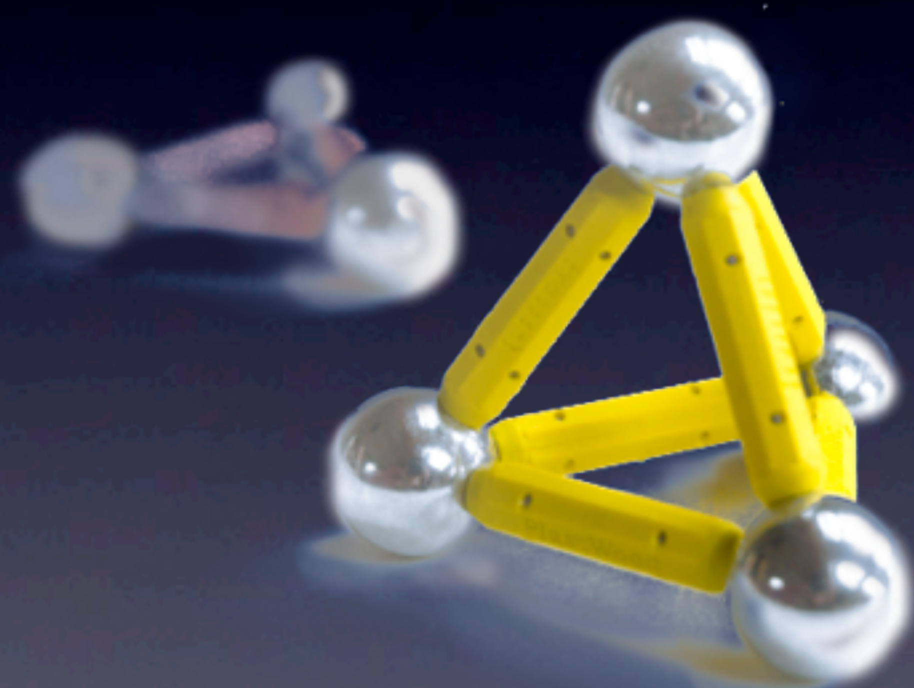
Einstein Telescope: The Interferometer Design



Andreas Freise

for the ET WP3 working group

24.11.2010, 3nd general ET workshop, Budapest

Overview

- ET in a global network
- Why a triangle?
- Why a Michelson?
- New technologies?
- Optical layout
- Sensitivity studies!

Assignment for WP3

- Target: Produce a reference design (no technical design) for a broadband interferometer with a tenfold sensitivity improvement versus the current state of the art (advanced detectors).
- Structure of the WP3 tasks:
  - Investigate the geometry of the ET detector (footprint of the entire detector, as defined by the optical systems)
  - Select a topology of the individual main interferometer (based on quantum noise reduction scheme)
  - Define the details of the interferometer configuration required for the design of the infrastructure, suspension and vacuum systems

Impact of possible global networks on the ET interferometer design

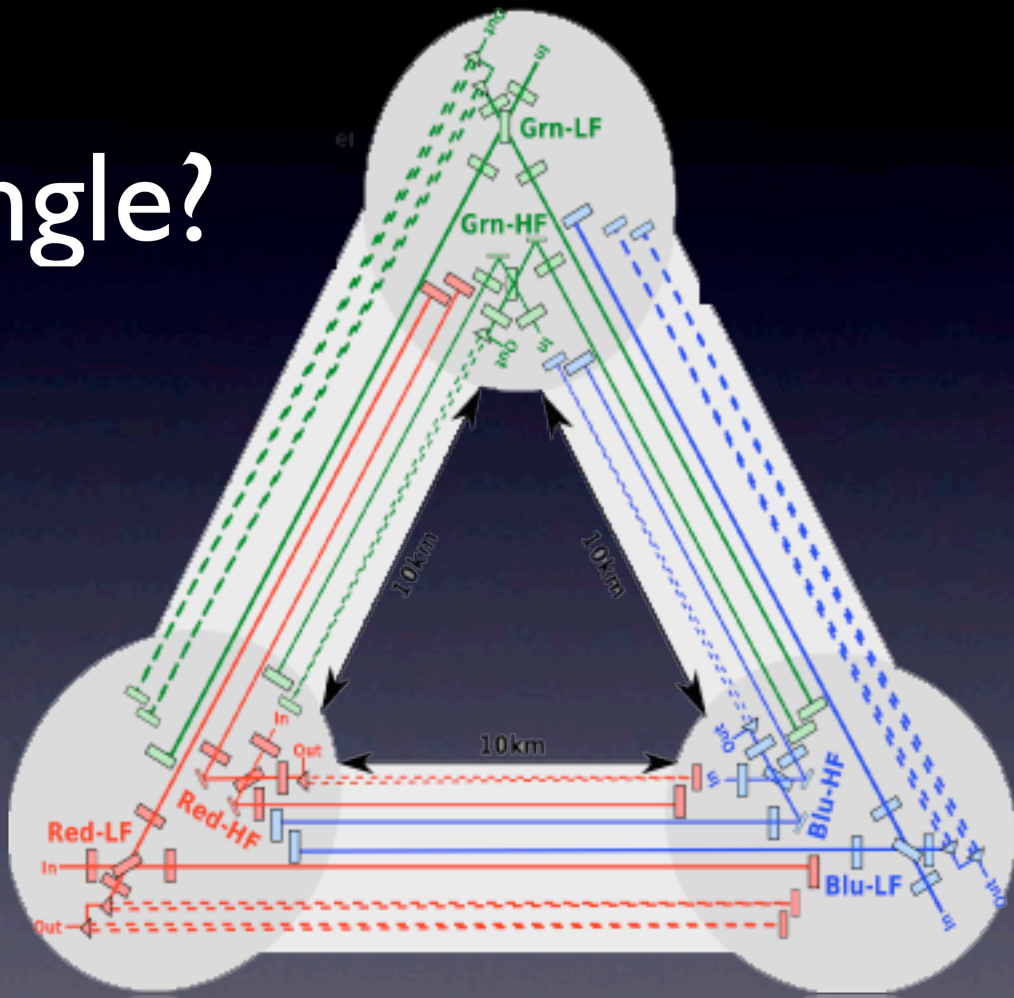
Functioning of ET in various conceivable scenarios of a global network:

- advanced detectors (Advanced LIGO, Advanced Virgo, LGCT, LIGO South, ...)
- advanced detectors plus third generation dectors in USA, Japan, …
- third generation detectors

Conclusion: different performance in different constellation, however, no influence on the optical design of the single site!

[A. Vicere in A. Freise et.al: `Optical Detector Topology for Third-Generation Gravitational Wave Observatories', *General Relativity and Gravitation,* **2010**]

Why the triangle?



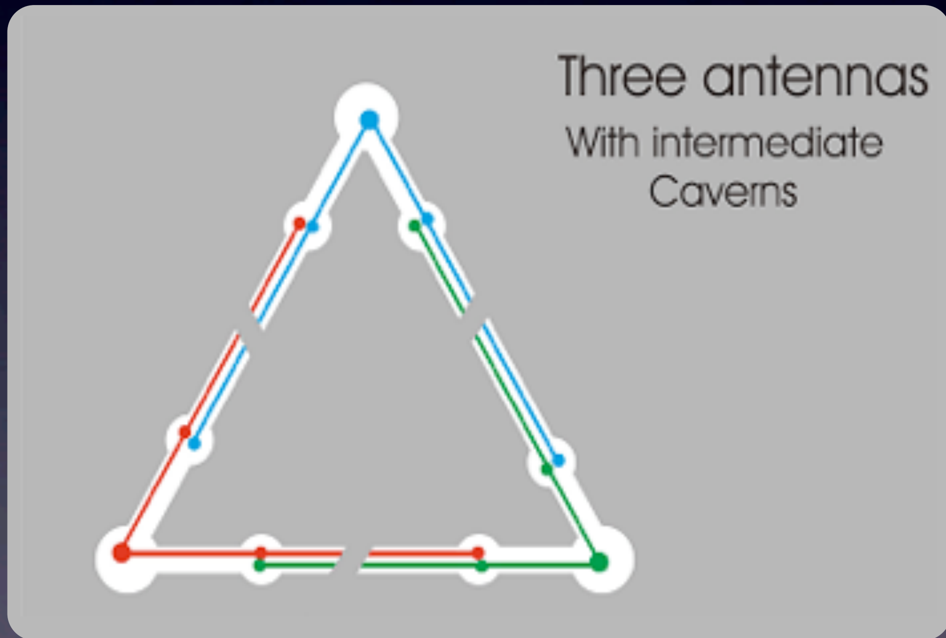
An old idea...

A detailed analysis of the how the triangle makes efficient use of `tunnel' length was presented by Ruediger in 1985.

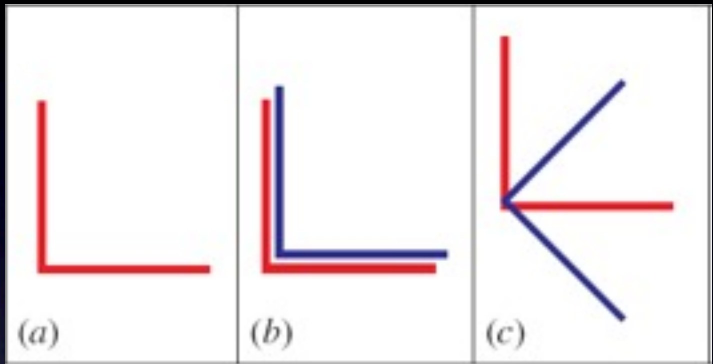
[W. Winkler et al.: Plans for a large gravitational wave antenna in Germany. Fourth Marcel Grossmann Meeting on General Relativity, **1986**, 621-630]

To my knowledge, no other early documentation on this idea exist! This design was reviewed for ET.

[A. Freise et. al.: Triple Michelson interferometer for a third-generation gravitational wave detector, Classical and Quantum Gravity, 2009, 26]



Multiple Interferometers

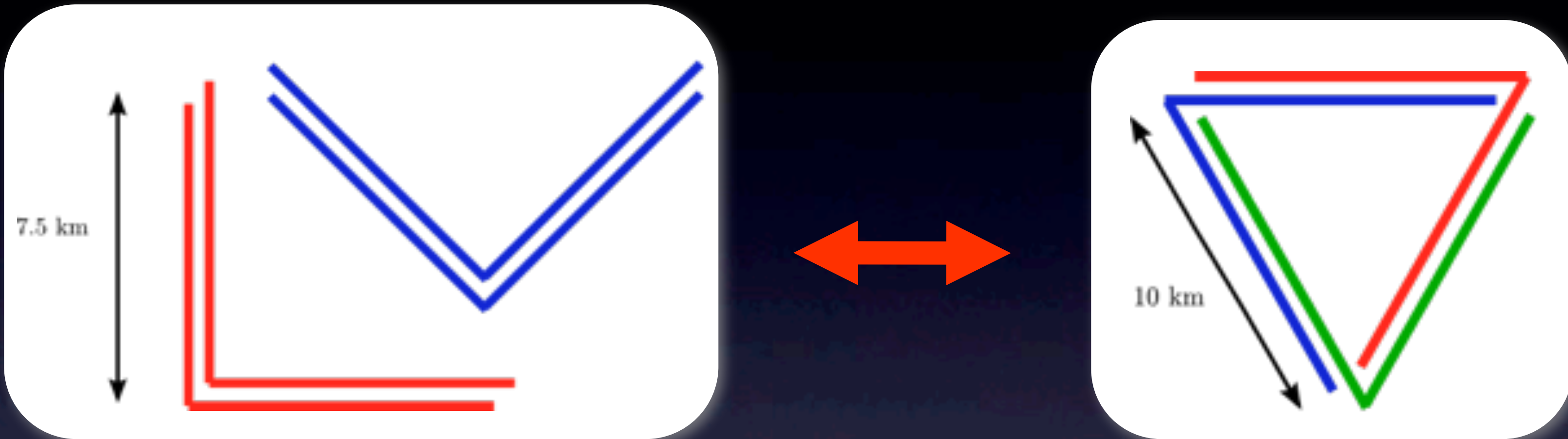


a. The L-shape provides the best form for a differential measurement of quadrupole waves

b. Two parallel interferometers provide redundancy (nullstream creation, operation during maintenance and upgrades)

c. Two interferometers under 45 degrees can resolve both polarisations

Multiple Interferometers

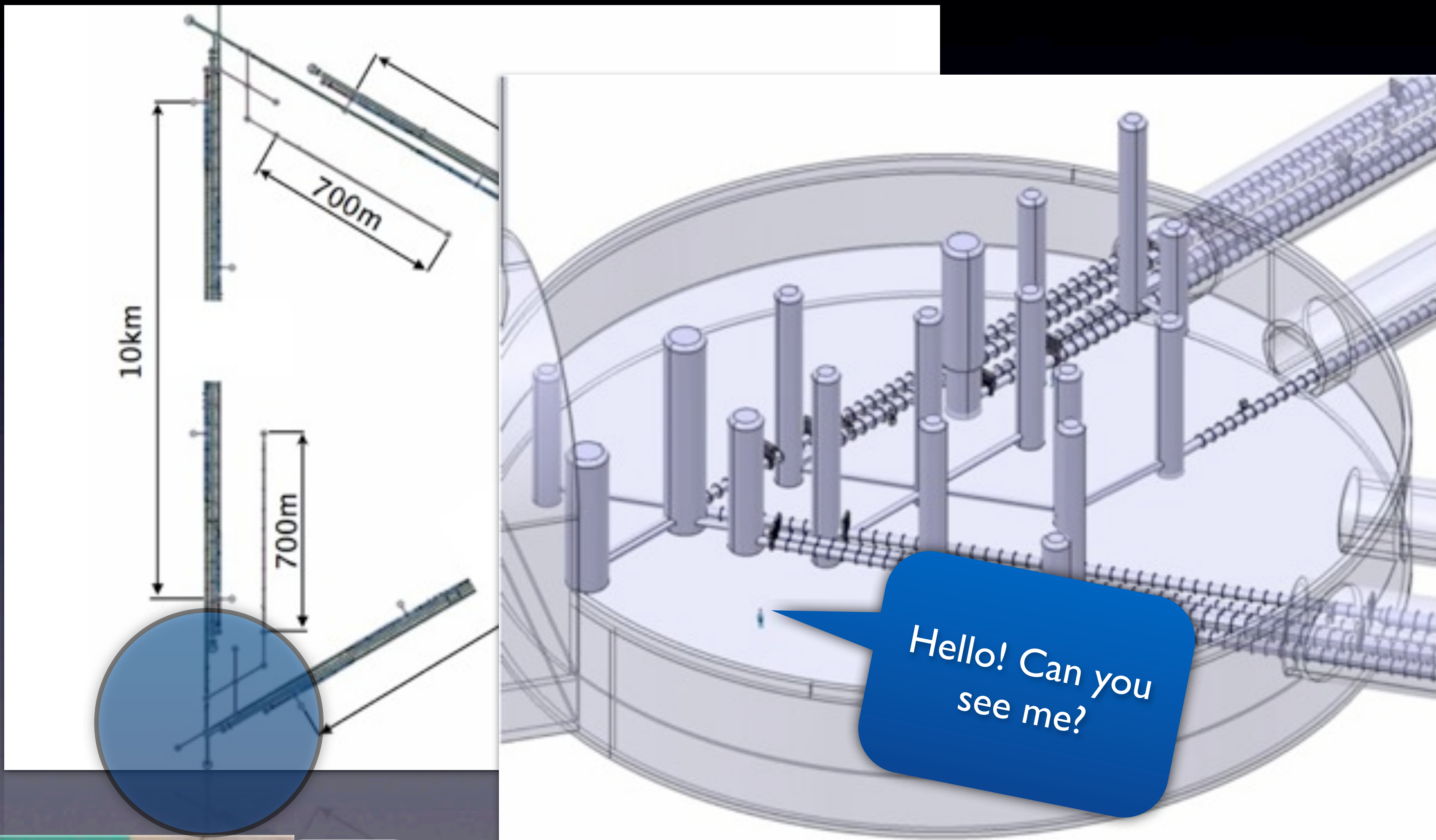


$$h(t) = F_+(t)h_+(t) + F_\times(t)h_\times(t)$$ [P Jaranowski et al, Phys Rev D 58 1998]

