Gravitational Waves and Interferometers on the Earth

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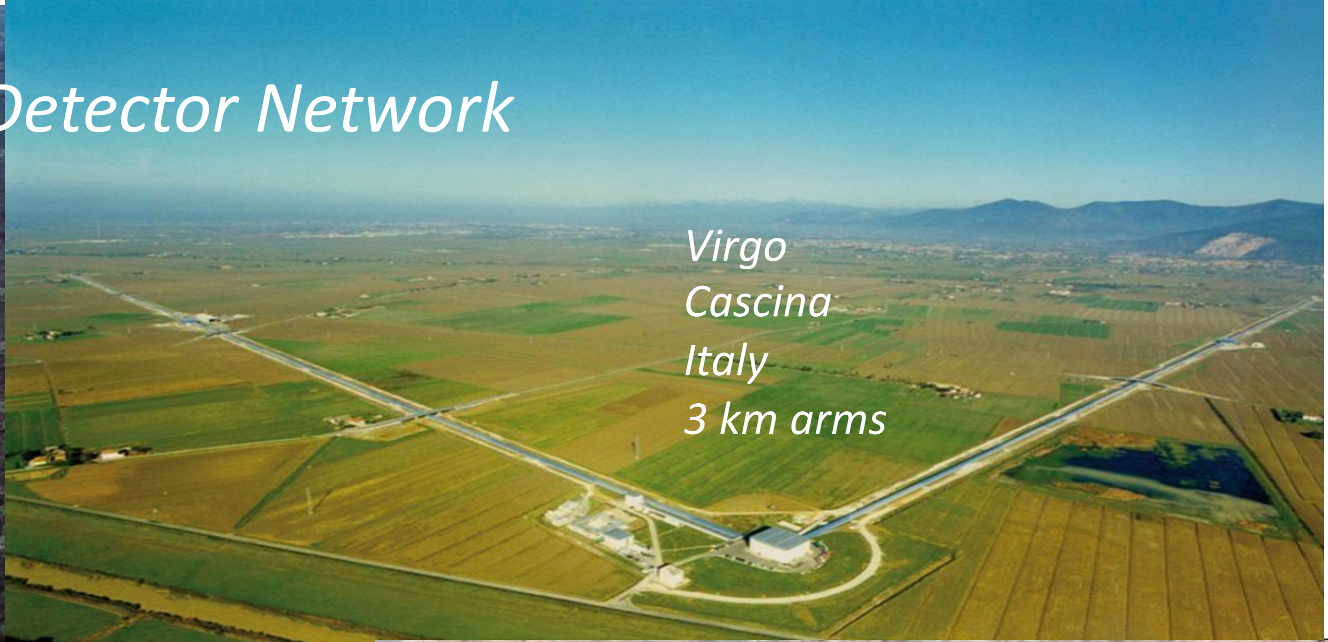
on behalf of the Virgo collaboration

Talk Outline

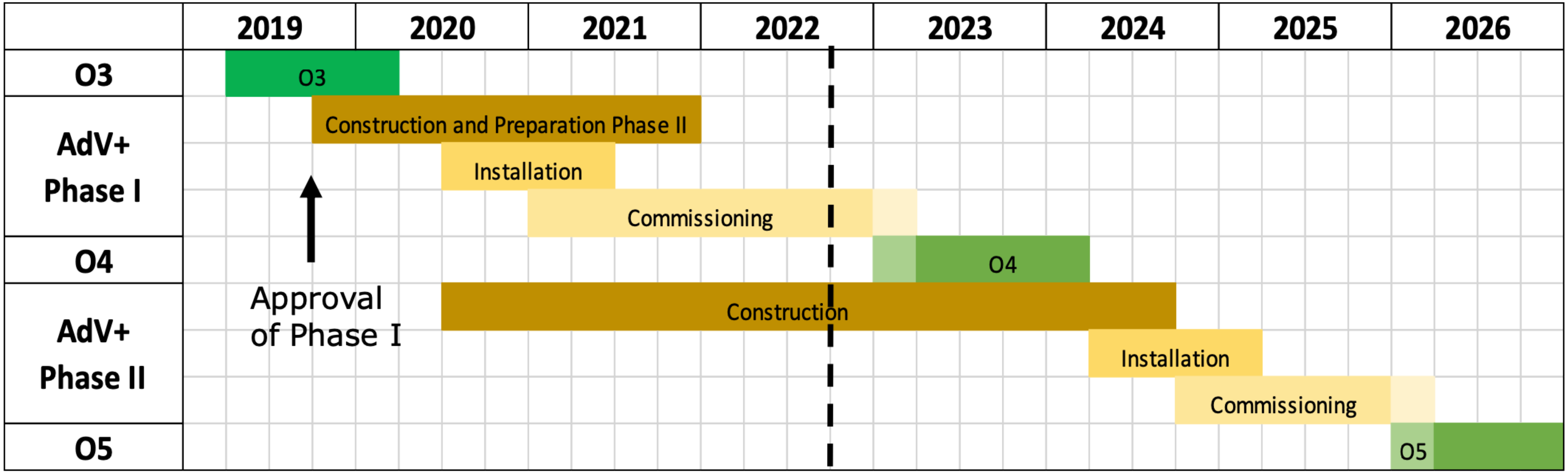
- News on GW detectors
  - LIGO
  - Virgo
  - KAGRA
- Highlights on GW discoveries and… new misteries
- Future evolution of the GW detectors in the next decade
- Conclusions

News on the GW detectors

The Global GW Detector Network



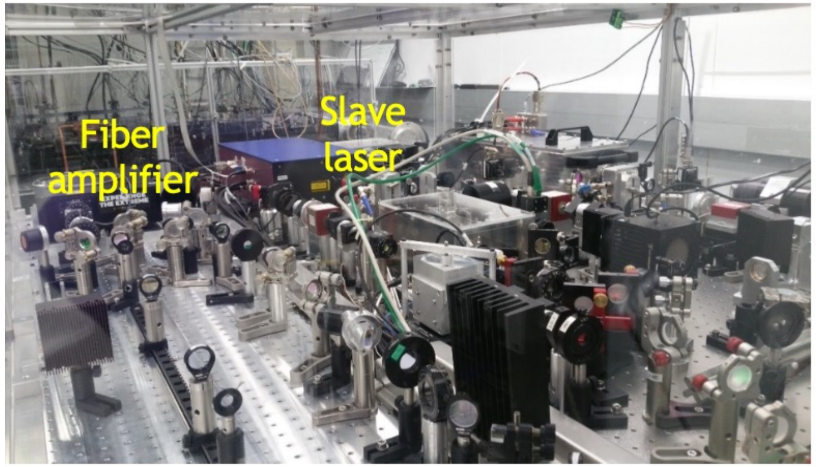
Advanced Virgo + : a two steps project

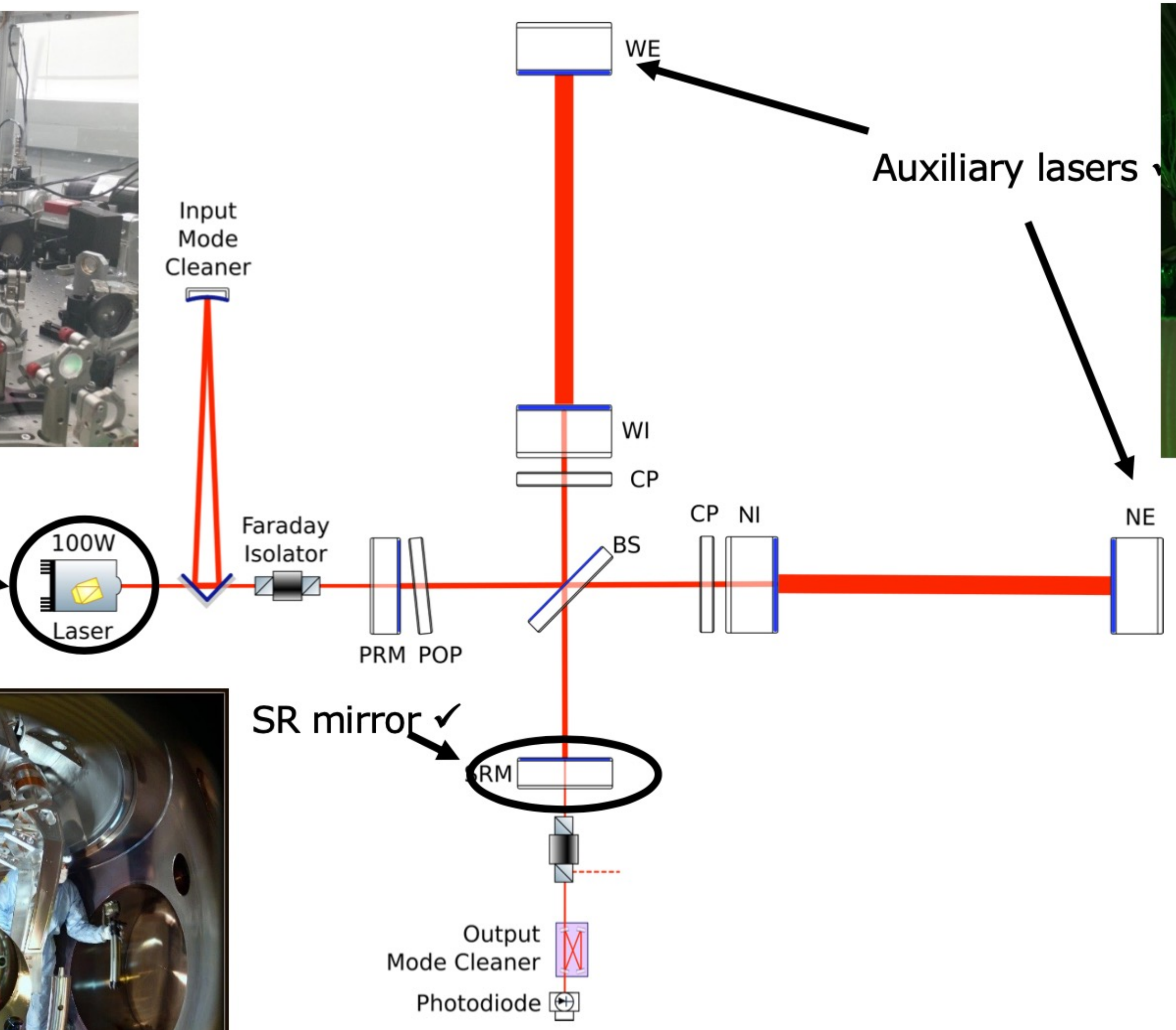


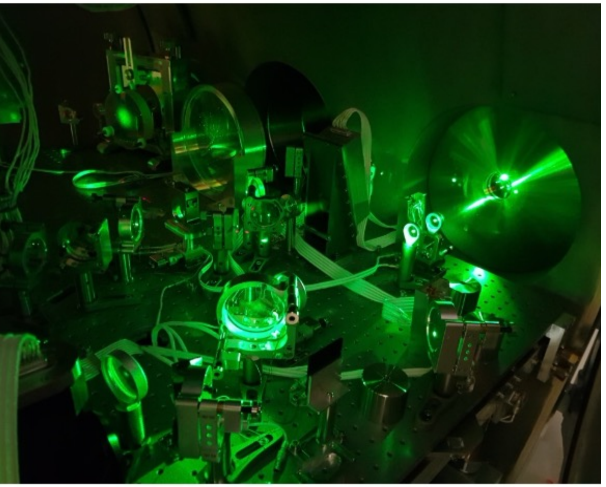
Phase I:
reduce quantum noise, hit against thermal noise. BNS range: 100 Mpc’s

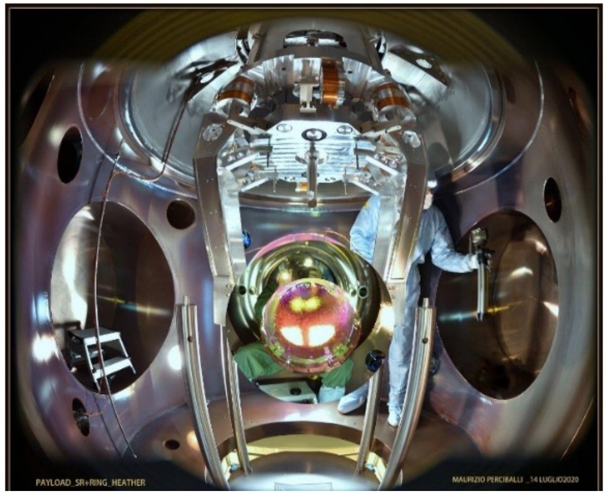
Phase II:
lower the thermal noise wall. BNS range: 200 Mpc’s or more

AdV+ Phase I: new experimental configuration - I



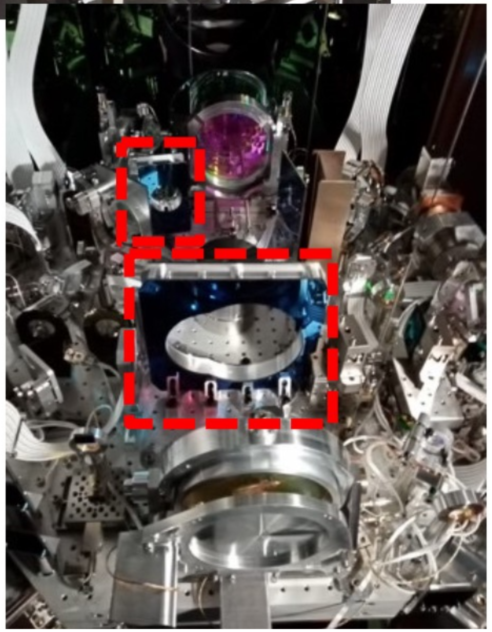






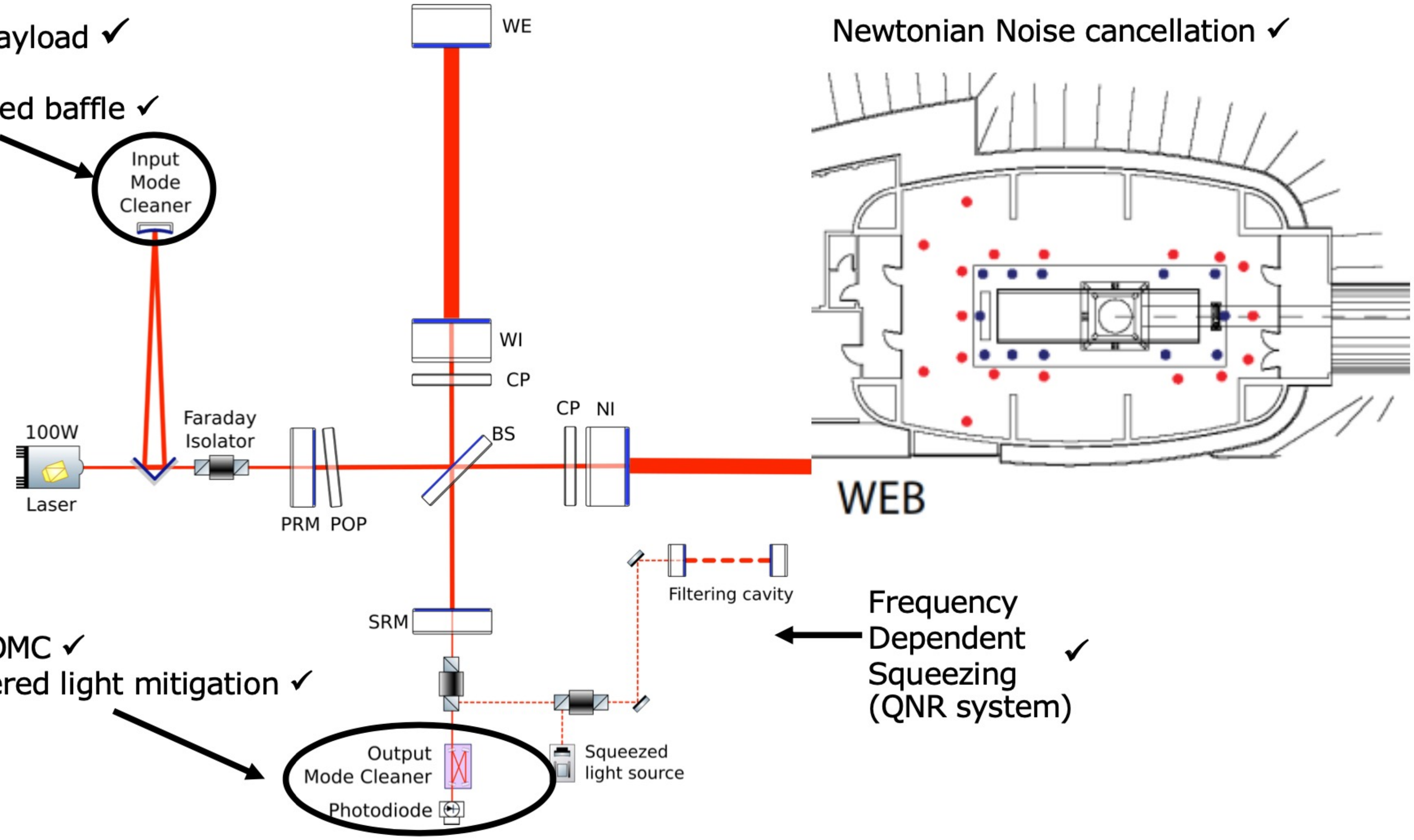
Credits: G. Losurdo

AdV+ Phase I: new experimental configuration - I I



New IMC payload ✓
+
Instrumented baffle ✓

Newtonian Noise cancellation ✓



New OMC ✓
Scattered light mitigation ✓

Frequency Dependent Squeezing (QNR system) ✓

Credits: G. Losurdo

Beating Quantum Noise and the Standard Quantum Limit

While shot noise contribution decreases with optical power, radiation pressure level increases:

