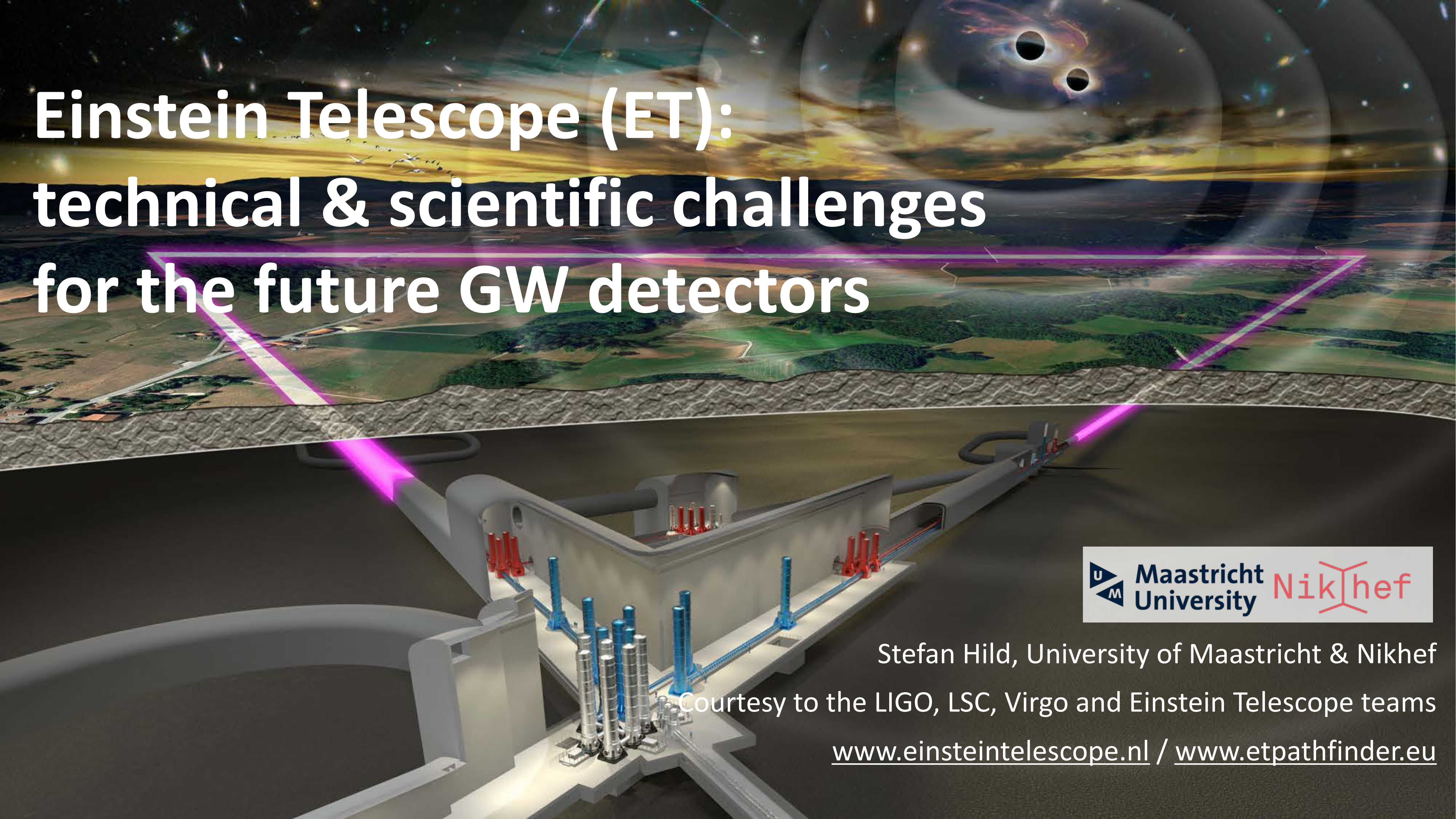
Einstein Telescope (ET): technical & scientific challenges for the future GW detectors



Stefan Hild, University of Maastricht & Nikhef

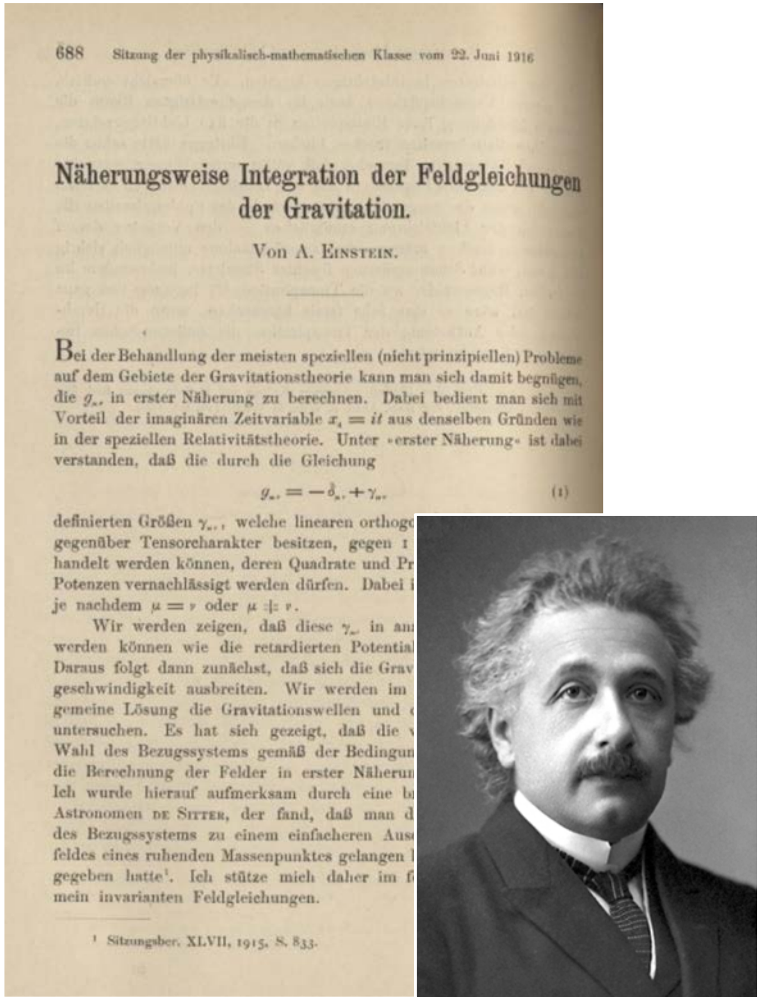
Courtesy to the LIGO, LSC, Virgo and Einstein Telescope teams

www.einsteintelescope.nl / www.etpathfinder.eu

Outline

- What have we learned from Gravitational Waves so far and why do we need ET?
- Overview of fundamental noises and technical challenges.
- Overview of some exmaples of ongoing R&D efforts
- Discussing some topics in more detail?

We have come a long way ....


688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

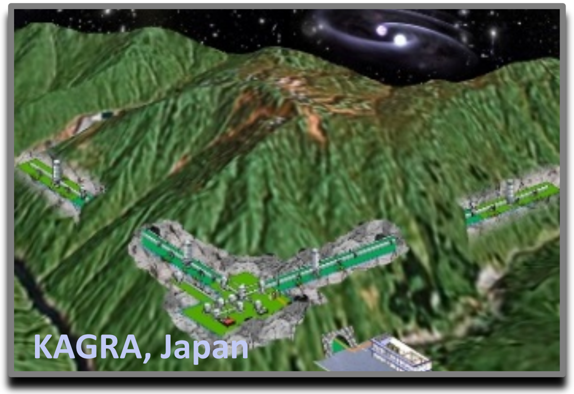
Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthog
gegenüber Tensorcharakter besitzen, gegen 1
handelt werden können, deren Quadrate und Pr
Potenzen vernachlässigt werden dürfen. Dabei i
je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in an
werden können wie die retardierten Potential
Daraus folgt dann zunächst, daß sich die Grav
geschwindigkeit ausbreiten. Wir werden im
gemeine Lösung die Gravitationswellen und
untersuchen. Es hat sich gezeigt, daß die
Wahl des Bezugssystems gemäß der Bedingun
die Berechnung der Felder in erster Näherun
Ich wurde hierauf aufmerksam durch eine b
Astronomen de Sitter, der fand, daß man d
des Bezugssystems zu einem einfacheren Aus
feldes eines ruhenden Massenpunktes gelangen
gegeben hatte[1]. Ich stütze mich daher im f
mein invarianten Feldgleichungen.

[1] Sitzungsber. XLVII, 1915, S. 833.



Many observations/discoveries

Select Language

LSC LIGO Scientific Collaboration

News | Detections | Our science explained | Multimedia | Educational resources | For researchers | About the LSC | LIGO Lab | Observing Plans

DETECTIONS

Information about gravitational-wave detections made by the LIGO-Virgo-KAGRA Collaborations to date.

Jump to a separate page for a specific event (listed in reverse-chronological order of announcement date), or see the General Detection Resources section below for further information on LIGO detections.

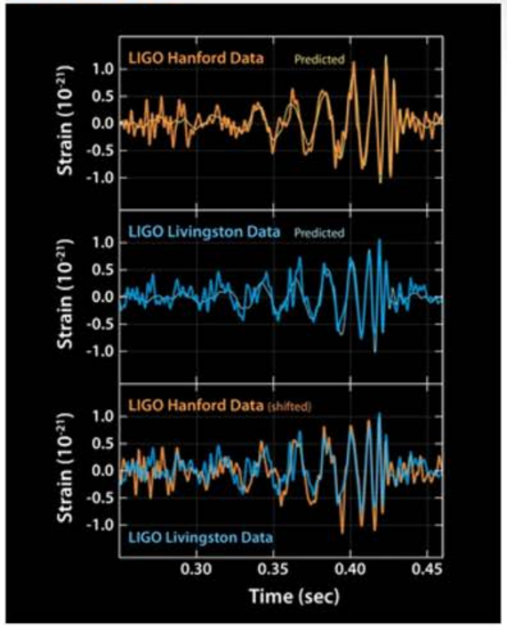
- GW200105 & GW200115 (First confirmed neutron star-black hole mergers.)
- O3a Catalog (GWTC-2: Summary of detections during the first half of the third observing run.)
- GW190521
- GW190814
- GW190412
- GW190425
- O1/O2 Catalog (Summary of detections during first and second observing runs.)
- GW170608
- GW170817 (First binary neutron star detection; first electromagnetic counterpart.)
- GW170814
- GW170104
- GW151226
- GW150914 (First detection.)

GENERAL DETECTION RESOURCES

DOCUMENTS, WEBSITES, & MULTIMEDIA

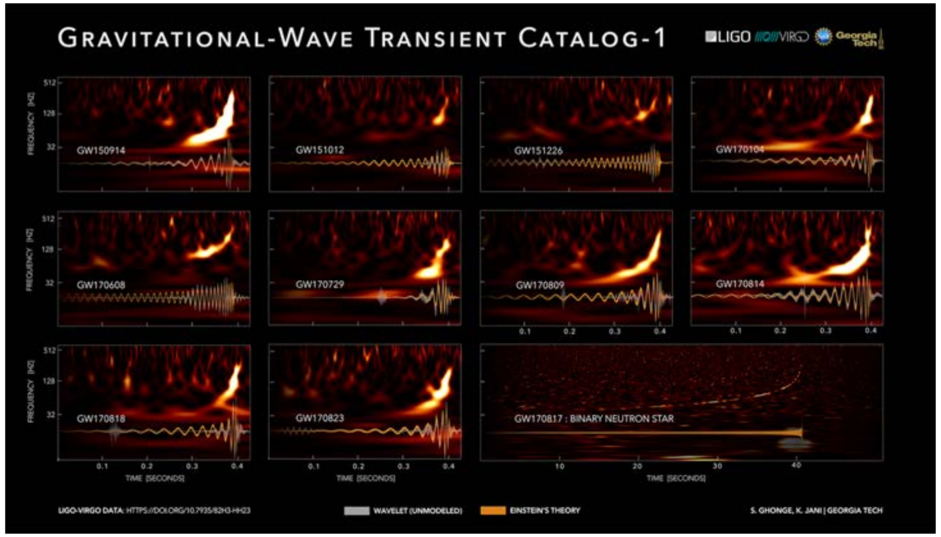
- Full list of LSC Publications. (See Runs O1 and higher for papers following the first detection.)
- Science Summaries
- Gravitational Wave Open Science Center (GWOSC): Download LIGO/Virgo data or explore tutorials on gravitational-wave data analysis. See also their data release page to download LIGO/Virgo data.

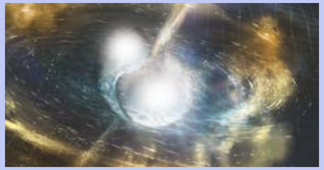
AT A GLANCE



GW150914 signal observed by the twin LIGO observatories at Livingston, Louisiana, and Hanford, Washington. The signals came from two merging black holes, each about 30 times the mass of our sun, lying 1.3 billion light-years away. The top two plots show data received at Livingston and Hanford, along with the predicted shapes for the waveform. These predicted waveforms show what two merging black holes should look like according to the equations of Albert Einstein's general theory of relativity, along with the instrument's ever-present noise. Time is plotted on the X-axis and strain on the Y-axis.

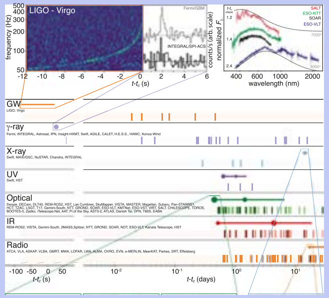
Fireworks of observations



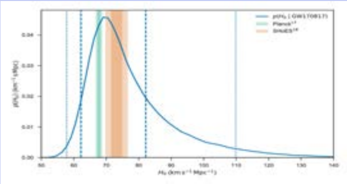


Confirmed BNS as origin for some GRBs

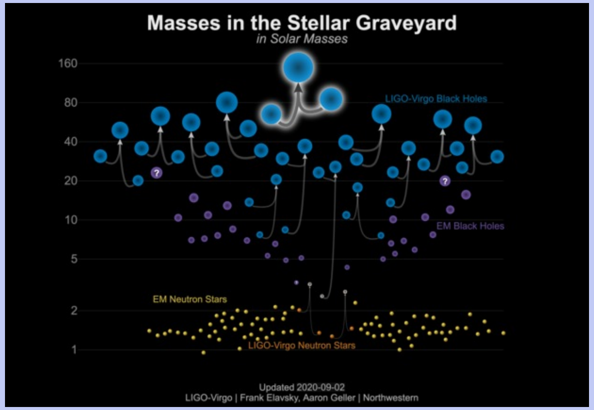
Ruled out some proposed EOS of neutron stars



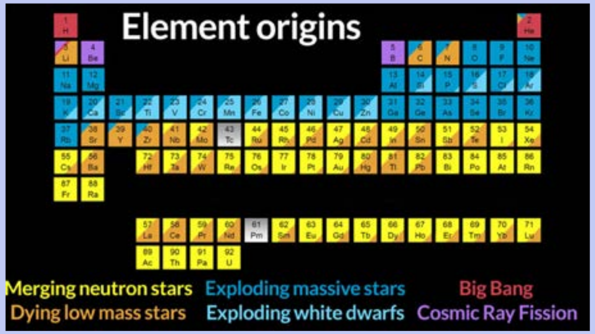
Start of GW multi-messenger astronomy



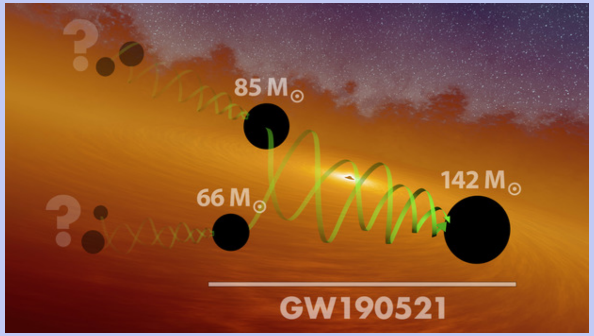
Cosmology independent of distance ladder



Found new class of heavy stellar mass BBH

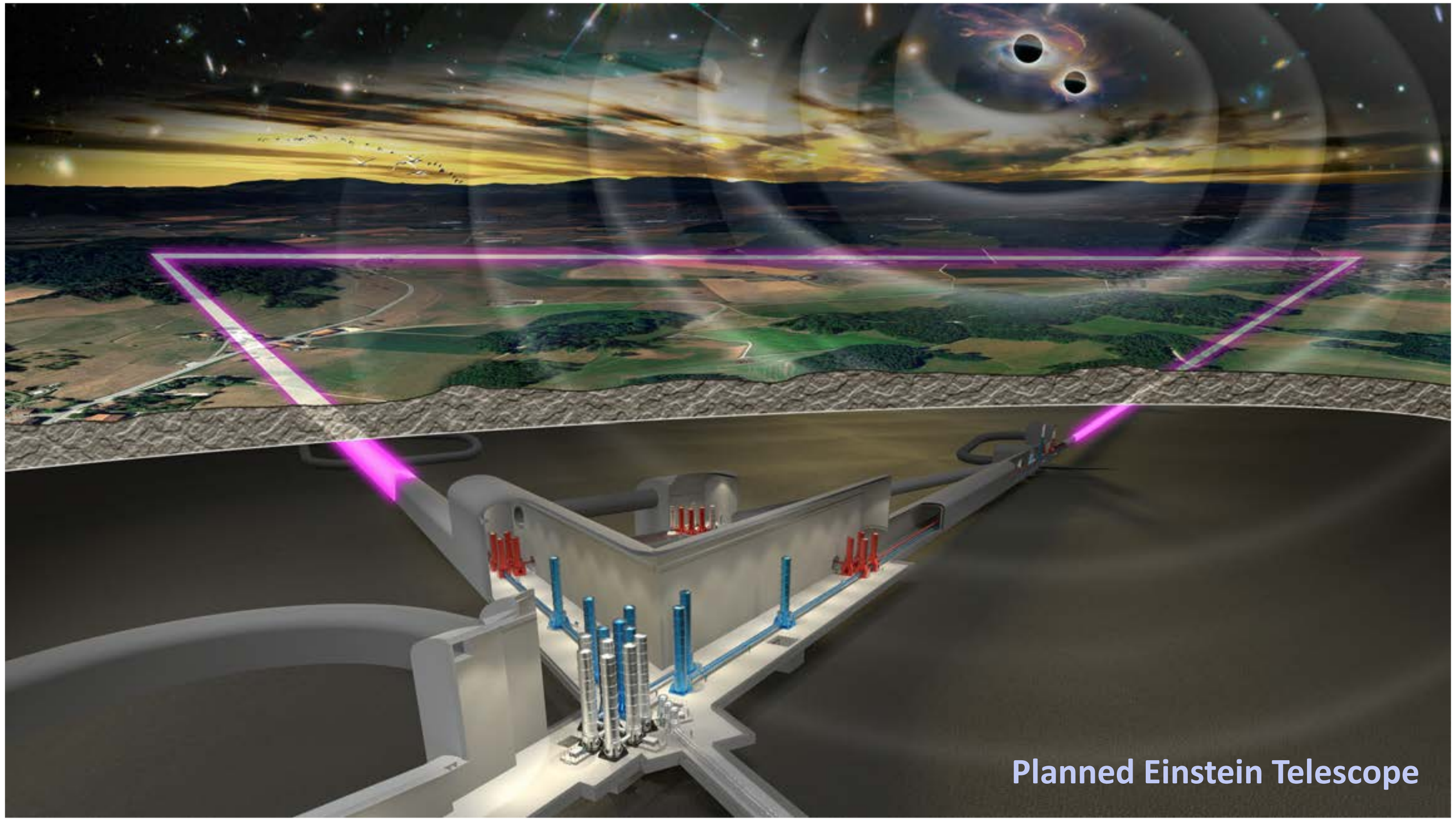


Confirmed Kilonova and R-process



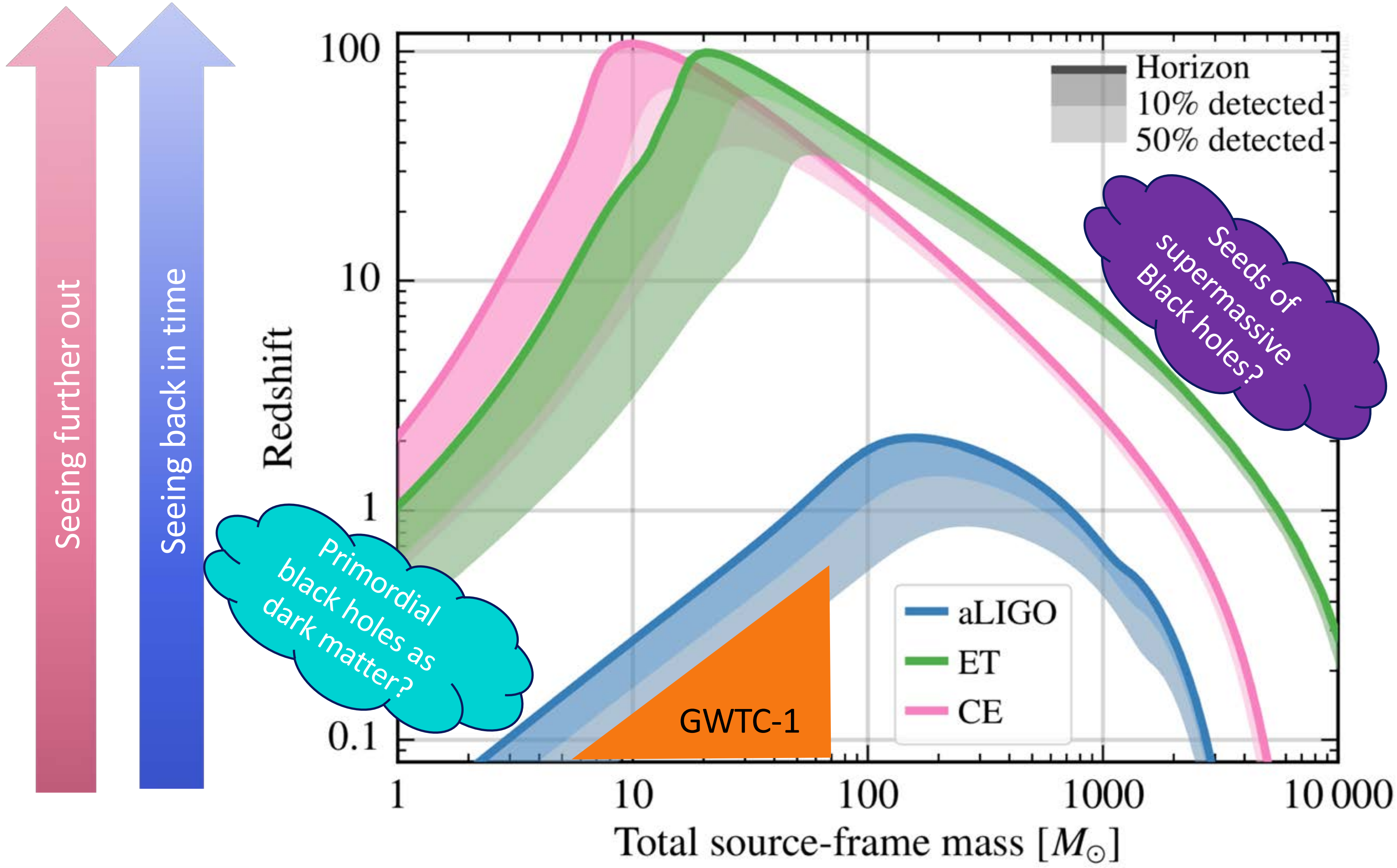
Proved existence of intermediate-mass black holes

From current detectors to ET



- Current detectors observe about one signal per week.
- ET will observe about 100.000 to 1.000.000 binary black holes mergers per year! And many other new sources => discovery space!

Reaching for the full cosmos!

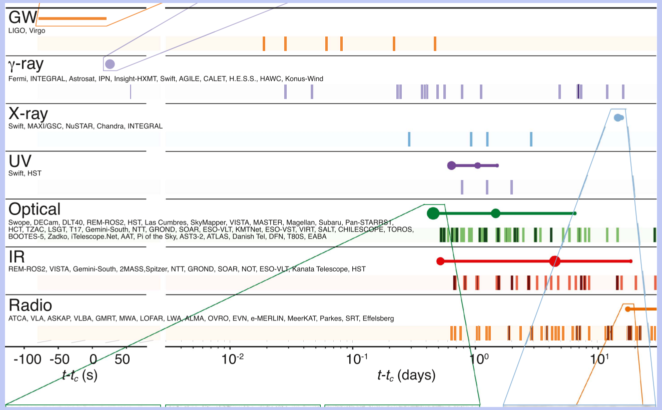


Binary Coalescences Overview:

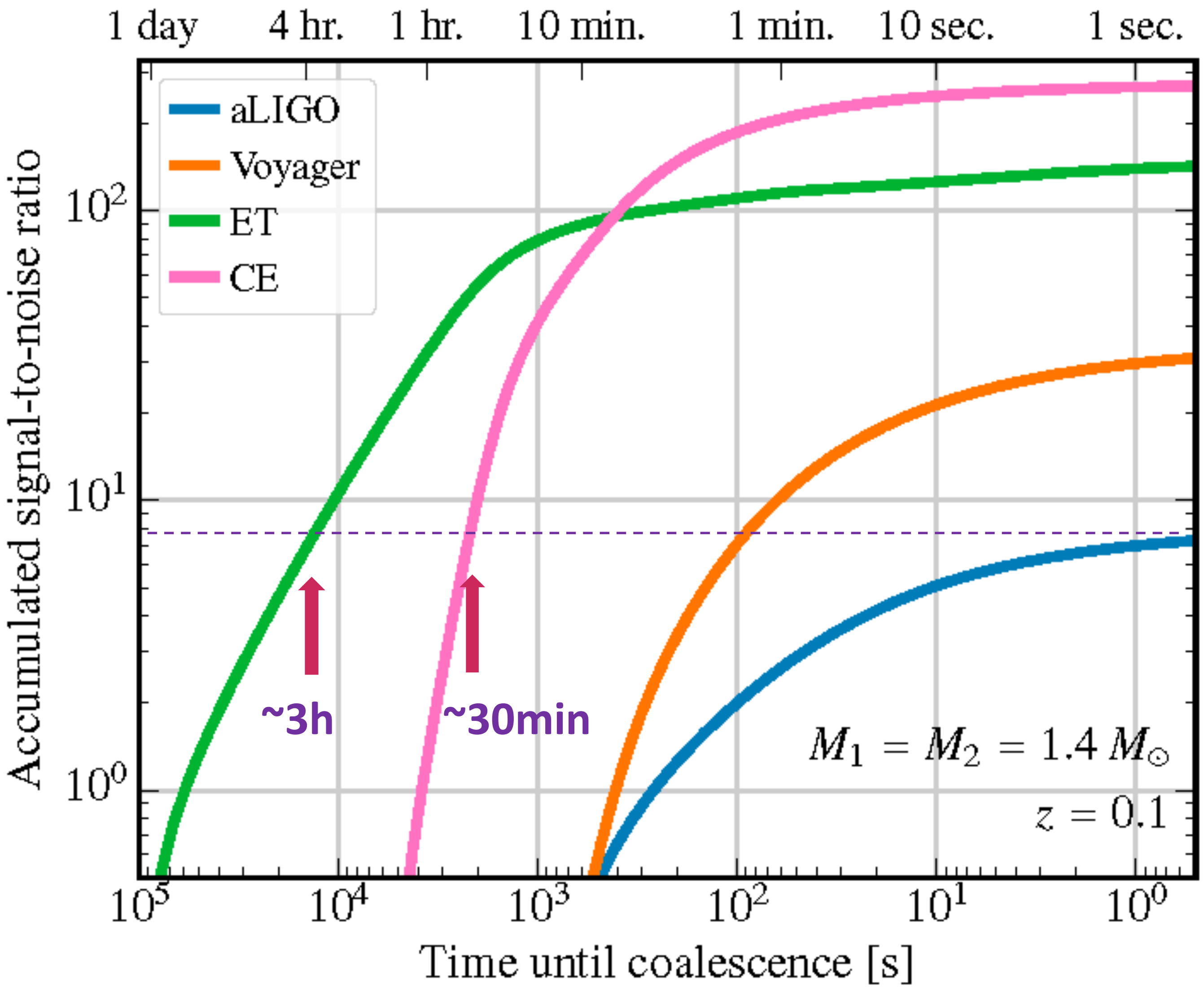
- Census of stellar and intermediate-mass BBH population over full Universe, 10^5-10^6 events per year;
- High SNR events will provide excellent precision to do accurate test of GR, nature of the BH, strong-field dynamics, black hole no-hair theorem etc;
- Extend the range of observed BBH masses towards >1,000M_{sol} and <1$M_{sol;}$
- Observe several 10,000 binary neutron star mergers per year.
- ET will determine NS EOS.

