Istituto Nazionale di Fisica Nucleare

Retreat Fisica Particelle Elementari - INFN Roma

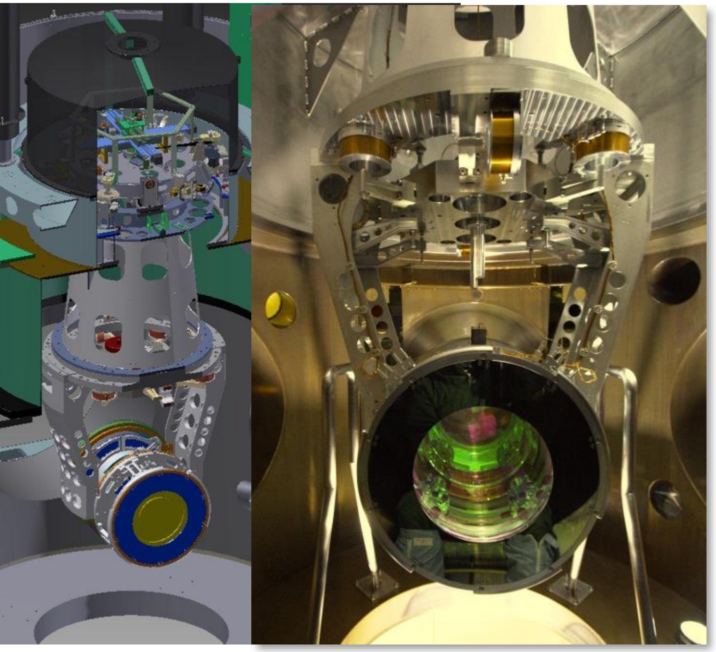
Onde gravitazionali: status e prospettive

Luca Naticchioni & Cristiano Palomba

(INFN Roma)

for the Rome Virgo group

Advanced Virgo in O2

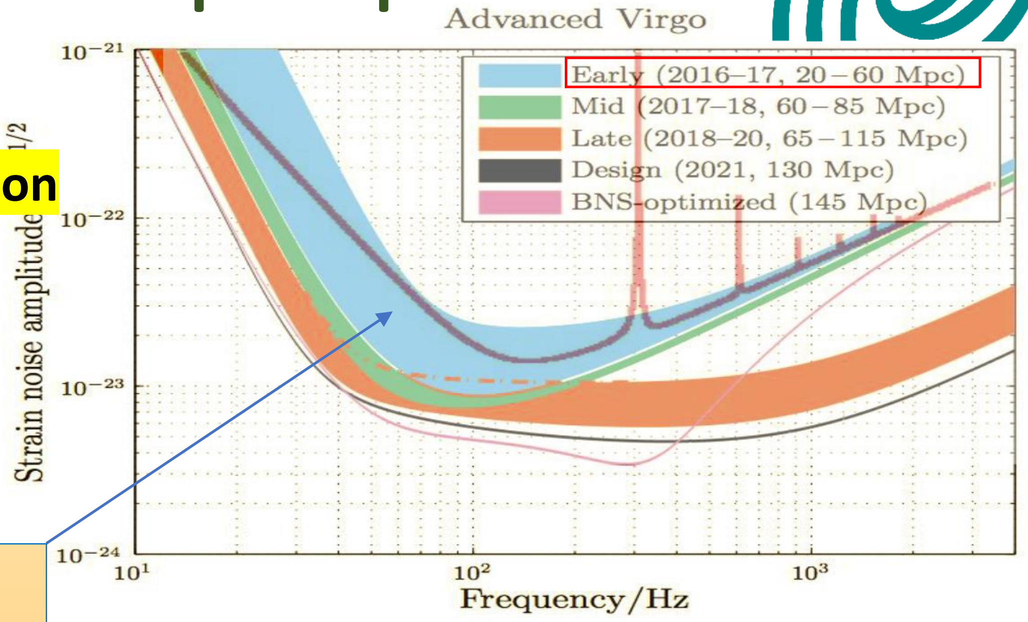


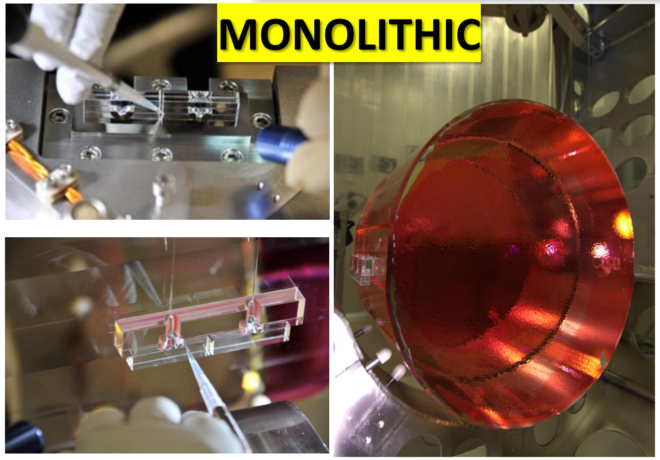
Vacuum system dust contamination

monolithic susp. failures

Steel-wire backup solution

Sensitivity with steel wires still compatible with the goal for the early phase

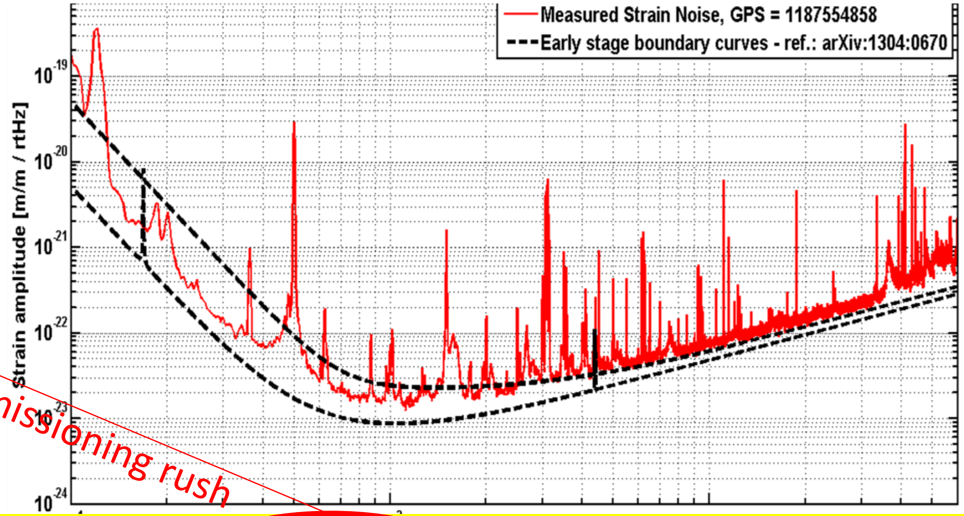




Steel ($\phi=10^{-3}$)
Range NS-NS - 45 Mpc
Range BH-BH - 202 Mpc

Monolithic
Range NS-NS - 101 Mpc
Range BH-BH - 985 Mpc

fast commissioning rush



BNS range ~ 28 Mpc → ***ready to join O2!***

Advanced Virgo in O2

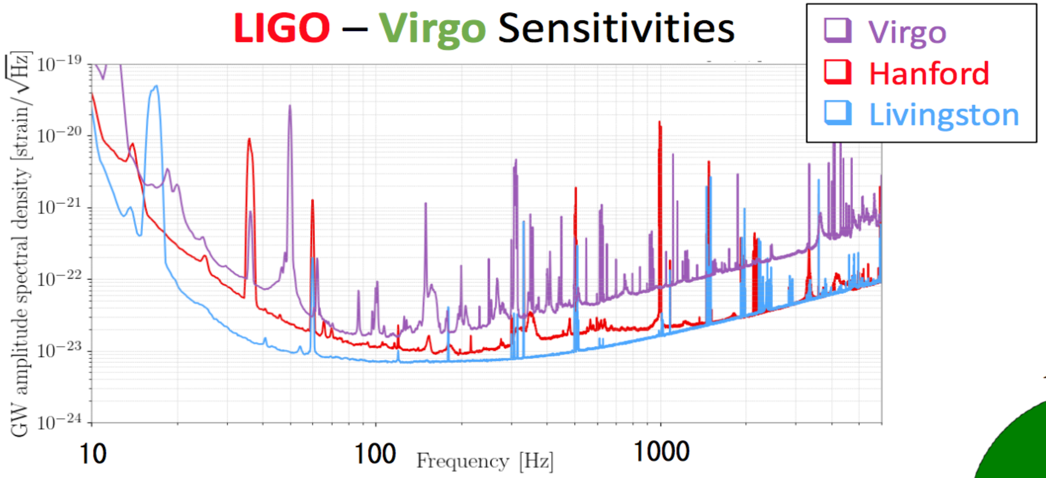
GW170814

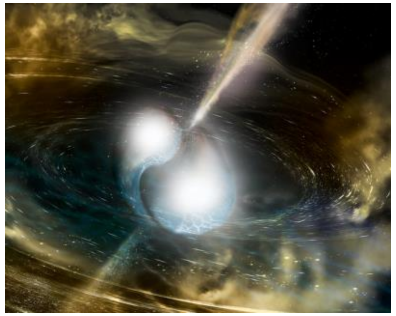
GW170817

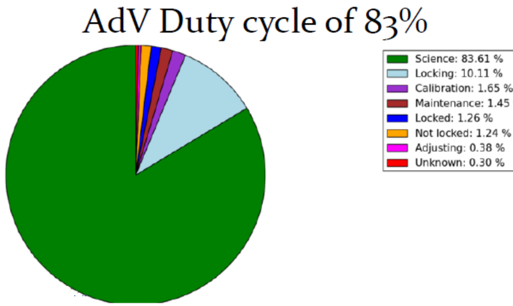
- **O1** ~***49 days*** of coincident **LIGO** data
- **O2** ~***120 days*** of coincident **LIGO** data
  ~***16 days*** of coincidence with **Virgo** data
  10 GW alerts for EM follow-up

Averaged distances to which
Binary Neutron Star could be detected

VIRGO : 26 Mpc
HANFORD : 55 Mpc
LIVINGSTON : 100 Mpc

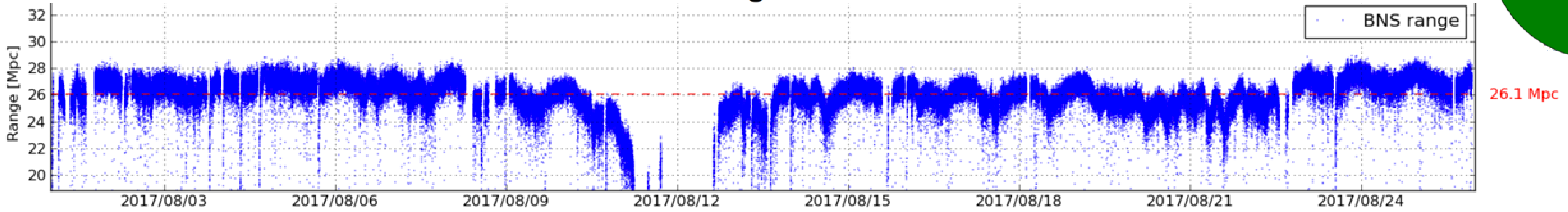






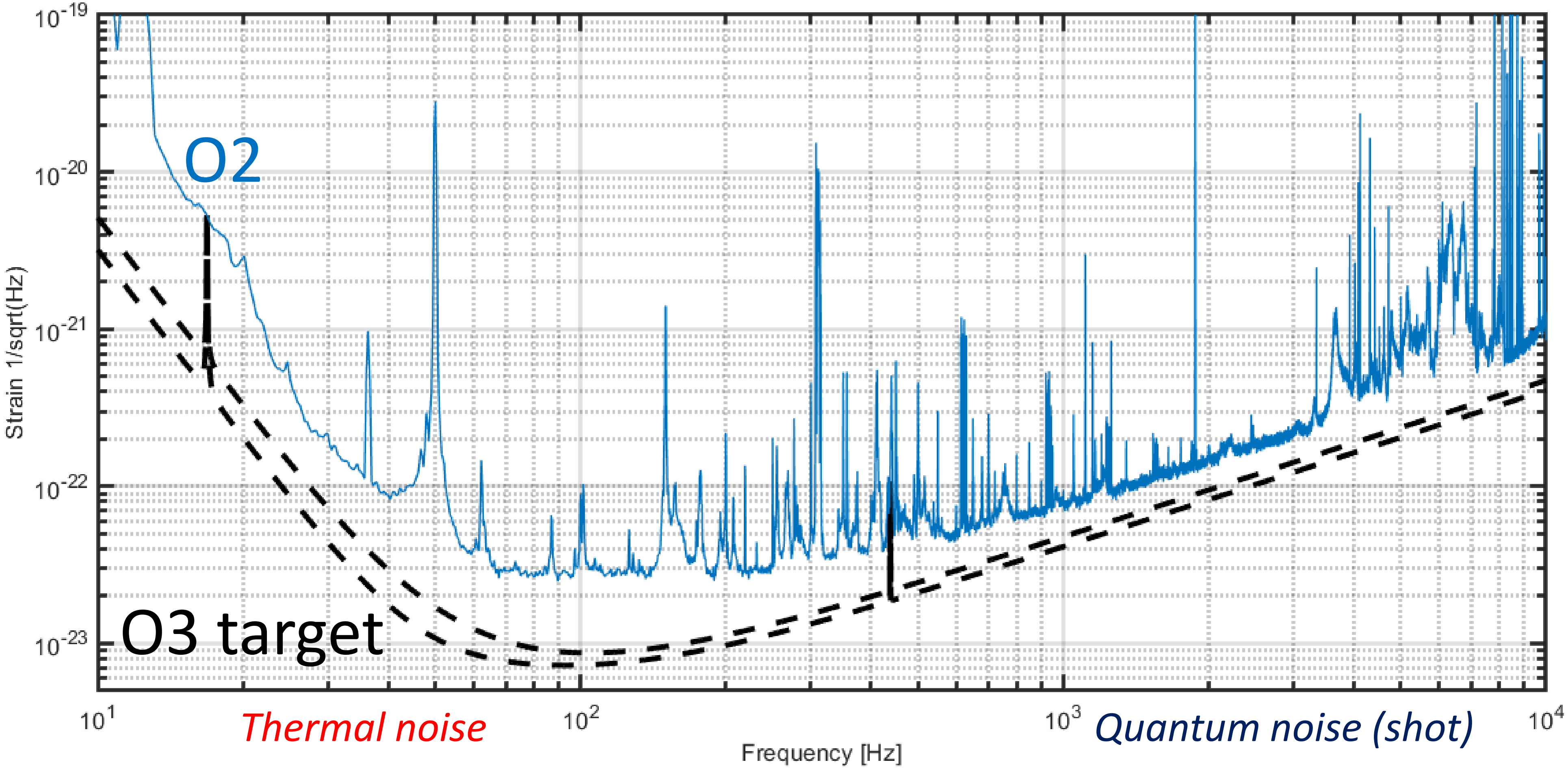
☐ observations 2015-17 vs 2010:

averaged observable volume of Universe : **~100x** gain for **BBH** like GW150914
~30x gain for **BNS** coalescence events



Advanced Virgo: from O2 to O3

Target: improving the sensitivity pushing the BNS horizon from 26-28 MPc to ~60 MPc (as foreseen in the mid-term observing scenario for AdV, *Living Rev Relativ 2018 21:3*)



Thermal noise

Quantum noise (shot)

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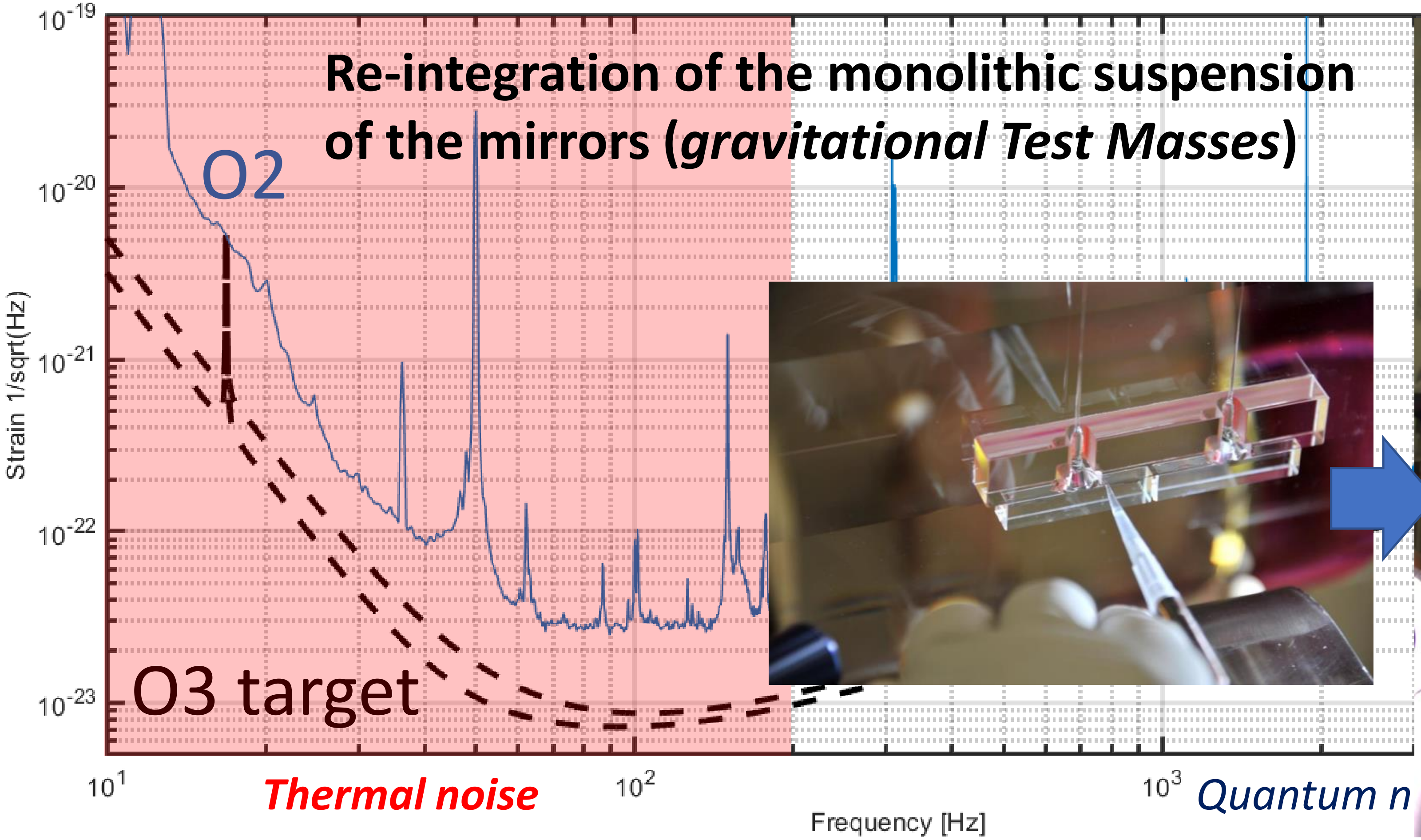
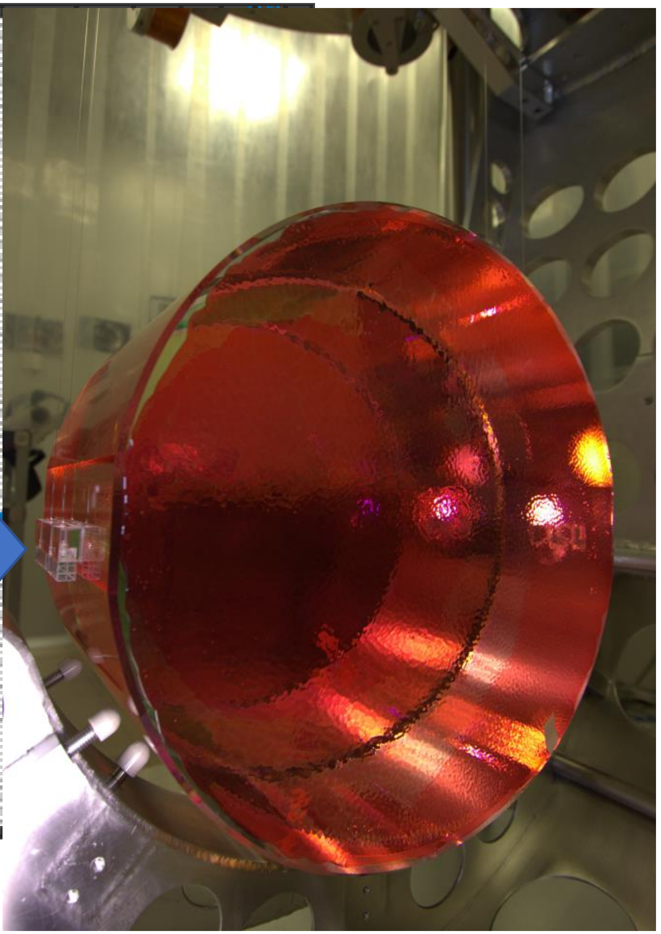


Re-integration of the monolithic suspension of the mirrors (*gravitational Test Masses*)

