VESF School 2009:

FUTURE INTERFEROMETERS

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University of Birmingham

Pisa, May 2009

Some remarks ahead …

- ‘Future interferometers’ is a very wide field … … and I apologise for only covering a small fraction of the most interesting topics.

- In order to reserve as much space as possible for the ‘cool future stuff’, I will build on the basics covered in previous lectures (‘Interferometers’, ‘Noise and Control’, ‘Current detectors’).

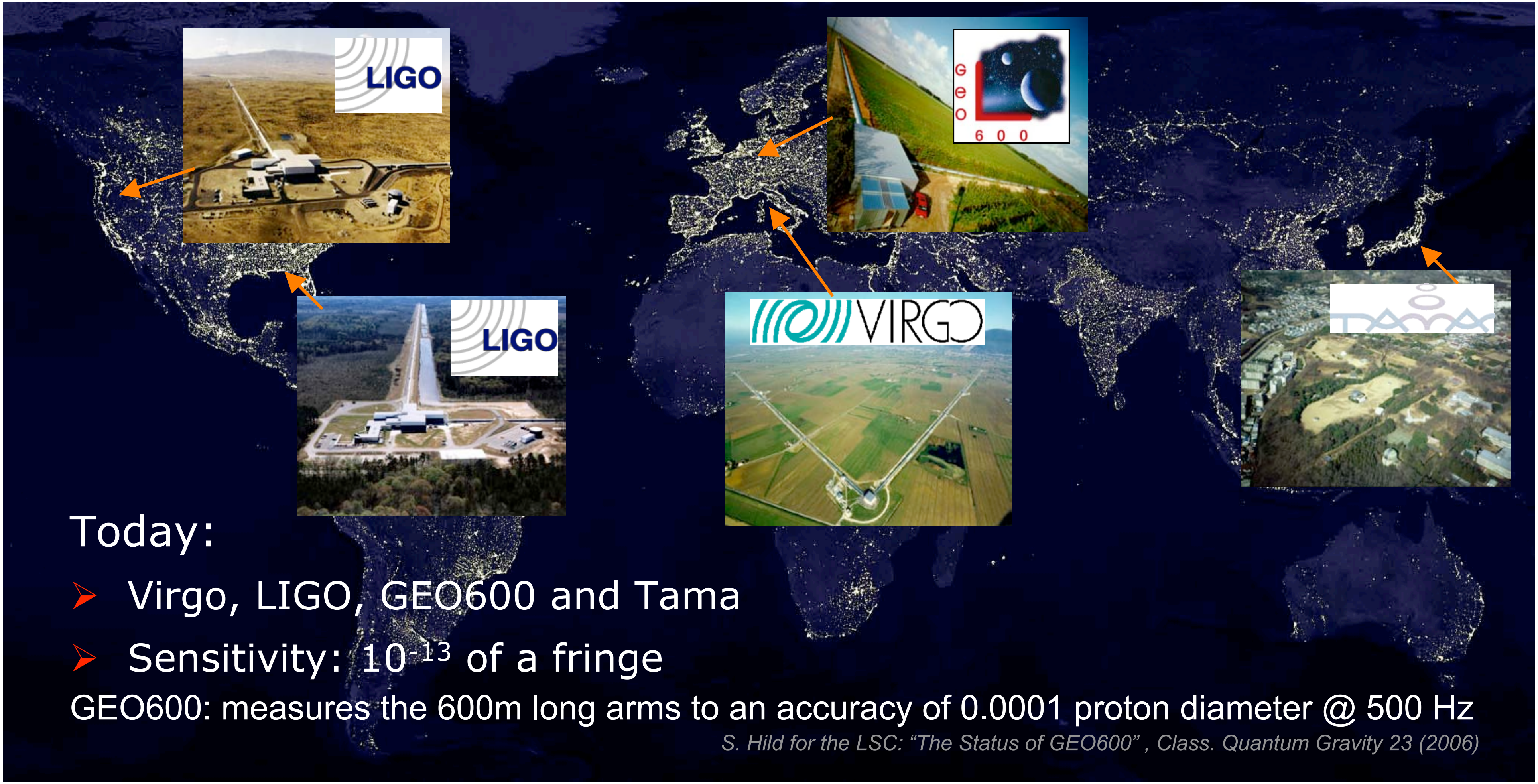
- If we come along anything you do not understand, PLEASE ASK !!!

What do I want you to take with you from this lecture?

- Get a good overview of all the exciting physics and technologies necessary for designing and building future interferometers.

- Get an intuitive understanding of the relevant technologies and underlying principles.

Today’s network of GW detectors



Today:

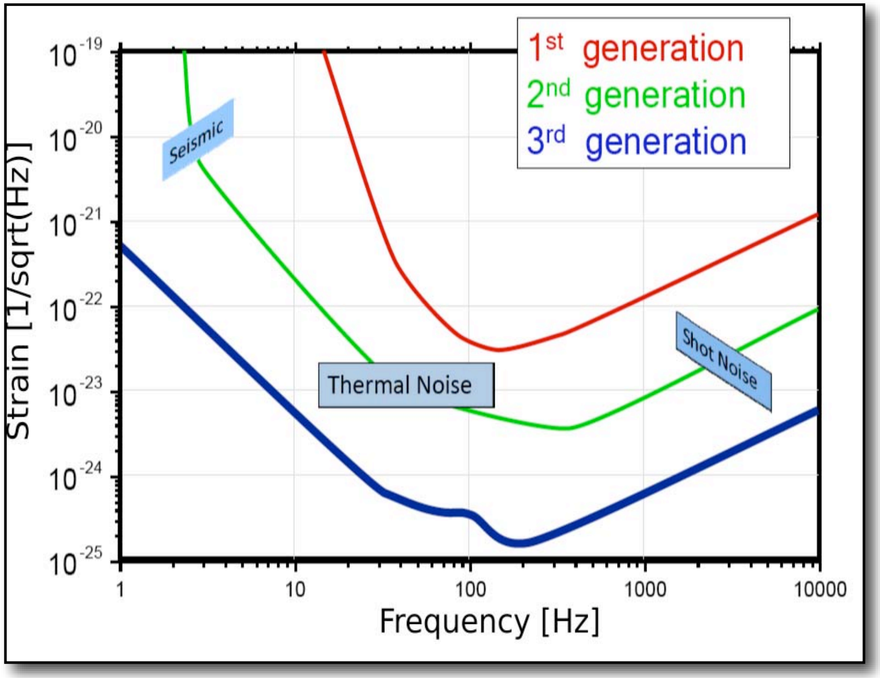
- Virgo, LIGO, GEO600 and Tama
- Sensitivity: 10^{-13} of a fringe

GEO600: measures the 600m long arms to an accuracy of 0.0001 proton diameter @ 500 Hz

S. Hild for the LSC: “The Status of GEO600” , Class. Quantum Gravity 23 (2006)

Status and future of GW observatories

- **1st** generation successfully completed:
  - Long duration observations (~1yr) in coincidence mode of 5 oberservatories.
  - Spin-down upper limit of the Crab-Pulsar beaten!
- **2nd** generation on the way:
  - End of design phase, construction about to start (or even started)
  - 10 times better sensitivity than 1st generation. => Scanning 1000 times larger volume of the Universe
- **3rd** generation at the horizon:
  - FP7 funded design study
  - 100 times better sensitivity than 1st generation. => Scanning 1000000 times larger volume of the Universe



Overview

What do we need to change to make our instruments 2nd Generation observatories ?

- Details of 2nd Generation interferometer: Example Advanced Virgo
  - Noise limits: Suspension thermal noise, Coating Brownian noise, Quantum noise
  - Important Techniques: Thermal compensation, NDRC, DC-readout
  - Sensitivity optimisation and observation prospects
- Other 2nd Generation GW Observatories
  - Advanced LIGO, LGCT, GEO-HF

What will a 3rd Generation Interferometer look like ?

- How to build the Einstein Telescope (ET)?
  - Geometry and shape
  - How to reach the sensitivity?

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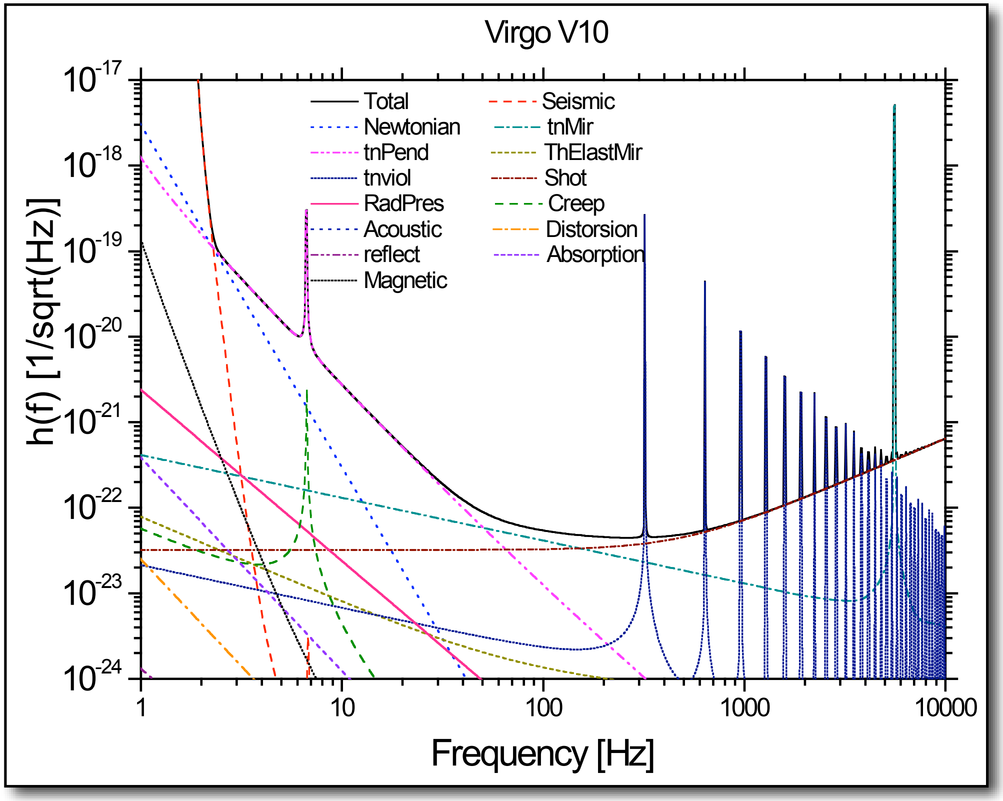
Main drivers for the design of future interferometers.

What will a 3rd Generation Interferometer look like ?

- How to build the Einstein Telescope (ET)?
  - Geometry and shape
  - How to reach the sensitivity?

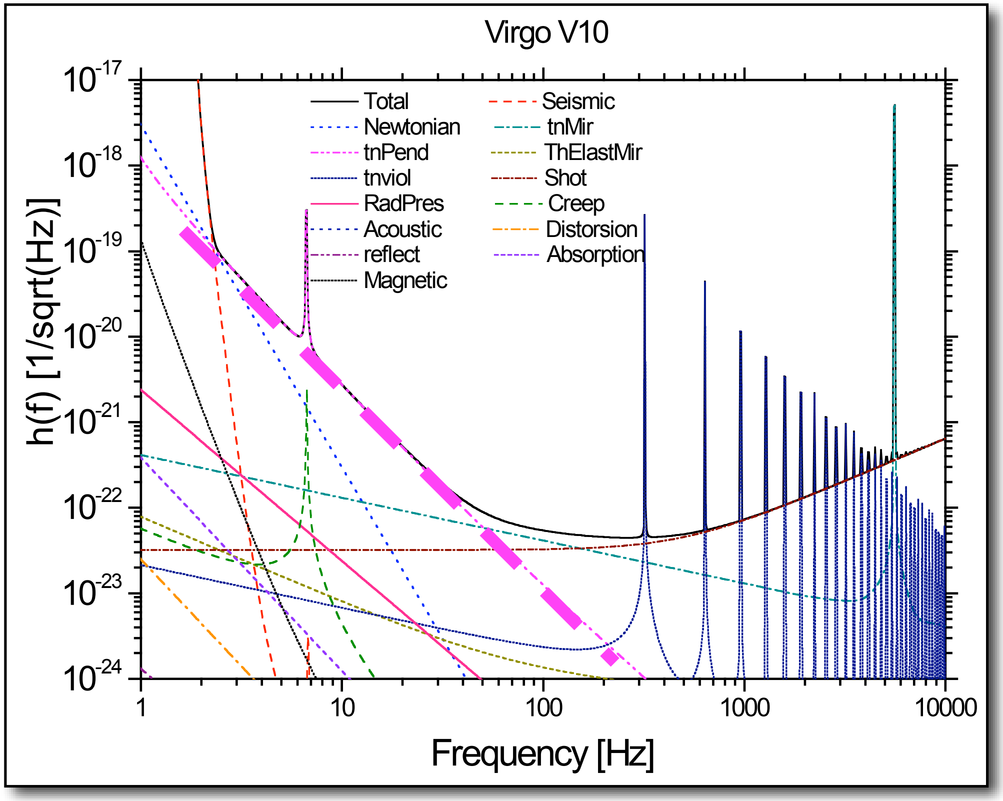
Which are the main fundamental noise sources limiting Virgo ?



http://wwwcascina.virgo.infn.it/senscurve/

Which are the main fundamental noise sources limiting Virgo ?

- Suspension thermal noise (low frequencies)



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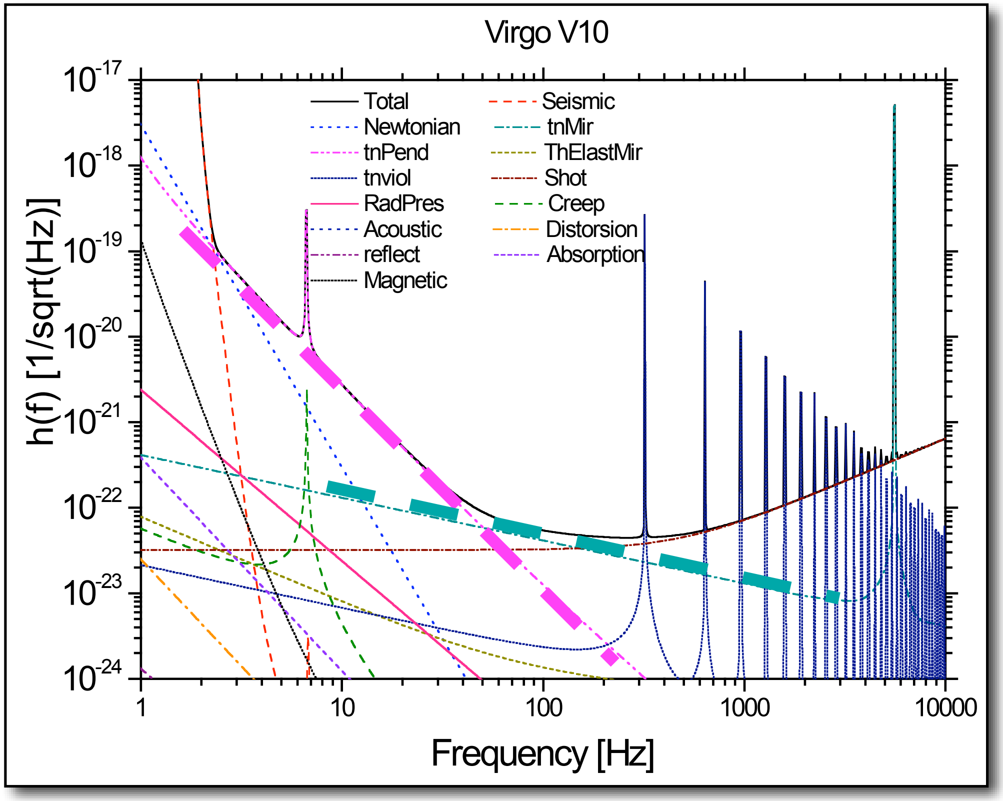
Which are the main fundamental noise sources limiting Virgo ?

- ➢ Suspension thermal noise (low frequencies)
- ➢ Mirror thermal noise (mid frequencies)



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Which are the main fundamental noise sources limiting Virgo ?

- Suspension thermal noise (low frequencies)
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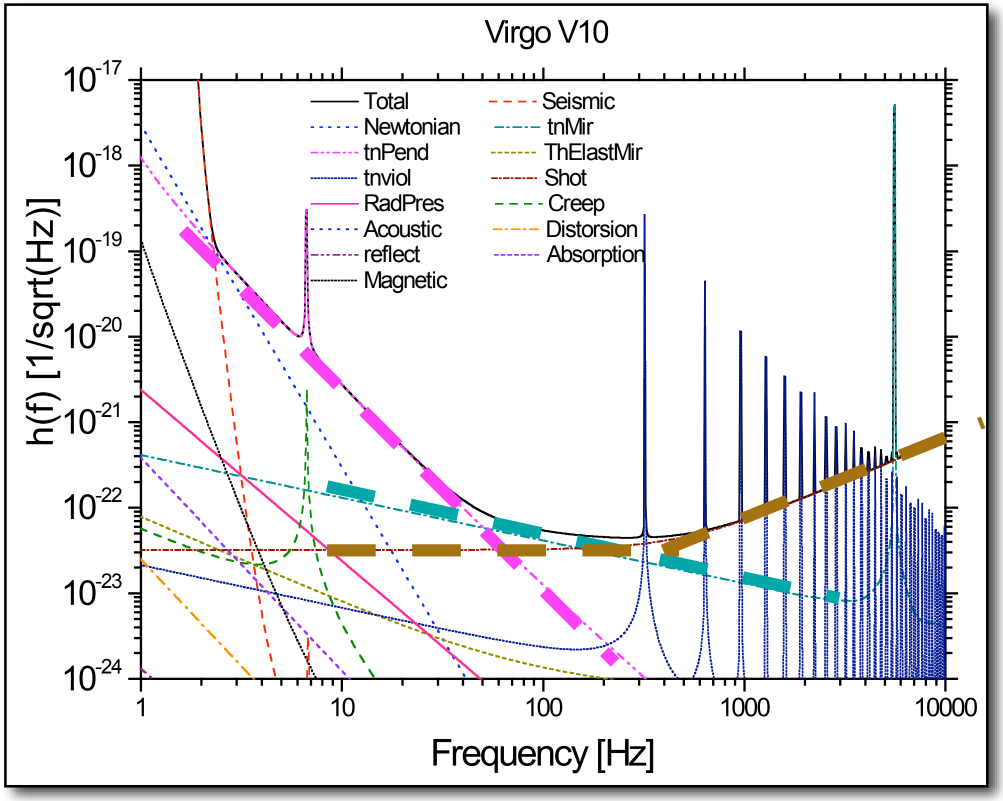
- Shot noise (high frequencies)



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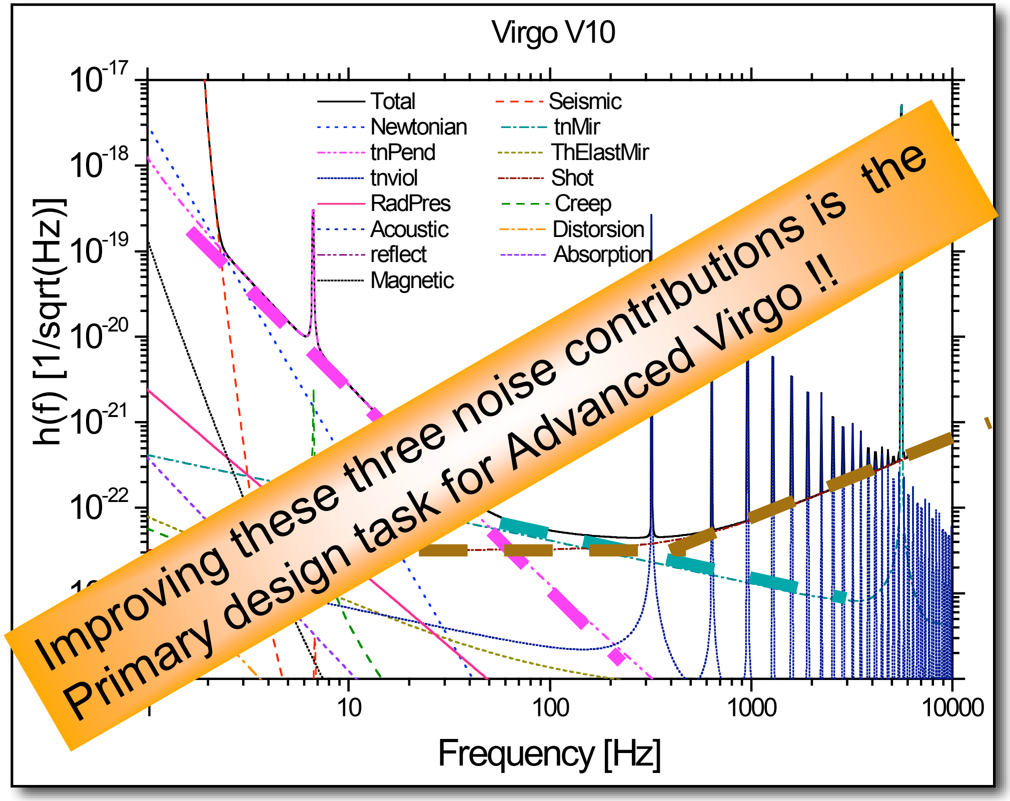
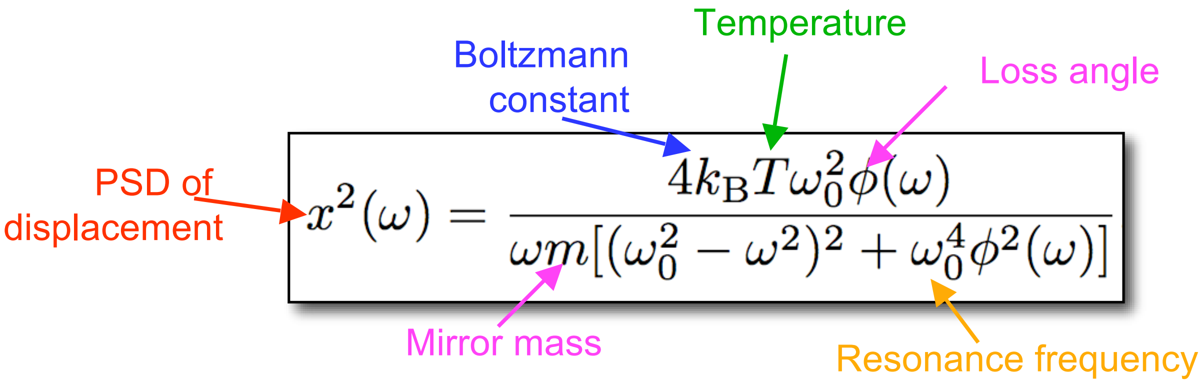


Improving these three noise contributions is the Primary design task for Advanced Virgo !!

http://wwwcascina.virgo.infn.it/senscurve/

How to reduce Suspension Thermal Noise?

- Suspension thermal noise of a simple pendulum:



Temperature

Boltzmann constant

Loss angle

PSD of displacement

$$x^2(\omega) = \frac{4k_\mathrm{B}T\omega_0^2\phi(\omega)}{\omega m[(\omega_0^2-\omega^2)^2+\omega_0^4\phi^2(\omega)]}$$

Mirror mass

Resonance frequency

How to reduce Suspension Thermal Noise?

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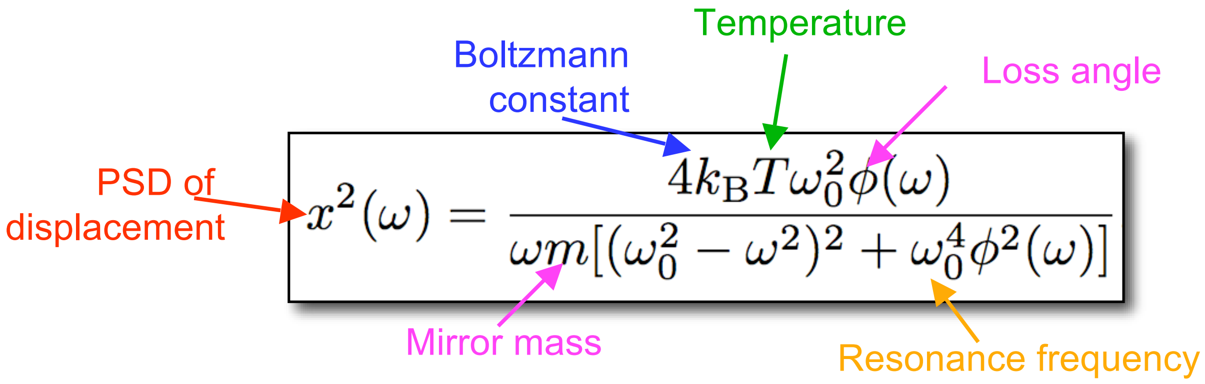

$$x^2(\omega) = \frac{4k_\mathrm{B}T\omega_0^2\phi(\omega)}{\omega m[(\omega_0^2-\omega^2)^2+\omega_0^4\phi^2(\omega)]}$$

Temperature

Boltzmann constant

Loss angle

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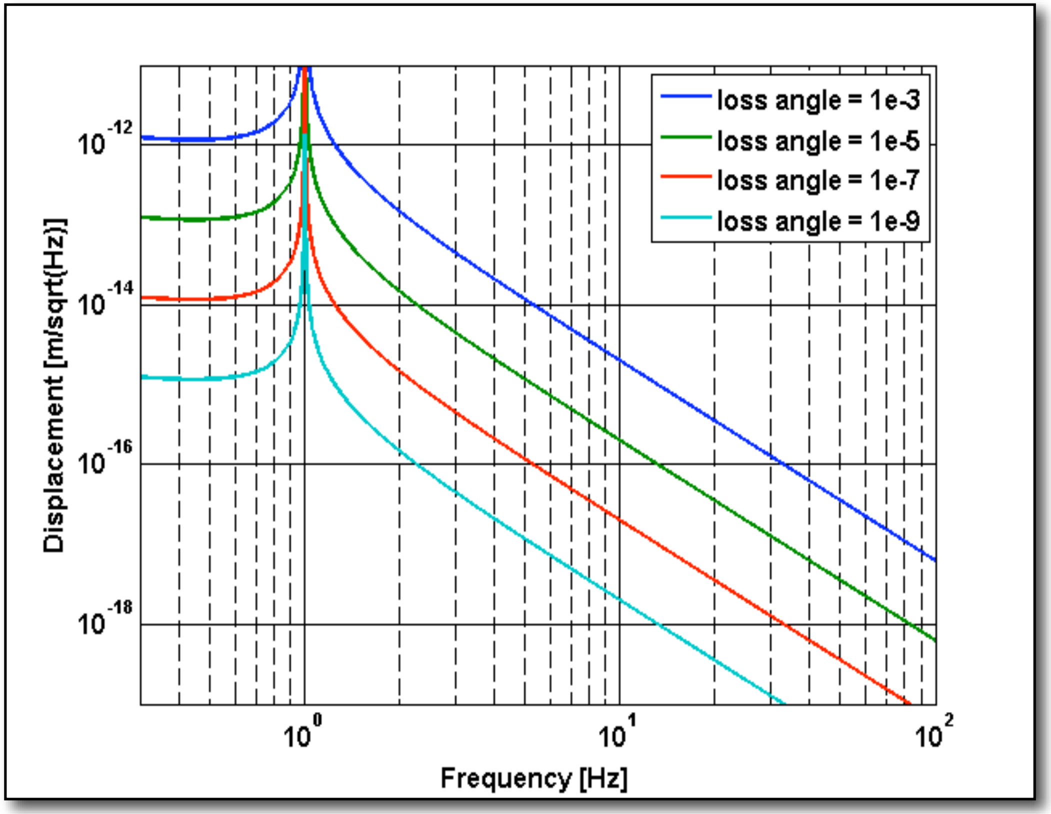
Mirror mass

Resonance frequency

- Suspension thermal noise can be reduced:
  - By cooling: proportional to sqrt(T)
  - By making the pendulum longer: proportional to w_0
  - By making the mirror heavier: proportional to sqrt(1/m)
  - By reducing the pendulum losses: proportional to sqrt(phi)

How to improve the loss angle of a suspension?

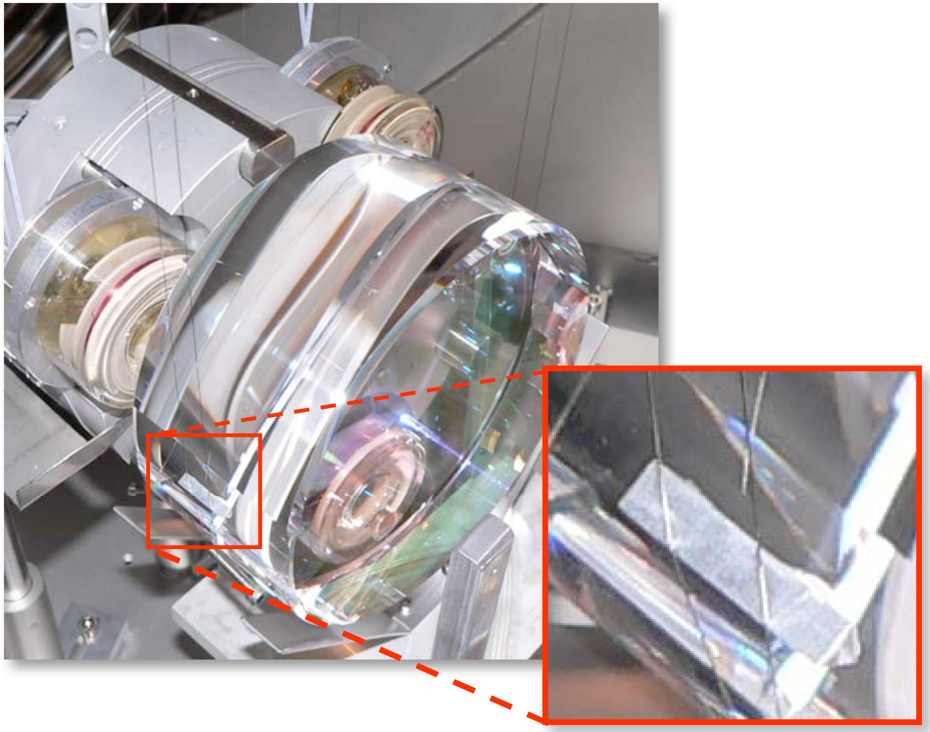
- Example: Displacement noise of a single pendulum:
  - Mass = 42kg
  - Room temperature
  - 1 Hz resonance frequency

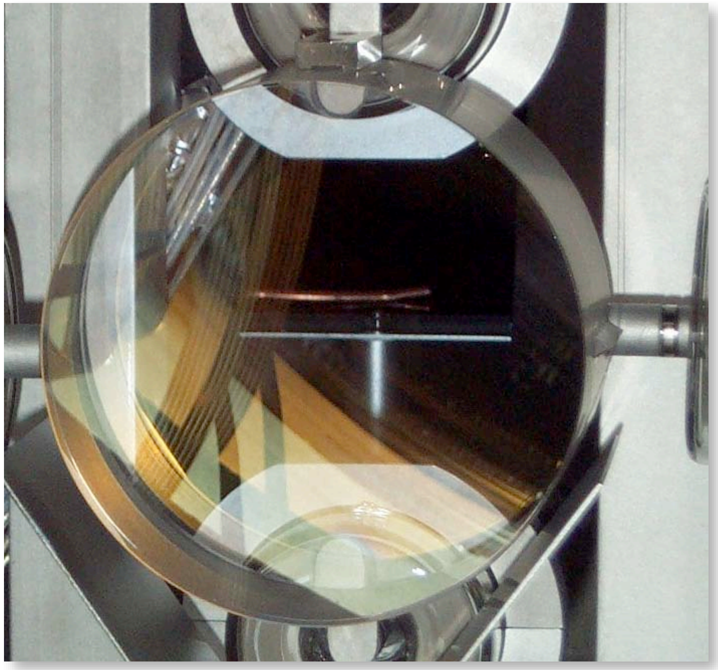


- How can we improve the loss angle?

