Xylophone Topologies
for the Einstein GW Telescope

Stefan Hild (University of Glasgow) ...

... and many others: S.Chelkowski, R.DeSalvo, J.Franc, R.Flaminio, A.Freise, N.Morgado, R.Nawrodt, K.Somiya, K.Strain ...

2nd ET General Meeting, Erice, Sicily, October 2009

Overview

- Some clarifications and general definitions
- A brief history of the Xylophone ideas
- Description of 2-tone antenna option for ET
  - Try to overcome the potential conflict of cryogenic mirrors with high power of ET-B.
  - Improve low frequency sensitivity
  - Short Excursion: Khalili cavities and their potential benefit for ET
- Slightly ‘crazy’ Xylophone ideas.

What are we talking about ??

- All ET-sensitivities (ET-B, ET-C …) on the sensitivity webpage (http://www.et-gw.eu/etsensitivities) are for a **single L-shaped** detector with **90 deg opening angle**. => It is not the sensitivity of a triangle.

- All the sensitivities shown in this presentation (this includes ET-B and ET-C) are based on a **'standard' Dual-Recycled Michelson** topology. *(Please see Helge's QND-document or Simon's talk for a more innovative topologies)*

- Xylophone: This term is kind of **misleading**. Perhaps better would be **multi-band antenna** or **multi-band microphone**. However, as the term 'Xylophone' is well established, let's go on with it (but keep in mind that it might be misleading).

Brief History of the Xylophone

- The xylophone concept was first suggested (DeSalvo / Shoemaker) for Advanced LIGO, proposing to complement the standard broadband interferometers with an interferometer optimized for lower frequency, thus enhancing the detection of high-mass binary systems.

  R.DeSalvo, CQG 21 (2004) S1145-S1154
  G.Conforto and R.DeSalvo, Nuc. Instruments 518 (2004) 228 - 232
  D.Shoemaker, presentation at Aspen meeting (2001), http://www.ligo.caltech.edu/docs/G/G010026-00.pdf

- The concept was then taken forward for underground observatories

  R.DeSalvo et al (Aspen), 2005, http://www.ligo.caltech.edu/docs/G/G050049-00/

- In parallel at GEO (Dissertation of A.Freise) a xylophone of several interferometers with different Signal Recycling detunings was proposed for reducing shot noise.
- So the Xylophone is an old idea. Now we just extend it for a 3rd generation detector

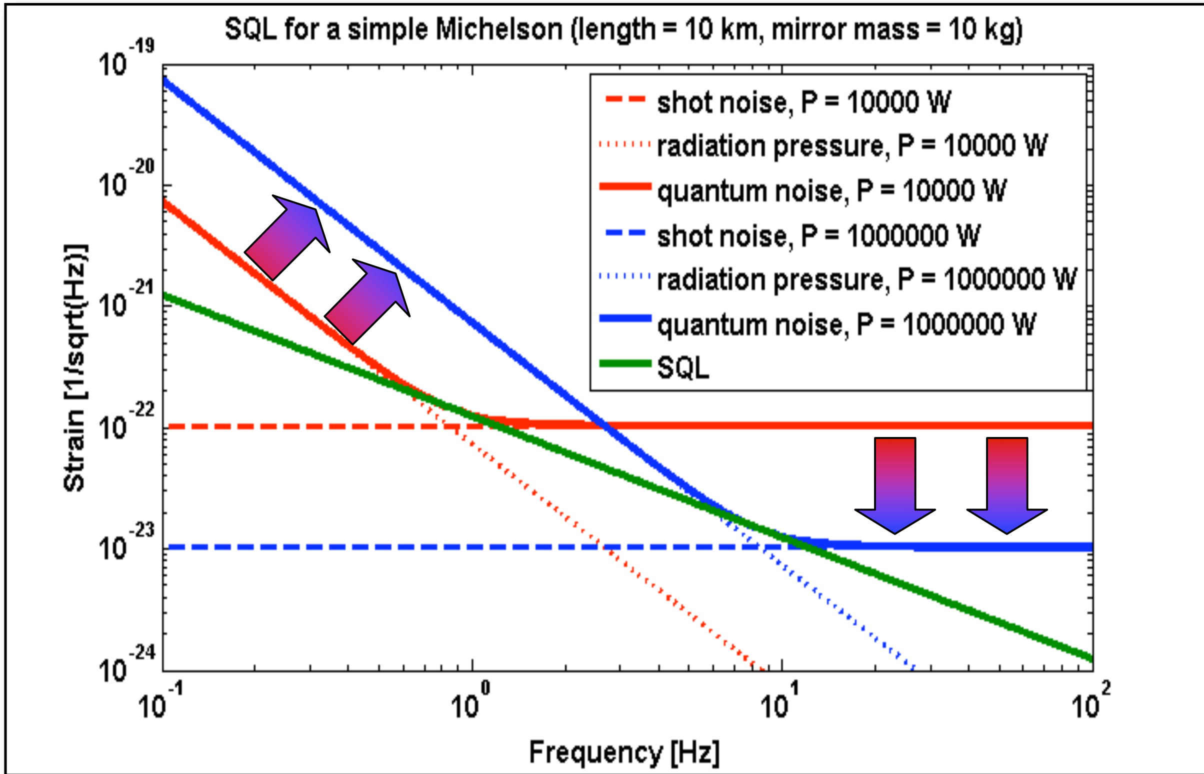
The Standard Quantum Limit (SQL)

- While shot noise contribution decreases with optical power, radiation pressure level increases:

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

wavelength
optical power
Arm length
Mirror mass

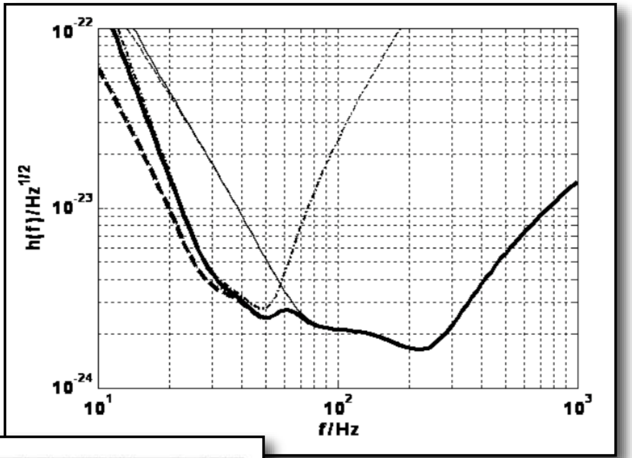
$$h_{rp}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$

