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Science & Technology Facilities Council

Concepts for Third Generation Gravitational Wave Observatories

Stefan Hild

LISA Symposium, Stanford, June 2010

ET EINSTEIN TELESCOPE

LSC

LIGO-G1000659-v1

We have come a long way …

- The first Michelson interferometer: Experiment performed by Albert Michelson in Potsdam 1881.
- Measurement accuracy 0.02 fringe (expected Ether effect ~0.04 fringes)

… to today's network of GW detectors

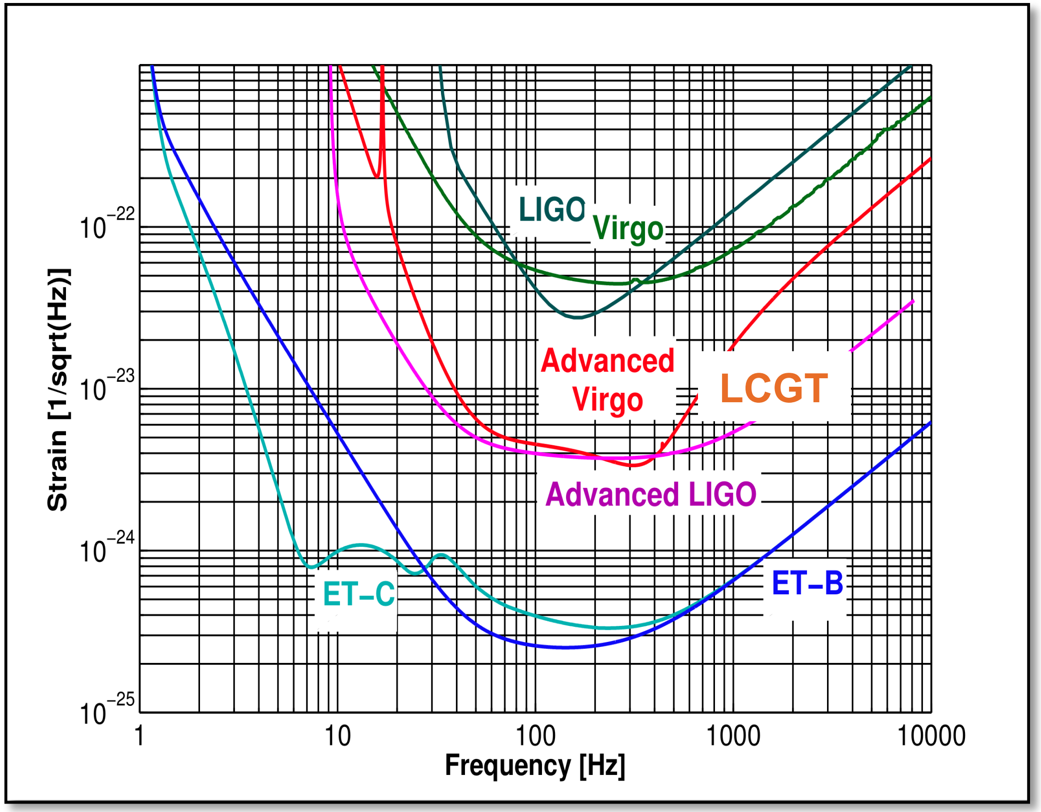
Today:

- Virgo, LIGO, GEO600 and Tama
- Sensitivity: 10^{-13} of a fringe

GEO600: measures the 600m long arms to an accuracy of 0.0001 proton diameter @ 500 Hz

Status and future of GW observatories

- **1st** generation successfully completed:
  - Long duration observations (~1yr) in coincidence mode of 5 oberservatories.
  - Spin-down upper limit of the Crab-Pulsar beaten!
- **2nd** generation on the way:
  - End of design phase, construction about to start (or even started)
  - 10 times better sensitivity than 1st generation. => Scanning 1000 times larger volume of the Universe
- **3rd** generation at the horizon:
  - FP7 funded design study in Europe
  - 100 times better sensitivity than 1st generation. => Scanning 1000000 times larger volume of the Universe



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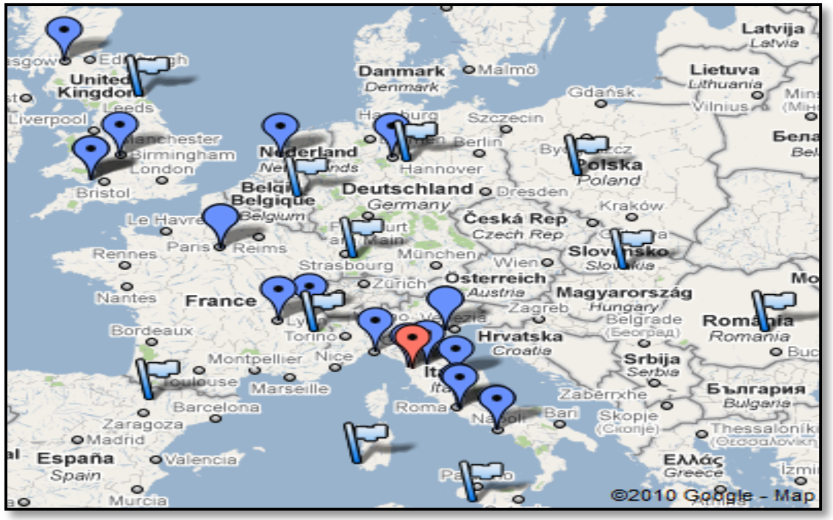
ET Design Study

- The Einstein Telescope project aims to the realization of a third generation of GW observatory.
- The Einstein Telescope project is currently in its conceptual design study phase, supported by the European Community FP7 with about 3M€ from May 2008 to July 2011.
- The target of this design phase is to understand the feasibility of a new generation of GW observatory that will permit to gain one order of sensibility
- The main deliverable, at the end of these 3 years, will be a conceptual design of such as infrastructure



Participant	Country
EGO	Italy/France
INFN	Italy
MPG	Germany
CNRS	France
University of Birmingham	UK
University of Glasgow	UK
Nikhef	NL
Cardiff University	UK

Overview of this presentation

- Some Warnings first …
- Where is the transition from 2nd to 3rd Generation?
- The Brute Force approach to achieve the 3rd Generation target sensitivity.
- Can we do it a bit more realistic? – The xylophone approach.
- A Zoo of even more fancy ideas

2G → 2.5G → 3G

Warnings

- Though much of the work and results shown on in these slides originate from the context of the Einstein Telescope (ET) design study, some of the views are my own and not vetted by the design study team.

- Due to lack of time I will not be able to give a comprehensive picture of the 3rd generation activities, but only a **subjective selection**.

- Also, I will **entirely concentrate on technologies** for 3rd generation GWD. For detailed information on the astrophysical motivation and benefits of 3rd generation detectors please have a look at for example:
  - Punturo et al: The third generation of gravitational wave observatories and their science reach, doi: 10.1088/0264-9381/27/8/084007
  - Einstein Telescope design study: Vision Document
    https://pub3.ego-gw.it/itf/tds/file.php?callFile=ET-031-09.pdf
  - Sathyprakash et al: Cosmography with the Einstein Telescope
    http://arxiv.org/abs/0906.4151

Astrophysics with 3rd generation

- Unveiling progenitors of short-hard GRBs
  - Short-hard GRBs are believed to be triggered by merging NS-NS and NS-BH
- Understanding Supernovae
  - Astrophysics of gravitational collapse and accompanying supernova?
- Evolutionary paths of compact binaries
  - Evolution of compact binaries involves complex astrophysics
    - Initial mass function, stellar winds, kicks from supernova, common envelope phase
- Finding why pulsars glitch and magnetars flare
  - What causes sudden excursions in pulsar spin frequencies and what is behind ultra high-energy transients of EM radiation in magnetars
    - Could reveal the composition and structure of neutron star cores
- Ellipticity of neutron stars
  - Mountains of what size can be supported on neutron stars?
- NS spin frequencies in LMXBs
  - Why are spin frequencies of neutron stars in low-mass X-ray binaries bounded
- Onset/evolution of relativistic instabilities
  - CFS instability and r-modes

Credits: Sathyaprakash + ET Science Team

Cosmology with 3rd Generation

- Cosmography
  - Hubble parameter, dark matter and dark energy densities, dark energy EoS w, variation of w with z
- Black hole seeds
  - Black hole seeds could be intermediate mass BH
  - Hierarchical growth of central engines of BH
- Dipole anisotropy in the Hubble parameter
  - The Hubble parameter will be "slightly" different in different directions due to the local flow of the Milkyway
- Anisotropic cosmologies
  - In an anisotropic Universe the distribution of H on the sky should show residual quadrupole and higher-order anisotropies
- Primordial gravitational waves
  - Quantum fluctuations in the early Universe could produce a stochastic b/g
- Production of GW during early Universe phase transitions
  - Phase transitions, pre-heating, re-heating, etc., could produce detectable stochastic GW

Credits: Sathyaprakash + ET Science Team

Fundamental Physics with 3rd generation

- Properties of gravitational waves
  - Testing GR beyond the quadrupole formula
    - Binary pulsars consistent with quadrupole formula but they cannot measure the properties of GW
  - How many polarizations?
    - In Einstein's theory only two polarizations; a scalar-tensor theory could have six
  - Do gravitational waves travel at the speed of light?
    - There are strong motivations from string theory to consider massive gravitons
- EoS of dark energy
  - GW from inspiralling binaries are standard sirens
- EoS of supra-nuclear matter
  - Signature of EoS in GW emitted when neutron stars merge
- Black hole no-hair theorem and cosmic censorship
  - Are BH (candidates) of nature BH of general relativity?
- Merger dynamics of spinning black hole binaries

Credits: Sathyaprakash + ET Science Team

Warnings continued

- Throughout this presentation **I will only talk about the so-called fundamental noise sources.**
- **This is only 10% of the full story!**
- Designs are driven at least partly also by technical noise sources.
- Actually most of our battle towards the 2nd and 3rd Generation will dominated by fighting and solving myriads technical problems such as:
  - Thermal distortions
  - Laser frequency and amplitude noise
  - Imperfect optics
  - Up-conversion
  - Scattered light noise
  - Mystery noise
  - Non-Gaussian behavior ….
  - Parametric instability
  - Beam jitter
  - Cooling of high power optics
  - Non-degenerate recycling cavities
  - …
  - and so on and on
  - …

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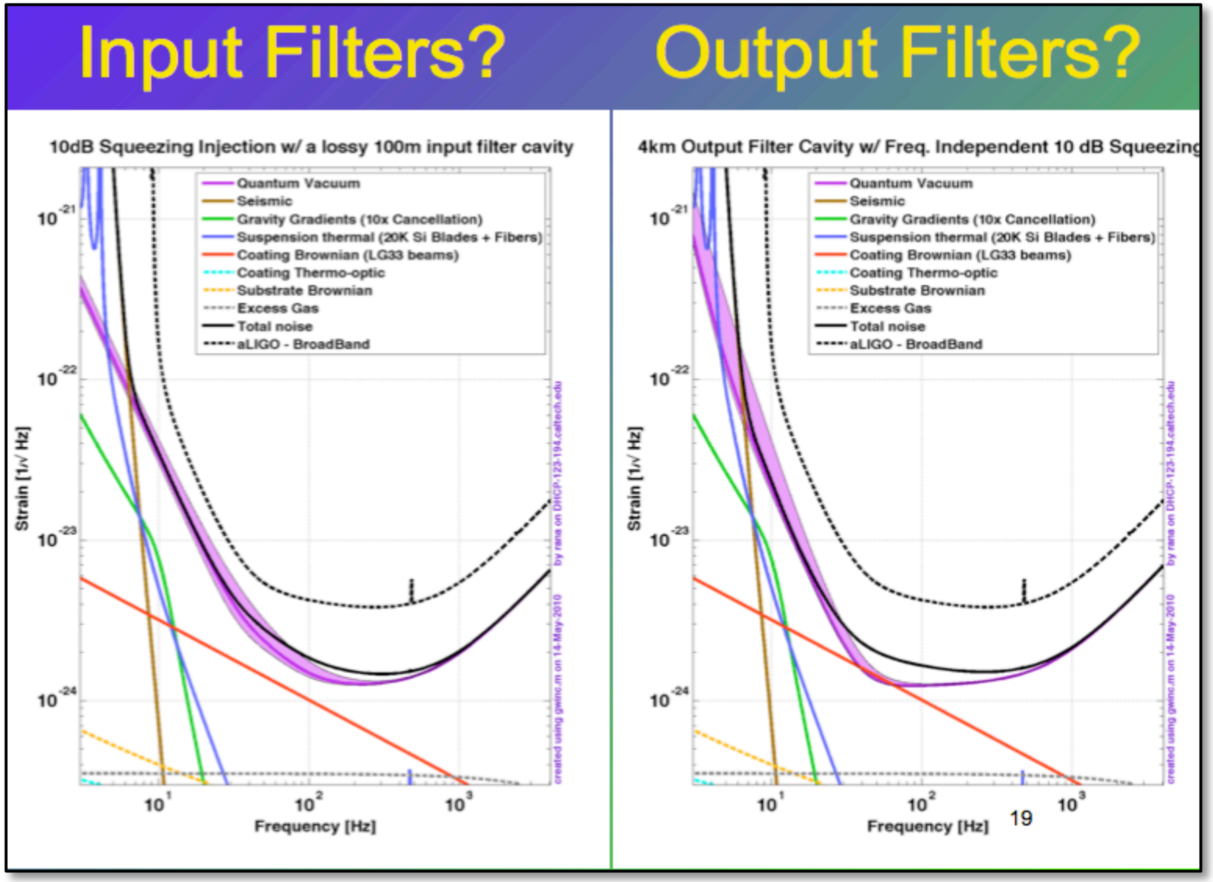
Enhancements of the Advanced Detectors

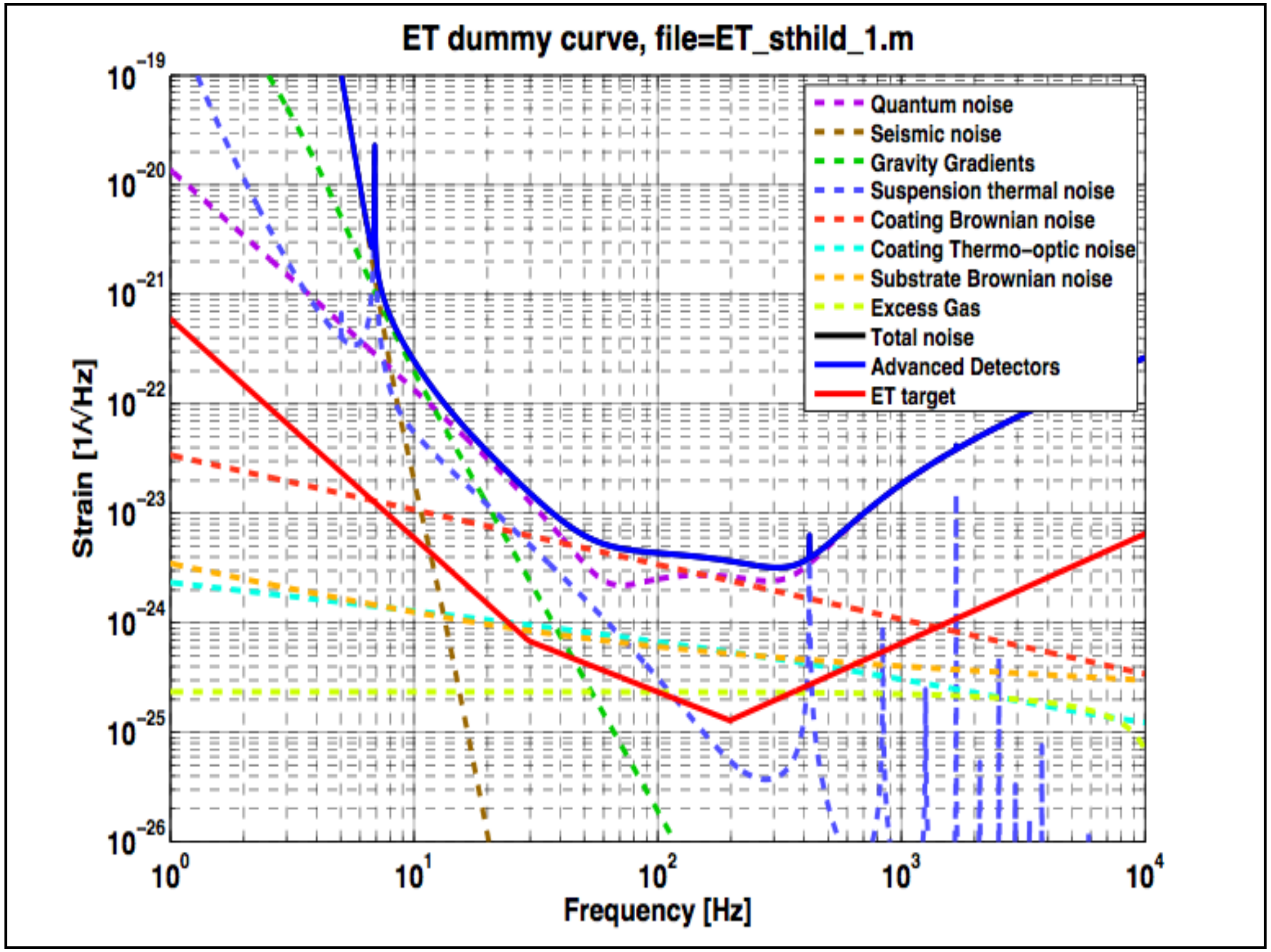
- People started to look into enhancements of the Advanced Detectors
  (see for example R. Adhikari's talk at GWADW 2010).

- Especially at high frequencies (and also in the mid-frequency range) improvements by a factor of a few seem potentially achievable.