Steel Wire Suspensions

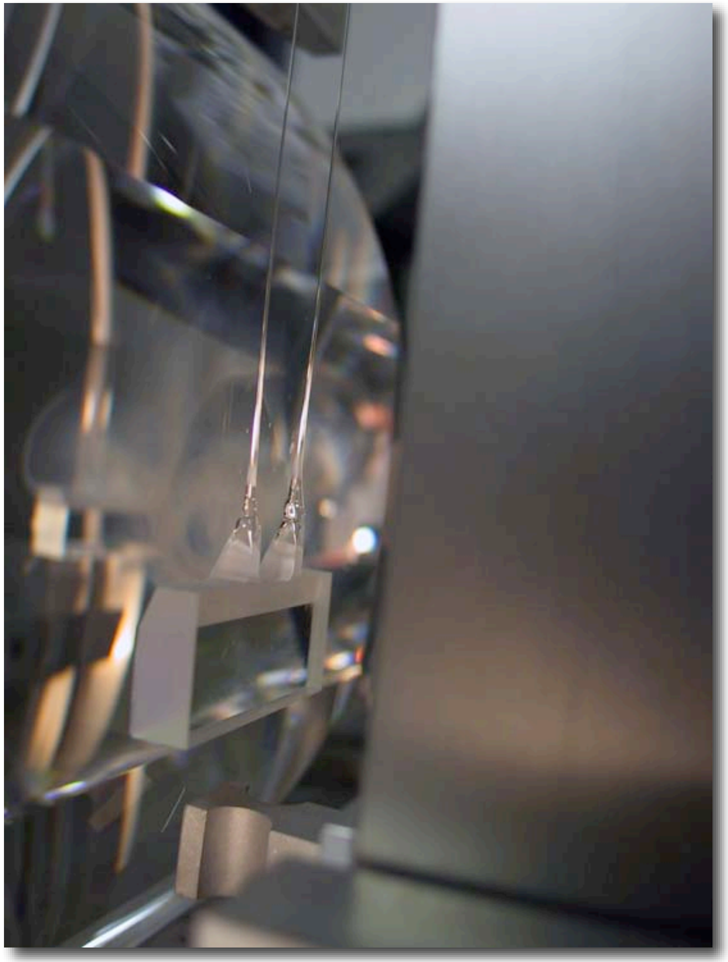
- Steel wire suspensions: loss angle of up to 1e-6
- Fairly easy to build and to handle …





Quasi-monolithic Fused Silica Suspension

- Using thin (few hundred microns) fused silica fibers welded or clamped onto fused silica mirrors.
- Breaking stress limit of fused silica fibers (2-4e9 Pa) comparable with steel wires.
- Quasi-monolithic fused silica suspensions: loss angle of up to 1e-8
- Fused Silica Suspensions are used in GEO600 for more than 5 years and will be the baseline for all 2nd generation interferometers.



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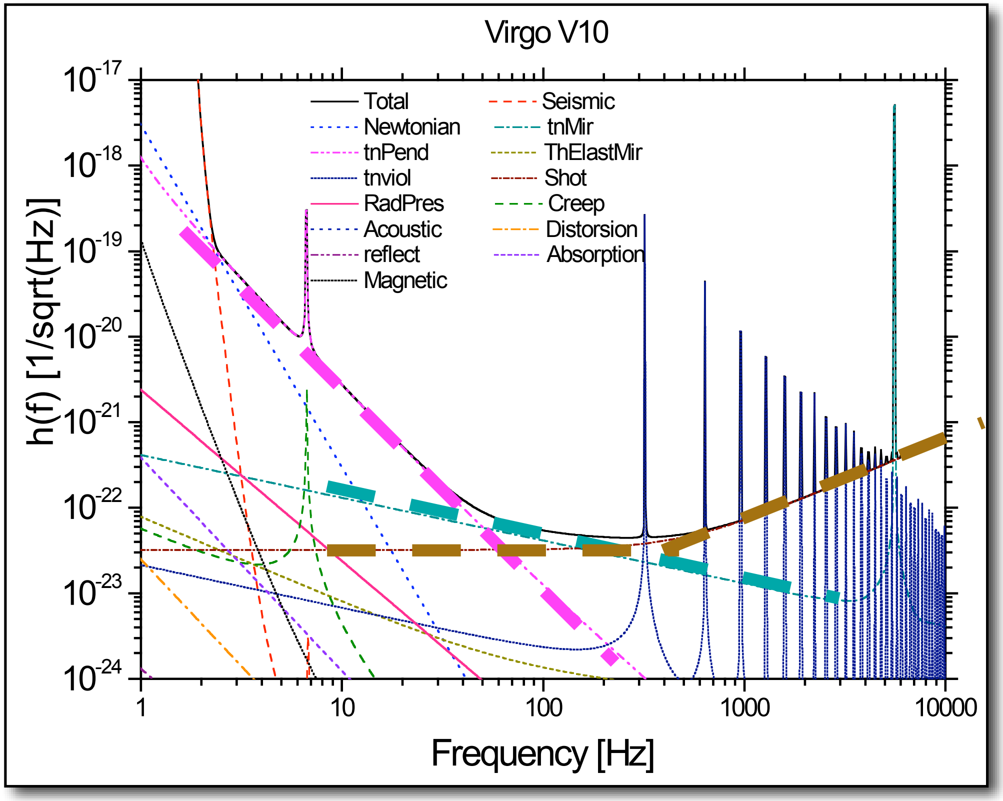

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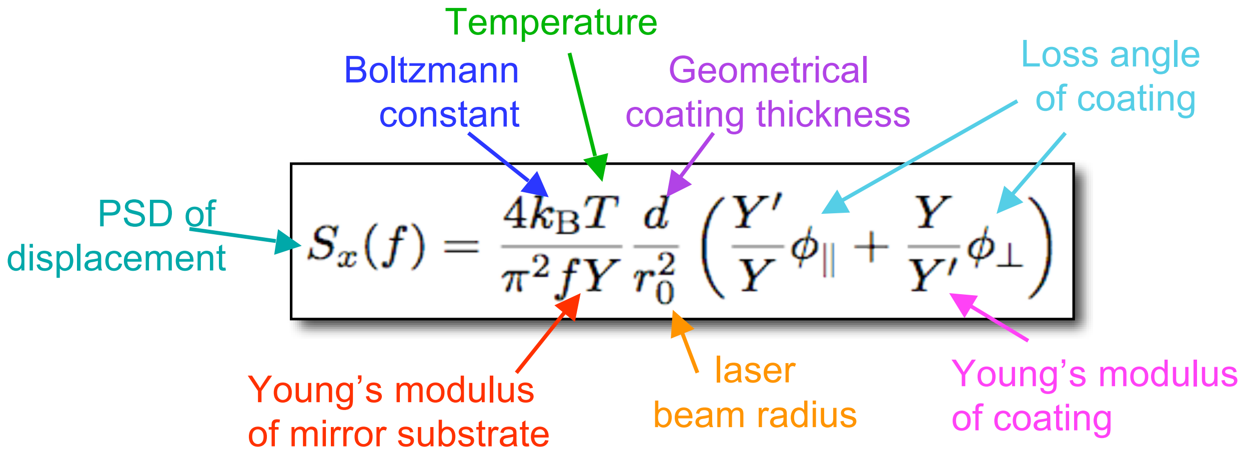
How to decrease Coating Brownian Noise ?



Temperature

Boltzmann constant

Geometrical coating thickness

Loss angle of coating

PSD of displacement

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

Young's modulus of mirror substrate

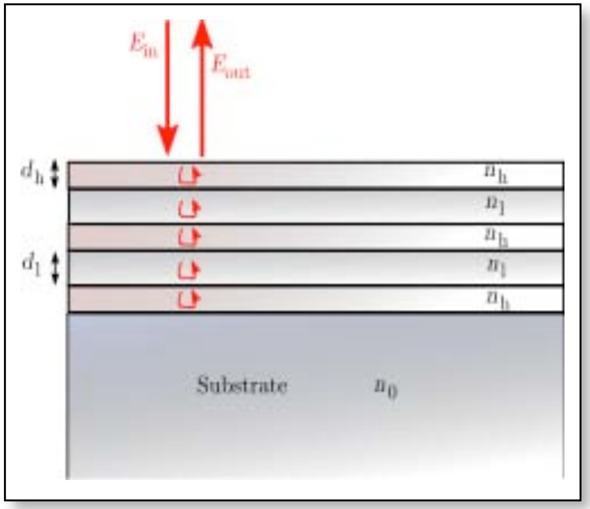
laser beam radius

Young's modulus of coating

- Coating Brownian noise can be reduced:
  - By cooling: proportional to sqrt(T)
  - By making the coating layers thinner: proportional to sqrt(d)
  - By making laser beam larger: proportional to 1/r_0
  - By reducing mechanical losses of the coating: proportional to sqrt(phi)

Can we make the coating thinner?

- **NO!** For a certain laser wavelength and coating materials the coating thickness is driven by the required reflectivities *(R)* of the mirrors.
- Coating made of ***k*** quarter-wave stacks, formed by alternating layers of high refraction index *(nH)* and low refraction index *(nL)*

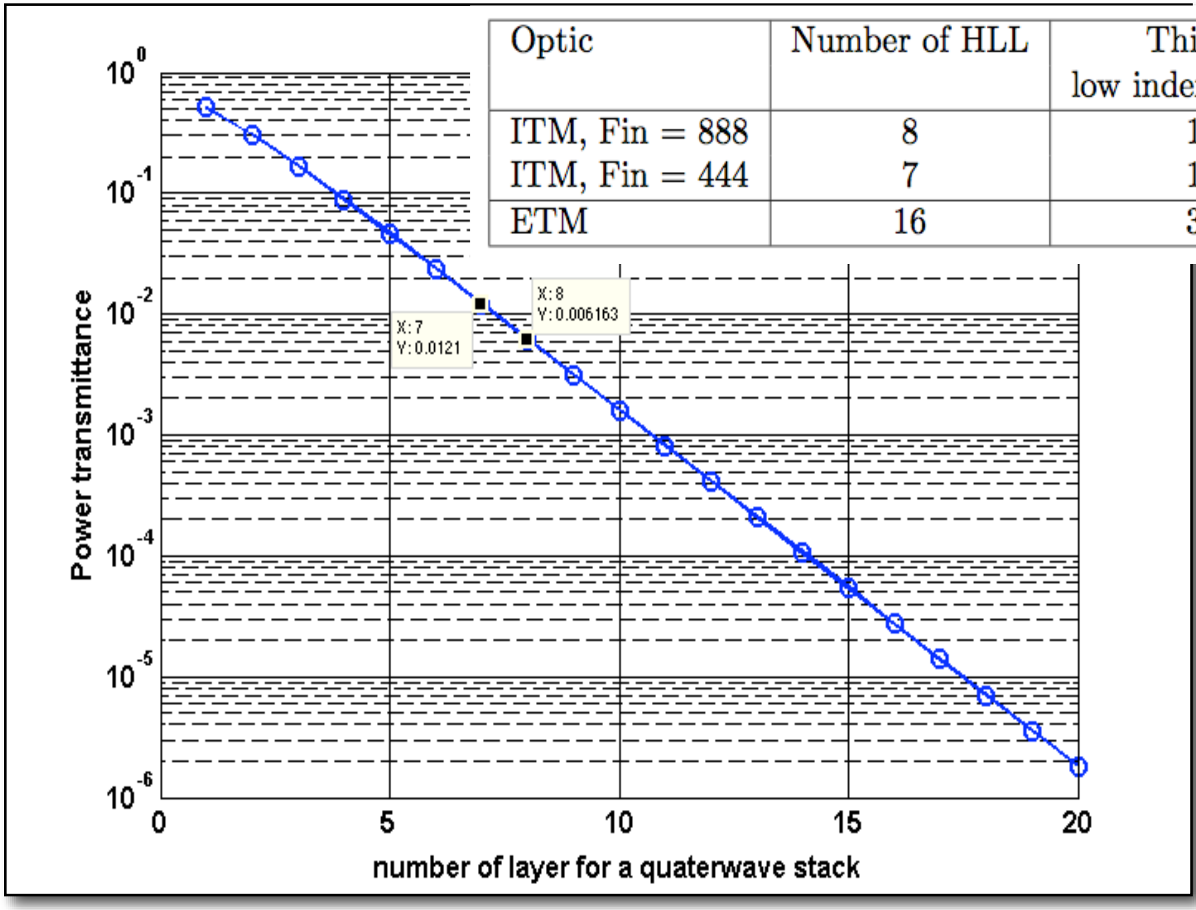


$$R = \left(\frac{1 - \left(\frac{nH}{nL}\right)^{2*k} * \frac{nH^2}{nS}}{1 + \left(\frac{nH}{nL}\right)^{2*k} * \frac{nH^2}{nS}} \right)^2$$

- PLEASE NOTE: If we would use different lasers the coating layer thickness would go down inverse proportional to the laser wavelength

Required coating thicknesses for the Advanced Virgo mirrors

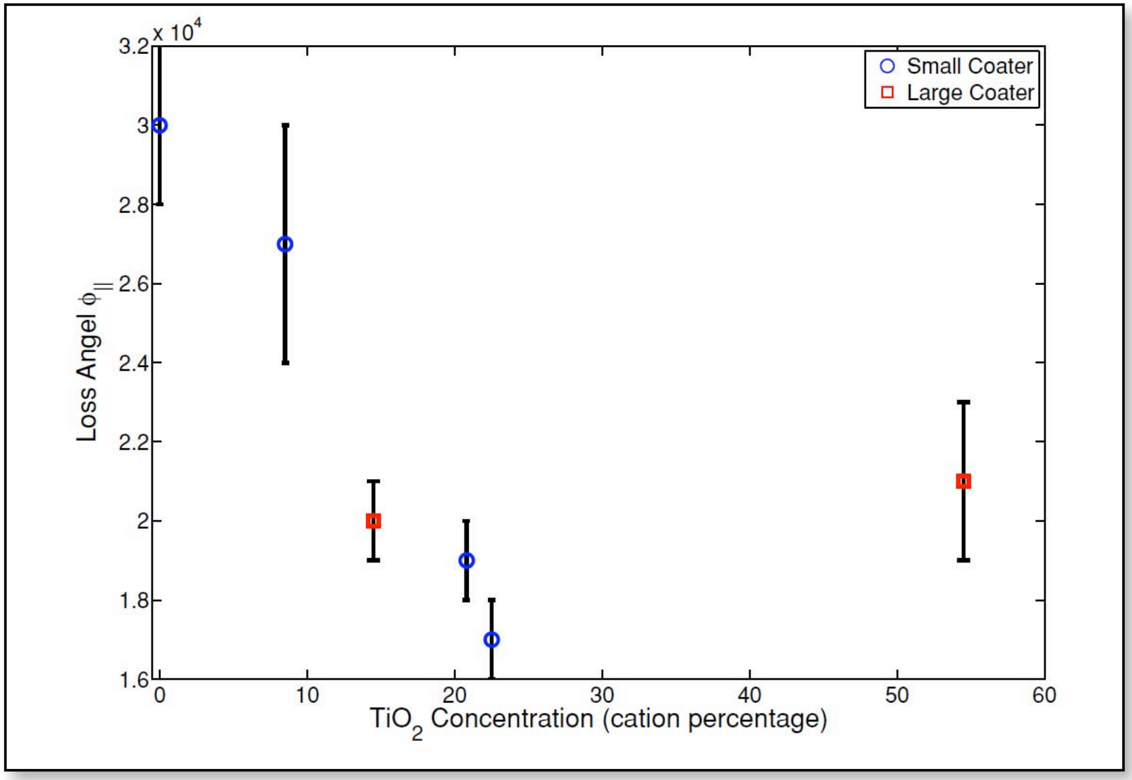
Optic	Number of HLL	Thickness of low index material [m]	Thickness of high index material [m]
ITM, Fin = 888	8	1.83e-6	1.05e-6
ITM, Fin = 444	7	1.65e-6	0.92e-6
ETM	16	3.30e-6	2.09e-6



- Input mirror: R=99.3%
- End mirror: R=99.9995%
- High refractive material: n=2.04
- Low refractive material: n=1.45

Can we use better coatings?

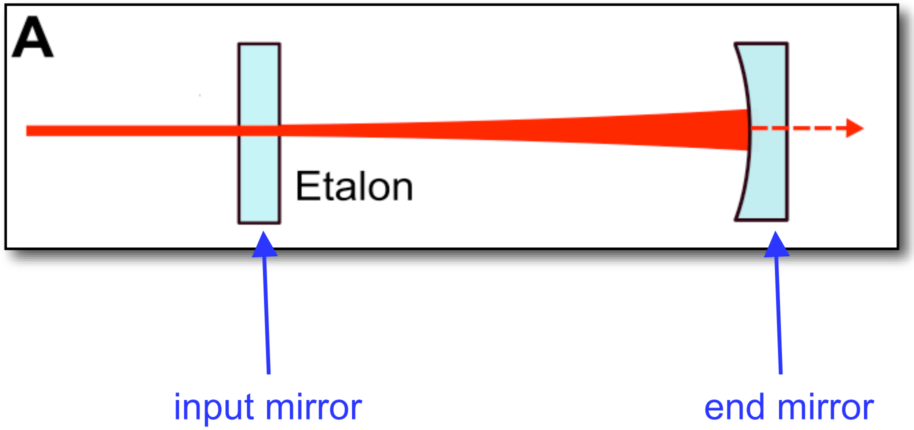
- Fortunately: **YES!**
- Coating research is one of the hot topics in the GW field.
- Standard high-refractive material is tantala.
- Doping the tantala with titania reduces the loss angle by about 30%.



G. Harry et al: 'Titania-doped tantala/silica coatings for GW detection' CQG, 2007, 24, 405-415

Where to put the cavity waist ?

- Initial Virgo has the waist on the input mirror:
  - Disadvantage: Coating noise is entirely dominated by small beam size of input mirror

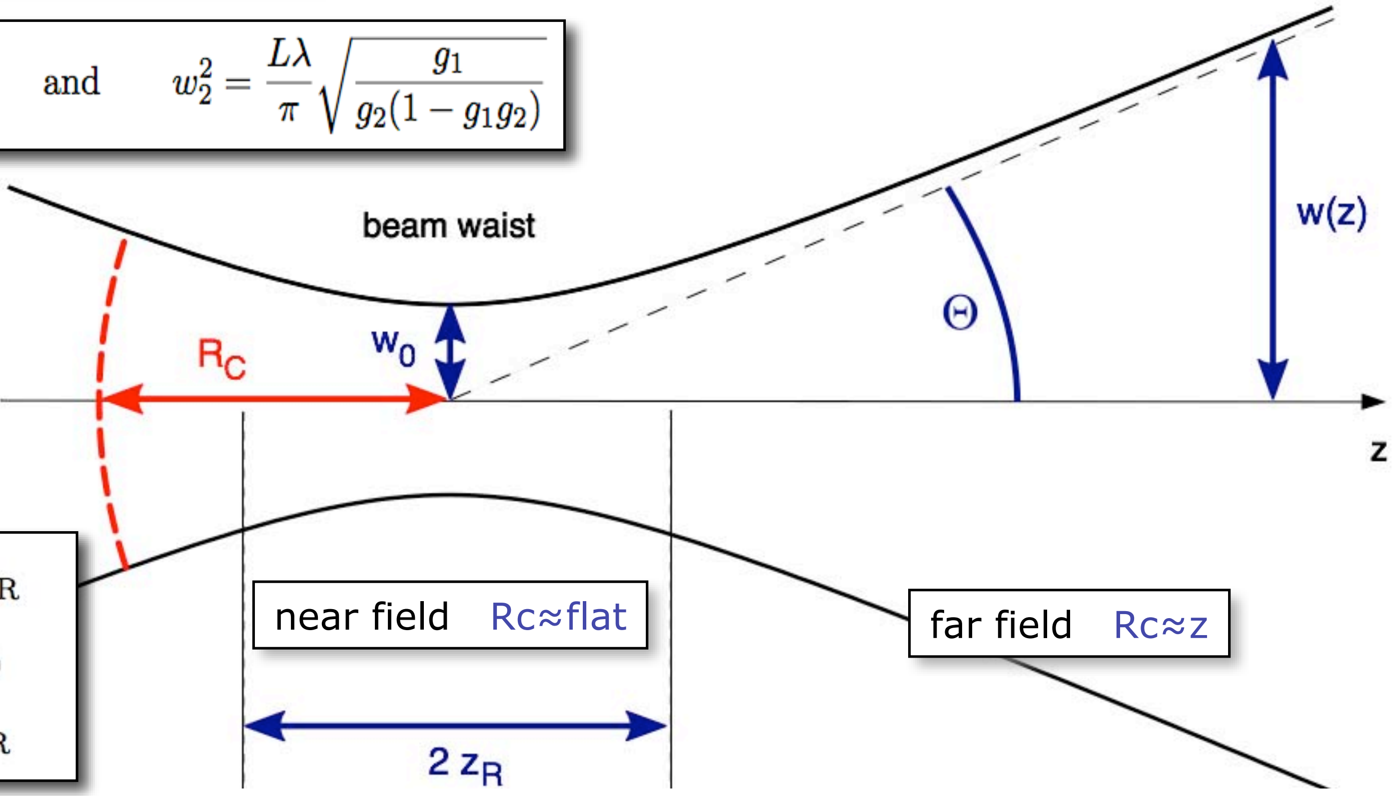


Gauss beams

Slide stolen from A.Freise

$$g_1 = 1 - \frac{L}{R_{C1}} \quad \text{and} \quad g_2 = 1 - \frac{L}{R_{C2}}$$

$$w_1^2 = \frac{L\lambda}{\pi}\sqrt{\frac{g_2}{g_1(1-g_1g_2)}} \quad \text{and} \quad w_2^2 = \frac{L\lambda}{\pi}\sqrt{\frac{g_1}{g_2(1-g_1g_2)}}$$

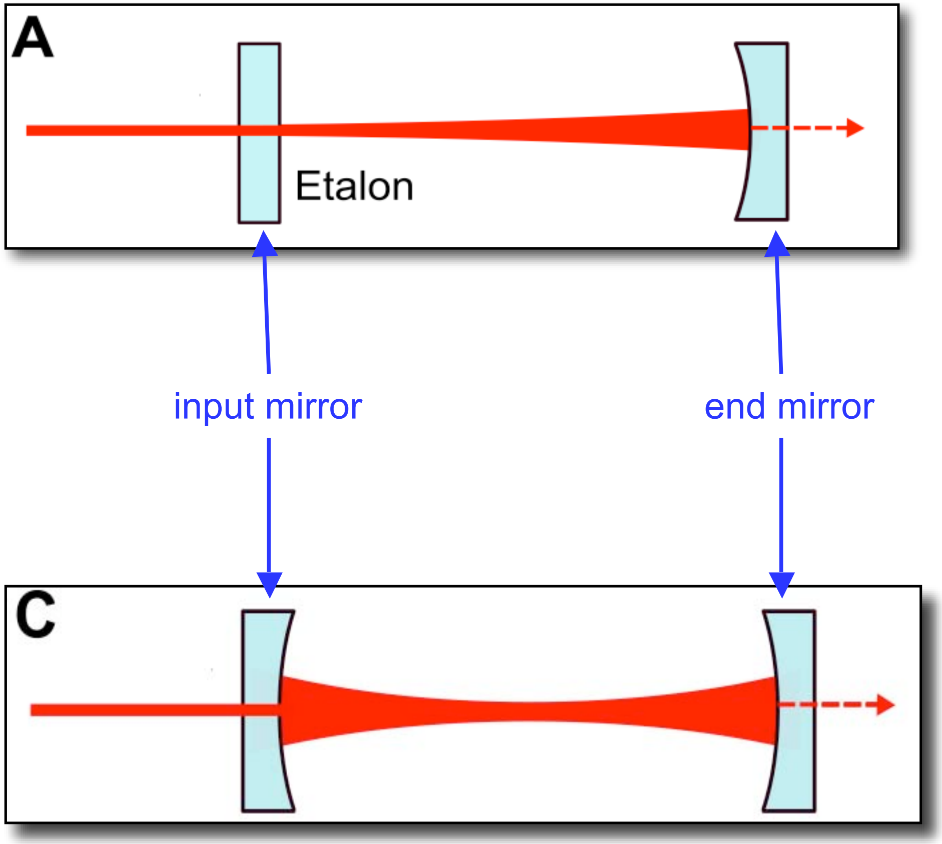


$$\begin{aligned} R_C &\approx \infty, & z - z_0 &\ll z_R \\ R_C &\approx z, & z &\gg z_R,\ z_0 \\ R_C &= 2z_R, & z - z_0 &= z_R \end{aligned}$$

Where to put the cavity waist ?

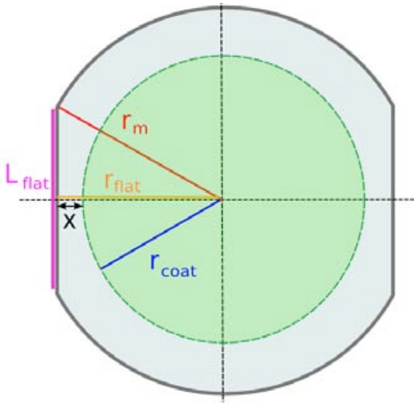
- Initial Virgo has the waist on the input mirror:
  - Disadvantage: Coating noise is entirely dominated by small beam size of input mirror

- Advanced Virgo will have the waist close to cavity center:
  - Disadvantage: large beams in the central IFO
  - Advantage: much lower coating Brownian noise!



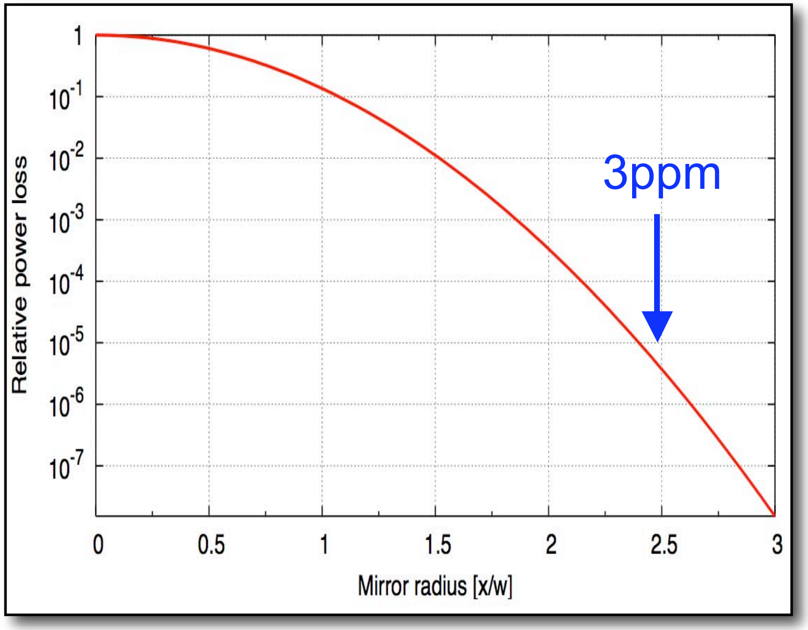
What is the maximum Beam Size ?

- Sensitivity
  - Need to make the beams as large as possible!
- Cavity stability
  - Large beams means pushing towards instability of the cavity.
  - Cavity degeneracy sets limit for maximal beam size
- Mirror size
  - The maximum coated area might also impose a limit for the beam size.



