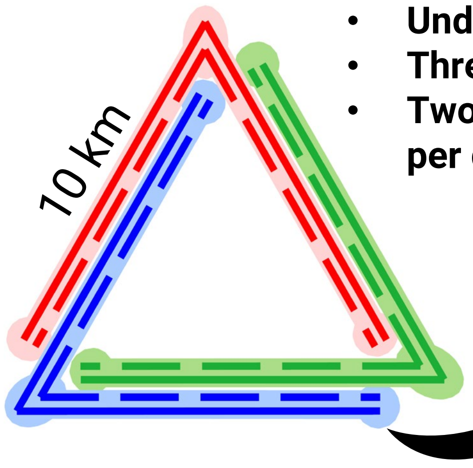
VACUUM AND CRYOGENICS IN INTERFEROMETRIC GW DETECTORS: MOTIVATIONS AND REQUIREMENTS

Gianluca Gemme

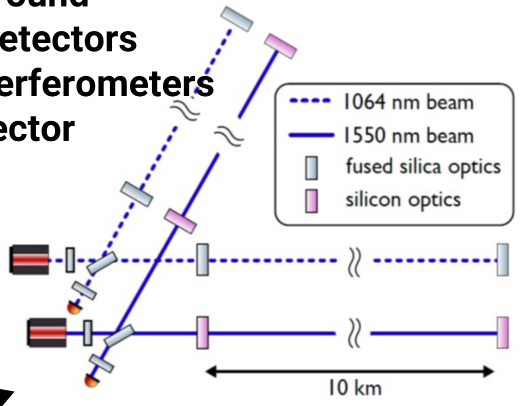
INFN Genova

Sept 29, 2022 - La Biodola, Isola d’Elba, Italy

THE ET CONCEPT

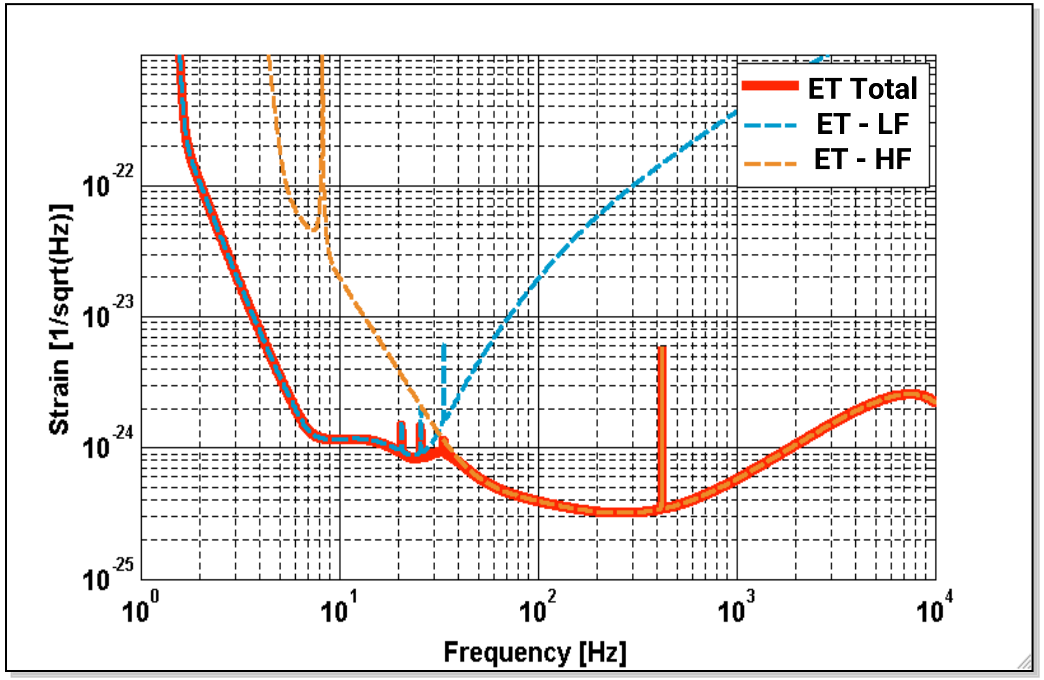


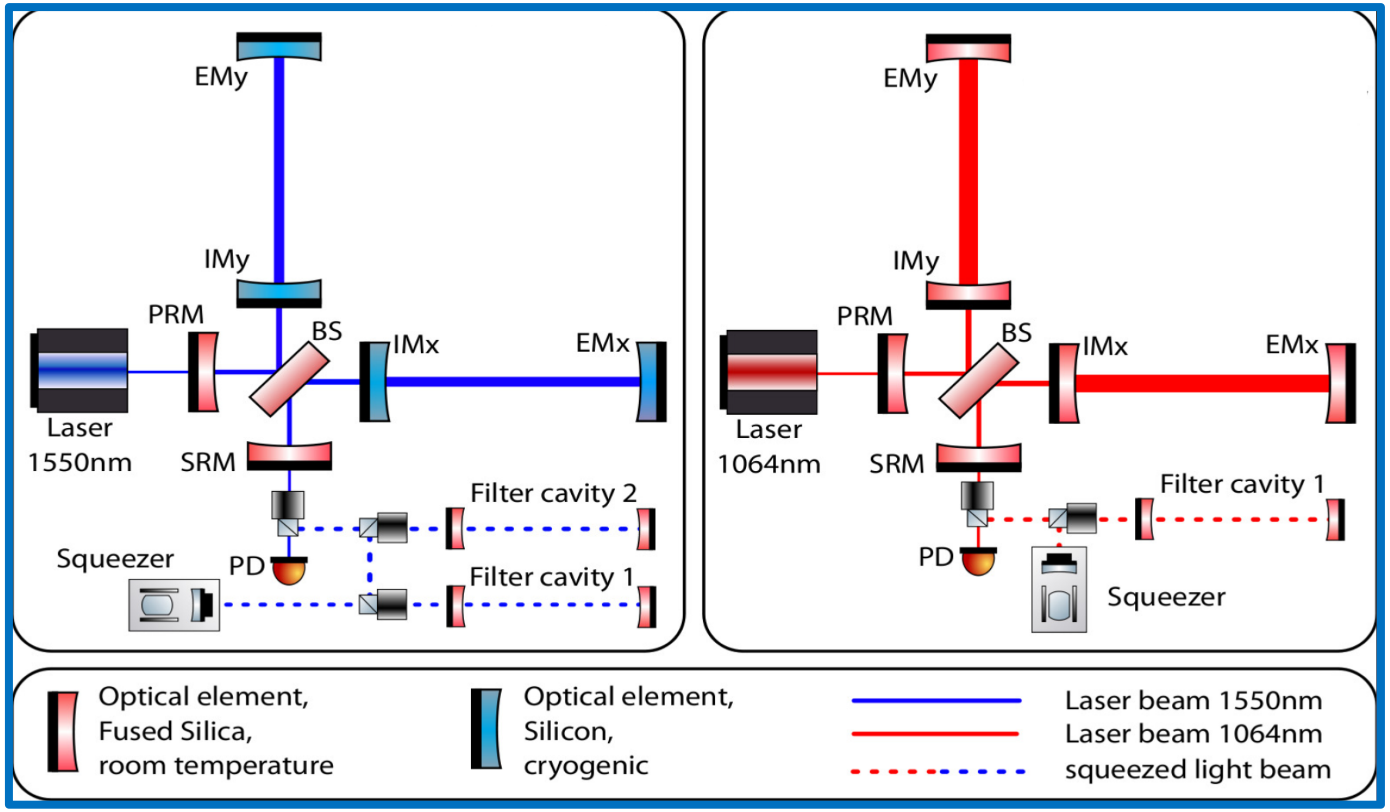
- Underground
- Three detectors
- Two interferometers per detector

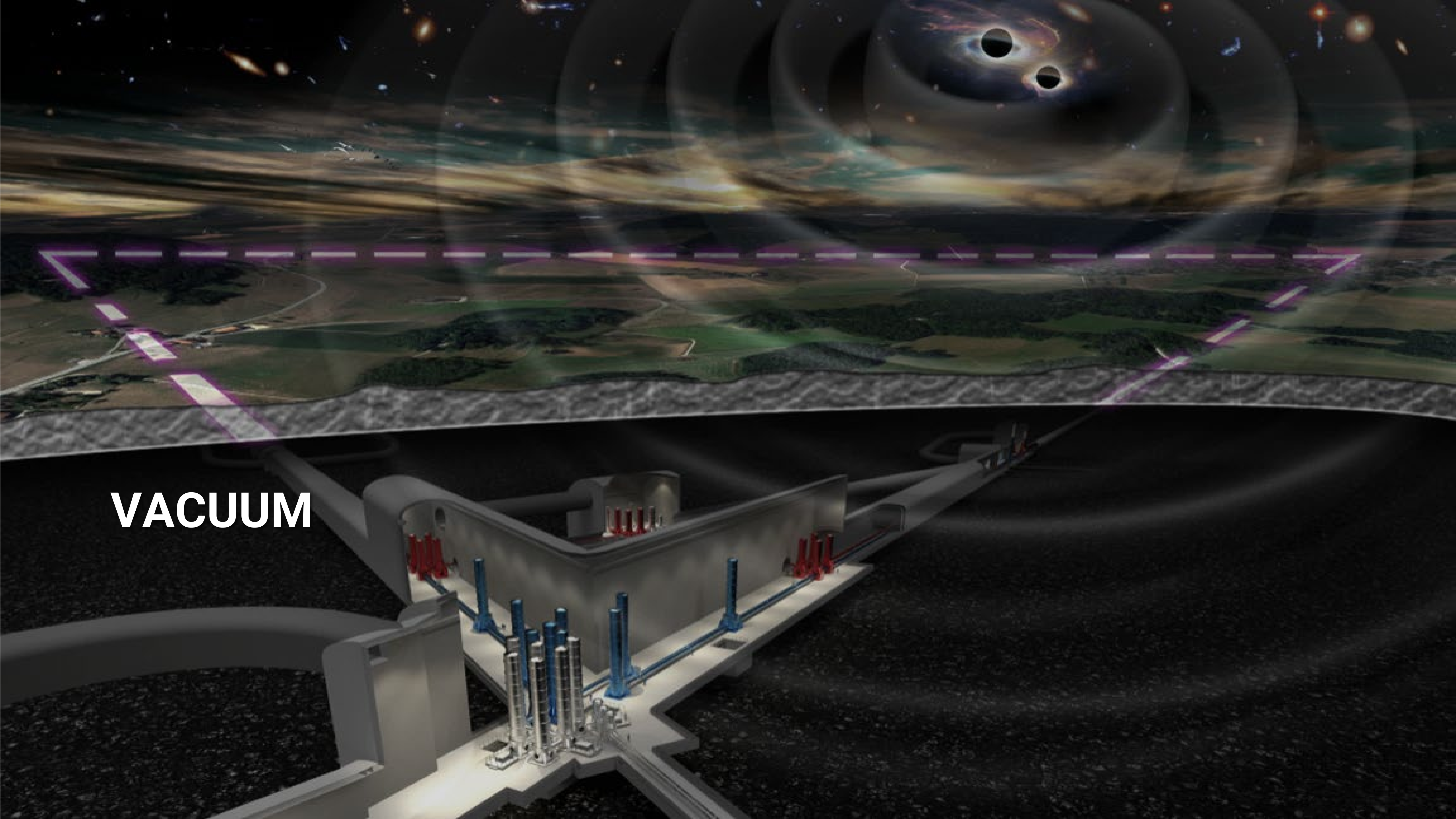


- ET - Low Frequency (LF): large cryogenic (10 - 20 K) silicon test masses, seismic suspensions, new wavelength, FDS, ..
- ET - High Frequency (HF): high power laser, high circulating light power, thermal compensation, large test masses, FDS, ..

