Gravitational-wave detection with ground-based interferometers

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outline

gravitational waves

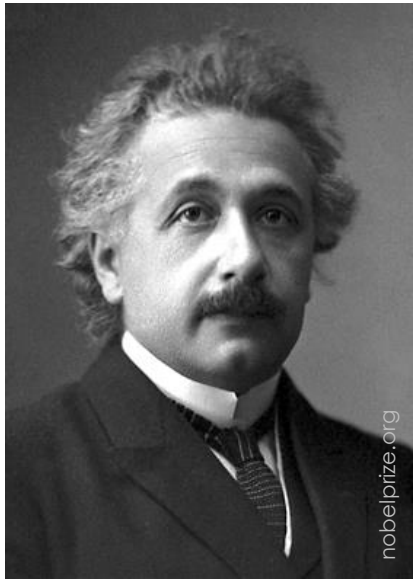
ground-based detectors

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

1st detection

outlook

1915 – General Relativity



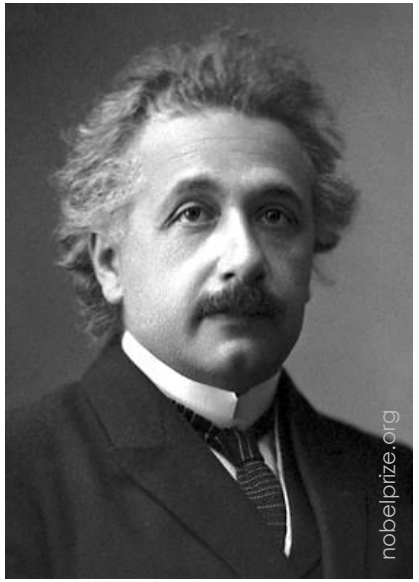
local space-time is dynamic

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



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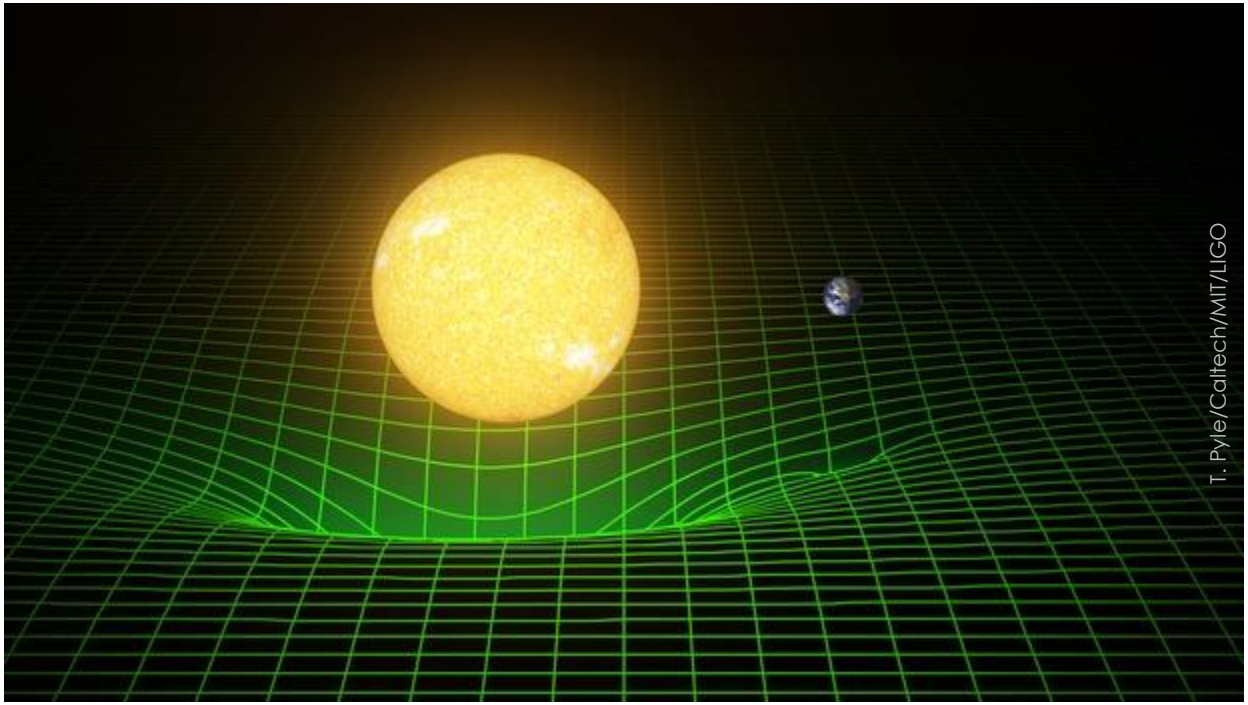
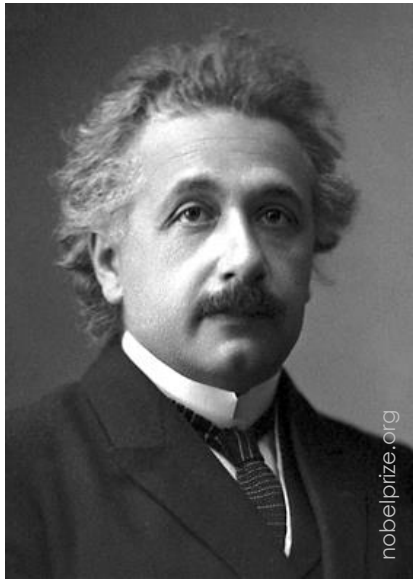


1916 – gravitational waves (GWs)



perturbative approach

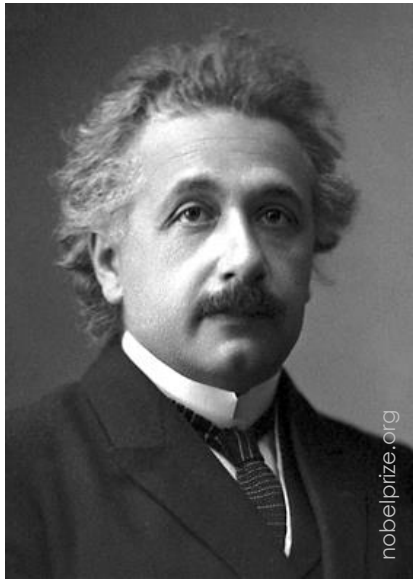
→ linearized field equations

→ 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

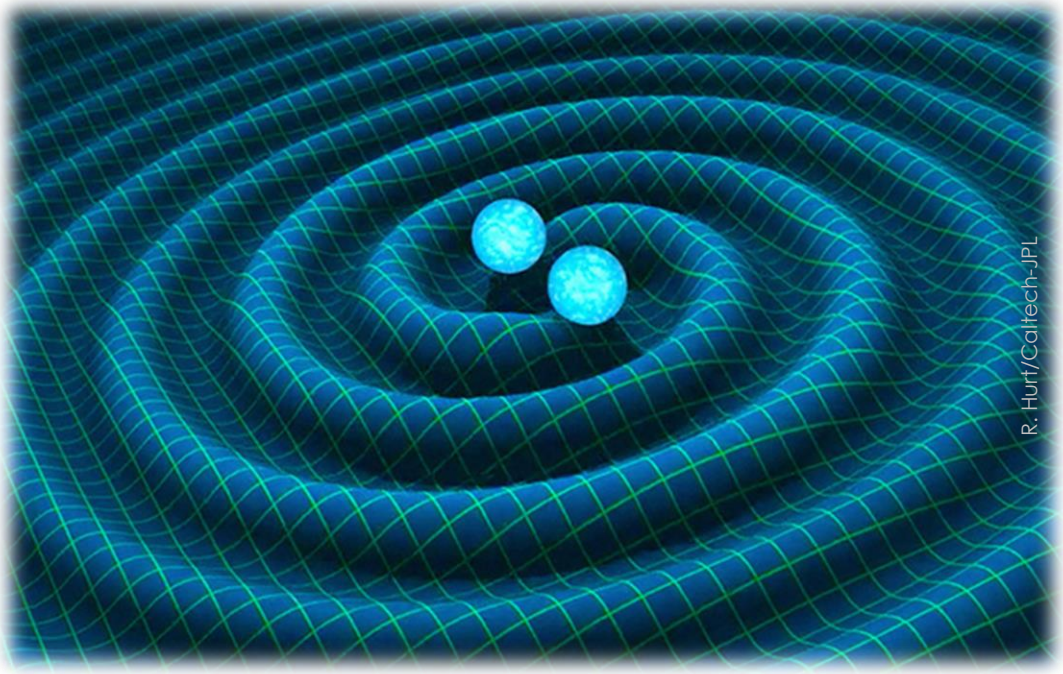
→ linearized field equations

→ 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

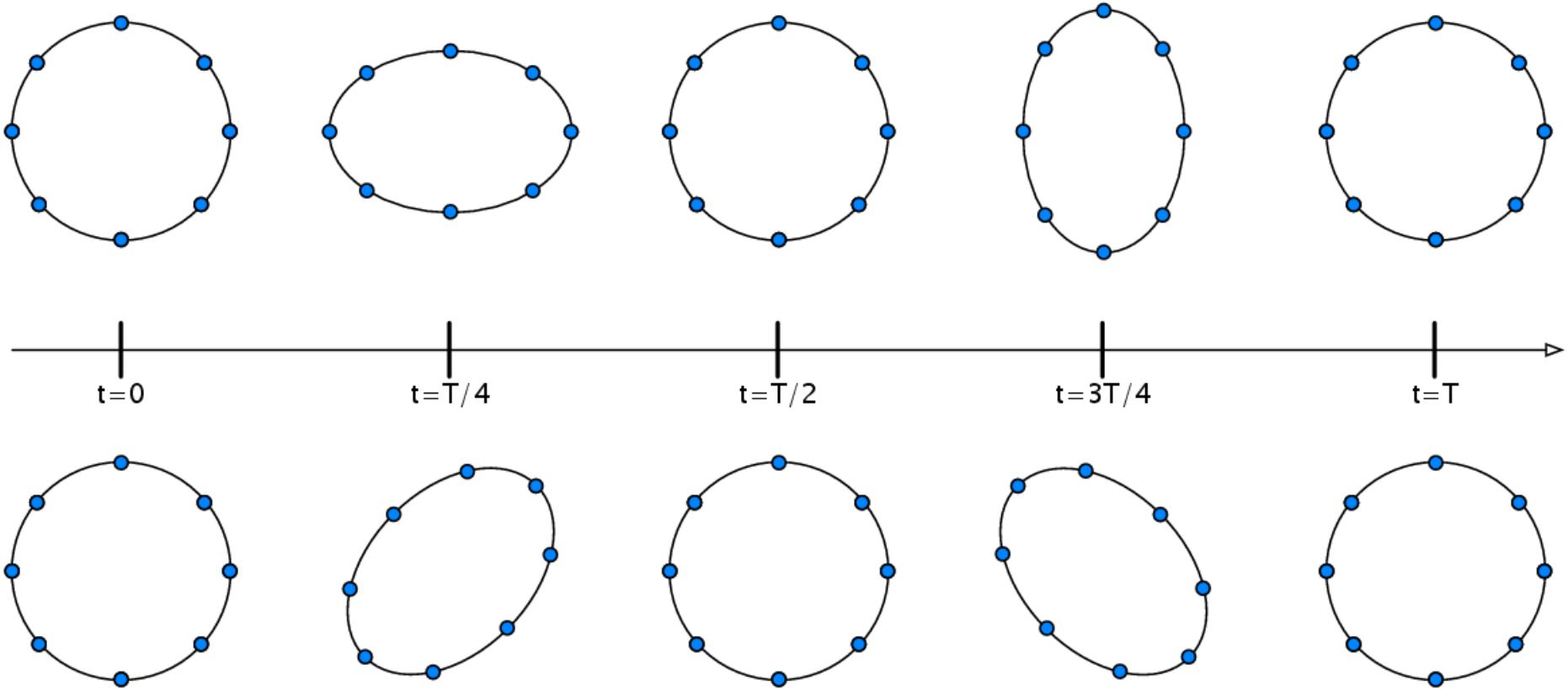
emitted by accelerated masses

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, […]

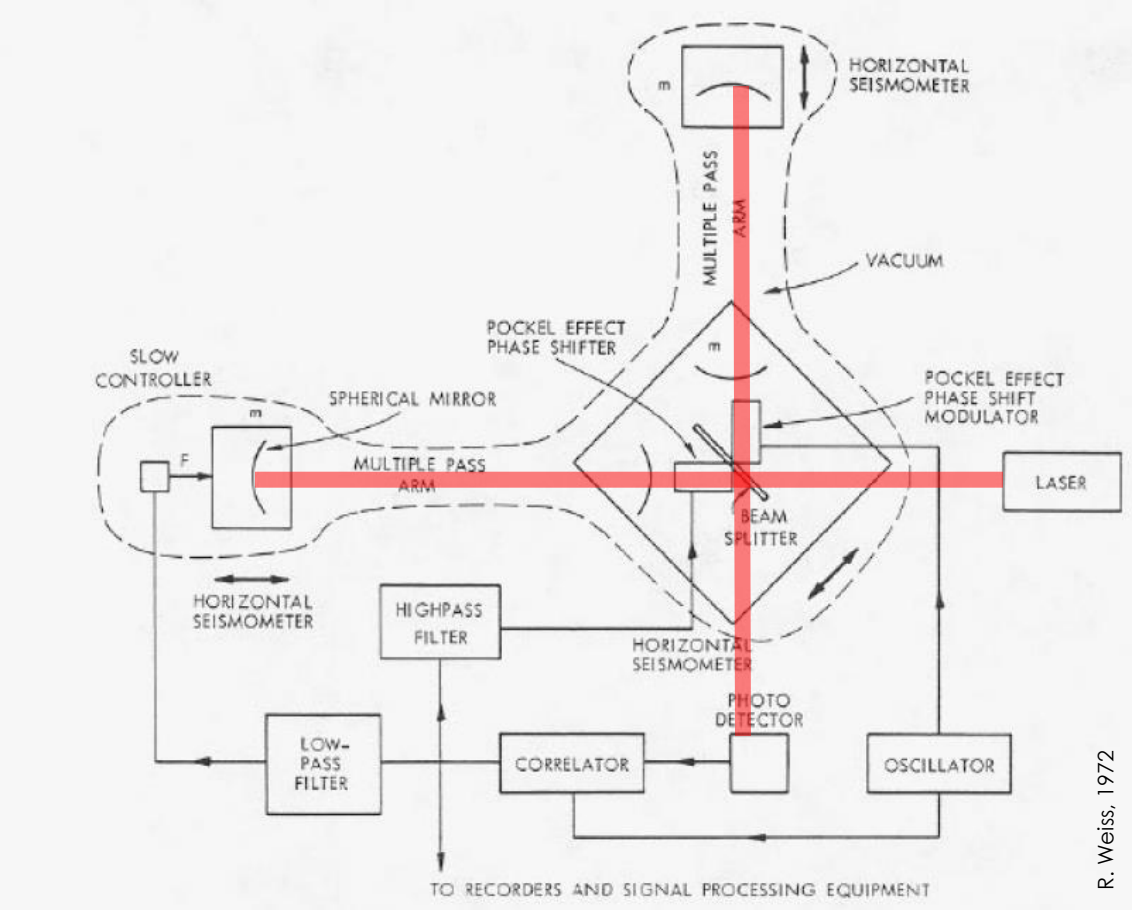
  1st international network (IGEC)