Clipping losses

- Why are clipping losses a problem?
  - Reduced power buildup.
  - Scattered light noise.
- In the ideal case a factor 2.5 (beam radius to mirror radius) seems to be fine = clipping loss of only a few ppm.
- Keep in mind: in reality
  - Mirror imperfections
  - Miscentering
  - Residual alignment fluctuations



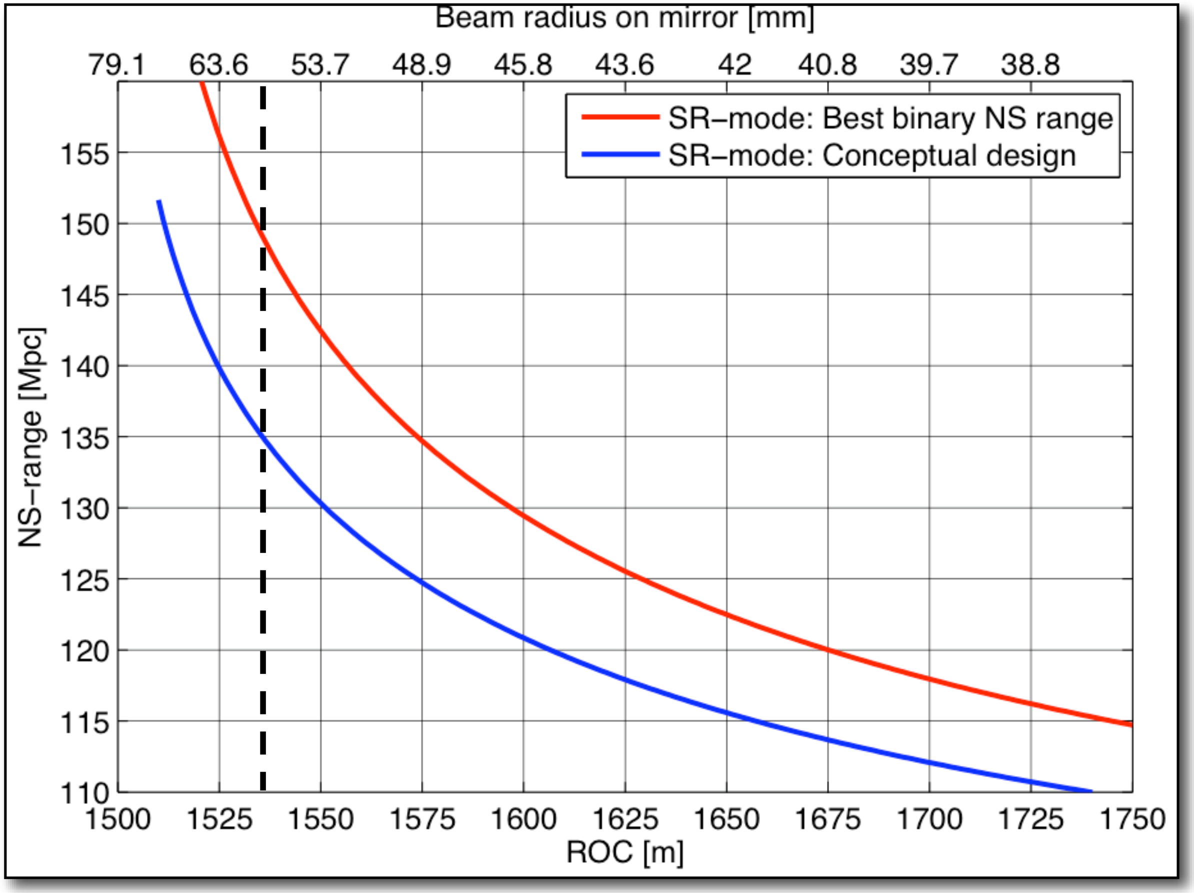
Advanced Virgo:

Mirror diameter 35cm

Maximal beam radius = 6.5cm

Sensitivity with symmetric radii of curvature (ROC)

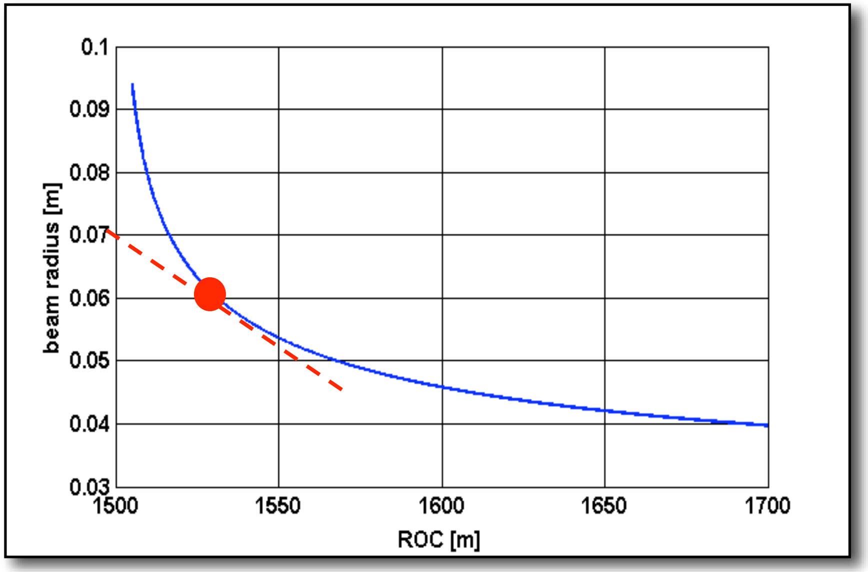
- With 6cm radius and 1530m ROC: Advanced Virgo obtains about 150 Mpc.



Example: cavity of 3km length and identical curvatures of input and end mirror.

Cavity Stability and Choice of ROCs

- The larger the beams the more accuracy is required for the mirror polishing !
- Account for potential manufacturing accuracy
  - 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.
- Advanced Virgo: Believe that we can go for ROCs 2% of instability.
- Corrective coating as baseline.

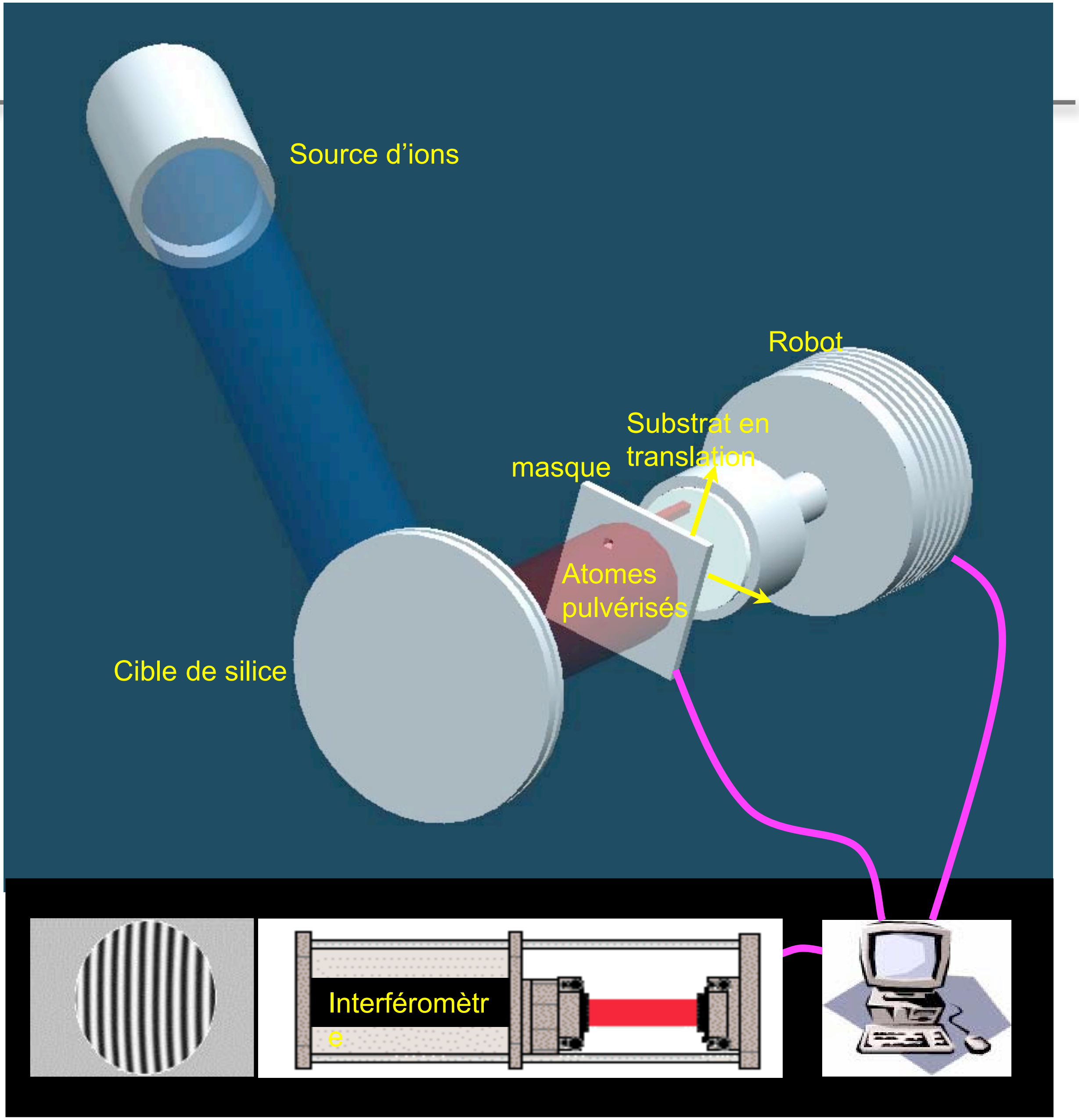


Example: cavity of 3km length and identical curvatures of input and end mirror.

Corrective Coating

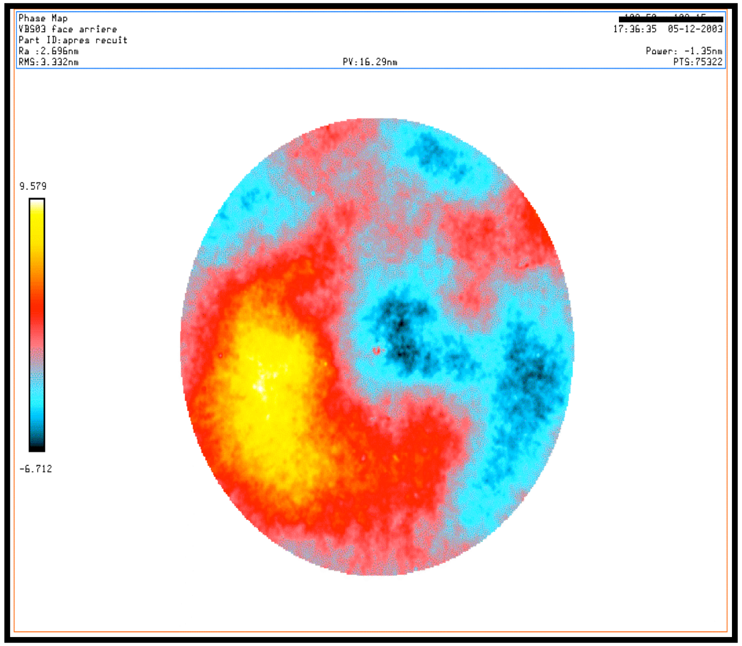
- A way to improve the mirrors flatness: corrective coating

- Two ingredients
  - Robot
  - Metrology



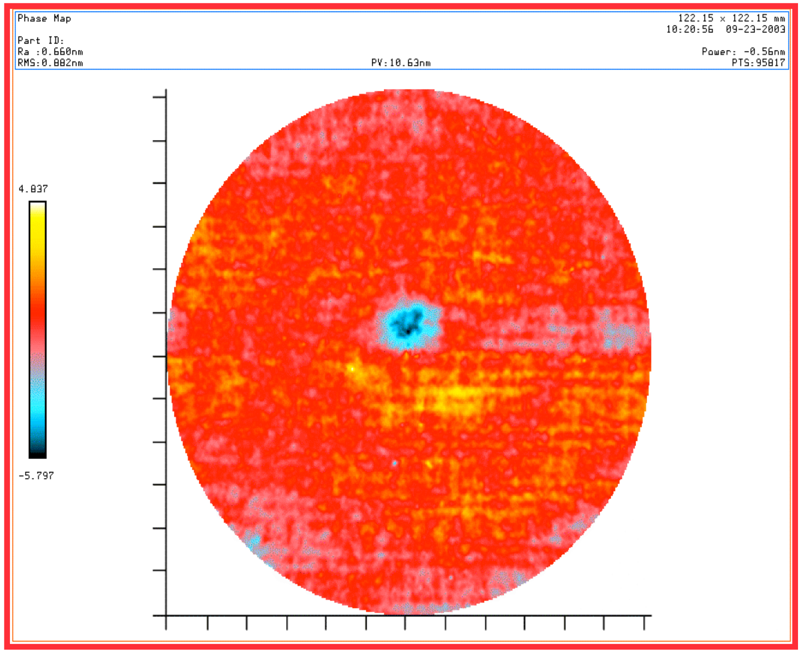
Slide stolen from R.Flaminio

Corrective coating from LMA



Phase Map
VBS03 face arriere
Part ID:apres recuit
Ra :2.696nm
RMS:3.332nm
PV:16.29nm
[redacted]
17:36:35 05-12-2003
Power: -1.35nm
PTS:75322

Before correction (∅120 mm)
3.3 nm R.M.S.
16 nm P.V.



Phase Map
Part ID:
Ra :0.660nm
RMS:0.882nm
PV:10.63nm
122.15 x 122.15 mm
10:20:56 09-23-2003
Power: -0.56nm
PTS:95817

After correction (∅120 mm)
0.98 nm R.M.S.
10 nm P.V.

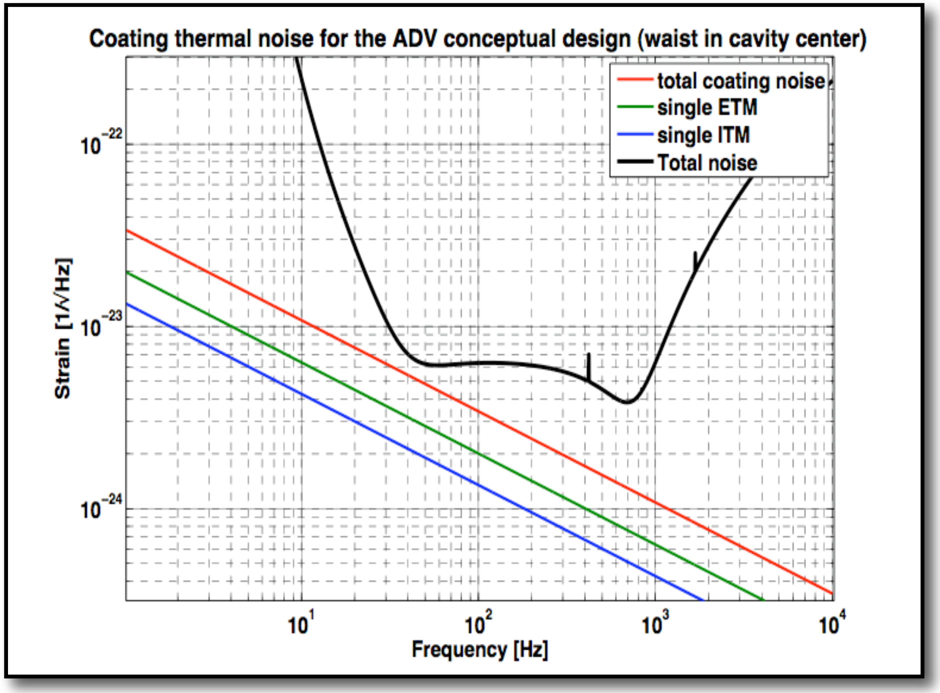
Symmetric ROCs of IM and EM ?

- Coating noise for ITM and ETM are different, due to their different number of coating layer:

Coating thickness

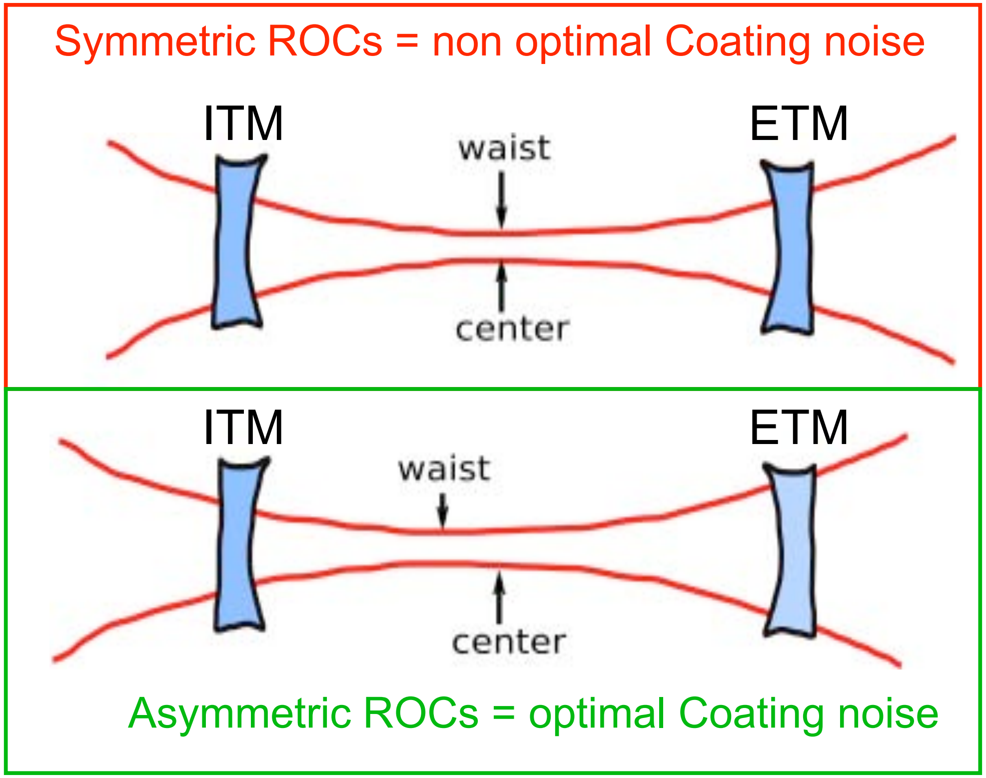
$$S_x(f) = \frac{4k_{\mathrm{B}}T}{\pi^2 f Y}\frac{d}{r_0^2}\left(\frac{Y'}{Y}\phi_{\parallel} + \frac{Y}{Y'}\phi_{\perp}\right)$$

- For equal beam size ETM has higher noise.


Coating thermal noise for the ADV conceptual design (waist in cavity center)

Optimal Waist Position

- In order to minimize the thermal noise we have to make the beam larger on ETM and smaller on ITM.
- Equivalent to moving the waist closer to ITM.
- Nice additional effect: the beam in the central area would be slightly smaller.



Symmetric ROCs = non optimal Coating noise

Asymmetric ROCs = optimal Coating noise

Cavity Stability and Choice of ROCs

- Definition of mode-non-degeneracy:
  - Gouy-phase shift of mode of order l+m:

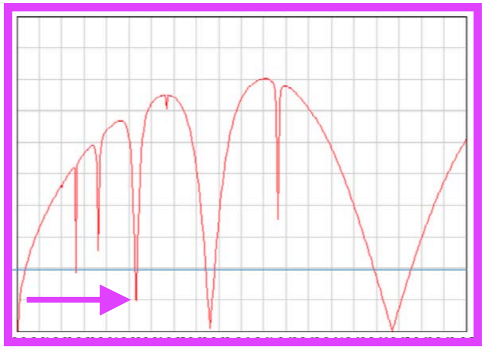
$$\phi_{l+m} = (l+m)\frac{1}{\pi}\arccos\sqrt{(1-\frac{L}{R_{c,i}})(1-\frac{L}{R_{c,e}})}.$$

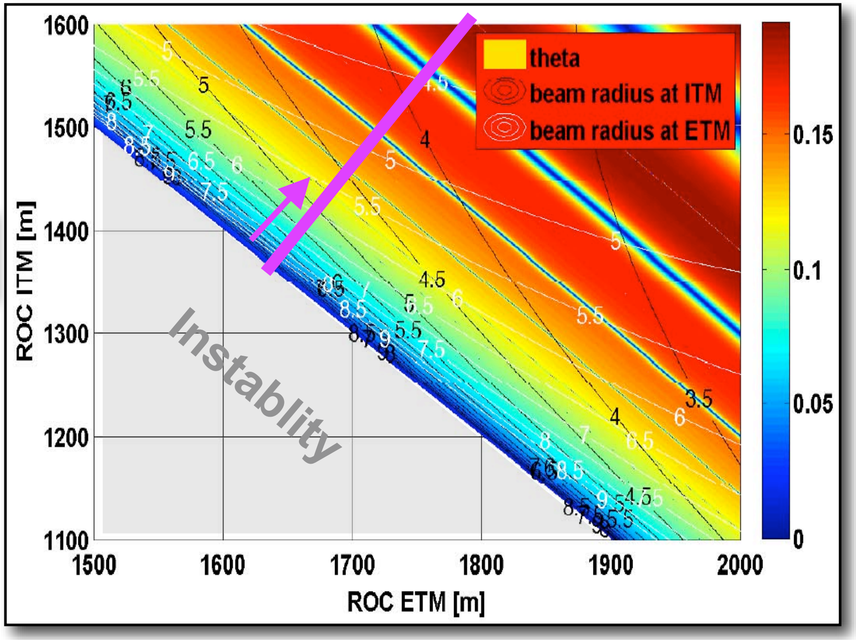
  - Mode-non-degeneracy for a single mode is:

$$\Psi_{l+m}(L,R_{c,i},R_{c,e}) = |\phi_{l+m} - \mathrm{round}(\phi_{l+m})|.$$

  - Figure of merit for combining all modes up to the order N:

$$\Theta_N(L,R_{c,i},R_{c,e}) = \frac{1}{\sqrt{\sum_{k=1}^{N}\frac{1}{\Psi_k^2}\frac{1}{k!}}}$$

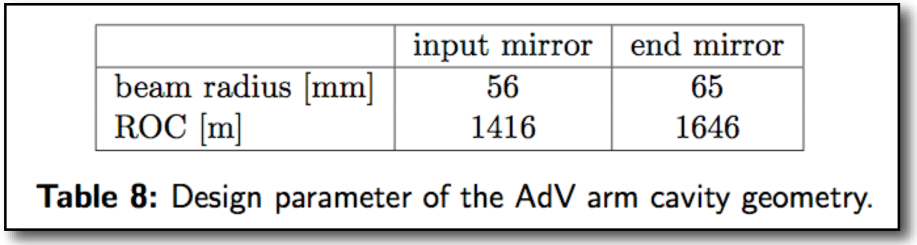




Choice of ROCs/beam size: Sensitivity vs Mode-non-degeneracy

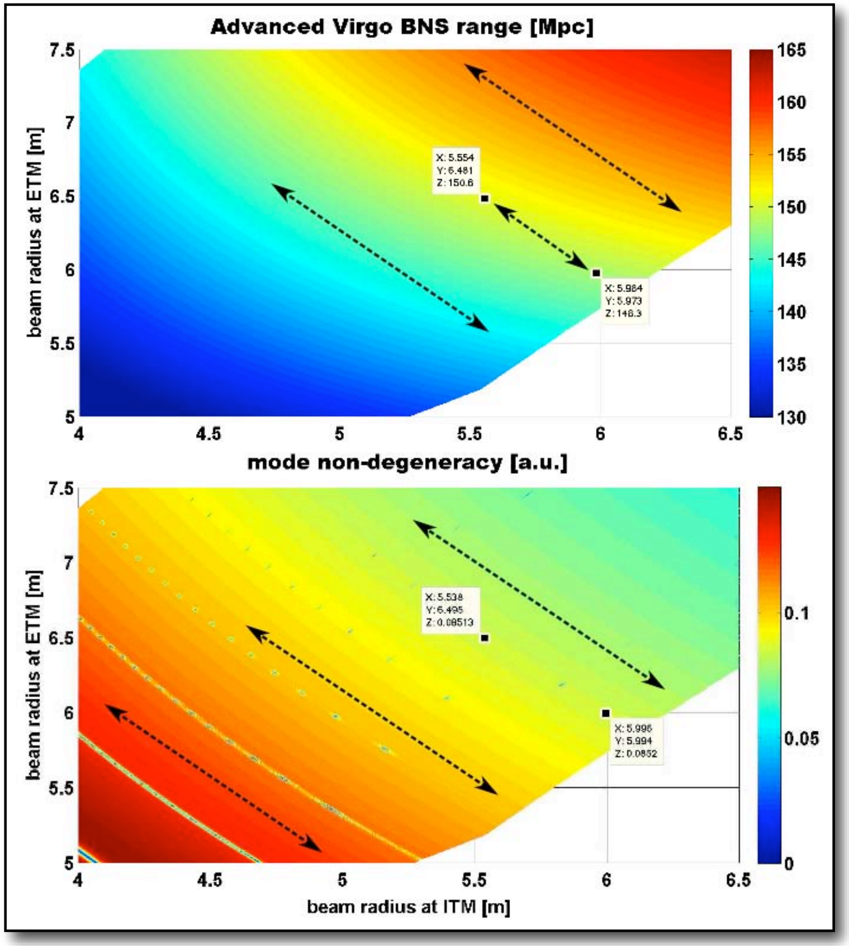
- In general mode-non-degeneracy and sensitivity go opposite.

- Asymmetric ROCs are beneficial:
  - For identical mode-non-degeneracy (parallel to arrows in lower plot) and even slightly increased senstivity we can reduce the beam size in the CITF from 6 to 5.5 cm.



	input mirror	end mirror
beam radius [mm]	56	65
ROC [m]	1416	1646

Table 8: Design parameter of the AdV arm cavity geometry.



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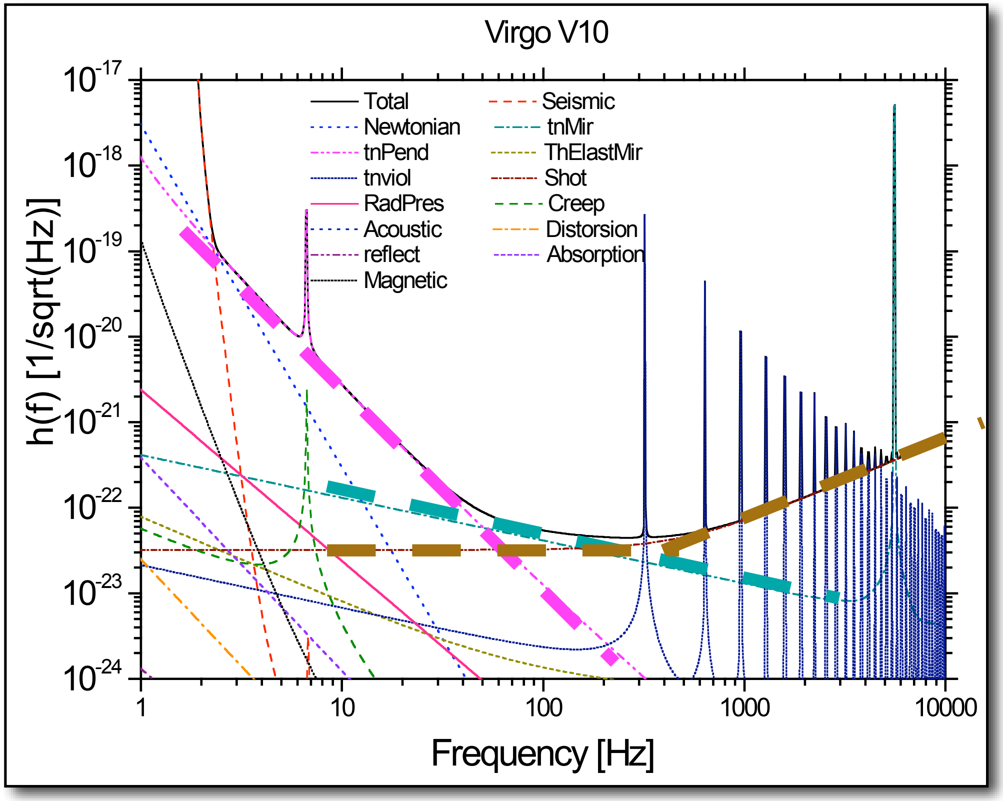


http://wwwcascina.virgo.infn.it/senscurve/

How can we reduce the shot noise contribution?

- Shot noise is proportional to sqrt(light power)
- Signal is directly proportional to light power
- In total our signal to shot noise ratio improves with sqrt(light power)
- Ways to increase the light power:
  - Bigger laser: Virgo = 20W, Advanced Virgo >165W
  - Higher arm cavity finesse
  - Stored light power: Virgo = 4kw, Advanced Virgo= 760kW

- Please note: Shot noise is only one of two components of the so-called quantum noise!

What is quantum noise?

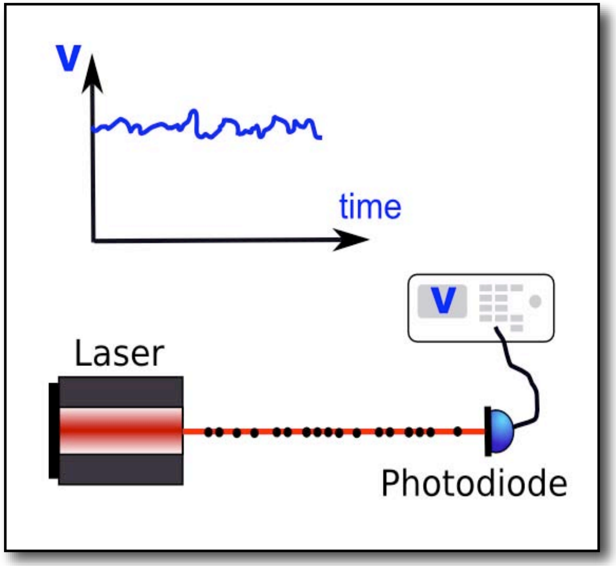
- Quantum noise is comprised of **photon shot noise** at high frequencies and **photon radiation pressure noise** at low frequencies.
- The photons in a laser beam are not equally distributed, but follow a Poisson statistic.

wavelength

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

optical power

Arm length



photon shot noise

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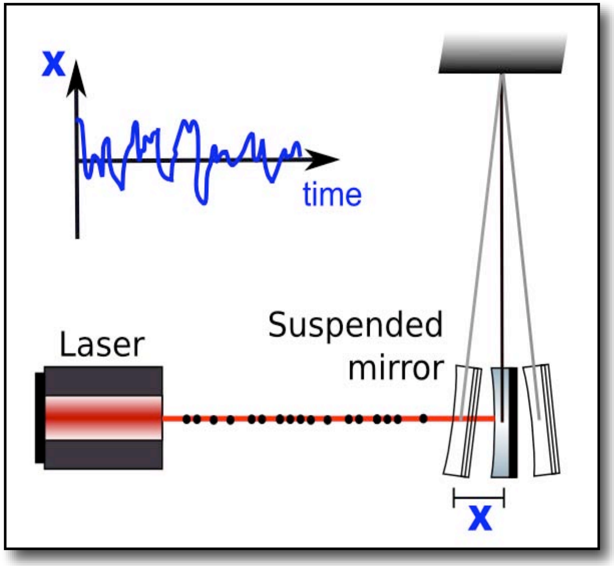


photon radiation pressure noise

wavelength

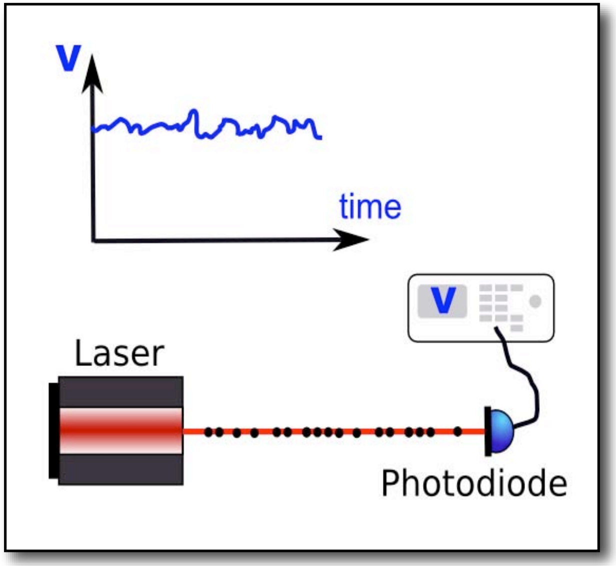
$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

optical
power

Mirror mass

Arm length

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



photon shot noise

The Standard Quantum Limit (SQL)

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

wavelength

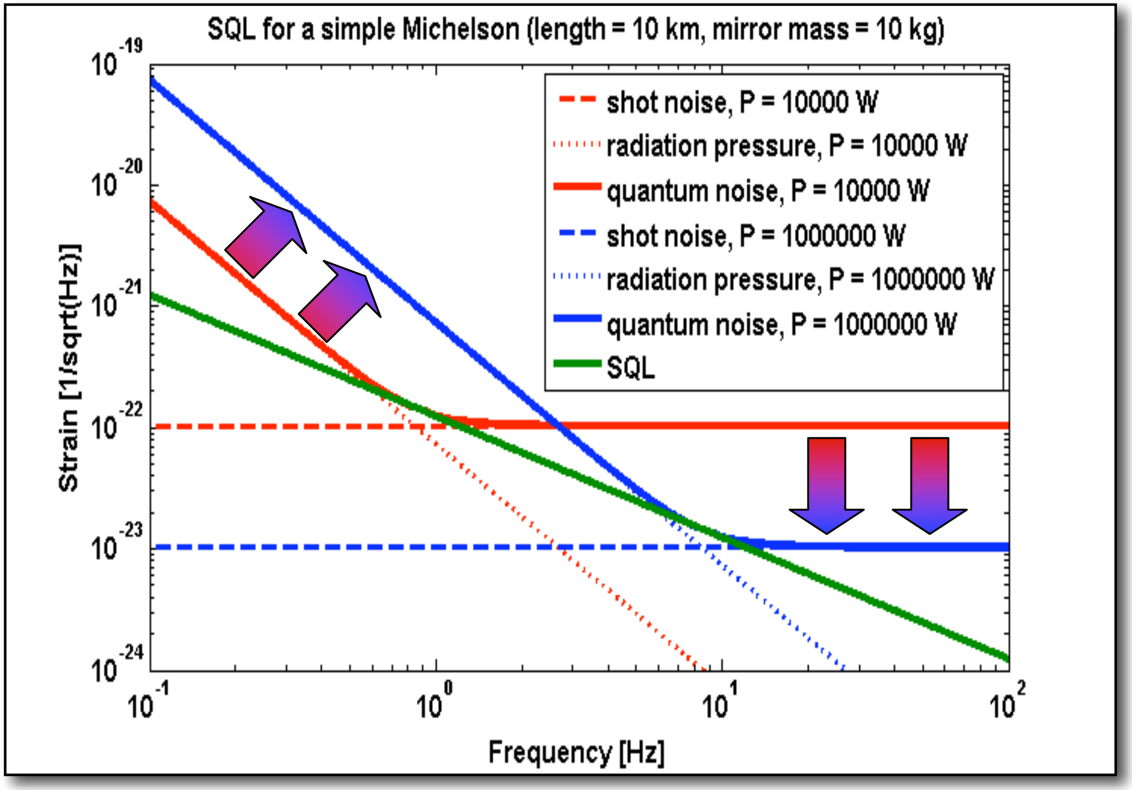
$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$

optical power

Arm length

Mirror mass

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



- The SQL is the minimal sum of shot noise and radiation pressure noise.
- Using a classical quantum measurement the SQL represents the lowest achievable noise.