Seeing BNS with GWs before merger!

GW170817: Optical counterpart located ~6 hours after merger.



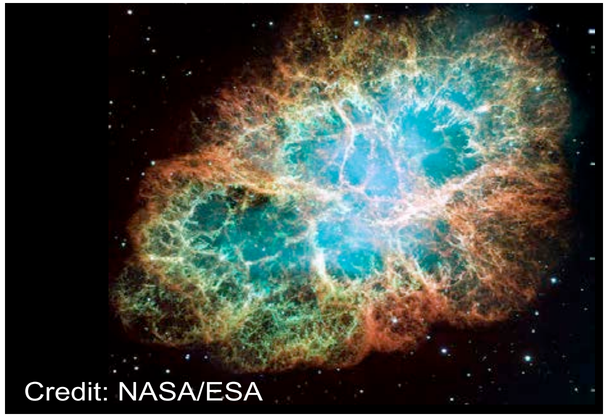
With ET we have a chance to observe the kilonova right from the beginning, observe fast radio emission and pin down the engine of short GRBs.

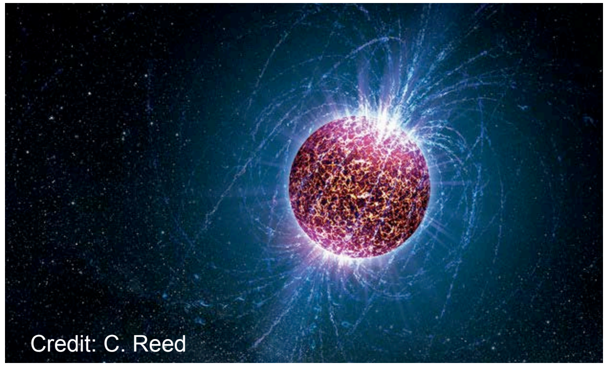


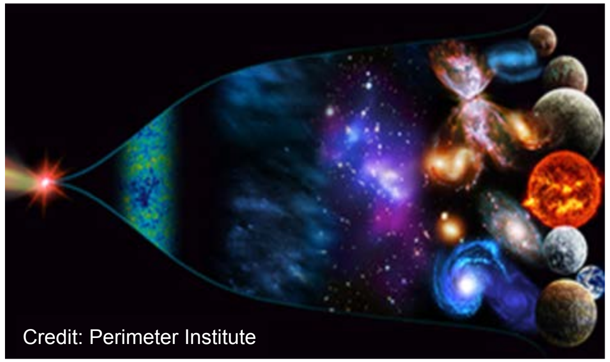
Credit: Evan Hall

More Science!

- Supernovae
- Isolated rotating neutron stars
- Testing of a variety of dark matter candidates
- Exploring the nature of dark energy
- Stochastic background of GWs, back to shortly after Big Bang
- What else might be out there what do we not think/know about yet?


Credit: NASA/ESA


Credit: C. Reed

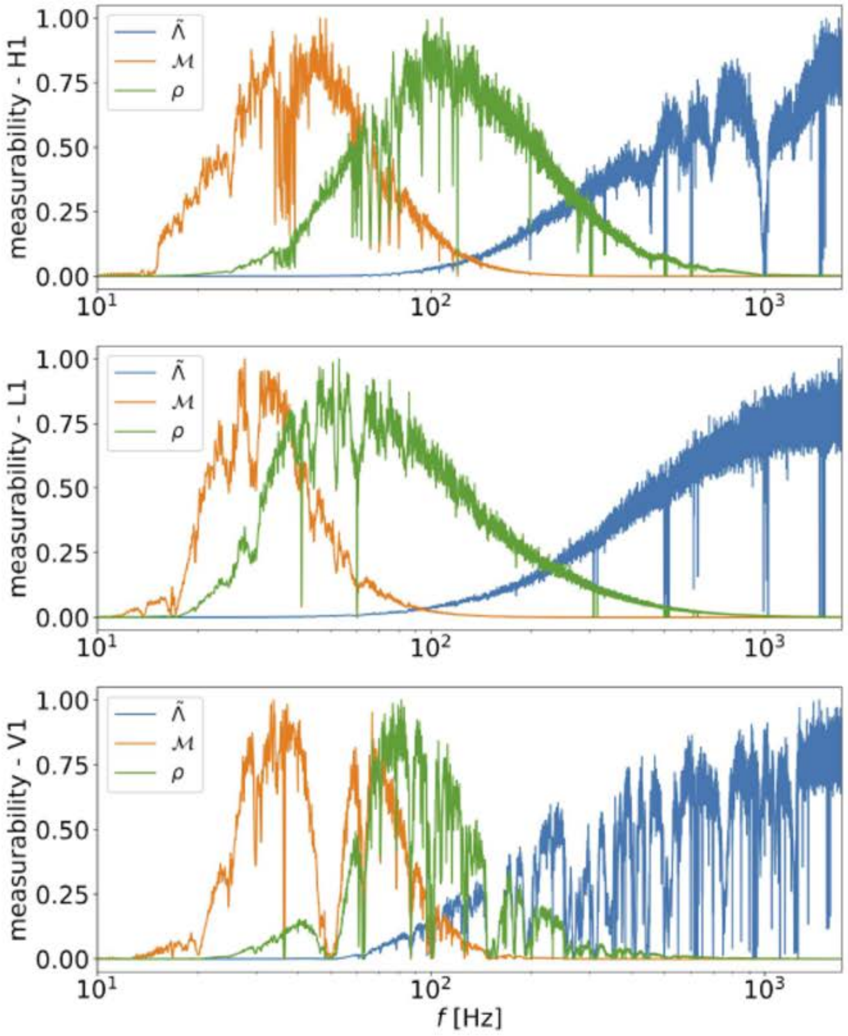

Credit: Perimeter Institute

Spectral contribution to science

Useful exercise: In which frequency band is information about certain source parameter accumulated?

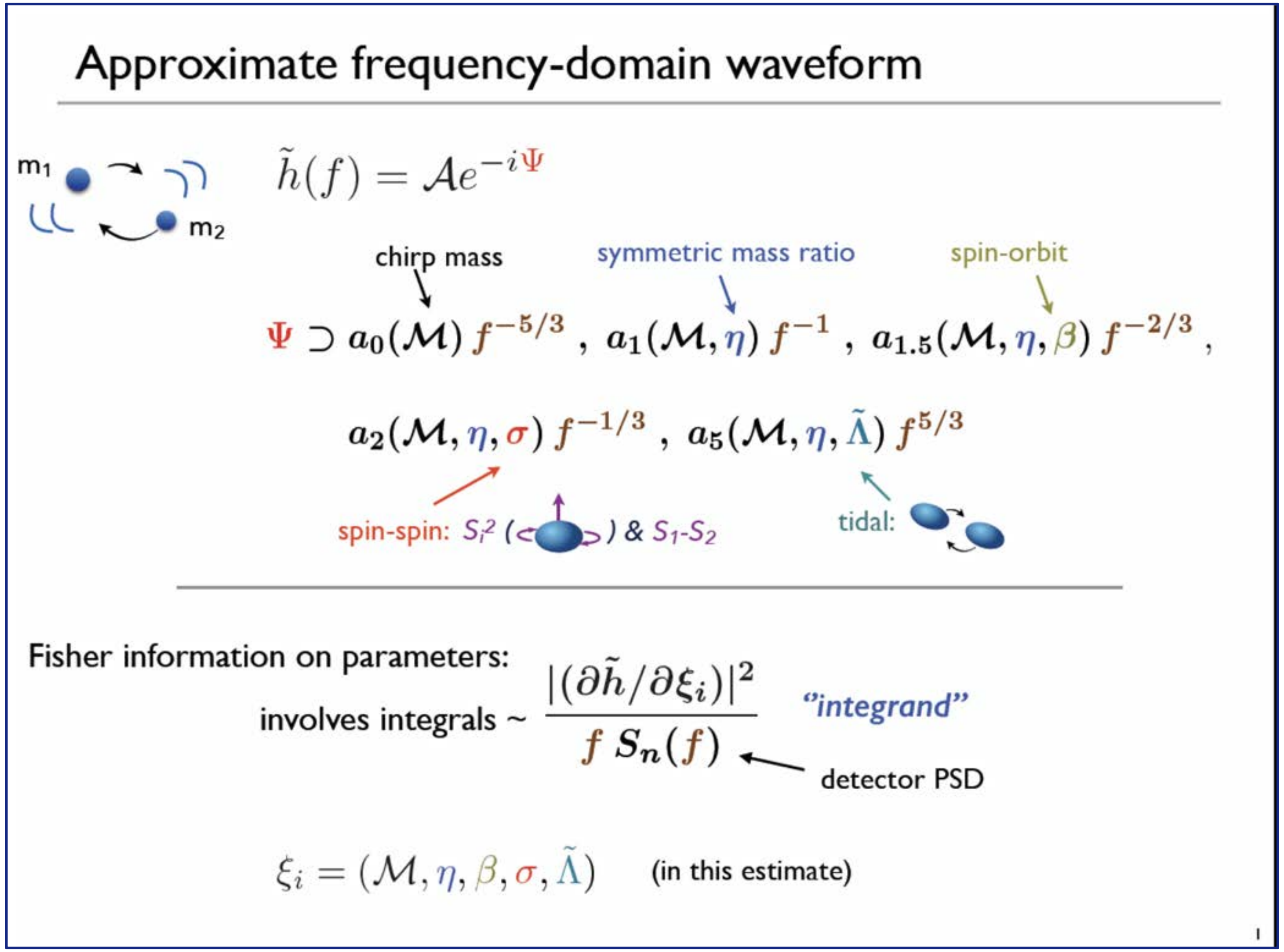
Example: GW170817

- Mid frequencies = SNR
- Low frequencies = Chirp Mass
- High frequencies = deformability



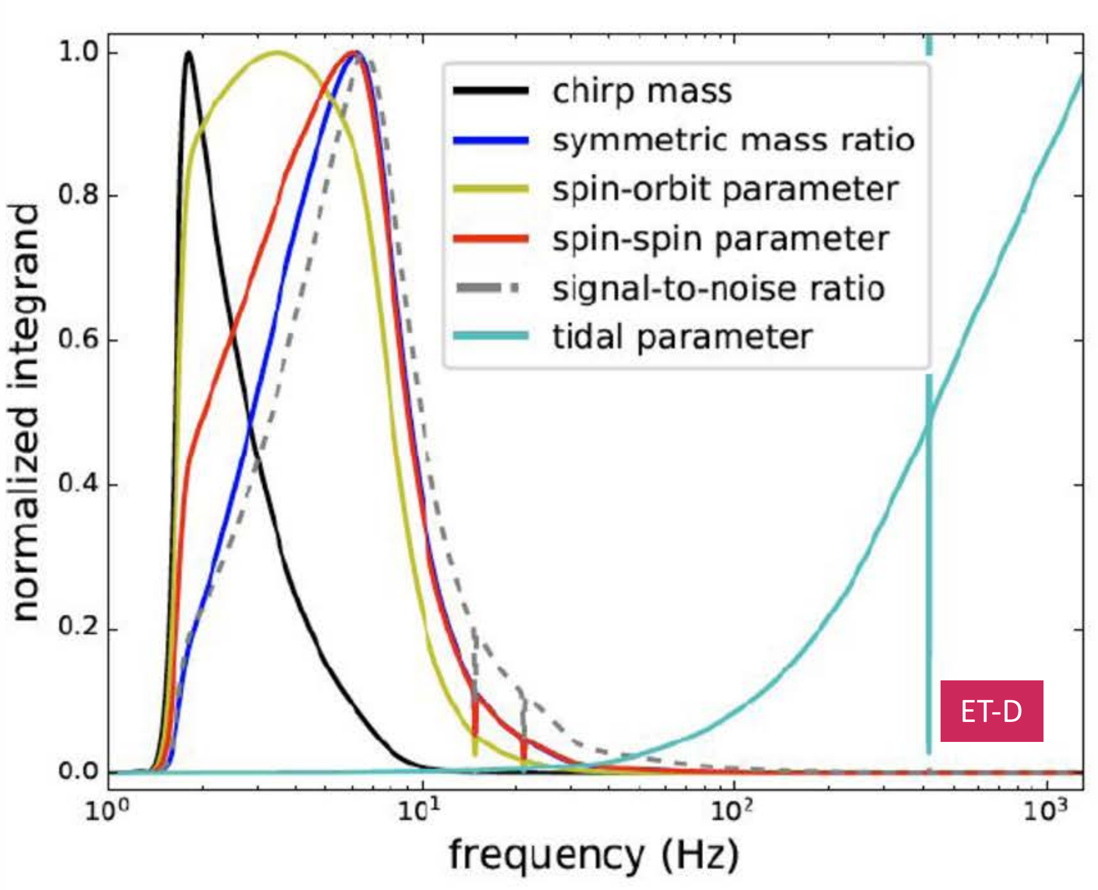
Credit: arXiv:1804.08583

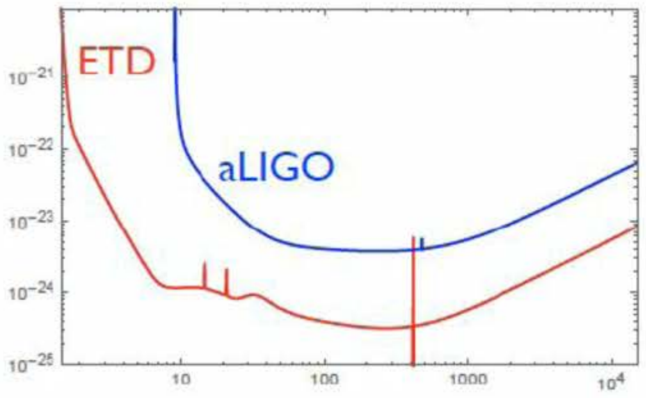
Spectral contribution to science



Slide credit: T. Hinderer

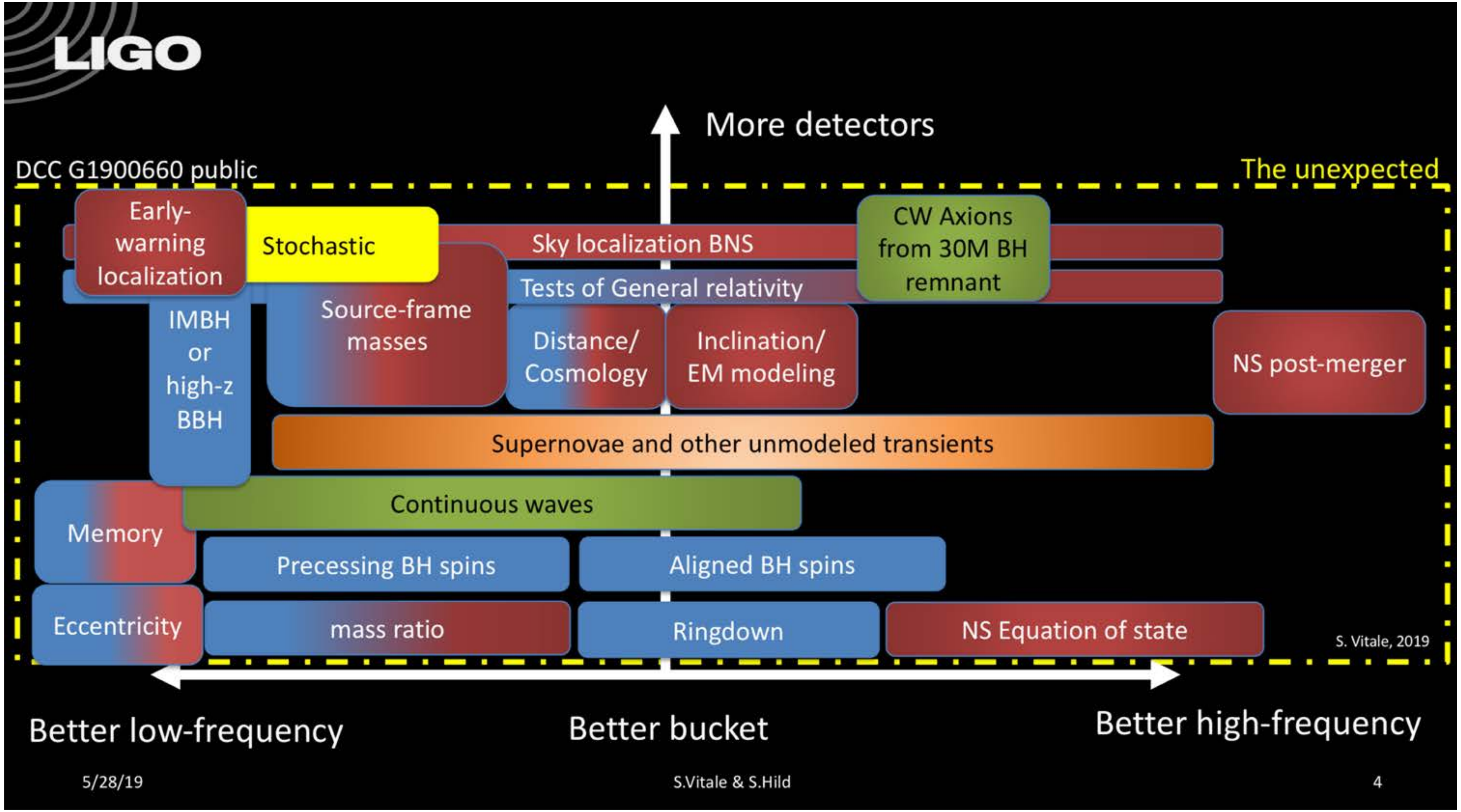
Spectral contribution to PE for ET

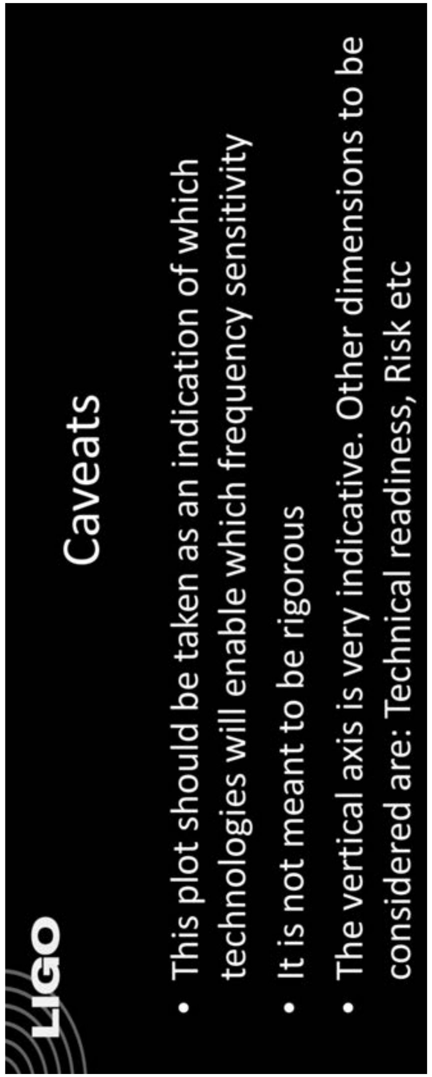




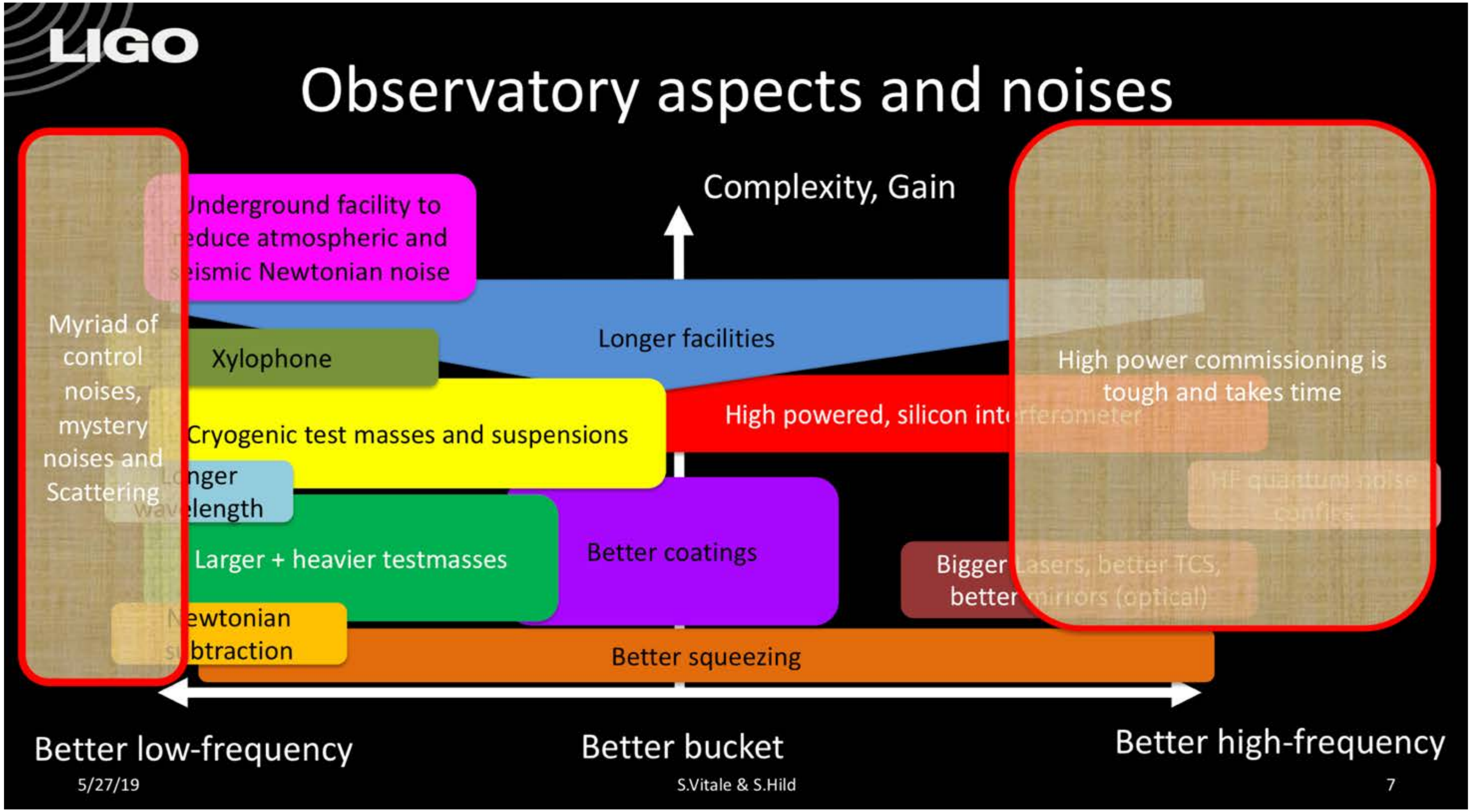
Credit: I. Harry, T. Hinderer, private communication

Continue with bucket approach?



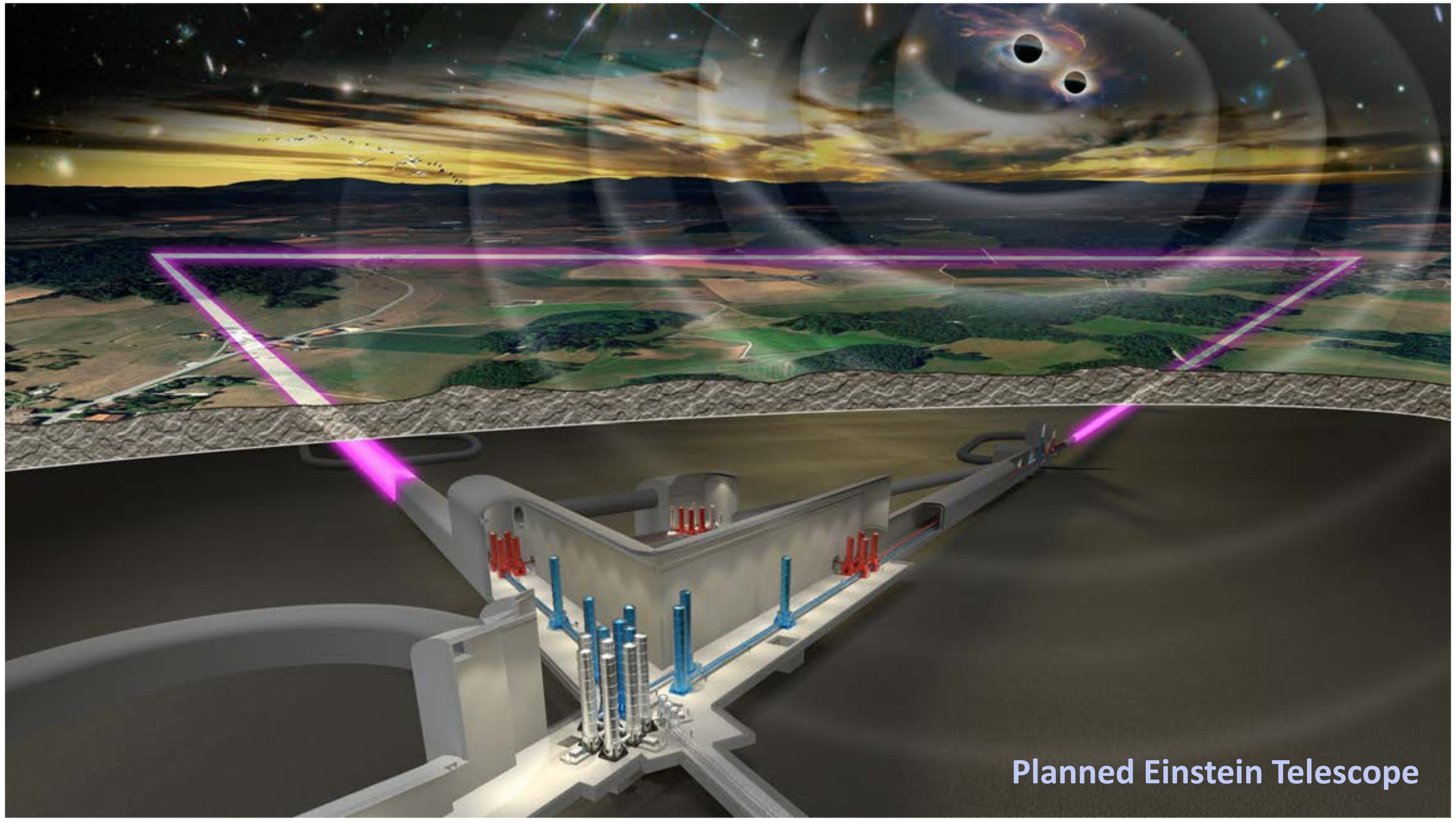


Continue with bucket approach?



From current detectors to ET

Current detectors started ~1990s



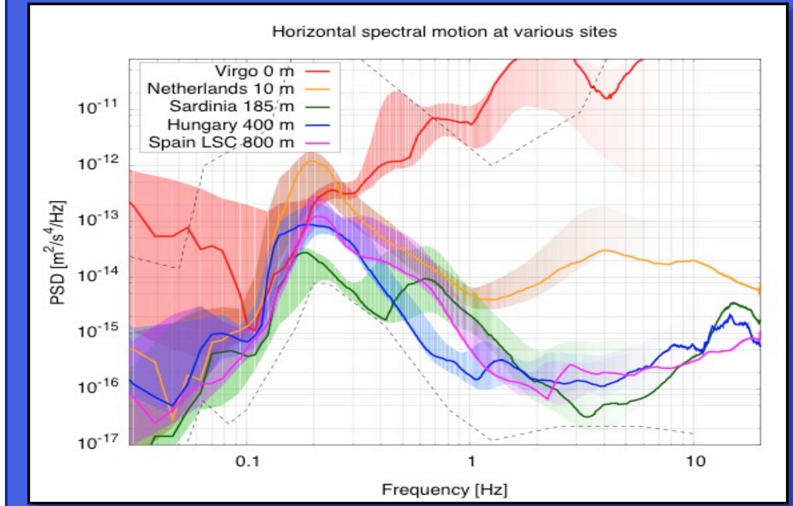
ET will be an infrastructure to provide observing power for half of the 21st century, i.e. from about 2035-2085!

Why does ET look so different compared to current interferometers?