  few detectors still operational

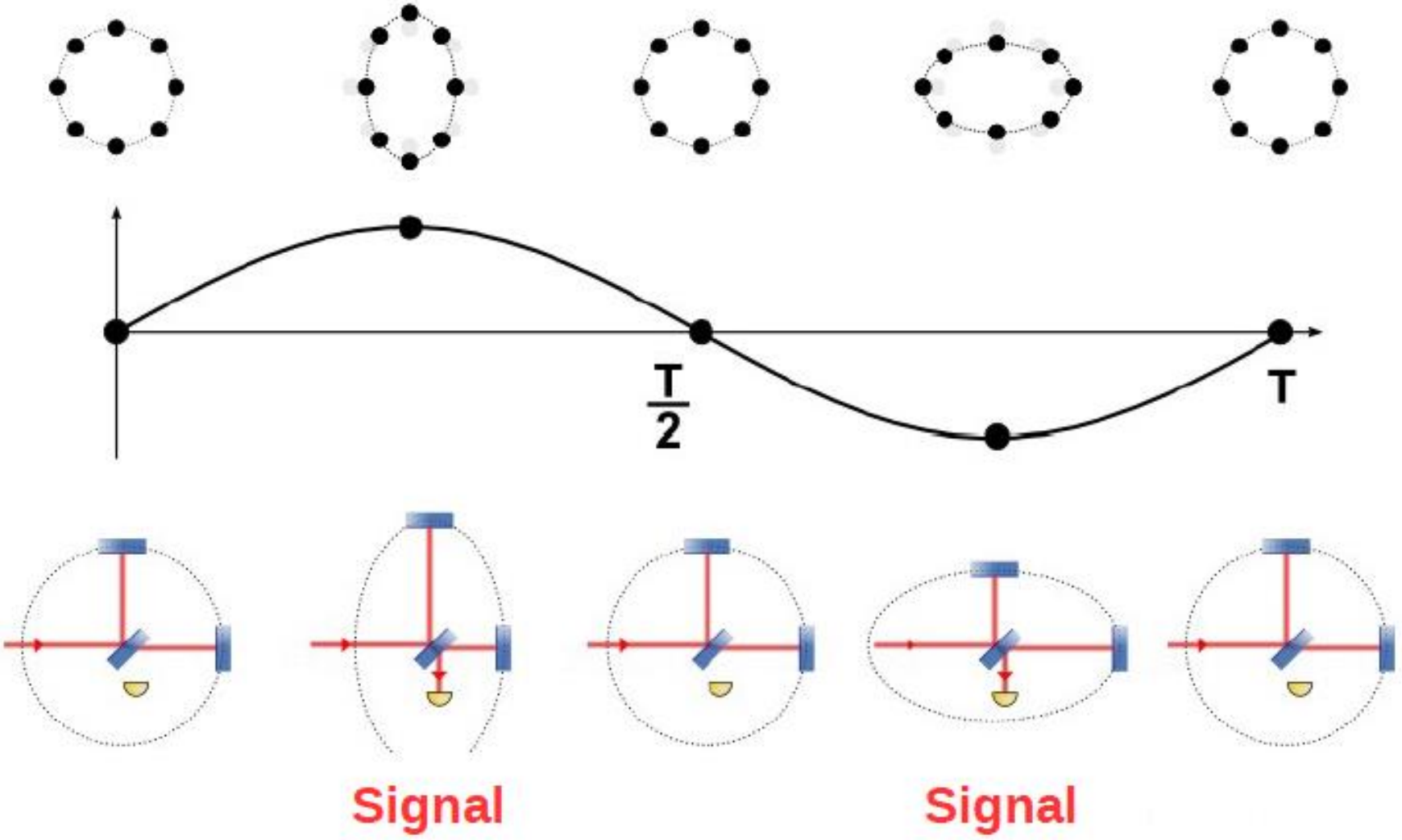
interferometers

optical transducers

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



interferometers



J. Degallaix

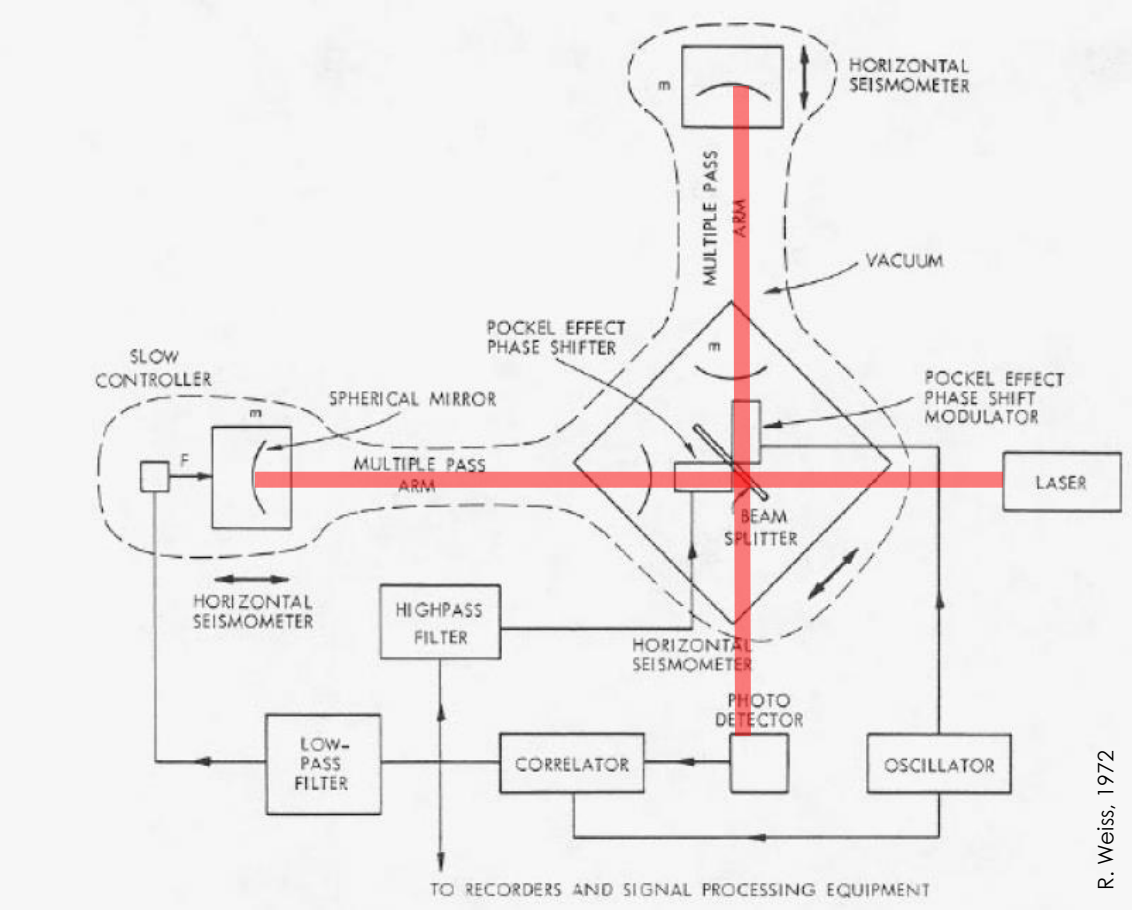
interferometers

optical transducers

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

km-scale arms

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

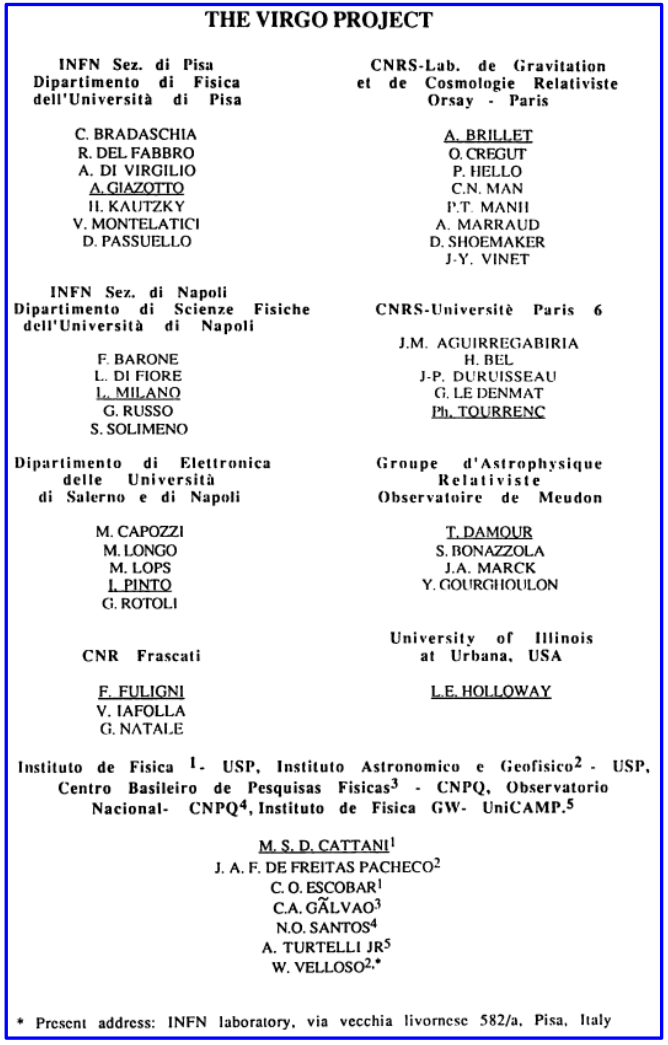


history

- '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

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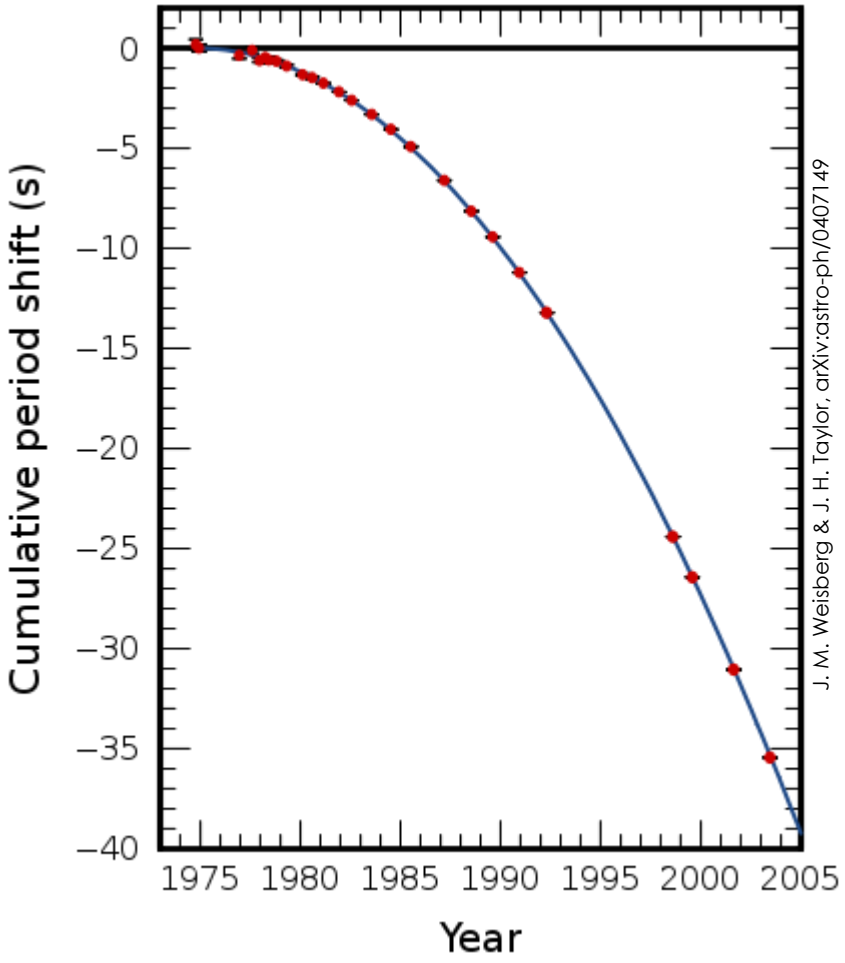
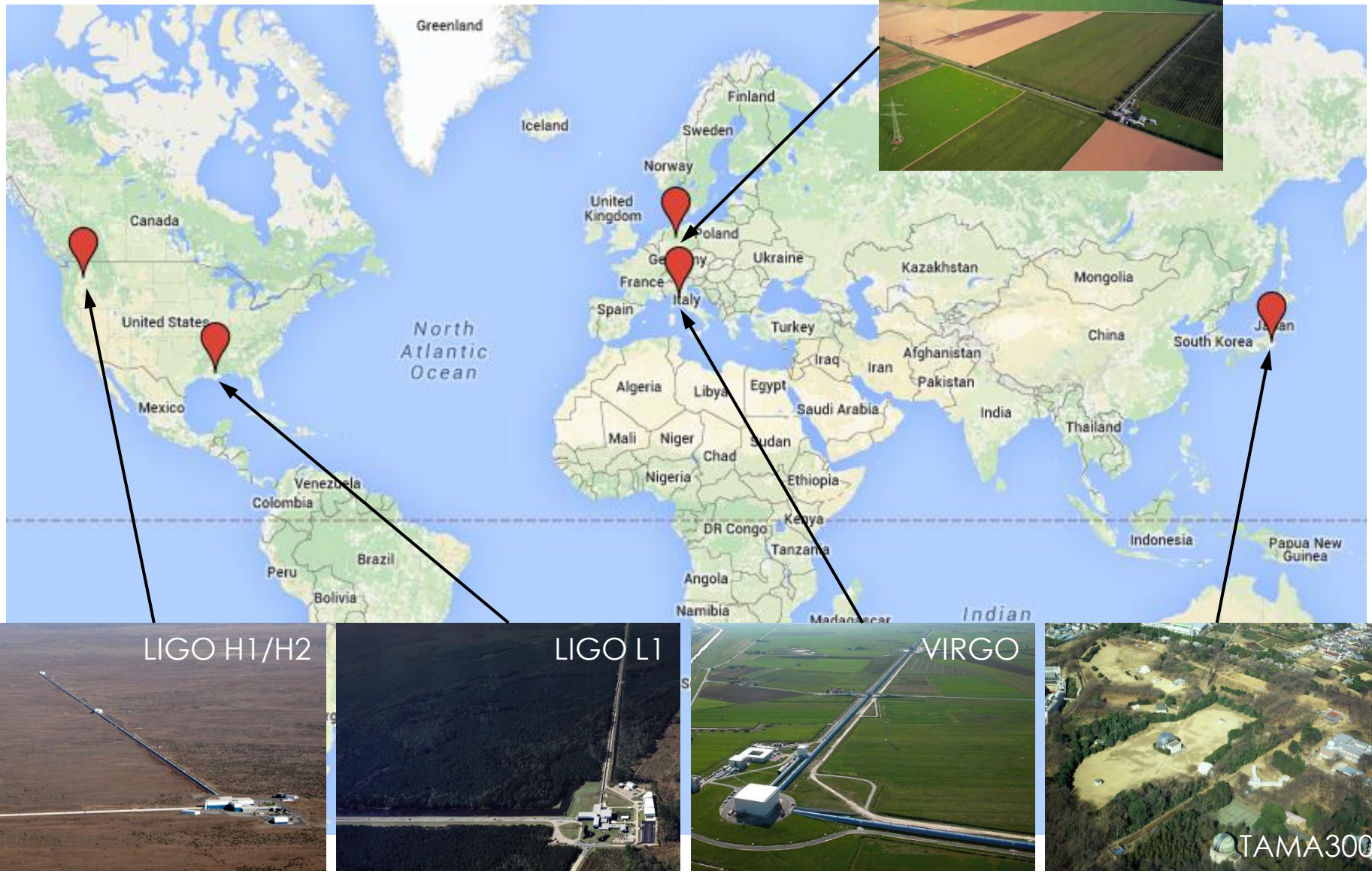
in the meanwhile

- 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

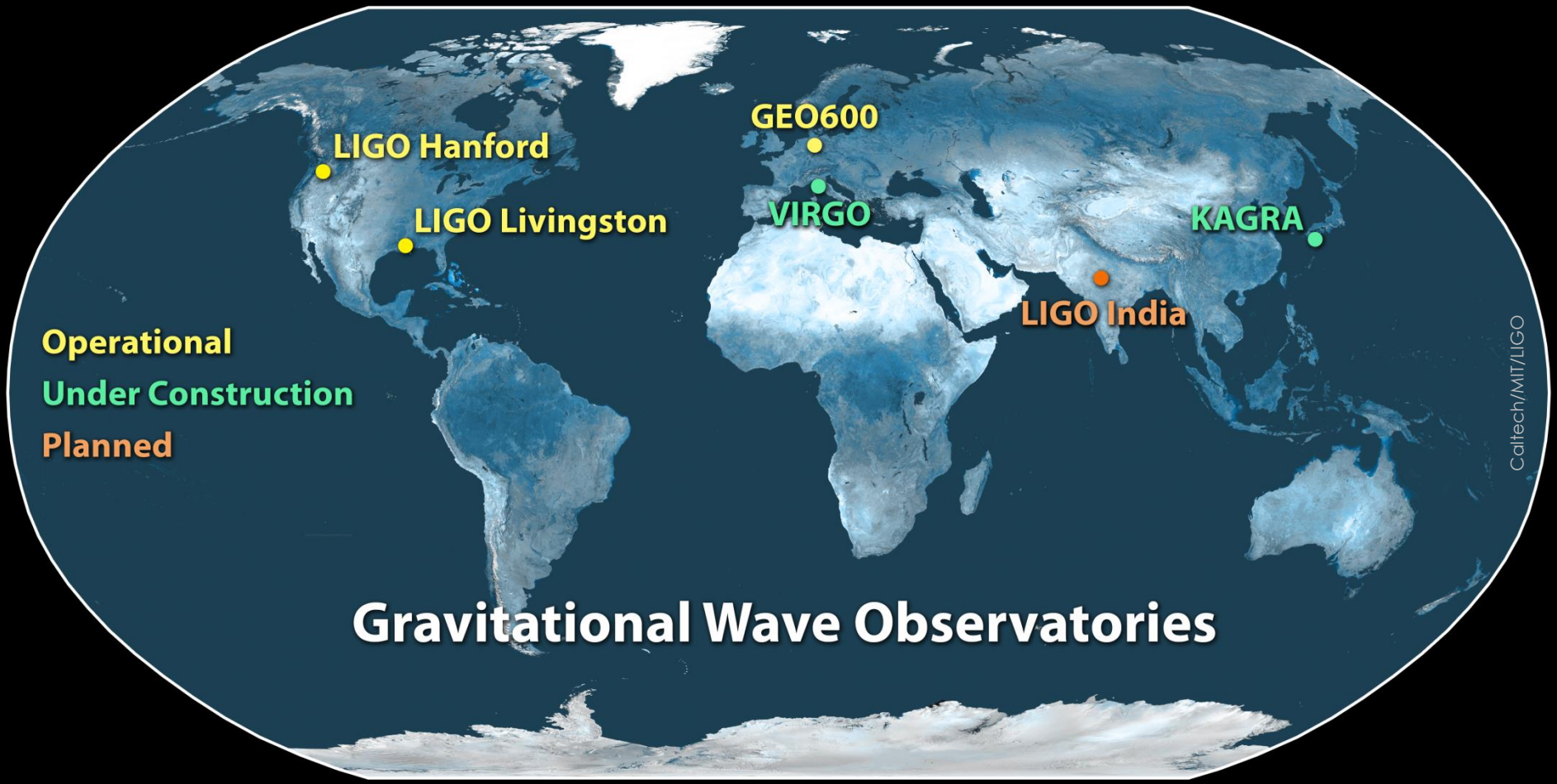
- demonstration of detection principle

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

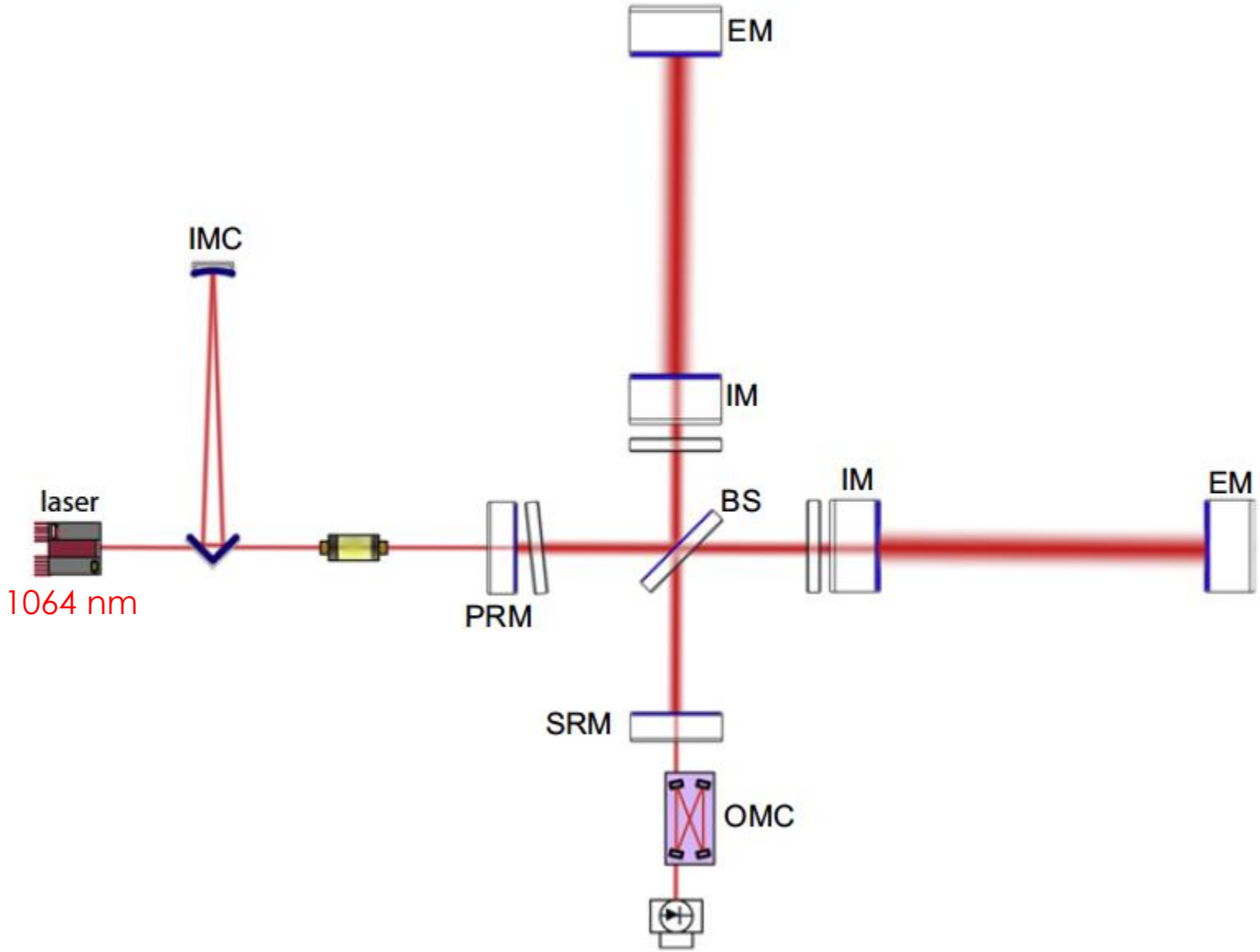
- collaborations with EM telescopes/satellites

