ET technologies

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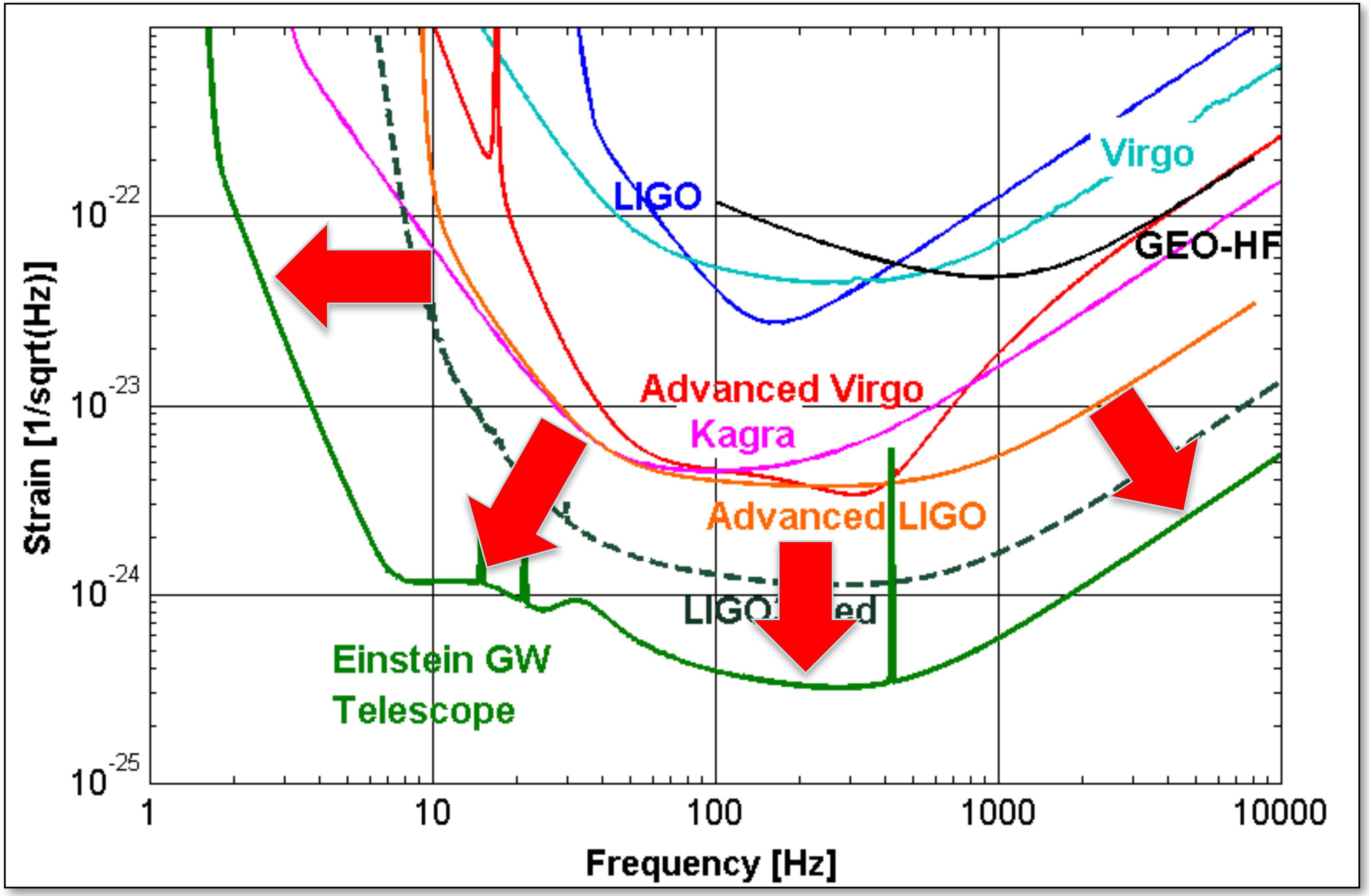
With input from M. Bader, M. Barsuglia, A. Bell, J. Degallaix, K. Dooley, V. Fafone, R. Falminio, A. Freise, H. Grote, R. Gouty, G. Hammond, J. Harms, H. Lueck, B. Mours, C. Mow-Lowry, I. Martin, M. Punturo, L. Rolland, A. Rossi, M. Tacca, B. Willke, J. van der Brand, JP. Zendri

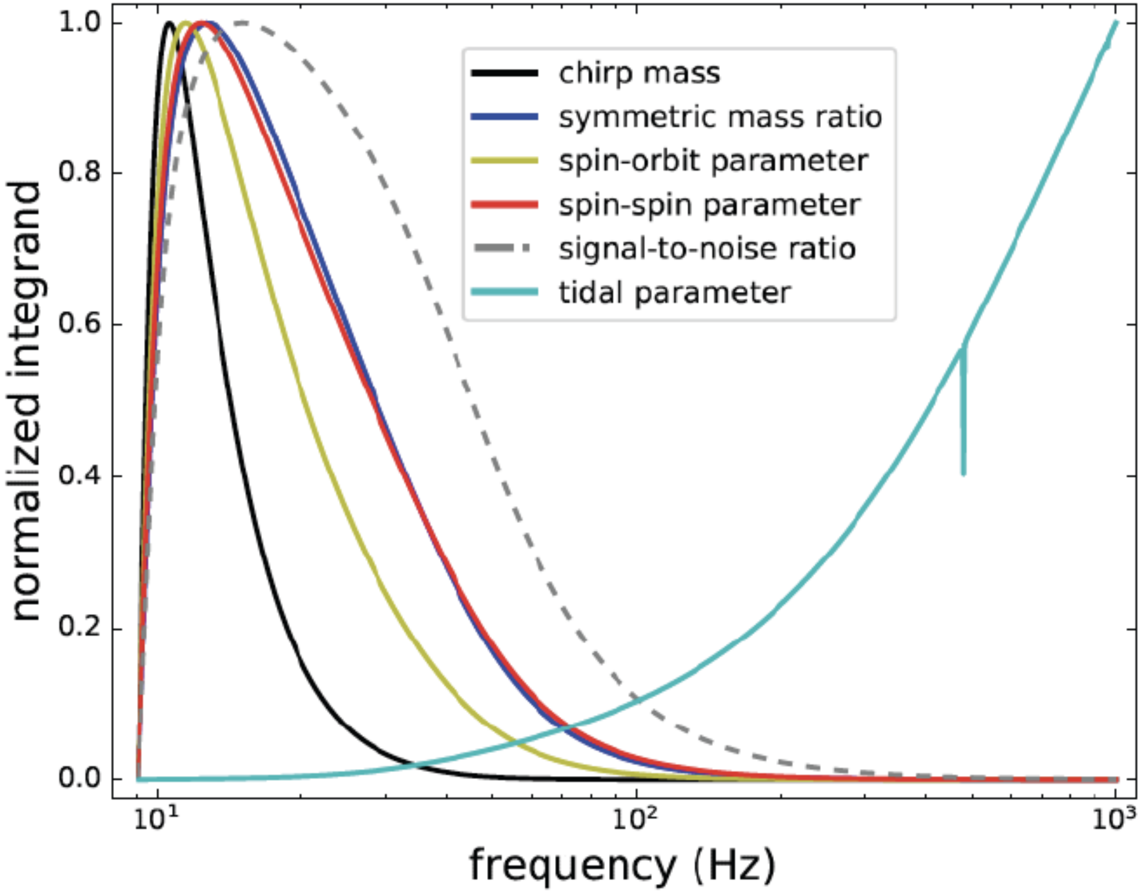
Overview

- Reminder: Sensitivity targets
- ET Top Level Design + Overview of ET Technologies
- Some thoughts on ET costs

ET sensitivity in context



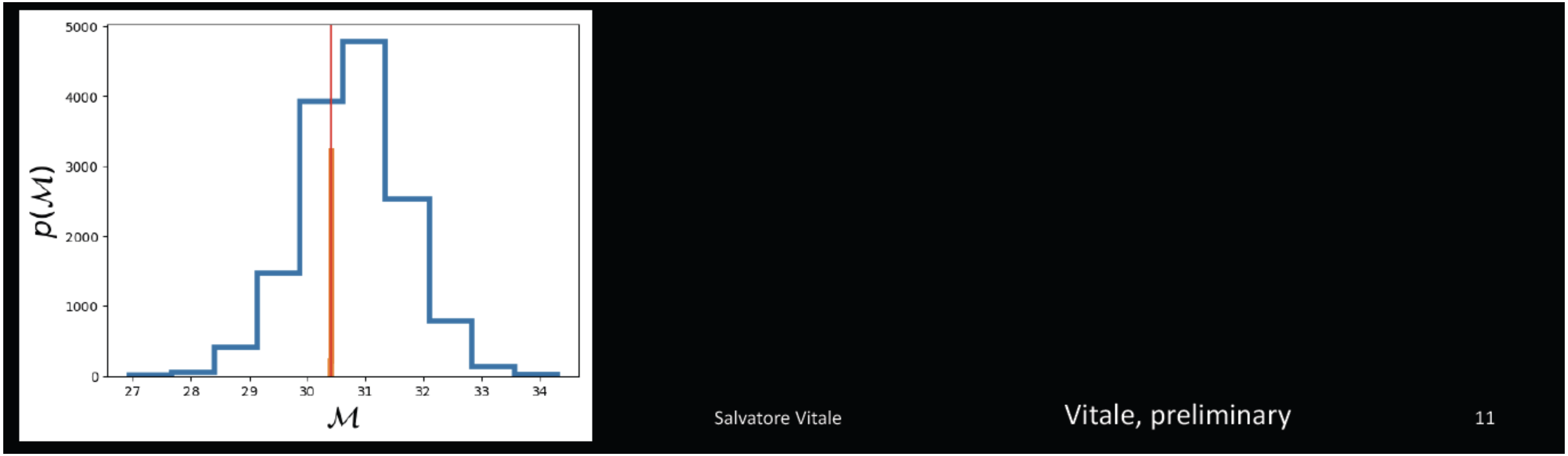
At what frequencies do we need to improve?



I. Harry & T. Hinderer arXiv:1801.09972

Source Parameter Estimation with ET

- How would GW150914 look in ET?