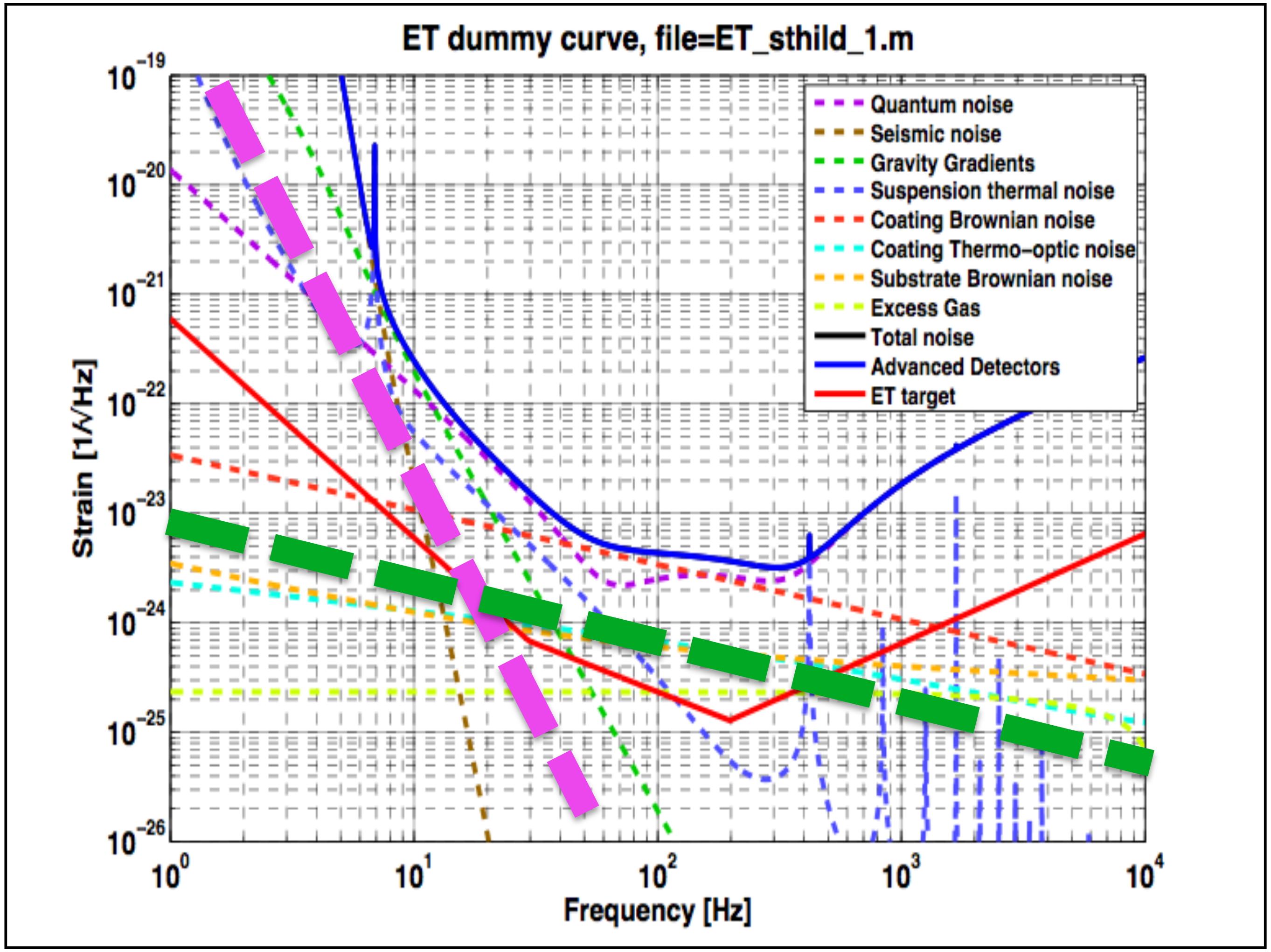
R.Adhikari: LIGO G100 0524

Facility limits of Advanced Detectors



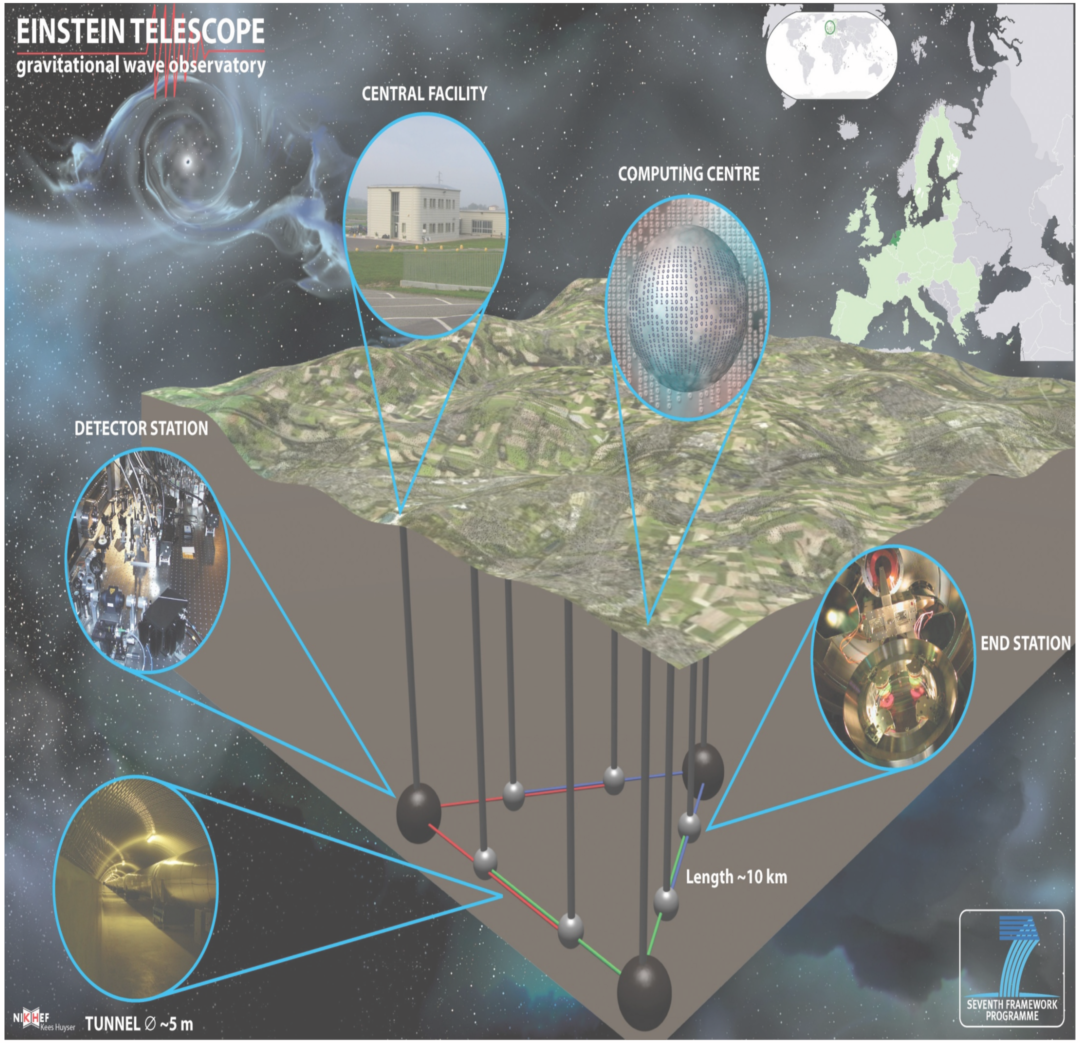
Facility limits of Advanced Detectors

- However, using currently available technology we will hit the facility limits.
- At all frequencies:
  - Arm length
- At **low** frequencies:
  - Gravity Gradient Noise.
  - Perhaps also Seismic
- At **mid** frequencies:
  - Thermal noise



3rd generation

- To surpass the facility limits of the 2nd generation instruments, **3rd Generation 'lives' in new infrastructures**
- 3rd generation GW detectors will be observatories that stay **'on air' for decades**.
- 3rd generation detectors and LISA are complementary, NOT competing.



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The starting point: 2nd Generation

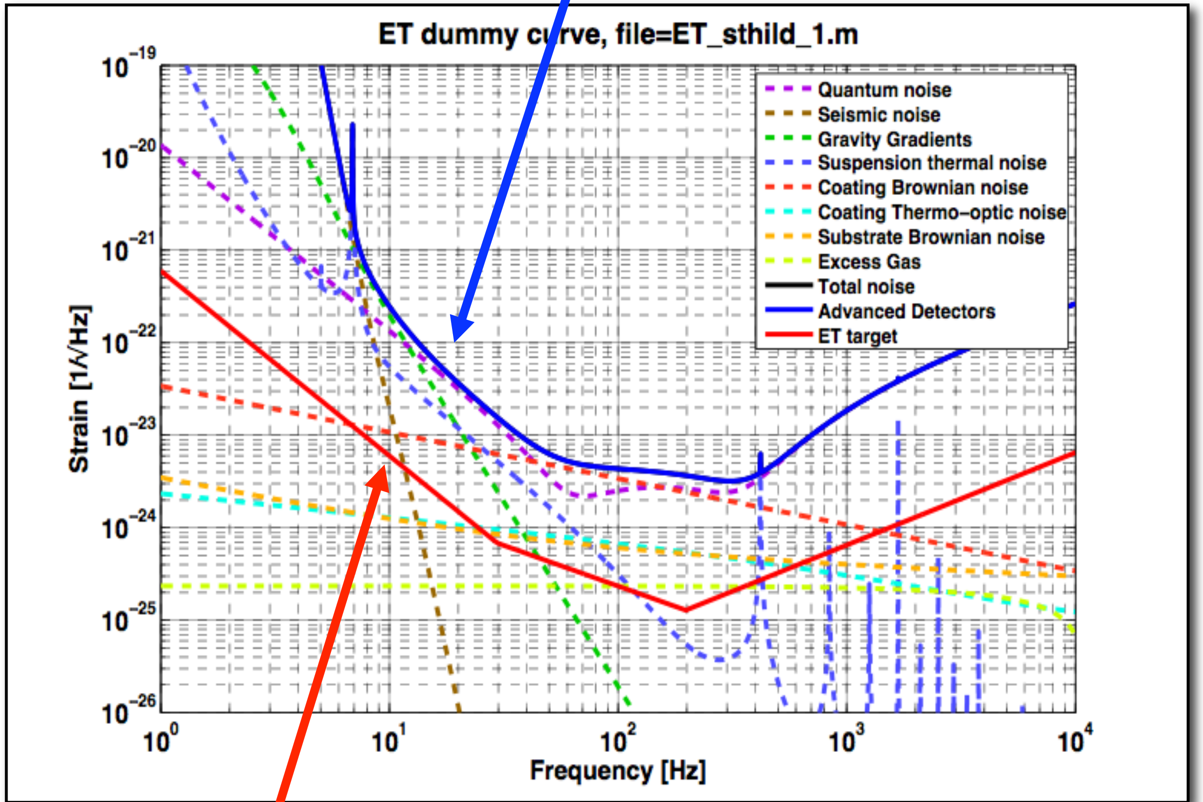
- We consider:
  - Michelson topology with dual recycling.
  - One detector covering the full frequency band
  - A single detector (no network)

- Start from a 2nd Generation instrument.

- Each fundamental noise at least for some frequencies above the ET target.

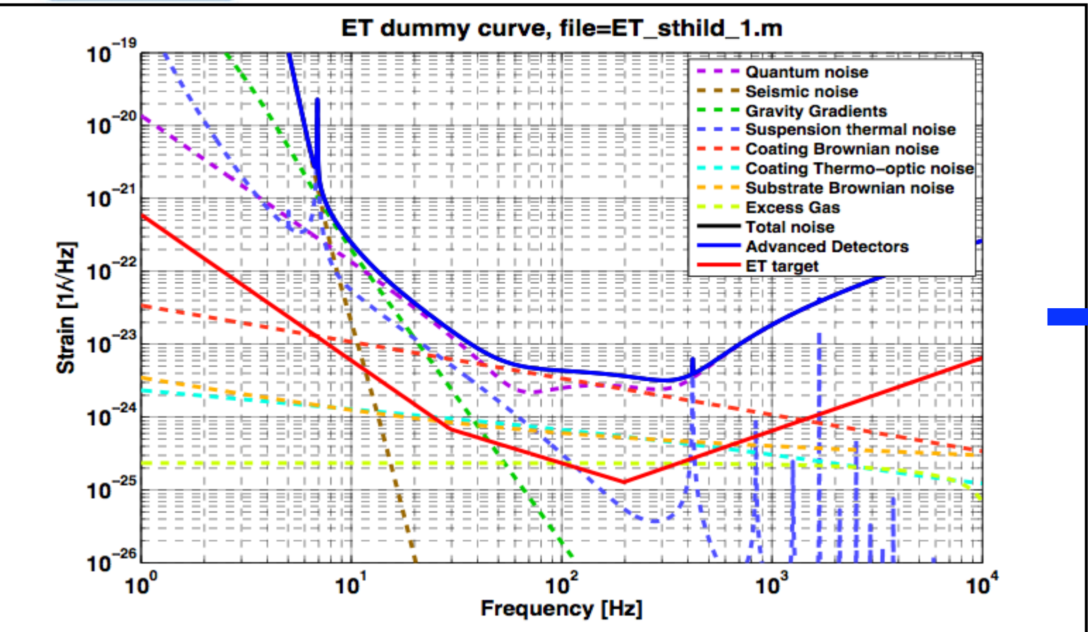
=> OUR TASK:
All fundamental noises have to be improved !!

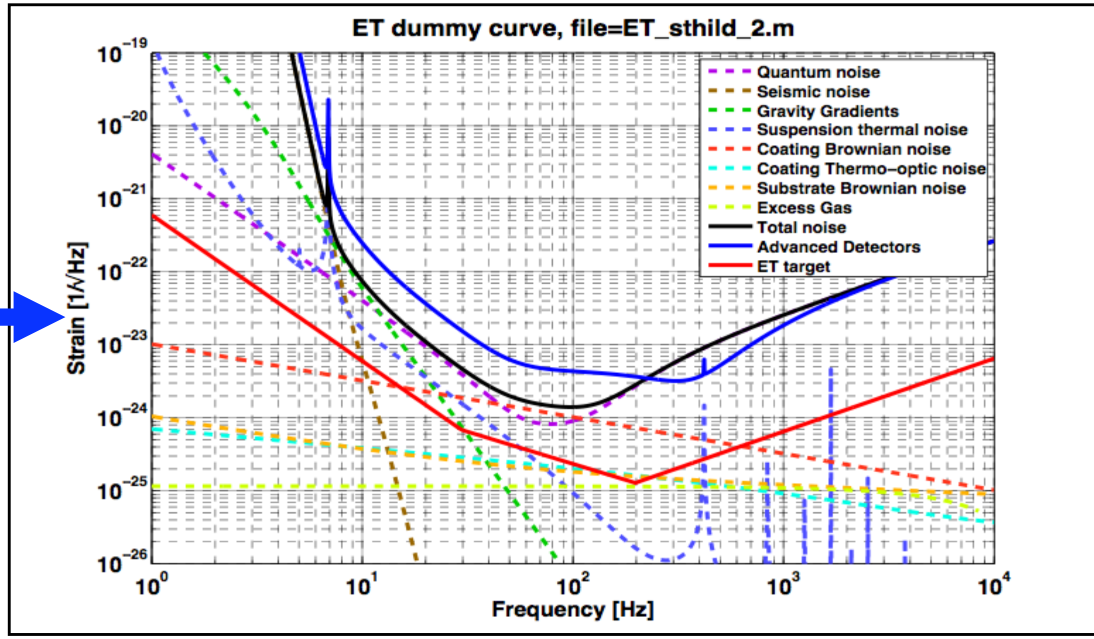
2nd Generation design sensitivity



3G target sensitivity (approximated)

Step 1: Increasing the arm length



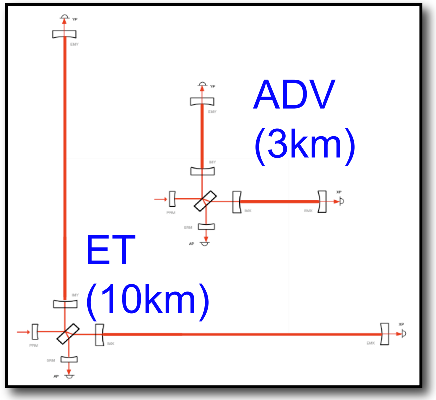


DRIVER: All displacement noises

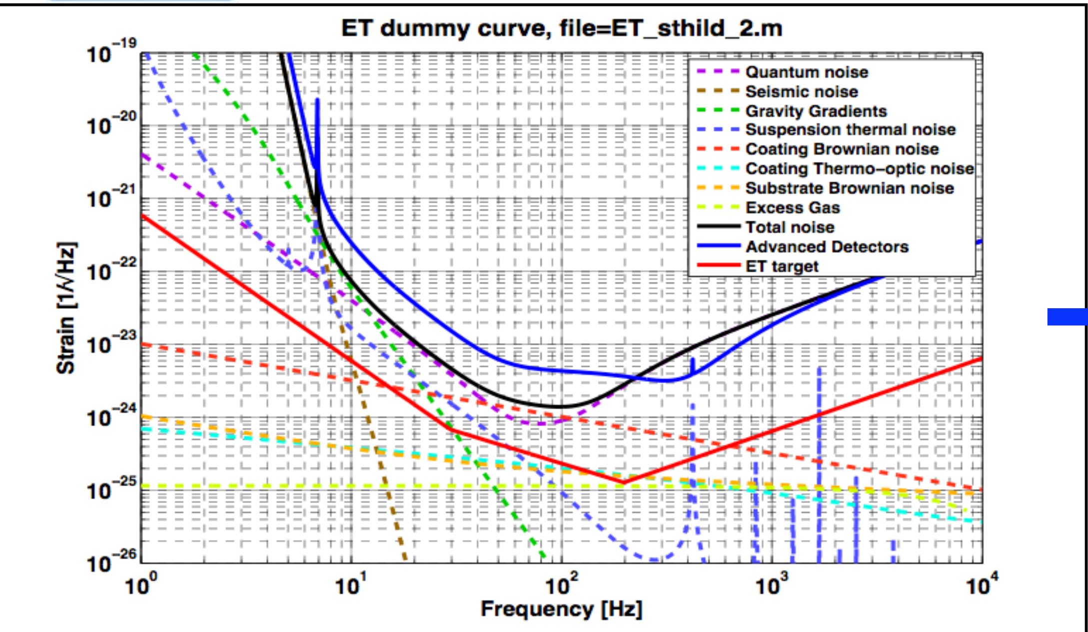
ACTION: Increase arm length from 3km to 10km