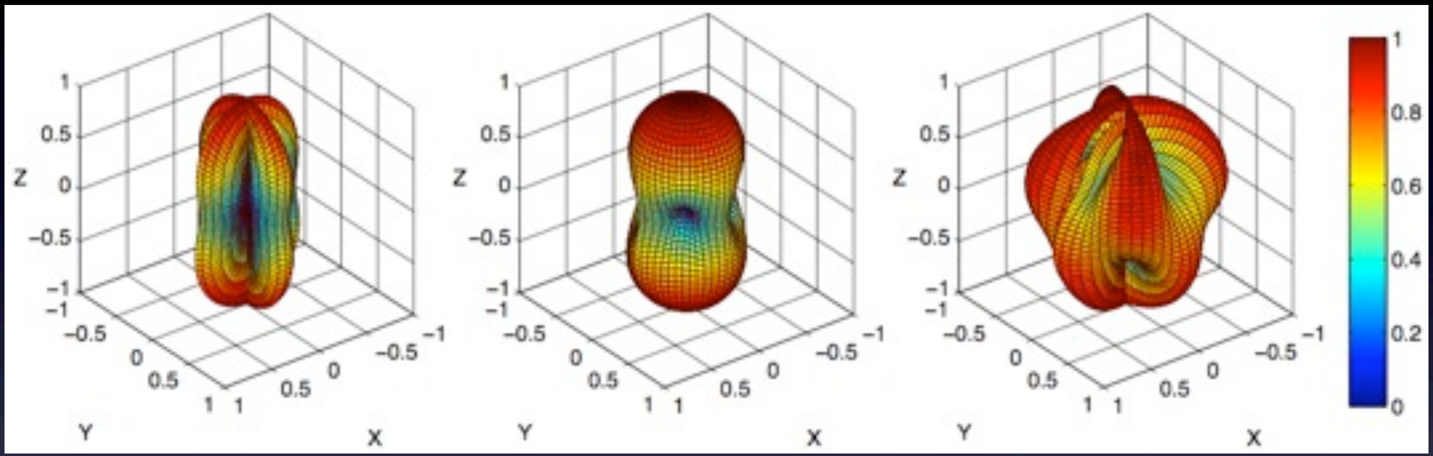
Both solutions have an integrated tunnel length of 30 km, they can resolve both GW polarisations, feature redundant interferometers and have equivalent sensitivity.

The triangle reduces the number of end stations and the enclosed area!

Large Infrastructure



The Triangle!



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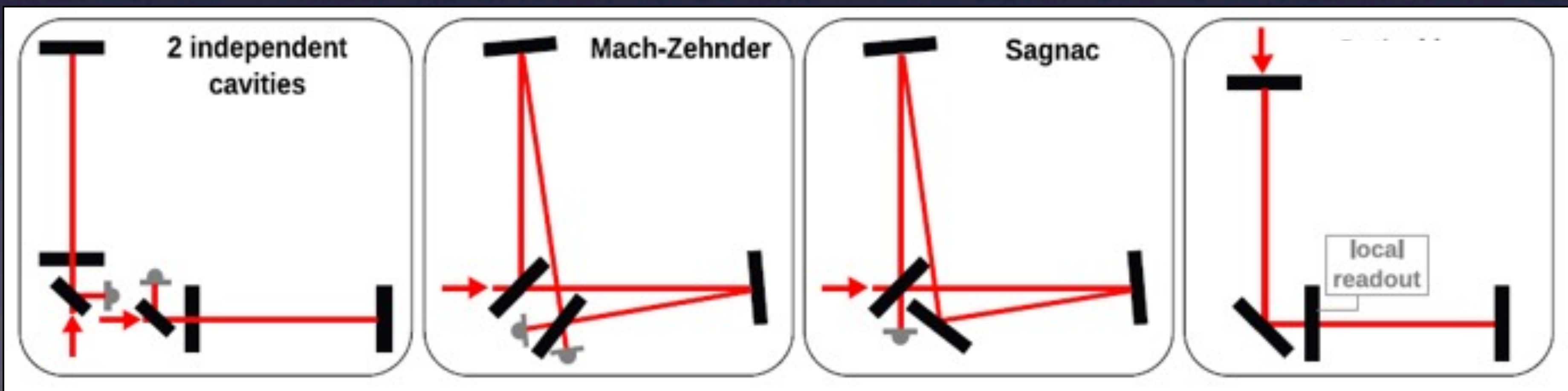
Interferometer Topology: Defined by Quantum Noise Reduction

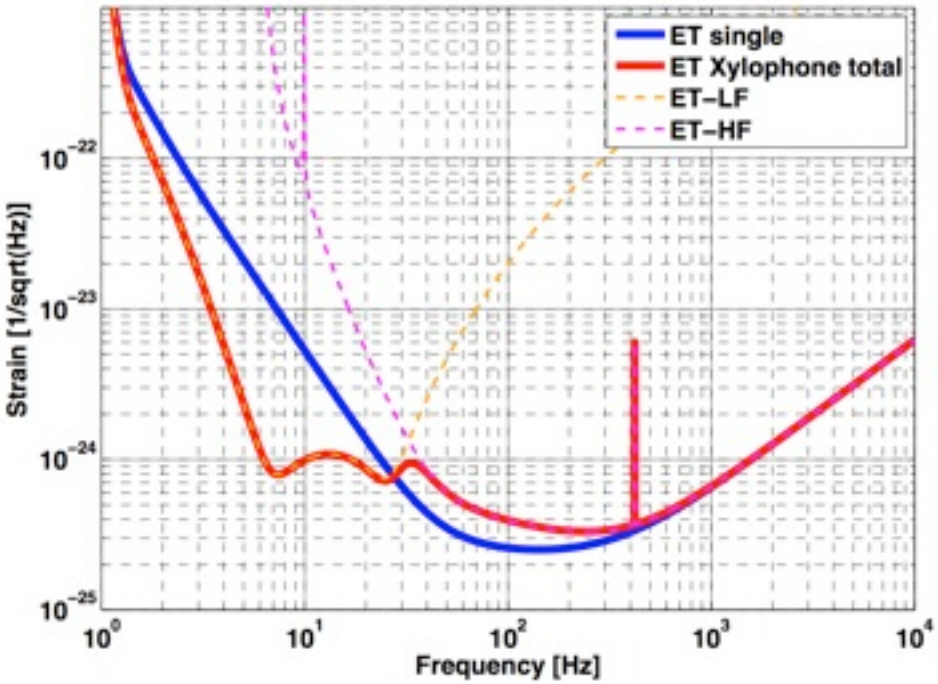
Several QNR topologies seem feasible:

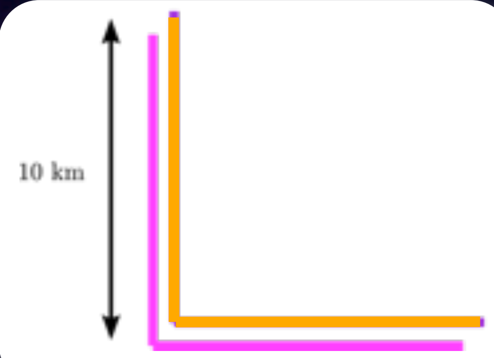
- Micheslon with SR, variational output, squeezing
- Sagnac or Mach Zehnder Interferometer with SR, …
- Optical bars, optical levers, double optical spring, …

All can be build using the L-shape form factor!



The Xylophone





- Low power (no thermal effects), cooled, long suspensions
- High power, squeezing, LG modes, room temperature, `normal' suspensions

[S Hild et al: A xylophone configuration for a third-generation gravitational wave detector, Classical and Quantum Gravity, **2010**, 27]

Summary so far

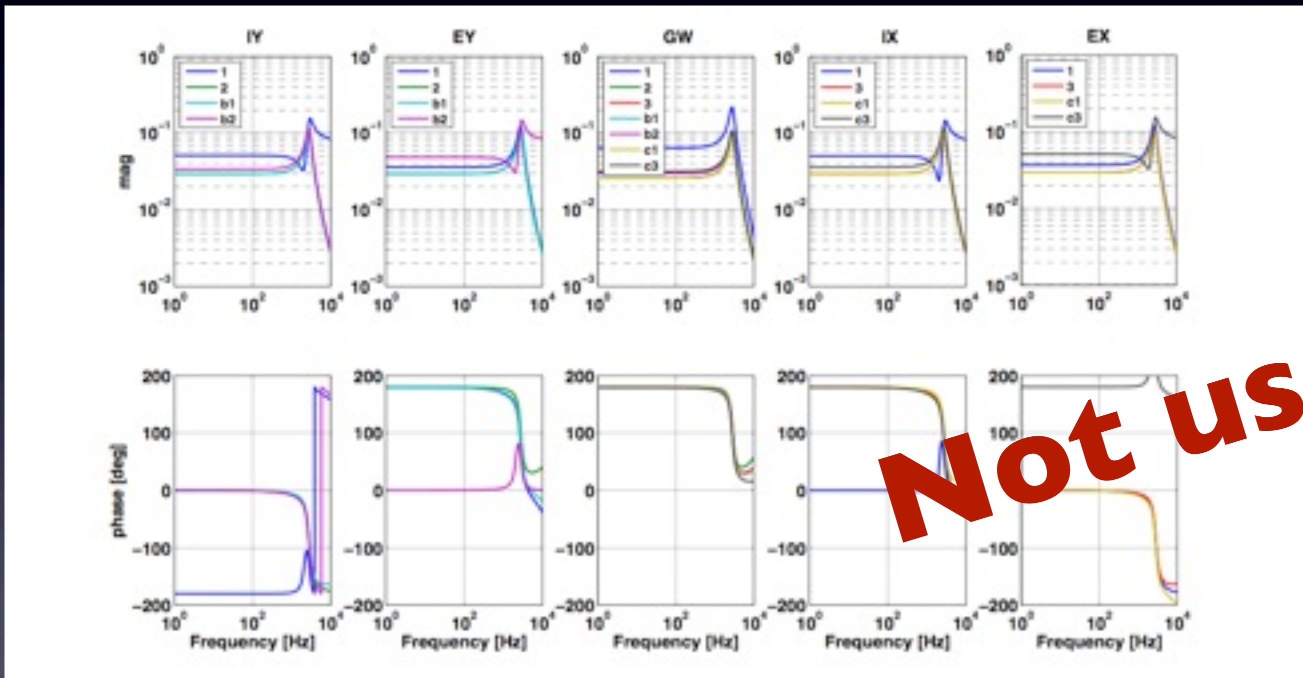
- Broadband detector
- Three L-shaped detectors in a triangle
- Each detector consists of two interferometers

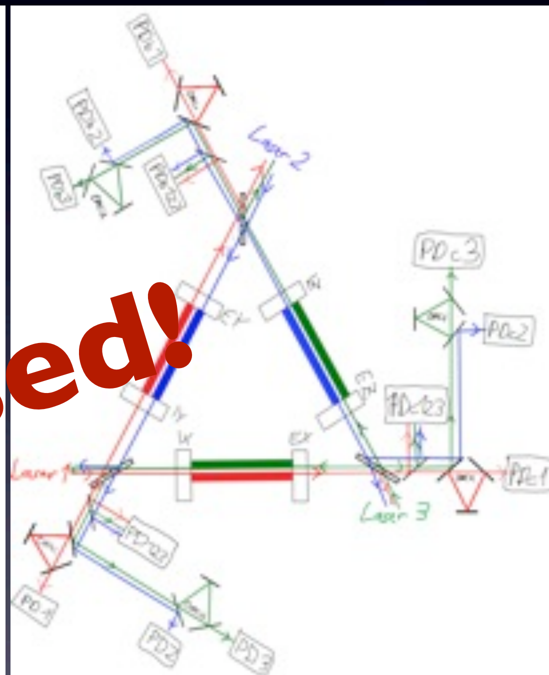
- Now for some details....

Technology reviews

- Technology reviews documented in internal notes and papers:
  - Quantum noise reduction
  - High power lasers
  - Diffractive interferometers
  - Squeezed light
  - Displacement noise free interferometry
  - Laguerre-Gauss modes and non-Gaussian beams
  - Waveguide coatings
  - Etalon mirrors (Khalili cavities)

Displacement Noise Free Interferometry

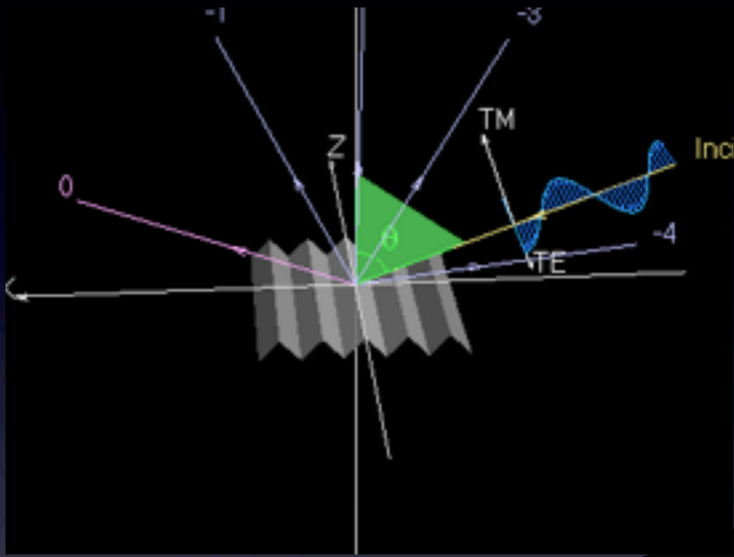




Not used!