Source Parameter Estimation with ET

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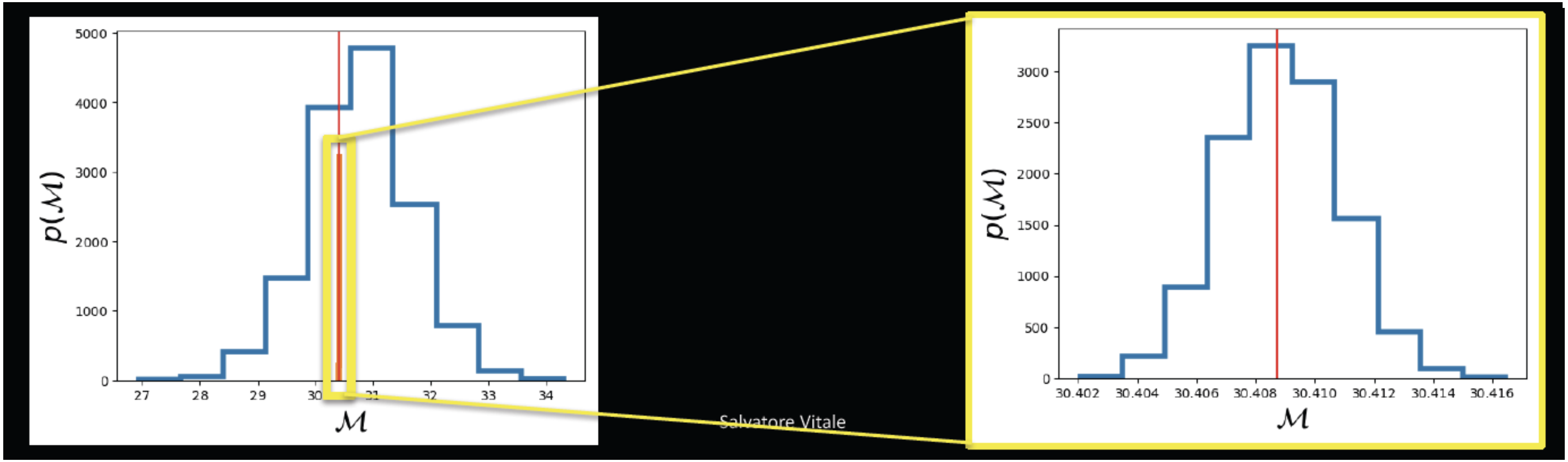
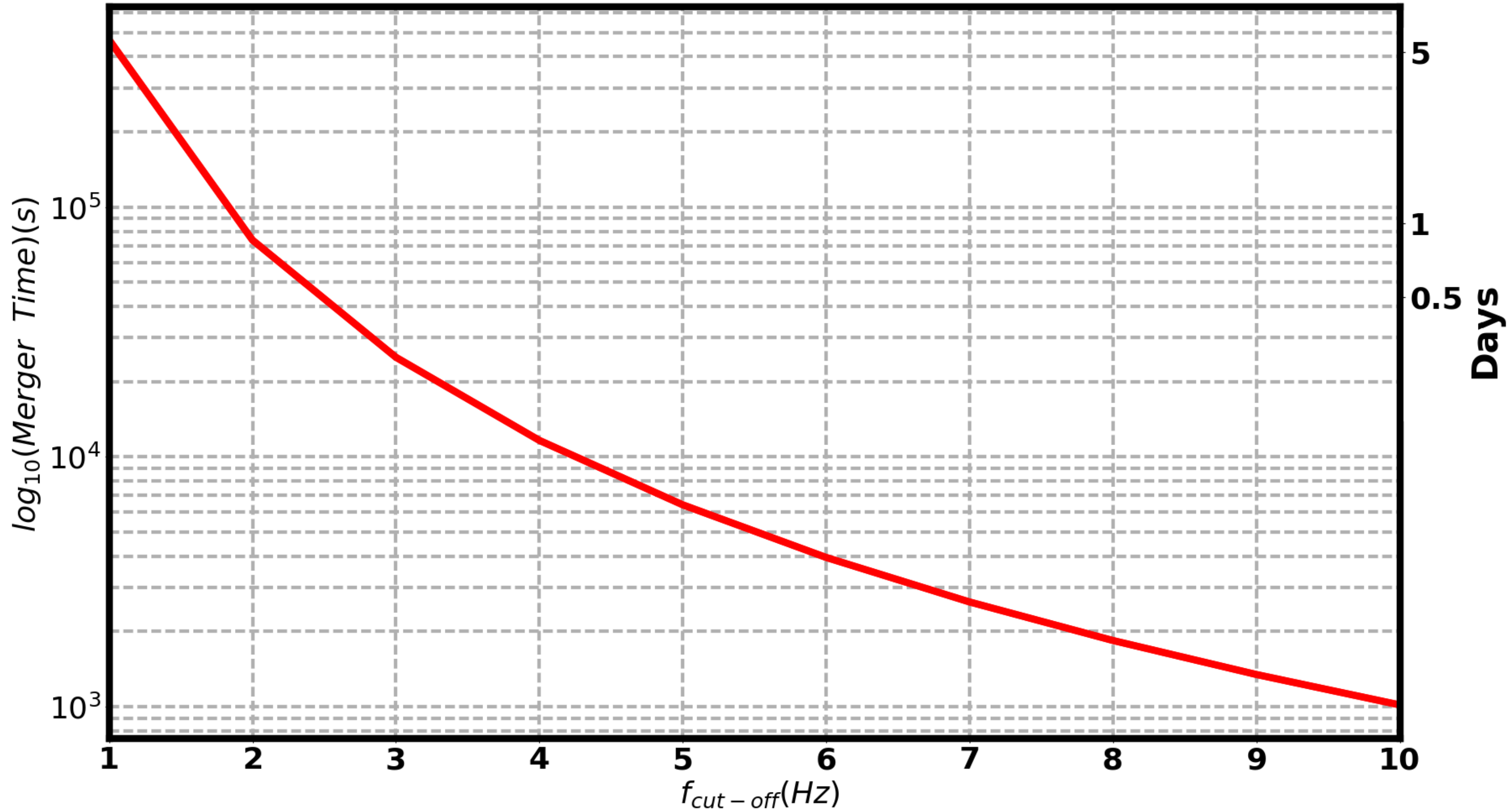


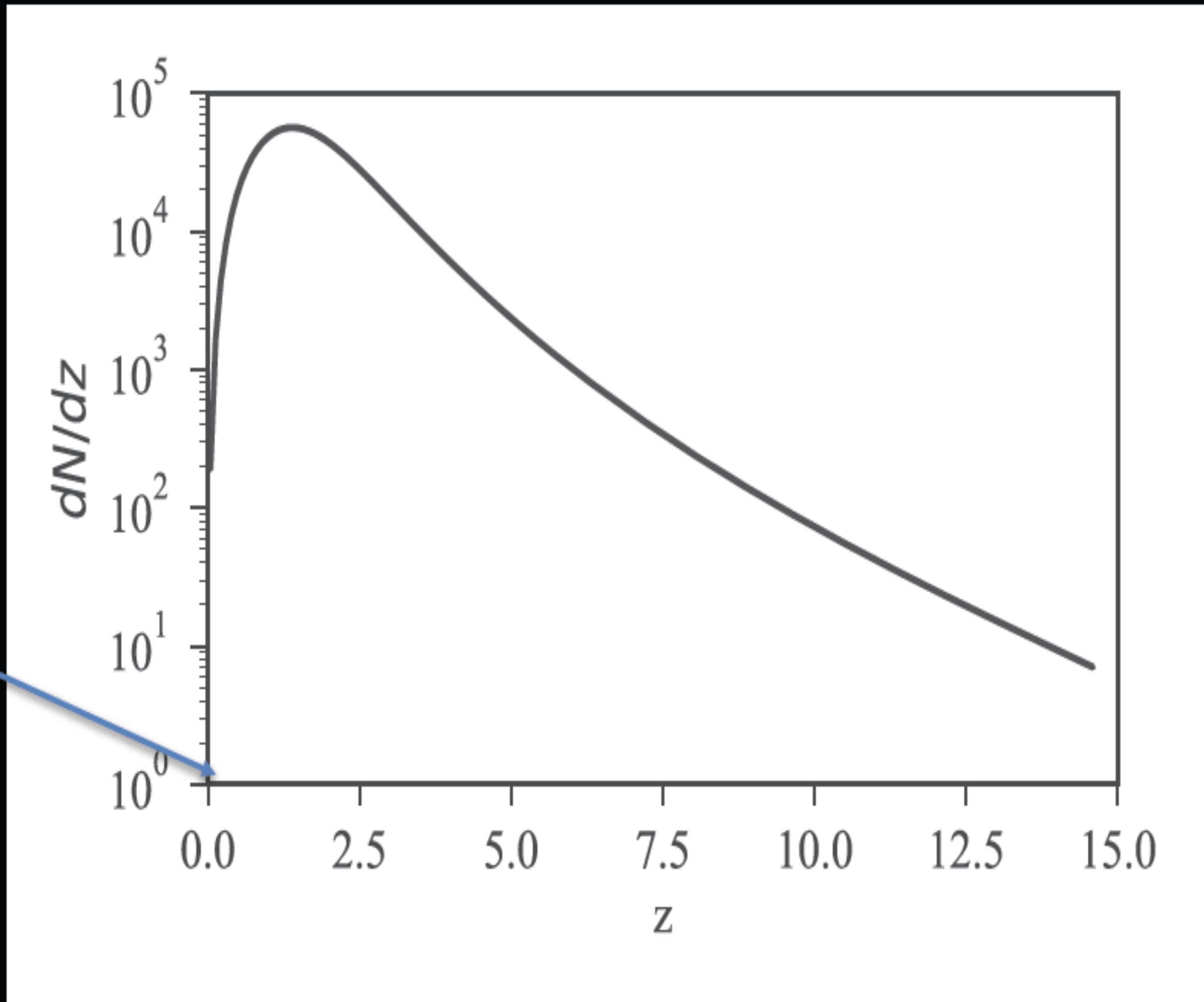
Inspiral times

- What is the gain from pushing from 10Hz down to 2Hz?



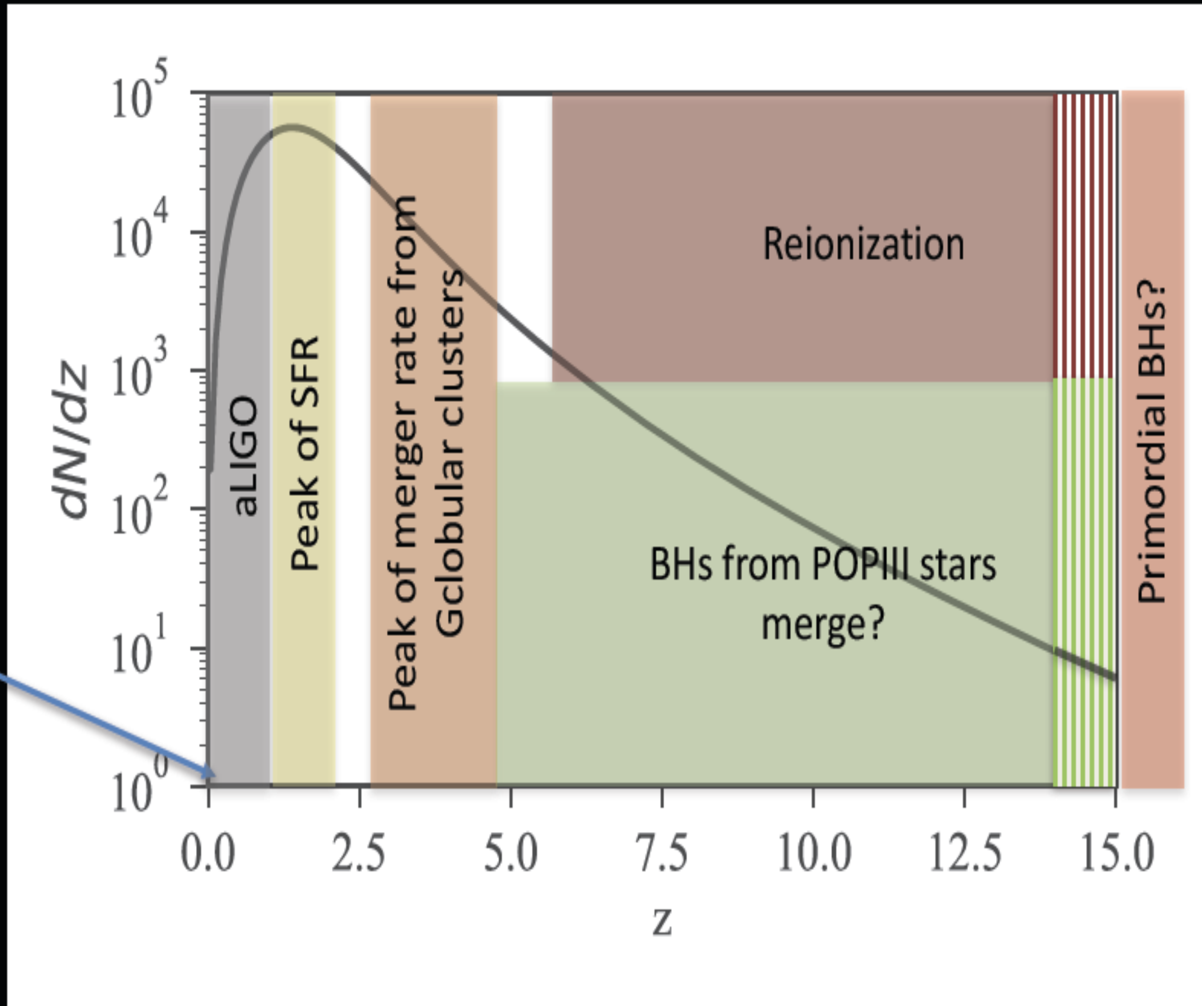
Where are we?

You are here!

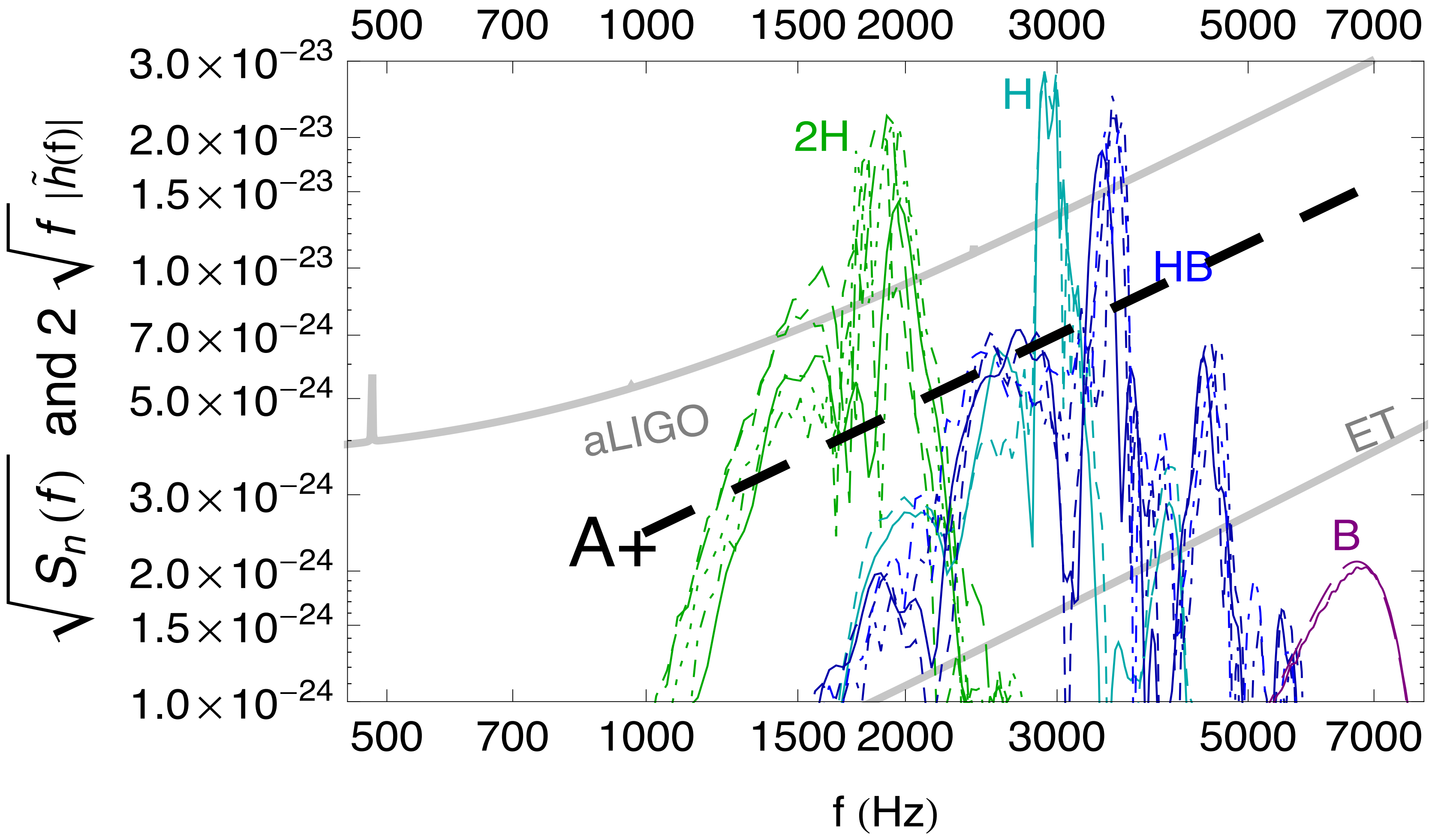


Where do we go from here?