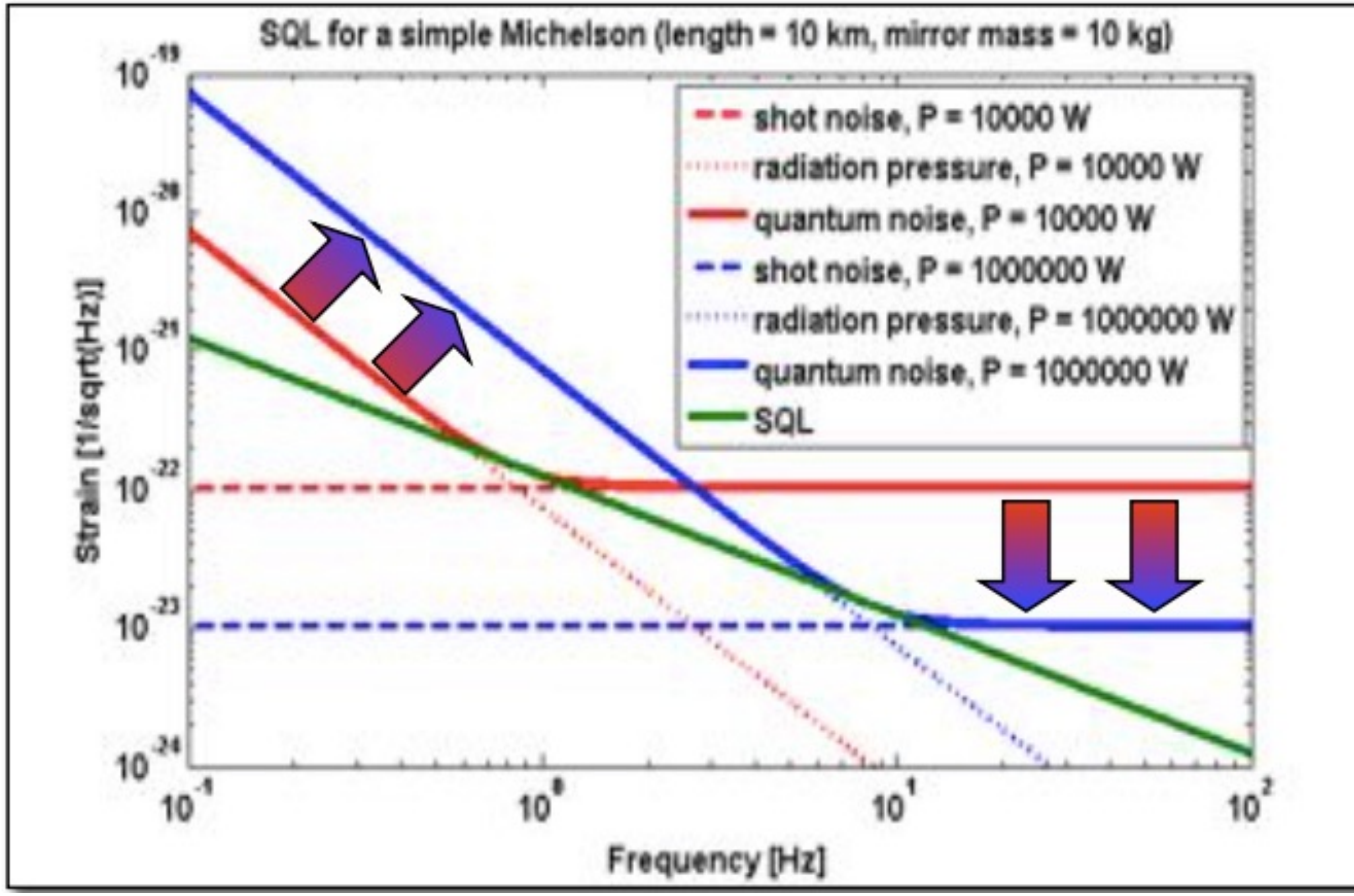
wavelength

$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

optical power

Mirror mass Arm length

$$h_{\mathrm{rp}}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$



- The SQL is the minimal sum of shot noise and radiation pressure noise
- Using a classical quantum measurement the SQL is the lowest achievable noise

V.B. Braginsky and F.Y. Khalili: Rev. Mod. Phys. 68 (1996)

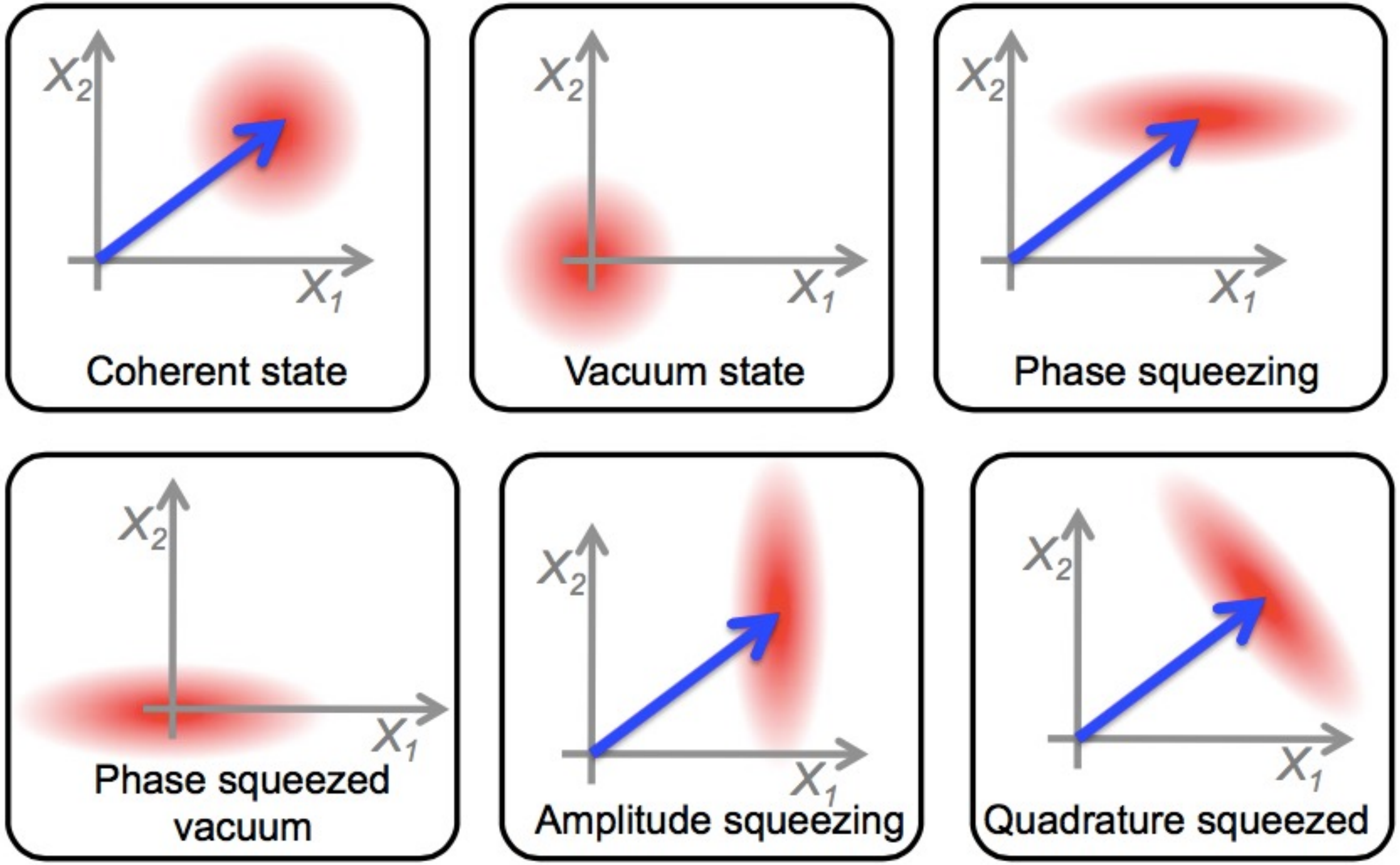
Quantum Interferometer with squeezed e.m. vacuum

- Electromagnetic fields are quantized:

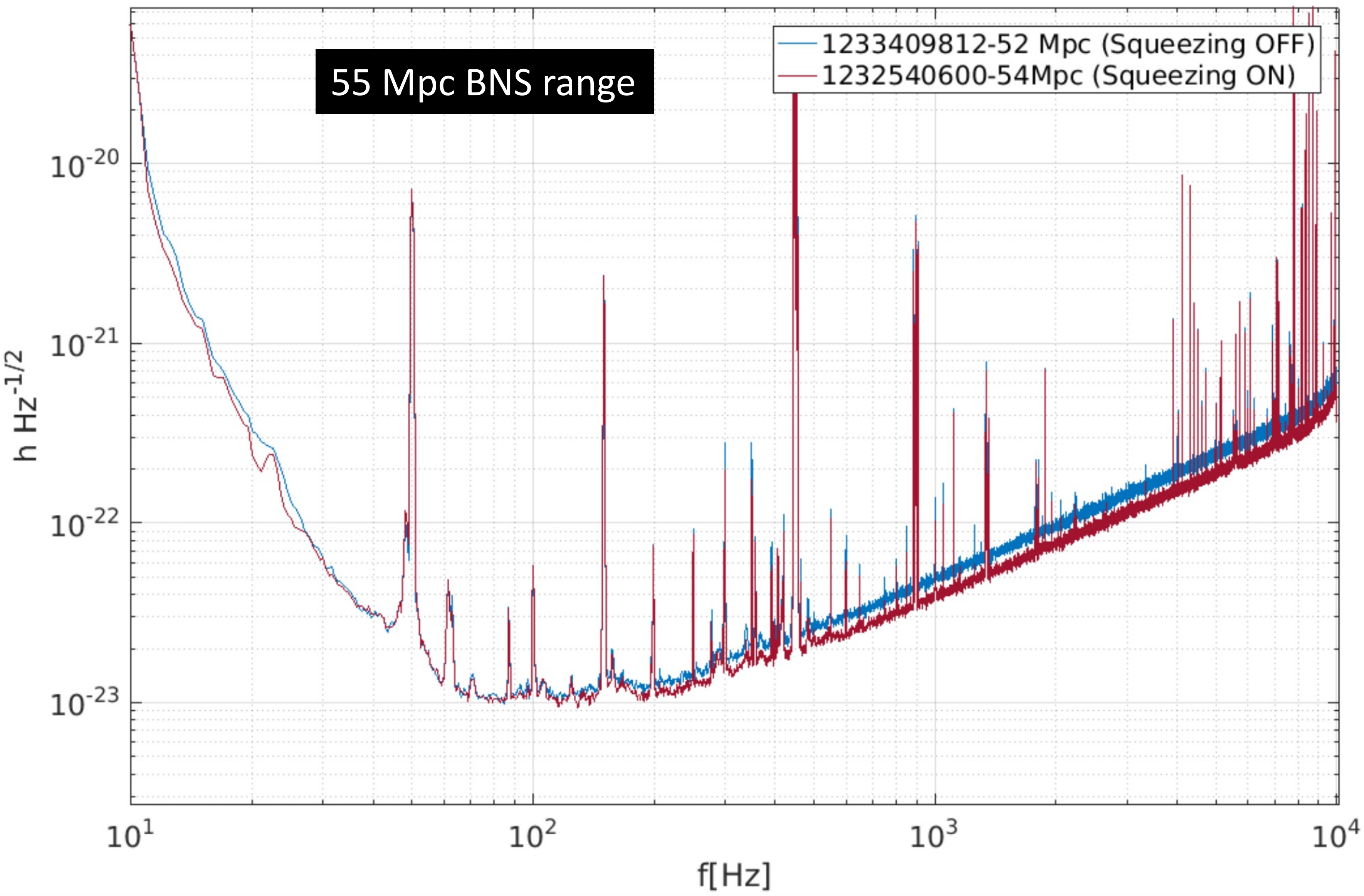
$$\hat{E} = \hat{X}_1 \cos\omega t + i\hat{X}_2 \sin\omega t$$

- Quantum fluctuations exist in the vacuum state:

$$\langle(\Delta\hat{X}_1)^2\rangle\,\langle(\Delta\hat{X}_2)^2\rangle \geq 1$$



Interferometer Sensitivity: Virgo

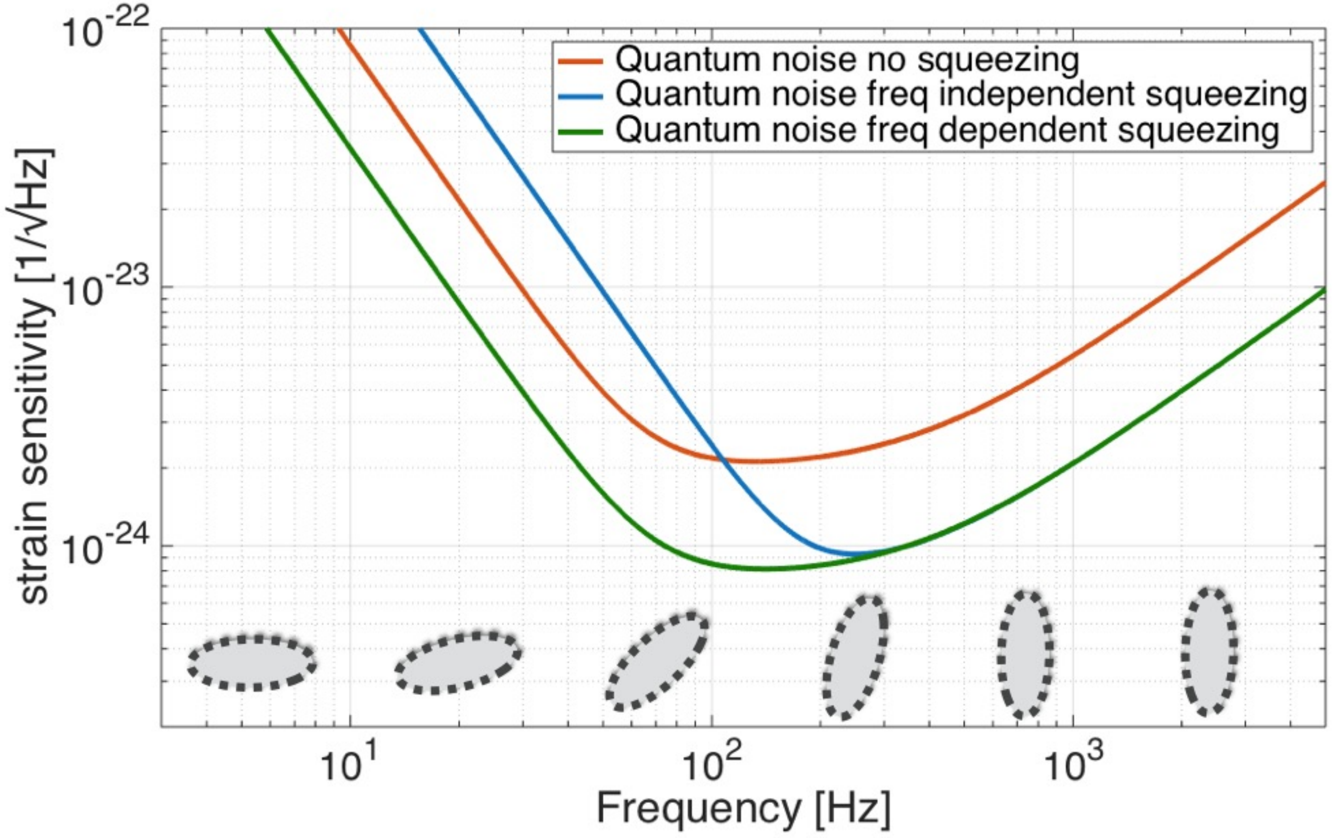


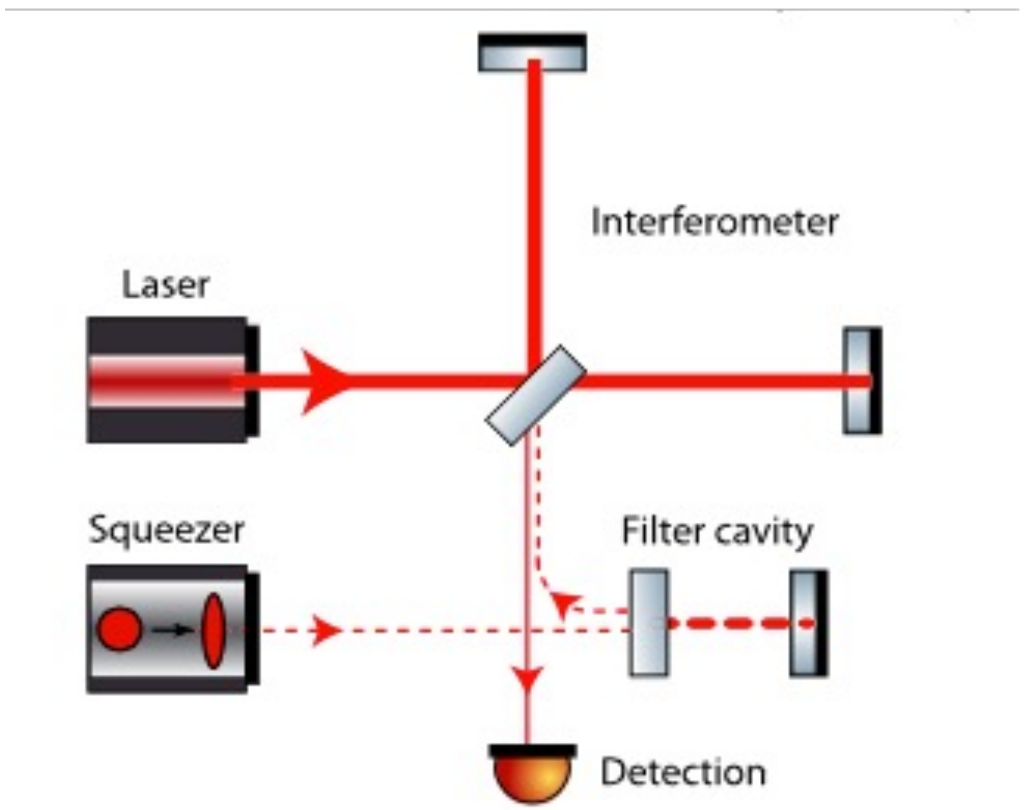
Next run O4. Main Improvement: higher laser power and frequency dependent squeezing

The driving idea
To simultaneously reduce shot noise at high frequencies and quantum radiation pressure noise at low frequencies requires a quantum noise filter cavity with low optical losses to rotate the squeezed quadrature as a function of frequency.

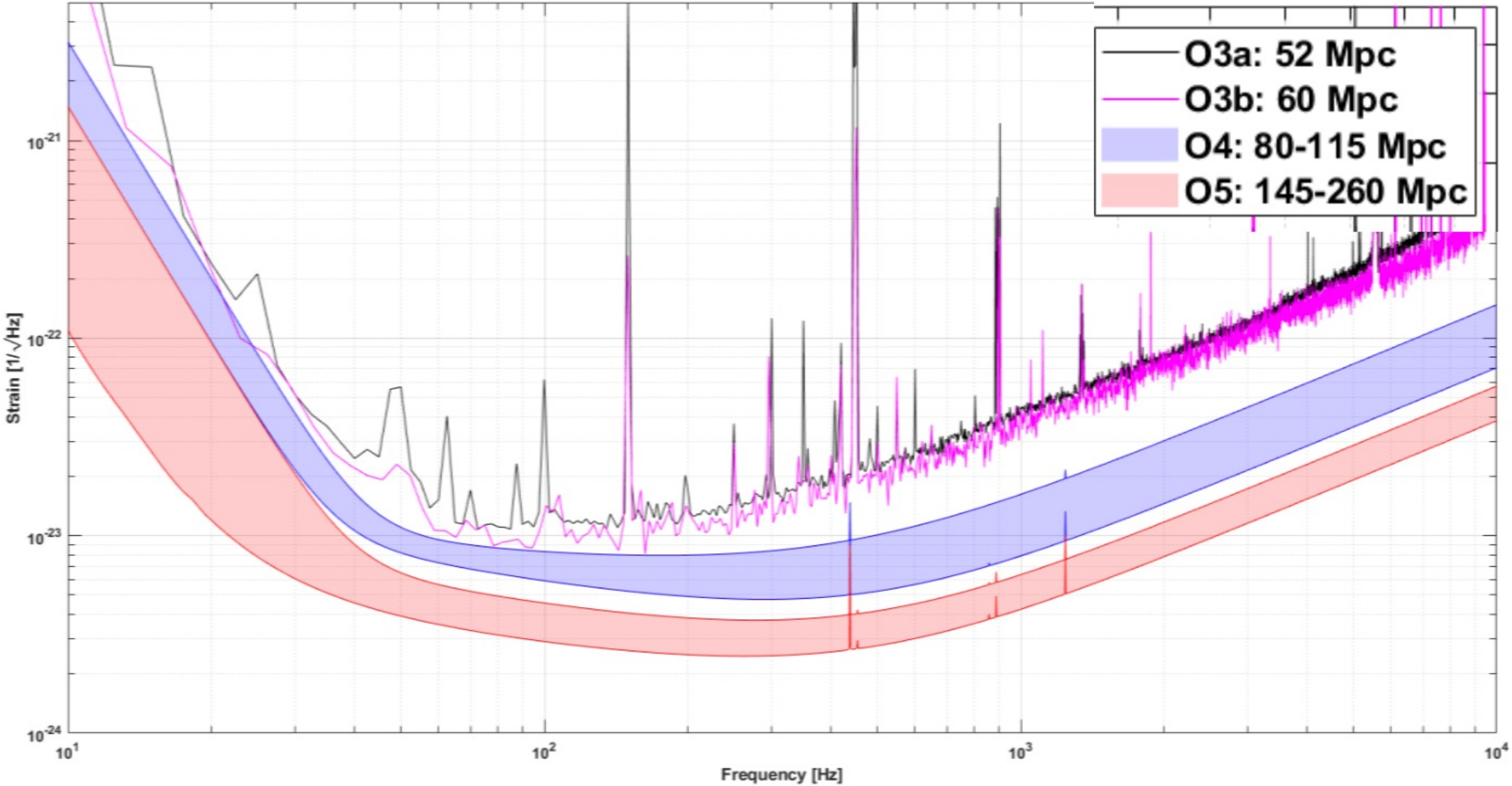
Adopted Method

- Reflect frequency independent squeezing off a detuned Fabry-Perot cavity
- Rotation frequency depends on the cavity line-width





AdV+ Phase I: sensitivity target of O4



LIGO: A+ in O4

Credits D. Reitze

Sensitivity goal for O4 for H1 and L1: 160 to 190 Mpc BNS range.

O4 Detector improvements:

- Replace y-arm Input Test Mass at LHO and x,y-arm test masses at LLO (and thereby reduce/eliminate inhomogeneous coating absorption)
- Upgrade LHO and LLO Pre-stabilized lasers (PSLs) to deliver 100W output powers into the interferometer
  - Achieves 400 kW in the arm cavities
- Deploy many baffles to minimize stray light noise

O4 A+ Project upgrades:

- Implement frequency-dependent squeezing; construct 300 m long filter cavity
- New low loss Faraday isolators (Fis) for reducing loss in the output port
- Implement adjustably deformable mirrors in the output port to tune up and maximize mode-matching into output mode cleaner (OMC) and filter cavity

LIGO Improvements

Credits D. Reitze

<u>Key detector improvement goals for O4:</u>

Upgrade Pre-stabilized Laser (PSL) to 140 W output power

Reduce light scattering noise through installation of baffles

Swap out test mass mirrors and replace with point absorber free test mass mirrors

PSL Upgrade: **COMPLETE AT LHO; UNDERWAY AT LLO**

LHO PSL upgrade completed in Jan 2022; produces 137 W with good mode quality, sufficient to reach performance goal of 100W into the H1 interferometer

LLO PSL upgrade began in early August; on track for completion in October

Installation of baffles to reduce scattered light **COMPLETE AT LHO AND LLO**

Includes HAM5,6 septum baffles, TM HR baffles, redesigned suspension baffles, arm cavity baffles, filter cavity tube baffles

Replacement of ETMS: **UNDERWAY AT LLO (NOT NECESSARY AT LHO)**

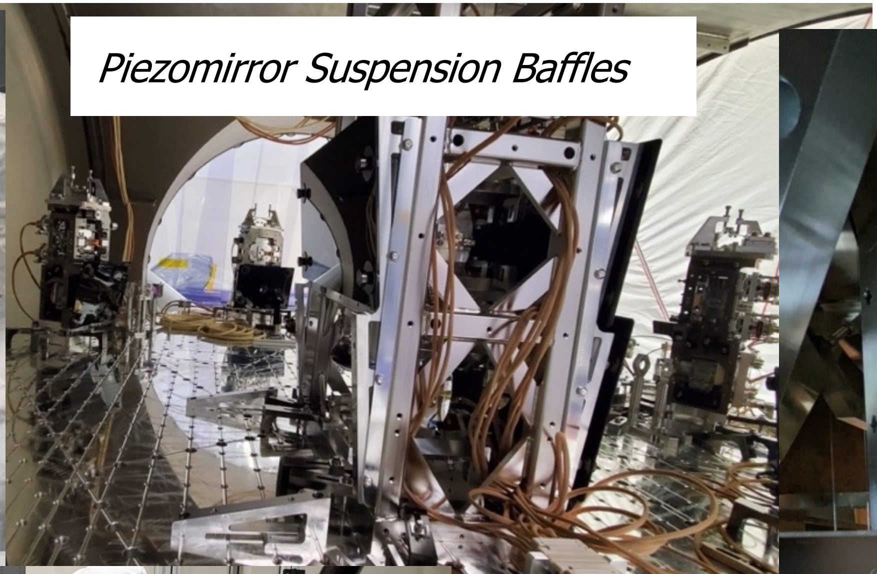
LHO replaced ITMy, but achieved needed performance; no need to replace ETMs

LLO has removed old ETMx, replaced with recoated ETMx, and welded fibers. ETMy is up next.