[S. Hild GWADW 2008,
S. Tarabrin ET-024-09]

Diffractive Interferometry



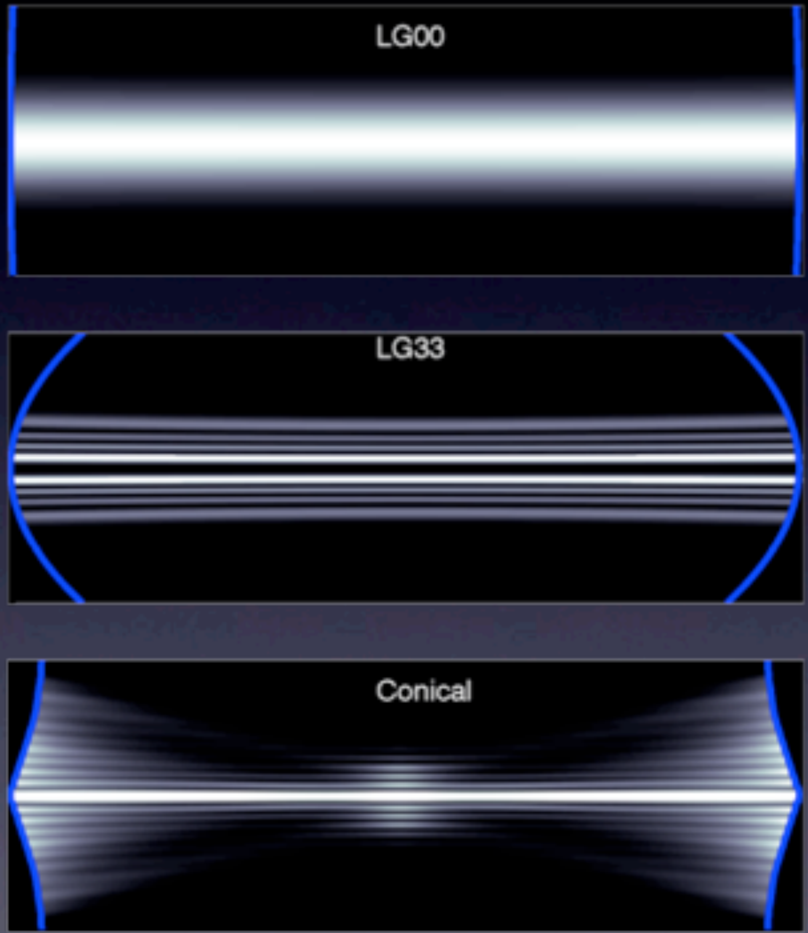
Not used!

Alignment limits from translational phase noise

$$\Delta\gamma < 9\cdot 10^{-24}\,\mathrm{rad}\left(\frac{h}{10^{-23}}\right)\left(\frac{4\,\mathrm{km}}{L}\right)\left(\frac{\cos(\alpha)}{\cos(30^\circ)}\right)\left(\frac{7.4\,\mathrm{km}}{R_C}\right)\left(\frac{d}{\lambda}\right)$$

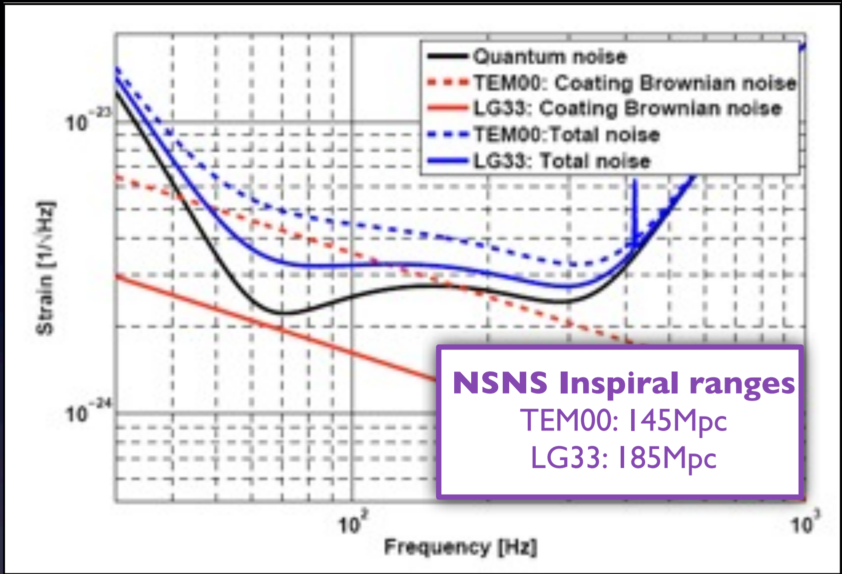
Wide beams: non-Gausssian or Laguerre-Gauss

- Wide beams can reduce thermal noise
- Under consideraration: non-Gaussian beams or Laguerre-Gauss modes
- To be tested: do these beam shapes work in high-precision interferometry?

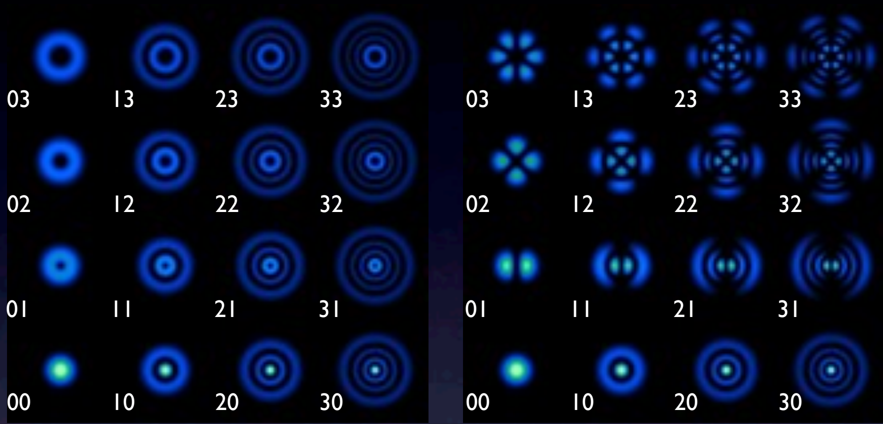


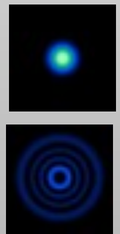
Laguerre Gauss modes

TN comparison for Adv.Virgo



Chelkowski et al. PRD 79 (2009) 122002





HG00: $S_x(f) = \frac{4\,k_B T}{\pi f}\frac{1}{Q}\,\delta_C\,\frac{(1+\sigma)(1-2\sigma^2)}{\pi Y\,w^2}$

LGnm: $S_x(f) = \frac{4\,k_B T}{\pi f}\frac{1}{Q}\,\delta_C\,\frac{(1+\sigma)(1-2\sigma^2)}{\pi Y\,w^2}\cdot\beta_n^m$

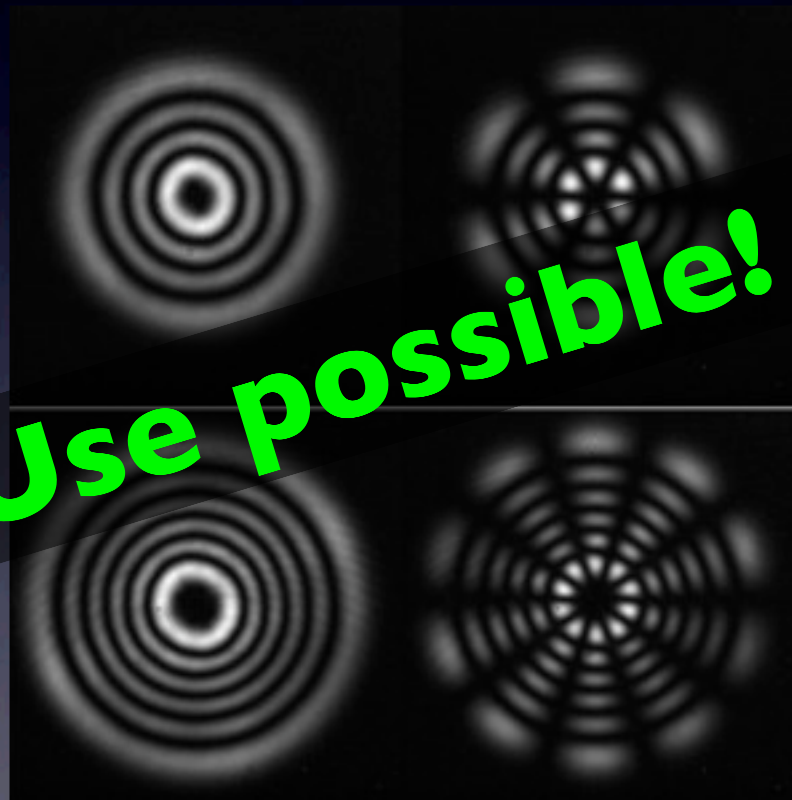
J.Y.Vinet, Living Reviews in Relativity, 12 (2009)

Improvement in h(t)

$$h_{33} = \frac{h_{00}}{2.7}$$

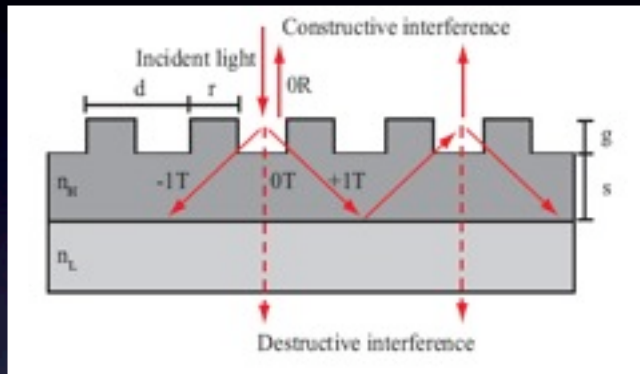
LG interferometry, recent results

First experimental results: successfully locked a mode-cleaner to various higher-order LG modes. Ouput mode purity >99% with no indication of problems due to mode degeneracy.

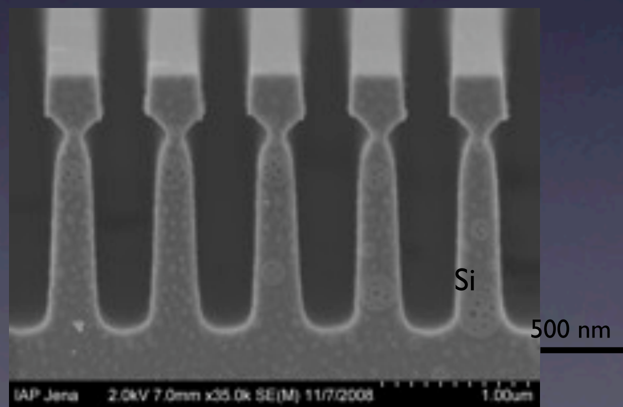


Waveguide Coatings

- Waveguides may provide another way to reduce coating Brownian noise.
- **Idea**: replacing the dielectric (lossy, thick) multi-layer stack by a (low loss, thin) mono-crystalline silicon nano-structure or a (thin) single layer diffractive coating.

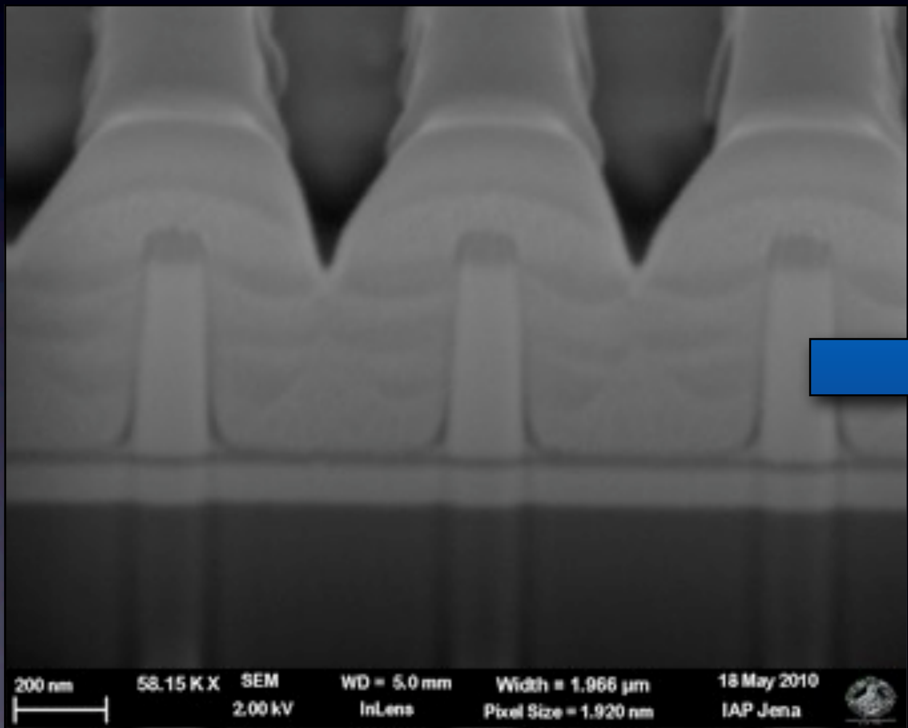


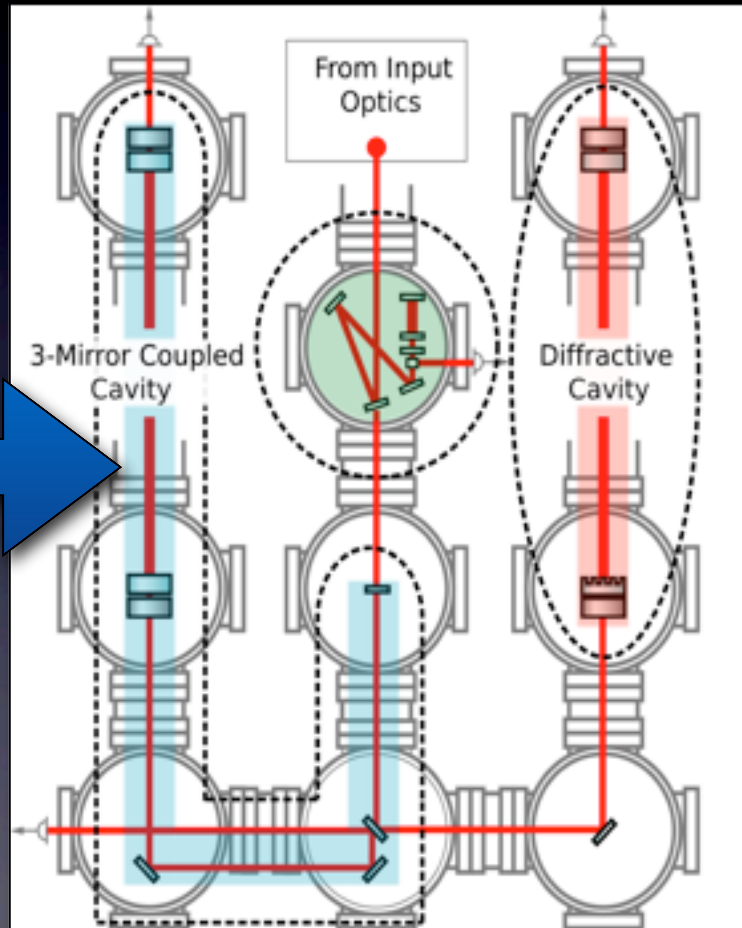
Brückner et al., Optics Express 17 (2009) 163 – 169