- infrastructures

today – 2nd generation

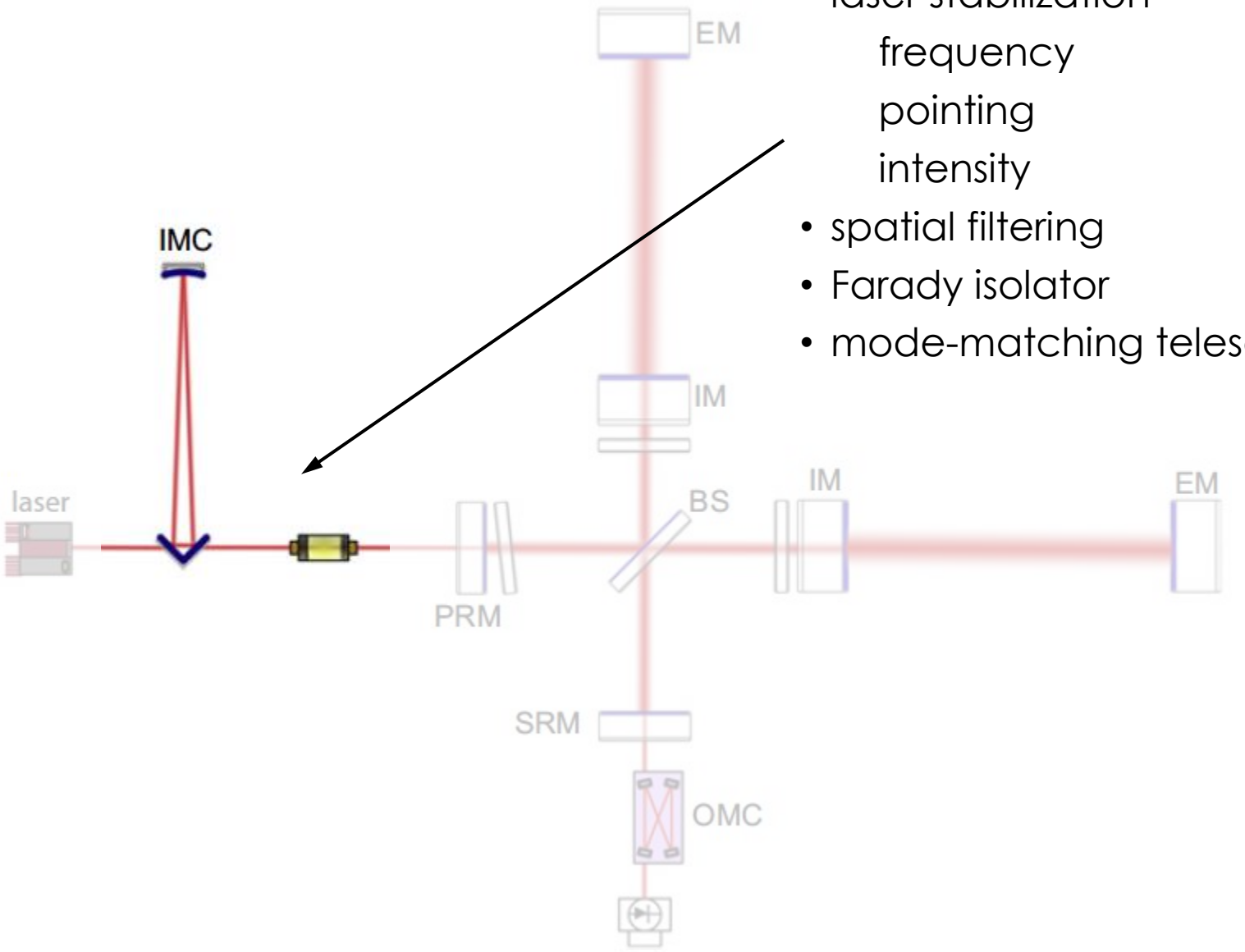


optical layout

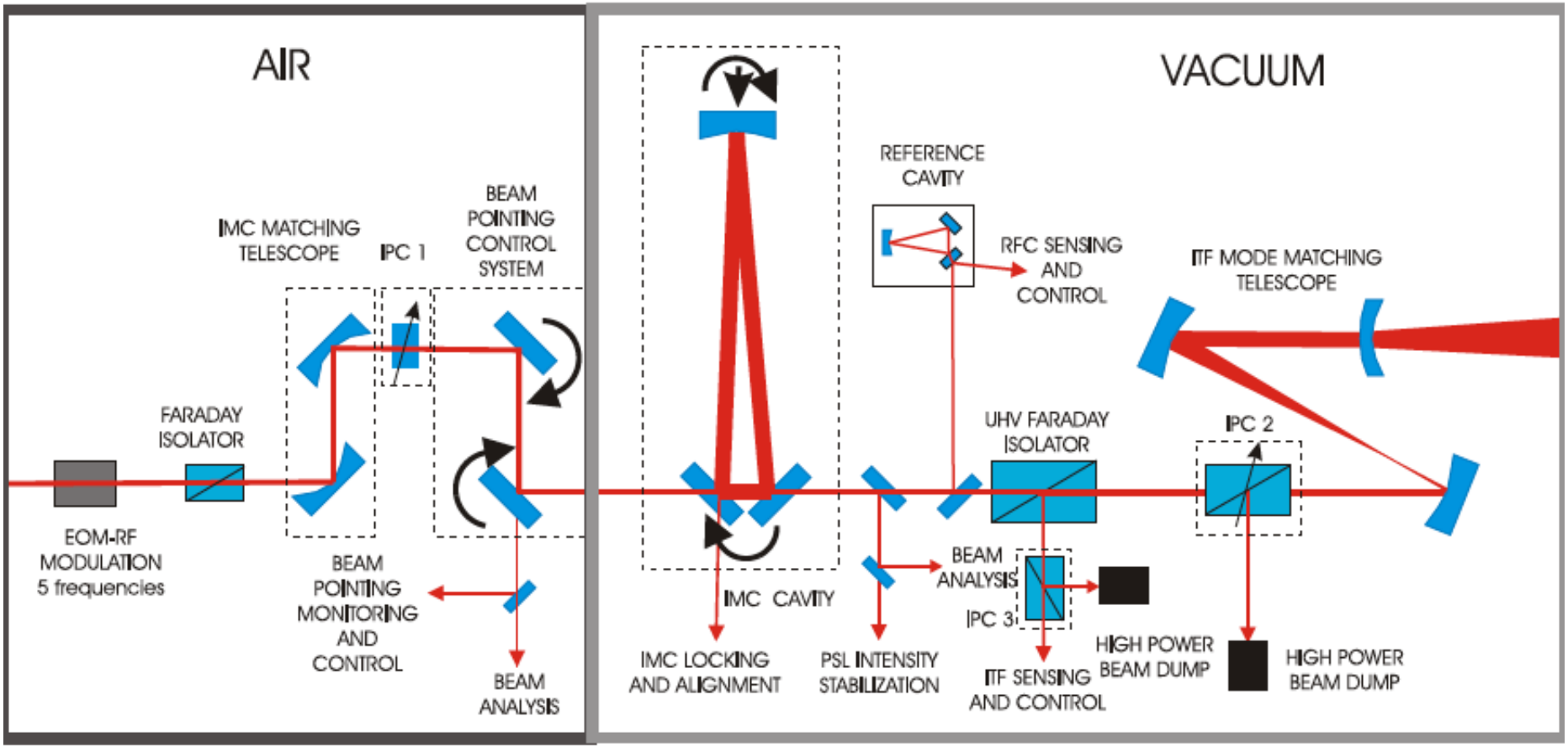


input optics

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

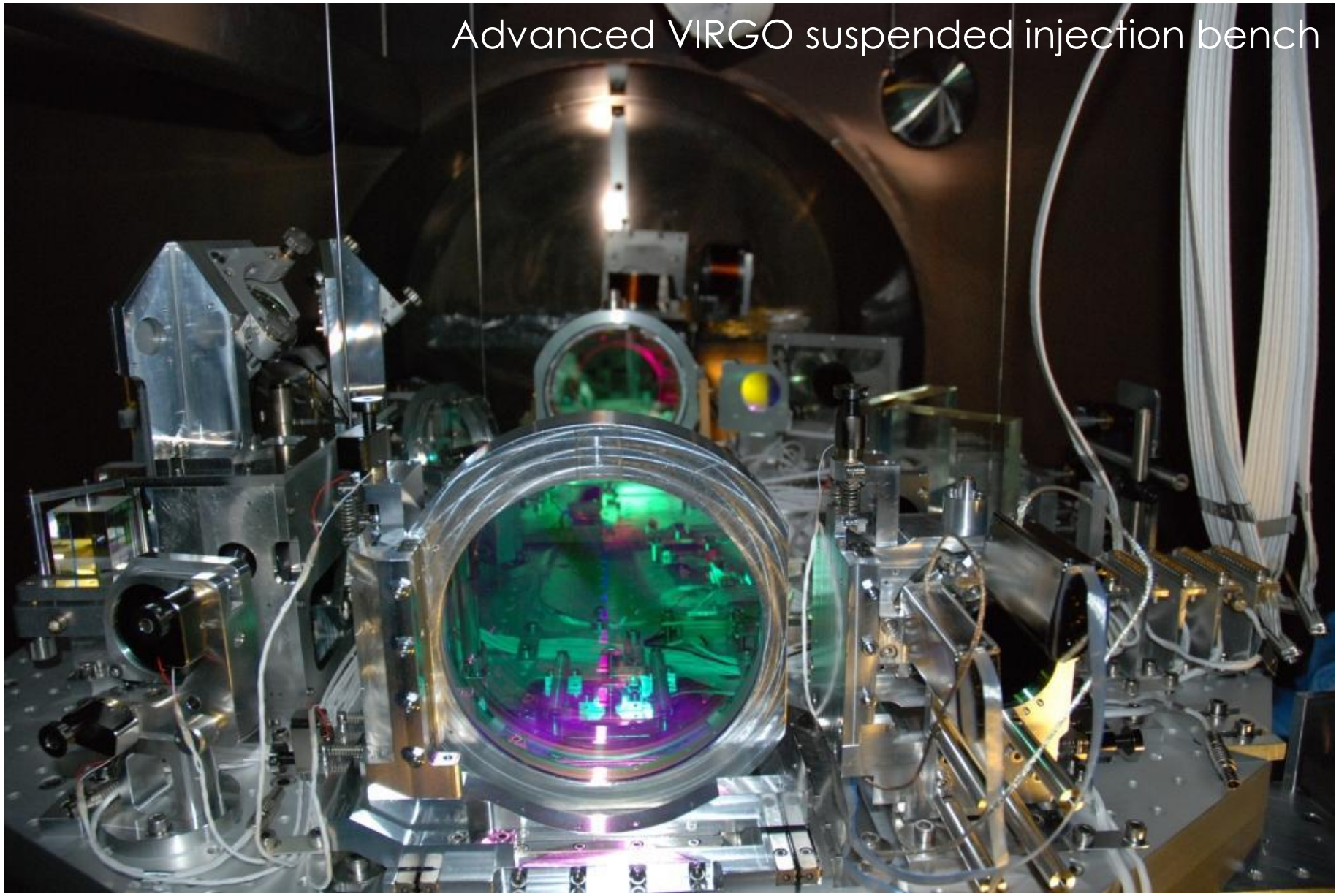


input optics



Advanced VIRGO

input optics



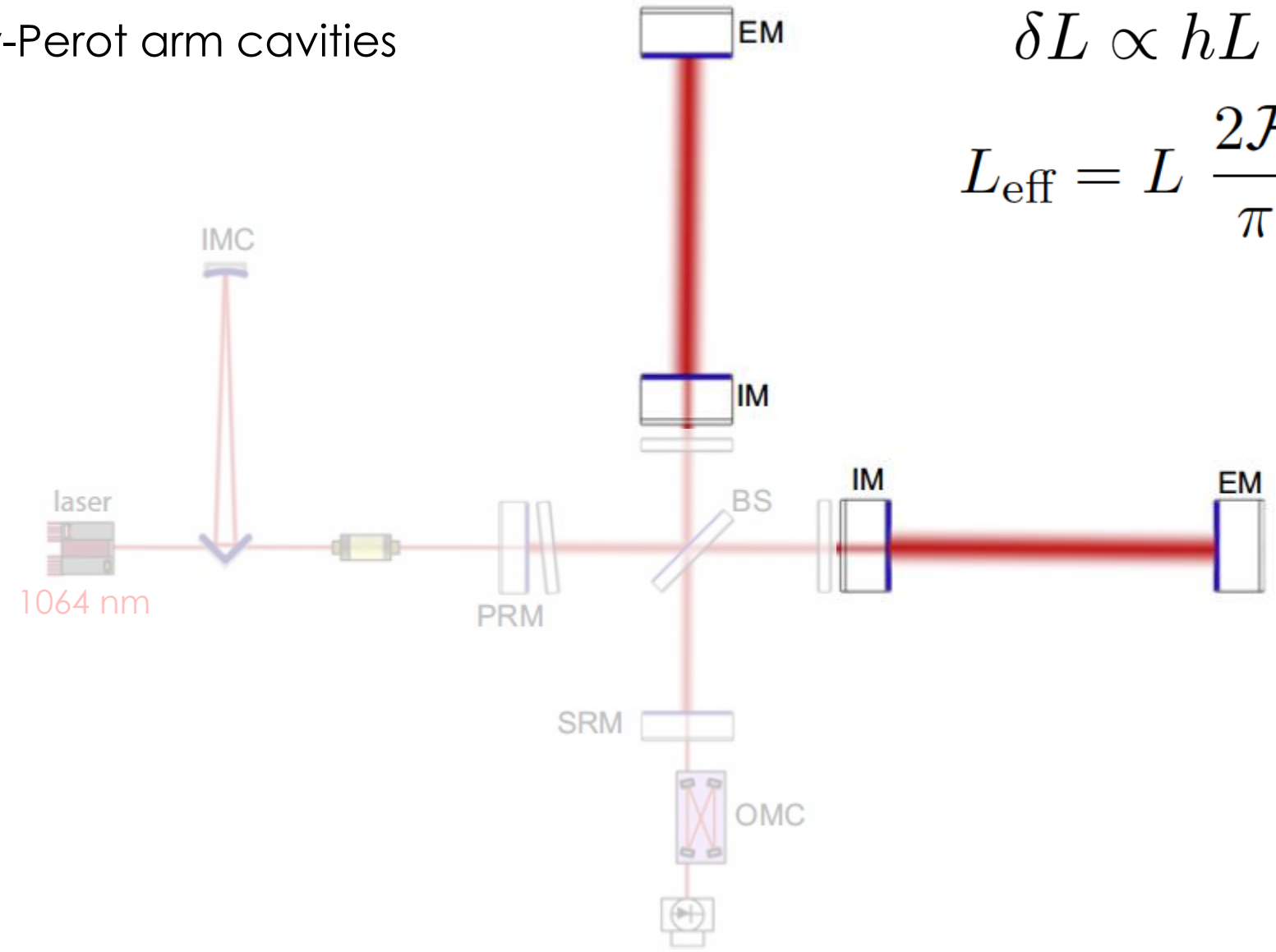
input optics

optical layout

Fabry-Perot arm cavities

$$\delta L \propto hL$$

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



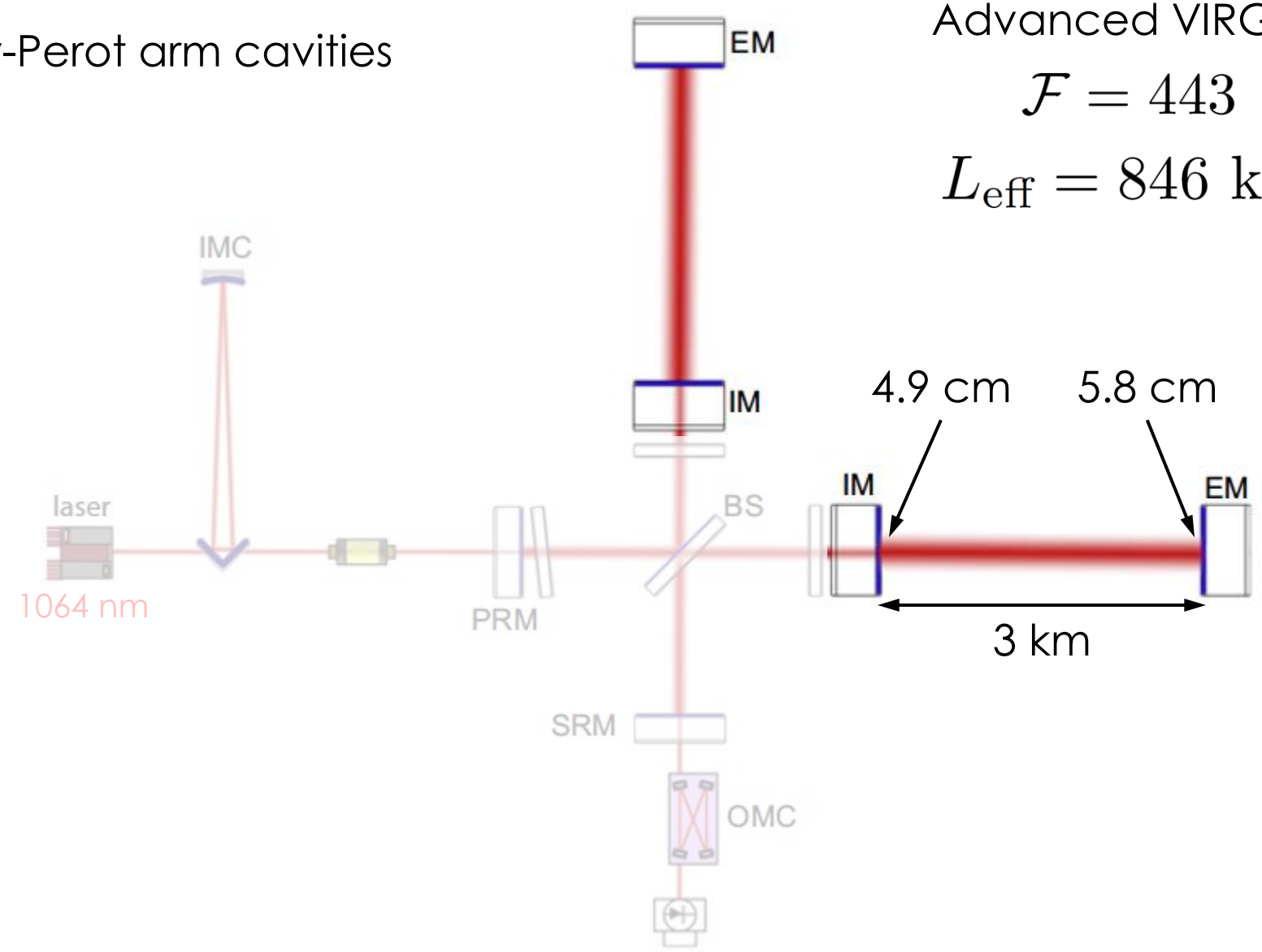
optical layout

Fabry-Perot arm cavities

Advanced VIRGO

