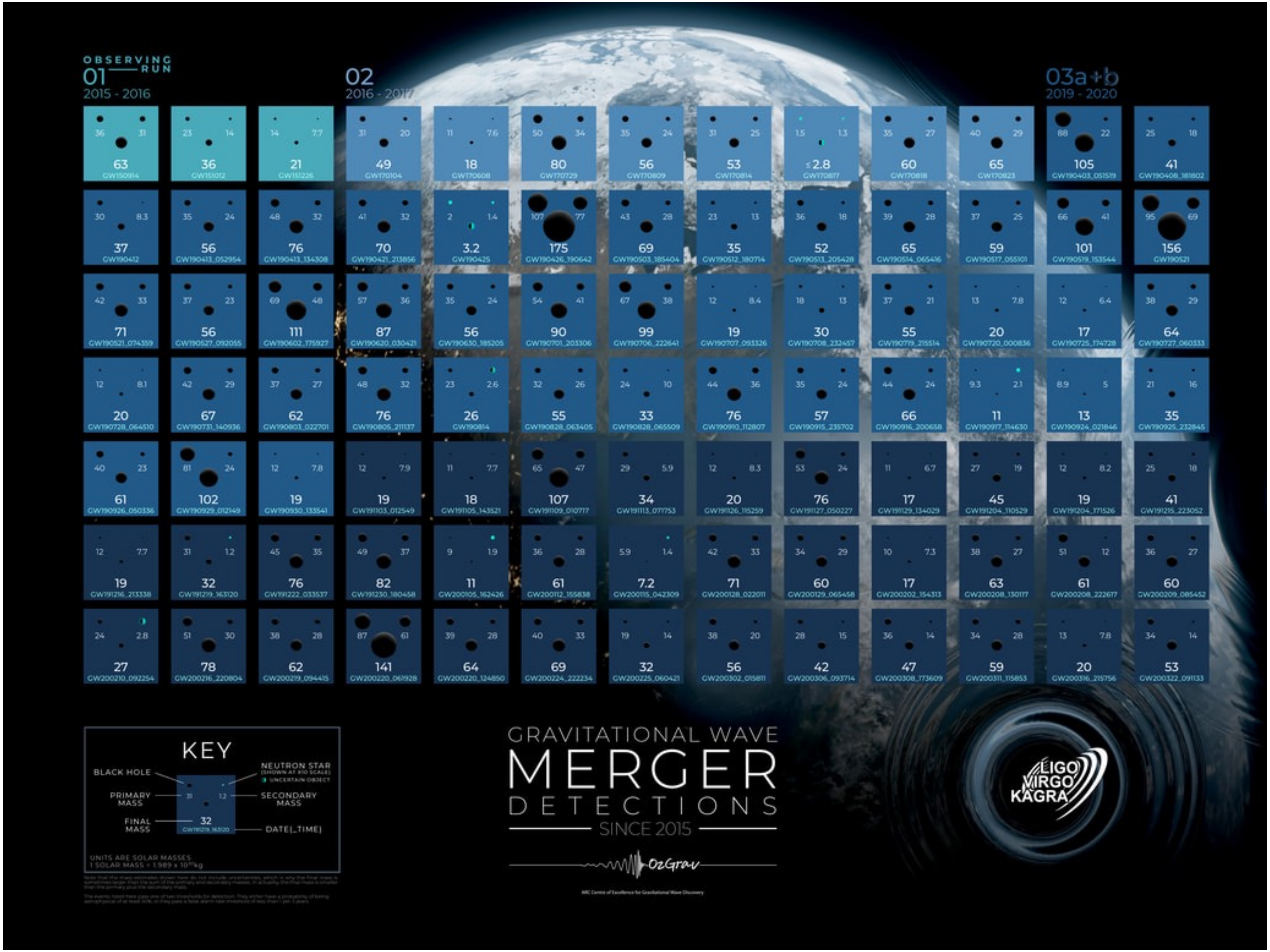
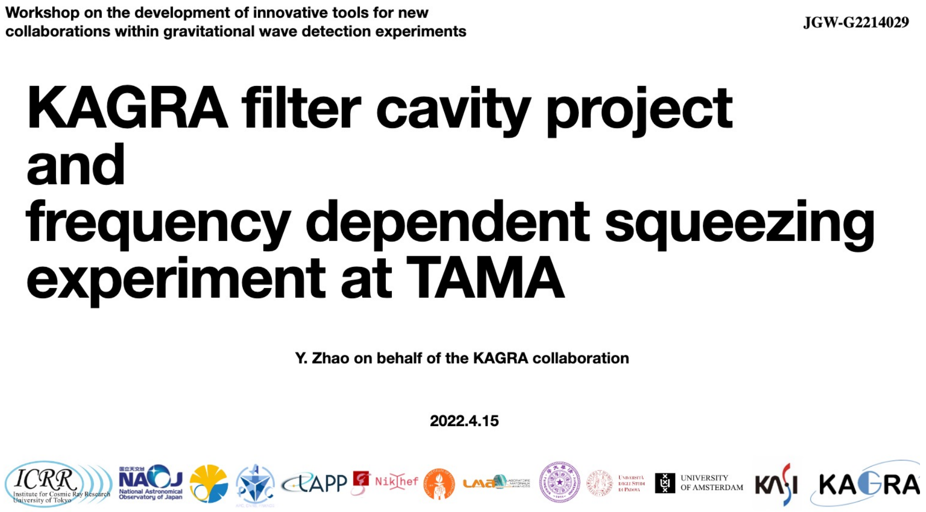
First ILANCE workshop on gravitational-waves