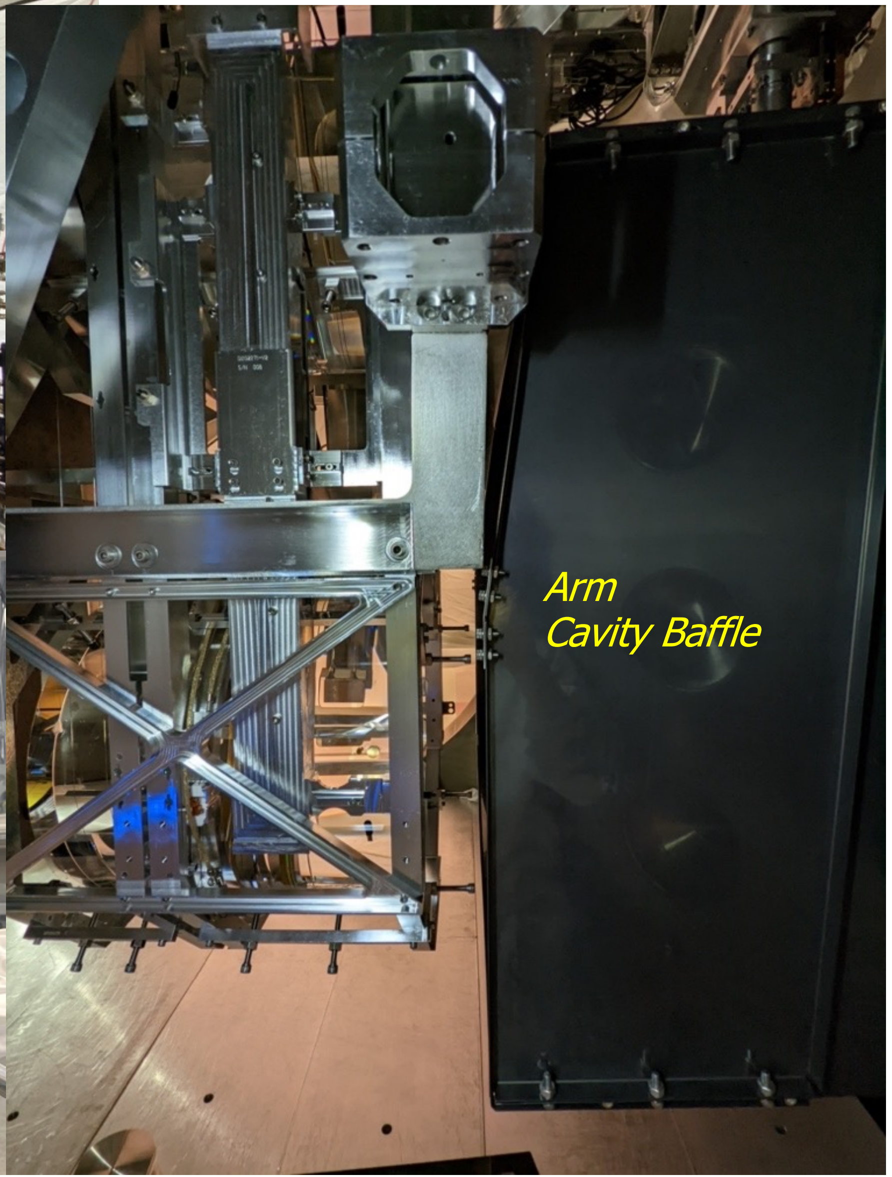
LIGO Pictures

Credits D. Reitze

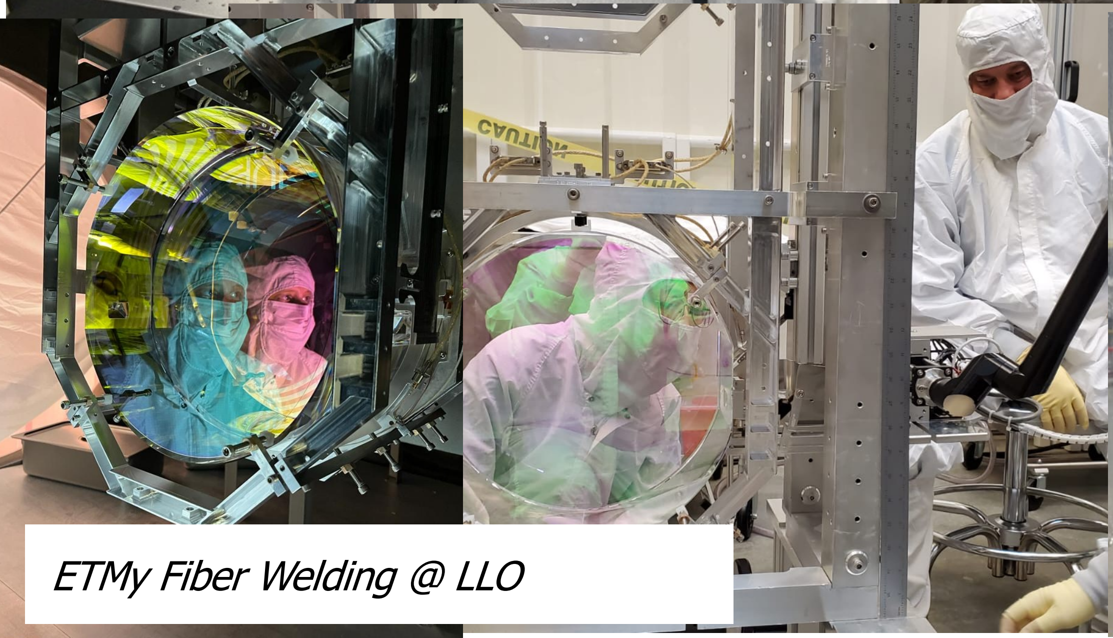
PSL Upgrade @ LLO



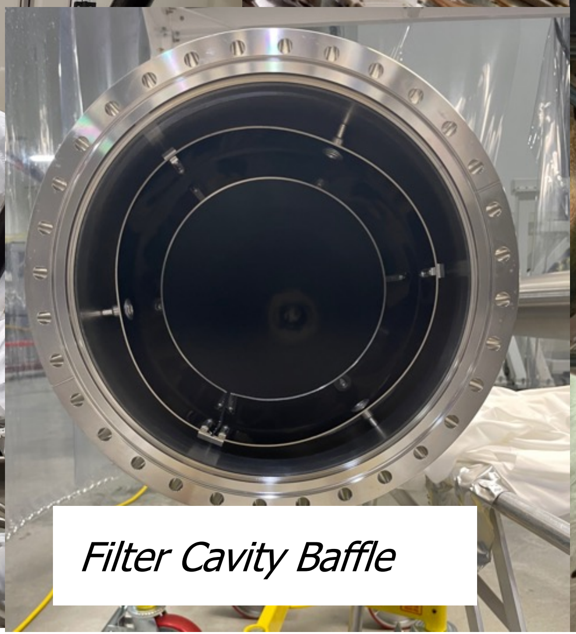
Piezomirror Suspension Baffles



Arm Cavity Baffle

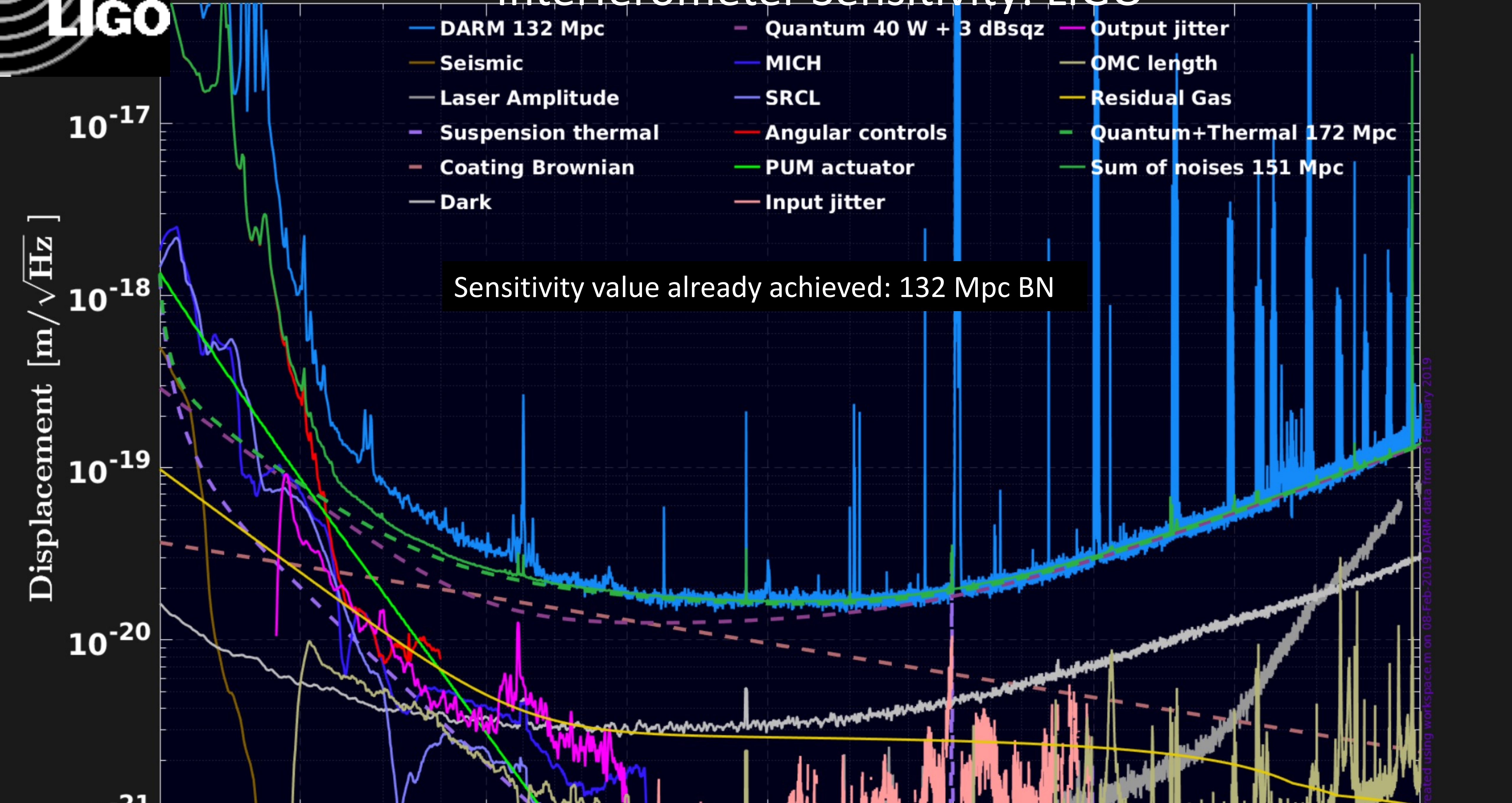


ETMy Fiber Welding @ LLO



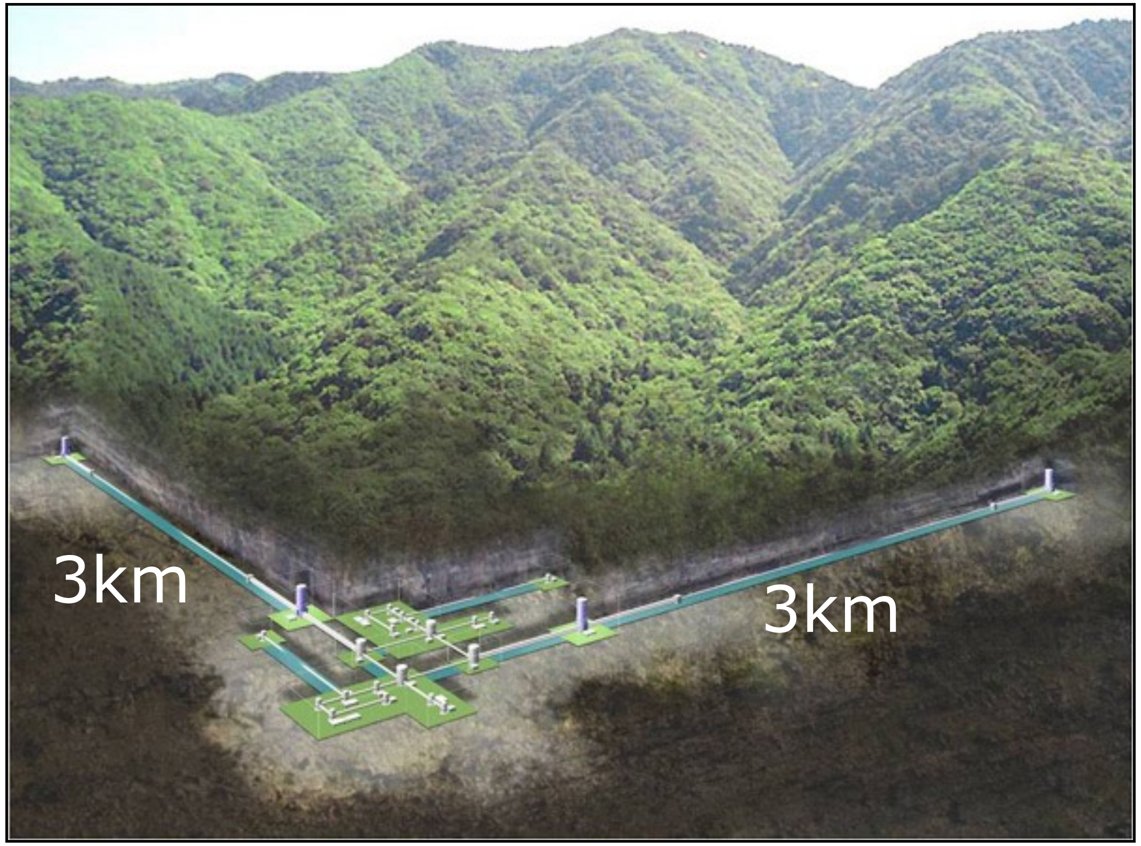
Filter Cavity Baffle

Interferometer Sensitivity: LIGO



KAGRA

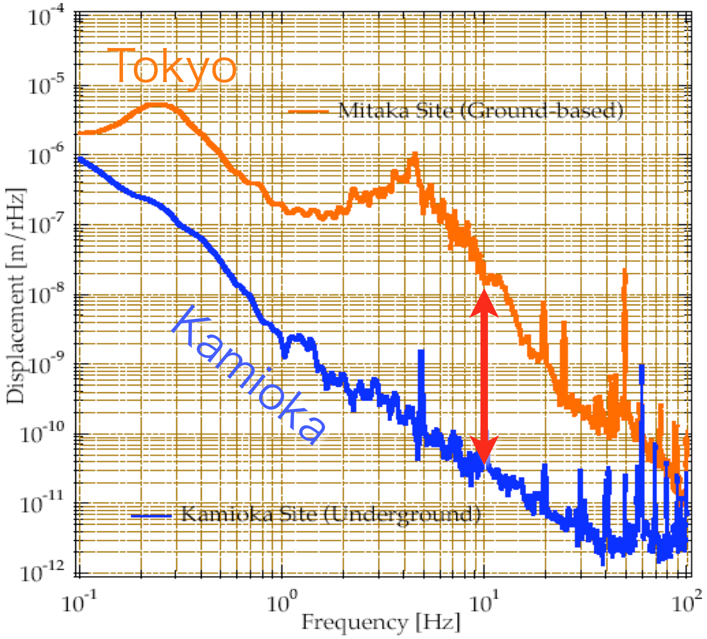
World’s first
2.5th generation GW detector



Fabry-Perot Michelson type
Laser interferometer

Cryogenic to reduce
thermal noises
(T=20K @mirrors)