V.B. Braginsky and F.Y. Khalili: Rev. Mod. Phys. 68 (1996)

The Standard Quantum Limit (SQL)

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

wavelength

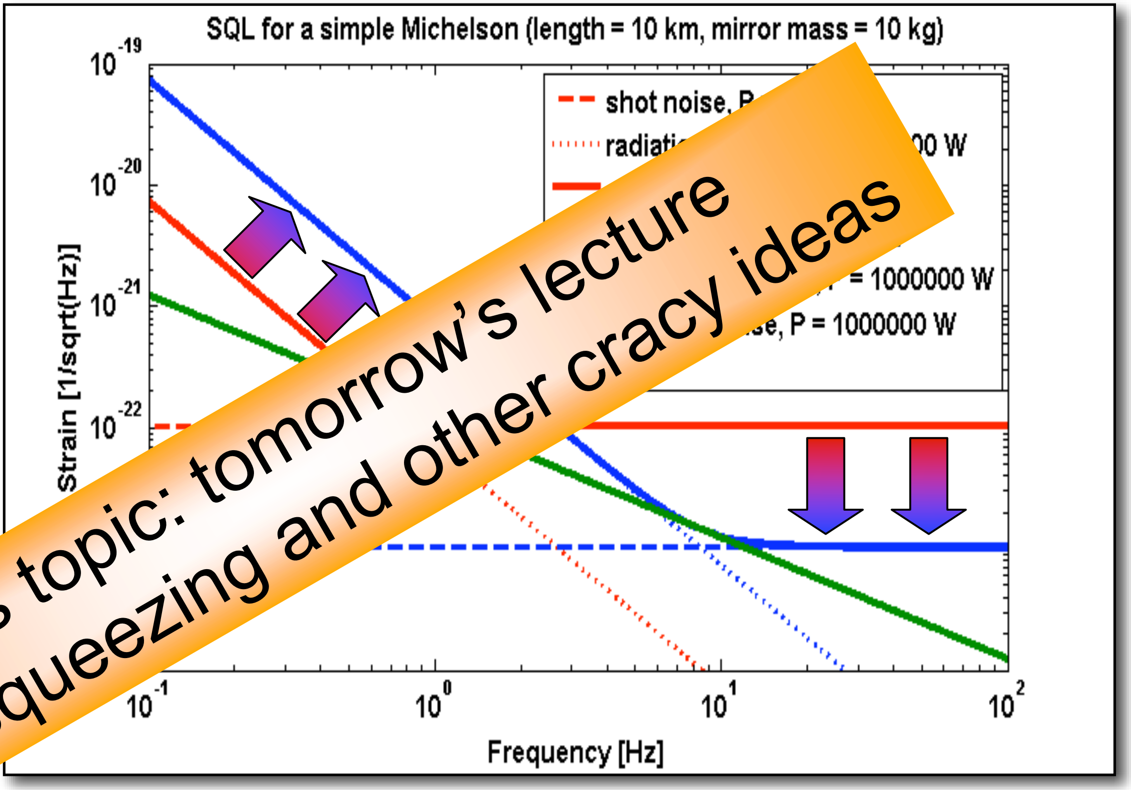
$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

optical power

Arm length

Mirror mass

$$h_{\mathrm{rp}}(f) = \frac{1}{mf^2L}\sqrt{\frac{\hbar P}{}}$$



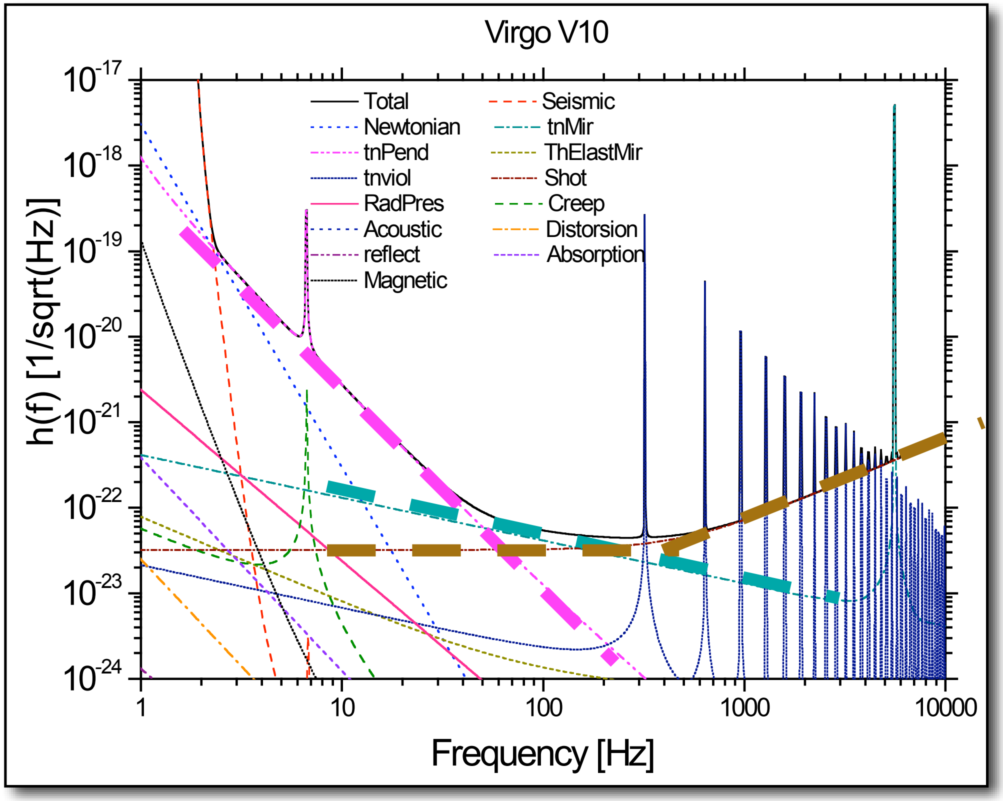
More on this topic: tomorrow's lecture on QND, squeezing and other cracy ideas

- The SQL is al sum of shot noise and radiation pressure noise.
- Using a class l quantum measurement the SQL represents the lowest achievable noise.

V.B. Braginsky and F.Y. Khalili: Rev. Mod. Phys. 68 (1996)

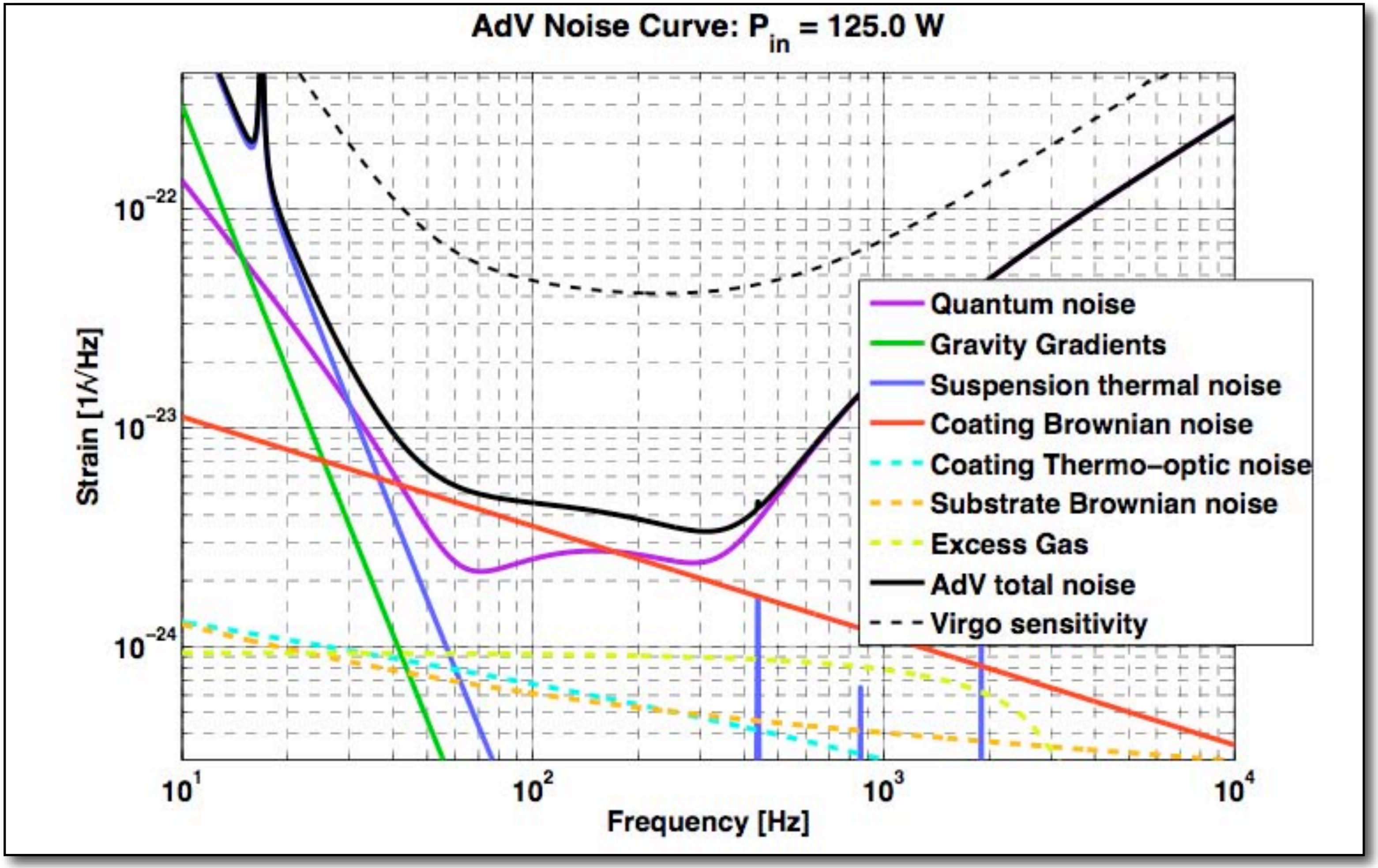
Which are the main fundamental noise sources limiting Virgo ?

- Suspension thermal noise (low frequencies)
- Mirror thermal noise (mid frequencies)
- Shot noise (high frequencies)



http://wwwcascina.virgo.infn.it/senscurve/

Advanced Virgo sensitivity



Overview

What do we need to change to make our instruments 2nd Generation observatories ?

- Details of 2nd Generation interferometer: Example Advanced Virgo
  - Noise limits: Suspension thermal noise, Coating Brownian noise, Quantum noise
  - Important Techniques: Thermal compensation, NDRC, DC-readout
  - Sensitivity optimisation and observation prospects
- Other 2nd Generation GW Observatories
  - Advanced LIGO, LGCT, GEO-HF

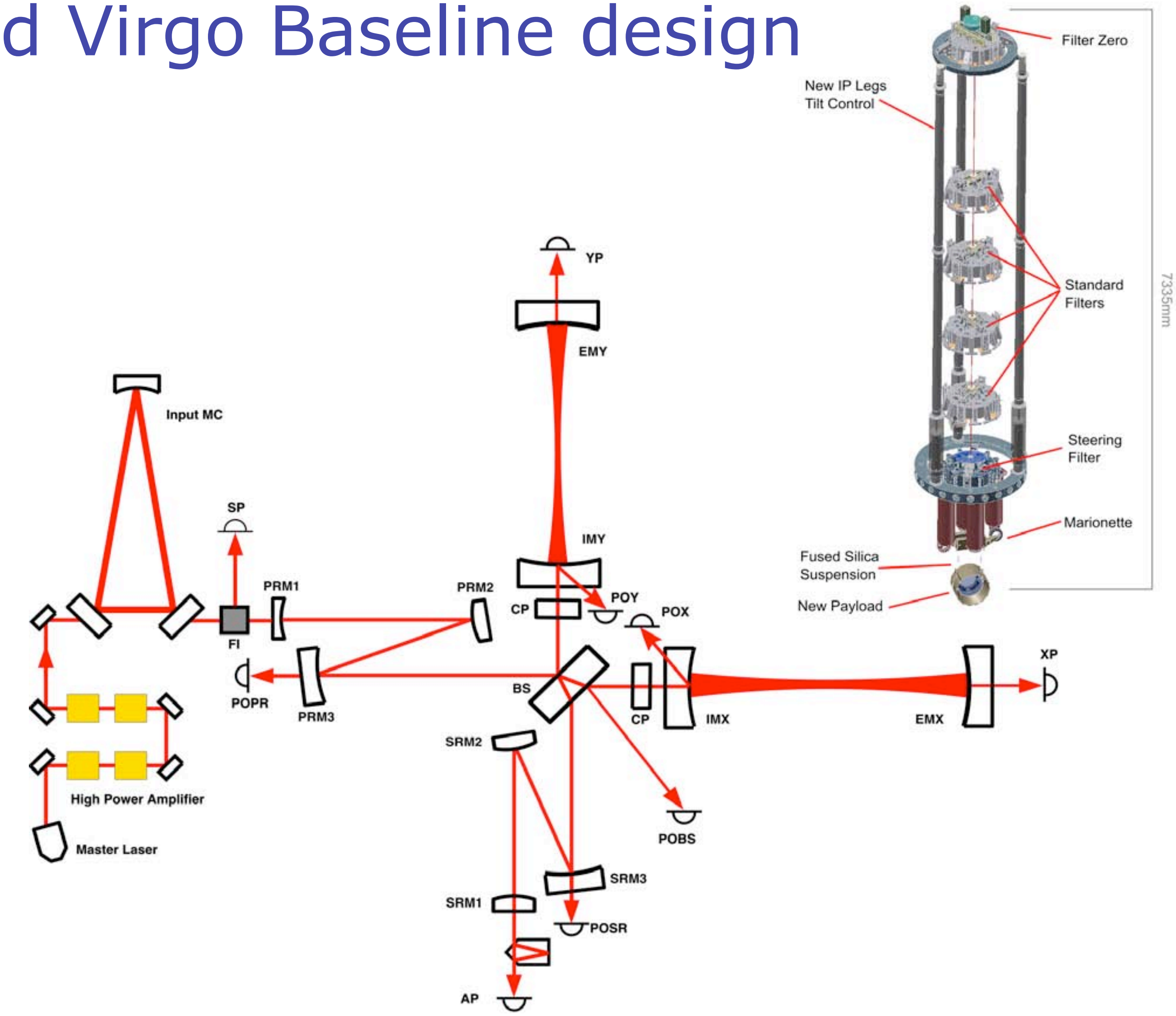
Techniques to make the interferometer more robust.

Just that you have heard about them …

What will a 3rd Generation Interferometer look like ?

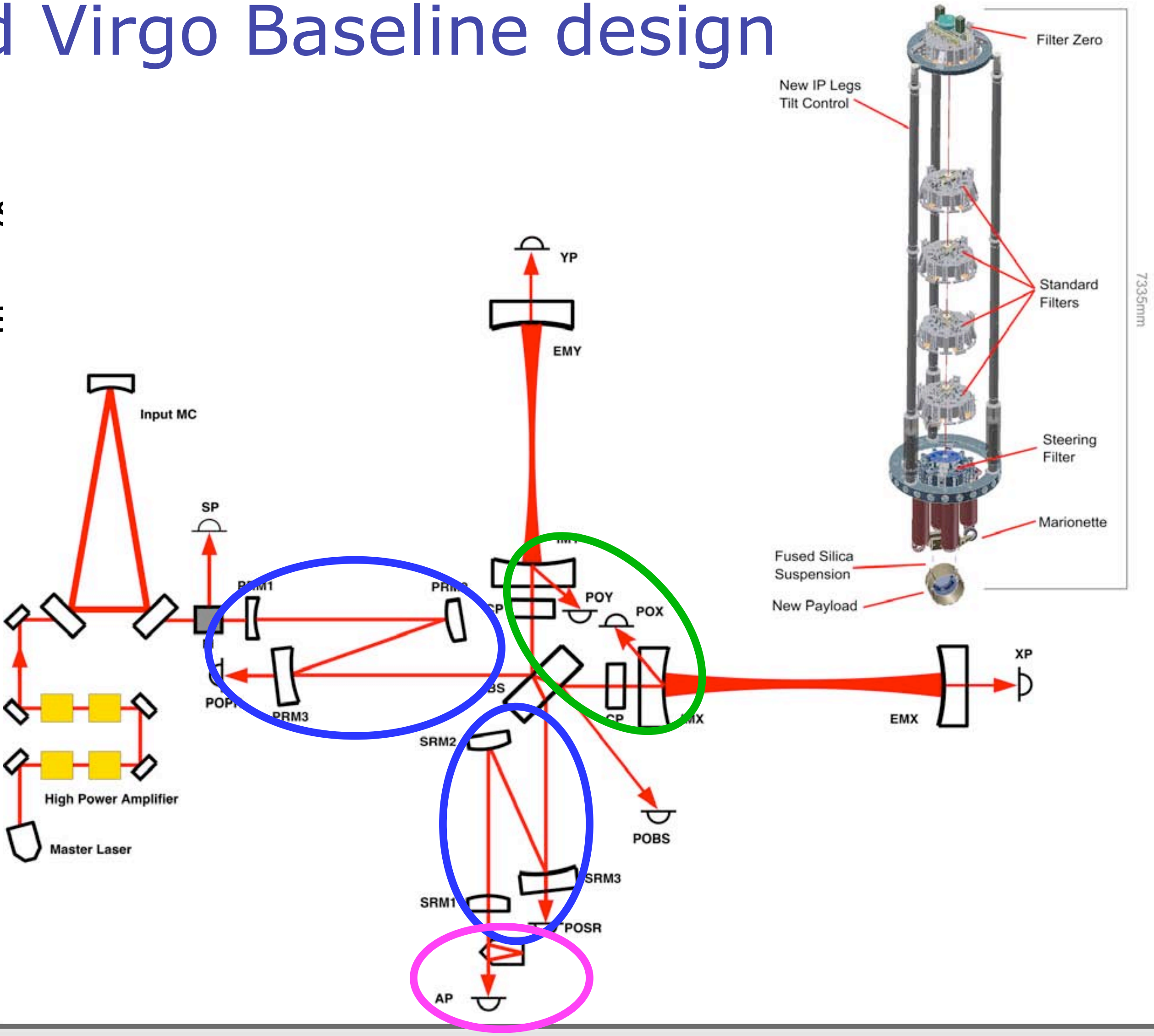
- How to build the Einstein Telescope (ET)?
  - Geometry and shape
  - How to reach the sensitivity?

Advanced Virgo Baseline design



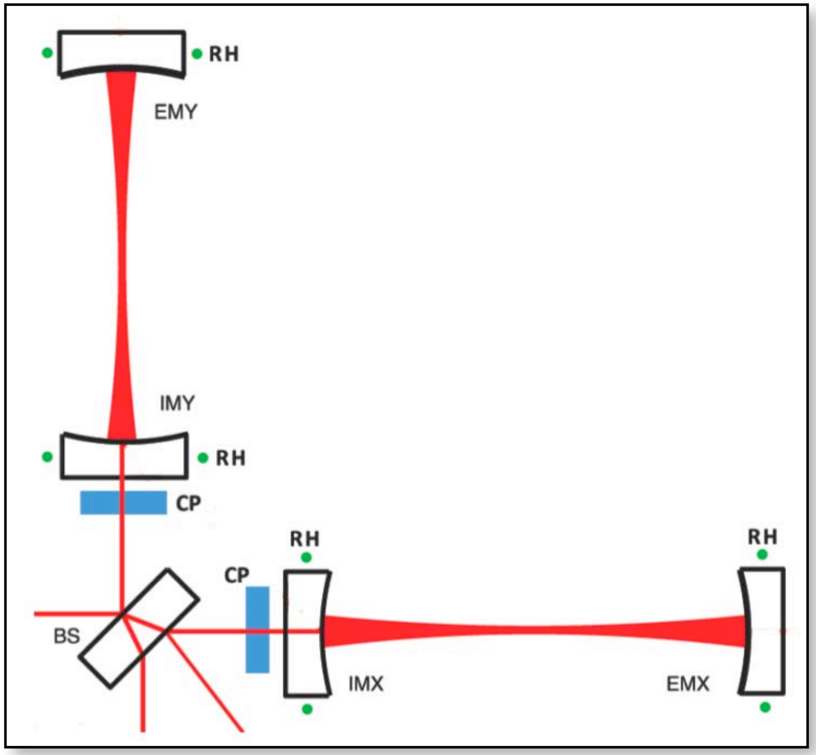
Advanced Virgo Baseline design

- Three examples of imprtant techniques to improve the detector robustness
  - Thermal compensation
  - Non-degenerate Recycling cavities
  - DC-readout



Thermal compensation

- Ring heater to change the curvature of each mirror:
  - Introducing temperature gradient in mirror substrate.
  - Thermal expansion bends the mirror.
- CO_2 act on compensation plates:
  - Relative intensity noise (radition pressure) prohibits to act directly on mirror.
  - Introducing additional silica plates and use the temperature dependent index of refraction to correct wavefront curvature.



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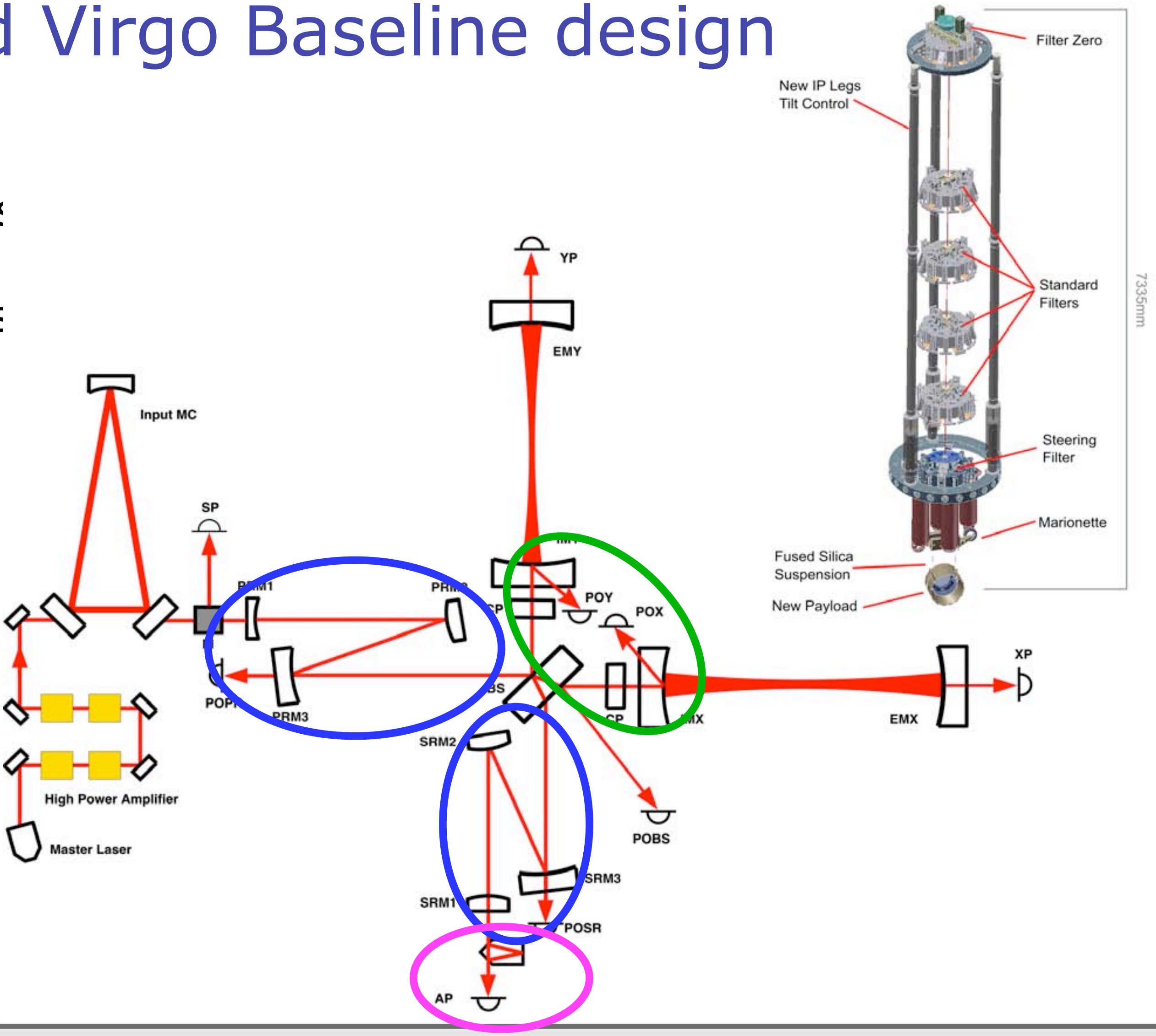
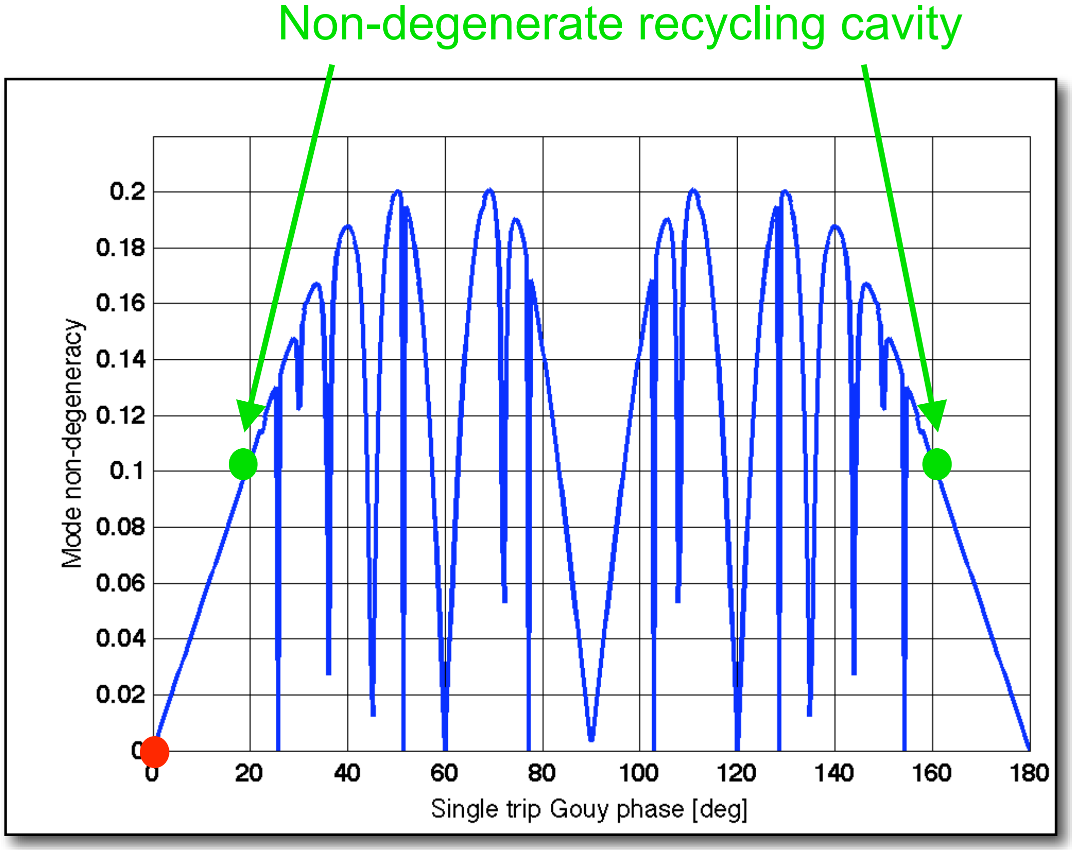


Non-degenerate Recycling cavities

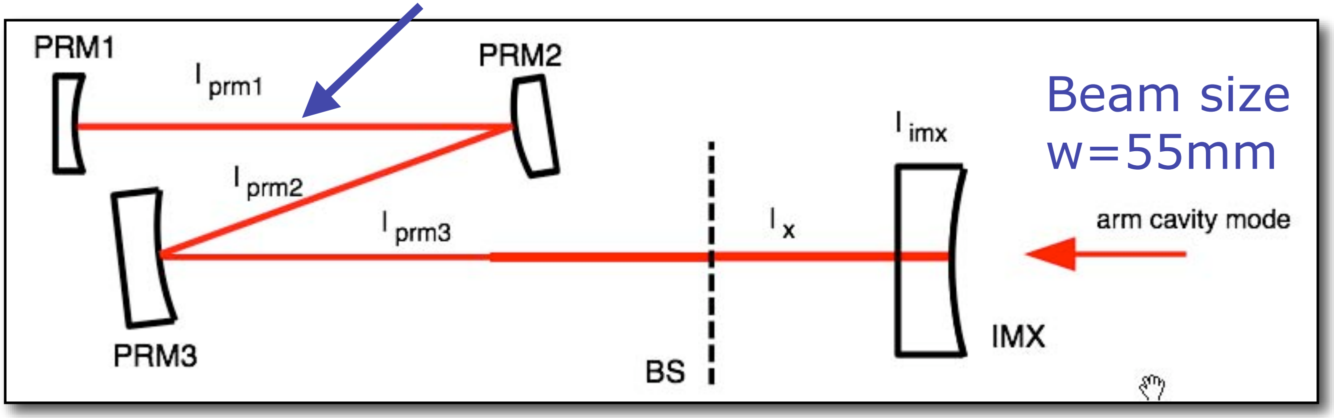
- **Motivation:** Thermal effects or misalignments scatter light into higher-order modes so that optical signal is lost. Non-degenerate cavities reduce this effect.

