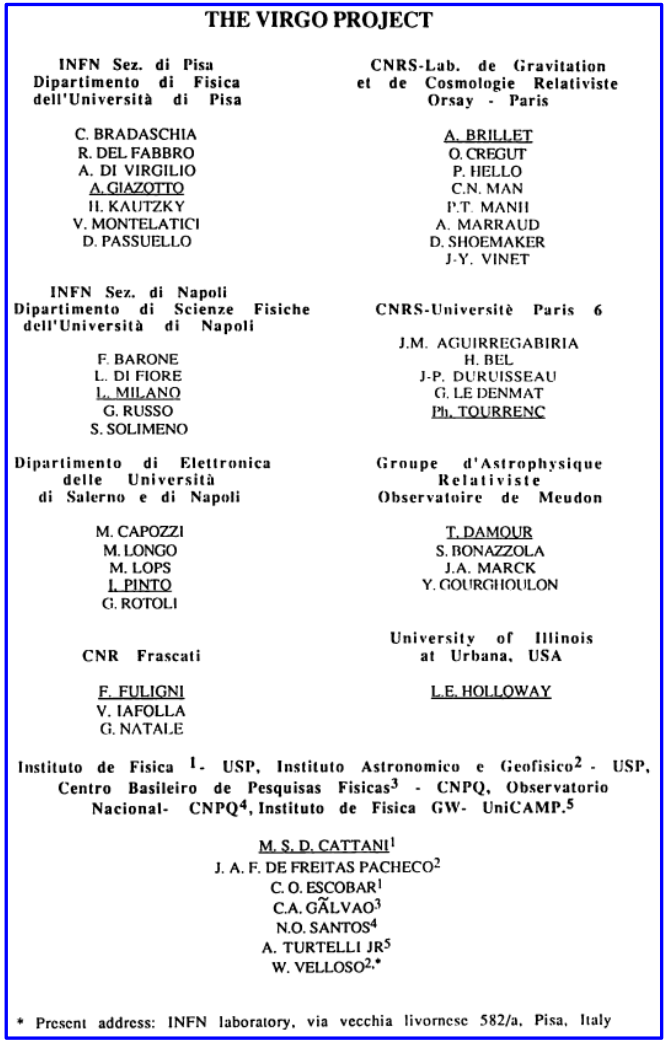


history

- '70s-'80s – 1st prototypes: IGR, MPA, MIT, Caltech
  10 – 40 m

- 1983-84: LIGO proposal – approved 1990
- 1989: proposals of
  GEO600 – approved 1994
  Virgo – approved 1992

  300 m – 4 km



THE VIRGO PROJECT

INFN Sez. di Pisa
Dipartimento di Fisica
dell'Università di Pisa

C. BRADASCHIA
R. DEL FABBRO
A. DI VIRGILIO
A. GIAZOTTO
H. KAUTZKY
V. MONTELATICI
D. PASSUELLO

CNRS-Lab. de Gravitation
et de Cosmologie Relativiste
Orsay - Paris

A. BRILLET
O. CREGUT
P. HELLO
C.N. MAN
P.T. MANH
A. MARRAUD
D. SHOEMAKER
J-Y. VINET

INFN Sez. di Napoli
Dipartimento di Scienze Fisiche
dell'Università di Napoli

F. BARONE
L. DI FIORE
L. MILANO
G. RUSSO
S. SOLIMENO

CNRS-Universitè Paris 6

J.M. AGUIRREGABIRIA
H. BEL
J-P. DURUISSEAU
G. LE DENMAT
Ph. TOURRENC

Dipartimento di Elettronica
delle Università
di Salerno e di Napoli

M. CAPOZZI
M. LONGO
M. LOPS
I. PINTO
G. ROTOLI

Groupe d'Astrophysique
Relativiste
Observatoire de Meudon

T. DAMOUR
S. BONAZZOLA
J.A. MARCK
Y. GOURGHOULON

CNR Frascati

F. FULIGNI
V. IAFOLLA
G. NATALE

University of Illinois
at Urbana, USA

L.E. HOLLOWAY

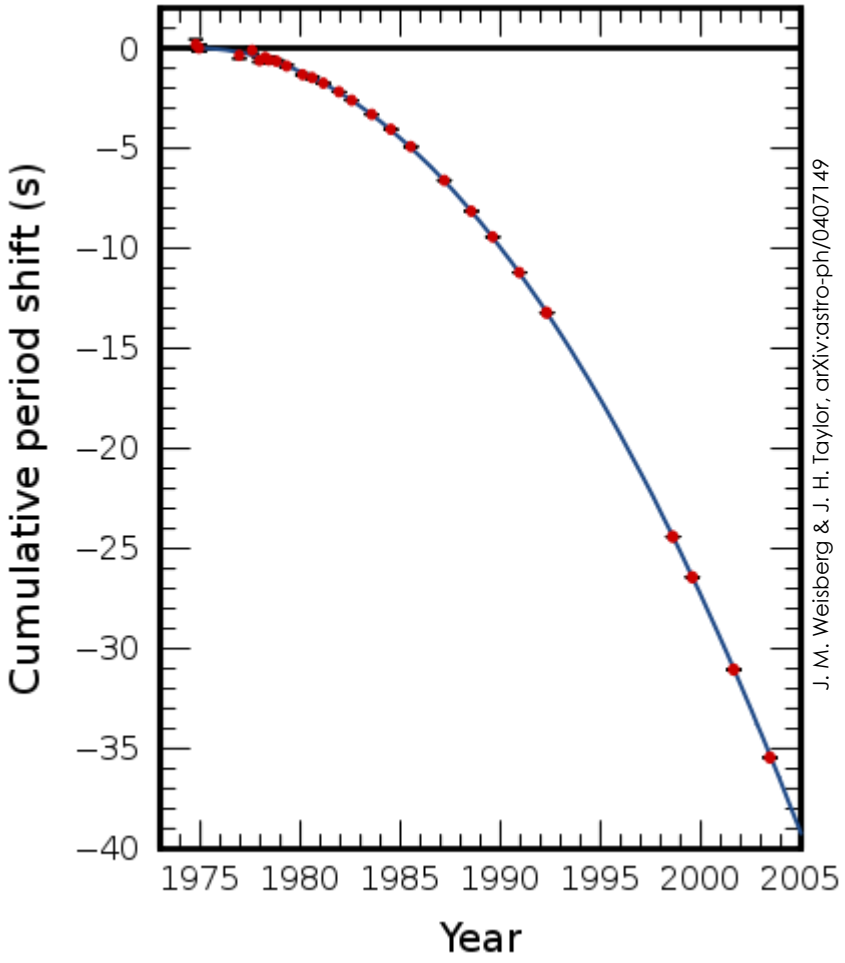
Instituto de Fisica [1] - USP, Instituto Astronomico e Geofisico[2] - USP, Centro Basileiro de Pesquisas Fisicas[3] - CNPQ, Observatorio Nacional- CNPQ[4], Instituto de Fisica GW- UniCAMP.[5]

M. S. D. CATTANI[1]
J. A. F. DE FREITAS PACHECO[2]
C. O. ESCOBAR[1]
C.A. GÃLVAO[3]
N.O. SANTOS[4]
A. TURTELLI JR[5]
W. VELLOSO[2,*]

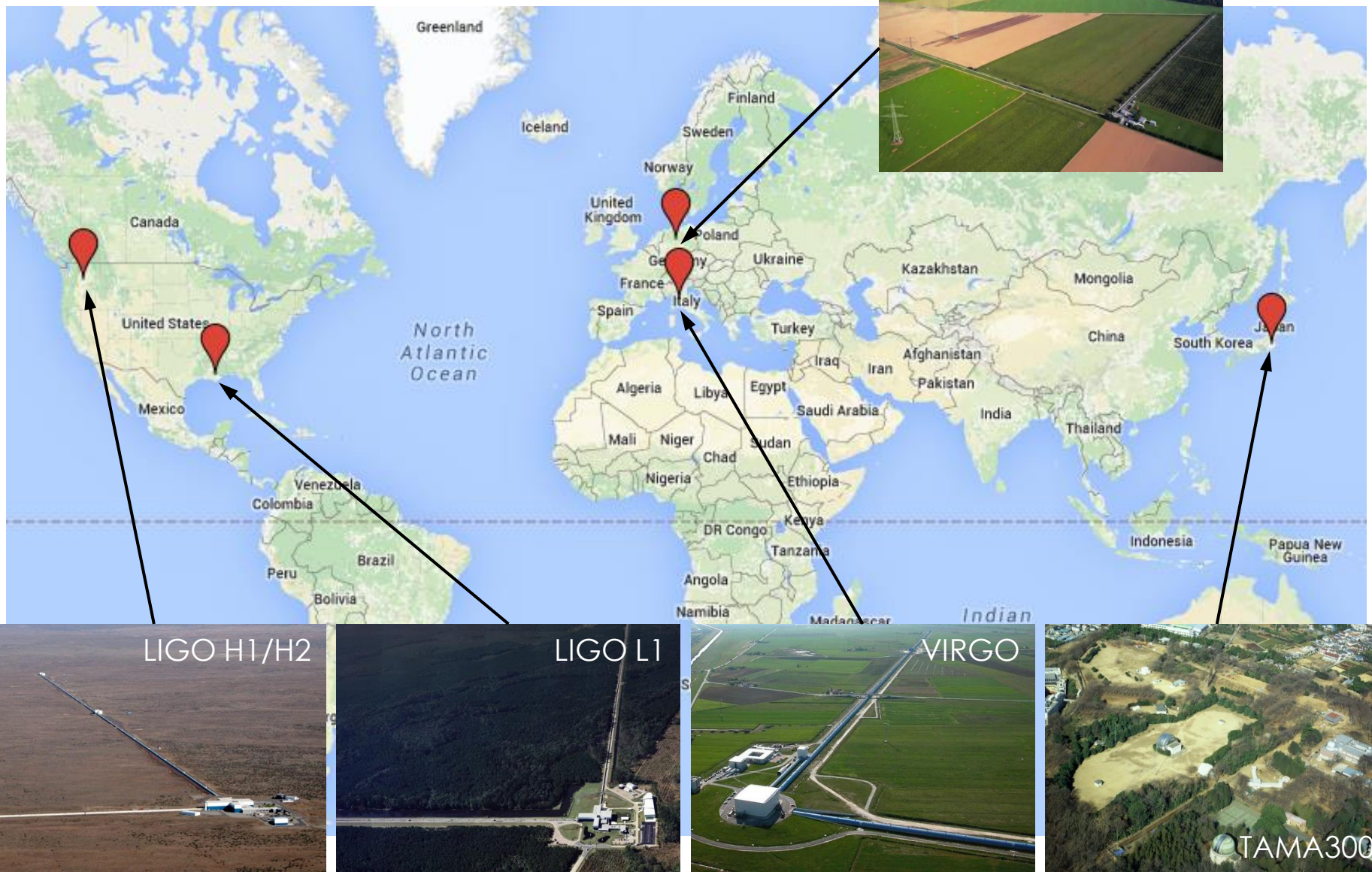
* Present address: INFN laboratory, via vecchia livornese 582/a, Pisa, Italy

in the meanwhile

- 1975: PSR 1913+16 discovery
  pulsar in a binary system
- orbital decay due to GW emission
- evidence of GW existence
- 1993: Nobel to R. Hulse & J. Taylor



1990s-2000s – 1st generation



1st generation legacy

- technological achievements
  - laser
  - suspensions
  - mirrors
  - vacuum
  - controls

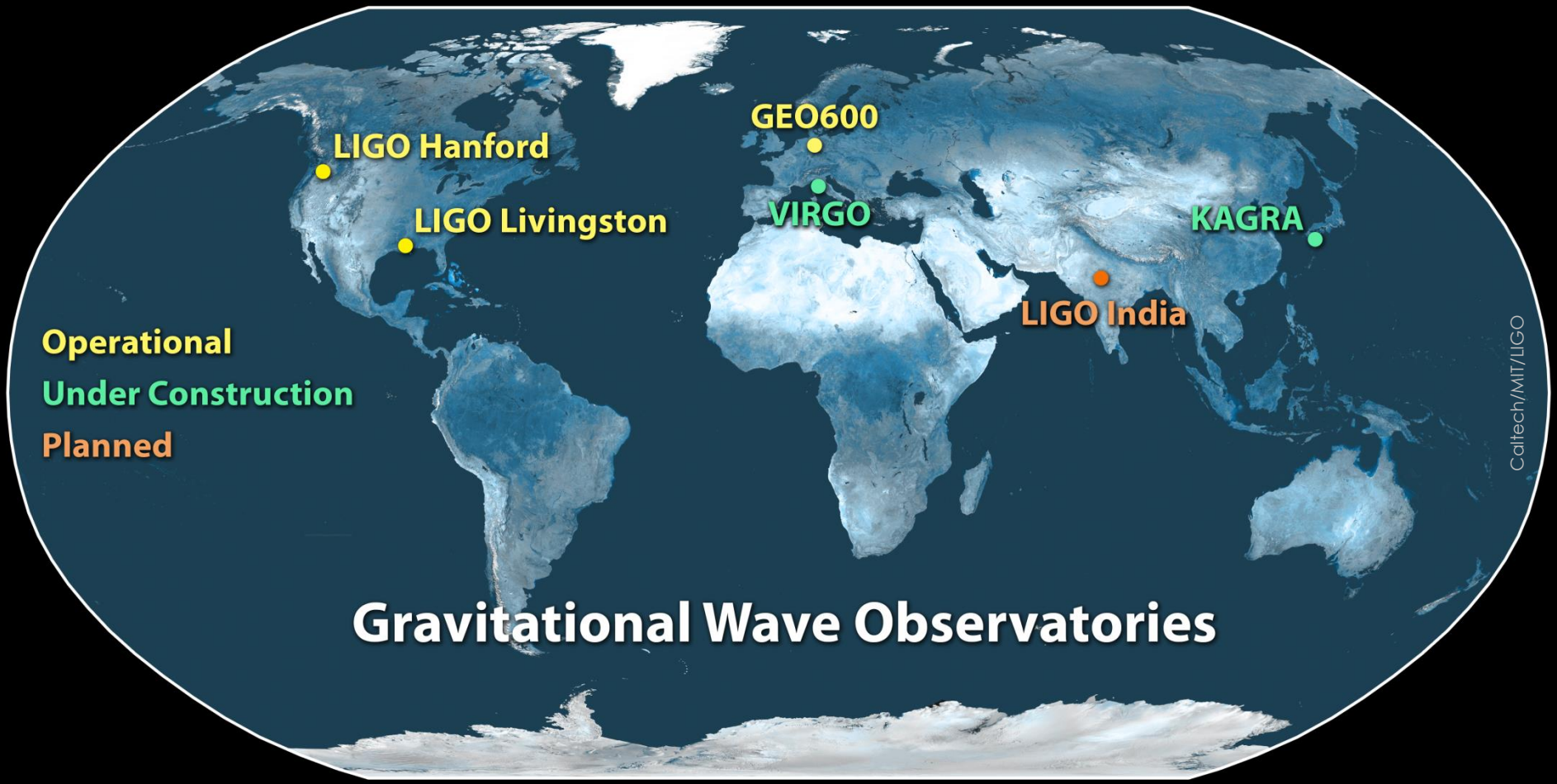
- demonstration of detection principle

- observational results: ~10^2 papers
  - amplitude/rate upper limits

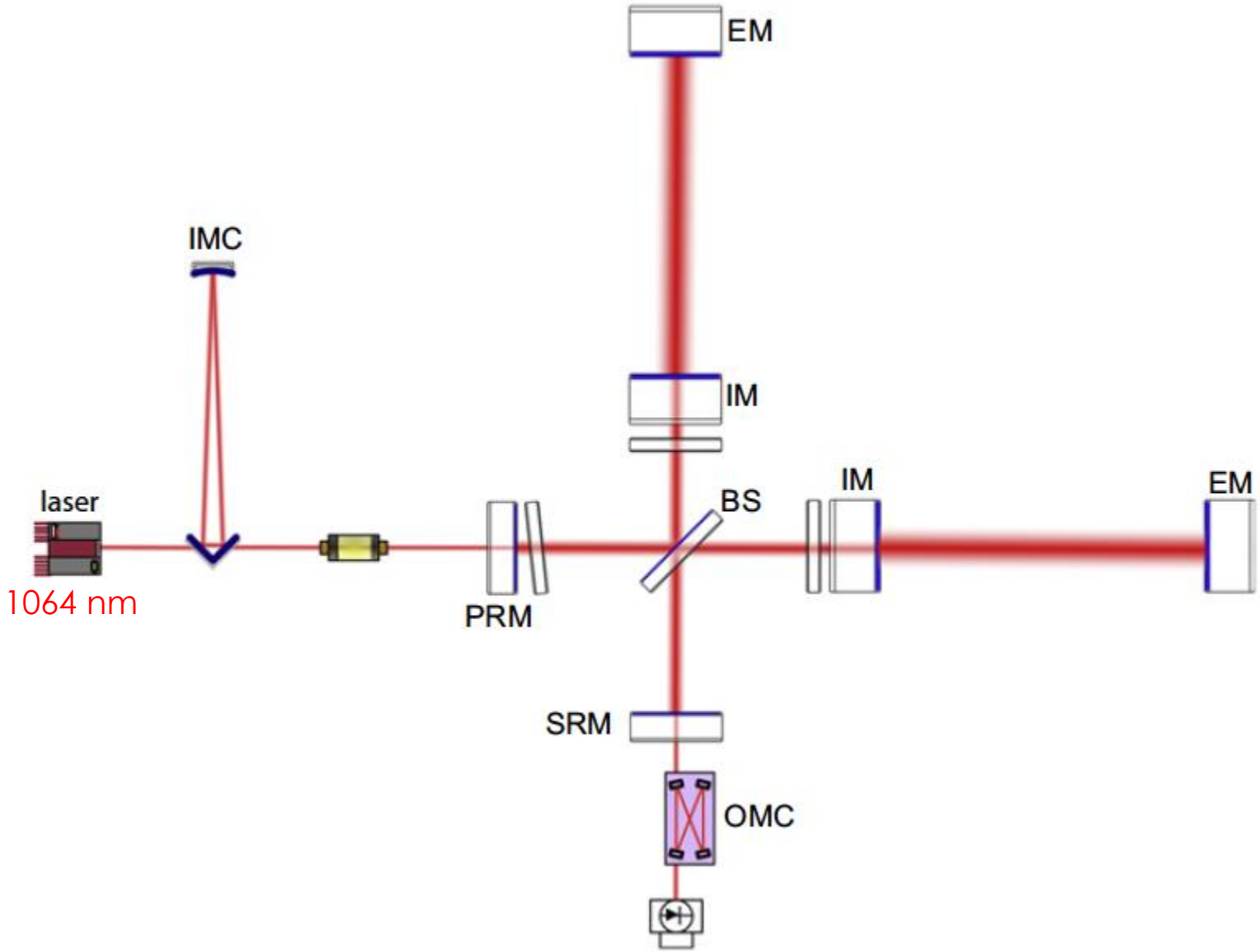
- collaborations with EM telescopes/satellites