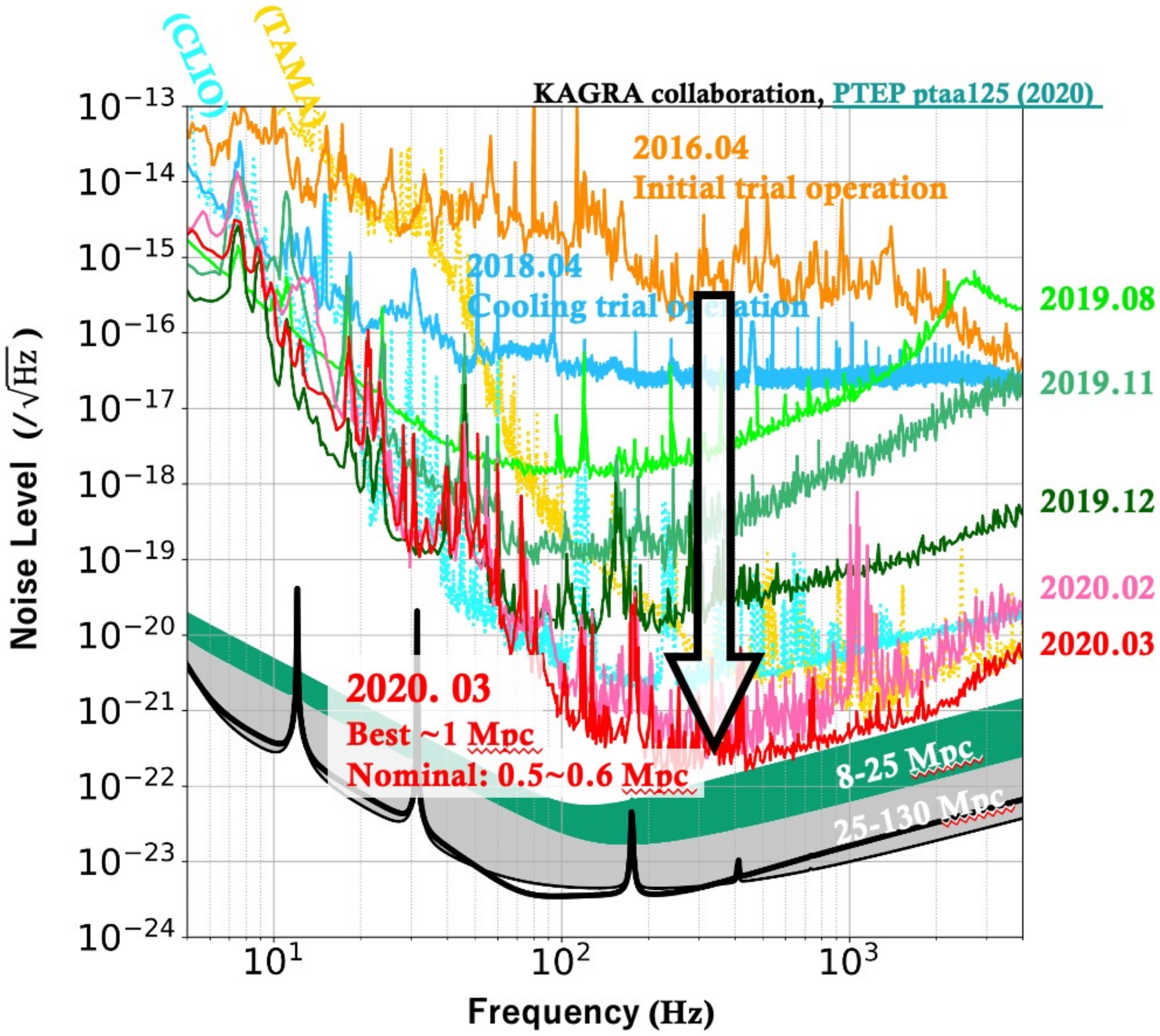
Underground to reduce
seismic noises

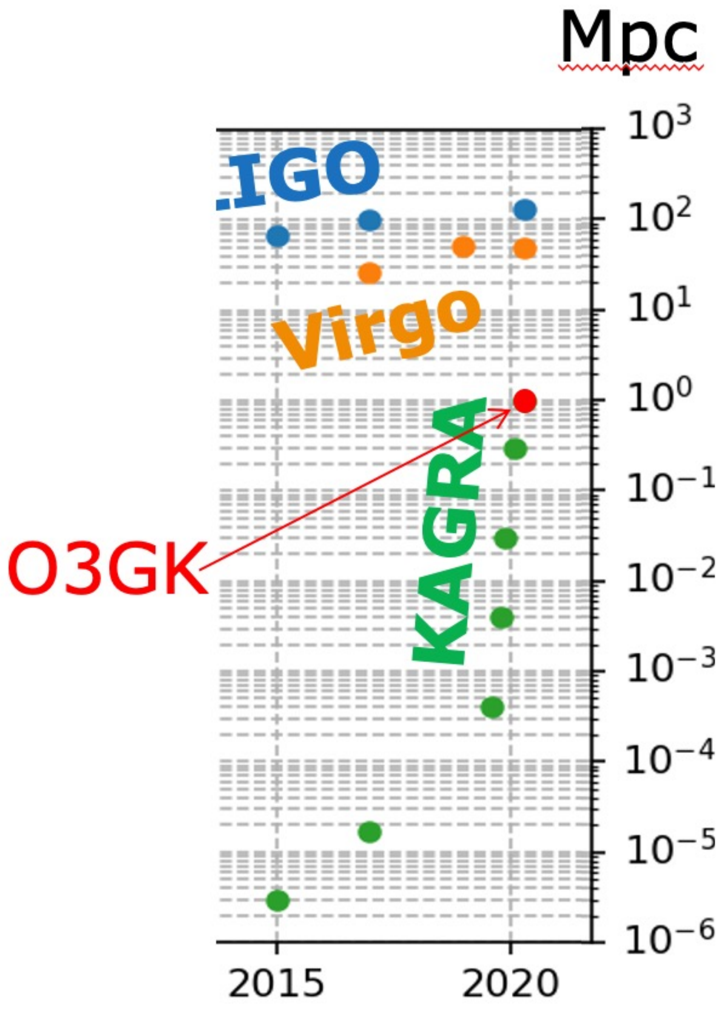


Amplitude of seismic motion

Evolution of the KAGRA sensitivity and BNS range

Credits Jun'ichi Yokoyama

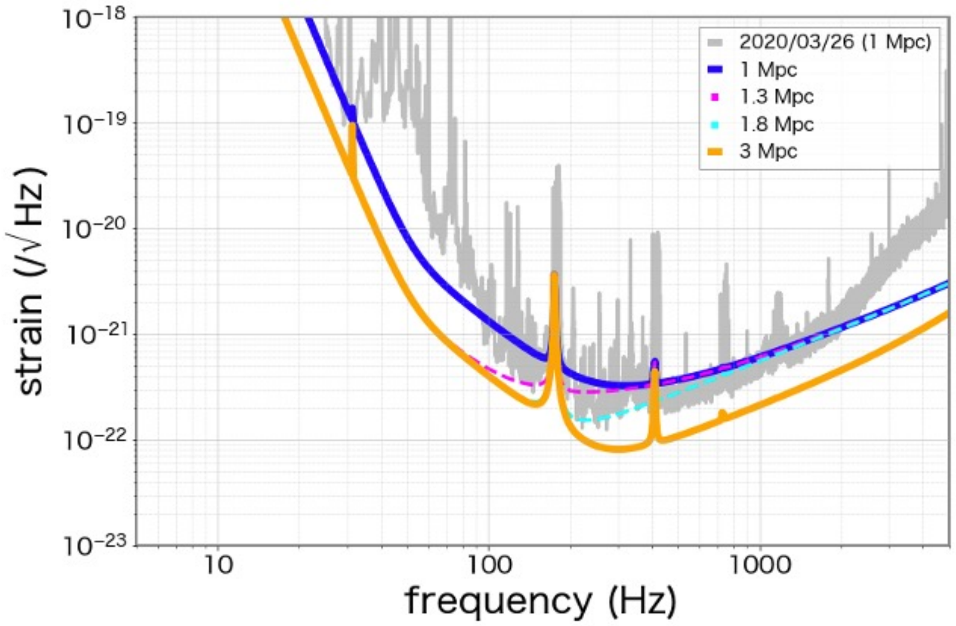




Expected Sensitiviy Improvements for KAGRA toward O4

Credits Jun'ichi Yokoyama

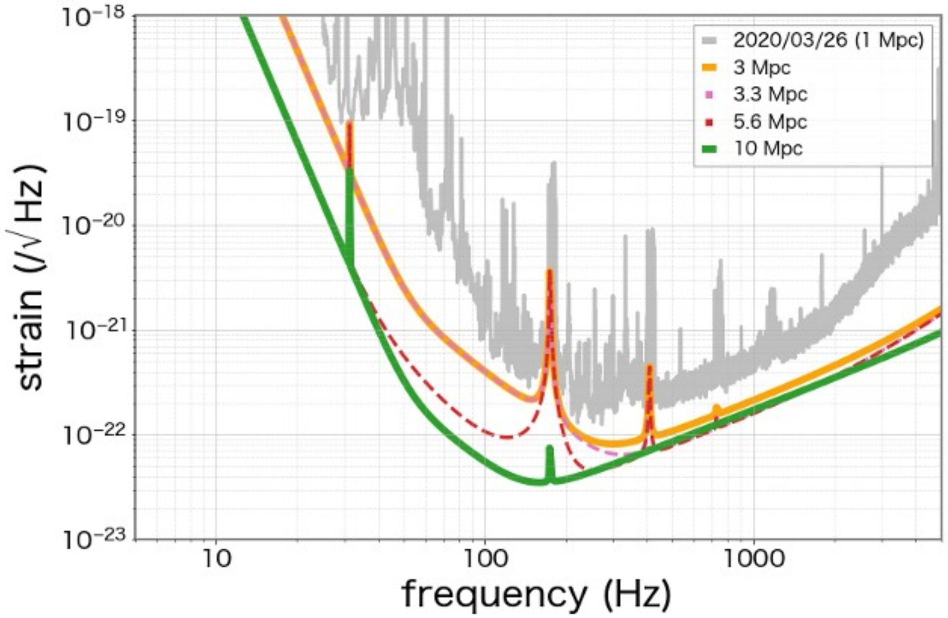
O4a



Improvement of suspension

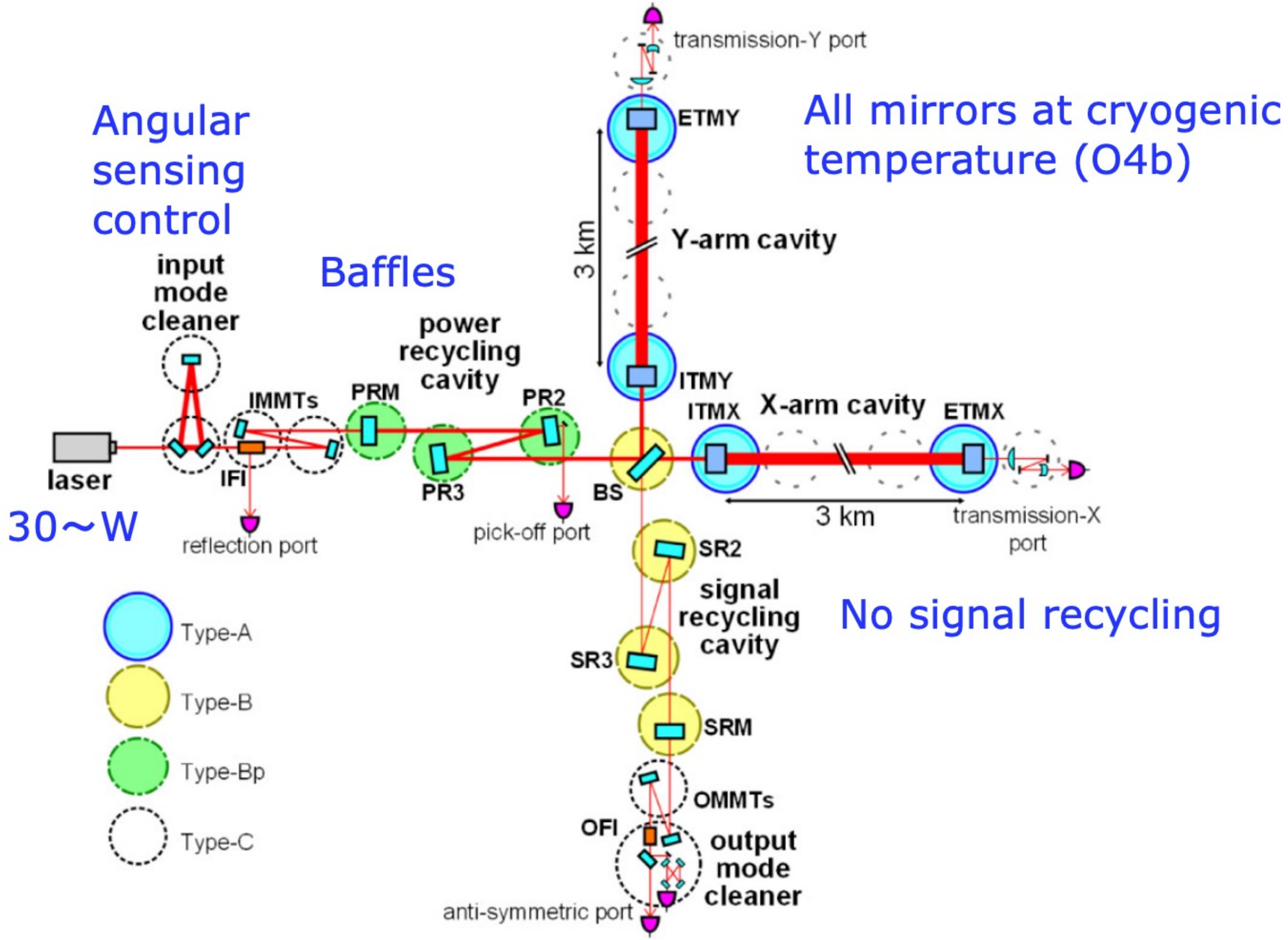
- Suppressing stray light with baffles
- Replacement of SRM

O4b



- Cool down the mirrors to <100K
- Improvement of low frequency region
- High power laser

KAGRA configuration for O4



Credits Jun'ichi Yokoyama

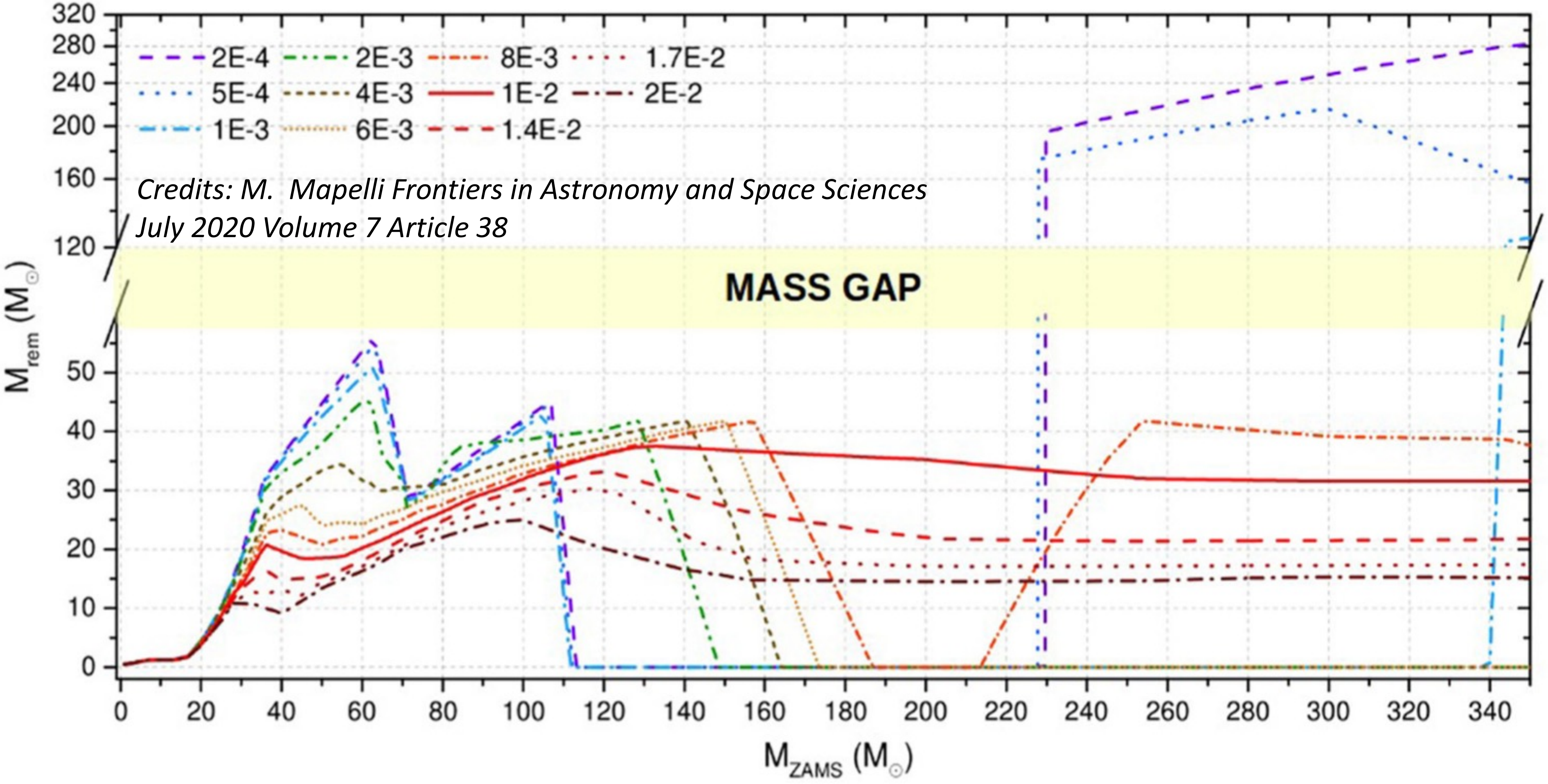
Highlights on GW discoveries and…
new misteries

Simulations of stellar evolution in 11 different metallicity cases

(Astronomers use the word "metals" as a short term for "all elements except hydrogen and helium")

REM – Remenant

Mrem: Mass of the compact object



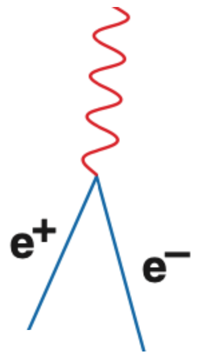
Credits: M. Mapelli Frontiers in Astronomy and Space Sciences July 2020 Volume 7 Article 38

[ZAMS - Zero Age Main Sequence] is the is the time when a [star] first joins the main sequence on the Hertzsprung-Russell diagram ([HR diagram]) by burning [hydrogen] in its core through fusion reactions.

Why do they predict the existence of a mass gap ?

The model

- In stars with a main-sequence mass of approximately 150 $M_\odot$–260 $M_\odot$, the conversion of photons to e^+ / e^- pairs inside the hot dense core drives a runaway collapse.
- *When this collapse is halted by oxygen-burning nuclear reactions, the energy produced leads to an explosion powerful enough to completely destroy the star. The Supernova dominated by the pair instability mechanism do not leave any BH remnant.*
- Conclusion: the stellar evolution model tells us that there should be no black holes with masses in the range 50 $M_\odot$–140 $M_\odot$



Data from LIGO/Virgo

- GW190521 LIGO/Virgo event results from a BBH merger of black holes with masses of 66 $M_\odot$ and 85 $M_\odot$
- *At least one of the two BHs is well in the mass gap challenging the pair instability model.*

Attempts to conciliate model and data

- It is possible to move the boundaries of the mass gap by including rotation or magnetic fields in the calculation, but physically reasonable values of these seems not to permit that isolated stars populate the mass gap. (*D. Branch and J.C. Wheeler, Supernova Explosions, - Springer, New York, 2017*)
- If an energy source is added throughout the star in addition to nuclear fusion, it is possible to end up with a BH remnant: *J. Ziegler and K. Freese suggest as additive mechanism the case of dark matter annihilation (Phys. Rev. D 104, 043015 (2021)*

An other open problem: GW190814 and its ‘mystery object’

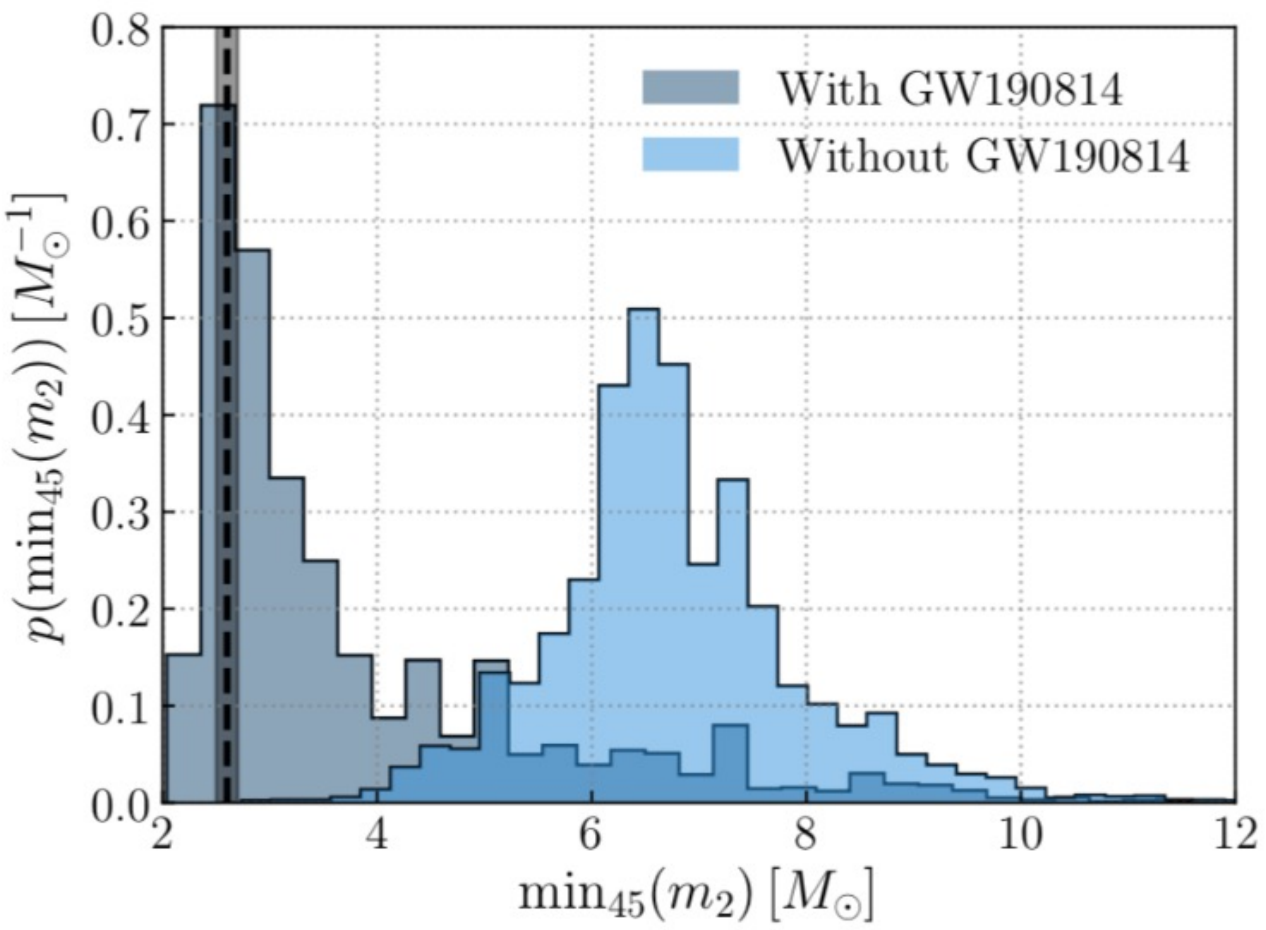
LVC, Astrophys.J.Lett. 896 (2020) 2, L44