- Commissioning experience shows that degenerate cavities cause problems for control signals. Y. Pan showed in 2006 that also GW signal is lost.



A possible optical layout

- Design of Non-degenerate Recycling Cavity

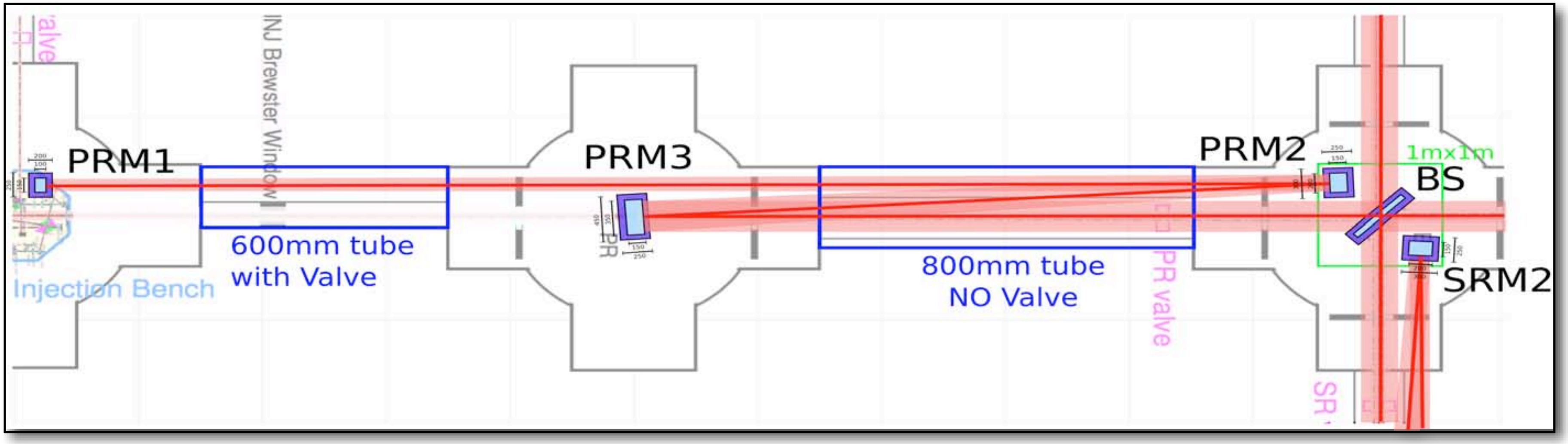


Beam waist

Beam size
w=55mm

- Proper design of the non-degenerate Recycling Cavity is rather complicated …
- Here I concentrate on a single aspect: Infrastructure

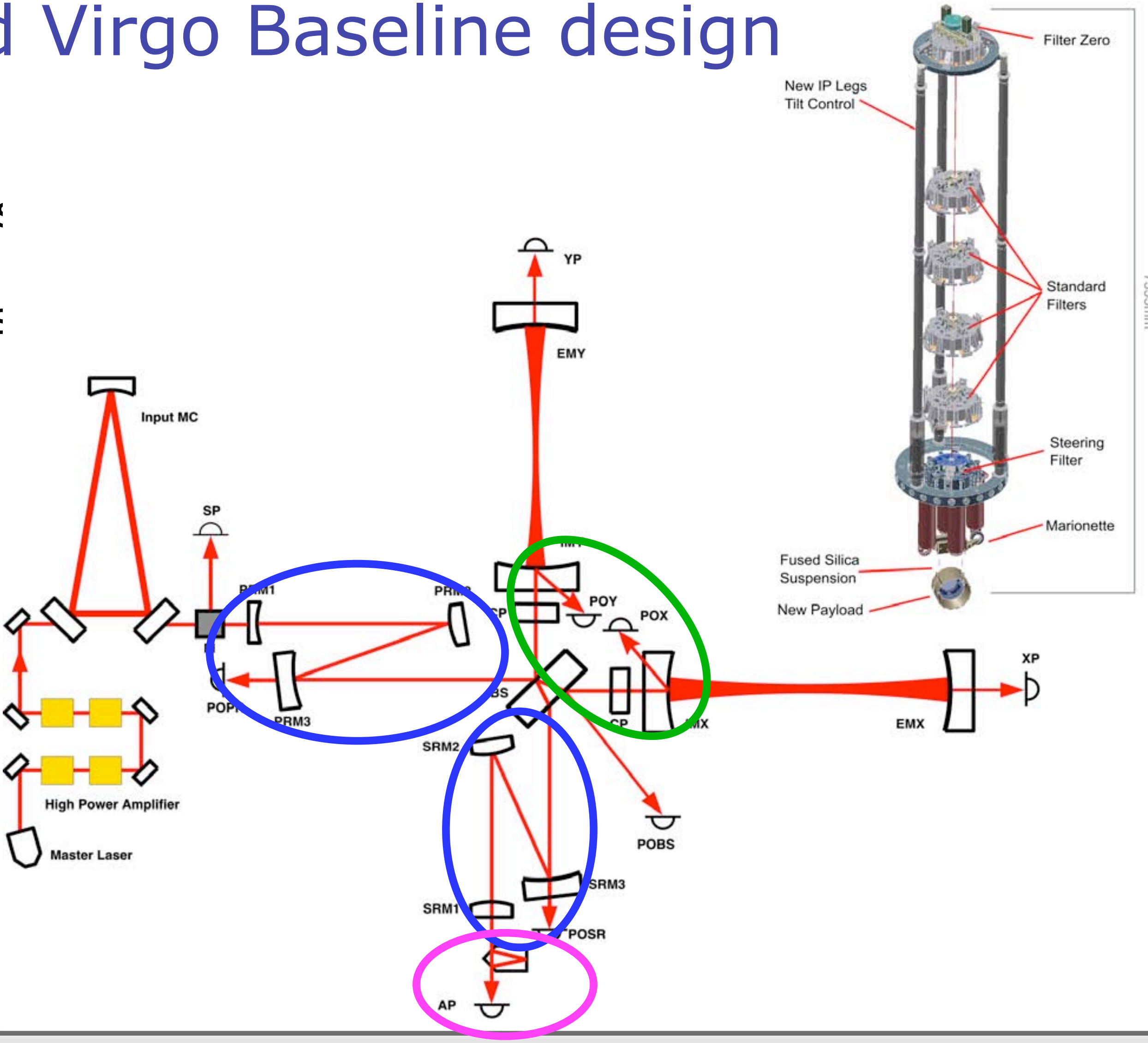
Advanced Virgo Baseline design



- Folded beam to increase recycling cavity length
- PRM3 and PRM2 are (de)focusing elements.
- Infrastructure problems:
  - Need to suspend more than 1 optic per vacuum tower
  - Need large vacuum tubes to fit (larger) folded beams
  - Non perpendicular angle of incidence = losses due to astigmatism

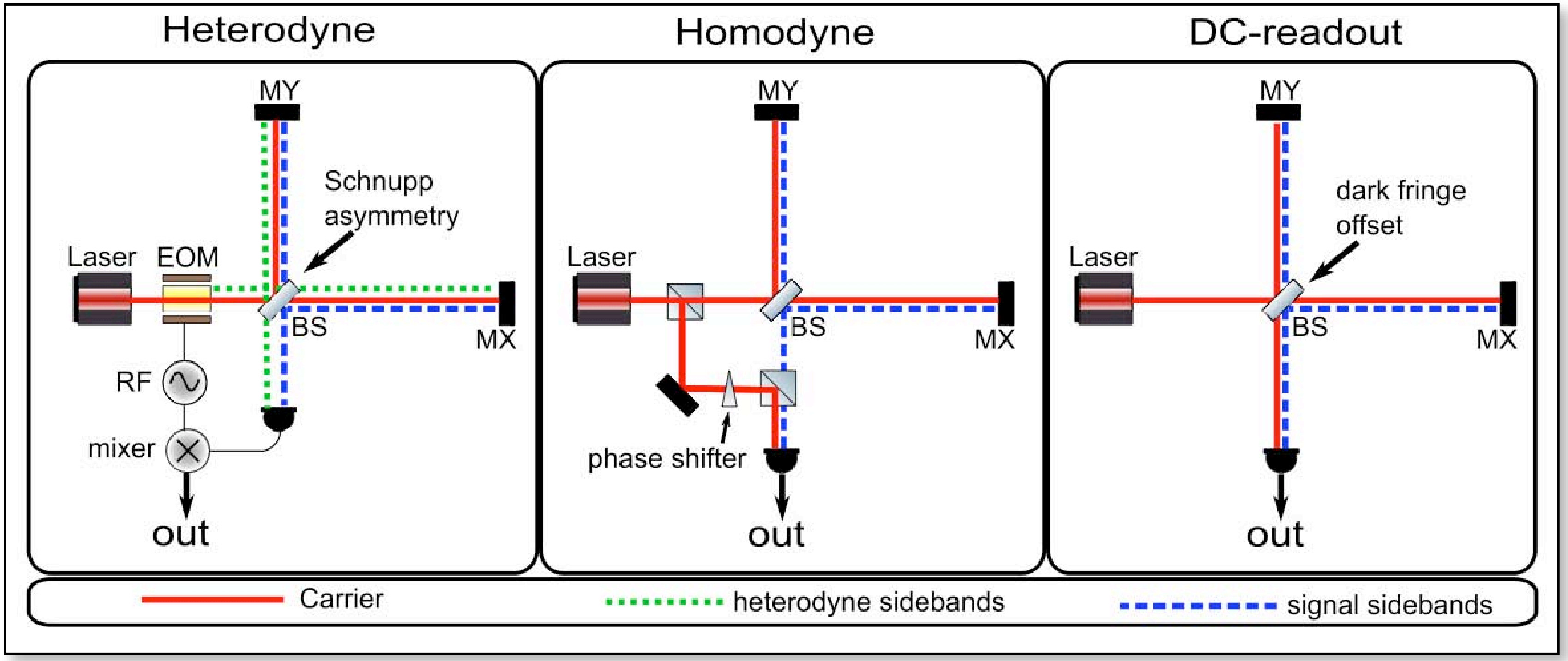
Advanced Virgo Baseline design

- Three examples of imprtant techniques to improve the detector robustness
  - Thermal compensation
  - Non-degenerate Recycling cavities
  - DC-readout

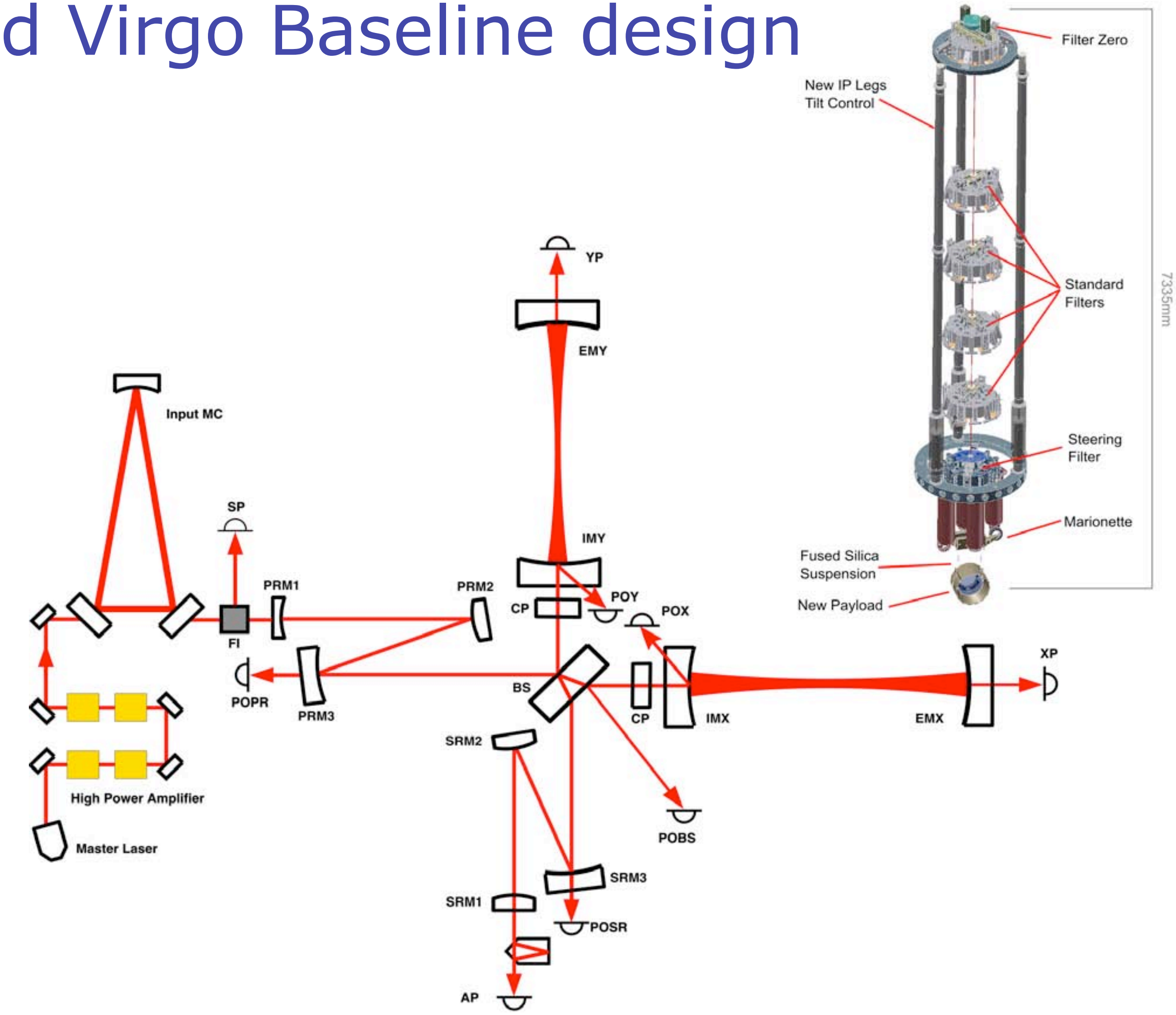


DC-readout

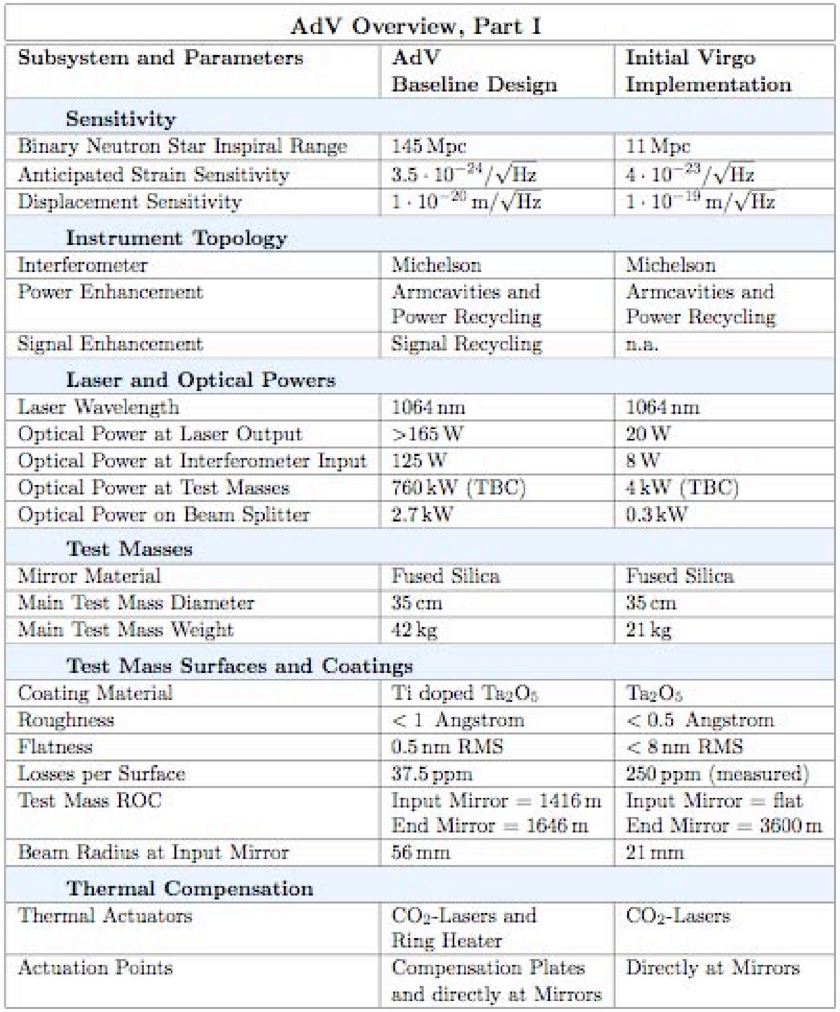
- Initial Virgo uses heterodyne readout for the GW signal.
- Advanced Virgo will use DC-readout (a special case of homodyne detection).



Advanced Virgo Baseline design

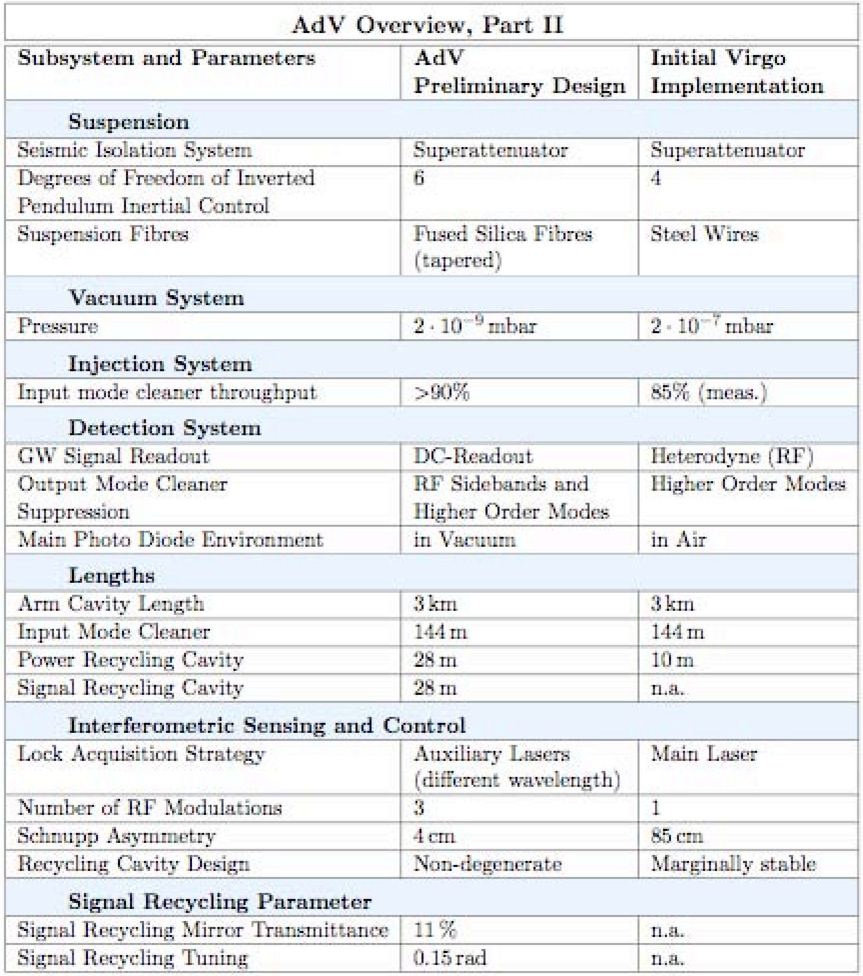


Advanced Virgo: Executive Summary



AdV Overview, Part I

Subsystem and Parameters	AdV Baseline Design	Initial Virgo Implementation
Sensitivity		
Binary Neutron Star Inspiral Range	145 Mpc	11 Mpc
Anticipated Strain Sensitivity	$3.5 \cdot 10^{-24}/\sqrt{\mathrm{Hz}}$	$4 \cdot 10^{-23}/\sqrt{\mathrm{Hz}}$
Displacement Sensitivity	$1 \cdot 10^{-20}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$	$1 \cdot 10^{-19}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$
Instrument Topology		
Interferometer	Michelson	Michelson
Power Enhancement	Armcavities and Power Recycling	Armcavities and Power Recycling
Signal Enhancement	Signal Recycling	n.a.
Laser and Optical Powers		
Laser Wavelength	1064 nm	1064 nm
Optical Power at Laser Output	>165 W	20 W
Optical Power at Interferometer Input	125 W	8 W
Optical Power at Test Masses	760 kW (TBC)	4 kW (TBC)
Optical Power on Beam Splitter	2.7 kW	0.3 kW
Test Masses		
Mirror Material	Fused Silica	Fused Silica
Main Test Mass Diameter	35 cm	35 cm
Main Test Mass Weight	42 kg	21 kg
Test Mass Surfaces and Coatings		
Coating Material	Ti doped Ta_2O_5	Ta_2O_5
Roughness	< 1 Angstrom	< 0.5 Angstrom
Flatness	0.5 nm RMS	< 8 nm RMS
Losses per Surface	37.5 ppm	250 ppm (measured)
Test Mass ROC	Input Mirror = 1416 m End Mirror = 1646 m	Input Mirror = flat End Mirror = 3600 m
Beam Radius at Input Mirror	56 mm	21 mm
Thermal Compensation		
Thermal Actuators	CO_2-Lasers and Ring Heater	CO_2-Lasers
Actuation Points	Compensation Plates and directly at Mirrors	Directly at Mirrors



AdV Overview, Part II

Subsystem and Parameters	AdV Preliminary Design	Initial Virgo Implementation
Suspension		
Seismic Isolation System	Superattenuator	Superattenuator
Degrees of Freedom of Inverted Pendulum Inertial Control	6	4
Suspension Fibres	Fused Silica Fibres (tapered)	Steel Wires
Vacuum System		
Pressure	$2 \cdot 10^{-9}$ mbar	$2 \cdot 10^{-7}$ mbar
Injection System		
Input mode cleaner throughput	>90%	85% (meas.)
Detection System		
GW Signal Readout	DC-Readout	Heterodyne (RF)
Output Mode Cleaner Suppression	RF Sidebands and Higher Order Modes	Higher Order Modes
Main Photo Diode Environment	in Vacuum	in Air
Lengths		
Arm Cavity Length	3 km	3 km
Input Mode Cleaner	144 m	144 m
Power Recycling Cavity	28 m	10 m
Signal Recycling Cavity	28 m	n.a.
Interferometric Sensing and Control		
Lock Acquisition Strategy	Auxiliary Lasers (different wavelength)	Main Laser
Number of RF Modulations	3	1
Schnupp Asymmetry	4 cm	85 cm
Recycling Cavity Design	Non-degenerate	Marginally stable
Signal Recycling Parameter		
Signal Recycling Mirror Transmittance	11 %	n.a.
Signal Recycling Tuning	0.15 rad	n.a.

Overview

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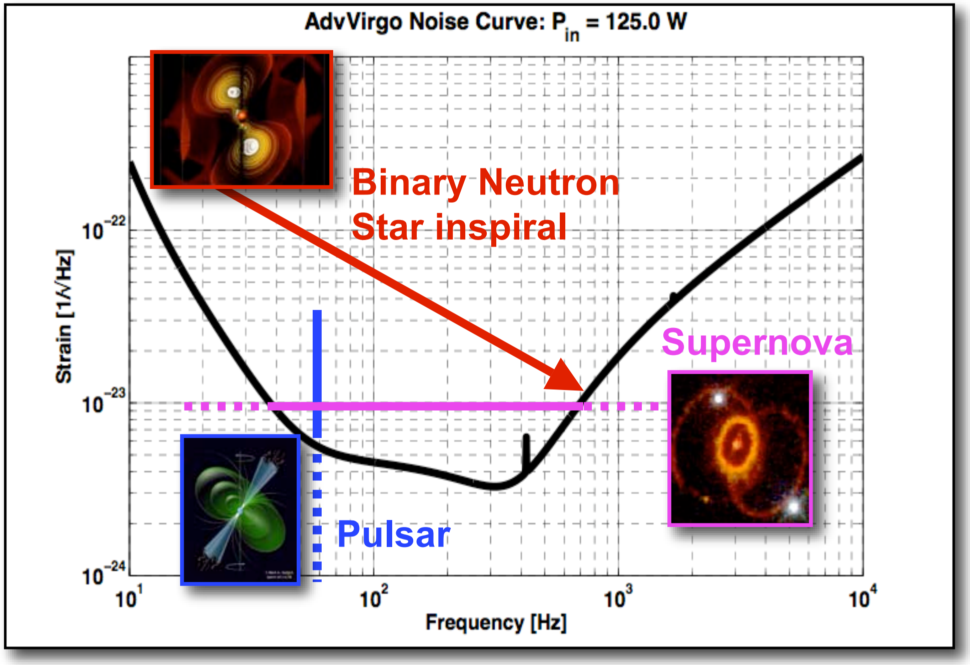
Signal Recycling: Possibility for tunable GW microphones

What will a 3rd Generation Interferometer look like ?

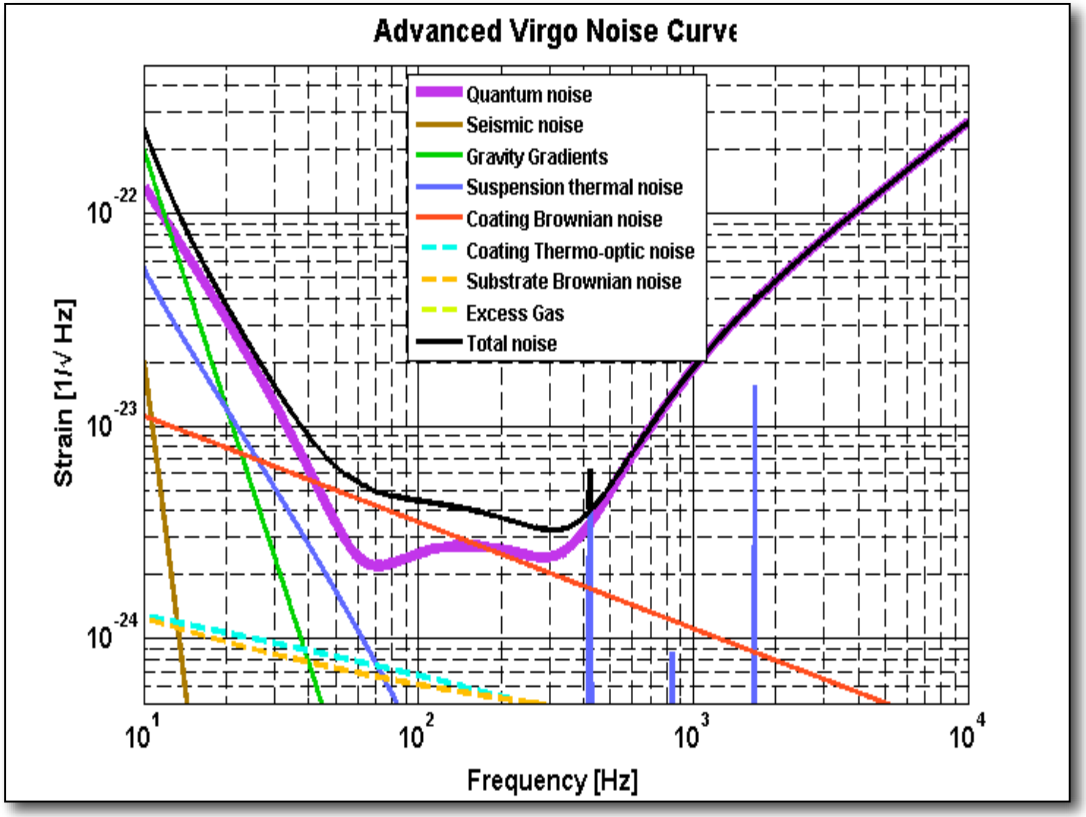
- How to build the Einstein Telescope (ET)?
  - Geometry and shape
  - How to reach the sensitivity?

How to listen to the Universe?

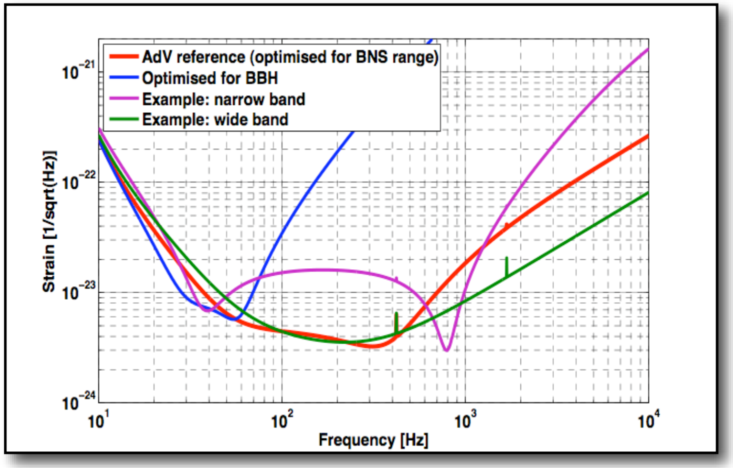


- Advanced Virgo is a hyper-sensitivity microphone to listen to the Universe.
- Each astrophysical source has its own sound or tone.
- This microphone can be tuned ‘similar’ to a radio receiver.