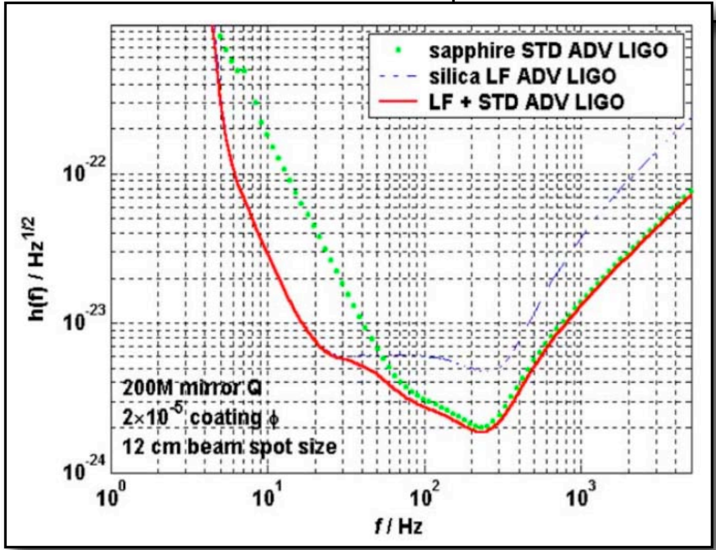


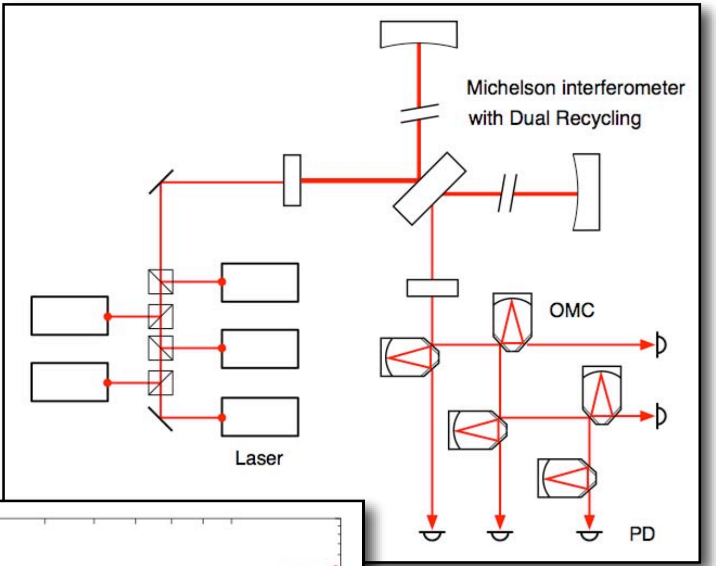
- So far the main driver building Xylophones was Quantum noise.

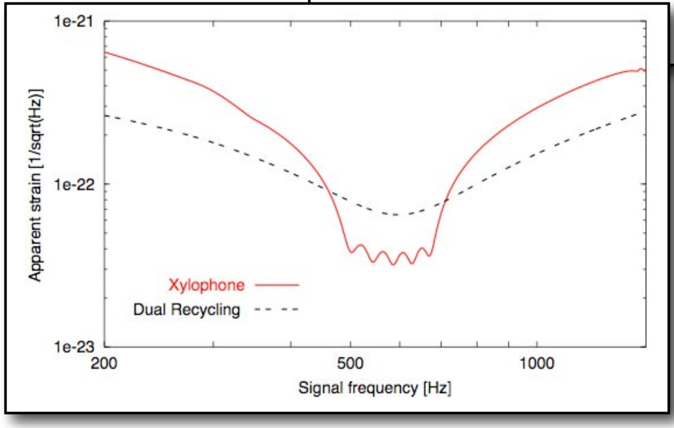
Some examples of previous Xylophone ideas

DeSalvo









Freise

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1 Year ago: Brute Force Approach

- Brute force approach + some magic.
- What changes are required to transform a Advanced Detector to ET?
- Very crude estimates = strawman-design!
- This is curve is what we call now ET-B.
- Details in arxiv:0810.0604

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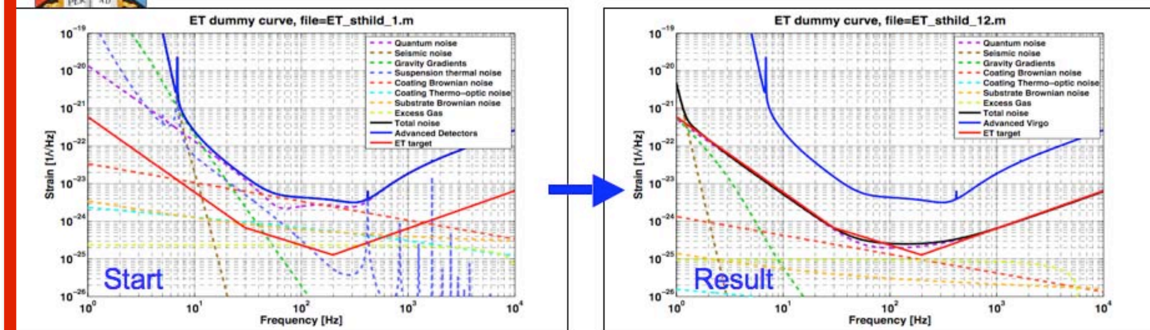
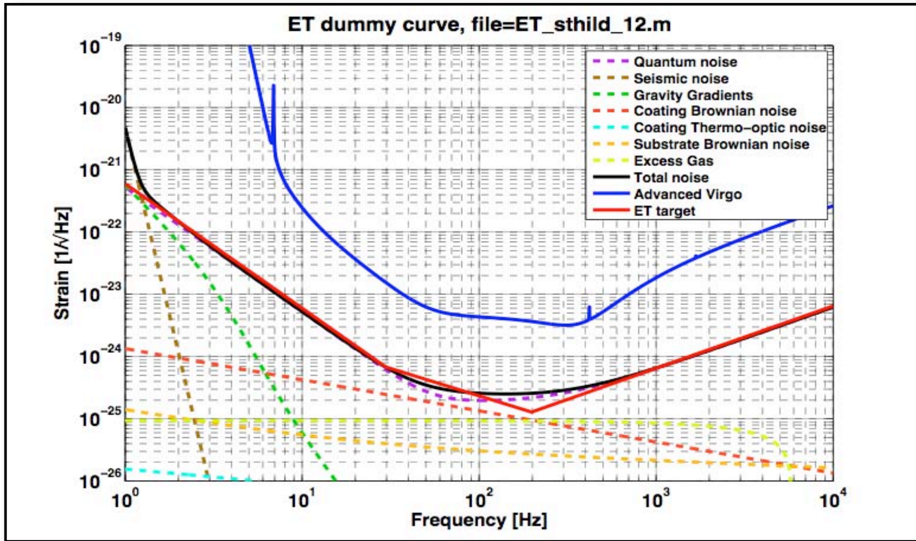


	advanced detector	potential ET design
Arm length	3 km	10 km
SR-phase	detuned (0.15)	tuned (0.0)
SR transmittance	11 %	10 %
Input power (after IMC)	125 W	500 W
Arm power	0.75 MW	3 MW
Quantum noise suppression	none	10 dB
Beam radius	6 cm	12 cm
Temperature	290 K	20 K
Suspension	Superattenuator	5 stages 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 (cave shaping)
Mirror masses	42 kg	120 kg
BNS range	150 Mpc	2650 Mpc
BBH range	800 Mpc	17700 Mpc

Stefan Hild ET-General, November 2008 Slide 21

Potential Problems of ET-B

- MAIN PROBLEM 1: No suspension thermal noise included.



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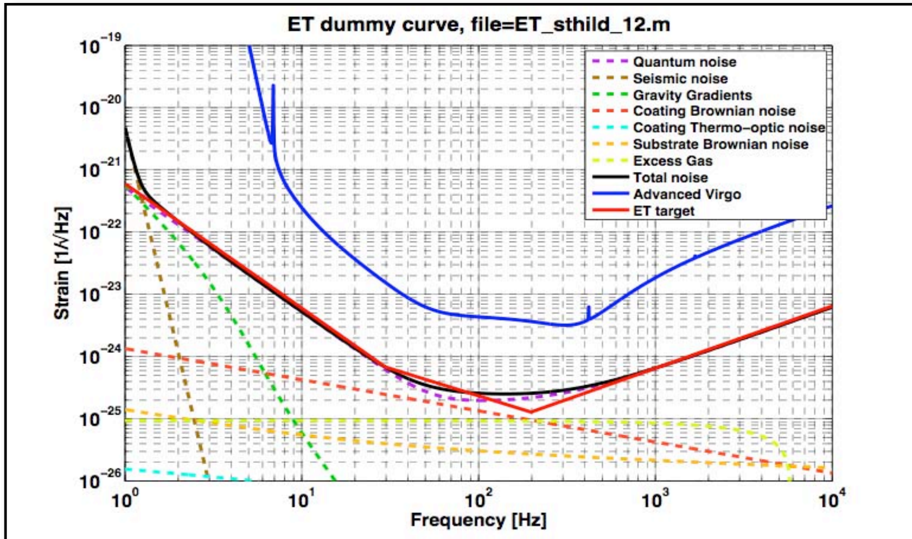

