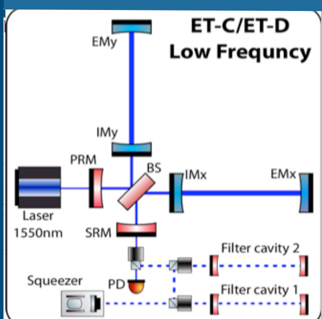
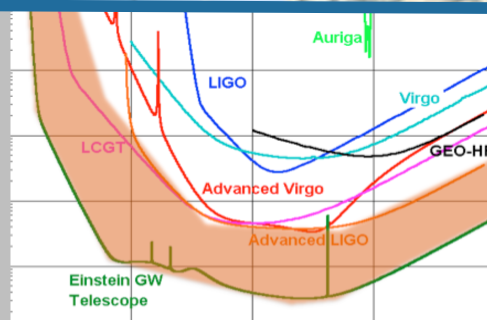
LIGO-G1100751

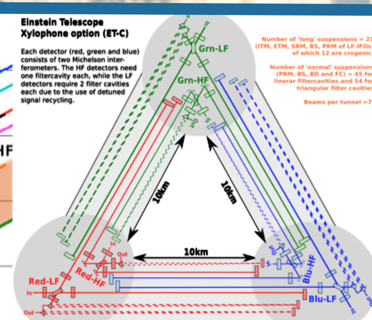
Beyond 2nd Generation GW detectors

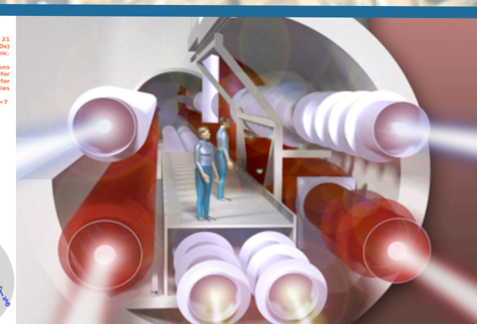
Stefan Hild

Amaldi 2011, Cardiff







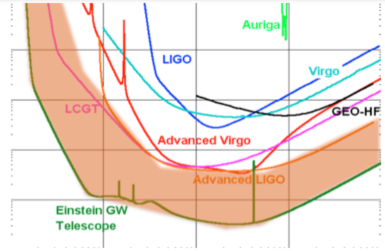


Introduction / Context

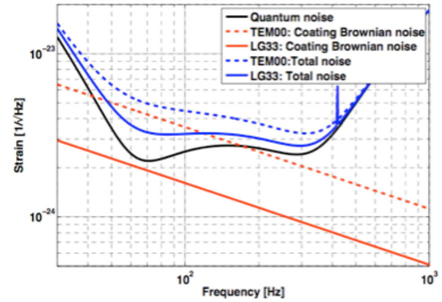
- What does 'Beyond the second generation' mean?
  - Let's assume: This means upgrades of second generation detectors plus the third generation.
- When does 'Beyond the second generation' actually start?
  - **Honestly no idea.** This will depend on plenty of factors (many of them might not be of scientific nature), such as: What do the 2G detectors find? What is the funding situation? How well are we prepared for these upgrades? …
- However, independent of when it will happen, we have already quite a good idea in which direction we will be heading.
- Please consider the choice of topics and content of this presentation as my personal/subjective view.
- Some slides have an orange colour scheme: The questions on these slides are in my view 'hot topics', which are essential to get a good feeling for.

Overview

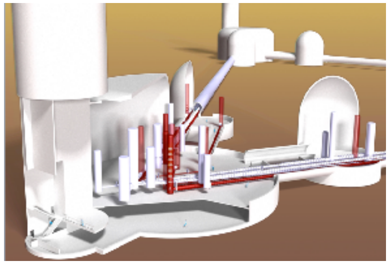
- Let's do some time travel …



- Let's find out how we can make the second generation detectors even better …



- Let's have a look at the Einstein Telescope …

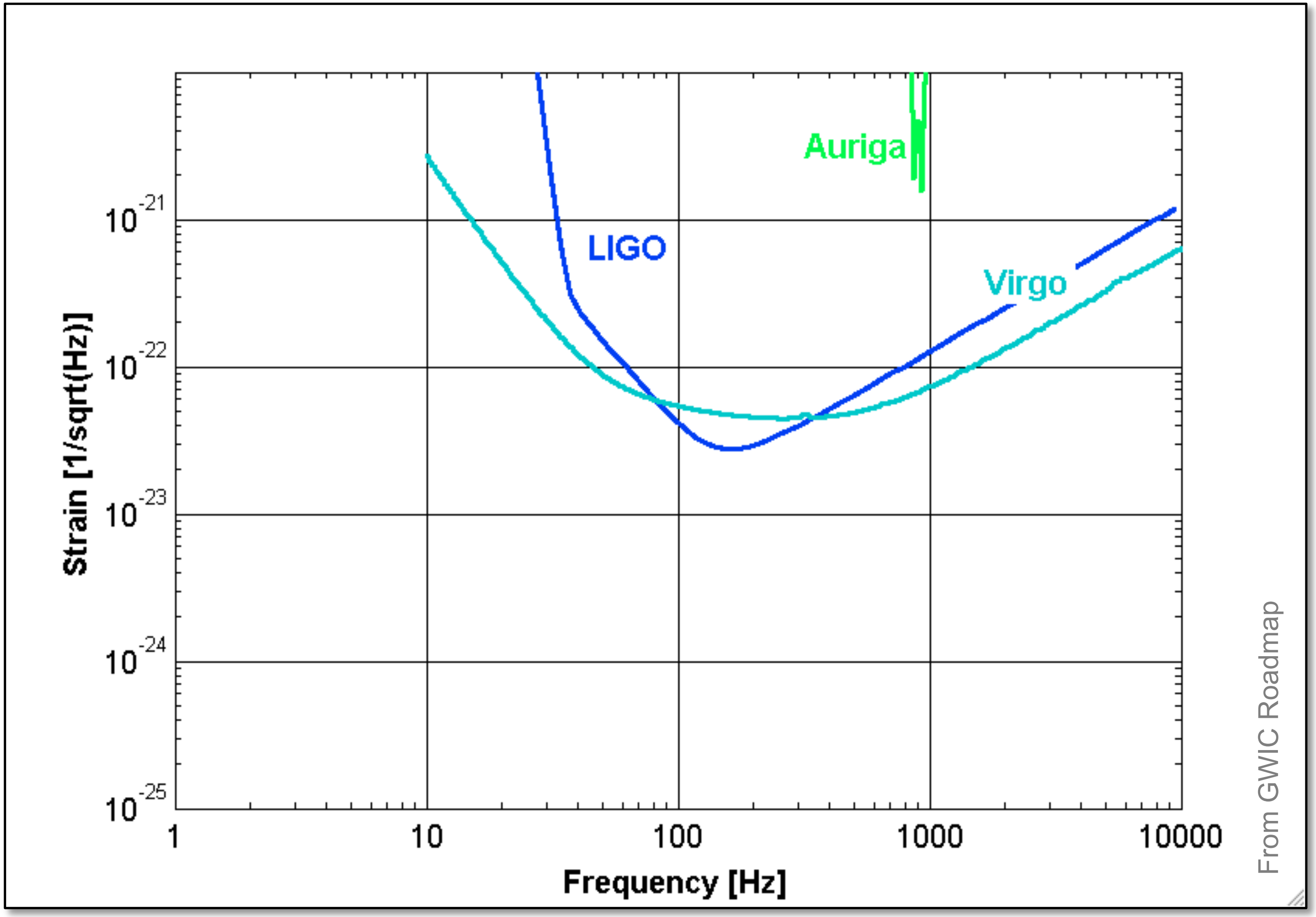


Our Starting Point

Today: After decades of hard work the 1st generation is completed.

2nd generation is funded and construction well underway.

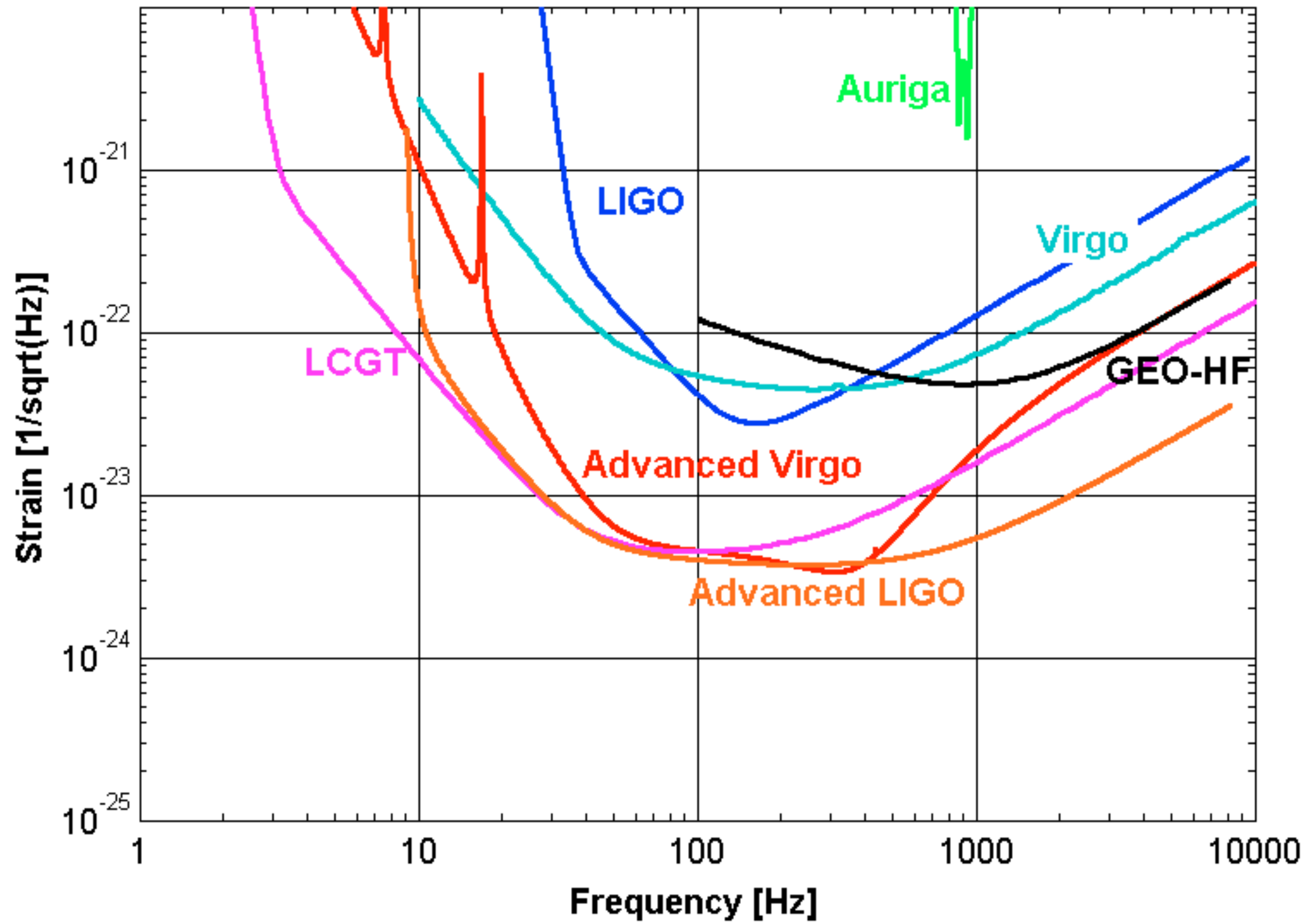
Let's jump into the future …



Our Starting Point

Let's assume for the rest of the talk that we are in the year 201X and have the following situation:

3 Advanced LIGO detectors (hope-fully one in Australia) + Advanced Virgo + GEO-HF and LCGT at design sensitivity.



From GWIC Roadmap

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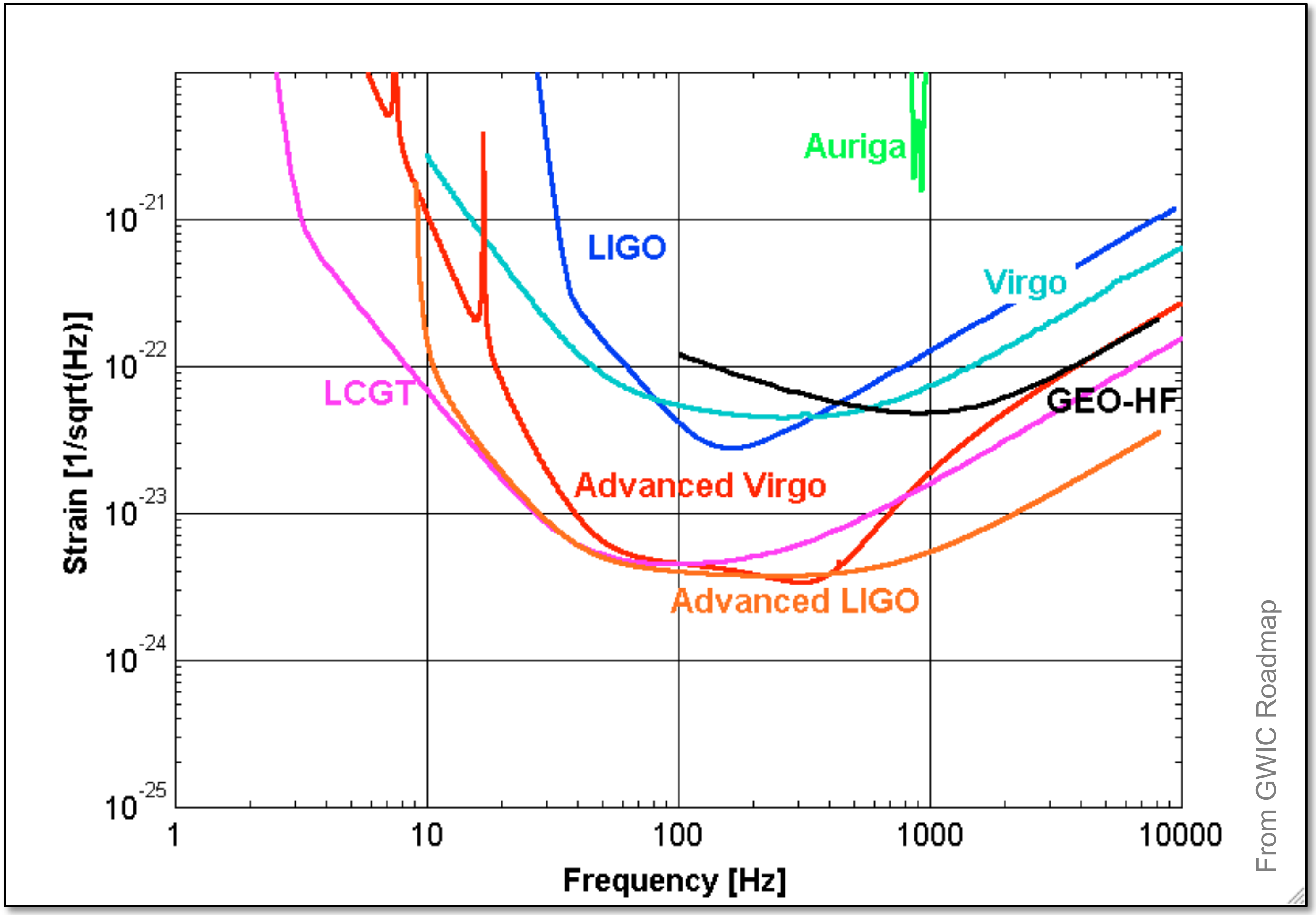
First detection has been achieved.



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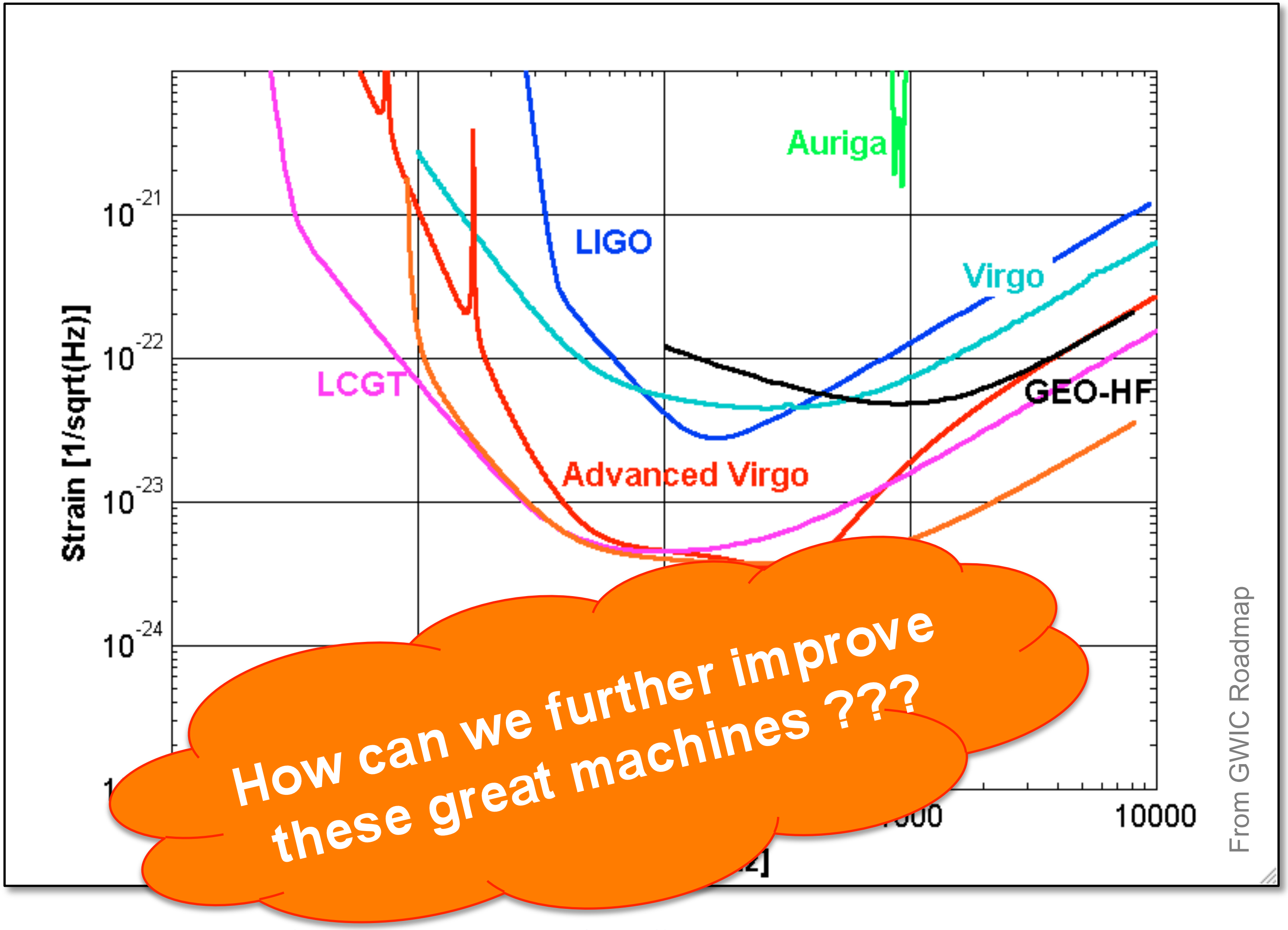