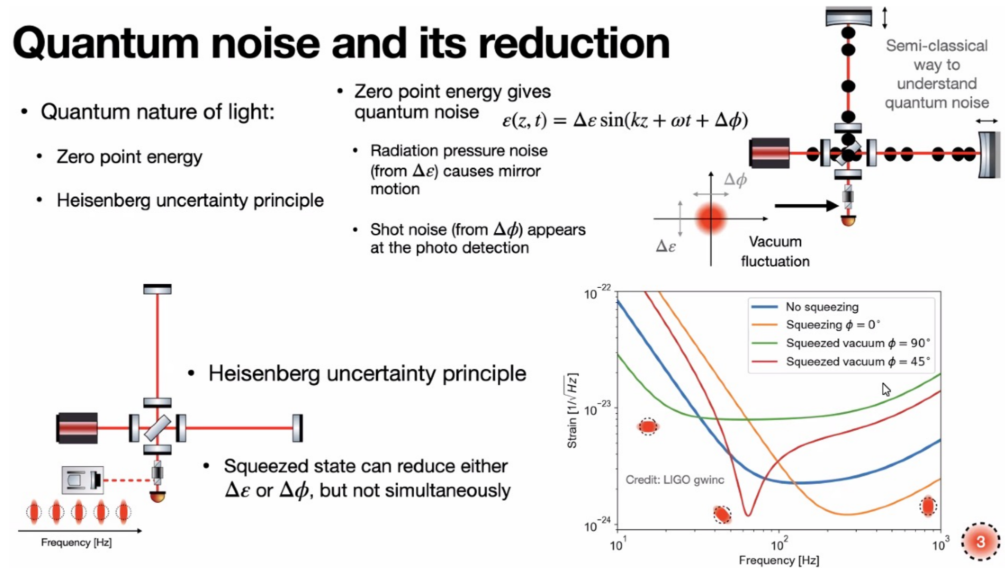
Summary

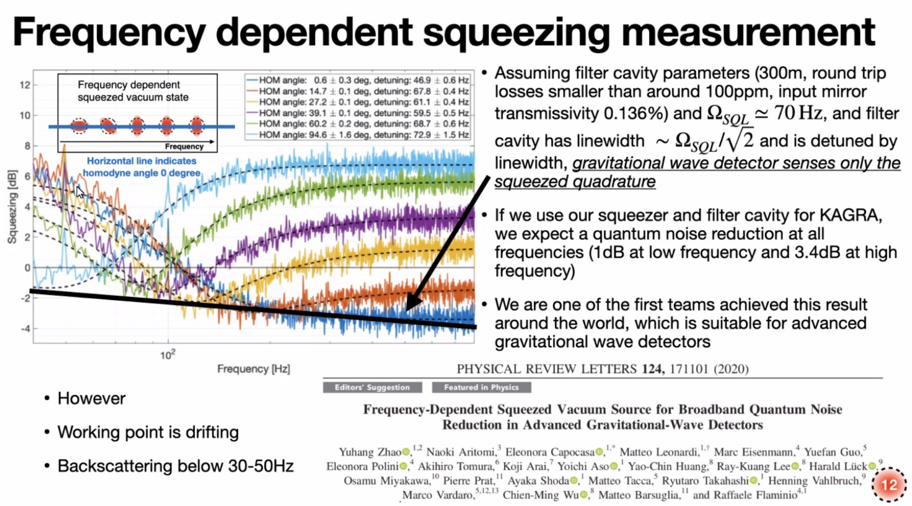
Matteo Barsuglia
CNRS/APC and ILANCE


OBSERVING RUN
O1
2015 - 2016
O2
2016 - 2017
O3a+b
2019 - 2020
36 31 63 GW150914
23 14 36 GW151012
14 7.7 21 GW151226
31 20 49 GW170104
11 7.6 18 GW170608
50 34 80 GW170729
35 24 56 GW170809
31 25 53 GW170814
1.5 1.3 ≤2.8 GW170817
35 27 60 GW170818
40 29 65 GW170823
88 22 105 GW190403_051519
25 18 41 GW190408_181802
30 8.3 37 GW190412
35 24 56 GW190413_052954
48 32 76 GW190413_134308
41 32 70 GW190421_213856
2 1.4 3.2 GW190425
107 77 175 GW190426_190642
43 28 69 GW190503_185404
23 13 35 GW190512_180714
36 18 52 GW190513_205428
39 28 65 GW190514_065416
37 25 59 GW190517_055101
66 41 101 GW190519_153544
95 69 156 GW190521
42 33 71 GW190521_074359
37 23 56 GW190527_092055
69 48 111 GW190602_175927
57 36 87 GW190620_030421
35 24 56 GW190630_185205
54 41 90 GW190701_203306
67 38 99 GW190706_222641
12 8.4 19 GW190707_093326
18 13 30 GW190708_232457
37 21 55 GW190719_215514
13 7.8 20 GW190720_000836
12 6.4 17 GW190725_174728
38 29 64 GW190727_060333
12 8.1 20 GW190728_064510
42 29 67 GW190731_140936
37 27 62 GW190803_022701
48 32 76 GW190805_211137
23 2.6 26 GW190814
32 26 55 GW190828_063405
24 10 33 GW190828_065509
44 36 76 GW190910_112807
35 24 57 GW190915_235702
44 24 66 GW190916_200658
9.3 2.1 11 GW190917_114630
8.9 5 13 GW190924_021846
21 16 35 GW190925_232845
40 23 61 GW190926_050336
81 24 102 GW190929_012149
12 7.8 19 GW190930_133541
12 7.9 19 GW191103_012549
11 7.7 18 GW191105_143521
65 47 107 GW191109_010717
29 5.9 34 GW191113_071753
12 8.3 20 GW191126_115259
53 24 76 GW191127_050227
11 6.7 17 GW191129_134029
27 19 45 GW191204_110529
12 8.2 19 GW191204_171526
25 18 41 GW191215_223052
12 7.7 19 GW191216_213338
31 1.2 32 GW191219_163120
45 35 76 GW191222_033537
49 37 82 GW191230_180458
9 1.9 11 GW200105_162426
36 28 61 GW200112_155838
5.9 1.4 7.2 GW200115_042309
42 33 71 GW200128_022011
34 29 60 GW200129_065458
10 7.3 17 GW200202_154313
38 27 63 GW200208_130117
51 12 61 GW200208_222617
36 27 60 GW200209_085452
24 2.8 27 GW200210_092254
51 30 78 GW200216_220804
38 28 62 GW200219_094415
87 61 141 GW200220_061928
39 28 64 GW200220_124850
40 33 69 GW200224_222234
19 14 32 GW200225_060421
38 20 56 GW200302_015811
28 15 42 GW200306_093714
36 14 47 GW200308_173609
34 28 59 GW200311_115853
13 7.8 20 GW200316_215756
34 14 53 GW200322_091133
KEY
BLACK HOLE
NEUTRON STAR (SHOWN AT X10 SCALE)
UNCERTAIN OBJECT
PRIMARY MASS
SECONDARY MASS
FINAL MASS
DATE(_TIME)
31 1.2 32 GW191219_163120
UNITS ARE SOLAR MASSES
GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015
OzGrav
LIGO VIRGO KAGRA

Y.Zhao – KAGRA filter cavity project and TAMA exp







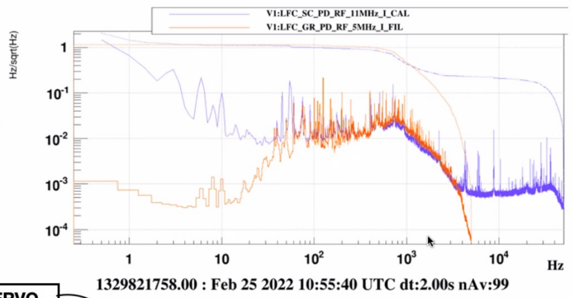
Y.Zhao – KAGRA filter cavity project and TAMA exp

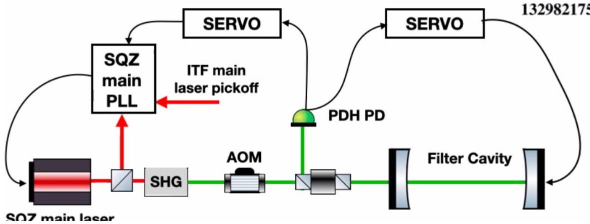
- TAMA: One of the first demonstration of squeezing in ~ 100 Hz bandwidth - full scale prototype
- Test bench for new control schemes: auxiliary frequency (green) and coherent control sidebands
- In the future: possible test bench for EPR, three-mirror cavity (tunable finesse)
- Already French-Japanese collaboration: exchanges of researchers and students → Continue the collaboration (also using NEWS and PROBES EU project from France)

E.Capocasa – squeezing in Virgo

Filter cavity longitudinal control with green beam

- Feedback to FC mirror up to 10 Hz
- Feedback to laser frequency up to ~900Hz (added later to suppress noise in the ~100 Hz region)
- Residual length noise ~1 Hz





- Working fine in standalone
- To be tested with ITF

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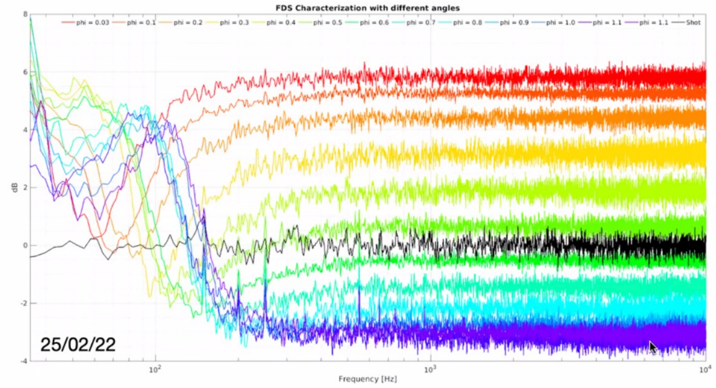
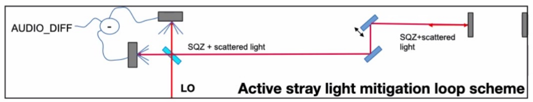
Frequency dependent squeezing measurement

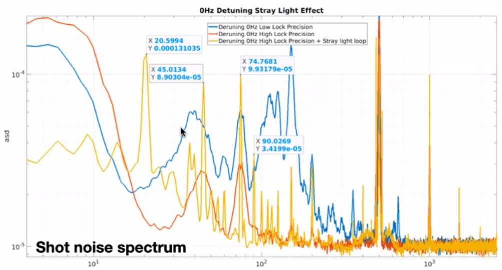


- Ellipse rotation at ~50Hz -> shot noise level at low frequency
- Excess of losses (~35%) -> sub optimal alignment conditions
- Detuning stability to be better characterised

Scattered light contamination

- Evidence of local oscillator scattered light by Homodyne PD
- Effect reduced with the locking precision improvement and active stray light mitigation