Sensitivity of ET (currently being updated)






VACUUM

VACUUM SYSTEM

Vacuum systems for planned 3G detectors are likely to be the largest UHV systems built

Preliminary estimated cost ~560 Meuro

Beam pipe is its largest component (~1/2 of the system cost)
120 Km - 1 m diameter UHV tubes, total volume ~10^5 m^3

Vacuum requirements: factor >5 more stringent than Virgo (for initial ET)
10^{-10} mbar for H_2, 10^{-11} mbar for N_2 and <10^{-14} mbar for Hydrocarbons

Joint development with CERN involving ET and CE

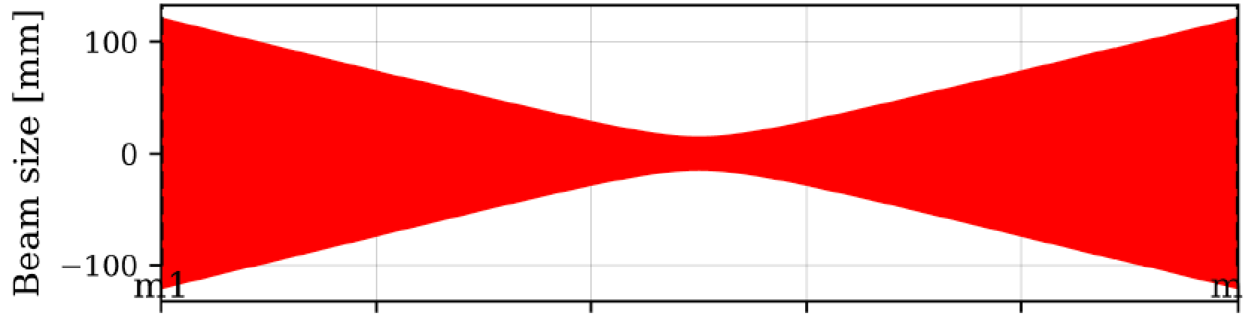
WHY UHV IN GW INTERFEROMETERS?

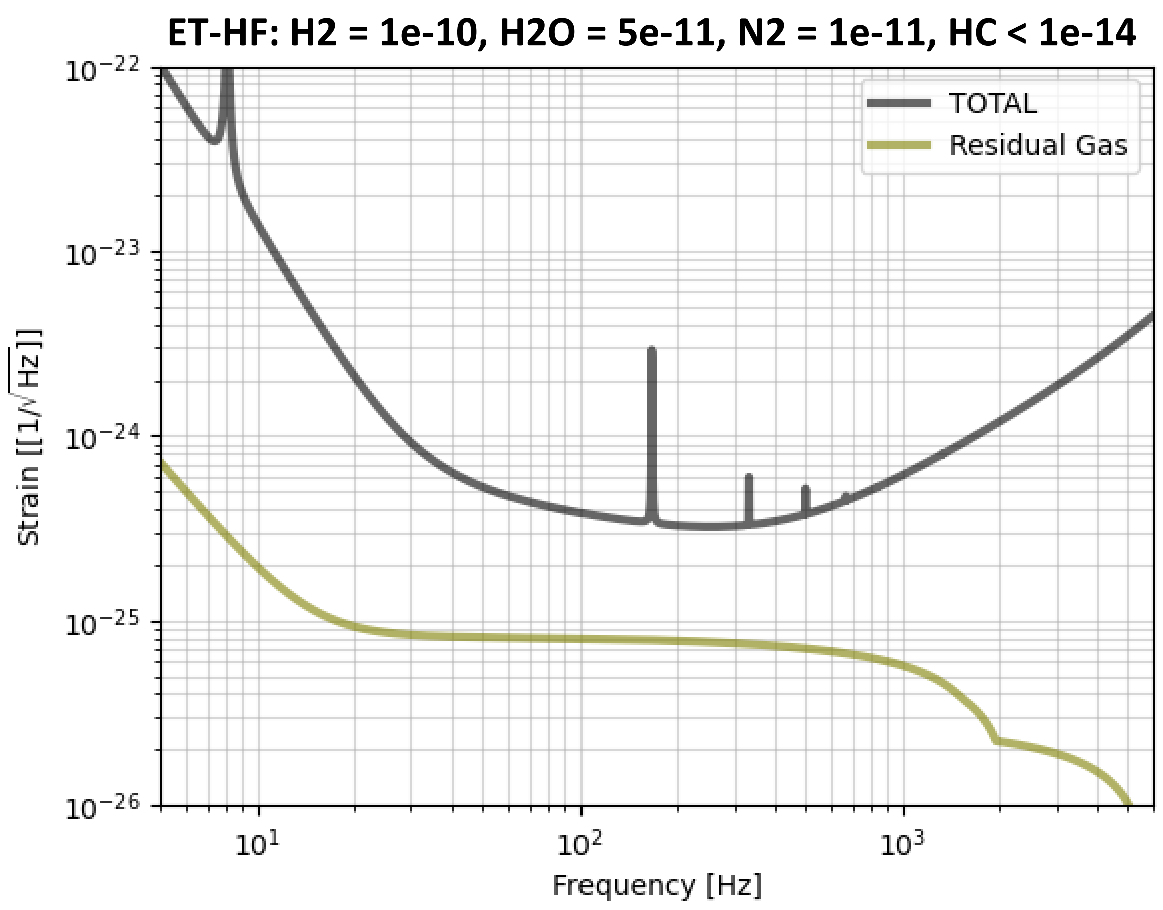
- Reduce the noise due to **refractive index fluctuations along the laser beam path**
- Reduce **test mass motion excitation due to the impact of residual gas molecules**
- Contribute the preservation of **cleanliness of the optical elements**
- Isolate test masses and other optical elements from acoustic noise
- Contribute to thermal isolation of test masses
- Vacuum boundary interacts with **light scattered** from and returning to the interferometer

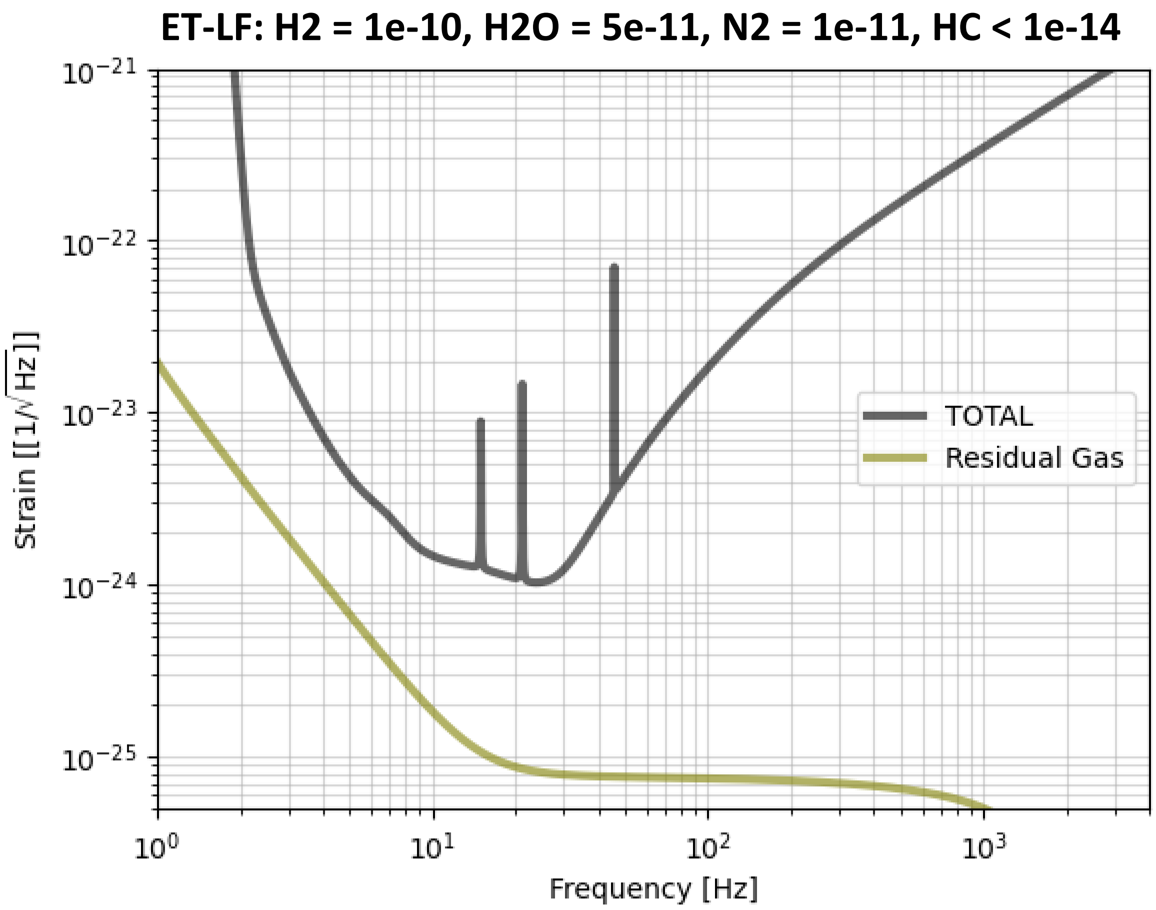
Optical layout, light scattering issues, vacuum conductance…

Optimal vacuum tube diameters

Tunnel size and costs







ET-HF: refractive index fluctuations along the laser beam path (beamtube)

ET-LF: test mass motion due to due to the impact of residual gas molecules (towers)

https://gitlab.et-gw.eu/et/isb/interferometer/ET-NoiseBudget

NOISE DUE TO VACUUM FLUCTUATIONS ALONG THE LASER BEAM PATH

Fluctuations of residual gas density induces fluctuations of refractive index and then of the laser beam optical path

Molecules number density

Gas optical polarizability

Interferometer arm lenght

Power spectral density fluctuations of optical path

$$S_L(f) = \frac{4\rho(2\pi\alpha)^2}{v_0} \int_0^{L_0} \frac{\exp\left[-2\pi f\; w(z)/v_0\right]}{w(z)}\, dz$$