You are here!



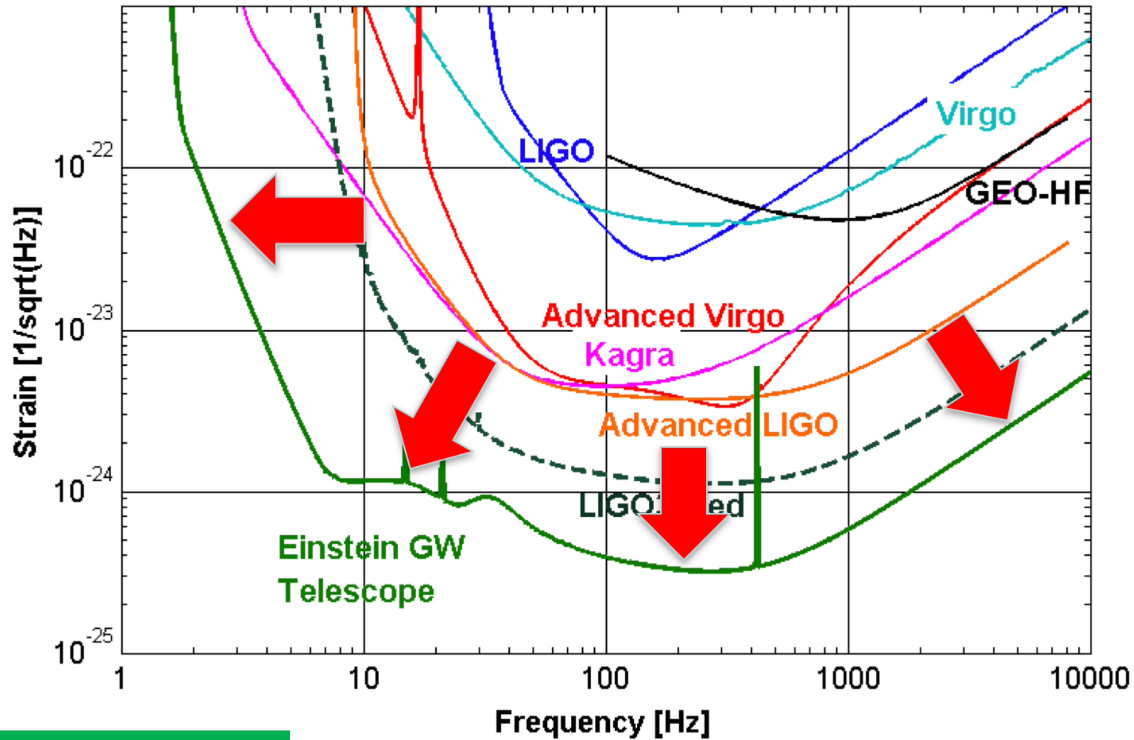
Neutron star modes



ET sensitivity in context

Signal length
=> Early warning

High redshift BHs
=> Probe earlier Universe



Supernova
core collapse

NS tidal deformation and ringdown
=> NS EOS

High SNR, Accurate PE
=> cosmology, BBH formation channels

+ Discovery space

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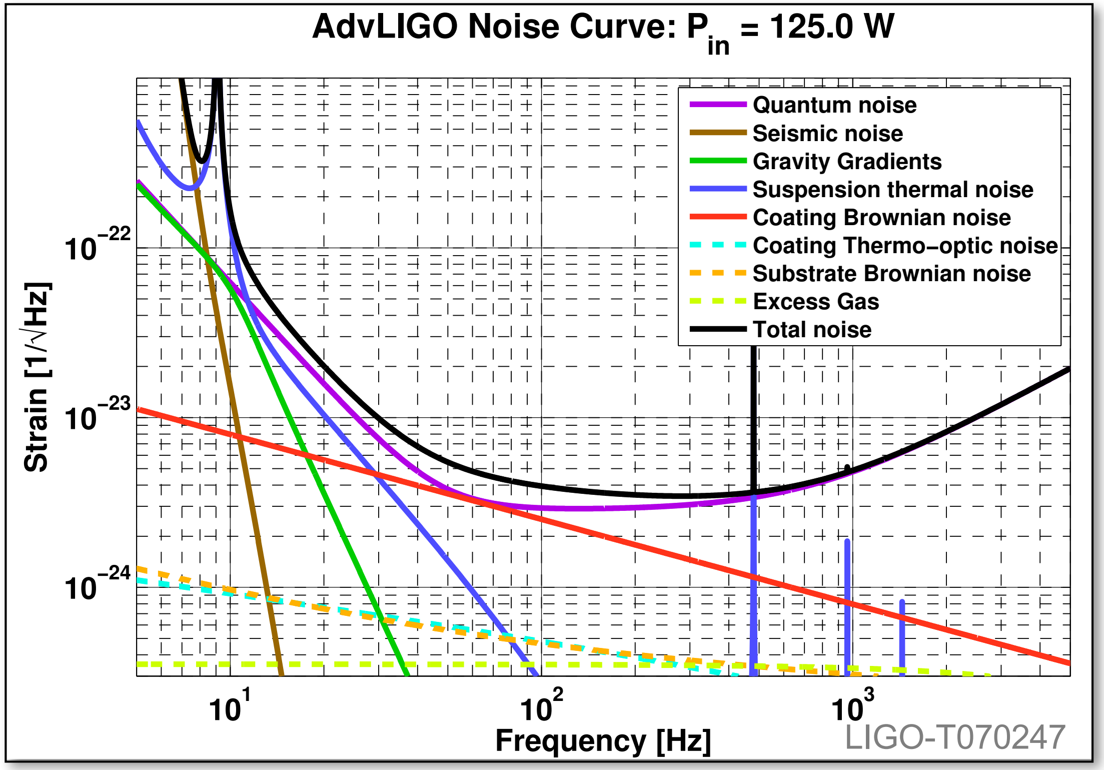
Noise Sources limiting the 2G

- **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.



Xylophone Concept

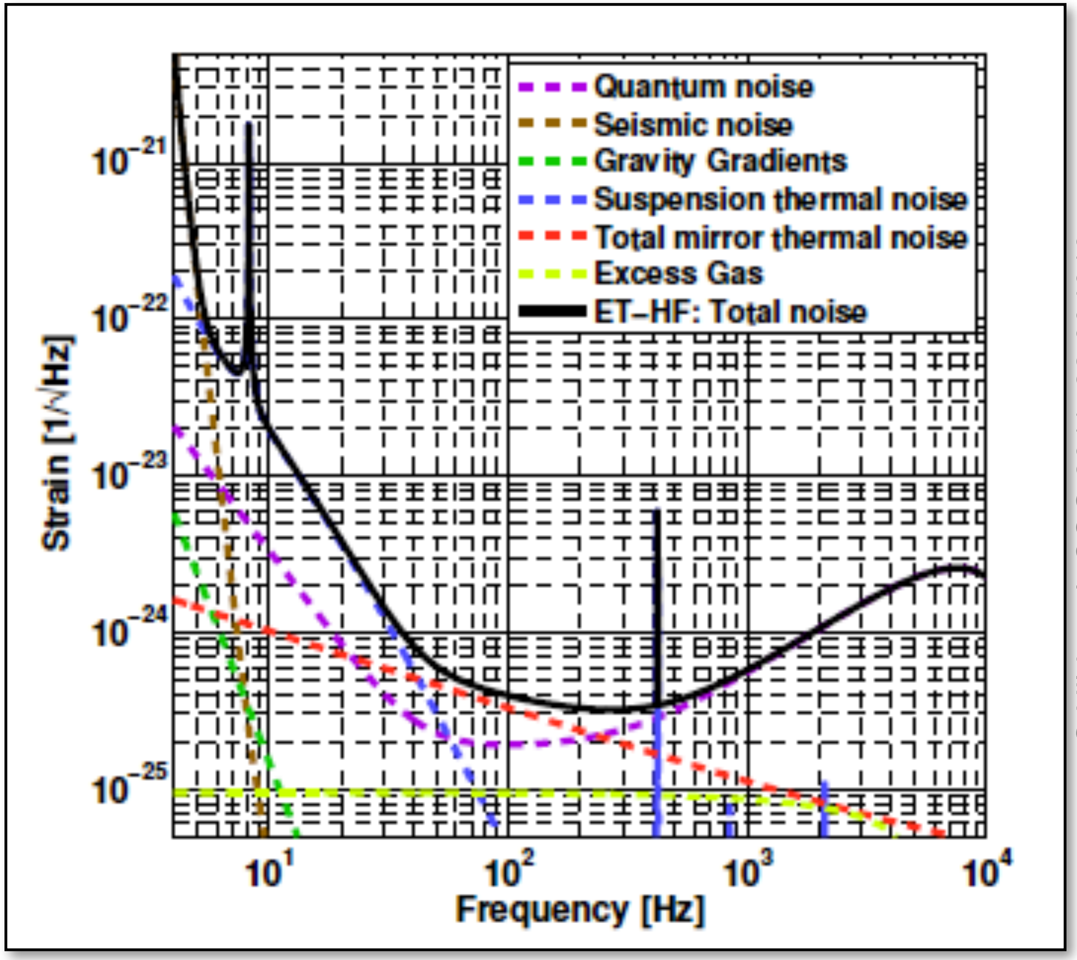
- As our detectors become more and more complex and at the same time aim increase even further the observation bandwidth the xylophone concept becomes more and more attractive.
- The xylophone concept was originally suggested for advanced LIGO:

  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

- Allows to overcome 'contradicting' requirements in the technical detector design:
  - To reduce shot noise you have to increase the light power, which in turn will reduce the sensitivity at low frequencies due to higher radiation pressure noise.
  - Need cryogenic mirrors for low frequency sensitivity. However, due to residual absorption it is hard to combine cryogenic mirrors with high power interferometers.
- For ET we choose the conservative approach (designing an infrastructure) and went for a 2-band xylophone: low-power, cryogenic low-frequency detector and a high-power, room-temperature high-frequency detector.