- infrastructures

today – 2nd generation

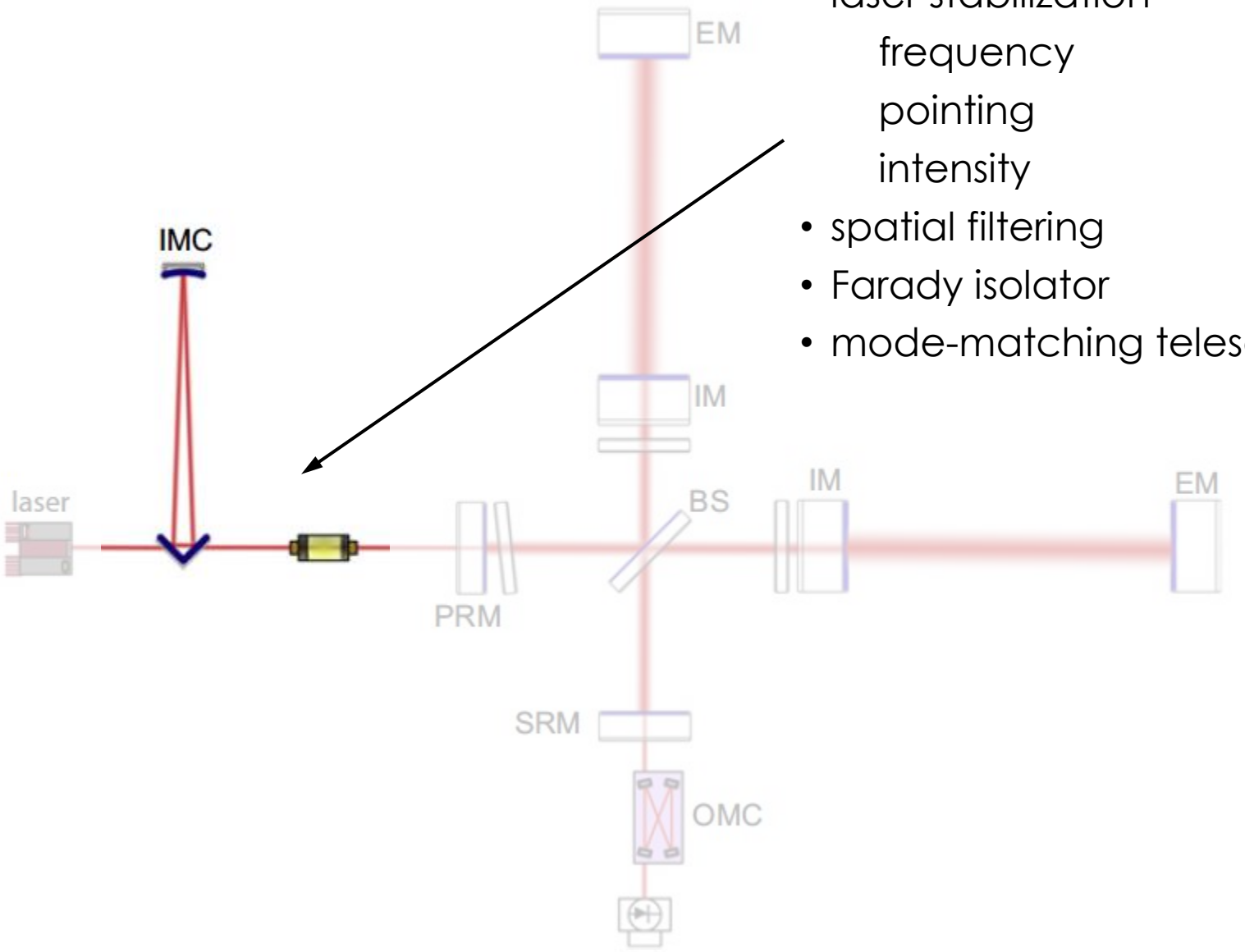


optical layout

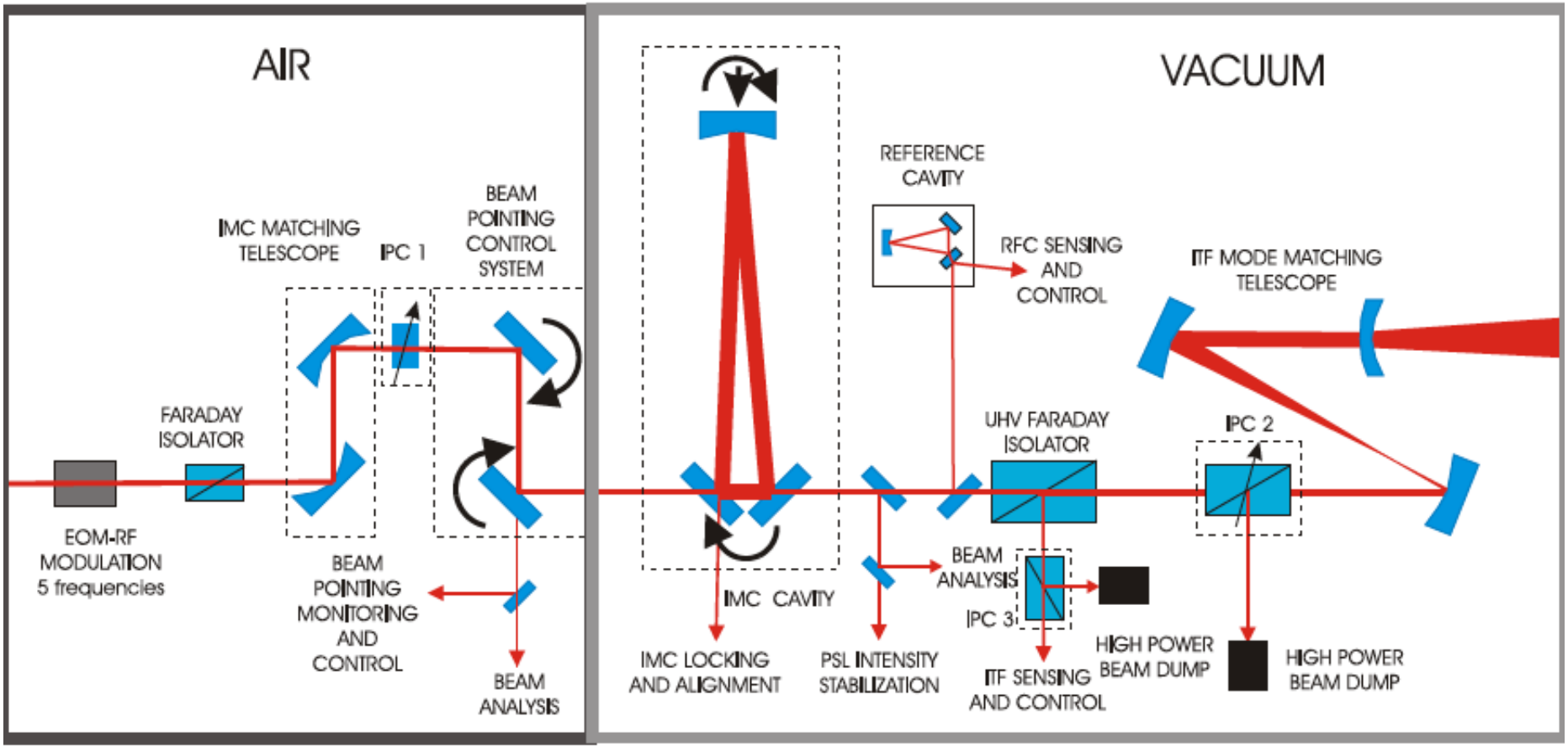


input optics

- RF phase modulation
- laser stabilization
  - frequency
  - pointing
  - intensity
- spatial filtering
- Farady isolator
- mode-matching telescope