Outline

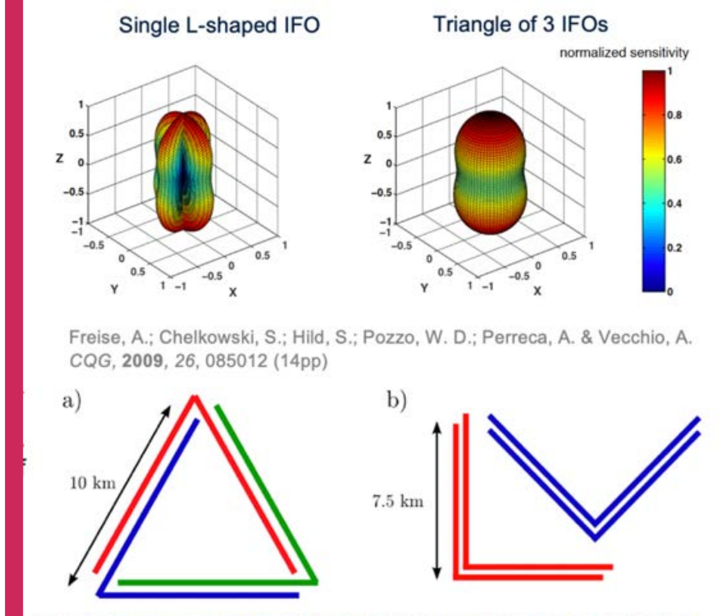
- What have we learned from Gravitational Waves so far and why do we need ET?
- Overview of fundamental noises and technical challenges.
- Overview of some exmaples of ongoing R&D efforts
- Discussing some topics in more detail?

Key concepts of ET in a single slide

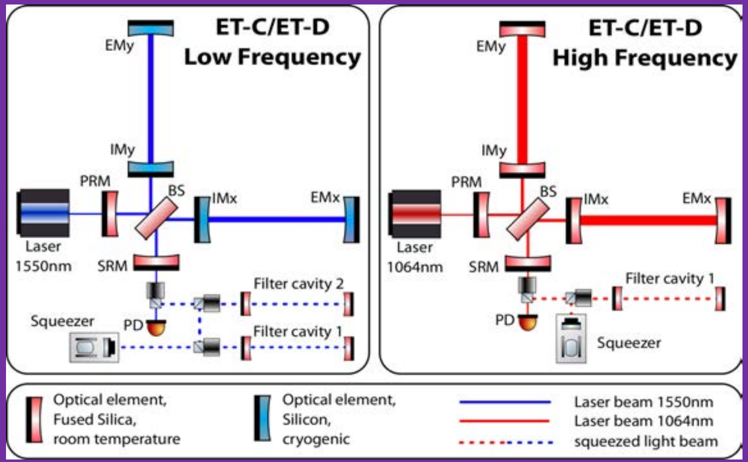


Underground location for Reduction of seismic and atmospheric GGN + long baseline

Triangular for full sky coverage and redundancy



Triangle first proposed:1985, MPQ-101. W.Winkler, K.Maischberger, A.Rüdiger, R.Schilling, L.Schnupp, D.Shoemaker,: Plans for a Large Gravitational Wave Antenna in Germany



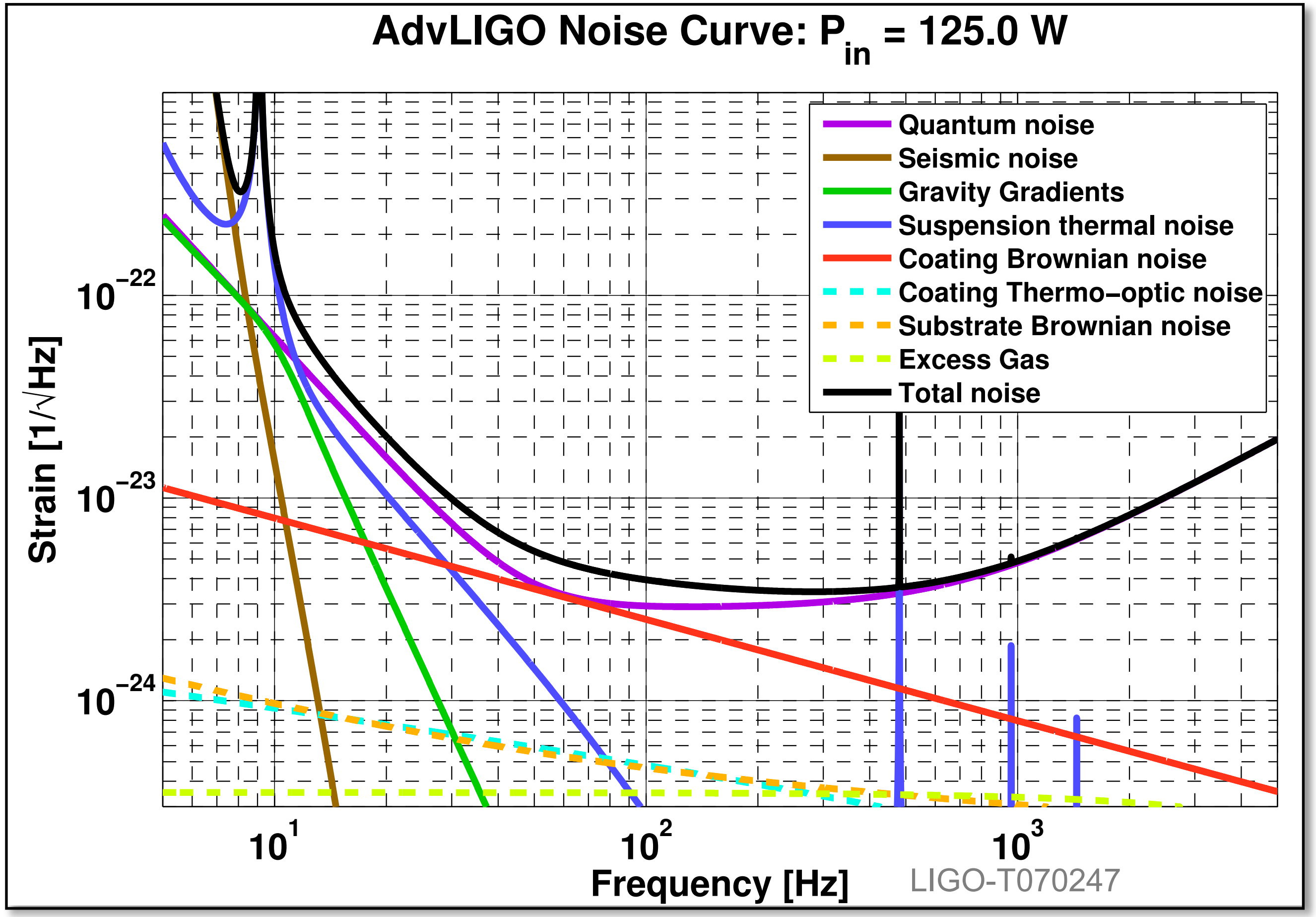
Xylophone concept

Many new technologies, like for instance cryogenic silicon mirrors

Noise Sources limiting the 2G

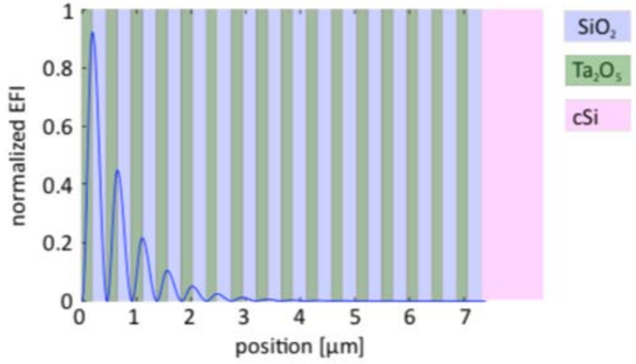
- **Quantum Noise** limits most of the frequency range.
- **Coating Brownian** limits in the range from 50 to 100Hz.
- Below ~15Hz we are limited by 'walls' made of **Suspension Thermal**, **Gravity Gradient** and **Seismic noise**.

- And then there are the, often not mentioned, 'technical' noise sources which trouble the commissioners so much.



Mirror Thermal Noise

- Due to thermal fluctuations the position of the mirror sensed by the laser beam is not necessarily a good representation of the center of mass of the mirror.
- Various noise terms involved: Brownian, thermo-elastic and thermo-refractive noise of each substrate and coating (or coherent combinations of these, such as thermo-optic noise).
- For nearly all current and future designs coating Brownian is the dominating noise source:



$$S_x(f) = \frac{4k_B T}{\pi^2 f Y} \frac{d}{r_0^2} \left(\frac{Y'}{Y}\phi_{\parallel} + \frac{Y}{Y'}\phi_{\perp} \right)$$

PSD of displacement

Boltzmann constant

Temperature

Geometrical coating thickness

Loss angle of coating

Young's modulus of mirror substrate

laser beam radius

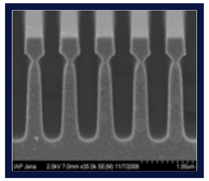
Young's modulus of coating

Harry et al, CQG 19, 897–917, 2002

How to reduce Mirror Thermal Noise?

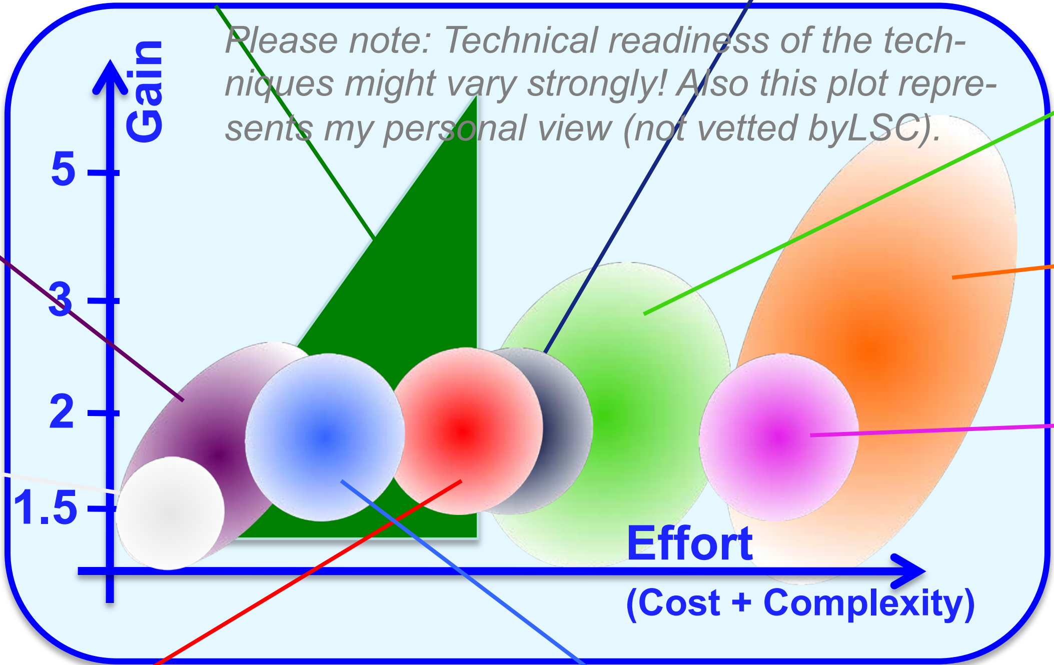
Improved coating materials (e.g. crystalline coatings like AlGaAs, GaPAs)
Cole et al, APL 92, 261108, 2008

Waveguide mirrors
Brueckner et al, Opt. Expr 17, 163, 2009
PhD thesis of D.Friedrich



Larger beam size (needs larger mirrors)
Harry et al, CQG 19, 897–917, 2002

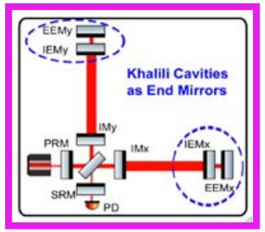
Optimisation (annealing, layer thickness, doping)

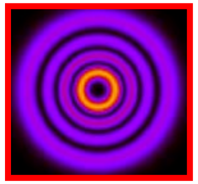


Cryogenic mirrors (120K)

Cryogenic mirrors (10-20K)
Uchiyama et al, PRL **108**, 141101 (2012)

Khalili cavities
Khalili, PLA 334, 67, 2005
Gurkovsky et al, PLA 375, 4147, 2011

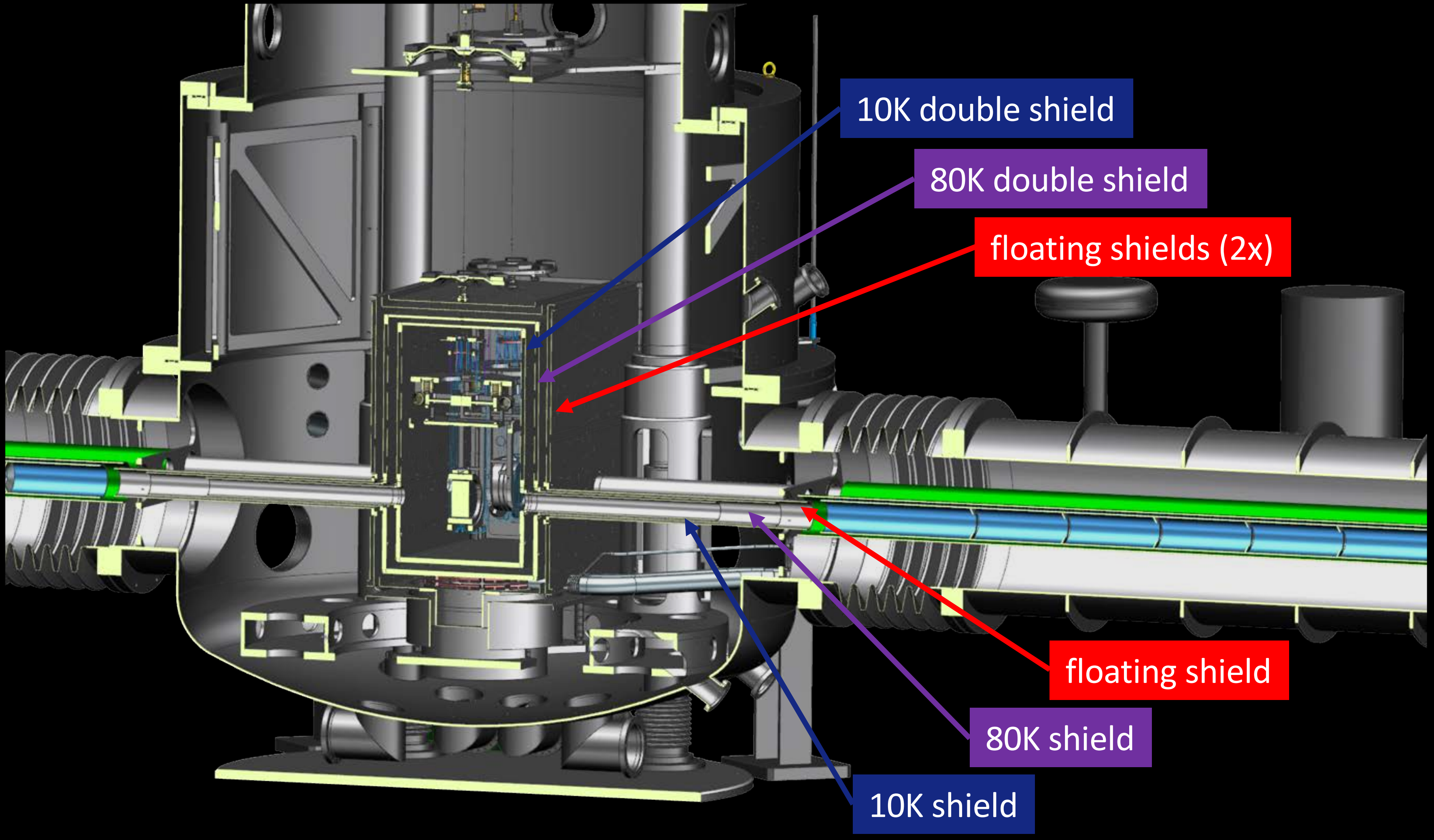




Different beam shape
Mours et al, CQG, 2006, 23, 5777
Chelkowski et al, PRD, 2009, 79, 122002

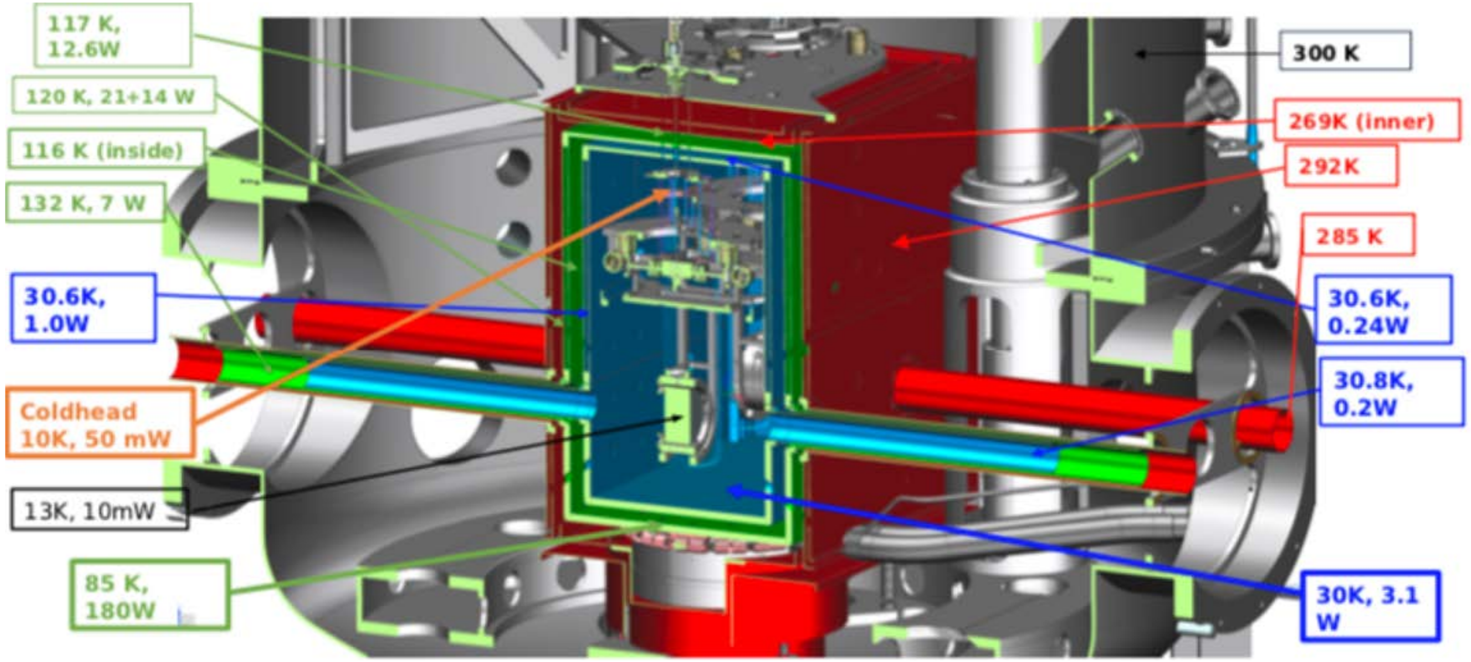
Amorphous Silicon coatings
Liu et al, PRB 58, 9067, 1998

Prototypiong cryogenic silicon mirrors

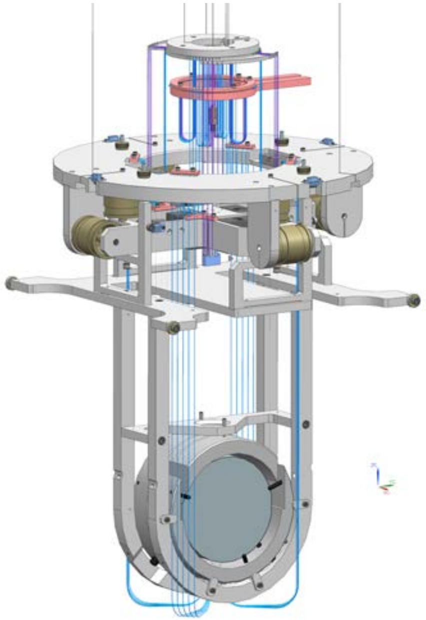


Cryogenics

- Mirrors need to be cooled to cryogenic temperatures (~15K, 123K), without introducing noise, i.e. cooling only possible via thin suspension wires.
- General approaches:
  - Dry system: pulse-tubes. Challenge = reduce and isolate vibrational noise.
  - Sorption coolers (base line in ETpathfider) = more quite, less cooling power.
  - Cryogenic Liquids: LN2, He, HeII. Challenege = avoid bubbling; transfer liquids from surface 300m above the caverns …

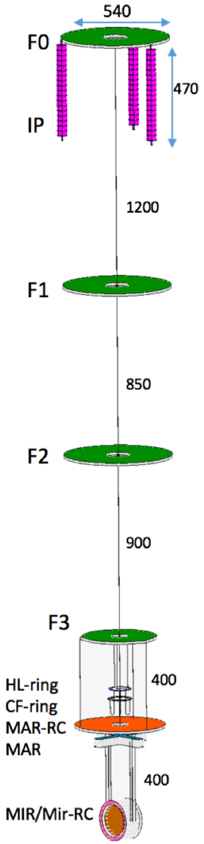


ETpathfinder cooling budget

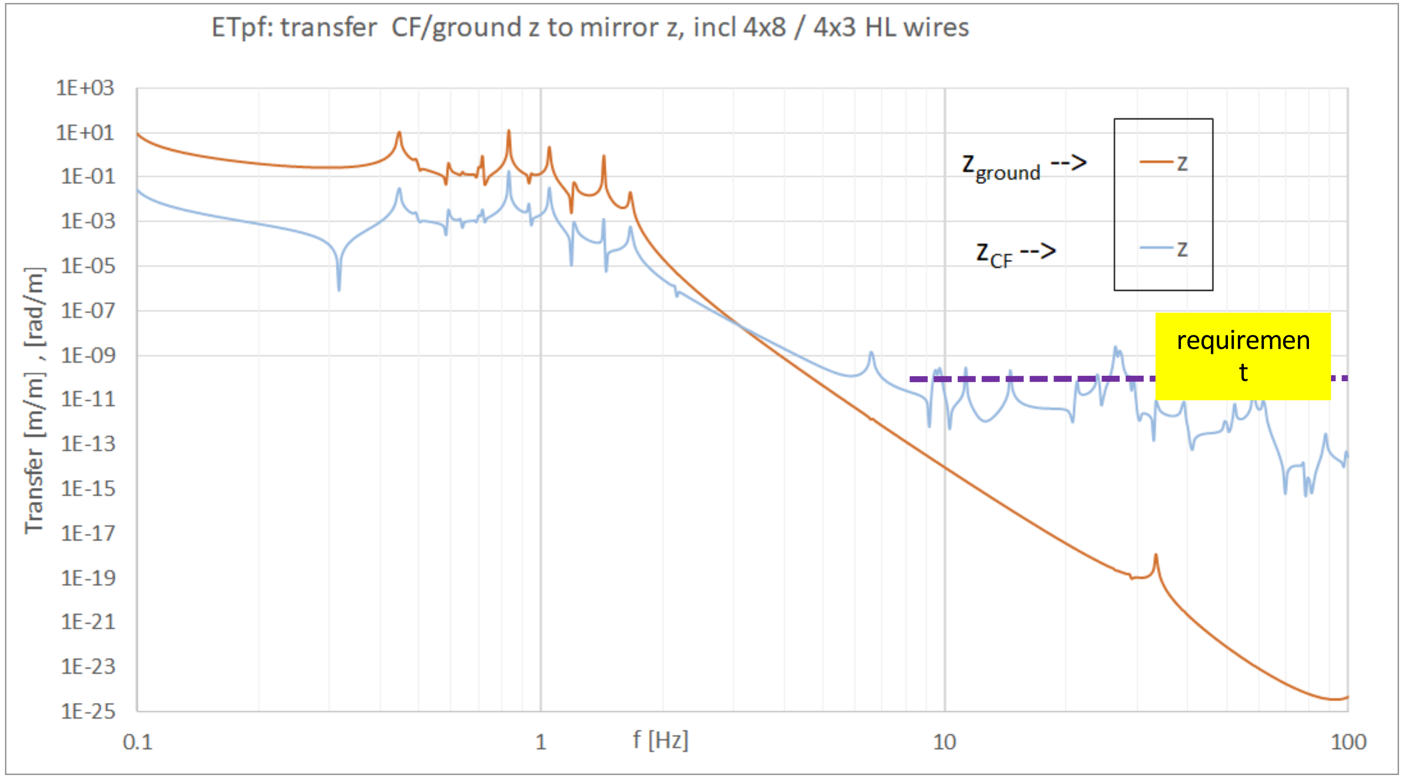

ETpathfinder payload

ET-PF payload

FEM simulated performance



Horizontal response



Ground vibration transmission from cold finger is still dominant…no safety margin

Suspension Thermal Noise

Boltzmann constant

Temperature

Loss angle

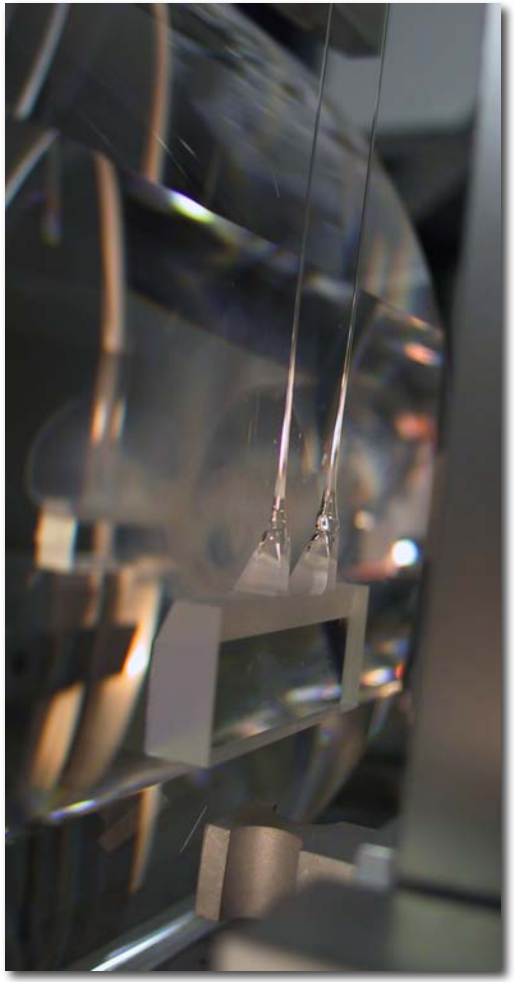
PSD of displacement

$$x^2(\omega) = \frac{4k_\mathrm{B}T\omega_0^2\phi(\omega)}{\omega m[(\omega_0^2 - \omega^2)^2 + \omega_0^4\phi^2(\omega)]}$$

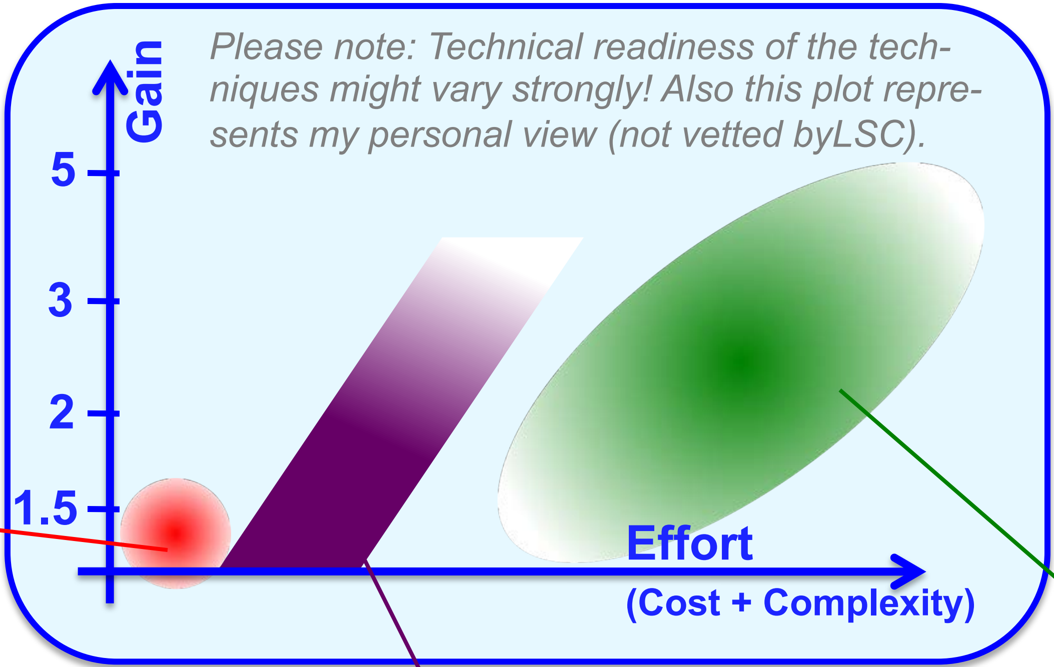
Mirror mass

Resonance frequency

- Mirrors need to be suspended in order to decouple them from seismic.
- Thermal noise in metal wires and glass fibres causes horizontal movement of mirror.
- Relevant loss terms originate from the bulk, surface and thermo-elastic loss of the fibres + bond and weld loss.
- Thermal noise in blade springs causes vertical movement which couples via imperfections of the suspension into horizontal noise.