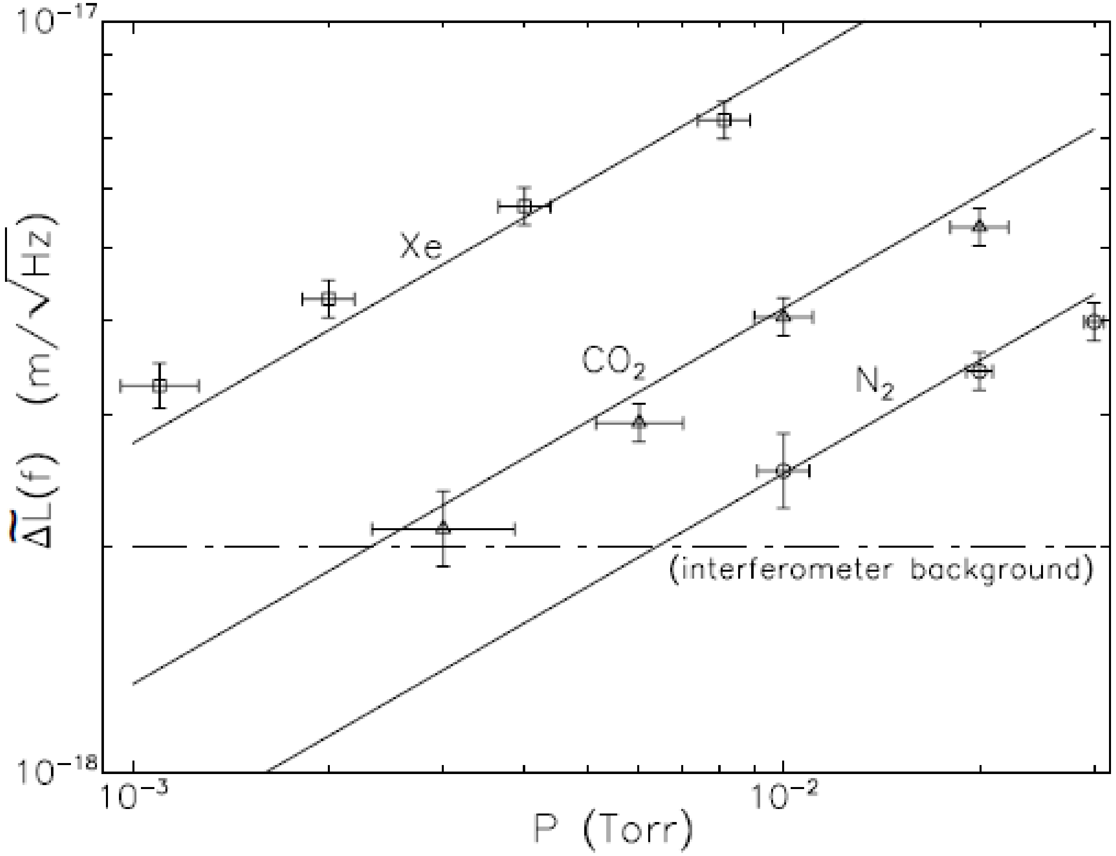
Average molecule speed

Laser beam gaussian radius

S. E. Whitcomb. Optical pathlength fluctuations in an interferometer due to residual gas. Technical report, California Institute of Technology, October 1984.

Courtesy: A. Grado

NOISE DUE TO VACUUM FLUCTUATIONS ALONG THE LASER BEAM PATH



Zucker and Whitcomb, 1996

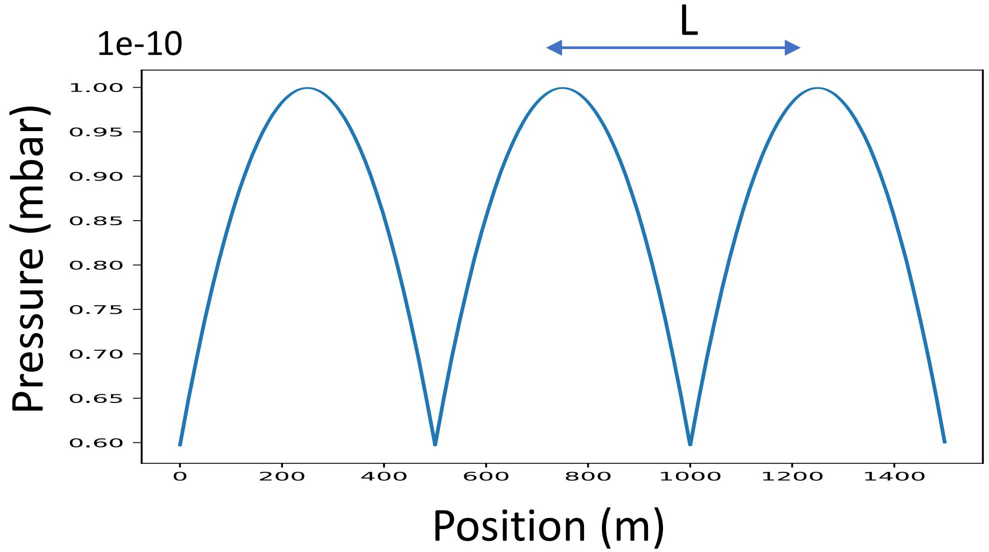
Gas	$R_{H_2} = \Delta\tilde{L}_{gas}/\Delta\tilde{L}_{H_2}$
H_2	$\equiv 1$
H_2O	3.3
N_2	4.2
CO	4.6
CH_4	5.4
HC_{100AMU}	38.4
HC_{400AMU}	208

Residual gas index fluctuation spectral density, normalized to H_2, for λ = 1064 nm

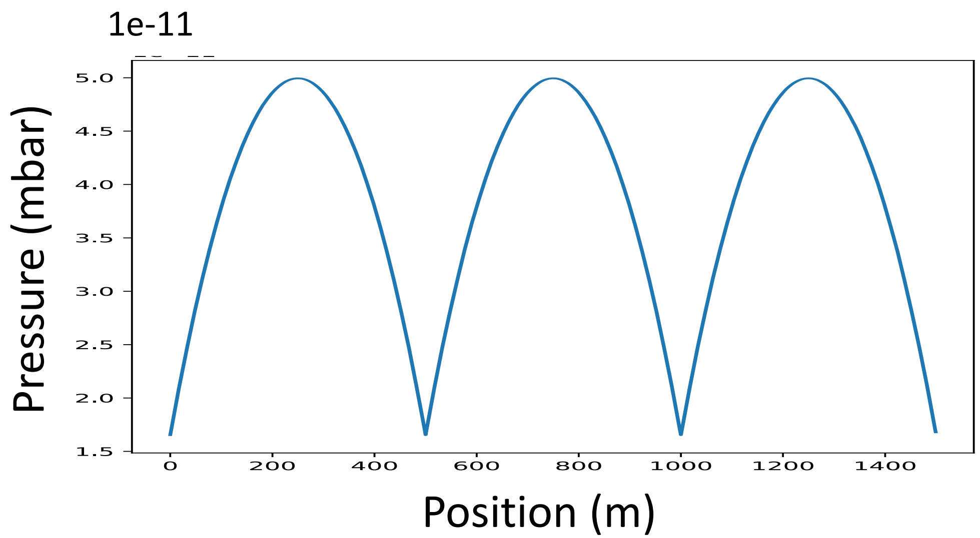
PRESSURE PROFILE ALONG THE TUBE DUE TO TUBE CONDUCTANCE

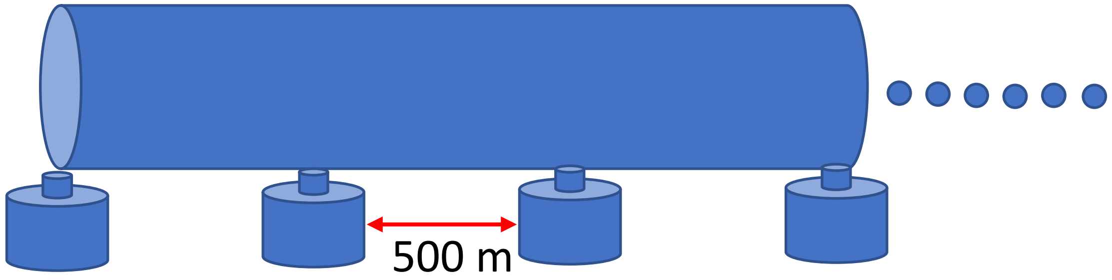
P(z)= Pmin+Q*(z/(C*L)-z²/(2*C*L²))

q = 1.9 e^{-14} mbar l/(s cm^2)
S = 5000 l/s
H_2 partial pressure variation: factor ~1.6



q = 5.3e-15 mbar l s^{-1} cm^{-2}
S = 5000 l/s
H_2O partial pressure variation: factor ~ 3





K.M Welch Volume 23, Issue 8, 1973, 271

Courtesy: A. Grado

PRELIMINARY REQUIREMENTS

	ET 2020 Updated design Report	Refined calculation	Margin 10 (single gas)
P^{max} H_2 (mbar)	$1*10^{-10}$		$3*10^{-10}$
q H_2 (mbar l/s cm^2)	$1.9*10^{-14}$		$5.7*10^{-14}$
Margin H_2	11.8	17.2	10
P^{max} H_2O (mbar)	$5*10^{-11}$		$6.6*10^{-11}$
q H_2O (mbar l/s cm^2)	$5.25*10^{-15}$		$7*10^{-15}$
Margin H_2O	5.4	11.6	10
Total margin (H2O + H2)	4.9	10.4	

PRELIMINARY

Seems OK, but…can this be obtained at a lower cost?

- Material cost (mild steel, ferritic steel, aluminum,…)
- Tube design (e.g. thin corrugated tubes…)
- Pre- and post-fabrication treatments (firing, bake-out,…)