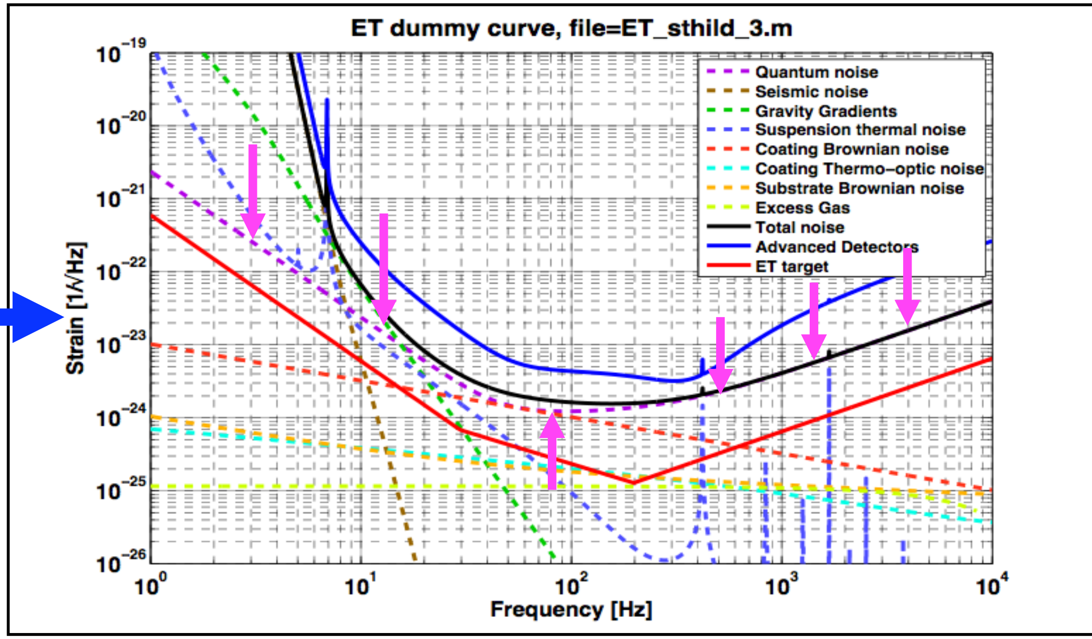
EFFECT: Decrease all displacement noises by a factor 3.3

SIDE EFFECTS:
- Decrease in residual gas pressure
- Change of effective Signal recycling tuning



Step 2: Optimising signal recycling

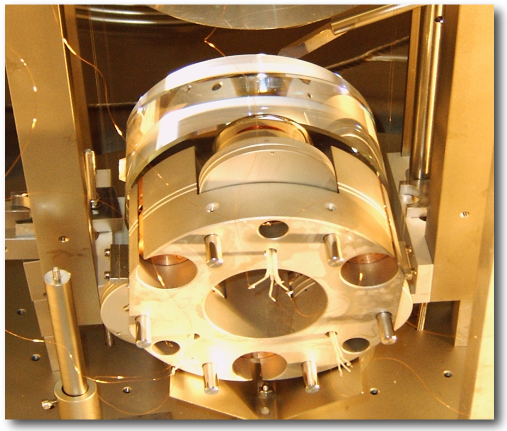




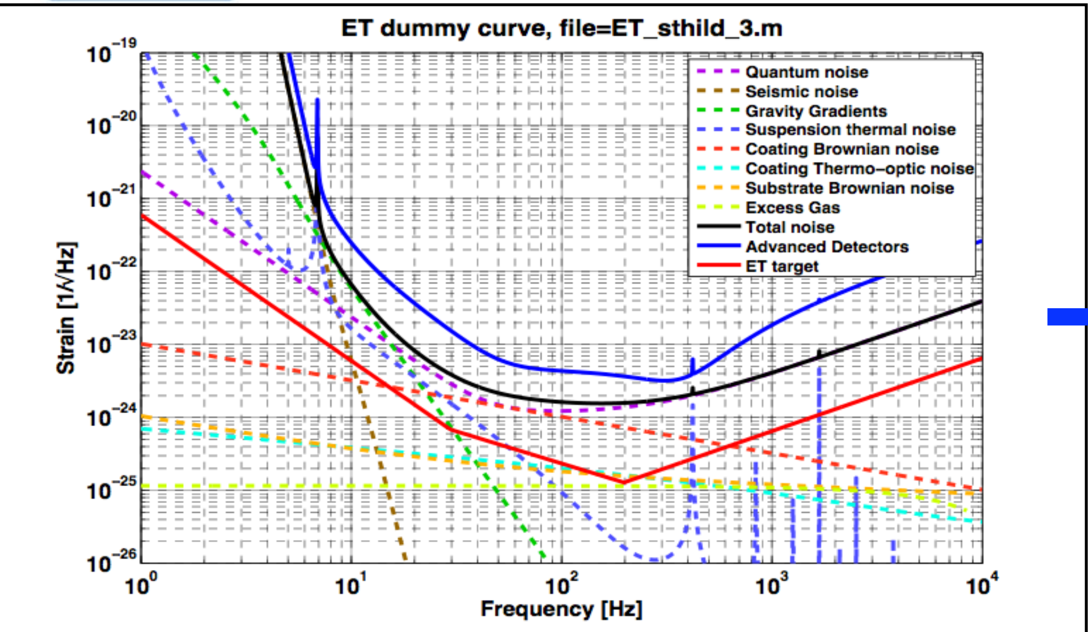
DRIVER: Quantum noise

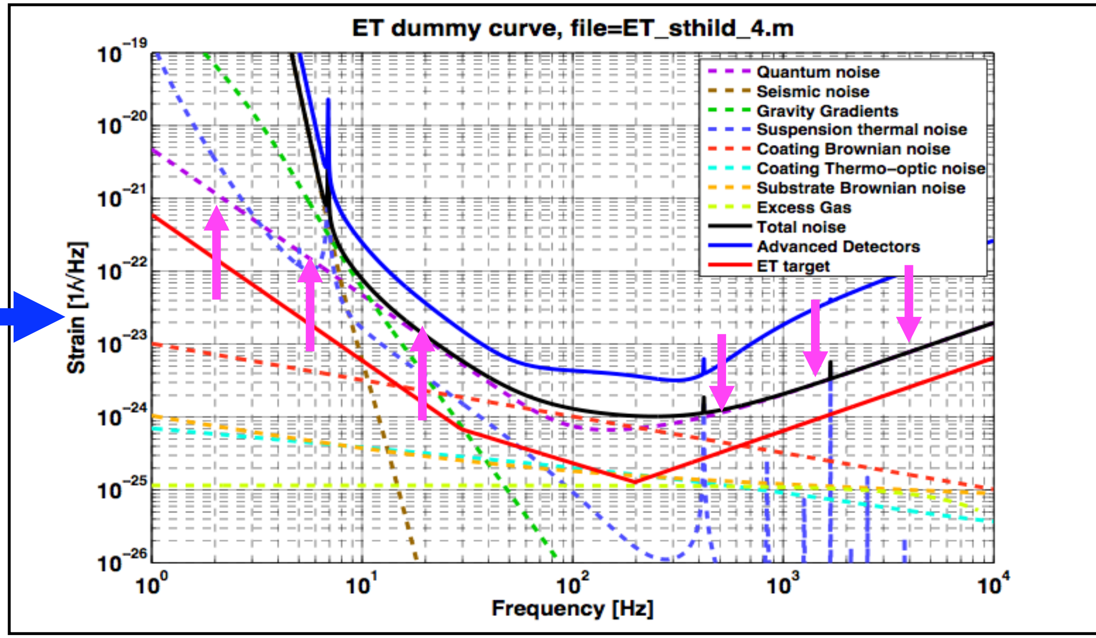
ACTION: From detuned SR to tuned SR (with 10% transmittance)

EFFECTS:
- Reduced shot noise by ~ factor 7 at high freqs
- Reduced radiation pressure by ~ factor 2 at low freqs
- Reduced peak sensitivity by ~ factor sqrt(2) :(



Step 3: Increasing the laser power



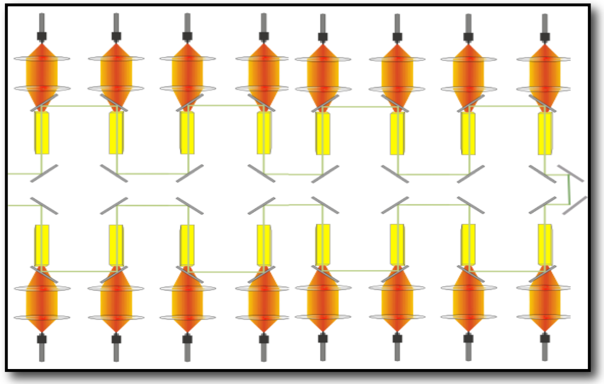


DRIVER: Shot noise at high frequencies

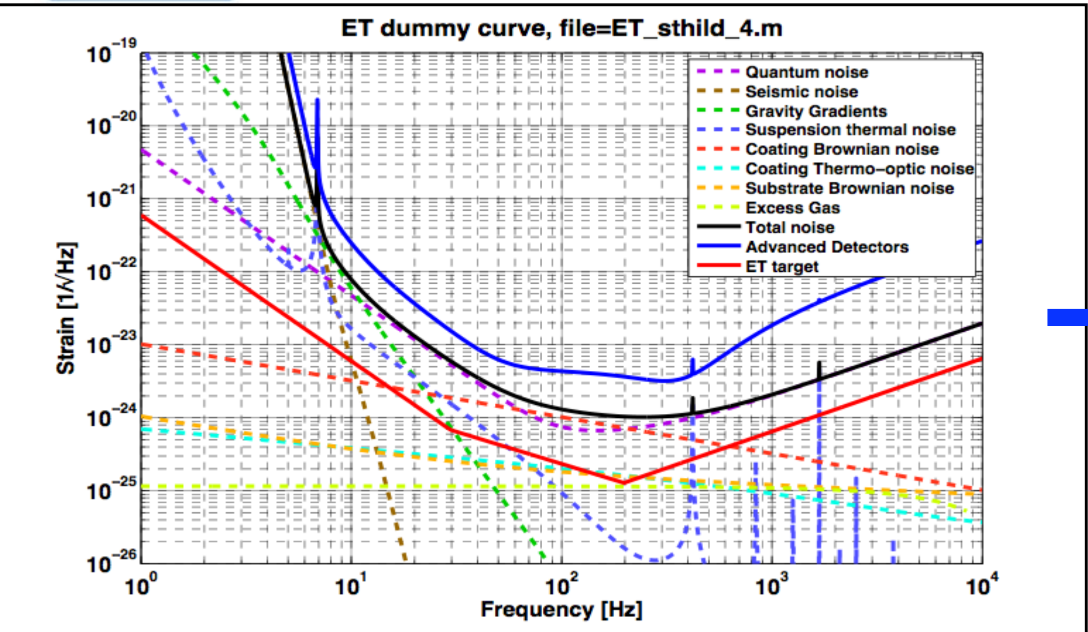
ACTION: Increase laser power (@ ifo input) from 125W to 500W

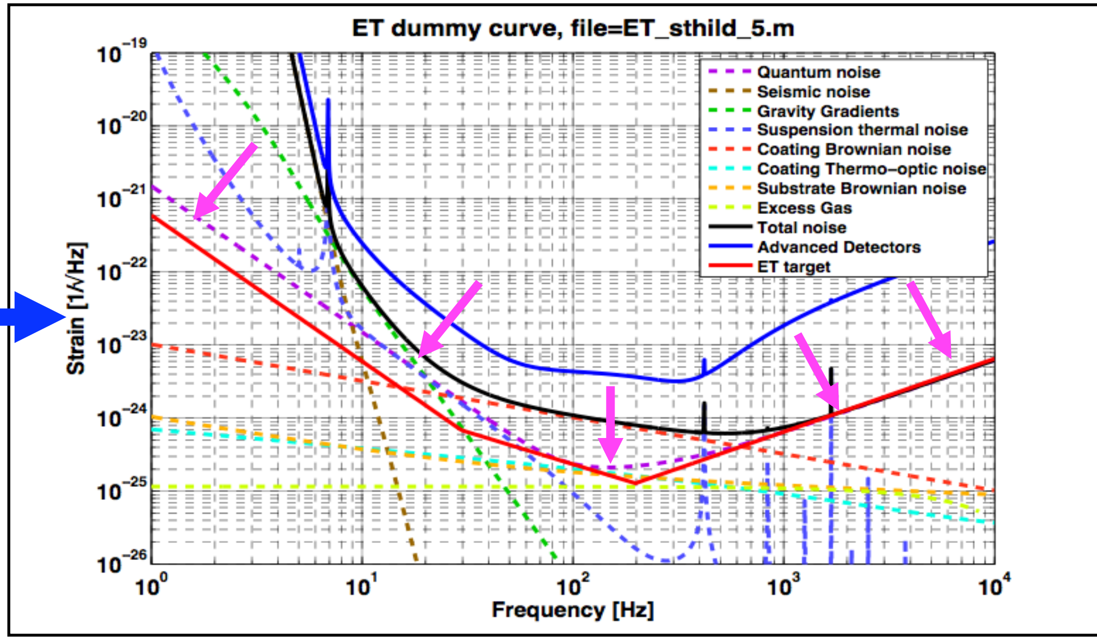
EFFECT: Reduced shot noise by a factor of 2

SIDE EFFECTS: Increased radiation pressure noise by a factor 2



Step 4: Quantum noise suppression



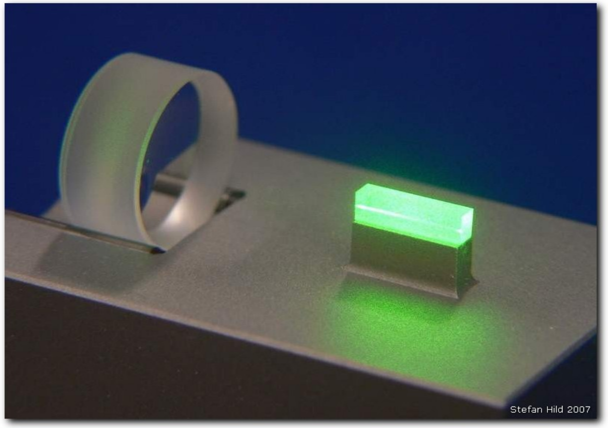


DRIVER: Shot noise at high frequencies

ACTION: Introduced 10dB of squeezing (frequency depend angle)

EFFECT: Decreases the shot noise by a factor 3

SIDE EFFECTS: Decreases radiation pressure noise by a factor 3



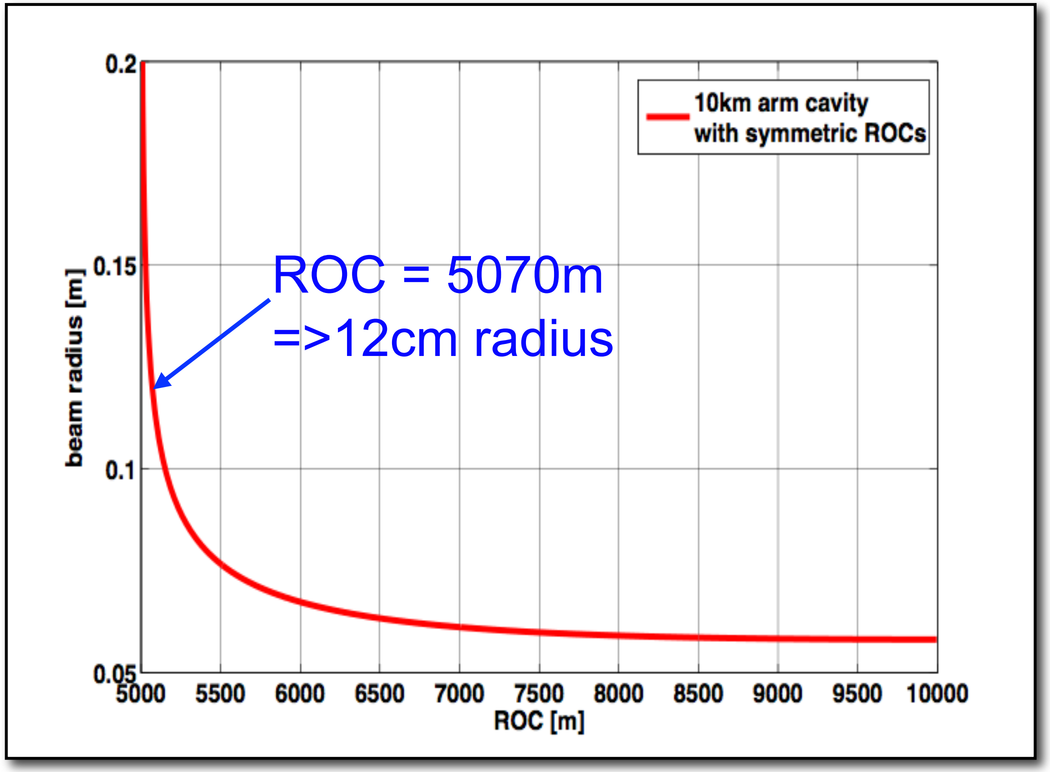
Increasing the beam size to reduce Coating Brownian noise

Increasing the beam size at the mirrors reduces the contribution of Coating Brownian.