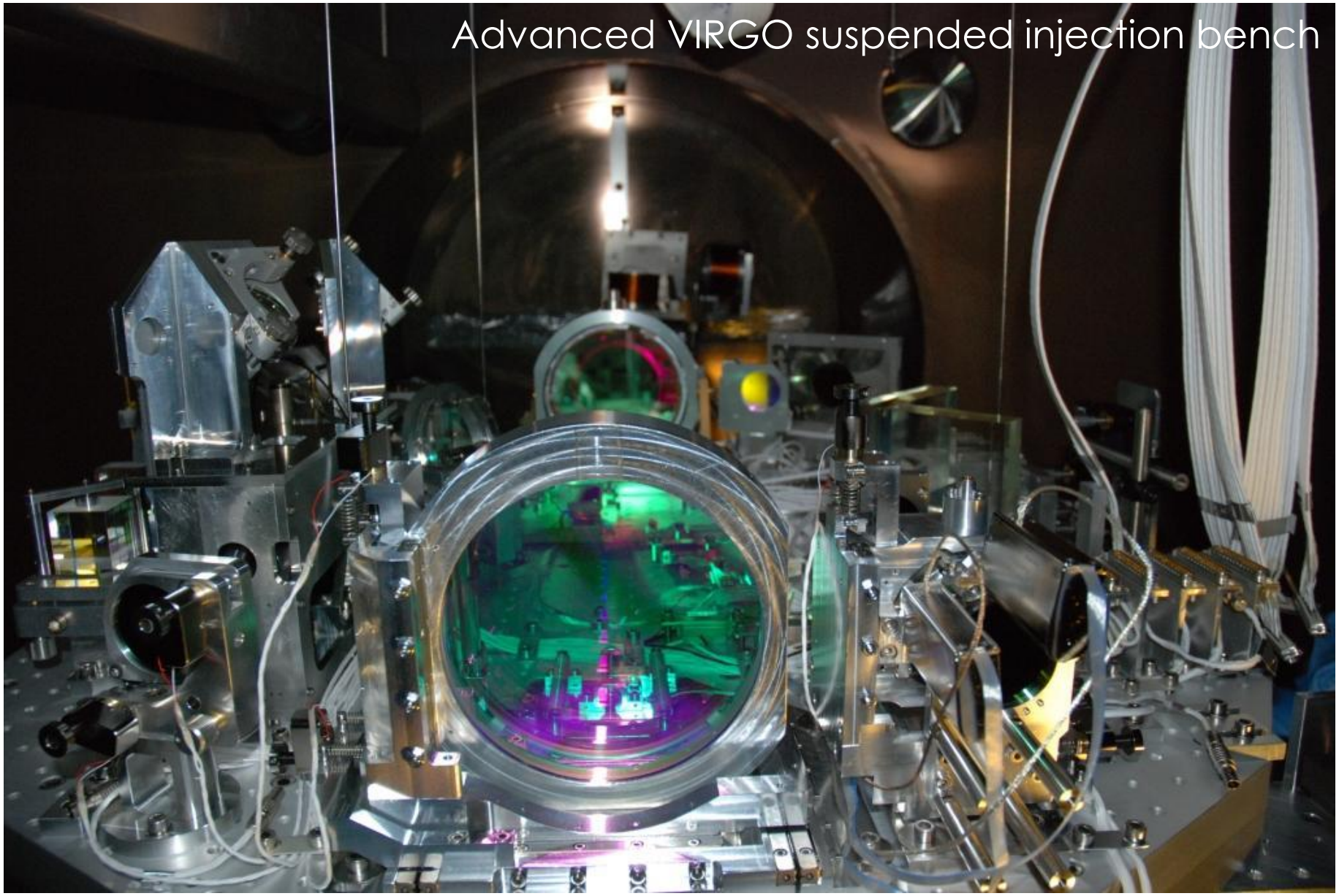


input optics



Advanced VIRGO

input optics



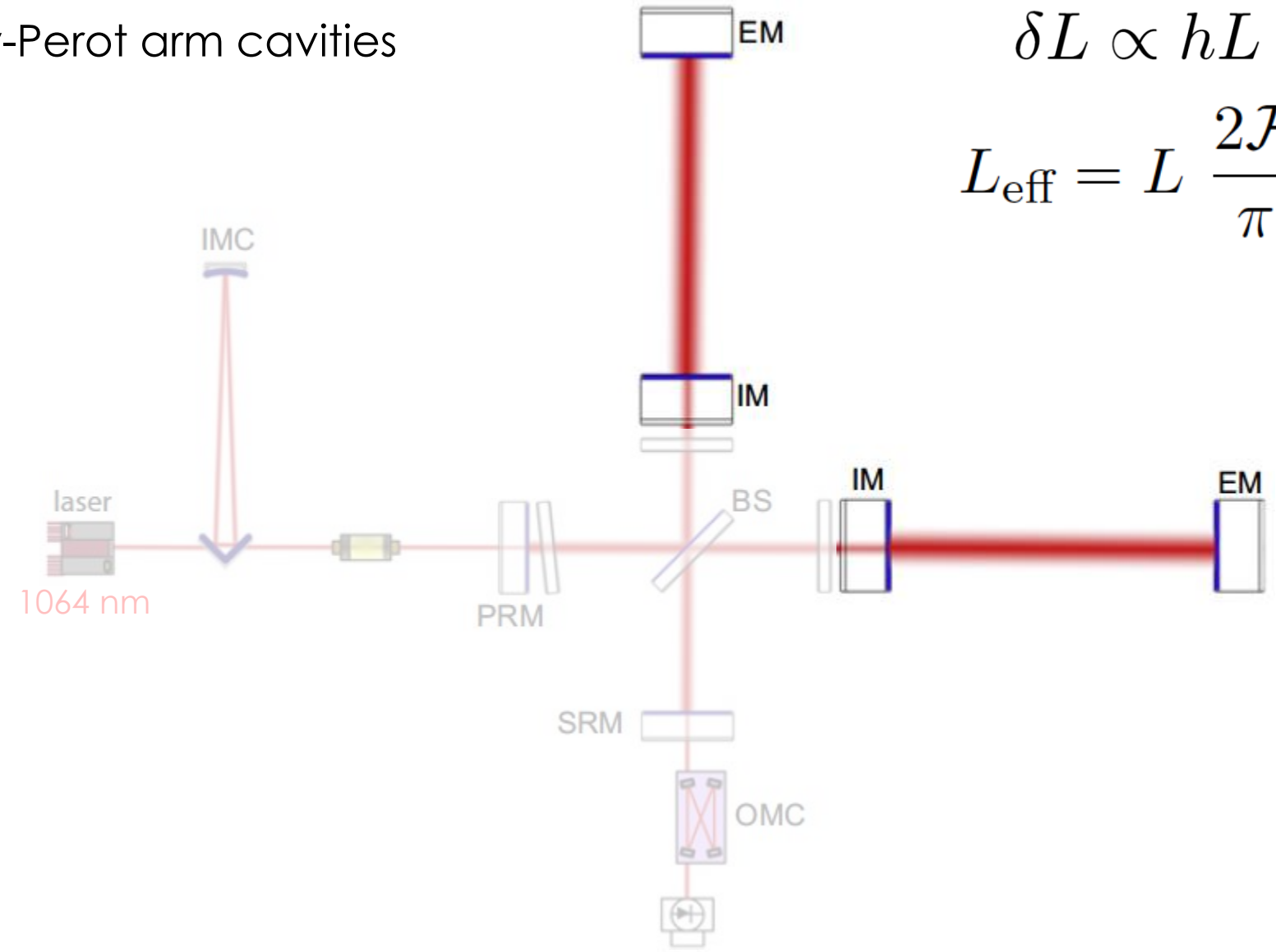
input optics

optical layout

Fabry-Perot arm cavities

$$\delta L \propto hL$$

$$L_{\text{eff}} = L \frac{2\mathcal{F}}{\pi}$$



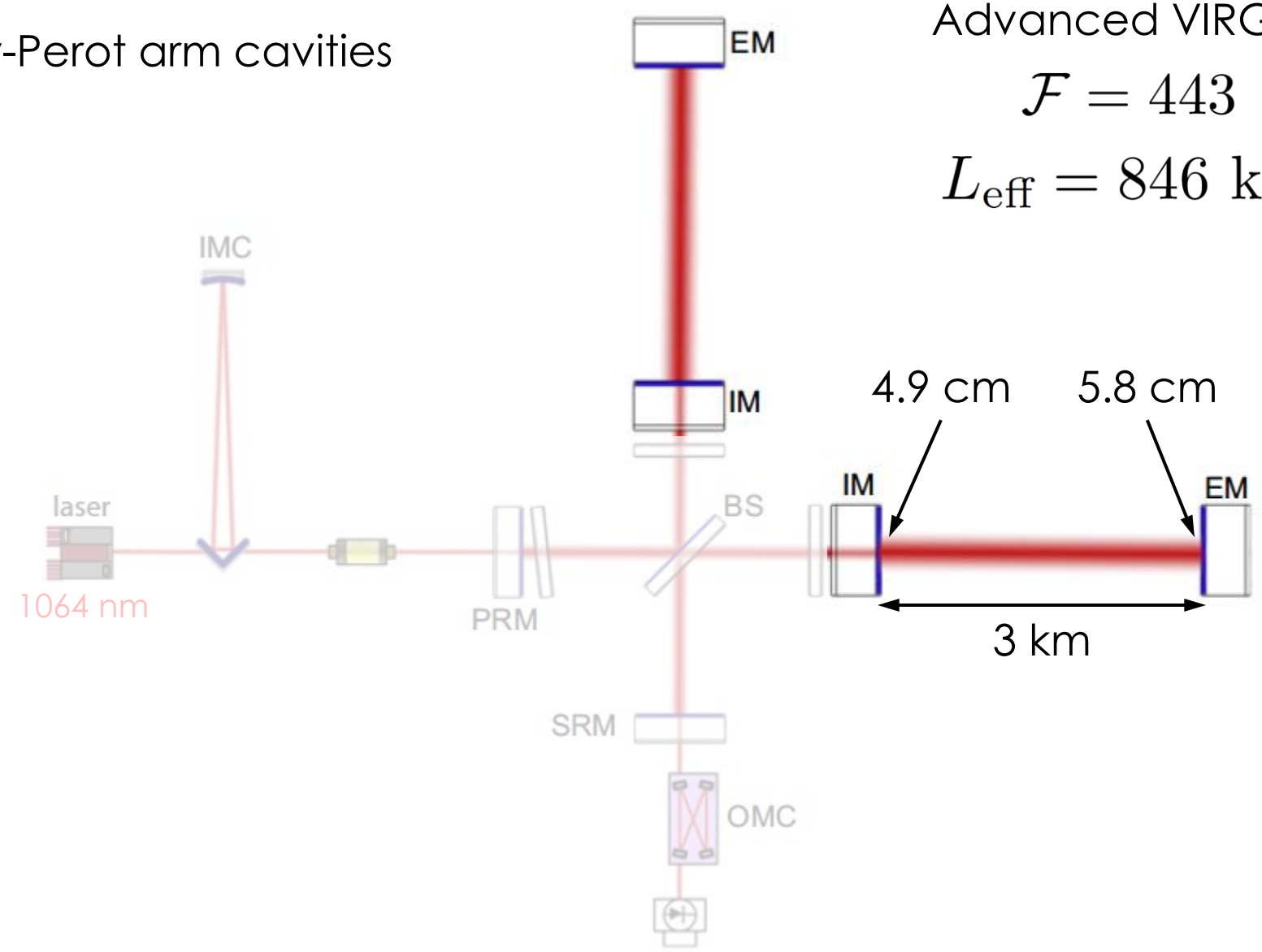
optical layout

Fabry-Perot arm cavities

Advanced VIRGO

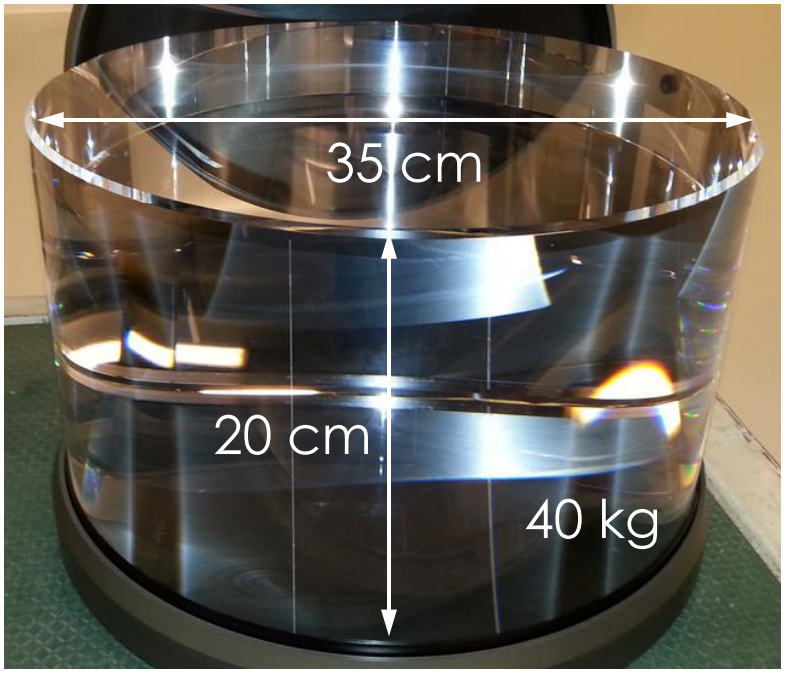
$$\mathcal{F} = 443$$

$$L_{\text{eff}} = 846 \text{ km}$$



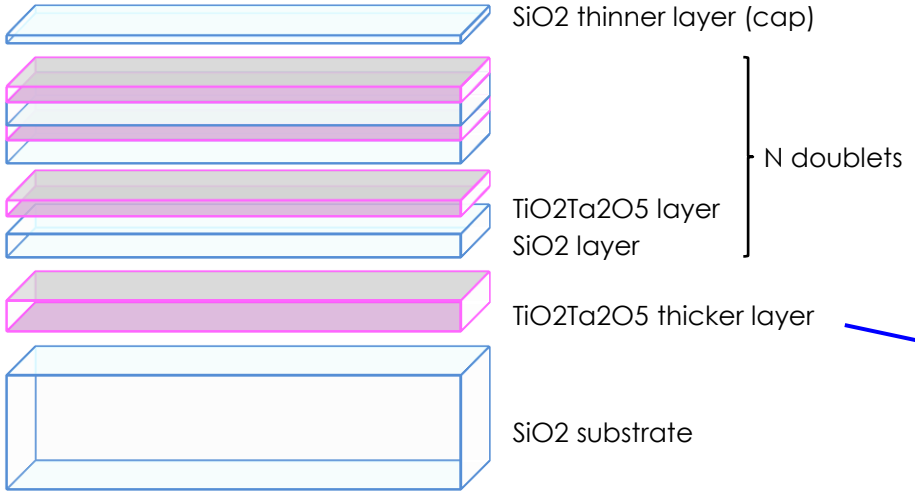
test masses

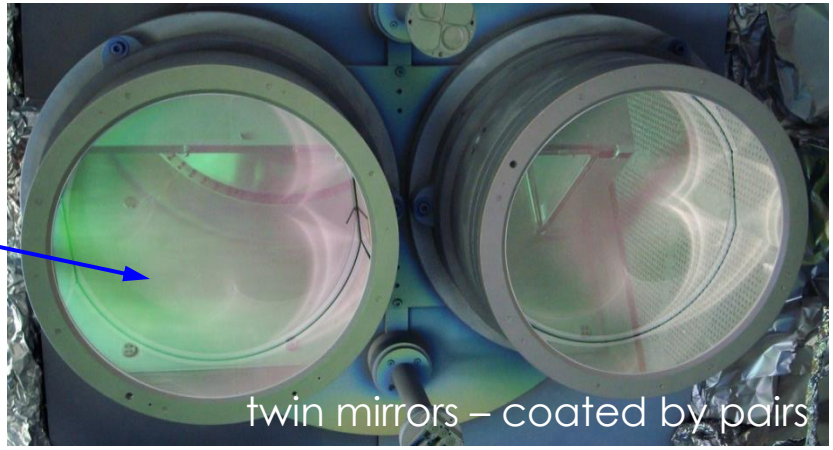
ultra-pure fused silica substrates



high-reflection coatings

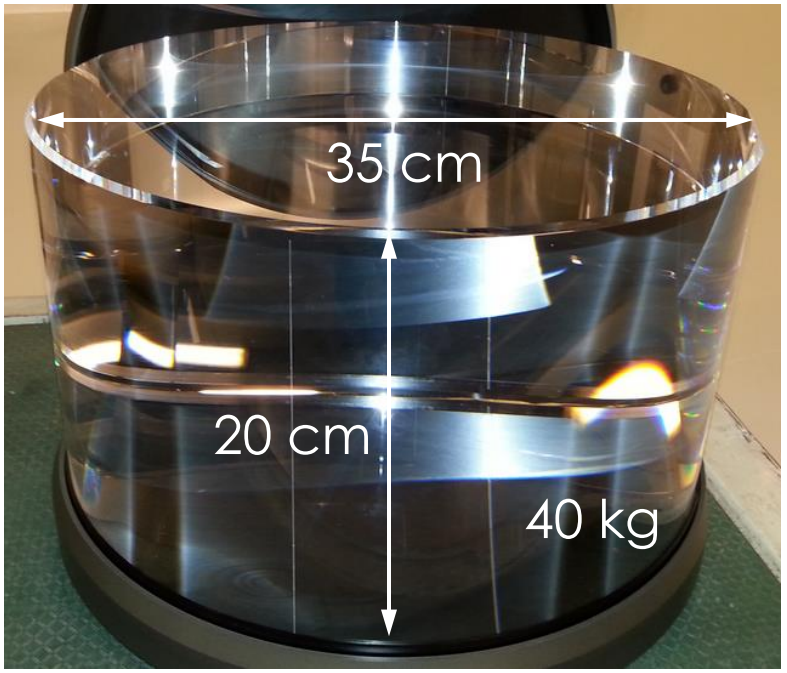
TiO2Ta2O5/SiO2 Bragg mirrors





test masses

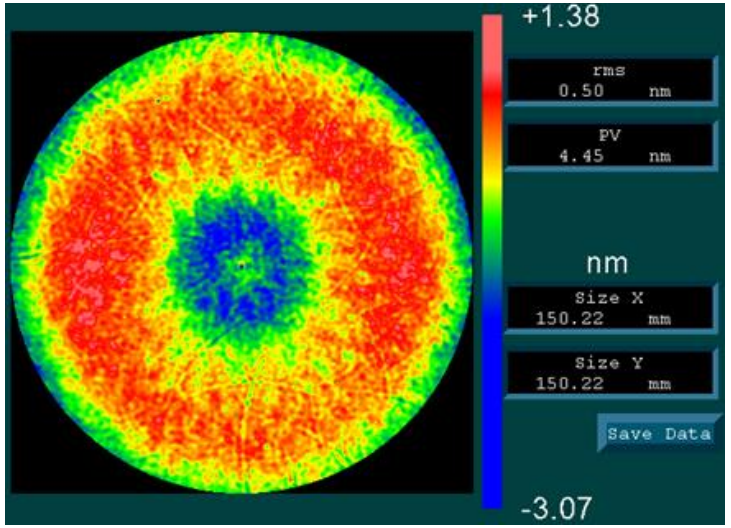
ultra-pure fused silica substrates



high-reflection coatings

TiO2Ta2O5/SiO2 Bragg mirrors

	IM	EM
t [µm]	2.8	5.9
T	1.4 %	4 ppm
rms ø150mm [nm]	0.3	0.5
absorption [ppm]	0.2	0.3
scattering [ppm]	4	5



Advanced VIRGO EM01

test masses

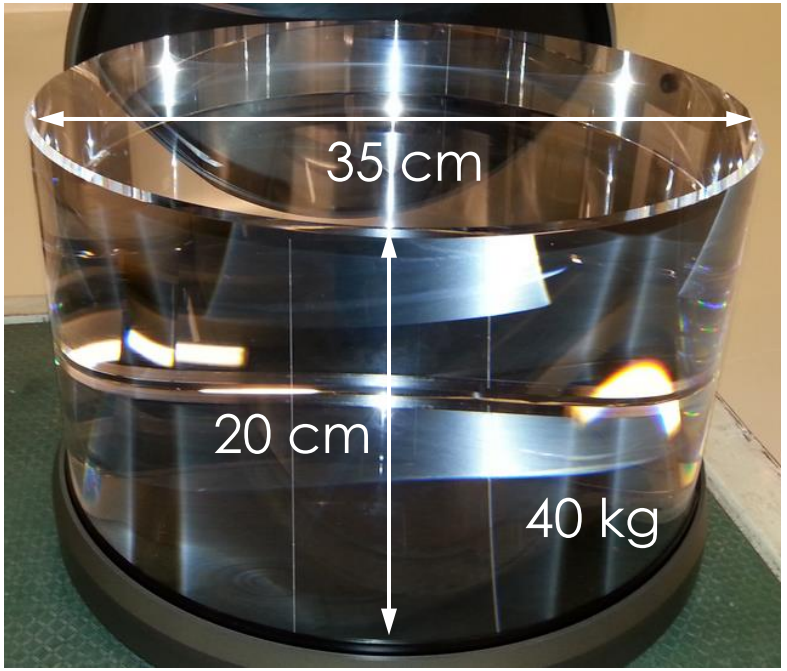
ultra-pure fused silica substrates

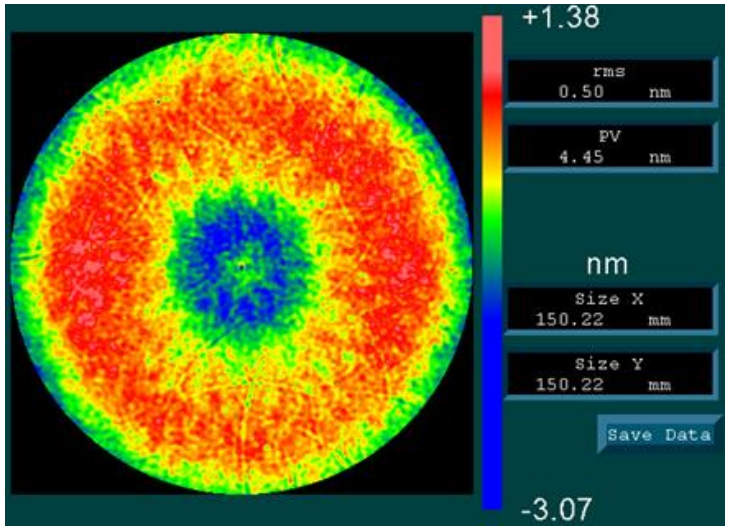
high-reflection coatings

TiO2Ta2O5/SiO2 Bragg mirrors

aLIGO, AdVIRGO and soon KAGRA

test masses coated @ LMA



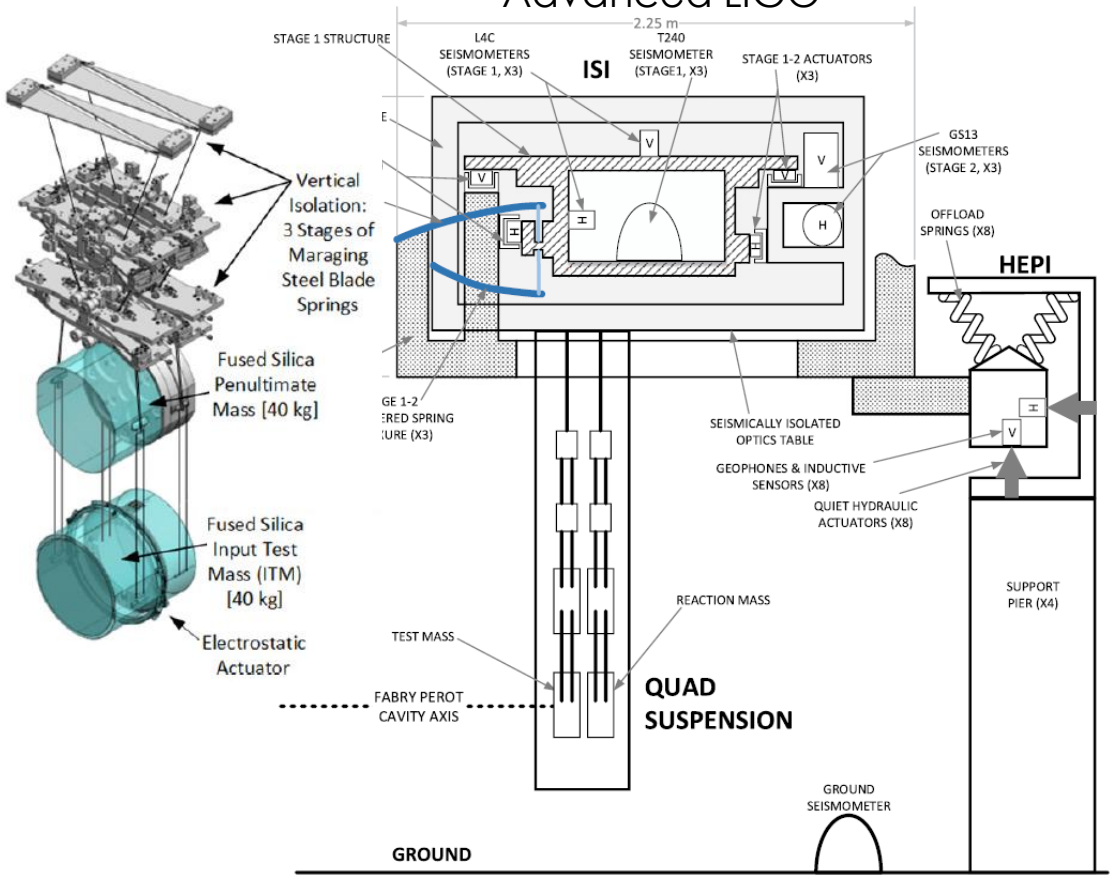


Advanced VIRGO EM01

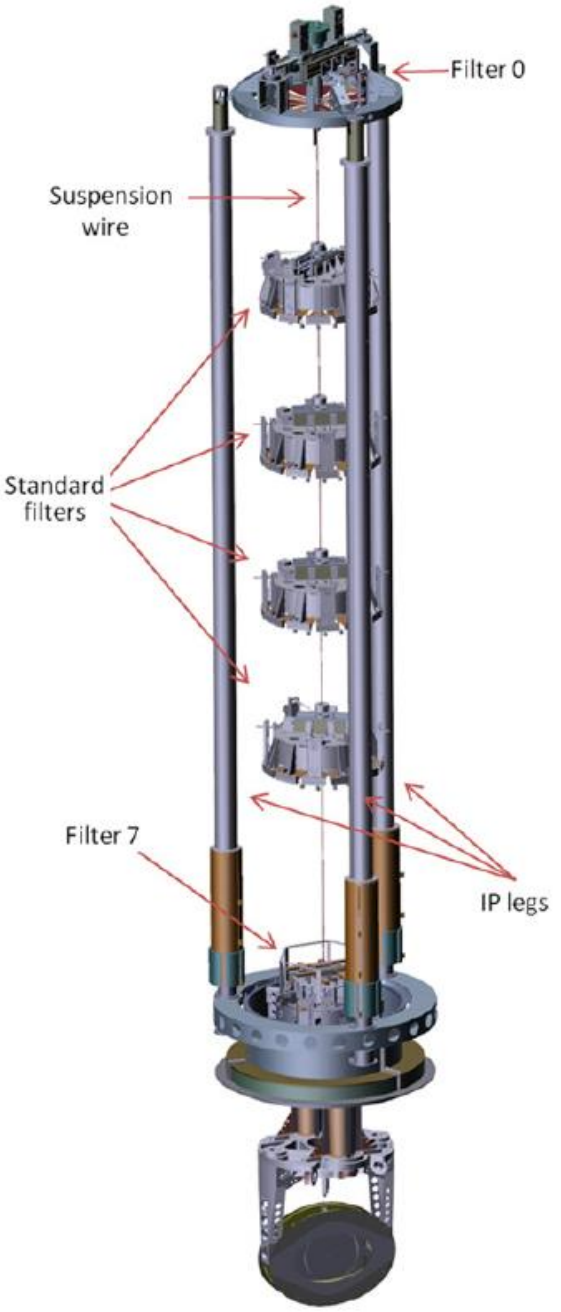
suspensions

- passive + active seismic isolation
  multiple-stage pendulum + sensing/actuation
- control
  alignement