Courtesy: A. Grado

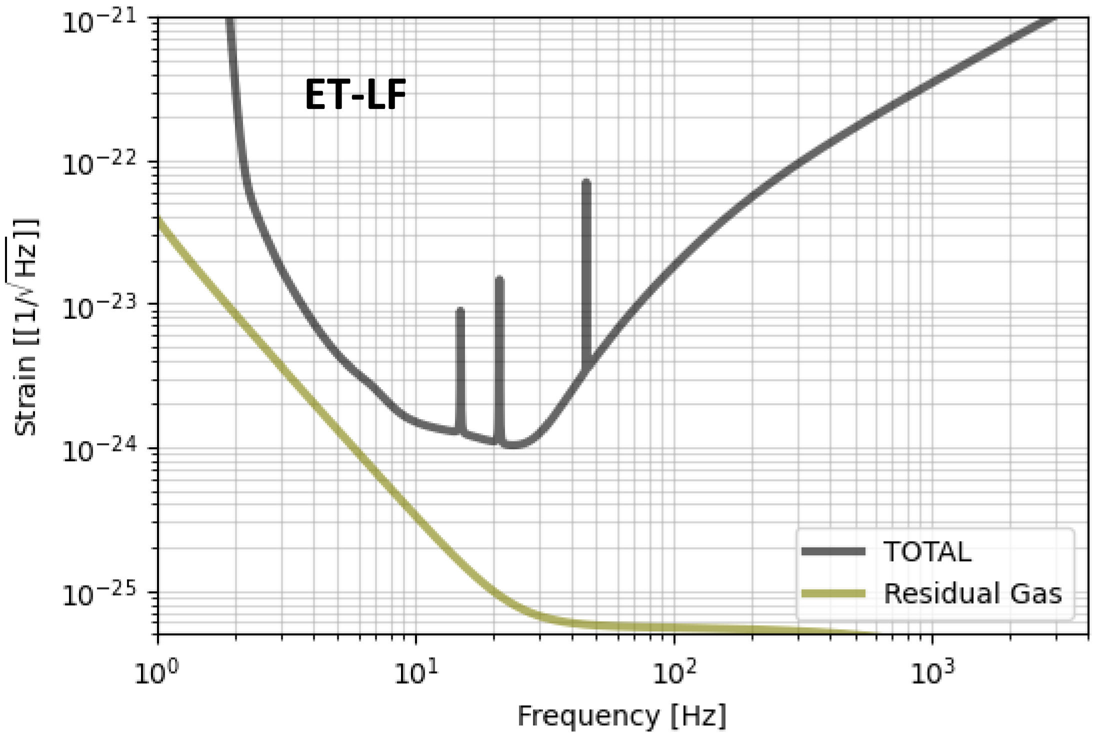
TEST MASS MOTION EXCITATION DUE TO THE IMPACT OF RESIDUAL GAS MOLECULES

Viscosity of the residual gas limits the Q of the suspended test masses

$$Q_P = \frac{\rho_{TM} H f_0}{P} \sqrt{\frac{\pi k_B T}{2m}}$$

The resulting displacement power spectral density is

$$S_x(f) = \frac{k_B T f_0}{2\pi^3 Q_P M_{TM} f^4}$$



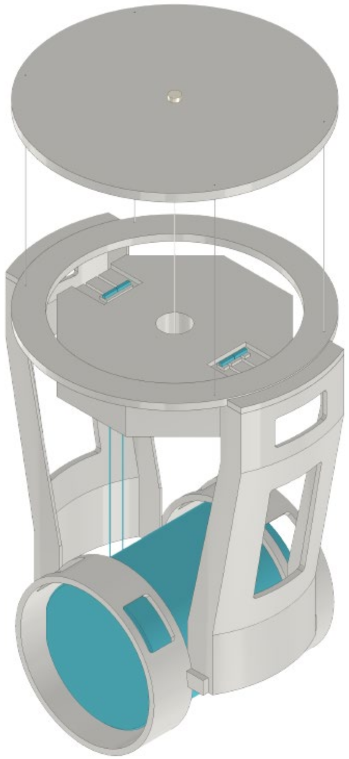
TEST MASS MOTION EXCITATION DUE TO THE IMPACT OF RESIDUAL GAS MOLECULES

Realistic interferometer configurations can exacerbate the viscous effect

- Local outgassing
- «Squeeze film» damping (factor of 5 worse than ideal in LIGO)

For third-generation interferometers, it is necessary for the design of the payload to take this effect into account

- Materials sorrounding the test mass (no outgassing)
- Overall geometry (no small gaps)



MIRROR CONTAMINATION

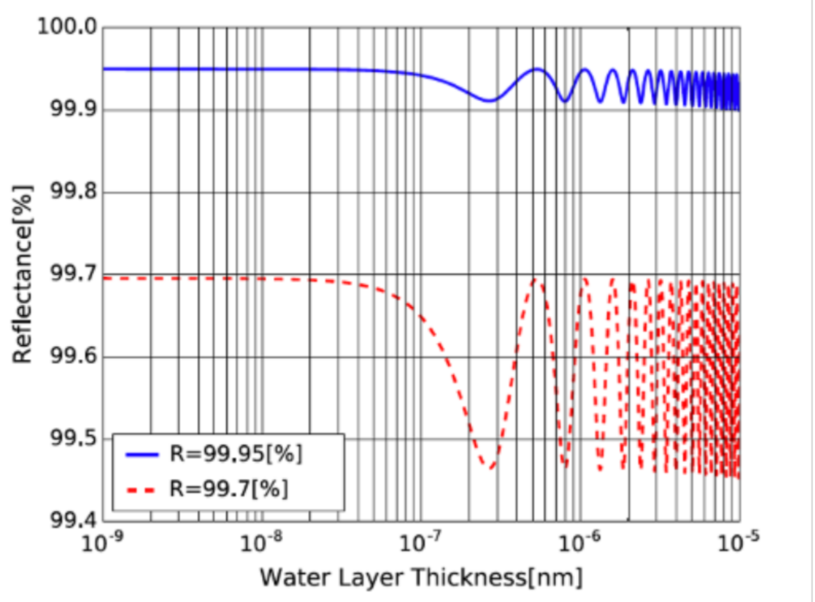
Condensates or dust particles degrade the low-loss optical surfaces

- ➢ Excess loss
- ➢ Increased scattering
- ➢ Absorption-induced heating → distortion
- ➢ Irreversible damage

Molecular adsorbed layer formation on cooled mirrors and its impacts on cryogenic gravitational wave telescopes

Kunihiko Hasegawa,[1,*] Tomotada Akutsu,[2] Nobuhiro Kimura,[3,4] Yoshio Saito,[1] Toshikazu Suzu
Takayuki Tomaru,[3,4] Ayako Ueda,[3] and Shinji Miyoki[1,†]
[1]Institute for Cosmic Ray Research, The University of Tokyo, Kashiwa, Chiba 277-8582, Japan
[2]National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
[3]High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan
[4]The Graduate University for Advanced Studies, Tsukuba, Ibaraki 305-0801, Japan

(Received 5 October 2018; published 31 January 2019)



Contamination is typically cumulative

Cryogenically cooled mirrors (ET-LF) are particularly challenging → formation of a «frost»multilayer on the surface

Contributed by Roberto Cimino and Christian Day

Cryogenic vacuum issues on GWD optics

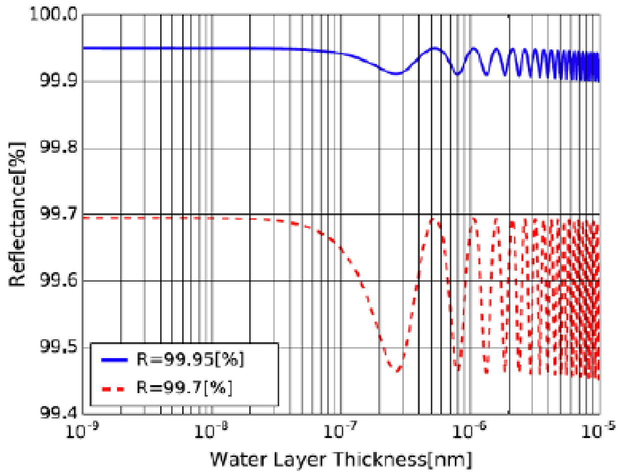
- From KAGRA experience, simulations indicate:
  - Reflectivity gets affected, already after 100 nm of H_2O ice
  - ET maximum thermal budget $(0.1 - 1.0\,\mathrm{W})$ is expected to be exceeded already after $\approx 1 - 10\,\mathrm{nm}$ of H_2O ice !!!

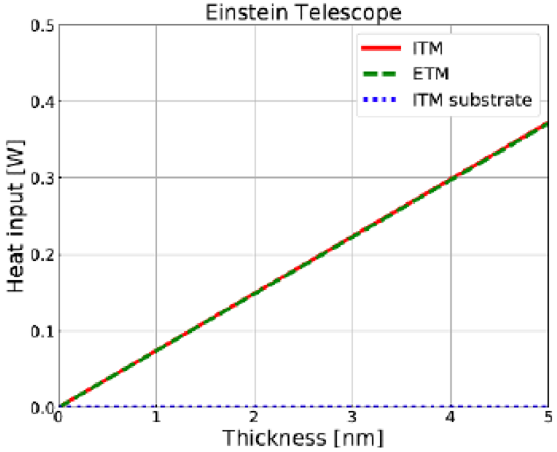
Molecular adsorbed layer formation on cooled mirrors and its impacts on cryogenic gravitational wave telescopes

Kunihiko Hasegawa,[1,*] Tomotada Akutsu,[2] Nobuhiro Kimura,[3,4] Yoshio Saito,[1] Toshikazu Suzuki,[1,3] Takayuki Tomaru,[3,4] Ayako Ueda,[3] and Shinji Miyoki[1,†]

[1]*Institute for Cosmic Ray Research, The University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[2]*National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan*
[3]*High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan*
[4]*The Graduate University for Advanced Studies, Tsukuba, Ibaraki 305-0801, Japan*

(Received 5 October 2018; published 31 January 2019)





Optical loss study of molecular layer for a cryogenic interferometric gravitational-wave detector

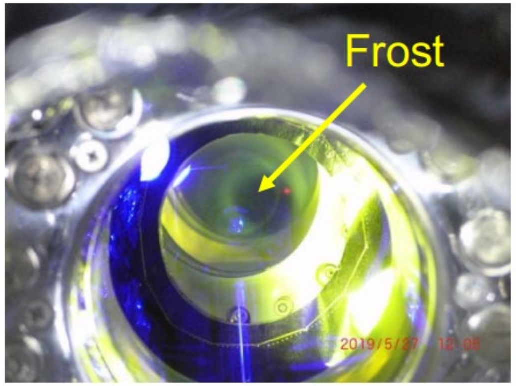
Setoshi Tanioka, Kunihiko Hasegawa, and Yoichi Aso
Phys. Rev. D **102**, 022009 – Published 27 July 2020

$$1 - 10\,\mathrm{nm}\ H_2O \rightarrow 3 - 30\,\mathrm{L}$$

If $p_{H_2O} \approx 1 \times 10^{-10}\,\mathrm{mbar} \rightarrow$ it takes $\left(10^4 \times (3-30)\,\mathrm{s}\right) = (9 - 90)\ \mathrm{h}$ to start observing detrimental effects!!!

Courtesy: S. Grohmann

THE KAGRA EXPERIENCE



Frosting on Mirrors → significantly degrading finesse and sensitivity

- Heaters were installed on intermediate mass to enhance the speed of heat up
- New requirement on acceptable vacuum leak level from 10^{-9} Pa m^3/sec to 10^{-10} Pa m^3/sec
- Mass spectrometers were set in each cryostat for monitoring N_2. O_2, H_2O
- Cool-down strategy

Frosting on windows where the oplev light pass through → Unreliable mirror alignment information → no P/Y damping control for mirrors →
No operation of IFO

- Heaters were installed around windows on the inner and outer radiation shields

Courtesy: Jun'ichi Yokoyama

MITIGATION STRATEGIES

Passive

- Low pressure in mirror chambers (p_{H2O} ~ 1e-12 mbar)
- Use of cryo-panels around the mirrors
- Careful cool-down strategy (mirror last to be cooled)
- Low gas flow from beam line
- Primary laser-beam-induced desorption

Active

- CO2 laser
- UV photons (risky for the coatings and the mirrors)
- Low energy electrons (risky for the coatings and the mirrors)

In ET the situation will differ from the one in KAGRA (lower partial pressure, cryotraps)

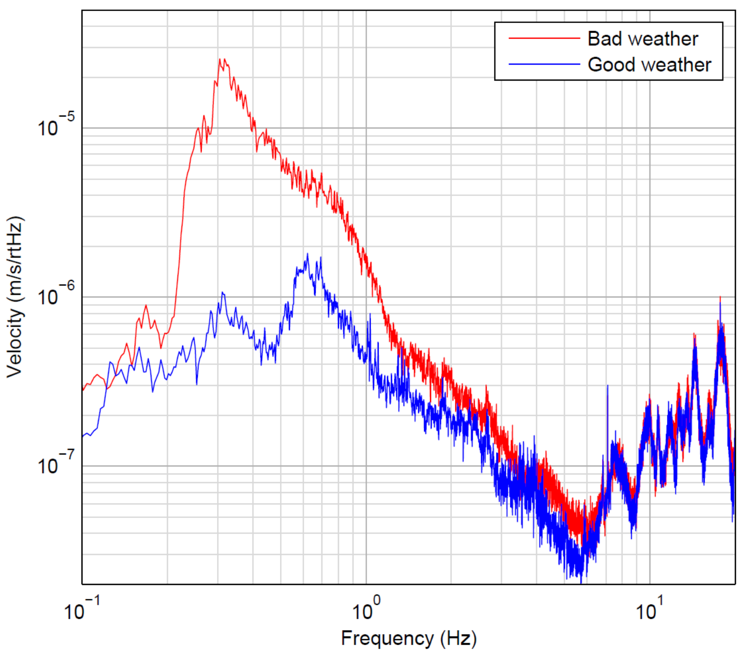
L. Spallino, et al, PHYSICAL REVIEW D 104, 062001 (2021)