- Note that local oscillator will be switched off during SQZ injection in ITF

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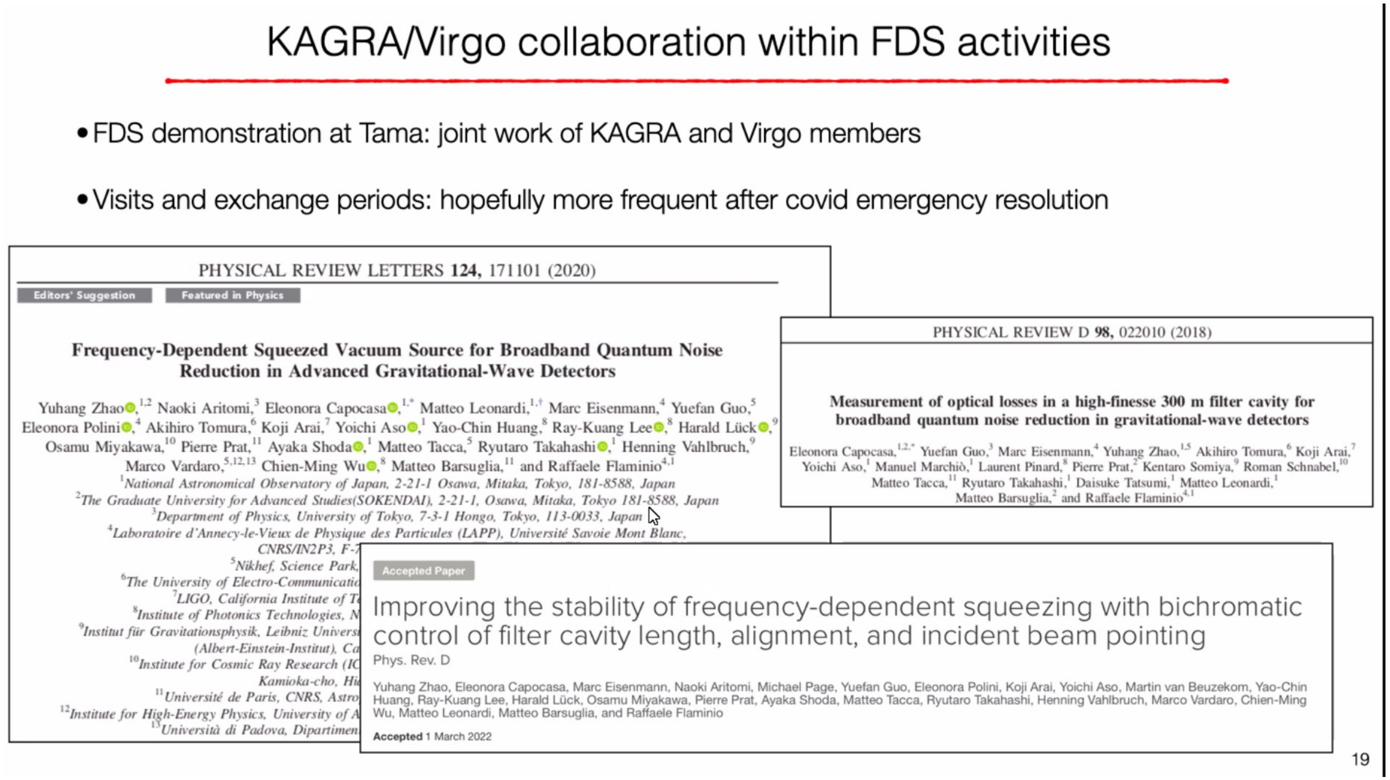
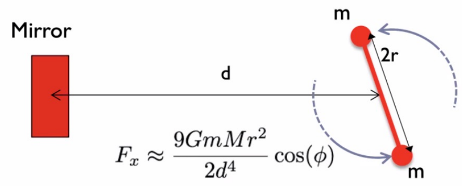
E.Capocasa – squeezing in Virgo



- Important testbench with squeezing injection in the interferometer
- Collaborations on-going (Y.Zhao @ Virgo for a month)

B.Mours – Newtonian calibrator

NCal basic principle



- Rotor made of two masses
  - Center of mass is not moving
  - The non linear Newtonian force creates the signal
  - Signal at twice the rotor frequency;
  - Signal proportional to $1/d^4$ effect → Mirror to NCal distance is critical
- Expected benefits
  - Signal depends mainly on the rotor geometry, mass and position
    - Mass of the mirror cancels out
    - Correction for a real mirror geometry compared to point particle: around 1%
  - No aging effect of the signal
  - Simple interface with the detector
    - Could be moved from one mirror or ITF to another
- An old principle, tested during O2:
  - "First test of a Newtonian calibrator on an interferometric gravitational wave detect
    CQG. 35, 235009, 2018

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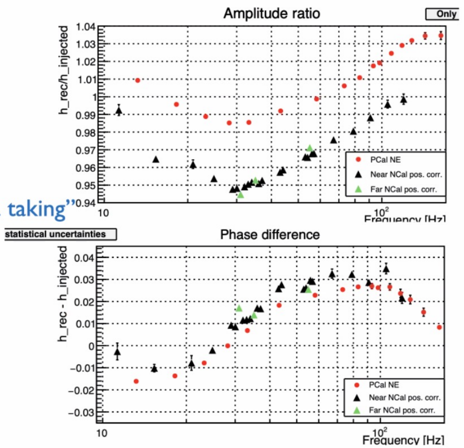
O3 results



- Accurate FEM simulation
- Results published: CQG **38**, 075012
  - "Newtonian calibrator tests during the Virgo O3 data taking"
- Probing h(t) up to 120 Hz (rotor @ 60 Hz)
- Same shape as PCal
- 3% amplitude offset between PCal and NCal
- Systematic uncertainties
  - At the level of the PCal uncertainties
  - Dominated by NCal-mirror distance

Parameter	uncertainty	formula	h_{rec}/h_{inj} near [%]	h_{rec}/h_{inj} far [%]
NCal to mirror distance d	6.4 mm	$4\delta d/d$	2.02	1.31
NCal to mirror angle Φ	5.0/3.3 mrad	$\delta\Phi \sin\Phi$	0.28	0.19
NCal vertical position z	1.3 mm	$5/2(z/d)^2$	0.03	0.01
Rotor geometry	see table 1		0.53	0.53
Modeling method	see end of section 4		0.018	0.017
Mirror torque from NCal	see end of section 4		0.05	0.03
Total	quadratic sum		2.1	1.4

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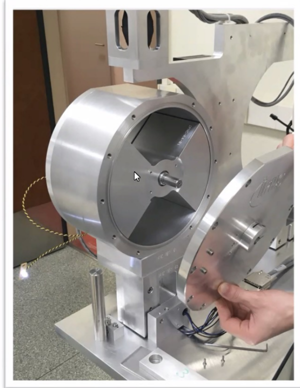
B.Mours – Newtonian calibrator

Improving the NCal rotor for O4

- Simpler geometry
  - Remove: the O3 external ring and central disk
- Make it thicker
- Benefit
  - Force x 2 compared to O3
  - Simplify the metrology and prediction
- Challenge: air motion → friction
  - Go to 70 W motor
- Current test: 80 Hz rotor speed achieved
  - Will are building a three sectors rotor to probe h(t) up to 200 Hz



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O5 NCal plans

- Improve the accuracy from less than 1 % (O4 goal) to less than 0.5 %.
  - Improve the knowledge (and stability) of the NCal position
- Install an NCal system on the West End tower,
  - To be able to inject accurate calibration signals on both arms.
- Extend the frequency band cover up to at least 250 Hz (in h(t)).
  - This corresponds roughly to the frequency where 95 % of the BNS SNR is accumulated.
    - → Work on new rotor
  - May need
    - To use denser material (could gain a factor 2.85 with stainless steel)
    - More powerful motor
    - Go to (partial vacuum)
    - Use magnetic bearing (also good to reduce the mechanical vibration
- Fix any issue that may be observed during O4

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- Important room for collaborations about on calibration (intercalibration, exchanges of N-cal / g-cal)

M.Leonardi – KAGRA sapphire mirrors

Introduction to “sapphire”

KAGRA mirrors: Aluminum oxide (corundum)

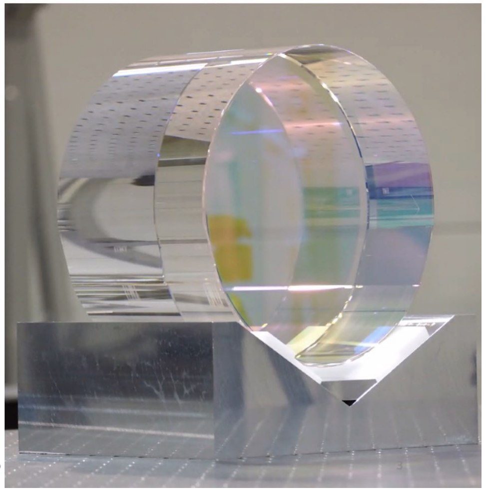
Pro:

- Very high thermal conductivity at cryogenic temperature
- Transparent at 1064nm
- High density
- Good industrial manufacture techniques
- …

Cons:

- Second hardest material in the world
- Birefringent material (in a-axis)
- …

2022-04-15 iLANCE workshop



- Candidate material for ET
- Virgo post-O5 1064 room temperature

Optical absorption in sapphire mirrors

To achieve a stable temperature for the test masses (ITM case):

$$P_{rad} + P_{BS}\alpha_{bulk}L + P_{arm}\alpha_{coat} < P_{cryo}$$

Right side depends mainly on fiber diameters

- Suspension thermal noise is determined by fibers geometry

Left side can be minimized optimizing PRG and arm Finesse

- This choice has impact on ITF quantum noise
- (design): $P_{BS}\alpha_{bulk}L \approx P_{arm}\alpha_{coat}$