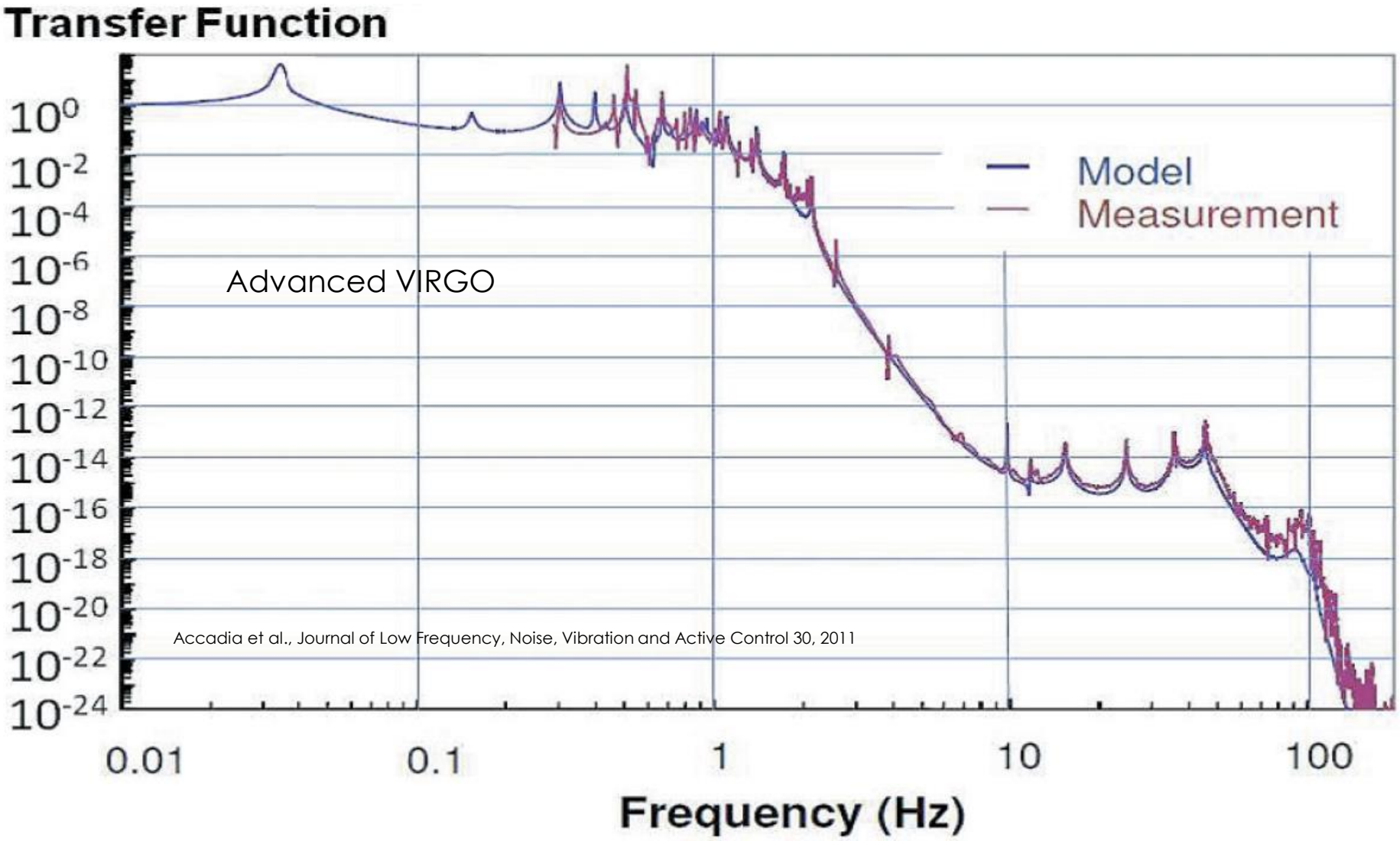
Advanced LIGO



Advanced VIRGO

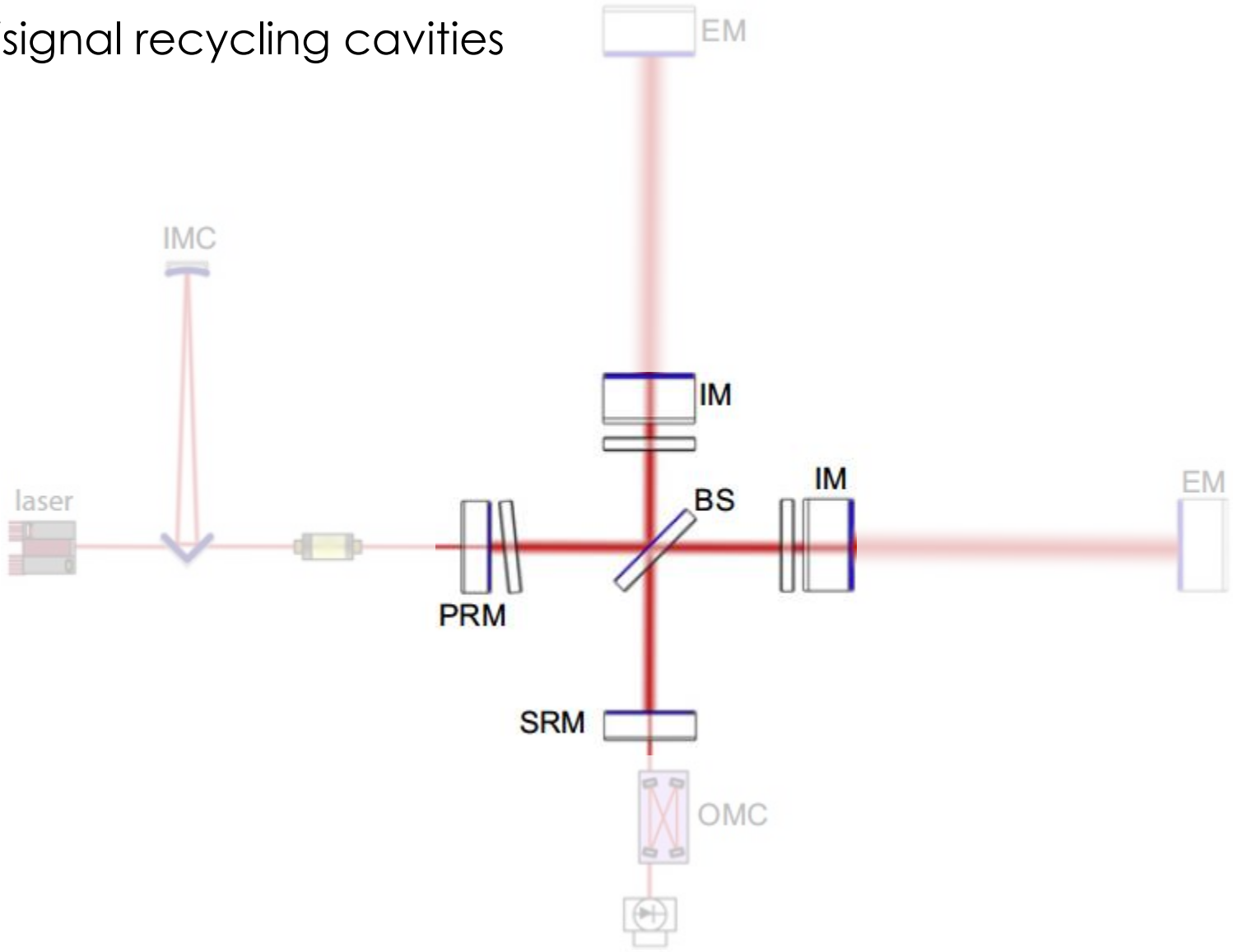


suspensions



optical layout

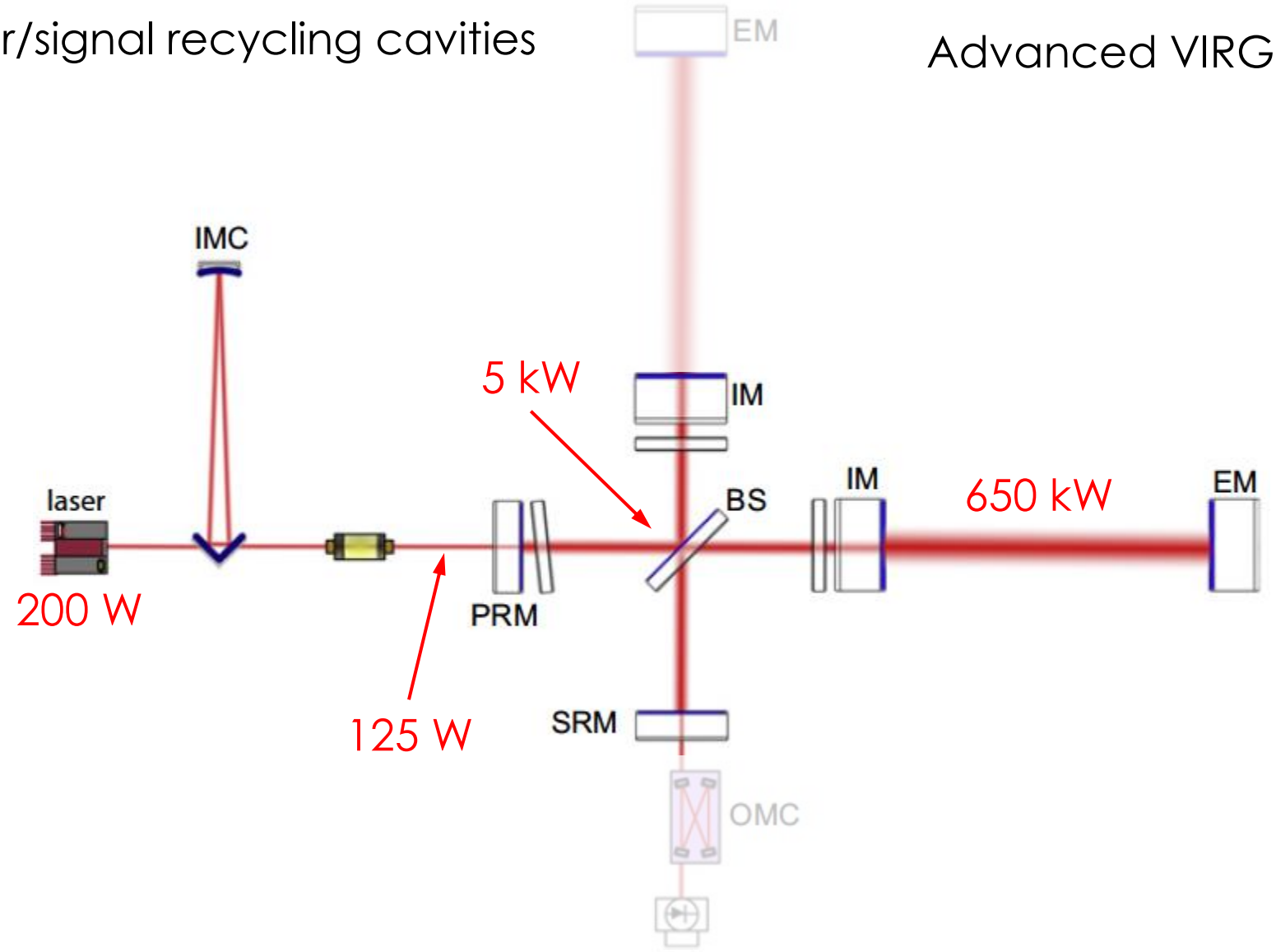
power/signal recycling cavities



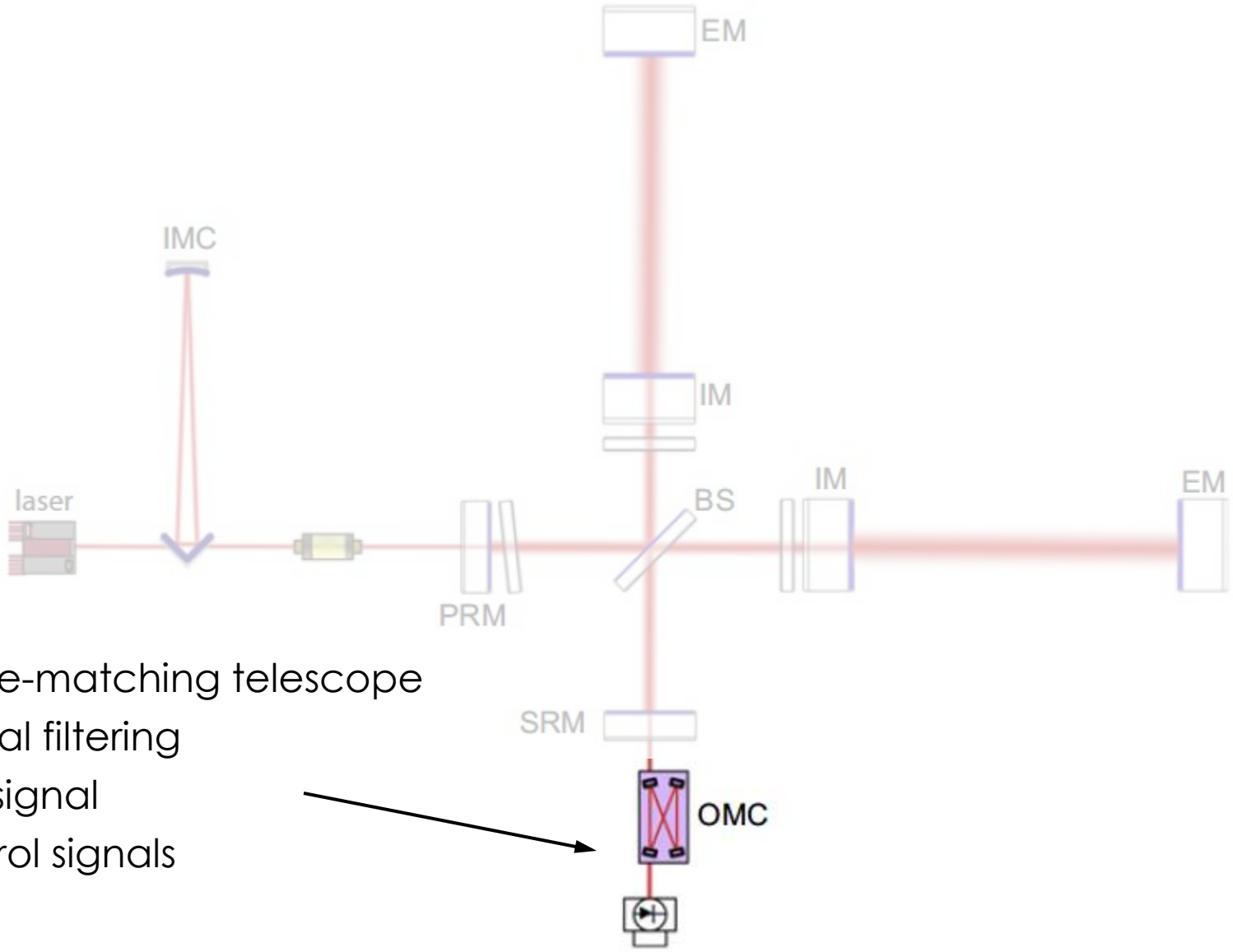
optical layout

power/signal recycling cavities

Advanced VIRGO



detection

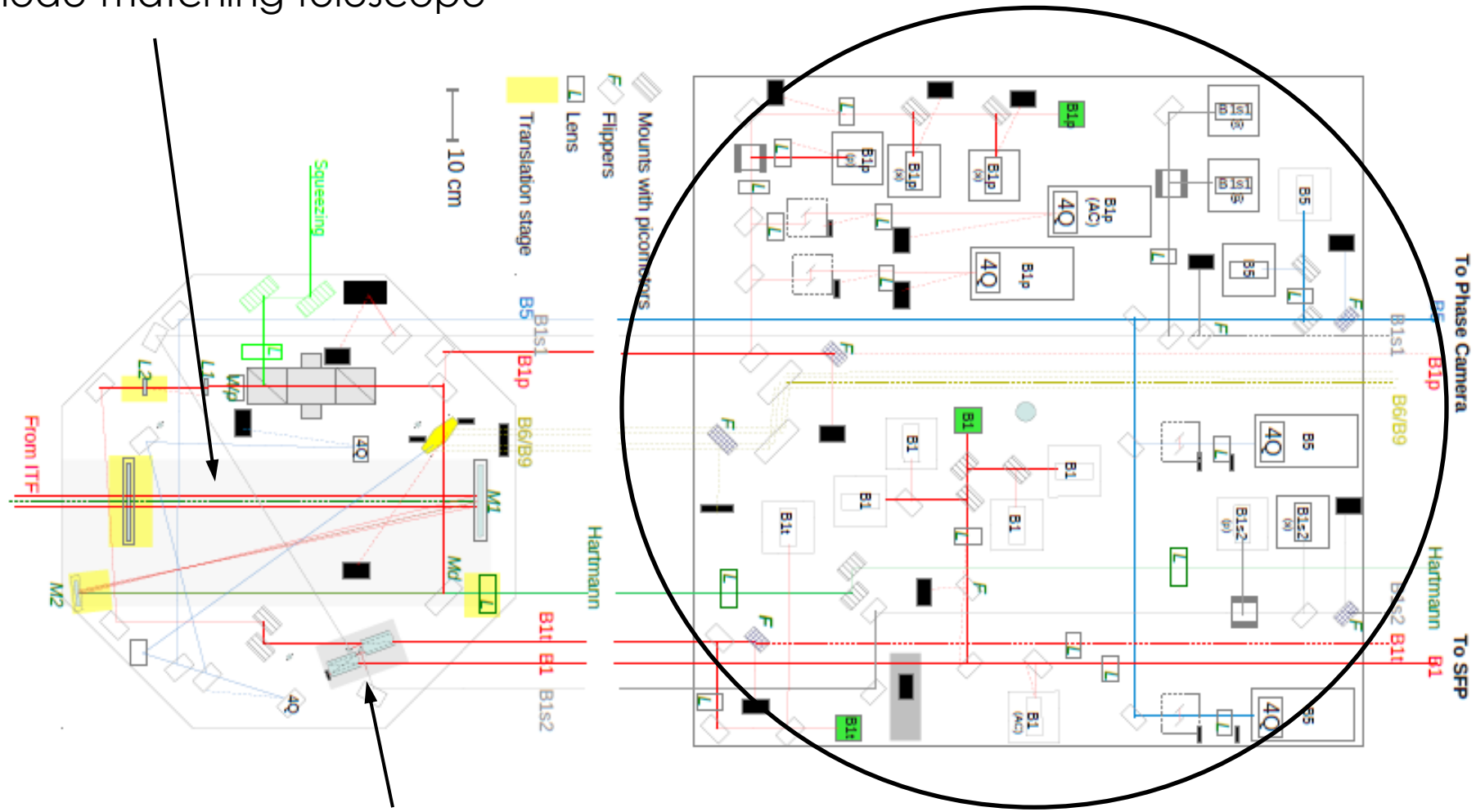


- mode-matching telescope
- spatial filtering
- GW signal