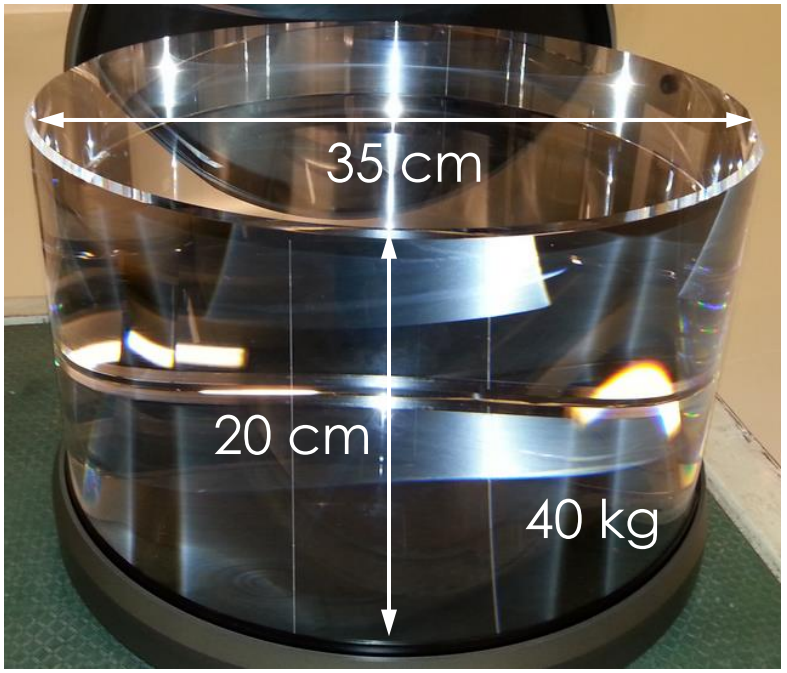
$$\mathcal{F} = 443$$

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



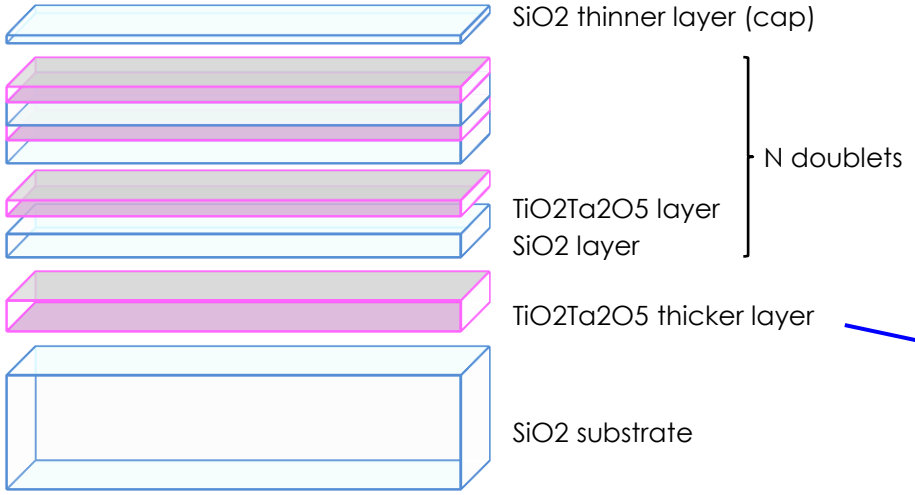
test masses

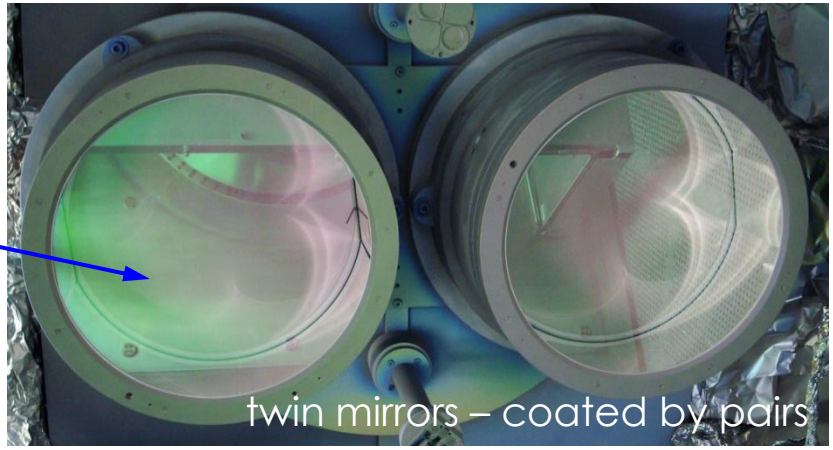
ultra-pure fused silica substrates



high-reflection coatings

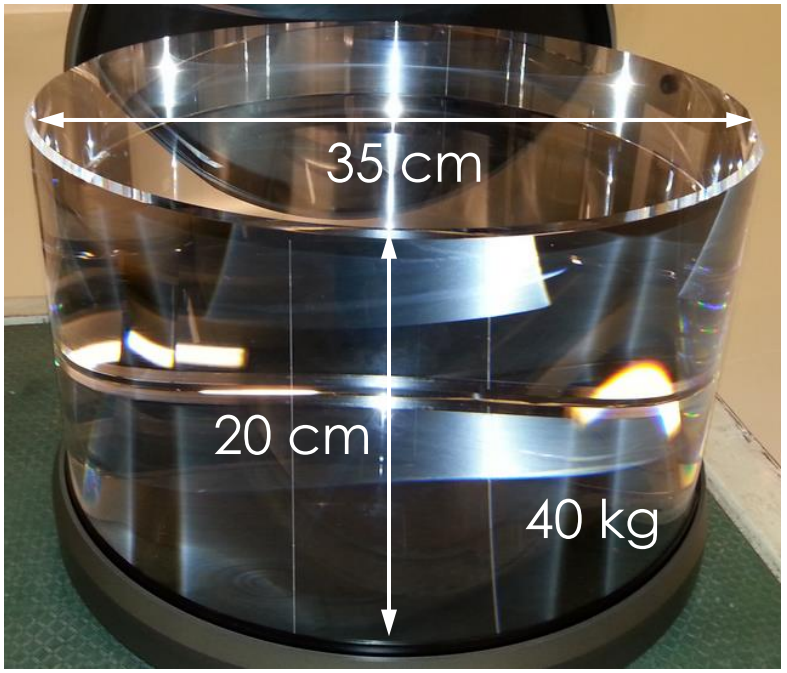
TiO2Ta2O5/SiO2 Bragg mirrors





test masses

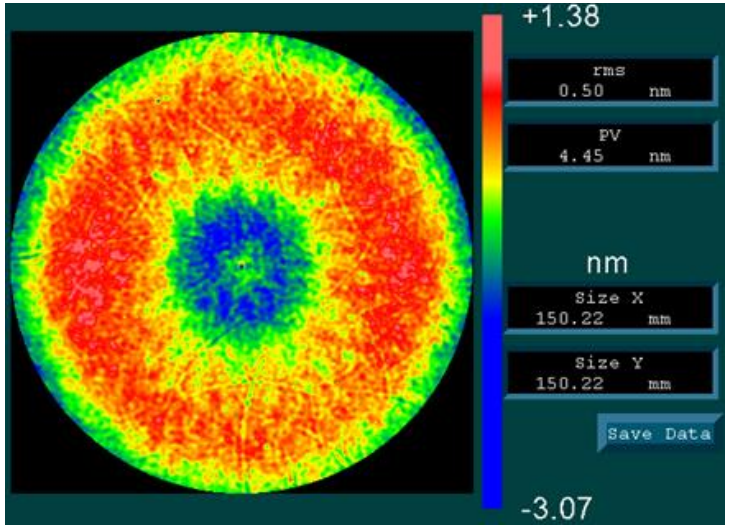
ultra-pure fused silica substrates



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

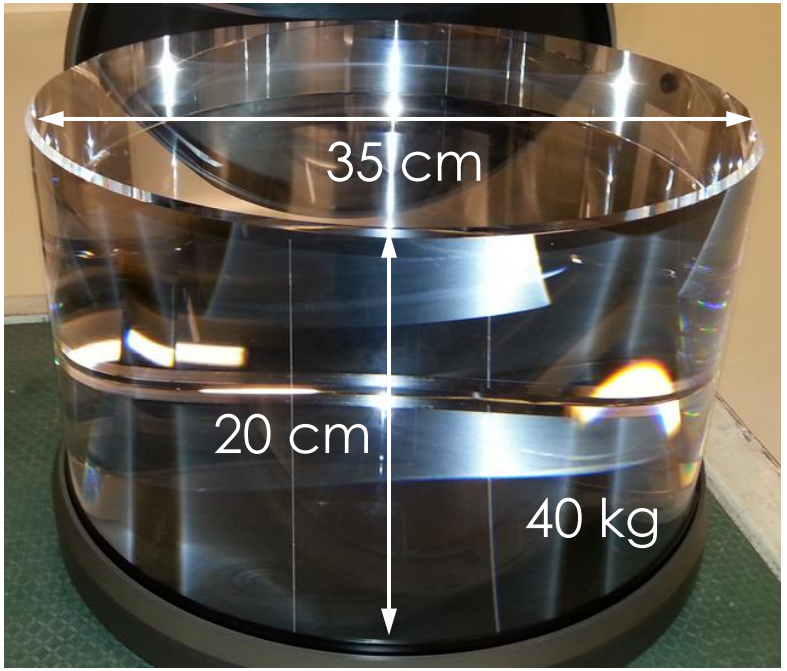
test masses

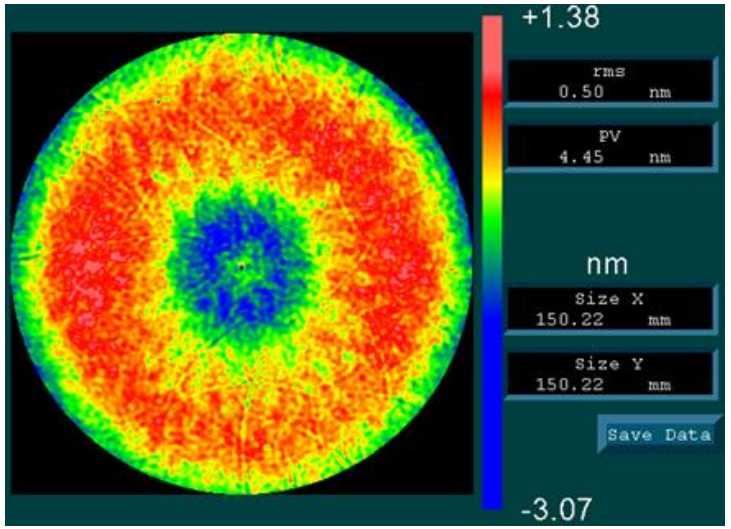