The High-Frequency Detector

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

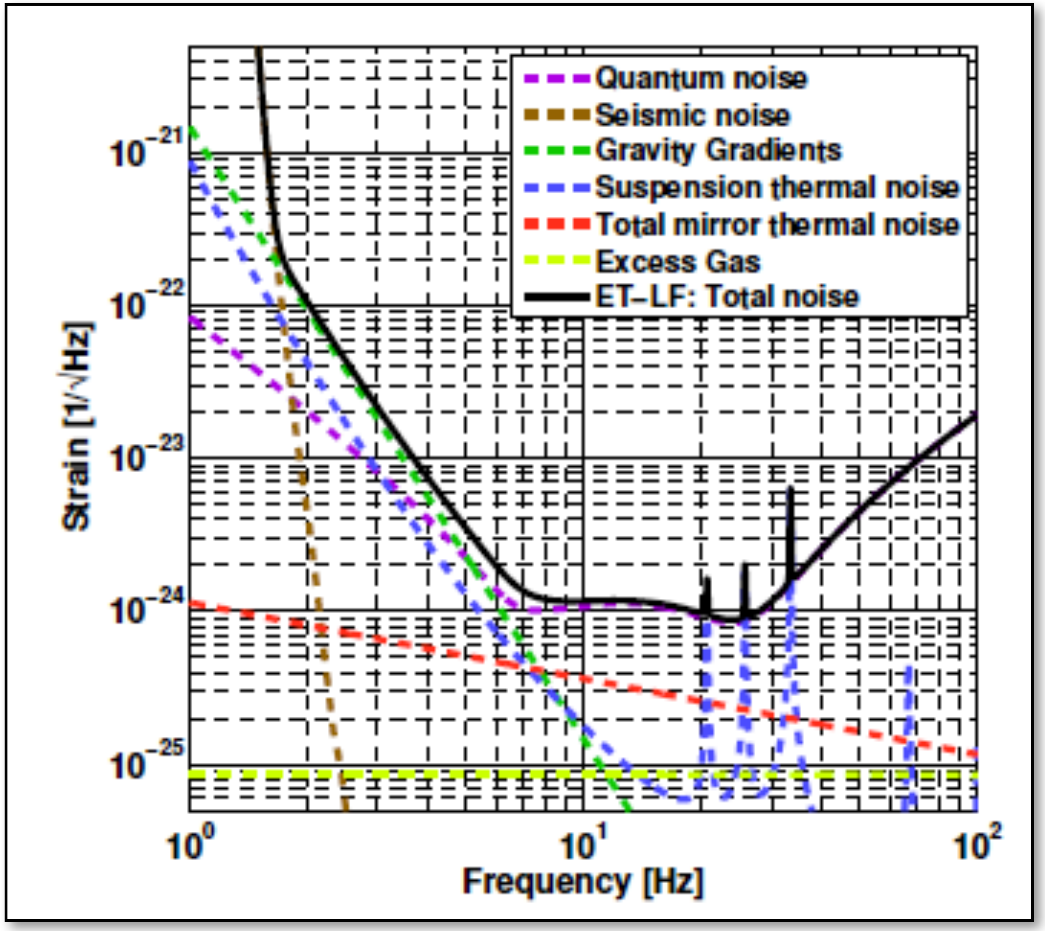


S.Hild et al, CQG 2011, **28** 094013

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

The Low-Frequency Detector

- **Quantum noise:** 18kW, detuned Signal-Recycling, 10 dB frequency dependent squeezing, 211kg mirrors, 1550nm.
- **Seismic:** 17m Superattenuator
- **Gravity gradient:** Underground, Black forest location
- **Thermal noise:** 10K, Silicon, 9cm beam radius, TEM00.
- **Suspension Thermal:** 3mm Silicon fibres. Penultimate mass at 2K.



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

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

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. ☹

Coupling constant (depends on type of seismic waves, soil properties, etc)

Gravitational constant

Density of ground

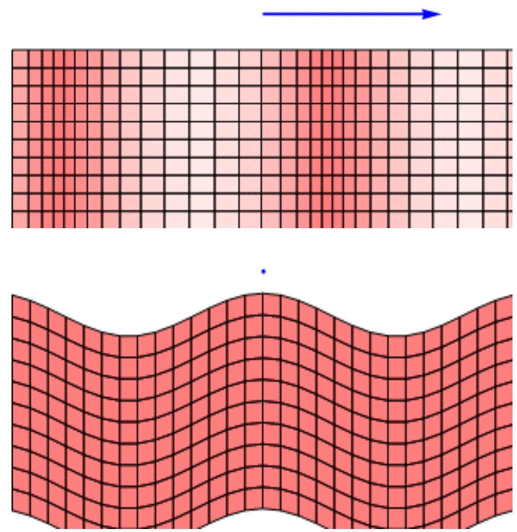
PSD of strain

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

Arm length

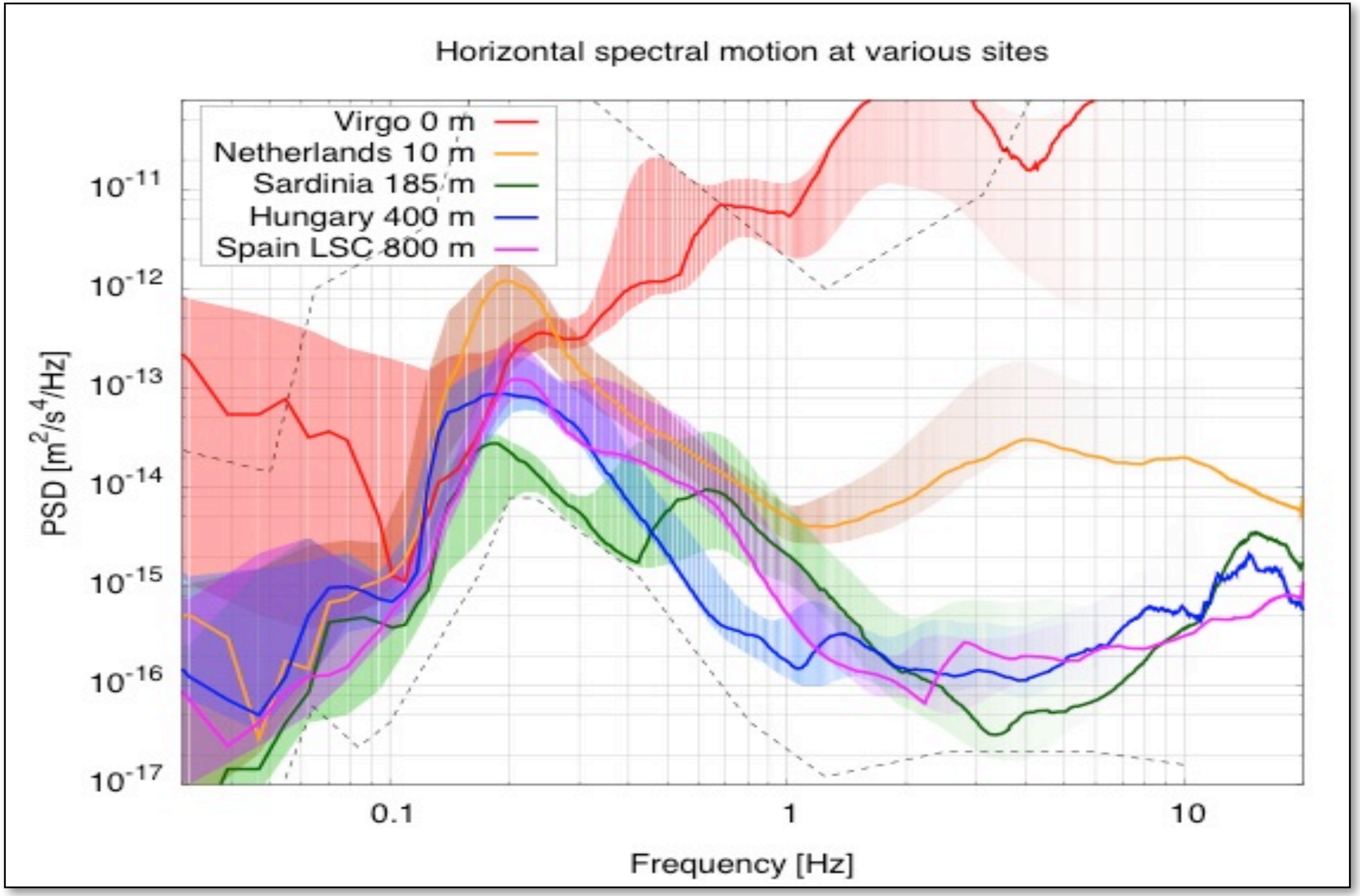
frequency

PSD of seismic



Images: courtesy G.Cella

ET will ‘go underground’



ET design study document

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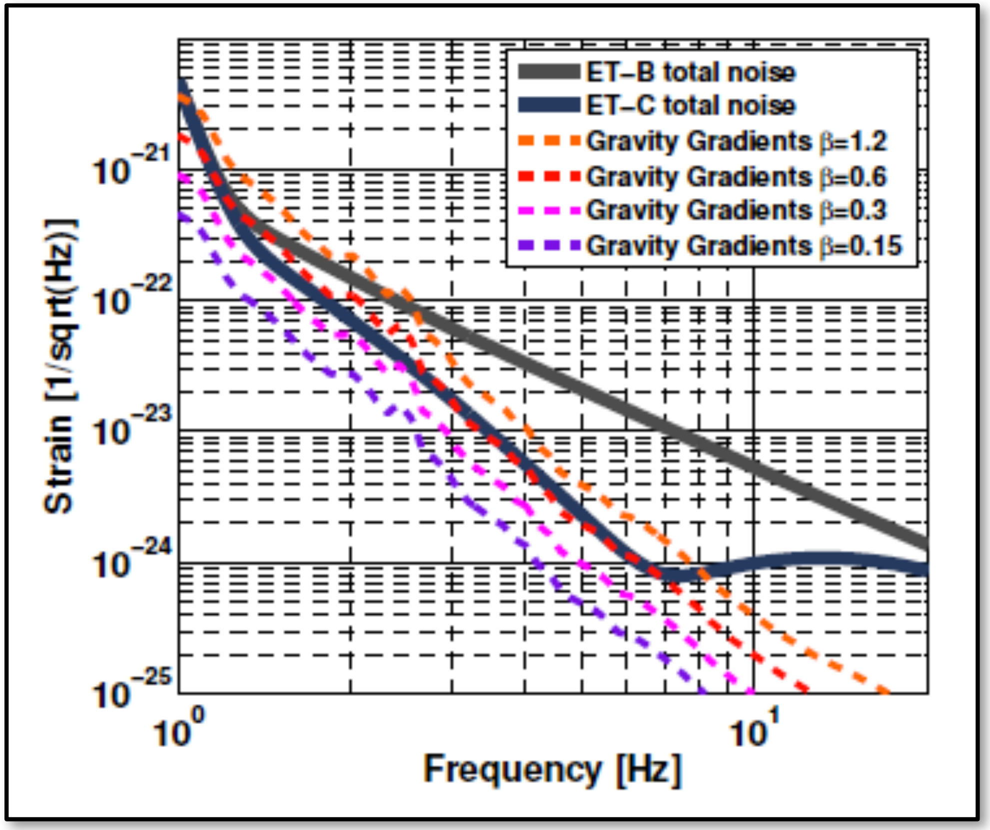
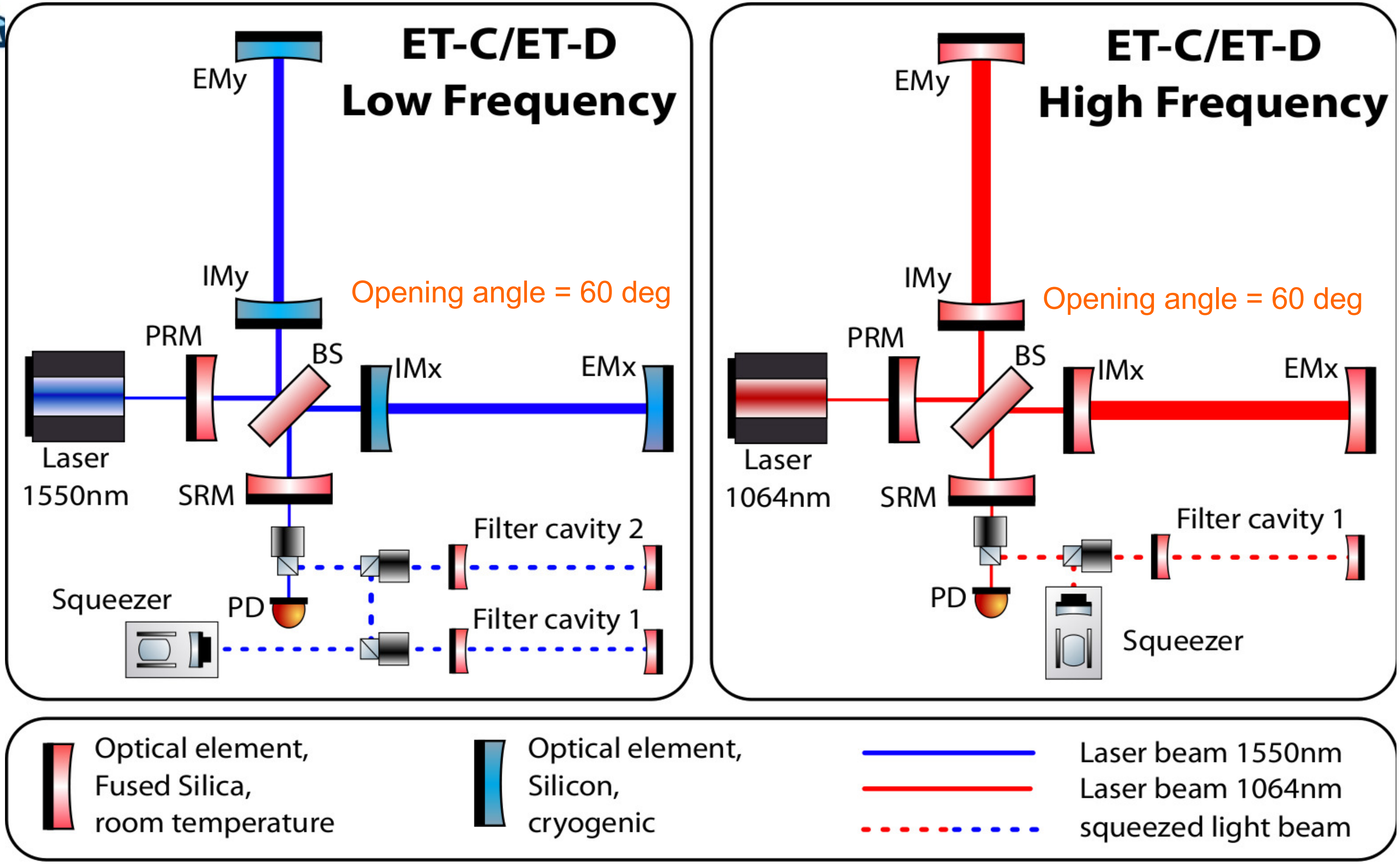
Gravity Gradient Noise