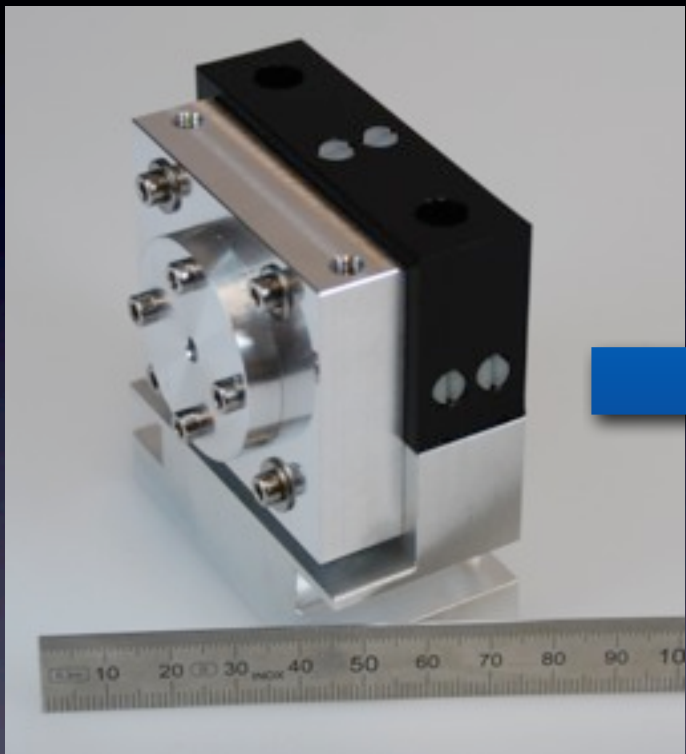
Brückner et al., Optics Letters 33 (2008) 264 - 266

Waveguide coatings, recent results



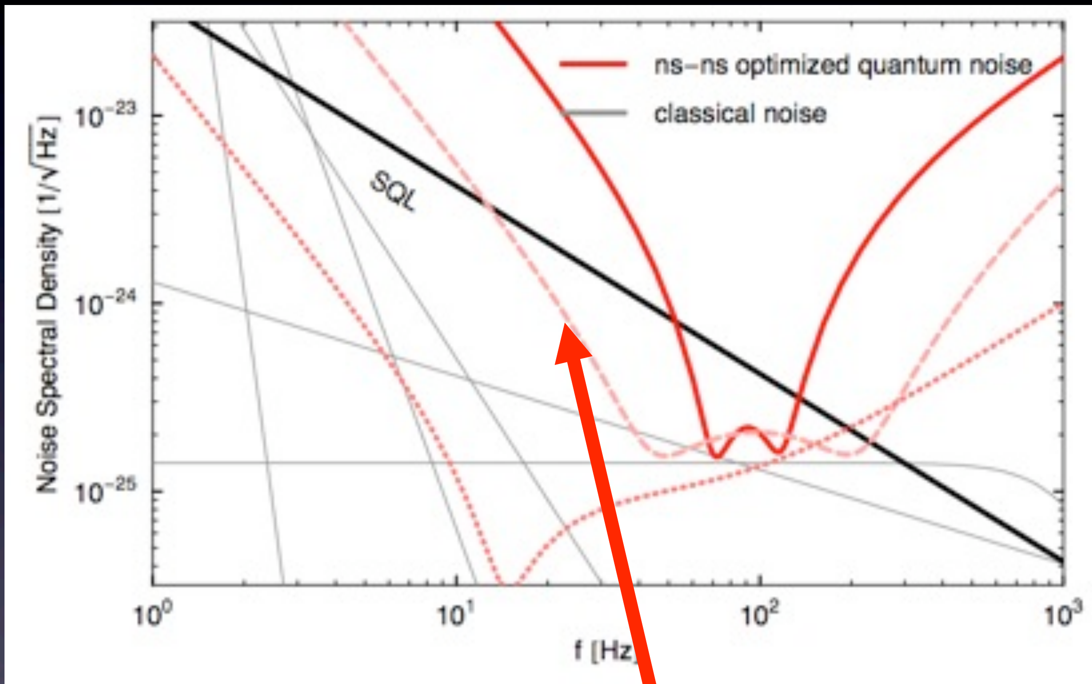


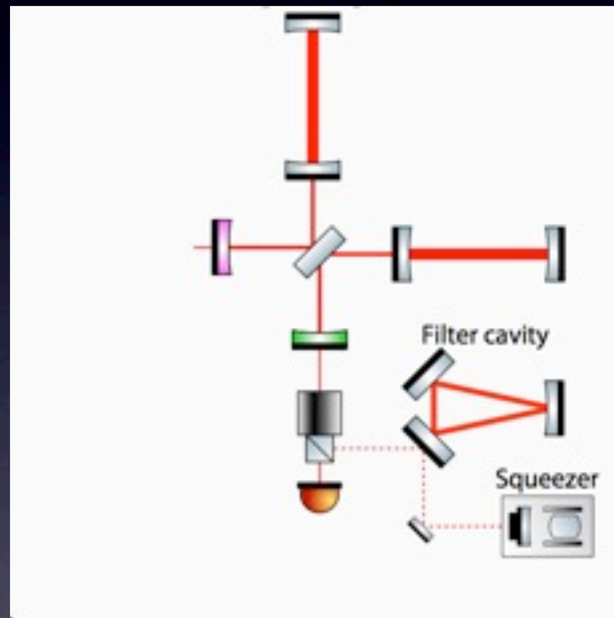
Squeezed Light



- Require 10dB effective squeezing for ET D sensitivity
- Good experimental results in GEO 600

Quantum Noise Reduction





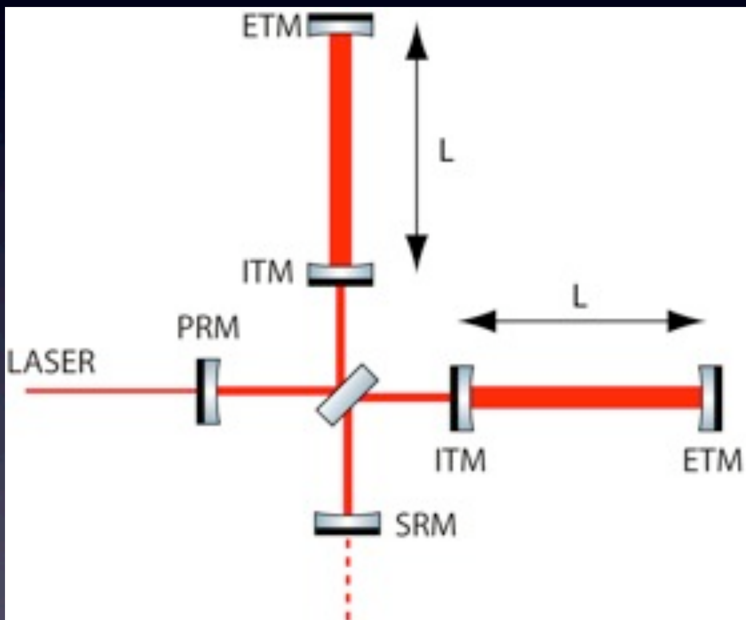
10dB frequency-dependent squeezing

See Helge and Andre's talks for details!

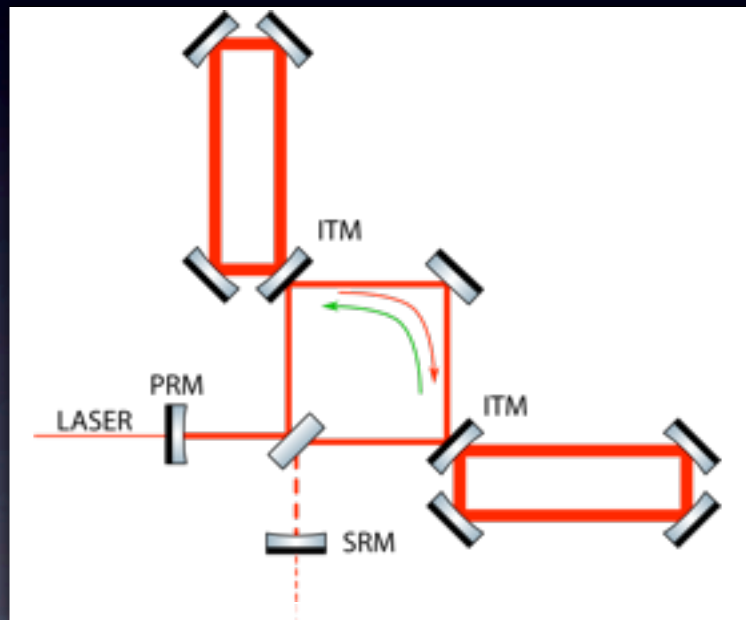
[H. Rehbein und H. Mueller-Ebhardt, ET note *ET-010-09* 2009]

Sagnac vs. Michelson

RSE

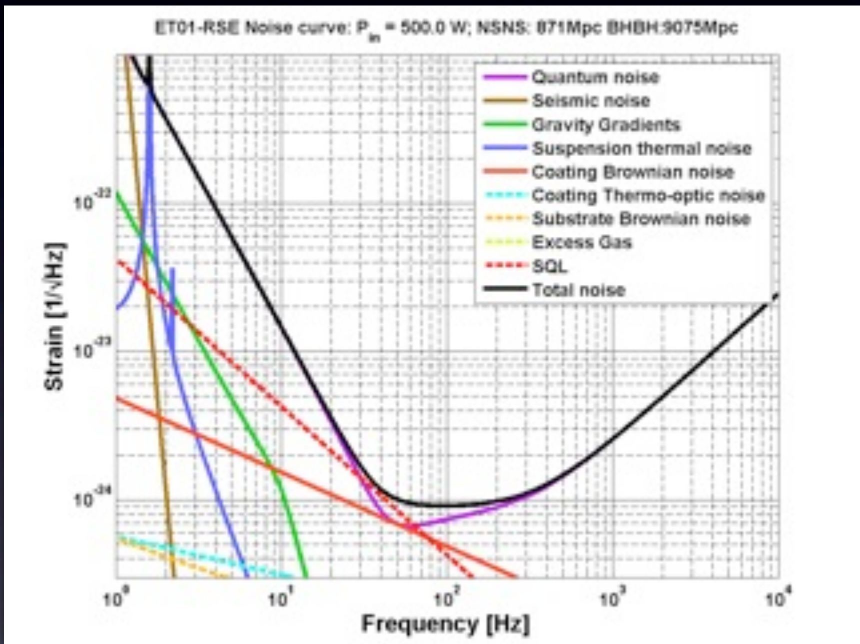


SAGNAC

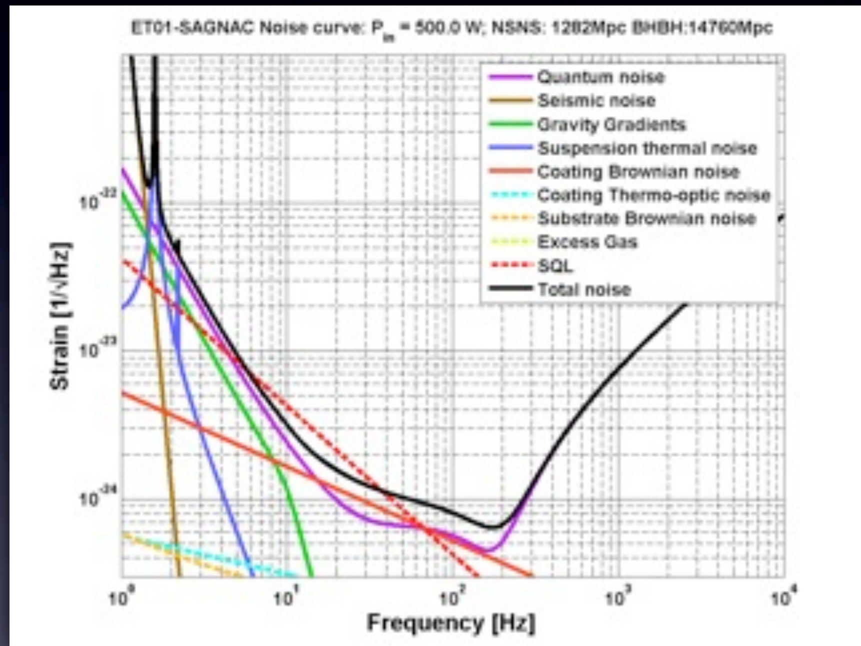


Sagnac vs. Michelson Example

RSE – tuned SR



SAGNAC-optimised



[S. Chelkowski, H. Müller-Ebhardt, S. Hild, 2009]

NSNS inspiral range for Sagnac topology 47% larger

Event rate increased by a factor of 3.2

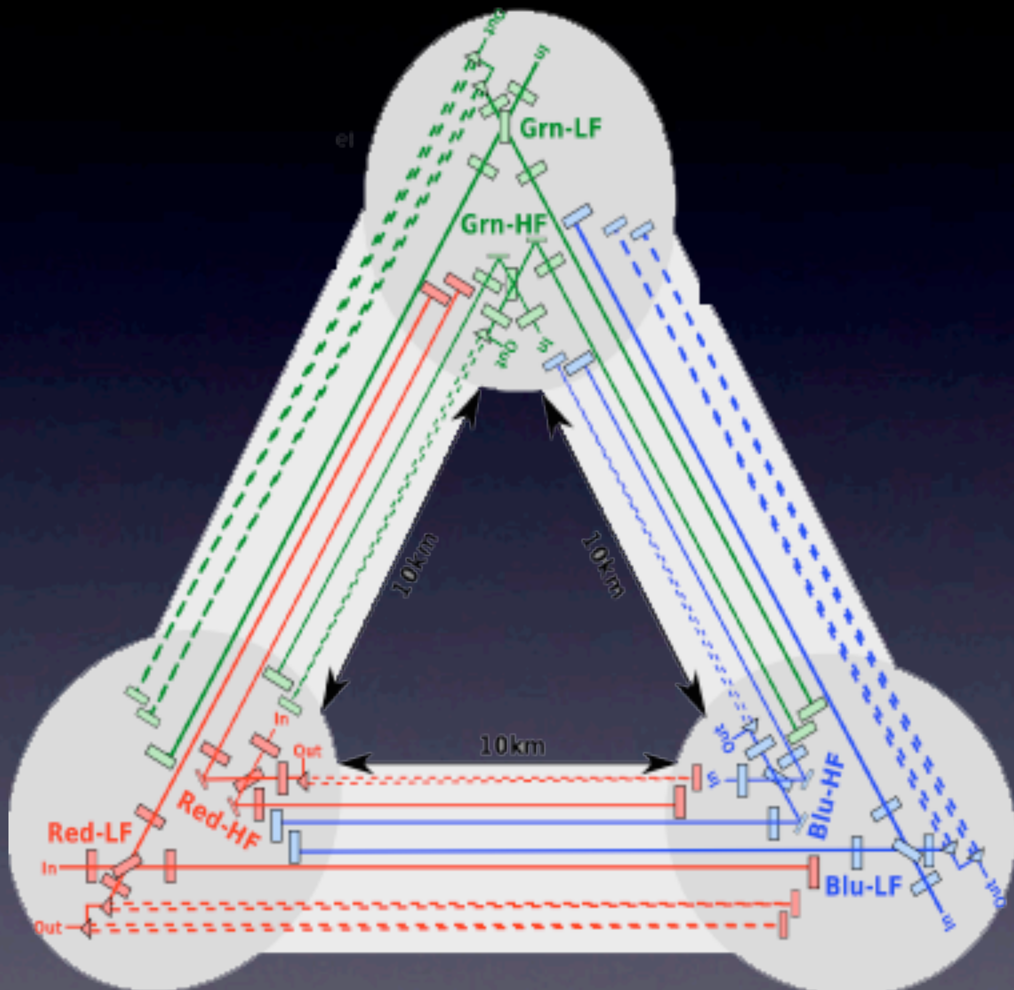
Topology summary

- Sagnac shows better quantum noise suppression
- However, it has one main practical problem, the ring-cavities in the arms
- All high-precision expertise so far is with the Michelson
- Michelson with RSE/SR and squeezing and filter cavities has been chosen as the reference design