Thermal noise

Quantum n



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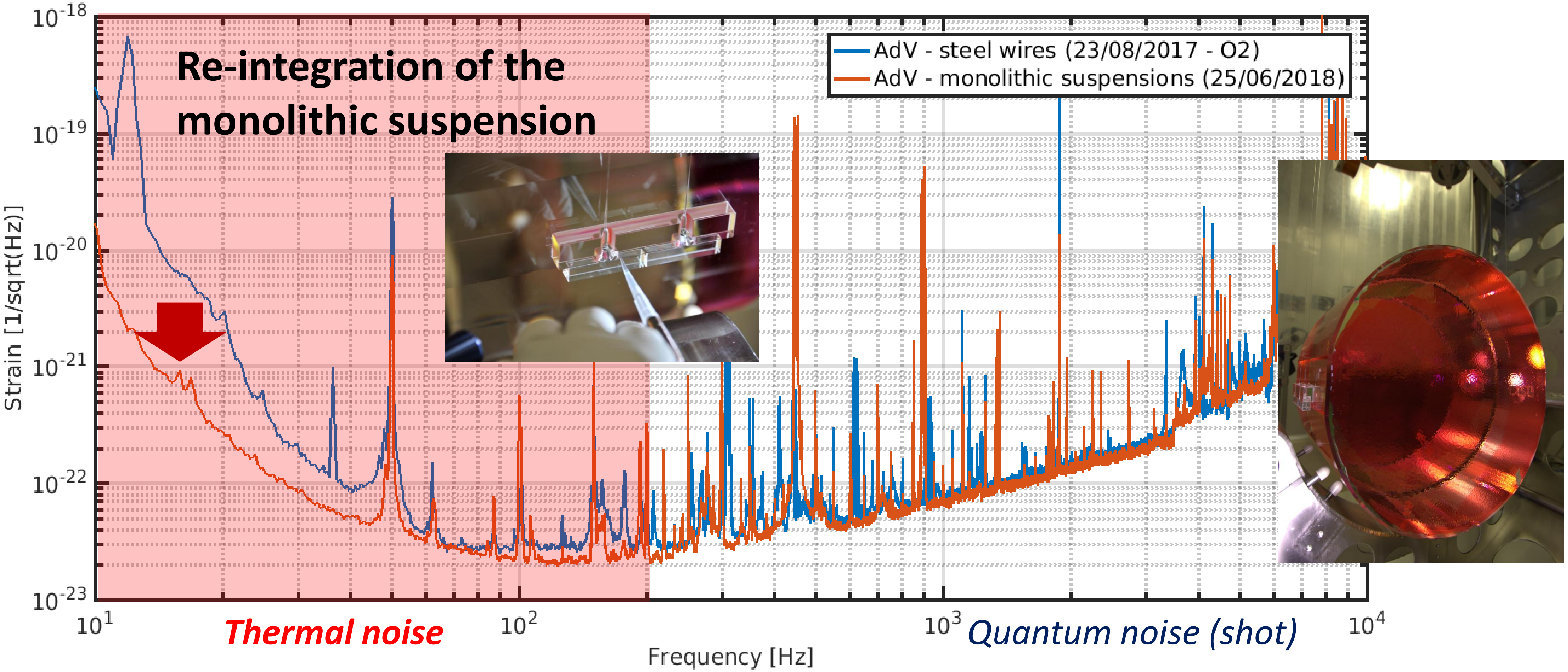

Re-integration of the monolithic suspension

Thermal noise

Quantum noise (shot)

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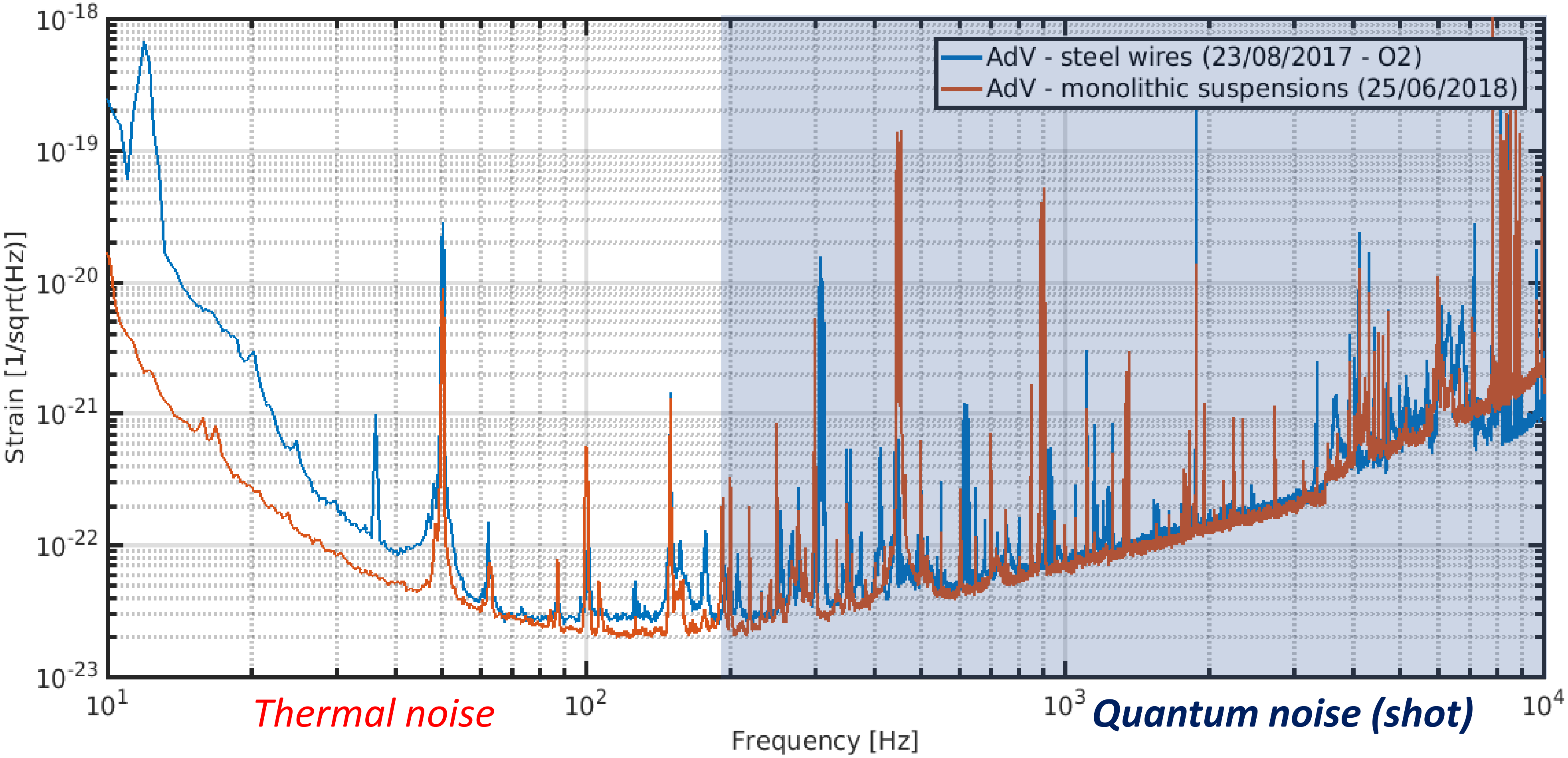

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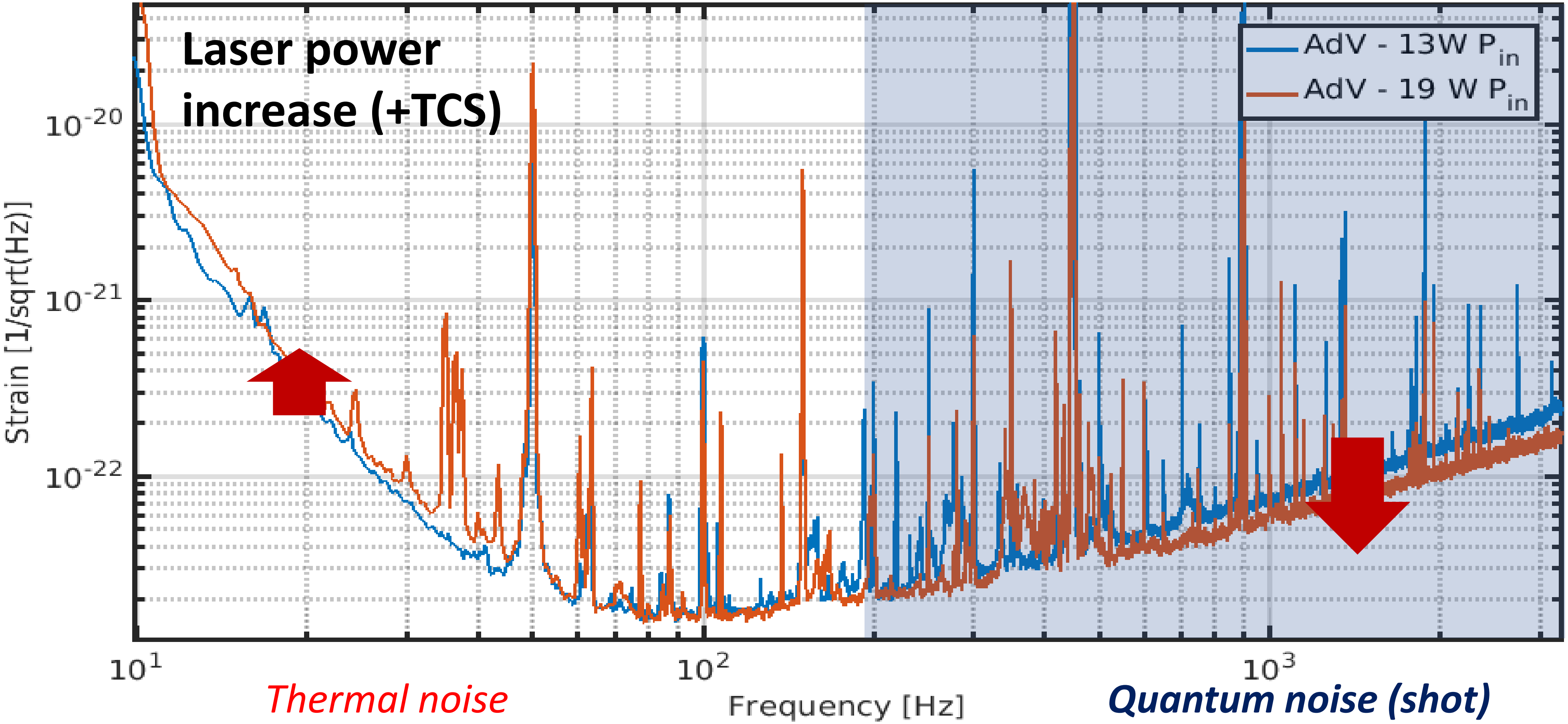

Laser power increase (+TCS)

Thermal noise

Quantum noise (shot)

Onde Gravitazionali: status e prospettive

Advanced Virgo: from O2 to O3

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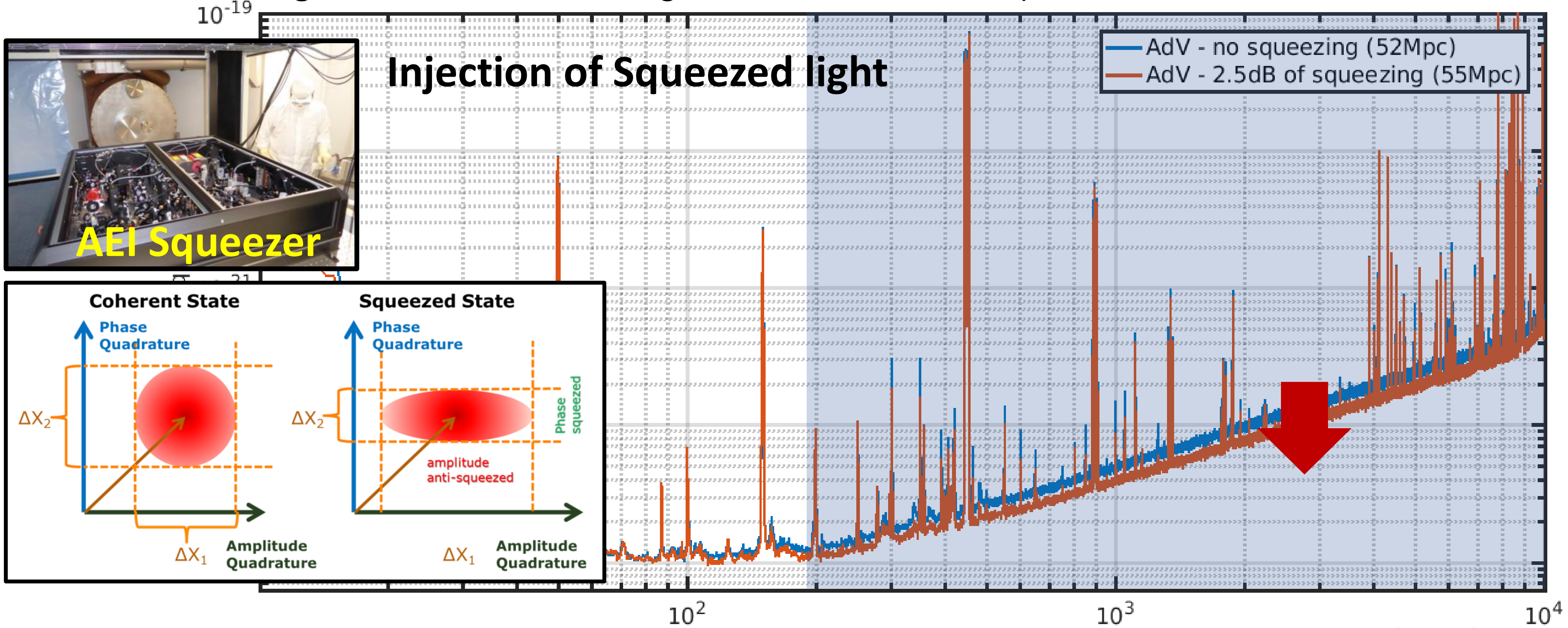


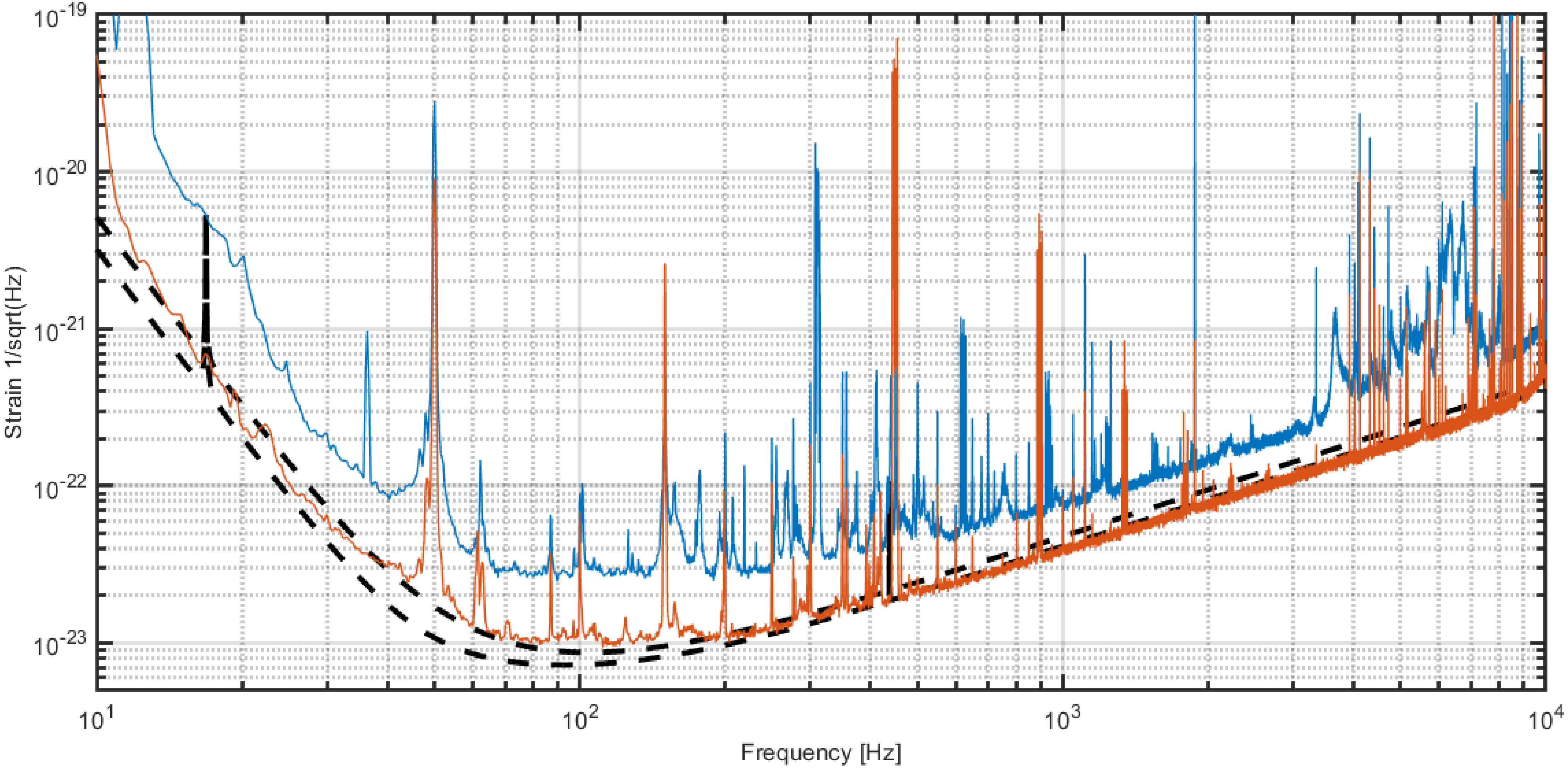
Injection of Squeezed light

Thermal noise

Quantum noise (shot)

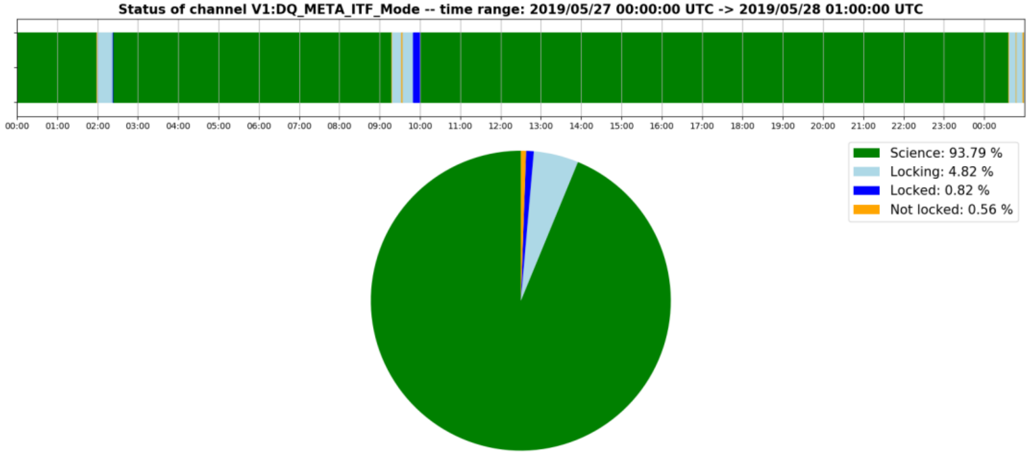
Onde Gravitazionali: status e prospettive

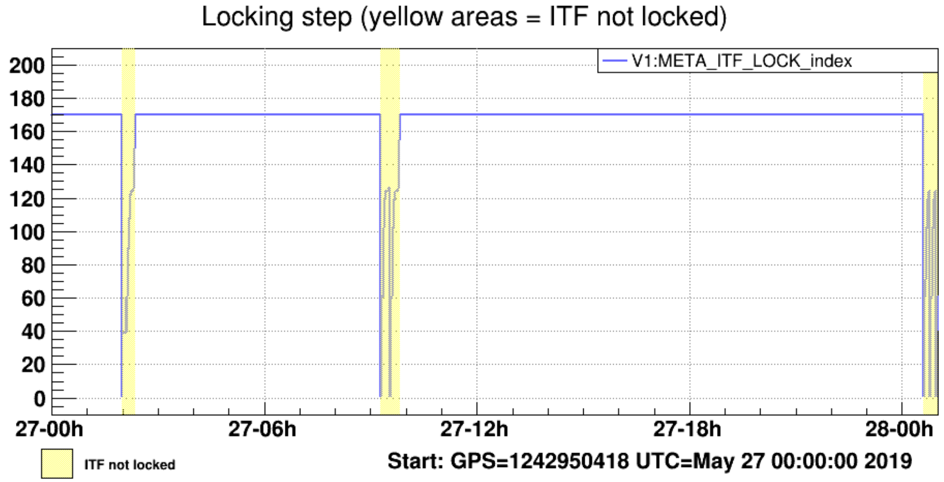
AdV Sensitivity, 2019 Feb 5th ➡ *55Mpc, ready for O3!*



Current status

- O3 started on April 1st and will last about 1 year;
- Sensitivity increased by ~ 85% wrt O2;
- Good stability (duty cycle ~ 90%);
- Observing advanced GW network: HLO+LLO+Virgo (KAGRA may join during O3)