Fundamental noise limits for Advanced Virgo

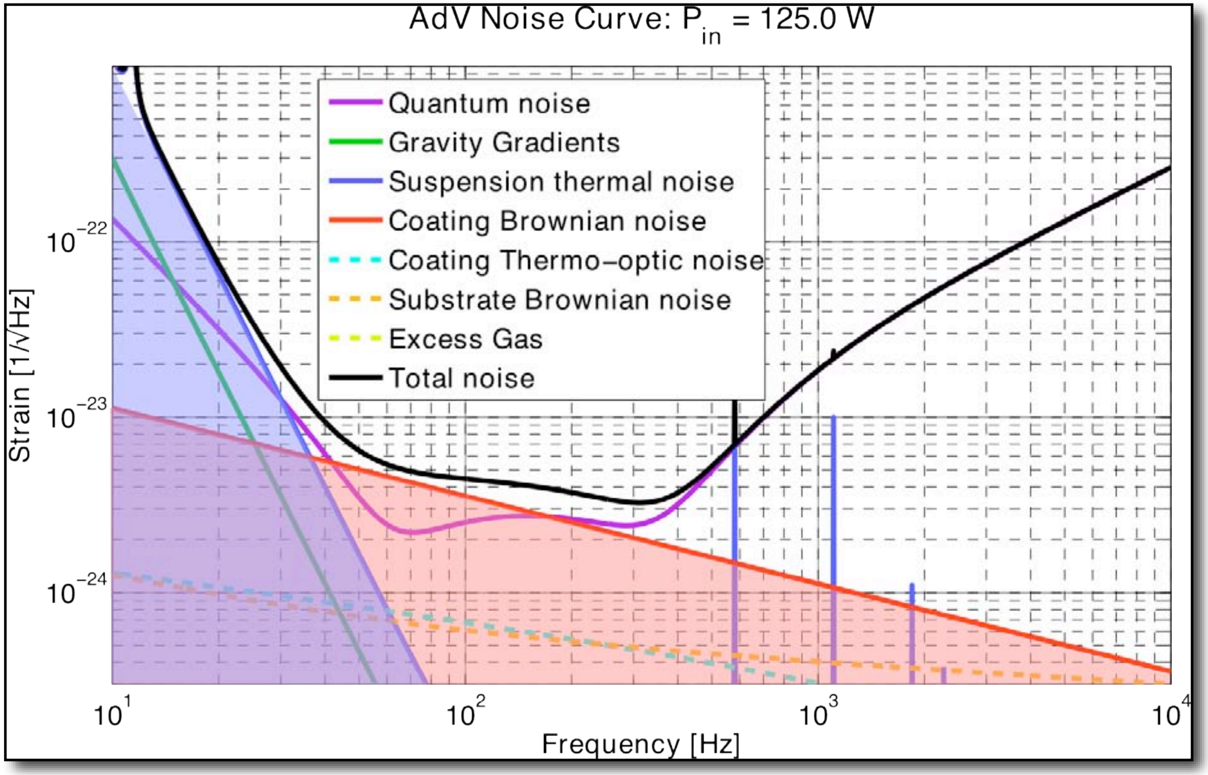


- Advanced Virgo will be limited by **quantum noise** at nearly all frequencies of interest.



- **GOAL: Optimise quantum noise for maximal science output.**

Limits of the optimization



- Our optimisation is limited by Coating thermal noise and Suspension thermal noise.
- **Quantum noise to be optimised!**

In order to understand the ‘Resonant Sideband Extraction’ of Advanced Virgo it is useful to first have a look at a simpler example:

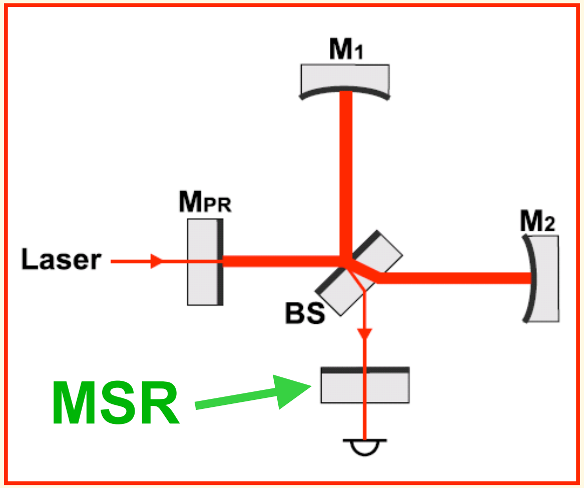
Signal Recycling in GEO600

- GEO600 is so far the only detector using Signal Recycling.
- Signal Recycling can beat the SQL.
- All advanced interferometers will use Signal Recycling !!
- Signal Recycling is easy to understand if you just think of it as an additional resonator for the GW-signal inside the ineterferometer.

Signal-Recycling in short

An additional recycling mirror (MSR) at the dark port allows:

- **enhancing the GW signal**
- **shaping the detector response**

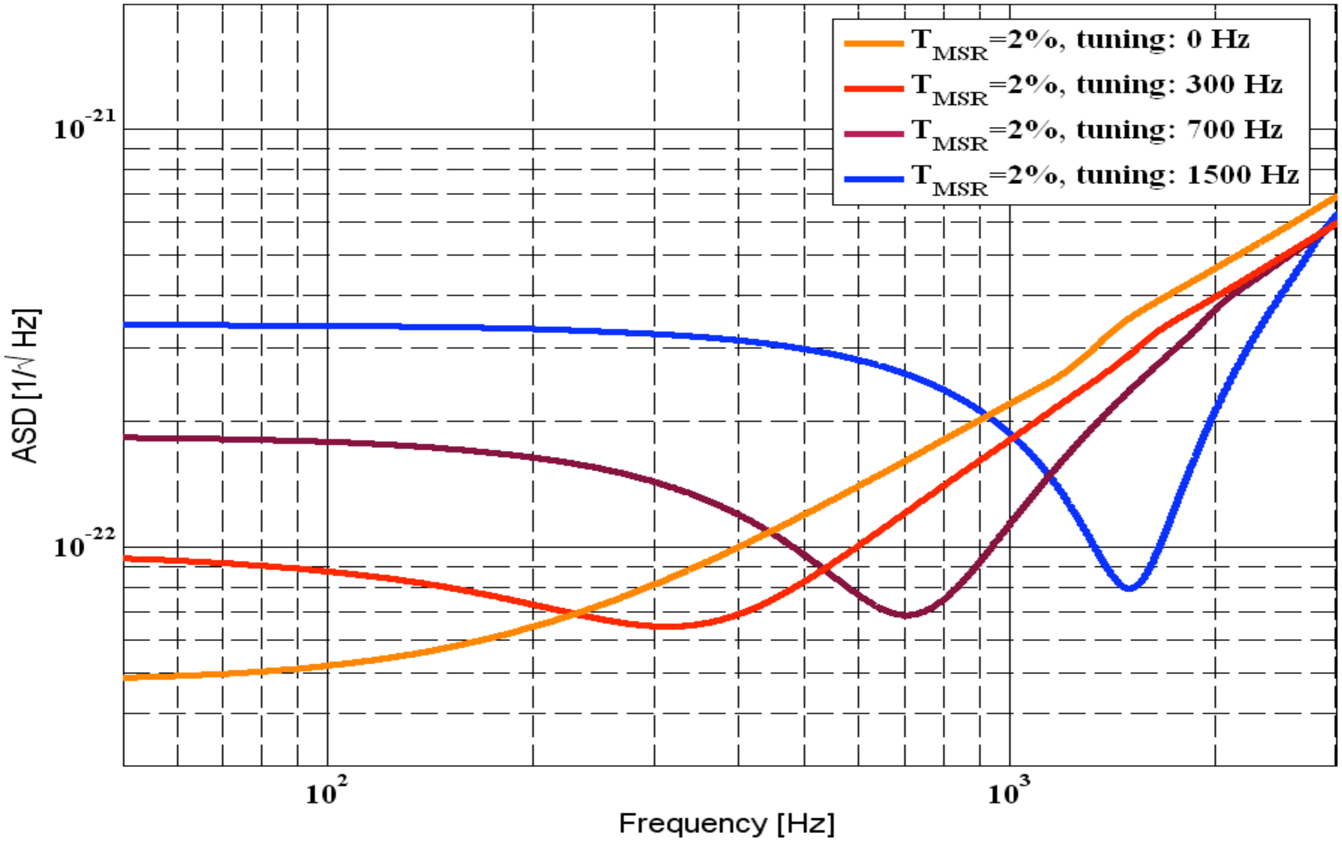


Two main parameters:

- **Bandwidth** (of the SR resonance) → broadband / narrowband
- **Tuning** (Fourier frequency of the SR resonance) → tuned / detuned

Tuning of Signal-Recycling

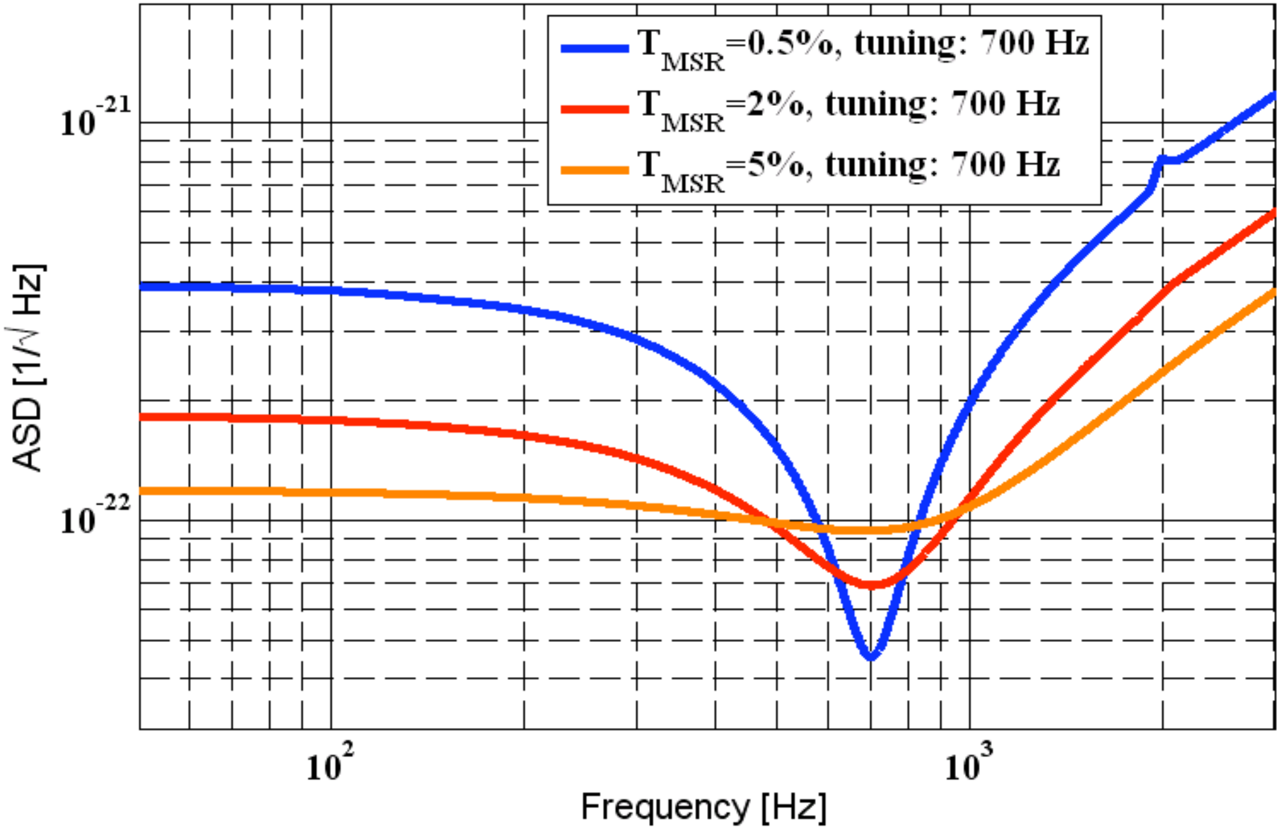
Shot noise for GEO600 with a light power of 1.8 kW @ beam splitter



The tuning of the Signal-Recycling resonance is determined by the microscopic position of the Signal Recycling mirror.

Bandwidth of Signal-Recycling

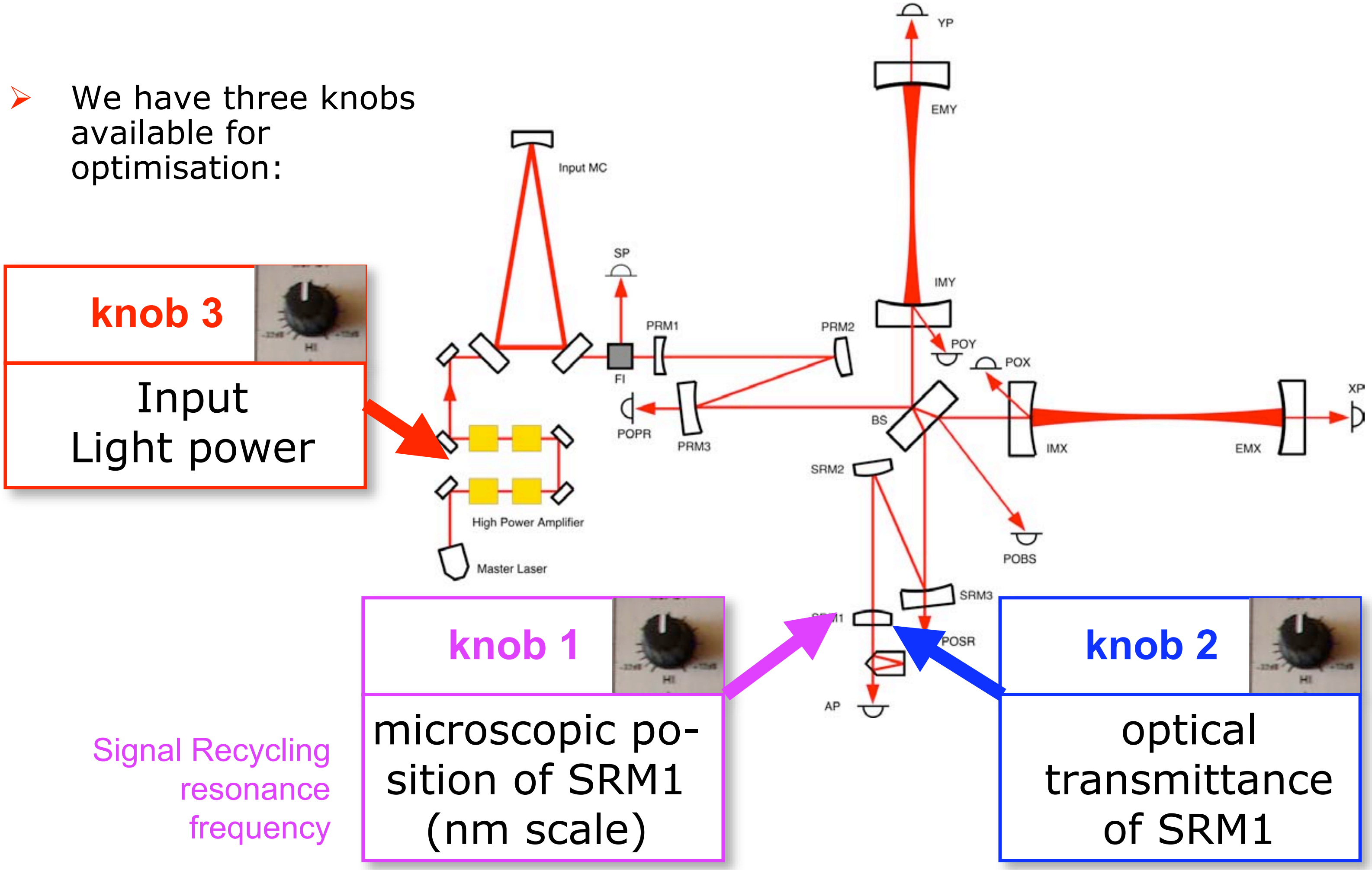
Shot noise for GEO600 with a light power of 10 kW @ beam splitter



The bandwidth of the Signal-Recycling resonance is determined by the reflectivity of Signal Recycling mirror.

Quantum noise knops in Advanced Virgo

- We have three knobs available for optimisation:



knob 3

Input Light power

knob 1

microscopic position of SRM1 (nm scale)

knob 2

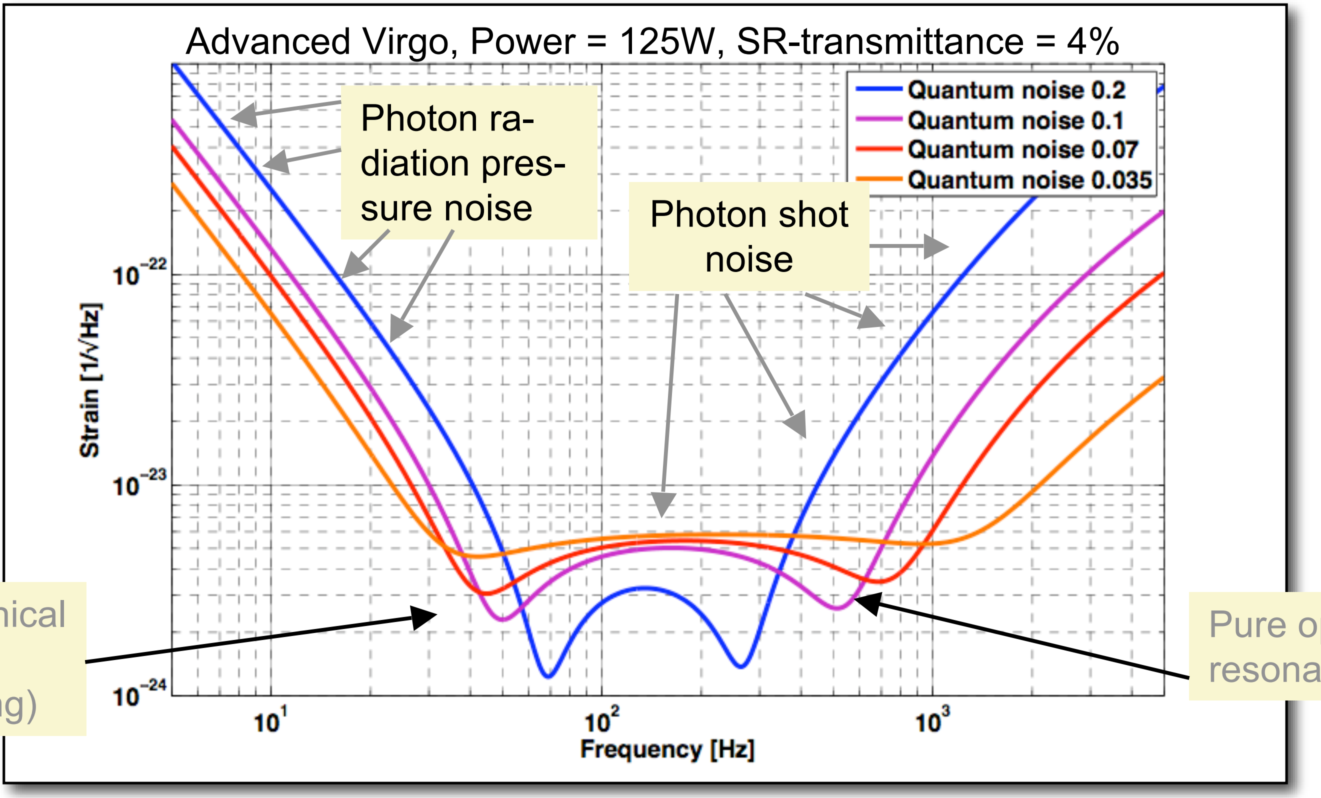
optical transmittance of SRM1

Signal Recycling resonance frequency

Signal Recycling bandwidth

Optimization Parameter 1: Signal-Recycling (de)tuning

knob 1



Photon radiation pressure noise

Photon shot noise

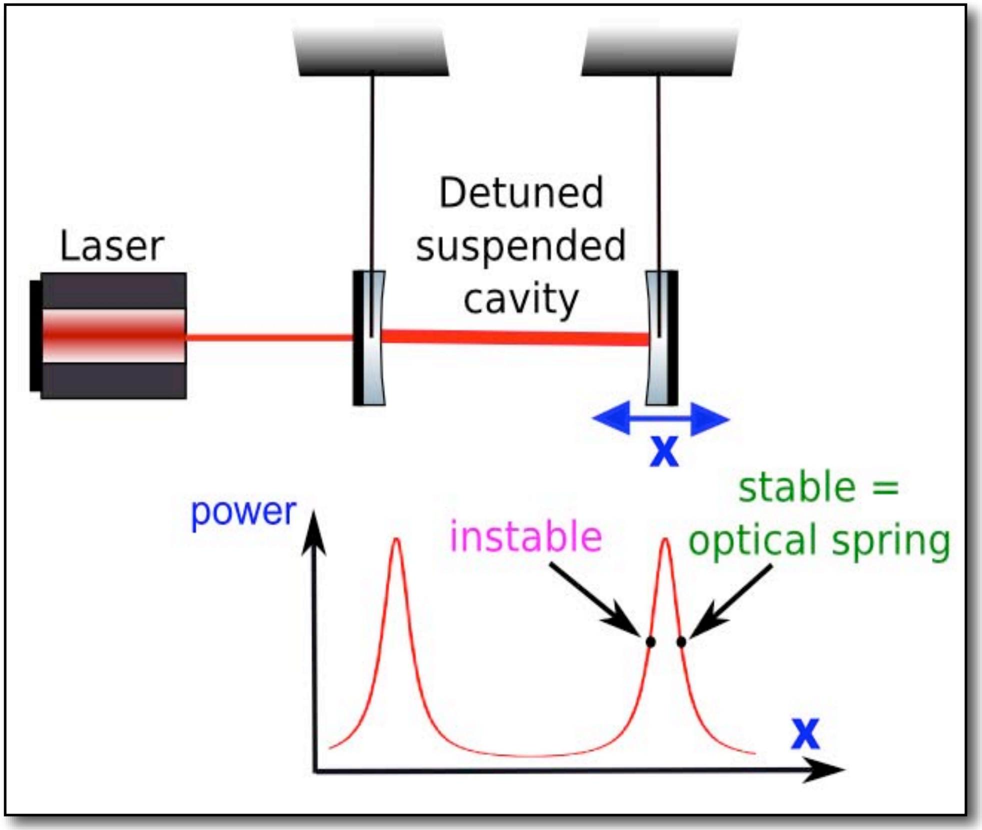
Opto-mechanical Resonance (Optical spring)

Pure optical resonance

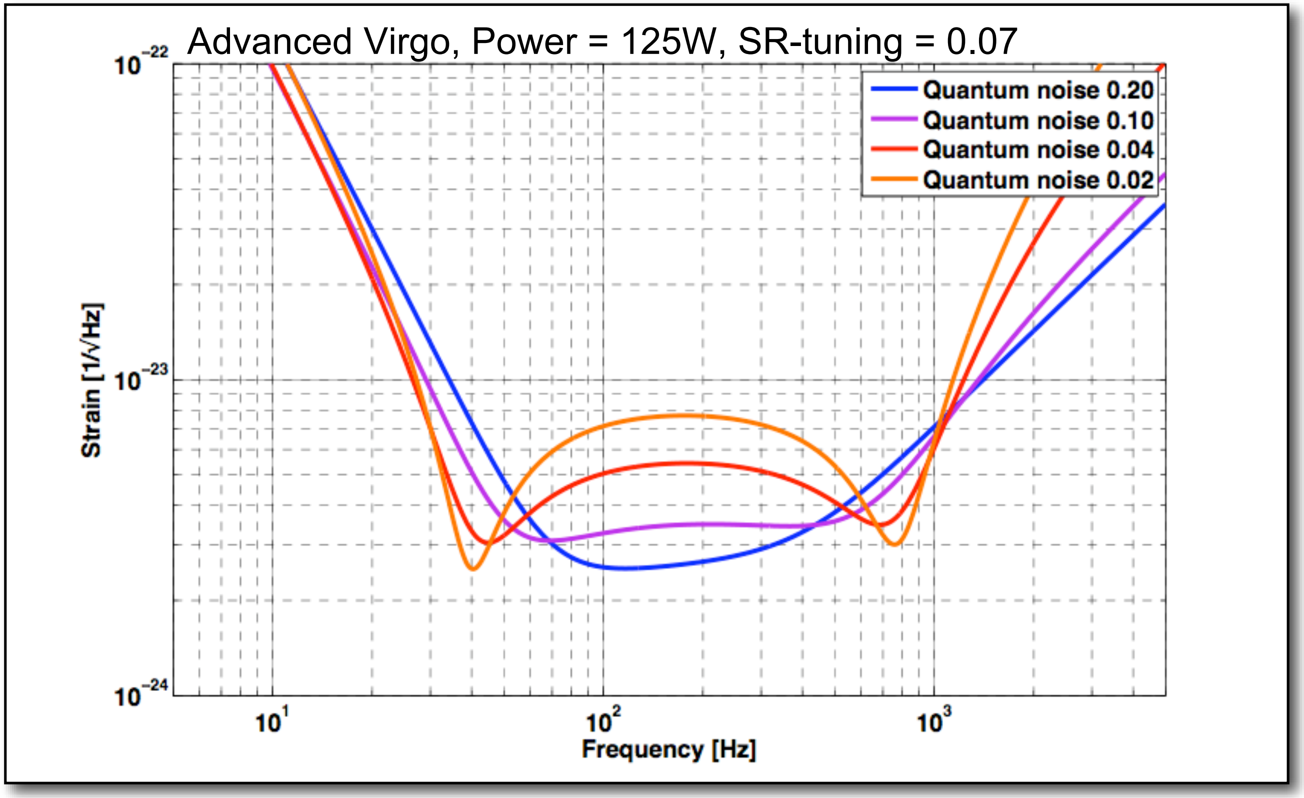
- ➢ Frequency of pure optical resonance goes down with SR-tuning.
- ➢ Frequency of opto-mechanical resonance goes up with SR-tuning

Optical Springs & Optical Rigidity

- Detuned cavities can be used to create optical springs.
- Optical springs couple the mirrors of a cavity with a spring constant equivalent to the stiffness of diamond.
- In a full Michelson interferometer detuned Signal Recycling causes an optical spring resonance.

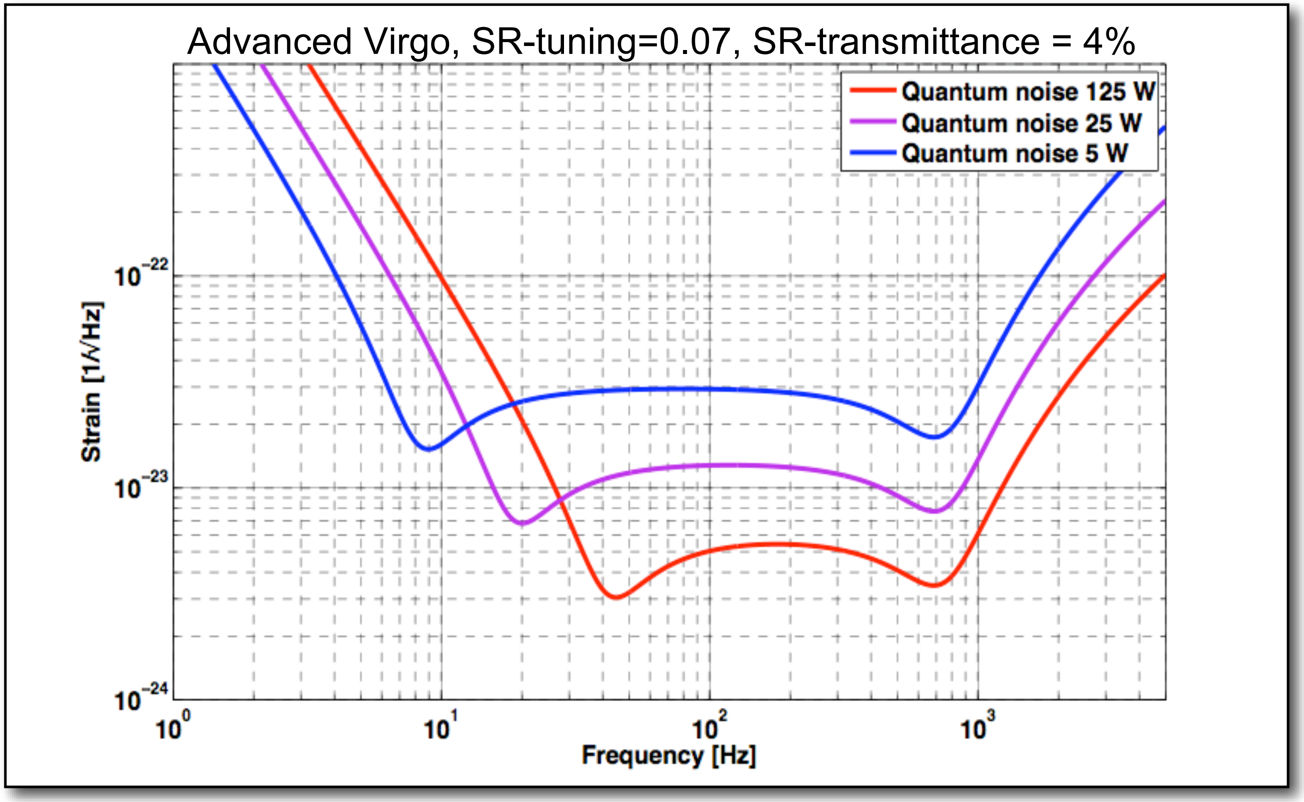


Optimization Parameter 2:
Signal-Recycling mirror transmittance



- ➢ Resonances are less developed for larger SR transmittance.