How to reduce Suspension Thermal Noise?



Improve fibre geometry/ profile

Bending points, energy stored via bending and neck profile can be potentially further optimised.

Increase length of final pendulum stage.

Allows the push suspension thermal noise out detection band.

Cooling of the suspension to cryogenic temperatures.

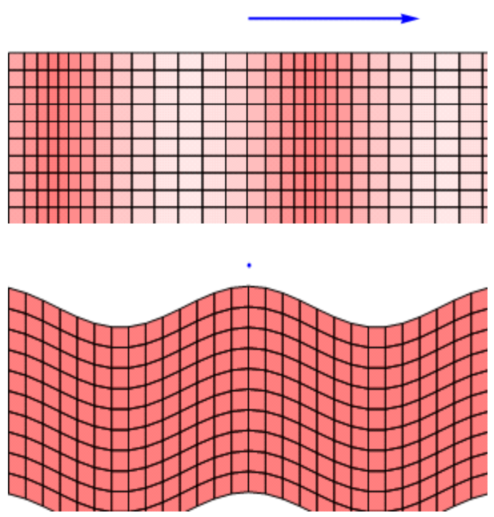
Usually also requires a change of materials.

Newtonian Noise

- Seismic causes density changes in the ground and shaking of the mirror environment (walls, buildings, vacuum system).
- These fluctuations cause a change in the gravitational force acting on the mirror.
- Cannot shield the mirror from gravity. ☹

$$N_{\rm GG}(f)^2 = \frac{4 \cdot \beta^2 \cdot G^2 \cdot \rho_r^2}{L^2 \cdot f^4} \cdot X^2_{\rm seis},$$

- PSD of strain: $N_{\rm GG}(f)^2$
- Coupling constant (depends on type of seismic waves, soil properties, etc): β
- Gravitational constant: G
- Density of ground: ρ_r
- Arm length: L
- frequency: f
- PSD of seismic: $X_{\rm seis}$



Images: courtesy G.Cella

Composition of Seismic Fields

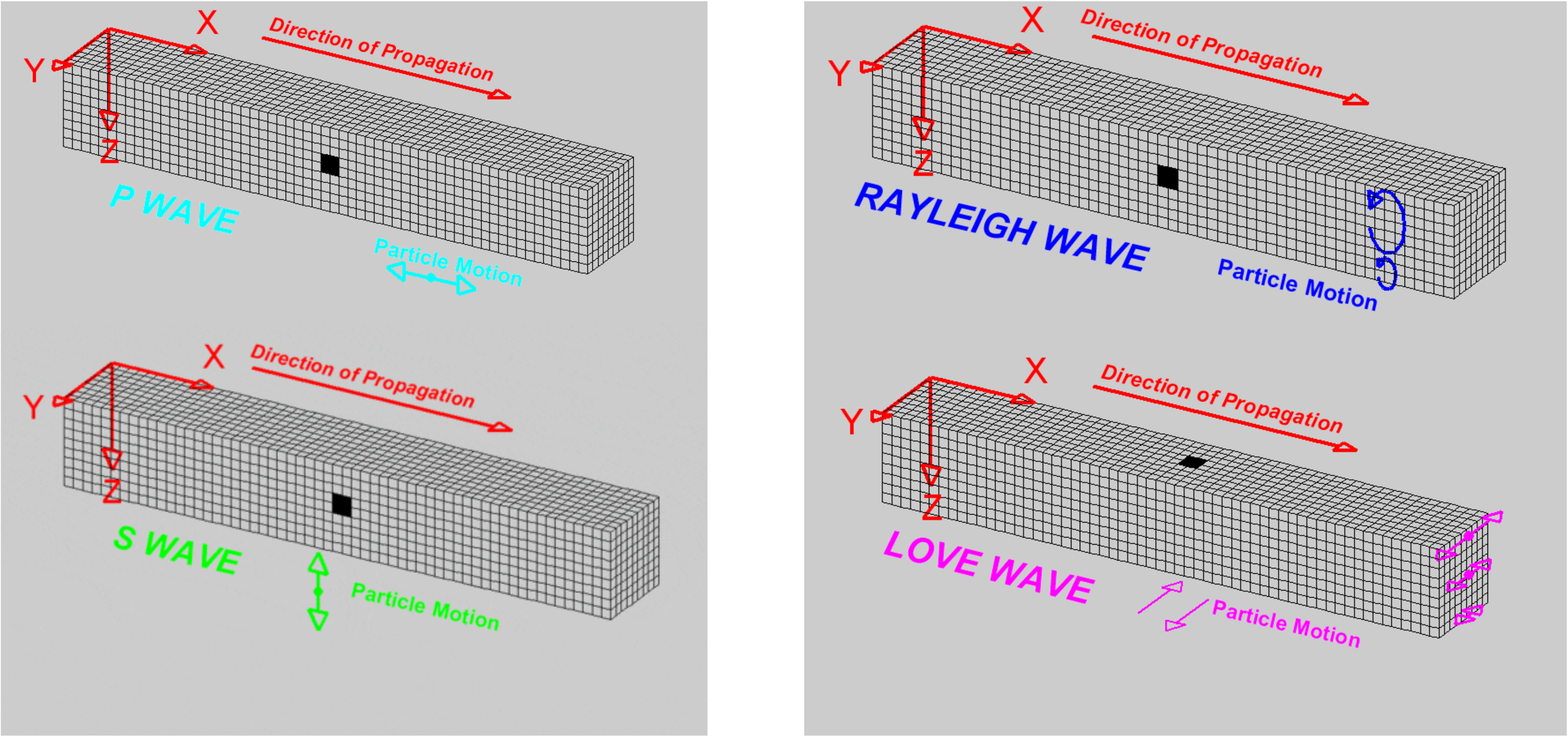
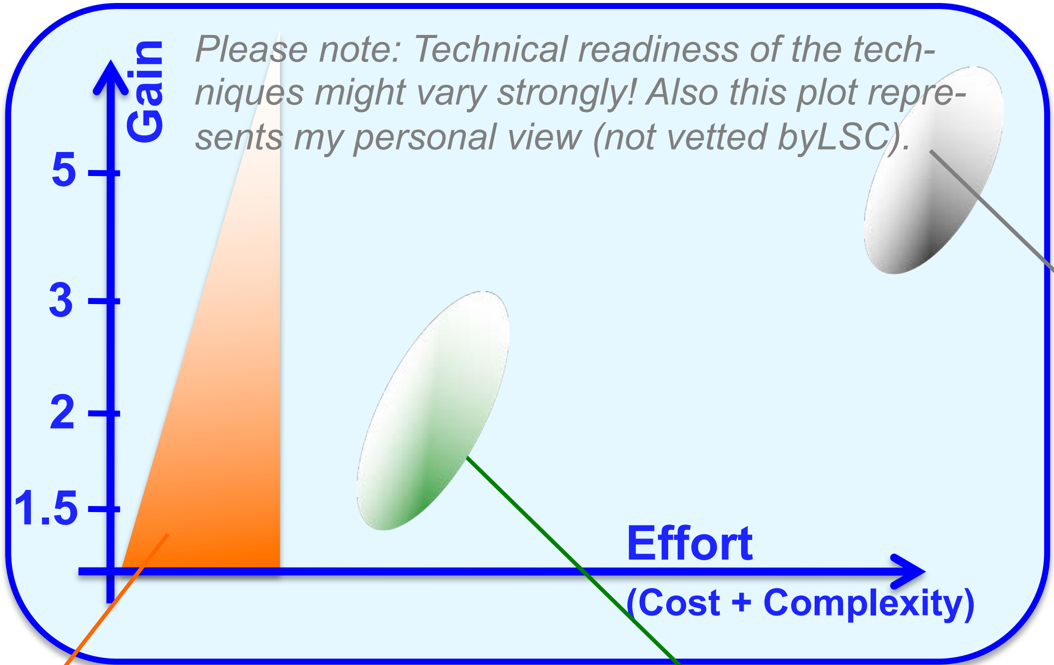


Image credits: http://www.geometrics.com/what-are-the-different-types-of-seismic-waves/

How to reduce Newtonian Noise?



Reduce seismic noise at site., i.e. select a quieter site, potentially underground.

Beker et al, Journal of Physics: Conference Series 363 (2012) 012004

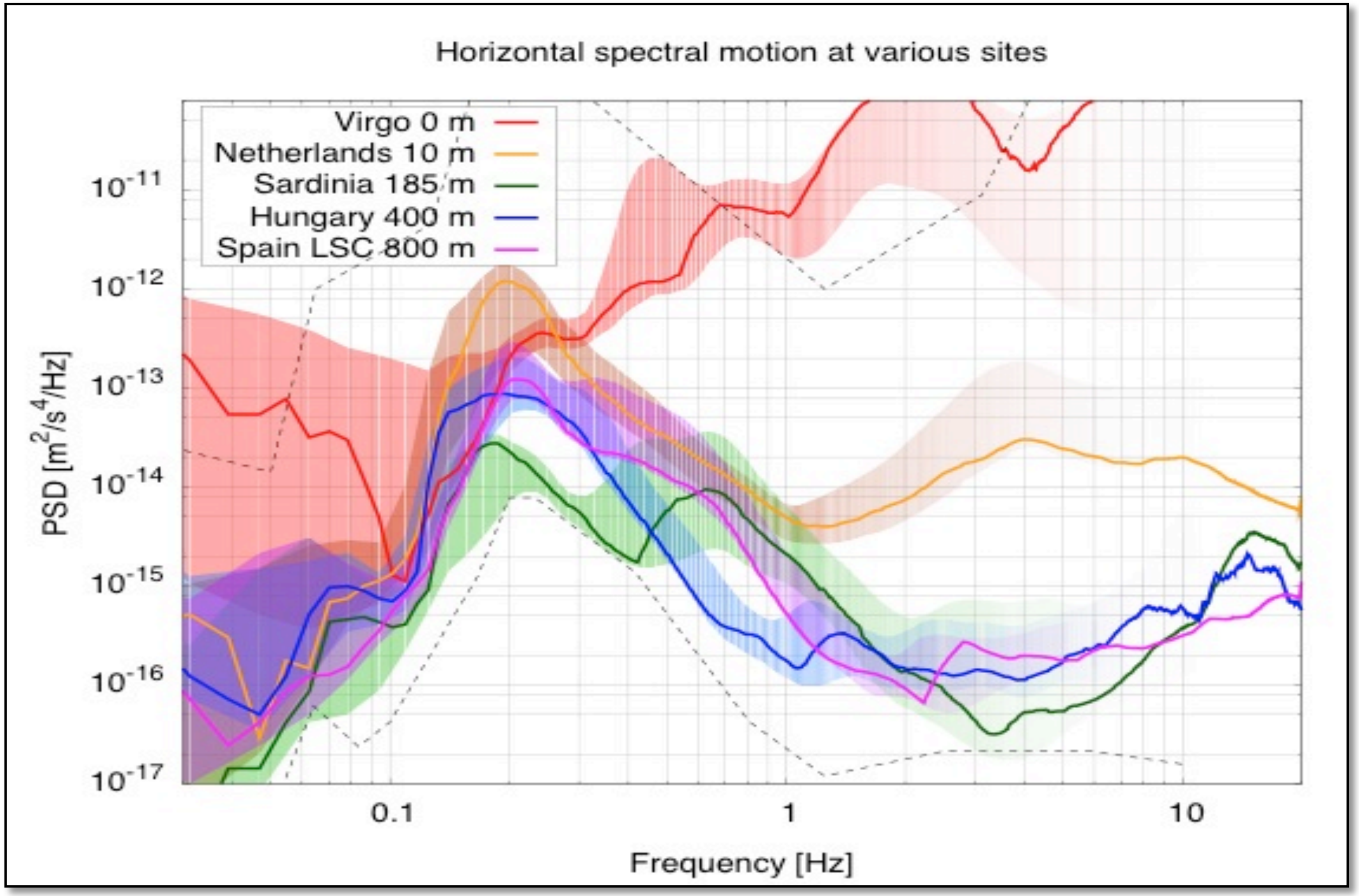
Subtraction of gravity gradient noise using an array of seismometers.

- Beker et al: General Relativity and Gravitation Volume 43, Number 2 (2011), 623-656
- Driggers et al: arXiv:1207.0275v1 [gr-qc]

Shaping local topography

- Harms et al, CQG Volume 31, Number 18, 2014

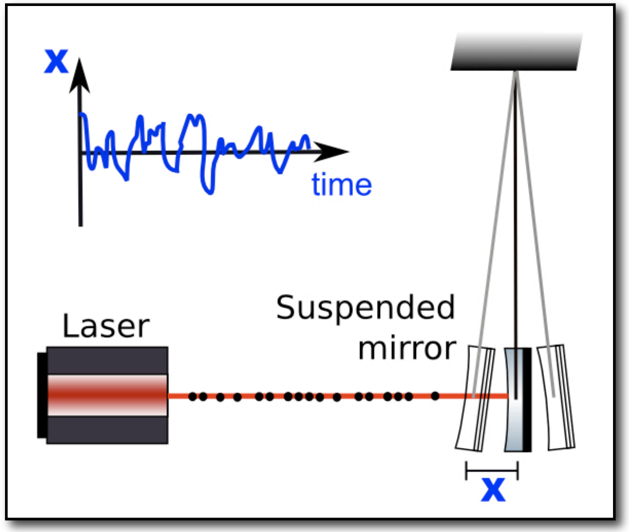
ET will ‘go underground’



ET design study document

Quantum Noise

- Quantum noise is a direct manifestation of the **Heisenberg Uncertainty Principle**.
- It is comprised of **photon shot noise (sensing noise)** at high frequencies and **photon radiation pressure noise (back-action noise)** at low frequencies.



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

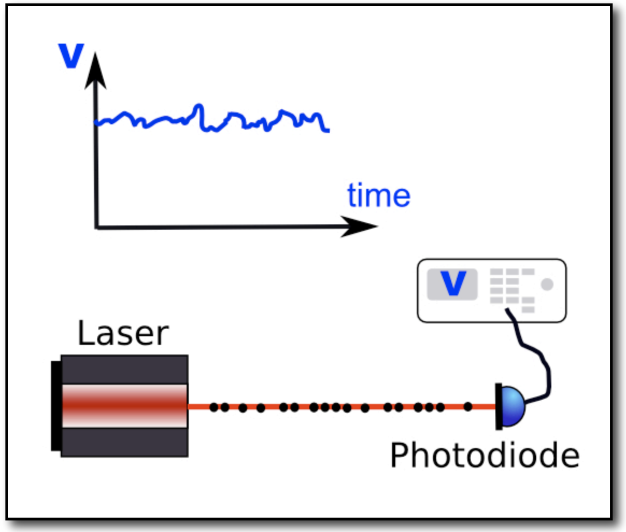
$$h_{\mathrm{rp}}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$

wavelength

optical power

Arm length

Mirror mass



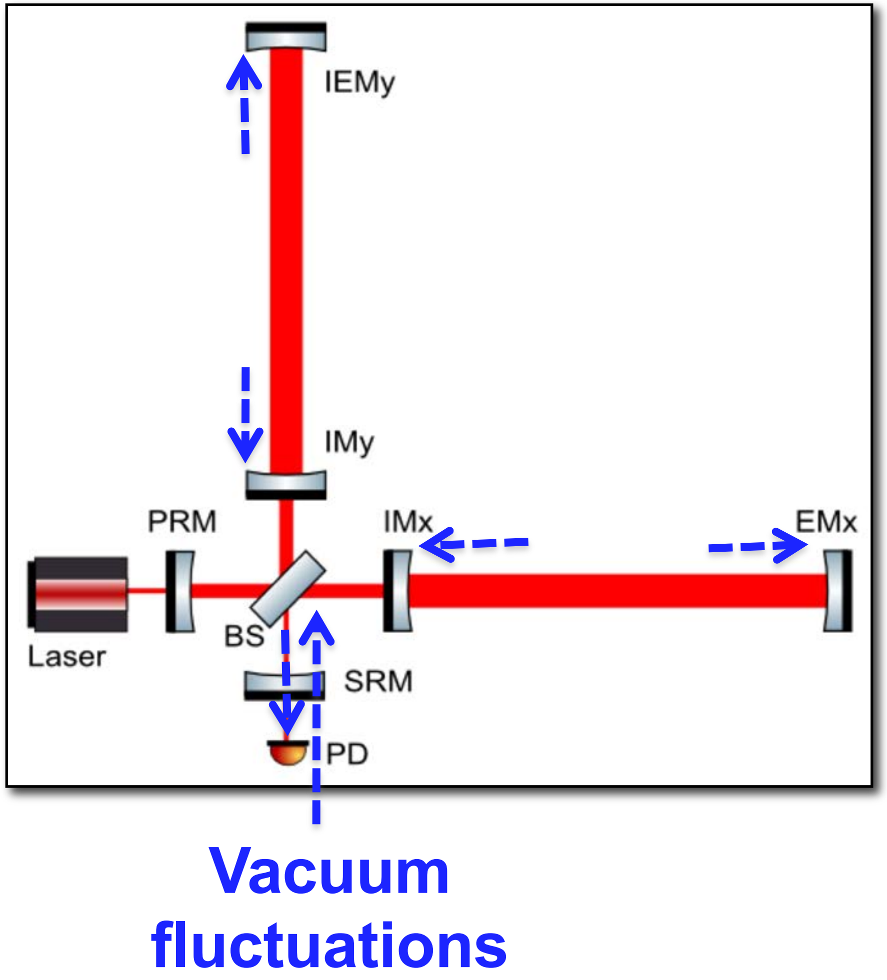
photon radiation pressure noise **photon shot noise**

Vacuum fluctuations

Quantum noise can also be understood as vacuum fluctuations entering the interferometer via any open port:

➲Fluctuations reflected from interferometer detected a photo-detector as shot noise

➲Fluctuations acting on mirrors cause radiation pressure noise

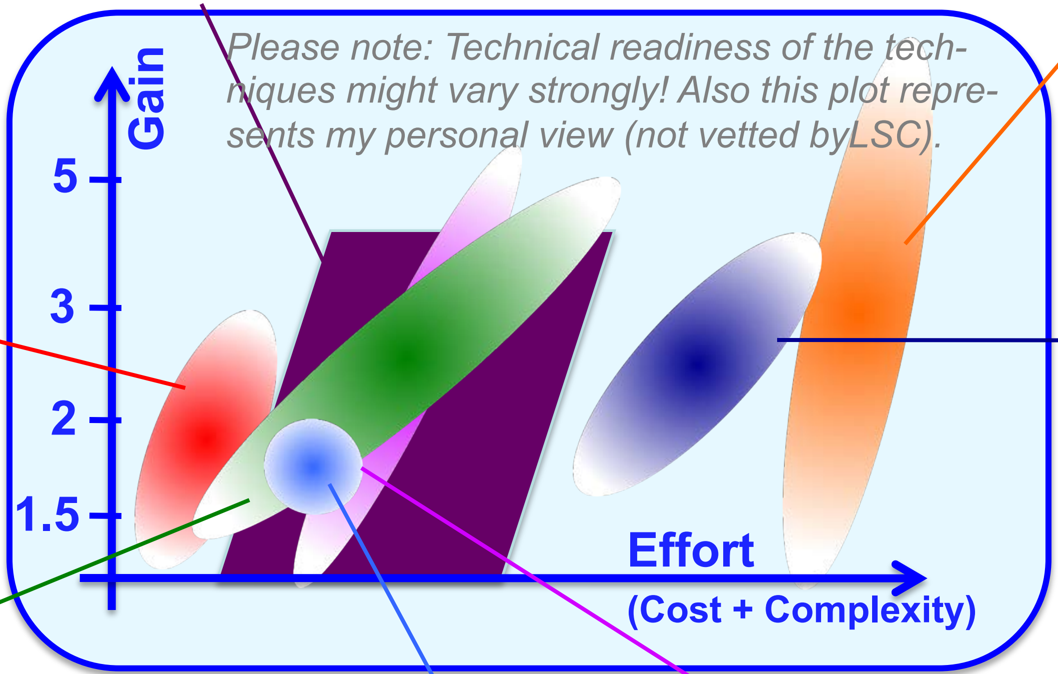


How to reduce Quantum Noise?

Squeezing with frequency dependent squeezing angle
Kimble et al, PRD 65, 2002

Speedmeter
Measures momentum of test masses and is therefore not susceptible to Heisenberg Uncertainty Principle.
Chen, PRD 67, 122004, 2003

Squeezed Light
LIGO Scientific collaboration, Nature Phys. 7 962–65, 2011



Optical Bar + Optical Lever
Khalili, PLA 298, 308-14, 2002

Increased Laser Power
Need to deal with thermal problems and instabilities

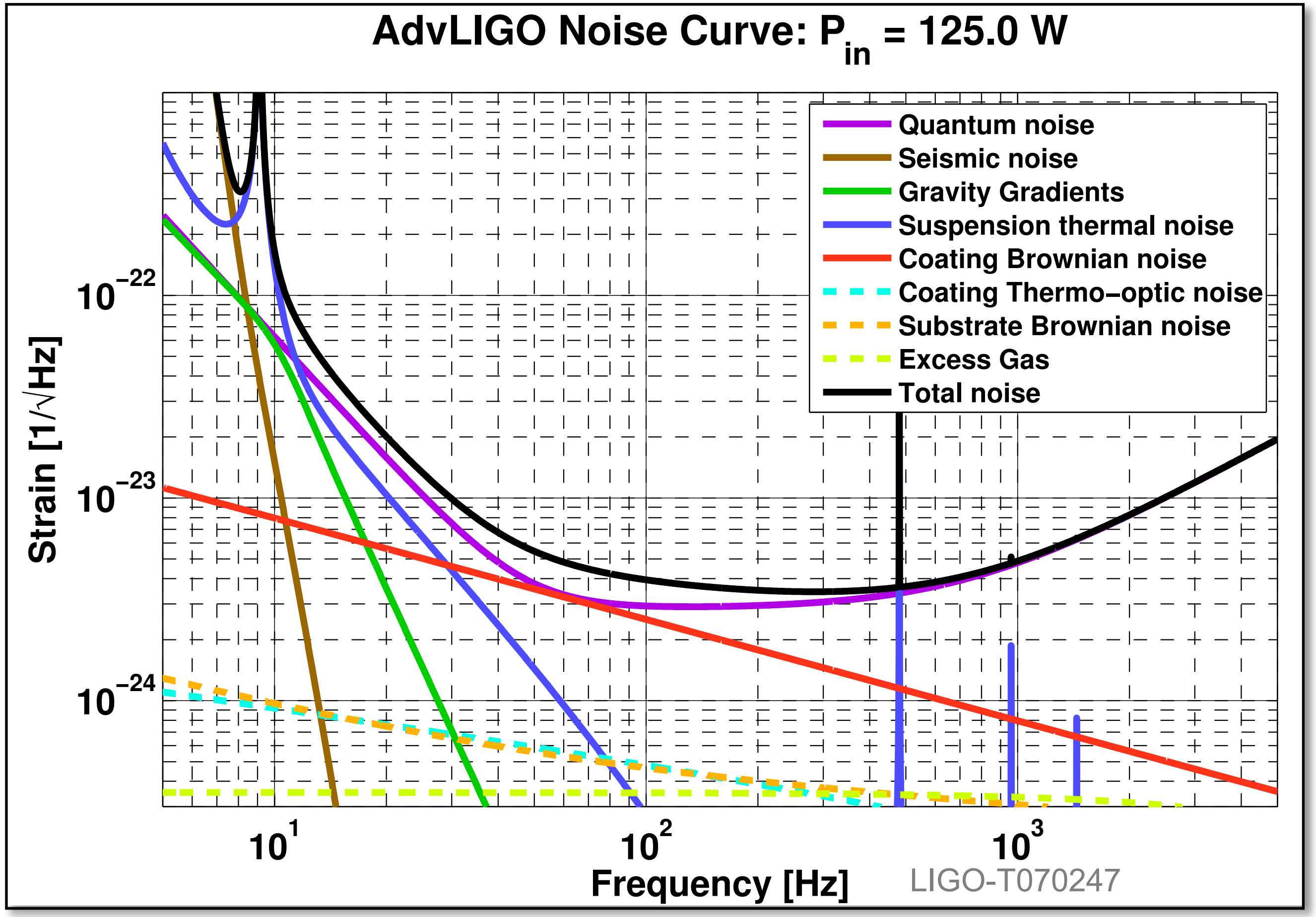
Local readout
Rehbein et al, PRD 78, 062003, 2008

Increased Mirror Weight
Need to deal with thermal problems and instabilities

Noise Sources limiting the 2G

- **Quantum Noise** limits most of the frequency range.
- **Coating Brownian** limits in the range from 50 to 100Hz.
- Below ~15Hz we are limited by 'walls' made of **Suspension Thermal**, **Gravity Gradient** and **Seismic noise**.

- And then there are the, often not mentioned, 'technical' noise sources which trouble the commissioners so much.

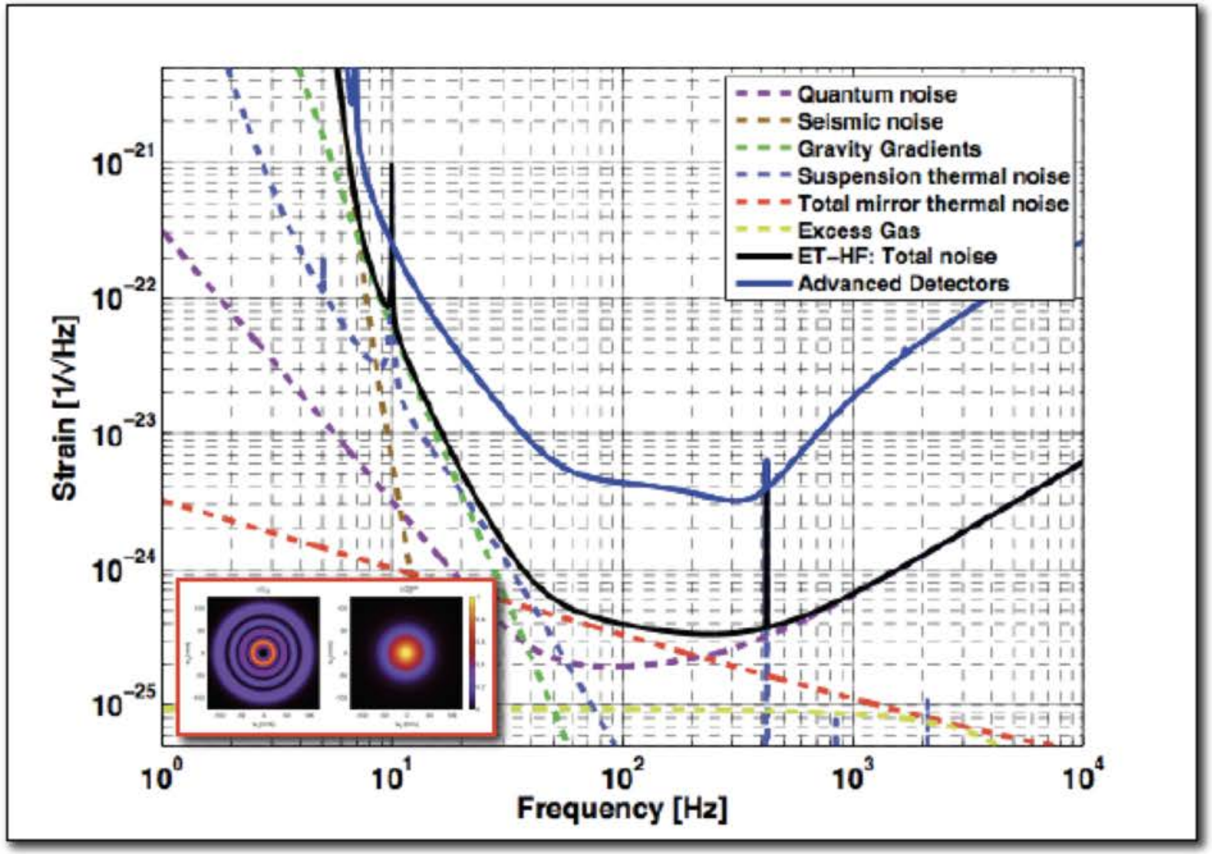


Motivation for Xylophone observatories

- Due to residual absorption in substrates and coatings high optical power (3MW) and cryogenic test masses (20K) don't go easily together.
- IDEA: Split the detection band into 2 or 3 instruments, each dedicated for a certain frequency range. All 'xylophone' interferometer together give the full sensitivity.
- Example of a 2-tone xylophone:
  - Low frequency: low power and cryogenic
  - High frequency: high power and room temperature

High Frequency Detector

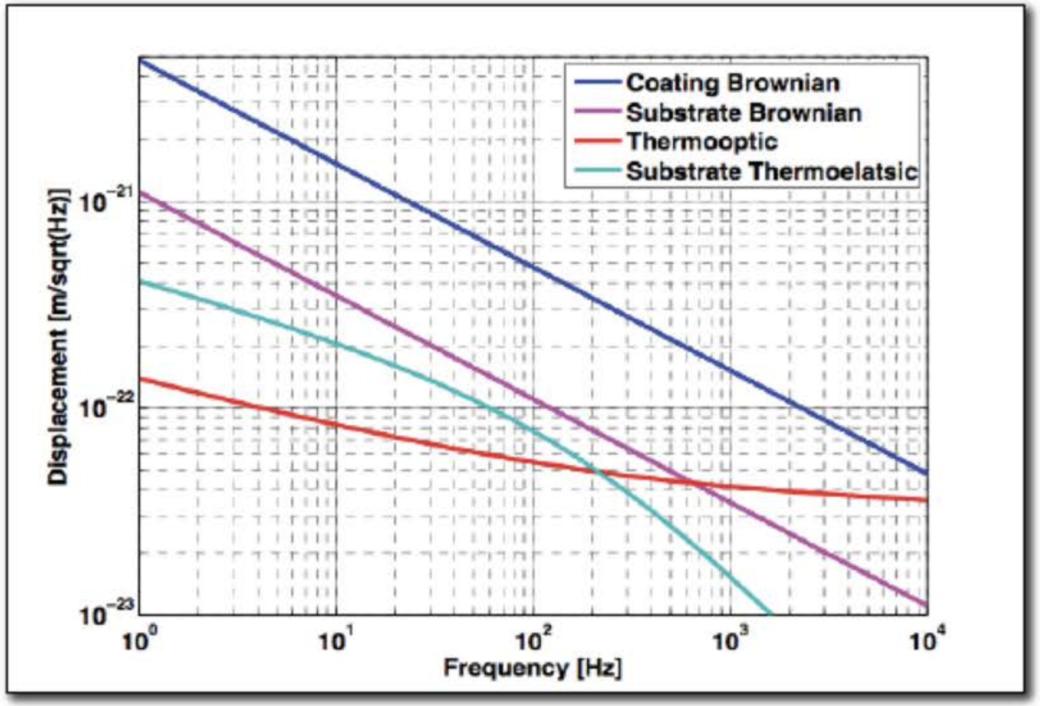
- **Quantum noise:** 3MW, tuned Signal-Recyling, 10dB Squeezing, 200kg mirrors.
- **Suspension Thermal and Seismic:** Superattenuator at surface location.
- **Gravity gradient:** No Subtraction
- **Thermal noise:** 290K, 12cm beam radius, fused Silica, LG33 (reduction factor of 1.6 compared to TEM00).