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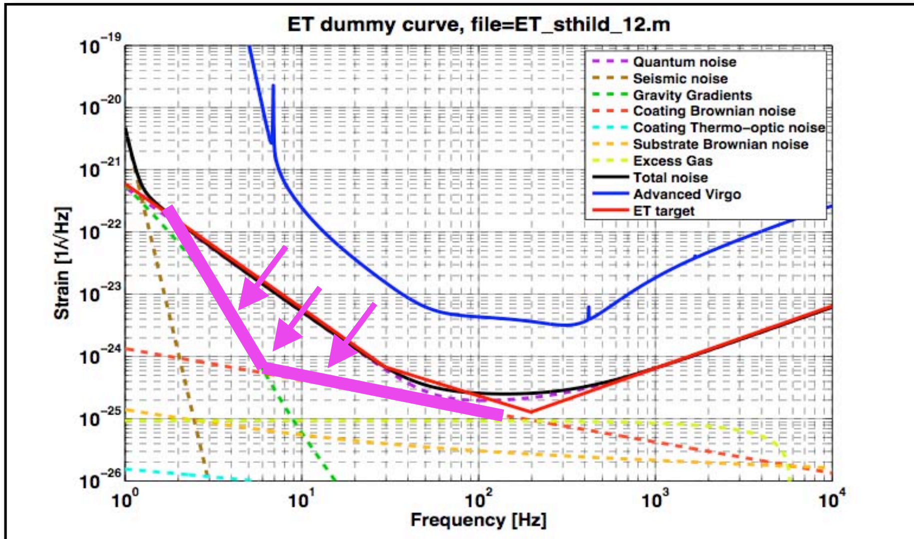
- **SIDE ISSUE:** If it is really possible to get gravity gradient, seismic and thermal noise down to the ET-B model, then we are wasting lots of sensitivity between 5 and 30Hz.



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Potential Problems of ET-B

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Not topic of this talk

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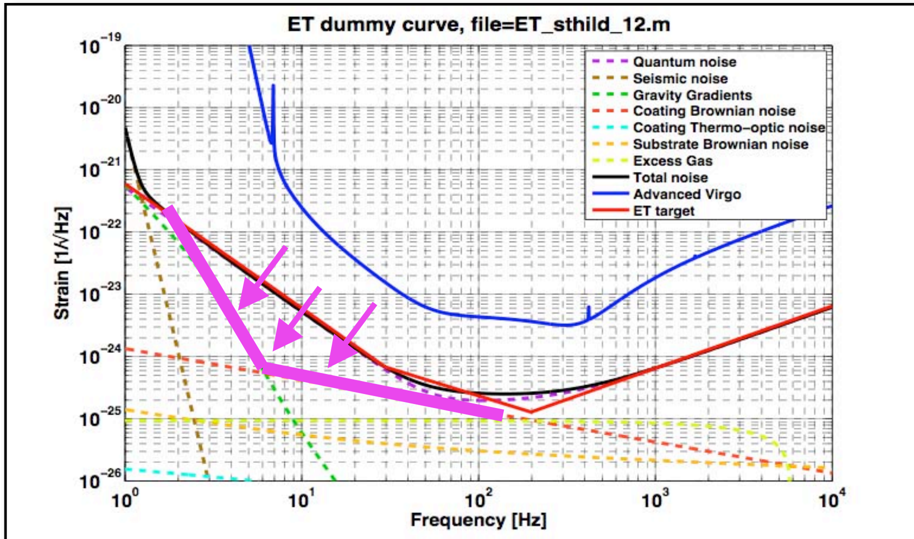
Can be solved by Xylophone



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Let’s build a 2-tone Xylophone

- High frequency detector:
  - Must: High optical power
  - Must: Roomtemperature
  - Perhaps: ‘short’ suspensions, no gravity gradient noise subtraction, surface location

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- Low frequency detector:
  - Must: Cryogenic test masses
  - Must: Low optical power
  - Must: Complicated suspensions
  - Must: Underground
  - Must: Gravity gradient subtraction
  - Perhaps: Silicon test masses, wavelength 1550nm

Let’s build a 2-tone Xylophone

- High frequency detector:
  - Must: High optical power
  - Must: Roomtemperature
  - Perhaps: ‘short’ suspensions, no gravity gradient noise subtraction, surface location

Fairly standard (‘boring’)

- Low frequency detector:
  - Must: Cryogenic test masses
  - Must: Low optical power
  - Must: Complicated suspensions
  - Must: Underground
  - Must: Gravity gradient subtraction
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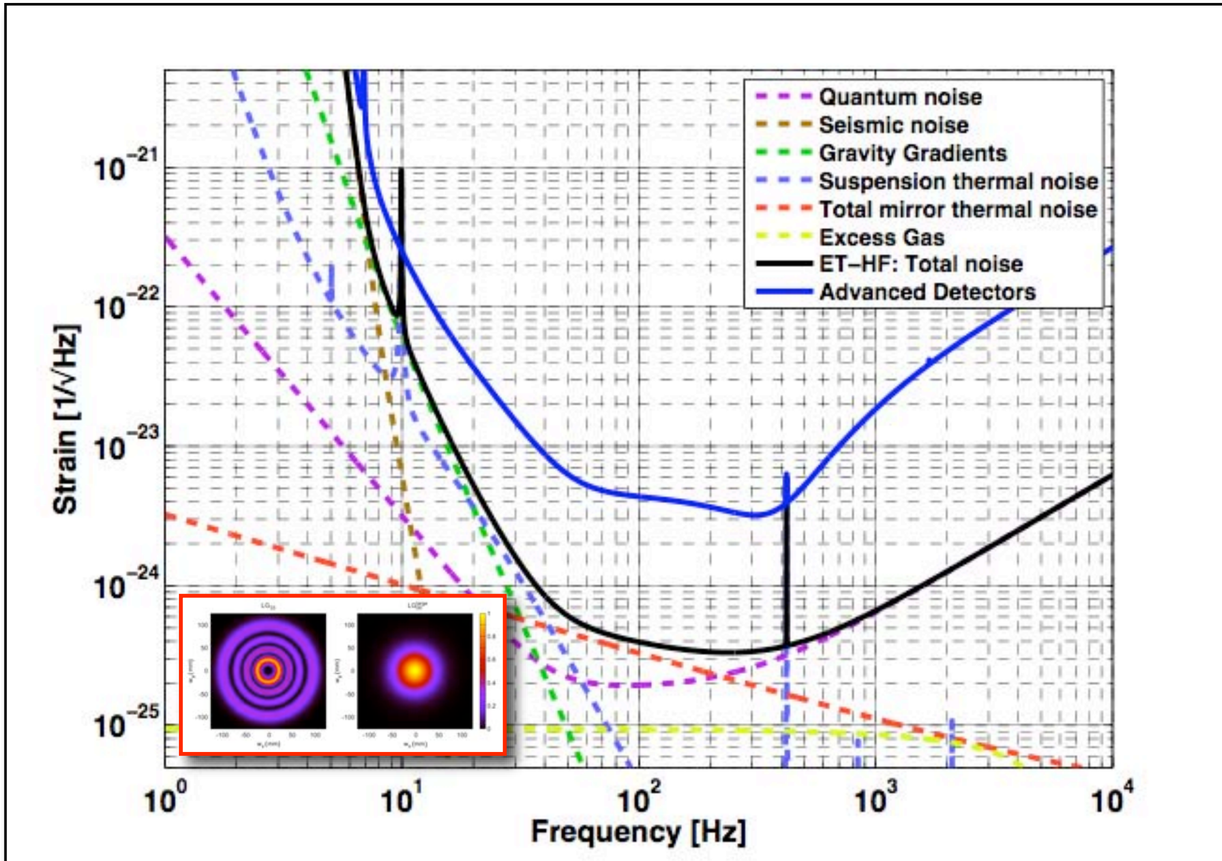
Challenging (‘lots of fun’)