Coating Brownian noise of one mirror:

$$S_x(f) = \frac{4k_\mathrm{B}T}{\pi^2 fY}\frac{d}{r_0^2}\left(\frac{Y'}{Y}\phi_{||} + \frac{Y}{Y'}\phi_\perp\right)$$

beam radius on mirror



Please note: a beam radius of 12cm requires mirrors of 60 to 70cm diameter

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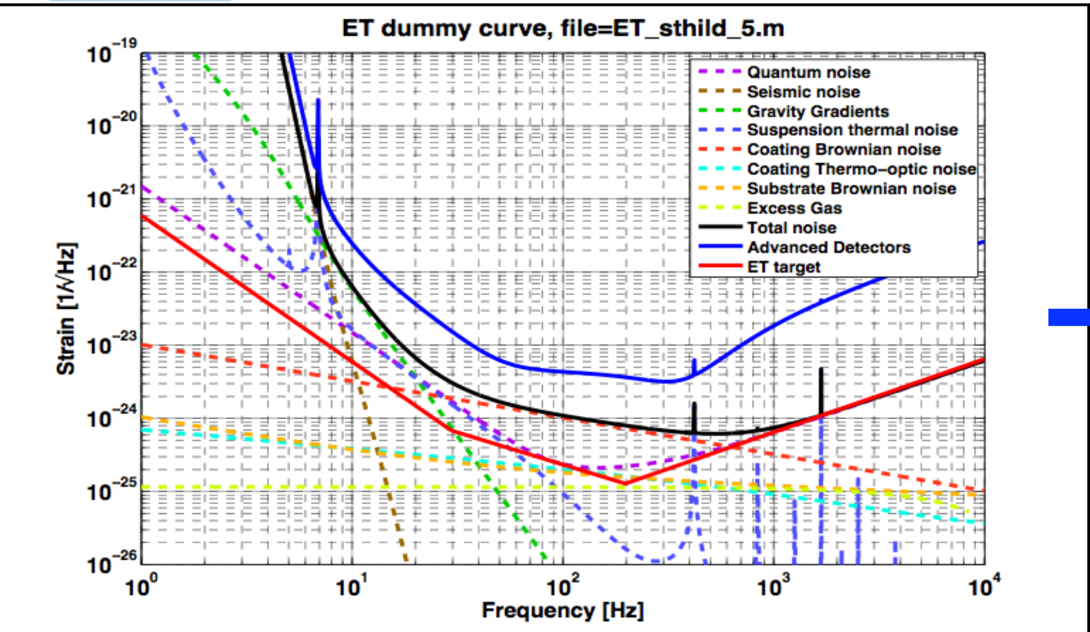
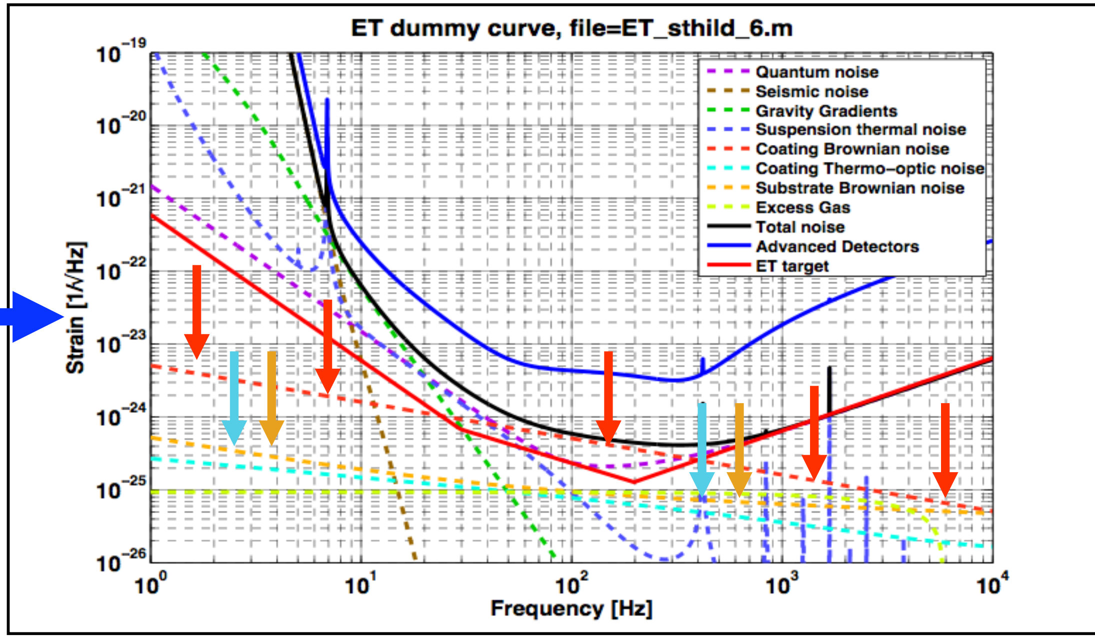
Step 5: Increasing the beam size





DRIVER: Coating Brownian noise

ACTION: Increase of beam radius from 6 to 12cm

EFFECT: Decrease of Coating Brownian by a factor 2

SIDE EFFECTS:

- Decrease of Substrate Brownian noise (~factor 2)
- Decrease of Thermo-optic noise (~factor 2)
- Decrease of residual gas pressure noise (~10-20%)

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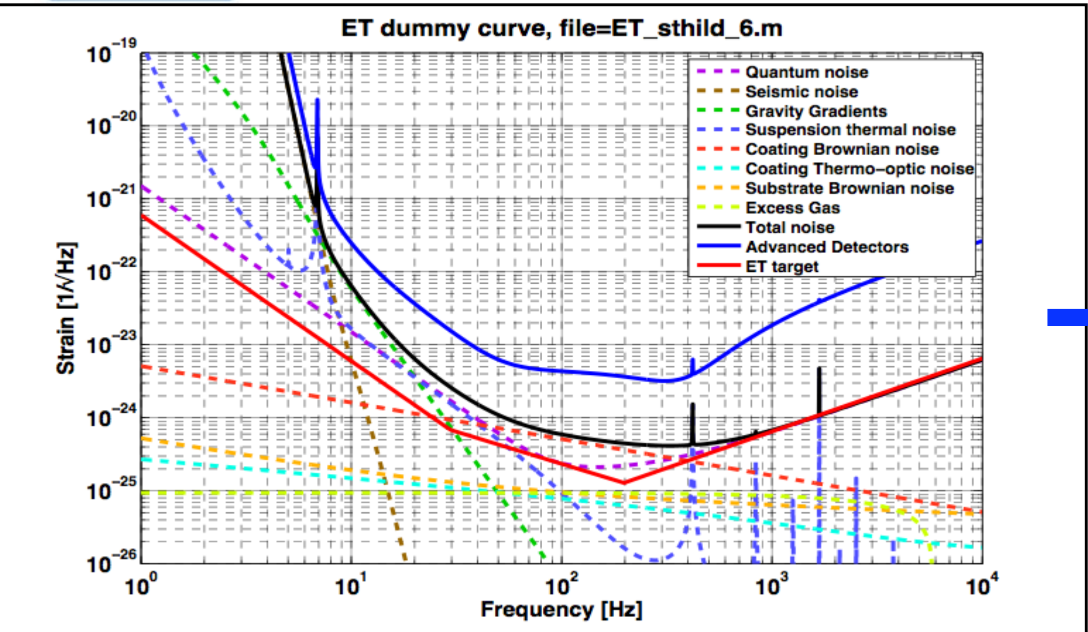
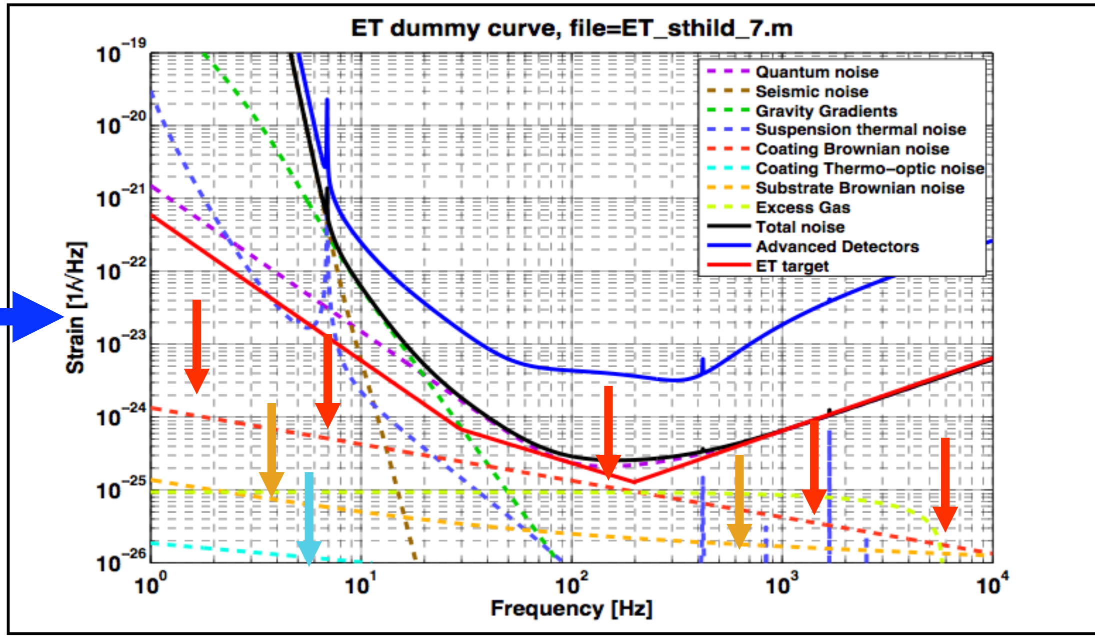
Step 6: Cooling the test masses



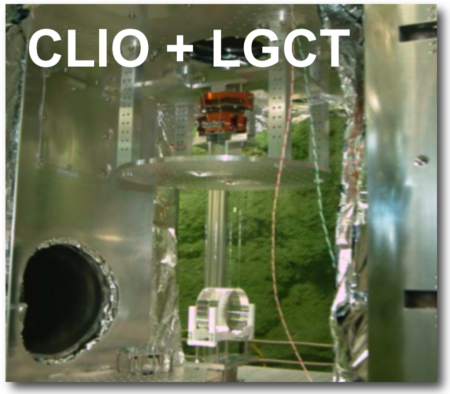


DRIVER: Coating Brownian noise

ACTION: Reduce the test mass temperature from 290K to 20K

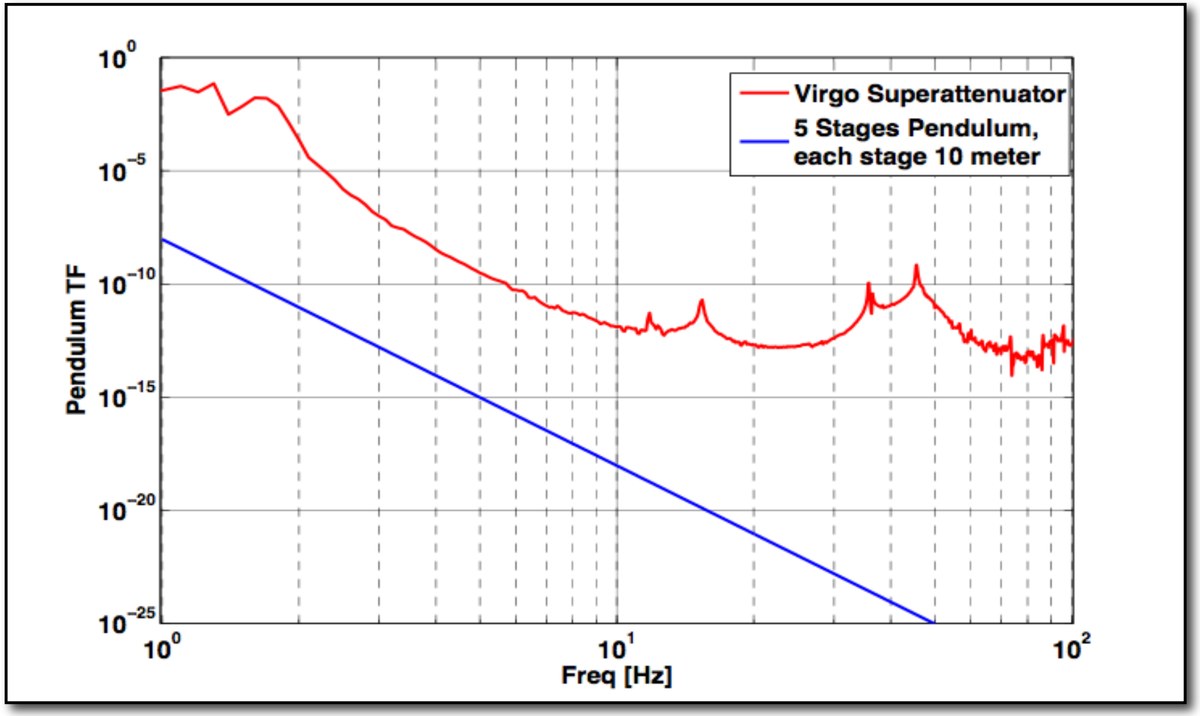
EFFECT: Decrease Brownian by ~ factor of 4

SIDE EFFECTS:
- Decrease of substrate Brownian
- Decrease of thermo-optic noise



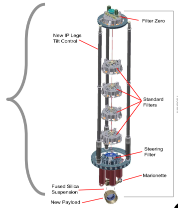
Kuroda 2008
LIGO-G080060

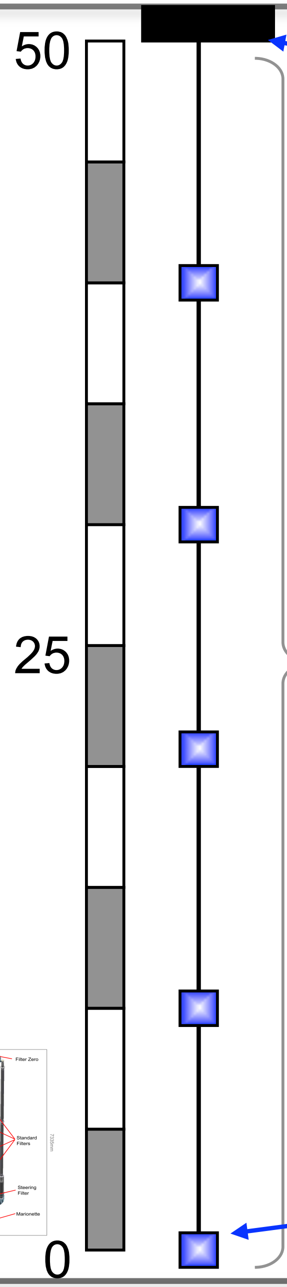
Seismic Isolation / Suspension



SA-data: G.Ballardin et al, Rev. Sci. Instrum., Vol.72, No.9 (2001)

Virgo Superattenuator (height ~ 8 meter)





Suspension point

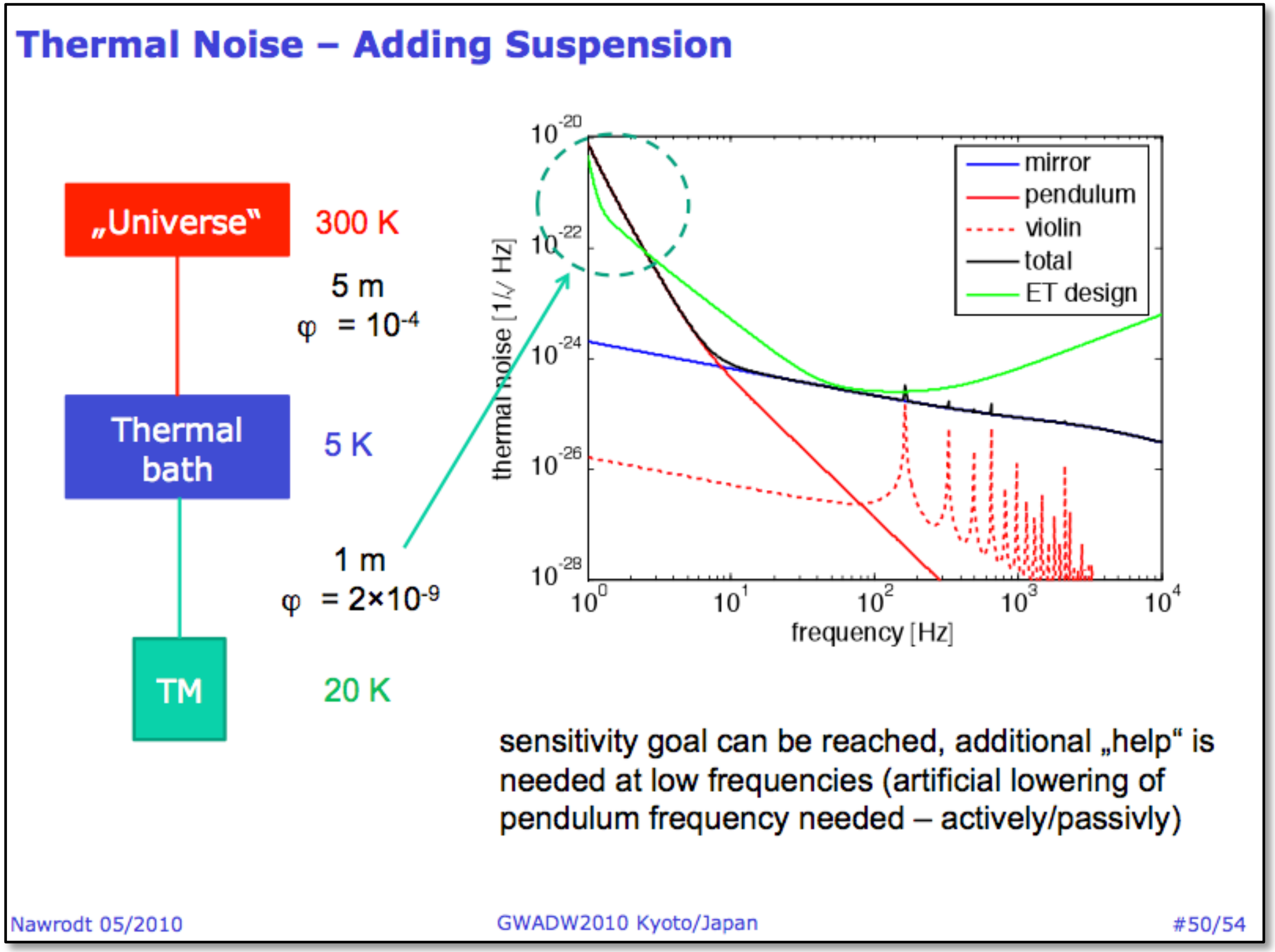
5 Stages of each 10 m height

corner freq = 0.158Hz

Main test mass

Suspension Thermal noise

- Suspension thermal noise is probably the main driver for going to cryogenic temperatures.
- Actual level strongly depends design details of suspension.