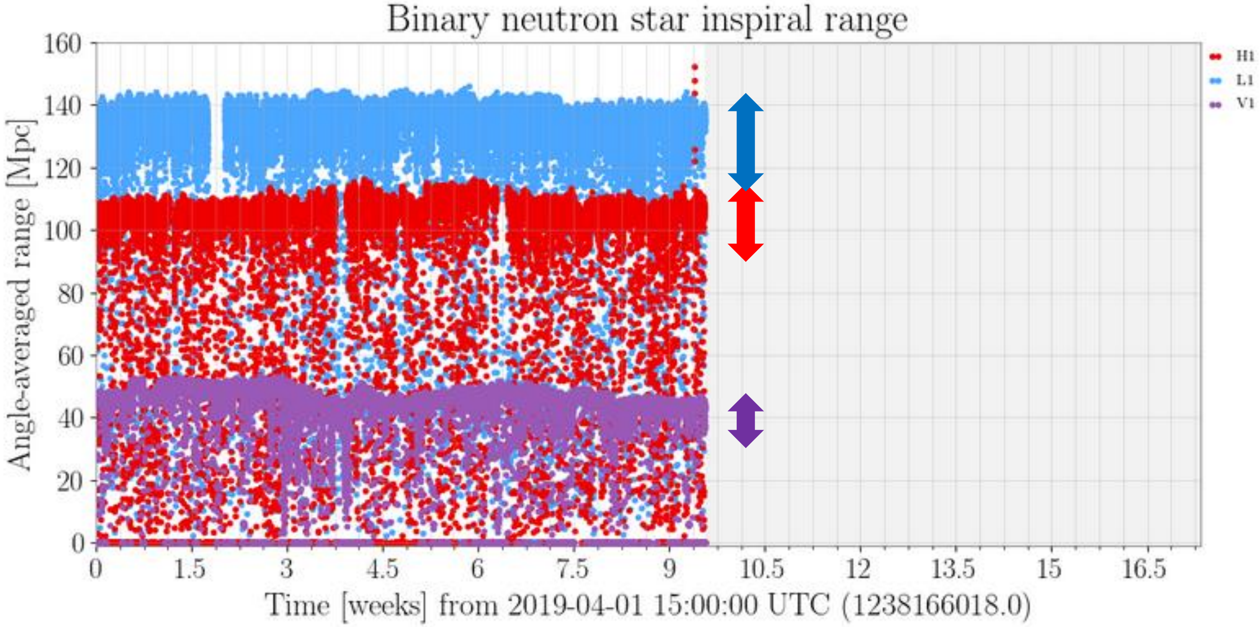


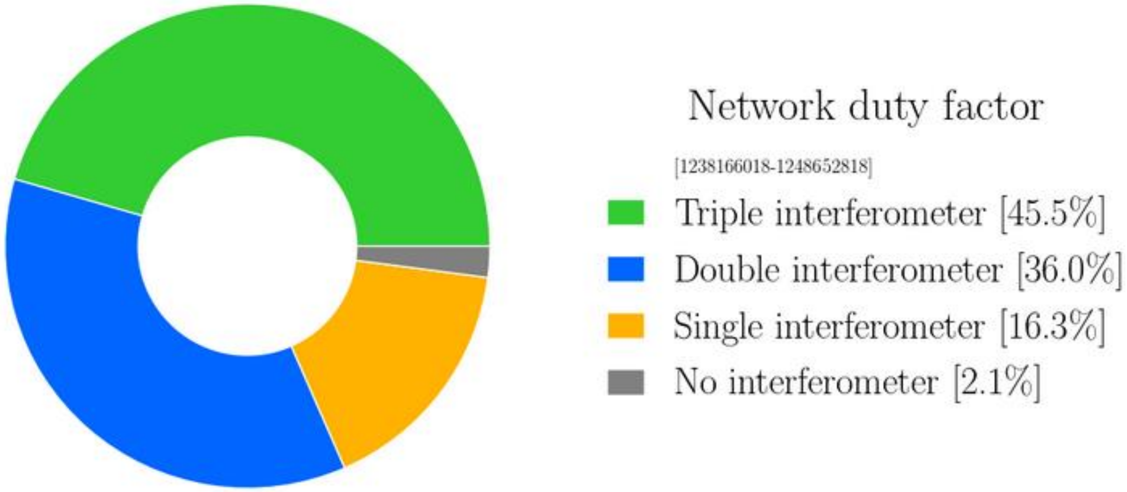


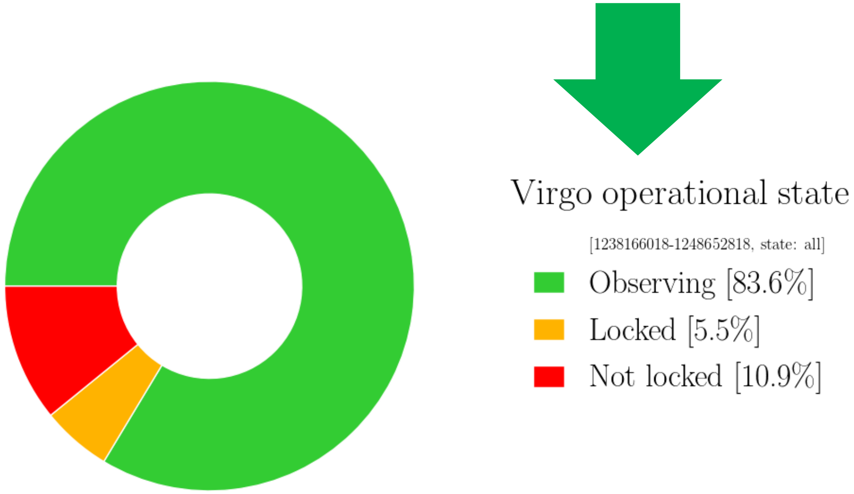
Onde Gravitazionali: status e prospettive

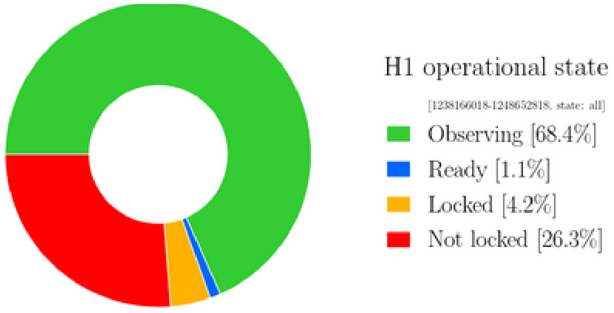
Status: https://www.gwopenscience.org/

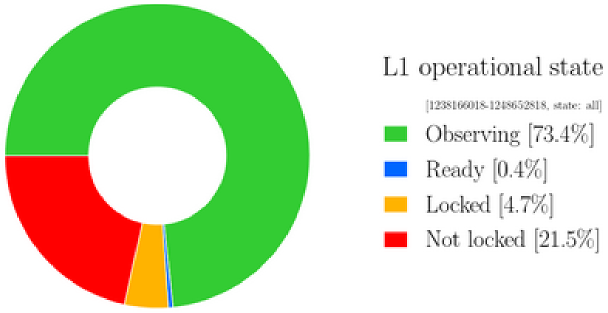
Public alerts: https://gracedb.ligo.org/latest/







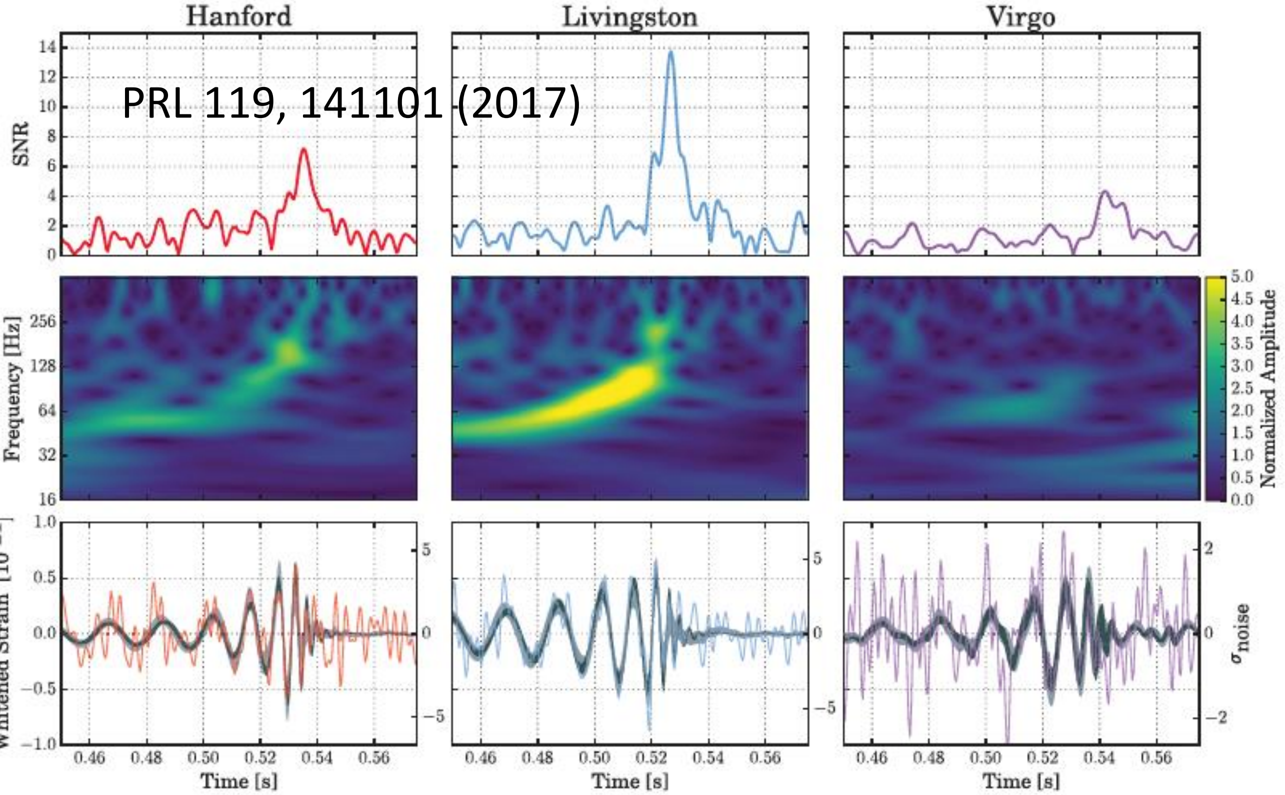




Onde Gravitazionali: status e prospettive

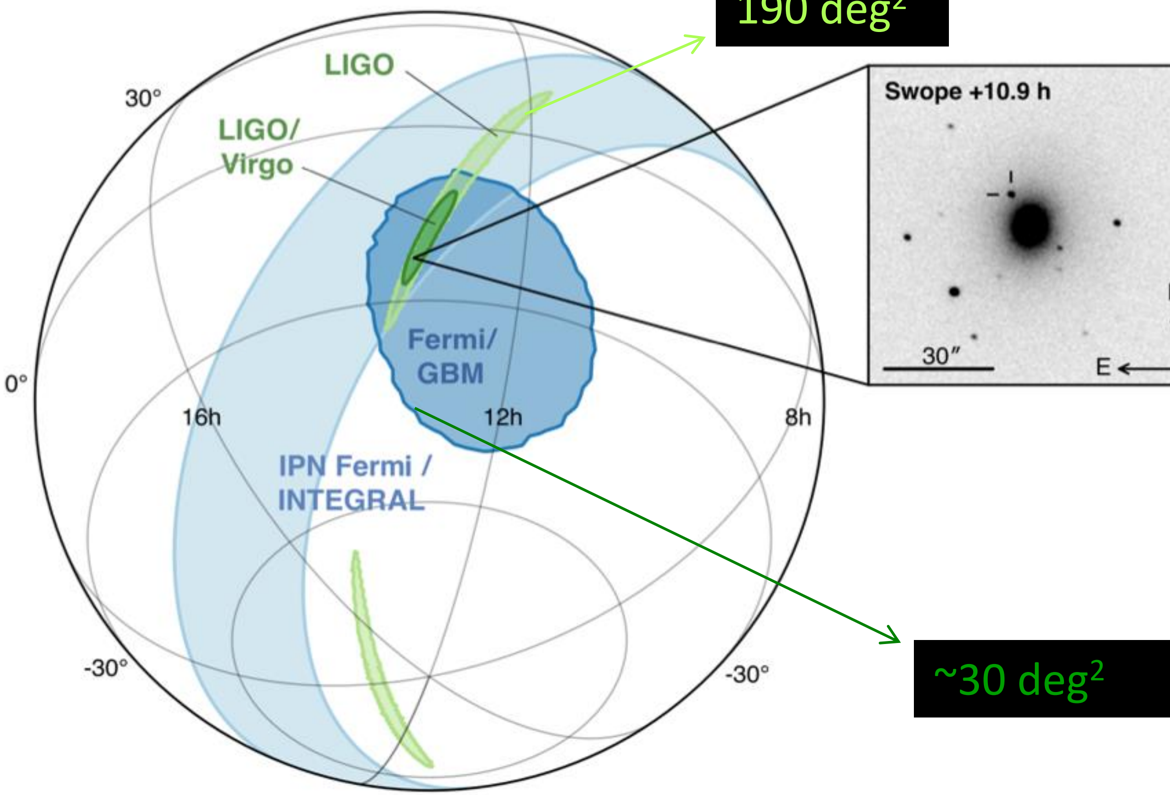
It works!

GW170814: the first BBH detection by Virgo



PRL 119, 141101 (2017)

GW170817: the first BNS detection by Virgo



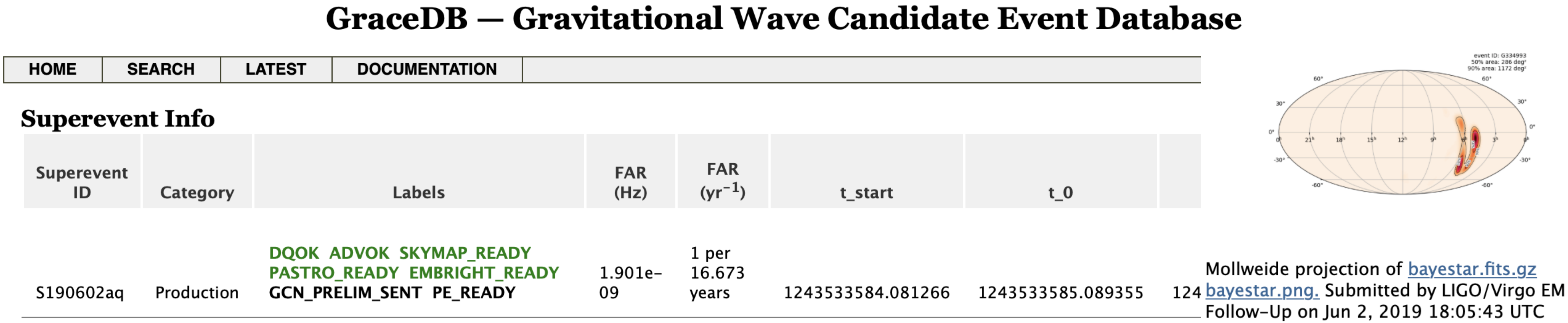
190 deg^2

~30 deg^2

PRL 119, 161101 (2017)

Since then:

- ❑ GWTC-1: the first GW catalog paper `[1811.12907]`: 10 BBH + 1 BNS
- ❑ O3 has started and public event alerts too: 14 candidates until now!



GraceDB — Gravitational Wave Candidate Event Database

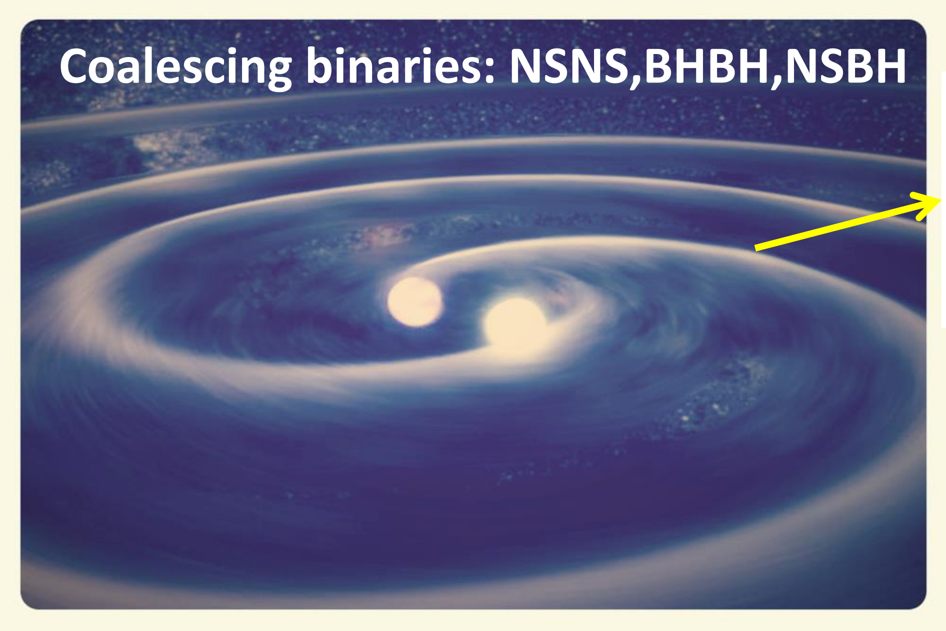
Superevent Info

Superevent ID	Category	Labels	FAR (Hz)	FAR (yr^{-1})	t_start	t_0	
S190602aq	Production	DQOK ADVOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY GCN_PRELIM_SENT PE_READY	1.901e-09	1 per 16.673 years	1243533584.081266	1243533585.089355	124

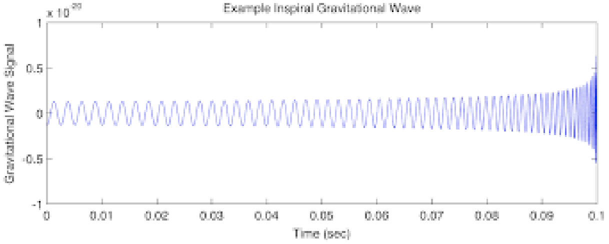
Mollweide projection of bayestar.fits.gz bayestar.png. Submitted by LIGO/Virgo EM Follow-Up on Jun 2, 2019 18:05:43 UTC

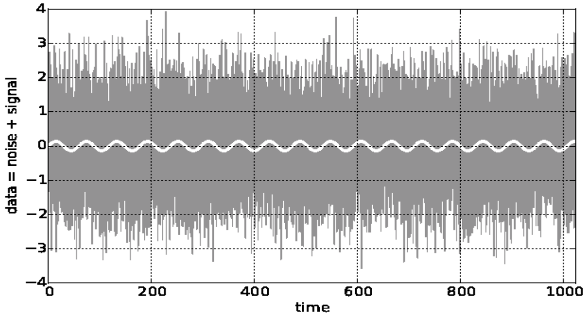
- ❖ NSs and BHs are expected to emit GWs of different 'flavours' : so far we have just looked at the tip of the iceberg