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

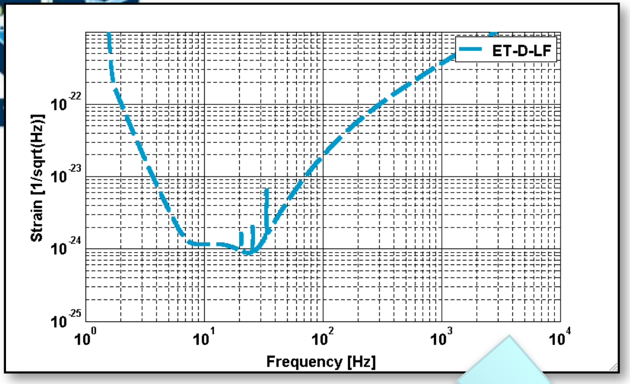
- ET-B and ET-C assume a medium quiet site + factor 50 GGN subtraction.
- ET-D considers very quiet underground site (about 5e-10/f2*m/sqrt(Hz)) at Black Forest.
- Please note:
  - ET measurement campaign showed several sites on the same level or even better than the BFO site.
  - Biggest uncertainty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

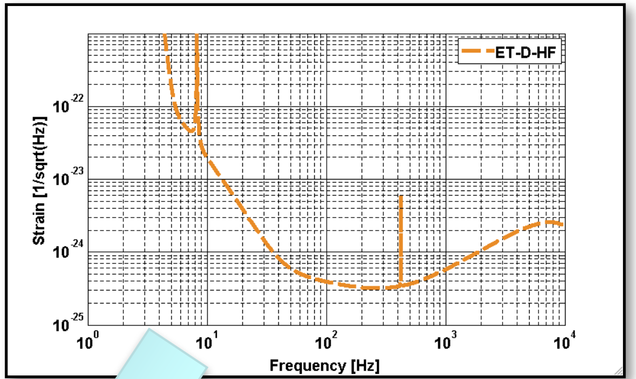


The ET core interferometers



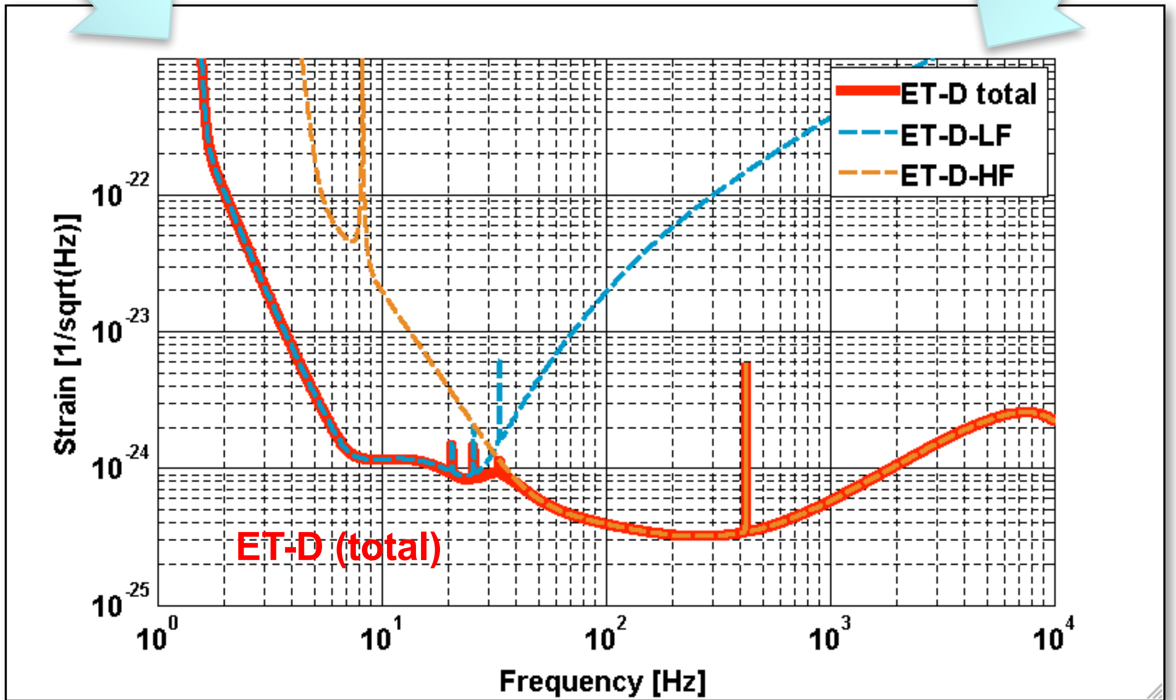
Combining 2 IFOs





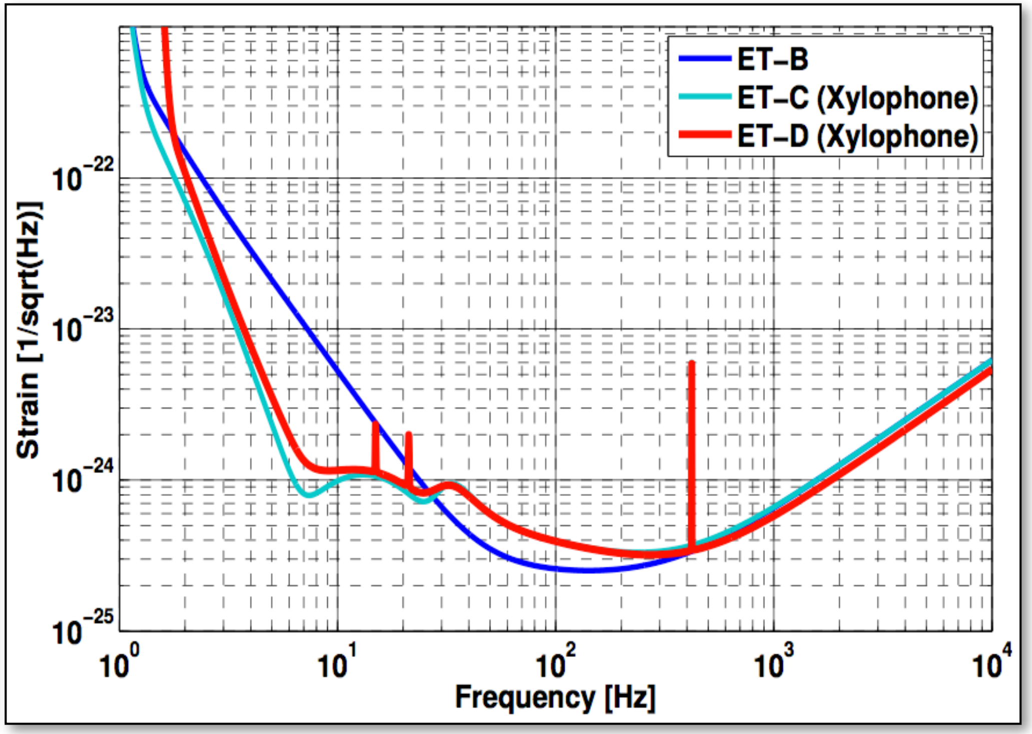
ET-D-LF

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)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
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.

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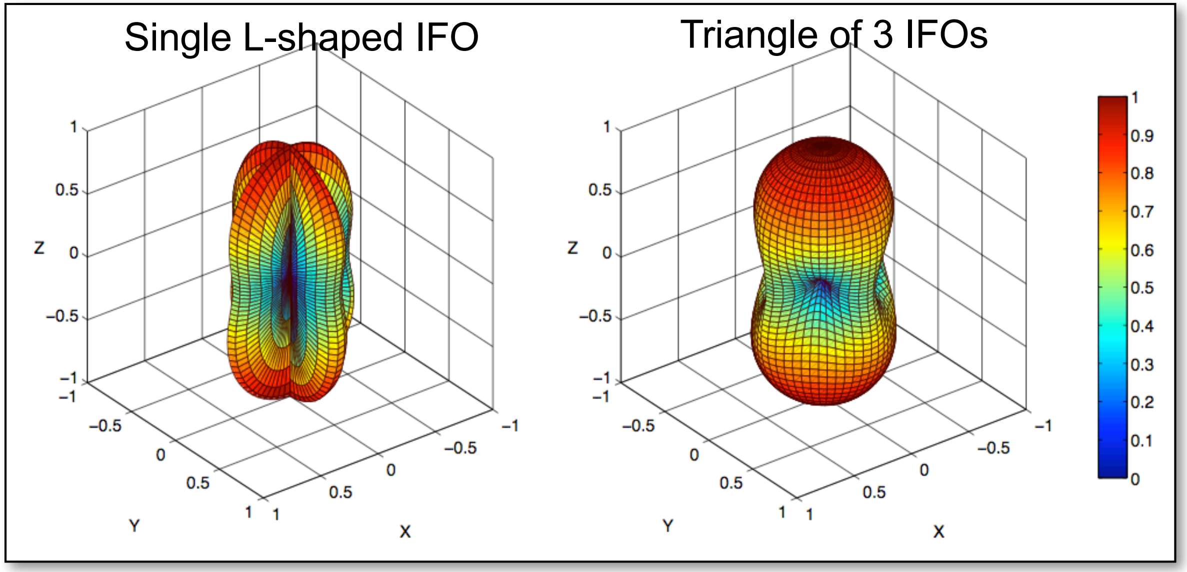
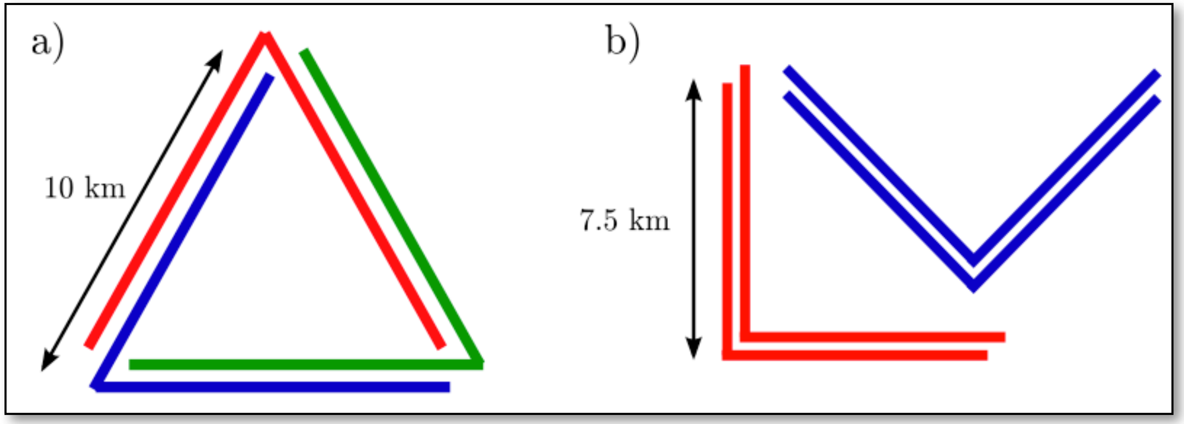
The ET Footprint

- As ET is a new infra-structure, we can start from scratch.
- What to see the full sky.
- Want to resolve both polarisations.
- Want to have redundancy.
- 1 Triangle vs 4 Ls:
  - Both have 30km integrated tunnel length
  - Both resolve both polarisations and offer redundancy.
  - Both give equivalent sensitivity.
  - Triangle reduces the number of end stations.
- **ET will be a triangle.**



Freise, A.; Chelkowski, S.; Hild, S.; Pozzo, W. D.; Perreca, A. & Vecchio, A. *CQG*, **2009**, *26*, 085012 (14pp)