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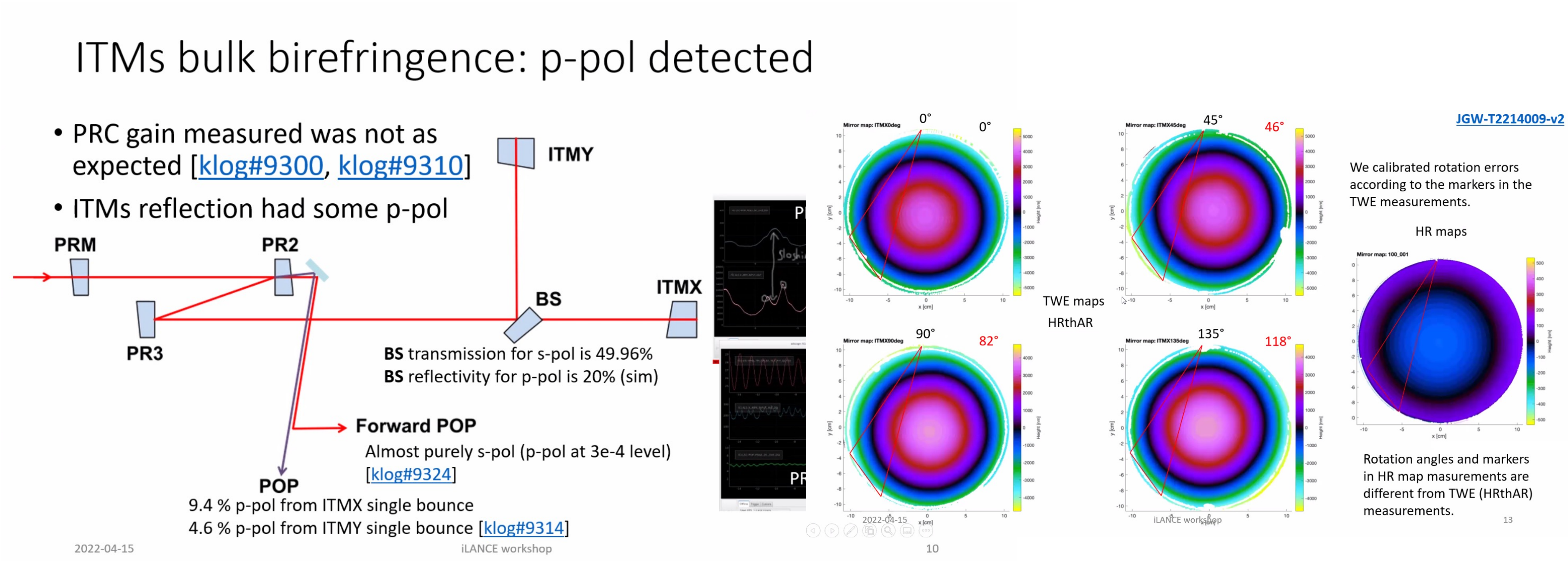
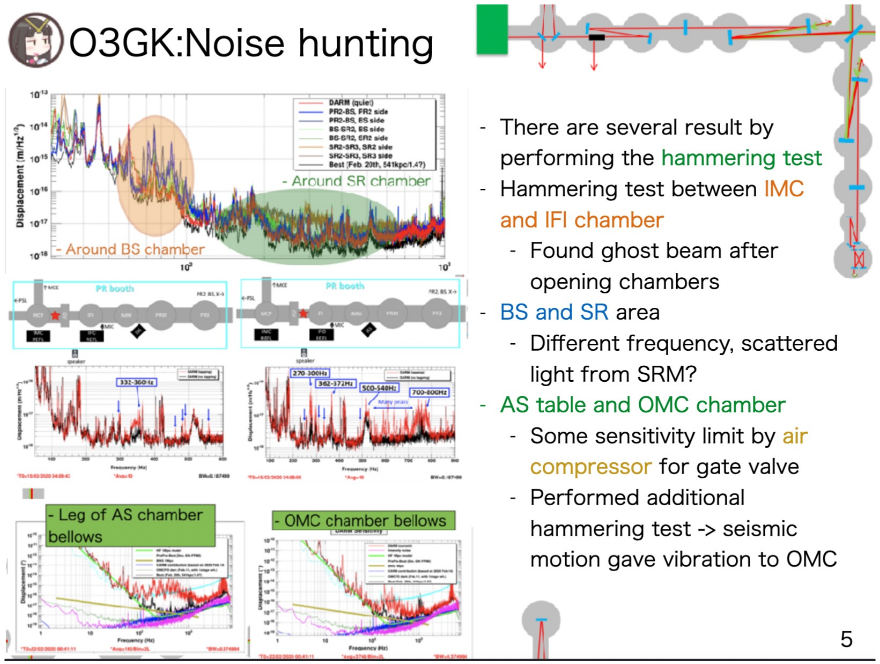
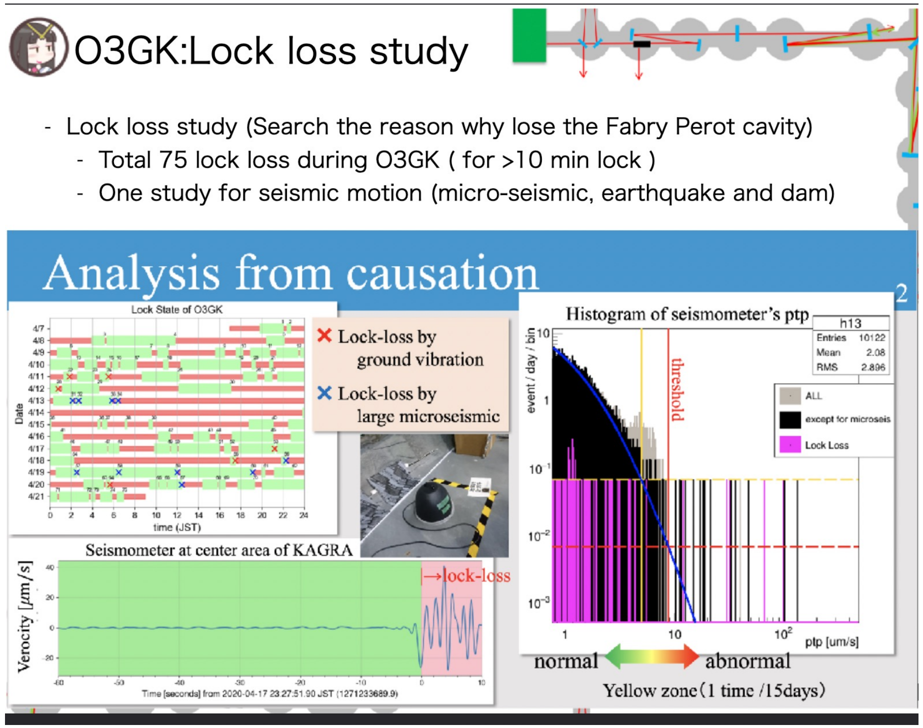
M.Leonardi – KAGRA sapphire mirrors



- Huge experience with sapphire mirrors in KAGRA !
- This will be crucial for the design of Einstein Telescope if sapphire selected
- Moreover: collaboration KAGRA-Virgo coating group, contacts with KAGRA-LMA

T. Yokozawa – Detchar in KAGRA





- PEM, lock losses, noise analysis and subtraction

T. Yokozawa – Detchar in KAGRA

Underground interferometer

- (My personal) Comment about underground environment
- Difficult (Hard) point
  - Access to experimental area
    - Some trouble (or need to turn on/off instruments) detected in control room -> 10 min to center area -> +15 min to end area
    - After heavy rain or snow melting water season, there are many waters in the experimental area
  - Limiting experiment space
    - Place of the essential instrument (Air compressor, pumps, coolers, …)
    - Machine, circuit, cabling, …
  - Temperature control
    - We need to keep the temperature within 0.5 deg, especially for suspensions. Turn on/off of the one instrument varied the temperature.

Summary

- KAGRA detector characterization
  - Managed under the Operations Division
- Various results are reported
  - Current DetChar activities
  - Noise hunting / acoustic injection toward the O3GK
  - Offline noise subtraction using ICA
  - Lock loss study
  - Telephoto camera
- Some personal opinions for the underground experiment
  - Good point and difficult point
- Welcome the question about DetChar for underground interferometer!