R. Nawrodt: http://gw.icrr.u-tokyo.ac.jp/gwadw2010/program/2010_GWADW_Nawrodt_ETWP2.pptx

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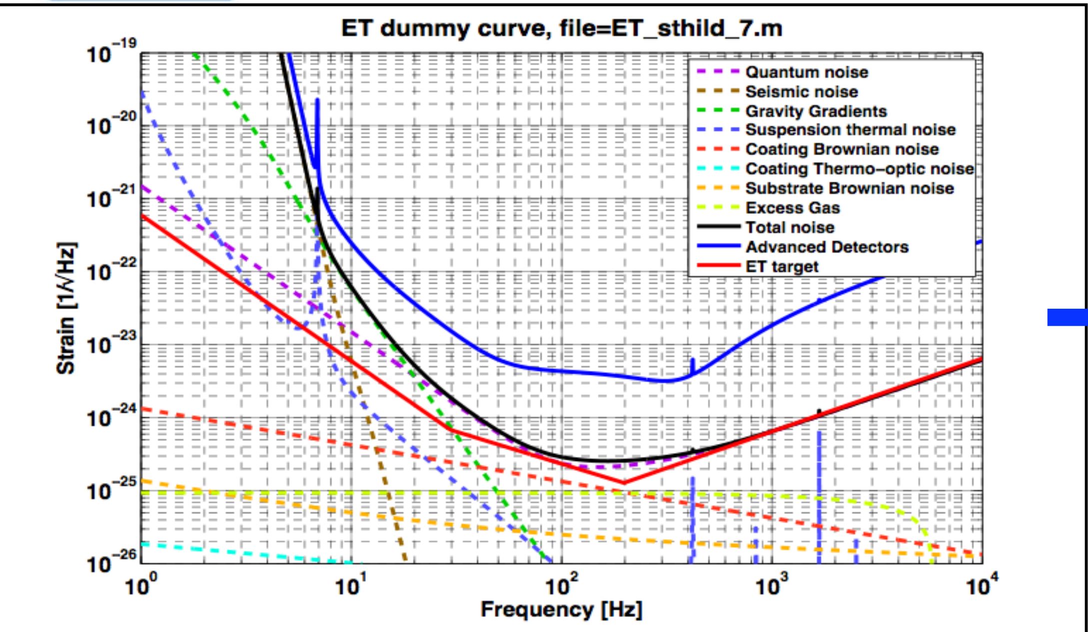
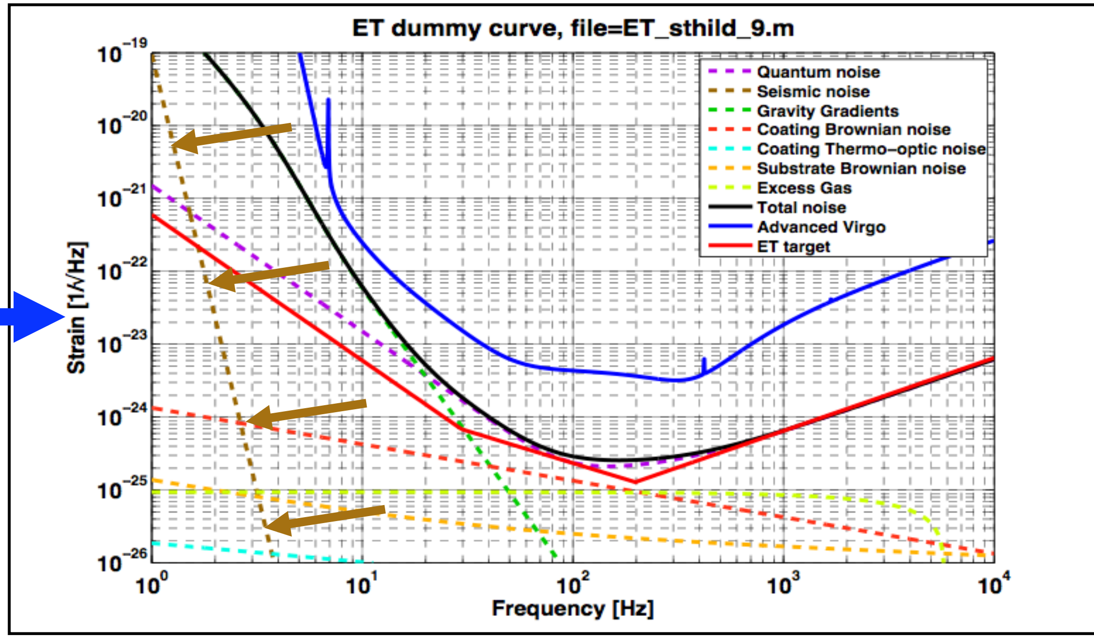
Step 7: Longer Suspensions





DRIVER: Seismic noise

ACTION: Build 50m tall 5 stage suspension (corner freq = 0.158 Hz)

EFFECT: Decrease seismic noise by many orders of magnitude
or pushes the seismic wall from 10 Hz to about 1.5 Hz

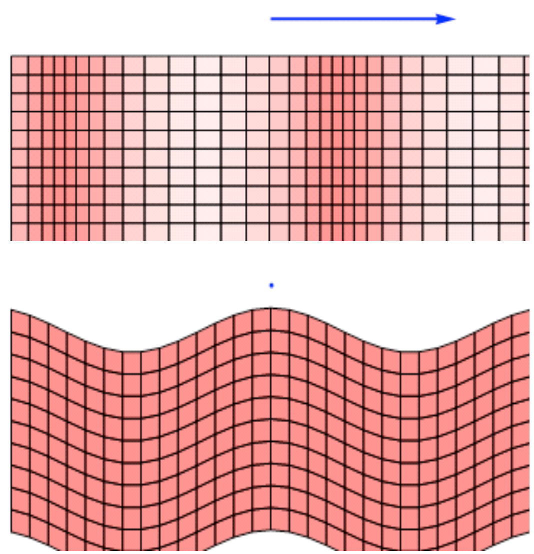
Same performance can be achived by a 17m high superattenuator S.Brachini: http://gw.icrr.u-tokyo.ac.jp/gwadw2010/program/2010_GWADW_Braccini.ppt

What is Gravity Gradient Noise

- Changes in the gravitational potential around a test mass.
- Causes 1: Humans, Lorries, Clouds etc
  - Hopefully not problematic because at frequency below detection band.
- Causes 2: Seismic driven changes
  - Density waves, shaking of cave walls etc
- Can be approximated by:

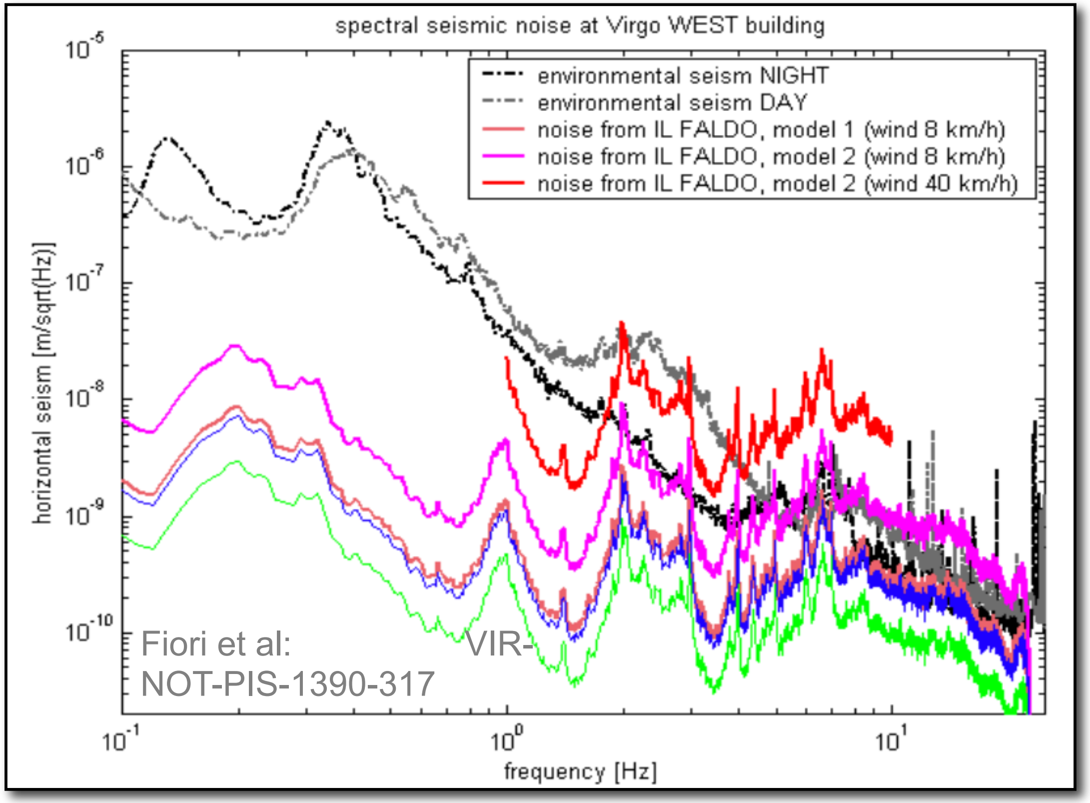
  Testmass Noise = Seismic Excitation x Coupling Transfer function

- Coupling Transfer function given by law of gravity. Not much we can do!
- Seismic Excitation can be reduced by finding a quiet site !



Images: G.Cella

Tackling Gravity Gradient noise: going underground



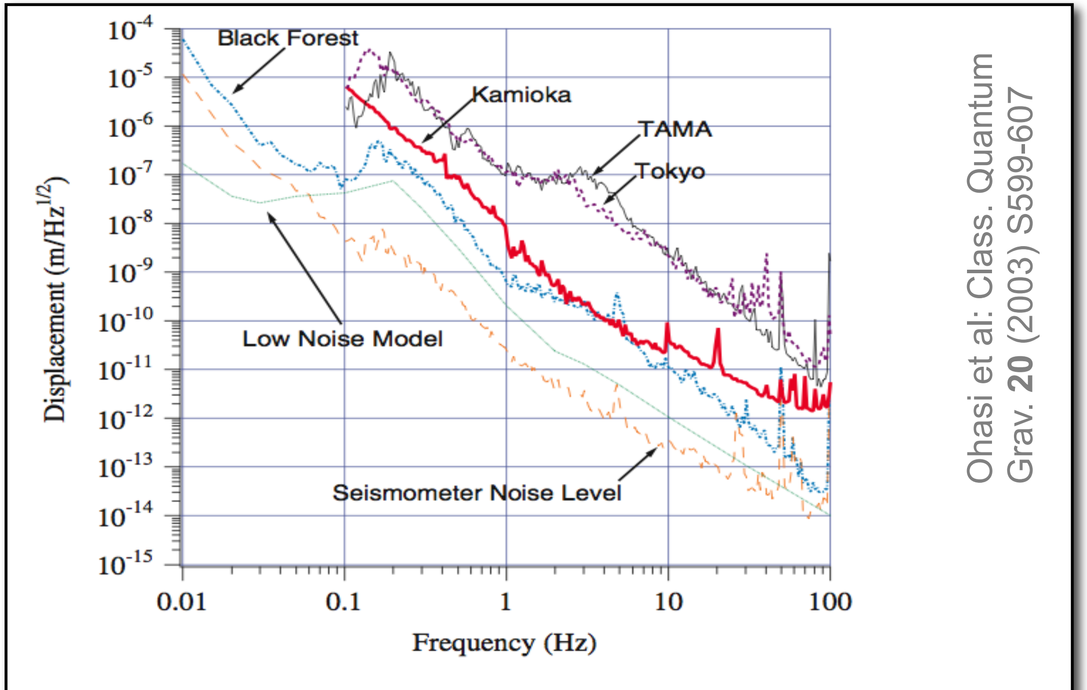


Figure 7. Low seismic noise environment at the Kamioka site. Displacement noises at Kamioka, TAMA site, Tokyo, Black Forest Geophysical Observatory (Germany) and a low noise model (a hybrid spectrum of quiet sites in the world) are described.

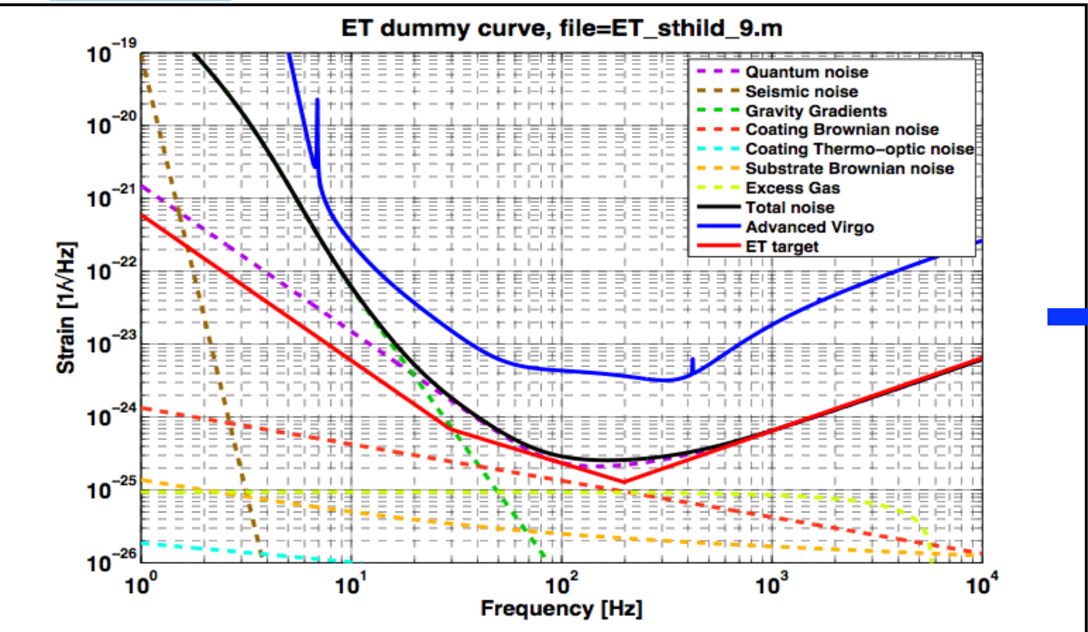
Surface (Cascina)

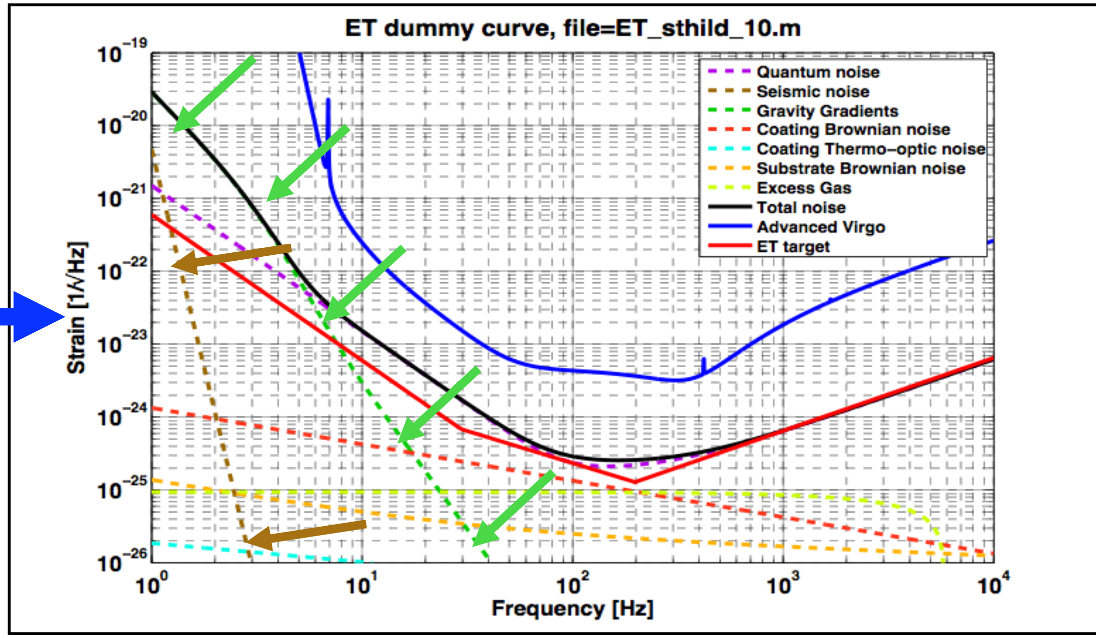
about $1 \cdot 10^{-7}\,\mathrm{m}/f^2$ for $f > 1\,\mathrm{Hz}$

Underground (Kamioka)

about $5 \cdot 10^{-9}\,\mathrm{m}/f^2$ for $f > 1\,\mathrm{Hz}$

Step 8: Going underground





DRIVER: Gravity gradient noise

ACTION: Go from the surface to underground location

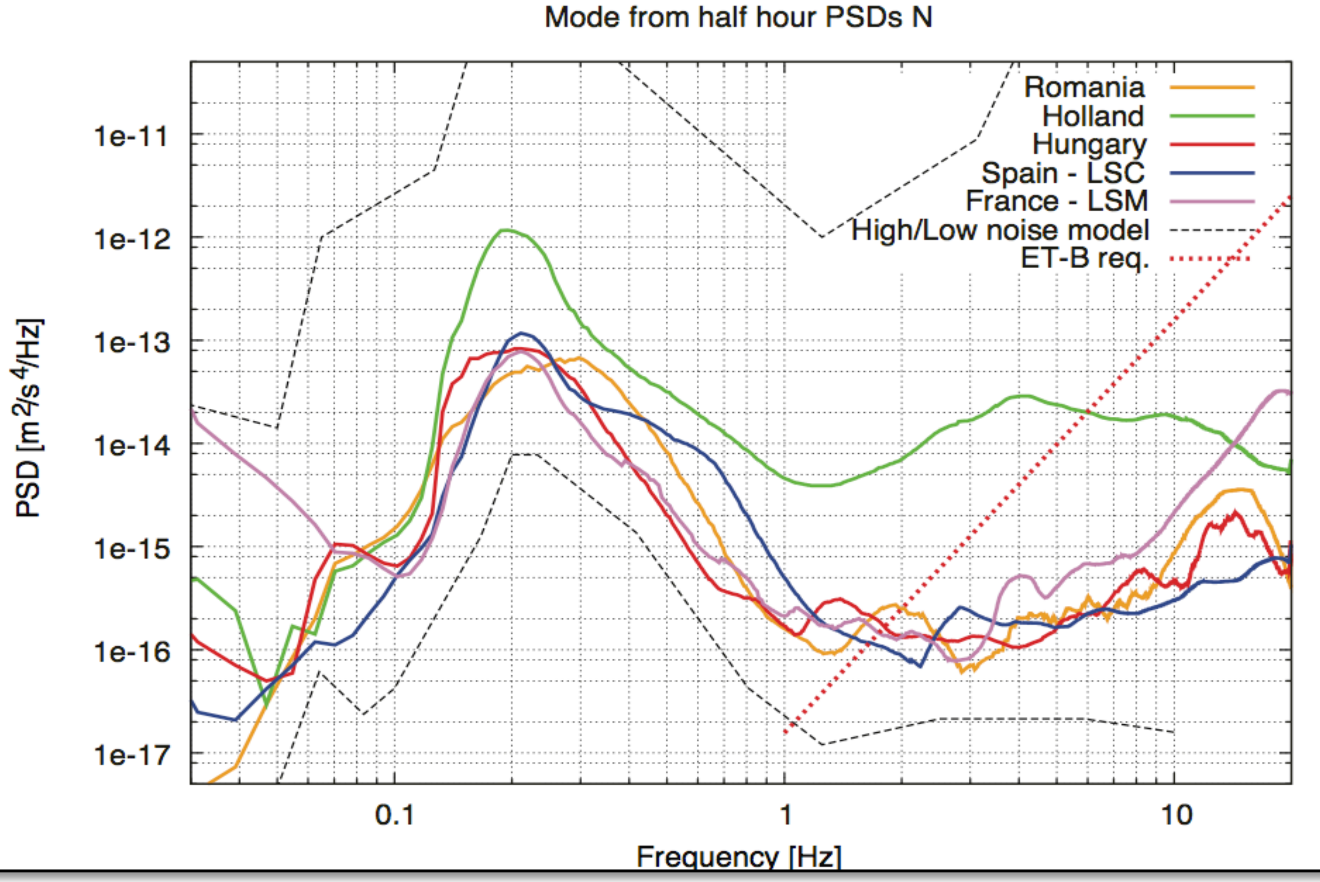
EFFECT: Decrease gravity gradients by a factor 20

SIDE EFFECTS: Decrease in seismic noise by a factor 20

Seismic measurements

- Seismic measurement campaign showed that there are several underground sites which have a seismic level even below Kamioka.
- Gravity gradient noise compitabile with 3rd generation sensitivity for frequencies above 2Hz.