Draft Optical Layout

Simple drawing of an optical layout consisting of:

- 3 independent detectors
- 2 interferometers per detector (LF+HF)
- 3 filter cavities per detector
- 21 long suspensions
- 45 short suspensions
- 12 cryogenic mirrors



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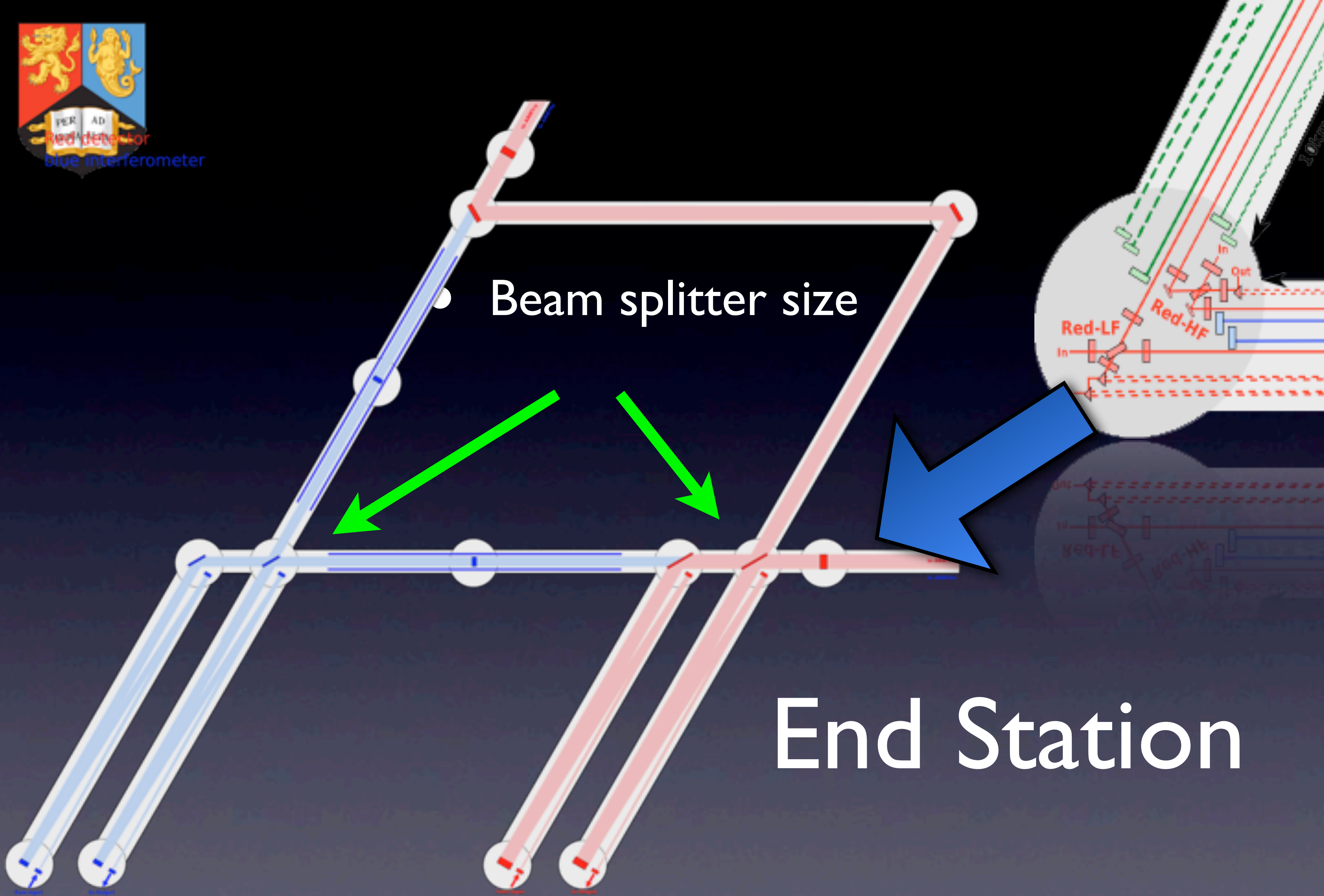


- Beam splitter size

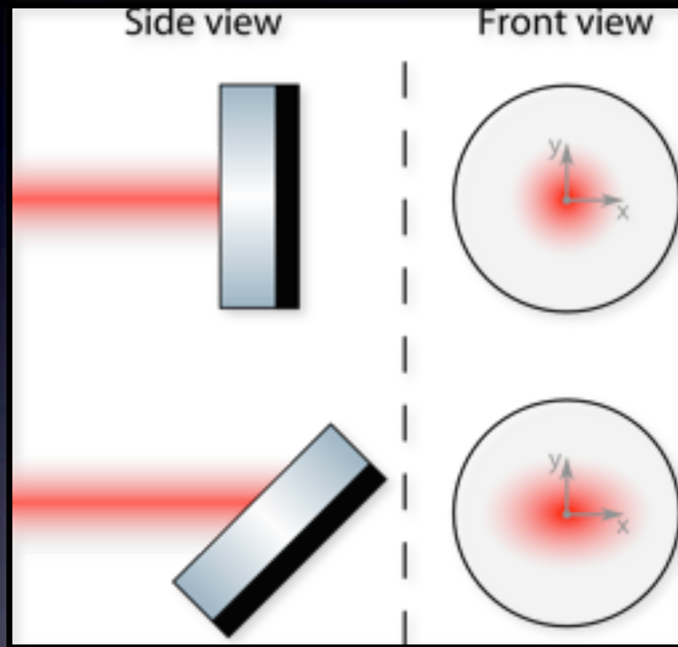
End Station

Mirror and Beamsplitter Size

Beam geometry on mirror surface depends on incidence angle:

$$I(x,y) = \frac{2}{\pi\, w_x\, w_y} \exp\left(\frac{-2x^2}{w_x^2}\right) \exp\left(\frac{-2y^2}{w_y^2}\right)$$

with $w_x > w_y$



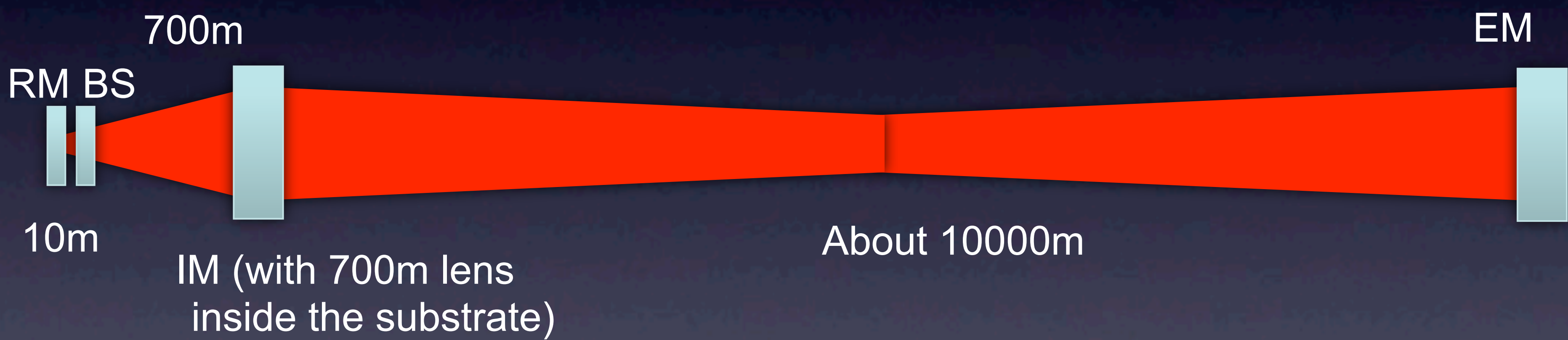
The horizontal beam size is $w_x = w_y / \cos(\alpha)$. Thus also mirrors and especially beam splitters must be larger by the same factor.

	BS diam. 45 deg	BS diam. 60 deg
LG33, 1064nm	80 cm	115 cm
LG00, 1550nm	60 cm	84 cm

→ These are considered to be too large.

Better Beam Sizes

- We want to have small beams in the central interferometer.
- This could be achieved by focusing the beam down between IM and BS



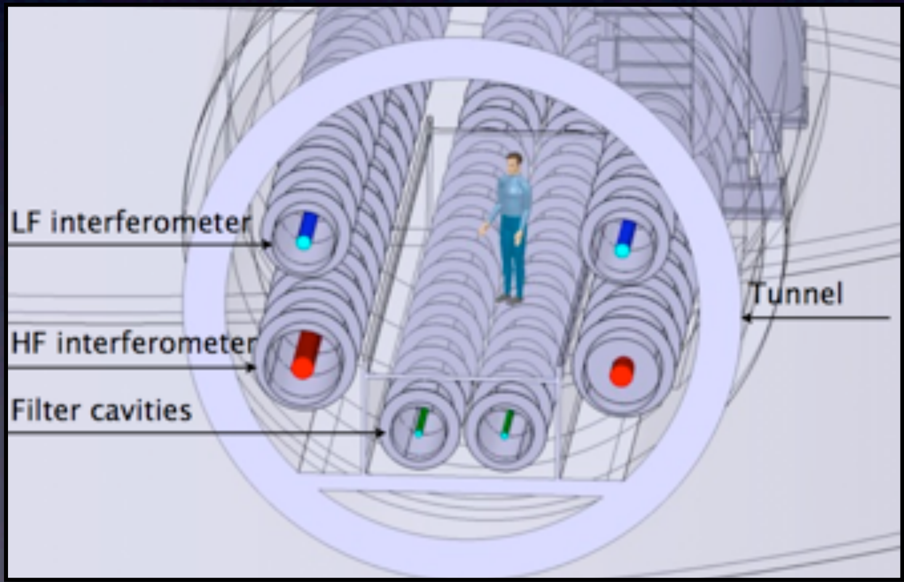
- In order to reduce problems from imperfect optics, the focusing should be rather gentle. For current design we assume 700m to focus from 8cm down to 1cm.

See Stefan's talk for details!

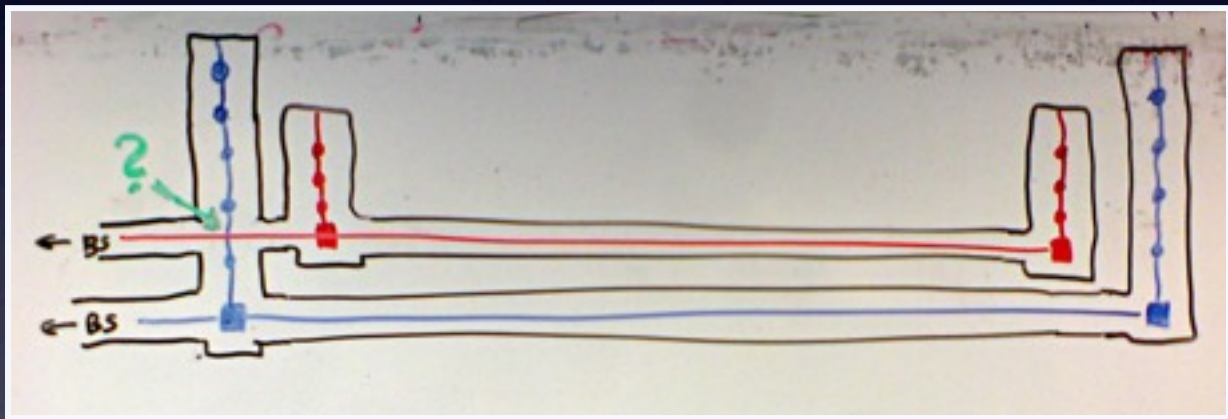
How to fit this into the tunnels?

Early ideas:

Current design:



Vertical stacking of interferometer beams



[Freise, Hild GWADW Kyoto 2010]