- control signals

detection

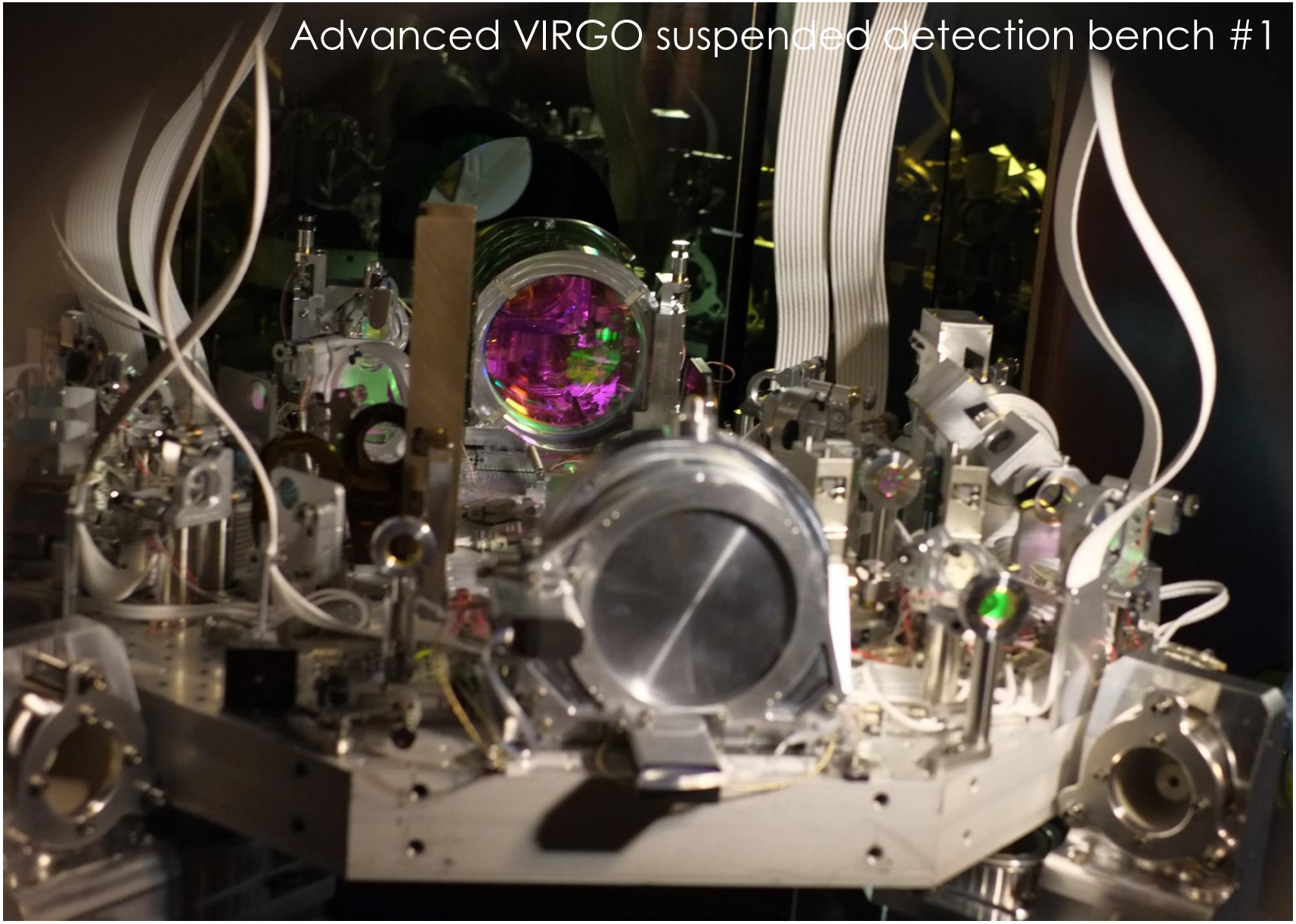
mode-matching telescope

photodiodes / wavefront sensors

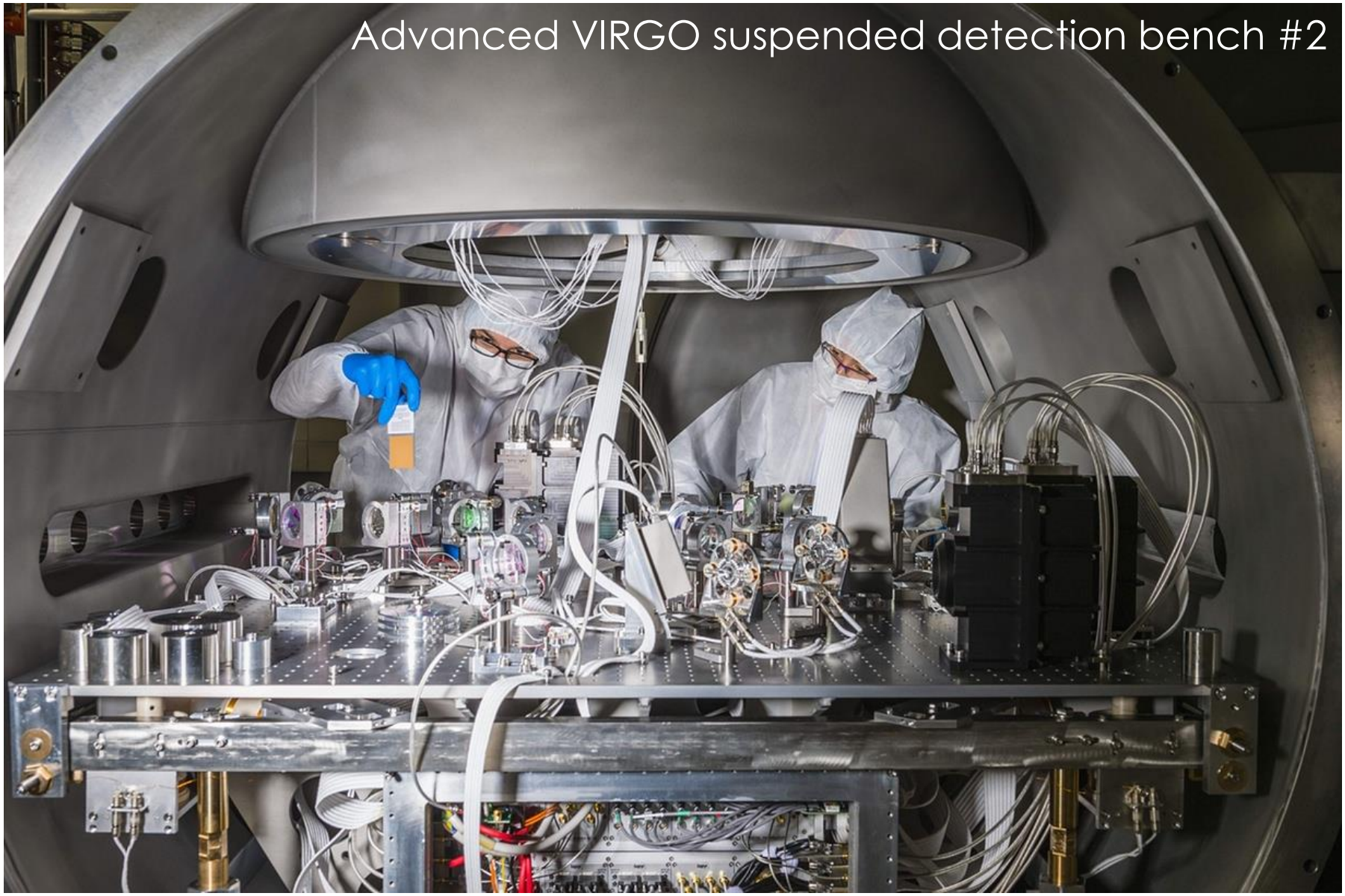


2 coupled output mode cleaners

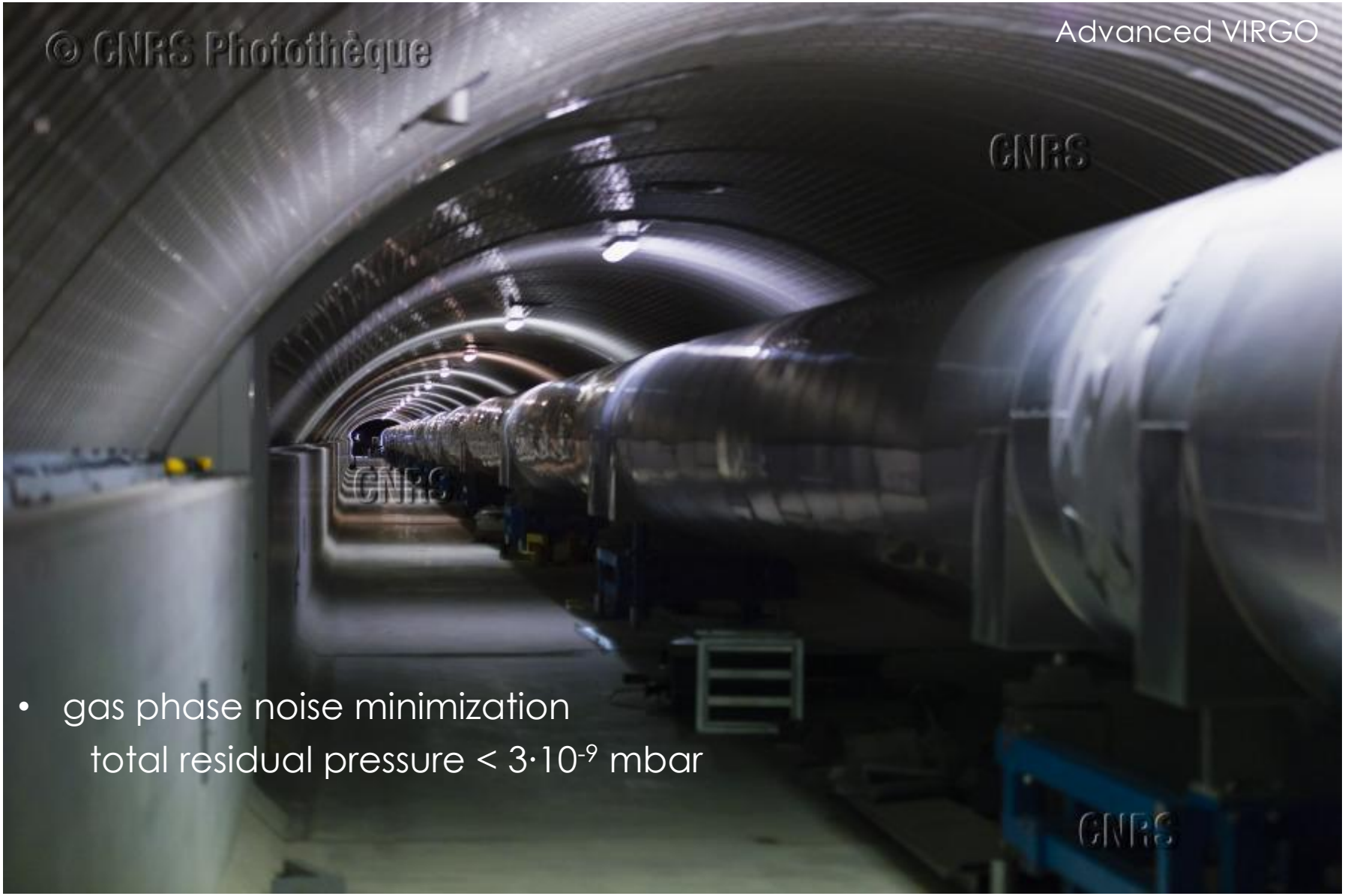
detection



detection

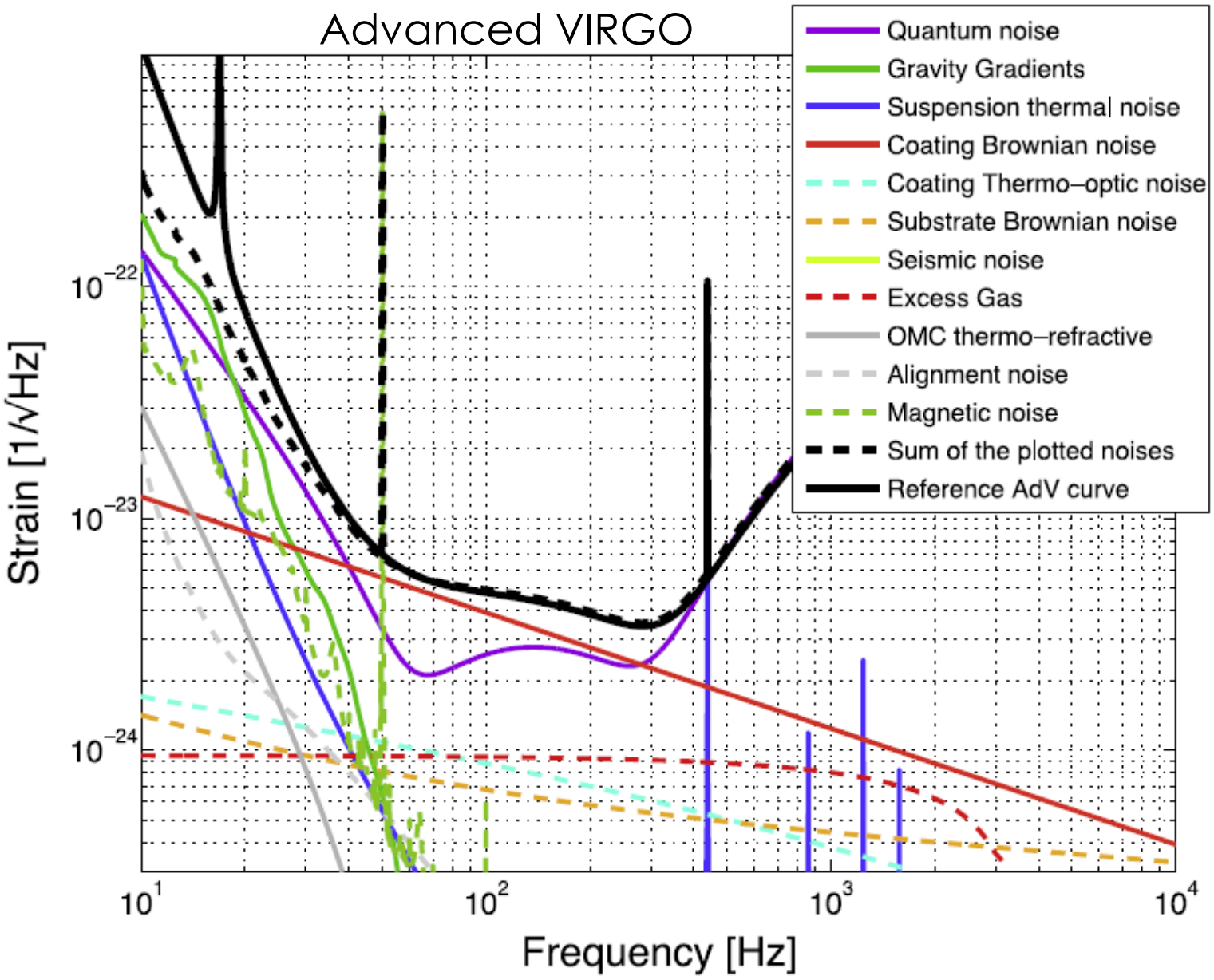


vacuum

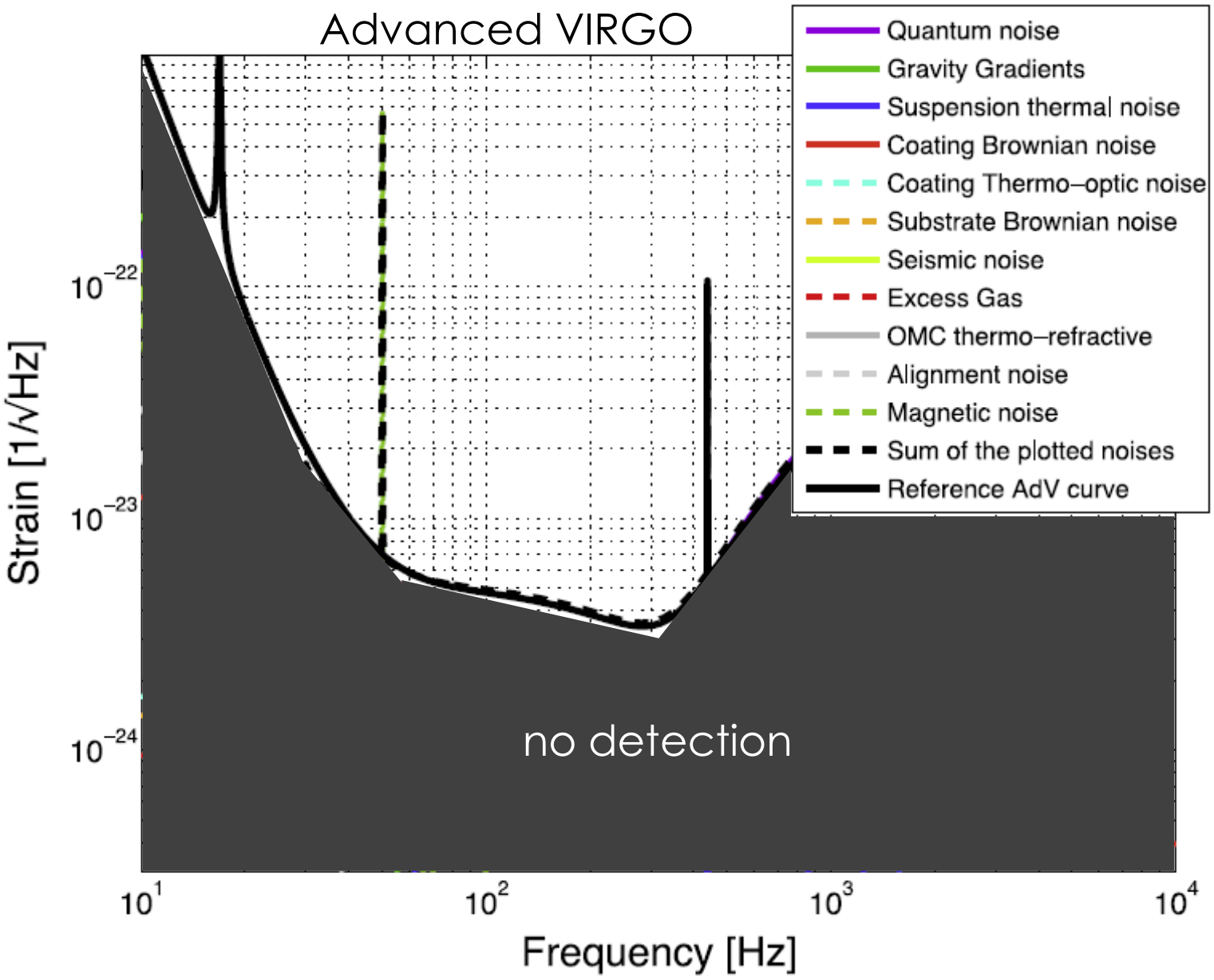


- gas phase noise minimization
  total residual pressure < $3 \cdot 10^{-9}$ mbar