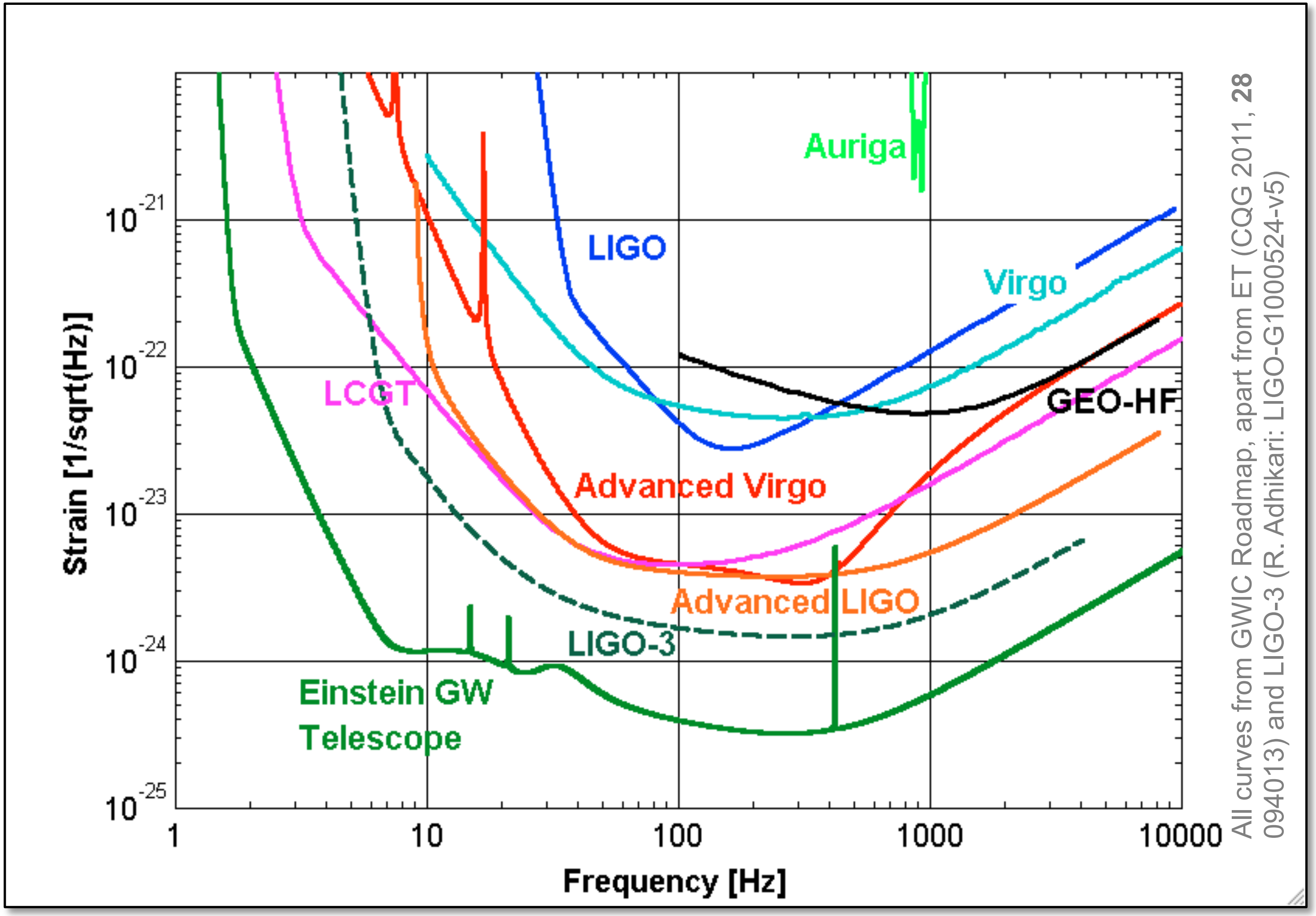
What is this talk about ?

- **Upgrades of the advanced detectors** are currently under investigation.

  see for example R. Adhikari's talk at GWADW 2010

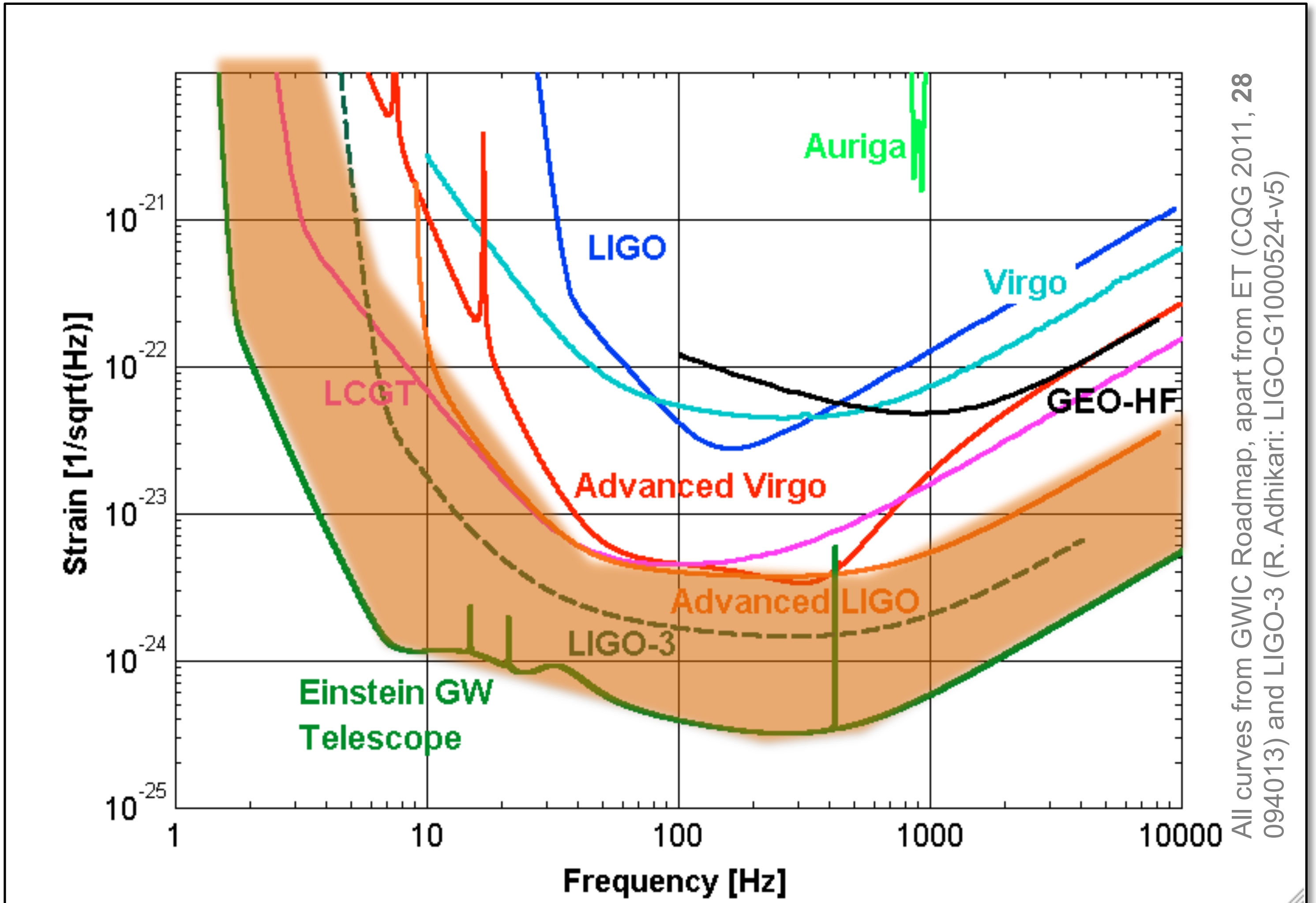
- In Europe the ET design study for a **3rd generation** GW detector has just been completed.

  http://www.et-gw.eu/etdsdocument



What is this talk about ?

- Look at the limiting noise sources in the orange band.
- What techniques do we need to apply and develop to dig into the orange band?



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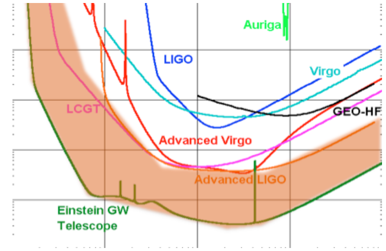

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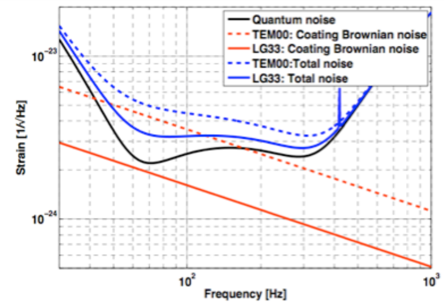

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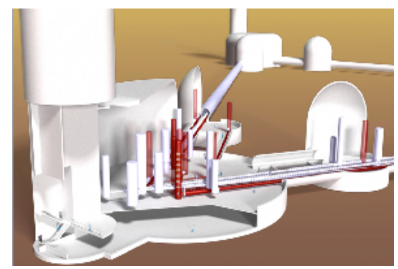
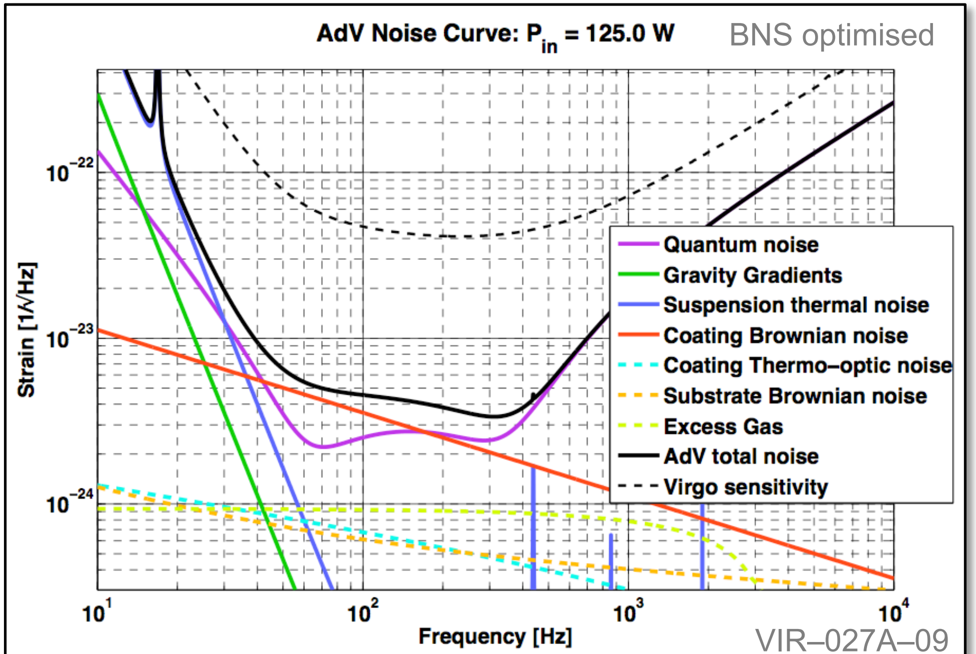
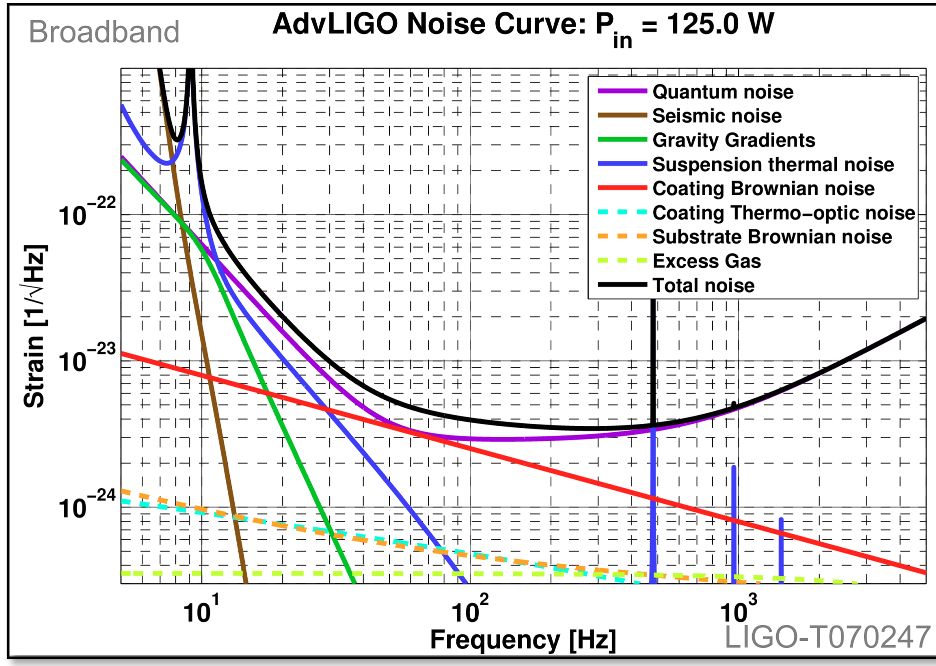


University of Glasgow

Noise Sources limiting the Advanced Detectors

- In order to understand how we can potentially improve 2G detectors, we need to see what they are limited by:

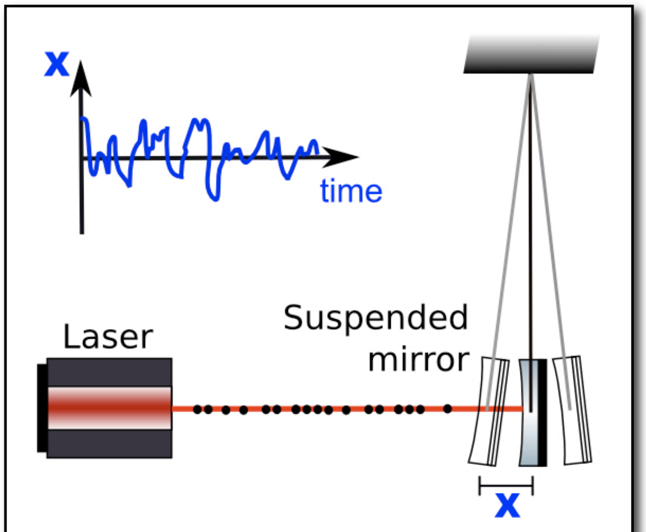




- Quantum Noise limits most of the frequency range.
- Coating Brownian limits (or is close) in the range from 50 to 100Hz.
- Below 50Hz we are limited by ‘walls’ made of Suspension Thermal, Gravity Gradient and Seismic noise.

What is quantum noise?

- Quantum noise is composed 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.



wavelength

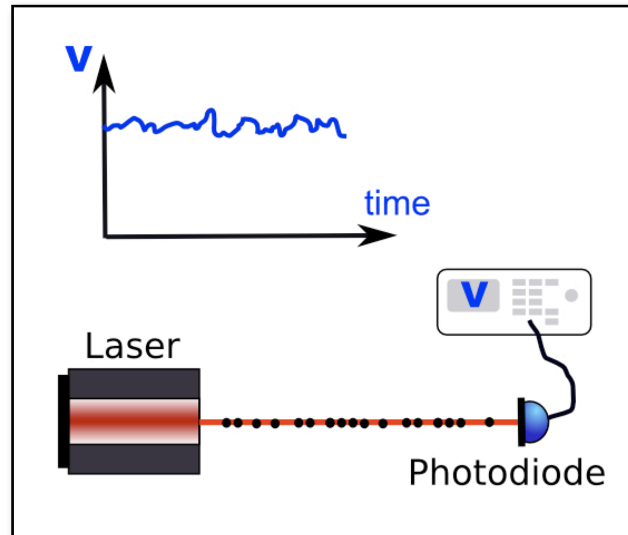
$$h_{\rm sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

optical power

Mirror mass

Arm length

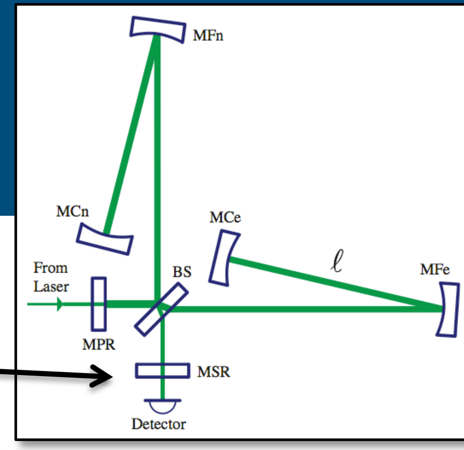
$$h_{\rm rp}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$



photon radiation pressure noise

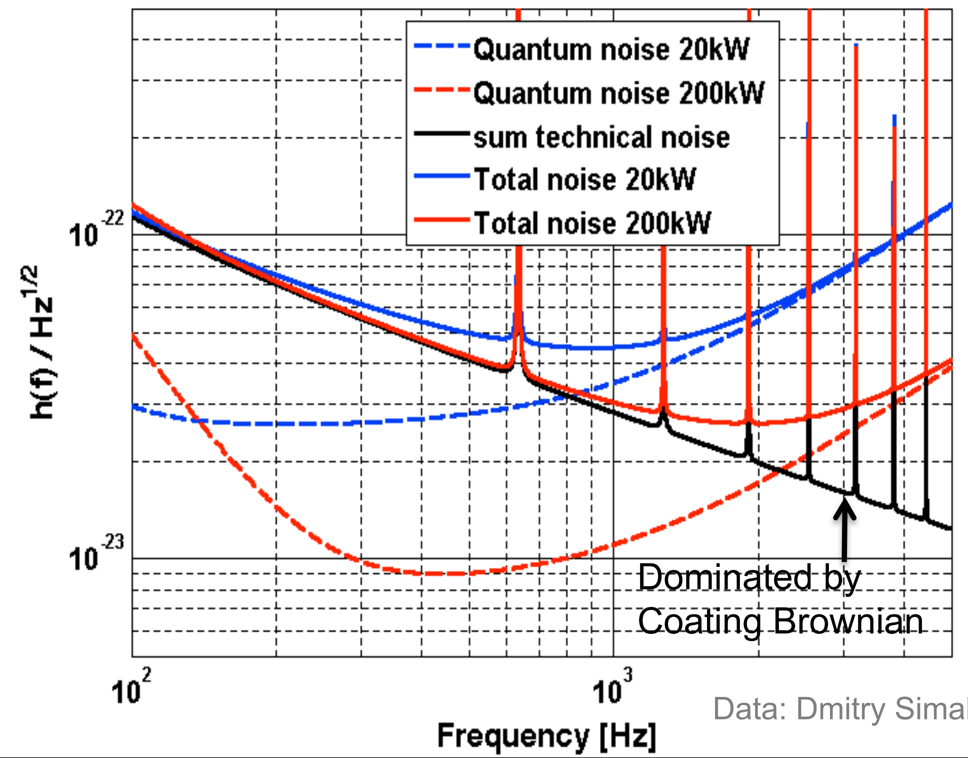
photon shot noise

GEO-HF upgrades



Signal Recycling mirror couples shotnoise and radiation pressure noise

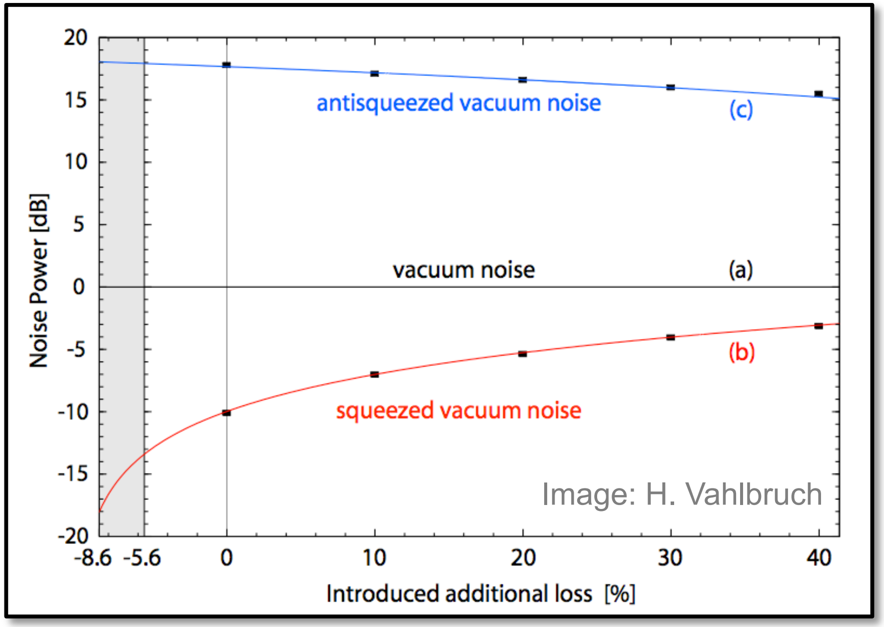
- GEO-HF design sensitivity: 20kW (30W laser), 6dB squeezing, 10% Signal Recycling mirror.
- Potential upgrade 1: Increase cavity power to 200kW, which requires 200 to 300W input.
  - Radiation pressure increased but still hidden below other noise sources
- Potential upgrade 2: new mirrors with better coatings
  - (Due to beam sizes coating noise dominated by MCe+MCn)
- Potential upgrade 3: Any chance to increase the squeezing level?