Coating Brownian reduction factors (compared to 2G):
3.3 (arm length), 2 (beam size) and 1.6 (LG33) = 10.5

LF-Detector: Cryogenic Test masses

- Thermal noise of a single cryogenic end test mass.
- Assumptions:
  - Silicon at 10K
  - Youngs Modulus = 164GP
  - Coating material similar to what is currently available for fused silica at 290K (loss angles of 5e-5 and 2e-4 for low and high refractive materials)

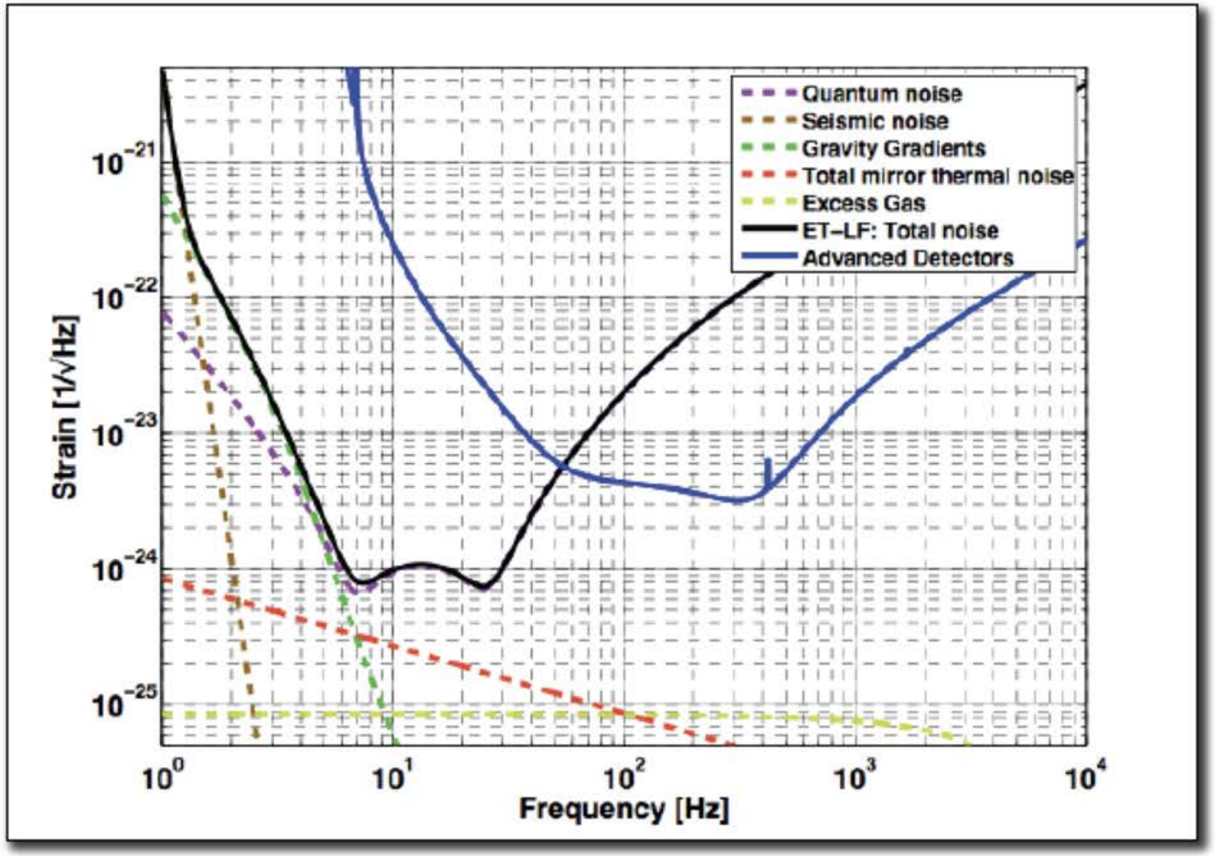


How to get from here to total mirror TN in ET?
- Sum over the 4 different noise types.
- Go from displacement to strain (divide by 10000).
- Uncorrelated sum of 2 end mirrors and 2 input mirrors

UNIVERSITY of GLASGOW

Low Frequency Detector

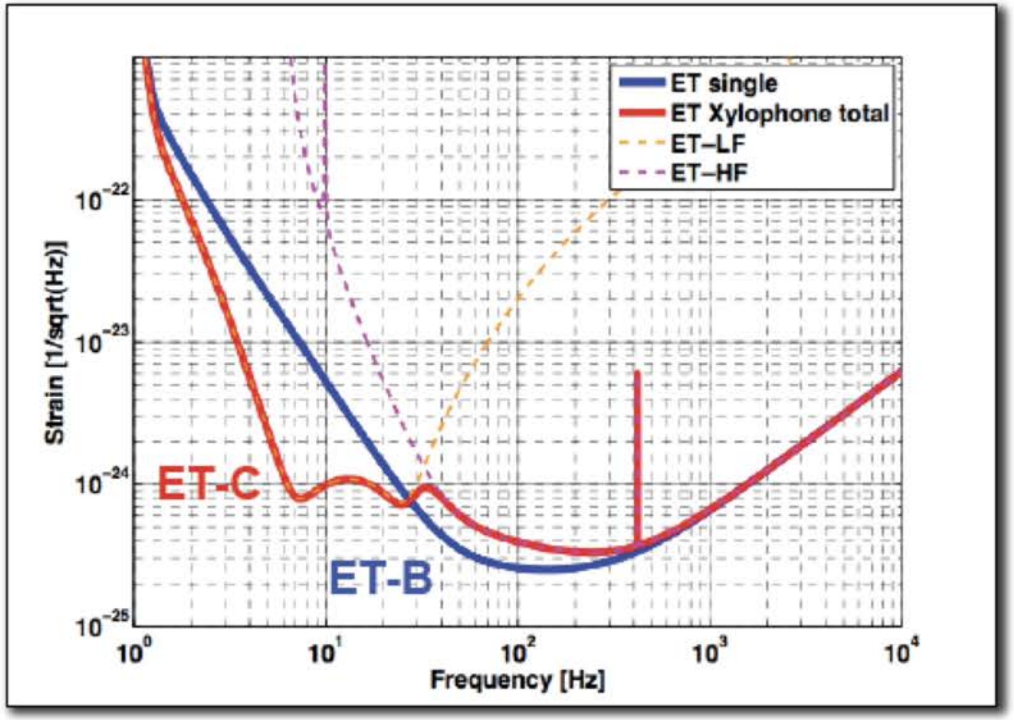
- **Quantum noise:** 18kW, detuned Signal-Recyling, 10 dB frequency dependent Squeezing, 211kg mirrors.
- **Seismic:** 5x10m suspensions, underground.
- **Gravity gradient:** Underground, factor 50 subtraction
- **Thermal noise:** 10K, Silicon, 12cm beam radius, TEM00.
- **Suspension Thermal:** not included. :(



As mirror TN is no longer limiting, one can relax the assumptions on the material parameters and the beam size…

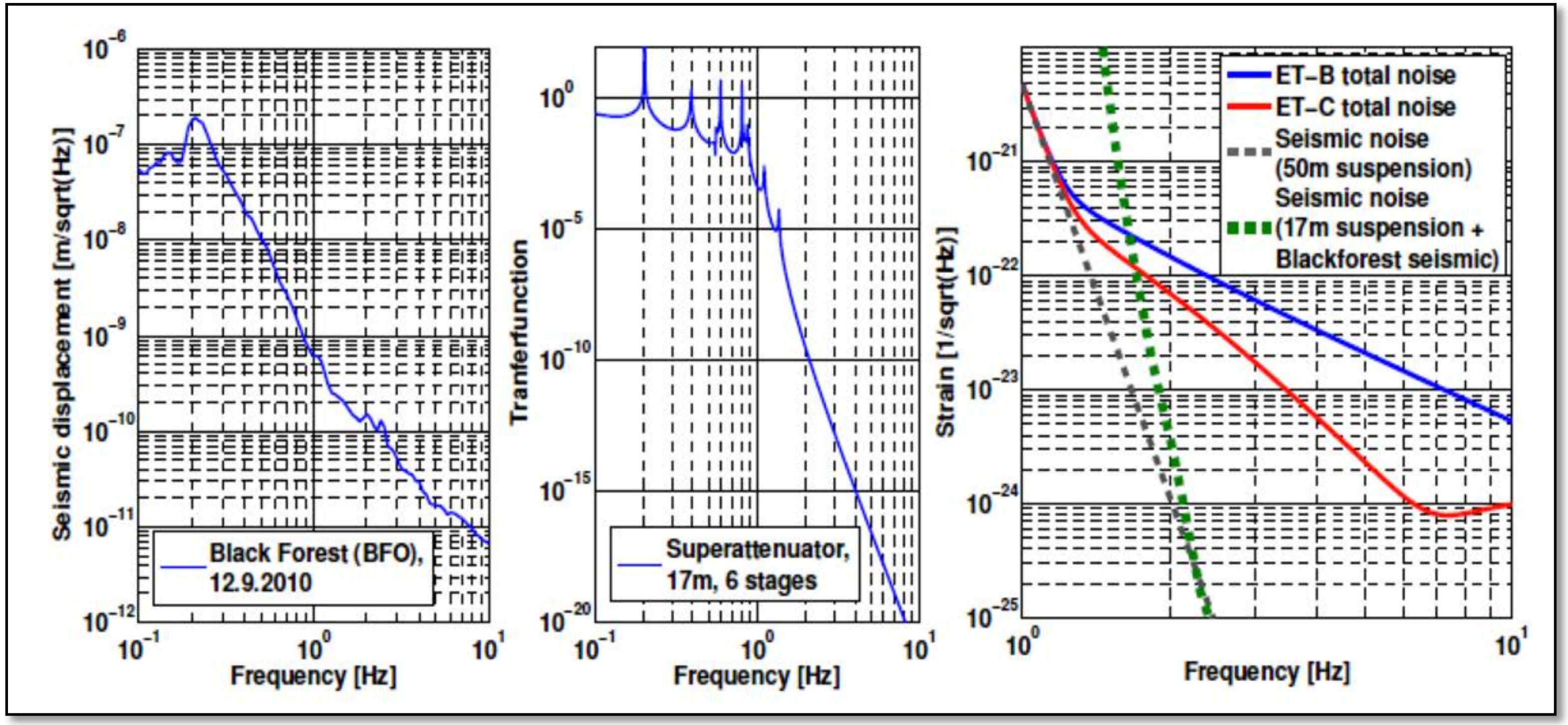
ET-Xylophone: ET-C

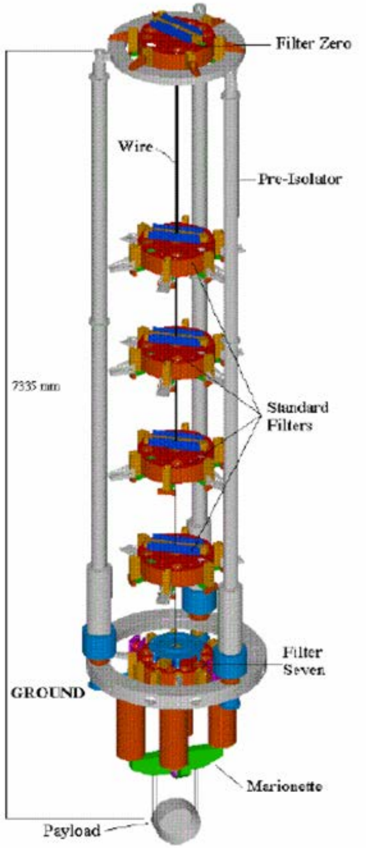
Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	Fused Silica	Silicon
Mirror diameter / thickness	62 cm / 30 cm	62 cm / 30 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	10 dB	10 dB
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	12 cm
Clipping loss	1.6 ppm	1.6 ppm
Suspension	Superattenuator	5 × 10 m
Seismic (for $f > 1$ Hz)	$1 \cdot 10^{-7}$ m/f^2	$5 \cdot 10^{-9}$ m/f^2
Gravity gradient subtraction	none	factor 50



- Data from ET-LF and ET-HF can be coherently or incoherently be added, depending on the requirements of the analysis.
- For more details please see S.Hild, S.Chelkowski, A.Freise, J.Franc, R.Flaminio, N.Morgado and R.DeSalvo: 'A Xylophone Configuration for a third Generation Gravitational Wave Detector', CQG 2010, 27, 015003

Seismic noise



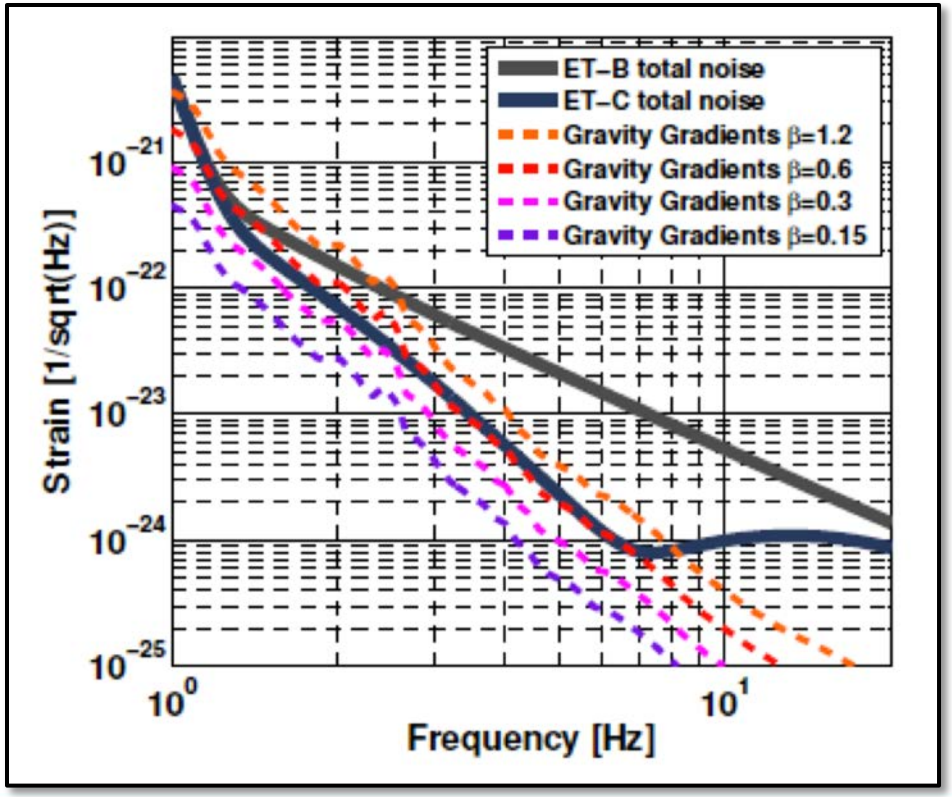


Seismic excitation x **17m SA Transfer function** = **Seismic noise contribution**

Gravity Gradient Noise

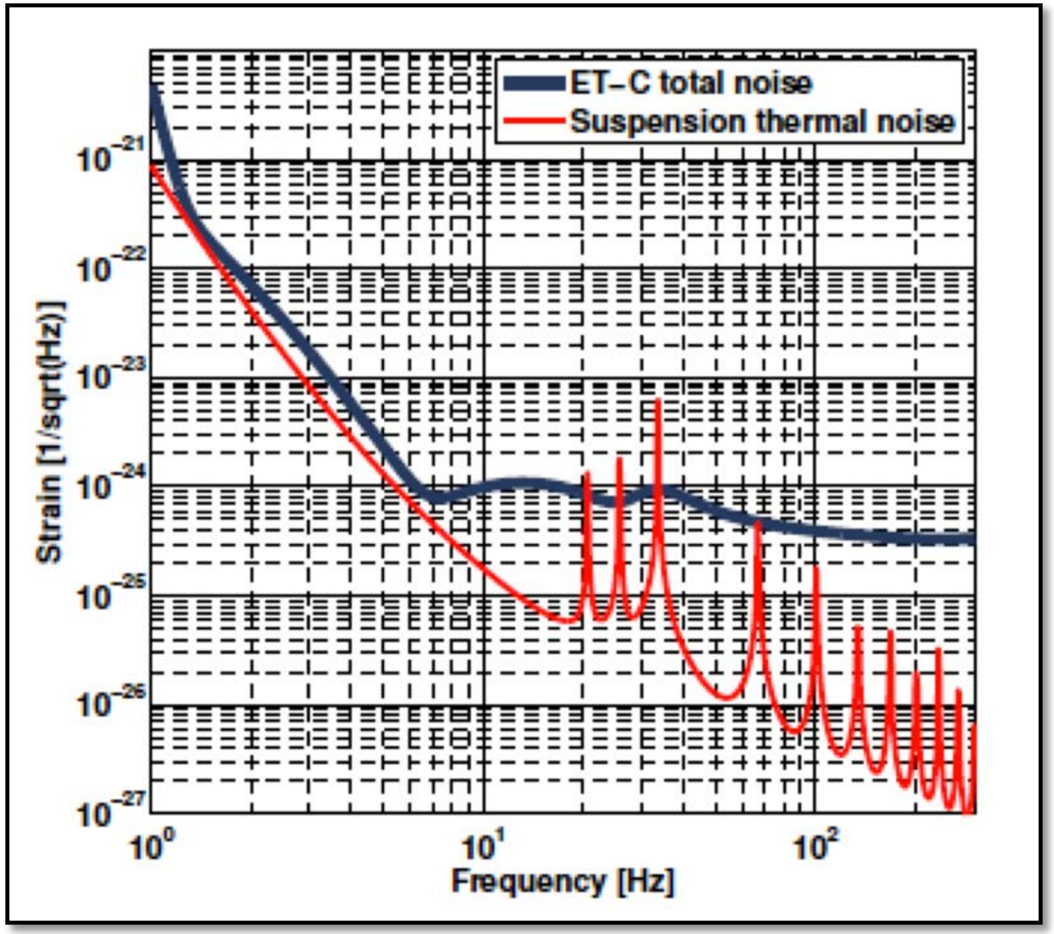
- ET-B and ET-C assume a medium quiet site + factor 50 GGN subtraction.
- ET-D considers very quiet underground site (about 5e-10/f2*m/sqrt(Hz)) at Black Forest.
- Please note:
  - ET measurement campaign showed several sites on the same level or even better than the BFO site.
  - Biggest uncertainty in beta

$$N_{GG}(f)^2 = \frac{4 \cdot \beta^2 \cdot G^2 \cdot \rho_r^2}{L^2 \cdot f^4} \cdot X_{seis}^2,$$



Suspension Thermal Noise

- Silicon fibers of 3mm diameter and 2m length.
- Test mass temperature = 10K
- Penulitmate mass temperature = 2K

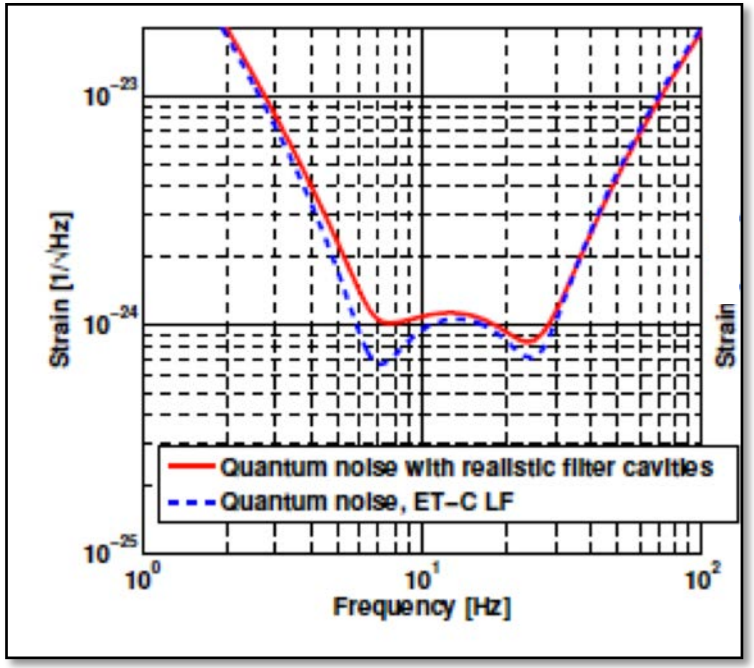


S.Hild et al, CQG 2011, **28** 094013

- P. Puppo, Journal of Physics: Conference Series 228, (2010) 012031
- P. Puppo and F. Ricci, General Relativity and Gravitation, Springer Netherlands, 2010, 1-13
- F.Ricci, presentation at GWADW 2010,Kyoto. Available at:http://gw.icrr.u-tokyo.ac.jp/gwadw2010/program/2010_GWADW_Ricci.pdf

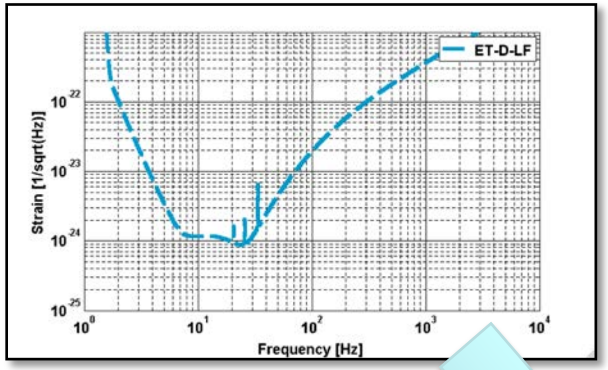
Quantum of Low-Frequency detector

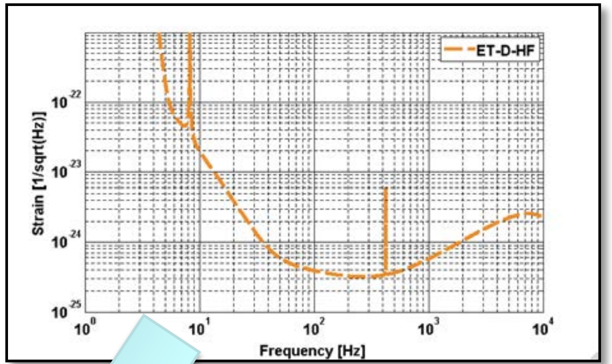
- Employs detuned signal recycling => needs two filter cavities.
- Required parameters for filter cavities challenging: Detuning of 25.4Hz and 6.6Hz and half bandwidths of 5.7Hz and 1.5Hz.
- To achieve such low bandwidths very long and/or very high finesse cavities are required.
- Total losses at resonance frequency are the product of roundtrip losses and filter cavity finesse.
- For ET we decided to be conservative: Assumed 37.5ppm loss per mirror and filter cavity lengths of 10km. Still at 7Hz the 10dB of squeezing are degraded to less than 3dB.