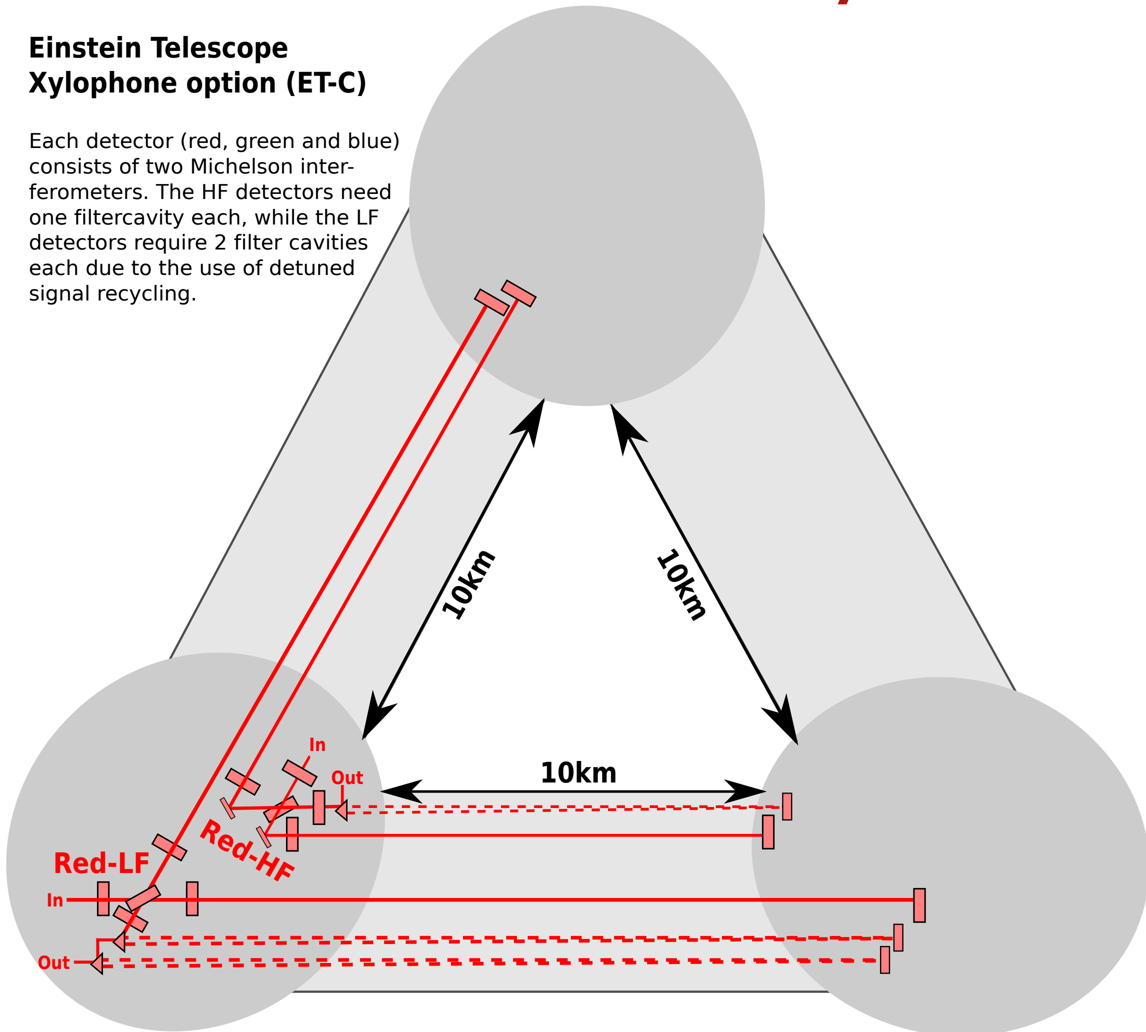
Triangle first proposed:1985, MPQ-101. W.Winkler, K.Maischberger, A.Rüdiger, R.Schilling, L.Schnupp, D.Shoemaker,: Plans for a Large Gravitational Wave Antenna in Germany

How to build an Observatory?

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

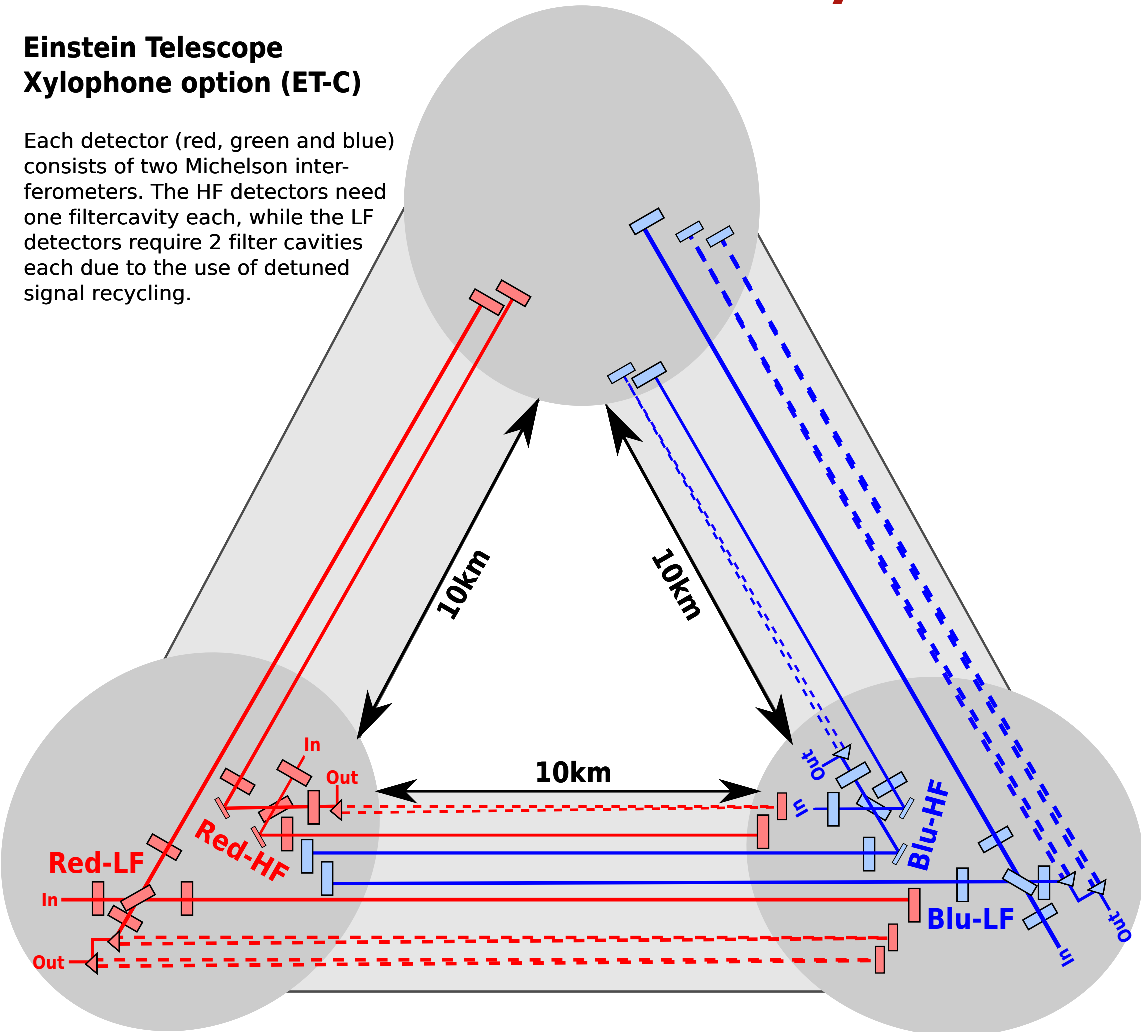
Einstein Telescope Xylophone option (ET-C)

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.



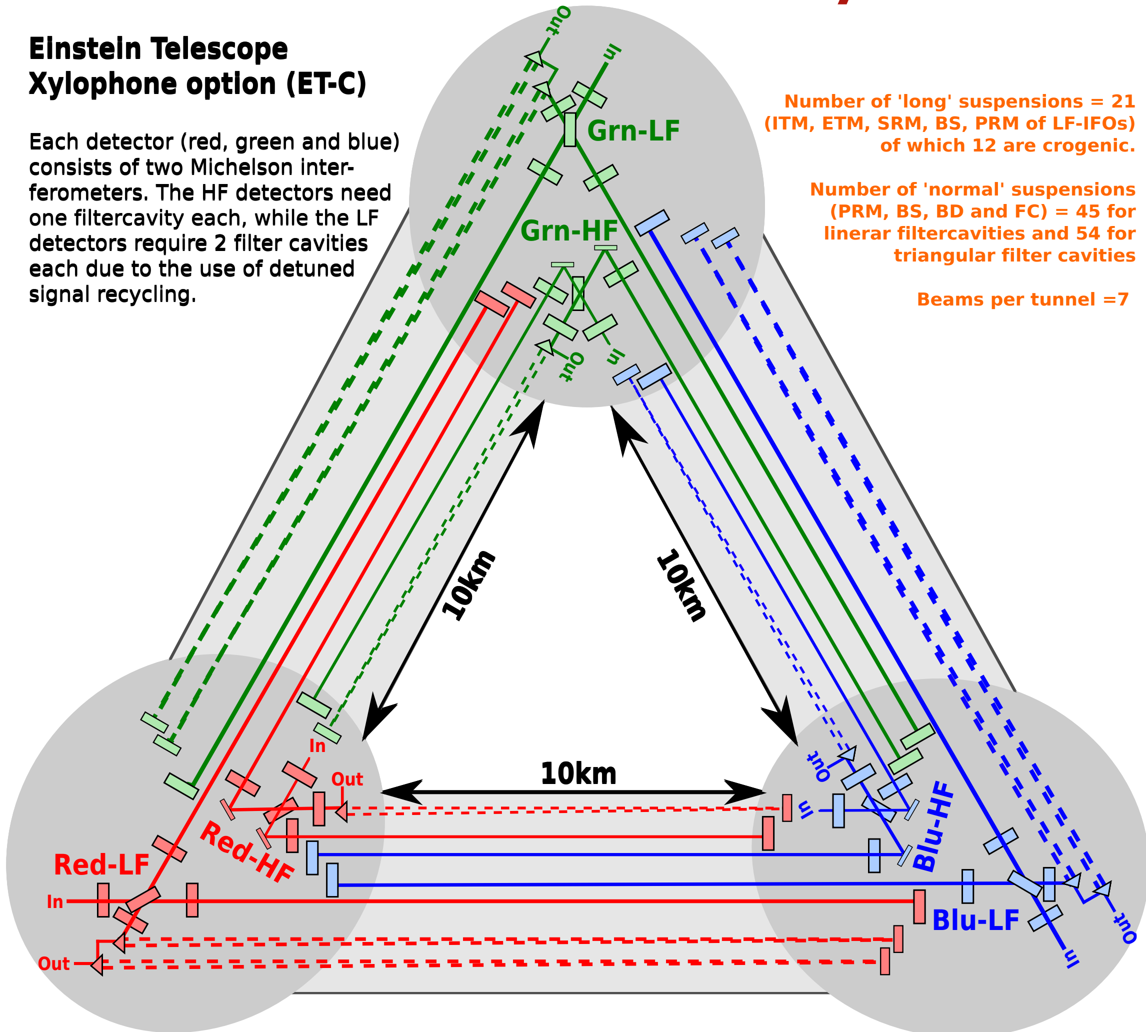
How to build an Observatory?

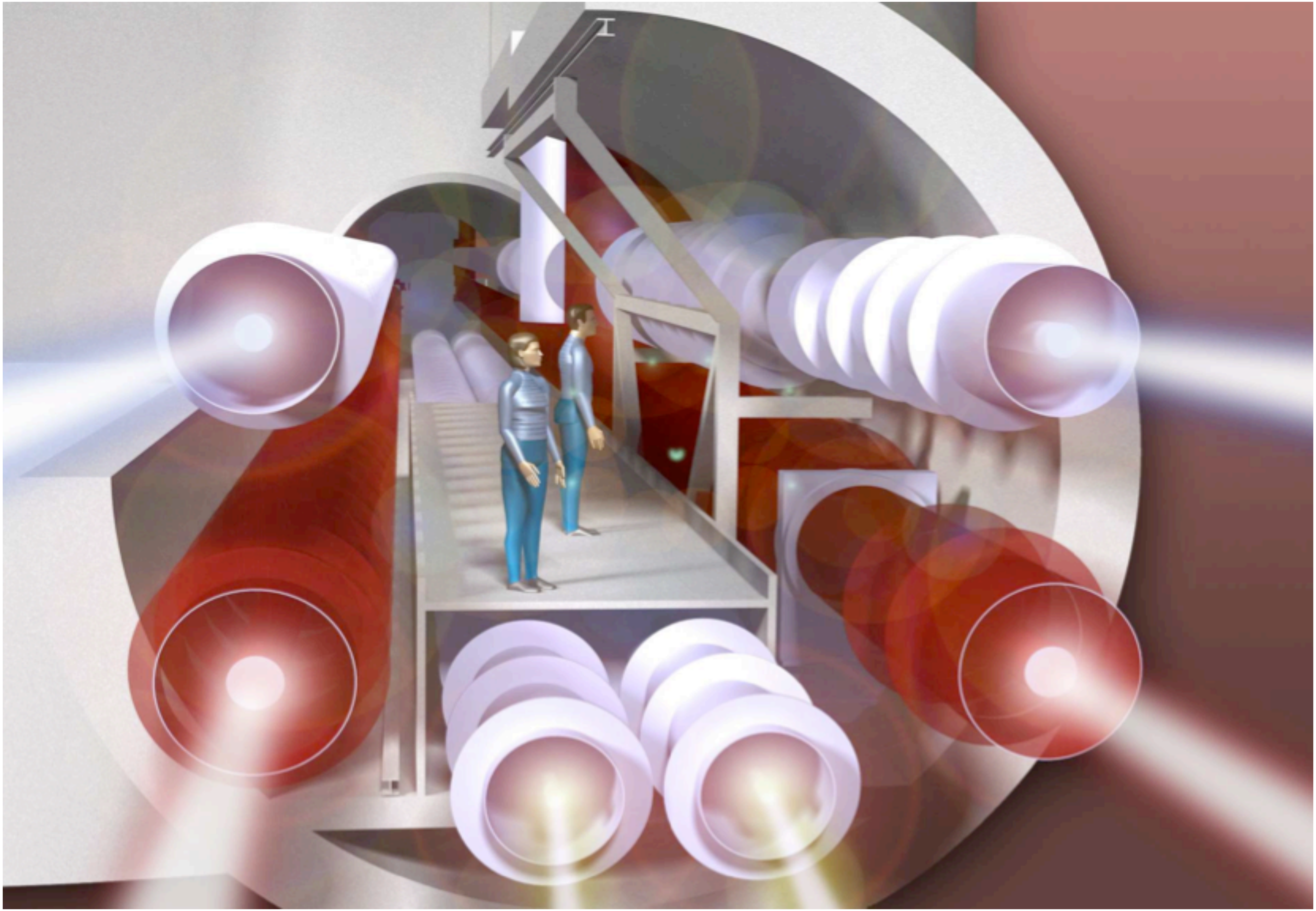
- For efficiency reasons build a triangle.
- Start with a single xylophone detector.
- Add second Xylophone detector to fully resolve polarisation.