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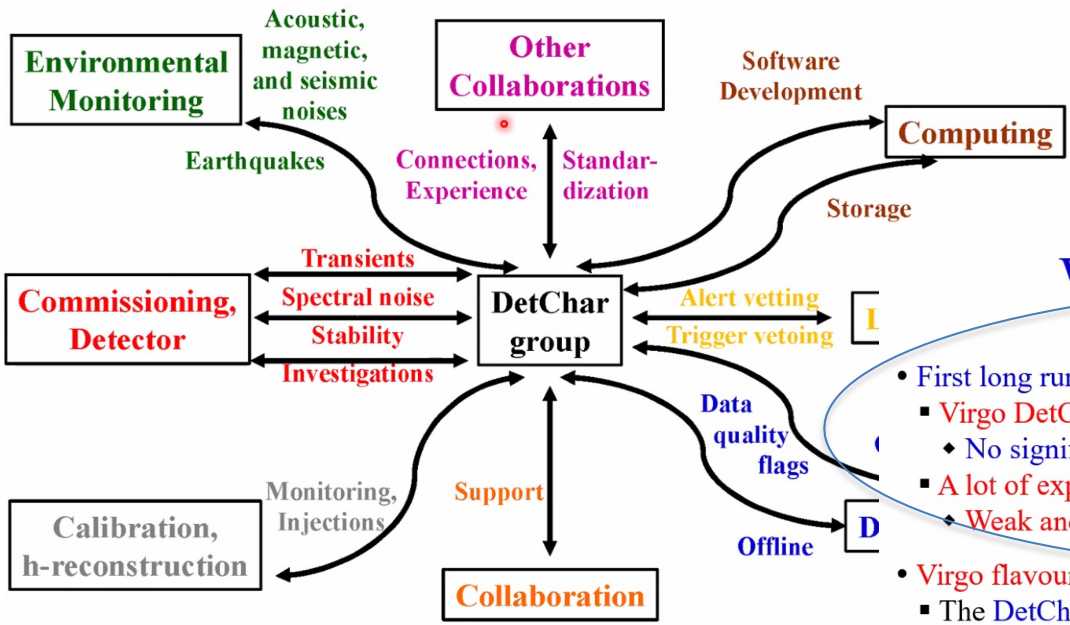
N.Arnaud – Detchar in Virgo

Virgo DetChar within Virgo & LVK



What worked well during O3

- First long run for Advanced Virgo
  - Virgo DetChar held on over 6+5 months
    - No significant failure/delay, major milestones achieved
  - A lot of experience gained for O4 preparation and data taking
    - Weak and strong points are clear
- Virgo flavour of the DQR
  - The DetChar group priority for O3: a new, key, development
    - Significant resource dedicated to it, well ahead of time
      → A real arbitration, given the global personpower shortage
- Partial but efficient internal feedback mechanism to review and improve tasks
  - Between O3a and O3b, using the 1-month commissioning break
  - But also during sub-runs as well
- Connection with the LIGO DetChar group
  - Already well-established for years!
- Virgo DetChar visibility
  - Within the Virgo collaboration and also more broadly within LVK

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N.Arnaud – Detchar in Virgo

Outlook

- Long and challenging O3 run
  → Unvaluable experience gathered during 11 months data-taking + offline analysis
- Transitioning from final O3 analysis to O4 preparation
  - Almost completed: now focus on O4
- Manifold improvements targeted
  - Group organization and support from collaboration
  - Mostly existing O3 frameworks
  - Not many new projects

→ Tight constraints from limited personpower
  - Not solved despite growing collaboration

- Benefiting from joint LVK activities
  - An asset to make progress
  → Happy to help KAGRA time- and resource-permitting

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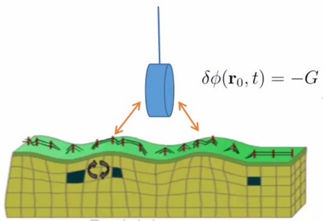
- Lot of lessons learned by O3 (during a long data taking campaign)
- Difficulties in having “standardized” Virgo-KAGRA-LIGO tools
- Possible common projects/tools/collaborations?

T.Washimi– Underground environment characterization

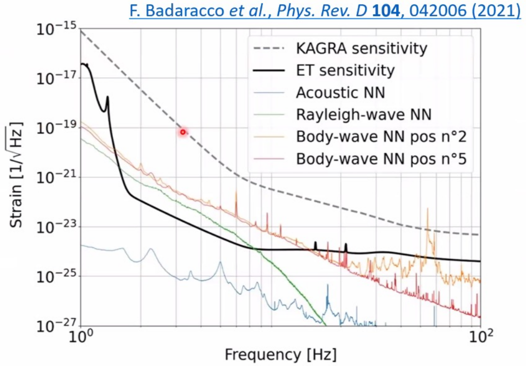
Seismic Newtonian noise (NN)

Perturbation of the gravity field due to a variation in the density (δρ) of the surrounding media.



$$\delta\phi(\mathbf{r}_0,t) = -G\int dV \frac{\delta\rho(\mathbf{r},t)}{|\mathbf{r}-\mathbf{r}_0|}$$

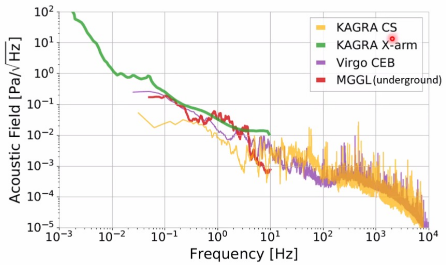
F. Badaracco *et al.*, *Phys. Rev. D* **104**, 042006 (2021)

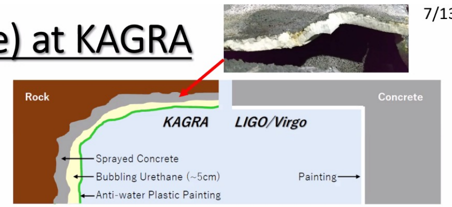


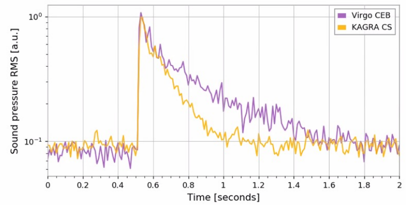
Estimated NNs are much below the design sensitivity of KAGRA, but larger than that of ET.

- Some new approaches (e.g. NN cancelation developing in Virgo) are necessary.

Acoustic field (air-pressure) at KAGRA







- The acoustic levels are similar the underground and the on-surface environment, at quiet conditions.
- The underground is more stable with respect to transient external disturbances

Reverberation time in the KAGRA site is much shorter than that of LIGO and Virgo.

- This is because of the difference in the inner surface of the walls, rather than the location.

Tonga volcano eruption signal at KAGRA

https://gwcenter.icrr.u-tokyo.ac.jp/en/tonga-20220115

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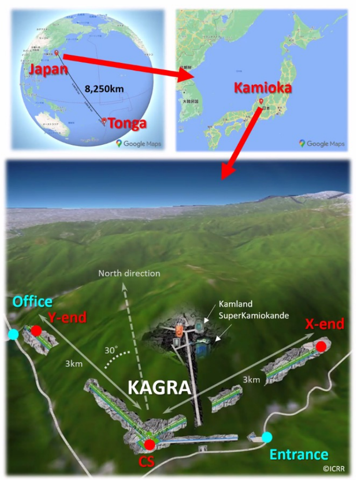
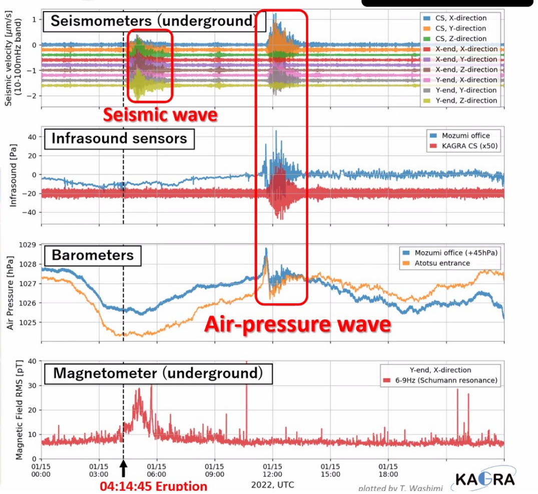
Analysis is ongoing





Tatsuki Washimi– Underground environment characterization

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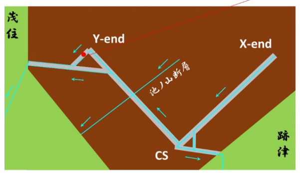
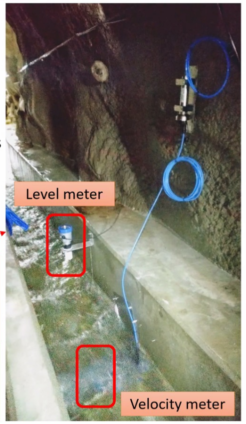
Underground water

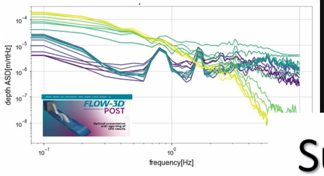
Water fluid in the drainpipes can cause Newtonian noise. So we are working on
- Monitoring the water fluid @ Y-end
- NN estimation with water simulation

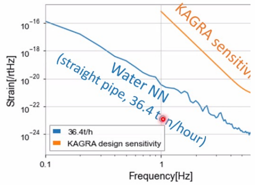
If we conclude this noise possibly affects the KAGRA design sensitivity and/or will be observed in O4 data, we need to mitigate this noise before O5 starts.