Data: Dmitry Simakov

How small can we really make the squeezing losses?

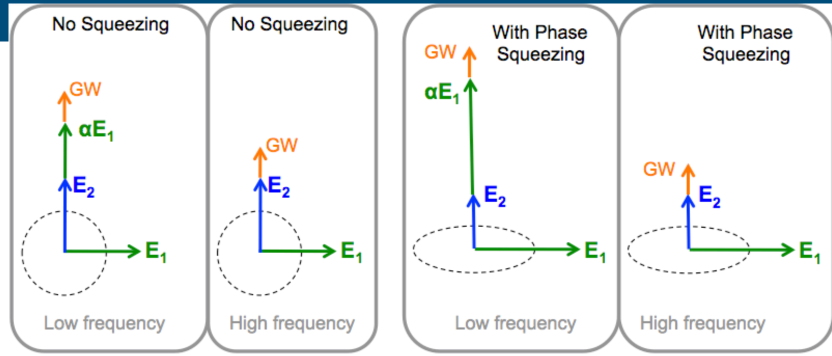
- Squeezing degenerates quickly through losses!
- GEO-HF design: 10dB squeezing after source + 20% of squeezing loss (from injection and within the interferometer) result in 6dB total noise reduction.
- Even if we were to start from 18dB after the squeezing source, with 20% loss we would only increase the overall squeezing win to 7dB.

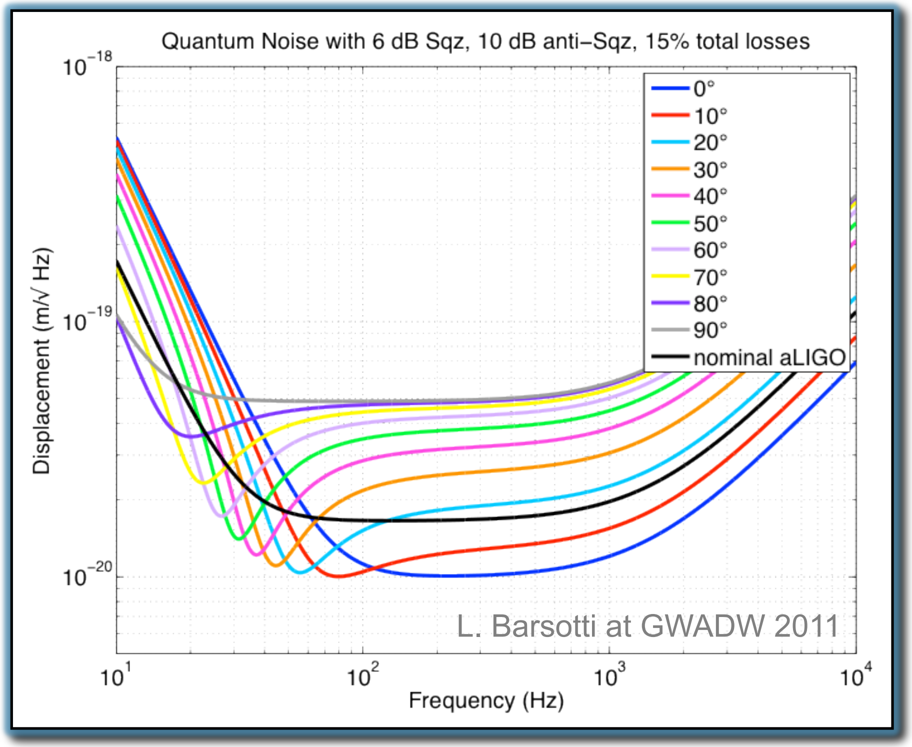


- **How much effective squeezing we can achieve in any 2nd or 3rd Generation detector, will probably not be limited by the squeezing source itself, but by the level of losses in the squeezing injection system and the main interferometer.**

Advanced LIGO with squeezed light

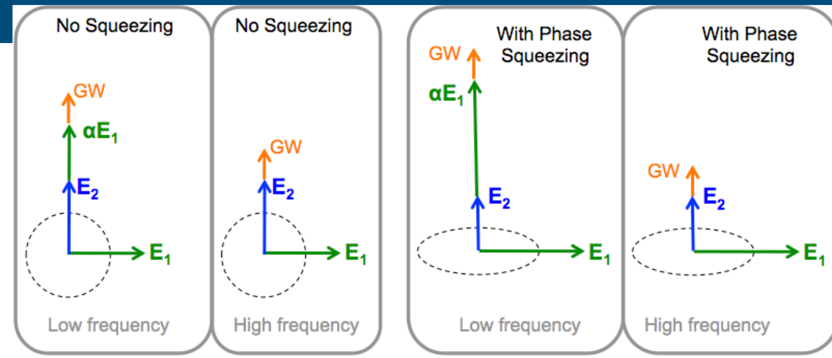
- Advanced LIGO limited by both: Shot noise and Radiation pressure noise.
- Therefore injection of ‘simple squeezed’ light will improve sensitivity on some frequency range and degrade it at other frequencies.

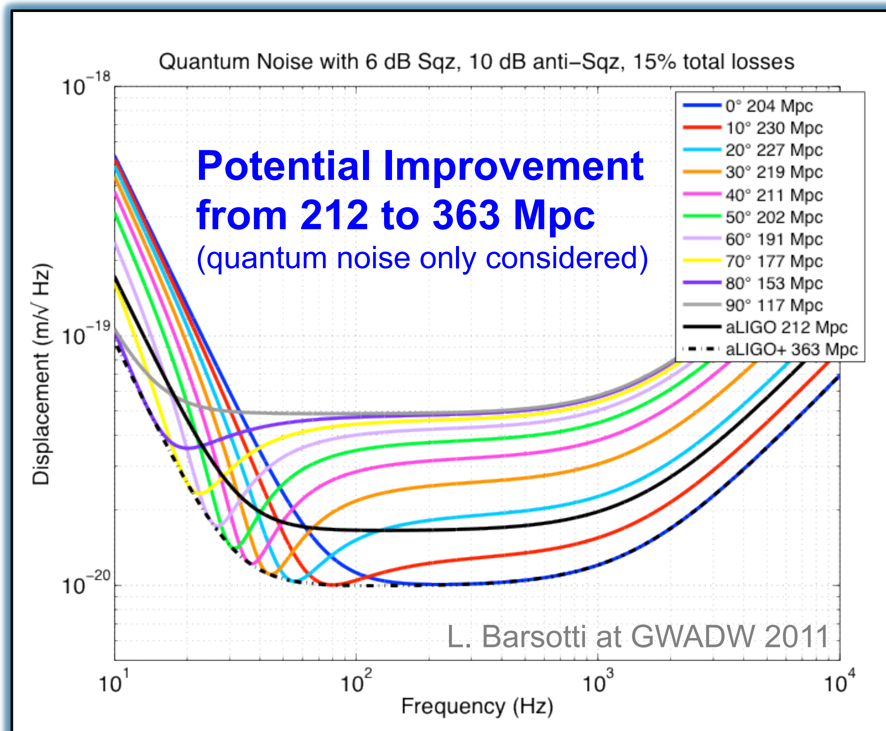


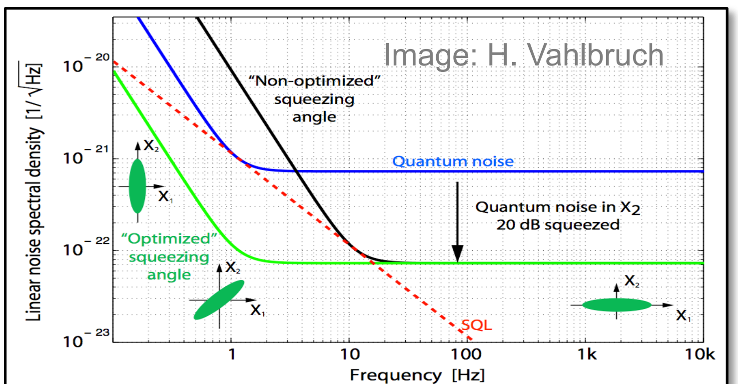


Advanced LIGO with squeezed light

- Advanced LIGO limited by both: Shot noise and Radiation pressure noise.
- Therefore injection of 'simple squeezed' light will improve sensitivity on some frequency range and degrade it at other frequencies.
- Solution: Use dispersion in reflection of a filter cavity to create a frequency dependent rotation of the squeezing ellipse.

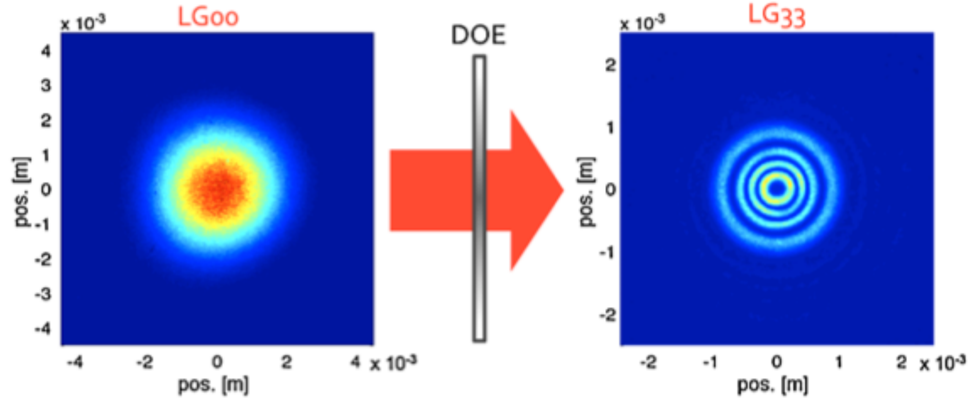




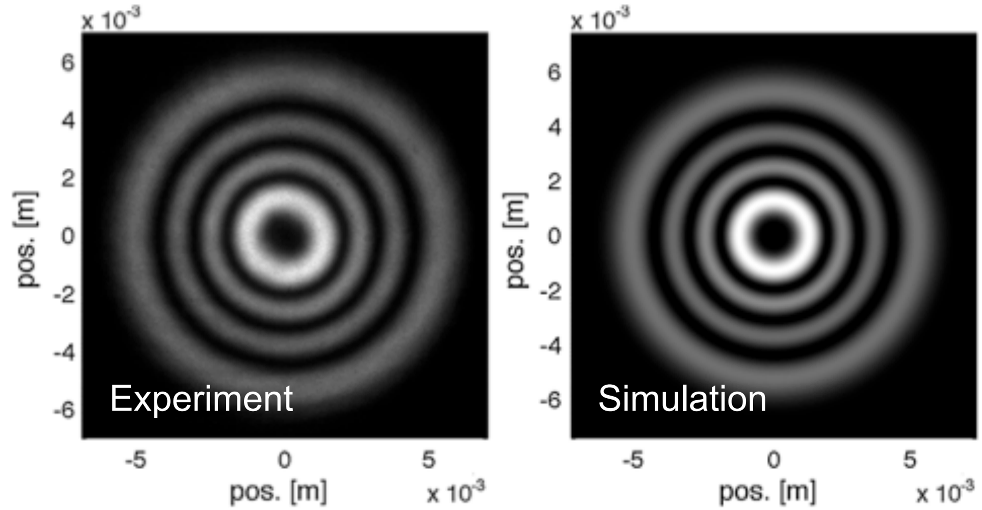


Use of alternative beam shapes in Advanced Virgo?

- Several alternative beam shapes (flat top, conical etc) have been suggested.
- All improve coating Brownian noise by distributing the power more homogeneously over the mirror surface (for the same clipping loss) and therefore better averaging over the local thermal fluctuations.
- Higher LG modes allow to work with standard mirrors (spherical ROC).
- Higher order LG modes included as upgrade option in the Advanced Virgo conceptual design. VIR–042A–07

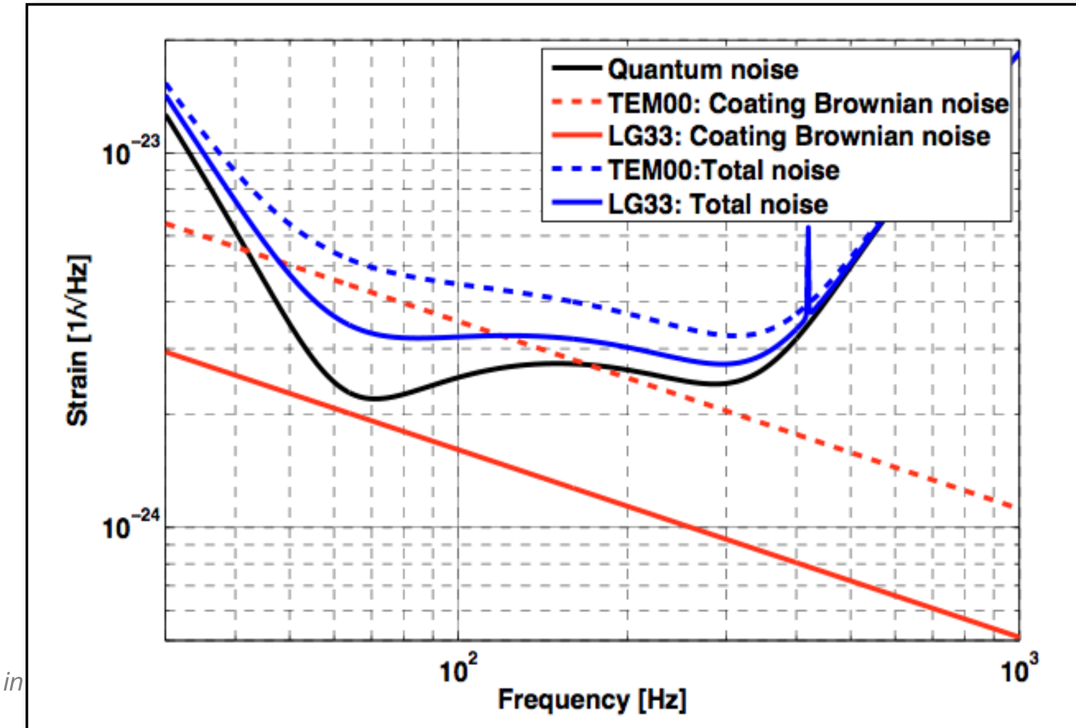


Granata, M.; Buy, C.; Ward, R. & Barsuglia, M. Higher-Order Laguerre-Gauss Mode Generation and Interferometry for Gravitational Wave Detectors, PRL 2010, 105, 231102



Potential Sensitivity Improvement of Advanced Virgo with LG_{33} beams

- Switch beam geometry from TEM_{00} to LG_{33}
- Requires mirror replacement (different ROC)
- Reduces coating Brownian by a factor 2.2.
  Vinet: personal communication
- Reduces substrate Brownian by a factor 2.7
  Mours, B.; Tournefier, E. & Vinet, J. Thermal noise reduction in interferometric GW antennas: using high order TEM modes, CQG, 2006, 23, 5777
- Increases thermo-elastic by a factor 1.7
  Vinet: personal communication

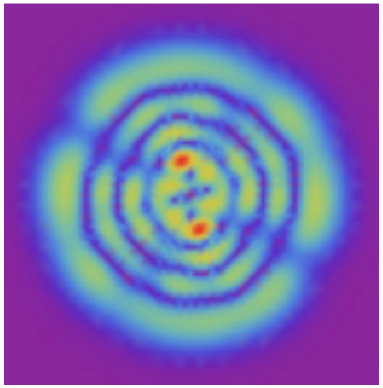


BNS Inspiral range increases from 148 Mpc to 195 Mpc => increase of event rate by a factor 2.3

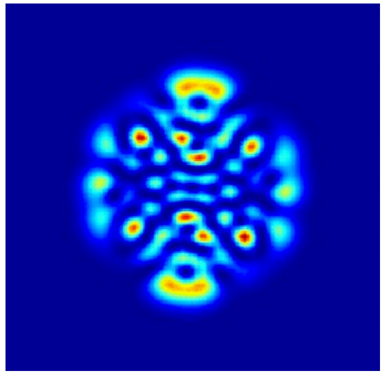
Chelkowski, S.; Hild, S. & Freise, A.: Prospects of higher-order Laguerre-Gauss modes in future gravitational wave detectors, *PRD,* **2009**, *79*, 122002

Will non-TEM_{00} beams ever become good enough?

- Simulations done by various groups (LMA, Caltech/ANU, Bham) indicate that with currently available mirror surfaces LG33 might become too much distorted for application in future gravitational wave detectors.



R. Adhikari's at GWADW 2010

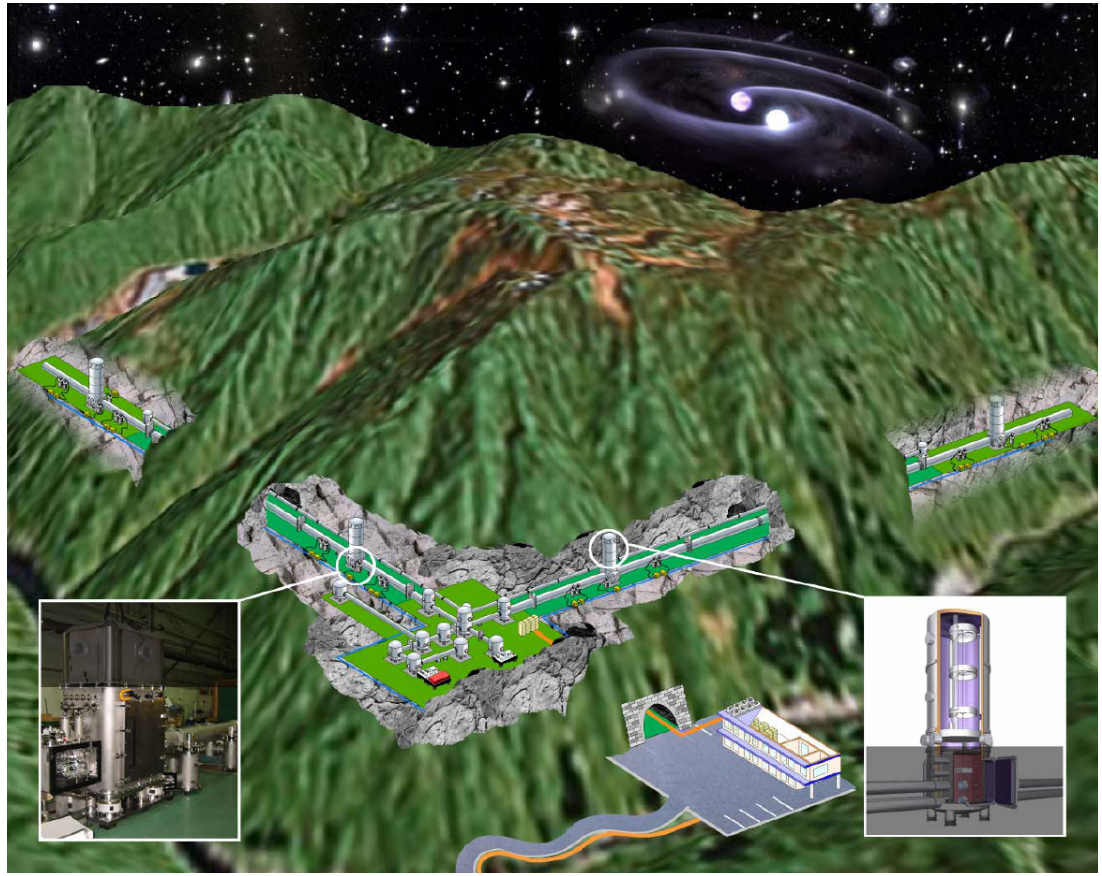


M. Galimberti at GWADW 2010

- Need to confirm simulations with experiments (see talk by B. Sorazu in Monday session).
- Need to define minimum requirements for mirror surface quality (see talk by C. Bond in Monday session)
- Can we improve surface quality to the required value?