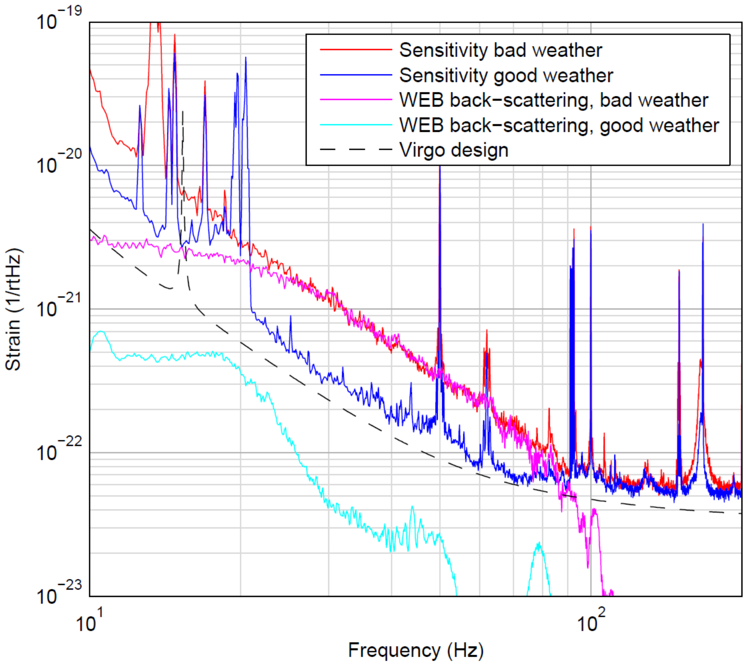
LIGHT SCATTERING FROM WALLS OR BAFFLES

The vacuum boundary intercepts and rescatters some light scattered from interferometers optics

Interference of this rescattered light with the original circulating field introduces a phase shift bearing the imprint of the wall’s vibration

Coupling of the ambient acoustic and seismic environment into the interferometer



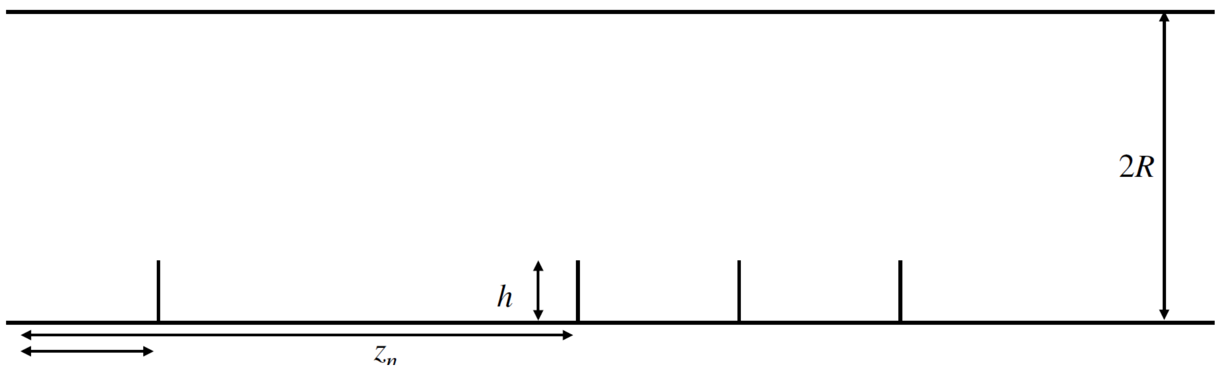


Classical and Quantum Gravity 27, 19 (2010) 194011

MITIGATION STRATEGIES

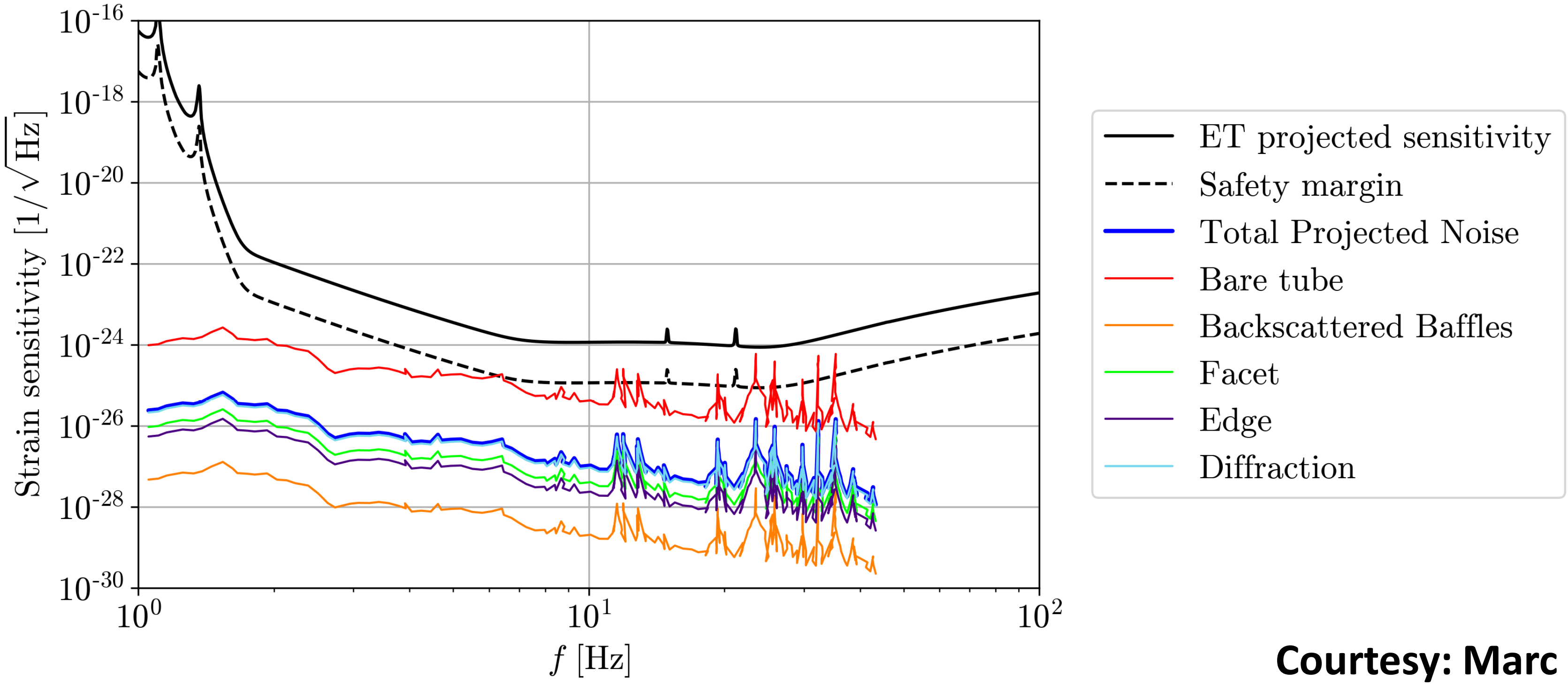
- Reduce environmental noise (underground , optical bench suspended in vacuum, …)
- Wide angle scattering: local baffles (possibly seismically isolated, special material to reduce secondary rescattergin) are interposed between the the optics and vacuum walls
- Narrow angle scattering: spatially distributed → impact on vacuum system design (and cost)
  - Noise varies ~inversely with beam tube radius
  - Internal baffles must be fitted to absorb and attenuate the worst projected scattering

ONGOING ACTIVITY



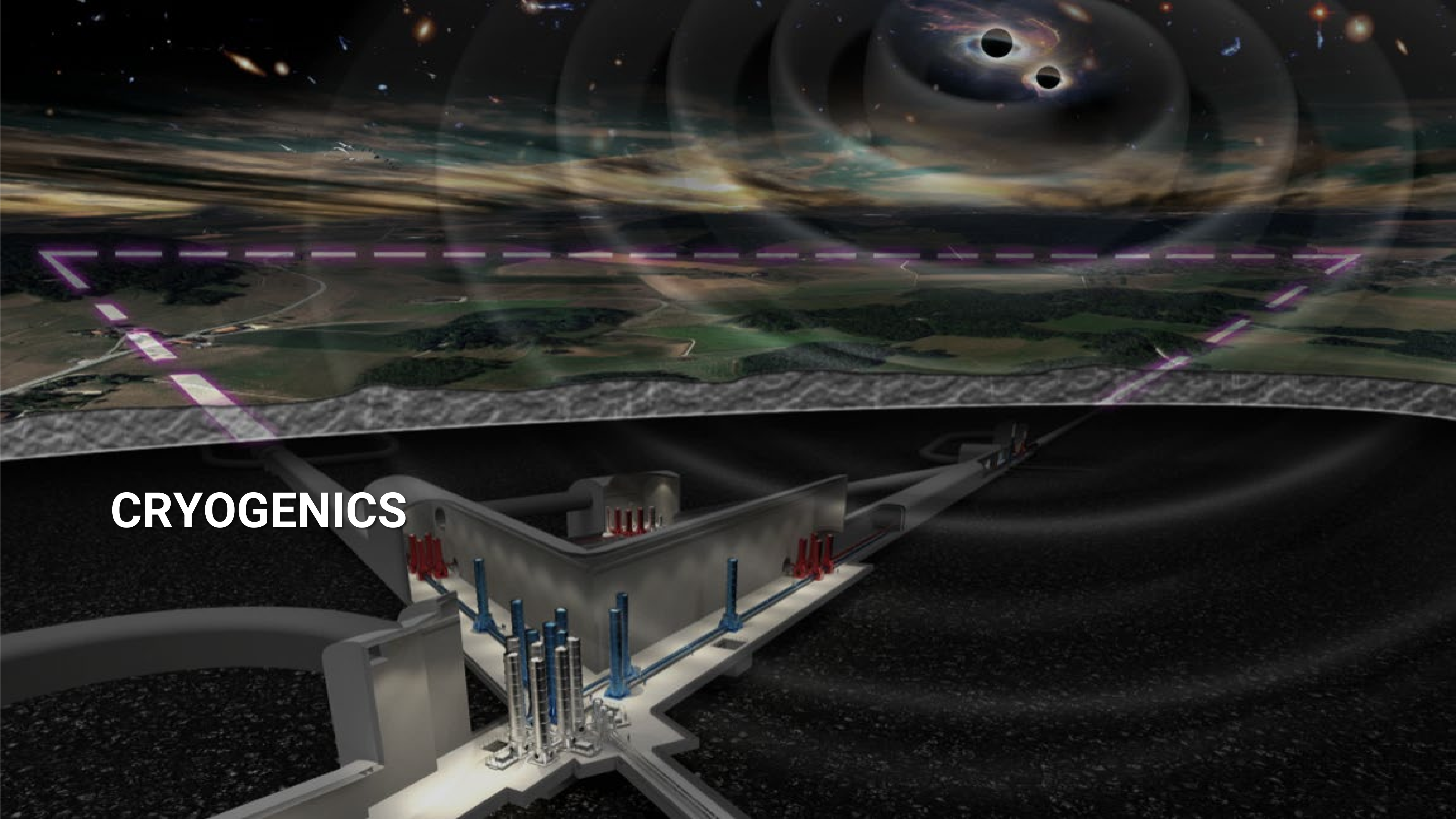
As stated in VIR-NOT-LAL-1390-123:

$$z_n = z_1 \left(a \frac{R}{R - h} \right)$$



Courtesy: Marc Andrés Carcasona

CRYOGENICS

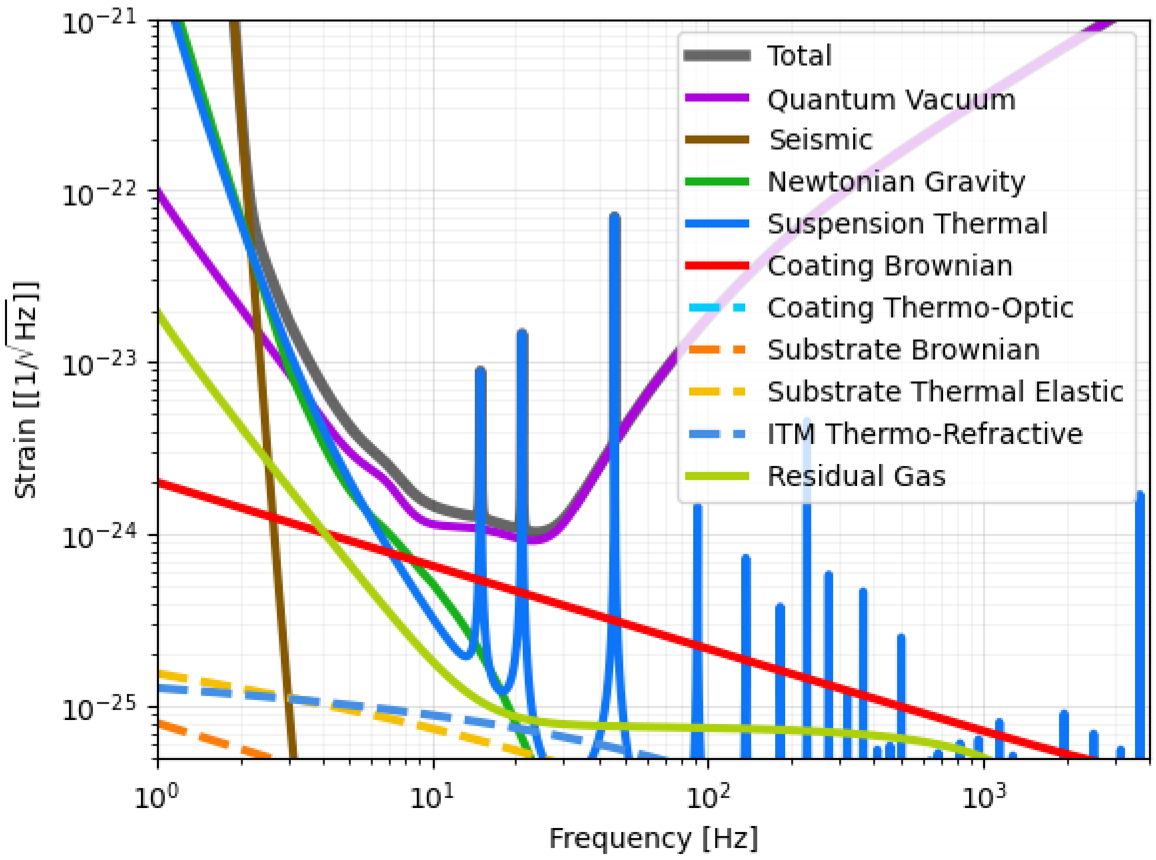


MOTIVATION AND IMPACT

Limit the thermal noise impact on the sensitivity

Cryogenic payload (test mass+suspension)

- Preserving mechanical isolation
- Guaranteeing an efficient thermal link
- Optical material (silicon, sapphire)
- Laser frequency (1550nm, 2000nm)
- Strong requirements on base operating vacuum in towers and/or mitigation strategies
- Requirement on length of thermal cycle



https://gitlab.et-gw.eu/et/isb/interferometer/ET-NoiseBudget

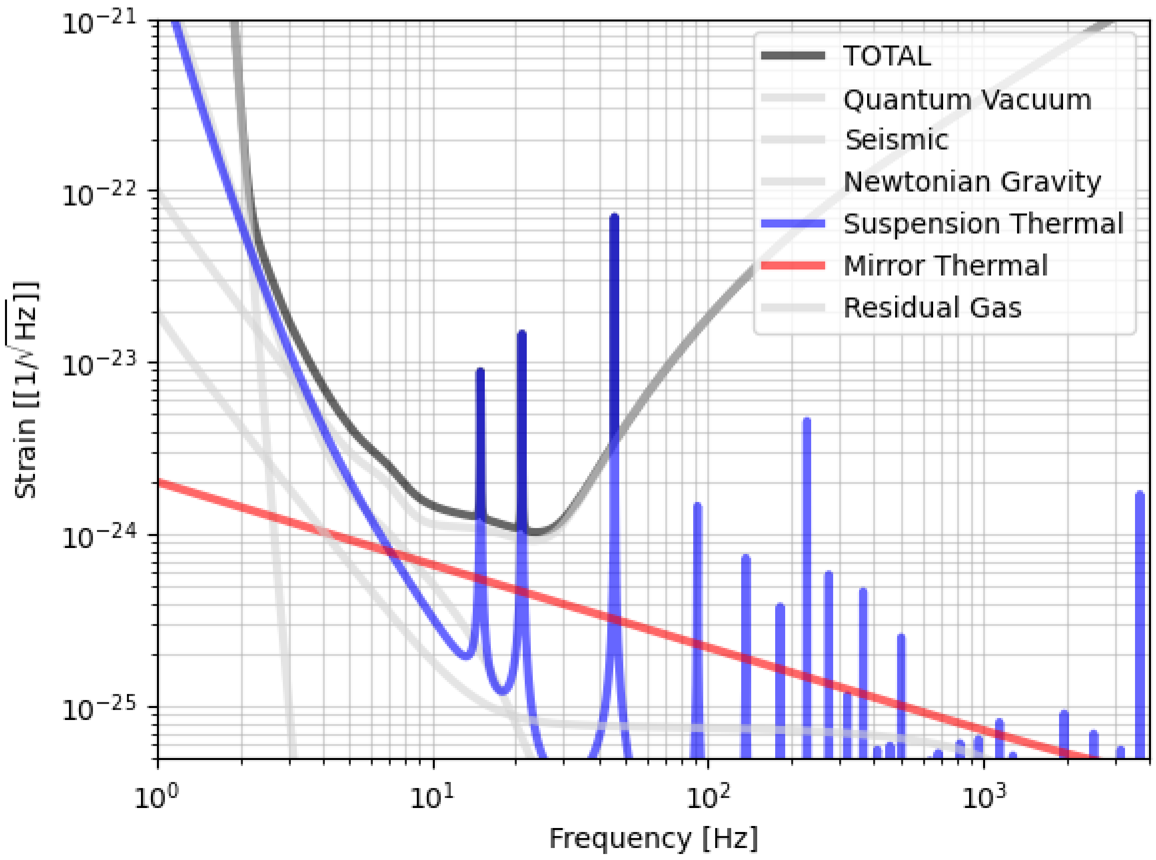
MOTIVATION AND IMPACT

Limit the thermal noise impact on the sensitivity

↓

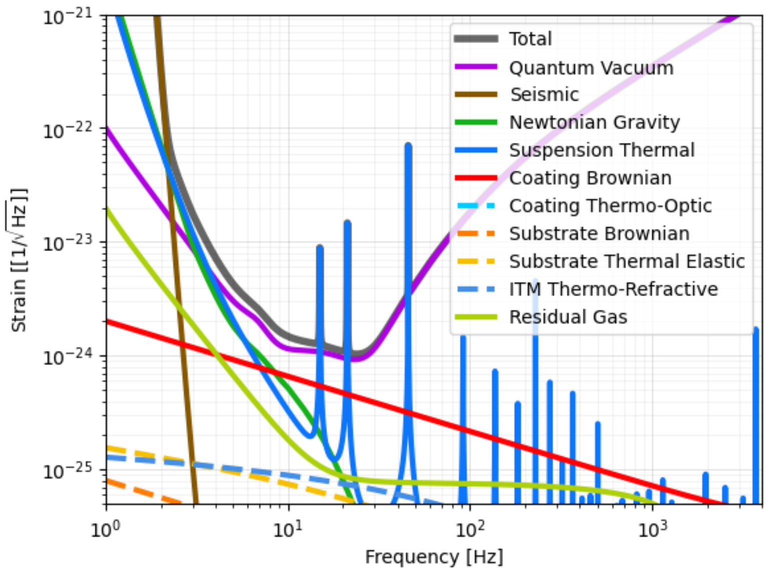
Cryogenic payload (test mass+suspension)

	Marionetta	Recoil Mass	Mirror
Masses for ETDLF (kg)	422	211	211
Wire Diameter (mm)	5	3	3
Wire length (m)	2	2	2
Wire Material	Ti6Al4V	Silicon	Silicon
Loss Angle	10^{-5}	10^{-8}	10^{-8}
Temperature (K)	2	10	10



https://gitlab.et-gw.eu/et/isb/interferometer/ET-NoiseBudget

CRYOGENIC PAYLOAD

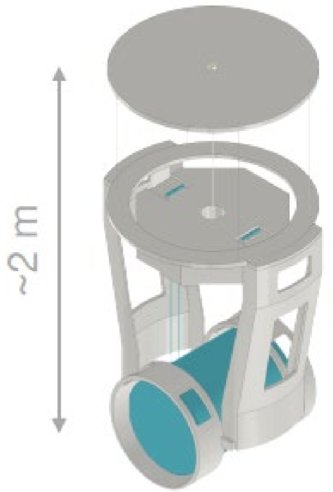


Thermal noise requirements

- Mirror Mass and dissipations (including coating)
- Mirror Suspension Frequencies and dissipations

Optical design requirements

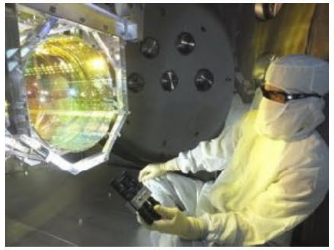
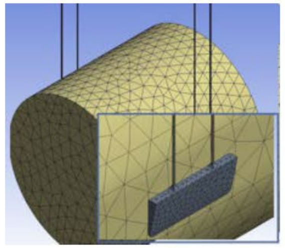
- Beam Size
- Input Power



- Dimensions and Material of Test Mass Mirrors and suspensions
- Operating temperature
- Dissipated power

Courtesy: P. Rapagnani

CORE OPTICS AND COATINGS

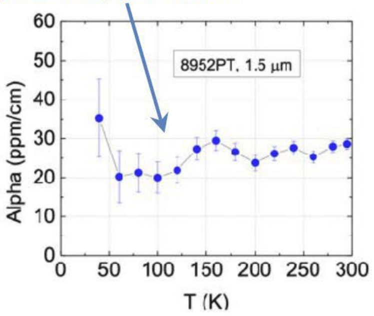



Advanced LIGO – 40 kg / ET 200 kg

Nikon SiO_2

Absorption of “best 45 cm” MCZ Si: 1.5um

Stanford/Glasgow/Berkeley/Caltech 2019



Substrates

- Substrate (ET-HF silica / ET-LF silicon) of 200 kg-scale, diam≥45cm, with required purity and optical homogeneity/absorption

Silicon

- Czochralski (CZ) method produced test masses could have the required size, but show absorption excesses due to the (crucible) contaminants
- Float Zone (FZ) produced samples show the required purity, but of reduced size (20cm wrt ≥45cm required)
- Magnetic Czochralski (mCZ) could be the possible solution (45cm + abs 20 ppm/cm)?