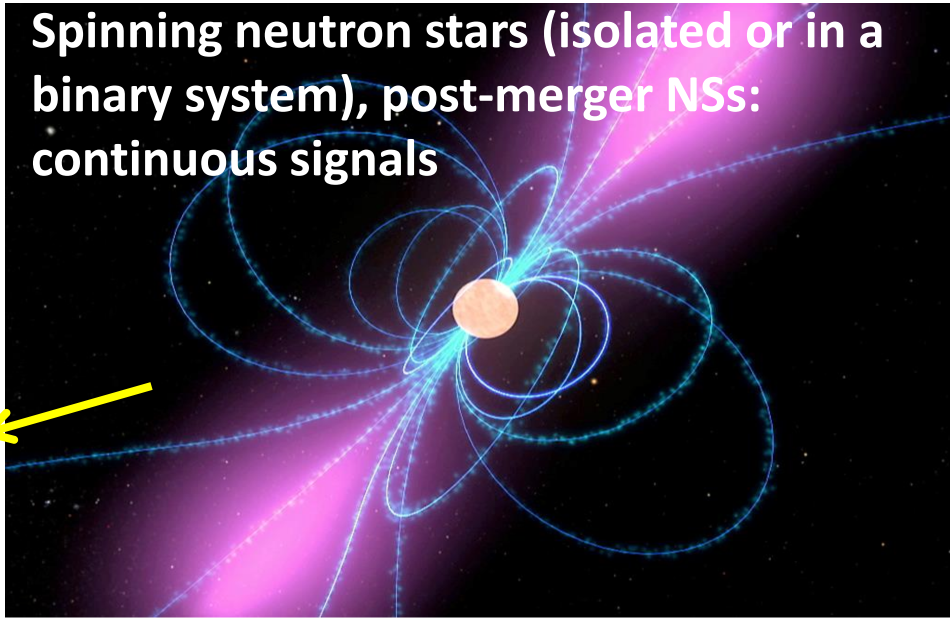
GW zoo



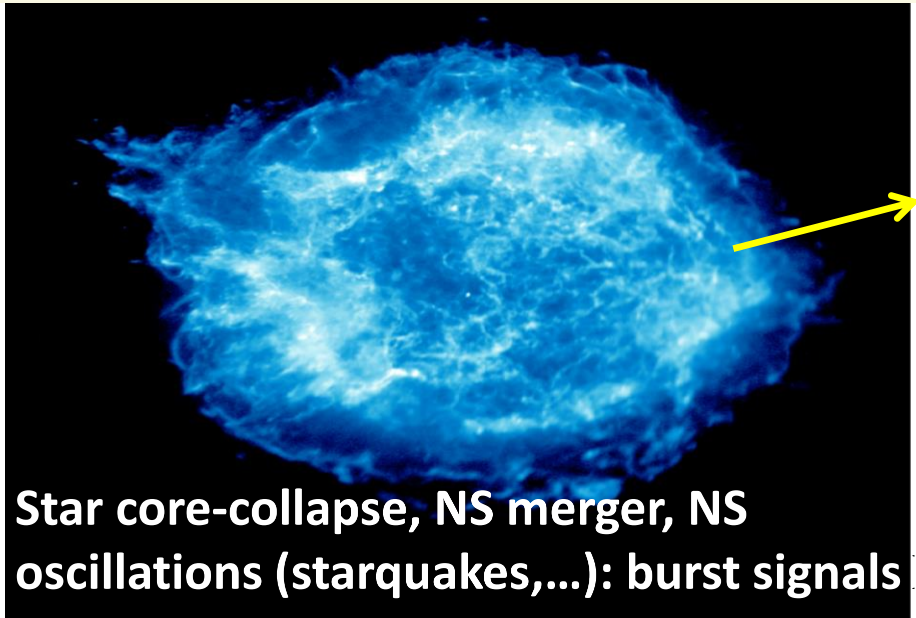
Coalescing binaries: NSNS,BHBH,NSBH



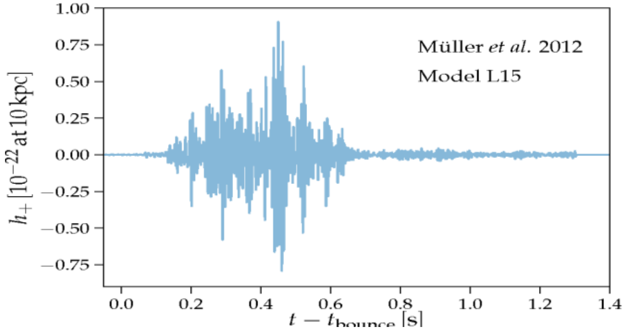


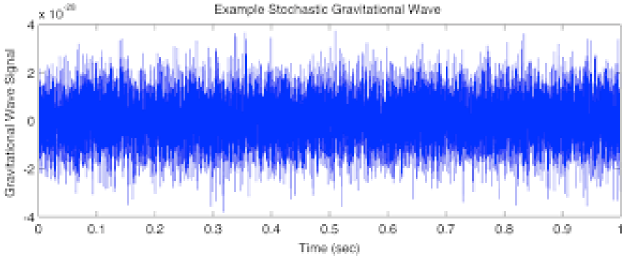


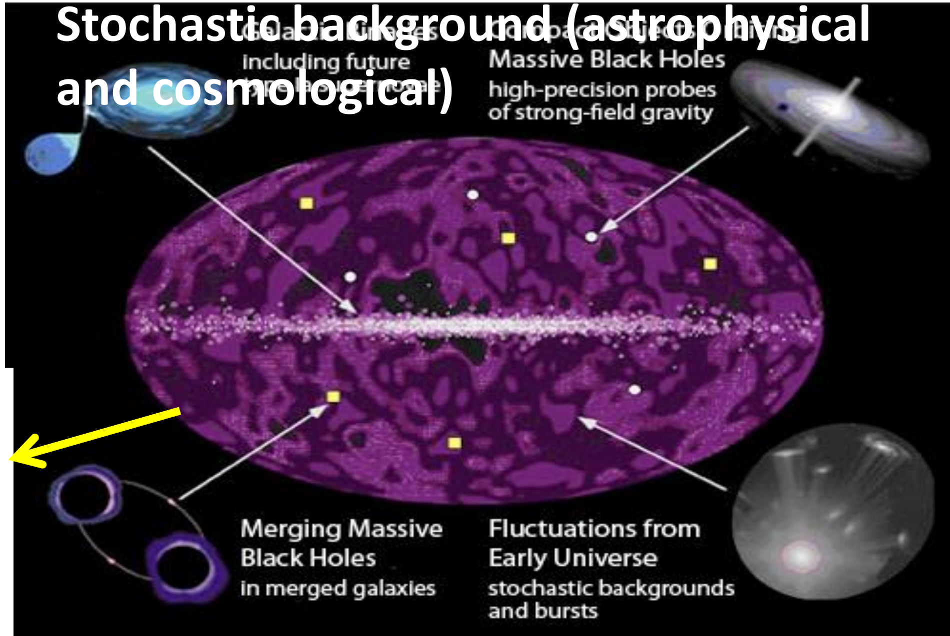
Spinning neutron stars (isolated or in a binary system), post-merger NSs: continuous signals



Star core-collapse, NS merger, NS oscillations (starquakes,…): burst signals







Stochastic background (astrophysical and cosmological)

Onde Gravitazionali: status e prospettive

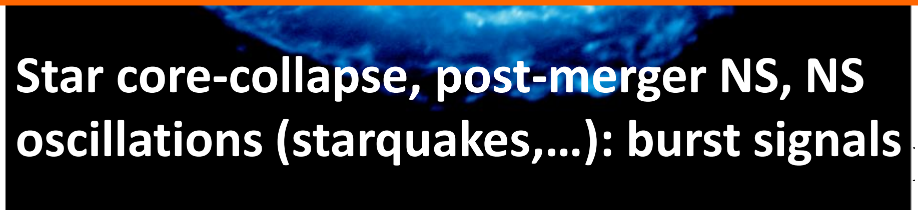
GW zoo

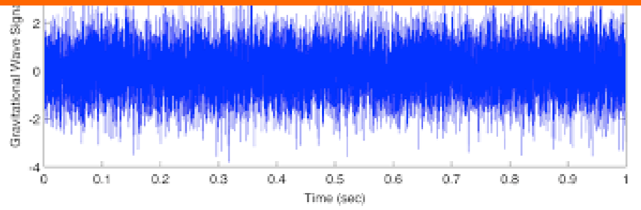

Coalescing binaries: NSNS,BHBH,NSBH


Spinning neutron stars (isolated or in a binary system)

The search of each kind of signal poses specific problems in terms of:

- ➢ DA algorithms to be used (matched filter → unmodeled search)
- ➢ Computational cost (laptop → geographically distributed resources)
- ➢ Impact of noise artifacts (time-domain glitches, spectral lines,…)
- ➢ Waveform modelling (analytic, numerical, # of parameters,…)
- ➢ Interpretation of the results (both detections and upper limits)


Star core-collapse, post-merger NS, NS oscillations (starquakes,…): burst signals



GW zoo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→ More details in Francesco's talk

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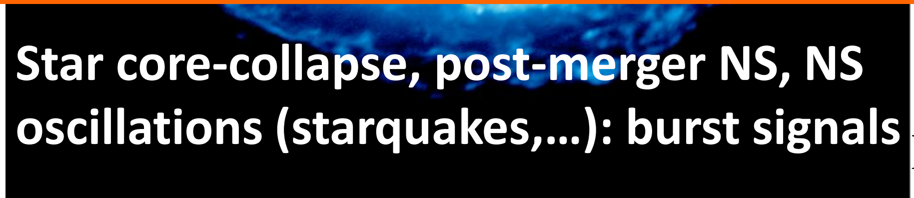
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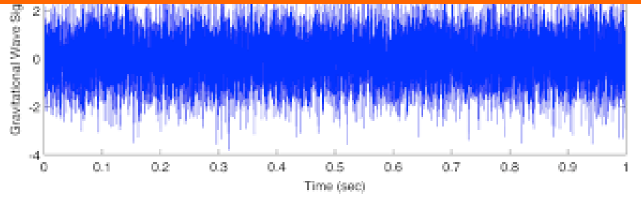
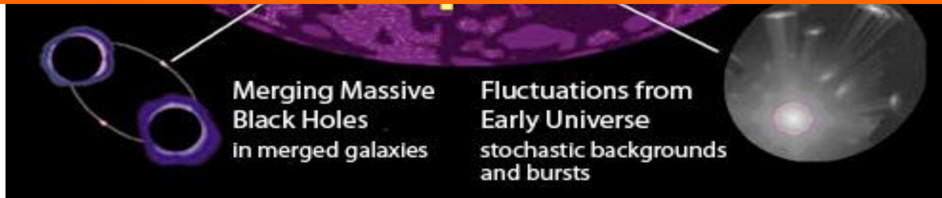




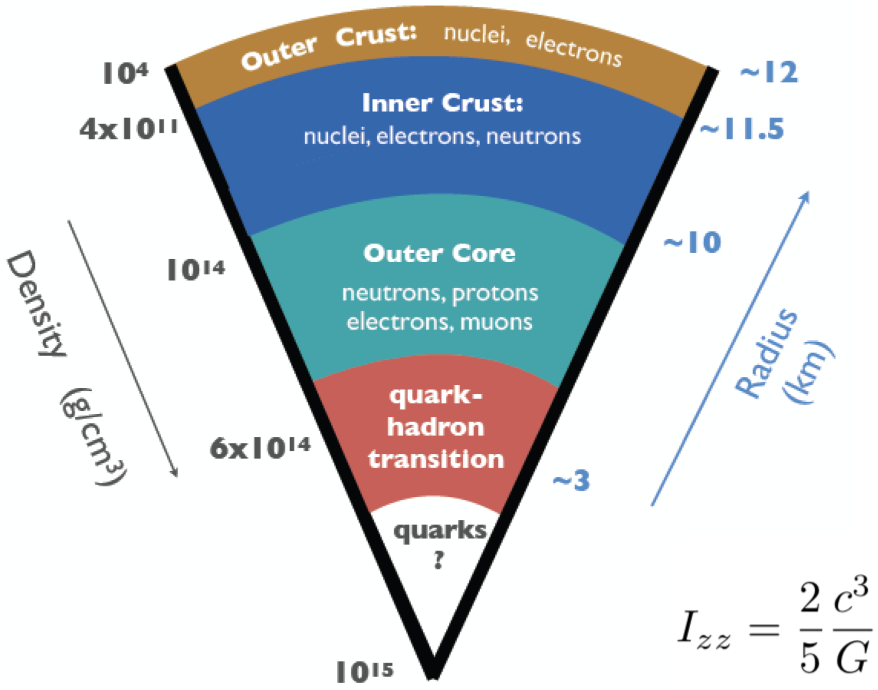
Is what we do relevant for INFN?

(Synergies/complementarity with other groups)

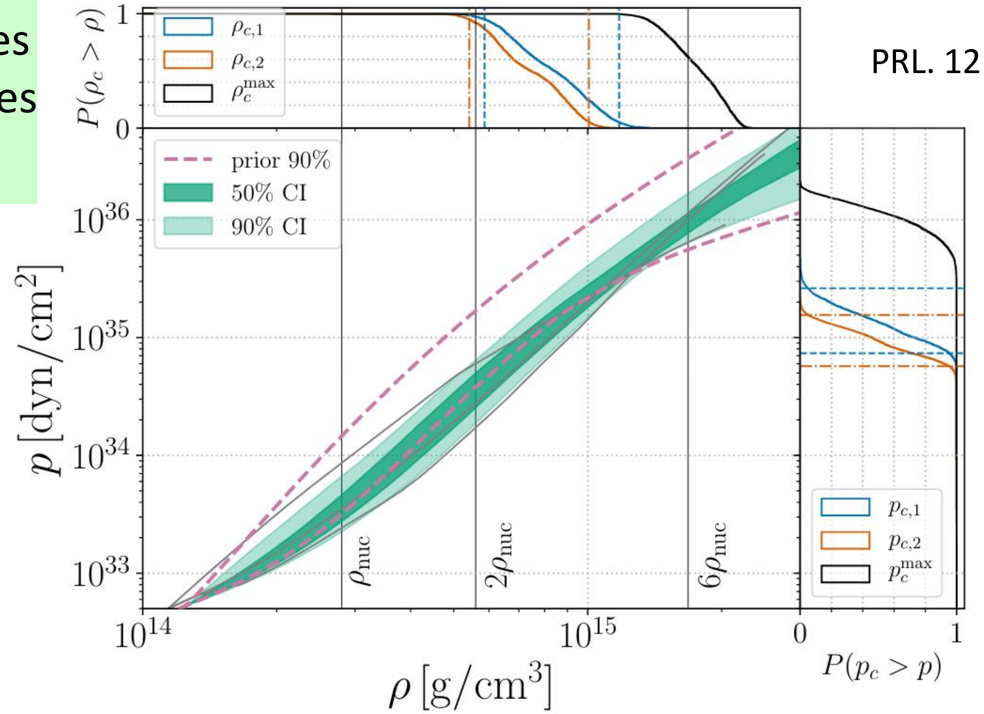
Example 1

Nuclear physics
(NS structure, high density matter EOS)

* Compact binaries
* Continuous waves
* NSs merger



Marginalized posterior of NS pressure vs density (GW170817)



PRL. 121, 161101 (2018)

NS moment of inertia from continuous wave emission:

$$I_{zz} = \frac{2}{5}\frac{c^3}{G}\frac{f}{|\dot{f}|}(h_0^{sd})^2 d^2 = 1.54 \cdot 10^{37}\left(\frac{f}{100\,\mathrm{Hz}}\right)\left(\frac{|\dot{f}|}{10^{-11}\,\mathrm{Hz\,s^{-1}}}\right)^{-1}\left(\frac{h_0^{sd}}{10^{-25}}\right)^2\left(\frac{d}{1\,\mathrm{kpc}}\right)^2 \; kg \cdot m^2$$

Example 2

Tests of General Relativity

(deviation from GR affects signal phase)

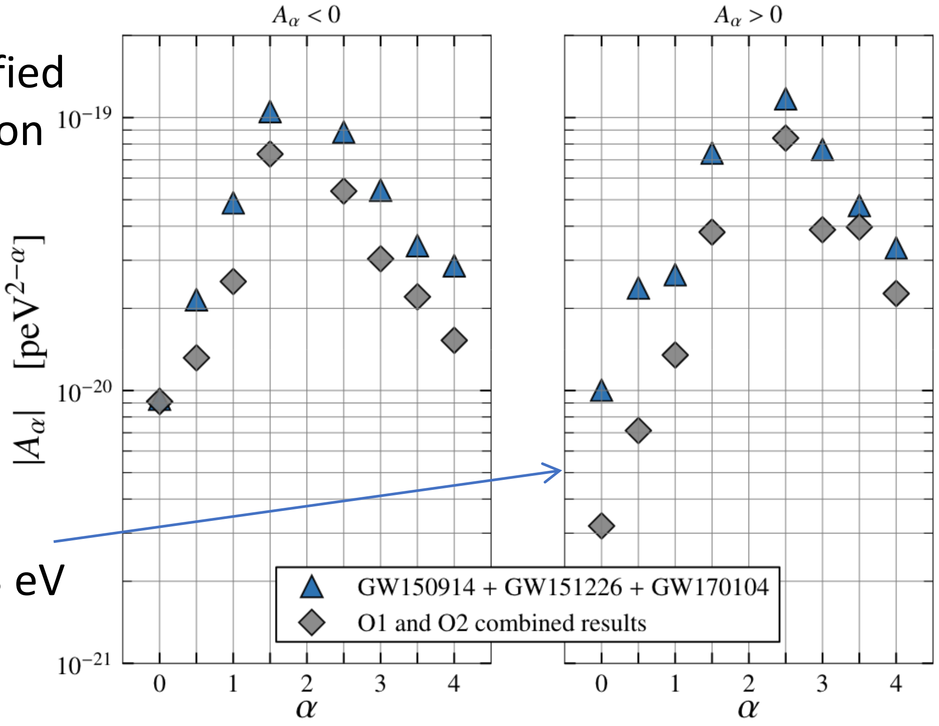
* Compact binaries

* BH QN modes

* Continuous waves

Constraints on modified GW dispersion relation

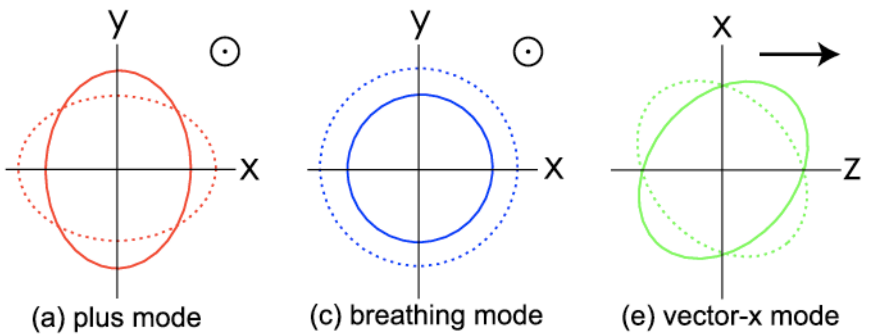
$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$



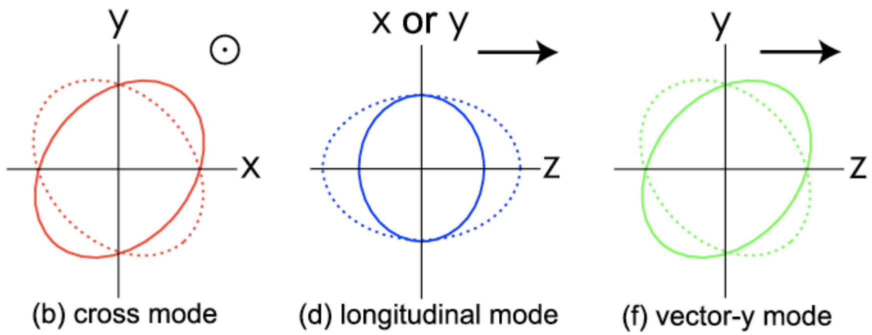
Graviton mass:
$m_g = A_0^{1/2}/c^2 < 5.5E\text{-}23$ eV

1903.04467

PHYSICAL REVIEW D 79, 082002 (2009)



(a) plus mode (c) breathing mode (e) vector-x mode



(b) cross mode (d) longitudinal mode (f) vector-y mode

GW polarizations

Log B ≈ 20 in favour of tensor polarizations w.r.t to vector or scalar [1811.00364]

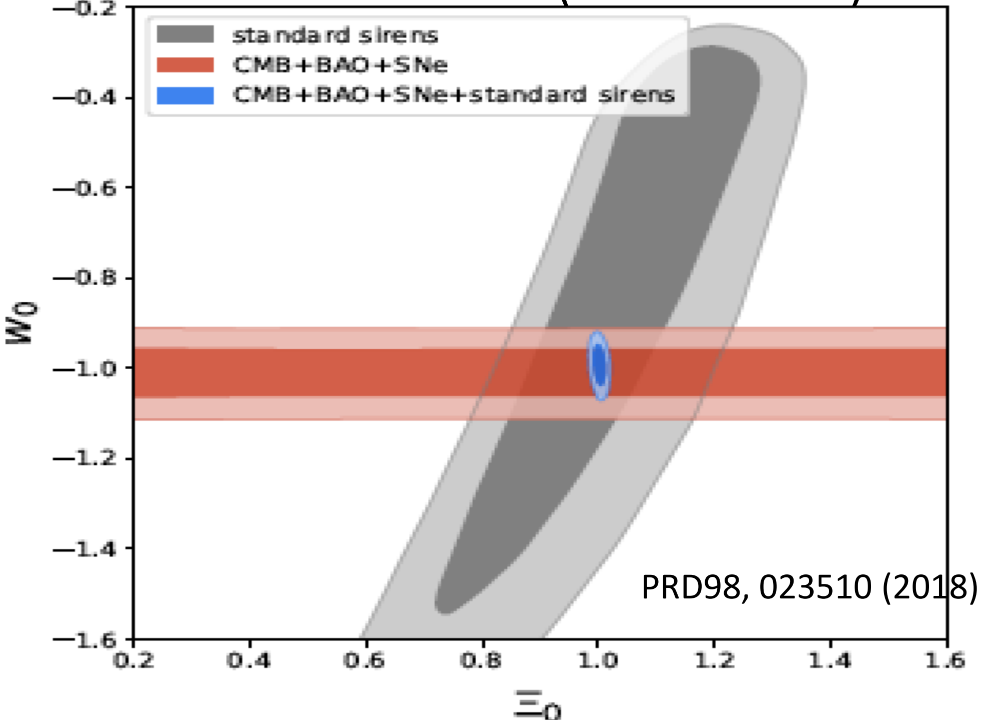
Example 3

Cosmological parameters

(H_0, dark energy,…)