Primary Object a BH of ~23 $M_\odot$,

Secondary Mass 2.50 -2.67 $M_\odot$:
a super-heavy NS or a super-light BH

Outlier in secondary mass & mass ratio distributions:
Probability <0.02% of seeing *as small* a m_2 or $q=m_2/m_1$ over 45 events

Indicates potential origin different from the majority of BBH detected up to now



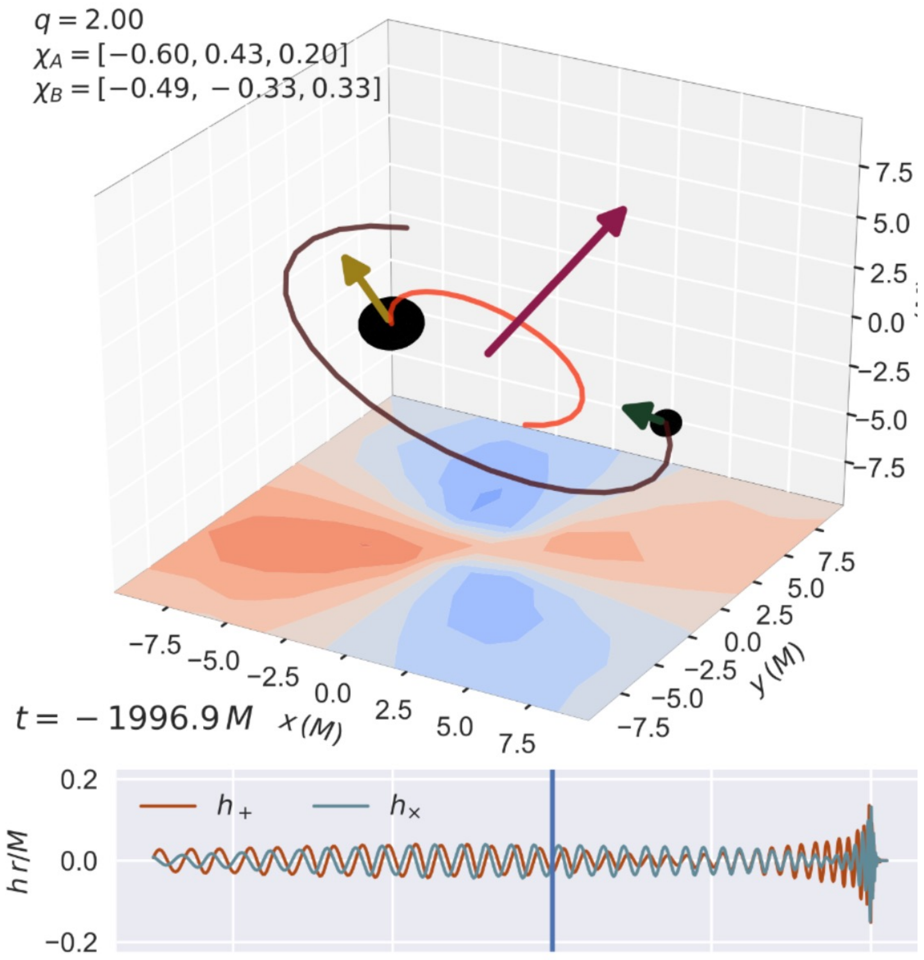
The role of the BH Spin in the Waveform analysis

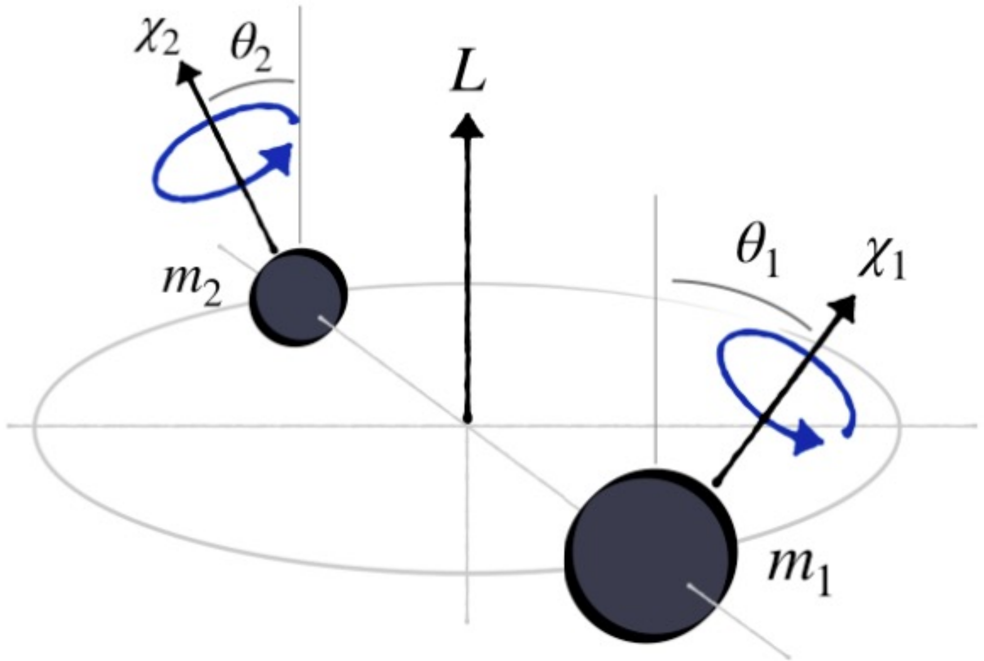
Effective spin

$$\chi_{\rm eff} = \frac{\chi_1 \cos\theta_1 + q\,\chi_2 \cos\theta_2}{1+q}$$

Effective precession spin

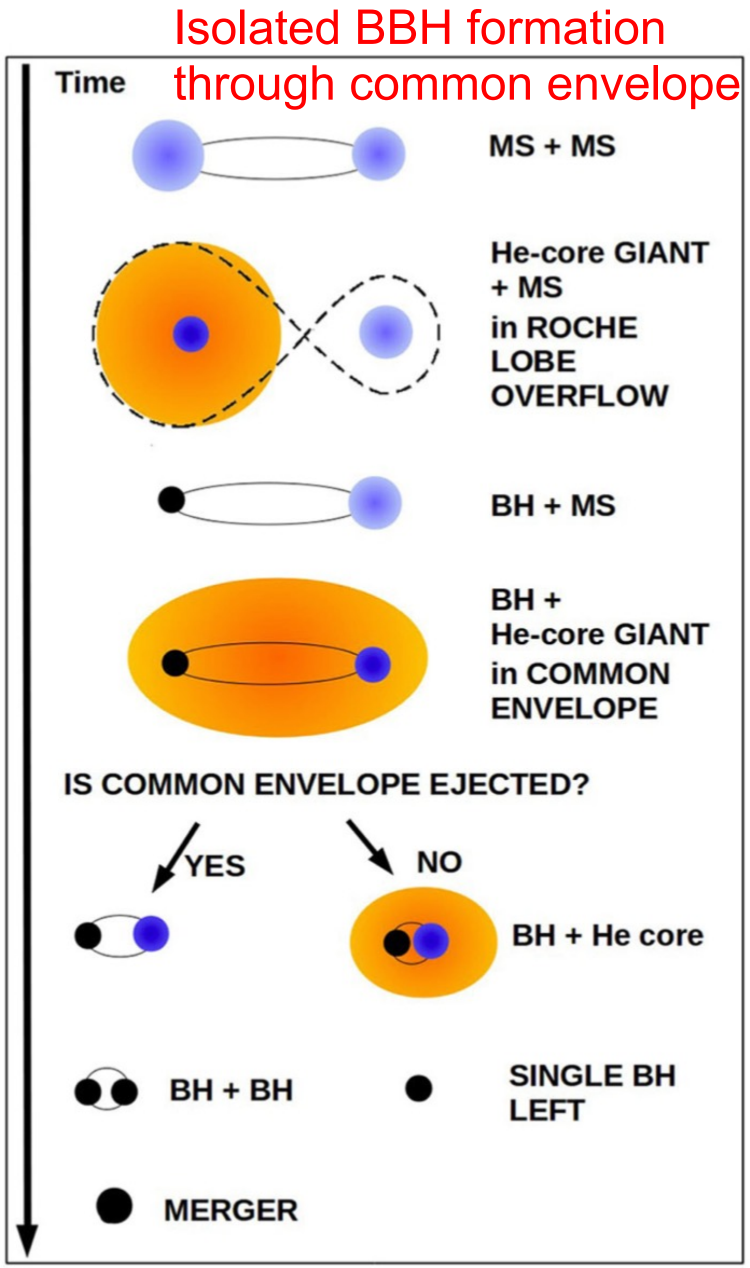
$$\chi_{\rm p} = \max\left[\chi_1 \sin\theta_1, \left(\frac{4q+3}{4+3q}\right) q\,\chi_2 \sin\theta_2\right]$$





q= m_2 /m_1

Two scenarios of formation for stellar mass BBHs



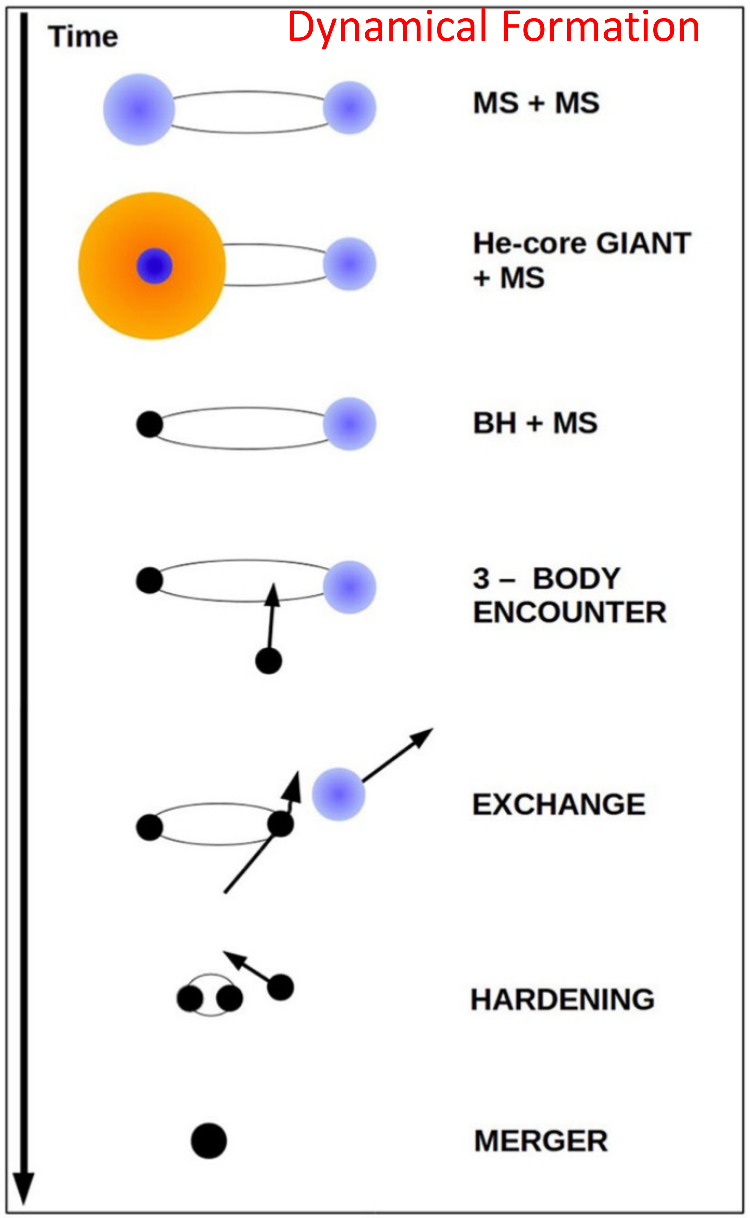
Isolated Formation

Strong gas drag from the envelope and loss of kinetic energy:

- inspiraling about each other and form a single BH
- If the envelop is ejected and the natal chick is low, BBH is formed

Dynamical Formation

During a three-body encounter, a binary star exchanges a fraction of its internal energy with the third body. If the binary is particularly tight (hard binary), such encounters tend to harden the binary star, i.e., to increase its binding energy by reducing its semi-major axis (*dynamical hardening*).

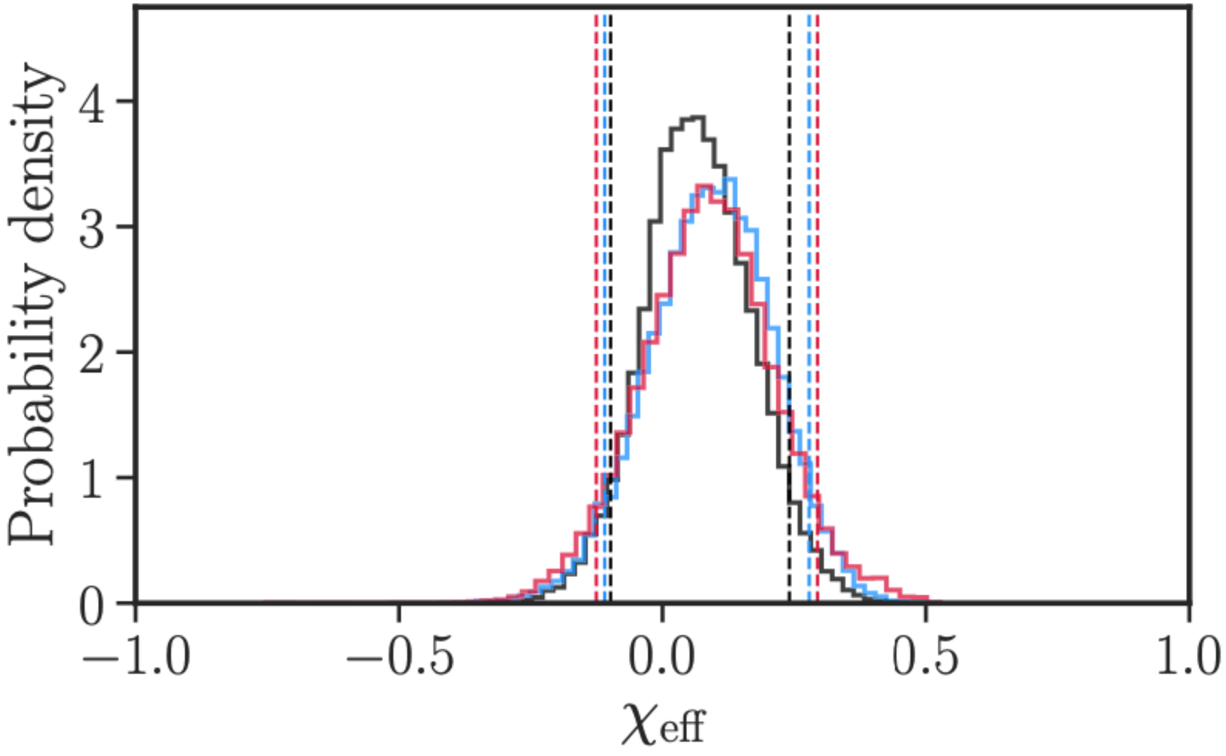


Spin and hints on BH population

- BHs in dynamically formed binaries in dense stellar environments expected to have spins distributed isotropically

- BHs formed in the isolated scenario of the stellar evolution are expected to induce BH spins preferentially aligned with the orbital angular momentum

