A Xylophone Configuration for a 3G Gravitational Wave Detector

S. Hild, S. Chelkowski, A.Freise
Birmingham University

J. Franc, N. Morgado, R. Flaminio
LMA - CNRS

R. De Salvo
CALTECH

ET: Goals

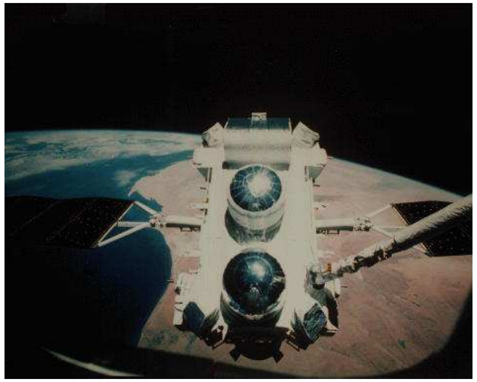
- Sensitivity100 times better than current instruments
  - Allowing to scan a one million times larger fraction of the Universe for astrophysical GW sources
- Strongly expanded bandwidth, covering the range from 1Hz to 10 kHz
  - Extension of the detection band towards the lower frequency
  - Increase the number and snr of observable gravitational wave signals
  - Enhance the astrophysical impact of third generation observatories

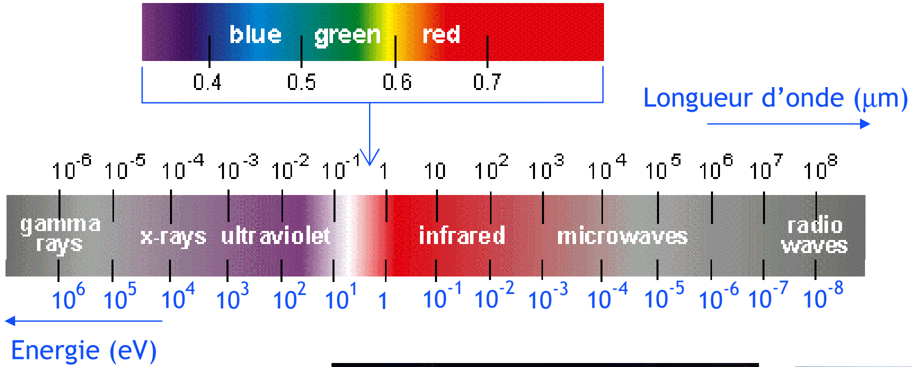
ET: Difficulty

- Spanning the detection band over four orders of magnitude in frequency is technically extremely challenging
  - Different noise types dominate the various frequency bands
  - Noises show opposite response to the involved design parameters.
- A well-known example: photon shot noise and photon radiation pressure noise
  - improve the shot noise limited sensitivity at high frequency
  - needs to increase circulating optical power
  - increases the radiation pressure noise
  - worsens the low frequency sensitivity.
  - and viceversa

Electro-magnetic astronomy approach

- Build telescopes for a specific EM spectrum band (visible, infrared, …)
- Combine the data from different wavelength bands later on





ET: The Xylophone Idea

- Build two or more GW detectors
  - each optimized for reducing the noise sources of one specific frequency band
  - altogether forming an observatory providing the desired broadband sensitivity

- For the first time the xylophone concept has been suggested for Advanced LIGO
  - proposal to accompany the standard broadband Advanced LIGO interferometers by a sophisticated low frequency interferometer
  - enhance the detection of high-mass binary systems
  - G. Conforto and R. DeSalvo, *Nuclear Instruments and Methods in Physics Research Section A* **518** (2004) 228-232