S.Hild et al, CQG 2011, **28** 094013

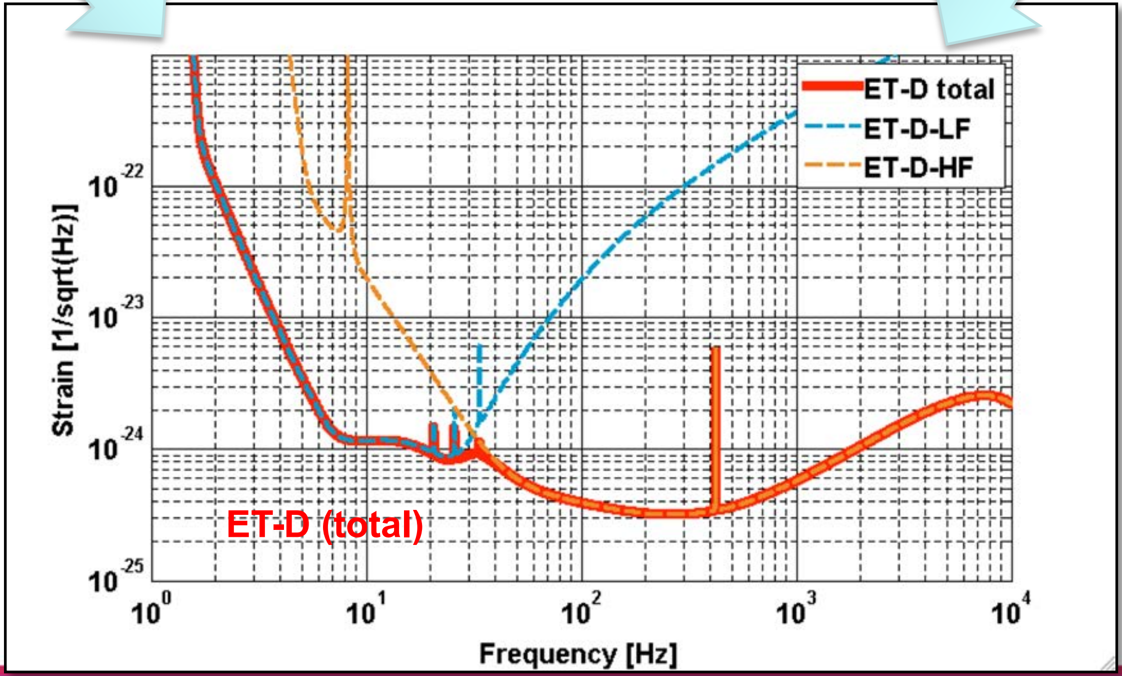
Combining 2 IFOs





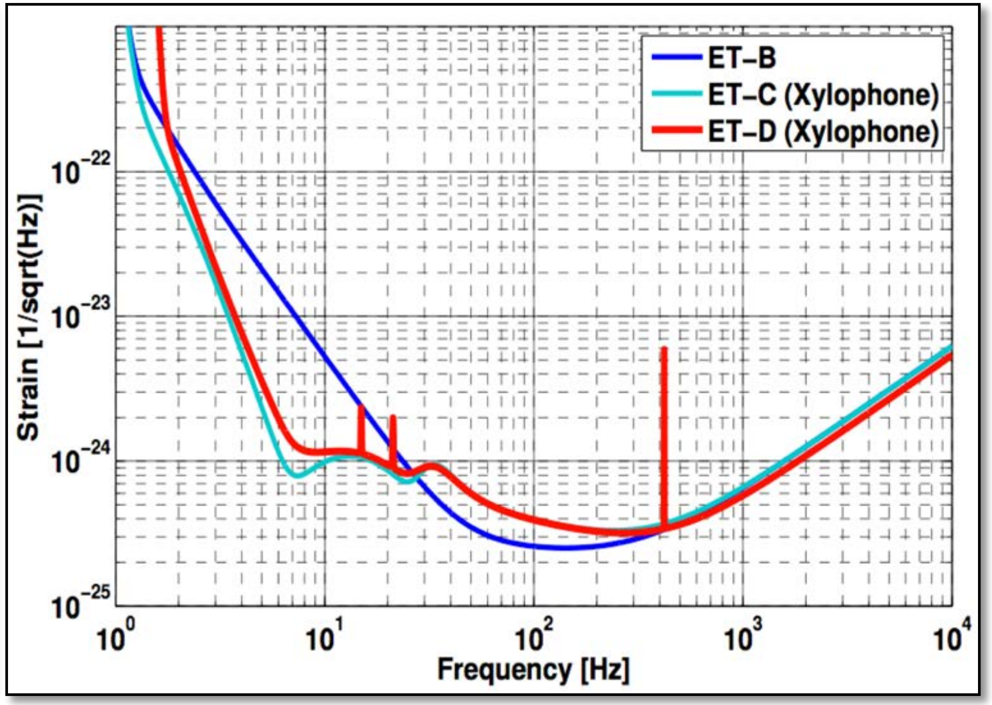
ET-D-LF

ET-D-HF



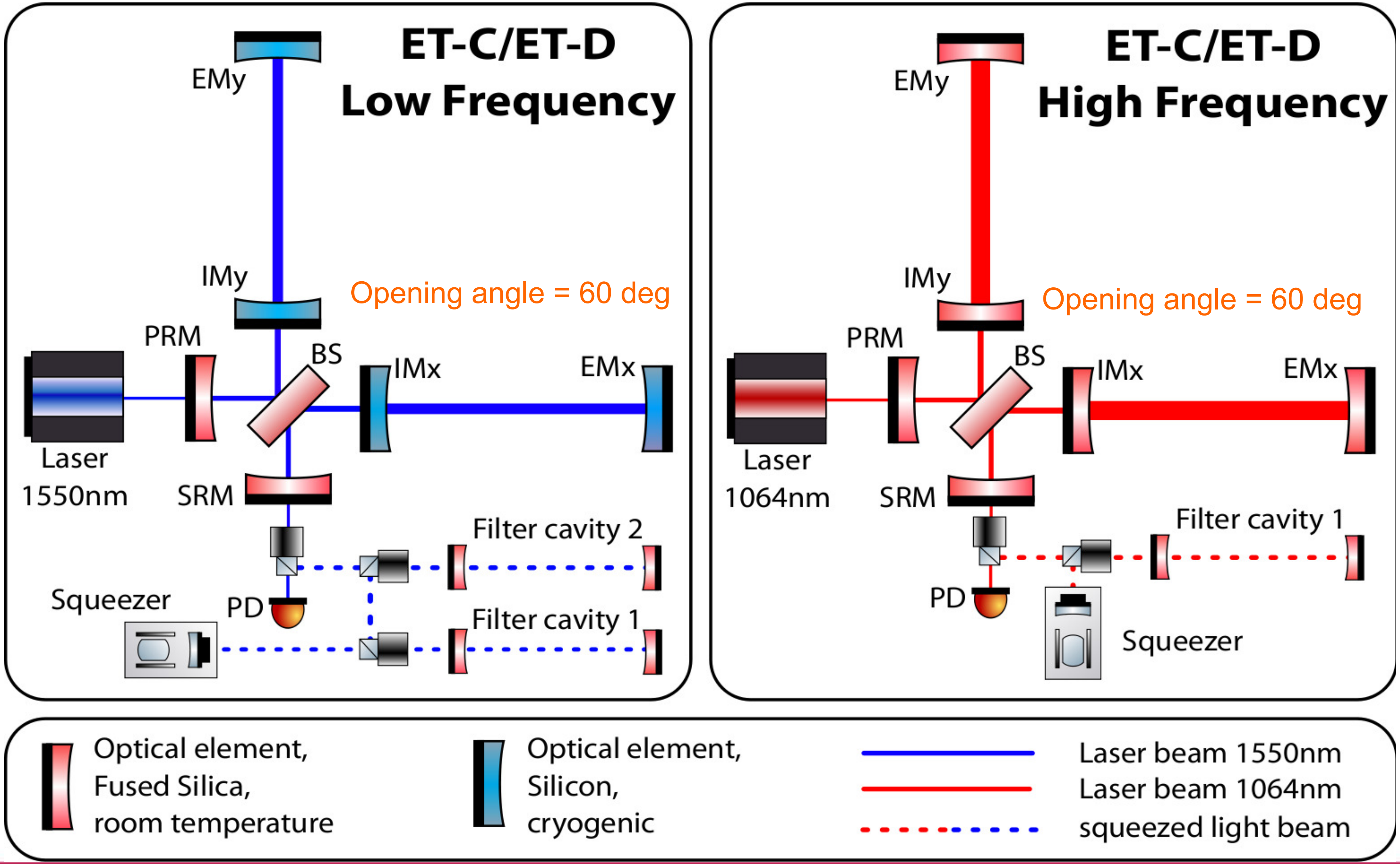
ET Sensitivity evolution

Parameter	ET-D-HF	ET-D-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 K
Mirror material	Fused silica	Silicon
Mirror diameter / thickness	62 cm / 30 cm	min 45 cm/ TBD
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1 × 10 km	2 × 10 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	9 cm
Scatter loss per surface	37.5 ppm	37.5 ppm
Partial pressurefor H_2O, H_2, N_2	10^{-8}, $5 \cdot 10^{-8}$, 10^{-9} Pa	10^{-8}, $5 \cdot 10^{-8}$, 10^{-9} Pa
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\ m/f^2$	$5 \cdot 10^{-10}\ m/f^2$
Gravity gradient subtraction	none	none



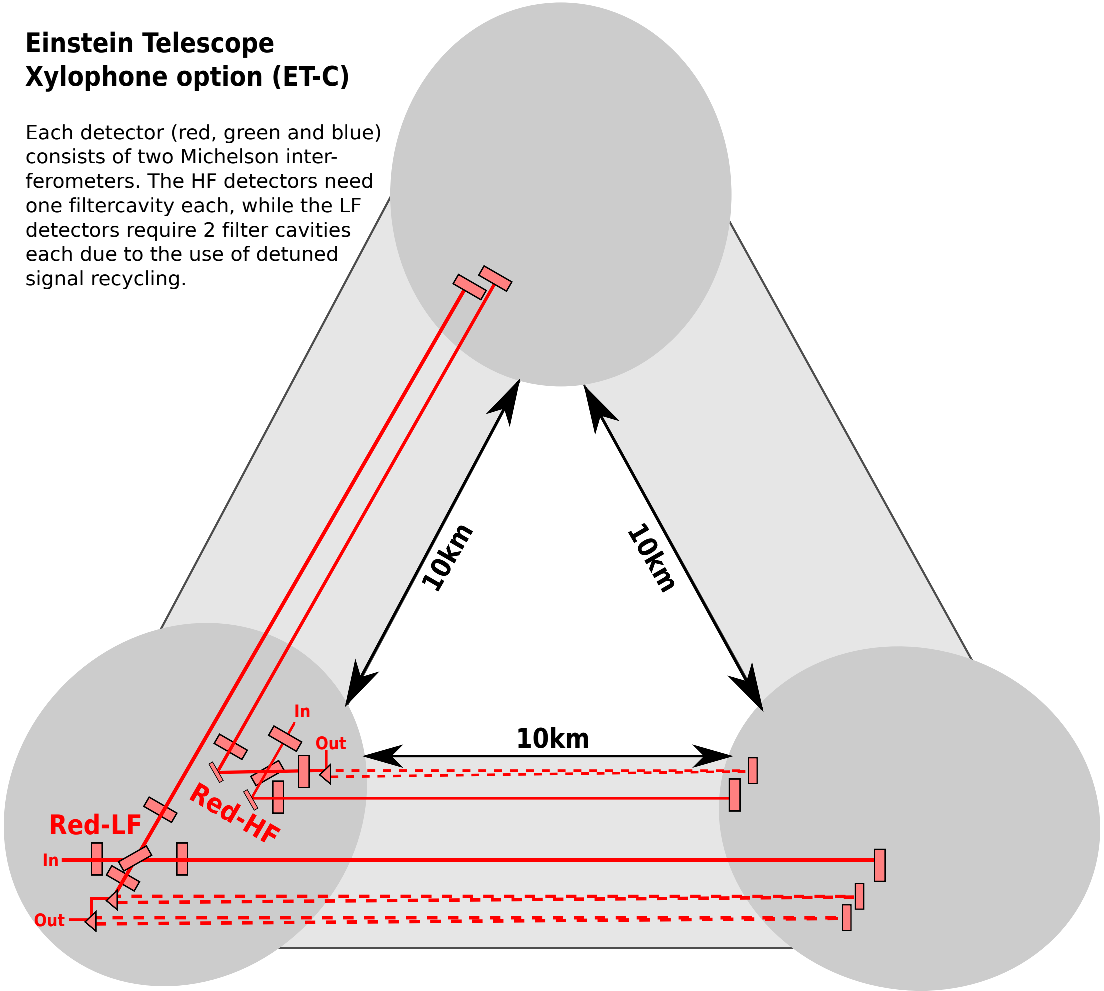
- Data from ET-LF and ET-HF can be coherently or incoherently be added, depending on the requirements of the analysis.
- Sensitivity data available for download at: http://www.et-gw.eu/etsensitivities
- For more details please see S.Hild et al: 'A Xylophone Configuration for a third Generation Gravitational Wave Detector', CQG 2010, **27**, 015003 and S.Hild et al: 'Sensitivity Studies for Third-Generation Gravitational Wave Observatories', CQG 2011, **28** 094013.

The ET core interferometers



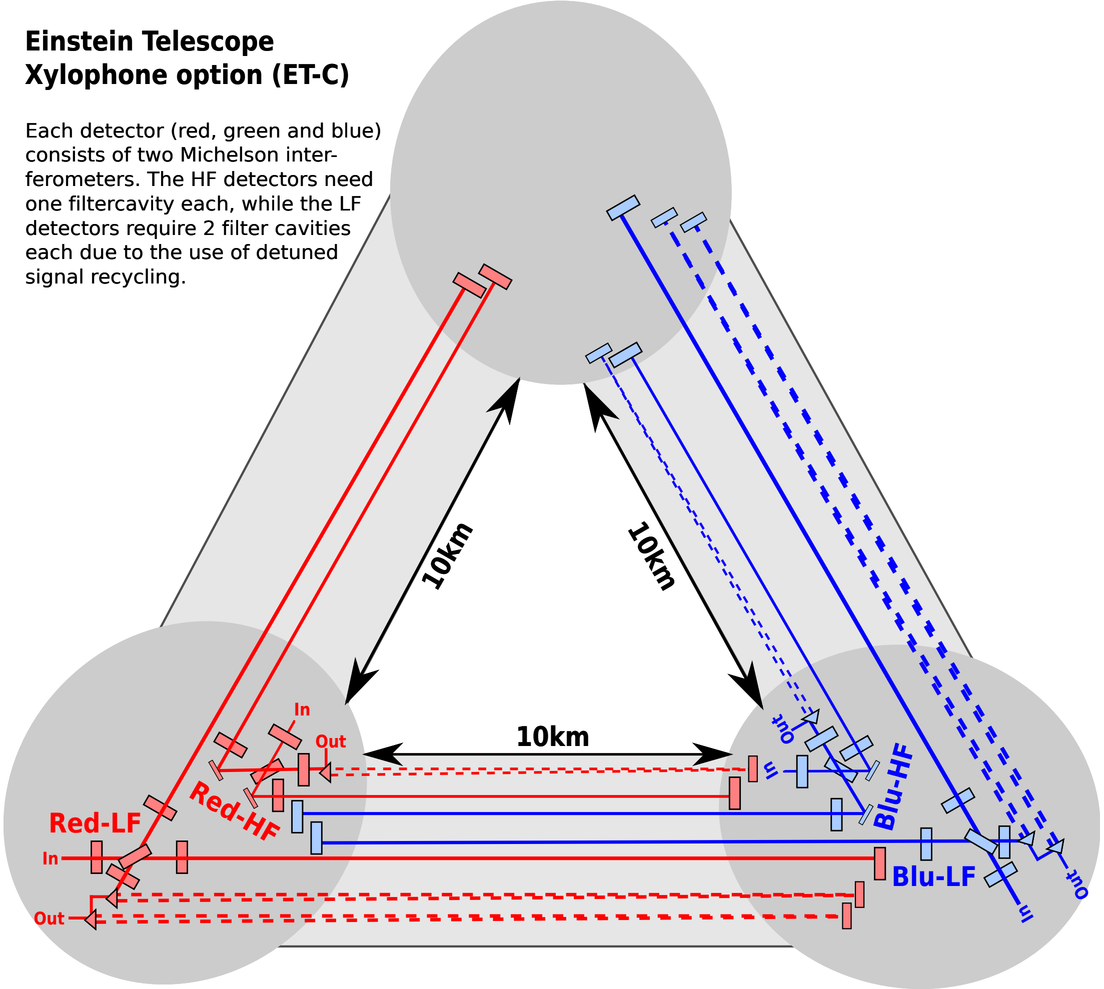
How to build an Observatory?

- For efficiency reasons build a triangle.
- Start with a single xylophone detector.



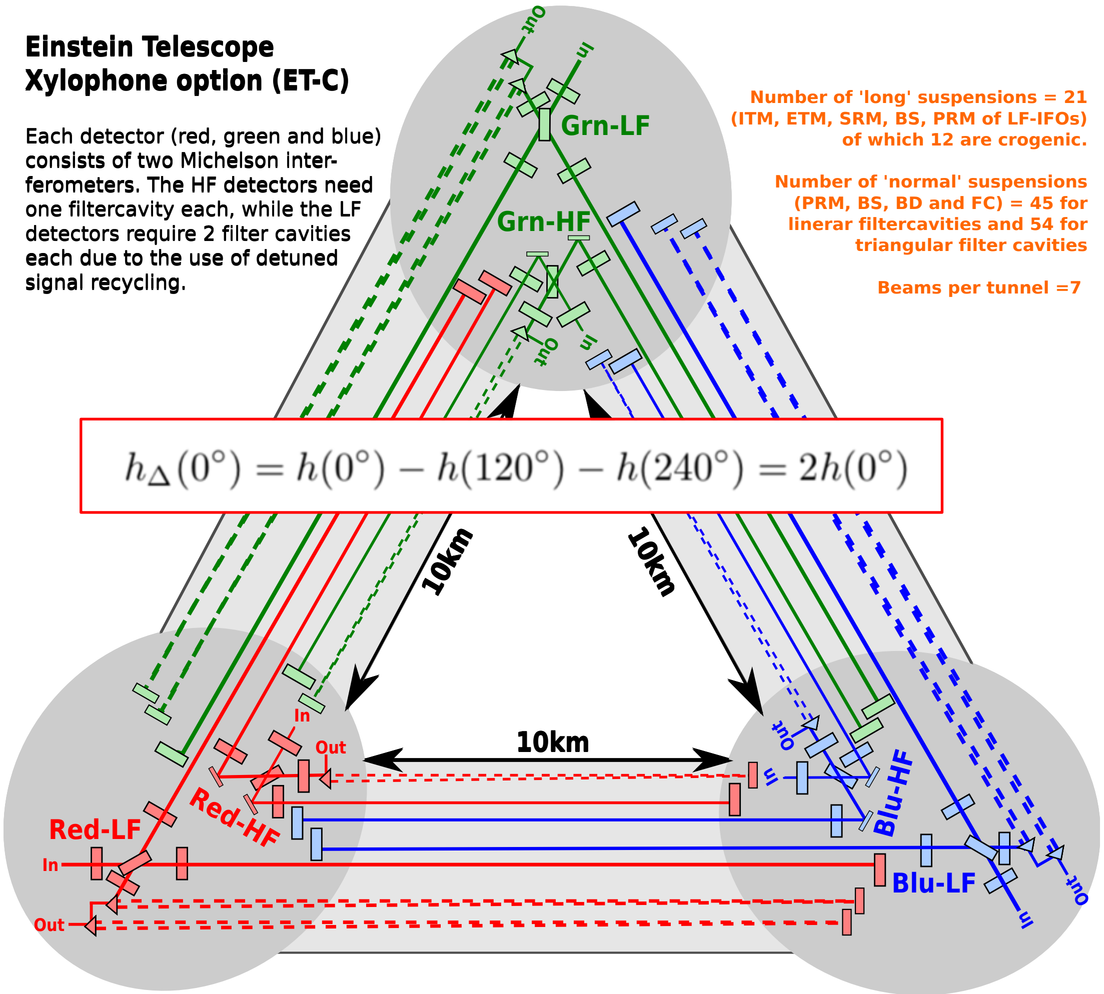
How to build an Observatory?

- For efficiency reasons build a triangle.
- Start with a single xylophone detector.
- Add second Xylophone detector to fully resolve polarisation.

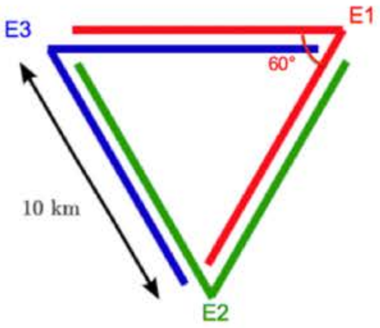


How to build an Observatory?

- For efficiency reasons build a triangle.
- Start with a single xylophone detector.
- Add second Xylophone detector to fully resolve polarisation.
- Add third Xylophone detector for redundancy and null-streams.



$$h_{\Delta}(0^{\circ}) = h(0^{\circ}) - h(120^{\circ}) - h(240^{\circ}) = 2h(0^{\circ})$$



Null Stream Analysis

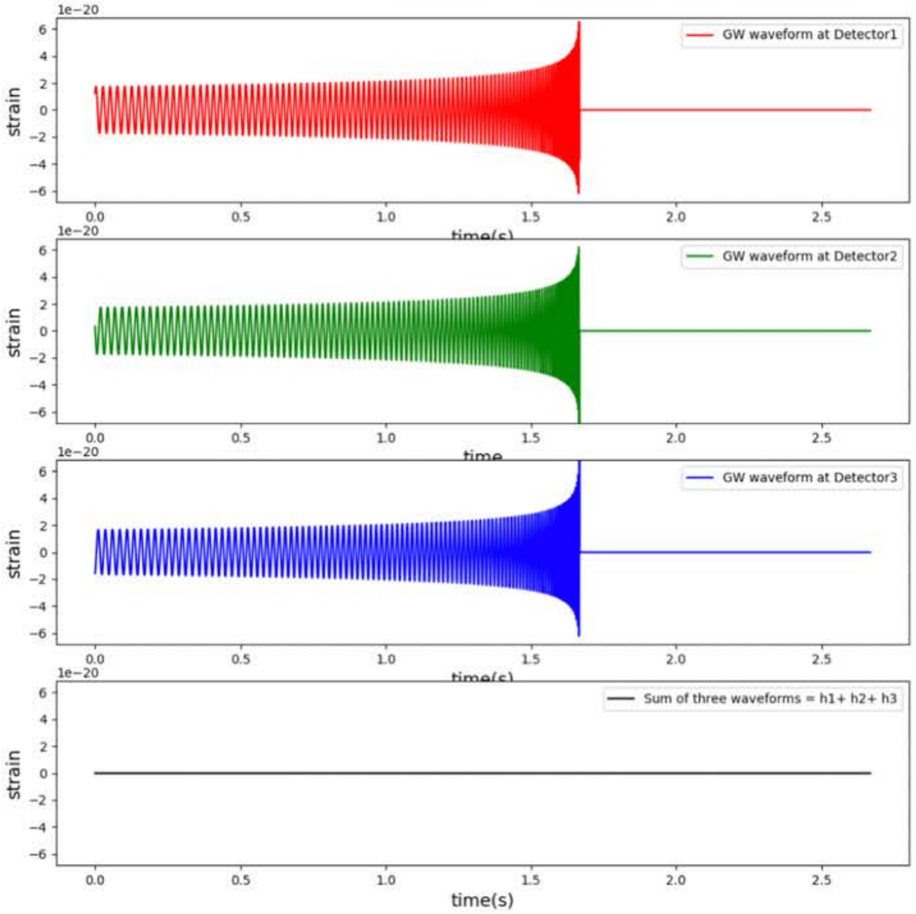
Data strain at each arm can be expressed as

$$x^A(t) = n^A(t) + d^A_{ij}h^{ij}(t)$$

- Null stream can be written as

$$X_{null}(t) = \sum_{A=1}^{3} x^A(t) = \sum_{A=1}^{3} n^A(t) + \sum_{A=1}^{3} d^A_{ij}h^{ij}(t)$$

$$= \sum_{A=1}^{3} n^A(t)$$



Singha, Hild

ET - telecon, May 2019

15

Newtonian noise

- Lots of progress in understanding seismic fields, via seismometer arrays (LHO, Homestake, Virgo) in 2D and 3D.
- Lots of progress in modelling of seismic newtonian noise towards more realistic setups
- Recently published: Newtonian noise from infrasound. => Supports the argument to go underground.

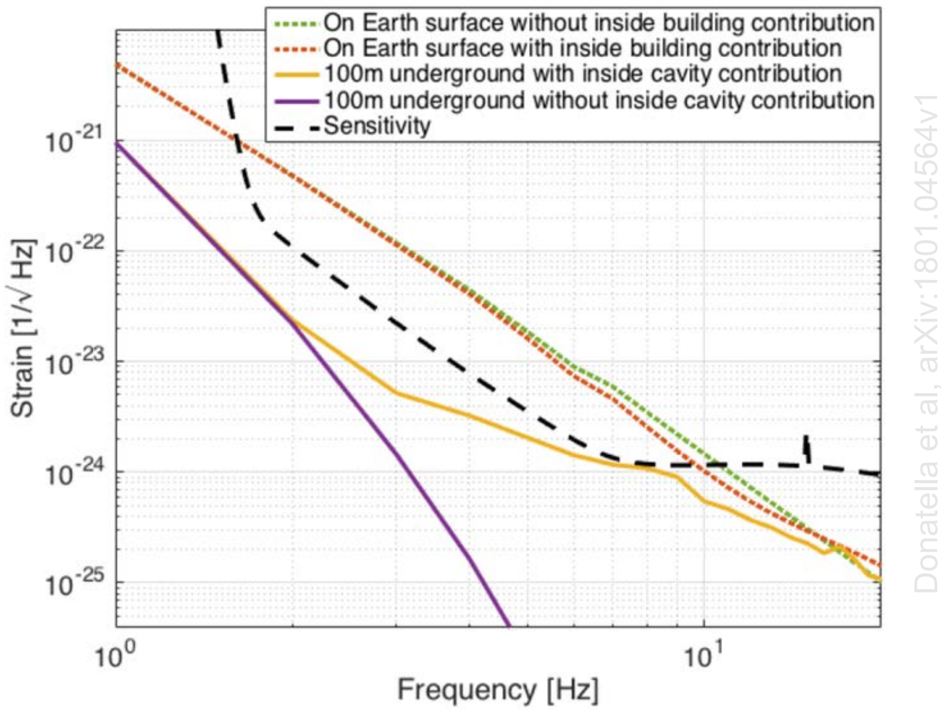
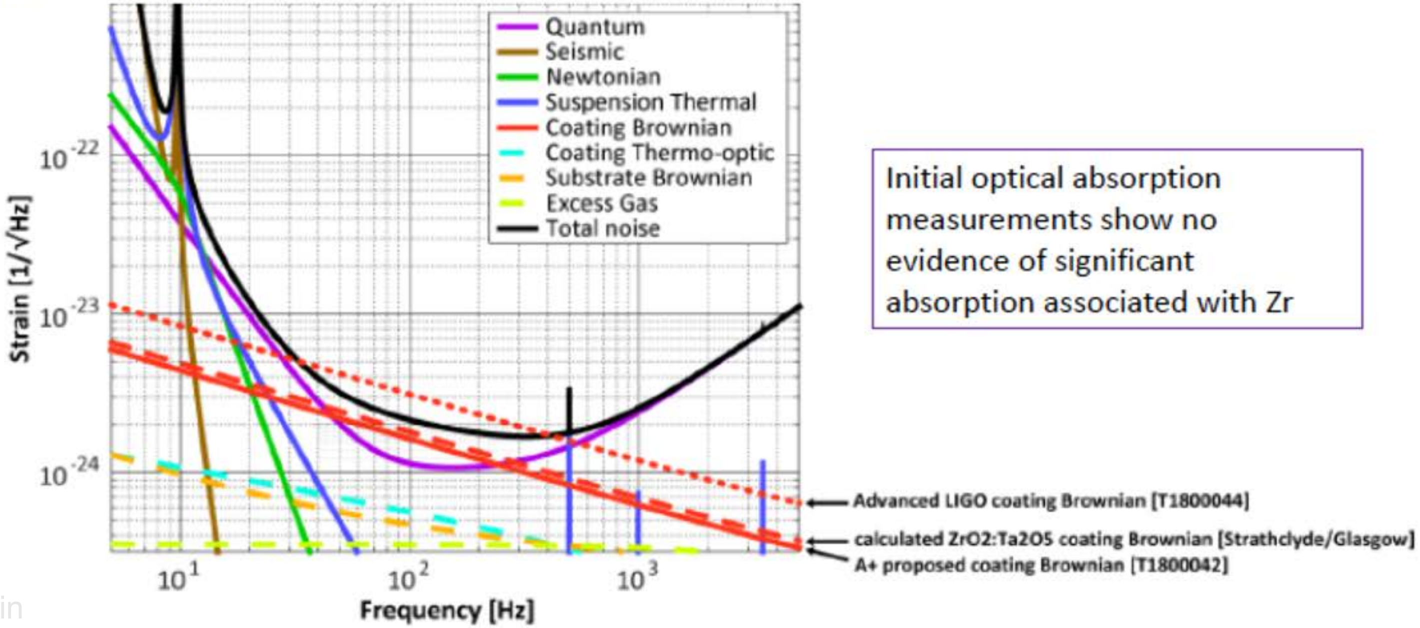


FIG. 11. Infrasound NN for an ET like laser interferometer.