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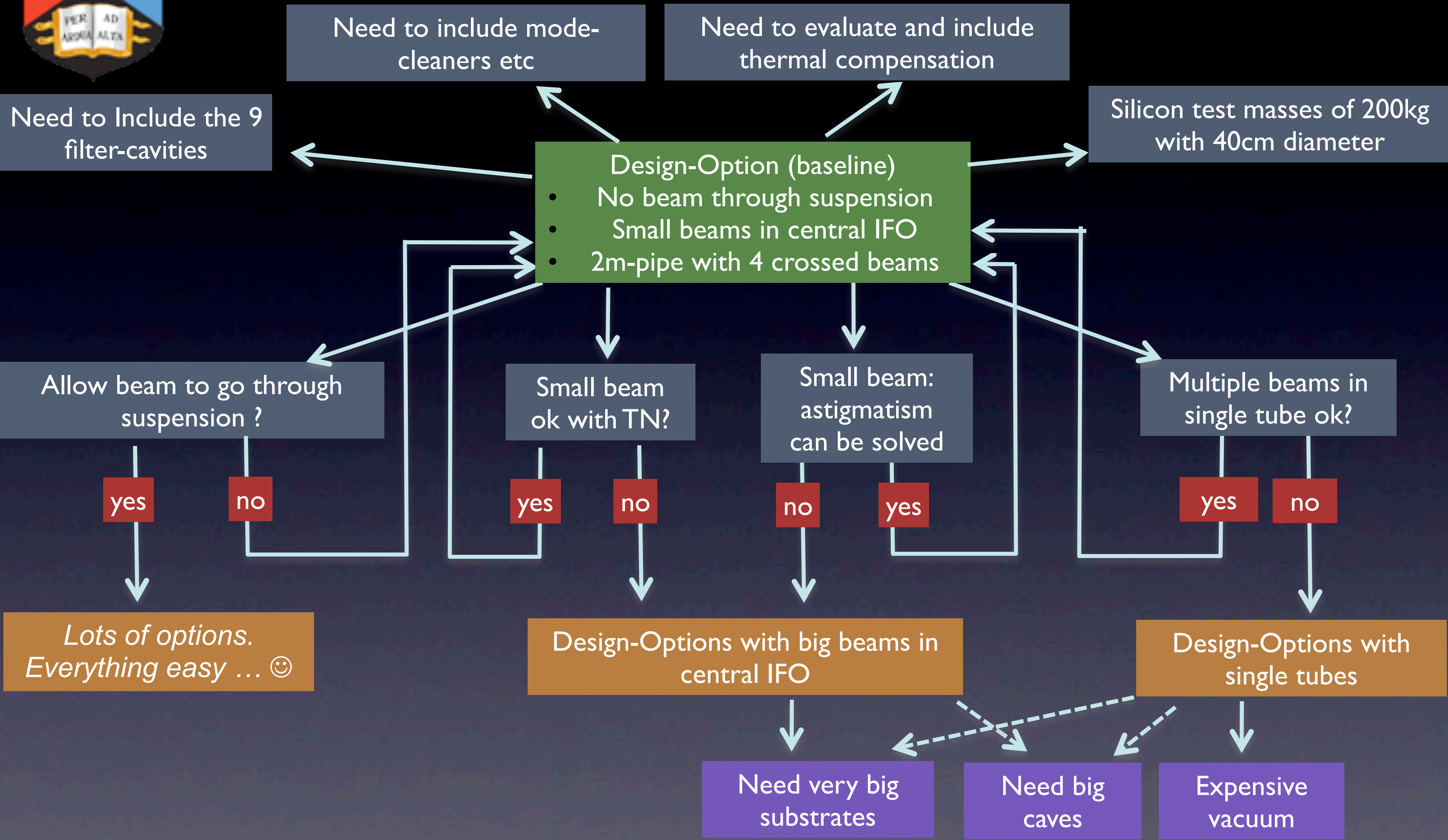
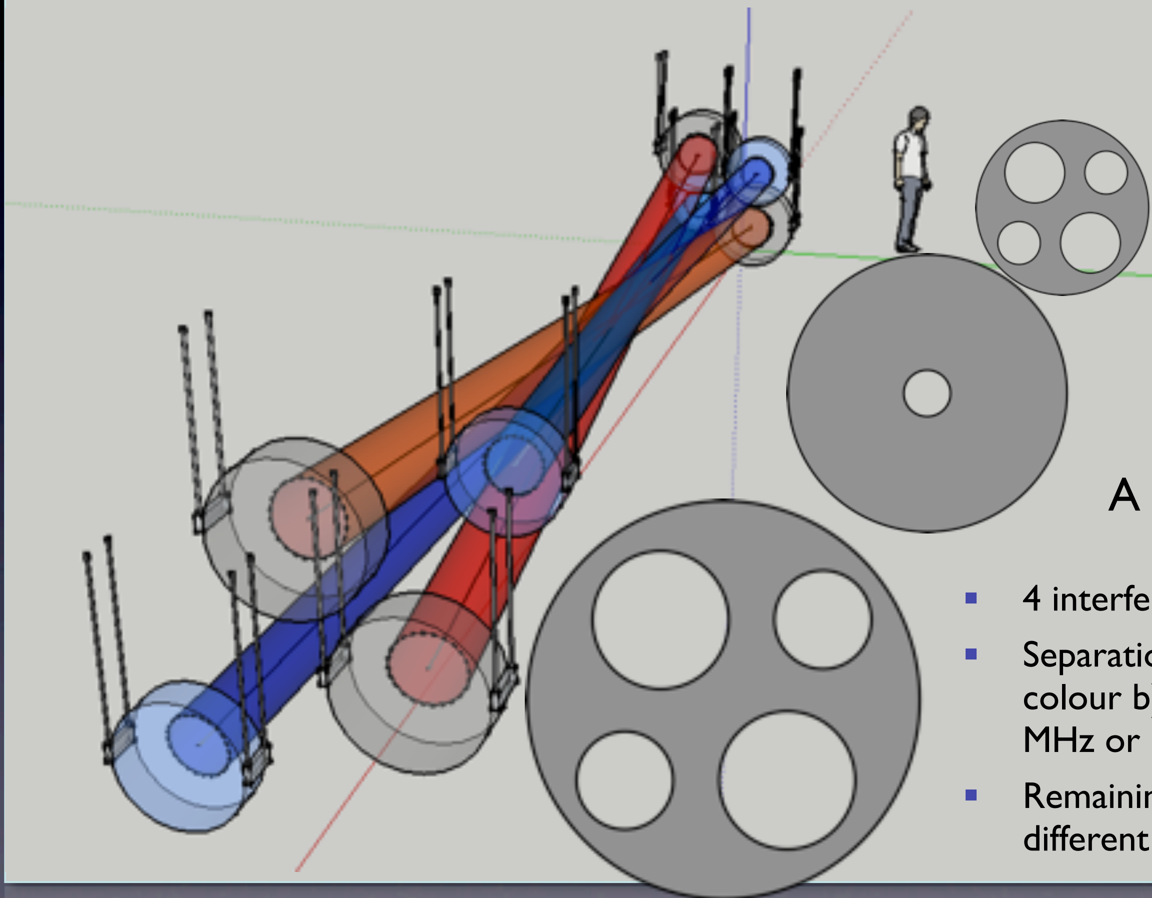
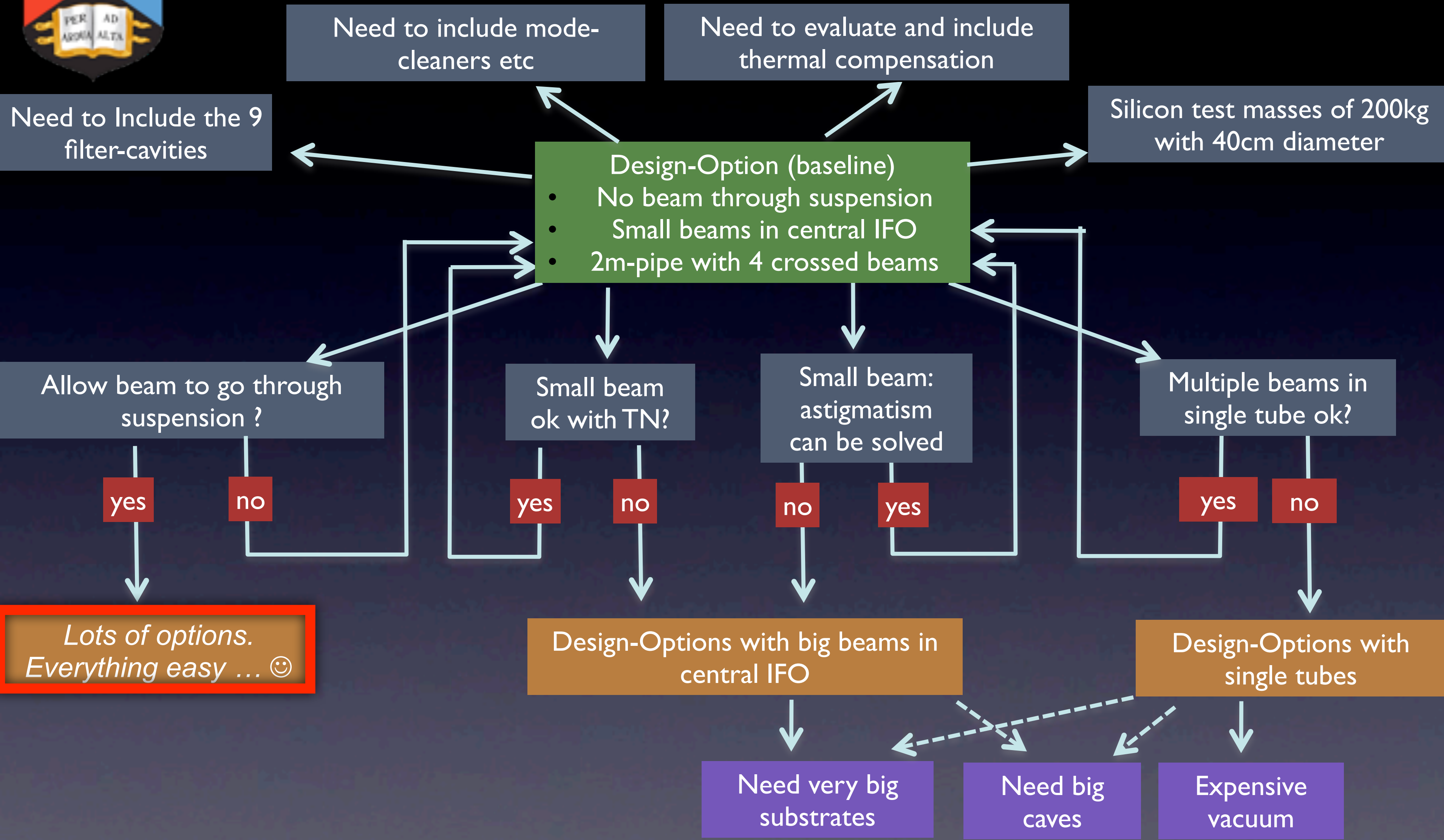

Need to include mode-cleaners etc
Need to evaluate and include thermal compensation
Need to Include the 9 filter-cavities
Silicon test masses of 200kg with 40cm diameter
Design-Option (baseline)
• No beam through suspension
• Small beams in central IFO
• 2m-pipe with 4 crossed beams
Allow beam to go through suspension ?
Small beam ok with TN?
Small beam: astigmatism can be solved
Multiple beams in single tube ok?
yes
no
yes
no
no
yes
yes
no
Lots of options. Everything easy … ☺
Design-Options with big beams in central IFO
Design-Options with single tubes
Need very big substrates
Need big caves
Expensive vacuum

Crossed beams in one tube



A possible design:

- 4 interferometers in a single tube.
- Separation of the 4 instruments: a) different colour b) same colour ifos will be shifted by MHz or GHz.
- Remaining PROBLEM: scattering into a different ifo and then back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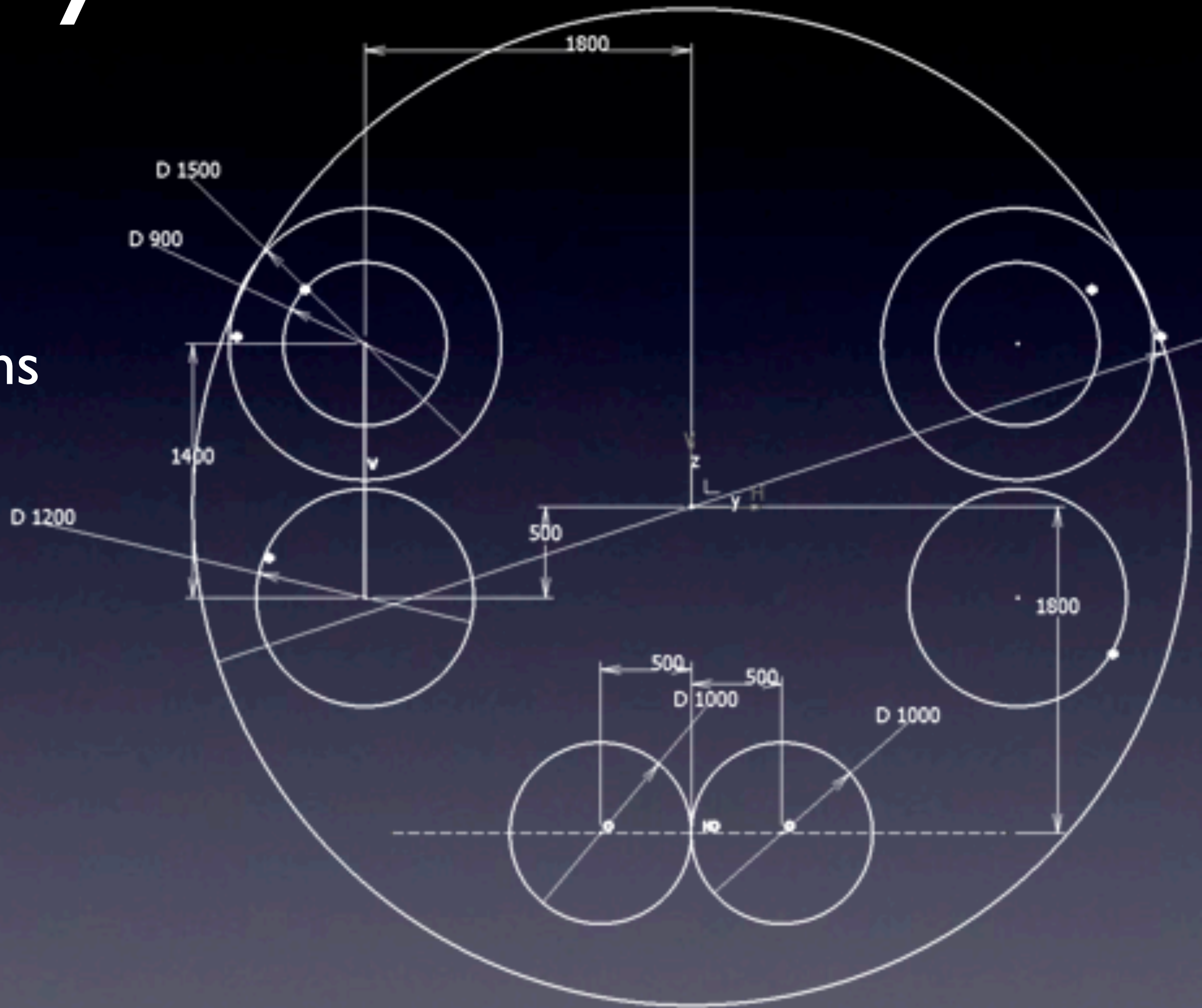
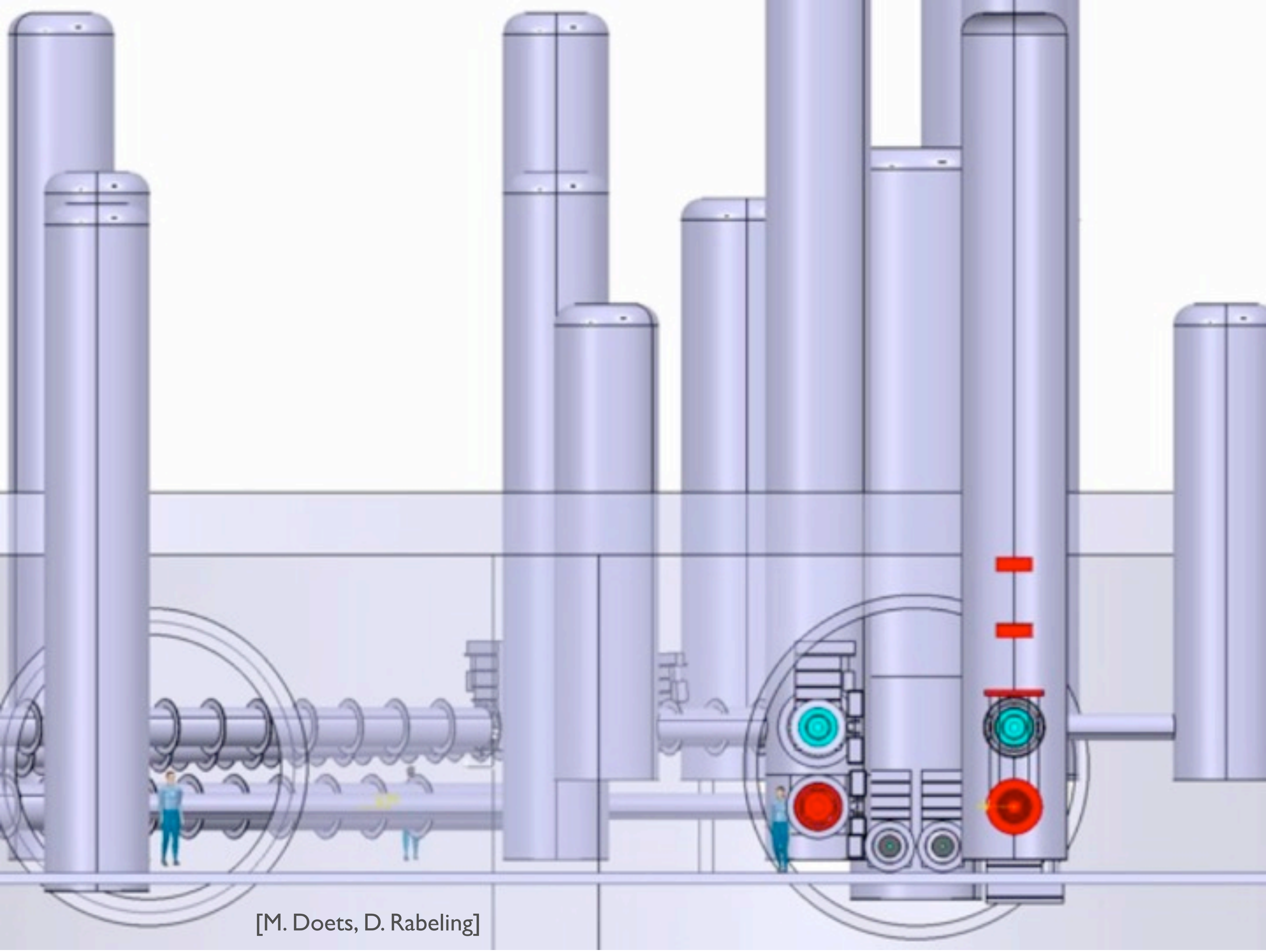
no
yes
yes
no
Lots of options. Everything easy … ☺
Design-Options with big beams in central IFO
Design-Options with single tubes
Need very big substrates
Need big caves
Expensive vacuum