Simulation study is ongoing
(T. Suzuki @ TITECH)





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Summary

- Underground is low-noise and good for GW detectors.
- Underground environment is be studying at KAGRA.
  - Seismic motion: Well reduced at observation frequency, but not at a lower frequency.
  - Acoustic field: Stationary level is not so different from on-surface, but more stable.
  - Magnetic field: The situation is a little bit complicated and understudying.
  - Water: One difficulty of underground
- Understanding the underground environment is important for the next generation GW detectors.

- A wealth of data useful for Einstein Telescope
- Many contacts with Virgo-ET communities.
- Try to see if and how French community can also collaborate

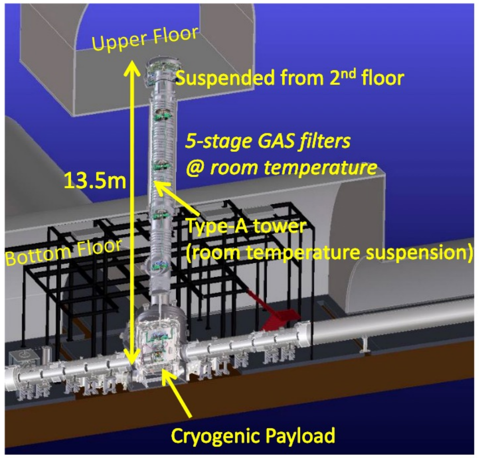
T. USHIBA – Cryogenics

Main mirror suspension (Type-A suspension) in KAGRA

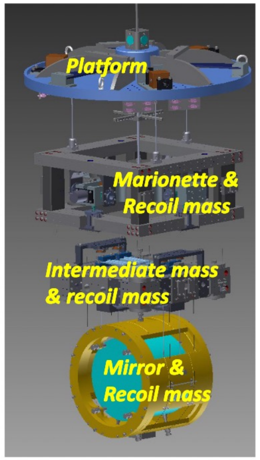
Cryogenic sapphire mirror is one of key features of KAGRA.

The sapphire mirror is suspended by four-stage cryogenic pendulum.

It is suspended from a huge tower called Type-A tower for vibration isolation.



Type-A suspension



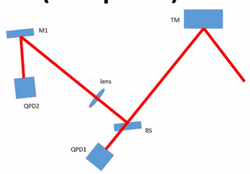
Cryogenic payload

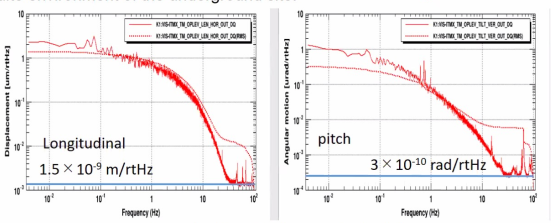
OpLevs and length-sensing OpLevs (LS OpLevs)

OpLevs configure gouy phase telescopes in order to distinguish beam shift and tilt.

→Three degrees of freedom can be detected by one set of OpLevs.

- Even though OpLevs measure the suspension motion with respect to the ground, noise level at high frequency is much better than PSs thanks to the quite environment of the underground site.





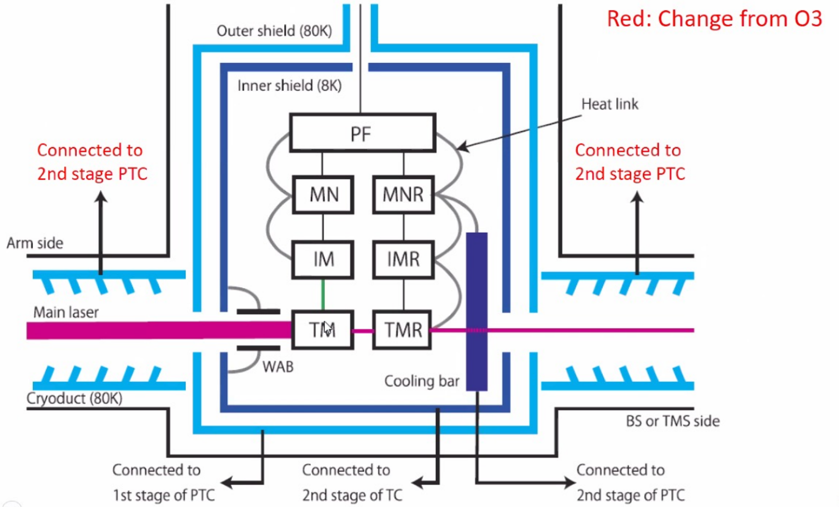
Example of spectra (suspension in air)

Large noise below 30Hz is due to air disturbances and decreases in the vacuum condition.

Cryogenic system in KAGRA

A cryogenic payload is stored inside the cryostat with two-layer radiation shields (80 K shield and 8 K shield).

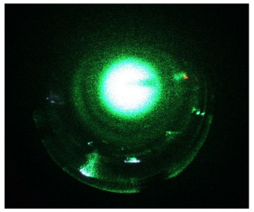
Both HR and AR side of a mirror, there are 5-m cryogenic duct shield for reducing the thermal radiation from the beam tubes,



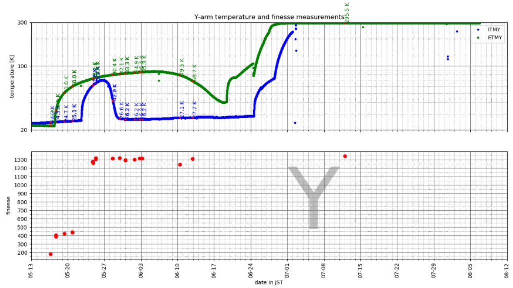
T. Ushiba – Cryogenics

Problem of the cooling (frosting issue)

- During the cooling, thick frost was formed on the mirrors, which causes drastic finesse drop of arm cavities.
- Since a part of finesse drop can be recovered when warming up the mirrors at 70 – 80 K, the main components of the frost seems N_2.



Mirror surface at cryo temp.



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Summary

- Using cryogenic sapphire mirror for reducing the thermal noise is one of key features of KAGRA.
- Sensors and actuators are designed, considering cryogenic compatibility.
  — Reflective PSs with large sensing range.
  — OpLevs and length-sensing OpLevs.
  — Coil-magnet actuators.
  — “Ropeway style” moving mass
- Cooling mirros can occure the serious problem: frosting on the mirror.
  — Vapor pressure of the molecules needs to be considered.
  —Step by step cooling seems effective.
- Preparation of the payload and a part of cooling is ongoing toward O4.
- We hope our cryogenic experiences can help future gravitational wave detectors such as Einstein telescope.

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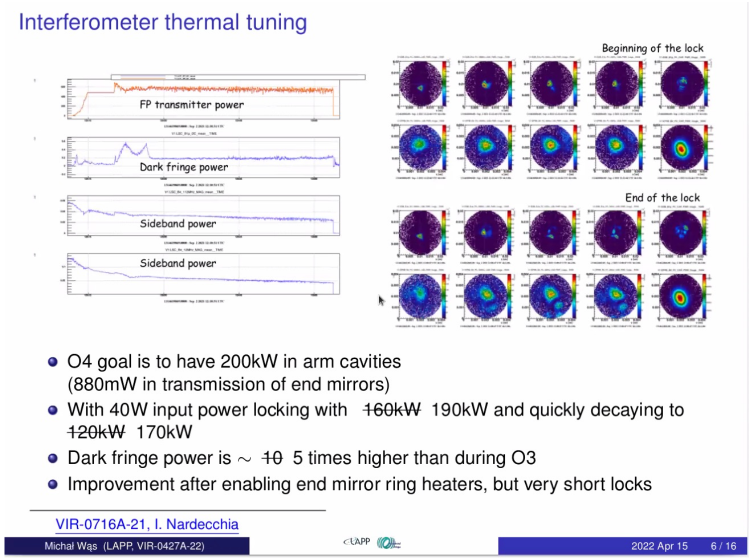
- Crucial experience for Eisntein Telescope !