LCGT

- LCGT will be the only second generation detector which:
  - Is located underground => strong reduction of seismic and gravity gradients.
  - Will make use of cryogenic test masses.
- For details on LCGT please see K.Somiya's talk in the Tuesday session.

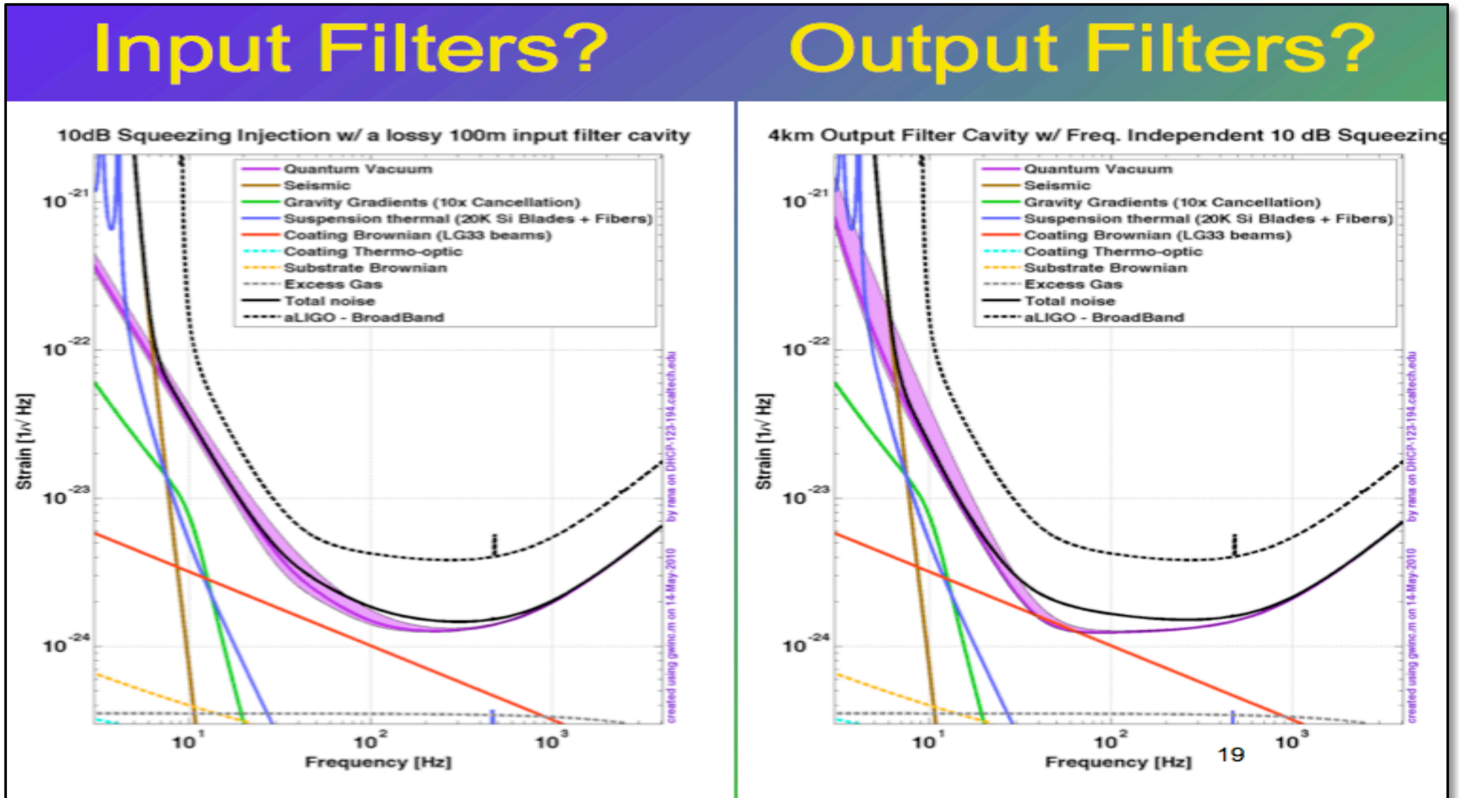


Other techniques for 2G upgrades

- Gravity gradient noise:
  - Gravity gradient subtraction methods have been suggested.
  - For more details please see J. van der Brand's talk in this session.
- Suspension thermal noise
  - Several improvements suggested (different materials, design modifications, perhaps even different temperature).
  - For more details please see G. Hammond's talk in this session.
- Seismic noise
  - Better sensors, especially for tilt.
- Quantum noise
  - Loads of other quantum noise reduction techniques have been suggested.
  - Please see talk by T. Corbitt in this session for more details.

How far can we push 2G upgrades?

- Let's take advanced LIGO as an example:

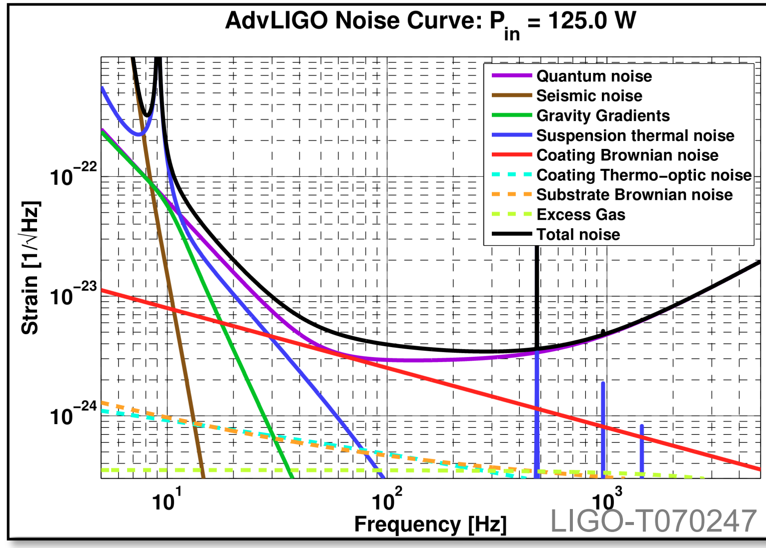


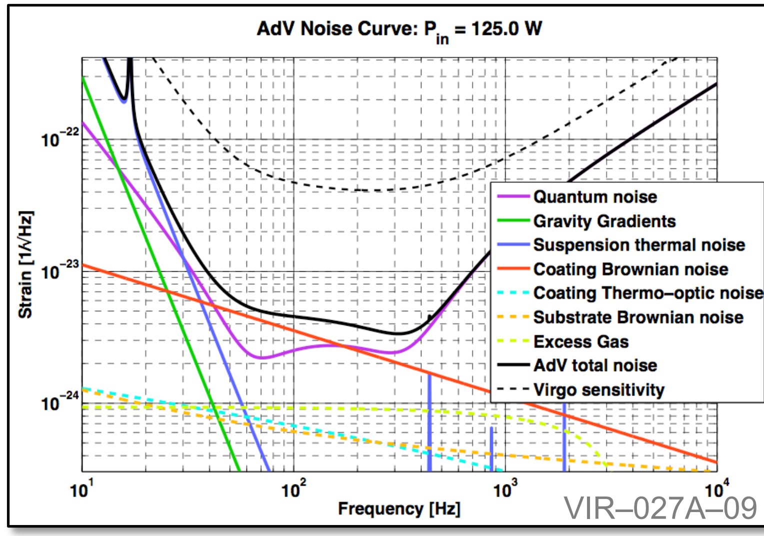
R.Adhikari: LIGO G100 0524

- **Studies indicate that there are lots of possibility for potential upgrades.**

Where are the 2G facility limits?

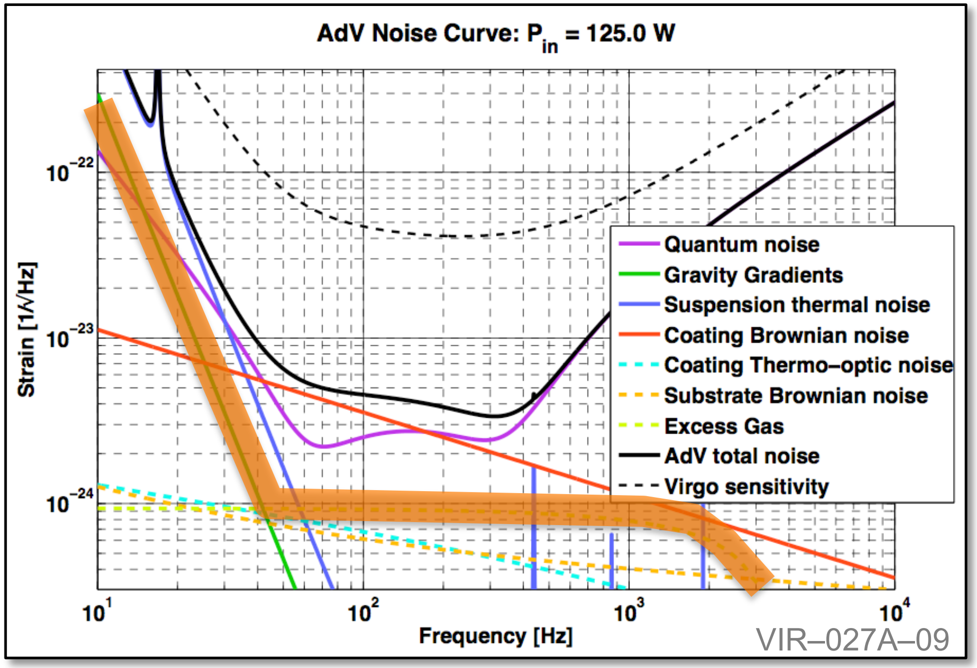
- To determine the actual facility limits we have to understand on which parameters the different noise sources depend.
- Quantum noise: Laser power, Signal recycling configuration, quantum noise reduction technique …
- Coating noise: materials, beam shape, beam size, mirror temperature …
- Suspension thermal noise: materials, dimensions, temperature …
- Gravity gradient: seismic environment.
- Seismic noise: Isolation system, seismic environment.
- Residual gas noise: Vacuum system.

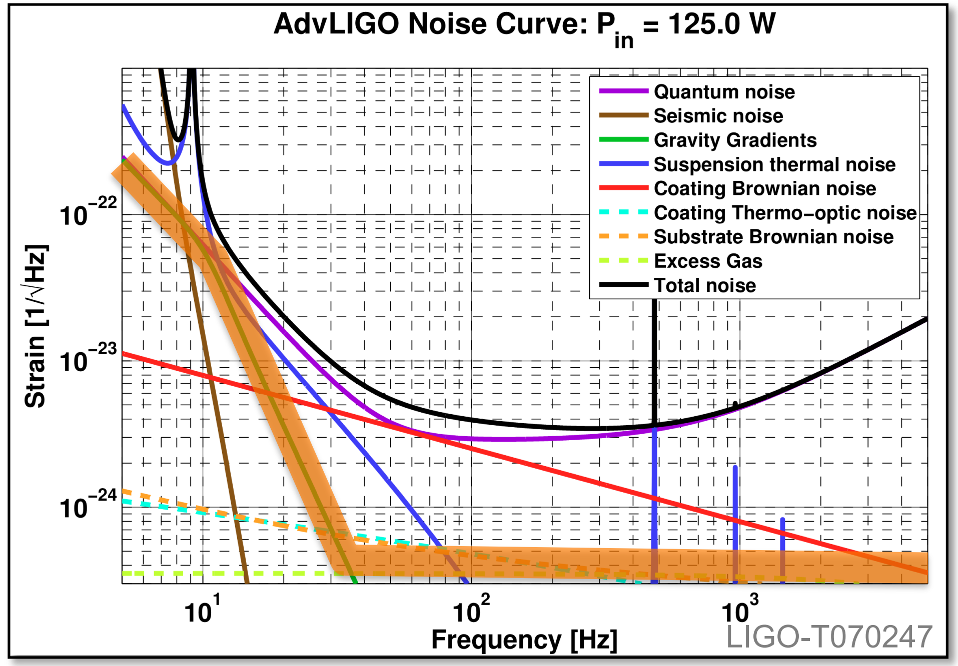




Where are the 2G facility limits?

- One (crude) way to set the facility limit is just to take gravity gradient and residual gas noise. …very optimistic for coating :)





- Need to find a more accurate definition of what the facility limits are and where they lie. --- Separate analysis for each project.

Overview

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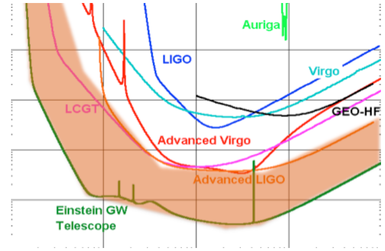

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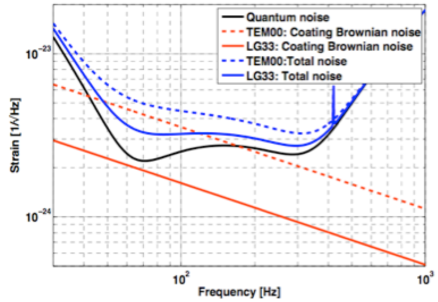

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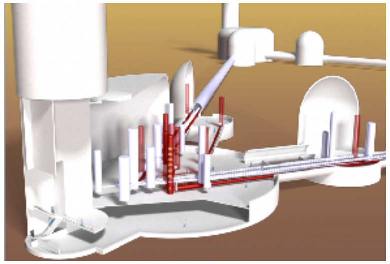
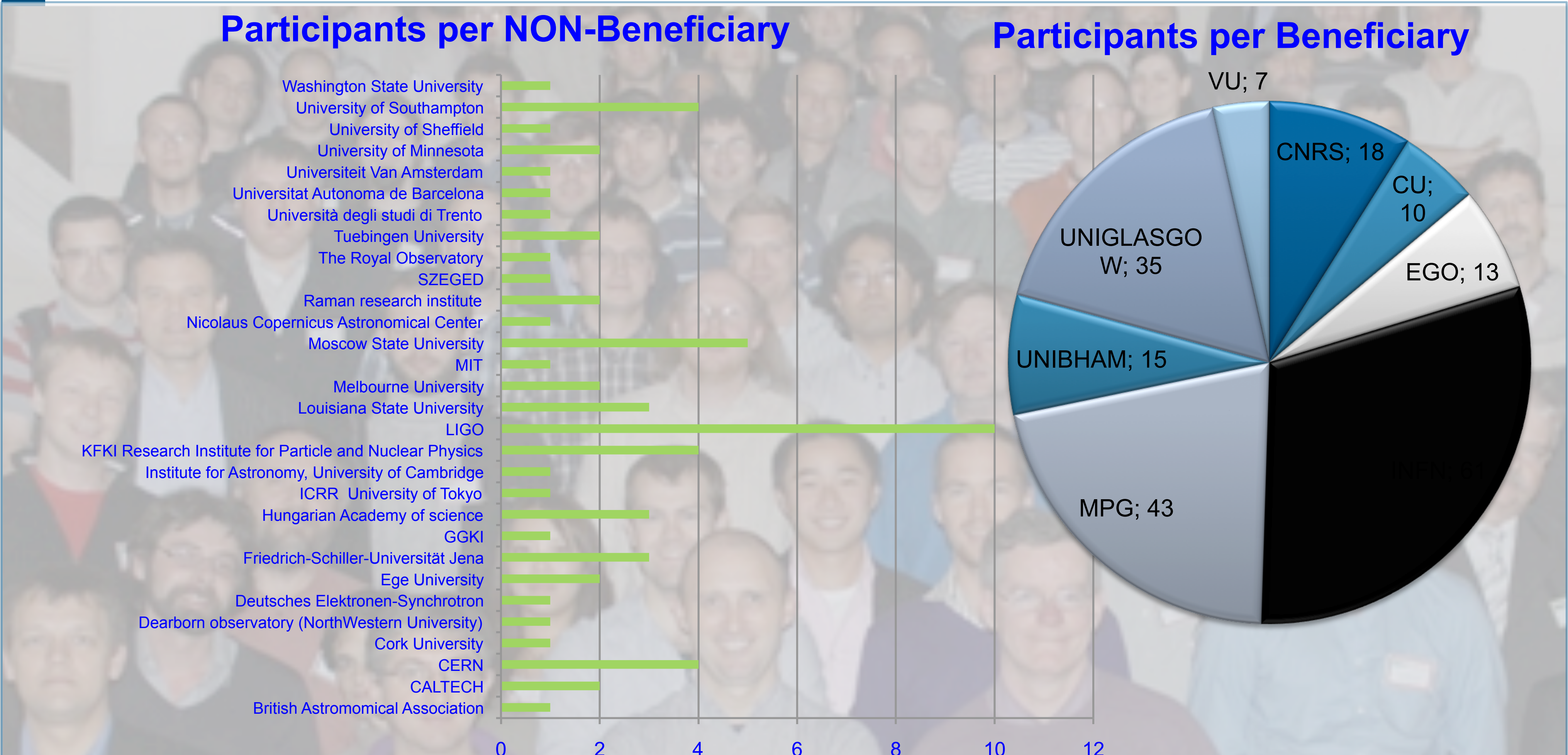


ET Design Study (history)

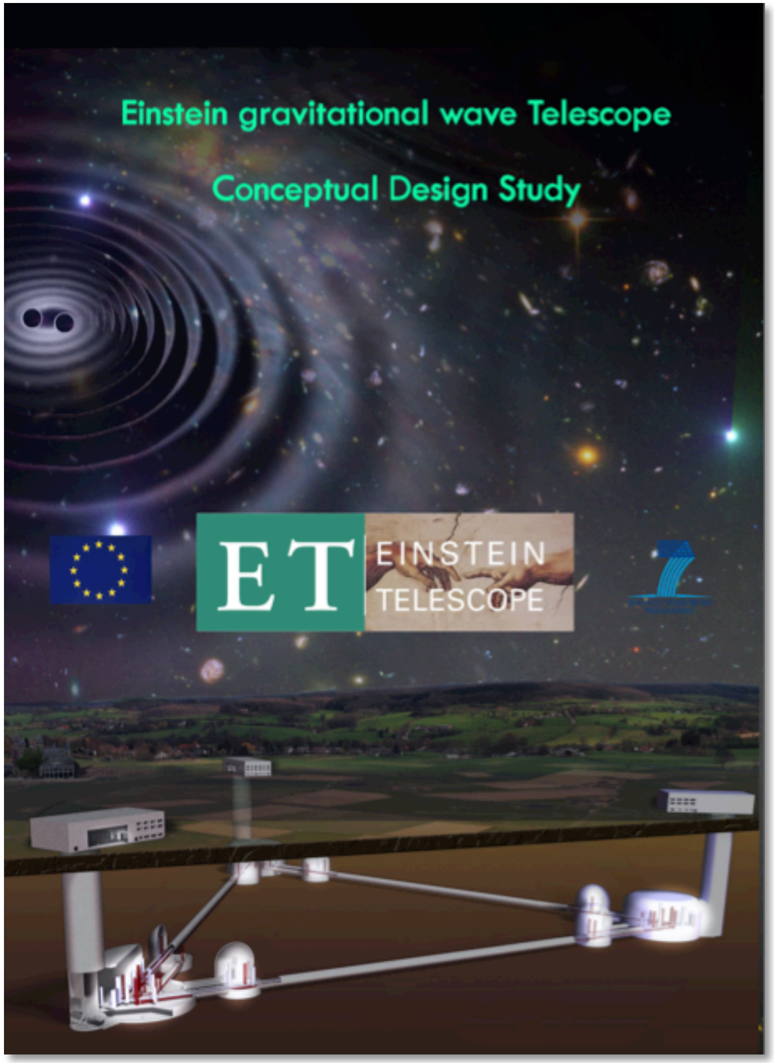
- The Einstein Telescope project aims to the realization of a third generation GW observatory.
- The Einstein Telescope project just finished its conceptual design study phase, supported by the European Community FP7 with about 3M€ from May 2008 to July 2011.
- The target of this design phase was to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

ET Science Team (~250 Scientists)



ET Design study now complete!