Room temperature coatings: Zirconia-doped Tantala

- Coatings produced by Strathclyde group, using novel IBS technique, show mechanical loss more than 2x lower than the Ti:Ta2O5 used in aLIGO (S. Angelova et al)
  - Follows predictions of (a) structural modelling (Bassiri et al) and (b) increase of crystallisation temperature (work by Penn et al, Tewg et al), allowing higher annealing temperatures to reduce mechanical loss



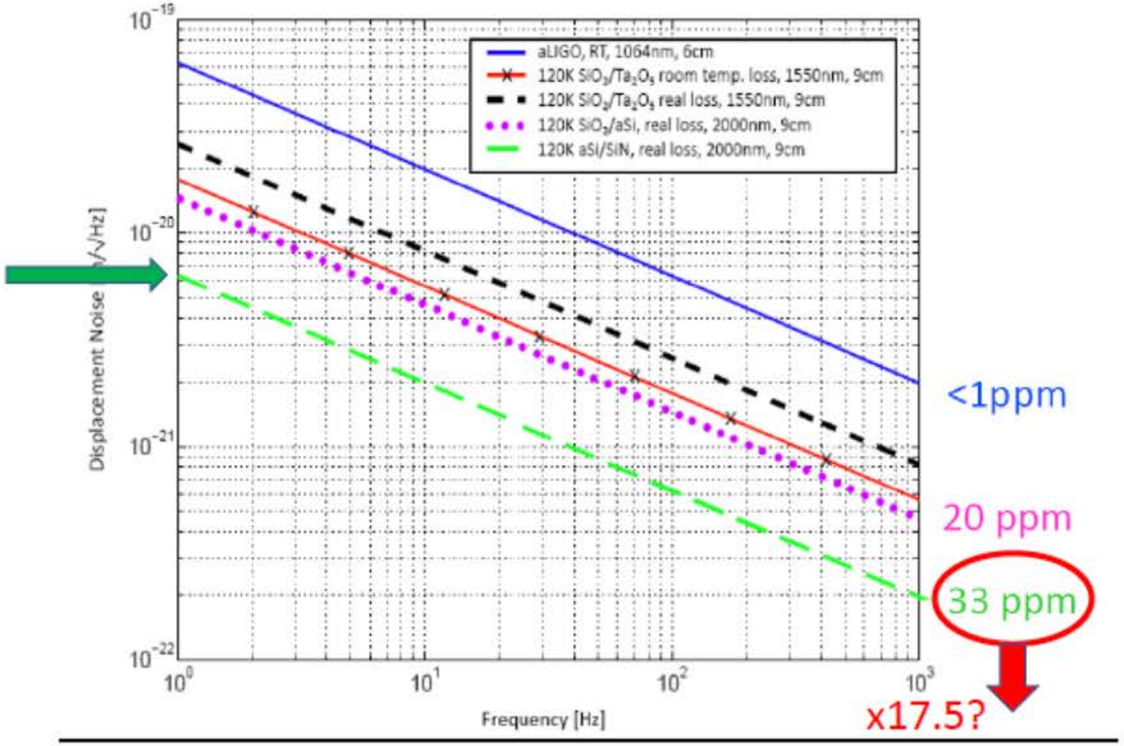
Initial optical absorption measurements show no evidence of significant absorption associated with Zr

Slide credit: I.Martin

Cryogenic coatings

Cryogenic aSi / SiN coatings at 120 K

- Very low optical absorption aSi coatings from UWS/Strathclyde deposited by ECR-IBS[1]
  - Combining with silicon nitride as a low index material is of interest[2,3]
  - Absorption measured at 1.55µm and 290K.
  - Other types of aSi show scope for reduction
    - ~x7 reduction through use of 2µm
    - ~x2.5 by cooling to 120 K
  - These reduction applied to this coating may give absorption of 1.9ppm



Slide credit: I.Martin

1 – Birney et al, in preparation
2 – Steinlechner et al, in preparation
3 – Chao et al, dcc.ligo.org/LIGO-G1300171/public

Silicon mirrors

- Free carrier noise (D. Heinert et al) and high absorption
- Floatzone vs MCz (see right + next slide).
- Other aspects which still need checking:
  - Surface roughness
  - Homogeneity
  - Birefringence
  - etc

Silicon Mirrors

Magnetic assisted Czochralski grown silicon

- MCz
  - Magnetic fields reduce convection currents in melt from which the crystal is pulled
  - Lower dissolved O_2 which comes from equilibrium reaction at the interface with SiO_2 crucible
  - Manufacturers resistivity measurements predict absorption might be x2 higher than where we would like it to be (bad thing)
  - First measurements indicate that it is actually ½ of what we need it to be (good thing)

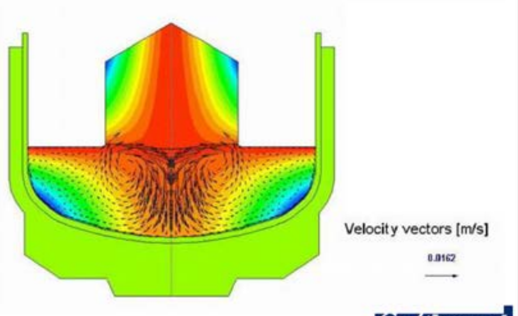
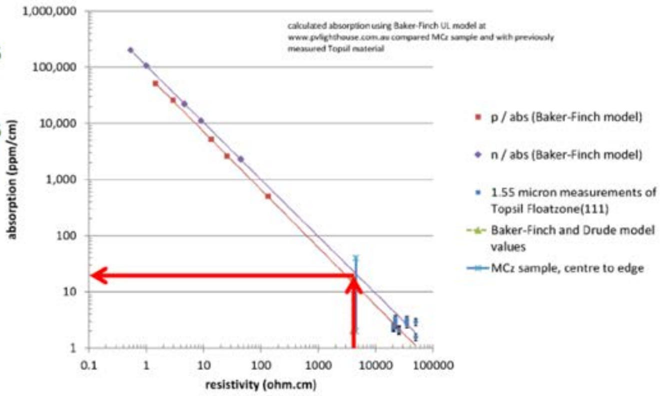


Image credit Softimpact

MCz – optical absorption

See next talk from Ashot Markosyan

- Manufacturers say resistivity is 4 kΩcm
- At 1550 nm this should be ~ 20 ppm/cm
- Just about good enough
- Actually, most of it is much better



Slides: A.Bell, LIGO-G1601711

Lasers

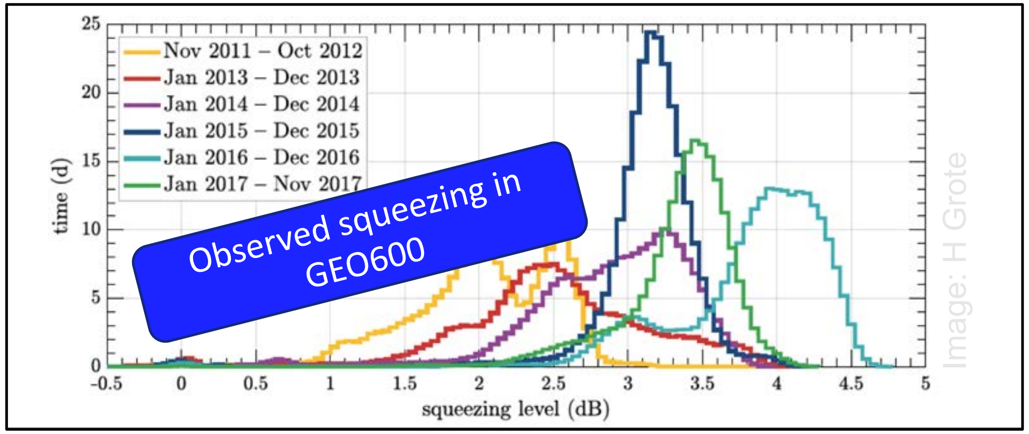
	Adelaide	AEI / LZH	ANU	Artemis	Caltech	EGO	Glasgow	Hamburg	IIT Madras	MIT	Nikhef
high power lasers at 1µm		x		x						x	
high power lasers at 1.5µm		x		x							
high power lasers at 2µm	x	x						x	x		
seed laser at 1.5µm and 2µm	x	x			x		x	x	x		
stabilization, high power FI		x		x		x	x				
high QE photodiodes at 1.5µm and 2µm			x		x		x	x			
squeezed light source at 1µm		x	x							x	x
squeezed light source at 1.5µm		x						x	x		
squeezed light source at 2µm			x					x	x		

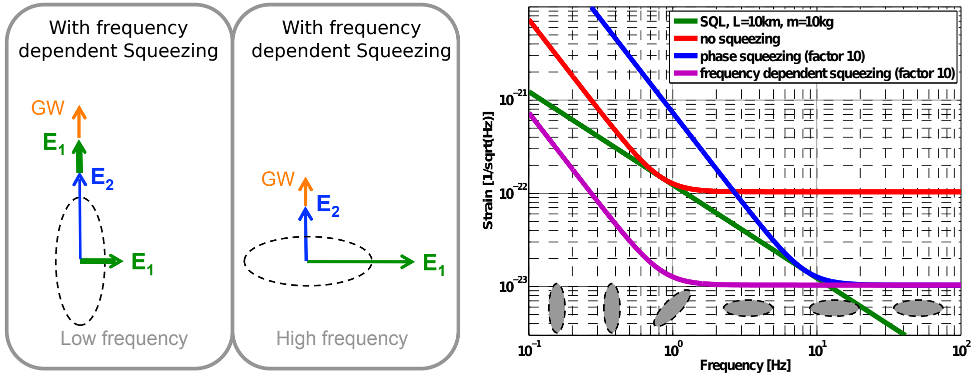
Credit: B. Willke

- 1064nm, TEM00 = 300W (LZH)
  - Theeg et al IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 24, NO. 20, OCTOBER 15, (2012)
- 1064nm, LG33 = 83W (Bham, AEI)
  - Carbone et al. PRL 110, 251101 (2013)
- 1550nm, TEM00 = 207W (non-GW)
  - Creeden et al. Fiber Lasers XIII: Technology, Systems, and Applications, edited by John Ballato, Proc. of SPIE Vol. 9728, 97282L (2016)

Configurations

- Baseline configuration is Dual-recycled FP-Michelson with frequency dependent squeezing.
- Lots of progress in squeezing generation (smaller footprint, different wavelength, etc)
- Long-term experience of squeezing in GEO600.
- FC experiments (MIT, TAMA)
- Experience will be gained from frequency depending squeezing in advanced detectors.



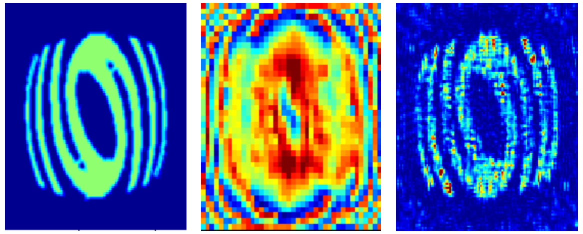


TCS for 3G at Tor Vergata

- Actuators
  - Quality of compensation relies on capability of producing the optimal heating pattern:
    - In the future there will be an increased need for non-symmetric heating patterns → laser based techniques: MEMS deformable mirrors under investigation.
    - Precise laser beam shaping requires good quality laser output beam. Wavelength choice dependent on TMs (CPs) substrate material. CO_2 might still be a good option for SiO_2 optics → ongoing activity to build a mode cleaner.
- Control strategy
  - Blending information from different sensors (HWS, Phase Cameras, ITF signals) to produce error signal;
  - Definition of actuation optics to decouple different DoFs (RoCs and lenses);
  - Dynamic control of mode matching on OMC.

Slide credit: Fafone/Rocci

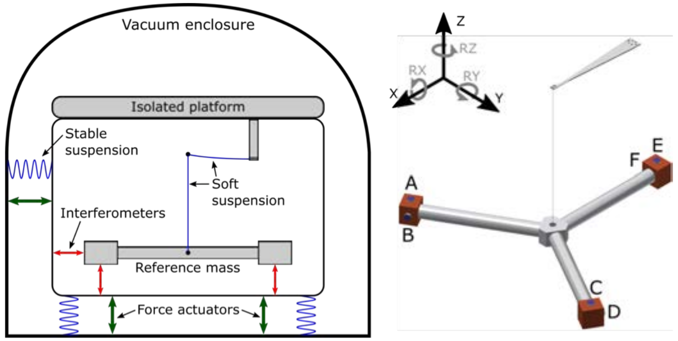
MEMS system under test at UTov

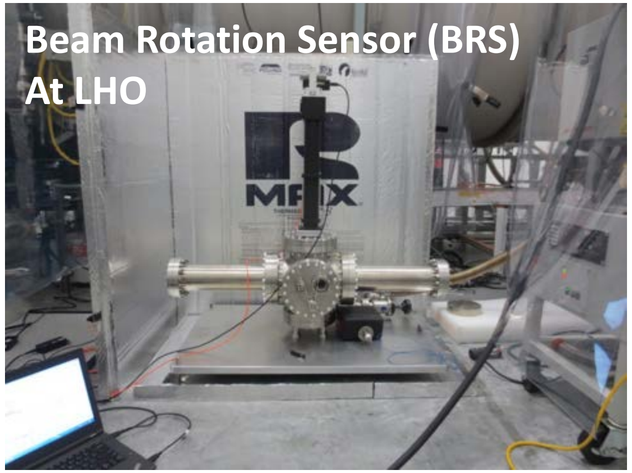


FFT simulation of the phase profile to be applied to a flat top beam to get the required pattern (AdV logo)
Simulation is obtained for flat incident intensity on an array of 40x40 micromirrors with 1 mm side

Technical Noises

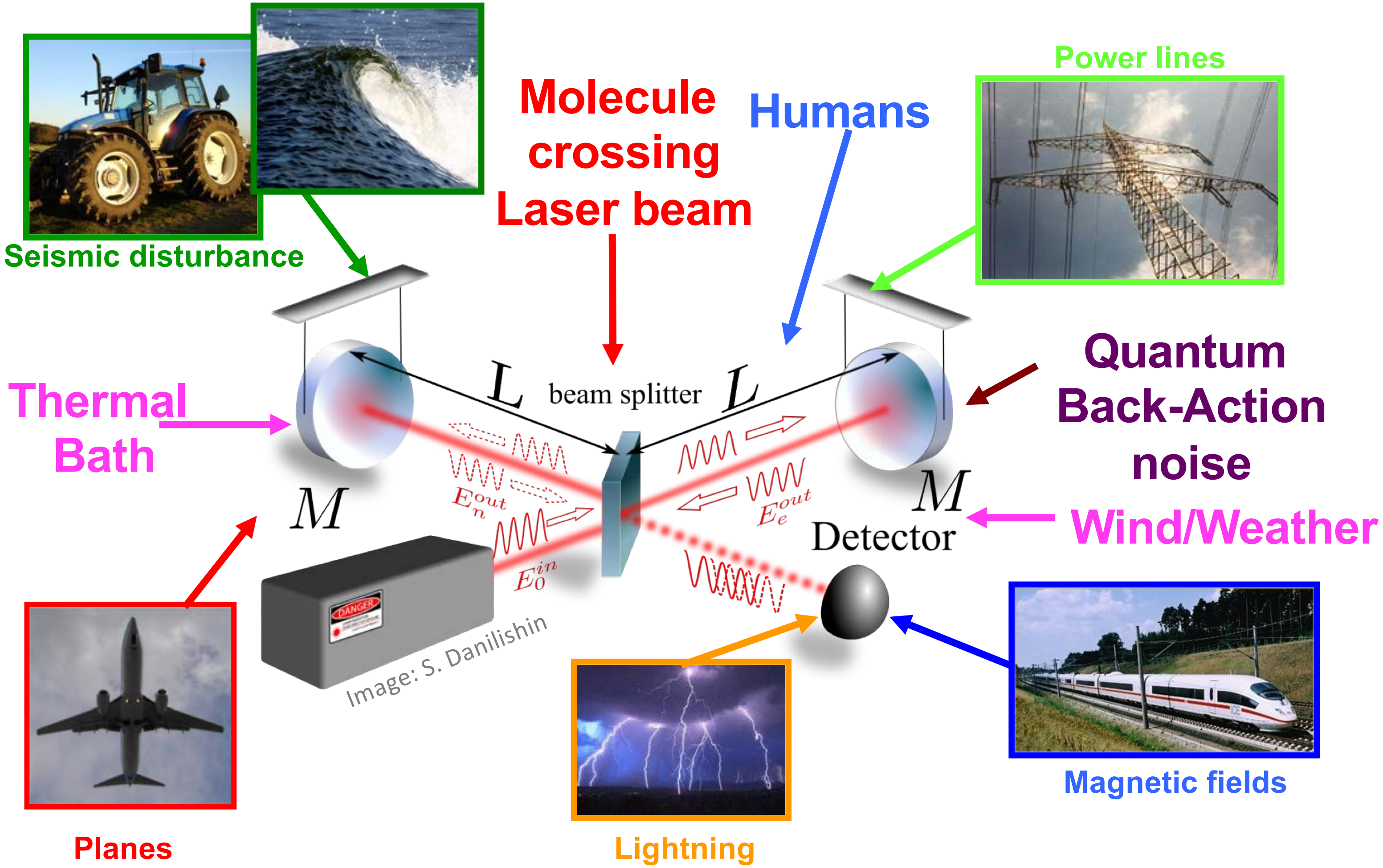
- Technical noise will need very significant effort. Especially as we push down in frequencies.
- Need to reduce fluctuations of mirrors (not only longitudinal degree of freedom).
- Lots of scattered light mitigation.
- Good examples of promising new sensors: Tilt sensors (K. Dooley), 6 DoF sensor (C. Mow-Lowry)

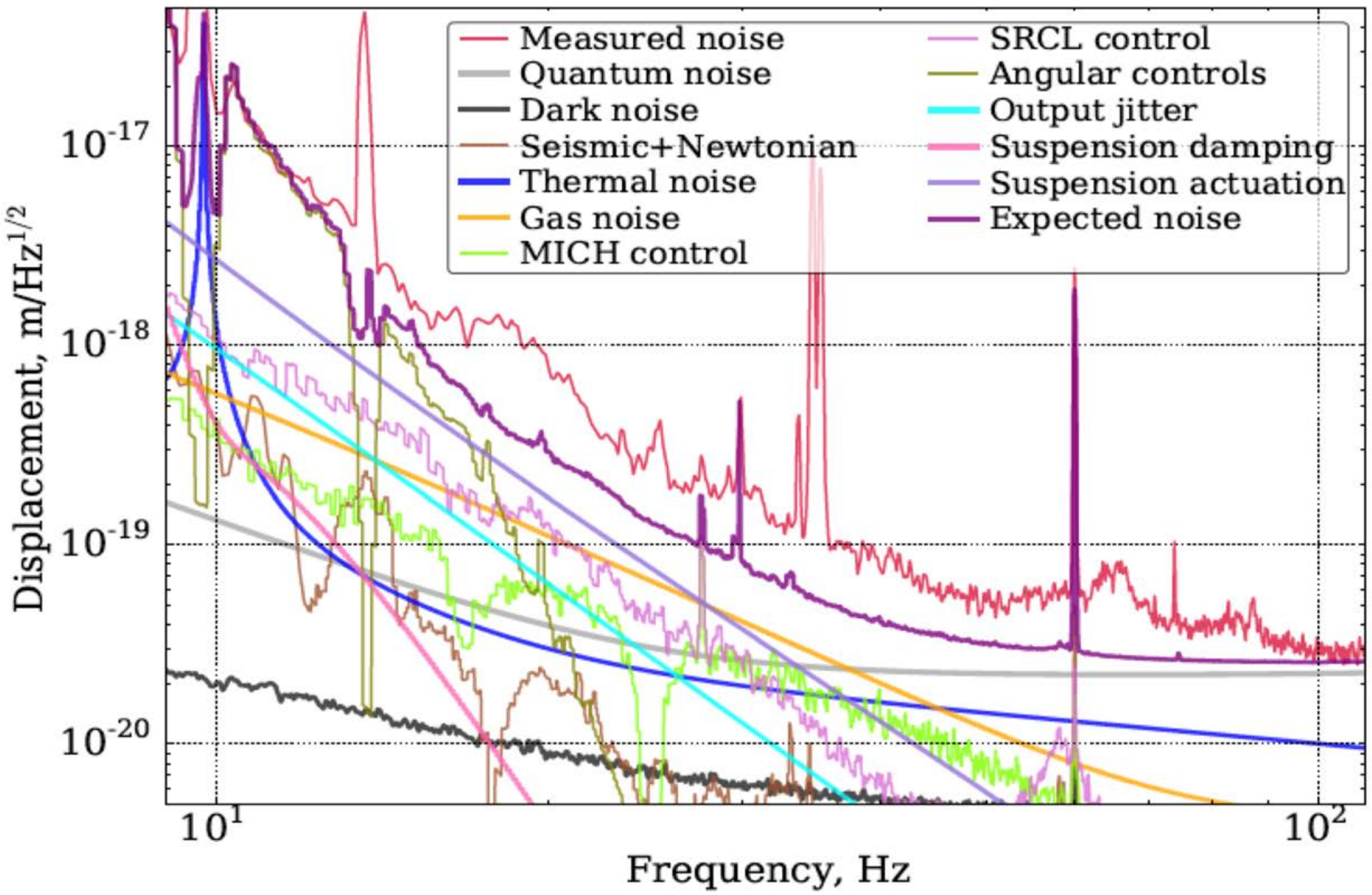




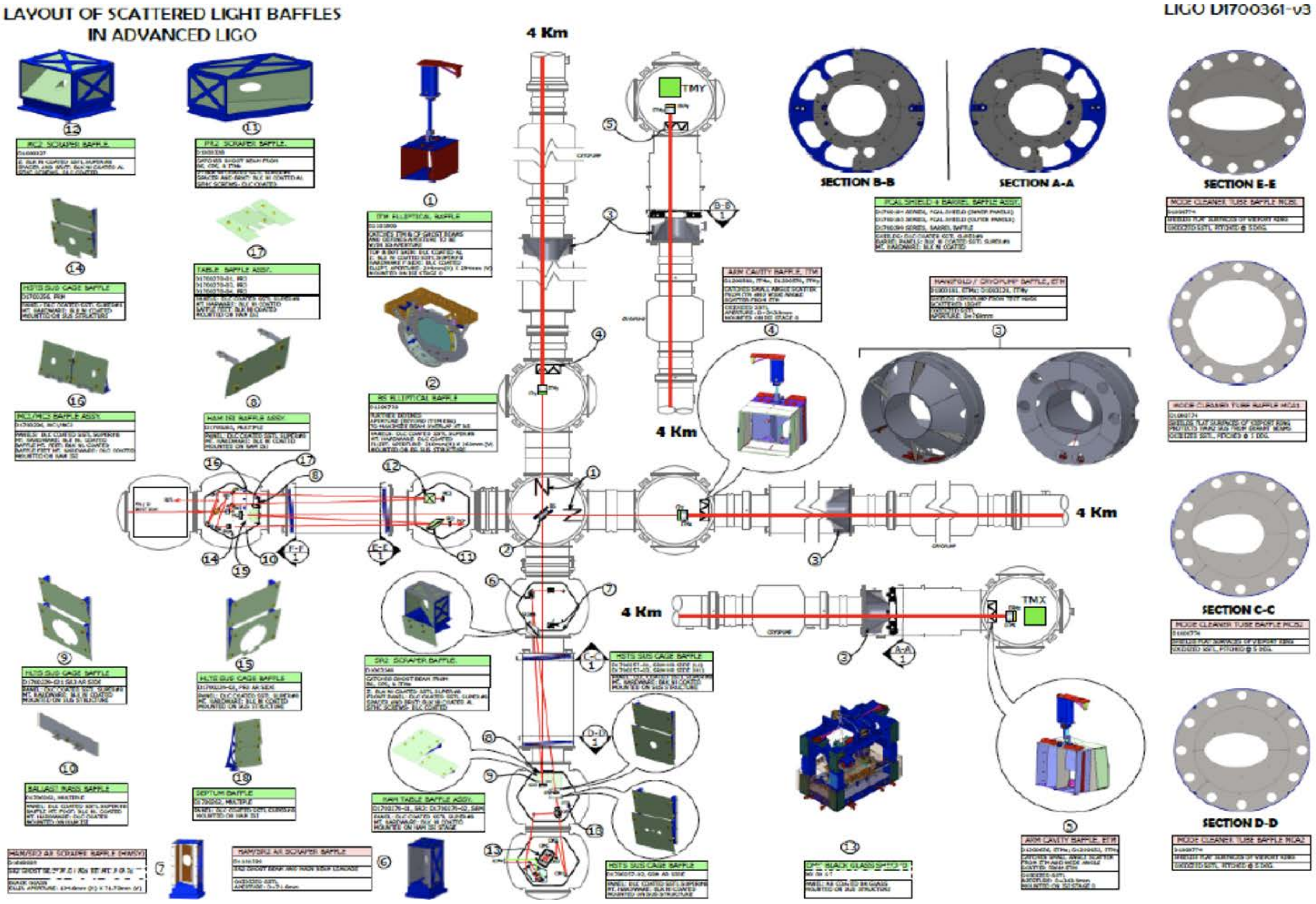
And now REALITY

Myriad of Disturbances





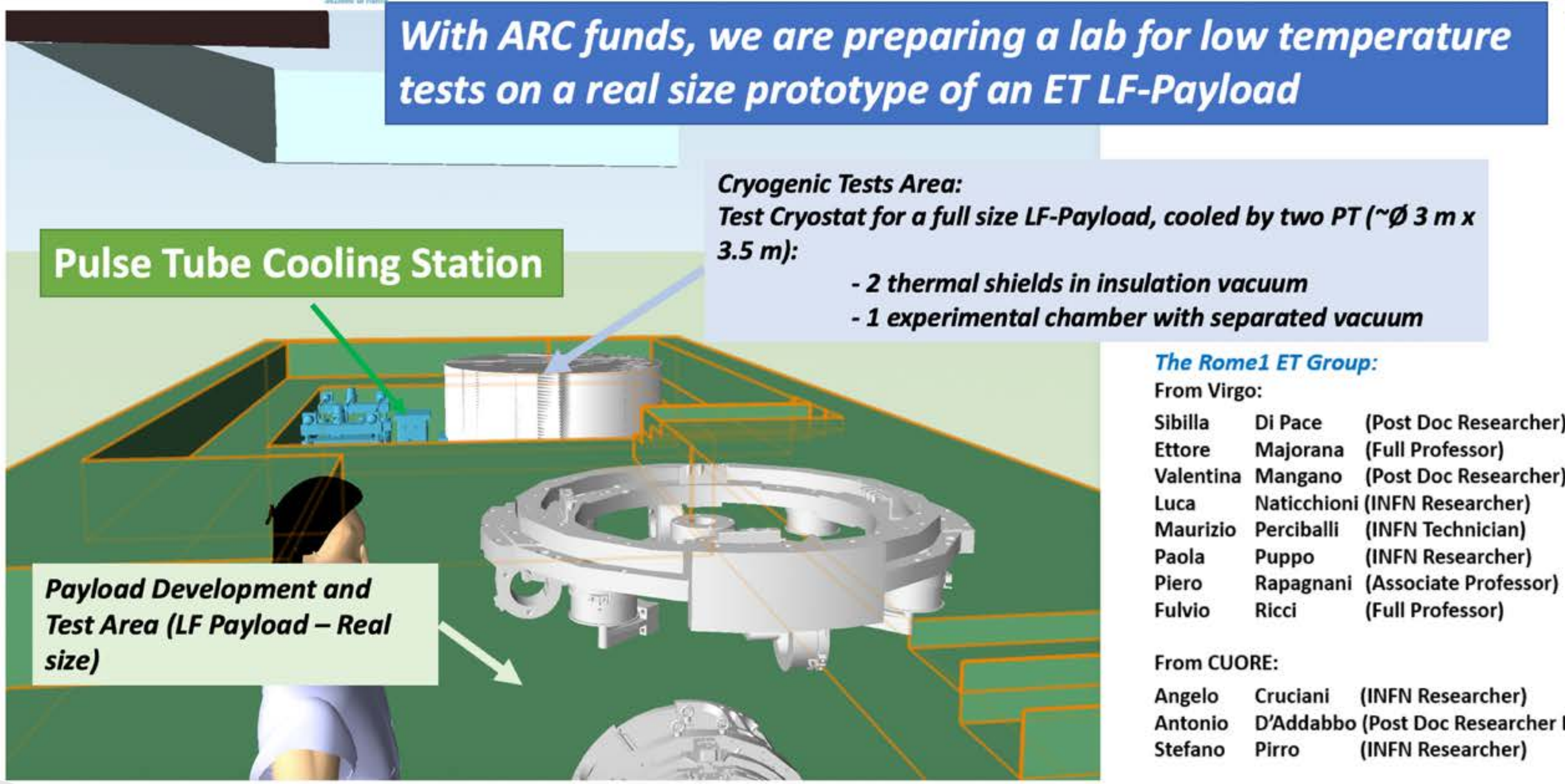
(a) LIGO Livingston Observatory


LAYOUT OF SCATTERED LIGHT BAFFLES
IN ADVANCED LIGO
LIGO D1700361-v3
4 Km
4 Km
4 Km
4 Km
TMY
TMX
SECTION B-B
SECTION A-A
SECTION E-E
SECTION C-C
SECTION D-D
PR2 SCRAPER BAFFLE
SR2 SCRAPER BAFFLE
ITM ELLIPTICAL BAFFLE
BS ELLIPTICAL BAFFLE
TABLE BAFFLE ASSY.
HSTS SUS CAGE BAFFLE
ARM CAVITY BAFFLE, ITM
ARM CAVITY BAFFLE, ETM
MANIFOLD / CRYOPUMP BAFFLE, ETM
MODE CLEANER TUBE BAFFLE MCA1
MODE CLEANER TUBE BAFFLE MCA2
MODE CLEANER TUBE BAFFLE MCB2
HLTS SUS CAGE BAFFLE
BALLAST MASS BAFFLE
SEPTUM BAFFLE
HAM TABLE BAFFLE ASSY.

Outline

- What have we learned from Gravitational Waves so far and why do we need ET?
- Overview of fundamental noises and technical challenges.
- Overview of some exmaples of ongoing R&D efforts
- Discussing some topics in more detail?