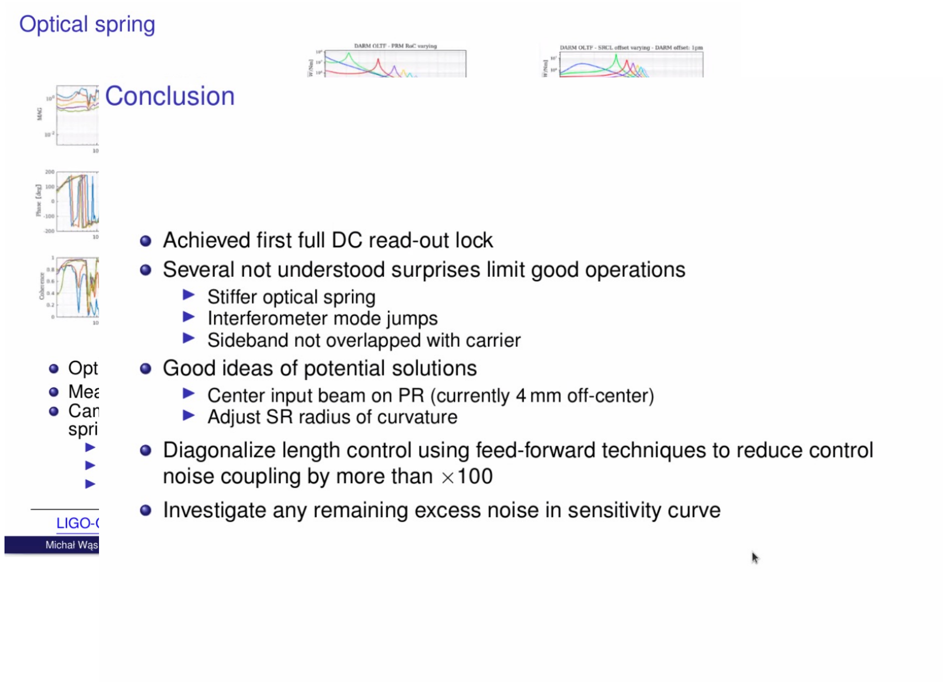
M.Was – Virgo commissioning

Interferometer commissioning highlights

- Upgrade sensors on optical bench suspensions
  - Scattered light pushed below 12 Hz
- Injection & Laser system robustness
  - 10 year old stability issues resolved
    $\Rightarrow$ Installed fiber EOM actuator with $\times 10$ larger dynamic ($\sim$ 20 rad)
  - losses slowly increasing
- Achieved lock acquisition at 25W and then at 40W, then reduced input power to 33W
- Thermal compensation enabled, CO2 laser actuator aligned
- Arm Fabry-Perot cavities optical characterization
- New output mode cleaner locked, and interferometer in DC read-out

M.Was – Virgo commissioning



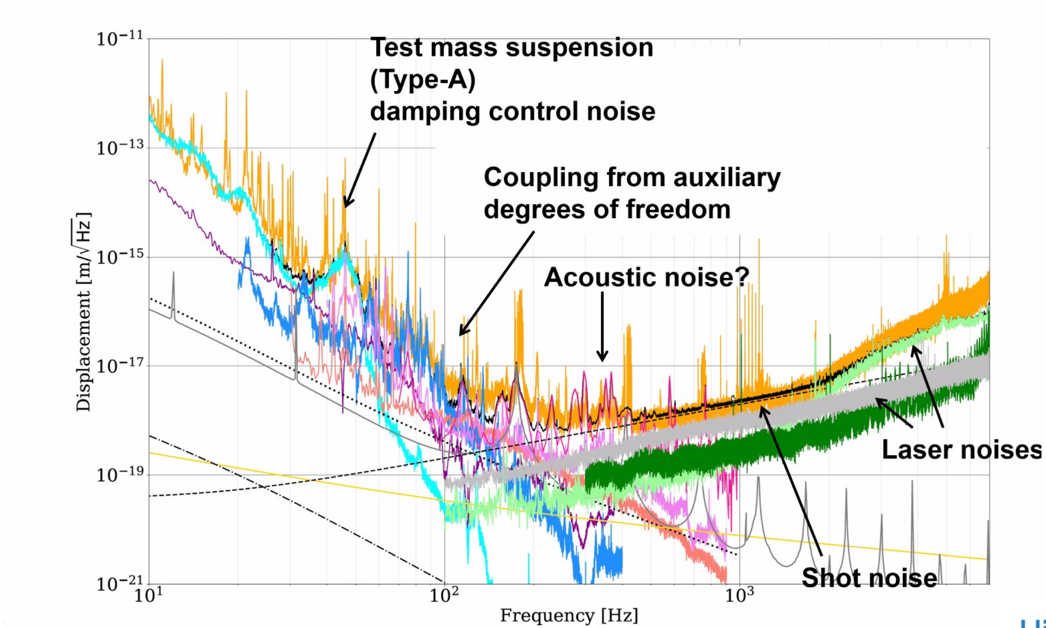


- New facts, difficulties (high power effects, optical spring, SR alignment)
- Role of the simulation!
- Possible collaborations, exchanges of commissioners and development of simulation

Y.Aso – KAGRA commissioning

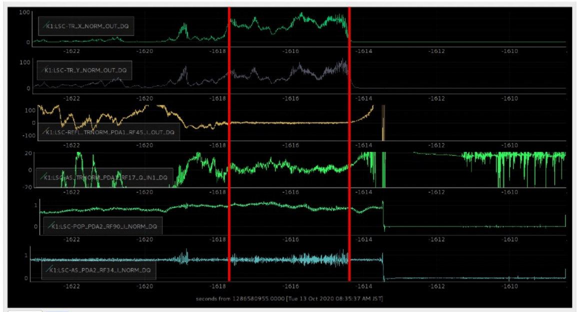
oise Budget

arXiv:2203.07011



RSE lock trial

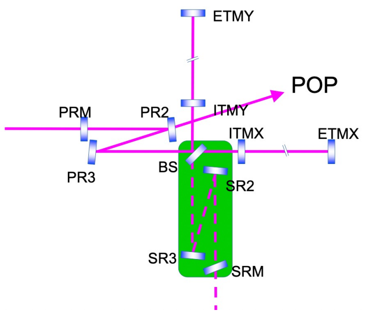
RSE lock ~ 2 sec

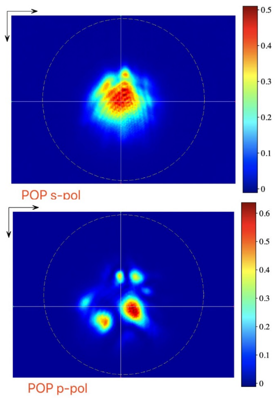


- Suspensions were not quiet enough
- No WFS implemented
- Not enough time to tune feedback filters

Alignment Sensing and Control

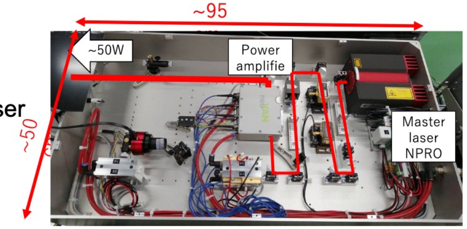
- ASC is much more difficult and messier than LSC (Universal Truth)
- It is especially hard for KAGRA because of the birefringence