Author list: **ET Science Team**

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Available at:
http://www.et-gw.eu/etdsdocument

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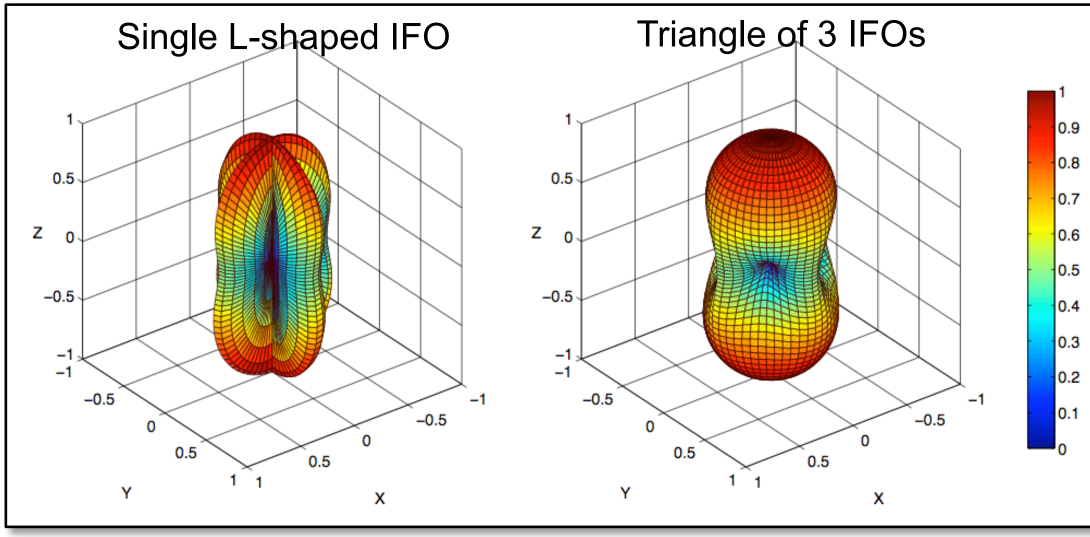
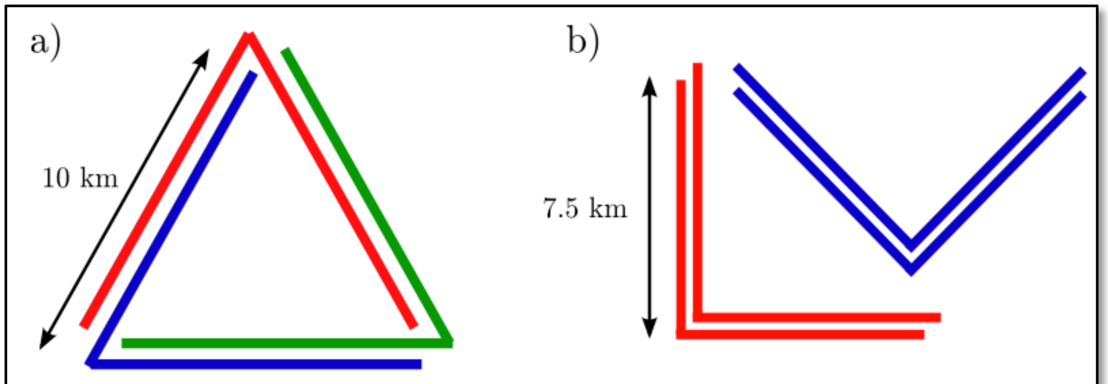
The ET Footprint

- 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.**



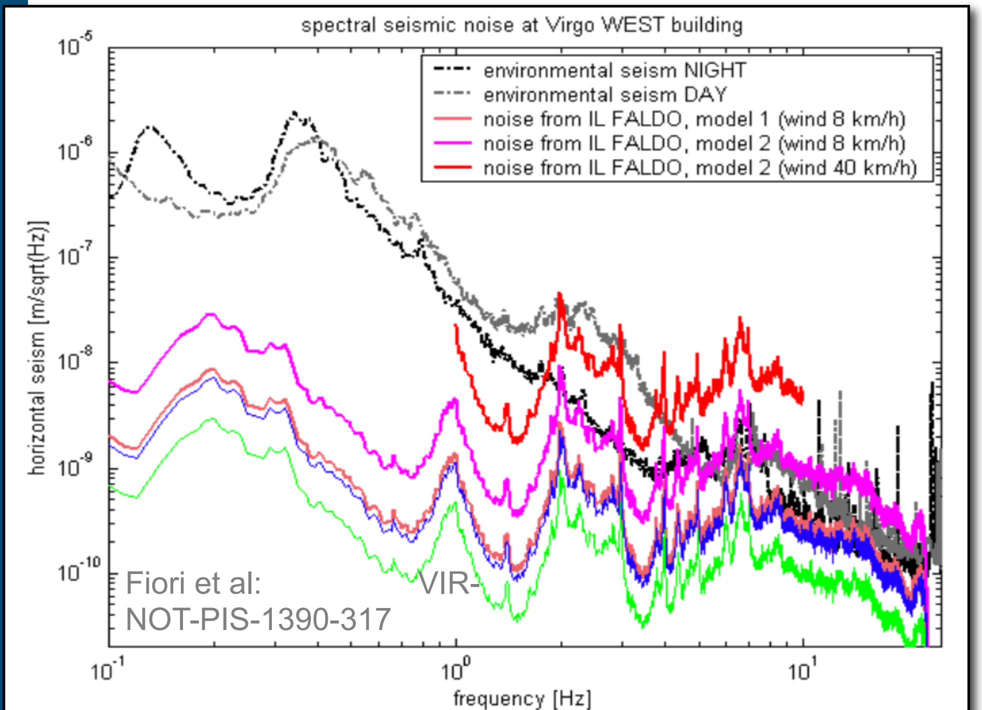
Freise, A.; Chelkowski, S.; Hild, S.; Pozzo, W. D.; Perreca, A. & Vecchio, A. *CQG*, **2009**, *26*, 085012 (14pp)



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

ET will 'go underground'

- Measurements show that underground locations have much lower seismic compared to Surface locations.



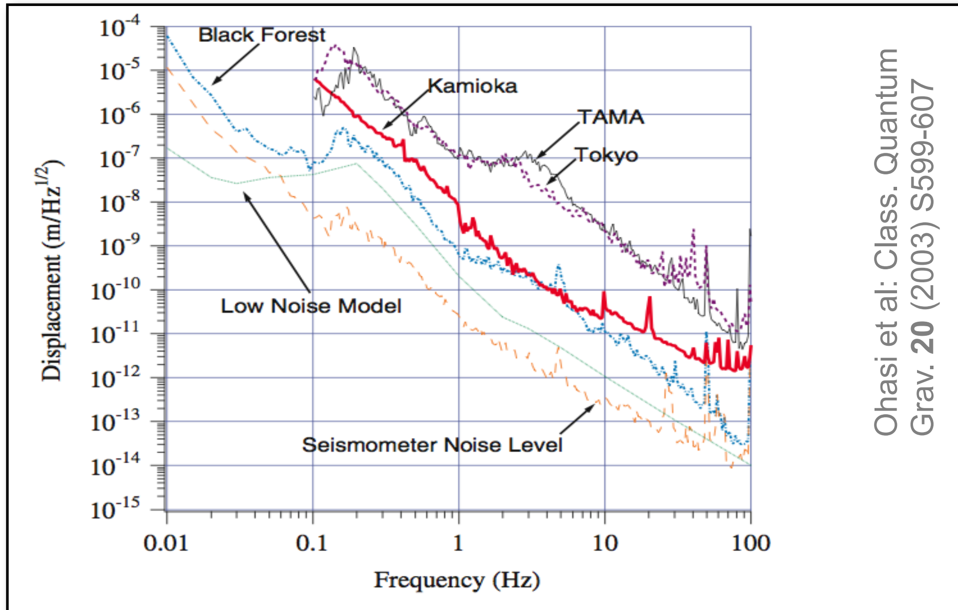


Figure 7. Low seismic noise environment at the Kamioka site. Displacement noises at Kamioka, TAMA site, Tokyo, Black Forest Geophysical Observatory (Germany) and a low noise model (a hybrid spectrum of quiet sites in the world) are described.

Ohasi et al: Class. Quantum Grav. **20** (2003) S599-607

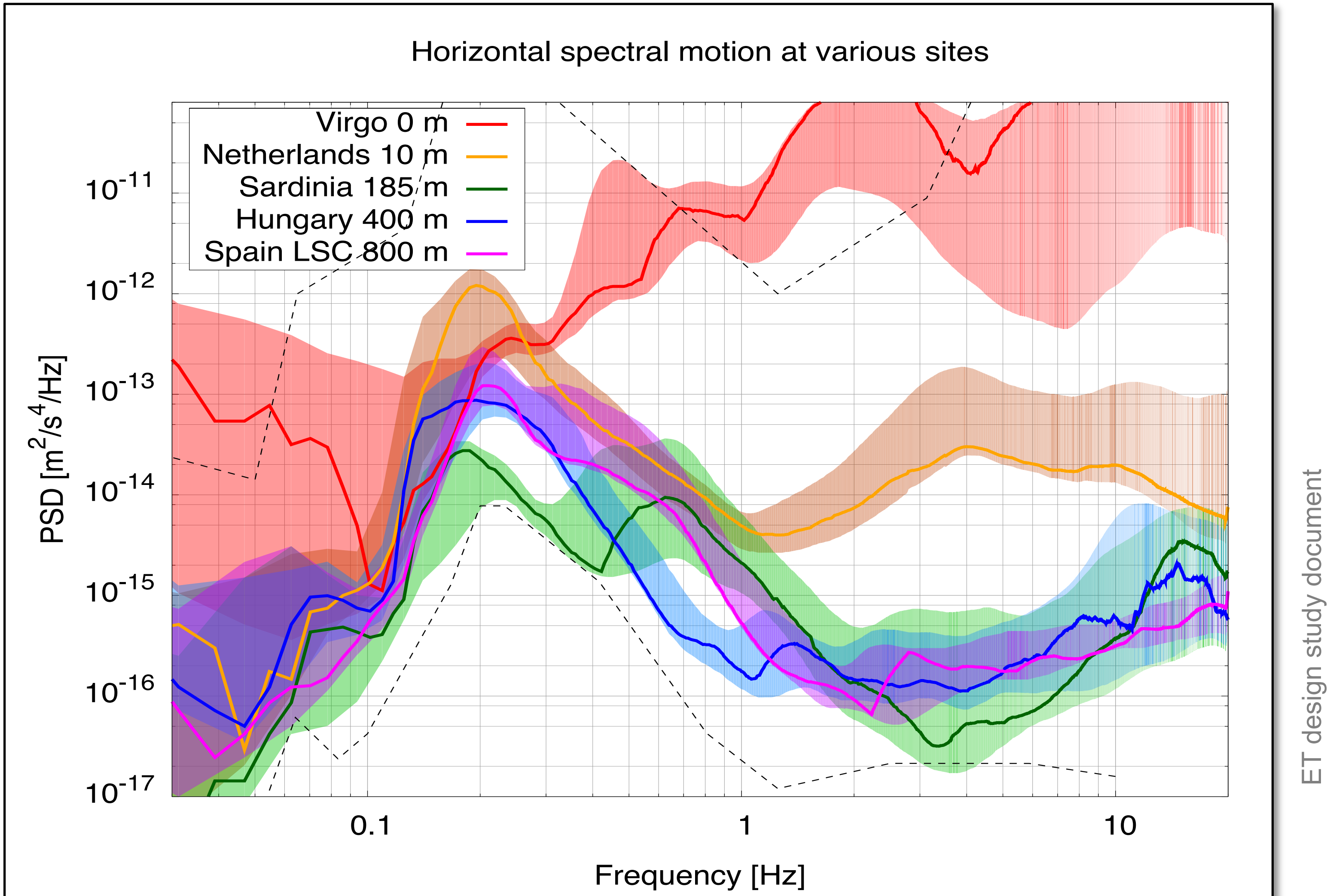
Surface (Pisa)

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 $f > 1\,\mathrm{Hz}$

ET will ‘go underground’



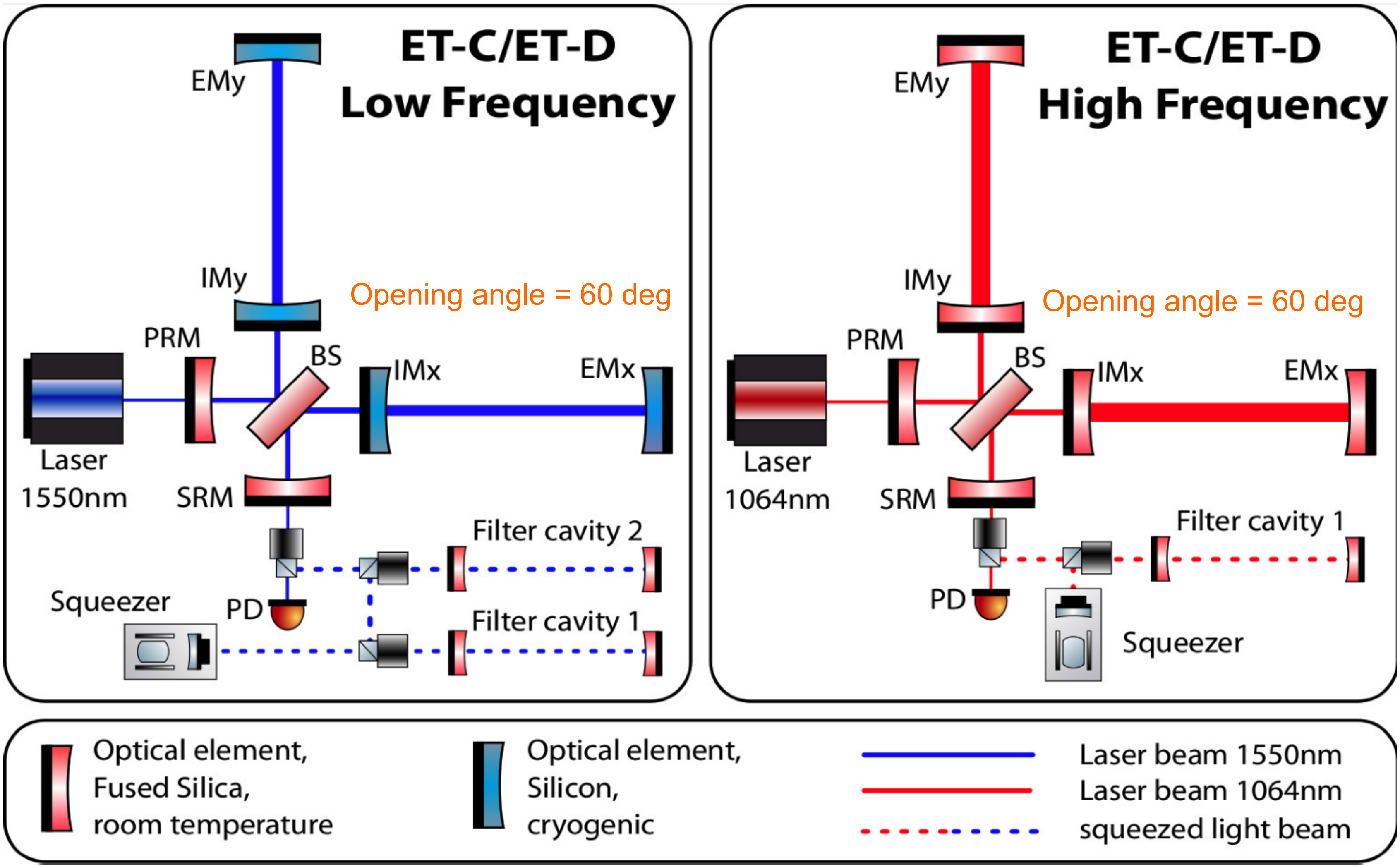
Xylophone Concept

- 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

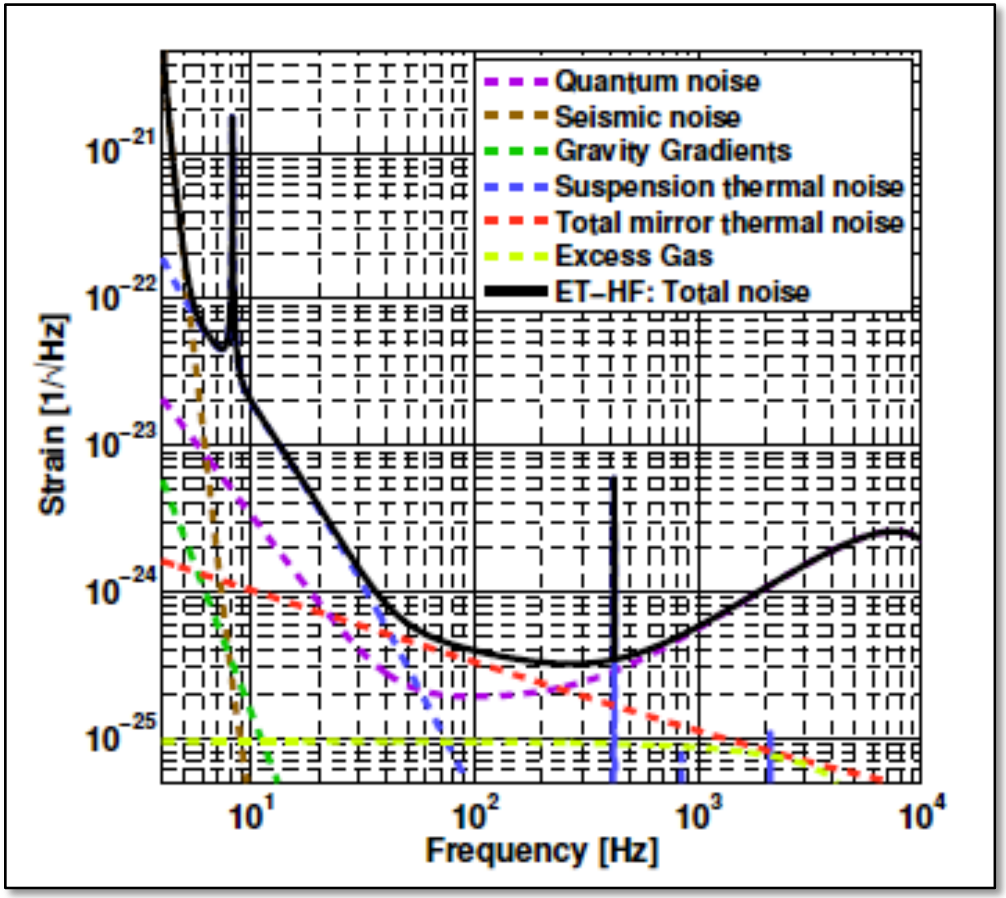
- Allows to overcome 'contradicting' requirements in the technical detector design:
  - To reduce shot noise you have to increase the light power, which in turn will reduce the sensitivity at low frequencies due to higher radiation pressure noise.
  - Need cryogenic mirrors for low frequency sensitivity. 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 ET core interferometers



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

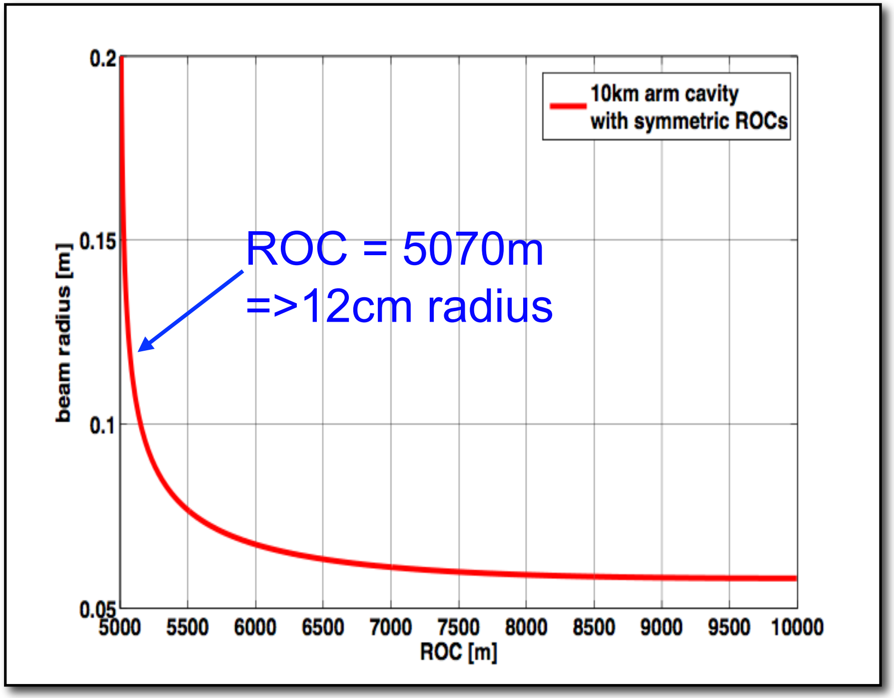
How large can we actually make beams

- Coating noise decreases inversely to beam size increase.