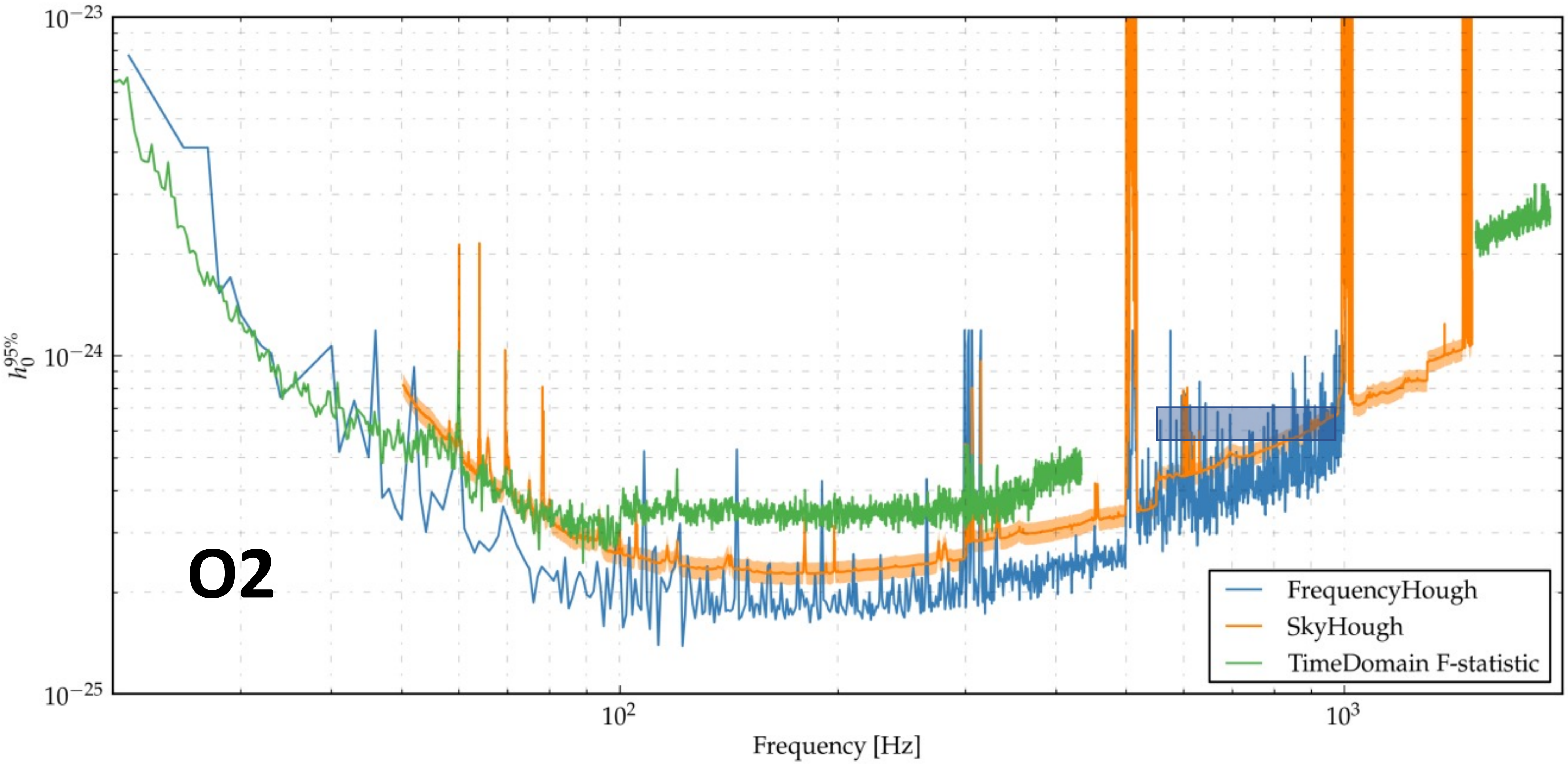
- In almost all the BBHs mergers events, the inferred probability posterior of $\chi_{\mathbf{eff}}$ clusters around zero and is rather narrowly peaked.



B. P. Abbott et al Phys. Rev X 9, 031040 (2019)

All-sky Continuous-Wave searches

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.100.024004

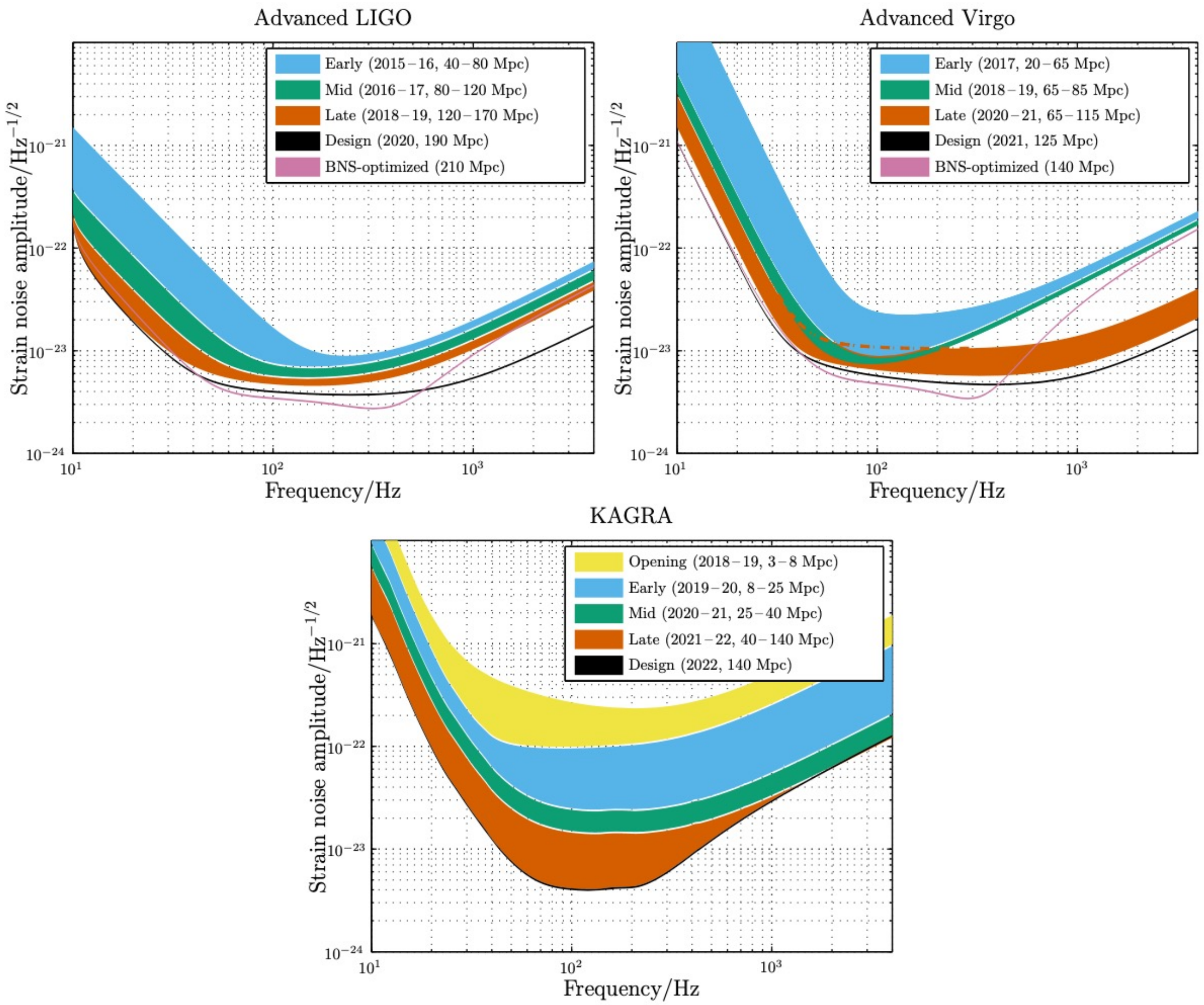


For O3 search results (currently under review), see https://arxiv.org/abs/2107.00600

Future evolution of the GW detectors in the next decade

➔ O5 and Post O5 Detectors +

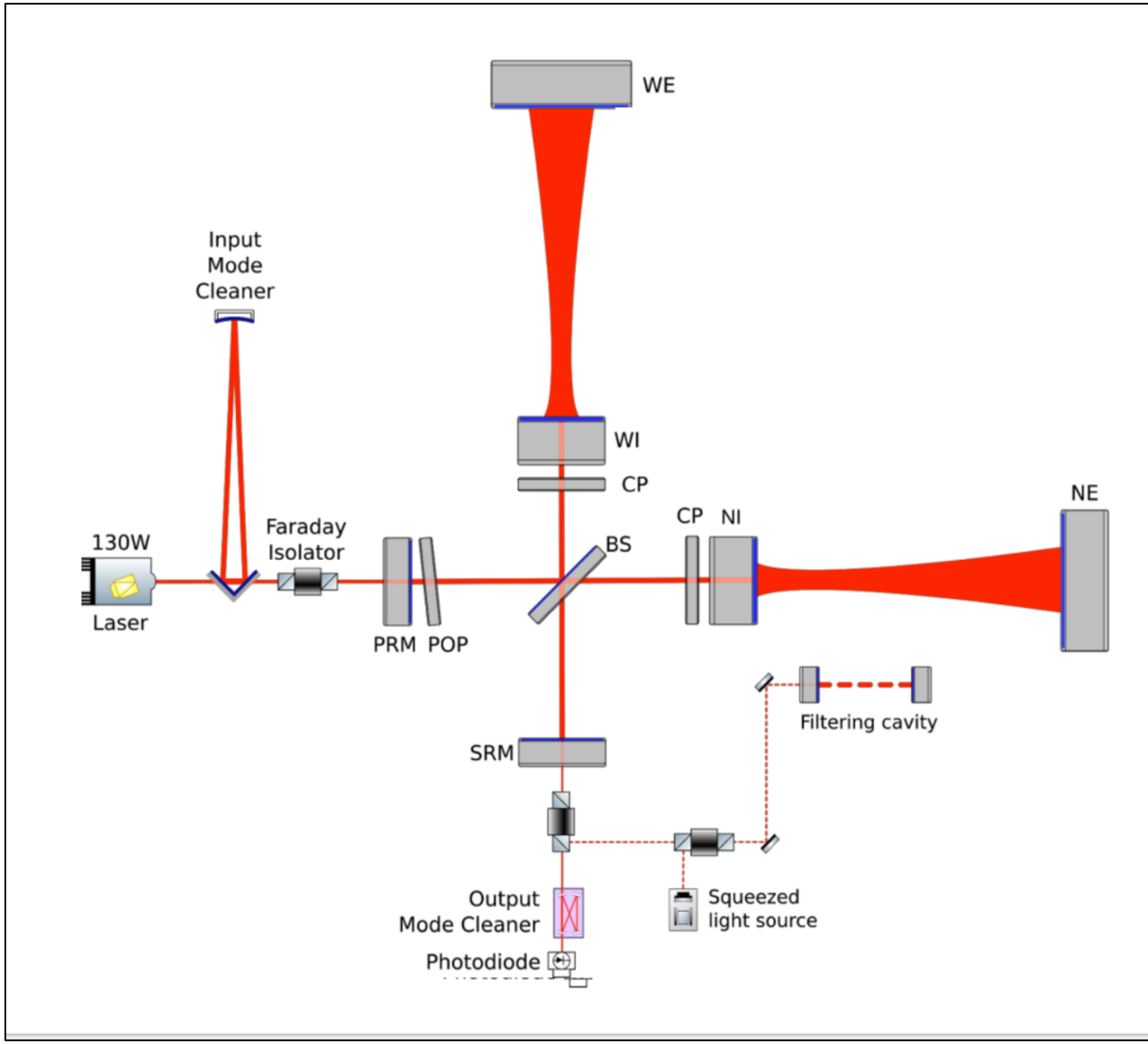
More events at high SNR needed to progress on GW physics



We have to detect still other kind of signals: neutron star emitters , supernovae, GW stocastic background

AdV + Phase II: toward O5

- Larger beams on end test masses
  - ➢ 6 cm radius ➔ 10 cm radius
- Larger end mirrors
  - ➢ 35 cm ϕ ➔ 55 cm ϕ
  - ➢ 40 kg ➔100 kg
- Better mirror coatings
  - ➢ Lower mechanical losses, less point defects, better uniformity
- New suspensions/seismic isolators for large mirrors
- Further increase of laser power



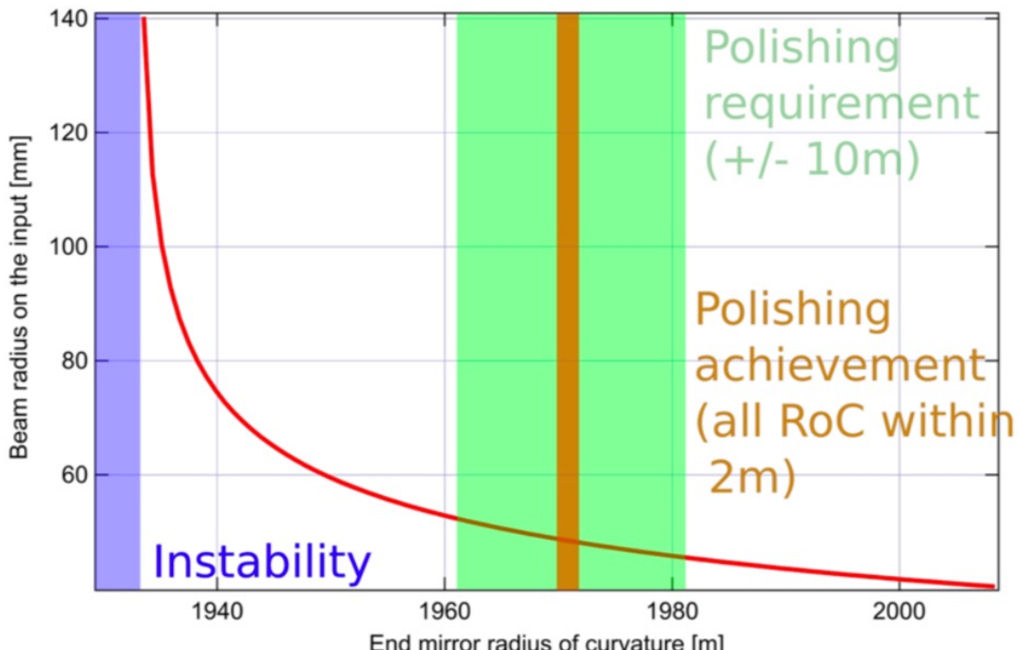
The main challenge

credits : A. Chiummo

The challenge comes from optical design:

to enlarge the beam on the test masses, arm cavities closer to instability

- Trickier controls
- Polishing requirements more strict
- More sensitive to aberrations



	Phase I	Phase II
End Mirror Diameter	350 mm	550 mm
Beam radious on End Mirrors	58 mm	91 mm
Beam radious on Input Mirrors	49 mm	49 mm
Radious of Curvature - End Mirror	1683 mm	1969 mm
Radious of Curvature - Input Mirror	1420 mm	1067 mm
g ➔ stability factor of the cavity	0.87	**0.95**

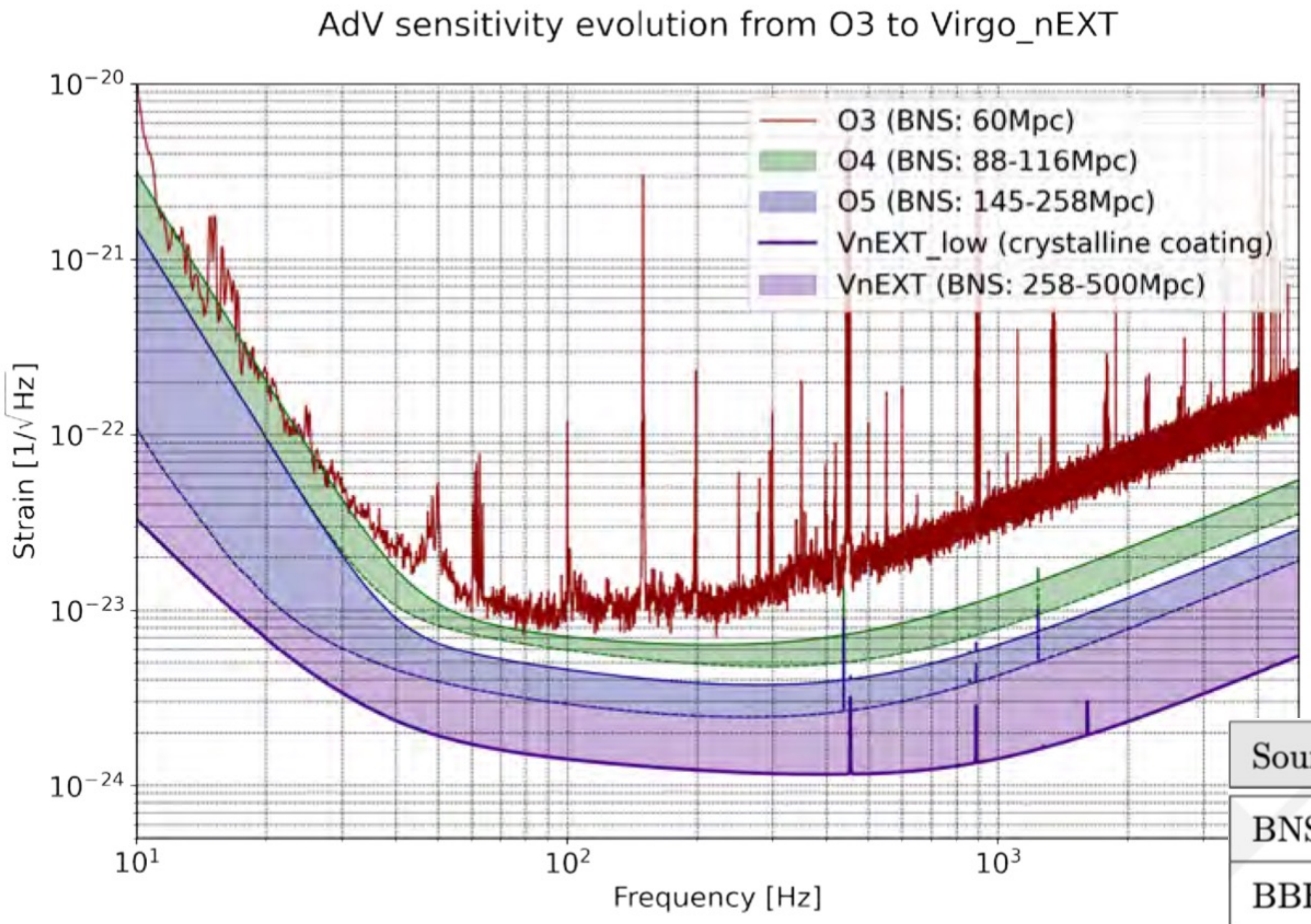
Larger g-factor requires:

- Tighter angular control requirements during pre-alignment ➔ 0.2 microrad
- Tight requirements RoC control ➔ ΔRoC~0.3 m

Action on Thermal Compensation System:

several upgrades foreseen for O5 on the sensing and actuation systems

Advanced Detectors in the post O5 era: the Virgo_nEXT case

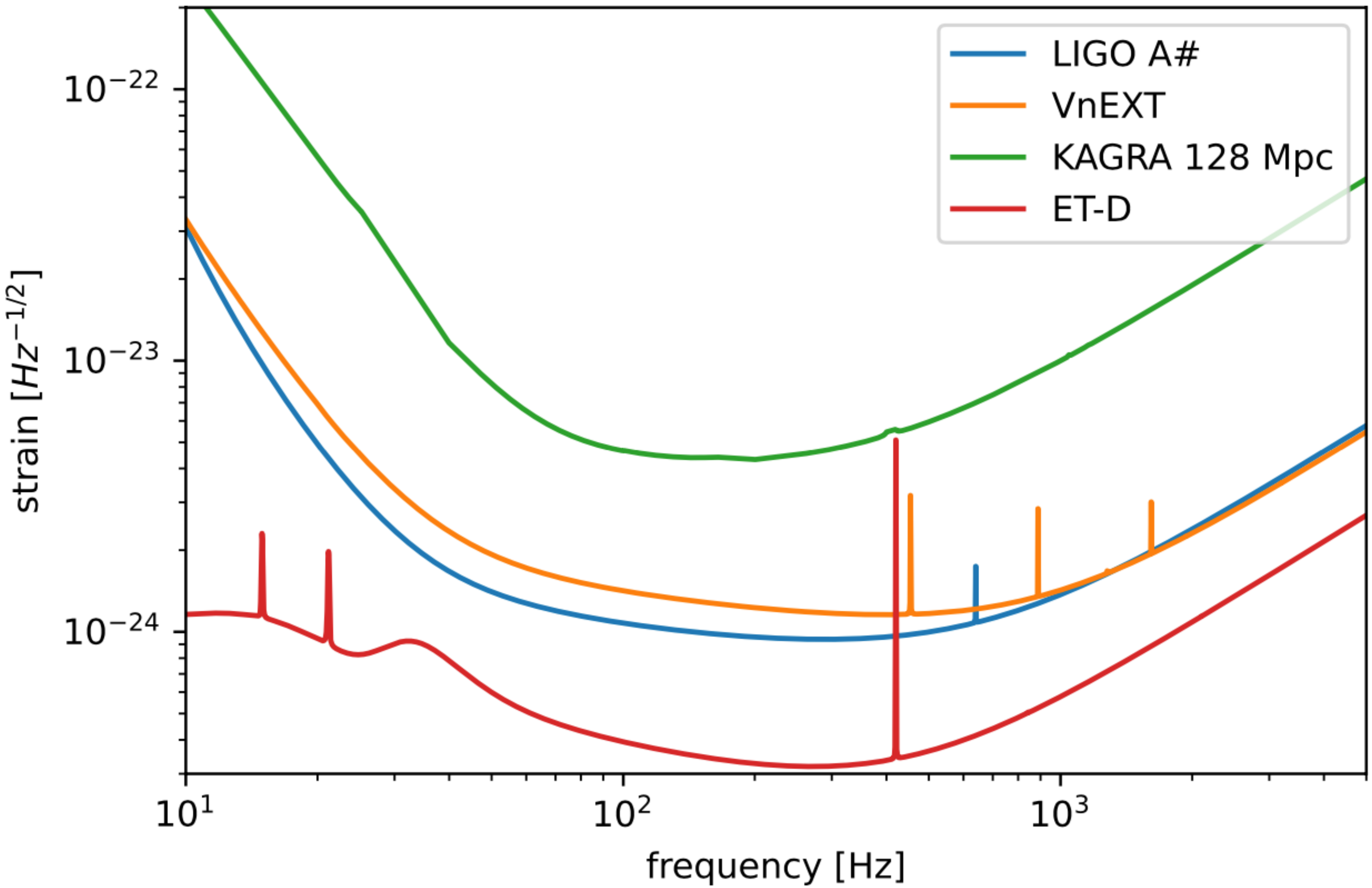


Source	O5 low	"post-O5low"
BNS range (Mpc)	258	500
BBH range ($30+30\,M_\odot$) (Mpc)	590	3320
Stochastic Omega	7.5e-10	2.3e-10
Supernova (kpc) [217]	18.3	51.0

From Advanced Virgo + to Virgo_nEXT: the system upgrades

Parameter	O4 high	O4 low	O5 high	O5 low	VnEXT_low
Power injected	25 W	40 W	60 W	80 W	277 W
Arm power	120 kW	190 kW	290 kW	390 kW	1.5 MW
PR gain	34	34	35	35	39
Finesse	446	446	446	446	446
Signal recycling	Yes	Yes	Yes	Yes	Yes
Squeezing type	FIS	FDS	FDS	FDS	FDS
Squeezing detected level	3 dB	4.5 dB	4.5 dB	6 dB	10.5
Payload type	AdV	AdV	AdV	AdV	Triple pendulum
ITM mass	42 kg	42kg	42 kg	42 kg	105 kg
ETM mass	42 kg	42kg	105 kg	105 kg	105 kg
ITM beam radius	49 mm	49 mm	49 mm	49 mm	49 mm
ETM beam radius	58 mm	58 mm	91 mm	91 mm	91 mm
Coating losses ETM	2.37e-4	2.37e-4	2.37e-4	0.79e-4	6.2e-6
Coating losses ITM	1.63e-4	1.63e-4	1.63e-4	0.54e-4	6.2e-6
Newtonian noise reduction	None	1/3	1/3	1/5	1/5
Technical noise	“Late high”	“Late low”	“Late low”	None	None
BNS range	90 Mpc	115 Mpc	145 Mpc	260 Mpc	500 Mpc

Looking into the future: 2G, 2.5G and….. 3G GW detectors on the Earth



Conclusions

The detectors of the LIGO-Virgo-KAGRA network are in the commissioning phase to improve their sensitivity with the aim to start the Science run O4 at the beginning of the spring 2023

At present 90 GW events have been collected and reported in the GW catalogue. These signals are mainly due to the BBH coalescence.

A couple of events provide hints toward new directions for the modelling the BH and BBH formation theories.

We need to collect new events at more and more high SNR to shed light on dark side of the Universe.

Advanced+ detectors will play this game waiting for….. EINSTEIN TELESCOPE

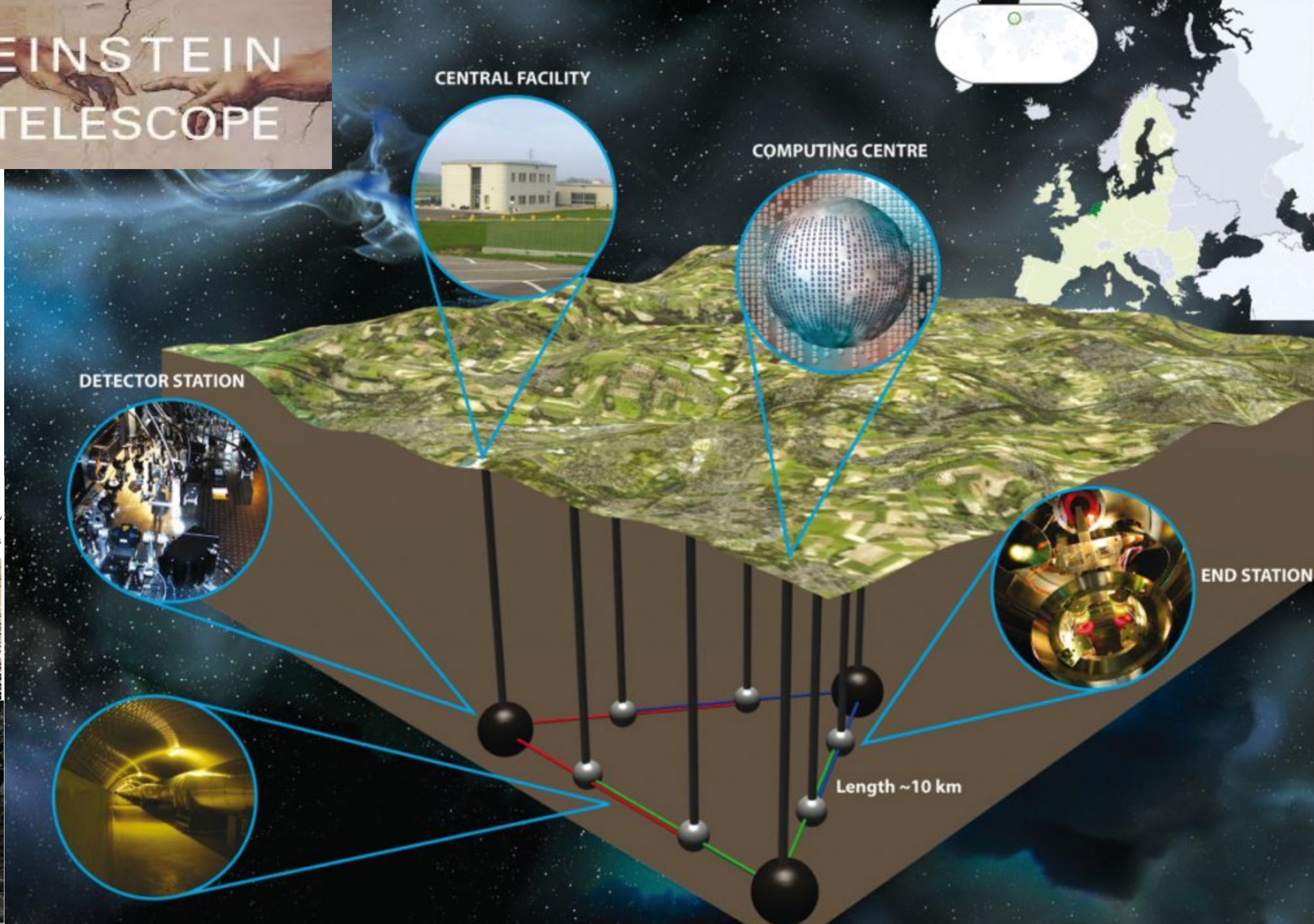
ET EINSTEIN TELESCOPE

Einstein Telescope, la sfida di Lula

Nel silenzio di Sos Enattos i 15 sismometri rilevano un sisma in Albania

Marilena Orunesu
INVIATA

LULA. Il primo sismometro, infisso nella collina che sovrasta la miniera, ha già registrato un terremoto in Albania: quarto grado. Altri strumenti, operativi sotto terra, in profondità, seguono il movimento delle correnti marine tra Francia e Corsica e perfino delle onde oceaniche a Gibilterra. Tutto pulsa nel vasto silenzio di Sos Enattos, miniera storica di Lula diventata laboratorio scientifico di prim'ordine al punto da concorrere all'Einstein Telescope, osservatorio internazionale d'avanguardia per lo stu-

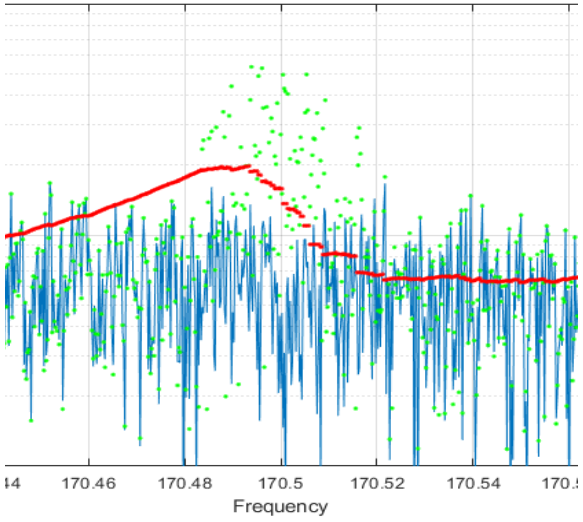


EXTRA SLIDES

Frequency-Hough: robustness for CW signal clusters

1

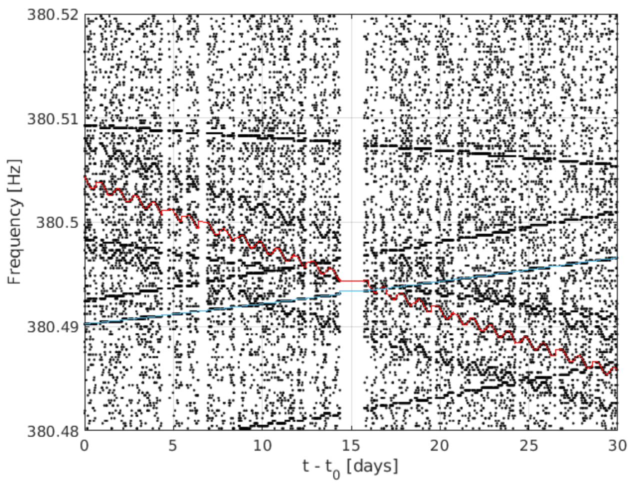
In general, if signals form dense clusters, the spectral autoregressive estimator (red) could be affected



[PRD, **106**, 042009 (2022)]

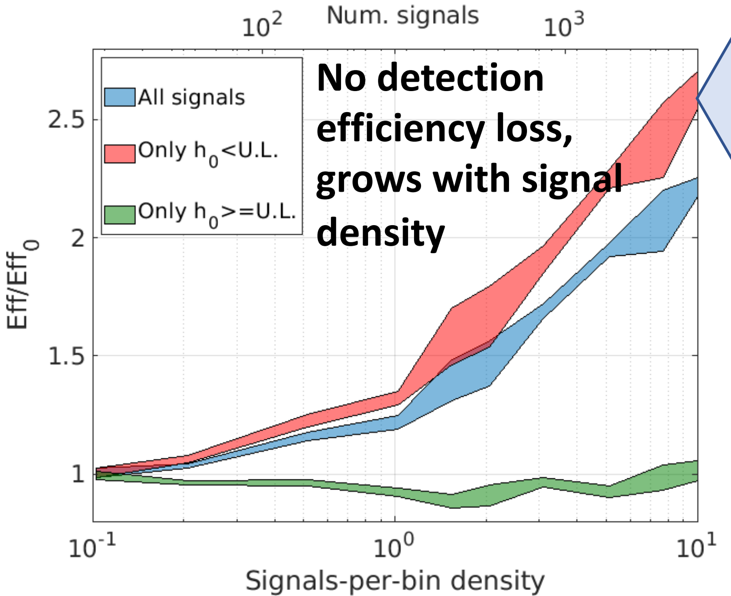
2

The annual and daily Doppler effects are a powerful signature to resolve signals from different sources



3

Crucial index: cluster frequency width VS spectral estimator memory



Frequency width $\lesssim$ estimator memory

The estimator is not fast enough to adapt to the signal mountain, which remains well above the noise floor

The estimator is able to adapt to the varied noise floor; signals can fall under the selection threshold

Frequency width $\gg$ estimator memory