High Frequency Detector

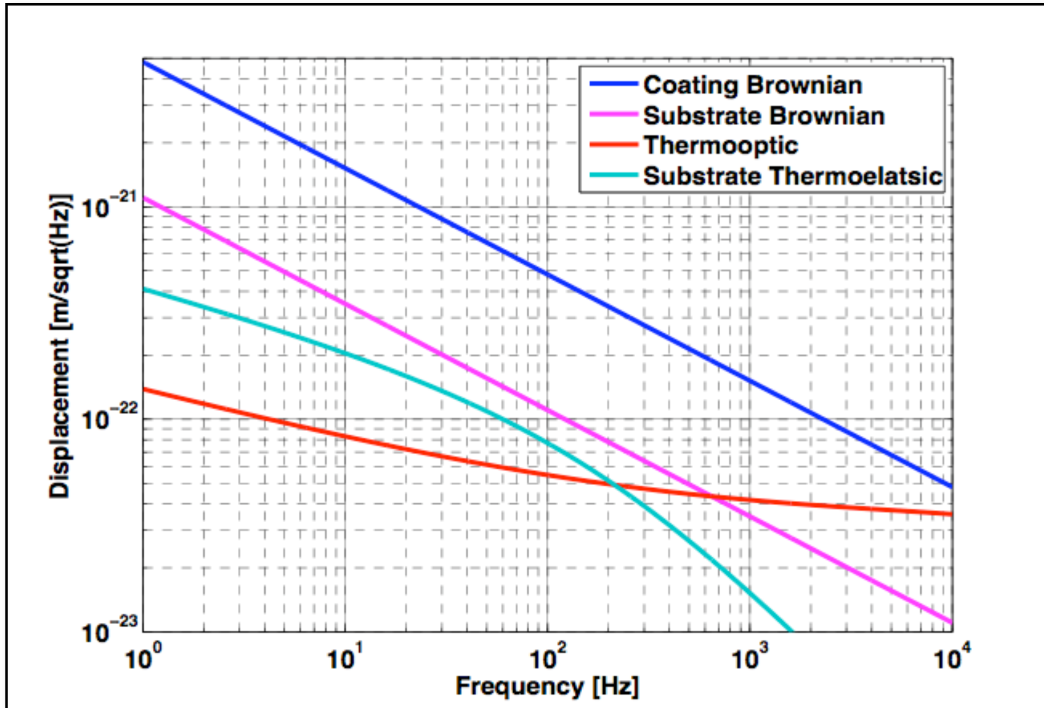
- **Quantum noise:** 3MW, tuned Signal-Recyling, 10dB Squeezing, 200kg mirrors.
- **Suspension Thermal and Seismic:** Superattenuator at surface location.
- **Gravity gradient:** No Subtraction
- **Thermal noise:** 290K, 12cm beam radius, fused Silica, LG33 (reduction factor of 1.6 compared to TEM00).



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

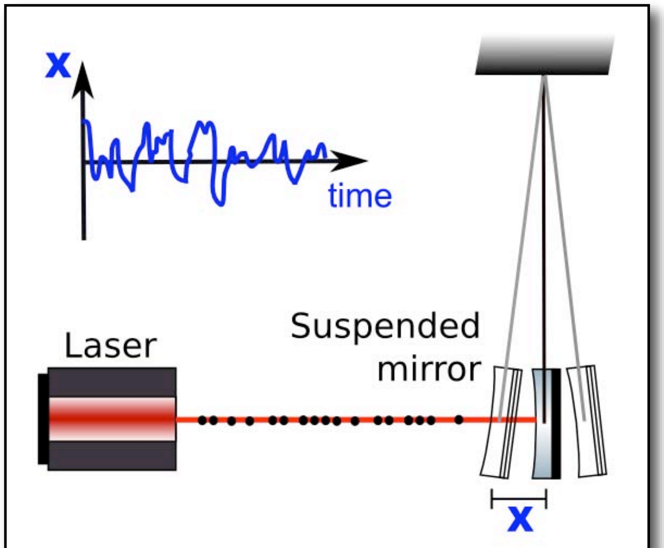
- Thermal noise of a single cryogenic end test mass.
- Assumptions:
  - Silicon at 10K
  - Youngs Modulus = 164GP
  - Coating material similar to what is currently available for fused silica at 290K (loss angles of 5e-5 and 2e-4 for low and high refractive materials)
- For more details please see talk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



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

Quantum noise changes with λ

- Quantum noise is comprised of **photon shot noise** at high frequencies and **photon radiation pressure noise** at low frequencies.
- The photons in a laser beam are not equally distributed, but follow a Poisson statistic.