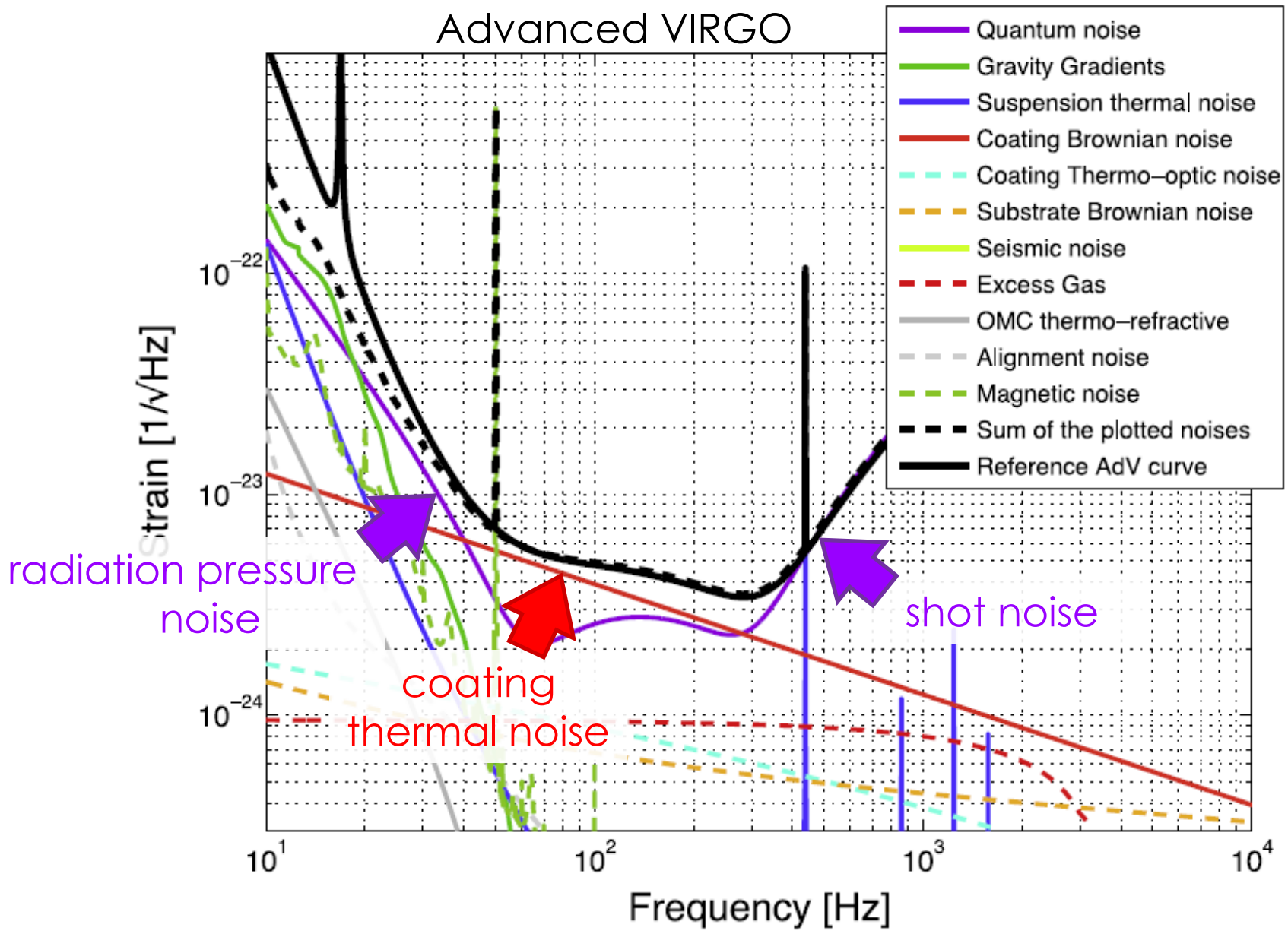
sensitivity



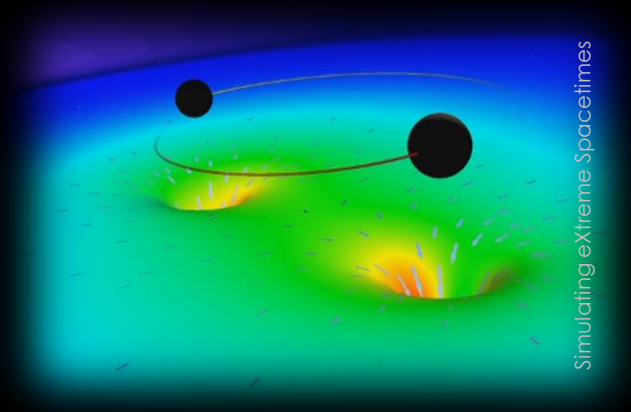
sensitivity



sensitivity



astrophysical sources

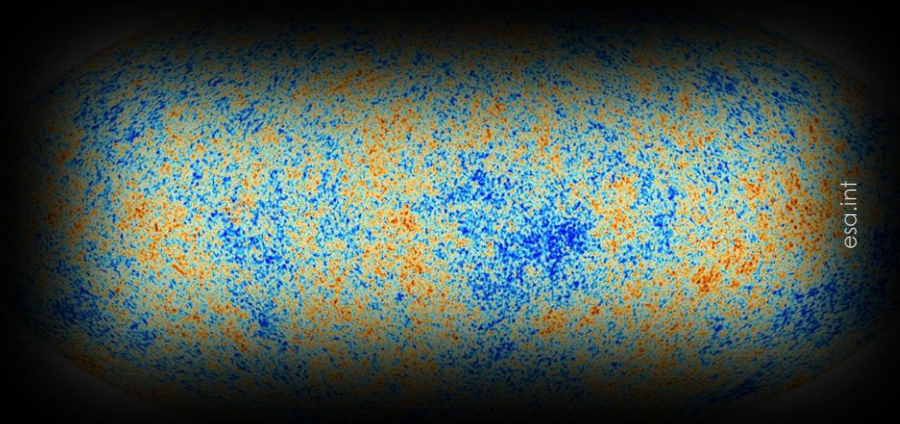


coalescing binaries

[neutron stars / black holes]

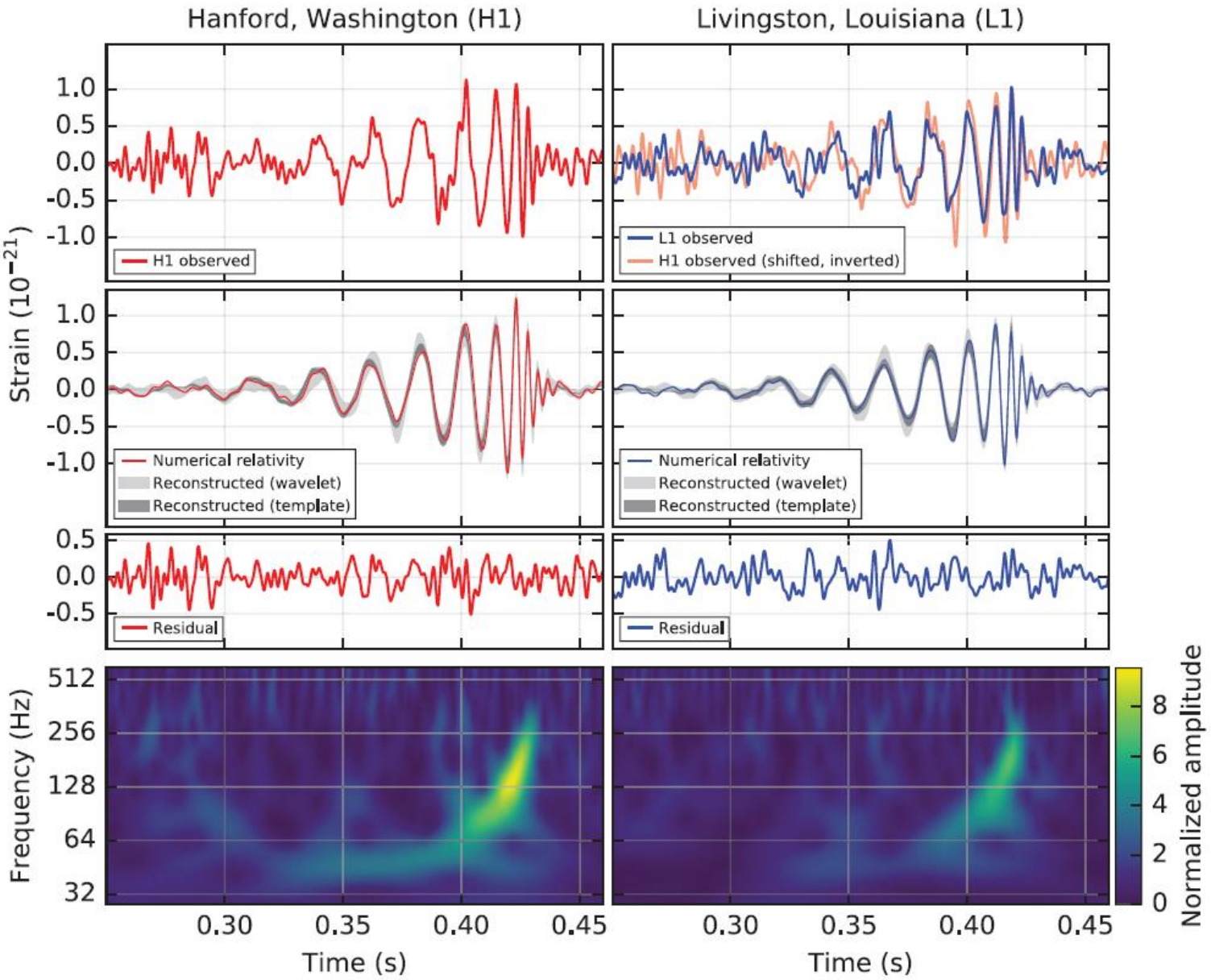
pulsars

supernovae

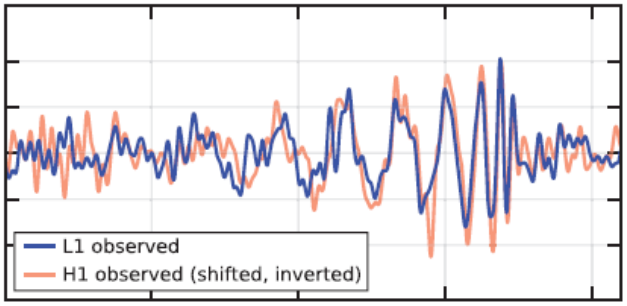


stochastic background

Sep 14, 2015 09:50:45 UTC



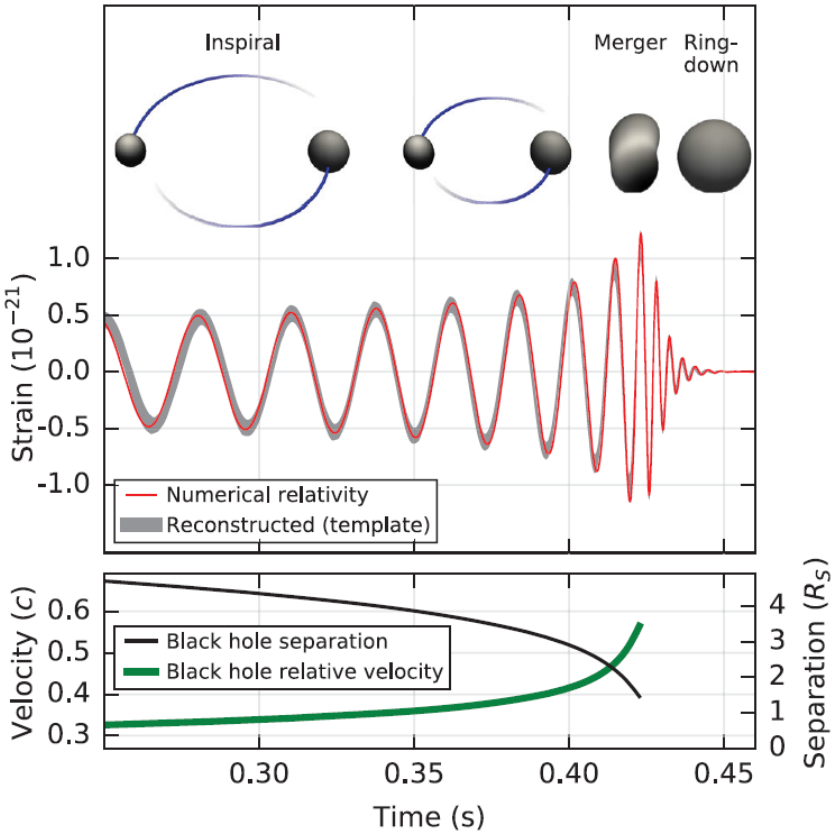
a black-hole binary



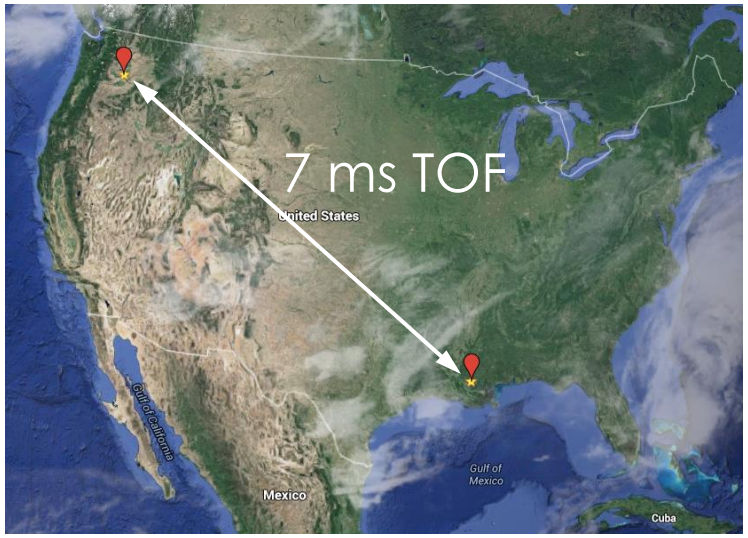
f_{GW} = 35 → 150 Hz over 0.2 s

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

$$\mathcal{M} \simeq 30 M_\odot \qquad \boxed{m_1 + m_2 \gtrsim 70 M_\odot}$$



detection case



- 2-detector coincidence
- signal morphology
- detectors in stable operation
- environment/instrument monitors

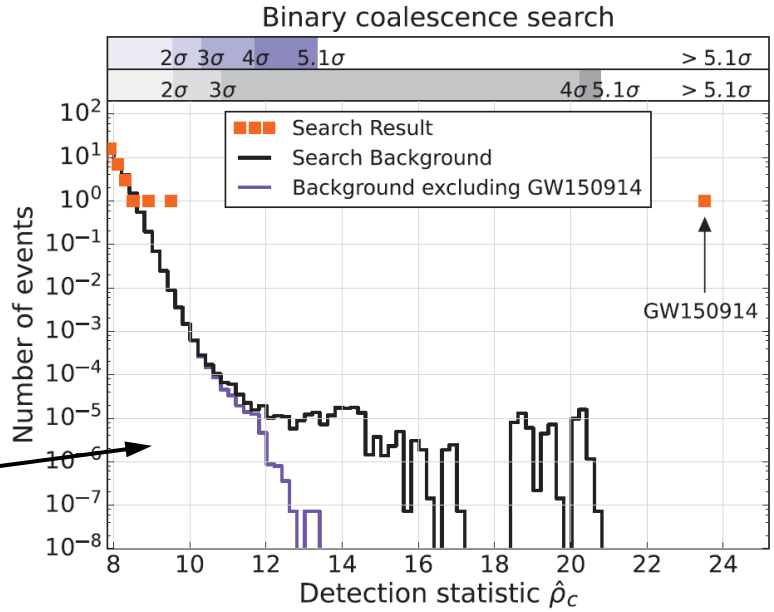
  ~$2 \cdot 10^5$ auxiliary channels

  status / loops / seismometers / accelerometers / microphones / magnetometers
  radio receivers / weather sensors / ac-power line monitors / cosmic-ray detector

- statistical significance

  false alarm rate 1/203 000 y^{-1}
  false alarm probability < $2 \cdot 10^{-7}$

matched filtering search



GW150914: an historical event

the 1st

- direct detection of GWs
- test of general relativity in strong-field regime
- direct observation of a black hole
- observation of a black hole binary system

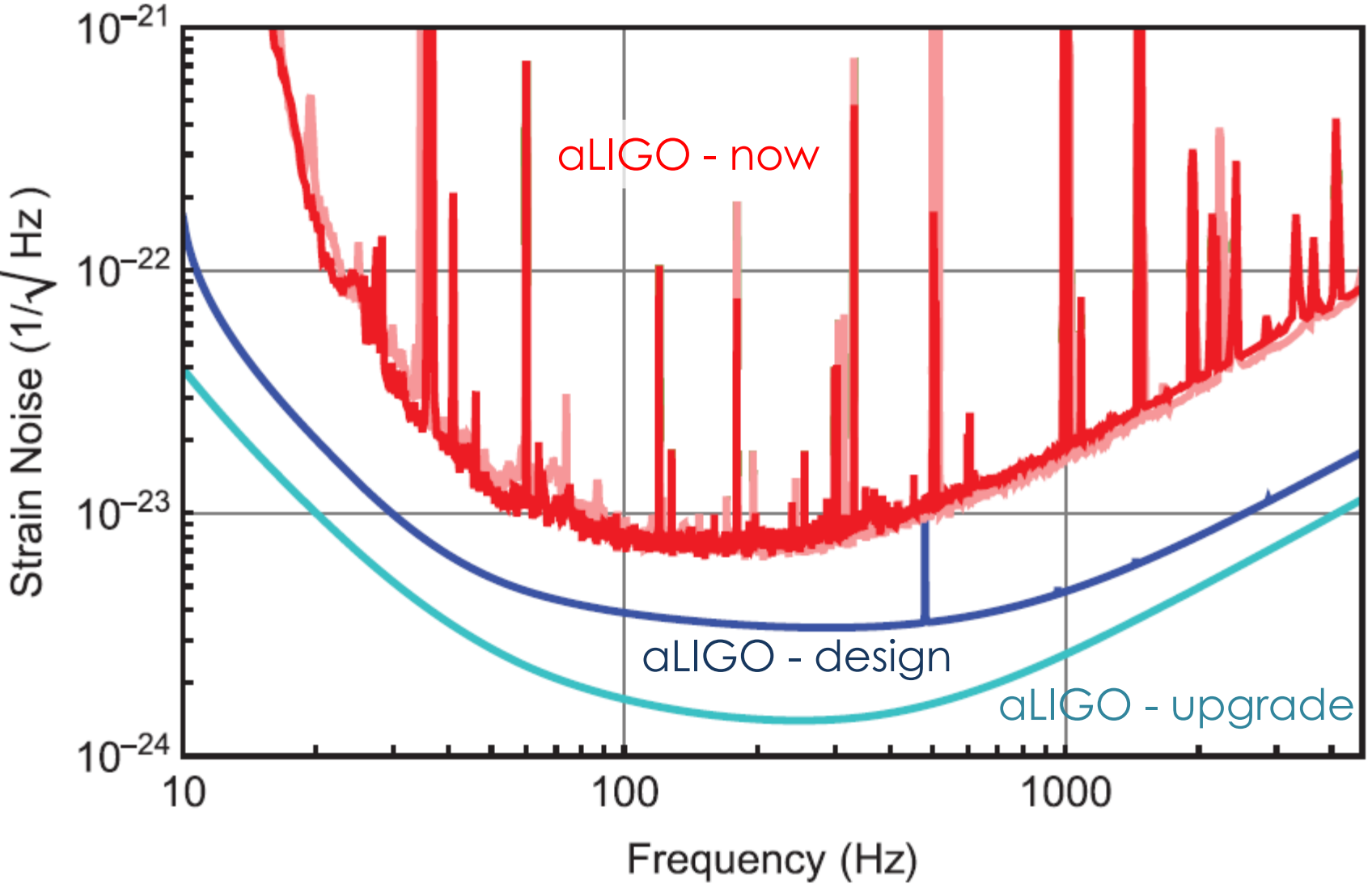
the most luminous event ever detected

$$3.0^{+0.5}_{-0.5} M_\odot c^2 \quad 3.6^{+0.5}_{-0.4} \times 10^{56}\ \mathrm{erg/s}$$