Tube Layout

With the beams stackable, the original arrangement for accommodating all beams in a 5m tunnel was finalised

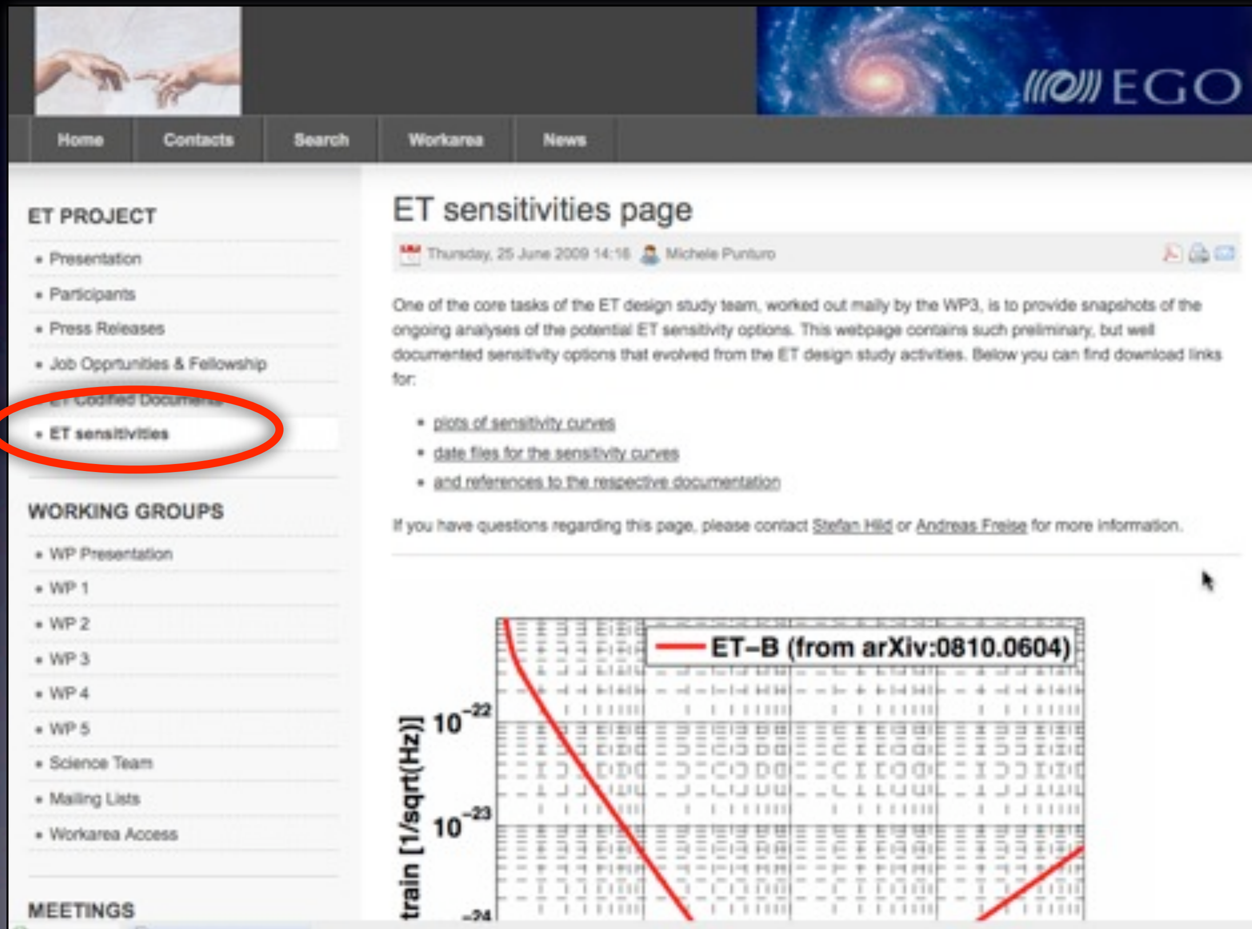
A draft design of the entire vacuum system followed...

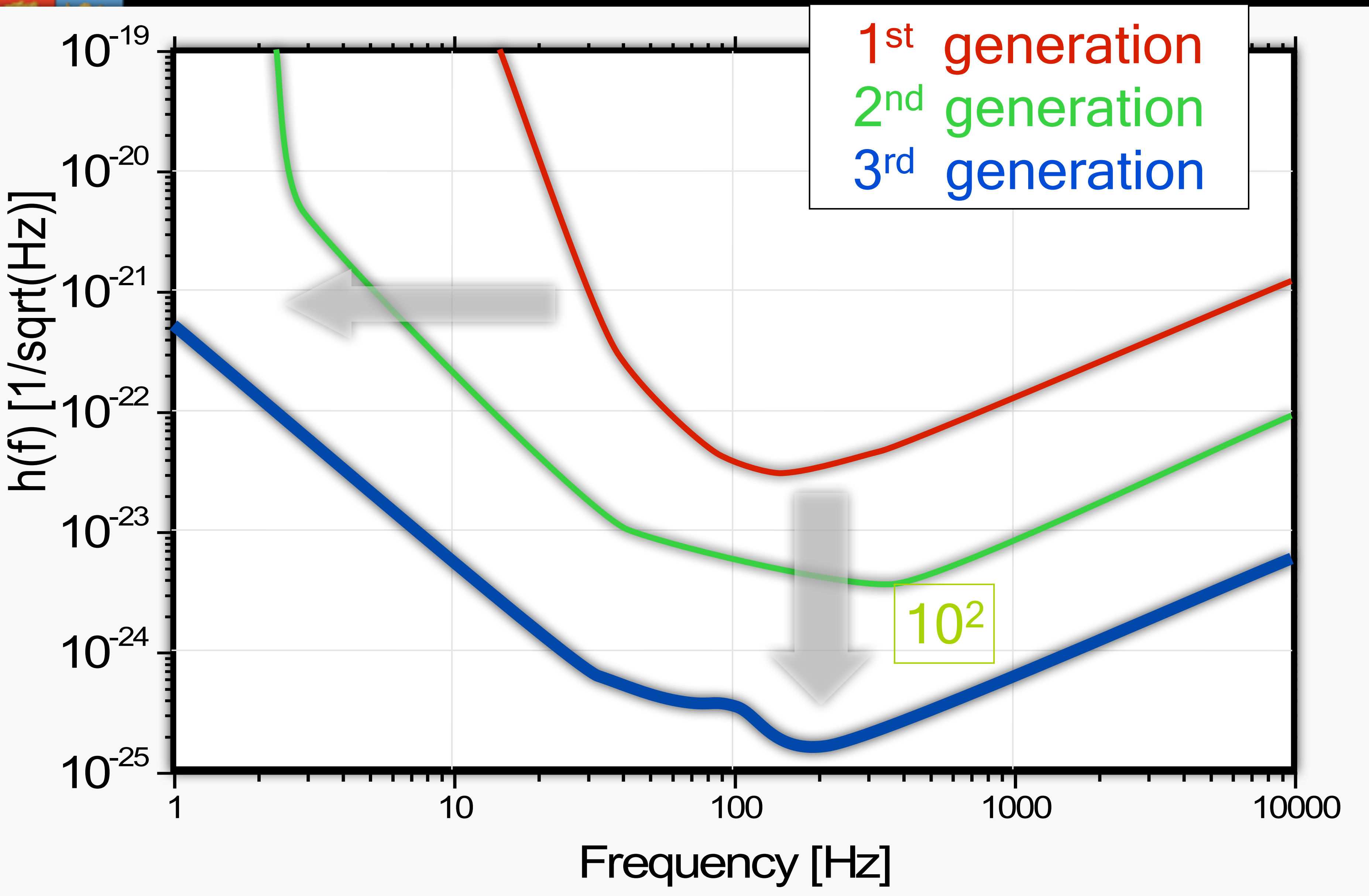



[M. Doets, D. Rabeling]

Sensitivity Studies

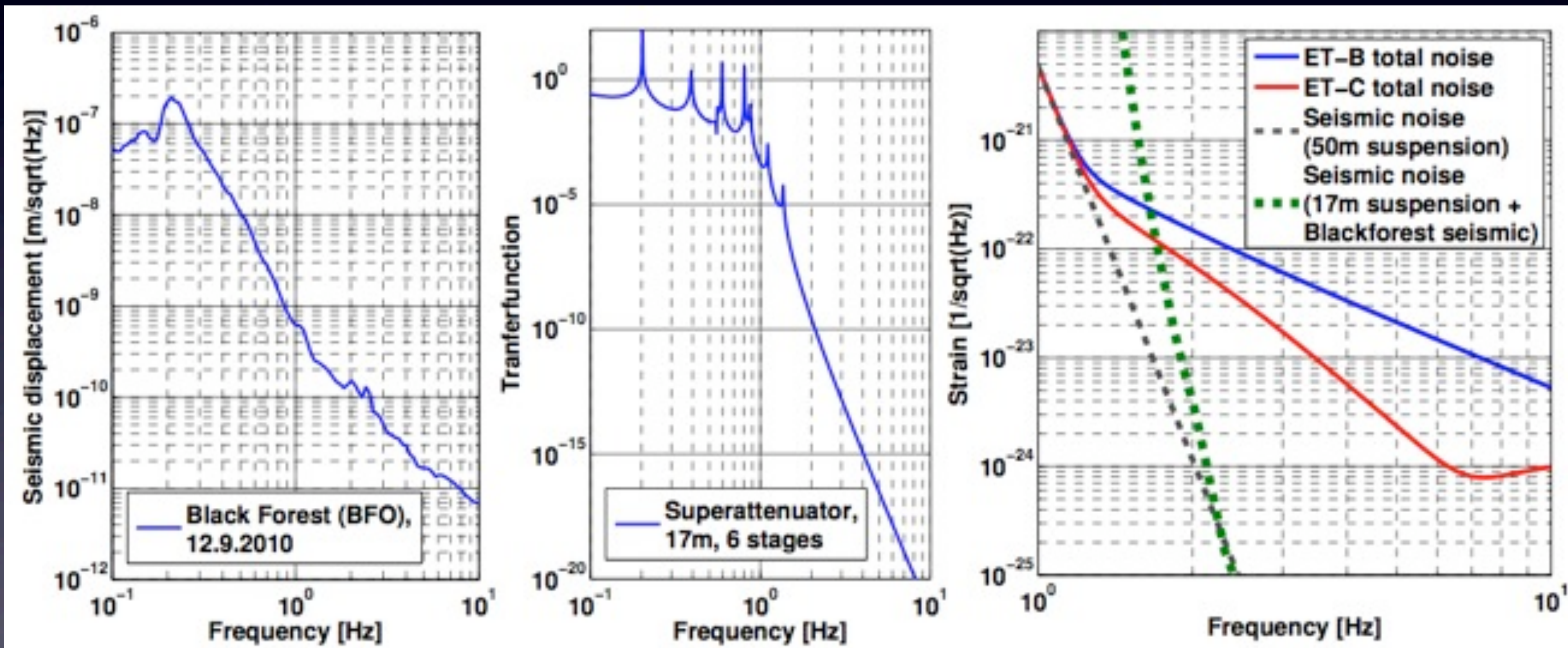
- One of the WG3 tasks is to provide official sensitivity curves
- Led by Stefan Hild but a transversal group effort: from sensitivity curve ET A, to ET B, ET C and now ET D.





1st generation
2nd generation
3rd generation
10^2
h(f) [1/sqrt(Hz)]
Frequency [Hz]
10-19
10-20
10-21
10-22
10-23
10-24
10-25
1
10
100
1000
10000

More Accurate Noise Models...



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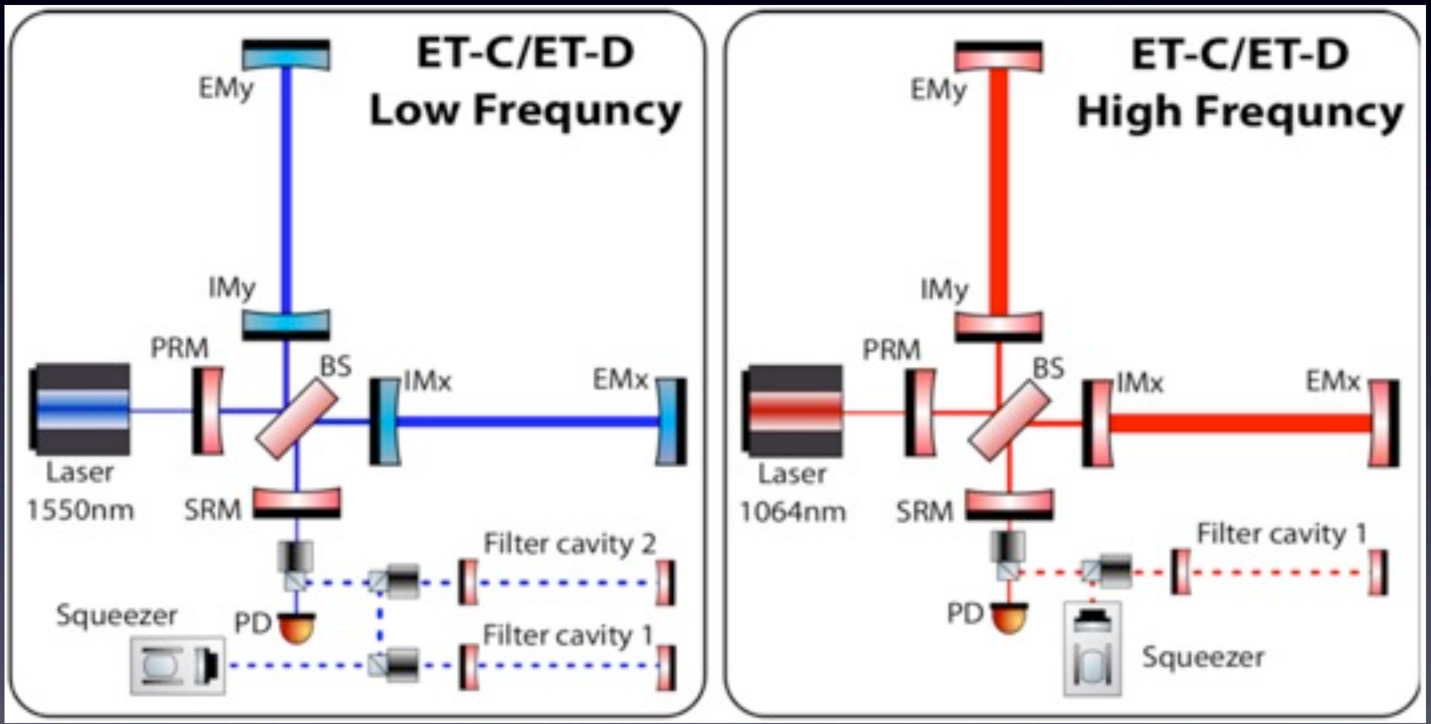
Used with a New Optical Layout