photon radiation pressure noise

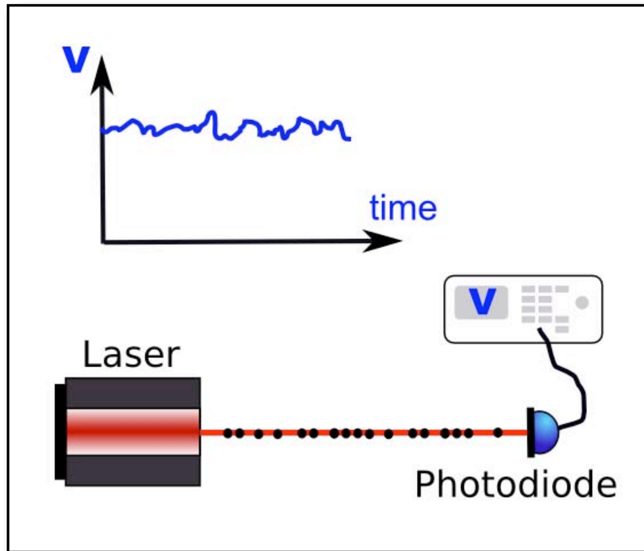
wavelength

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

optical power
Arm length
Mirror mass

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

wavelength

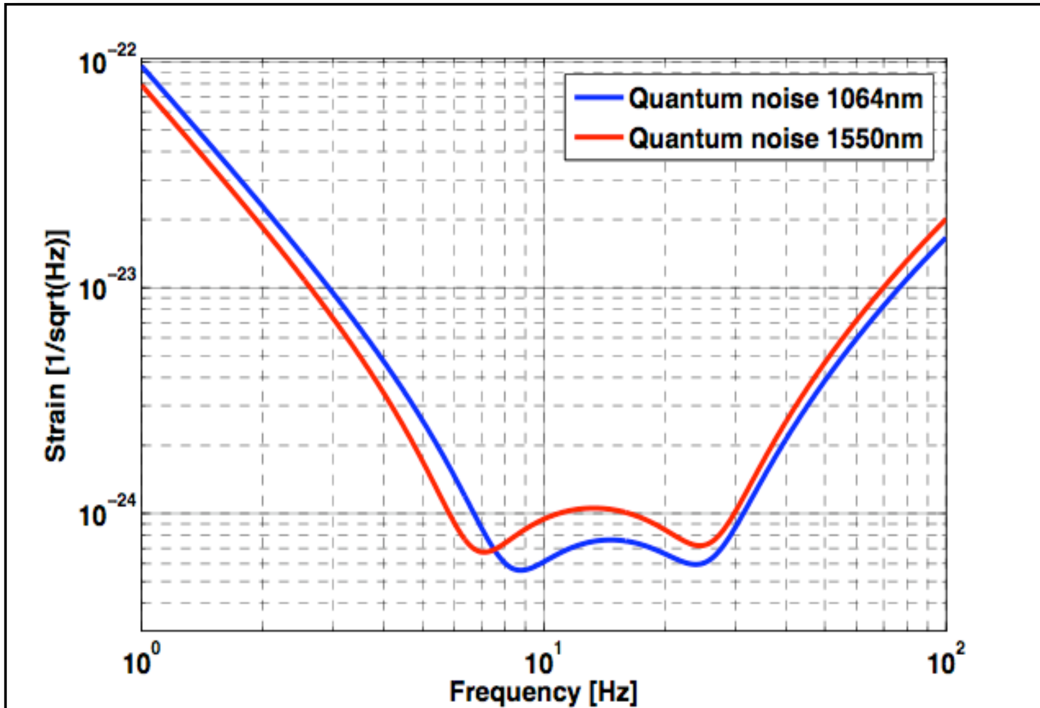


photon shot noise

Quantum noise for ET-LF at 1550nm

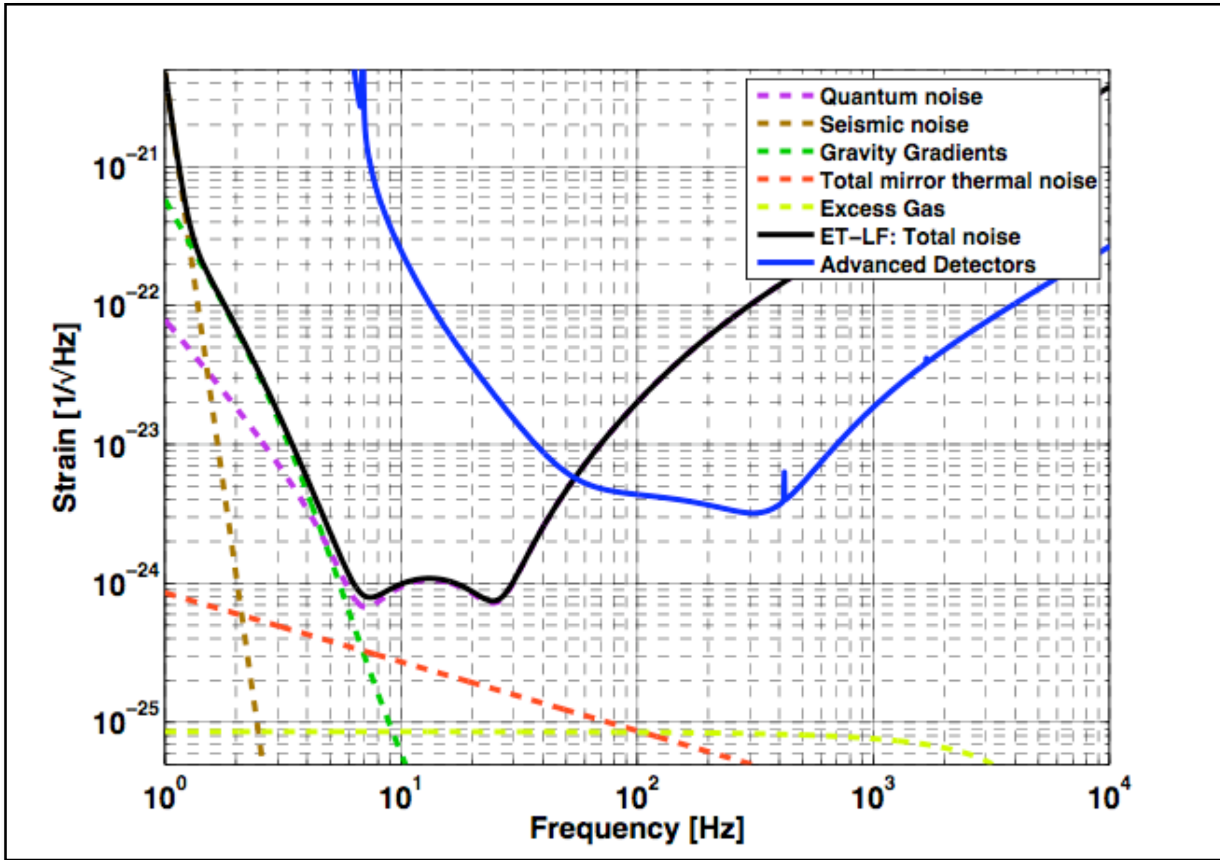
- When using Silicon test masses we will have to change from 1064nm to 1550nm.
- Quantum noise depends on wave length:
  - 1550nm: less radiation pressure noise
  - 1550nm: increased shot noise

Quantum noise of ET-LF



Low Frequency Detector

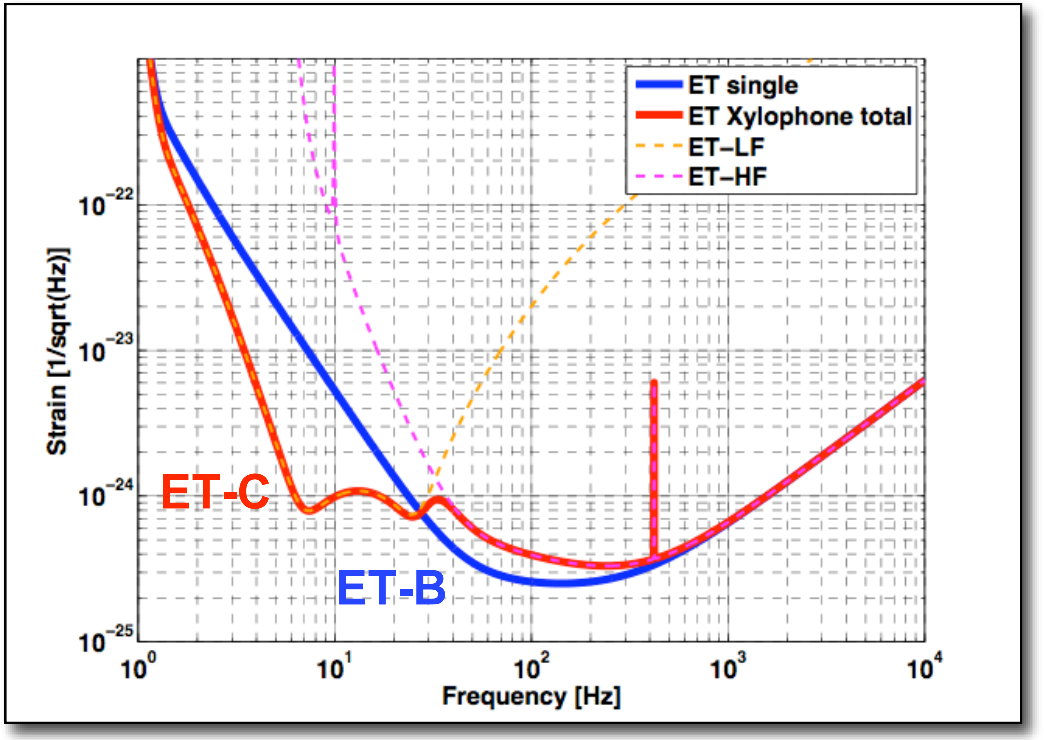
- **Quantum noise:** 18kW, detuned Signal-Recyling, 10dB Squeezing, 211kg mirrors.
- **Seismic:** 5x10m suspensions, underground.
- **Gravity gradient:** Underground, factor 50 subtraction
- **Thermal noise:** 10K, Silicon, 12cm beam radius, TEM00.
- **Suspension Thermal:** not included. :(



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

ET-Xylophone: ET-C (arxiv:0906:2655)