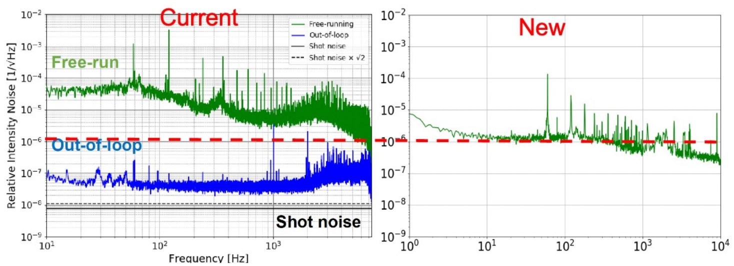




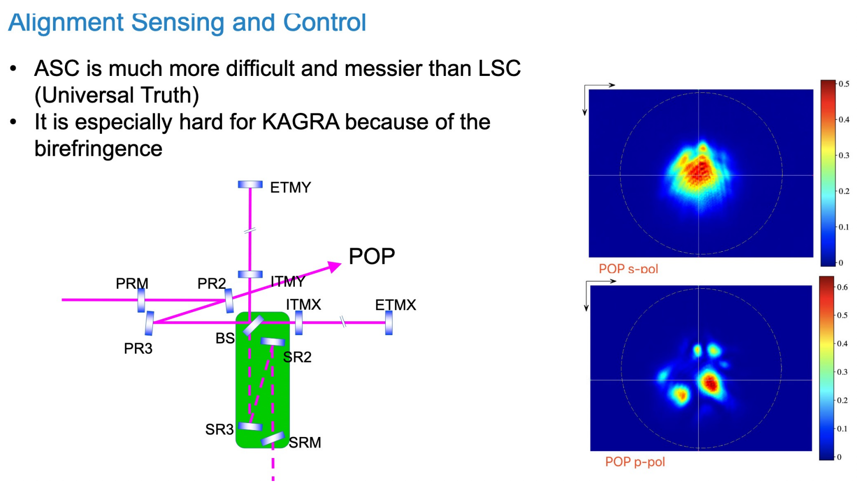
High power laser

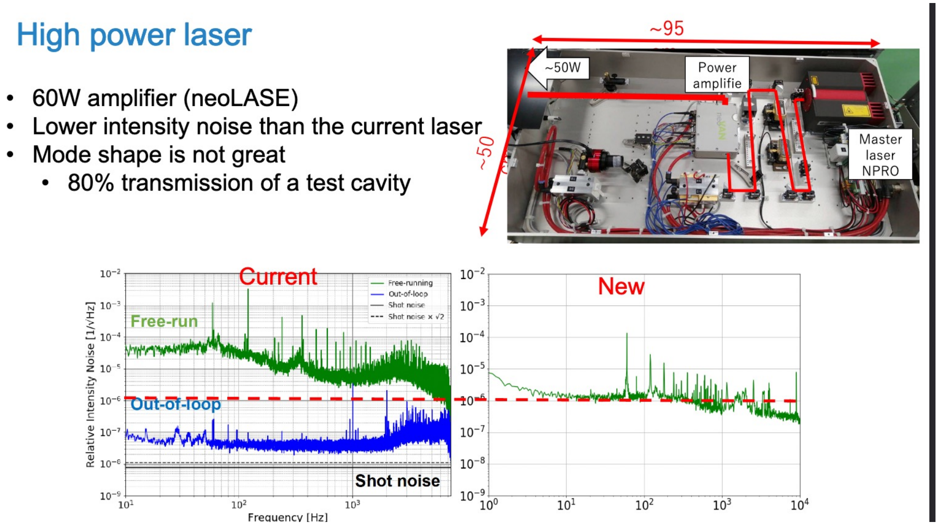
- 60W amplifier (neoLASE)
- Lower intensity noise than the current laser
- Mode shape is not great
  - 80% transmission of a test cavity





Y.Aso – KAGRA commissioning



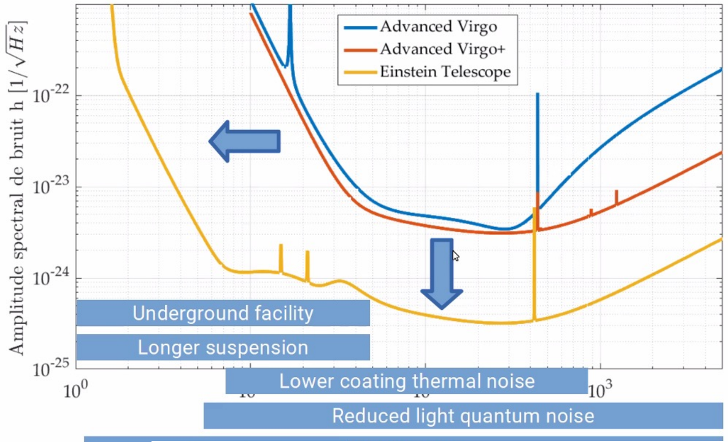


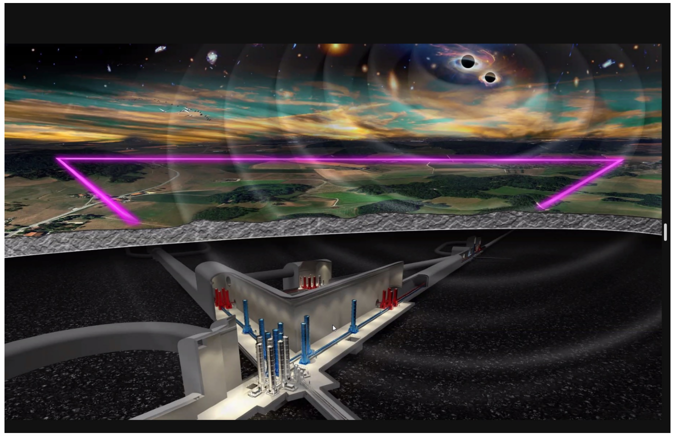
- Possibility to collaborate on several commissoning items
  - Exchange of commissioners and co-tutoring of students
  - Regular meetings (already a few LIGO-Virgo common calls)
  - Sharing of simulation tools

J.Degallaix – Einstein Telescope

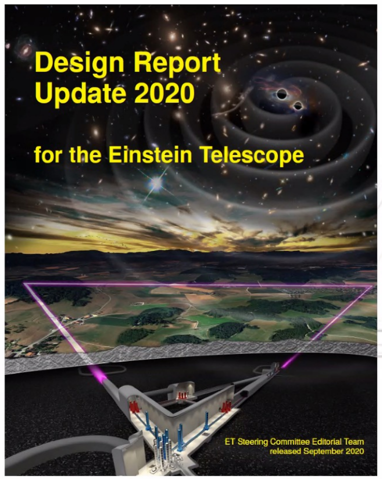
Goal of Einstein Telescope: to be 10 times more sensitive

compared to 2nd generation LIGO and Virgo





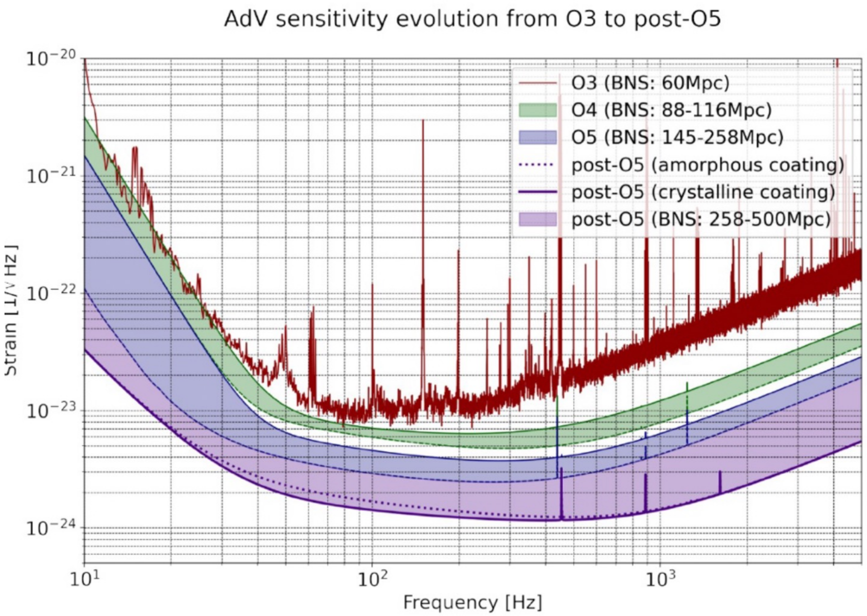
The key parameters



https://apps.et-gw.eu/tds/ql/?c=15418

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon (sapphire ?)
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	factor of a few

J.Degallaix – Einstein Telescope (and post-O5)



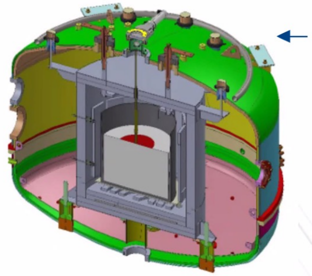
Parameter	O4 high	O4 low	O5 high	O5 low	VnEXT_low
Power injected	25 W	40 W	60 W	80 W	277 W
Arm power	120 kW	190 kW	290 kW	390 kW	1.5 MW
PR gain	34	34	35	35	39
Finesse	446	446	446	446	446
Signal recycling	Yes	Yes	Yes	Yes	Yes
Squeezing type	FIS	FDS	FDS	FDS	FDS
Squeezing detected level	3 dB	4.5 dB	4.5 dB	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

J.Degallaix – Einstein Telescope (and post-O5)

Crystalline substrates

- strong dynamic in Lyon to push for large sapphire substrates



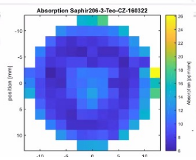


Unique oven to melt 500 kg of alumina

Tests in progress

+ fiber production

- Study absorption vs growth parameters on smaller samples

Best (and latest) results: ~ < 15 ppm/cm at 1064 nm

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What about the coating ?

- research right now focusing on large coating for O5
- material candidate to replace Ti:Ta2O5 → Ti:GeO2
- further reduction in coating loss angle for post-O5

- ET will benefit in all the coating development for LIGO/Virgo
- dedicated cryogenic coating ?
- crystalline coating ?

- Huge inputs from KAGRA to Einstein Telescope !
  - Cryogenics, mirrors, materials, underground environment,…

- Thanks to T.Kajita and S.Katsanevas for the very inspiring welcome talks!
- Thanks to T.Kajita and M.Gonin, ILANCE directors