Coating

- Amorphous dielectric coating solutions often either satisfy thermal noise requirement (3.2 times better than the current coatings) **or** optical performance requirement (less than 0.5ppm) – not both
- AlGaAs Crystalline coatings could satisfy ET-LF requirements, but currently limited to 200mm diameter. No physical/procedural showstopper to go to larger sizes but needs significant investment in technology development.
- Crystalline oxides?

ET-LF LASER WAVELENGTH

- ET-LF wavelength workshop (3rd/16th September 2021) : https://wiki.et-gw.eu/ISB/Optics/ET-LFworkshop
  - Aim : weight pros and cons for possible wavelengths (1.06, 1.5 and 2.0 um) and establish the needed R&D
  - Participation of other Divisions (ITF, SUSP, VAC&CRYO), LIGO Voyager and KAGRA
  - Outcome: **1550nm is still the preferred choice but other options should be kept open as alternatives/upgrades**
  - Summary document to be published on ET TDS (draft on Overleaf: https://www.overleaf.com/read/bffsvvfqdffy)

List of possible wavelengths: technologies, properties/known issues "decision matrix"

Wavelength	1064	1550	1950	1980/5	2050	2090	2128
Substrate (material and properties)	Sapphire Absorption (20-200pm/cm) still too high and not reproducible (devpt needed) issues= biref, polishing, cost	Silicon abs=5-10ppm/cm (T>50K) Large size devpt needed Issues = large size - biref??	Silicon abs=5-10ppm/cm(T>50K) Large size devpt needed Issues = large size? Biref? Low abs only in smaller segments -> composite mirrors?				
Coating (type, expected/known properties: absorption, loss,..)	Amorphous: no coating or mixed material design that will meet noise requirements? Yet... Crystalline: AlGaAs very promising (v. low abs & losses) but scaling issues. AlGaN is lattice matched to Al2O3 but not suitably developed.	Amorphous: mixed material designs (*e.g.* Craig *et al.*, Phys. Rev. Lett. 122, 231102, 2019) Crystalline: AlGaAs very promising but scaling issues. AlGaP?	a-Si likely good choice here (lower absorption than at 1.5)- possibly any shift to longer wavelength helpful? Low absorption could allow the increase of power (but depends also on radiation heat load which could be dominant) to compensate for optical losses (QE, FI,...) SiN? Amorphous: mixed material designs (*e.g.* Craig *et al.*, Phys. Rev. Lett. 122, 231102, 2019)				
Laser (technology, performances, issues...)	Power:OK Stabilisation: LF noise to be improved	Power:OK Stabilisation: LF noise to be improved	Power : development ongoing, lot of reliability studies to be done. Stabilisation: PSL components to be developed, low noise performances to be demonstrated				(OPO conversion of 1064.) For Power and stabilisation see left cell. Maybe some advantages coming from 1064nm pump.
Photodet and other optical elements	InGaAs QE>99%	InGaAs QE>99%	InGaAs, QE~80-85%, large 1/f noise - HgCdTe QE~92% - InAsSb QE~80% Development of low loss Faraday isolator needed Optical losses limit QN improvement above ~10Hz				
Losses and scattering	scattering losses -> FC cavity loss limits SQZ perf at LF More scattered light noise (cut off freq propto 1/lambda)						
Others or comments			Water vapor absorption: is it an issue for the laser components and for IOO?			Is fused silica absorption an issue (120ppm/cm at 2128) for BS?	

CRYOGENIC LOAD ESTIMATES (PER TOWER)

Component	Temperature level / K	Cooling power / W
Arm pipe cryotraps	50...80	$x \ldots 10^4$
Outer thermal shield	50...80	$x \ldots 10^3$
Inner thermal shield	5	$x \ldots 10^2$
Payload heat sink	2	$x \ldots 10^0$

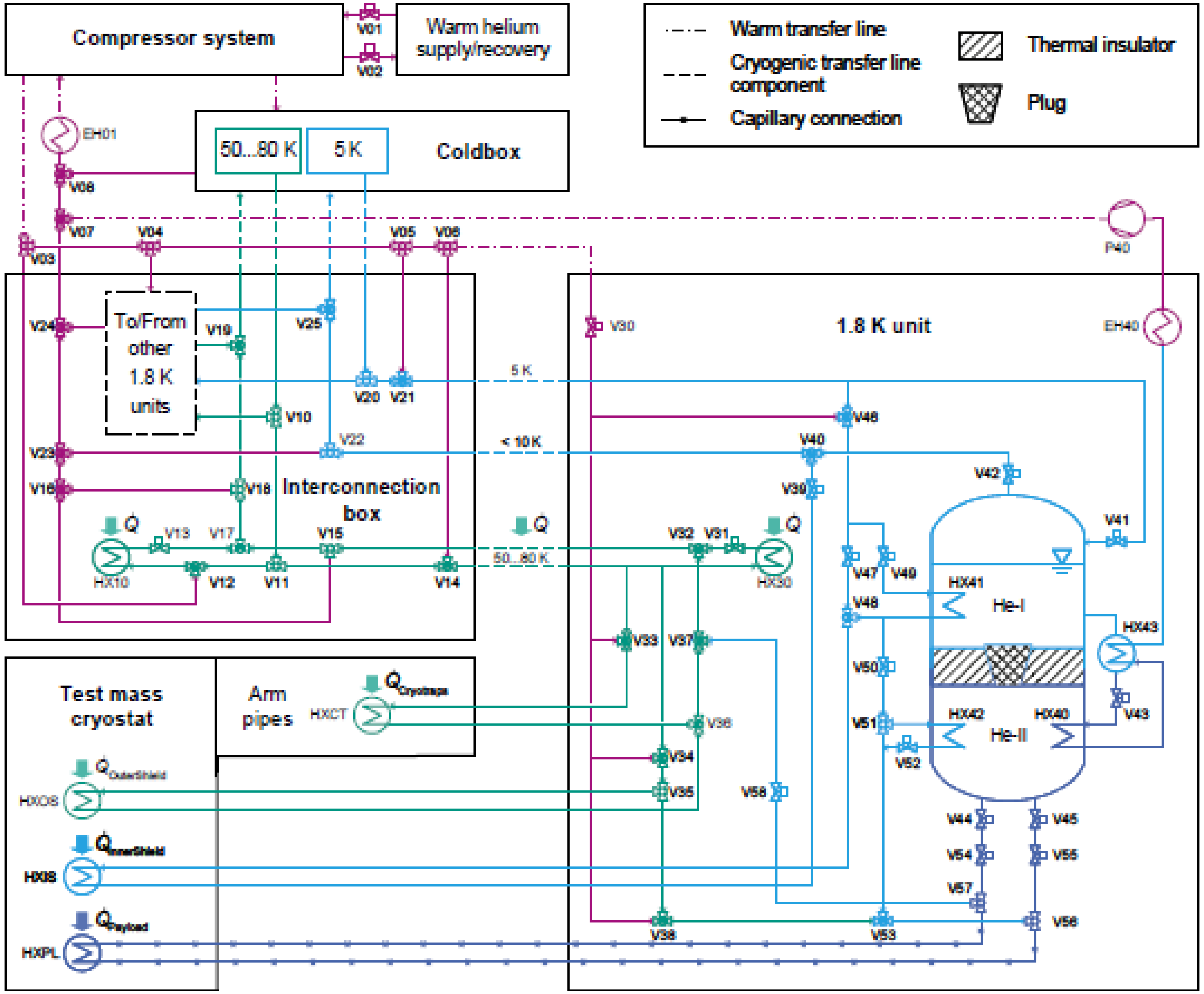
Determines cryogenic infrastructure design!

Small influence on overall cost

Courtesy: S. Grohmann

CRYOGENIC INFRASTRUCTURE CONCEPT

- ➢One He cooling plant in each vertex
- ➢Cooling power for cryotraps, thermal shields and detector at three differen temp levels
- ➢Surface compressors
- ➢Underground coldbox
- ➢Cryogenic transfer system to towers



Courtesy: S. Grohmann

https://apps.et-gw.eu/tds/?content=3&r=17648

COOLING CYCLE: THE KAGRA EXPERIENCE

Turn On
2 coolers

Step 1 → 250K → Step 2 → 82K → Step 3 → Final Step → Goal

21 days | 11 days | 24 days | 10 days | **TOTAL: 66 days**

Step 1
- ✓ Vacuum pumping
- ✓ Internal pressure $< 10^{-4}$ Pa
- ✓ No leakage $> 10^{-10}$ Pa m^3/s

Step 2
- ✓ Cooling down radiation shield ducts
- ✓ Radiation Temp. 90 K ~ 150 K
- ✓ Trap H_2O

Step 3
- ✓ Cooling down inner/outer shields
- ✓ Radiation Temp. 20 K ~ 30K
- ✓ Trap O_2 and N_2