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



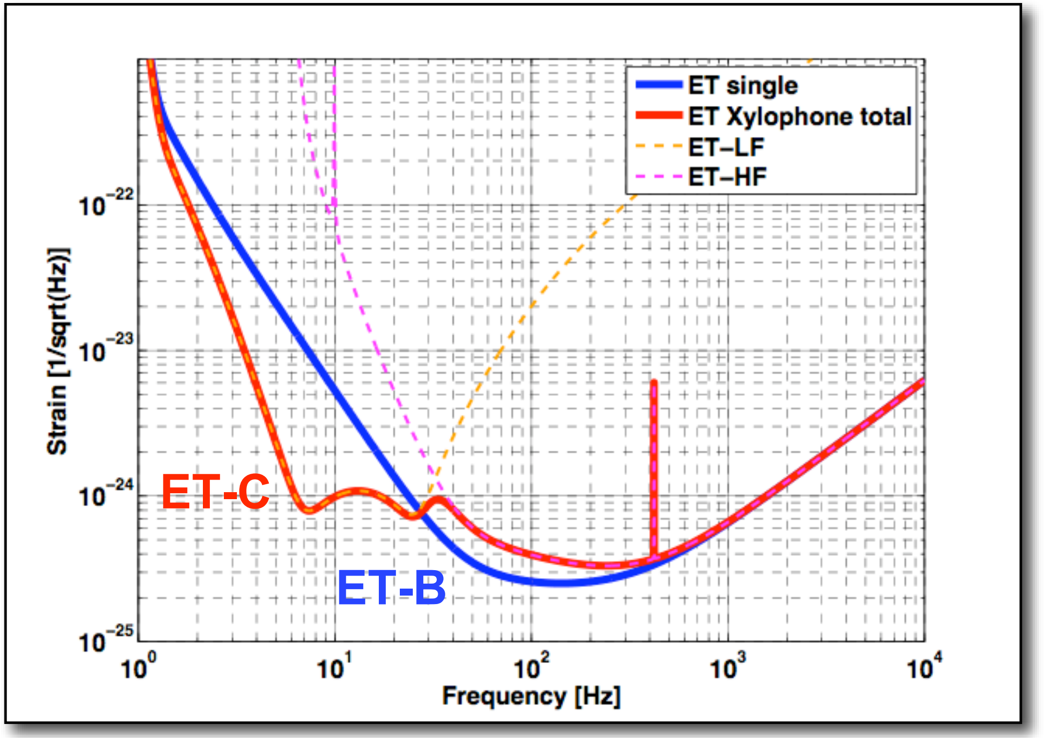
- Data from ET-LF and ET-HF can be coherently or incoherently be added, depending on the requirements of the analysis.
- For more details please see S.Hild, S.Chelkowski, A.Freise, J.Franc, R.Flaminio, N.Morgado and R.DeSalvo: 'A Xylophone Configuration for a third Generation Gravitational Wave Detector', arxiv:0906.2655 (and hopefully soon also published in CQG)

Some more detailed remarks on ET-C

- The difference in test mass weight between ET-LF (211kg) and ET-HF (200kg) originate from the different densities of fused silica and silicon. (test mass geometries are assumed to be similar)
- ET-HF is not limited by radiation pressure. Why using so heavy mirrors? For reducing Coating Brownian noise we need 60cm mirror diameter. The Brownian Coating noise analysis for finite size mirror from Somiya and Yamamoto reveals that a mirror thickness in the same order as the mirror diameter is required.
- Why are the used beam radii different in ET-LF and ET-HF? This originates from the different definition of beam radius for TEM00 and LG33. The radii are chosen in a way that both beams encounter the same clipping loss (1.6ppm) on mirror coating of 60cm diameter. Please also note that different ROCs are required for the different beams.
- We considered 62cm test mass diameter, but assumed that only 60cm are coated, leaving a 1cm rim for phase etc.
- The optical power for ET-LF was chosen by optimising the quantum noise at frequencies below 30Hz.
- As ET-LF makes use of detuned Signal Recycling, long low-loss filter cavities will be required in order to achieve a broadband quantum-noise suppression.
- Tests showed that operating the ET-LF with tuned Signal Recycling, will not give satisfactory low frequency sensitivity.
- ET-B = 2650Mpc(BNS) and 25000Mpc(BBH), ET-C = 3200Mpc(BNS) and 38000Mpc (BBH)
- For ET-HF most of the technology is available. The only things that haven't be demonstrated so far are the factor 4 higher power than in 2G, interferometry with LG33 and fused silica mirrors in the proposed dimensions.
- For ET-LF the situation is quite different. Apart from detuned Signal recycling and the low light power nearly none of the required technologies are currently available. Especially 62cm Silicon mirrors seem far away. Also the coating materials at low Temperature show much worse properties than our optimistic assumptions. Also seismic isolation levels considered in our analysis (ET-B and ET-C) haven't been demonstrated. So far no gravity gradient noise subtraction has been demonstrated.

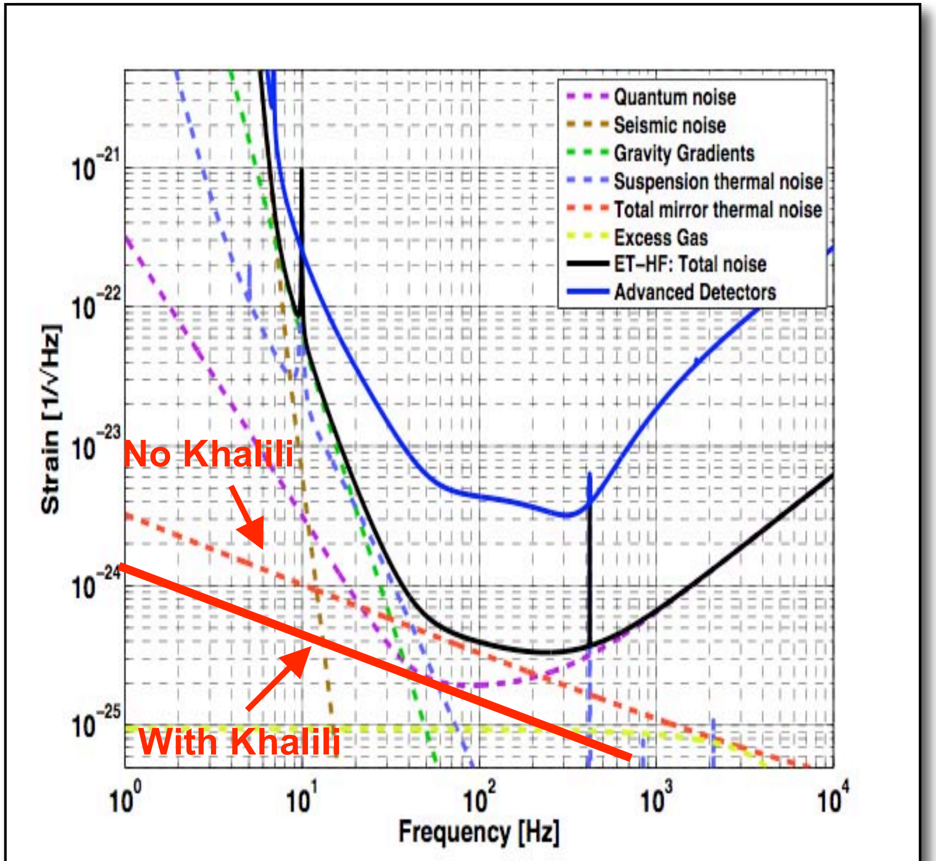
Does ET-C fulfill our aims?