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

beam radius on mirror

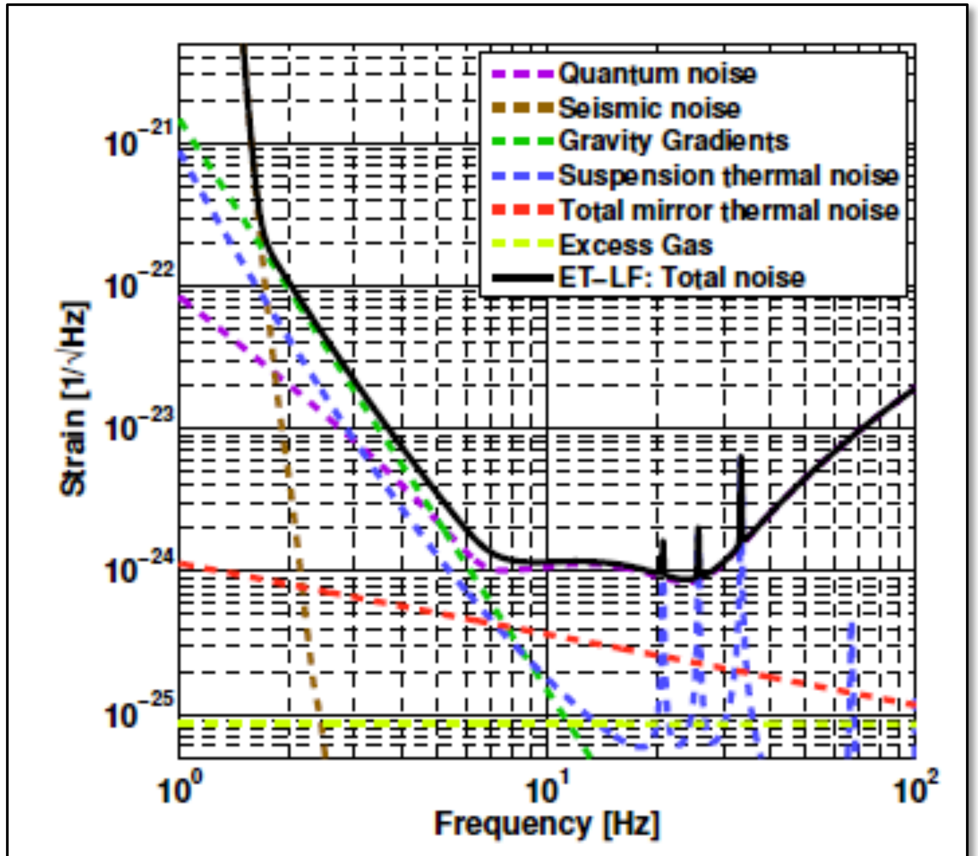
- Have to answer the question: How big can we actually make the beams on the test masses, without obtaining unstable cavities or strong dark fringe degeneration?
- Question also interesting for 2G upgrades.
- See C. Graefs talk on this topic regarding the experimental program at the AEI-10m.



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

The Low-Frequency Detector

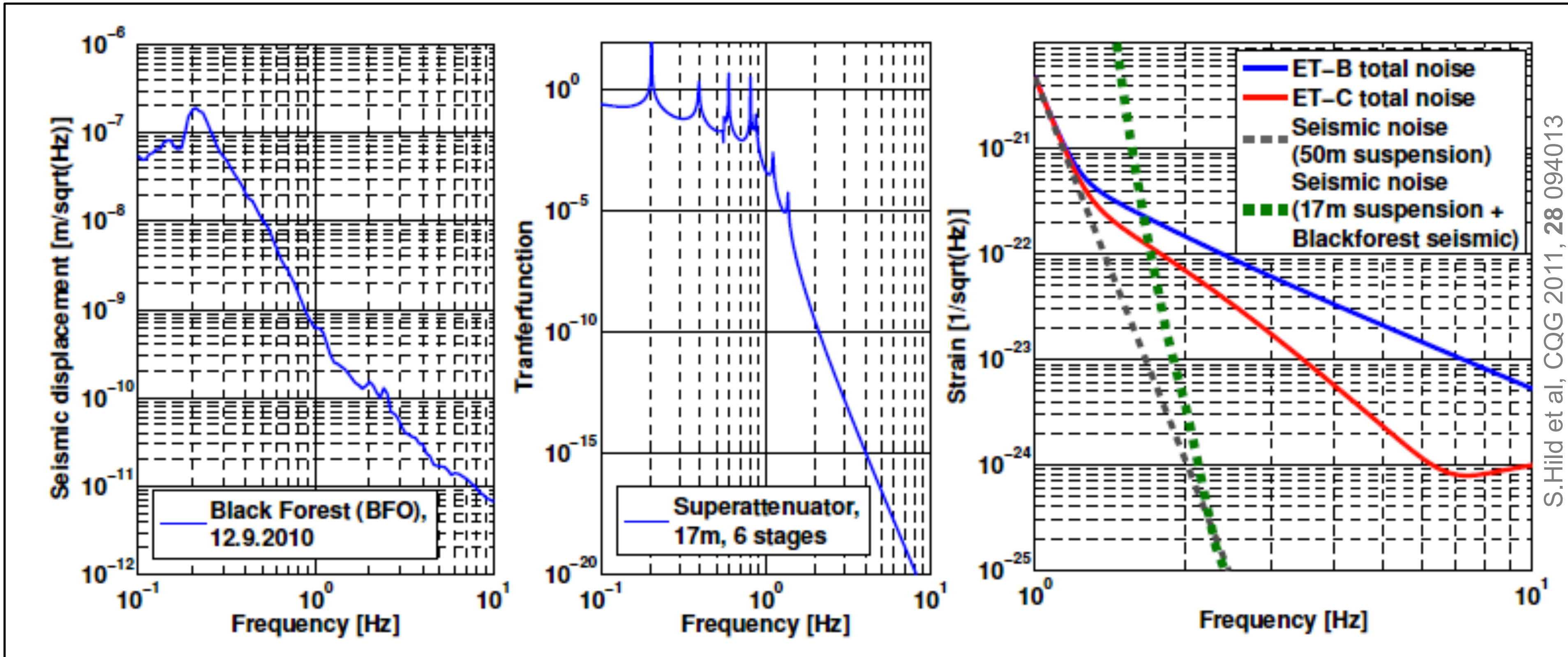
- **Quantum noise:** 18kW, detuned Signal-Recycling, 10dB frequency dependent squeezing, 211kg mirrors, 1550nm.
- **Seismic:** 17m Superattenuator
- **Gravity gradient:** Underground, Black forest location
- **Thermal noise:** 10K, Silicon, 9cm beam radius, TEM00.
- **Suspension Thermal:** 3mm Silicon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

Seismic noise

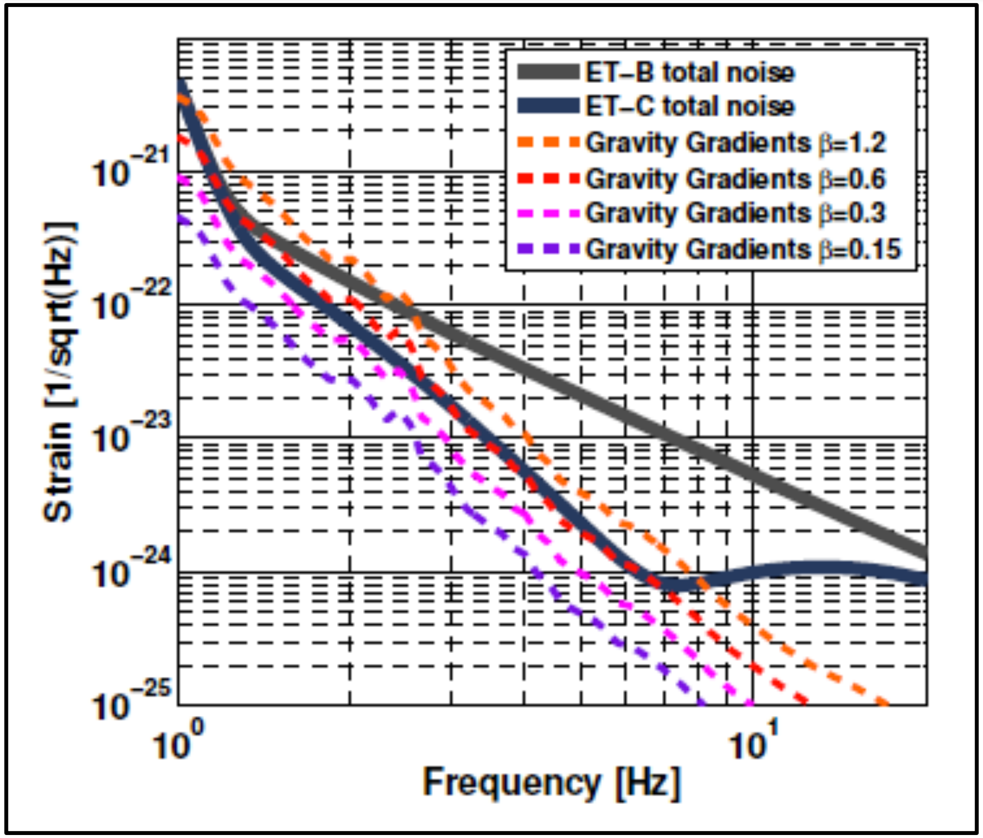


Seismic excitation x **17m SA Transfer function** = **Seismic noise contribution**

S.Braccini et al: presentation at GWADW 2010, Kyoto.

Gravity Gradient Noise

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



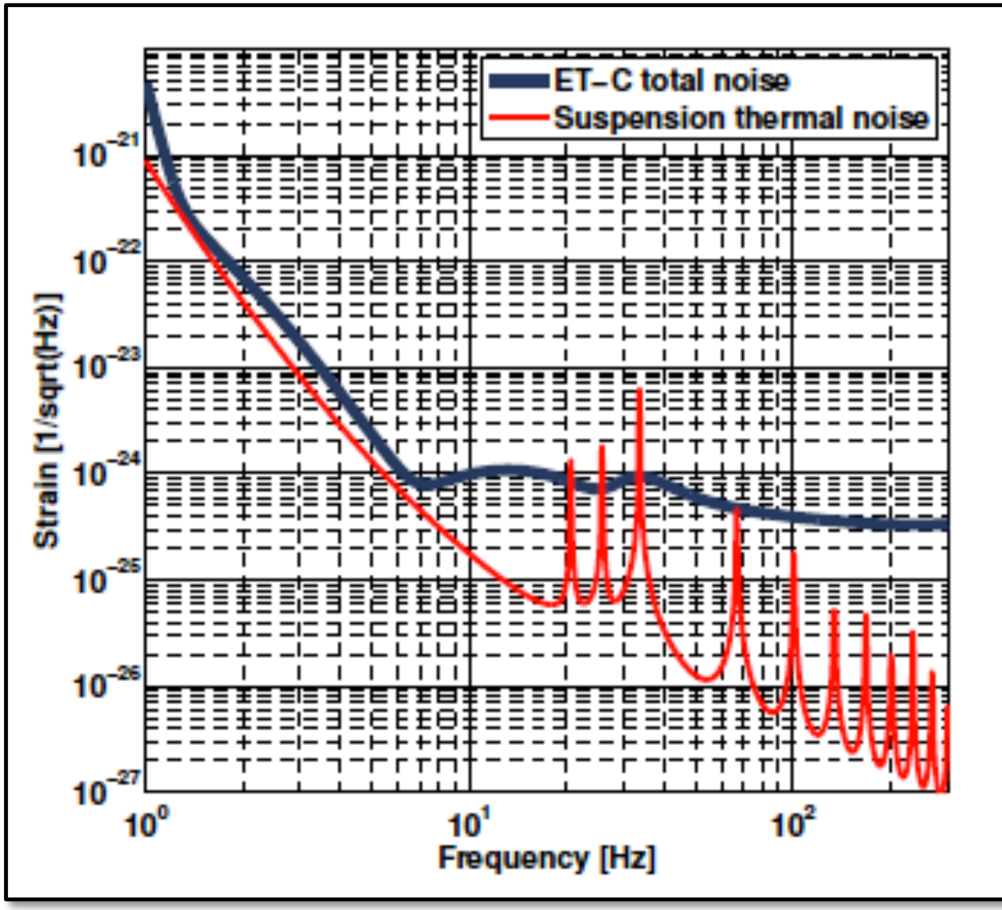
S.Hild et al, CQG 2011, **28** 094013

- ET-D considers very quiet underground site (about 5e-10/ f^2*m/sqrt(Hz)) at Black Forest.
- Please note:
  - ET measurement campaign showed several sites on the same level or even better than the Black Forest Observatory site (see talk by Jo van der Brand in this session).
  - Biggest uncertainty in beta.

Suspension Thermal Noise

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

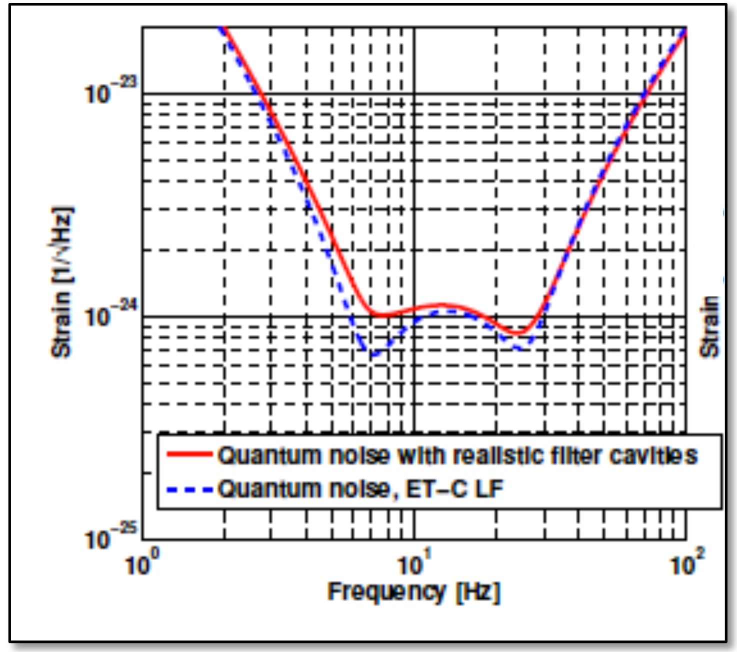
- P. Puppo, Journal of Physics: Conference Series 228, (2010) 012031
- P. Puppo and F. Ricci, General Relativity and Gravitation, Springer Netherlands, 2010, 1-13
- F.Ricci, presentation at GWADW 2010,Kyoto. Available at:http://gw.icrr.u-tokyo.ac.jp/gwadw2010/program/2010_GWADW_Ricci.pdf



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

Quantum of Low-Frequency detector

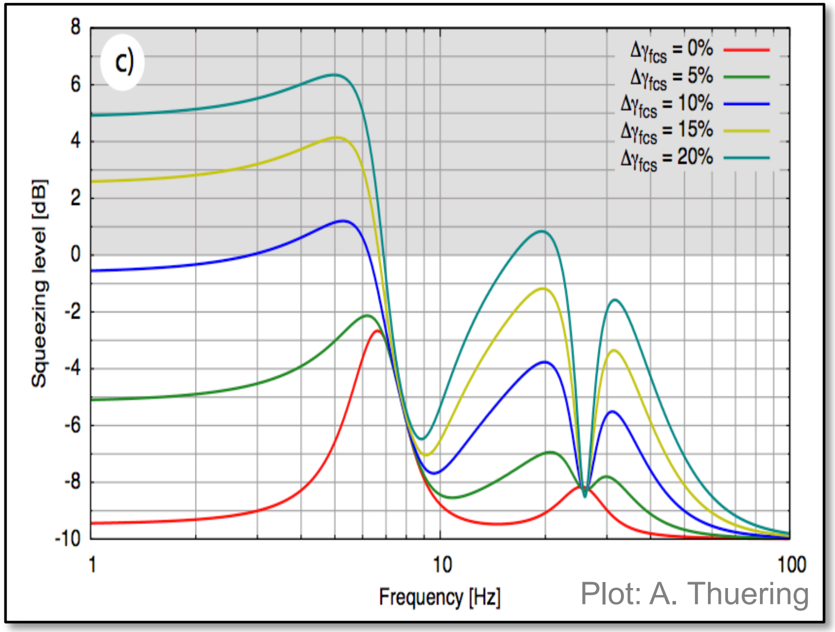
- Employs detuned signal recycling => needs two filter cavities.
- Required parameters for filter cavities challenging: Detuning of 25.4Hz and 6.6Hz and half bandwidths of 5.7Hz and 1.5Hz.
- To achieve such low bandwidths very long and/or very high finesse cavities are required.
- Total losses at resonance 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

How short can we make filter cavities?

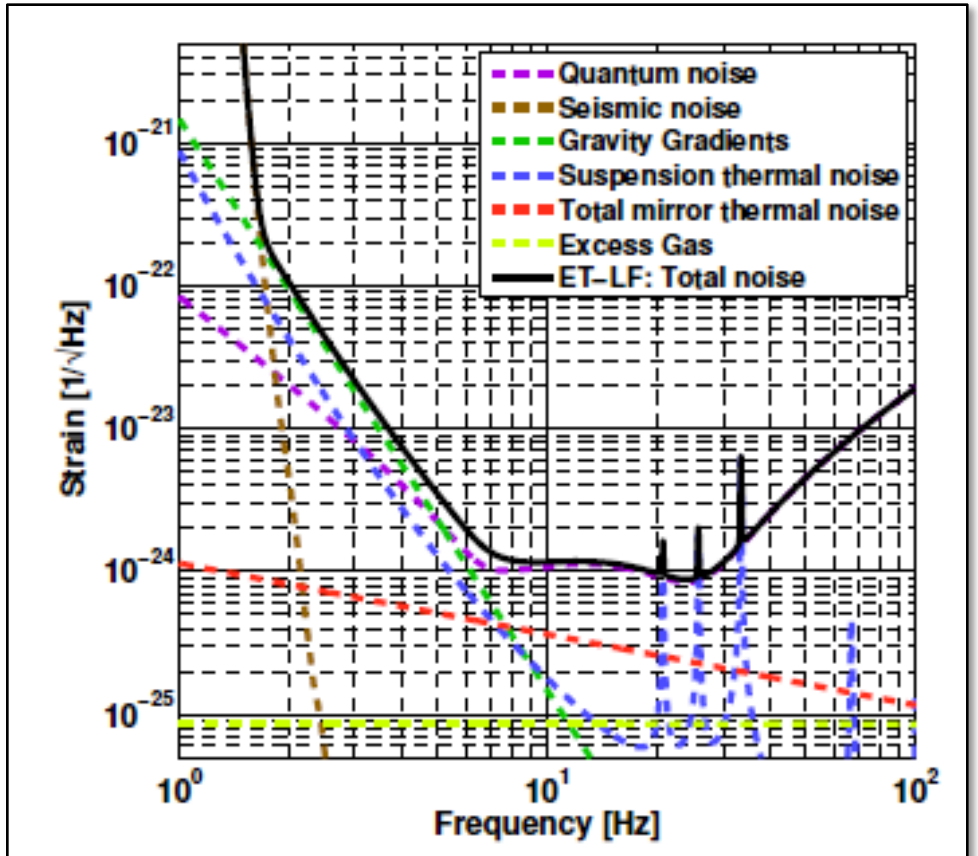
- If we go for shorter filter cavities we can reduce the beam size and therefore maybe also the scatter loss. Which in turn would allow to increase the finesse of the filter cavity …
- So we need to understand how the losses of a cavity scale with the length of the cavity for realistic curvatures and state of the art surface quality.
- A second point that needs to be addressed is how accurately we can hit the required bandwidth? Does the required bandwidth change over time (dirt accumulation on mirrors)? Do we need to use etalons rather than fixed mirrors in our filter cavities?