Locations in Hungary, France and Spain have shown to be within ET-B requirements > 2 Hz

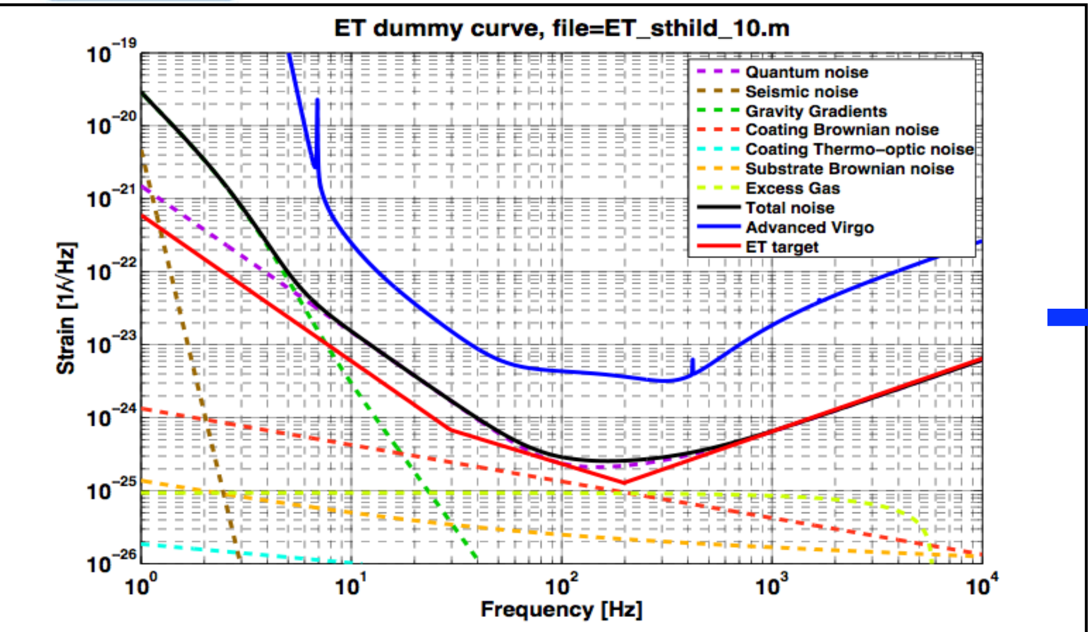


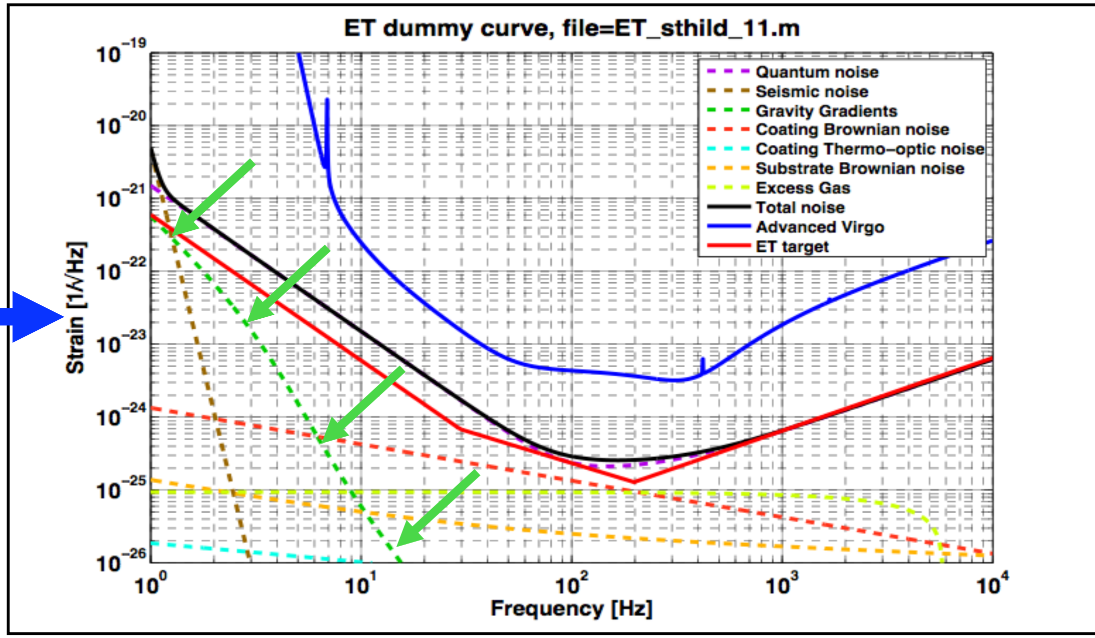
M.Baker: http://gw.icrr.u-tokyo.ac.jp/gwadw2010/program/2010_GWADW_Beker.pdf

Is there any chance to substract the gravity gradient noise?

- Theoretically = YES.
- If it is possible to determine the seismic 'all around' the test masses and the corresponding coupling transfer functions to a certain accuracy it should be possible to subtract gravity gradient noise from h(t).
- This would require a big 3D array of seismometers, very homogenous rock, etc
- Has never been done … work in progress (and probably our only chance to get to the ET target sensitivity below about 2-3Hz).

Step 9: Gravity gradient suppression



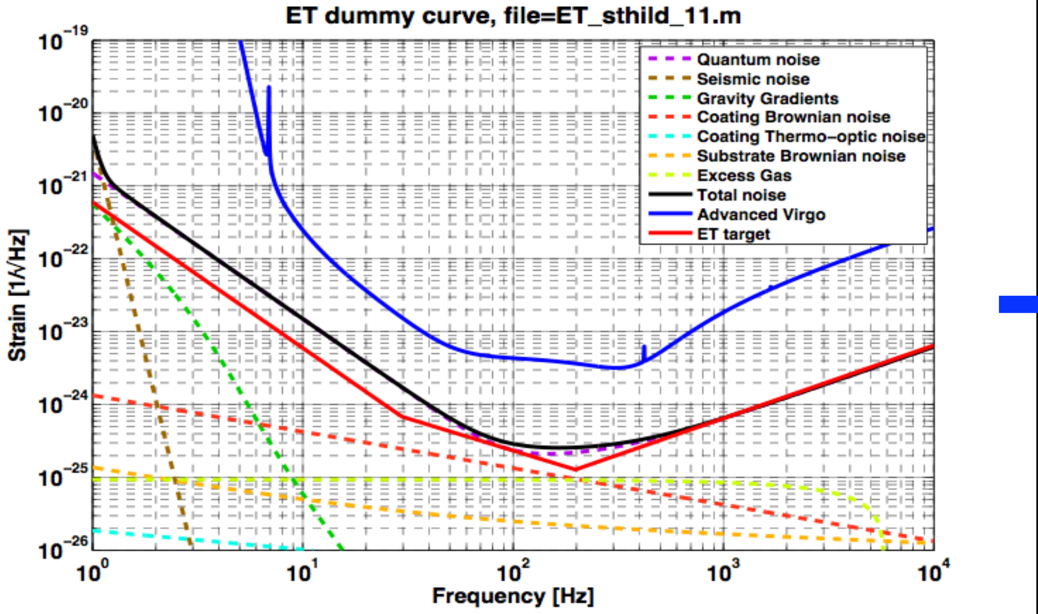


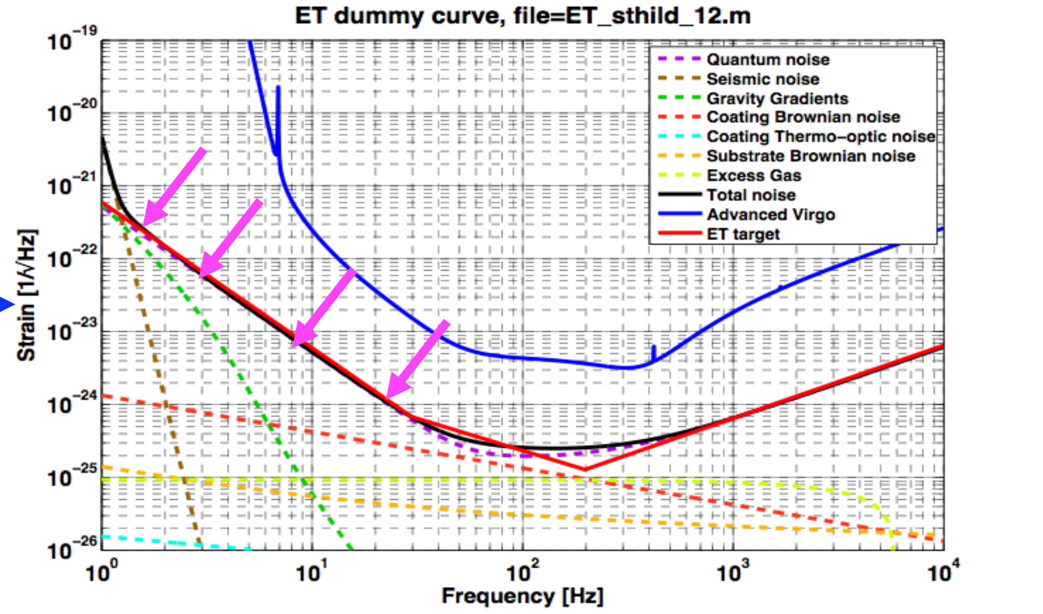
DRIVER: Gravity gradient noise

ACTION: Very quite underground site + active subtraction of the gravity gradients below a few Hz

EFFECT: Decrease gravity gradient noise by a factor 50.

Step 10: Heavier mirrors

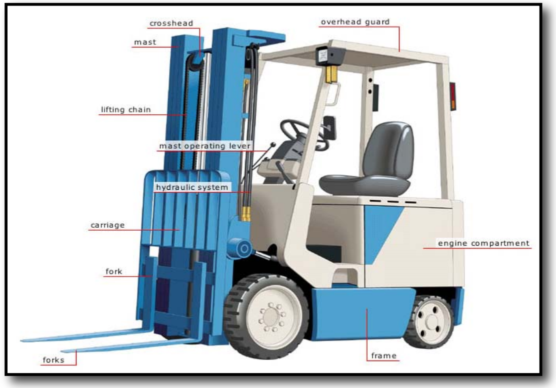


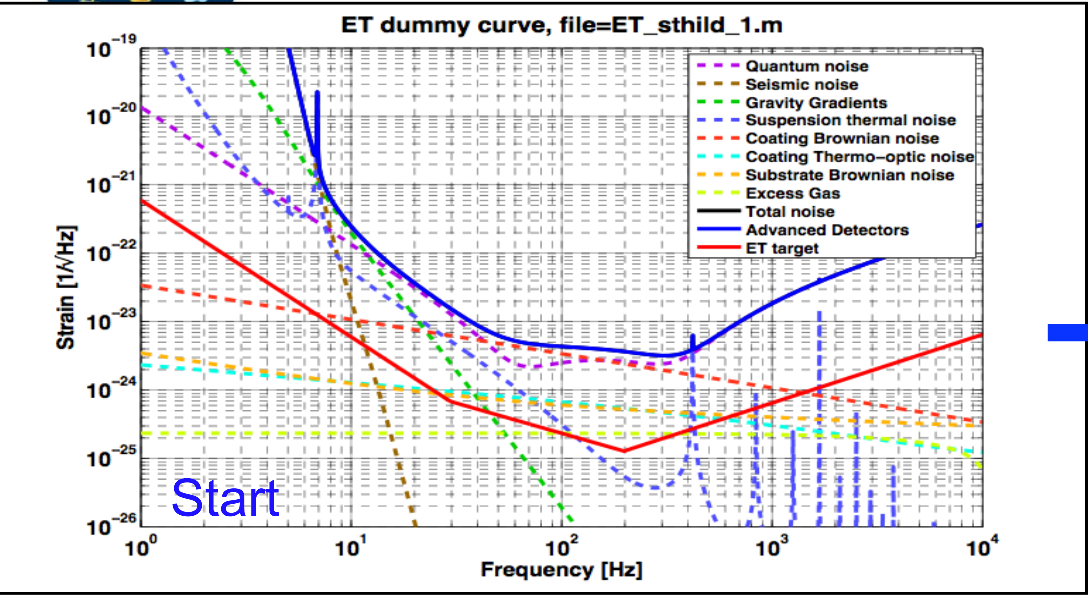


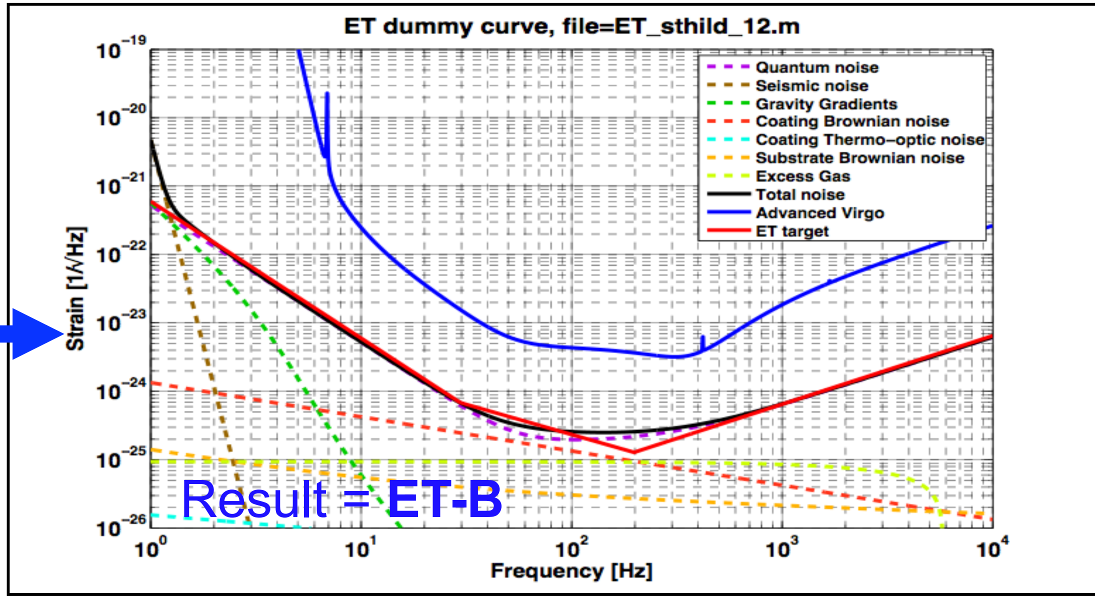
DRIVER: Quantum noise at low frequencies

ACTION: Increase test mass weight from 42 kg to 120 kg (or even 200 kg)

EFFECT: Decrease of radiation pressure noise







	advanced detector	potential ET design
Arm length	3 km	10 km
SR-phase	detuned (0.15)	tuned (0.0)
SR transmittance	11 %	10 %
Input power (after IMC)	125 W	500 W
Arm power	0.75 MW	3 MW
Quantum noise suppression	none	10 dB
Beam radius	6 cm	12 cm
Temperature	290 K	20 K
Suspension	Superattenuator	5 stages of each 10 m length
Seismic	$1 \cdot 10^{-7}\,\mathrm{m}/f^2$ for $f > 1$ Hz (Cascina)	$5 \cdot 10^{-9}\,\mathrm{m}/f^2$ for $f > 1$ Hz (Kamioka)
Gravity gradient reduction	none	factor 50 required
Mirror masses	42 kg	120 kg
BNS range	150 Mpc	2650 Mpc
BBH range	800 Mpc	17700 Mpc

S.Hild et al: arXiv:0810.0604

Overview of this presentation

- Some Warnings first …

2G → 2.5G → 3G

- Where is the transition from 2nd to 3rd Generation?

- The Brute Force approach to achieve the 3rd Generation target sensitivity.

- Can we do it a bit more realistic? – The xylophone approach.