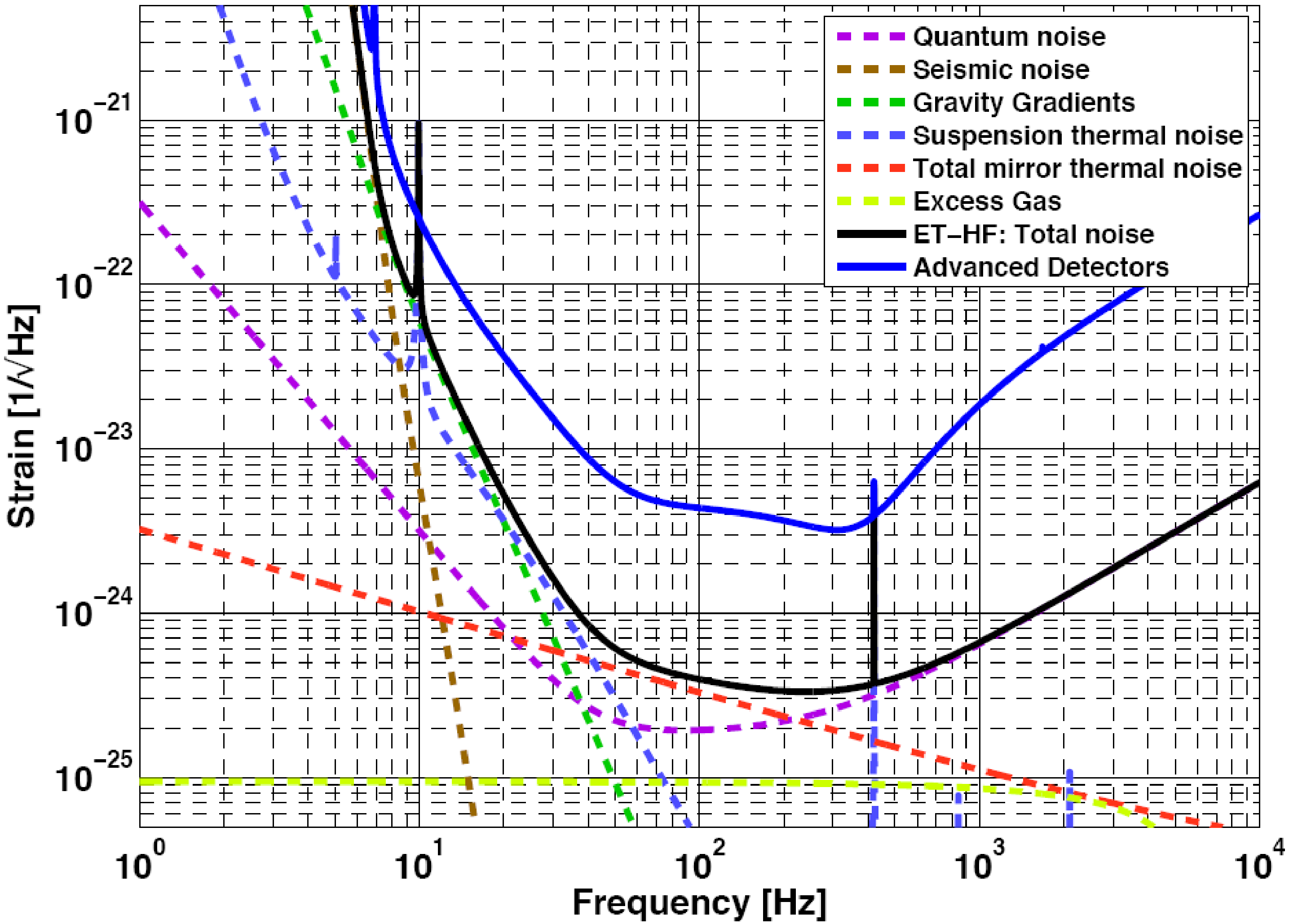
ET-HF and ET-HLF

- In order to reduce thermal noise to a compliant level in the low frequency band, it is expected that cryogenic test masses are required.
- Even though tiny, the residual absorption of the dielectric mirror coatings deposits a significant amount of heat in the mirrors
  - difficult to extract, without spoiling the performance of the seismic isolation systems
  - limiting the maximum circulating power of a cryogenic interferometer.
- Split a third generation observatory in to a low-power, low-frequency interferometer and a high-power high-frequency interferometer
  - resolves the controversy of shot noise and radiation pressure noise
  - allows to avoid the combination of high optical power and cryogenic test masses
- ET-HF and ET-LF