ultra-pure fused silica substrates

high-reflection coatings

TiO2Ta2O5/SiO2 Bragg mirrors

aLIGO, AdVIRGO and soon KAGRA test masses coated @ LMA



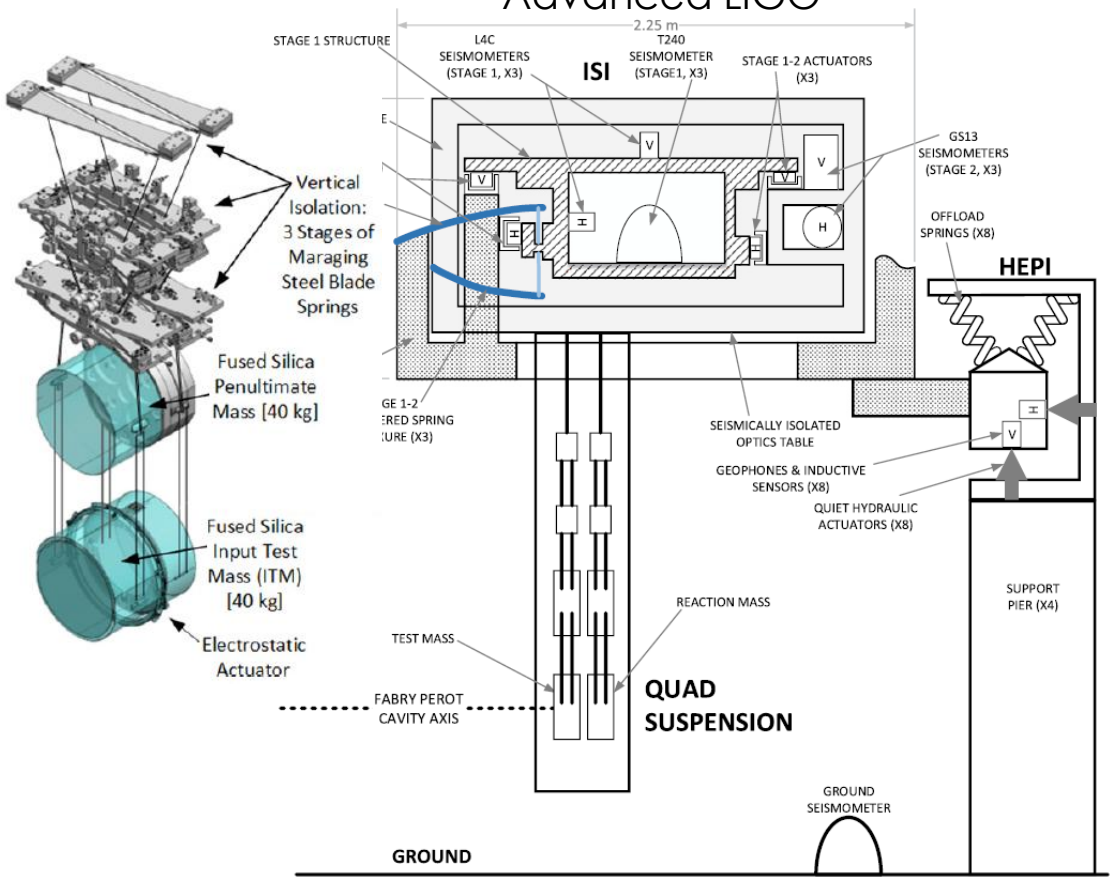


Advanced VIRGO EM01

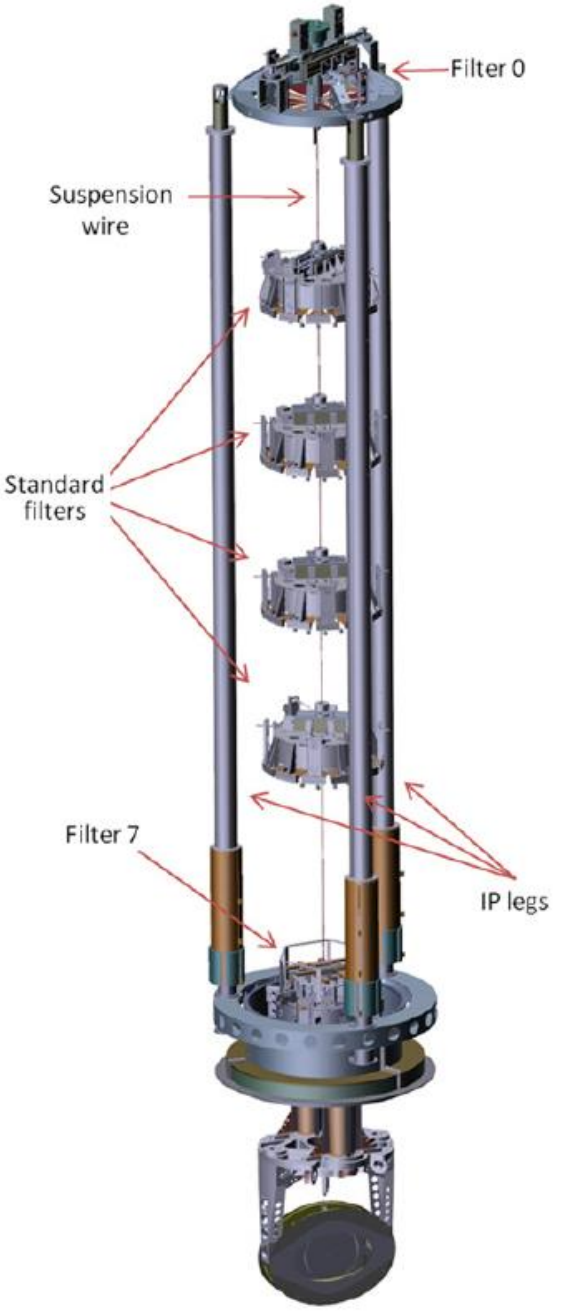
suspensions

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

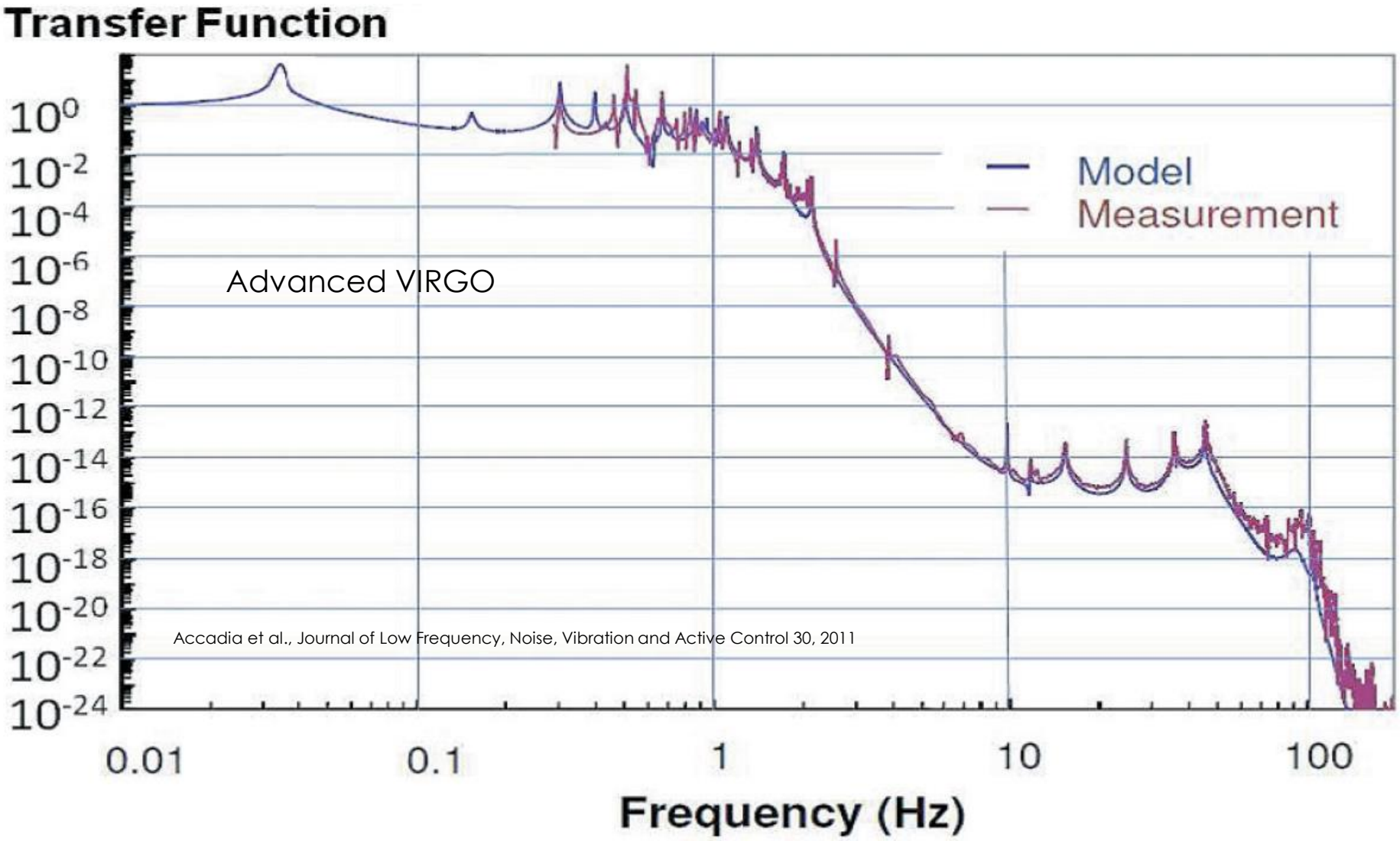
Advanced LIGO



Advanced VIRGO

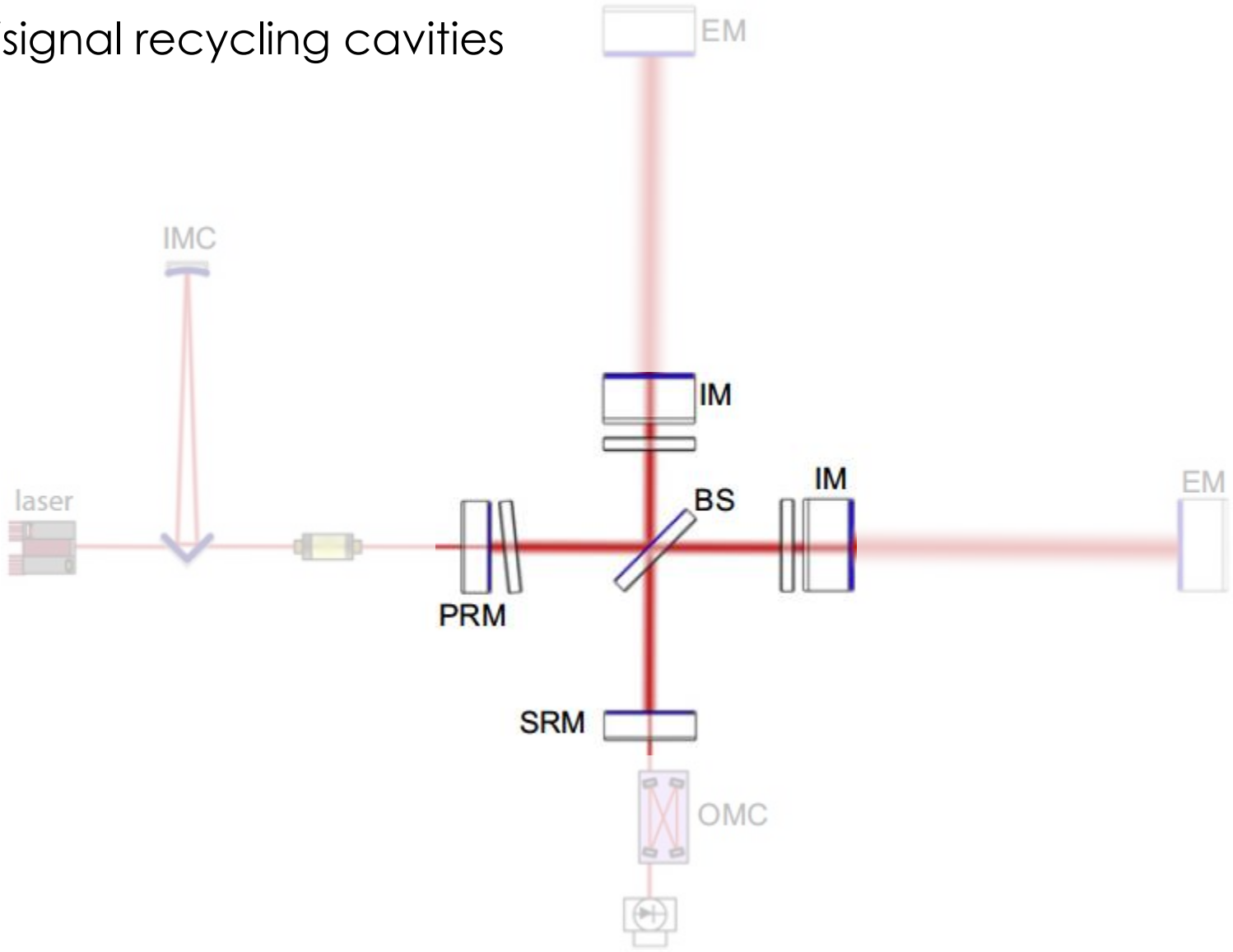


suspensions



optical layout

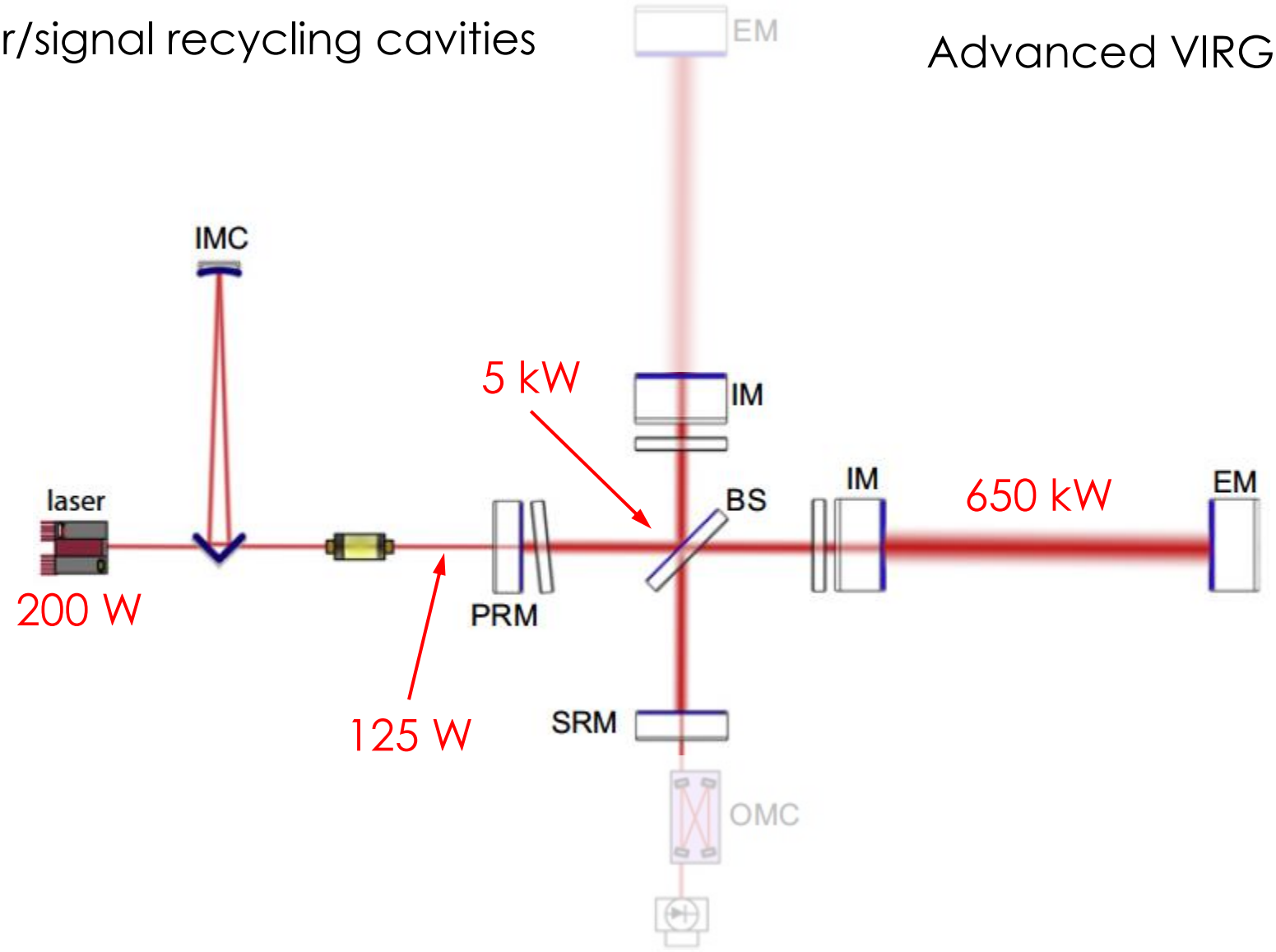
power/signal recycling cavities



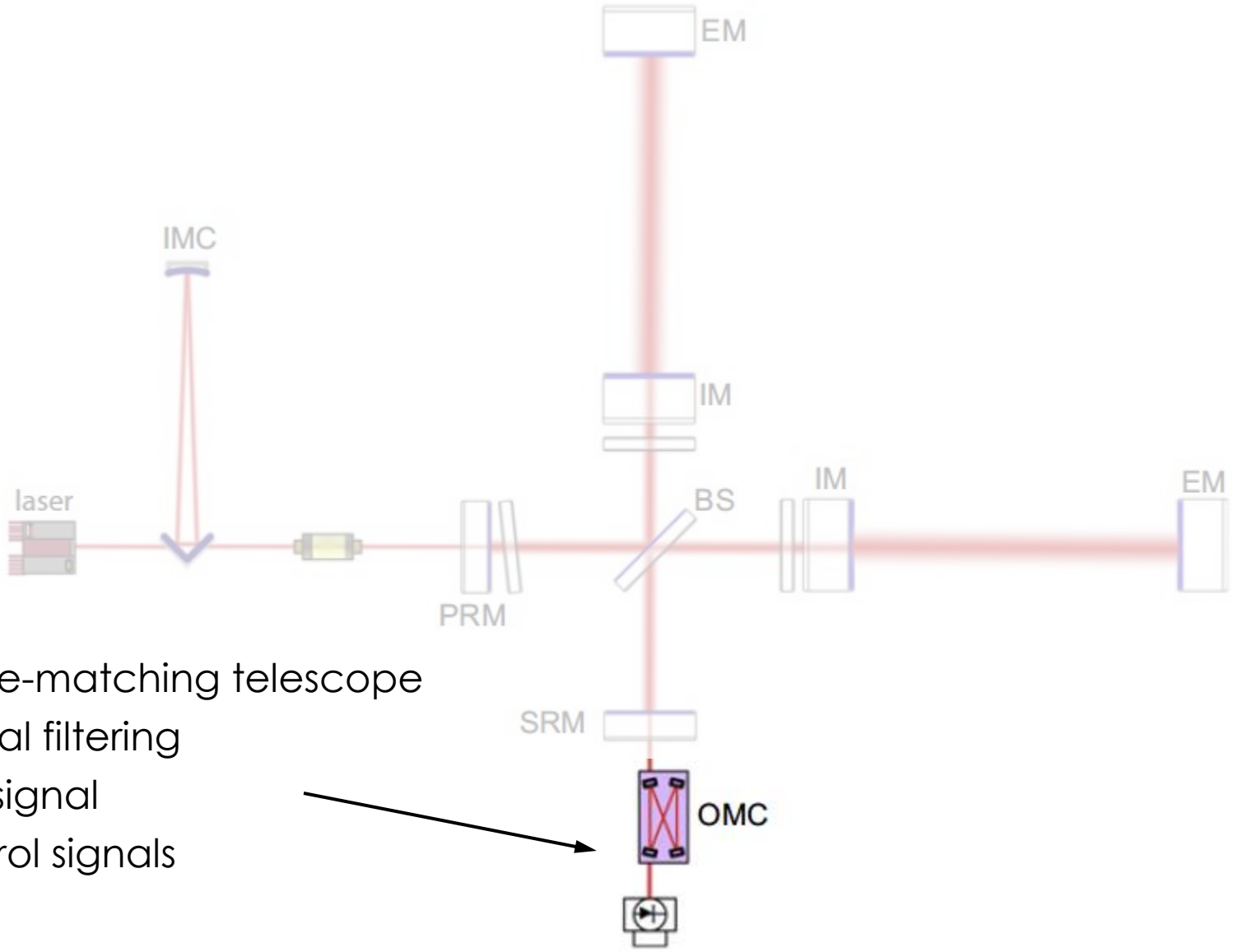
optical layout