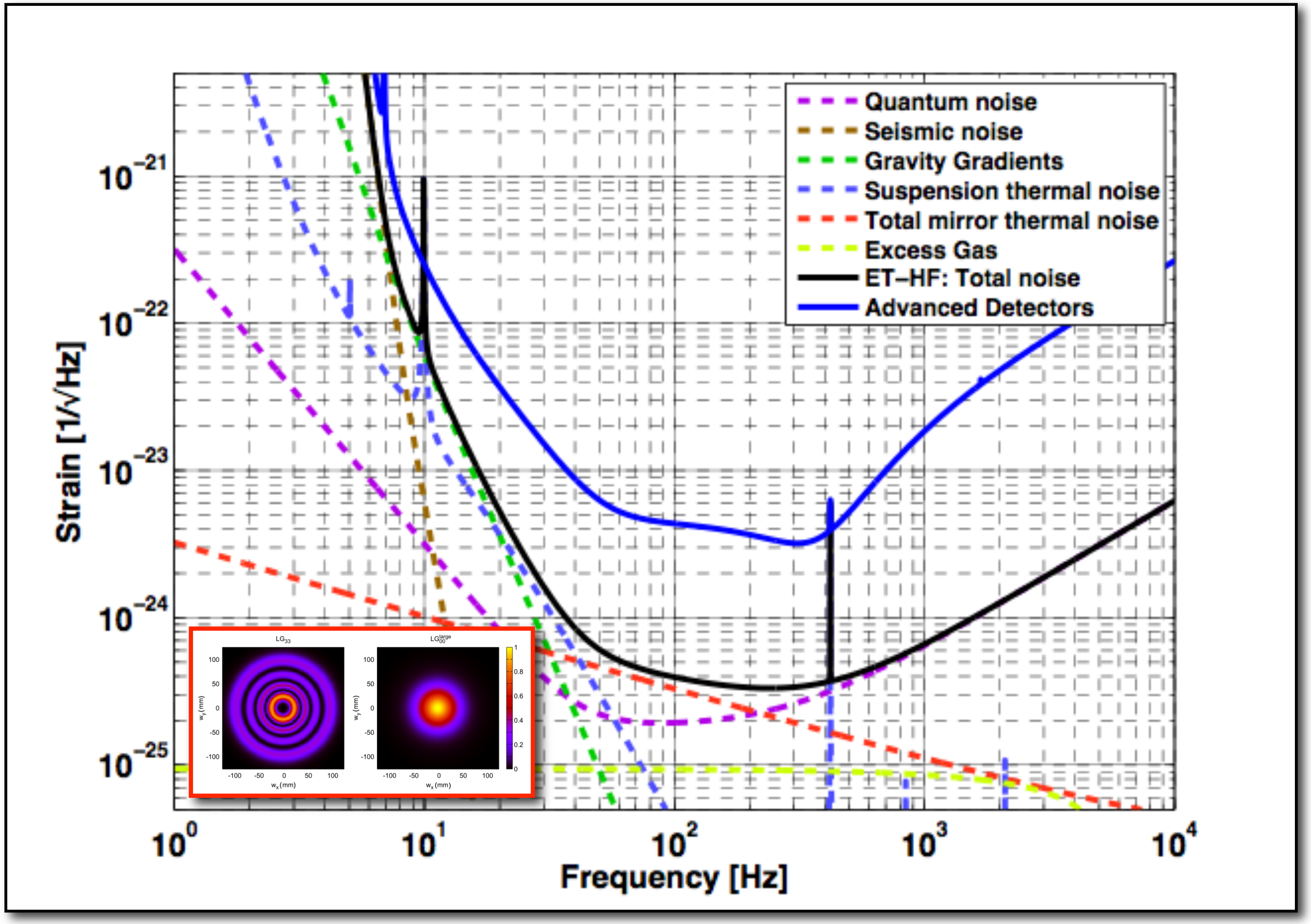
- A Zoo of even more fancy ideas

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

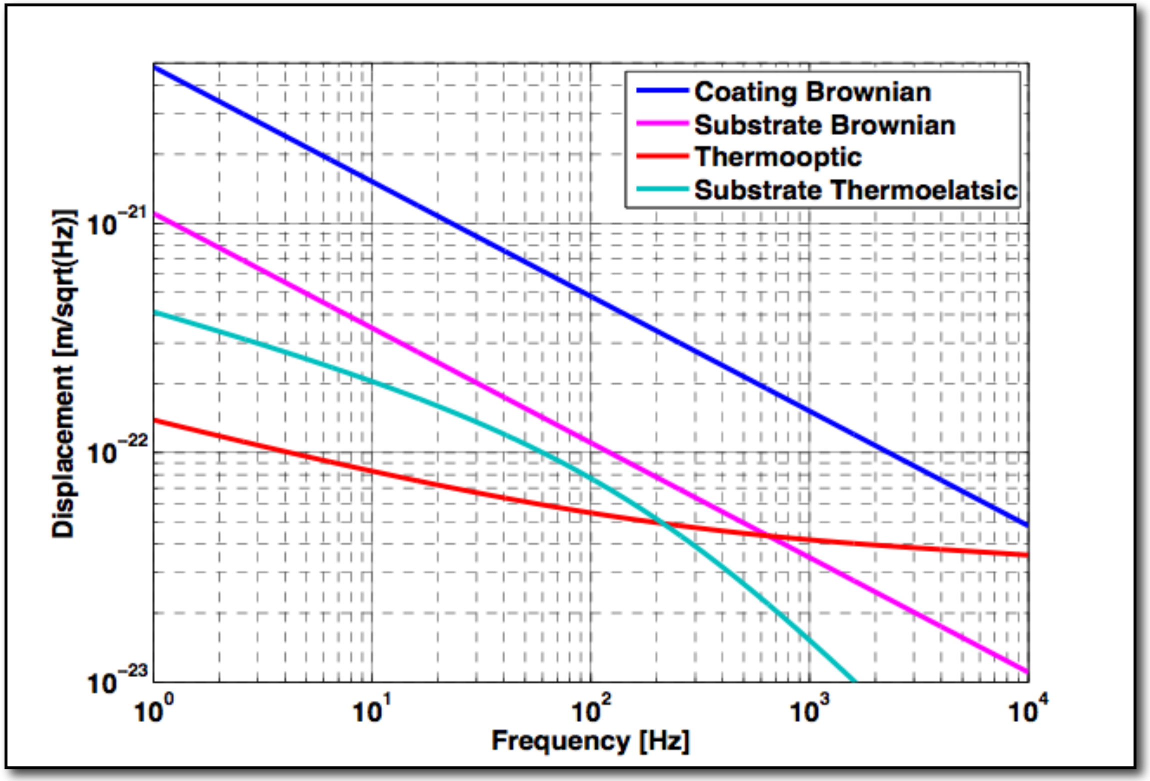
- **Quantum noise:** 3MW, tuned Signal-Recyling, 10dB Squeezing, 200kg mirrors.
- **Suspension Thermal and Seismic:** Superattenuator at surface location.
- **Gravity gradient:** No Subtraction
- **Thermal noise:** 290K, 12cm beam radius, fused Silica, LG33 (reduction factor of 1.6 compared to TEM00).



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

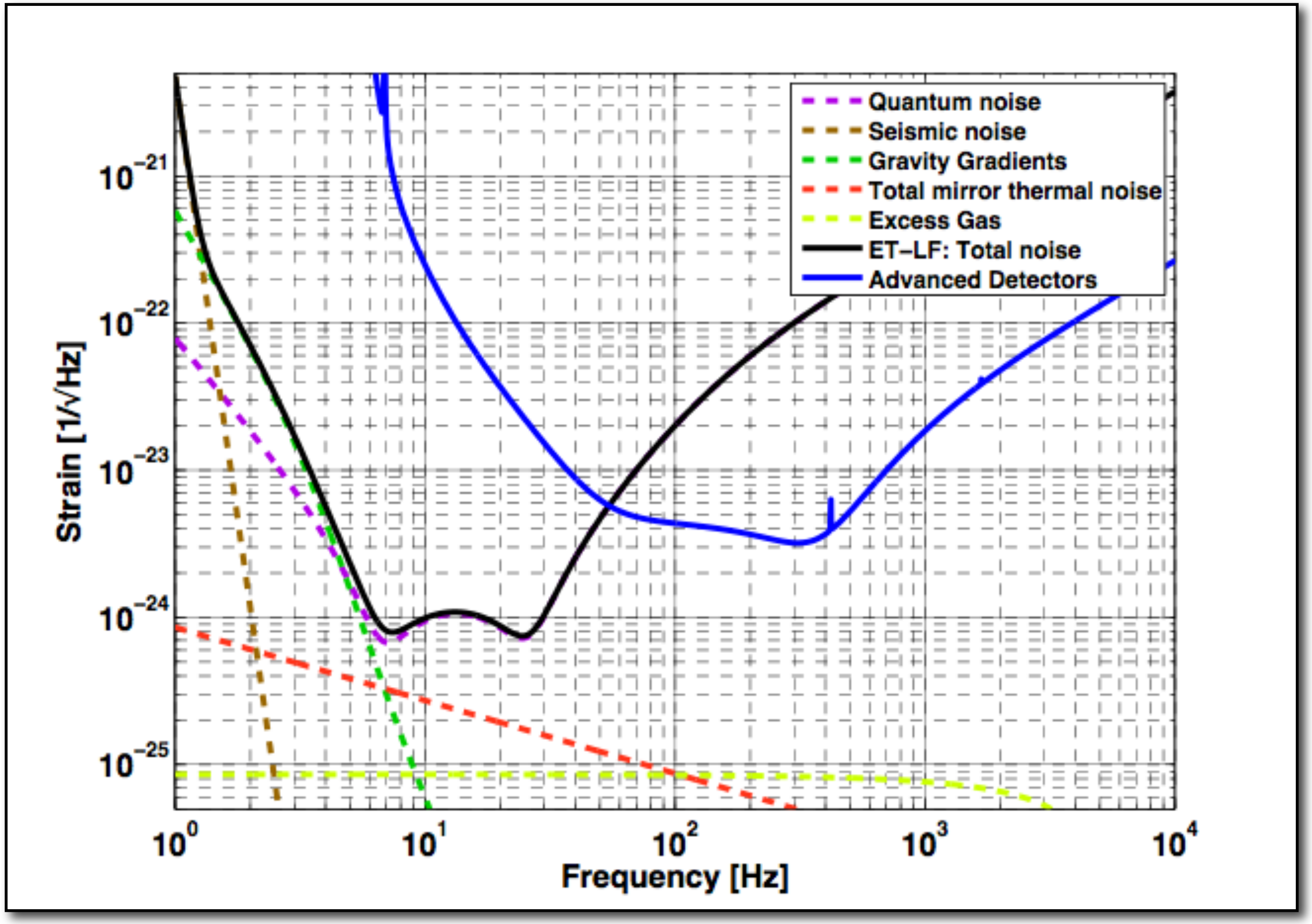
- Thermal noise of a single cryogenic end test mass.
- Assumptions:
  - Silicon at 10K
  - Youngs Modulus = 164GP
  - Coating material similar to what is currently available for fused silica at 290K (loss angles of 5e-5 and 2e-4 for low and high refractive materials)



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

Low Frequency Detector

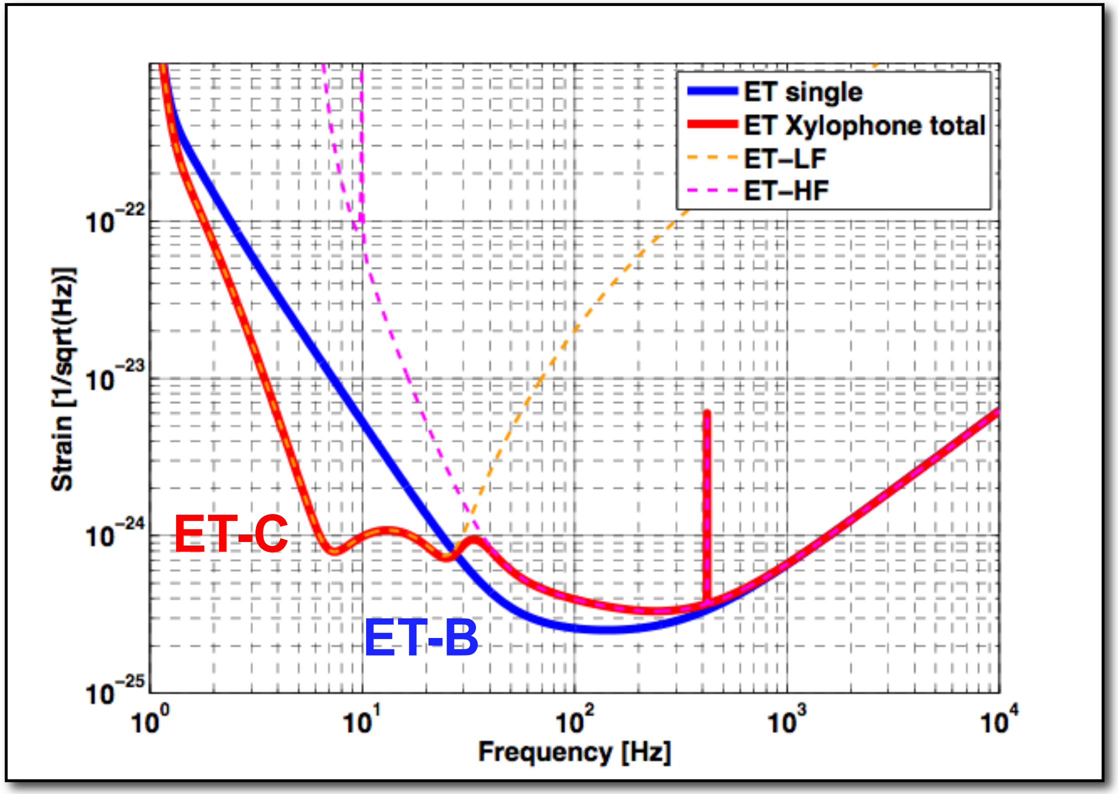
- **Quantum noise:** 18kW, detuned Signal-Recyling, 10 dB frequency dependent Squeezing, 211kg mirrors.
- **Seismic:** 5x10m suspensions, underground.
- **Gravity gradient:** Underground, factor 50 subtraction
- **Thermal noise:** 10K, Silicon, 12cm beam radius, TEM00.
- **Suspension Thermal:** not included.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



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)	$1 \cdot 10^{-7}\ \mathrm{m}/f^2$	$5 \cdot 10^{-9}\ \mathrm{m}/f^2$
Gravity gradient subtraction	none	factor 50



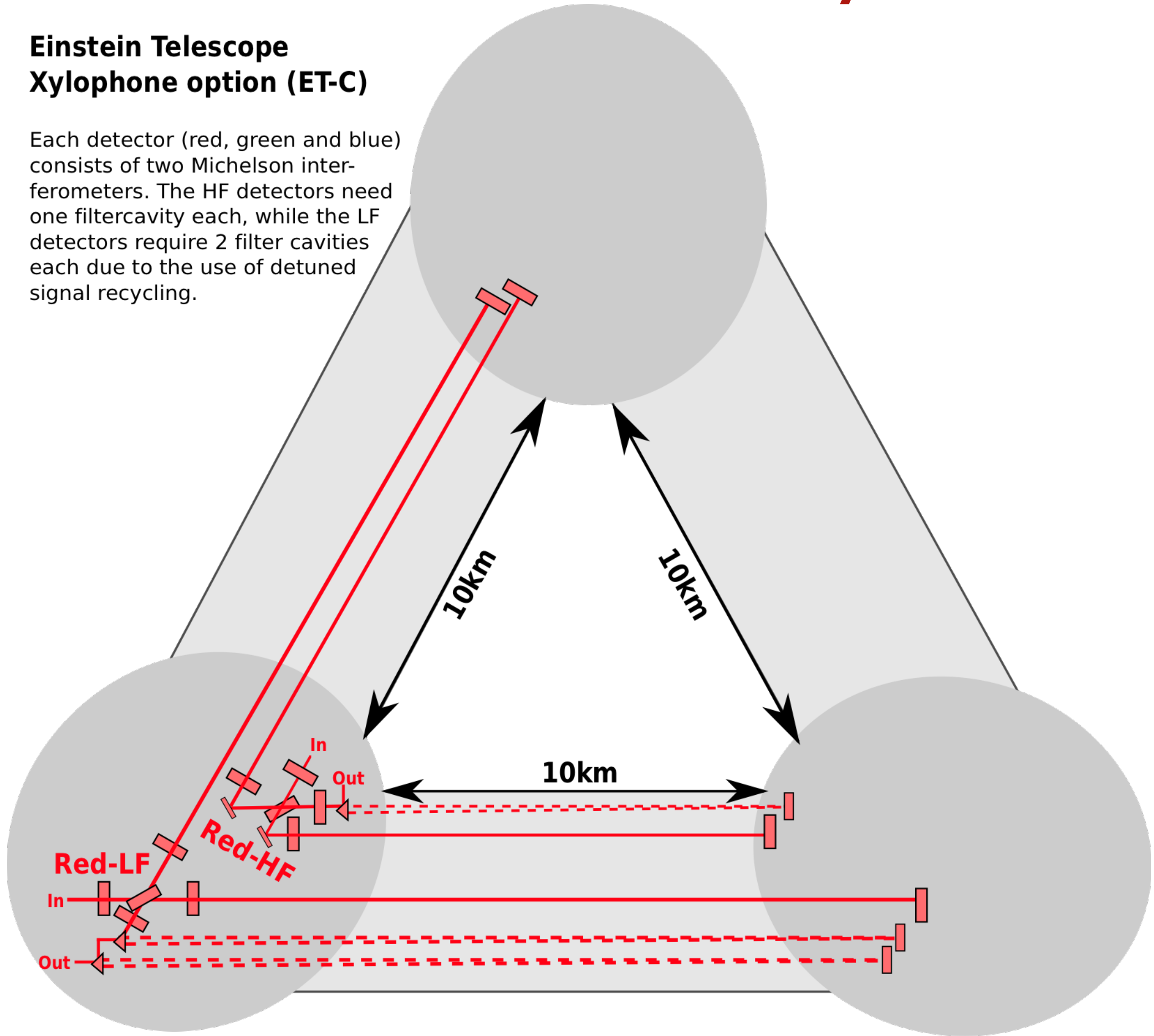
- Data from ET-LF and ET-HF can be coherently or incoherently be added, depending on the requirements of the analysis.
- For more details please see S.Hild, S.Chelkowski, A.Freise, J.Franc, R.Flaminio, N.Morgado and R.DeSalvo: 'A Xylophone Configuration for a third Generation Gravitational Wave Detector',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

How to build an Observatory?

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

Einstein Telescope Xylophone option (ET-C)

Each detector (red, green and blue) consists of two Michelson interferometers. The HF detectors need one filtercavity each, while the LF detectors require 2 filter cavities each due to the use of detuned signal recycling.