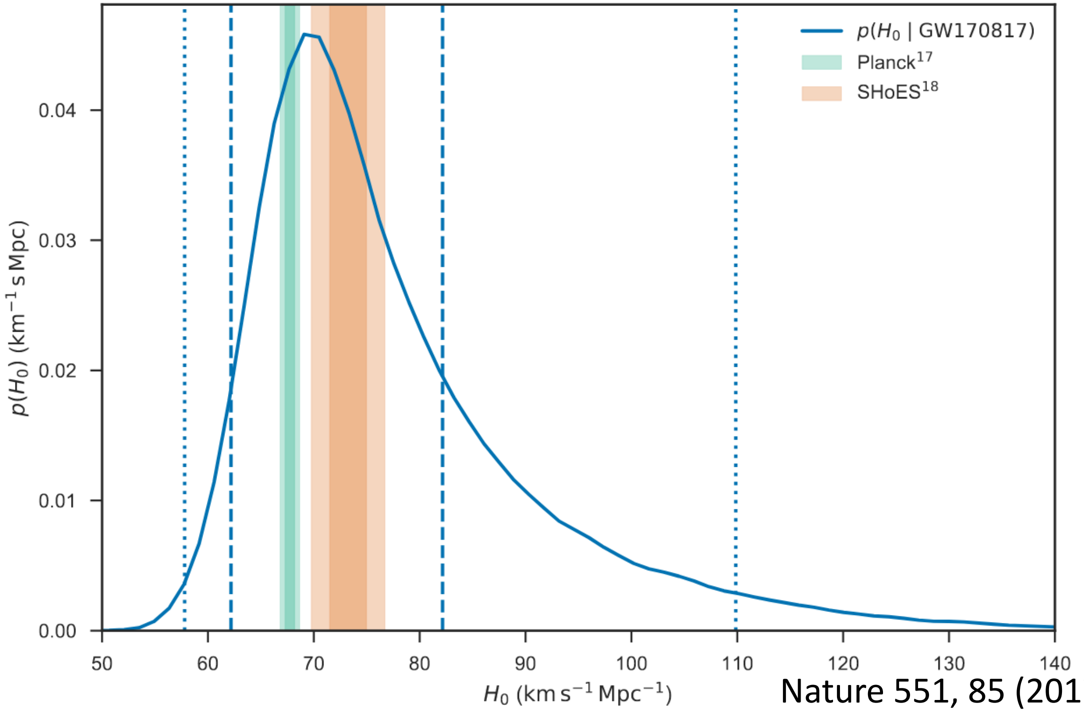
*Compact binaries
*Multi-messenger

Constraints on dark energy parameters with standard sirens (3G detectors)



PRD98, 023510 (2018)

Marginalized posterior density for the Hubble constant (GW179817)



Nature 551, 85 (2017)

Luminosity distance:

$$d_L(z) = \frac{1+z}{H_0} \int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_M (1+\tilde{z})^3 + \rho_{\mathrm{DE}}(\tilde{z})/\rho_0}}$$

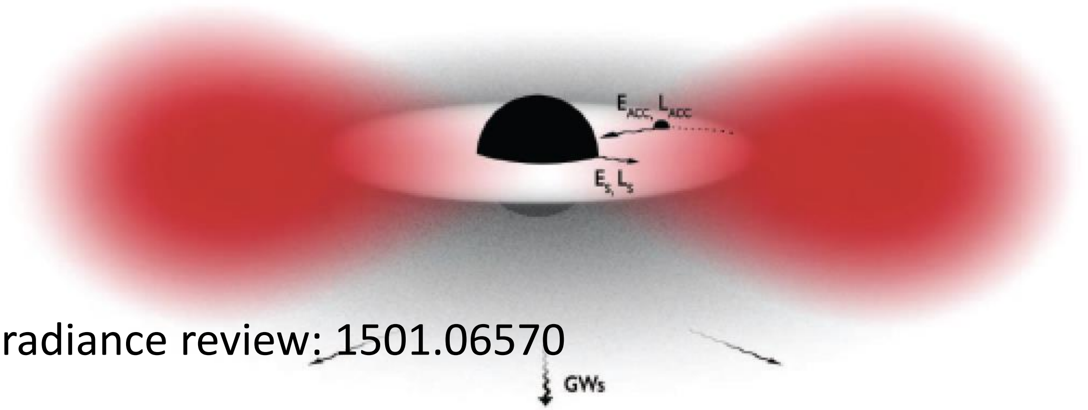
Example 4

Dark matter
(ultra-light bosons, primordial black holes)

*Compact binaries
*Continuous waves

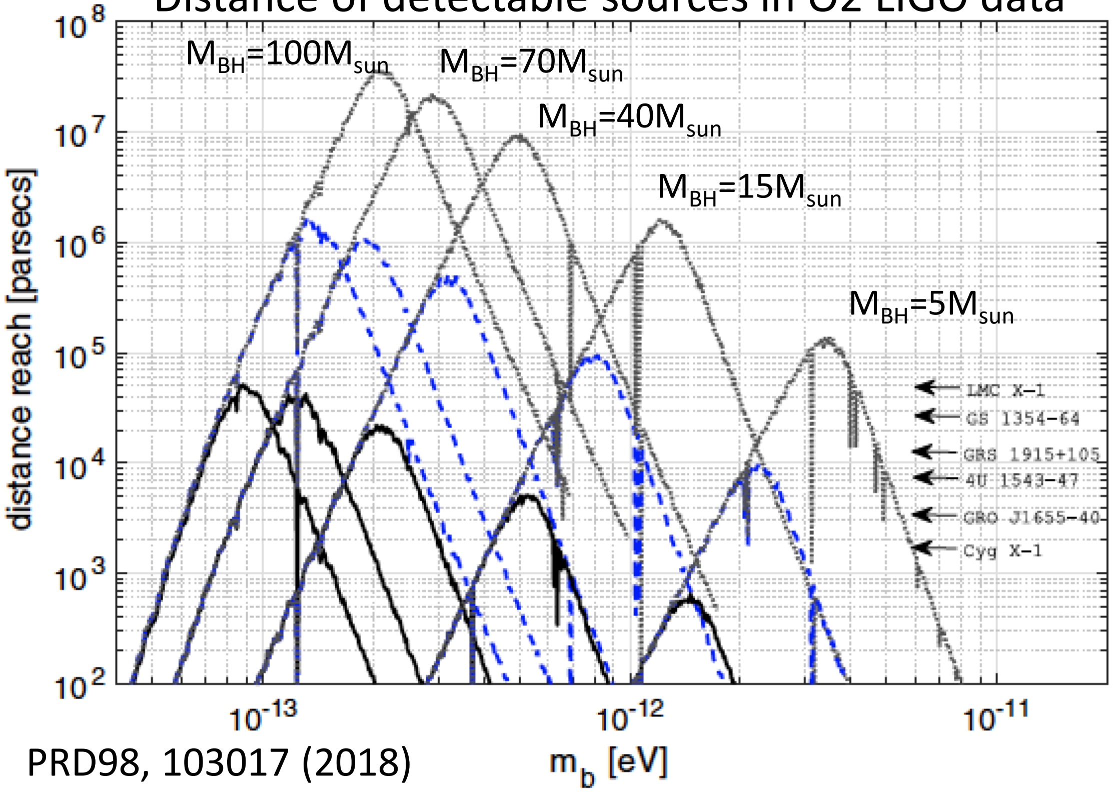
more in Francesco’s talk

GW emission from the ‘boson cloud’ forming around a spinning BH → boson annihilation in the language of particle physics



Superradiance review: 1501.06570

Distance of detectable sources in O2 LIGO data

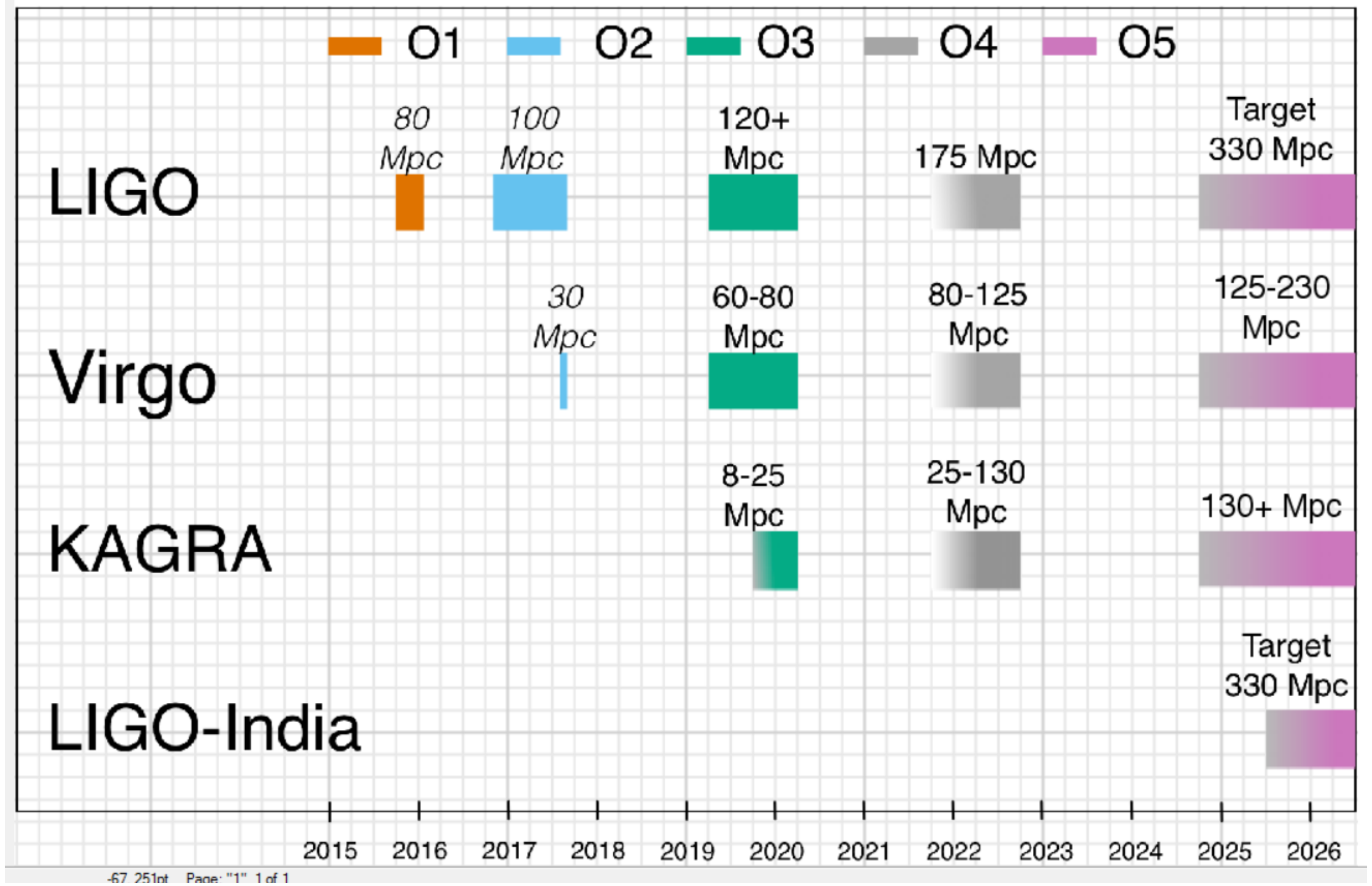


PRD98, 103017 (2018)

What’s next?

Onde Gravitazionali: status e prospettive

Long-term timeline



- What can we do after AdV to exploiting at the best the infrastructure
- **AdV+: a two-step approach, 120 Mpc/230 Mpc, 6-year**

Beyond O3…

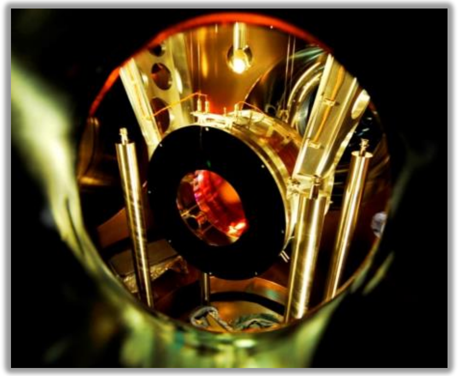
AdV+, phase I (between O3 and O4):

Reaching AdV full target (~120Mpc)

Complete the AdV program:

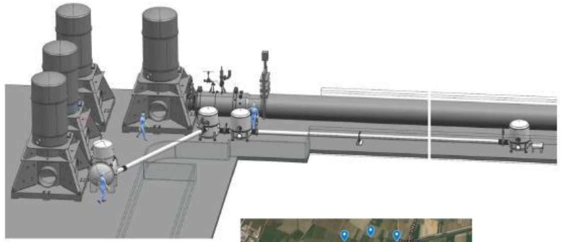
40W laser (18W in O3)

Signal recycling

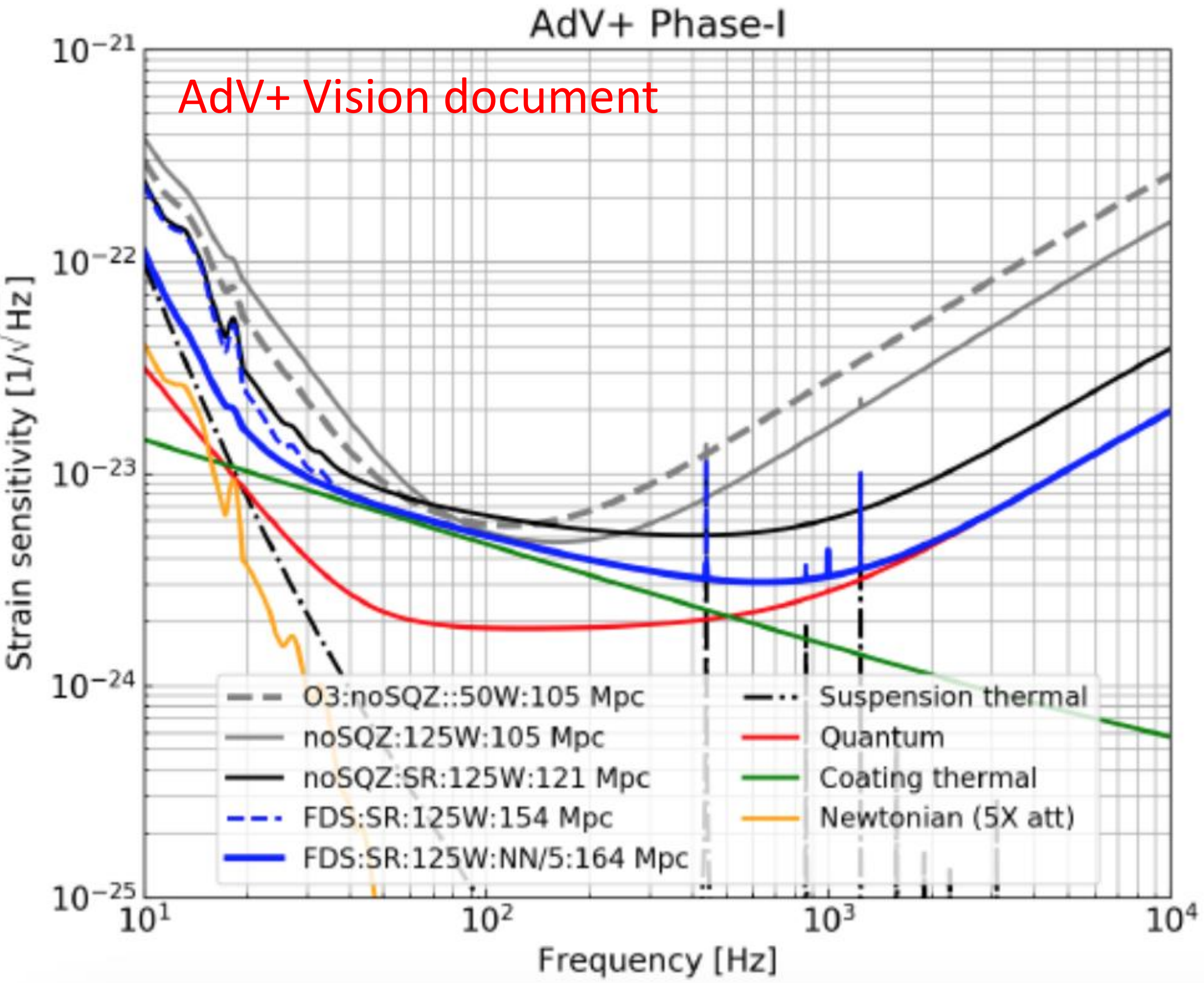


Frequency Dependent Squeezing

300 m-long filter cavity



Newtonian Noise Cancellation


AdV+ Vision document

Beyond O3…

AdV+, phase II (between O4 and O5) :

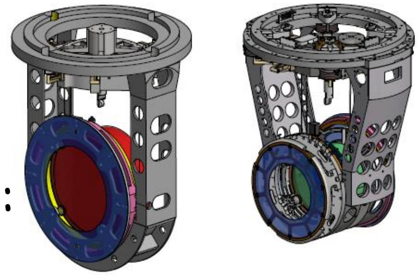
Thermal noise reduction, large beams, high power laser

Larger mirrors

Diameter: 550 mm, thickness: 200 mm, mass: 100-120

Scenario 1: **ETM-only** → 200 Mpc range

Scenario 2: **Full** → 230 Mpc range



In parallel coating improvements:

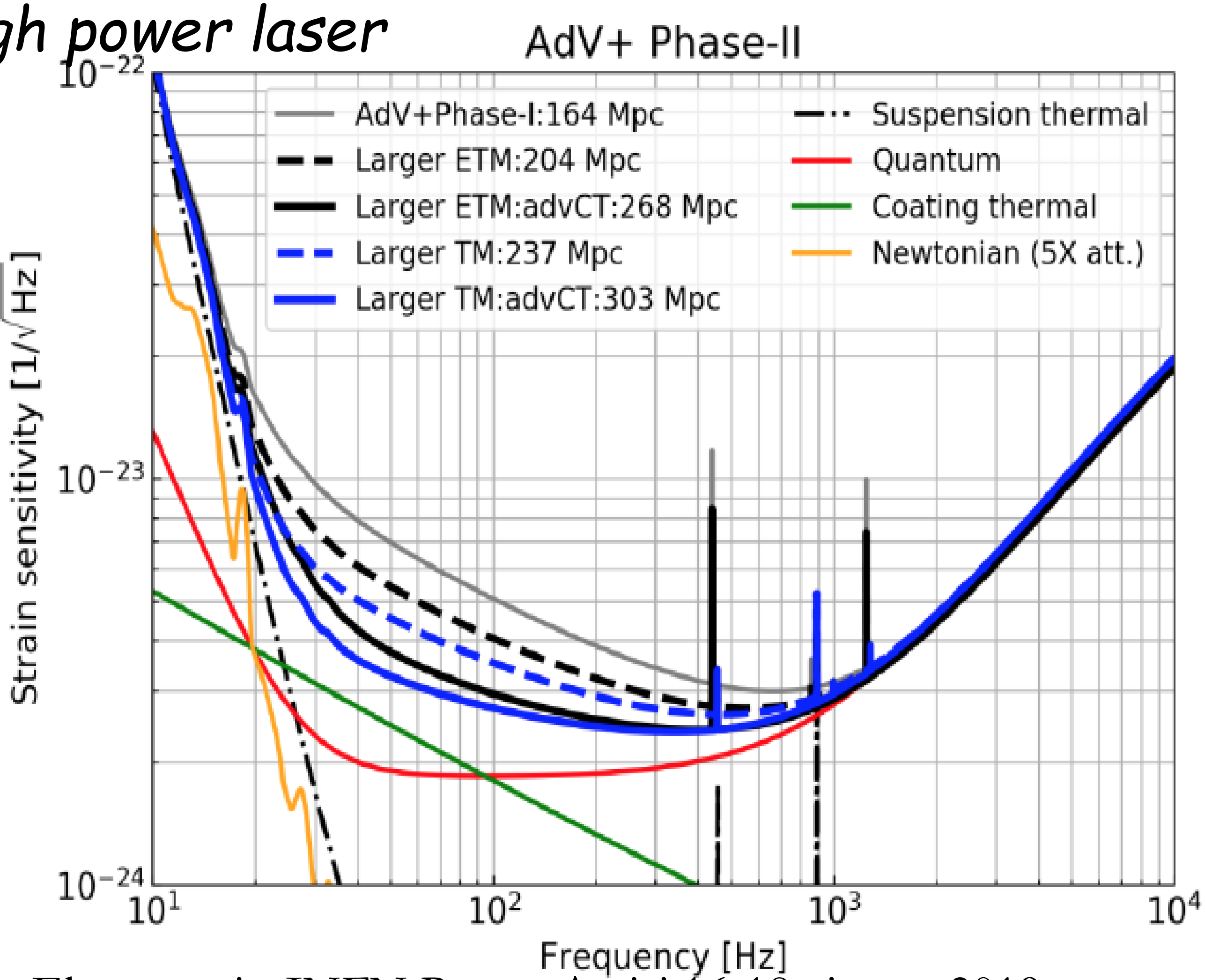
If factor 3 reduction in **Coating TN**:

Scenario 1: ETM-only

Scenario 2: full upgrade

Several challenges, **feasibility under study**:

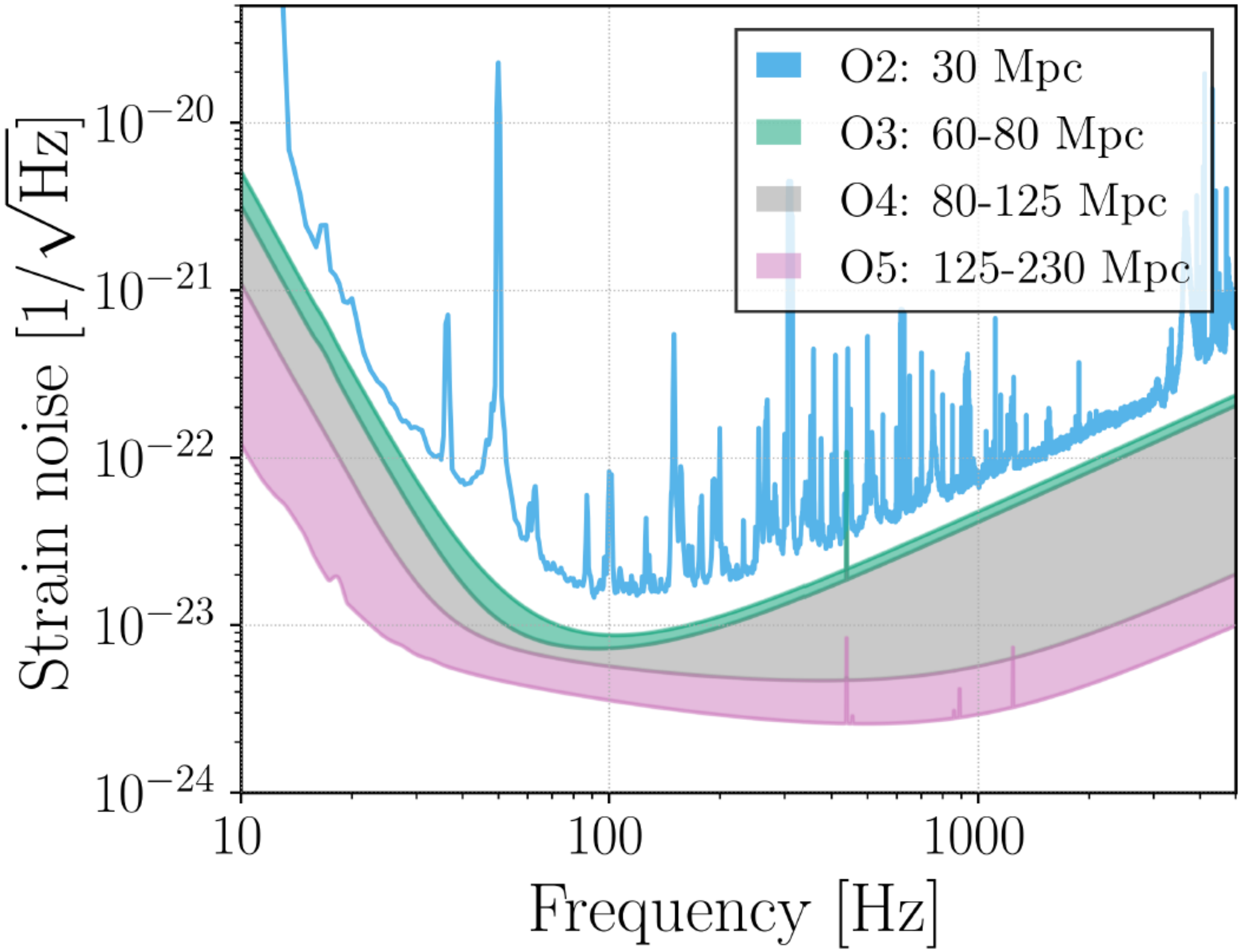
- Handling large masses (100kg-150kg for BS)
- Handling and integrating the payloads into present/modified VACUUM system
- Folded VS marginally stable Recycling FP
- Design of very large baffles …



Onde Gravitazionali: status e prospettive

Beyond O3…

AdV+

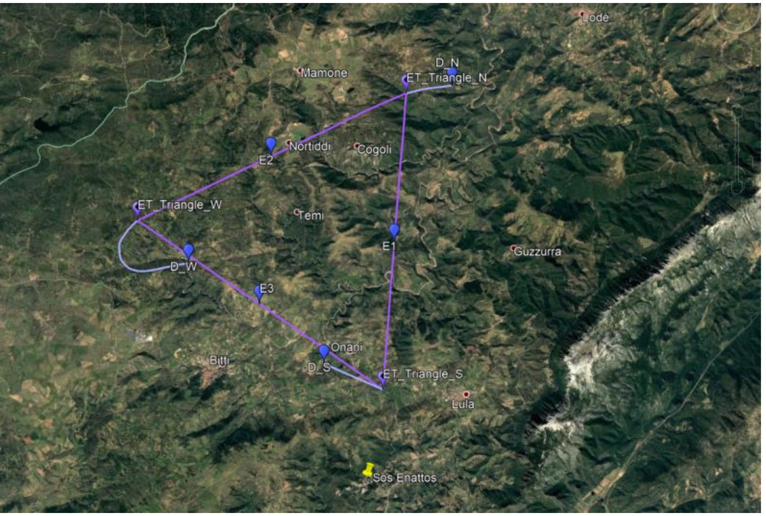


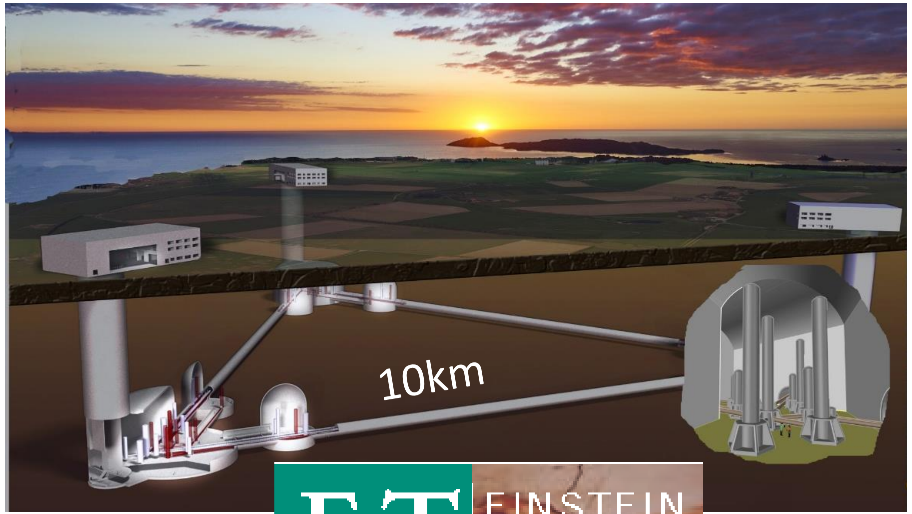
AdV+ phase 1

AdV+ phase 2

Onde Gravitazionali: status e prospettive

Towards the **third generation** detectors: **ET**



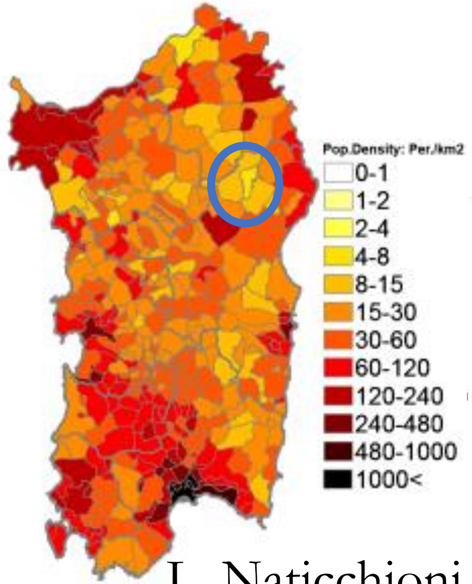


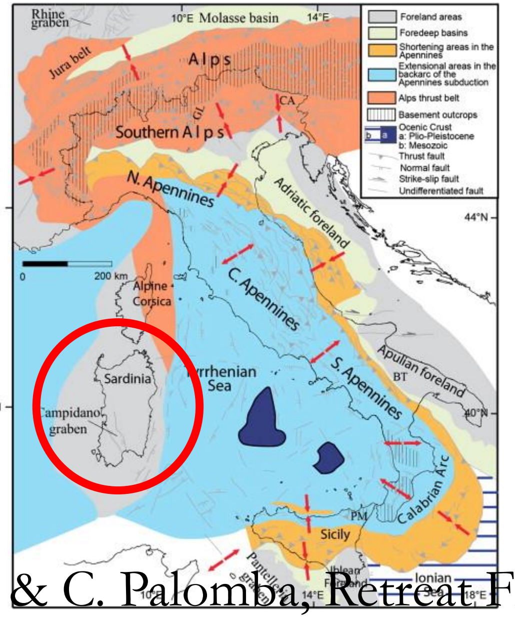
ONDE GRAVITAZIONALI: MIUR, INFN E UNISS CANDIDANO LA REGIONE SARDEGNA A OSPITARE IL FUTURO OSSERVATORIO INTERNAZIONALE

Pubblicato: 22 Febbraio 2018

COMUNICATO CONGIUNTO MIUR/INFN/REGIONE SARDEGNA/UNISS_Il Ministero dell'Istruzione, dell'Università e della Ricerca sosterrà la candidatura della Regione Sardegna a ospitare un Centro europeo per l'Osservatorio delle onde gravitazionali nella miniera di Sos Enattos a Lula. Il MIUR, la Regione, l'Istituto Nazionale di Fisica Nucleare e l'Università di Sassari hanno firmato un Protocollo d'intesa finalizzato a mettere in atto ogni iniziativa utile a favorire l'insediamento della infrastruttura Einstein Telescope nell'Isola, anche con lo scopo di entrare nella lista delle infrastrutture di ricerca riconosciute a livello europeo. Il progetto era stato presentato lo scorso 7 febbraio a Roma alla ministra Valeria Fedeli dal presidente della Regione Francesco Pigliaru e dall'assessore della Programmazione

ET EINSTEIN TELESCOPE





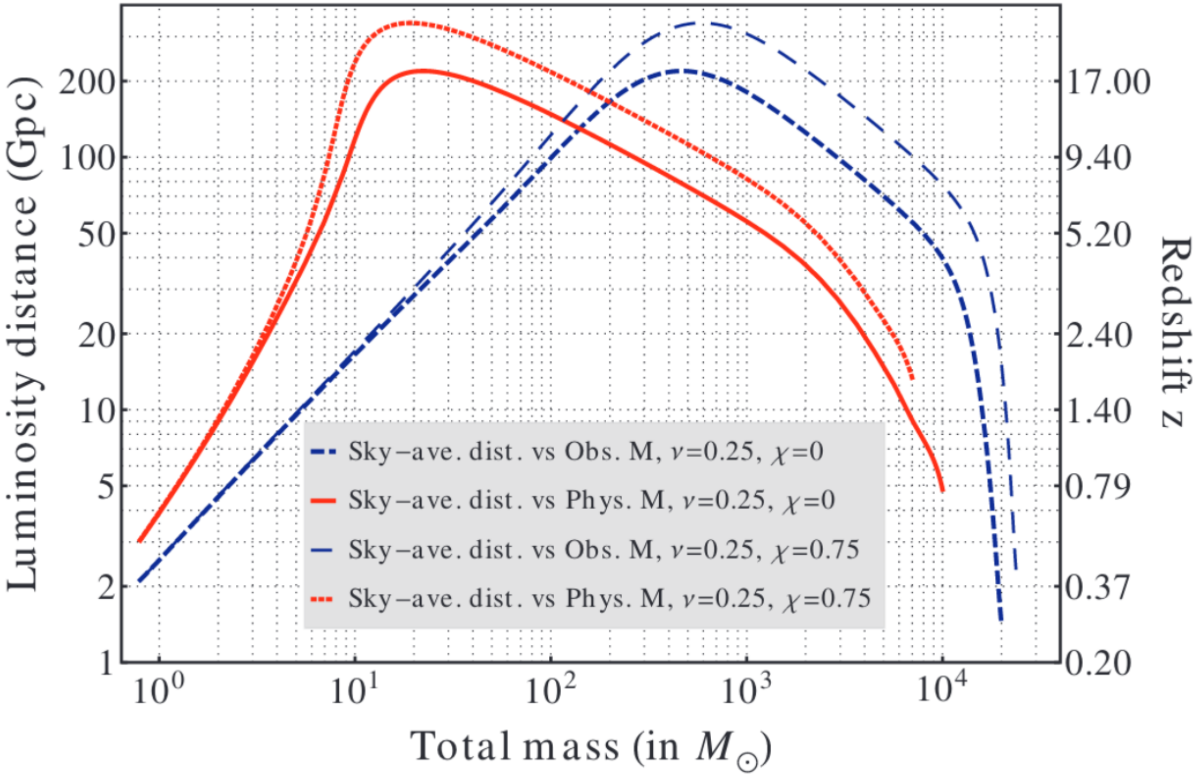
- Italian site proposed for ET: **Sos Enattos (Sardinia)**
- Currently one of the two candidates in Europe (*favorable geology, seismic noise, population density*)
- Site studied since 2010 by INFN ROMA1 Virgo group
- Official endorsement by Italian Government (MIUR, INFN, Reg. Sardegna, UNISASS)
- Financial support for ET R&D, SARGRAV laboratory
- ET site selection in 2021-2022

Onde Gravitazionali: status e prospettive

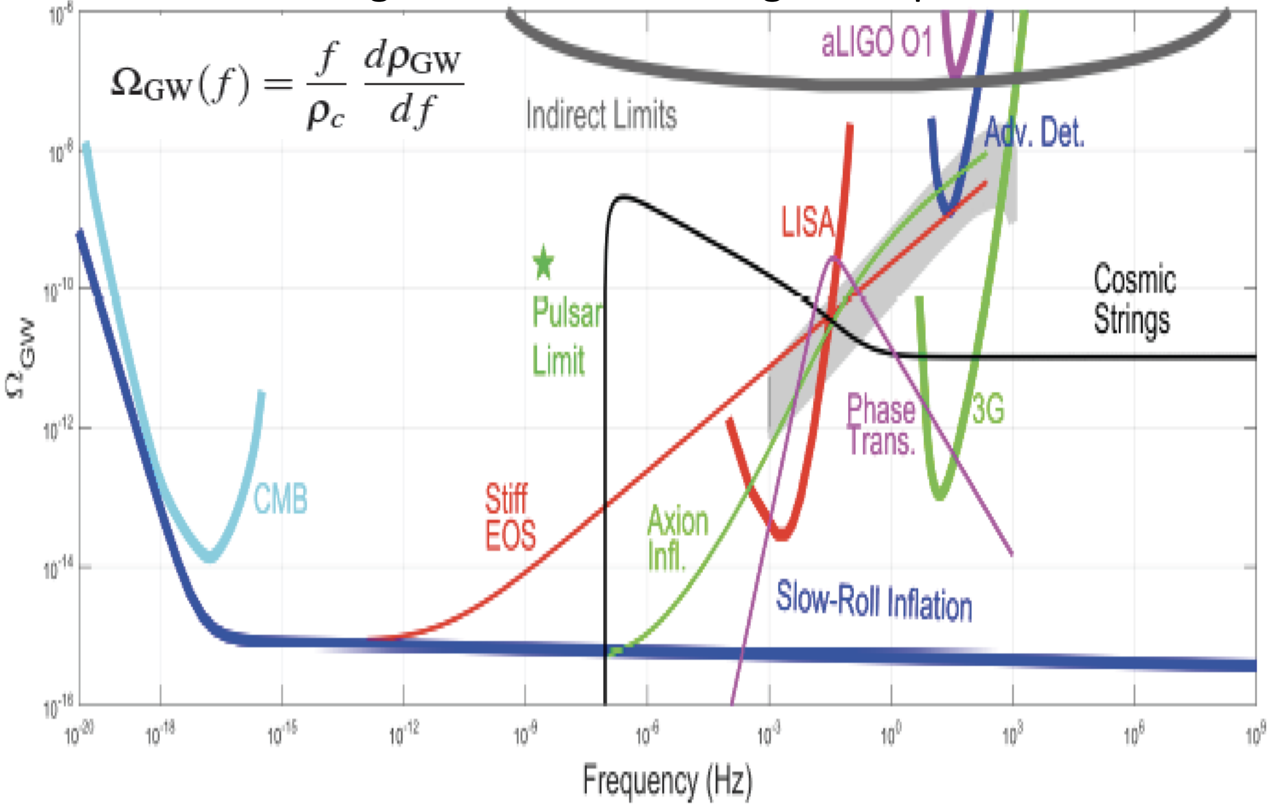
“Deeper, wider, sharper”

- ☐ Big challenges in terms of DA and computing: longer signals, subtle physics effects, huge number of events, ‘noise’ foreground,…
- ☐ But the reward will be impressive

ET detectability distance of coalescing binaries



Cosmological stochastic background predictions



What do we do, in practice?

What do we do (Experimental)?

- ☐ Development and realization of ITF payloads
  - New payloads for AdV+ (105kg test mass)
  - Local control system
  - Thermal noise study for current and future payloads
- ☐ FEA and parametric instabilities in AdV and AdV+
- ☐ AdV commissioning
- ☐ Squeezed light injection and detection
- ☐ R&D on cryogenic sensors / accelerometers and materials for test mass suspension (ET)
- ☐ R&D on payloads for 3G (ET)
- ☐ Site characterization for 3G detectors (ET)

What do we do (DA)?

- ☐ Development and application of DA methods for the search of GWs from neutron stars and BHs (and interpretation of the results).
  - Signal processing (extraction of weak signals from noise)
  - Image processing
  - Machine learning
  - HTC (Grid, GPU, code optimization)
- ☐ Waveform modelling
- ☐ Neutron stars and BH phenomenology
- ☐ Noise studies/detector characterization
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Synergies/complementarity with other Rome groups' activities are clear for both the science targets and the tools and competences

Onde Gravitazionali: status e prospettive

Who are we

P. Astone, S. Frasca, P. Leaci, E. Majorana

L. Naticchioni, C. Palomba, F. Pannarale, P. Puppo

P. Rapagnani, F. Ricci

M. Perciballi

(Tecn. INFN)

S. Di Pace, V. Mangano, O. J. Piccinni

PostDoc

S. Mastrogiovanni

(now @APC-Paris)

G. Intini, A. Miller, F. Muciaccia

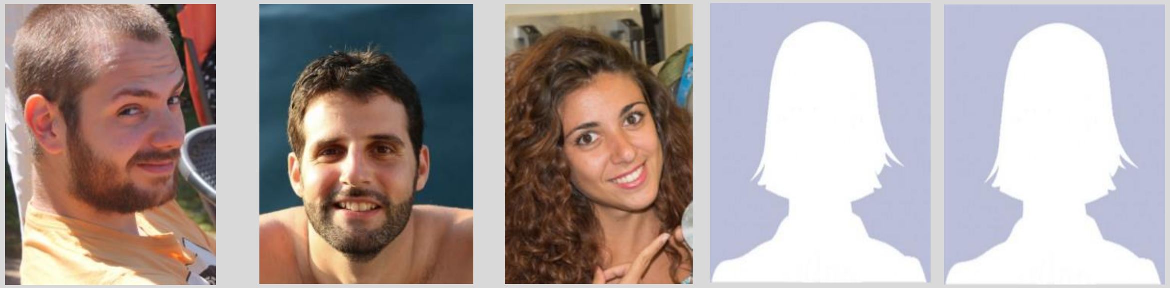
PhD

I. La Rosa

(now @Annecy)

M. Boldrini, L. Pierini, E.Polini, G. C. Santoro, E. Nitoglia

Grad students



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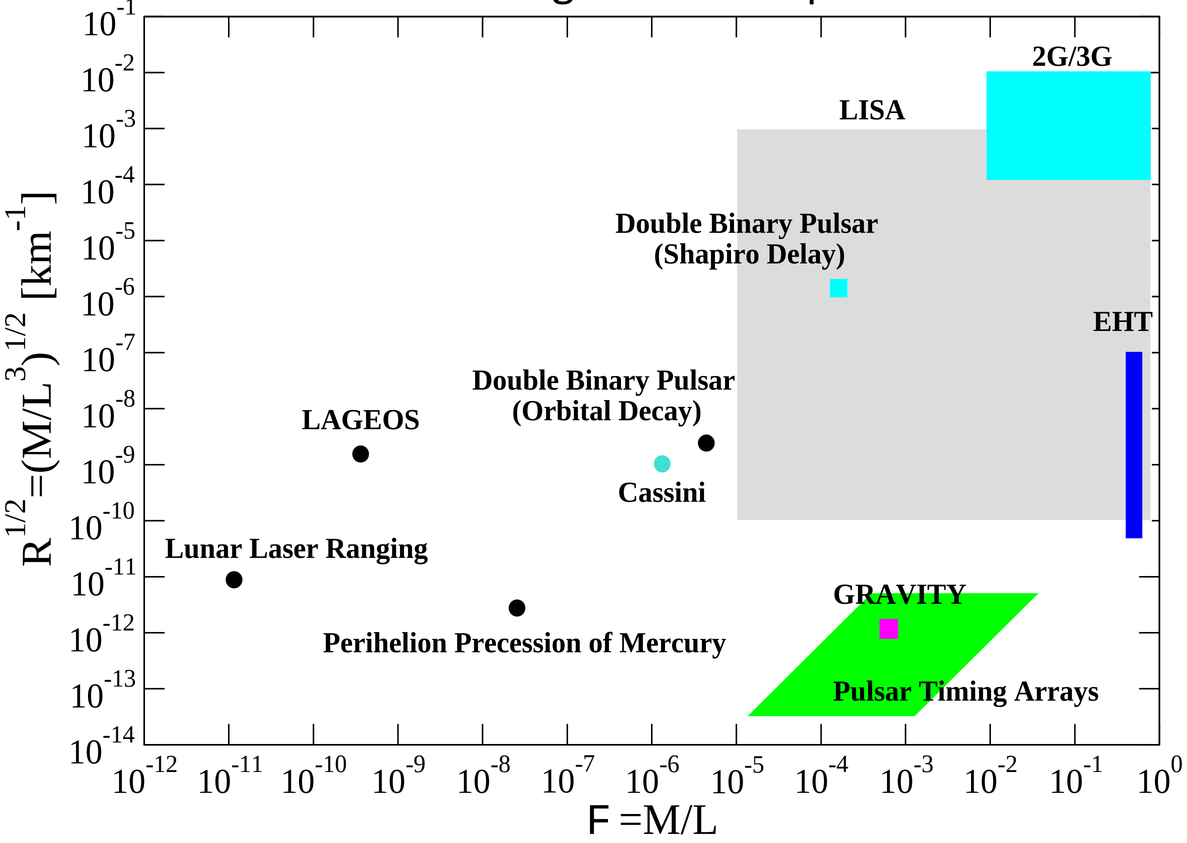
- ☐ *positions* (PhD, PostDoc…) and career perspectives;
- ☐ We need clear and convinced support from our Director;
- ☐ Effective support from mechanical workshop.