The frequency dependent squeezing can be degraded not only by losses in the filter cavities (red line), but also by deviations from the design bandwidth of the filter cavities (other colours).

The Low-Frequency Detector

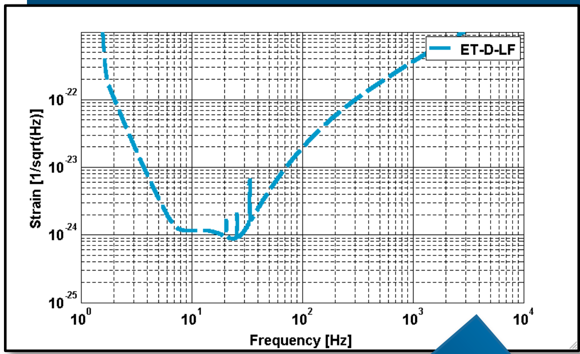
- **Quantum noise:** 18kW, detuned Signal-Recycling, 10 dB frequency dependent squeezing, 211kg mirrors, 1550nm.
- **Seismic:** 17m Superattenuator
- **Gravity gradient:** Underground, Black forest location
- **Thermal noise:** 10K, Silicon, 9cm beam radius, TEM00.
- **Suspension Thermal:** 3mm Silicon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

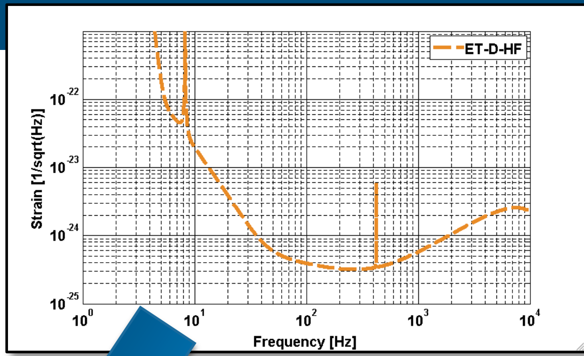


S.Hild et al, CQG 2011, **28** 094013

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

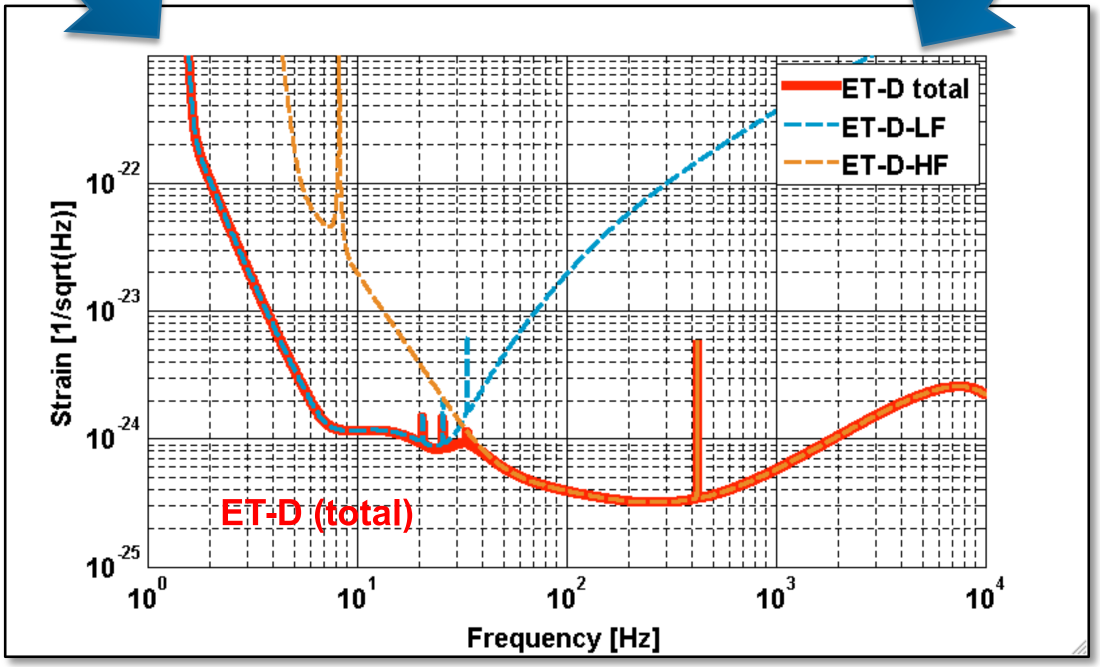
Combining 2 IFOs





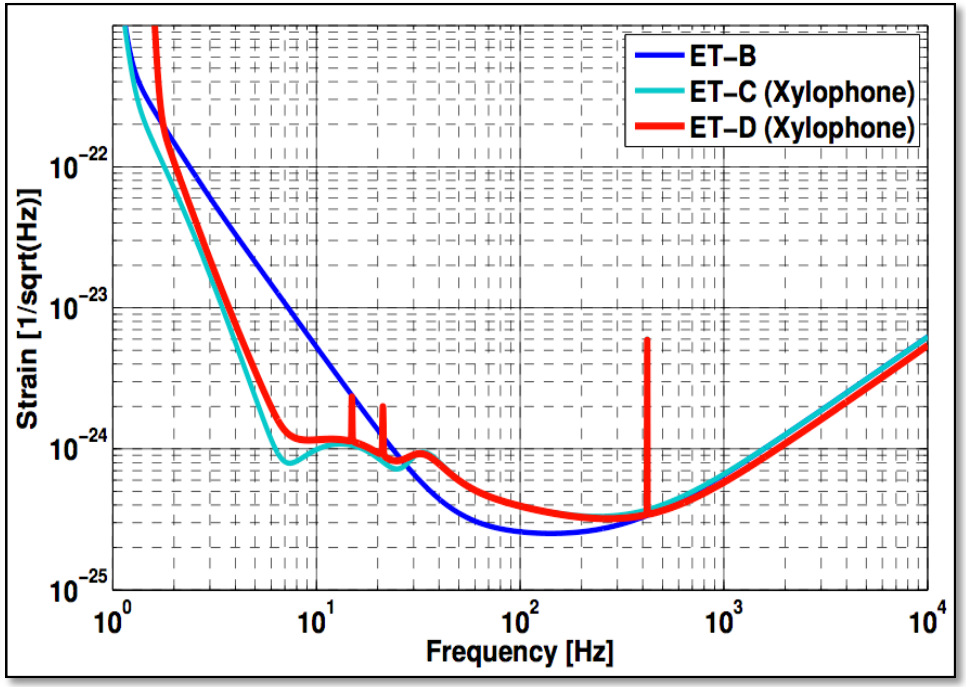
ET-D-LF

ET-D-HF



ET Sensitivity evolution

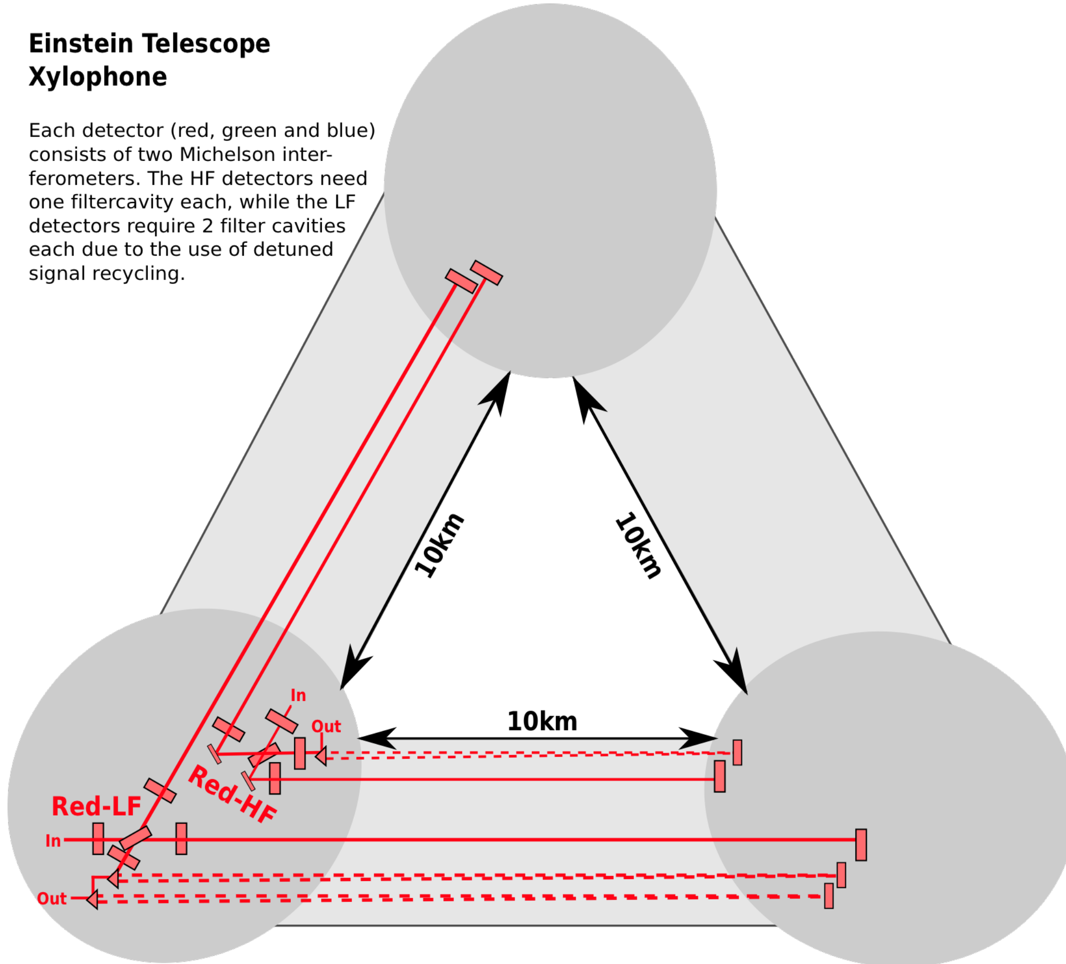
Parameter	ET-D-HF	ET-D-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	Fused silica	Silicon
Mirror diameter / thickness	62 cm / 30 cm	min 45 cm/ TBD
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	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.

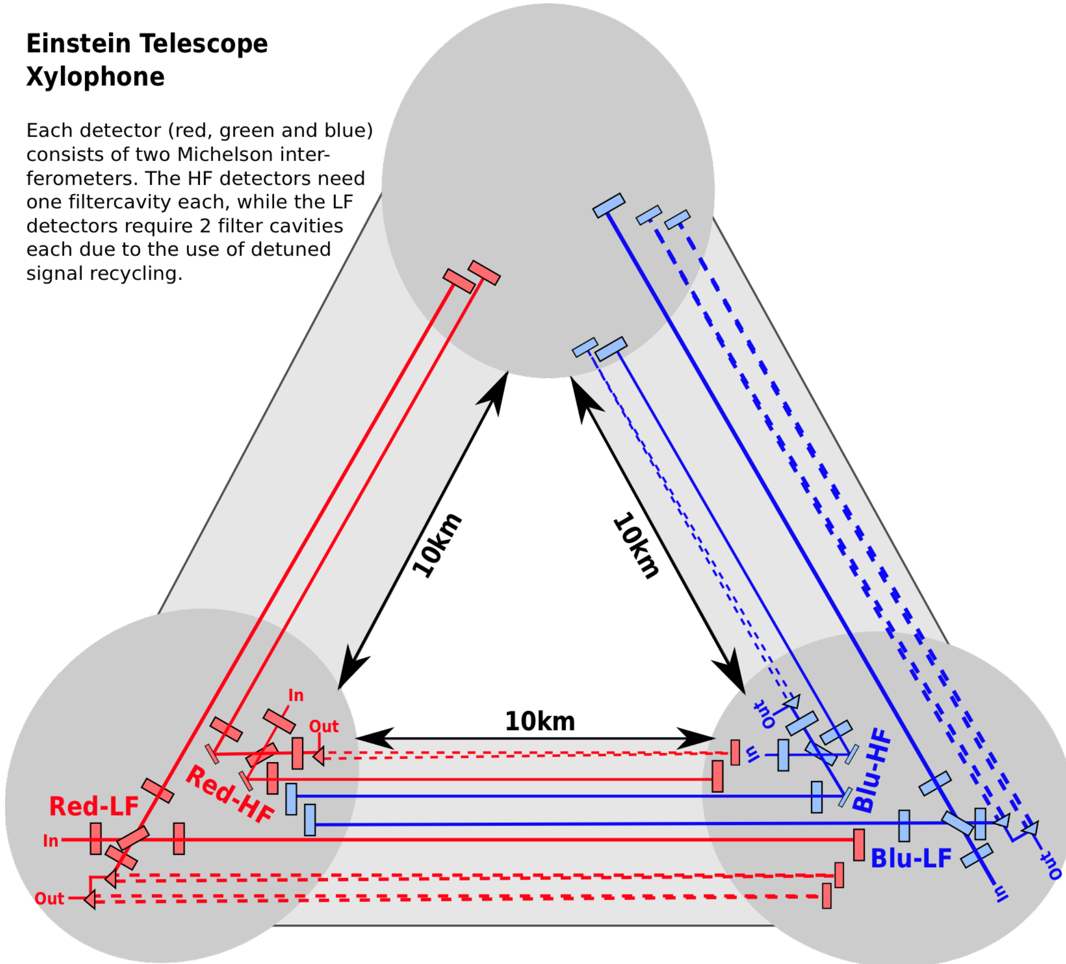
How to build an Observatory?

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



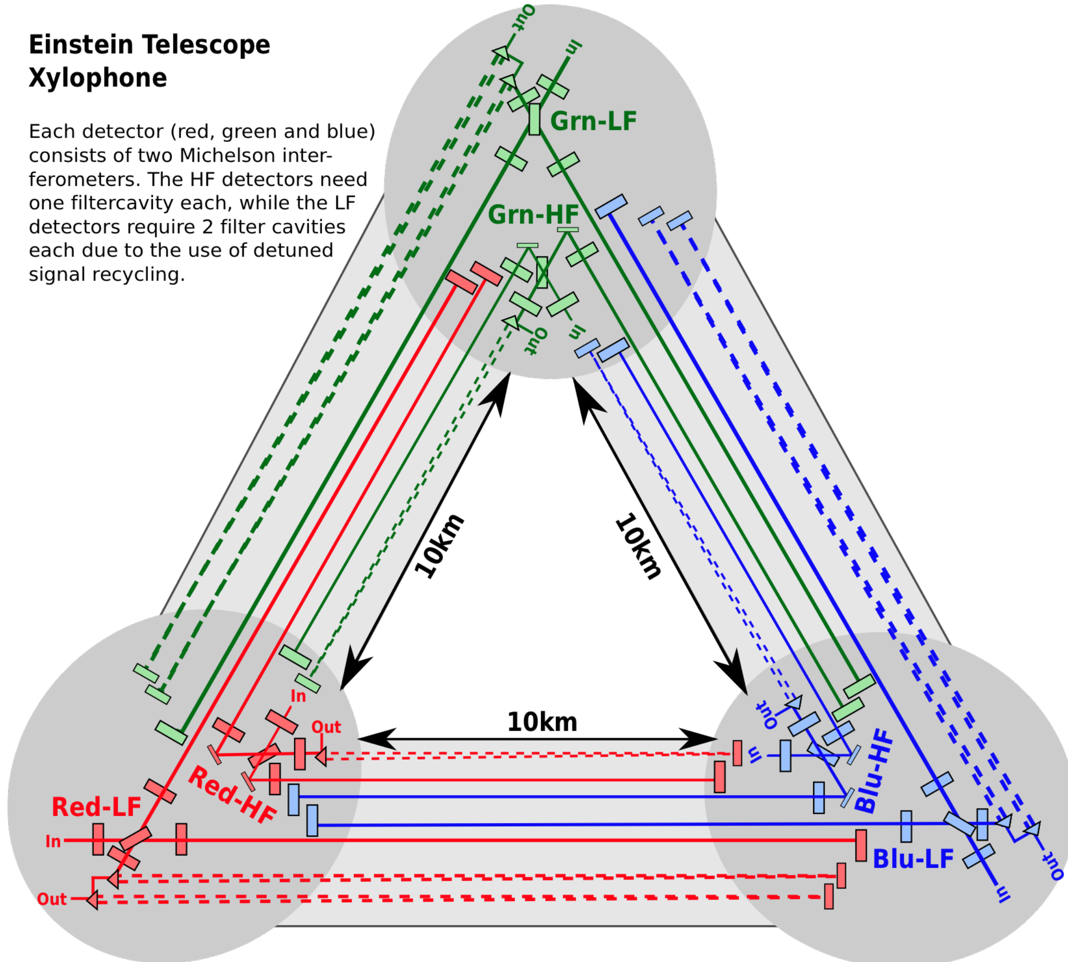
How to build an Observatory?

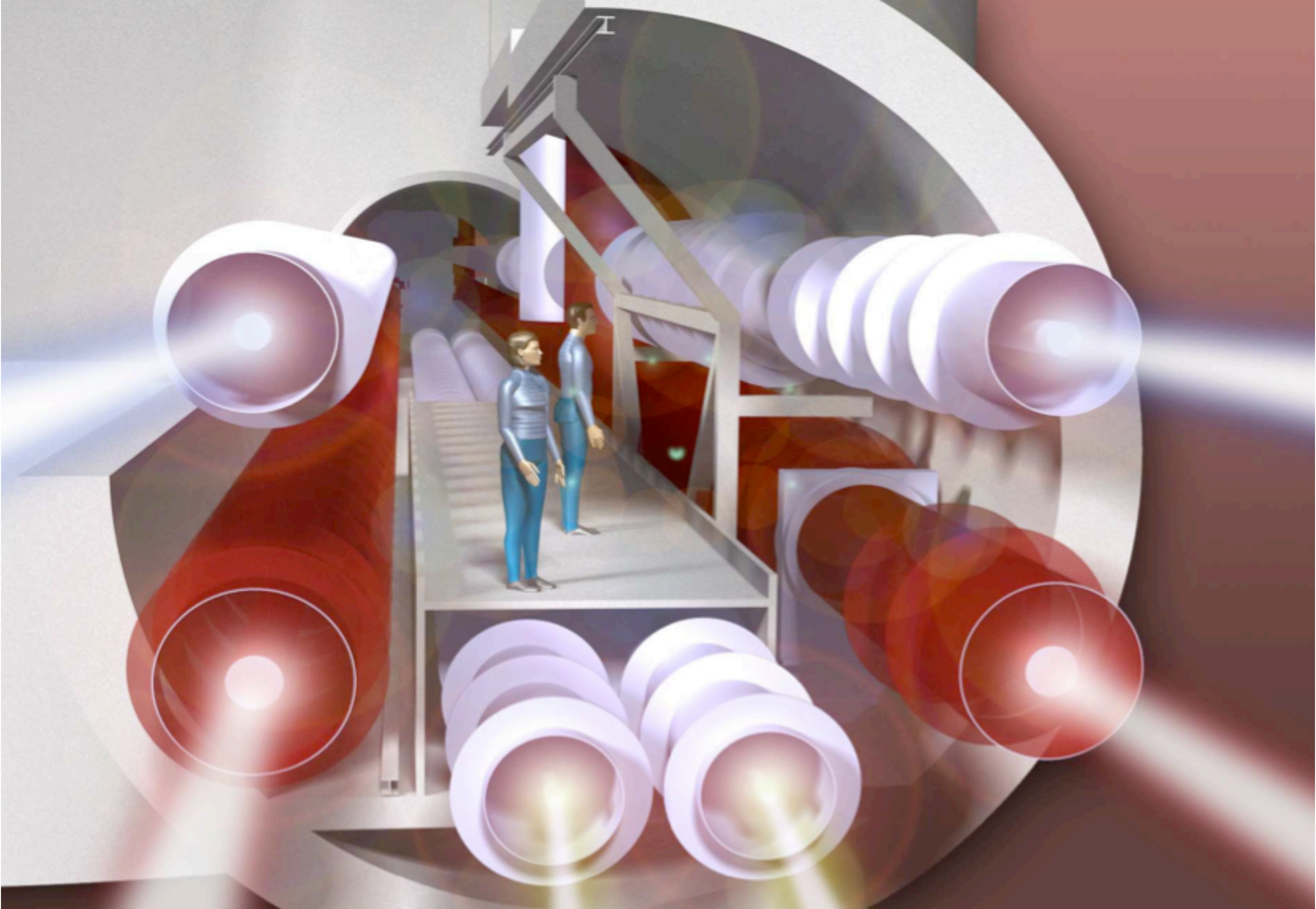
- For efficiency reasons build a triangle.
- Start with a single xylophone detector.
- Add second Xylophone detector to fully resolve polarisation.