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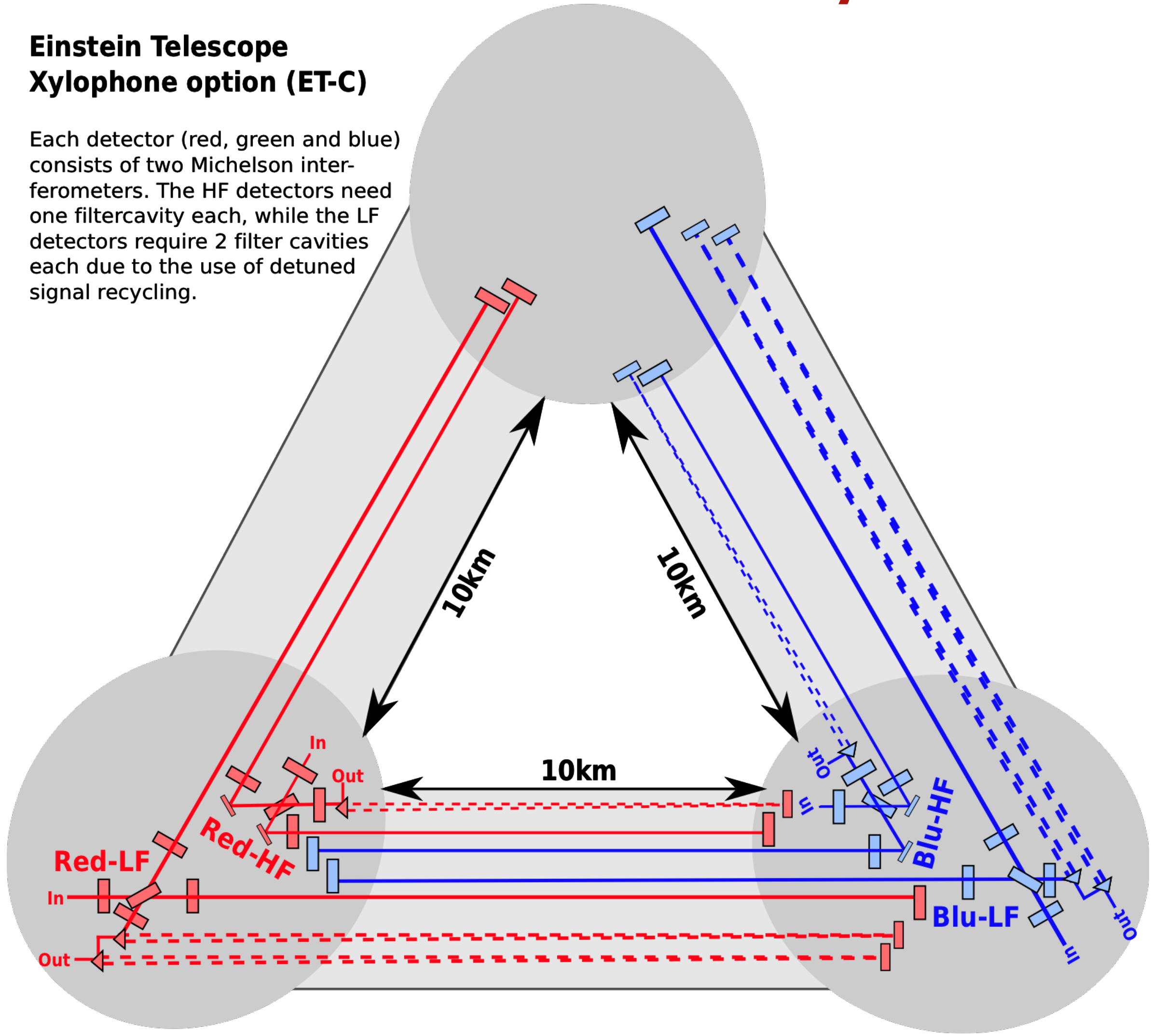
How to build an Observatory?

- 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.

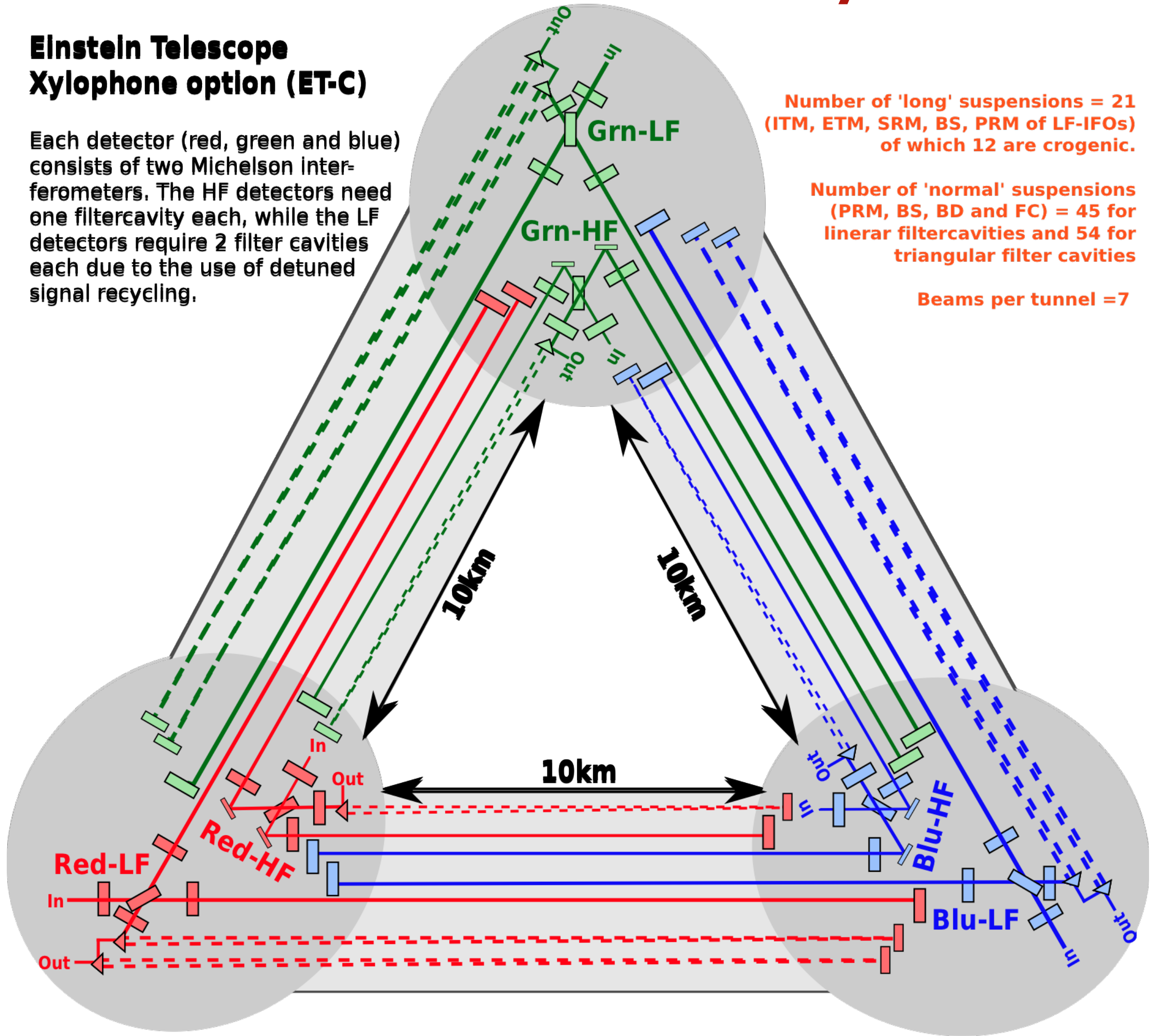
Einstein Telescope Xylophone option (ET-C)

Each detector (red, green and blue) consists of two Michelson interferometers. The HF detectors need one filtercavity each, while the LF detectors require 2 filter cavities each due to the use of detuned signal recycling.

Number of 'long' suspensions = 21 (ITM, ETM, SRM, BS, PRM of LF-IFOs) of which 12 are crogenic.

Number of 'normal' suspensions (PRM, BS, BD and FC) = 45 for linerar filtercavities and 54 for triangular filter cavities

Beams per tunnel =7



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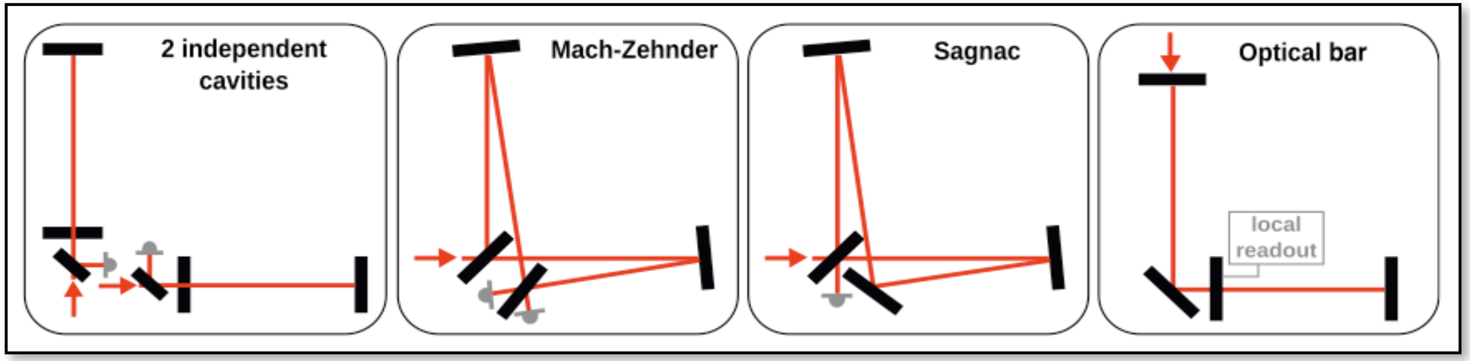
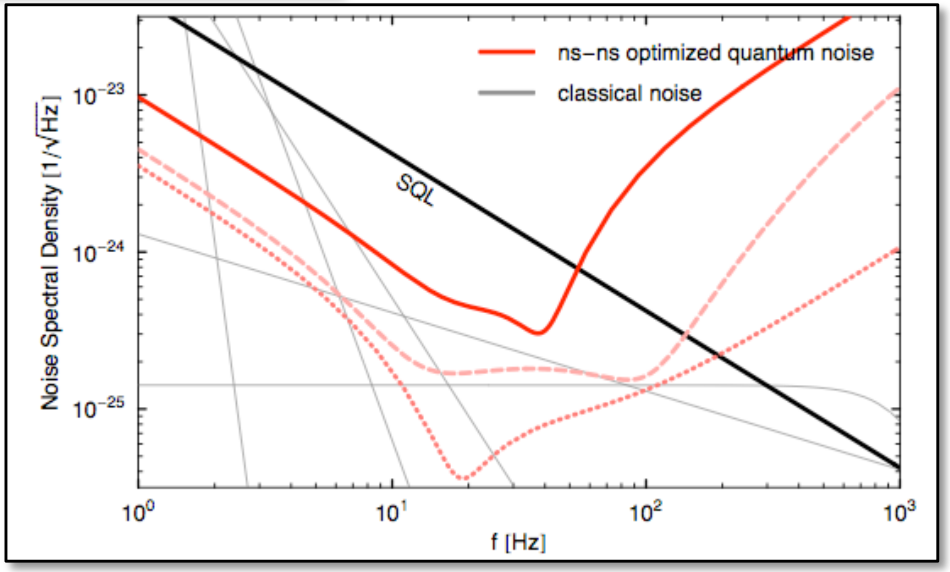
Other Quantum-Non-demolition Techniques



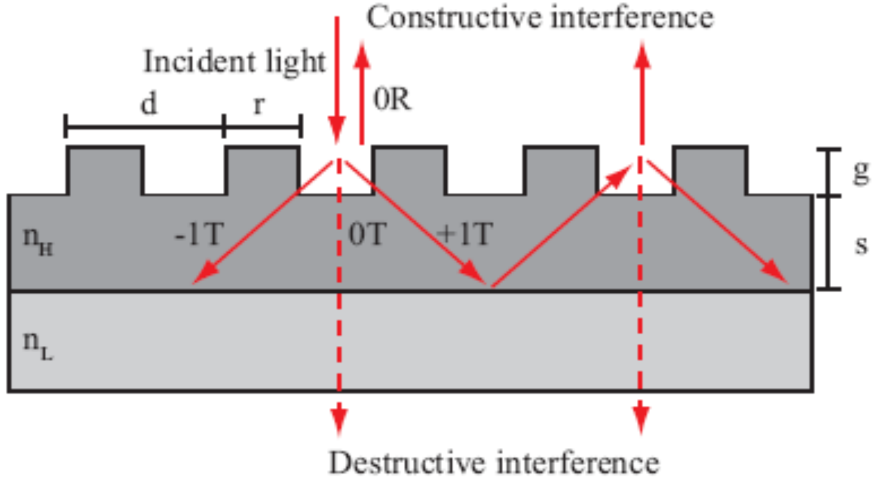
- Detector topologies different than Michelson might offer even better quantum noise reduction, i.e. Dual Recycled Sagnac with arm cavities or Optical Bar / Optical Lever topologies.



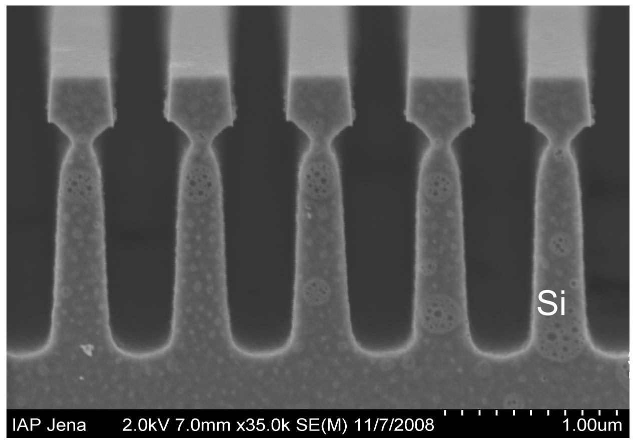
Speedmeter sensitivity.
H. Mueller-Ebhardt et al:
https://pub3.ego-gw.it/itf/tds/file.php?callFile=ET-010-09.pdf

Waveguide Coatings

- Waveguide might provide a way to reduce coating Brownian noise.
- Idea: replacing the dielectric (lossy) multilayer stack by a mono-crystalline silicon micro structure



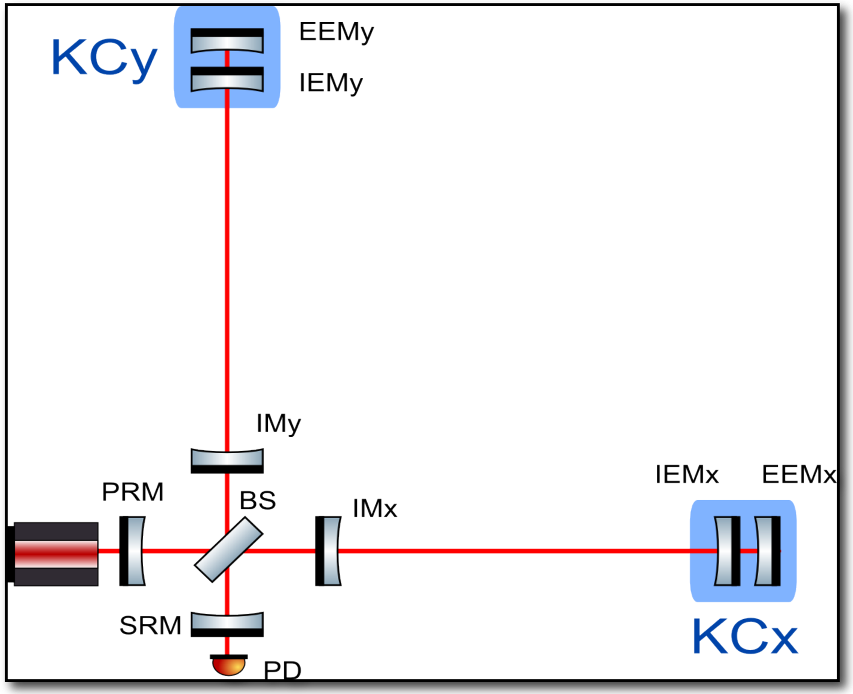
Brückner et al., Optics Express 17 (2009) 163 – 169

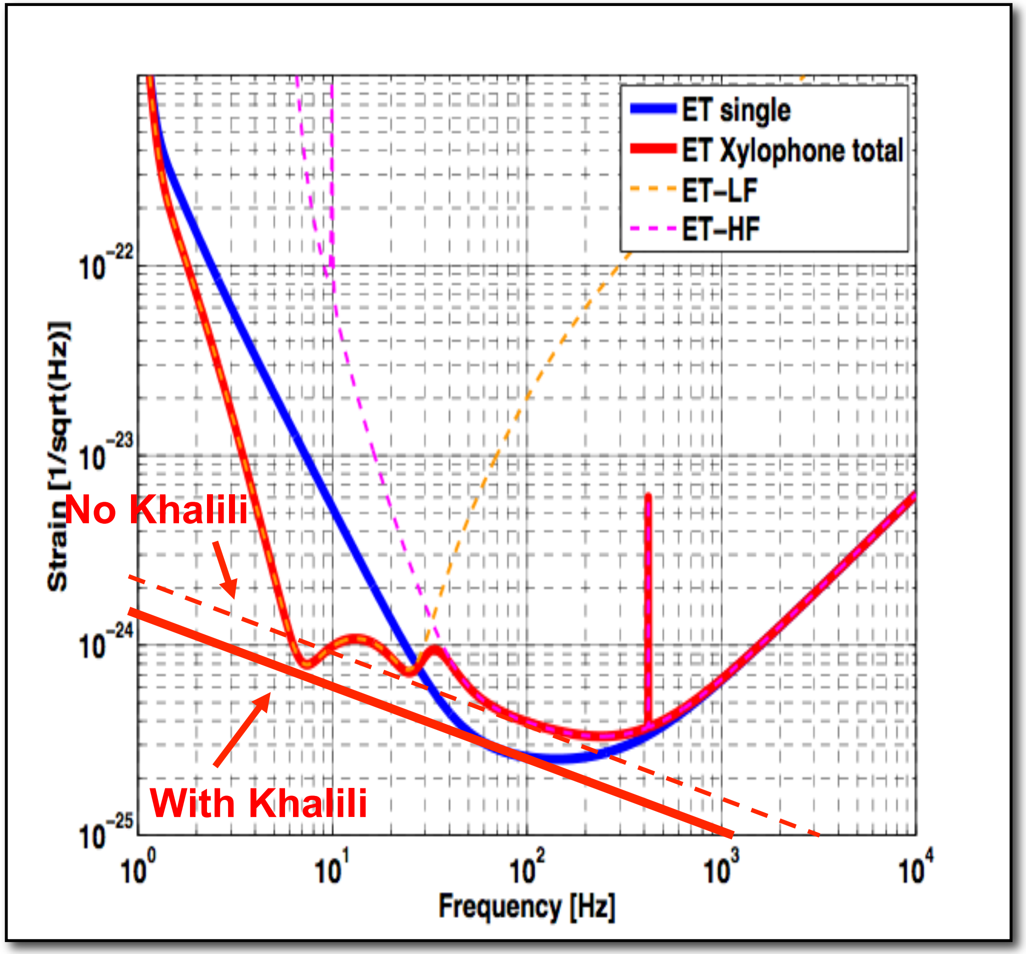


Brückner et al., Optics Letters 33 (2008) 264 - 266

End mirror (Khalili) cavities

- Khalili cavities (F.Khalili *Physics Letters A*, **2005**, *334*, 67 - 72) allow to reduce the influence of coating Brownian noise.





- Using Khalili-cavities as end mirrors, we can reduce the total mirror thermal noise of the whole interferometer by about a factor 1.5.

Summary

- 3rd Generation starts where the enhancements of the Advanced detectors hit the facility limits.
- There are many approaches to achieve the sensitivity targets … some more elegant/clever than others.
- In principle we believe it should be possible to achieve the 3rd generation sensitivity target (about factor 10 better than 2nd generation + pushing down towards a few Hz).
- Lot's of exciting challenges ahead of us!

Please join …

…. for instance by joining the ET-Science team *http://www.et-gw.eu/science-team*

EXTRA SLIDES

Time Lines (from GWIC Roadmap)