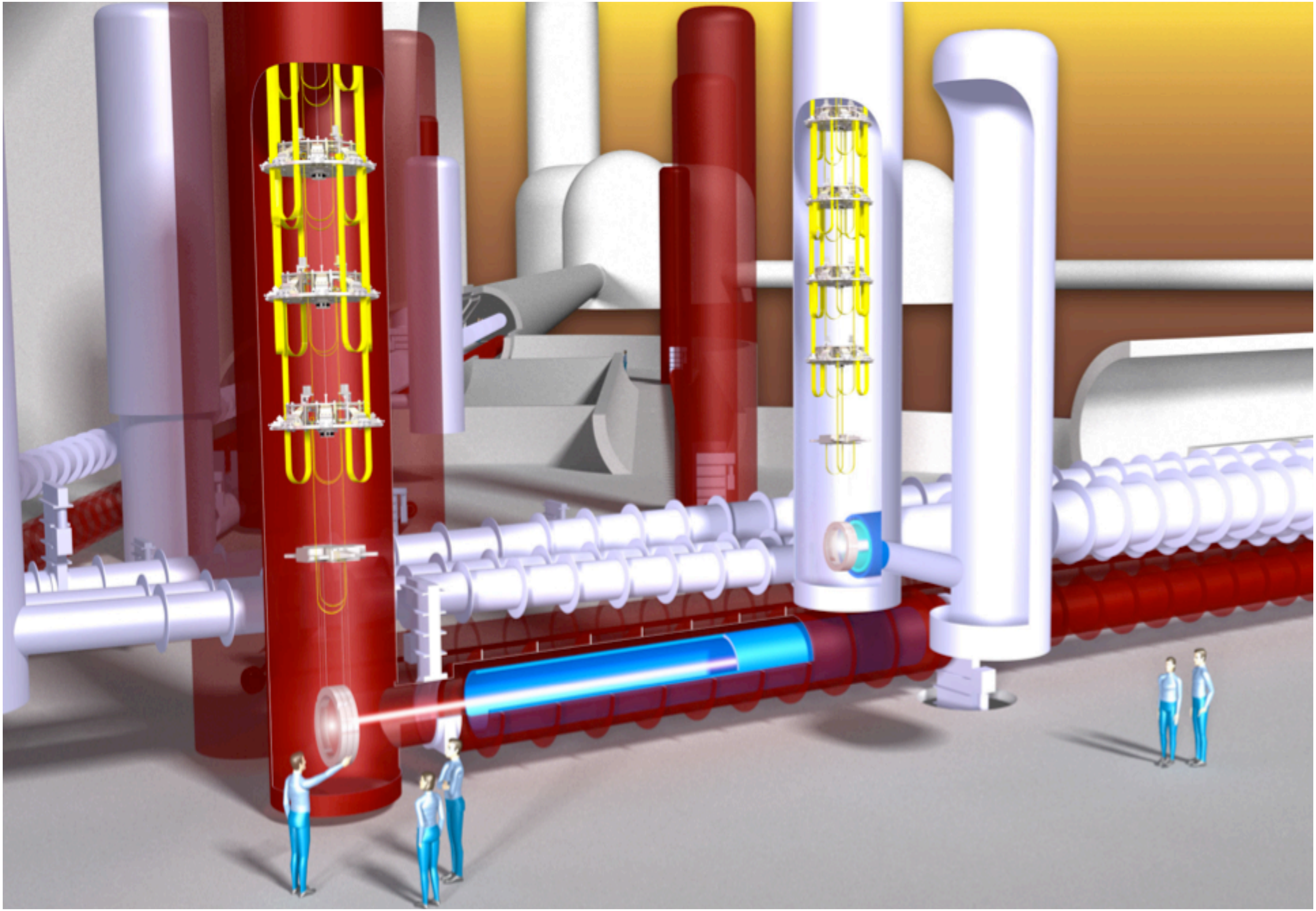


How to build an Observatory?

- 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.







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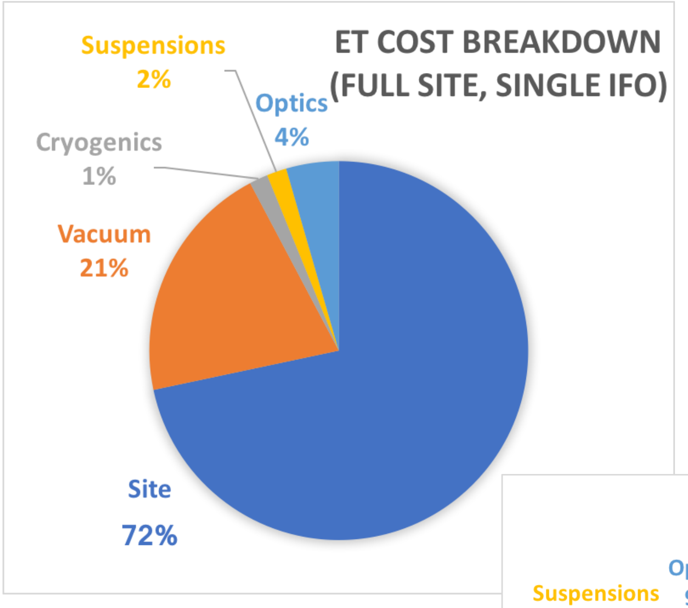
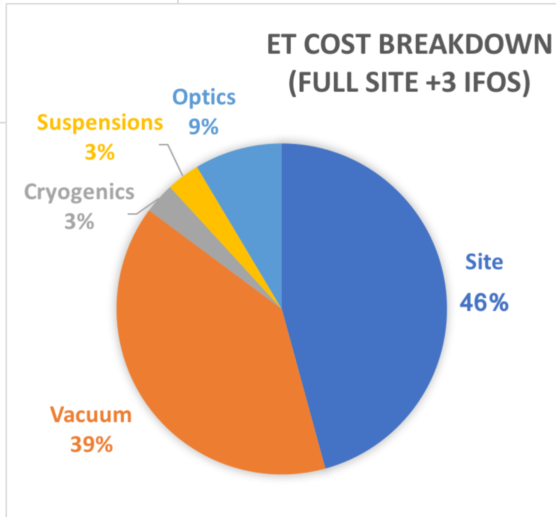
Are there ways to reduce costs?

Total Construction (M€)	827
contingency	30%
Total with contingency	1075

IDsystem	System	Configuration	Option	Subtotal (k€)
1	Site	Xylophone - Triangular	=Baseline OR =Commor	591.746
2	Vacuum	Xylophone - Single detector	=Baseline	169.864
3	Cryogenics	Xylophone - Single detector	ALL	13.200
4	Suspensions	Xylophone - Single detector	<>	14.274
5	Optics	Xylophone - Single detector	=Baseline	37.590
			Construction Totals	826.674

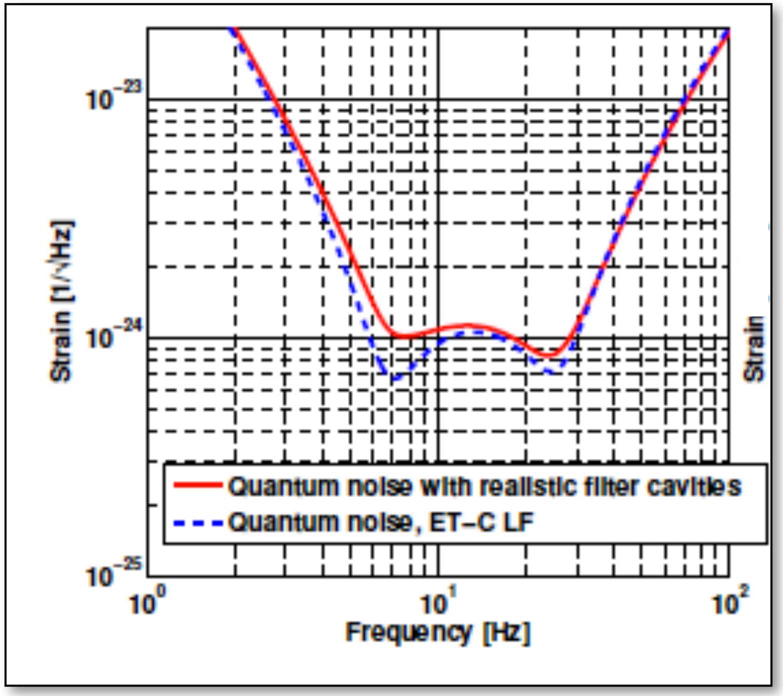




- According to design study numbers >85% of cost is in site and vacuum.
- These are the obvious points to look for savings (if we have to?).
- For example: can we think of less tall (<17m) towers to achieve 2Hz sensitivity target?

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.

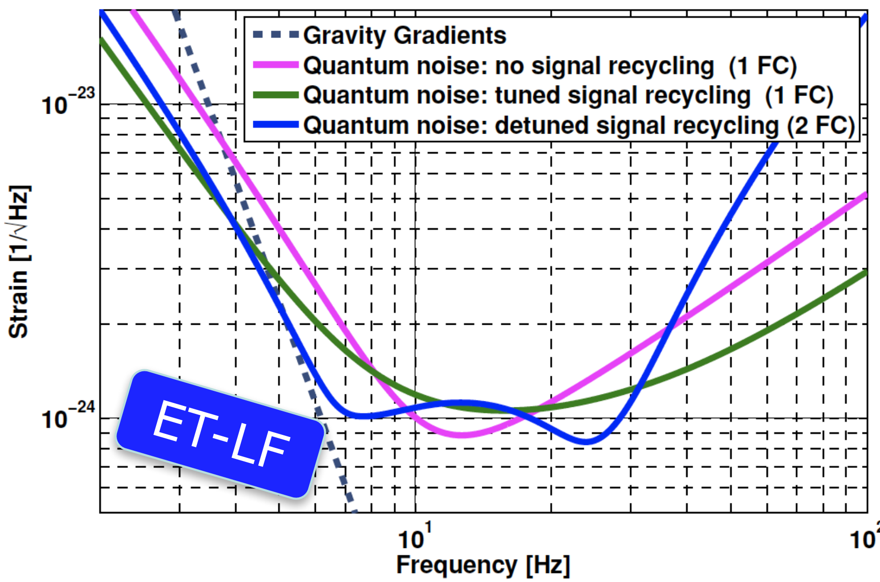


S.Hild et al, CQG 2011, **28** 094013

Filter cavities for squeezing

- Can we reduce the length of the filter cavities or even get rid of some completely? (would reduce tunnel requirements as well as vacuum costs)

Class. Quantum Grav. **28** (2011) 094013



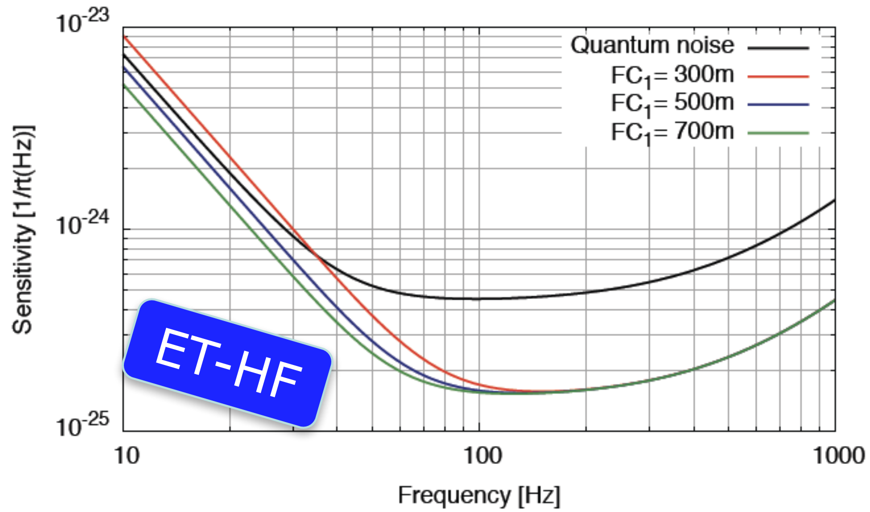


Figure 174: Sensitivity curves for ET-D-HF assuming various lengths for the filter cavity. Parameters used: round-trip loss 75ppm, 9% frequency independent propagation loss, pure 20dB squeezing injected.