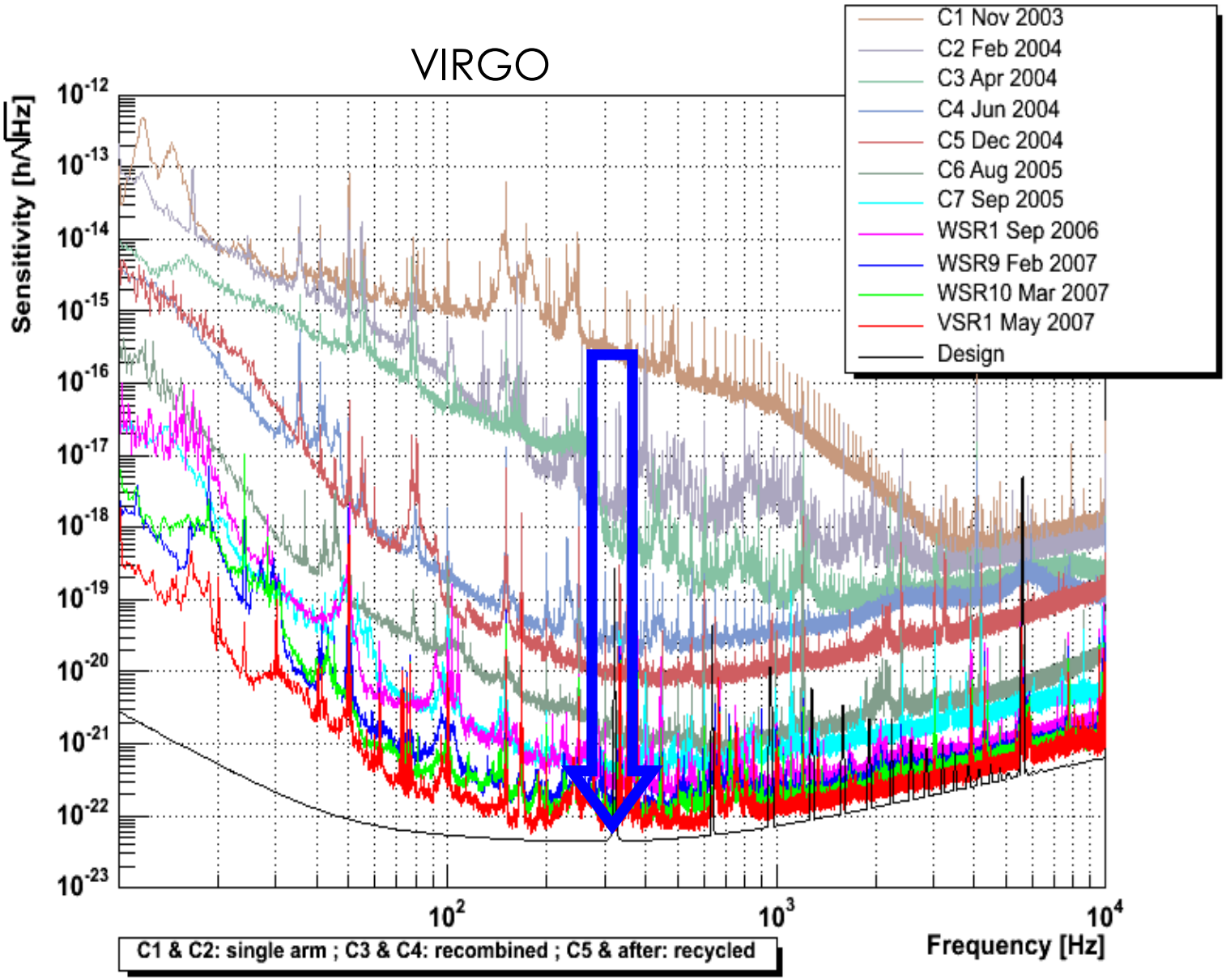
the beginning of GW astronomy

outlook

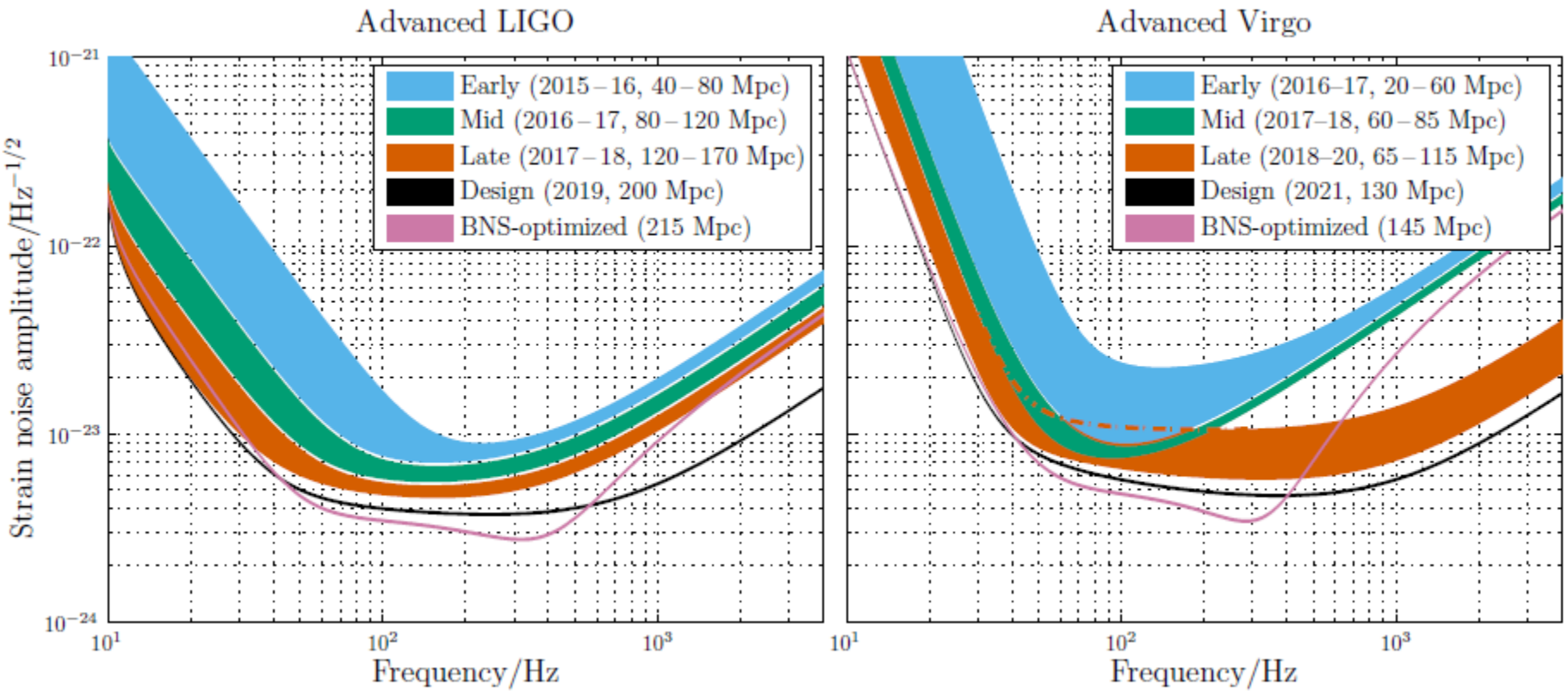
next steps


aLIGO - now
aLIGO - design
aLIGO - upgrade
Strain Noise (1/√Hz)
Frequency (Hz)
10^-21
10^-22
10^-23
10^-24
10
100
1000

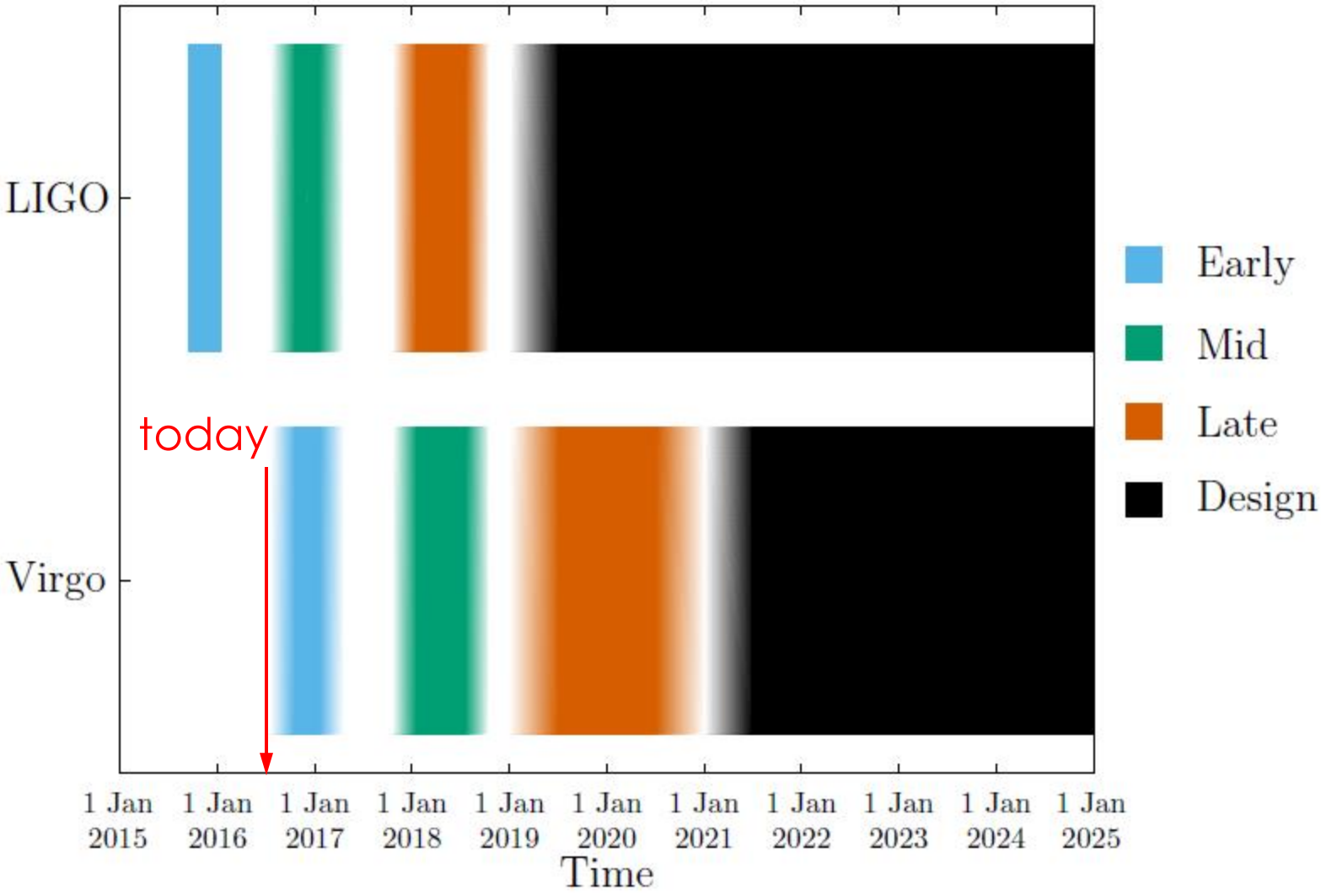
a long way down



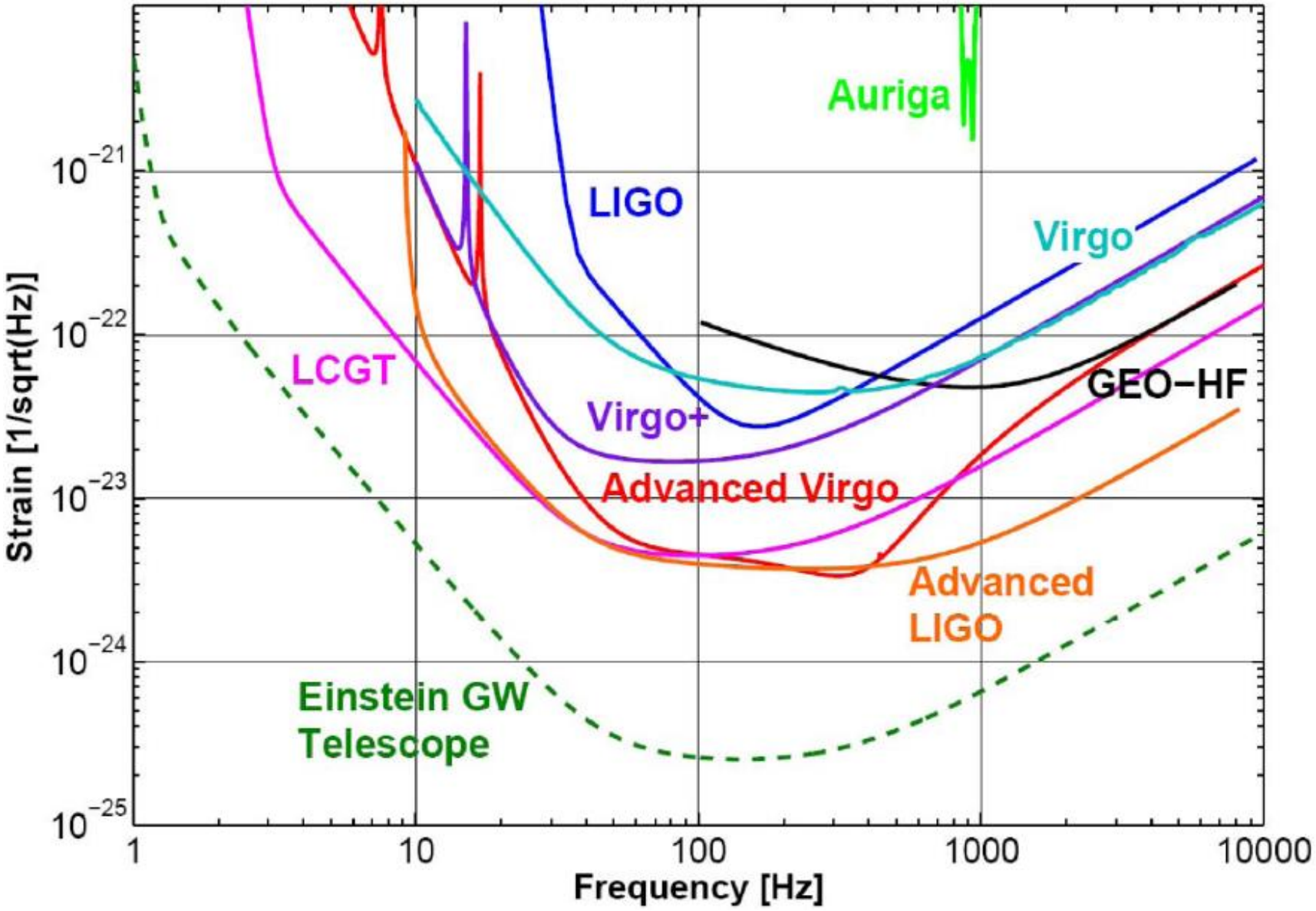
observing scenario



observing scenario



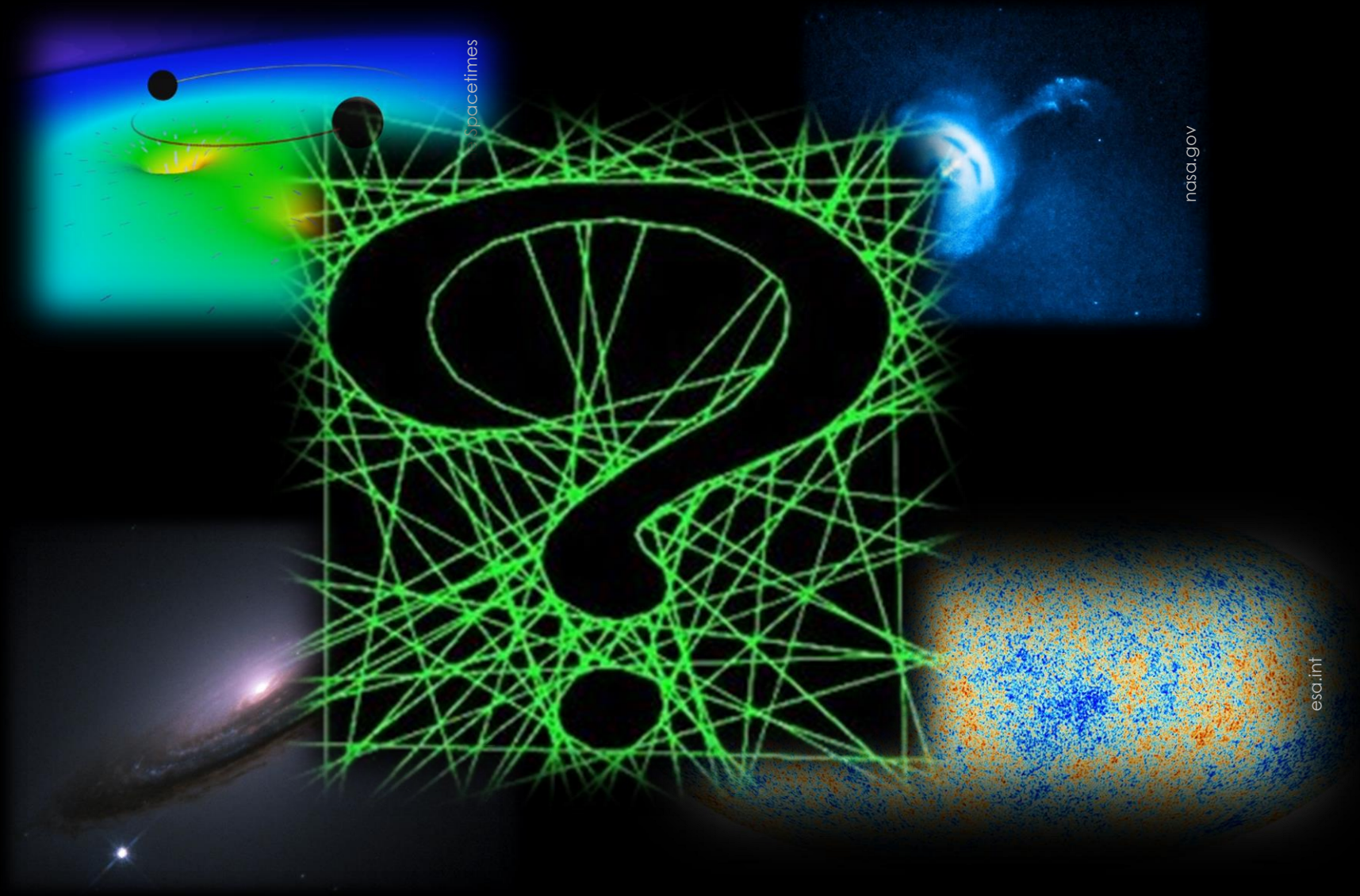
looking forward



the quest for the1st detection has ended

the observation of the gravitational Universe has just begun

astrophysical sources



references

- Advanced VIRGO
  Virgo coll., technical report VIR–0128A–12 (2012) – https://tds.ego-gw.it/itf/tds/
  Acernese et al., Class. Quantum Grav. 32, 024001 (2015)

- Advanced LIGO
  Aasi et al., Class. Quantum Grav. 32, 074001 (2015)
  Abbott et al., Phys. Rev. Lett. 116, 131103 (2016)

- observing scenario
  Abbott et al., Living Rev. Relativity, 19, (2016)

- Einstein Telescope
  ET science team, technical report ET-0106C-10 (2011) – https://tds.ego-gw.it/itf/tds/

- GW150914
  Abbott et al., Phys. Rev. Lett. 116, 061102 (2016)
  LIGO magazine: http://www.ligo.org/magazine/
  h – the gravitational voice: http://www.ego-gw.it/public/hletter/doc/hDiscovery.pdf