power/signal recycling cavities

Advanced VIRGO



detection

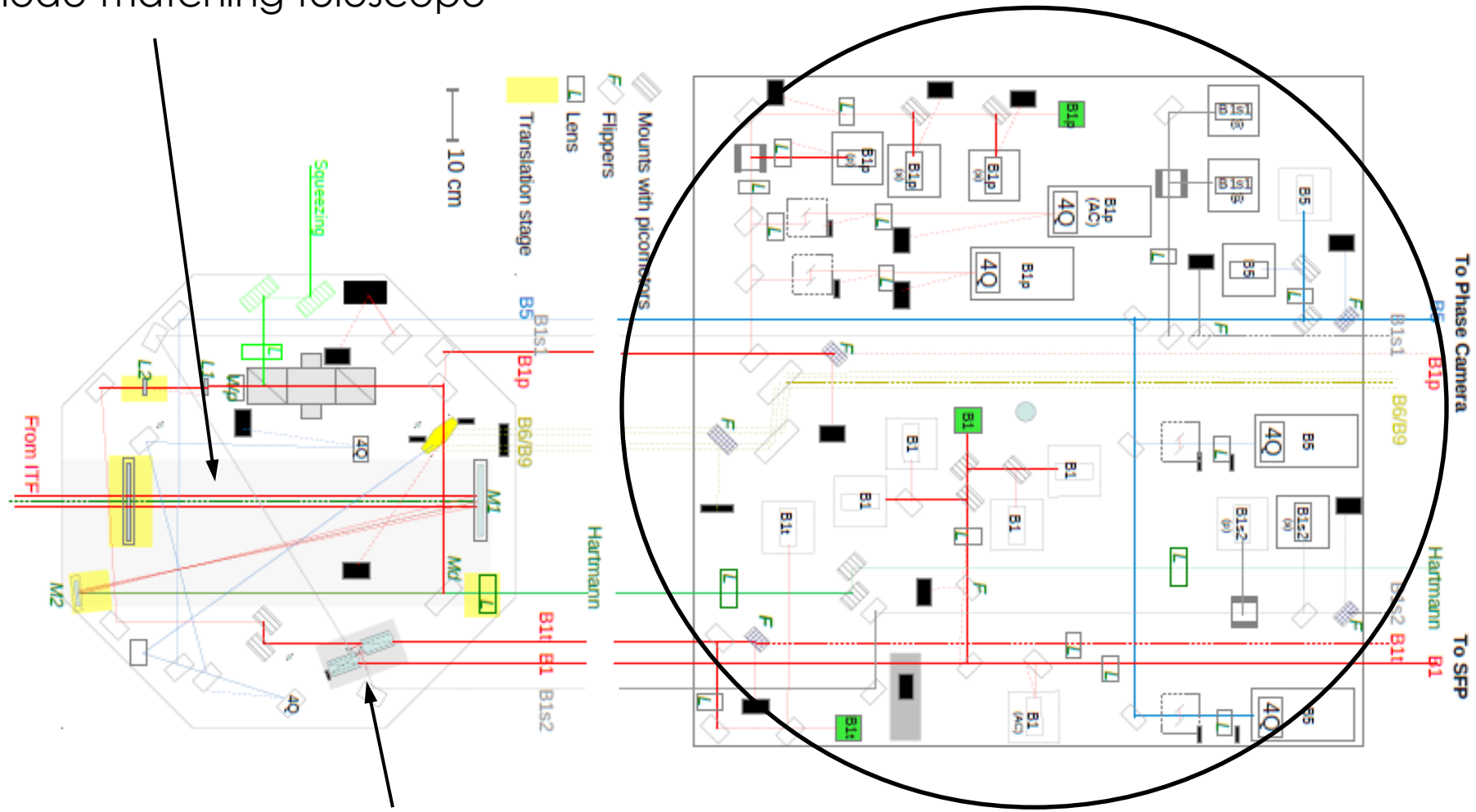


- mode-matching telescope
- spatial filtering
- GW signal
- control signals

detection

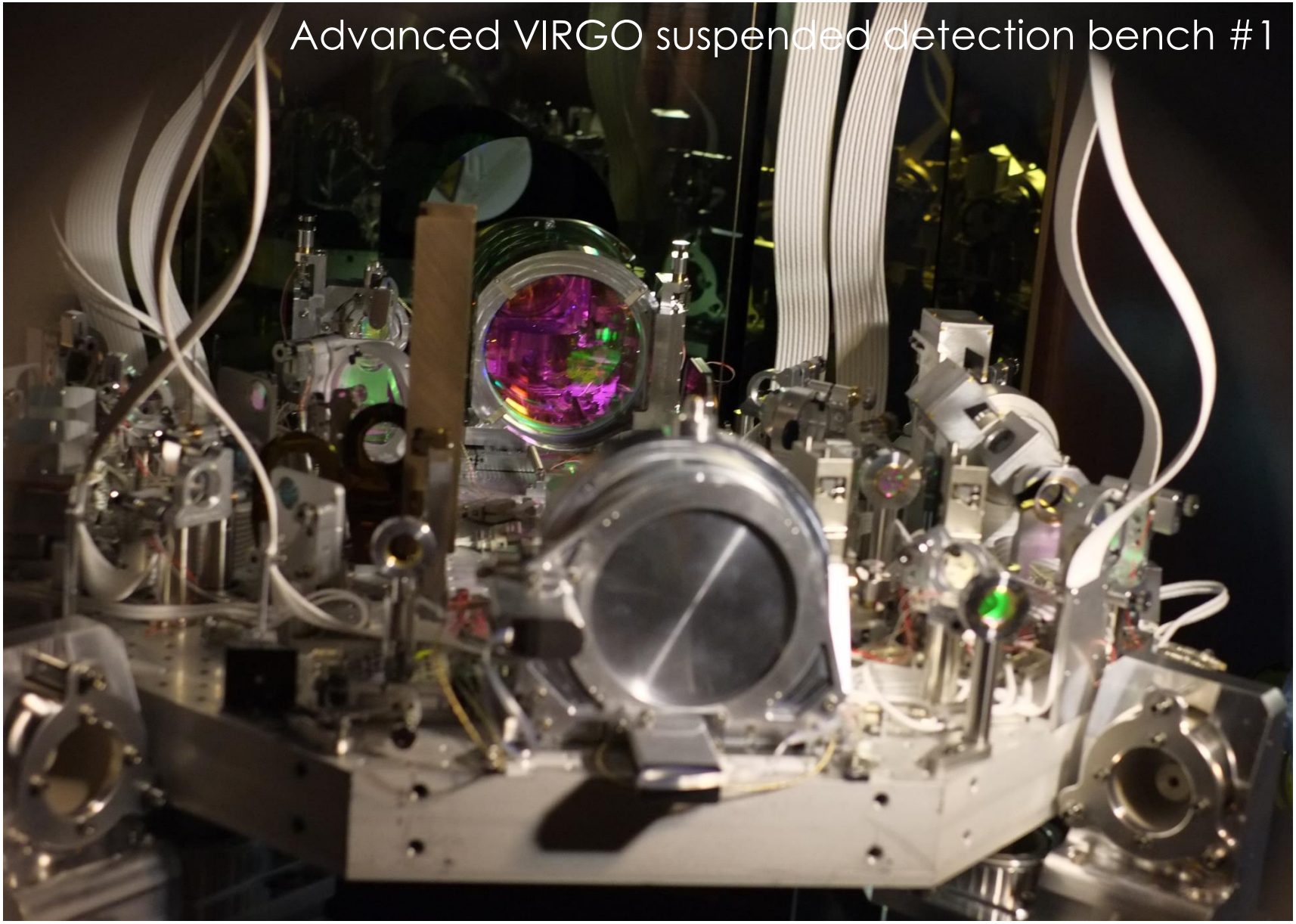
mode-matching telescope

photodiodes / wavefront sensors

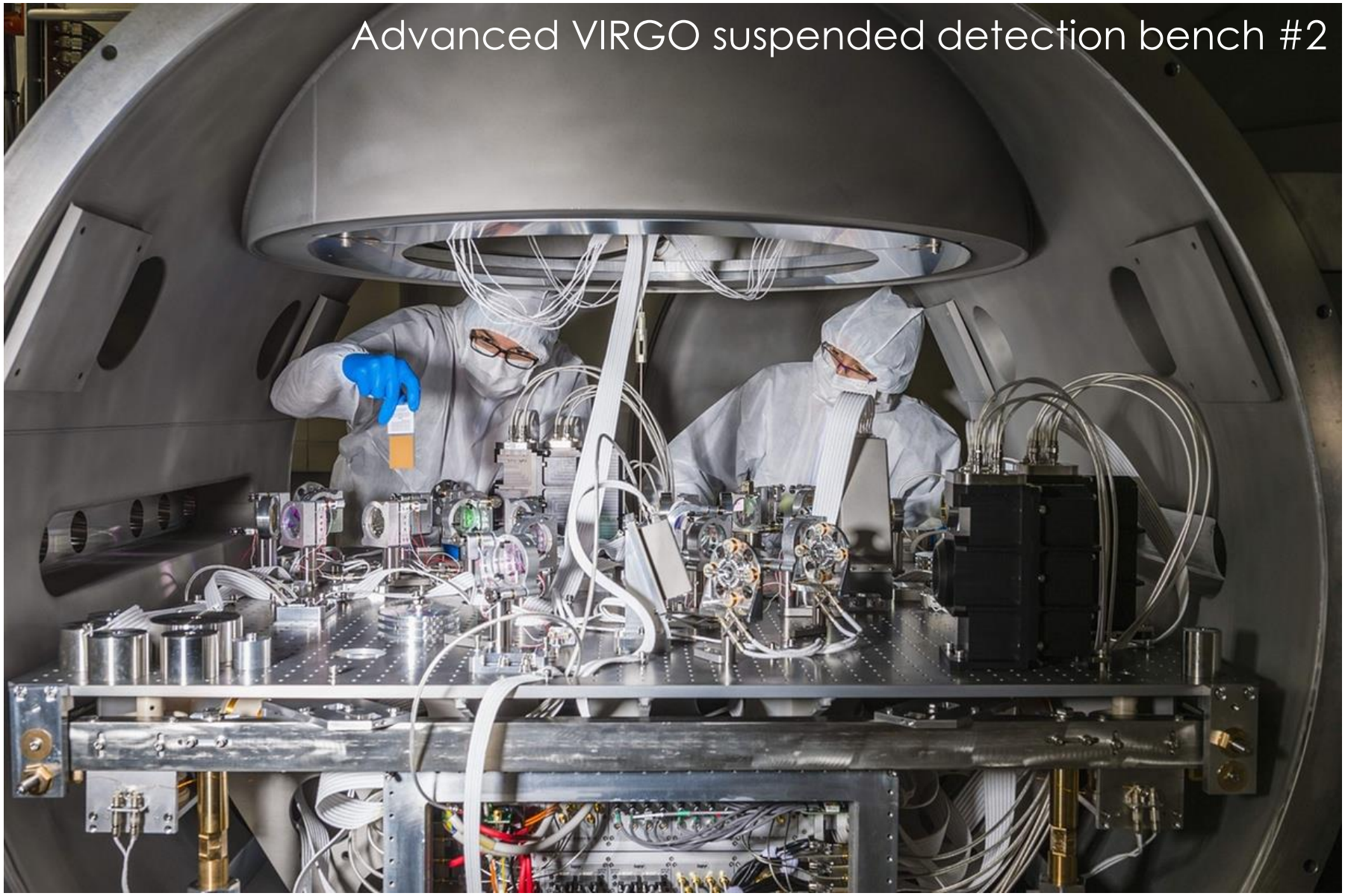


2 coupled output mode cleaners

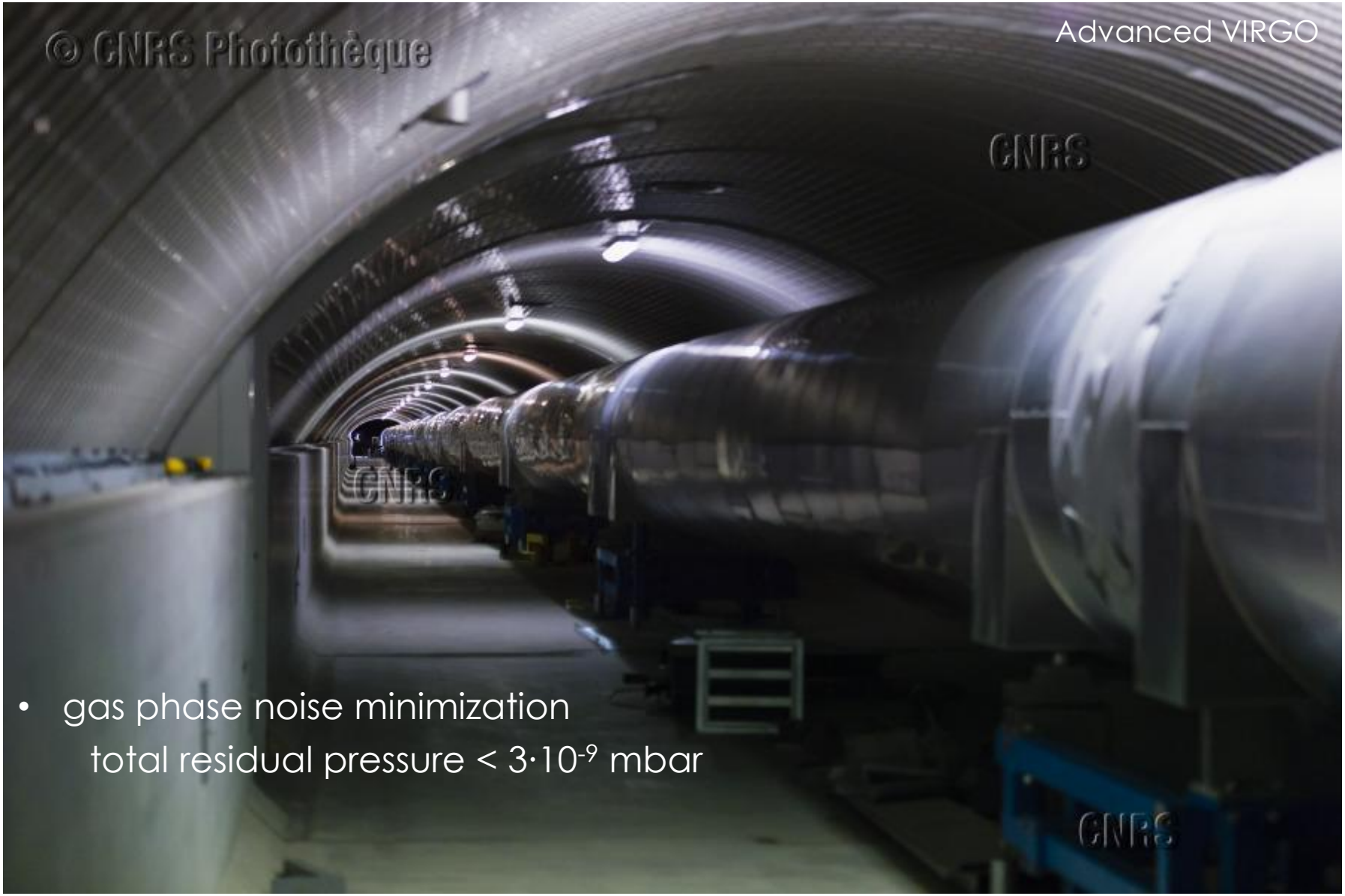
detection



detection

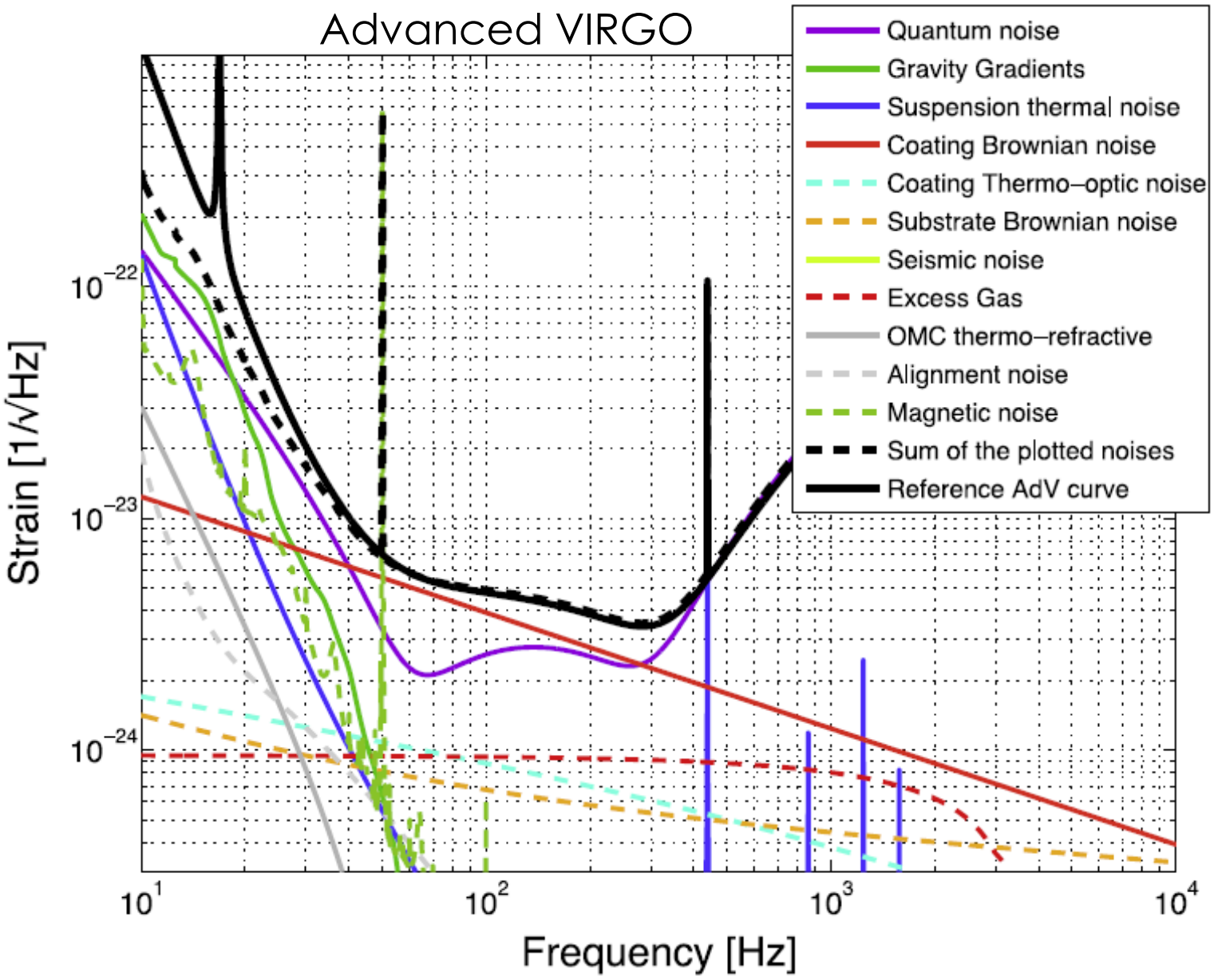


vacuum

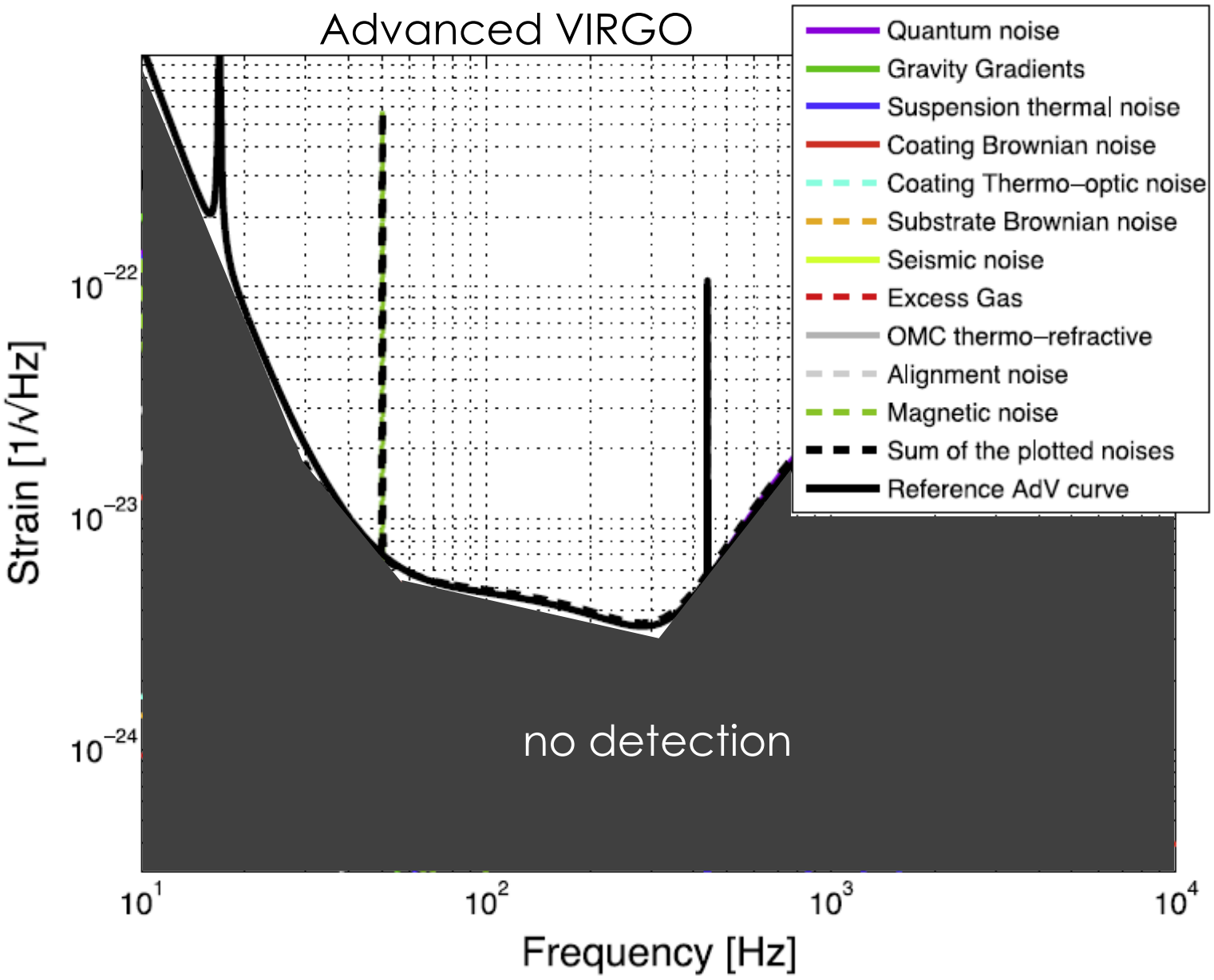


- gas phase noise minimization
  total residual pressure < $3 \cdot 10^{-9}$ mbar