Optimization Parameter 3: Laser-Input-Power



- ➢ High frequency sensitivity improves with higher power (Shotnoise)
- ➢ Low frequency sensitivity decreases with higher power (Radiation pressure noise)

Figure of merit: Inspiral

- Inspiral ranges for BHBH and NSNS coalesence:

Symmetric mass ratio

Frequency of last stable orbit (BNS = 1570 Hz, BBH = 220 Hz)

Total mass

Spectral weighting = $f^{-7/3}$

$$d = \frac{m^{5/6}}{\rho_0 \pi^{2/3}} \left(\frac{5\eta}{6}\right)^{1/2} \left[\int_0^{f_{\rm lso}} df \, \frac{f^{-7/3}}{S_h(f)}\right]^{1/2}.$$

Detector sensitivity

[1] Damour, Iyer and Sathyaprakash, Phys. Rev. D 62, 084036 (2000).
[2] B. S. Sathyaprakash, "Two PN Chirps for injection into GEO", GEO Internal Document

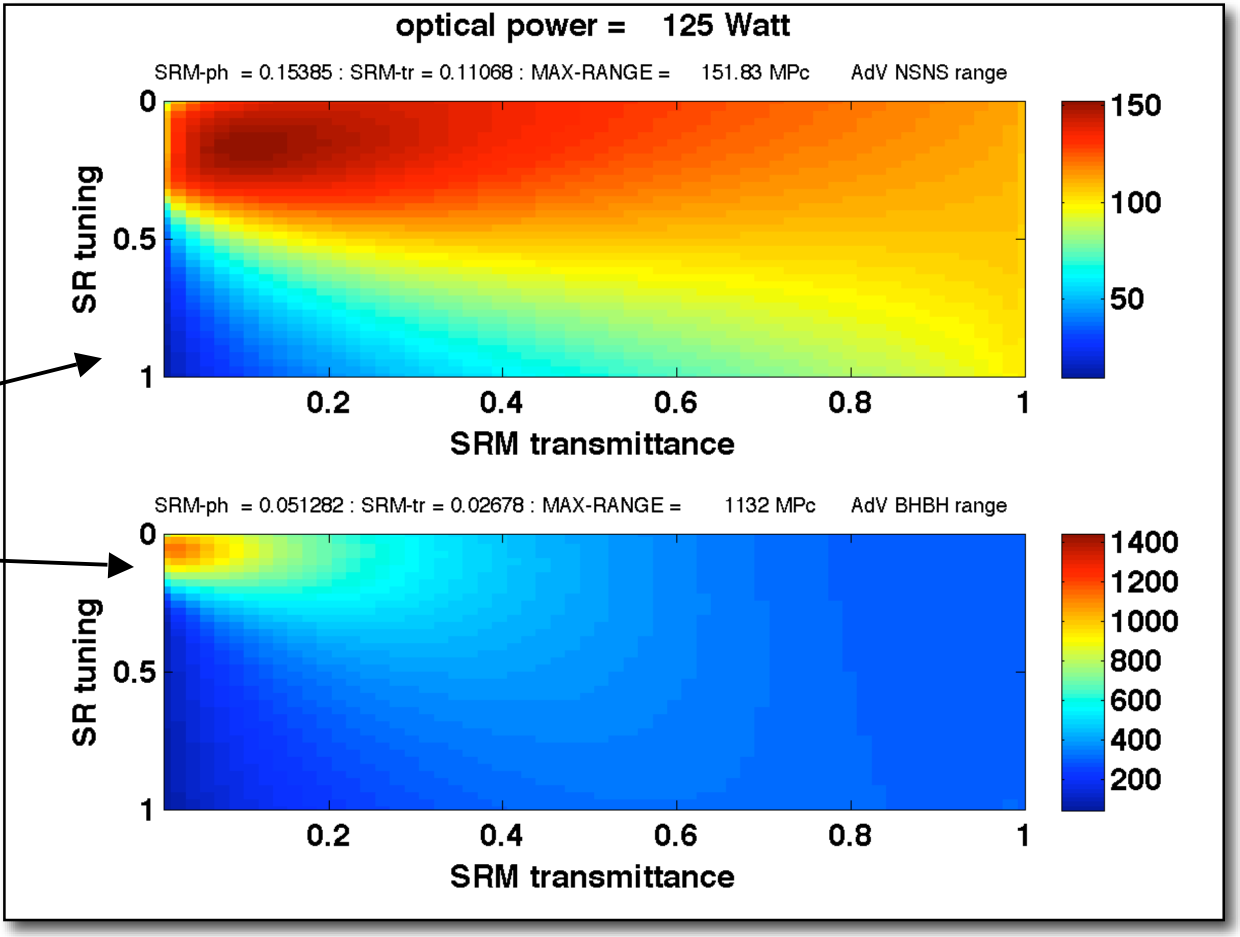
- Parameters usually used:
  - NS mass = 1.4 solar masses
  - BH mass = 10 solar masses
  - SNR = 8
  - Averaged sky location

Example: Optimizing 2 Parameters

- Inspiral ranges for free SR-tuning and free SRM-transmittance, but fixed Input power

NSNS-range

BHBH-range



Example: Optimizing 2 Parameters

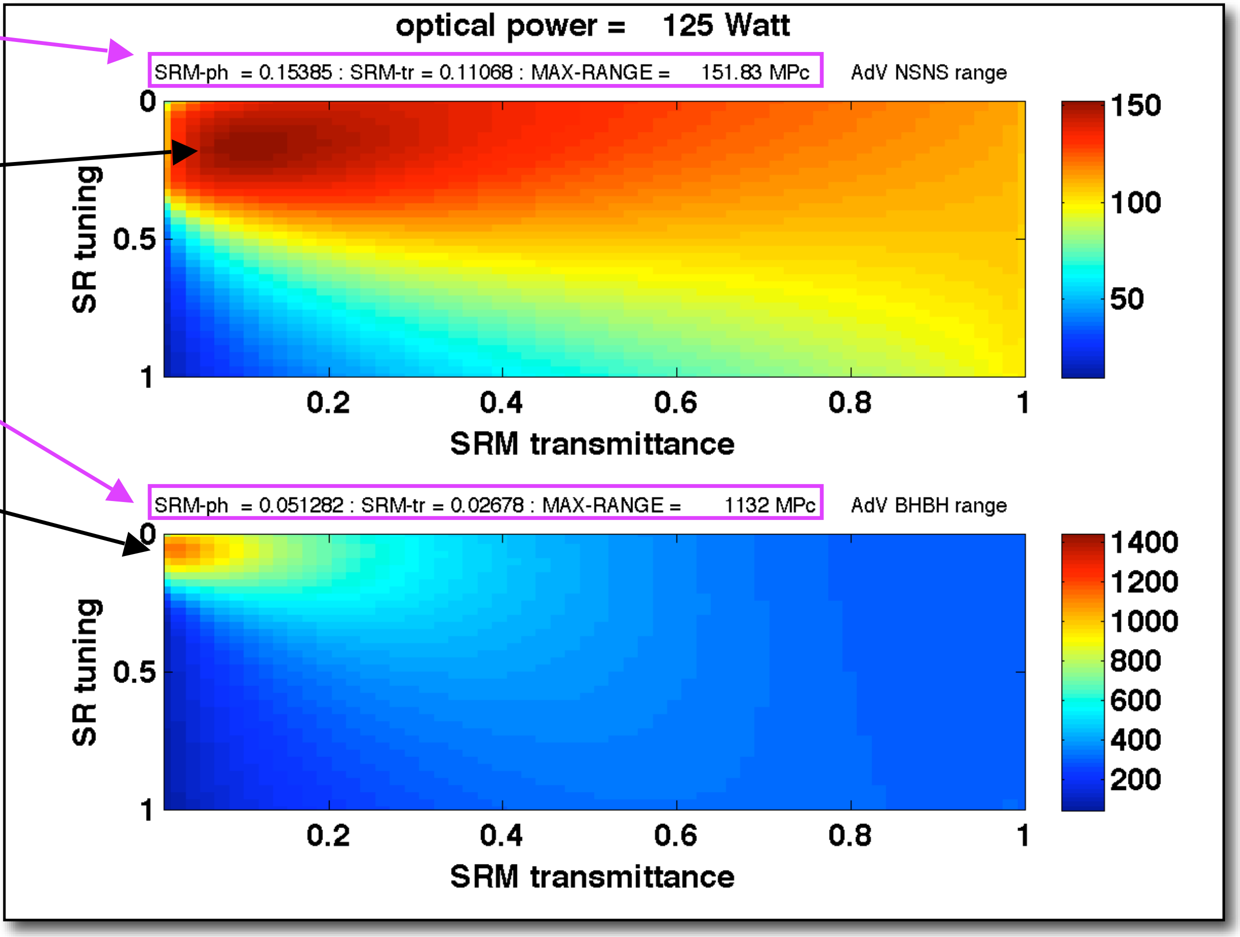
Parameters for maximum

Maximum NSNS-range

Parameters for maximum

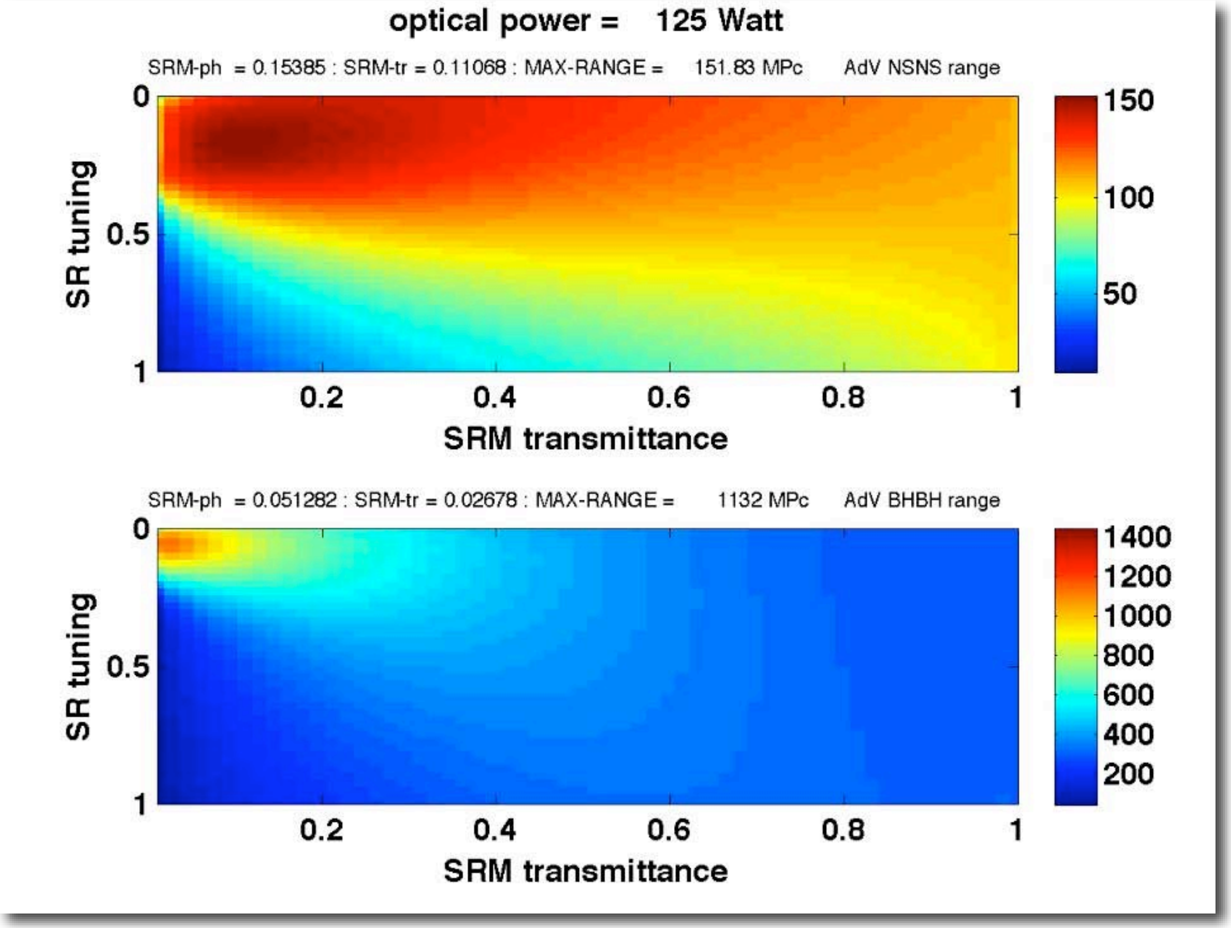
Maximum BHBH-range

- Different source usually have their maxima at different operation points.
- It is impossible to get the maximum for BNS **AND** BBH both at the same time !

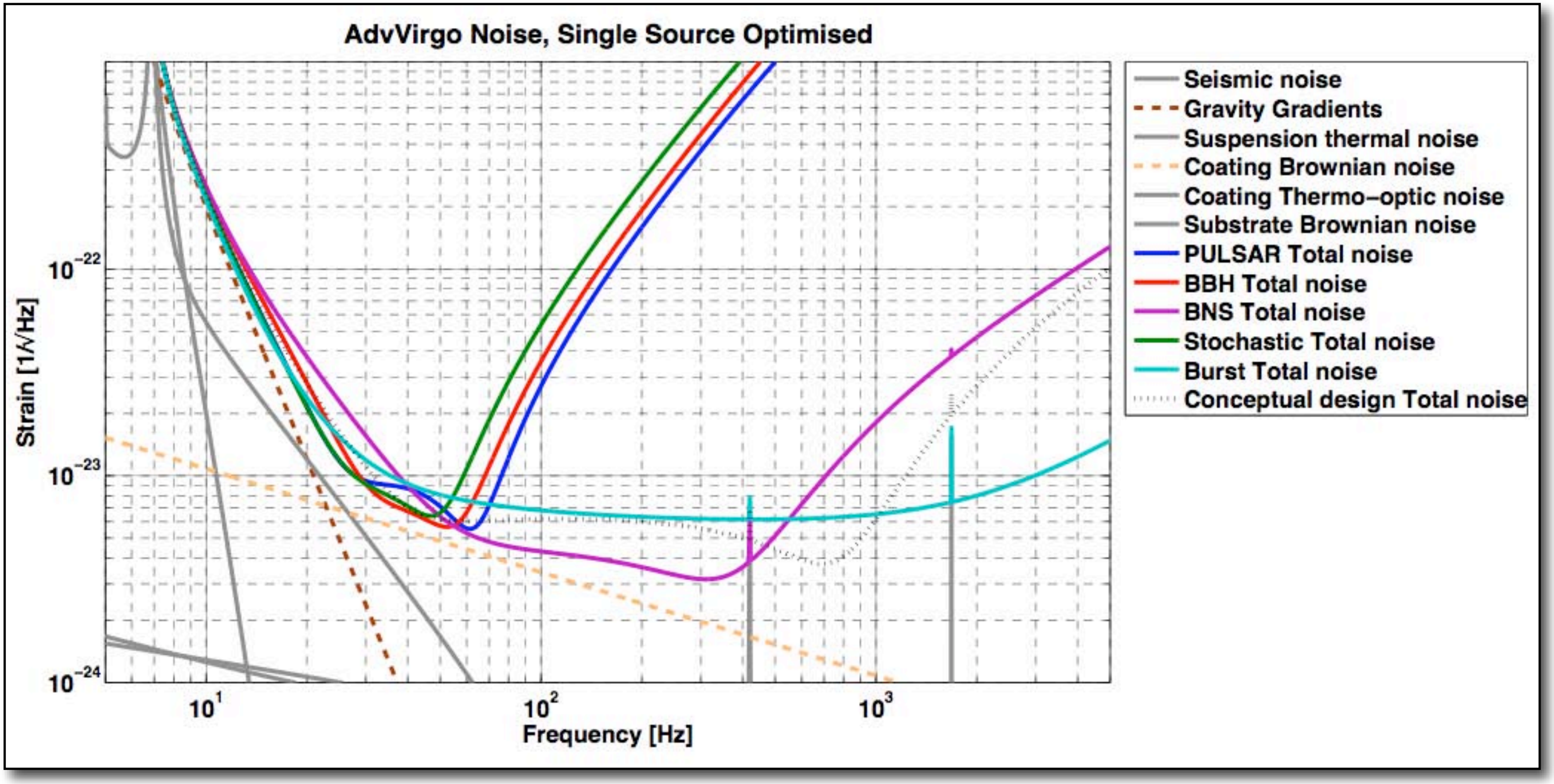


Example: Optimizing 3 Parameter for Inspiral range

- Scanning 3 parameter at the same time:
    - SR-tuning
    - SR-trans
    - Input Power
- Using a video to display 4th dimension.



Optimal configurations



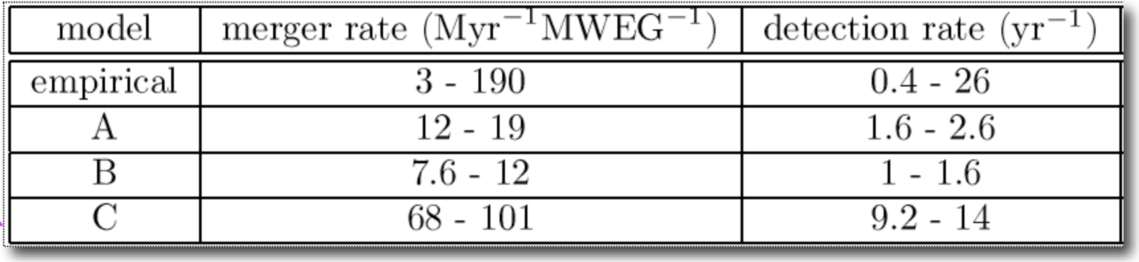
Curves show the optimal sensitivity for a single source type.

Which is the most promising source?

Binary neutron star inspirals:

Based on observations of existing binary stars

Based on models of binary star formation and evolution

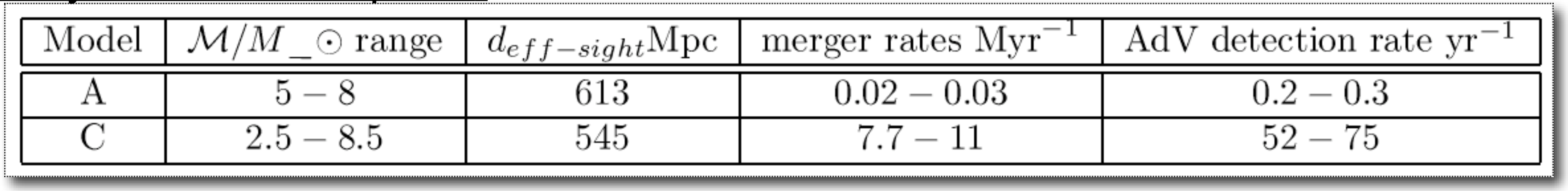


model	merger rate ($\mathrm{Myr}^{-1}\mathrm{MWEG}^{-1}$)	detection rate (yr^{-1})
empirical	3 - 190	0.4 - 26
A	12 - 19	1.6 - 2.6
B	7.6 - 12	1 - 1.6
C	68 - 101	9.2 - 14

Expected event rates seen by Advanced Virgo: ~1 to 10 events per year.

Binary neutron star inspirals are chosen to be the primary target for Advanced Virgo.

Binary black hole inspirals:



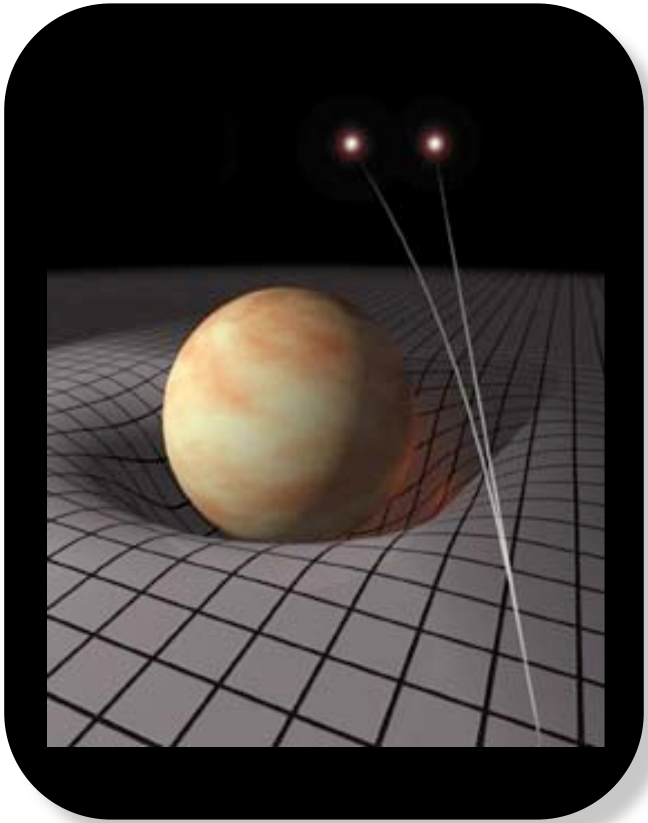
Model	$\mathcal{M}/M\_\odot$ range	$d_{eff-sight}$Mpc	merger rates Myr^{-1}	AdV detection rate yr^{-1}
A	5 – 8	613	0.02 – 0.03	0.2 – 0.3
C	2.5 – 8.5	545	7.7 – 11	52 – 75

C.Kim, V.Kalogera and D.Lorimer: “Effect of PSRJ0737-3039 on the DNS Merger Rate and Implications for GW Detection”, astro-ph:0608280 http://it.arxiv.org/ abs/astro-ph/0608280.

K.Belczynski, R.E.Taam, V.Kalogera, F.A.Rasio, T.Buli:, “On the rarity of double black hole binaries: consequences for gravitational-wave detection”, The Astrophysical Journal 662:1 (2007) 504-511.

When will we detect gravitational waves ??

- When Advanced Virgo and Advanced LIGO come online **WE WILL SEE GRAVITATIONAL WAVES!**
- … if not, then something is completely **wrong** with our understanding of **General Relativity**.



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What else is around in other parts of the world?

What will a 3rd Generation Interferometer look like ?

- How to build the Einstein Telescope (ET)?
  - Geometry and shape
  - How to reach the sensitivity?

Specialties of other 2nd generation instruments

- Advanced LIGO:
  - 3 instruments of 4km length
  - Construction already started !!
  - Design pretty similar to Advanced Virgo, apart from seismic isolation: 4 stage pendulums (boosted GEO design)
- LGCT:
  - Cryogenic temperatures (reduce thermal noises)
  - Underground location in Kamioka mine.
- GEO-HF:
  - Quantum noise reduction by means of squeezed light injection.

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- Other 2nd Generation GW Observatories
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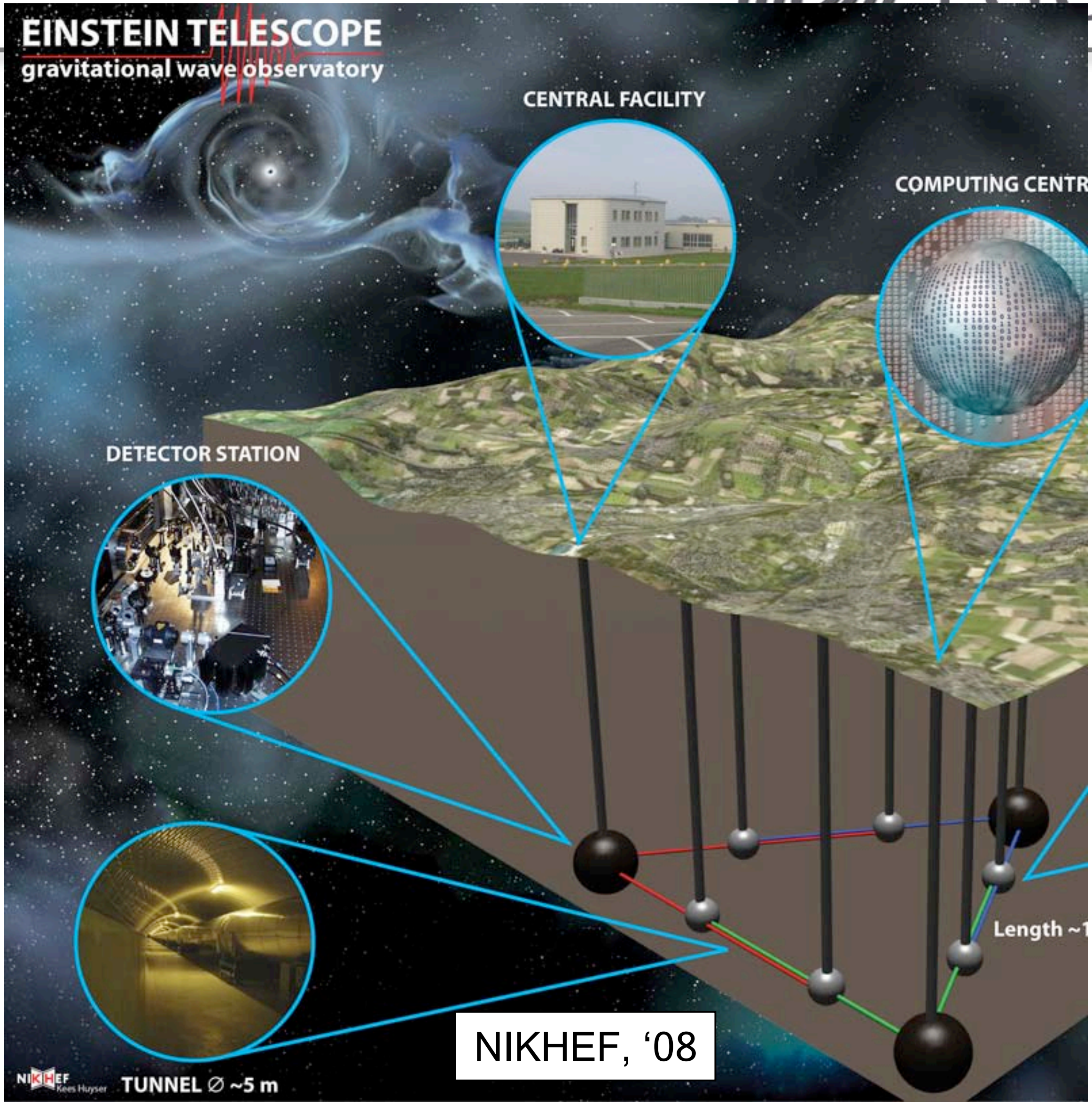
What will a 3rd Generation Interferometer look like ?

- How to build the Einstein Telescope (ET)?
  - Geometry and shape
  - How to reach the sensitivity?

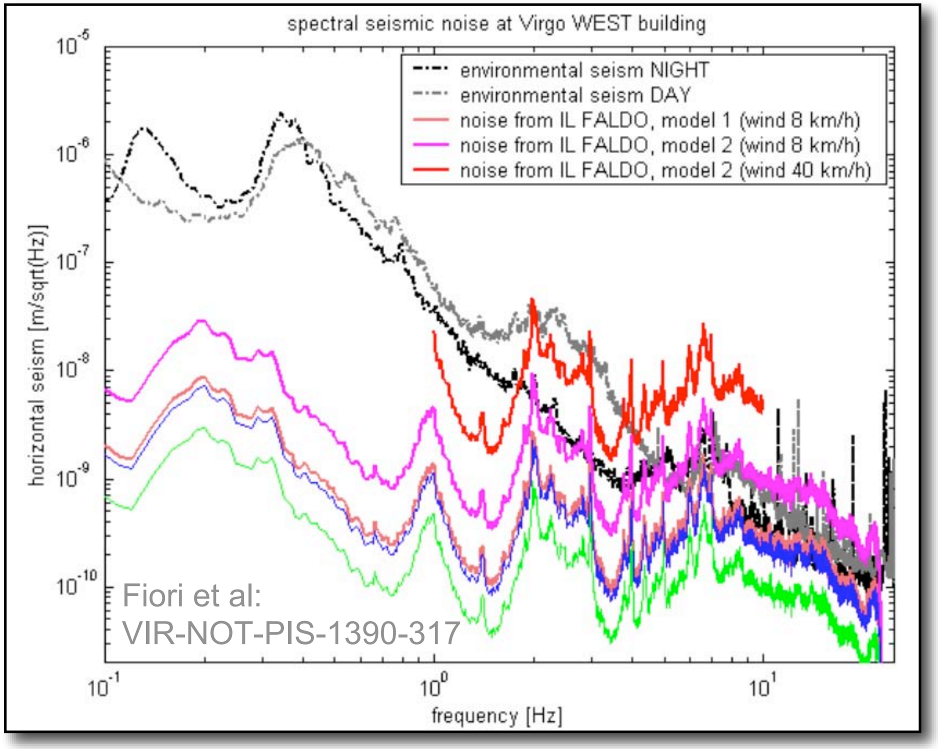
What else is around in other parts of the world?

- Start around 2020(?)
- Underground location
- ~30km integrated tunnel length (?)
- **Myriads of new possibilities and challenges !!**
- **Plenty of new Science…**



NIKHEF, '08

Main driver for going underground: Gravity Gradient noise



Fiori et al:
VIR-NOT-PIS-1390-317

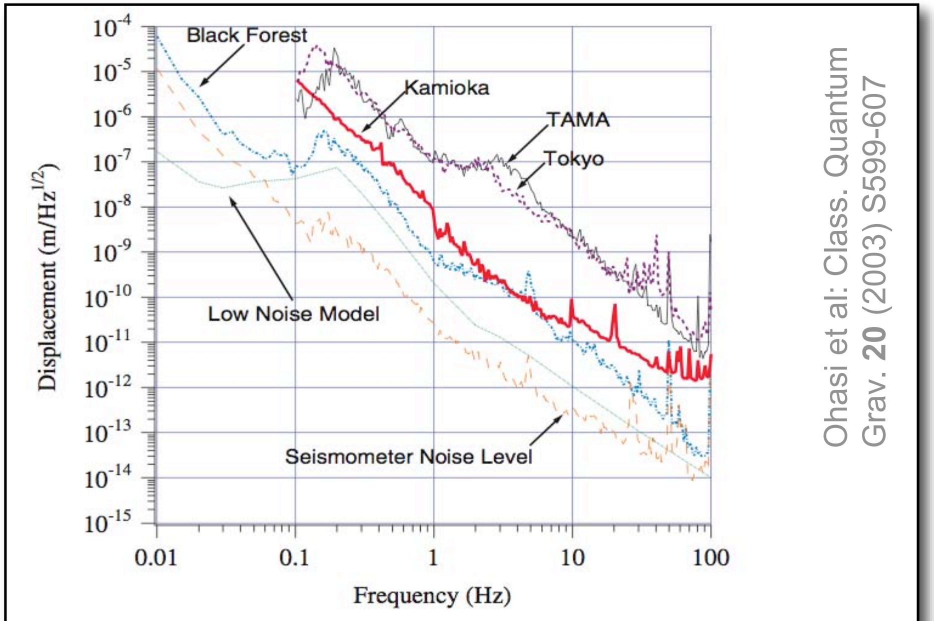


Figure 7. Low seismic noise environment at the Kamioka site. Displacement noises at Kamioka, TAMA site, Tokyo, Black Forest Geophysical Observatory (Germany) and a low noise model (a hybrid spectrum of quiet sites in the world) are described.

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

What will be the shape of ET?

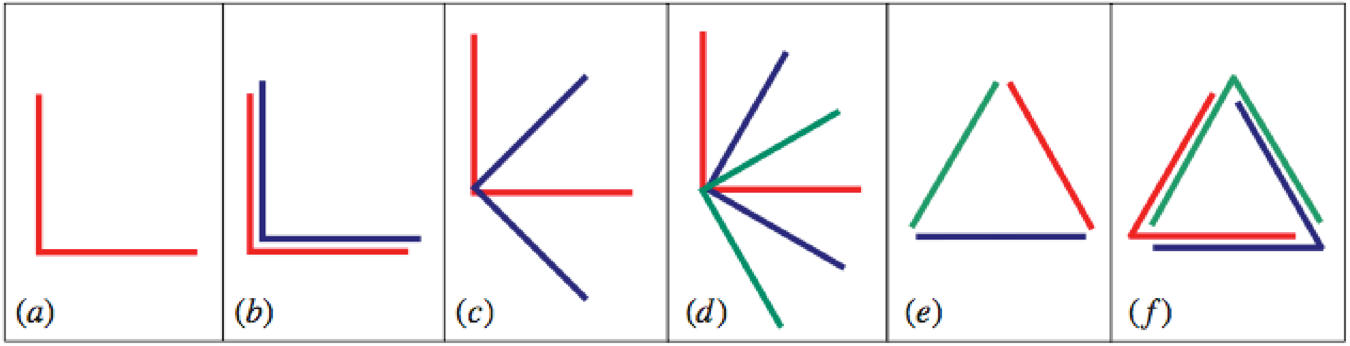
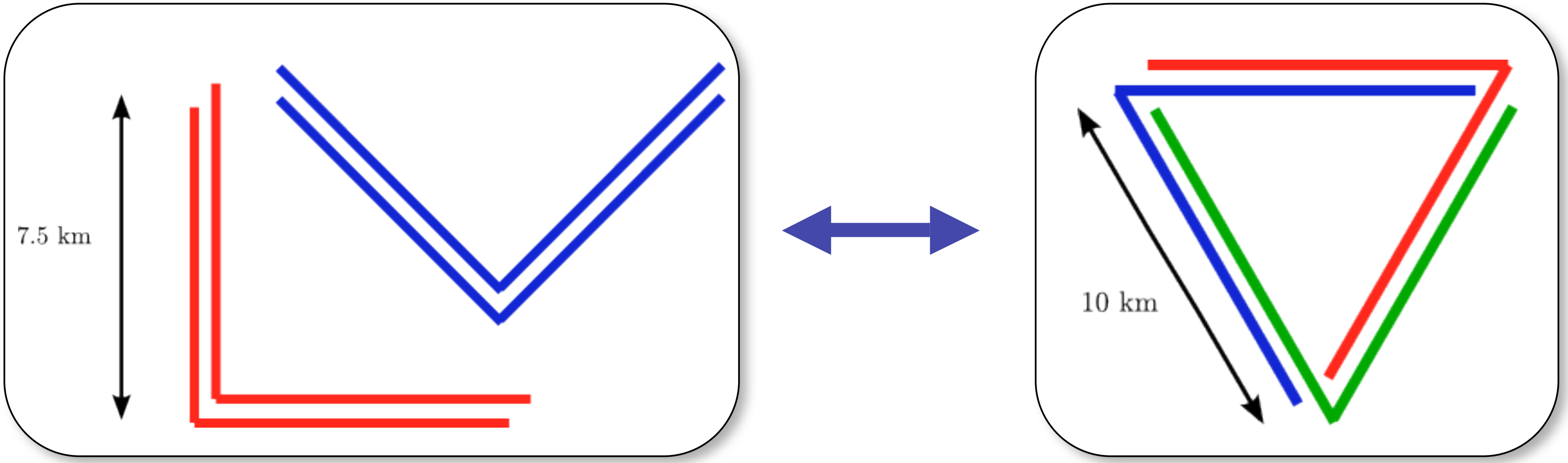


Figure 2. A comparison of several geometries for future ground-based detectors: (*A*) A simple Michelson interferometer is sensitive only to a linear combination of the two polarization amplitudes. (*B*) Two co-aligned Michelson interferometers provide redundancy and the possibility to generate a null-stream (and as for case A are sensitive only to a linear combination of the two polarization amplitudes). (*C*) Two Michelson interferometers rotated by 45° with respect to each other can fully resolve both polarization amplitudes. (*D*) Three rotated Michelson interferometers provide redundancy and the possibility to generate a null-stream. They also can measure both polarizations (the geometries shown as C and D feature intersection tubes. Similar geometries in which the Michelson interferometers do not overlap might be more practical, depending on the properties of the detector site, see [14]). (*E*) A LISA-like triangular configuration, in which the interferometer arms are single cavities and there is no optical recombination. (*F*) A triple Michelson interferometer configuration consisting of three individual Michelson interferometers.