ET-HF

- Up-scaled version of a second generation interferometer
  - arm length of 10 km
  - circulating light power of 3MW
  - squeezed light: 10 dB
  - tuned signal recycling
  - reduce the thermal noise contributions,
    - » silica/1064 nm
    - » mirror radius/thickness/weigth: 62 cm, 30 cm, 200 kg
    - » higher order Laguerre Gauss LG33
    - » beam size 12 cm (effective i.e. 1.6 ppm losses)
  - suspension system
    - » identical to second generation GW observatory
    - » but has to cope with 200 kg mass mirror

ET-HF sensitivity

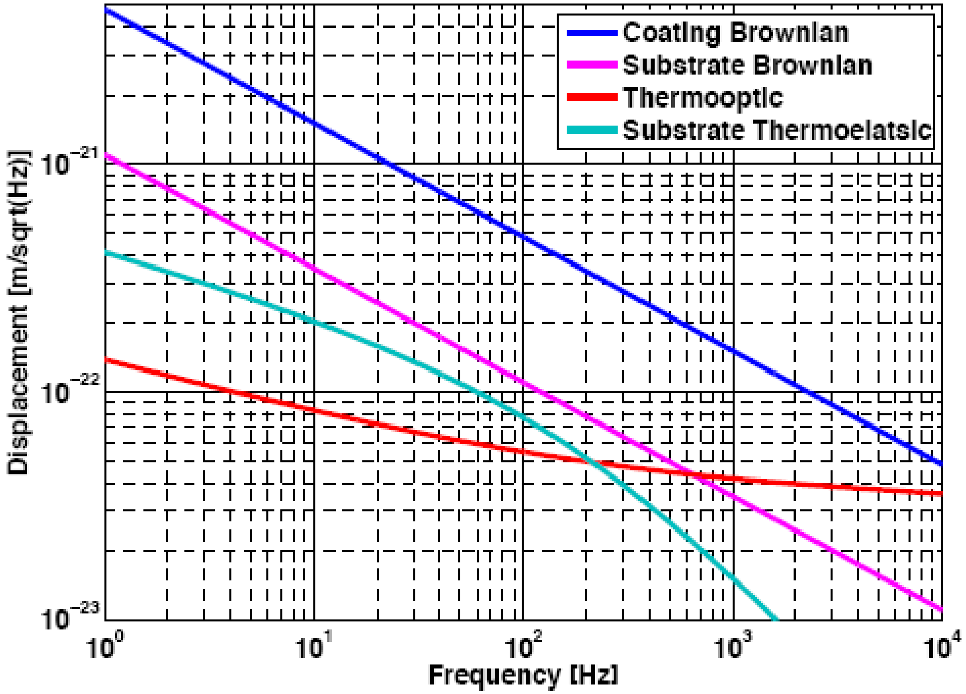


ET-LF (I)

- Low frequency xylophone interferometer features several innovative techniques
  - Extremely long suspension system: 5 suspension stages of each 10m height
  - Reduced seismic excitation of an underground location
  - Gravity gradient noise reduction of a factor 50 from subtraction technique
- Thermal noise sources significantly reduced using cryogenic test masses
  - Not impossible possible since optical power only 18kW (comparable to 1st generation)
  - Sapphire and silicon have been proposed as substrates
  - Costs, material properties and available bulk dimensions seems to slightly favor silicon.
  - Silicon test masses cooled to a temperature of 10K considered here
  - Change laser wavelength from 1064 nm to 1550 nm where Silicon is highly transmitting and has only very low absorption