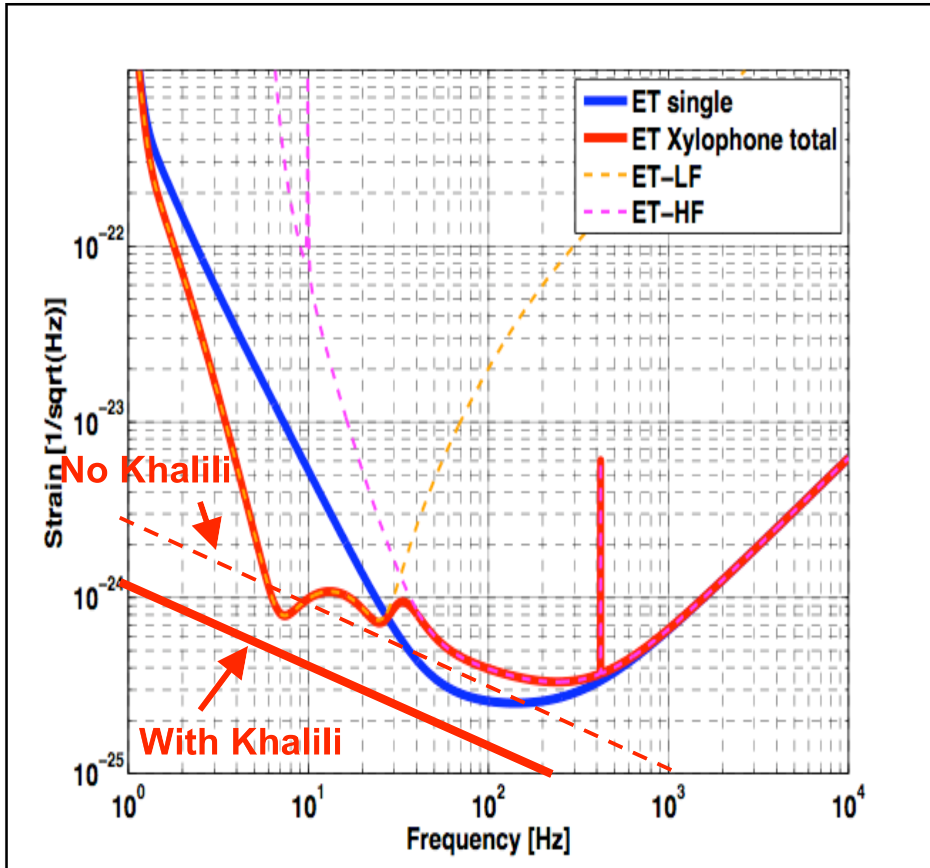
- The xylophone allows us to solve the potential high-power vs low-temperature conflict.
- The xylophone allows us to dig deeper at frequencies below 30Hz.
- However, with the xylophone we lose some sensitivity between 30 and 300 Hz (coating Brownian noise).



- *Perhaps, one potential solution would be to use Khalili-cavities as end mirrors?*

ET with Khalili-cavities (real numbers)

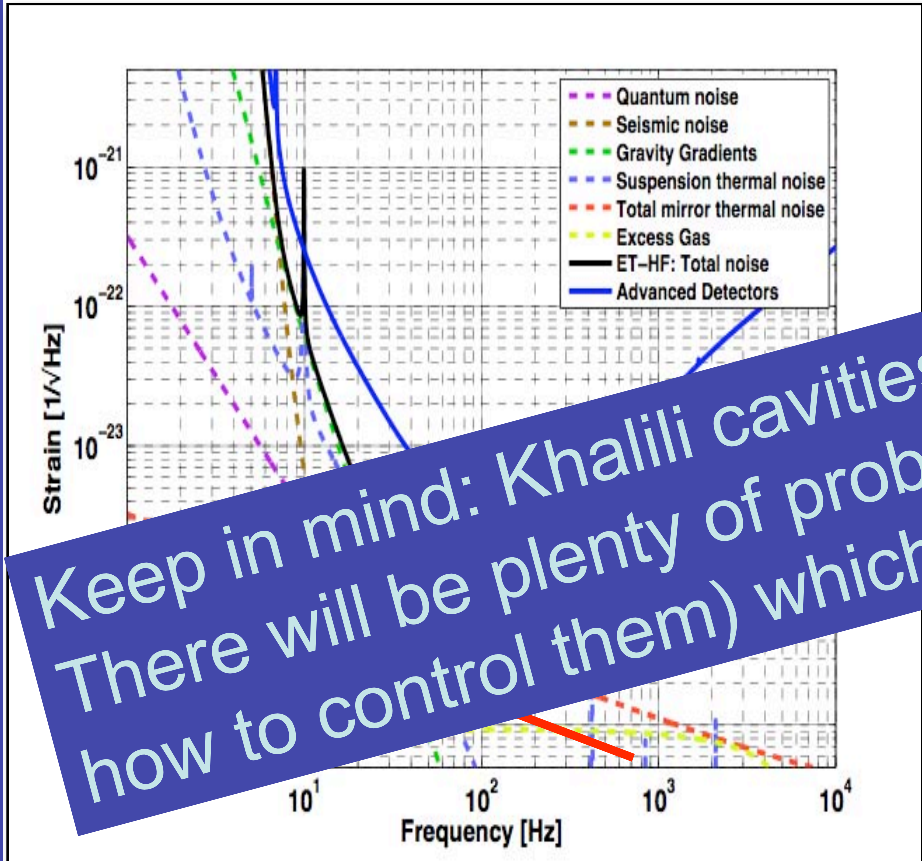


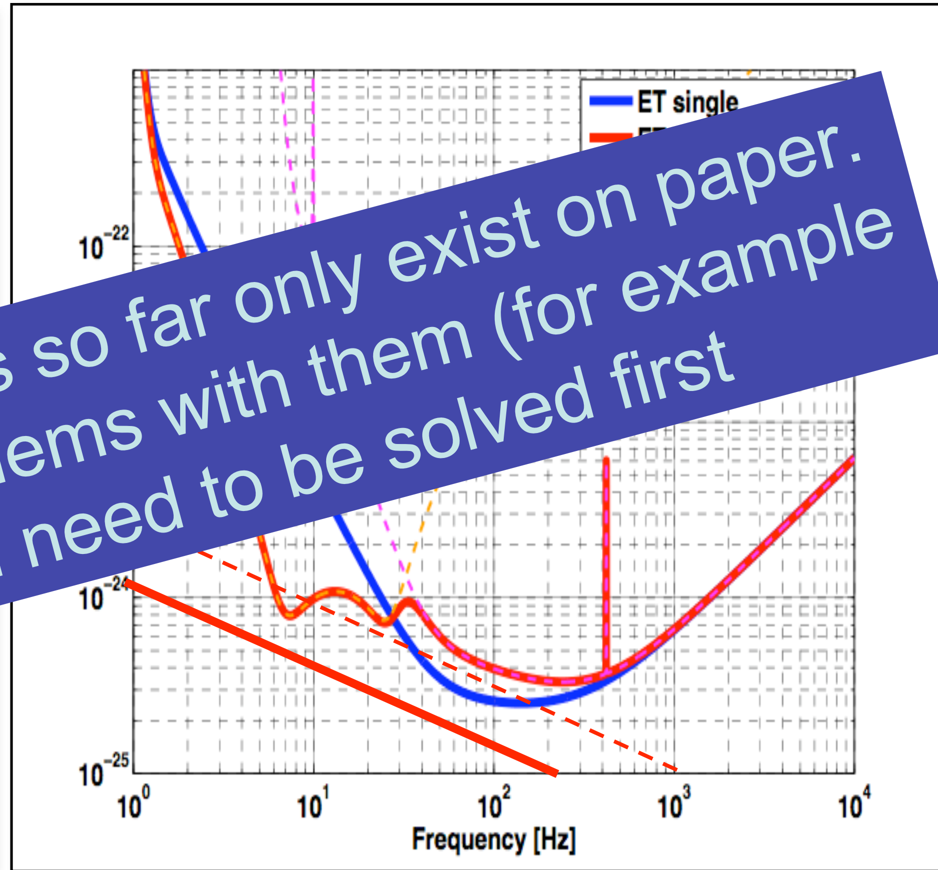


- Using Khalili-cavities as end mirrors, we can reduce the total mirror thermal noise of the whole interferometer by a factor 2.46.