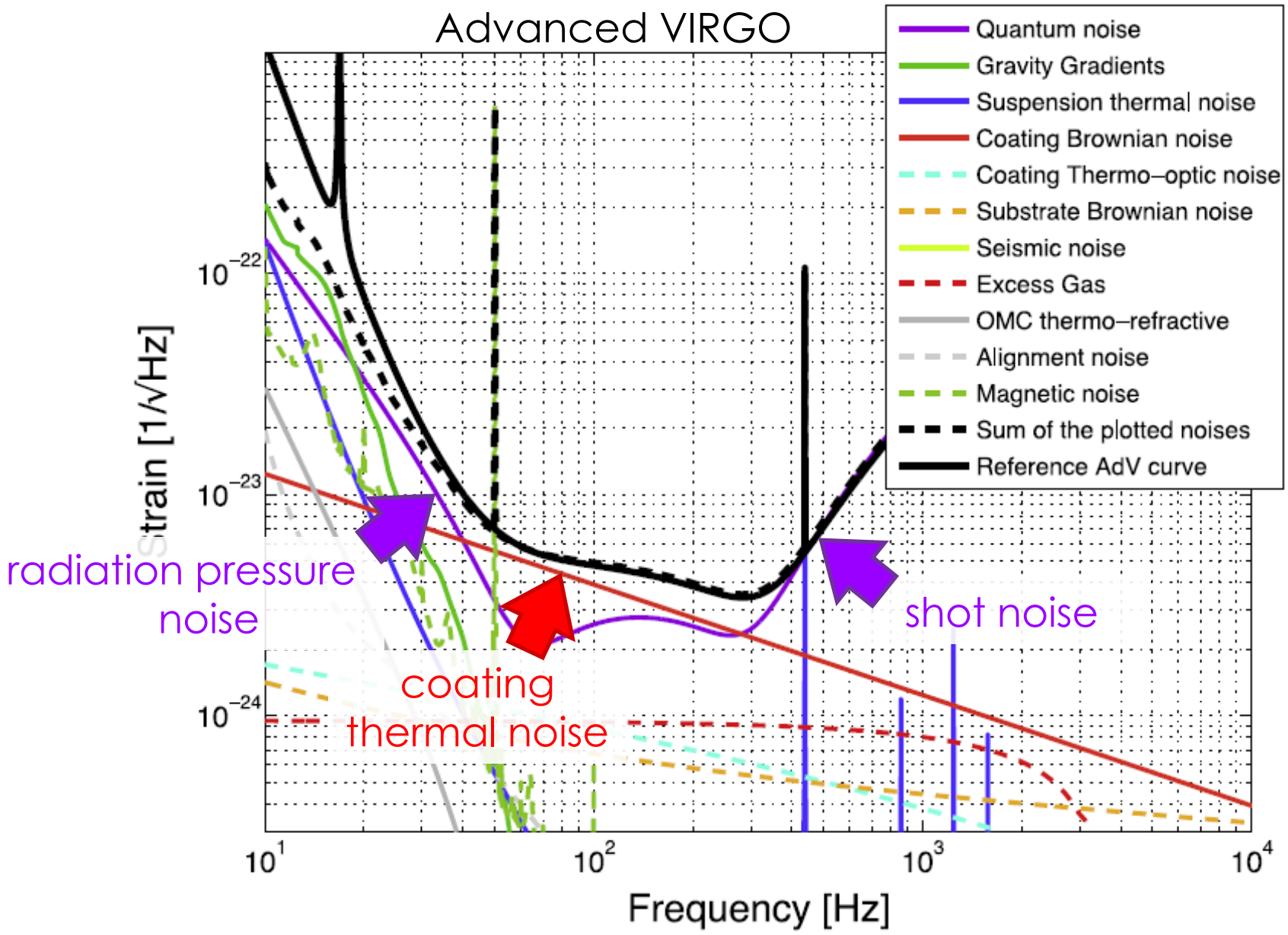
sensitivity



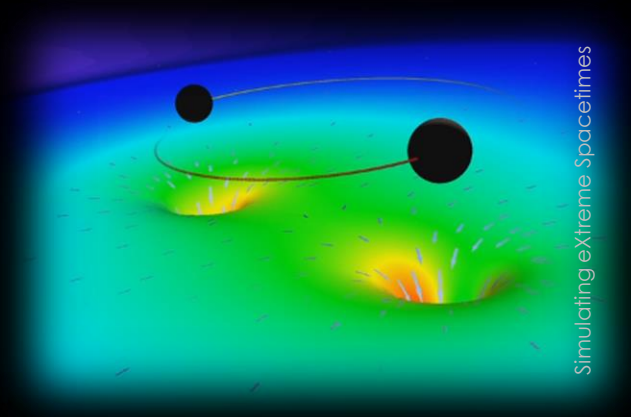
sensitivity



sensitivity



astrophysical sources

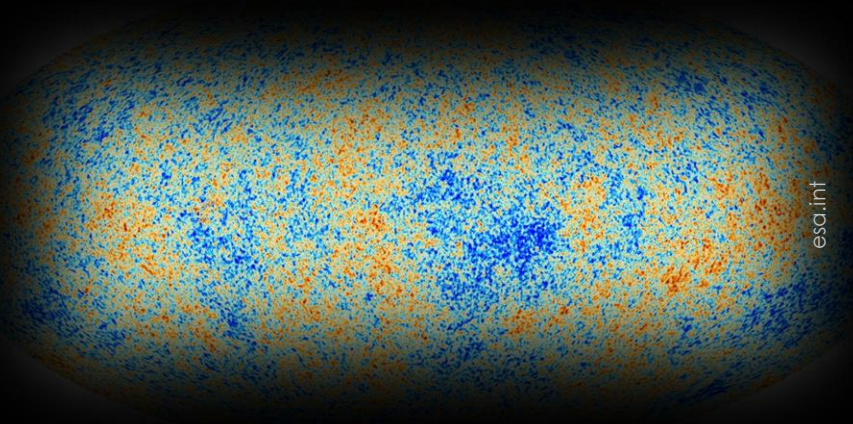


coalescing binaries

[neutron stars / black holes]