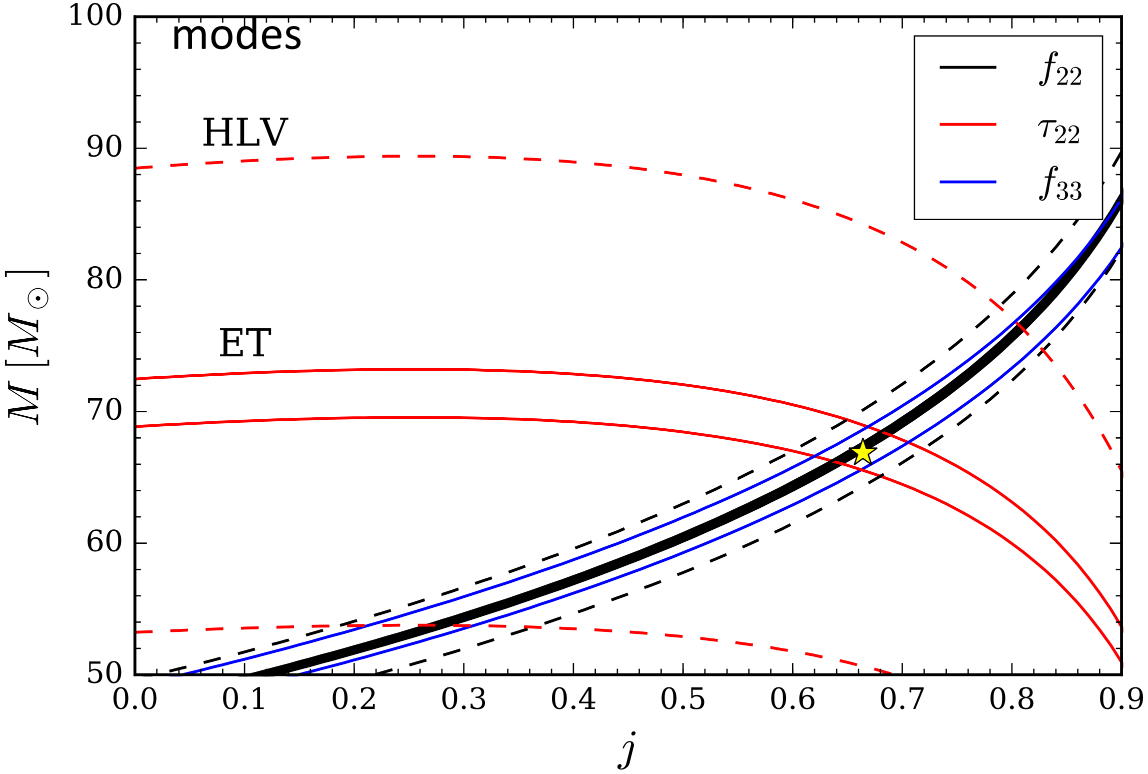

WE NEED YOU!

Backup slides

Curvature vs gravitational potential



Testing BH no-hair conjecture with BH quasi-normal modes



- There is no known mechanism for the formation of compact objects with masses well below a solar mass within the standard model of particle physics and the standard ΛCDM model of cosmology.

- A detection of a sub-solar mass object in a merger would therefore be a clear signal of new physics. Indeed, there are several proposals that link sub-solar mass compact objects to proposals for the nature of dark matter. One possibility is that black holes with masses accessible to ground based interferometers could have formed deep in the radiation era from the prompt collapse of large primordial over-densities on the scale of the early time Hubble volume.

- An alternative inflationary mechanism proposes that vacuum bubbles nucleated during inflation may result in black holes (with masses that can be around a solar mass) after inflation ends.

- dark matter may have a sufficiently complex particle spectrum to support cooling mechanisms that allow dense regions to collapse into black holes at late times.

1904.08976

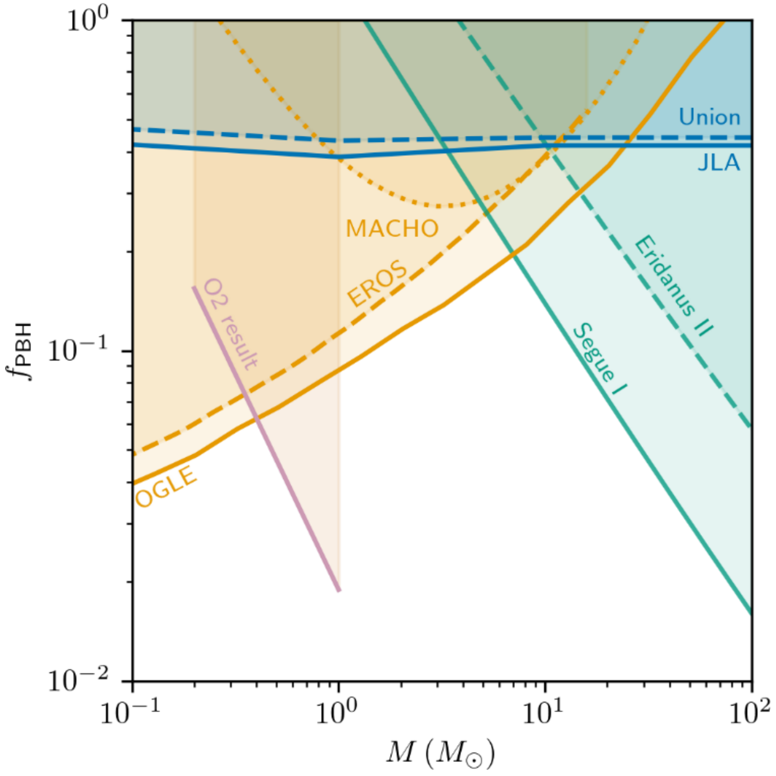


FIG. 2. Constraints on the fraction of dark matter comprised of delta-function distributions of primordial black holes ($f_{\mathrm{PBH}} = \rho_{\mathrm{PBH}}/\rho_{\mathrm{DM}}$). Shown here are (pink) Advanced LIGO constraints from the O2 ultracompact binary search presented here (solid), (orange) microlensing constraints provided by the OGLE (solid), EROS (dashed) [57], and MACHO (dotted) collaborations [58], (cyan) dynamical constraints from observations of Segue I (solid) [59] and Eridanus II (dashed) [60] dwarf galaxies, and (blue) supernova lensing constraints from the Joint Light-curve Analysis (solid) and Union 2.1 (dashed) datasets [61]. There is an inherent population model dependency in each of these constraints. Advanced LIGO and Advanced Virgo results carry an additional dependence on the binary fraction of the black hole population. Advanced LIGO and Advanced Virgo results use the Planck "TT,TE,EE+lowP+lensing+ext" cosmology [62].

1903.04467

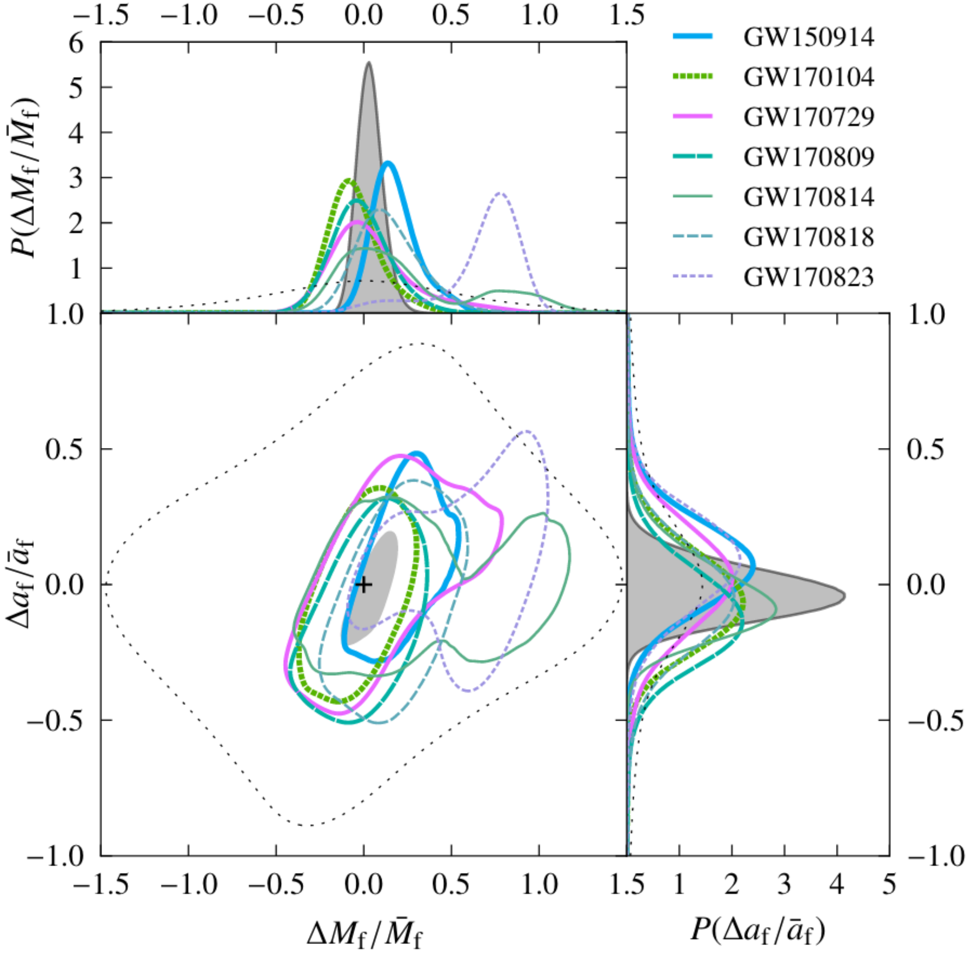


FIG. 2. Results of the inspiral-merger-ringdown consistency test for the selected BBH events (see Table I). The main panel shows 90% credible regions of the posterior distributions of $(\Delta M_f/\bar{M}_f, \Delta a_f/\bar{a}_f)$, with the cross marking the expected value for GR. The side panels show the marginalized posteriors for $\Delta M_f/\bar{M}_f$ and $\Delta a_f/\bar{a}_f$. The thin black dashed curve represents the prior distribution, and the grey shaded areas correspond to the combined posteriors from the five most significant events (as outlined in Sec. III and Table I).

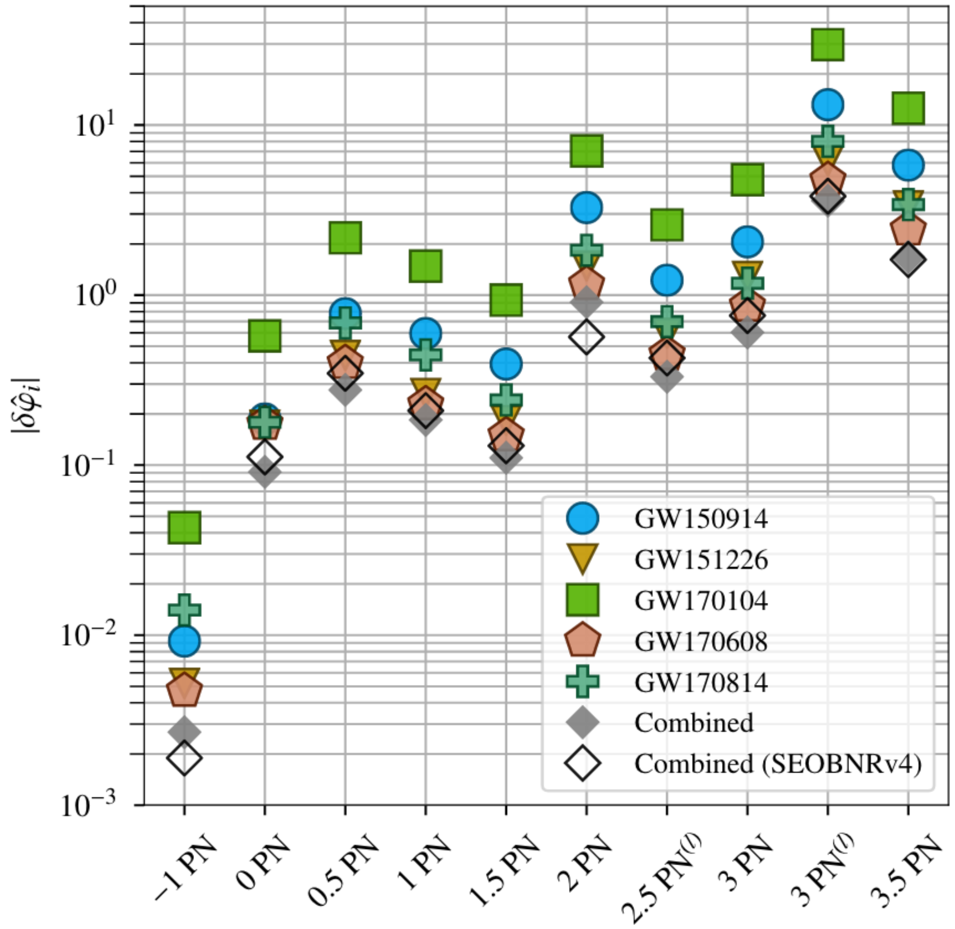


FIG. 4. 90% upper bounds on the absolute magnitude of the GR-violating parameters $\delta\hat{\varphi}_n$, from −1PN through 3.5PN in the inspiral phase. At each PN order, we show results obtained from each of the events listed in Table I that cross the SNR threshold in the inspiral regime, analyzed with IMRPhenomPv2. Bounds obtained from combining posteriors of events detected with a significance that exceeds a threshold of FAR $< (1000\text{ yr})^{-1}$ in both modelled searches are shown for both analyses, using IMRPhenomPv2 (filled diamonds) and SEOBNRv4 (empty diamonds).

1903.01901

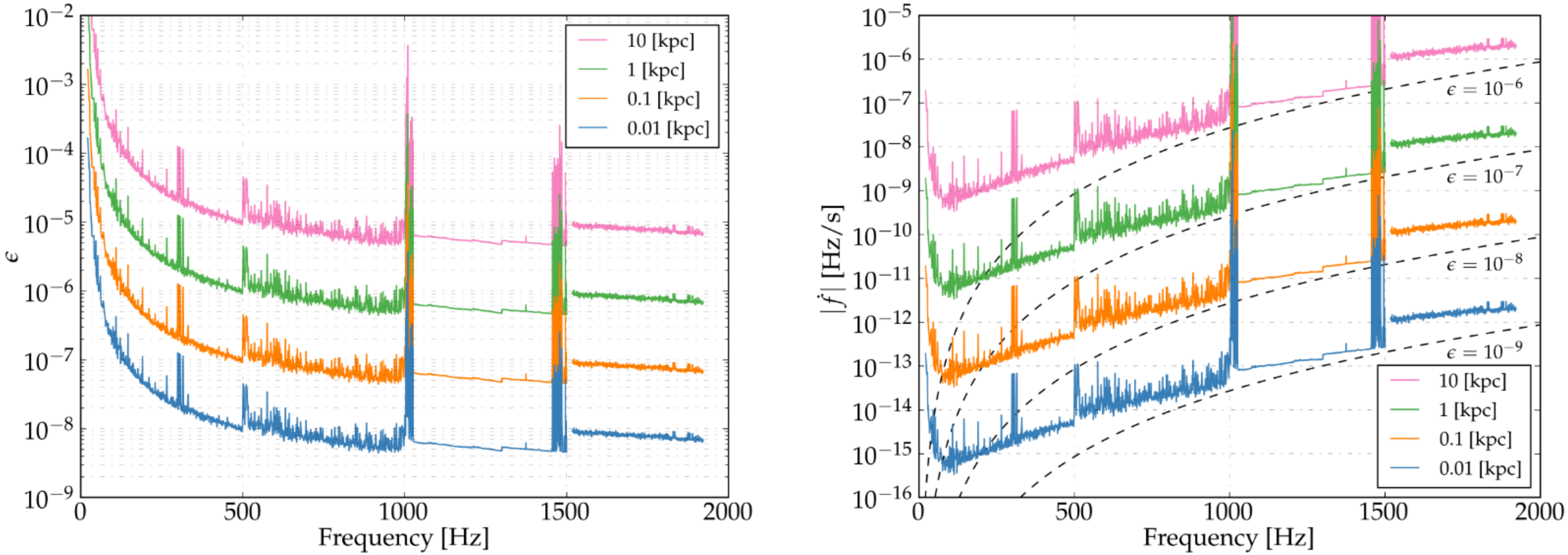


FIG. 4. The left panel shows the detectable ellipticity given by equation (22) as a function of frequency for neutron stars at 10 pc, 100 pc, 1 kpc and 10 kpc for a canonical moment of inertia $I_{zz} = 10^{38}$ kg·m^2. The right panel shows the relation between the absolute value of the first frequency derivative and the frequency of detectable sources as a function of the distance, assuming their spin-down is due solely to the emission of gravitational waves. The different colors correspond to the same distances of the left panel. Black dashed lines are lines of constant source ellipticity, from $\varepsilon = 10^{-9}$ (bottom dashed line) to $\varepsilon = 10^{-6}$.

1902.08507

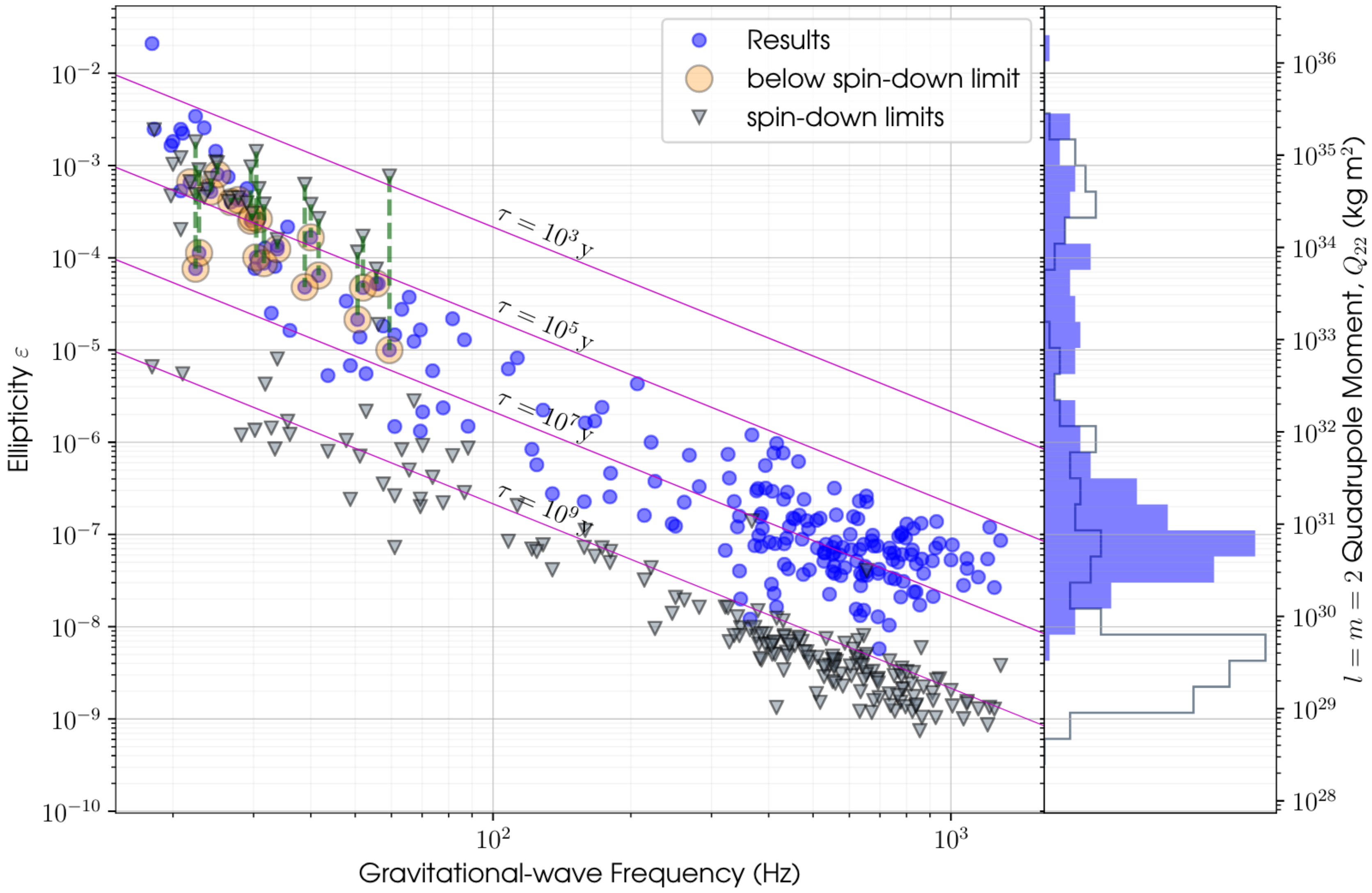


Figure 4. Upper limits on mass quadrupole Q_{22} and fiducial ellipticity ε for 221 pulsars. The filled circles show the limits as derived from the observed upper limits on the gravitational-wave amplitude h_0 assuming the canonical moment of inertia and distances given in Tables 1 and 2. Triangles show the limits based derived from each pulsar's observed spin-down. The diagonal lines show contours of equal characteristic age τ assuming braking is entirely through gravitational-wave emission. The distributions of these limits are also show in histogram form to the right of the figure, with the filled and unfilled histograms showing our observed limits and the spin-down limits, respectively.