Khalili-Excursion

ET with Khalili-cavities (real numbers)





Keep in mind: Khalili cavities so far only exist on paper. There will be plenty of problems with them (for example how to control them) which need to be solved first

Khalili-Excursion

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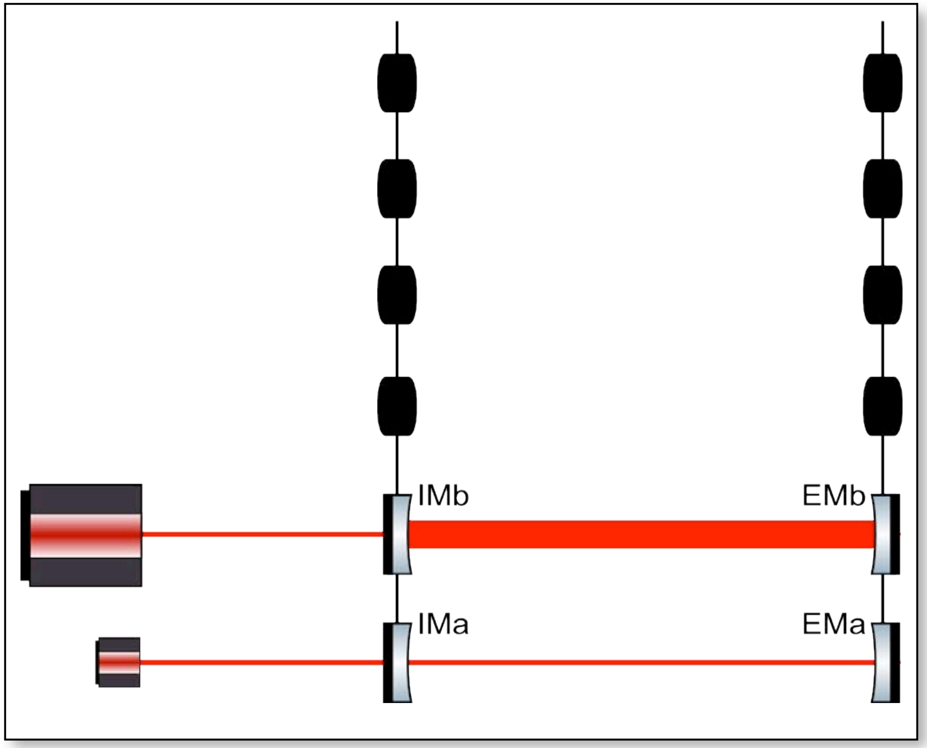
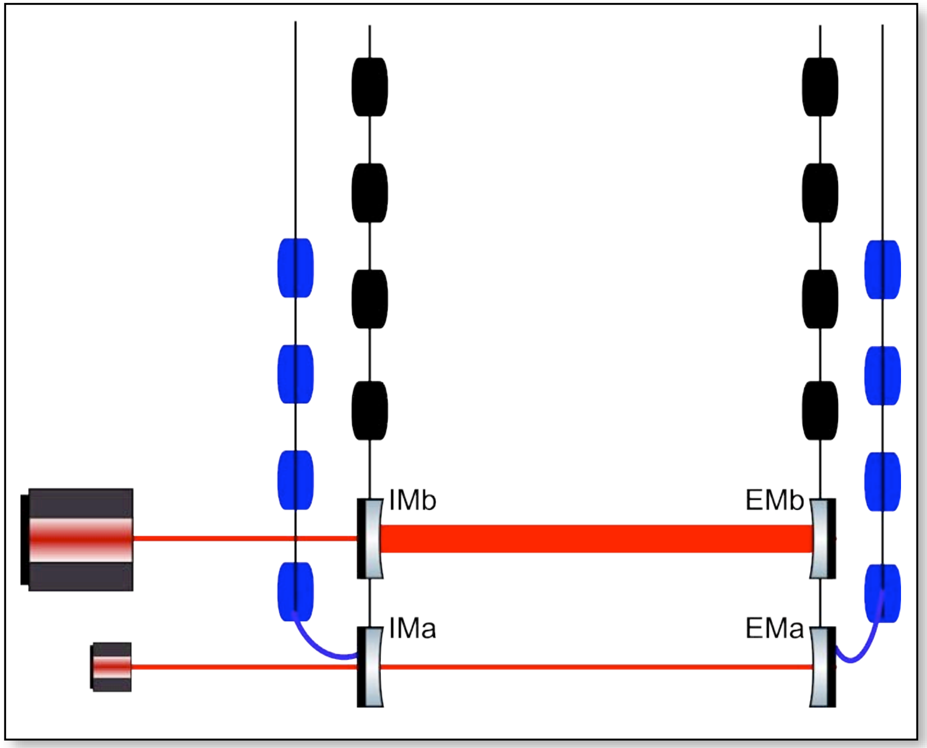
Slightly ‘crazy’ Xylophone

- Idea (Aso, Somiya, Evans) related to suspension point interferometer.
- Suspend a low-power, low-frequency interferometer below a high-power, high-frequency interferometer.
- Benefit: Just a single suspension per 2 mirrors.
- Disadvantage: Does not solve high-power, low-temperature problem.
- Technical issue: Need DC-forces on the mirrors for alignment, as fused silica fibers cannot be aligned well enough during suspension fabrication.



Slightly more 'crazy' Xylophone

- If you want to make the lower IFO cryogenic, then you have to directly connect 'the cold' to the mirror.
- Disadvantage: probably need a separate cooling chain.
- However, the cooling suspension only needs to filter, but does not need to be controlled. => Compared to a Xylophone of 2 independent IFO one might still win … ?



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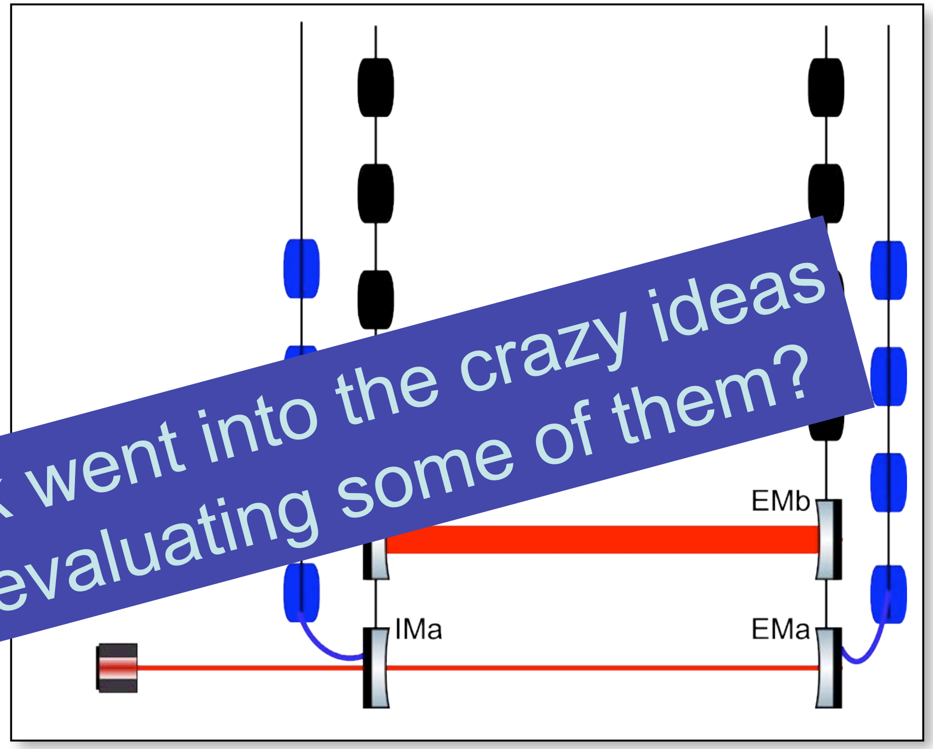

So far only very little work went into the crazy ideas
Perhaps it is worthwhile evaluating some of them?

Summary and Outlook

- Xylophones might be useful for ET:
  - Better sensitivity
  - Less technical problems
- We developed a dummy design for an ET-Xylophone (ET-C):
  - Resolves potential problem of high-power and cryogenic mirrors
  - Improves low frequency sensitivity.
- If Khalili cavities can be made working, they could potentially reduce coating Brownian (=> Even at room temperature coating Brownian below ET target at all frequencies).
- Further development of ET-B and ET-C:
  - Need to include suspension thermal noise (Input required!)
  - Need to evaluate what gravity gradient noise subtraction can realistically be achieved (Input required!)

Thanks very much for your attention!