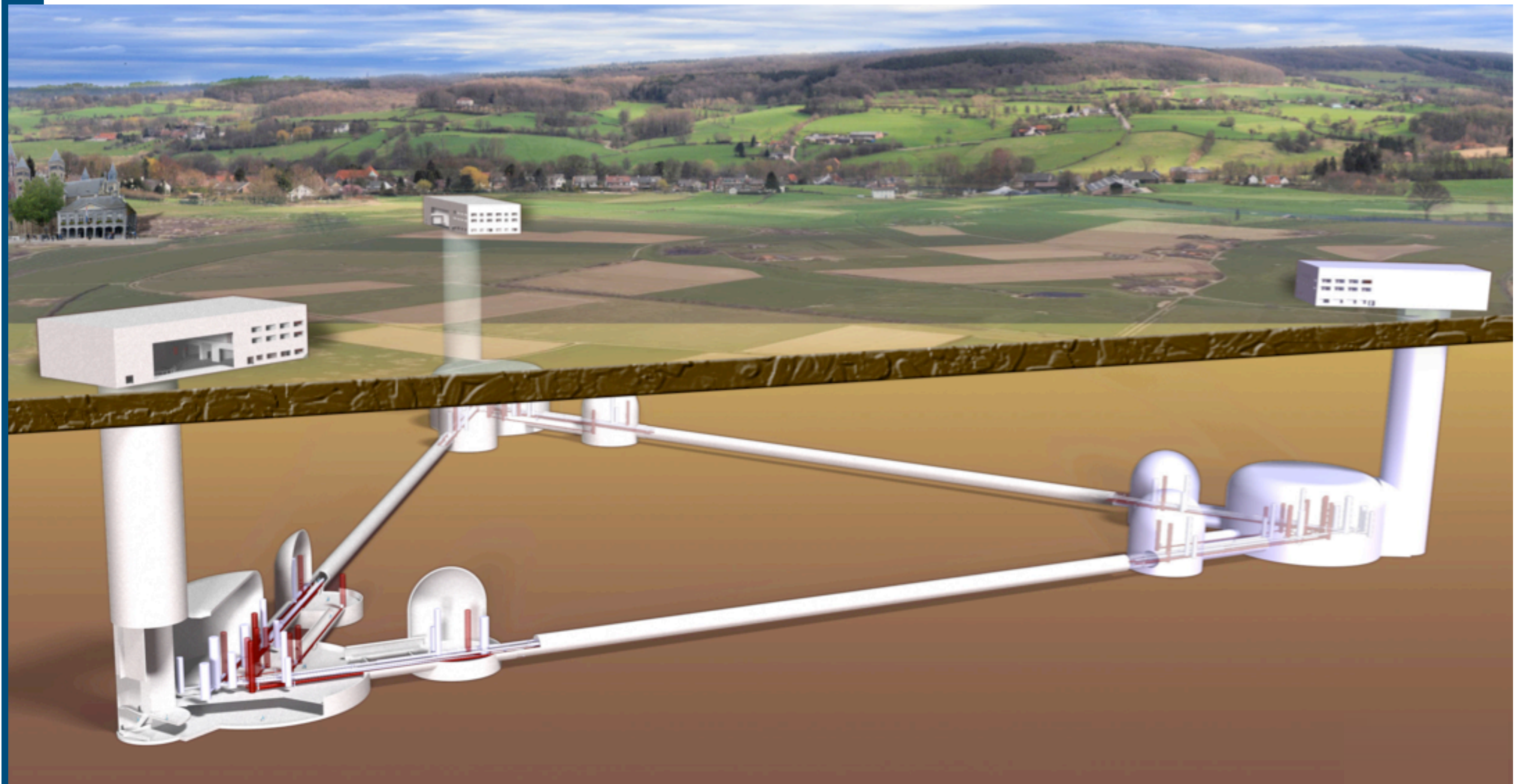
How to build an Observatory?

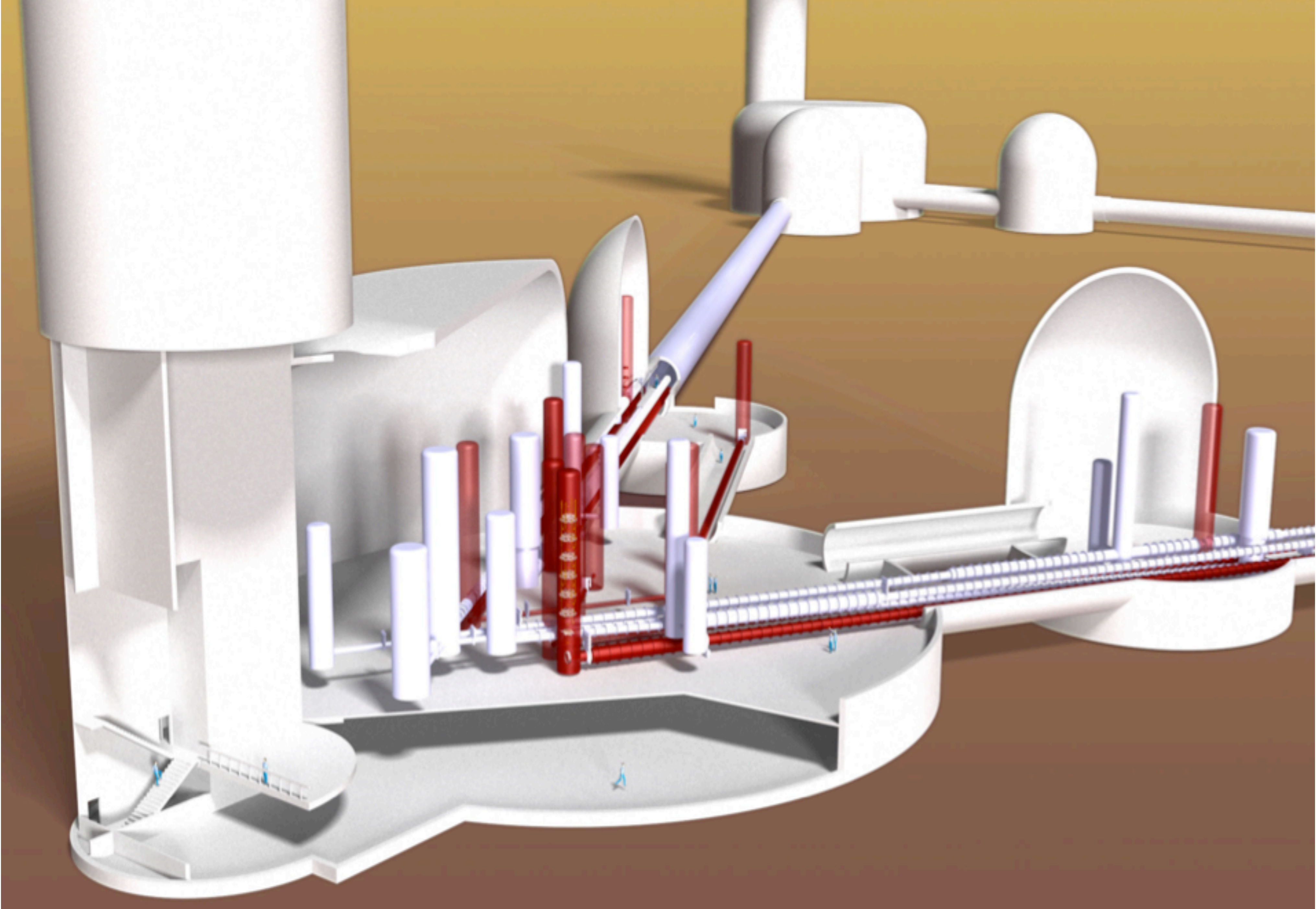
- For efficiency reasons build a triangle.
- Start with a single xylophone detector.
- Add second Xylophone detector to fully resolve polarisation.
- Add third Xylophone detector for redundancy and null-streams.

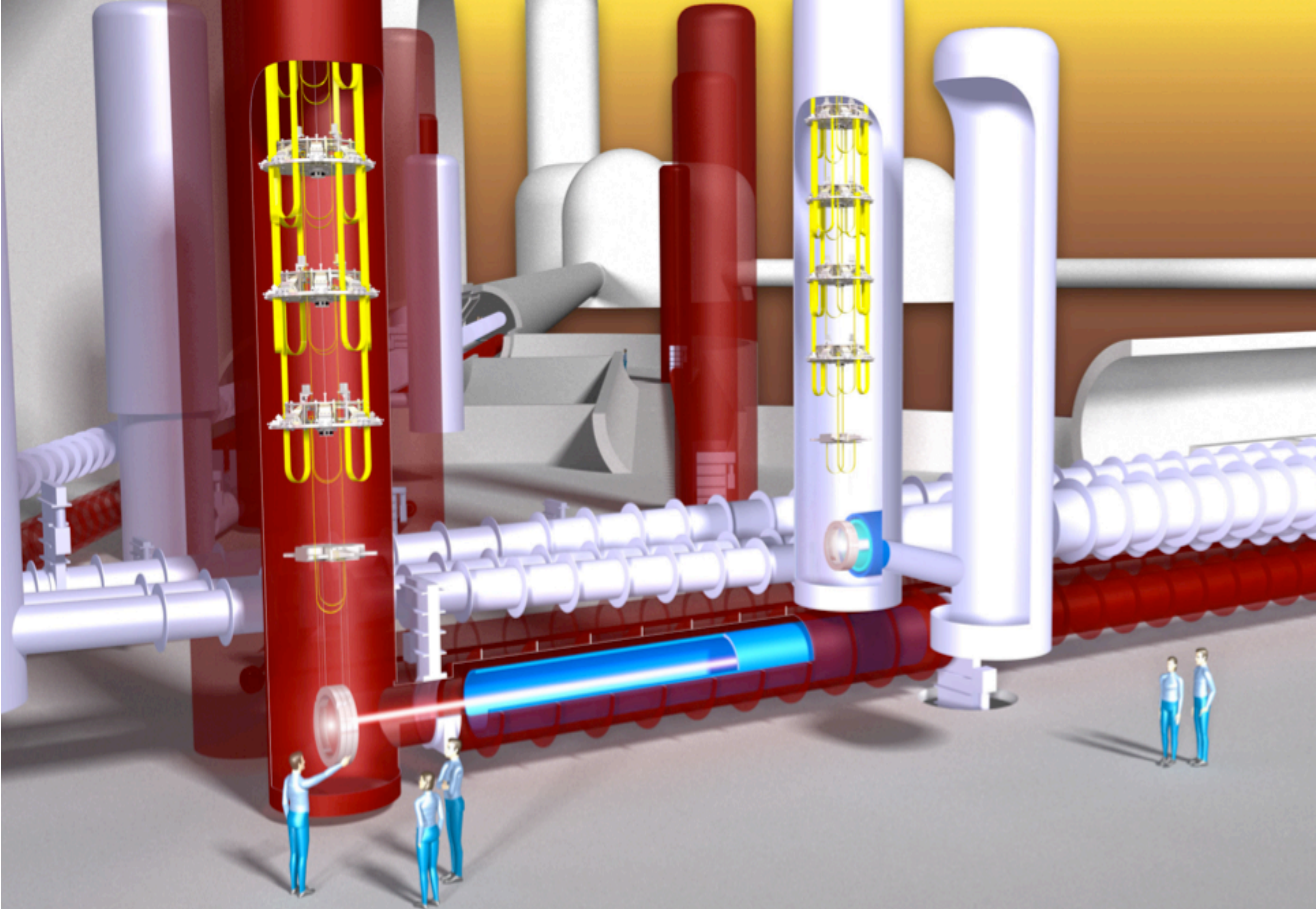




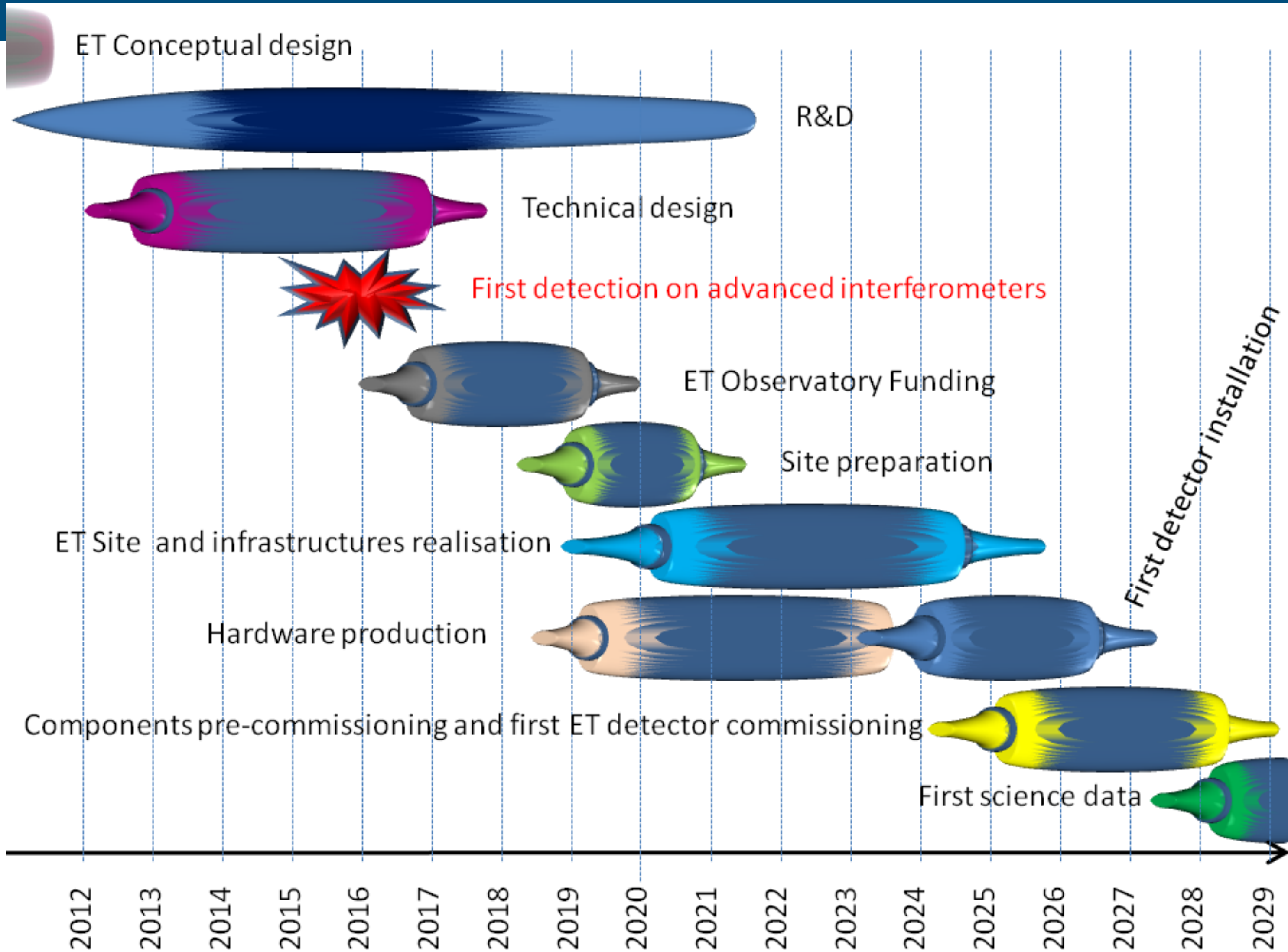
Artist's View of ET







ET Timeline



ET Conceptual design
R&D
Technical design
First detection on advanced interferometers
ET Observatory Funding
Site preparation
ET Site and infrastructures realisation
Hardware production
First detector installation
Components pre-commissioning and first ET detector commissioning
First science data
2012
2013
2014
2015
2016
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2018
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2020
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2029

Thanks very much for your attention!

Thanks to all the people who contributed to the content of this presentation. Special thanks to Rana Adhikari, David Shoemaker, Giovanni Losurdo, Kazuaki Kuroda, Harald Lueck and Michele Punturo.

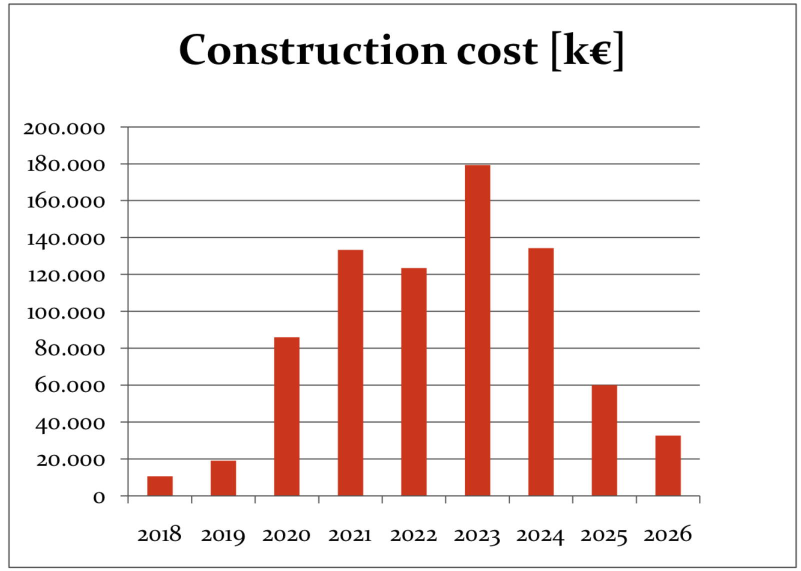
Extra Slides

ET Budget

ET Observatory Costs Evaluation

Configuration: Xylophone configuration, 30 km arm total length, 100 m underground

Total Construction (M€)	779
contingency	30%
Total with contingency	1013



IDsystem	System	Configuration	Option	Subtotal (k€)	2018	2019	2020	2021	2022	2023	2024	2025	2026	Subtot (M€)
1	Site	Xylophone - Triangular	=Baseline OR =Commo	547.746	4876	11261	77783	1E+05	1E+05	135352	82789	10566	4501	548
2	Vacuum	Xylophone - Single detector	=Baseline	169.864	5730	7800	6800	10210	10960	30566	38079	38079	21639	170
3	Cryogenics	Xylophone - Single detector	ALL	13.200	0	0	0	720	3880	2640	2640	3320	0	13
4	Suspensions	Xylophone - Single detector	<>	14.274	0	0	0	0	2211	2847,6	3973	2975	2267	14
5	Optics	Xylophone - Single detector	=Baseline	33.555	0	0	1400	4630	3604	7895	6778	5101	4148	34
			Construction Totals	778.639	10606	19061	85983	1E+05	1E+05	179301	1E+05	60041	32555	778,639