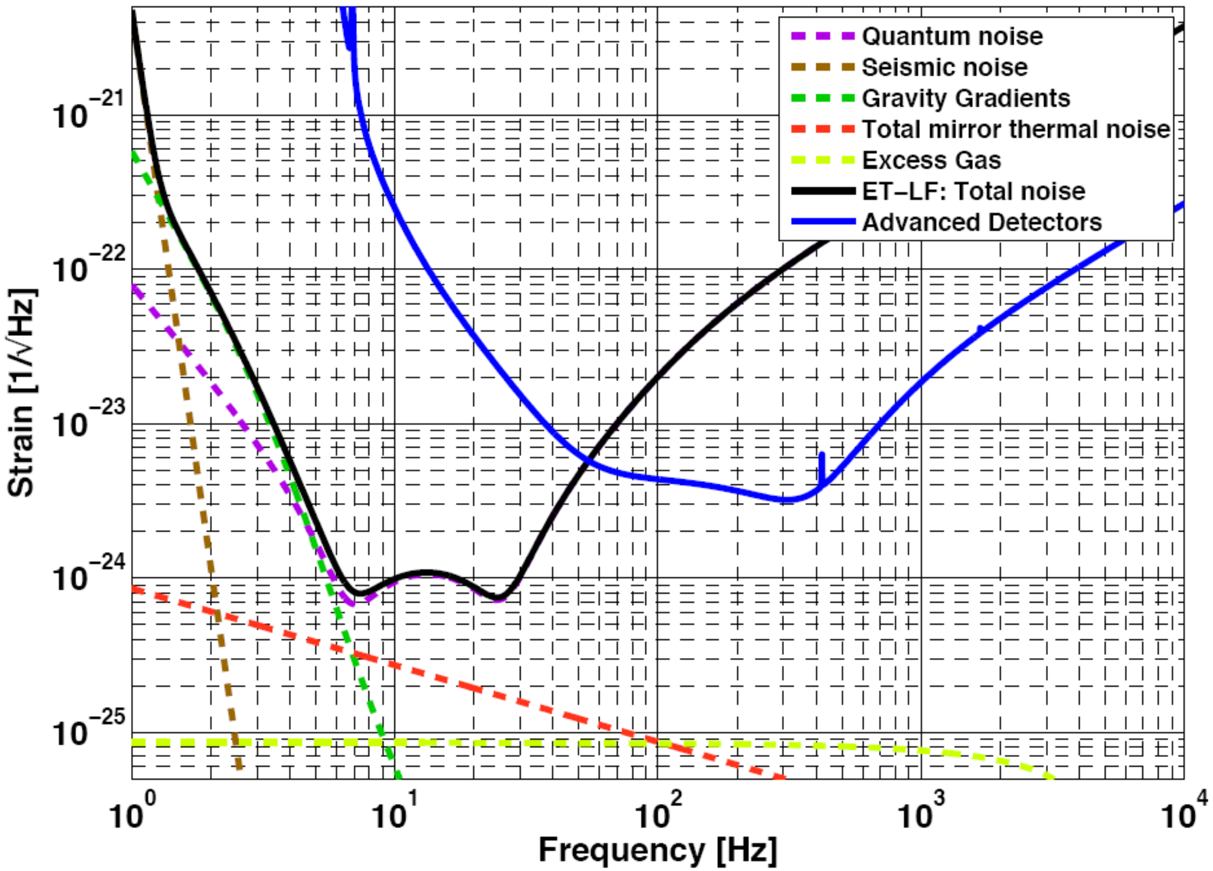
ET-LF (II)

- Coating thermal noise
  - Available measurements indicate higher loss angles for the coating materials at cryogenic temperatures than at room temperature.
  - Since research on cryogenic coatings just started recently, we optimistically assumed that by the time construction of third generation instruments starts, coatings will be available featuring the same loss angles as current coatings at room temperature.
- Resulting thermal noise contributions of a single cryogenic silicon test mass