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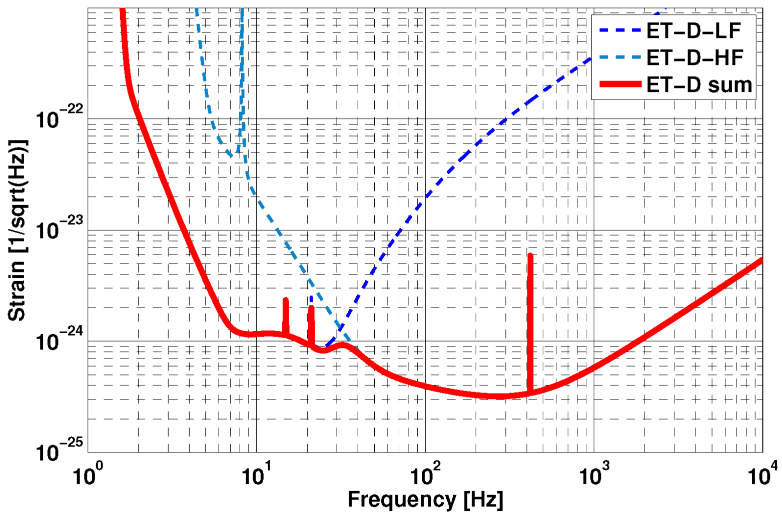
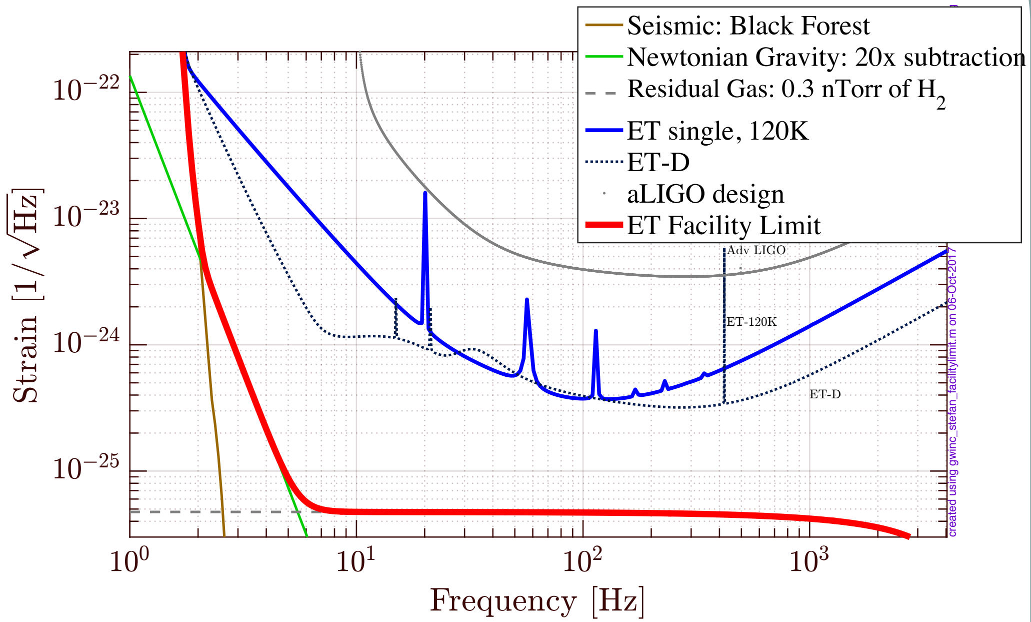
Discussion: Xylophone vs Single detector

ET Design study, ca 2010



- Emphasis was set on designing long lasting infrastructure (did not go for optimistic elegance but worst case complexity).
- Resulted in very costly design

Potential way to market ET in future?



- Instead of showing a single sensitivity curve we show an initial sensitivity curve of a relative simple and cheap detector + the facility limit to highlight future potential

Work carried out by all participants of ET workshop in Glasgow

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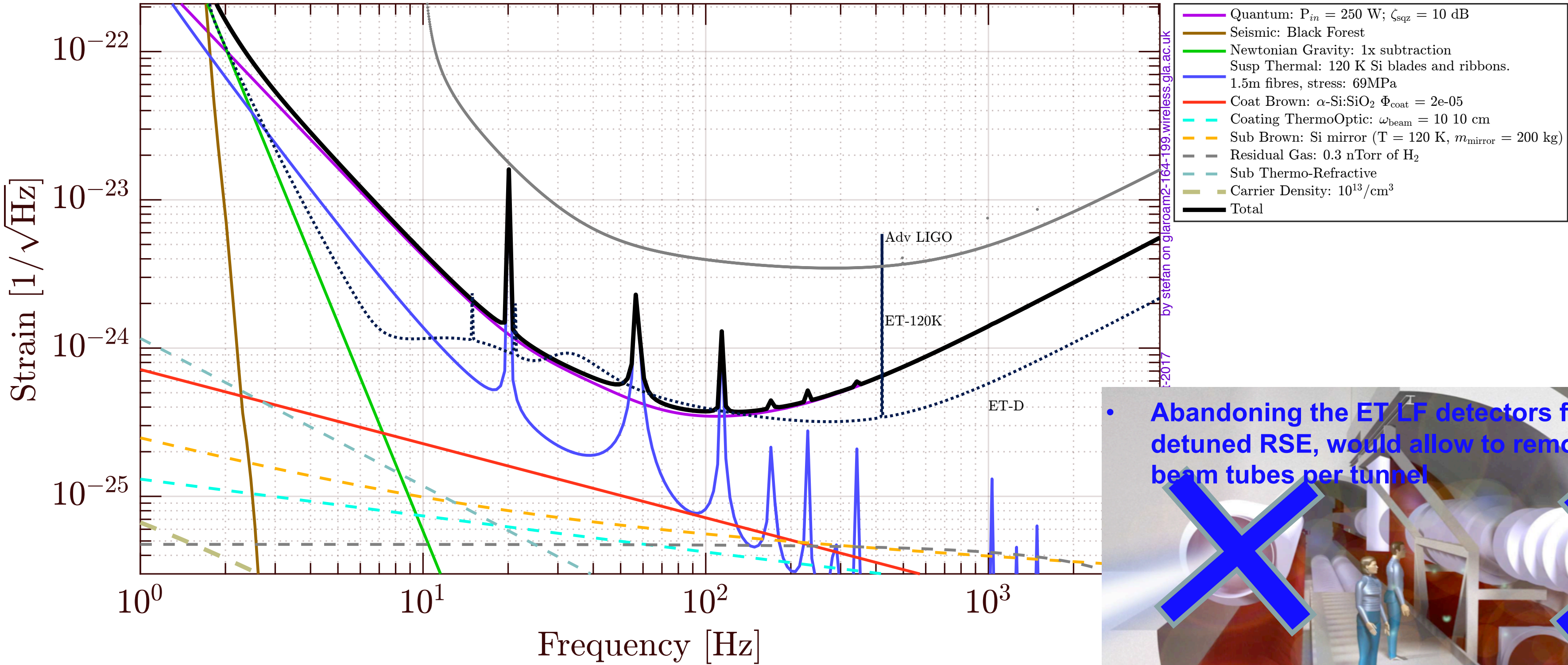
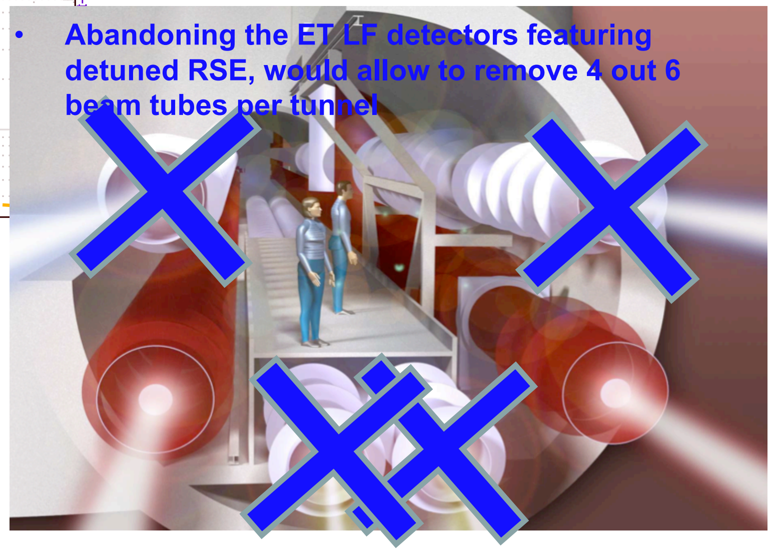
Discussion: Single detector for all frequency?

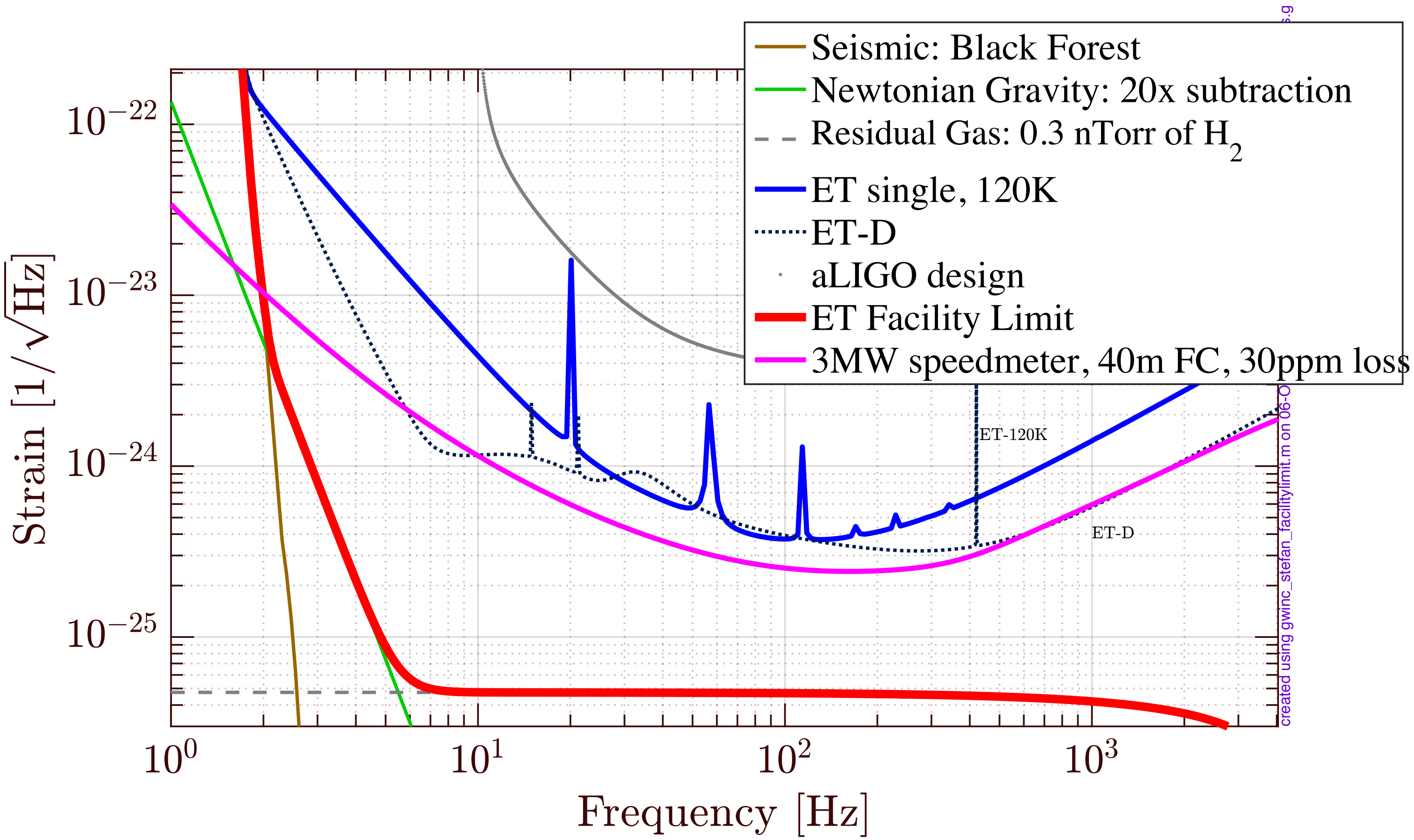




- Single detector design relies on 120K + silicon 3MW, Dual Recycled Michelson, Squeezing + short filter cavity, no GG noise subtraction, etc

Work carried out by all participants of ET workshop in Glasgow

Example a of a more ambitious single detector sensitivity



Work carried out by all participants of ET workshop in Glasgow


Thank you very much
for your attention
Picture: LIGO magazine