Amaldi Research Center for Cryogenics, Rome



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:

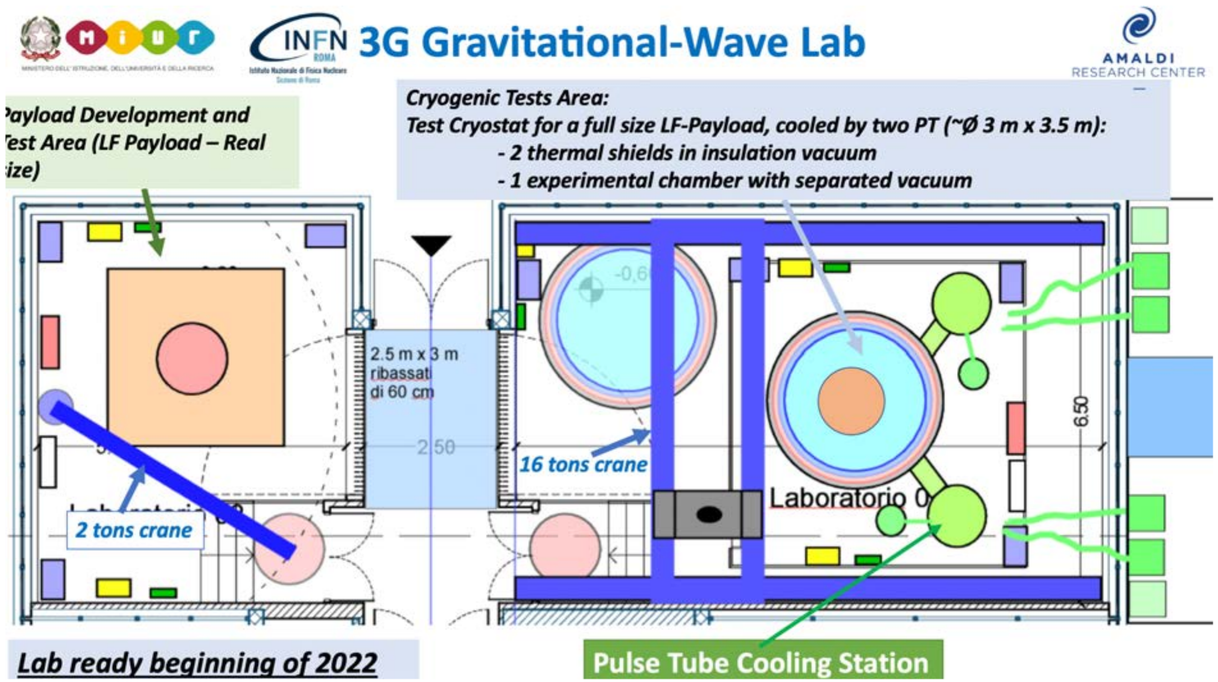
Angelo	Cruciani	(INFN Researcher)
Antonio	D'Addabbo	(Post Doc Researcher LNGS)
Stefano	Pirro	(INFN Researcher)

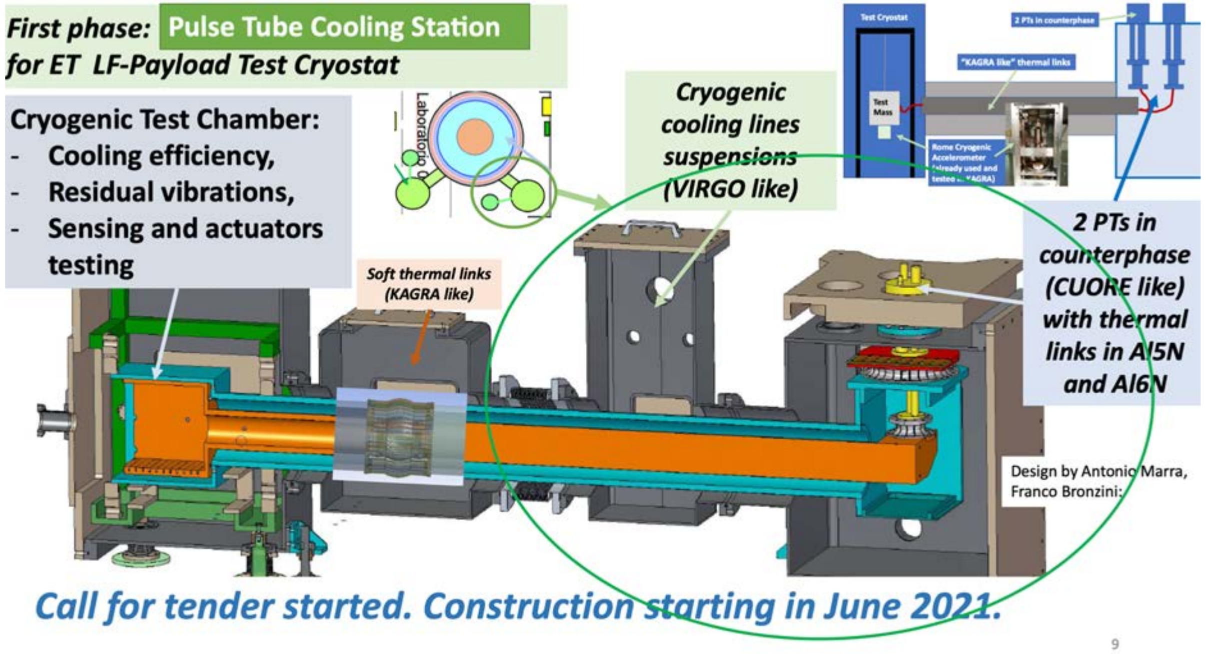
From EGO:

Paolo Ruggi (EGO Researcher)

Global investment of 11Meuro

Amaldi Research Center for Cryogenics, Rome





SarGrav Overview

The SarGrav Laboratory

Founded with 3.5 M€ by the Regione Autonoma della Sardegna (RAS) to host low seismic noise underground experiments (low seismic noise experiments, cryogenic payloads, low frequency and cryogenic sensor development)

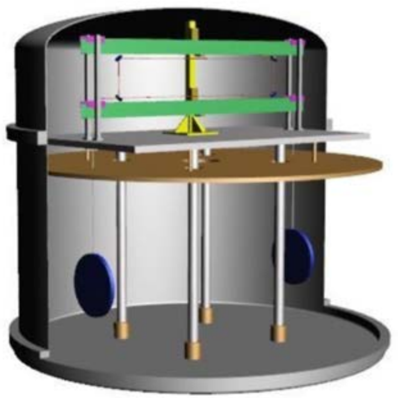
- ~ 900 m^2 surface Laboratory
- 3 Underground stations equipped for measurements at different depths
- ~ 50 m^2 underground area available
- planned a 250 m^2 underground Lab
- First experiment: Archimedes (founded by INFN)

The candidature of the ET site in Sardinia is supported with about 17M€ by the Italian ministry of research.

SarGrav Activities (I)

First Experiment: Archimedes

- Experimental Goal: measurement of the interaction between vacuum fluctuations with gravity weighting a Casimir multi-cavity while changing the reflectivity of its layers. A change in the reflectivity corresponds into a variation of the internal vacuum state energy.
- Apparatus: high sensitivity balance working in cryogenic conditions (~90 °K)

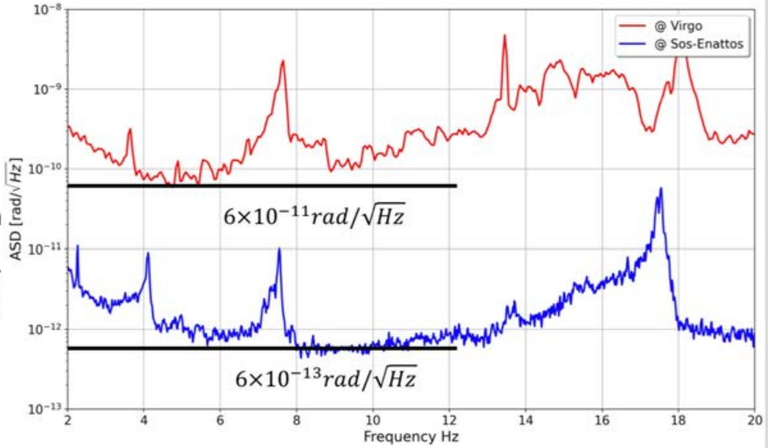


- High-T_c superconductors (i.e. YBCO) as natural Casimir multi-cavities;
- Measurements taken in HV (10^{-8} mbar) at criogenic temperature ($T = T_c \approx 90$ K);
- Reflectivity changed via thermal actuation;
- Flexible thin joints with low thermal noise;
- Two suspended arms to apply coherent noise subtraction;
- Interferometric read-out system;
- Feedback control;
- Low seismic noise site.

7

ARCHIMEDES for ET: the tiltmeter

- Quality check of the site with a fundamental physics experiment
- Direct tilt measurement from 2 Hz to 20 Hz (region of interest for ET): best sensitivity in the world for a tiltmeter in the region 2 Hz – 20 Hz (paper In preparation)
- At our knowledge Sos Enattos has shown the lowest tilt noise ever measured



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SarGrav Activities (II)

Site monitoring and characterization

See talk by **L. Naticchioni**
Session "Third Generation Infrastructures"

- Measurement stations
  - ✓ SarGrav surface Lab
  - ✓ SOE0 (surface)
  - ✓ SOE1, SOE2, SOE3 (-86 m, -111 m, -160 m)
- Sensors on site
  - ✓ 4 broadband triaxial seismometers;
  - ✓ 5 short-period triaxial seismometers (first *seed* of a new array);
  - ✓ 2 magnetometers (1 buried at surface, 1 underground);
  - ✓ High precision tiltmeter (Archimedes prototype)
  - ✓ Weather station
- New sensors expected to be installed in the next months (seismometers, geophones, microphones, magnetometers)
- Data acquired at the SarGrav control room, transmitted via UMTS link to remote server (INGV-PI server → ET repository), and accessible through an INFN access point.

Site Characterization and monitoring

- Long-term seismic and environmental monitoring
- First year of seismic characterization measurements at Sos Enattos published
  - ✓ **JPCS** 1468, 2020 https://doi:10.1088/1742-6596/1468/1/012242
https://doi:10.1088/1742-6596/1468/1/012242
  - ✓ **SRL** 2020, https://doi.org/10.1785/0220200186,
  - ✓ **EPJP** 2021, https://doi.org/10.1140/epjp/s13360-021-01450-8
- In the 1-10Hz is among the quietest sites in the world
- Very low environmental noise

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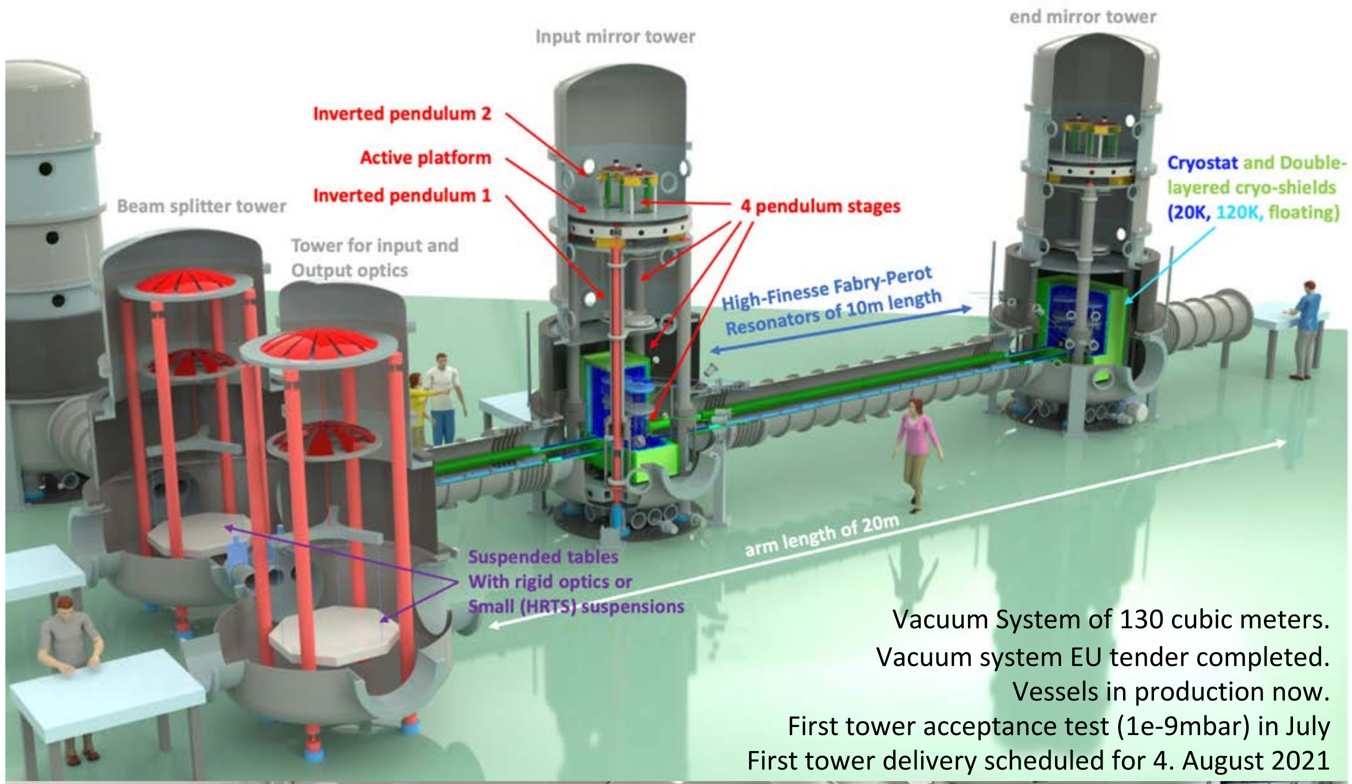
ETpathfinder Overview

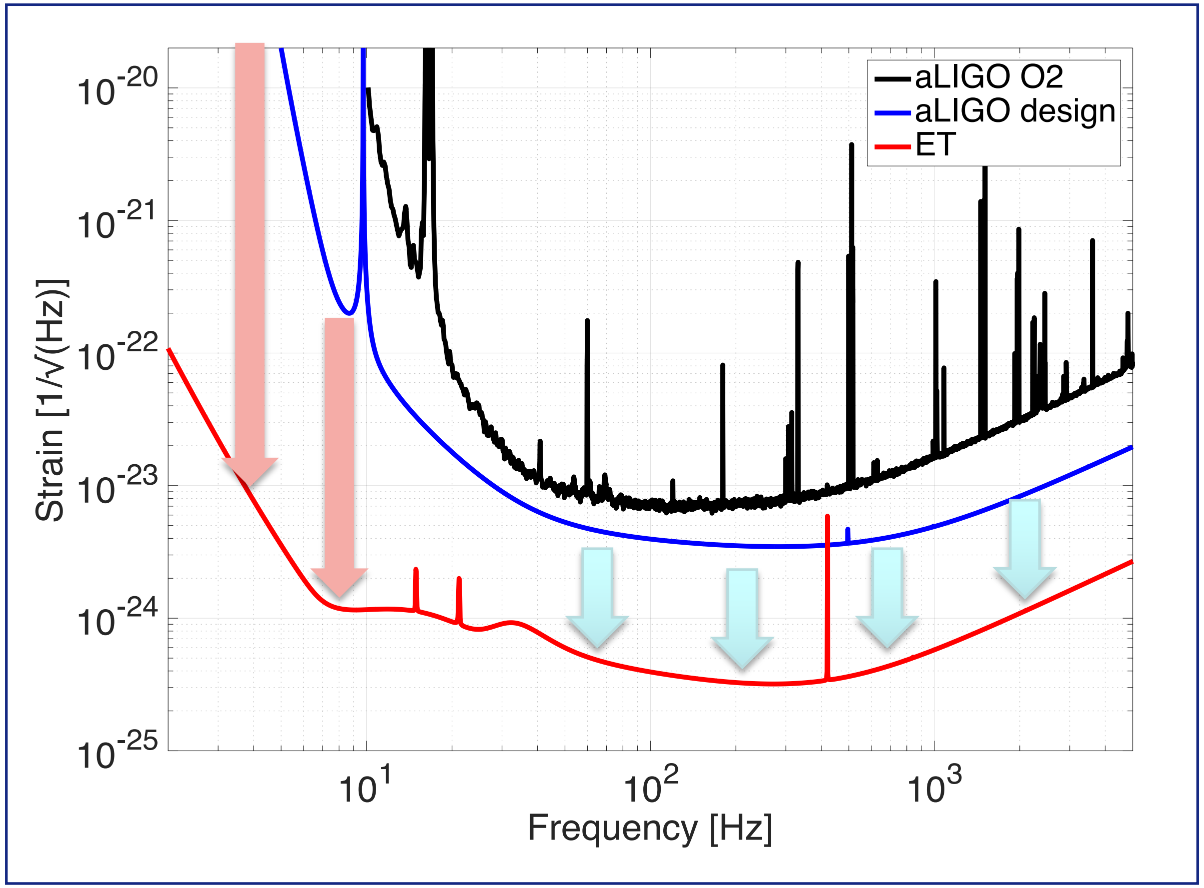
- New facility for testing ET technology in a low-noise, full-interferometer setup.
- Key aspects: Silicon mirrors (3 to 100+kg), cryogenics cryogenic liquids and sorption coolers, water/ice management), “new” wavelengths (1550 and 2090nm), coatings
- Start with 2 FPMI, one initially at 120K and one 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.
- www.etpathfinder.eu



Why ETpathfinder needed?

The Low-Frequency Challenge:

- At mid and high frequency we aim for factor ~10 improvement.
- At low frequency we are aiming for factors 100, 1000 and more improvement.
- **Needs fundamental changes in technology and concepts, that need testing and prototyping.**



New Technologies

ET requires technological advances on all fronts:

- New mirror material => Silicon
- New temperature => 10-20K
- New laser wavelength => 1.5-2.1 microns
- Advanced quantum-noise-reduction schemes

From ETpathfinder Advisory Board (STAC) report

- […] Overall, the ETPF-STAC was very impressed with the vision for the facility, the technical capability of the leader and team, and the scope of the effort. It will be transformative for the field to have a facility and a research program covering the foreseen capabilities of the installation, and it can become a very natural center for technical innovation and scientific breakthroughs in precision measurement, interferometry, cryogeny for gravitational-wave detectors, and for the formation of a next generation of gravitational-wave scientists (to handle the next generation of gravitational-wave detectors). The growth of the team (and of the institutions interested in participating) is an exciting development and speaks to the timeliness and centrality of this infrastructure. […]
- The ETPF-STAC is very excited to be part of the establishment and exploitation of this unique facility and this dynamic team.


Start Construction: April 2020


Drilling 170 pillars

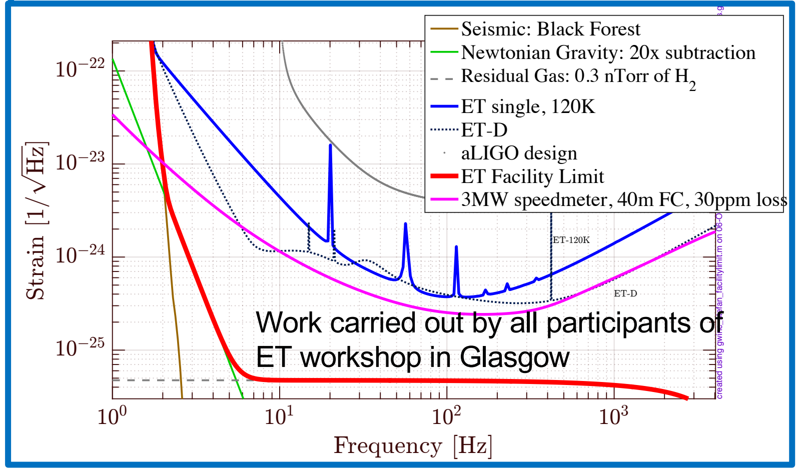

July: ~1000 t of concrete poured

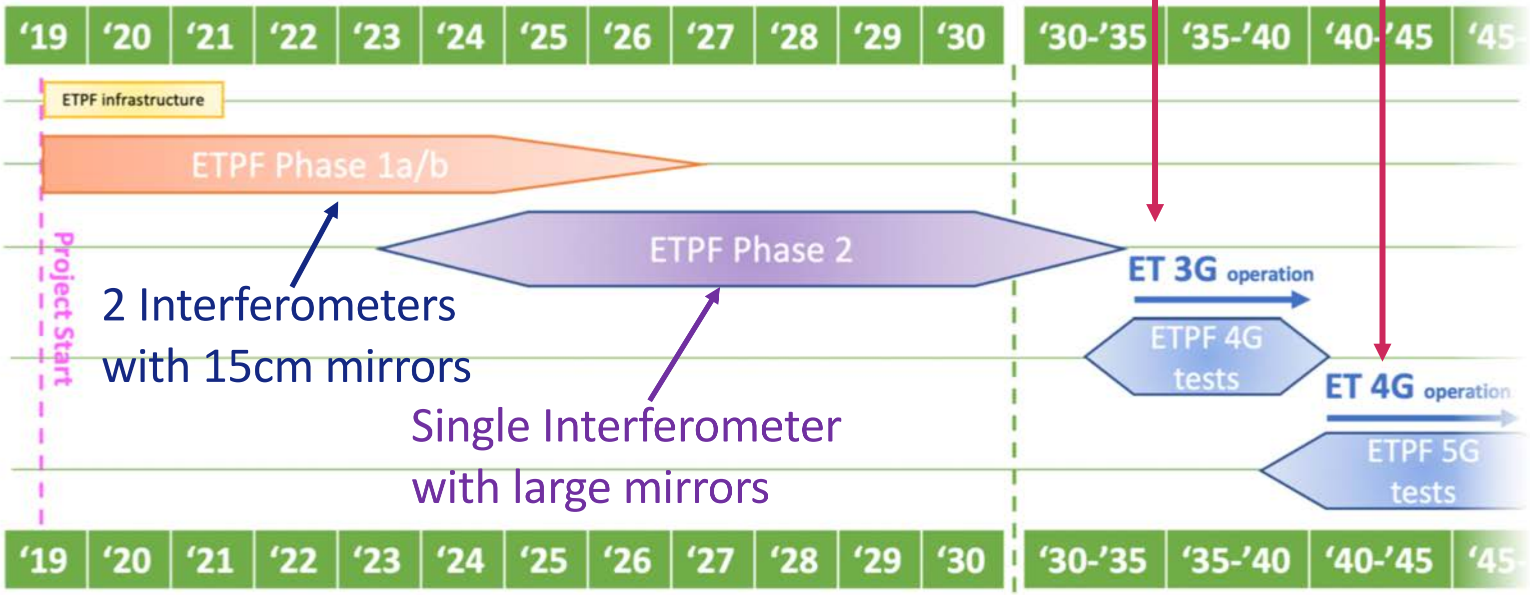

Oct : First cleanroom walls being installed.

Cleanroom in operation ~ March 2021

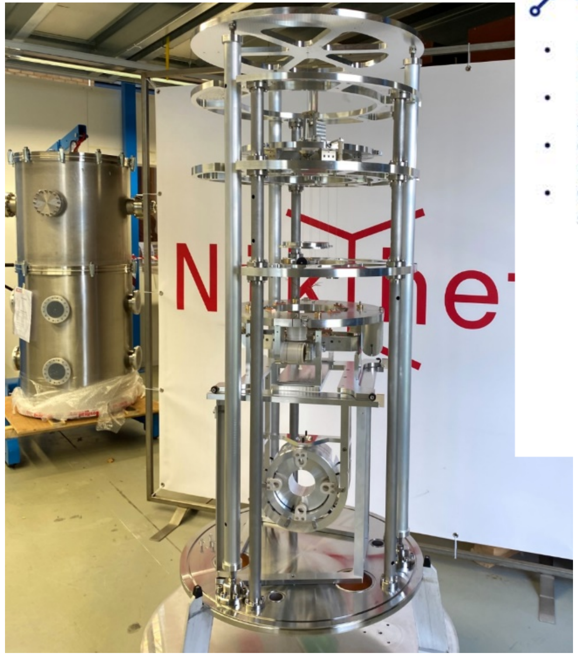
ETpathfinder is a longterm acitivity (and independ of ET site decision)

- ESFRI application states ET will be operational from 2035 to 2085.
- Expect many ET detector upgrades over the 50 years.
- While ET operates and observes in “generation X technology” ETpathfinder can do R&D for “generation X+1 technology”



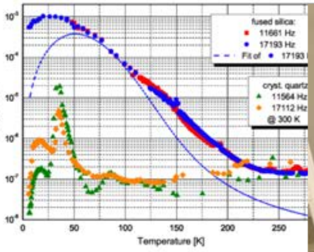


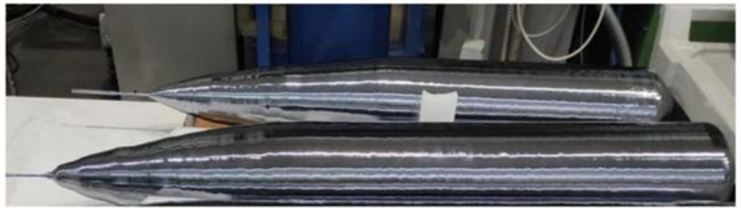
Some Highlights of recent ETpathfinder Activities

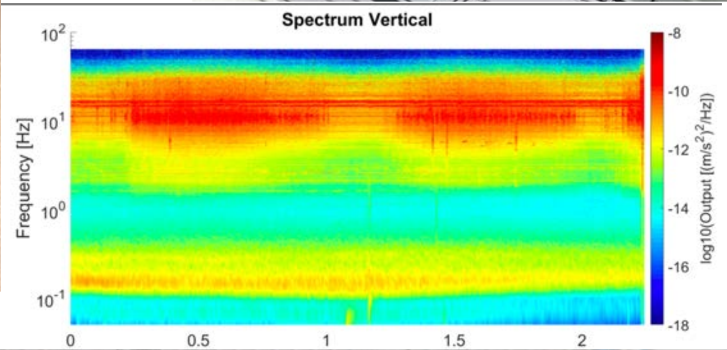


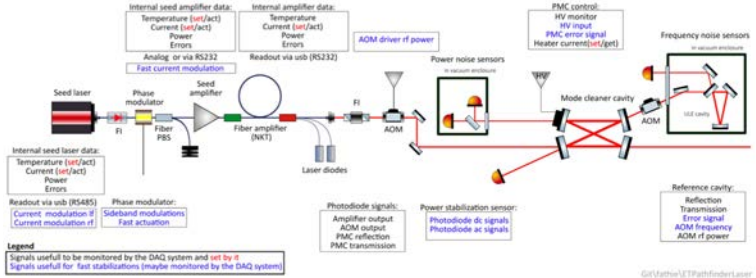
Silicon Optics

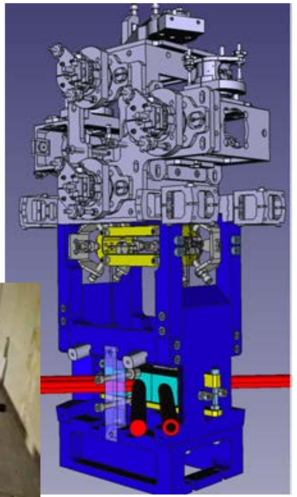
- Fused silica has high mechanical loss at low temperatures, need to move to crystalline materials: silicon
- Need high-purity (high resistivity) silicon to keep optical absorption as low as possible
- Obtained Silicon ingots of moderate resistivity (> 1kOhm cm)
- Currently being cut into more manageable pieces before shipping to Maastricht

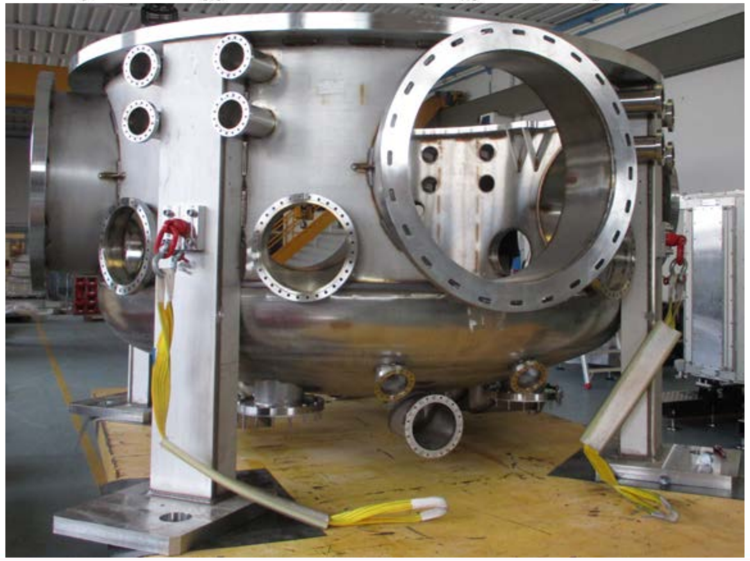


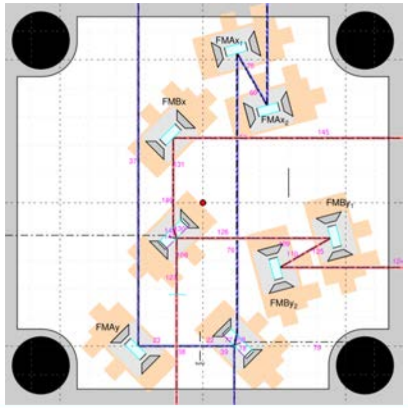




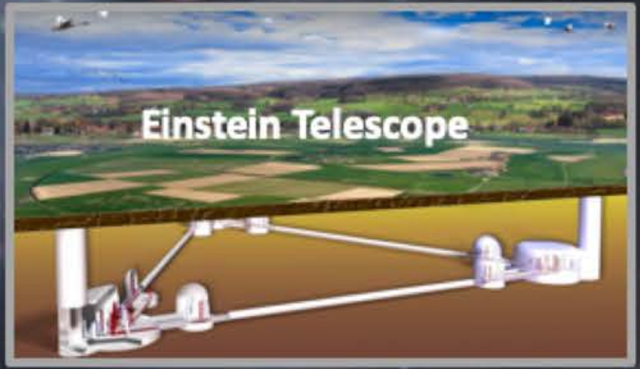








Actually, really exciting times ahead on all gravitational wave fronts!



+ LIGO India

+ Pulsar Timing Array

+ many other future projects

Outline

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Thank you for your attention.

Questions?