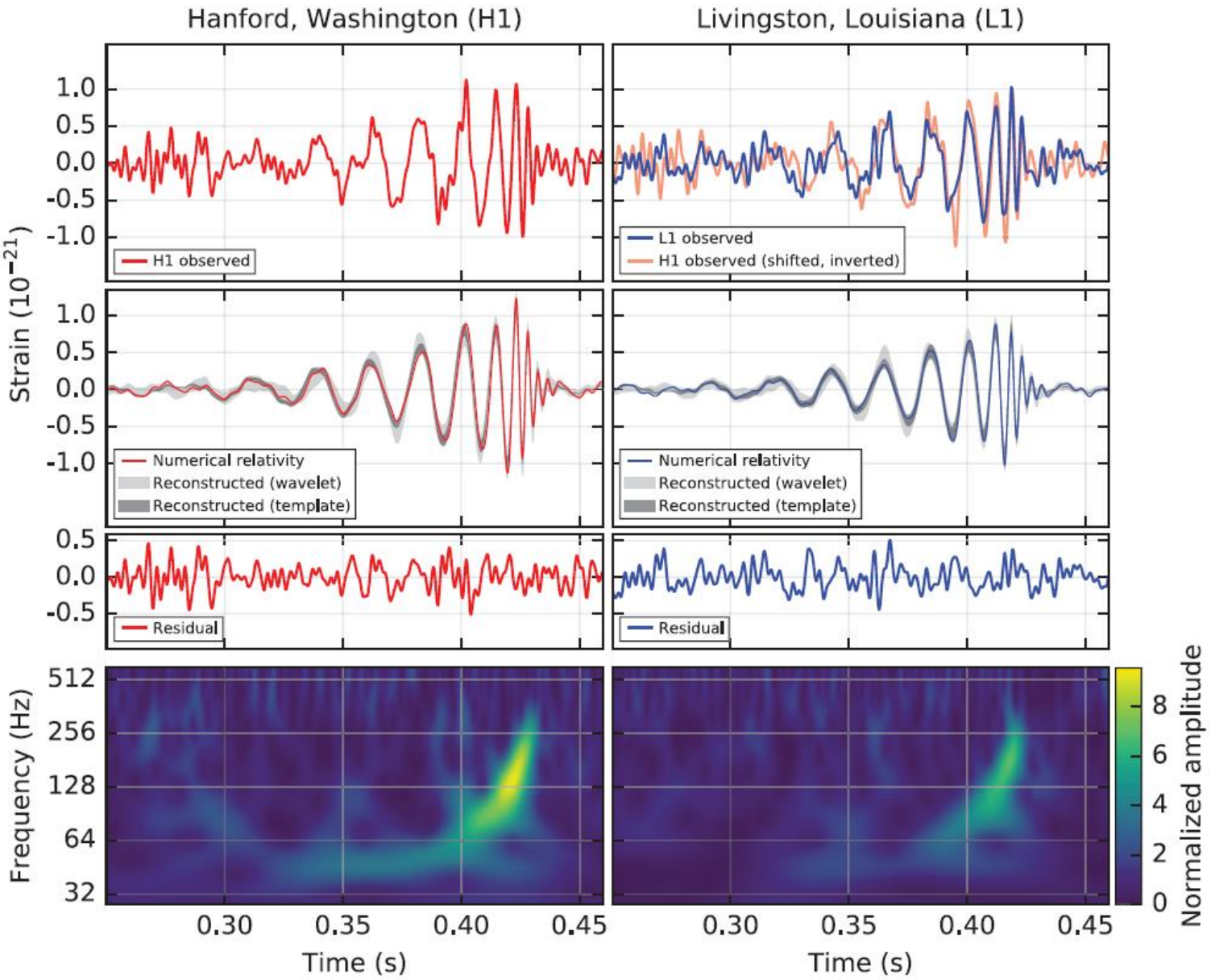
pulsars

supernovae

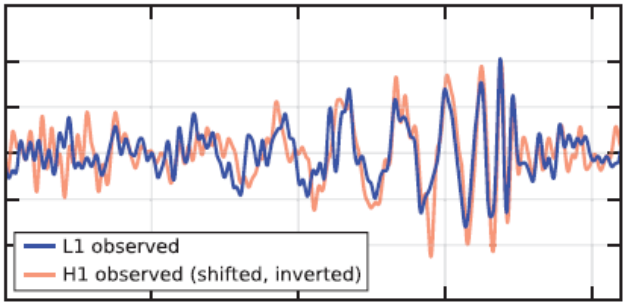


stochastic background

Sep 14, 2015 09:50:45 UTC



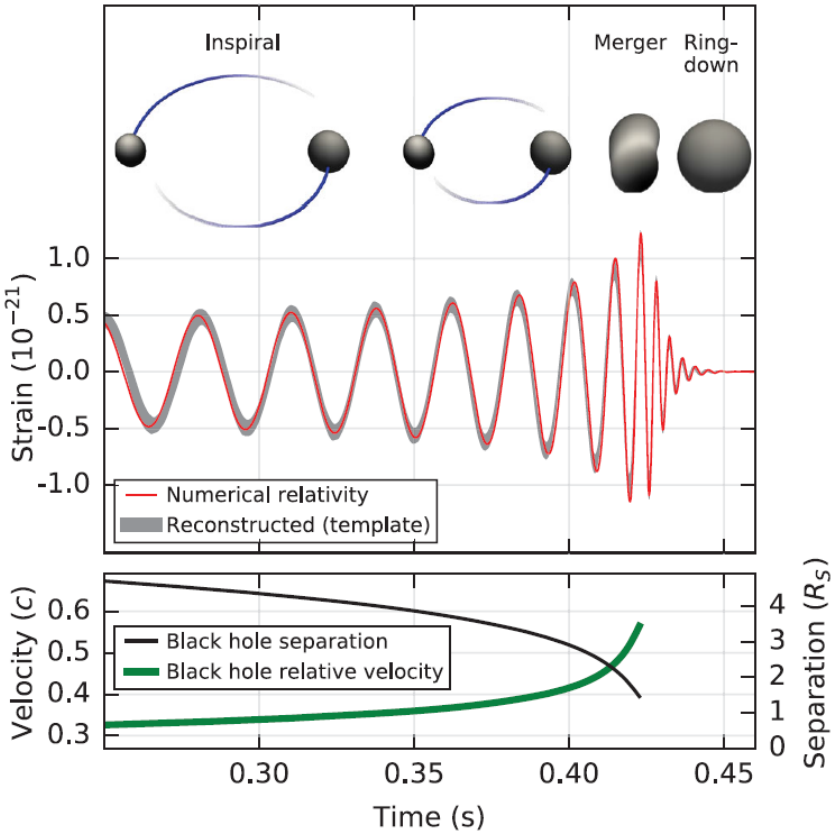
a black-hole binary



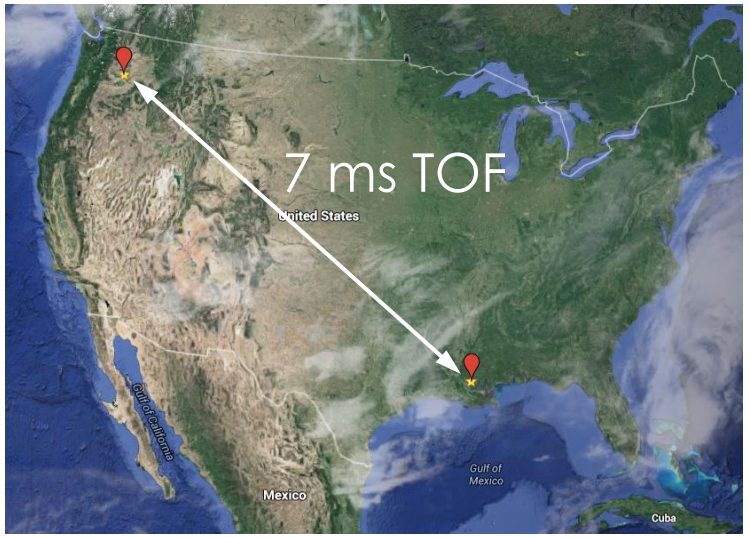
f_{GW} = 35 → 150 Hz over 0.2 s

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

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



detection case



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

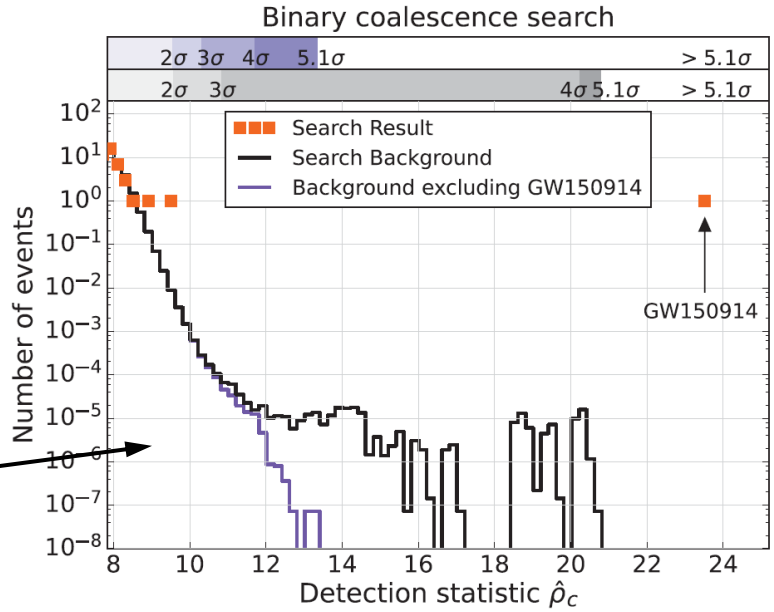
  ~$2 \cdot 10^5$ auxiliary channels

  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

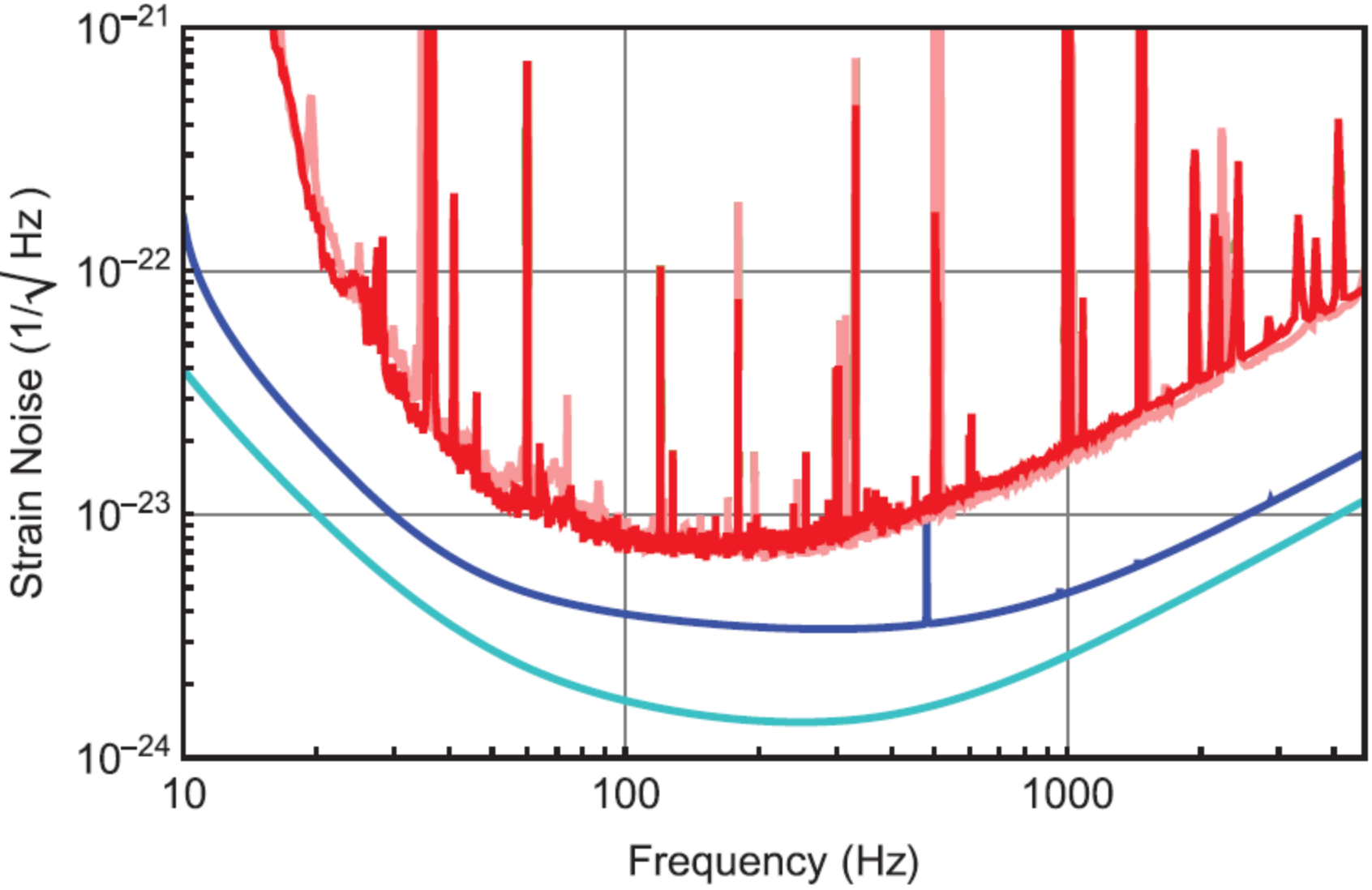
the most luminous event ever detected

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

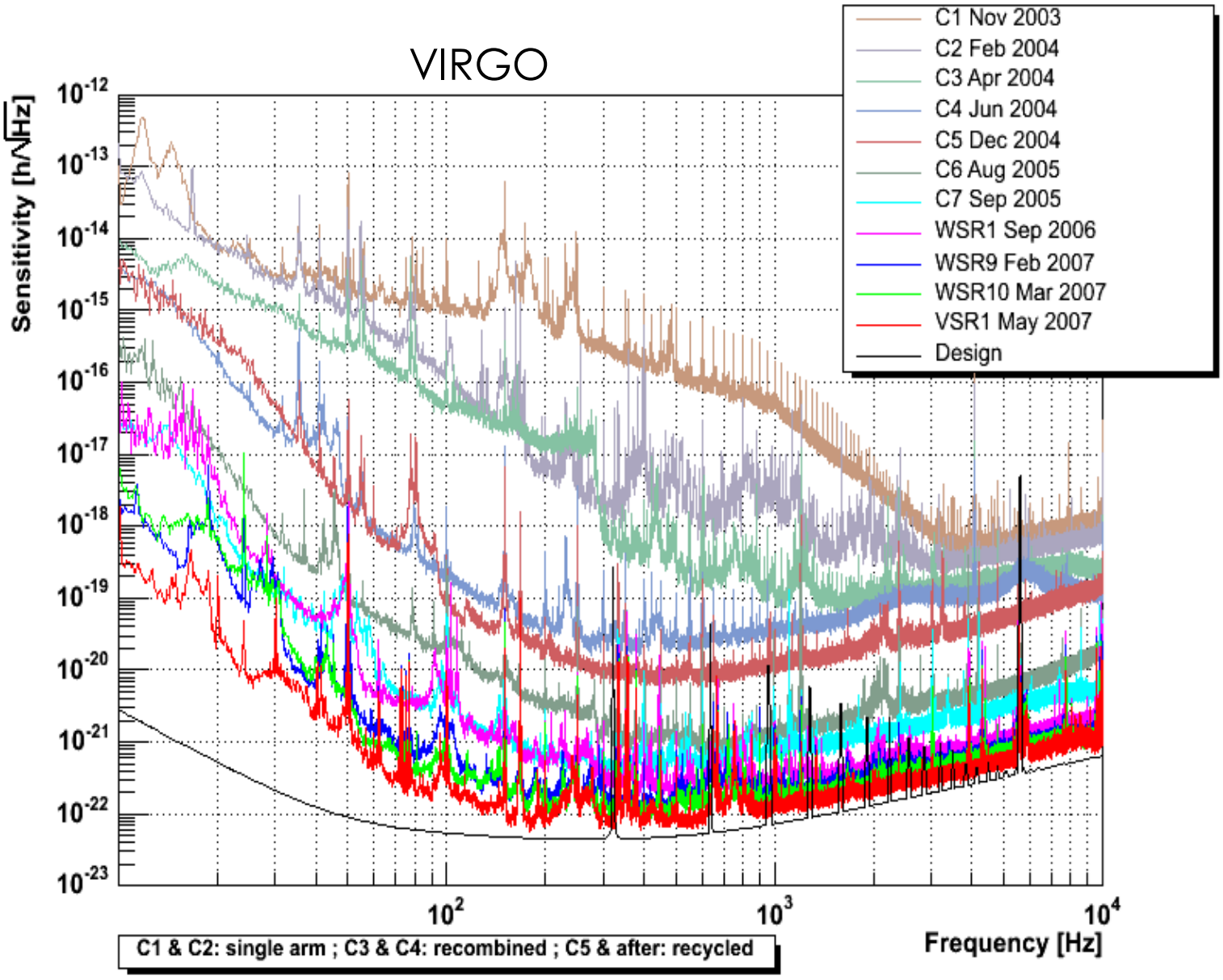
the beginning of GW astronomy

outlook

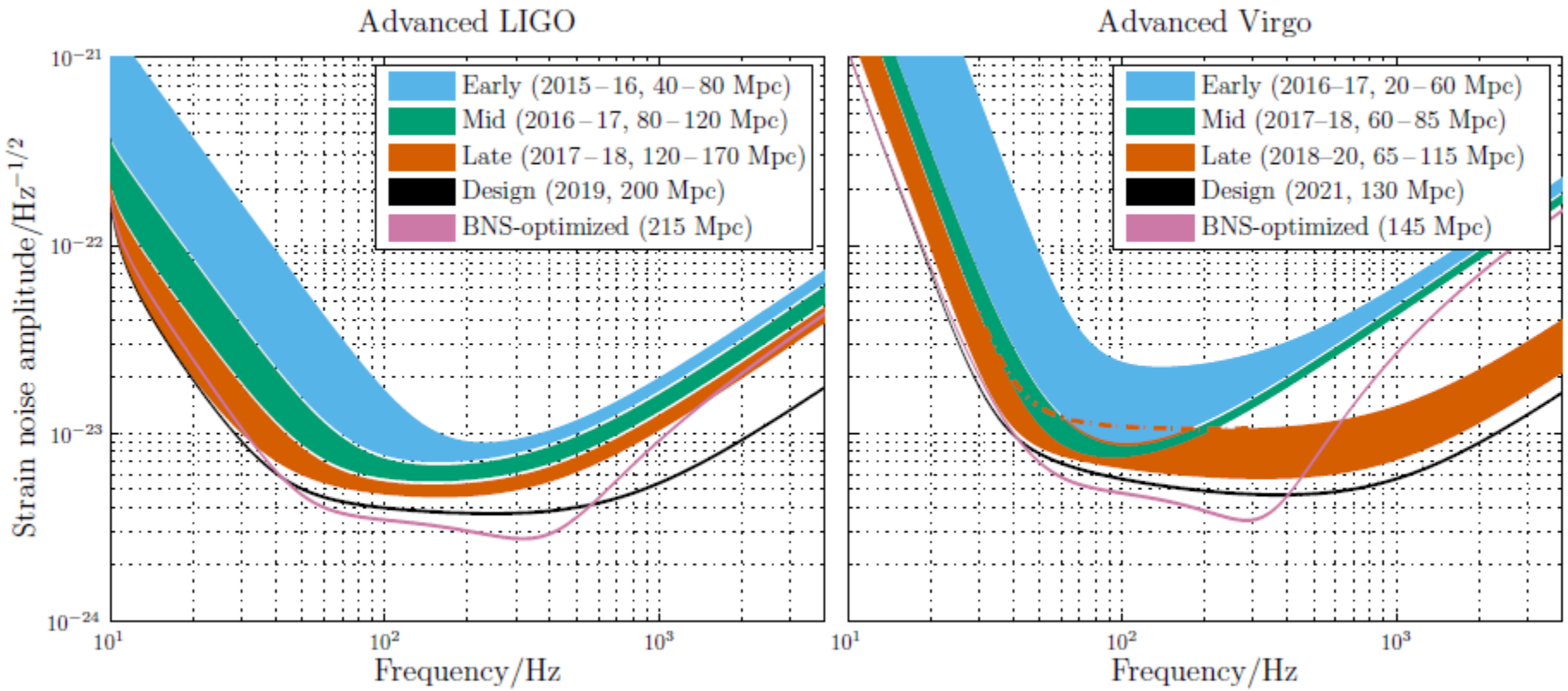
next steps


10^{-21}
10^{-22}
10^{-23}
10^{-24}
Strain Noise ($1/\sqrt{\text{Hz}}$)
10
100
1000
Frequency (Hz)

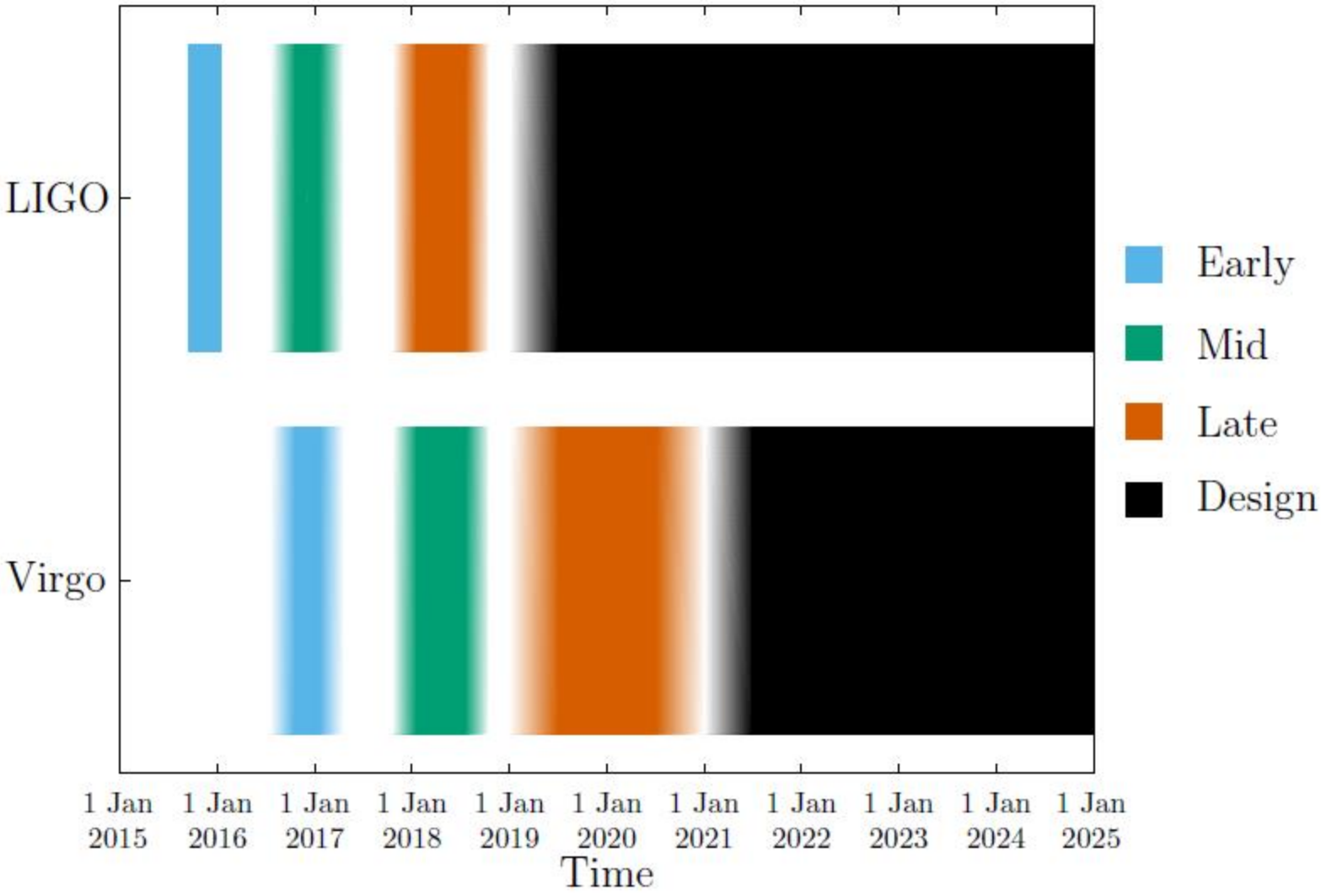
a long way down



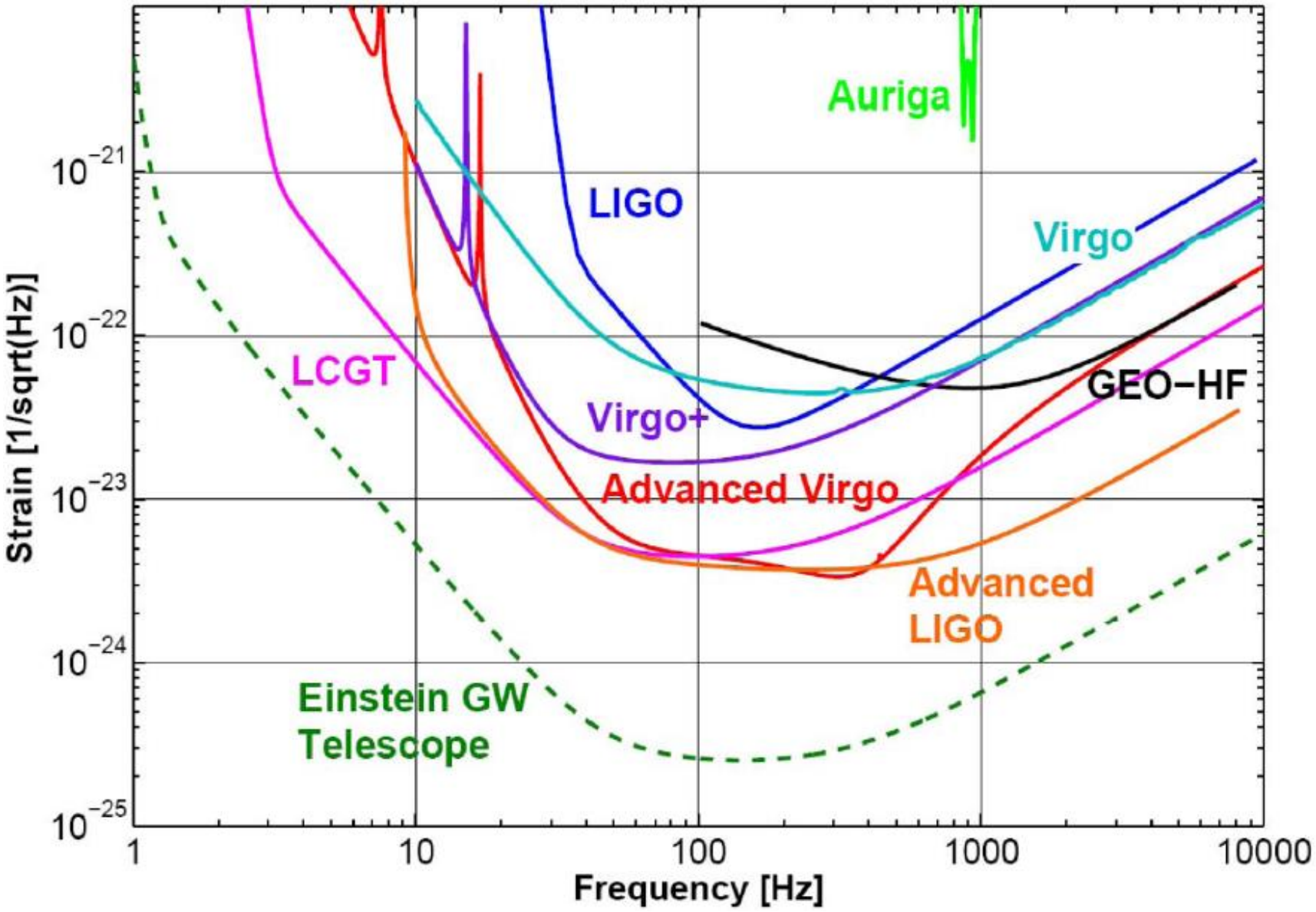
observing scenario



observing scenario



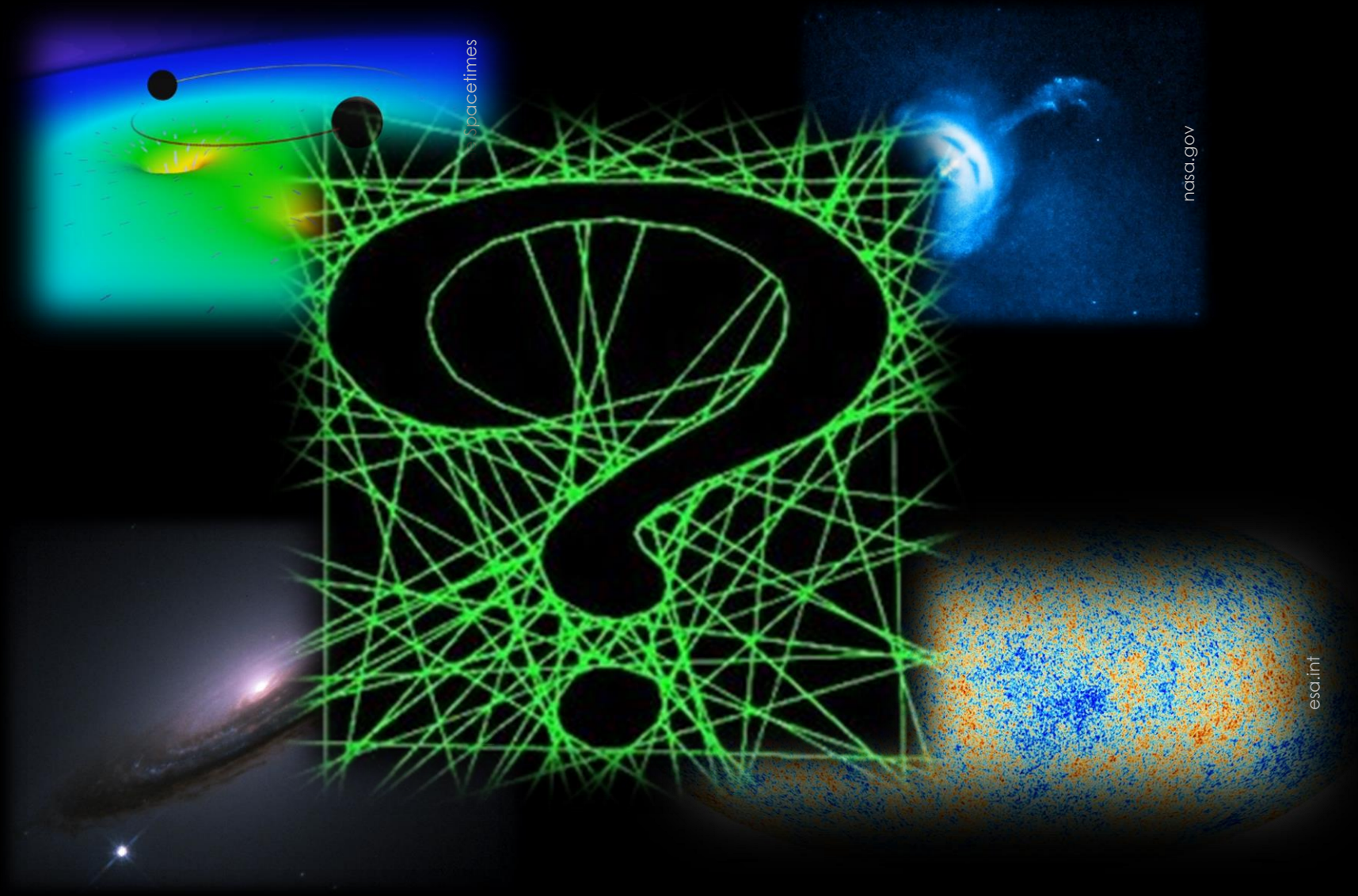
looking forward



the quest for the1st detection has ended

the observation of the gravitational Universe has just begun

astrophysical sources



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many thanks to

Jerôme Degallaix

Eric Chassande-Mottin

thank you for your attention

the GW spectrum