1801.07204

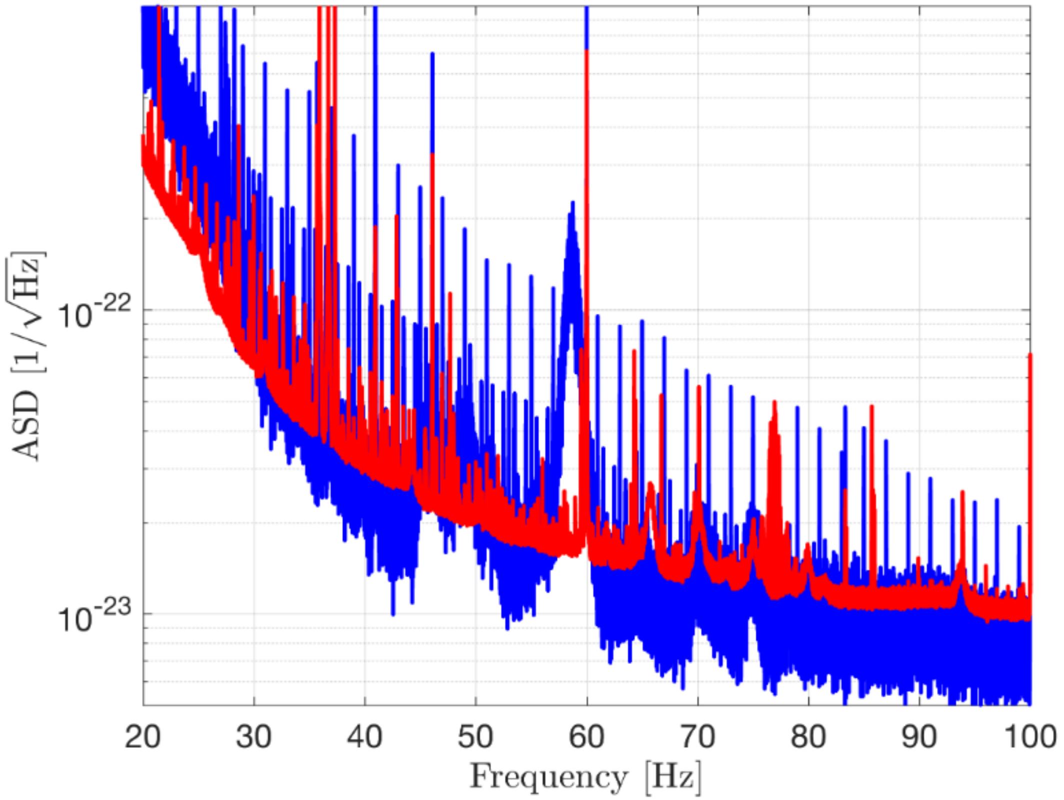


FIG. 13. Comparison of noise-weighted averaged ASD using L1 data from 14 May 2016 (blue trace, CPS timing fanout on) with noise-weighted averaged ASD from 8 June 2017 to 25 August 2017 (red trace, CPS timing fanout off). The ~ 2 Hz comb with 1 Hz offset is mitigated in the second period.

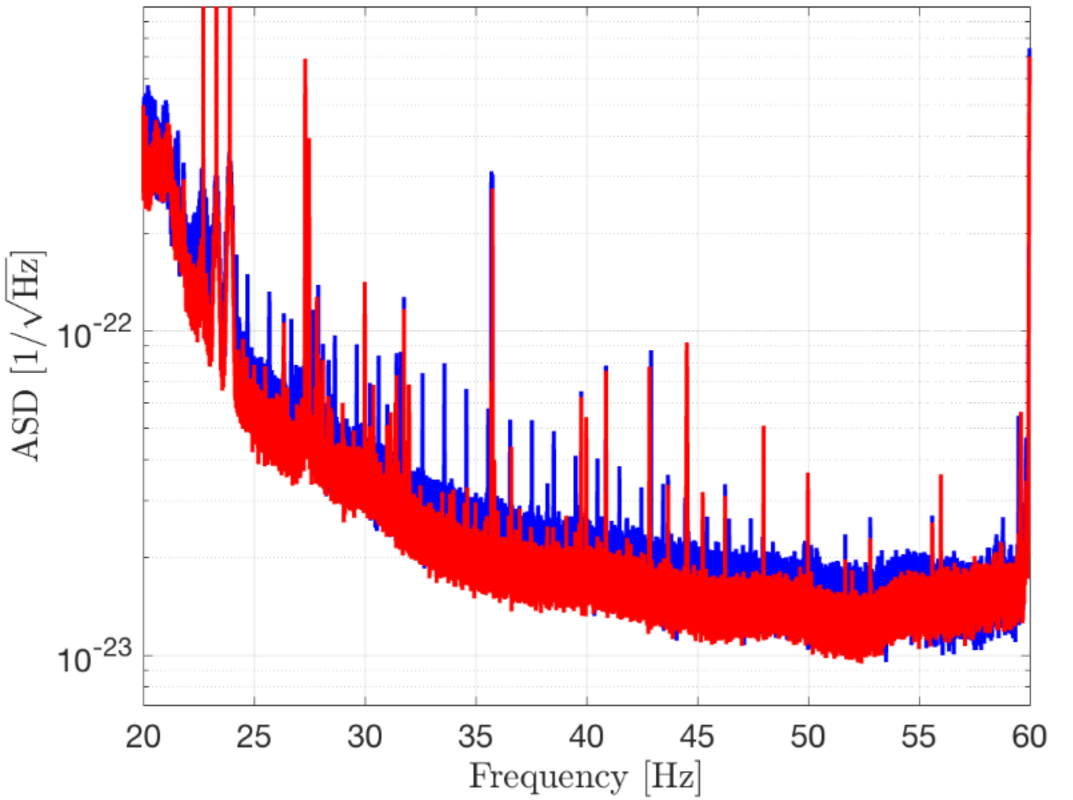
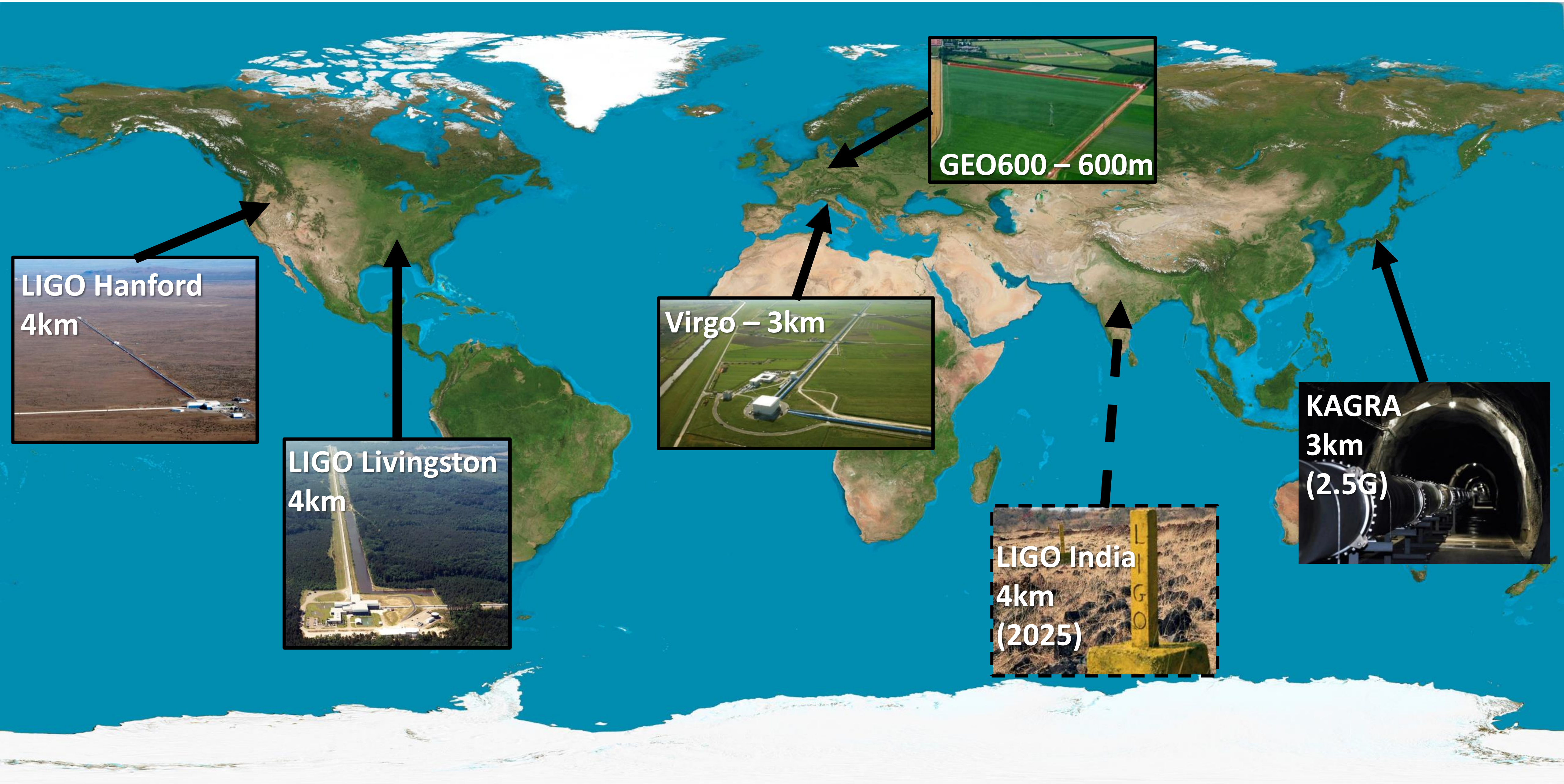


FIG. 14. Comparison of noise-weighted averaged ASD using L1 data from 23 January 2017 to 30 January 2017 (blue trace, remote control chassis on) with noise-weighted averaged ASD from 1 February 2017 to 8 February 2017 (red trace, remote control chassis off). The 0.5 Hz / 2.24 Hz comb is attenuated in the second period.

2G gravitational wave detectors world network



LIGO Hanford
4km

LIGO Livingston
4km

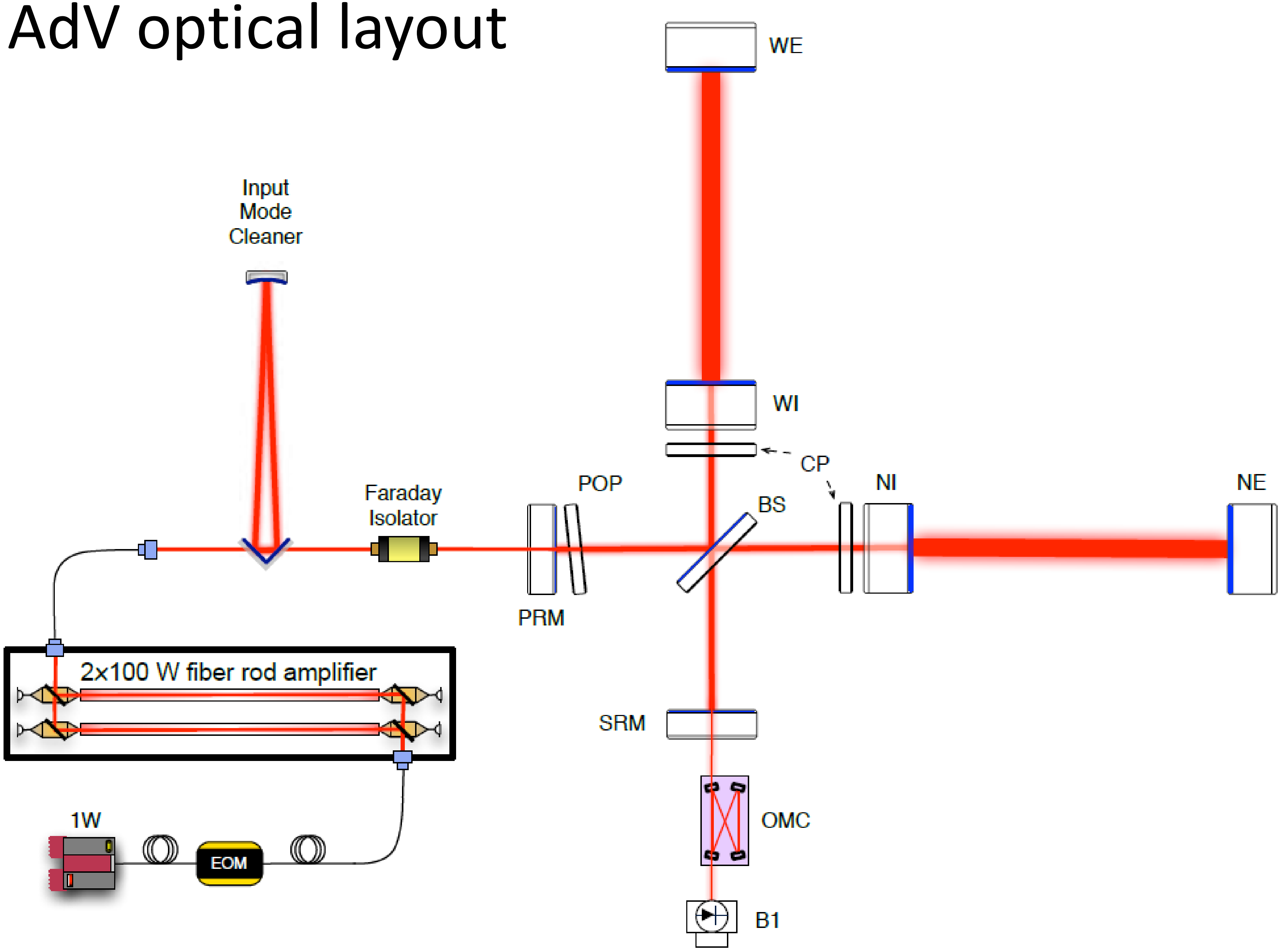
Virgo – 3km

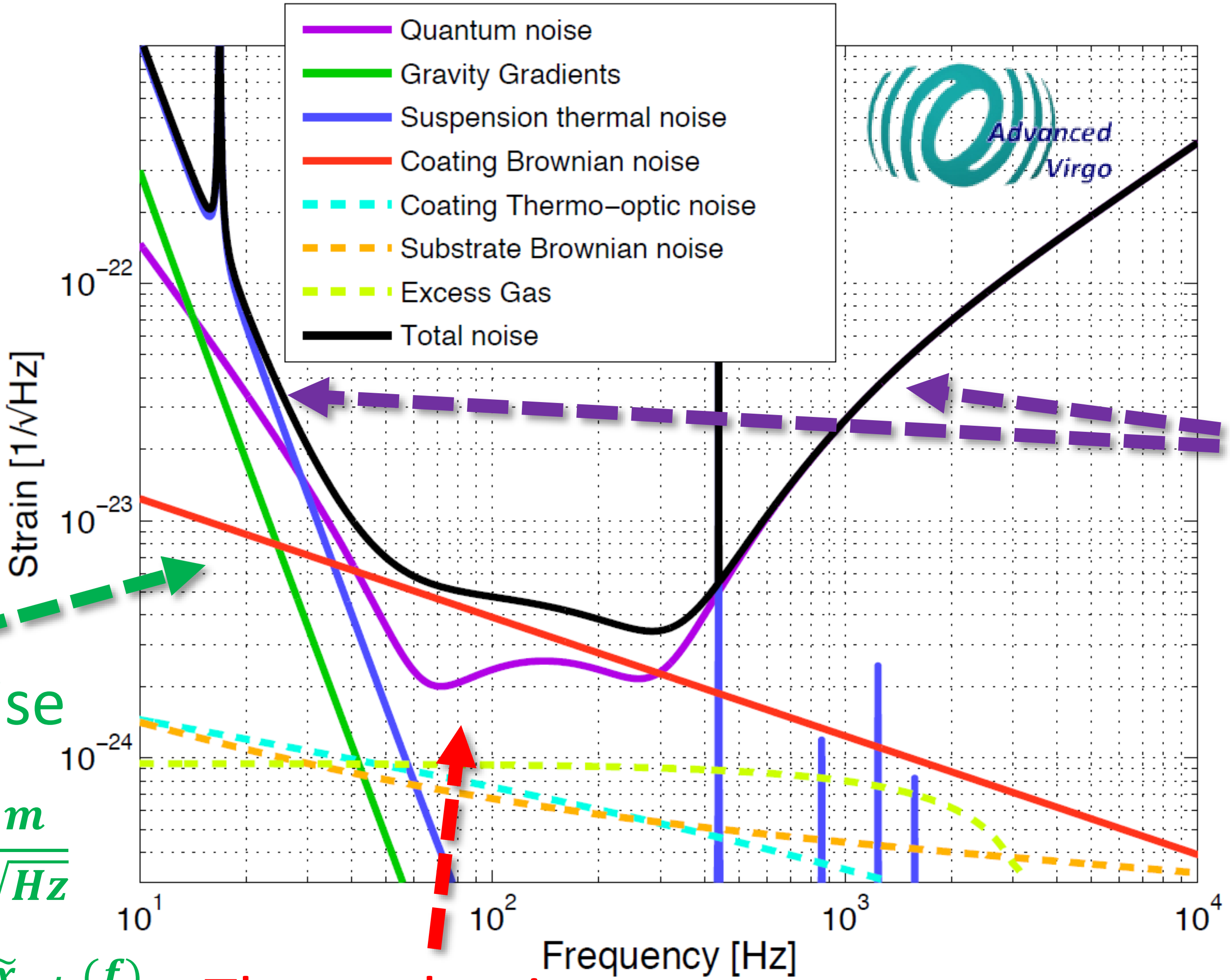
GEO600 – 600m

LIGO India
4km
(2025)

KAGRA
3km
(2.5G)

AdV optical layout





Seismic & Newtonian noise

$$\begin{cases} \tilde{x}_{seis}(f) \sim \dfrac{10^{-7}}{f^2}\dfrac{m}{\sqrt{Hz}} \\ \tilde{S}^h_{NN}(f) = \dfrac{3\cdot 10^{-11}}{f^2}\tilde{x}_{seis}(f) \end{cases}$$

$$TF_{seis} \propto e^{-4\frac{d}{\lambda}}$$

Thermal noise

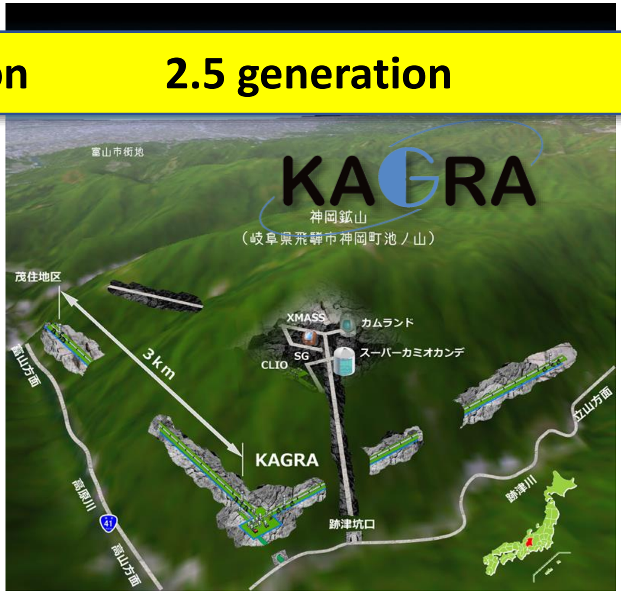
$$\tilde{x}_{th}(f) \sim \sqrt{T}$$

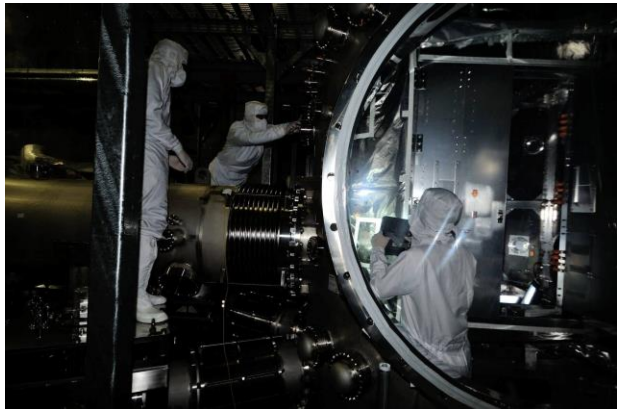
Quantum noise (RP & Shot)

$$\begin{cases} \tilde{x}_{RP}(f) \propto \dfrac{\mathcal{F}}{mL}\sqrt{\dfrac{G_{pr}P}{f^4}\left(1+\dfrac{f^2}{f^2_{cut}}\right)^{-1}} \\ \tilde{x}_{SN}(f) \propto \dfrac{1}{\mathcal{F}L}\sqrt{\dfrac{1}{G_{pr}P}\left(1+\dfrac{f^2}{f^2_{cut}}\right)} \end{cases}$$

2nd generation 2.5 generation 3rd generation

2015





2030 Einstein Telescope