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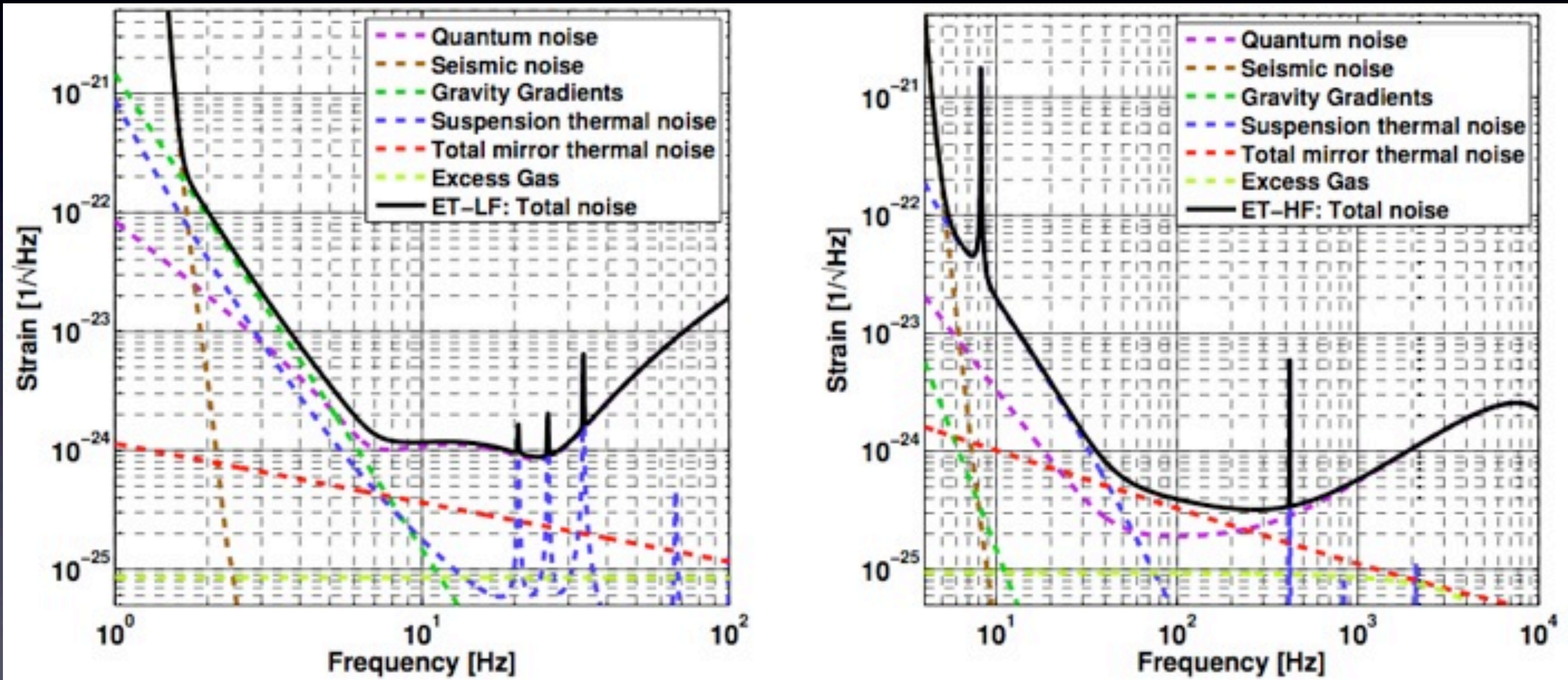
ET D Sensitivity



ET D Parameters

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
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

This looks easy enough, I can do it!

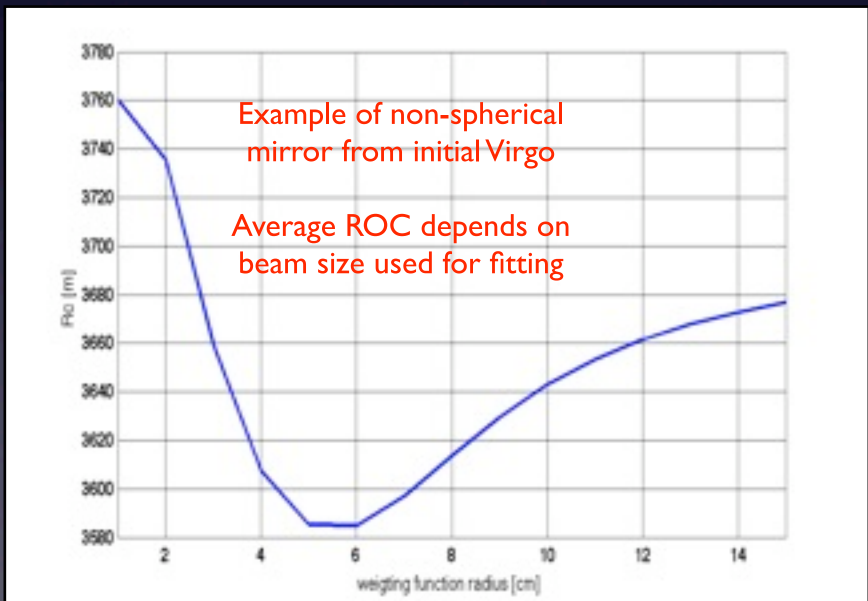
Coming soon at:

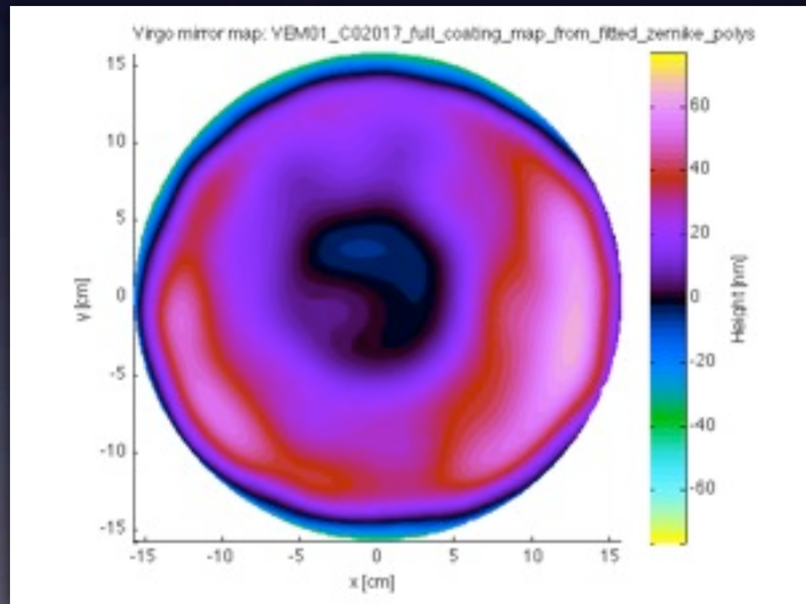
www.gwoptics.org

...end

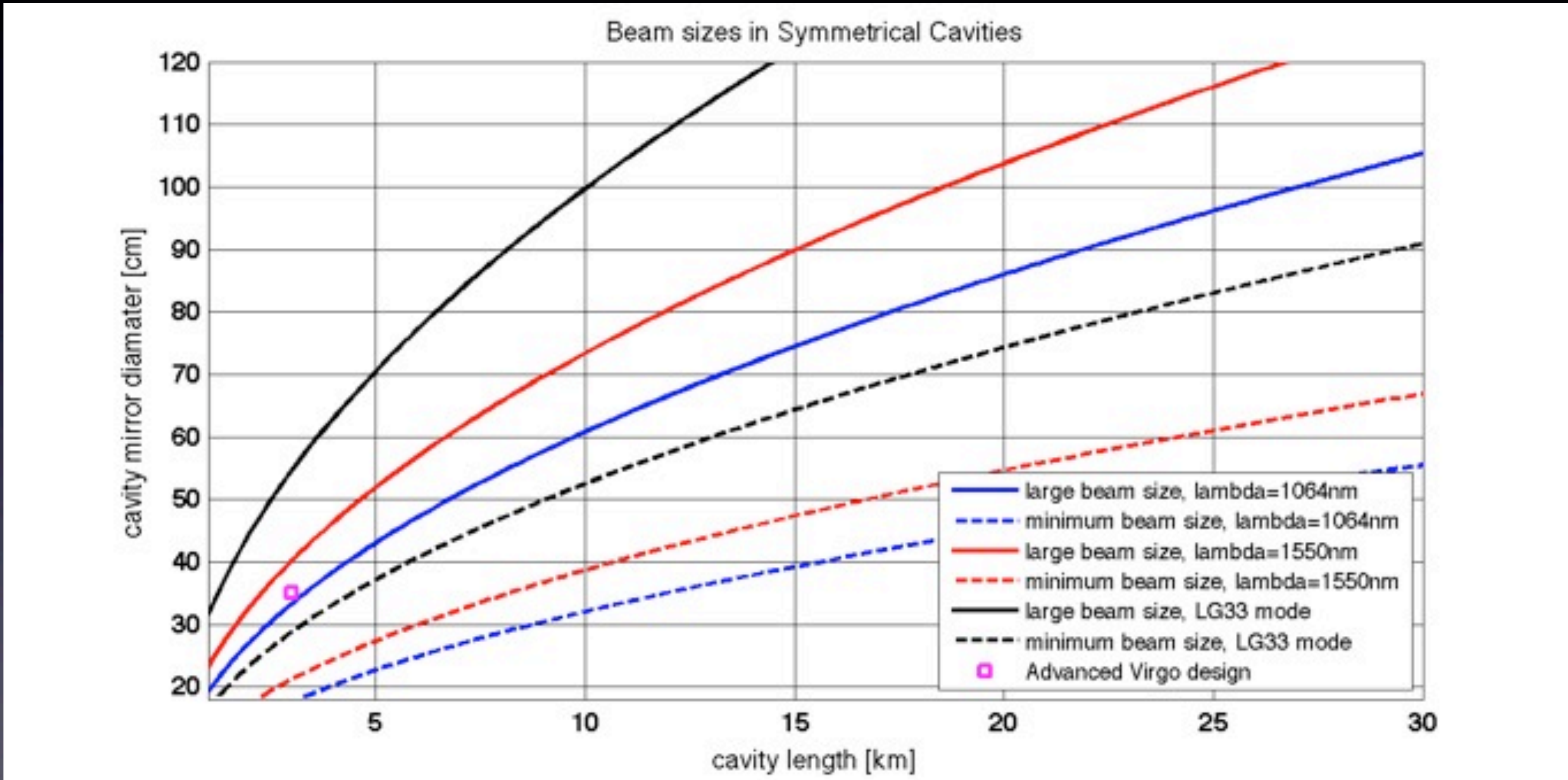
Mirror Sphericity

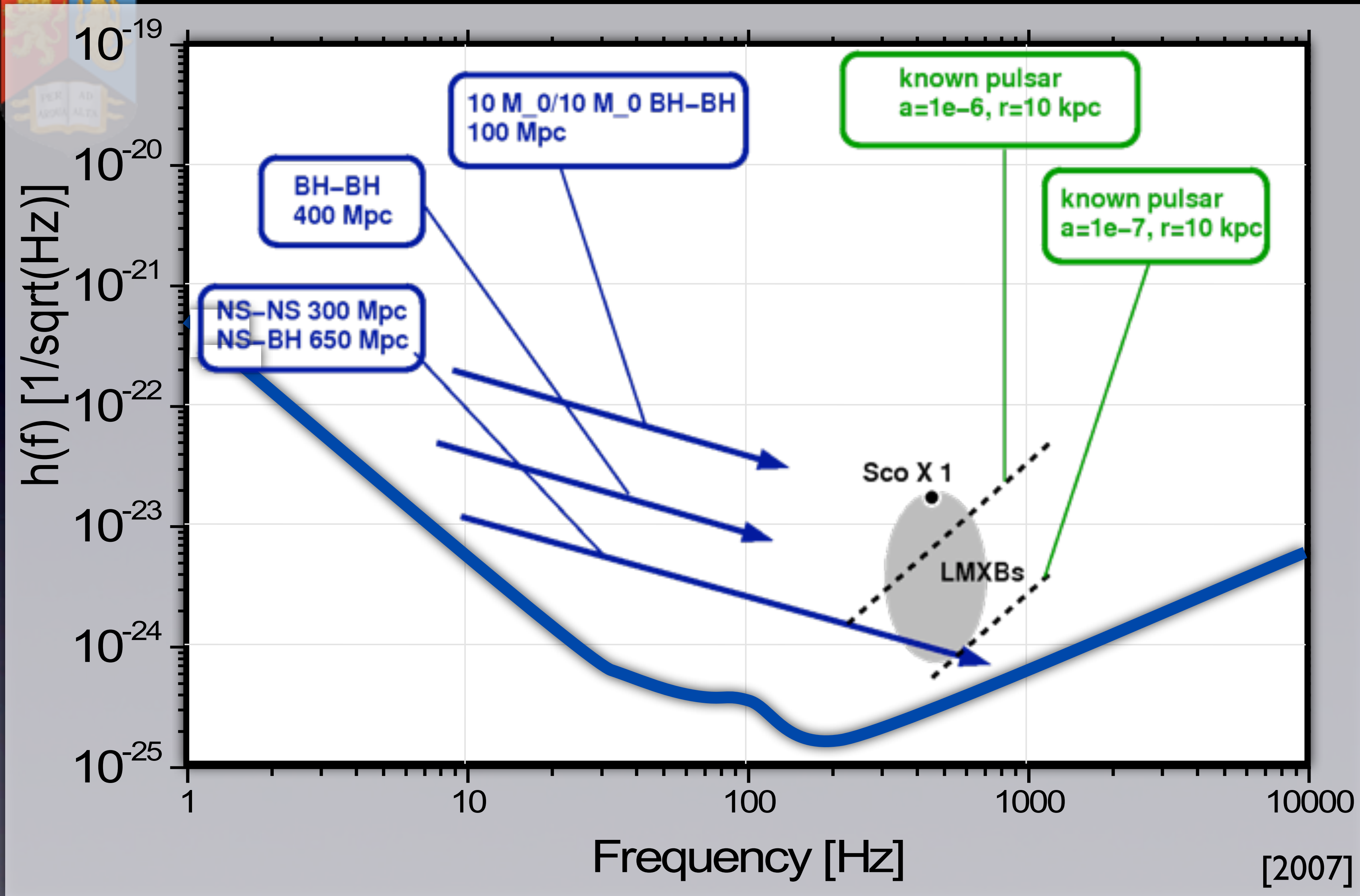
- AdVirgo example: L = 3000m, beam radius at ITM and ETM =6cm
- ROCs of 1531m are required
- Deviation of only a few ten meters can make cavity instable
- Additional problem: polished spheres are not spherical





Minimal beam size





10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
h(f) [1/sqrt(Hz)]
10 M_0/10 M_0 BH–BH
100 Mpc
BH–BH
400 Mpc
NS–NS 300 Mpc
NS–BH 650 Mpc
known pulsar
a=1e–6, r=10 kpc
known pulsar
a=1e–7, r=10 kpc
Sco X 1
LMXBs
1
10
100
1000
10000
Frequency [Hz]
[2007]