ET-LF sensitivity

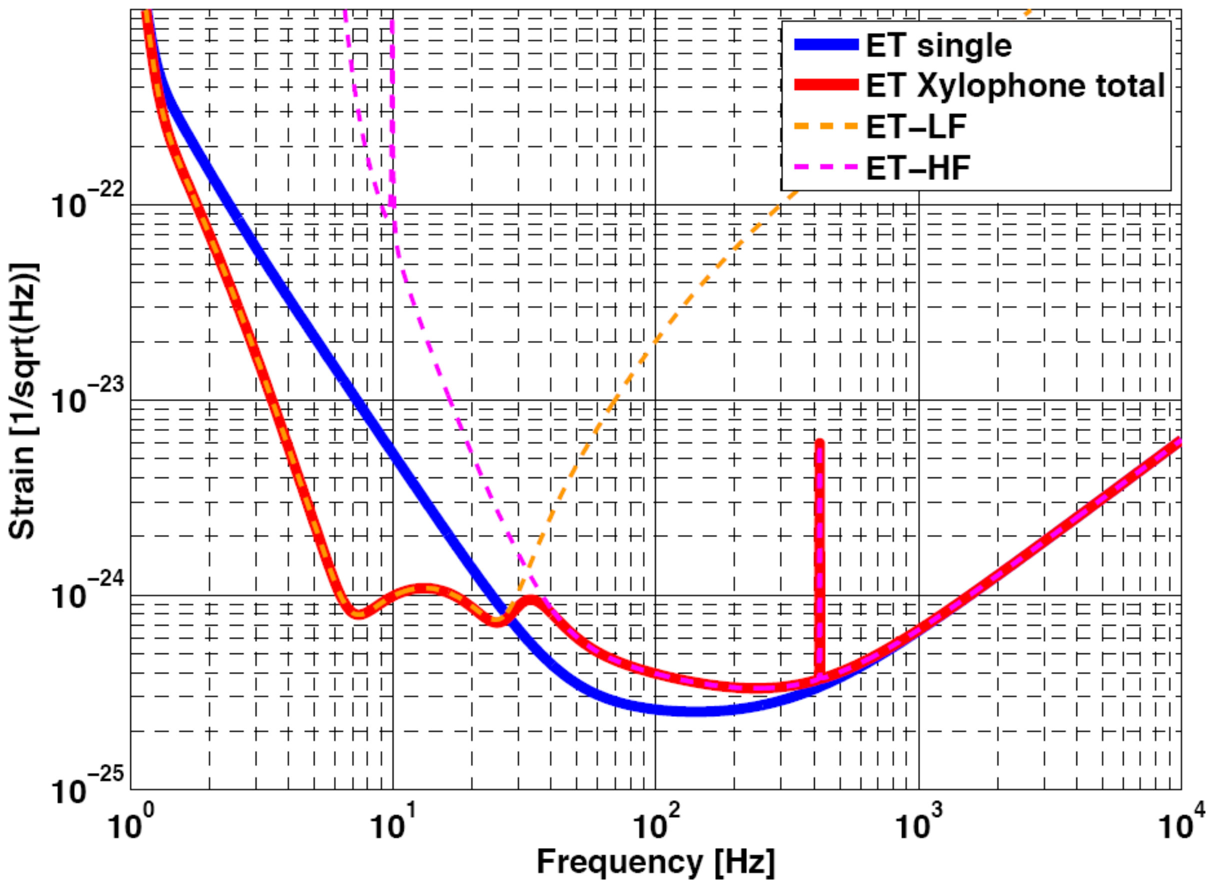
- Suspension thermal noise explicitly omitted
  - no mature noise estimates for this sources in combination with cryogenic, low-frequency suspensions exist.



ET-HF and ET-LF parameters

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

ET-Xilophone sensitivity



- Astrophysics reach
  - BNS: Single 2.65 GPc, Xylophone 3.2 Gpc
  - BBH: Single 25 GPc, Xylophone 38 GPc

Conclusions and Perspectives

- Xylophone improves technical feasibility compared to a single broadband interferometer
  - resolving the controversy of high-power and cryogenic mirrors

- Xylophone also to give significantly improved sensitivity
  - BNS: Single 2.65 GPc, Xylophone 3.2 Gpc
  - BBH: Single 25 GPc, Xylophone 38 GPc

- Investigate prospects and feasibility of a 3-tone xylophone interferometer