Final Step
- ✓ Cooling down Test Mass

Goal
- ✓ T_{TM}=~20 K

Courtesy: Jun'ichi Yokoyama

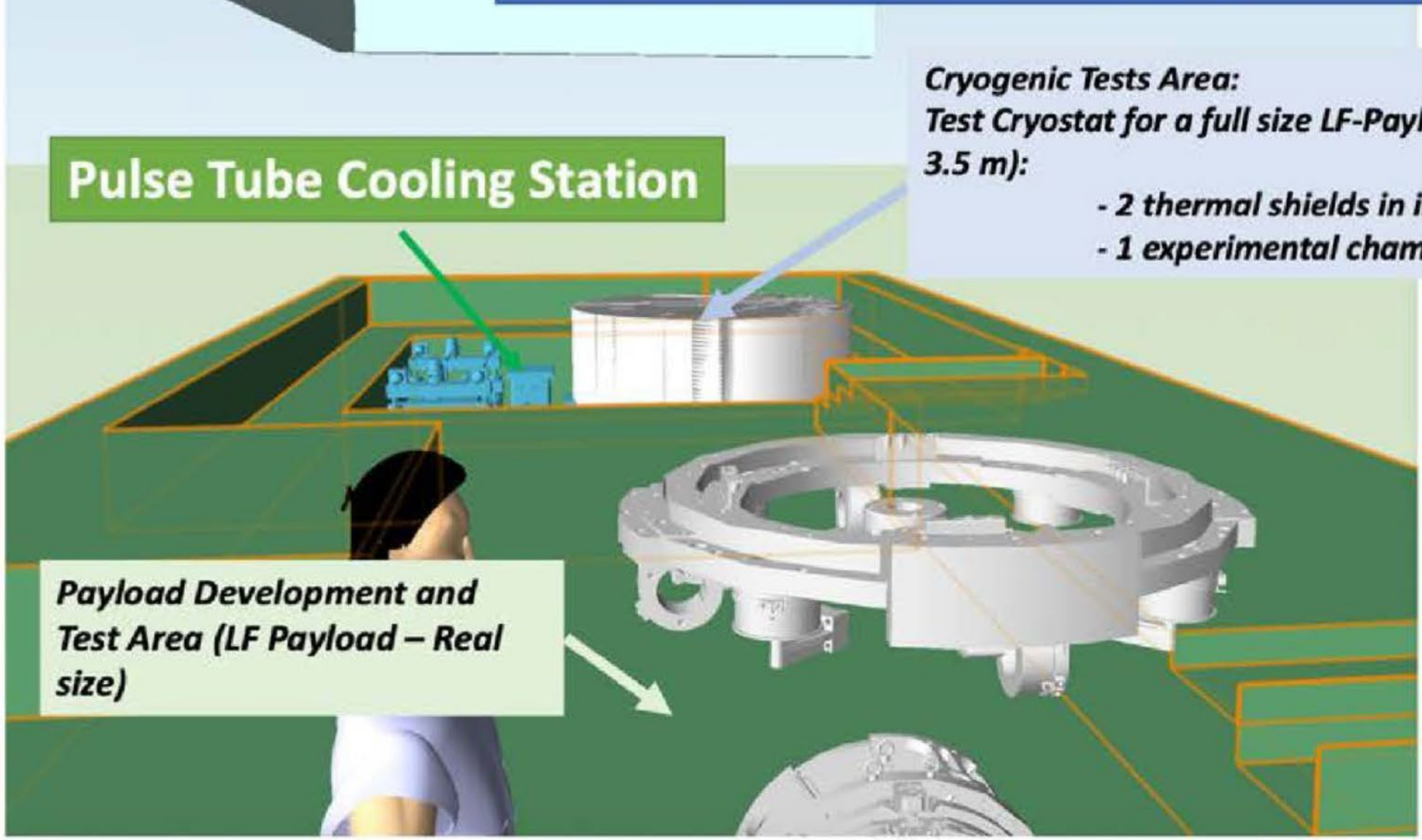
3G Gravitational-Wave Lab

MINISTERO DELL' ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA

INFN ROMA Istituto Nazionale di Fisica Nucleare Sezione di Roma

AMALDI RESEARCH CENTER

With ARC funds, we are preparing a lab for low temperature tests on a real size prototype of an ET LF-Payload



Cryogenic Tests Area:
Test Cryostat for a full size LF-Payload, cooled by two PT (~Ø 3 m x 3.5 m):
- ***2 thermal shields in insulation vacuum***
- ***1 experimental chamber with separated vacuum***

The Rome1 ET Group:

From Virgo:

Sibilla	Di Pace	(Post Doc Researcher)
Ettore	Majorana	(Full Professor)
Valentina	Mangano	(Post Doc Researcher)
Luca	Naticchioni	(INFN Researcher)
Maurizio	Perciballi	(INFN Technician)
Paola	Puppo	(INFN Researcher)
Piero	Rapagnani	(Associate Professor)
Fulvio	Ricci	(Full Professor)

From CUORE:

Angelo	Cruciani	(INFN Researcher)
Antonio	D'Addabbo	(Post Doc Researcher LNGS)
Stefano	Pirro	(INFN Researcher)

From EGO:

Paolo Ruggi (EGO Researcher)

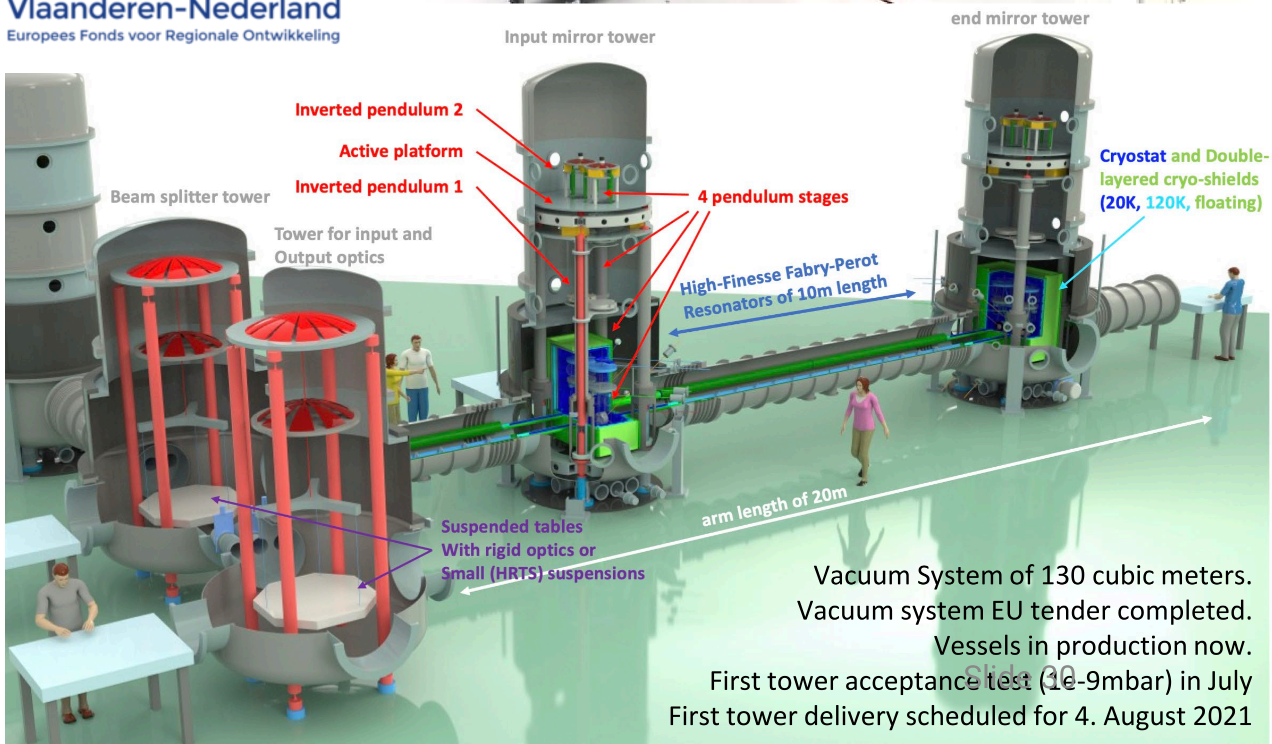
ET-PATHFINDER

- New facility for testing ET-LF technology in a low-noise, full-interferometer setup
- Key aspects: Silicon mirrors (3 to 100+kg), cryogenics cryogenic liquids and sorption coolers, water/ice management), "new" wavelengths (1550 and 2090nm), coatings etc
- Start with 2 FPMI, one initially at 120K and one 15K (2022+)
- >20 partners from NL/B/G/FR/SP/UK
- Initial capital funding of 14.5 MEuro
- Detailed Design Report available at apps.et-gw.eu/tds/?content=3&r=17177
- **Open for everyone interested to join**
- For more information please see:

  www.etpathfinder.eu

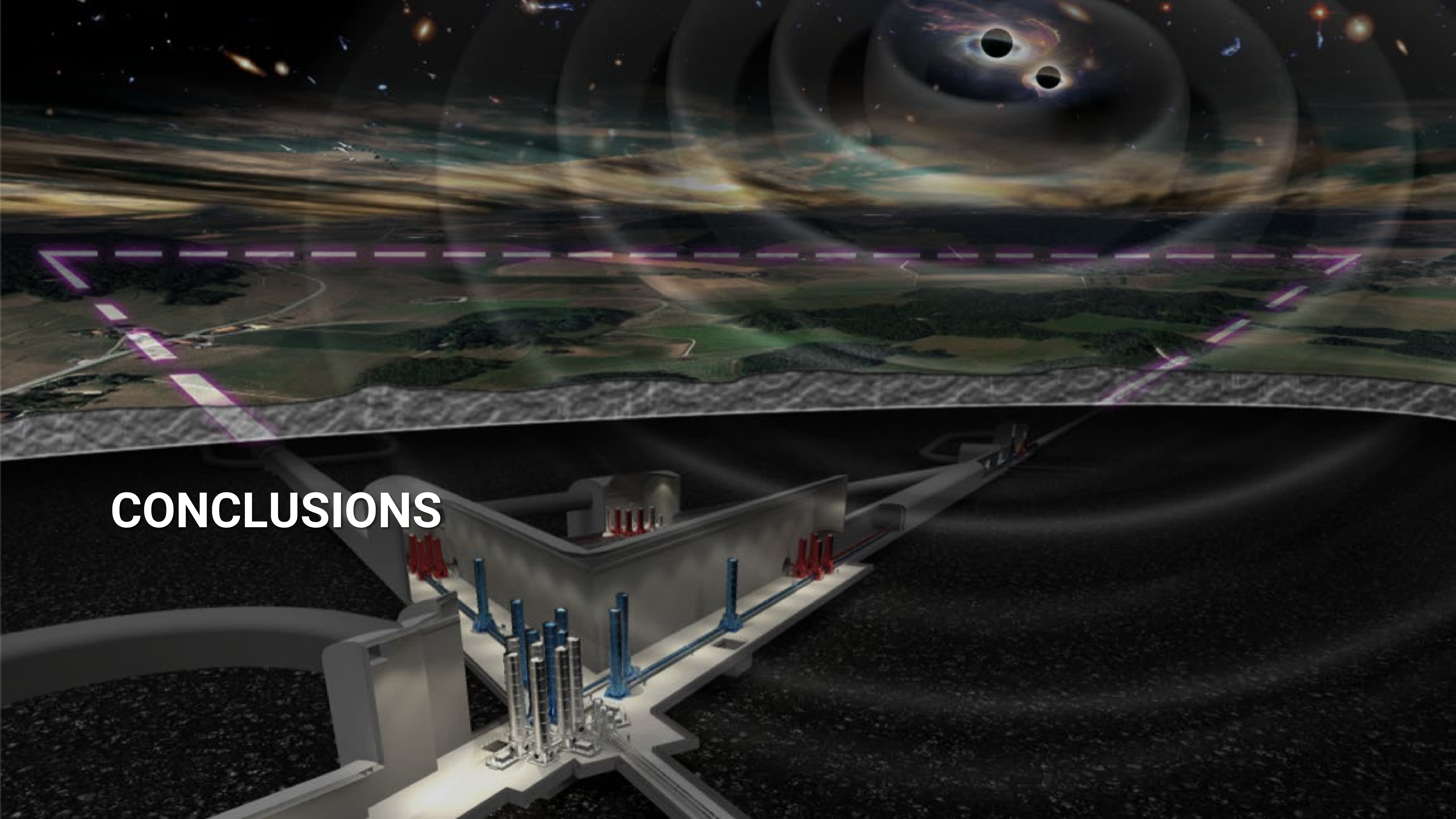
CREDIT: S. Hild

Interreg
Vlaanderen-Nederland
Europees Fonds voor Regionale Ontwikkeling



Vacuum System of 130 cubic meters.
Vacuum system EU tender completed.
Vessels in production now.
First tower acceptance test (1e-9mbar) in July
First tower delivery scheduled for 4. August 2021

CONCLUSIONS



CONCLUSIONS

- Scientifically and engineering-intensive objectives, with major impacts on the cost and performance of the infrastructure
- Important synergies with existing (KAGRA) and future (CE) detectors
- Collaboration initiated with new groups with crucial and complementary expertise
- Large-scale R&D activities already ongoing

Challenging, requiring R&D, **BUT** it is indeed **FEASIBLE**!