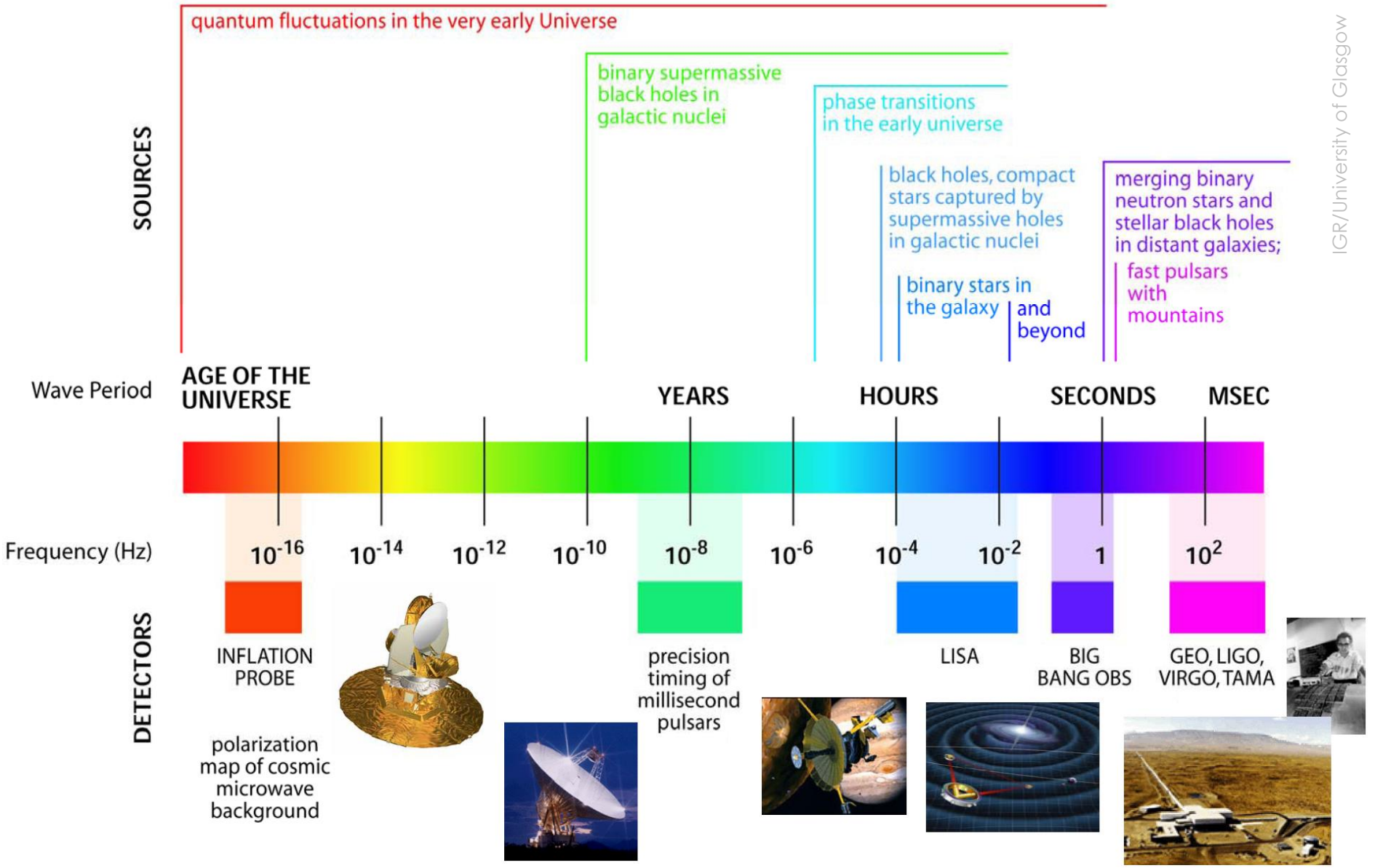
many thanks to

Jerôme Degallaix

Eric Chassande-Mottin

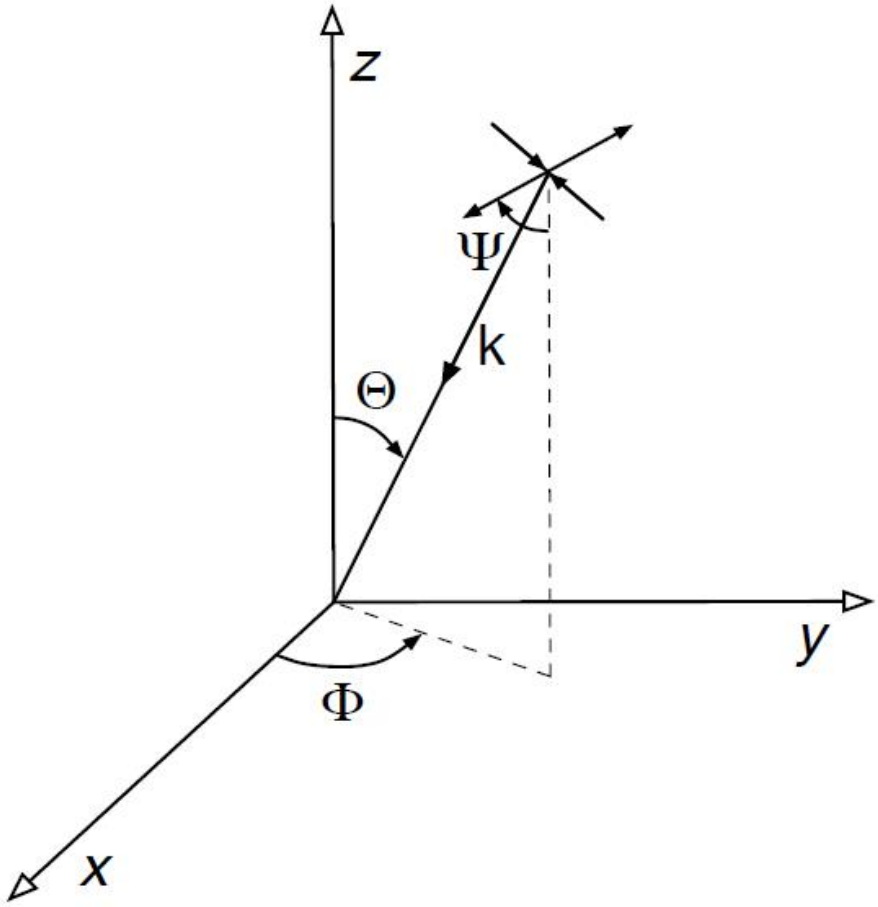
thank you for your attention

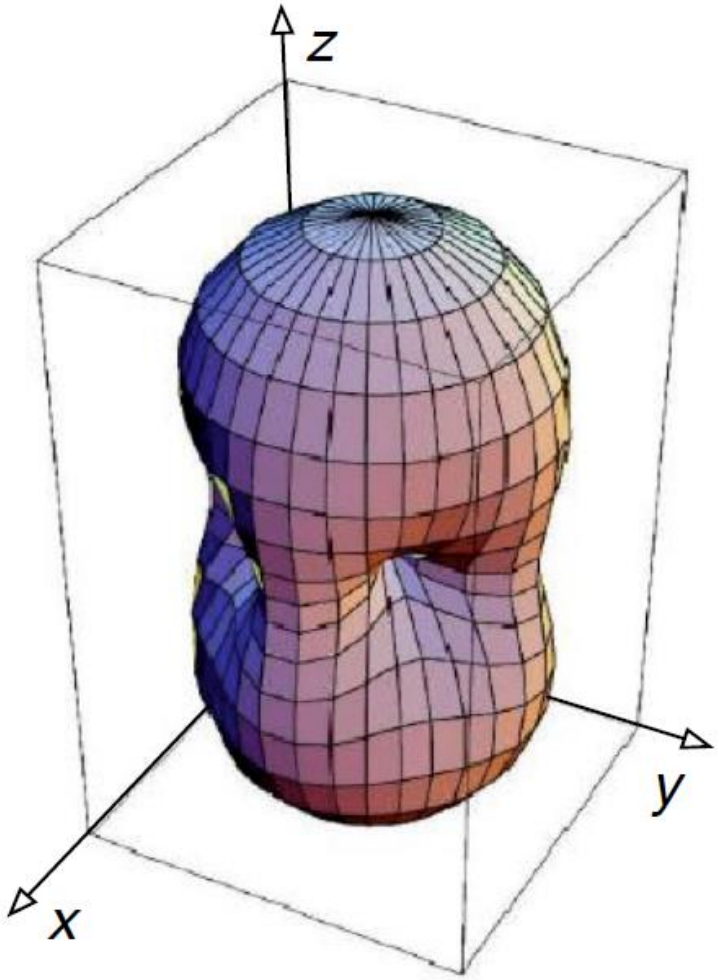
the GW spectrum



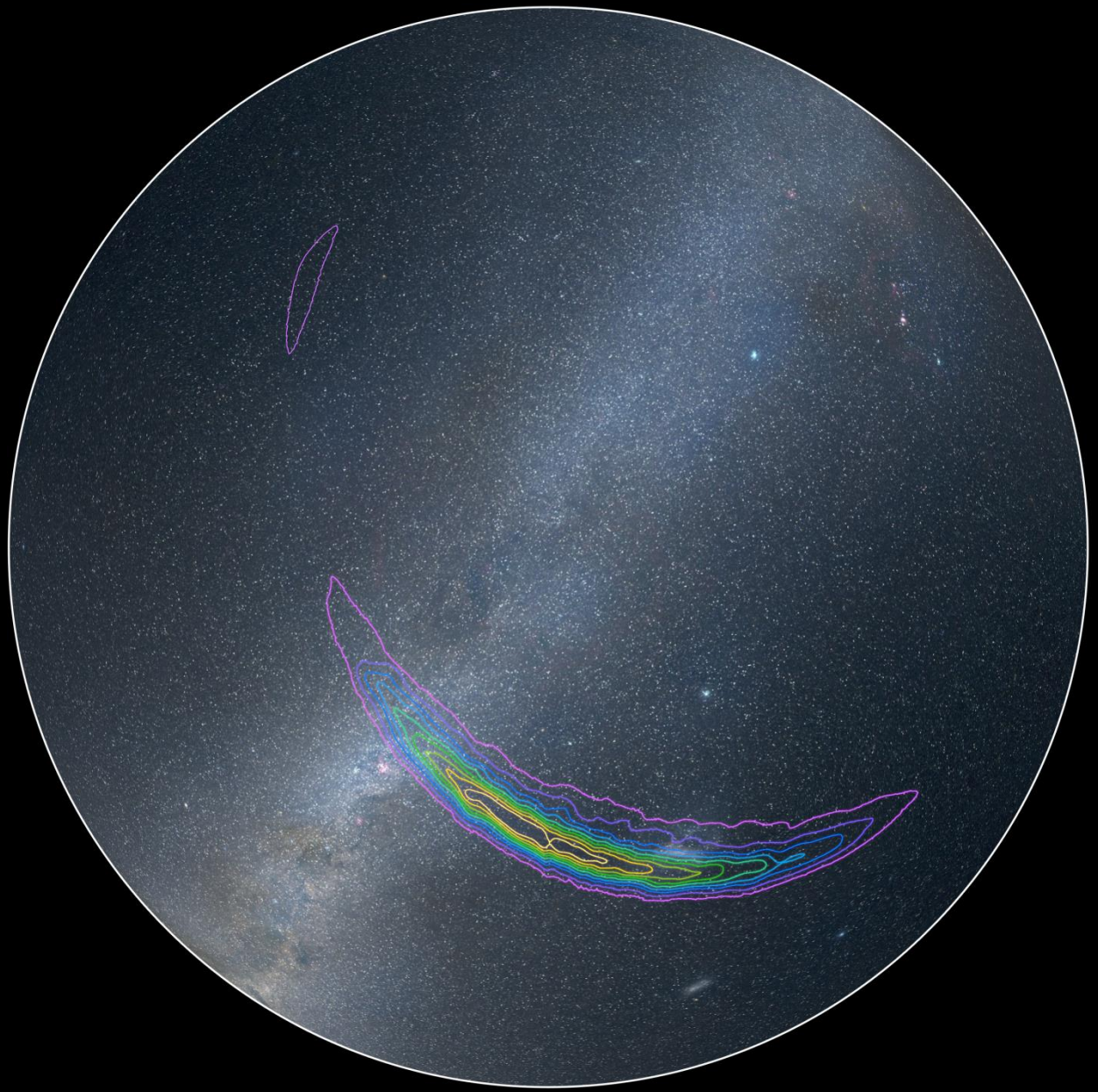
IGR/University of Glasgow

antenna pattern



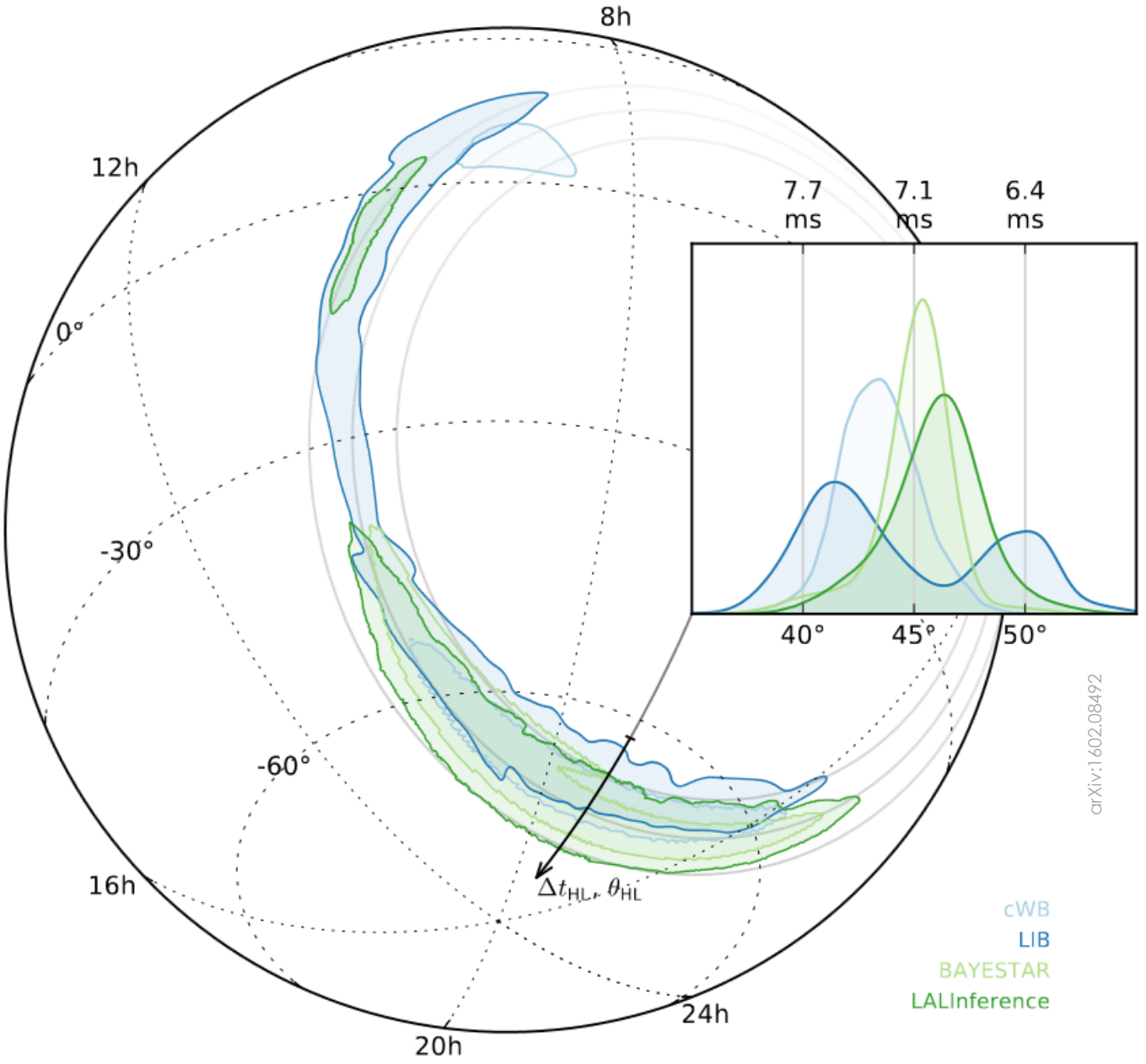


GW150914 sky localization

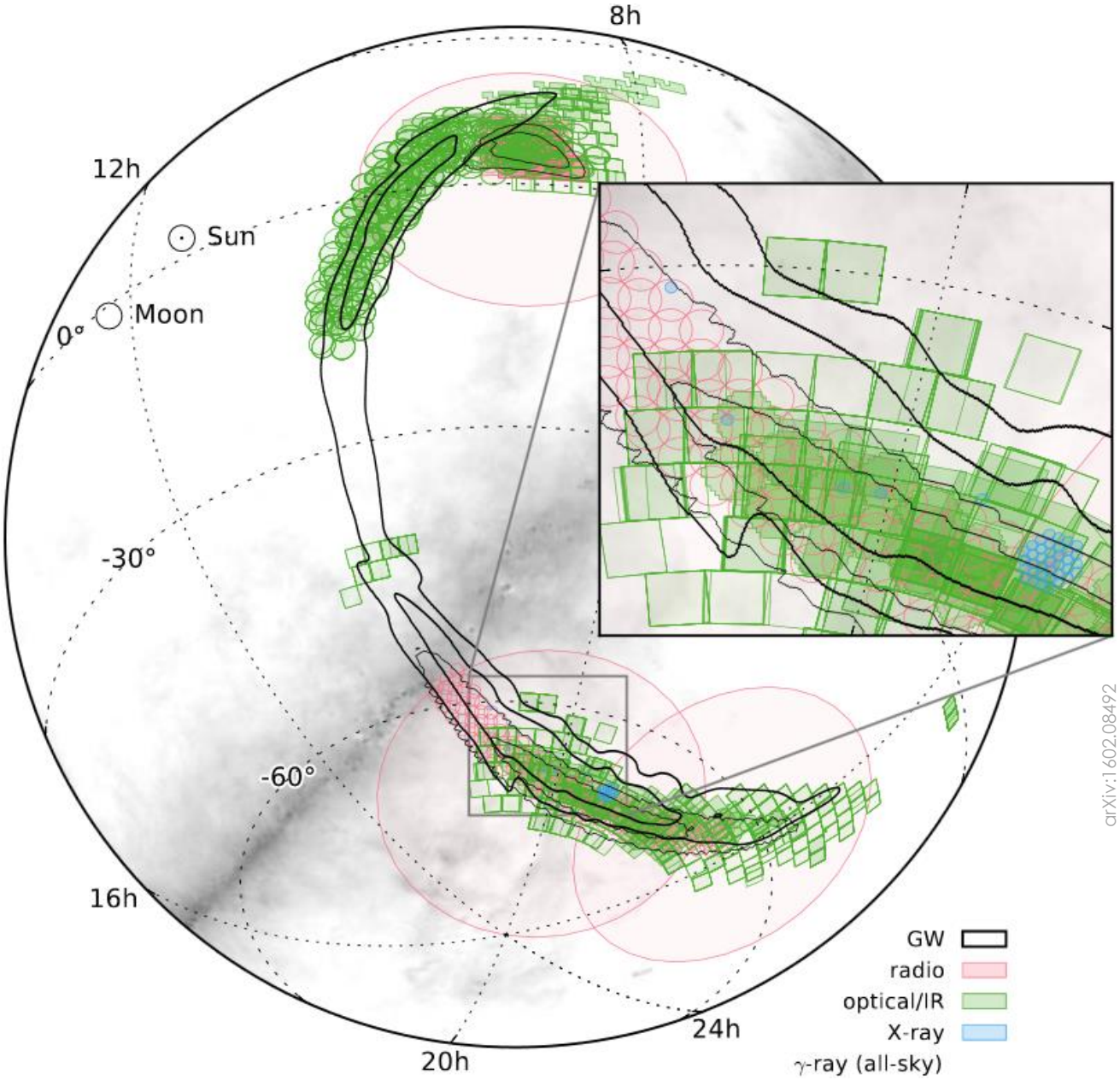


Caltech/MIT/LIGO

GW150914 sky localization



GW150914 broad-band follow-up



Einstein Telescope

- 10-km triple xylophone
- underground
- cryogenic
- high power