What will be the shape of ET?

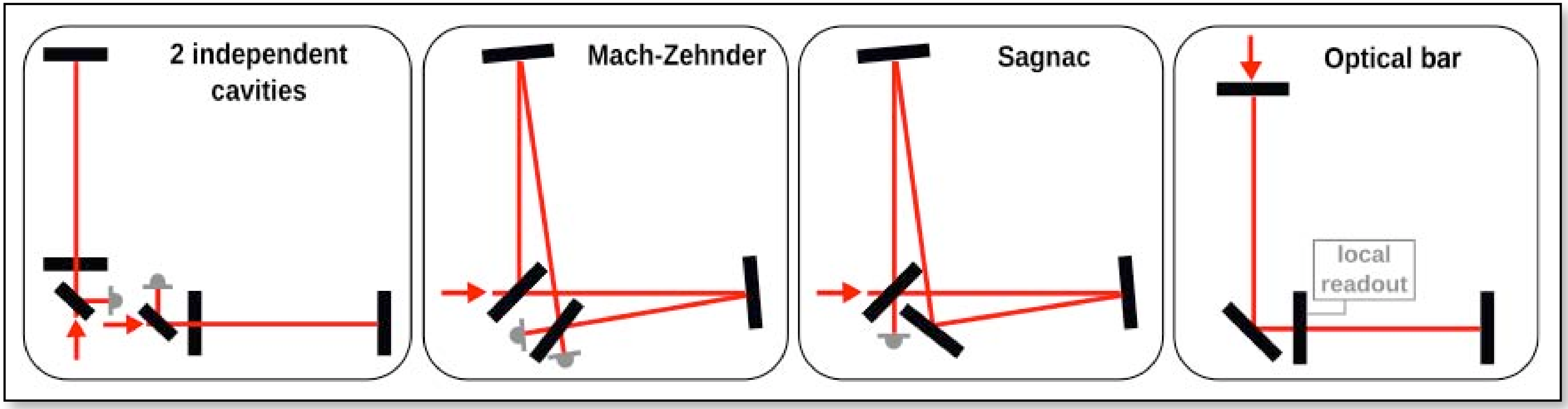


Both solutions have an integrated tunnel length of 30 km, they can resolve both GW polarisations, feature redundant interferometers and have equivalent sensitivity.

The triangle reduces the number of end stations and the enclosed area!
(Possibly, better vetos or noise reductions are possible in the triangle)

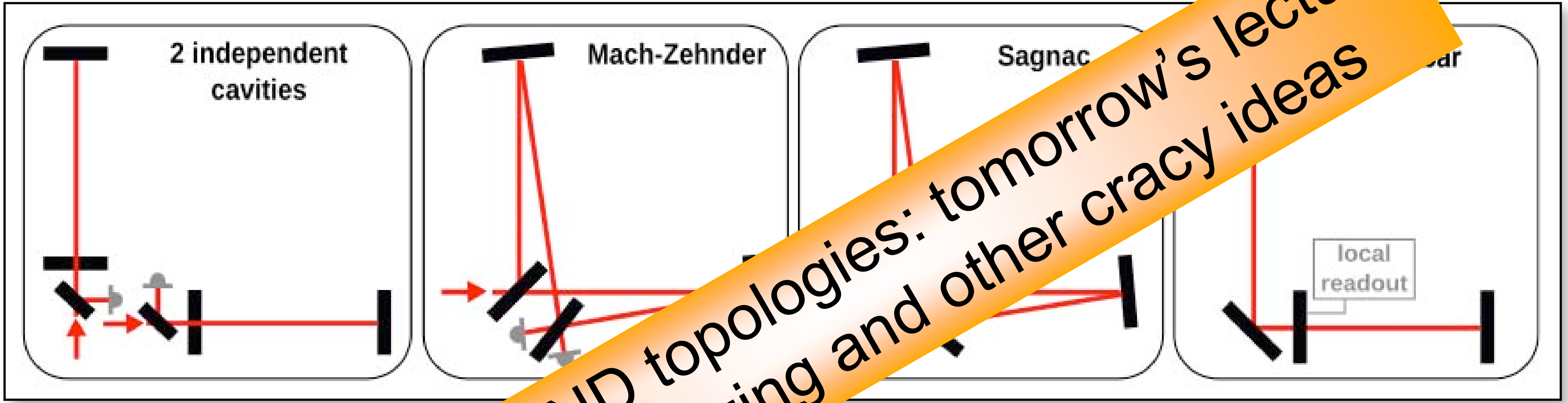
Slide stolen from A.Freise

Shape independent of actual interferometer configuration



- All different interferometer types can be formed into L-shape

Shape independent of actual interferometer configuration



- All different int pes can be formed into L-shape

More on QND topologies: tomorrow's lecture on QND, squeezing and other cracy ideas

Overview

What do we need to change to make our instruments 2nd Generation observatories ?

- Details of 2nd Generation interferometer: Example Advanced Virgo
  - Noise limits: Suspension thermal noise, Coating Brownian noise, Quantum noise
  - Important Techniques: Thermal compensation, NDRC, DC-readout
  - Sensitivity optimisation and observation prospects
- Other 2nd Generation GW Observatories
  - Advanced LIGO, LGCT, GEO-HF

What will a 3rd Generation Interferometer look like ?

- How to build the Einstein Telescope (ET)?
  - Geometry and shape
  - How to reach the sensitivity?

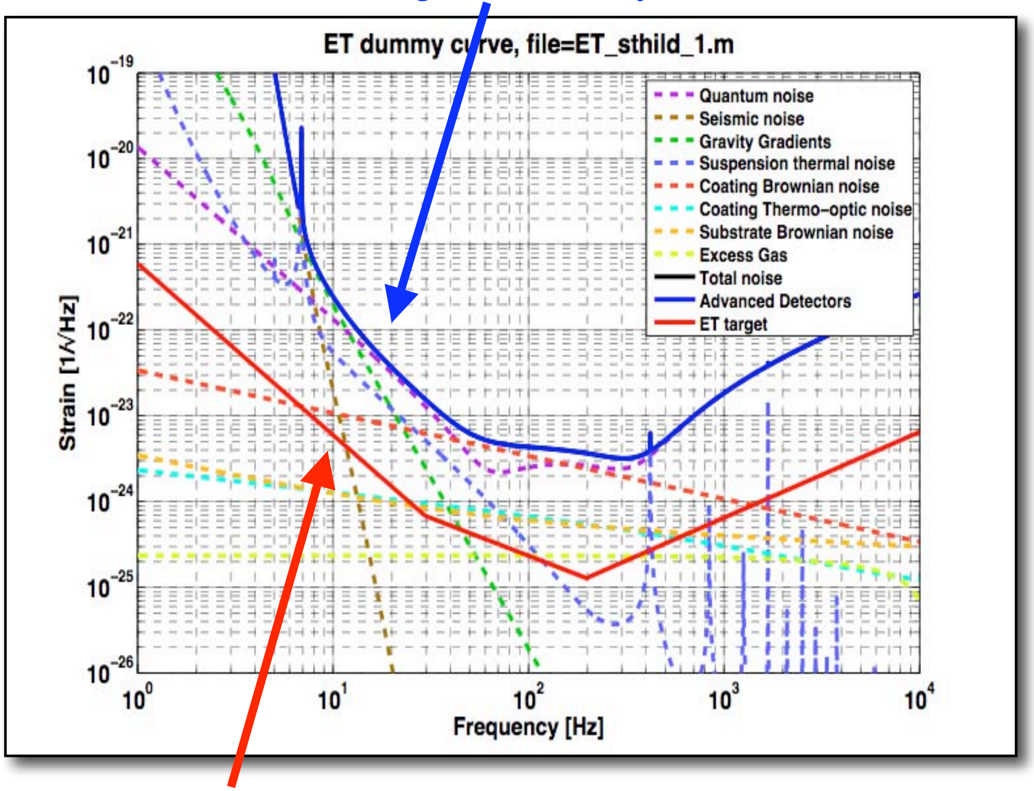
Brute Force Approach?
Xylophone?

The starting point

- We consider:
  - Michelson topology with dual recycling.
  - One detector covering the full frequency band
  - A single detector (no network)
- Start from a 2nd Generation instrument.
- Each fundamental noise at least for some frequencies above the ET target.

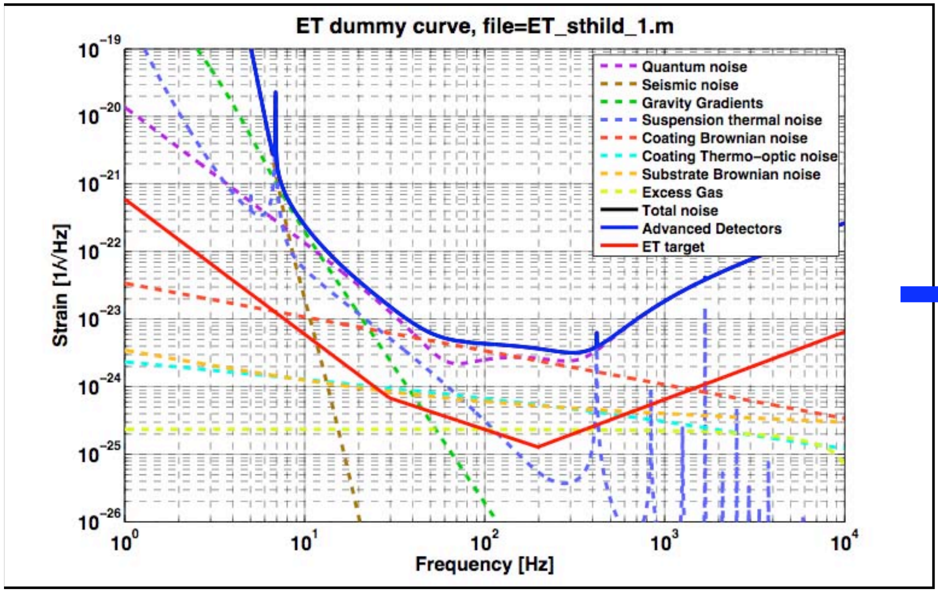
=> OUR TASK:
All fundamental noises have to be improved !!

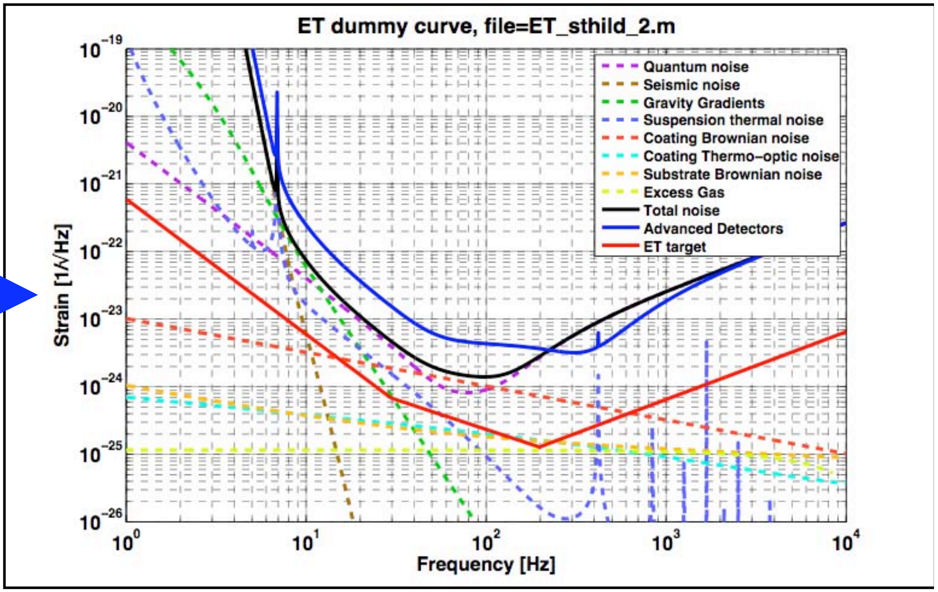
2nd Generation design sensitivity



ET target sensitivity (approximated)

Step 1: Increasing the arm length



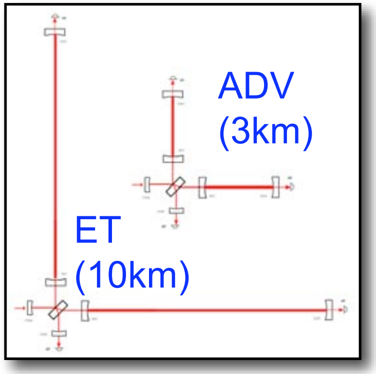


DRIVER: All displacement noises

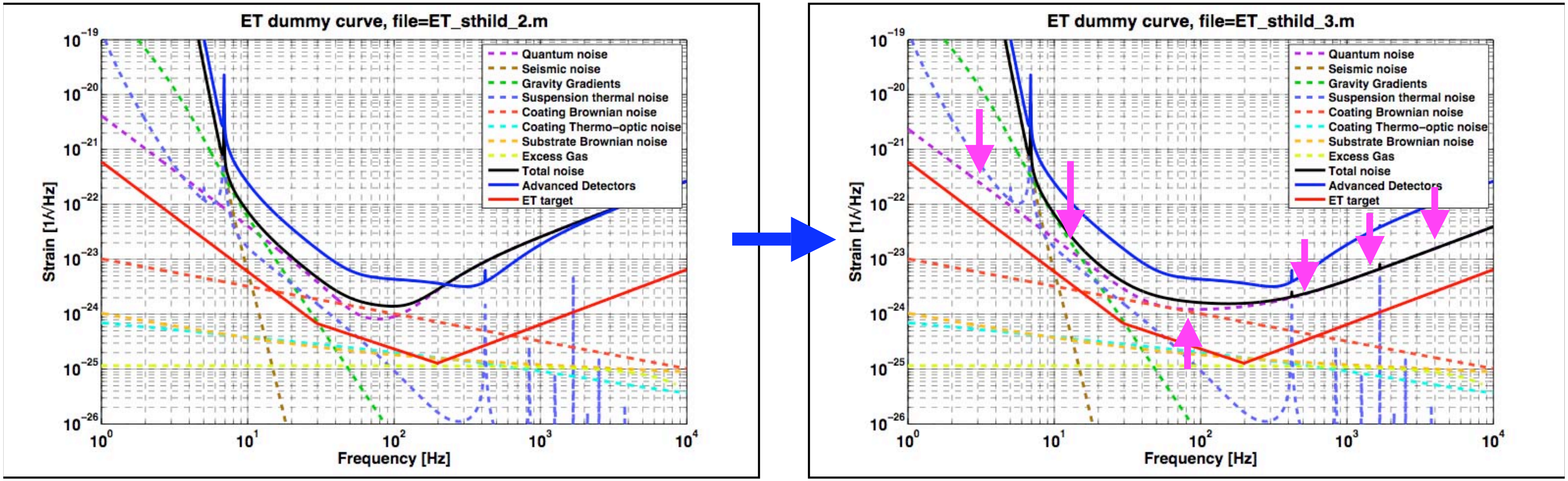
ACTION: Increase arm length from 3km to 10km

EFFECT: Decrease all displacement noises by a factor 3.3

SIDE EFFECTS:
- Decrease in residual gas pressure
- Change of effective Signal recycling tuning



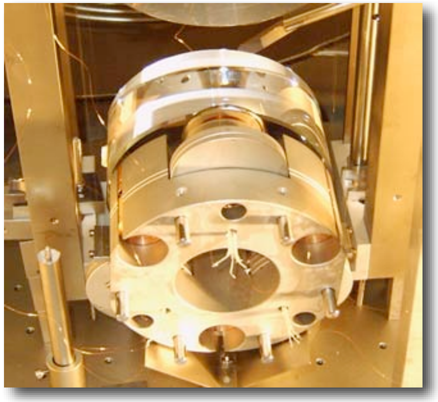
Step 2: Optimising signal recycling



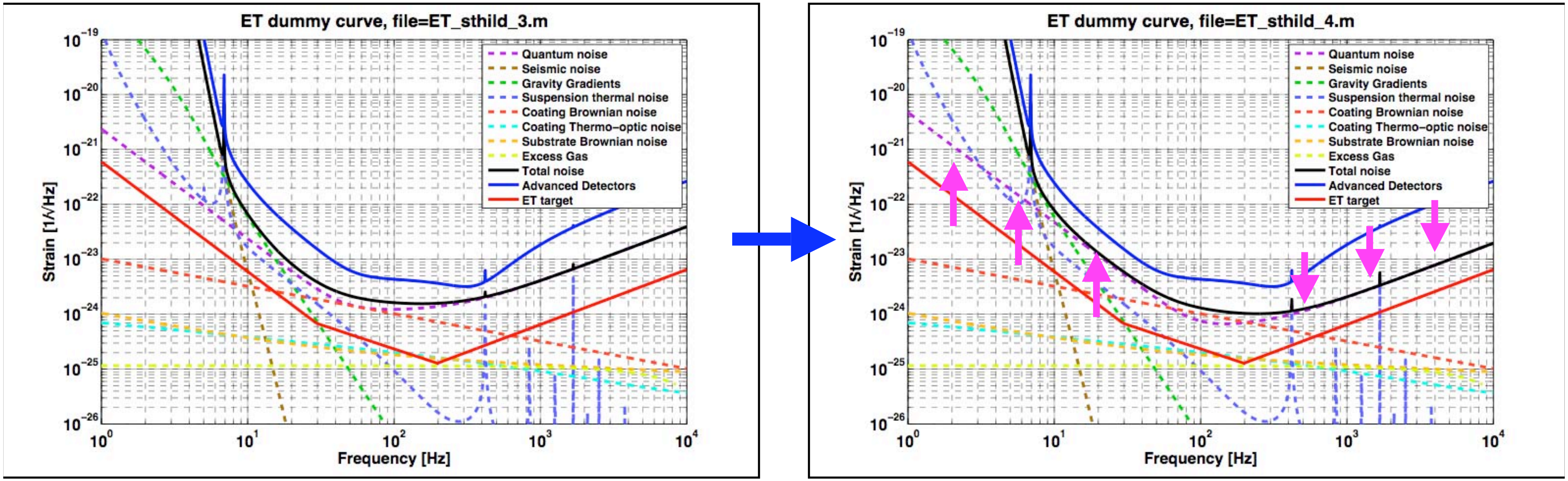
DRIVER: Quantum noise

ACTION: From detuned SR to tuned SR (with 10% transmittance)

EFFECTS:
- Reduced shot noise by ~ factor 7 at high freqs
- Reduced radiation pressure by ~ factor 2 at low freqs
- Reduced peak sensitivity by ~ factor sqrt(2) :(



Step 3: Increasing the laser power

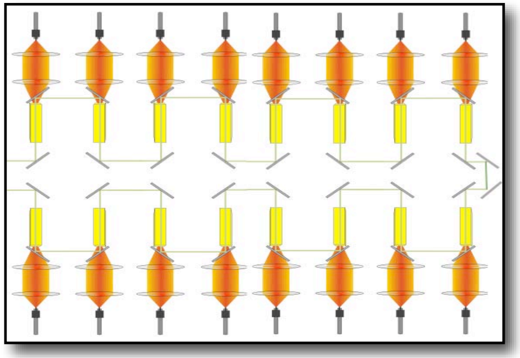


DRIVER: Shot noise at high frequencies

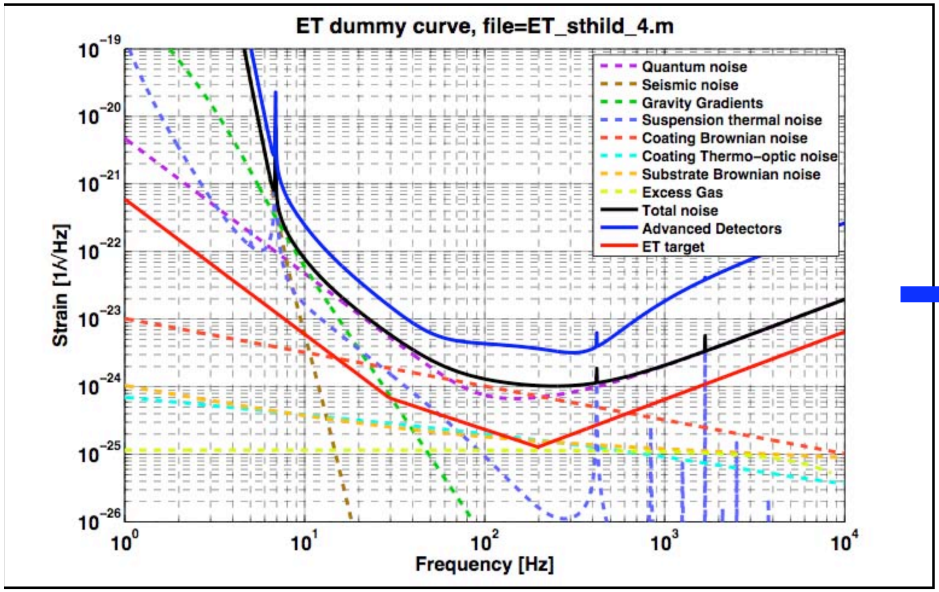
ACTION: Increase laser power (@ ifo input) from 125W to 500W

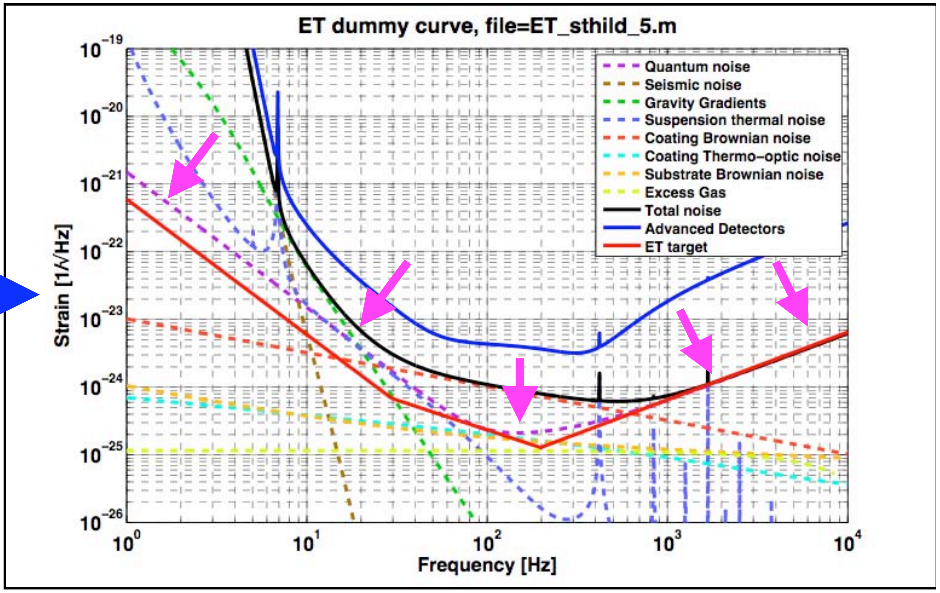
EFFECT: Reduced shot noise by a factor of 2

SIDE EFFECTS: Increased radiation pressure noise by a factor 2



Step 4: Quantum noise suppression



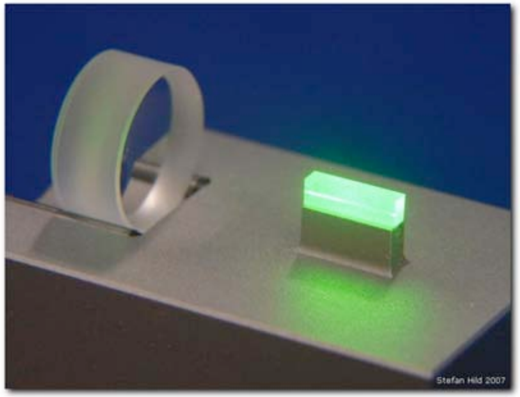


DRIVER: Shot noise at high frequencies

ACTION: Introduced 10dB of squeezing (frequency depend angle)

EFFECT: Decreases the shot noise by a factor 3

SIDE EFFECTS: Decreases radiation pressure noise by a factor 3



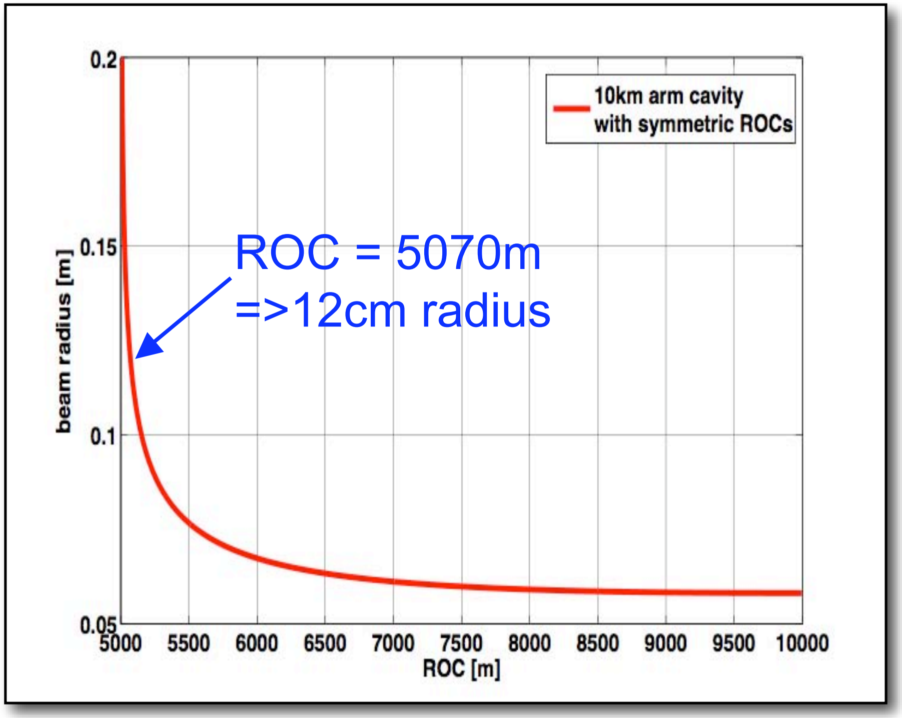
Increasing the beam size to reduce Coating Brownian noise

Increasing the beam size at the mirrors reduces the contribution of Coating Brownian.

Coating Brownian noise of one mirror:

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

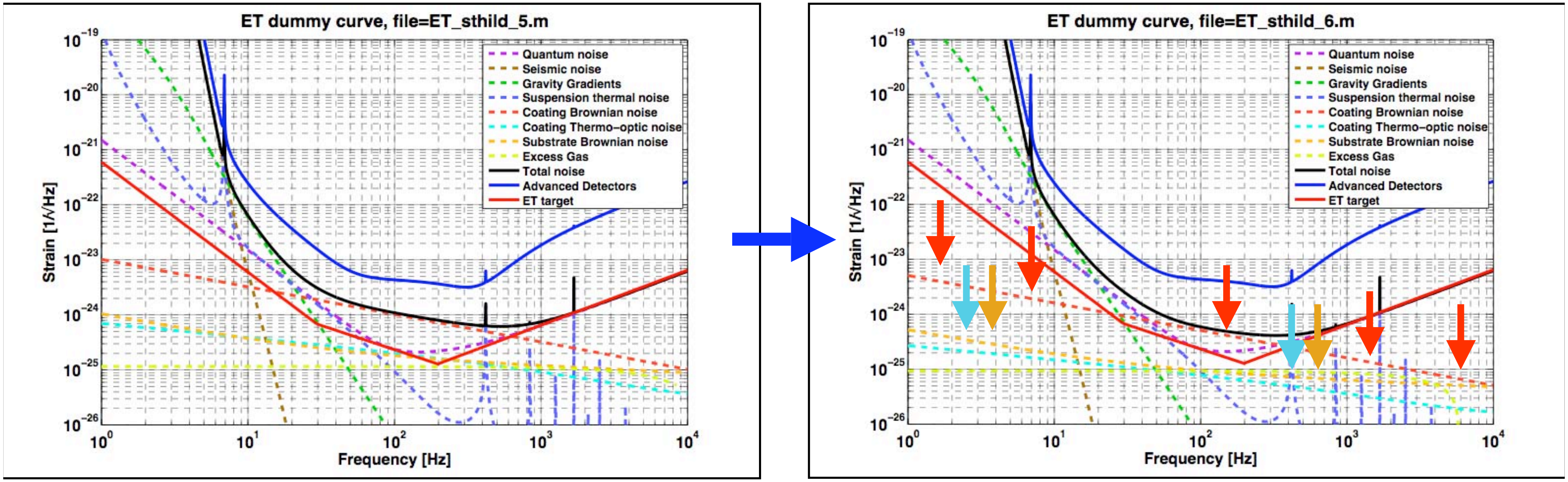
beam radius on mirror



ROC = 5070m
=>12cm radius

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

Step 5: Increasing the beam size



DRIVER: Coating Brownian noise

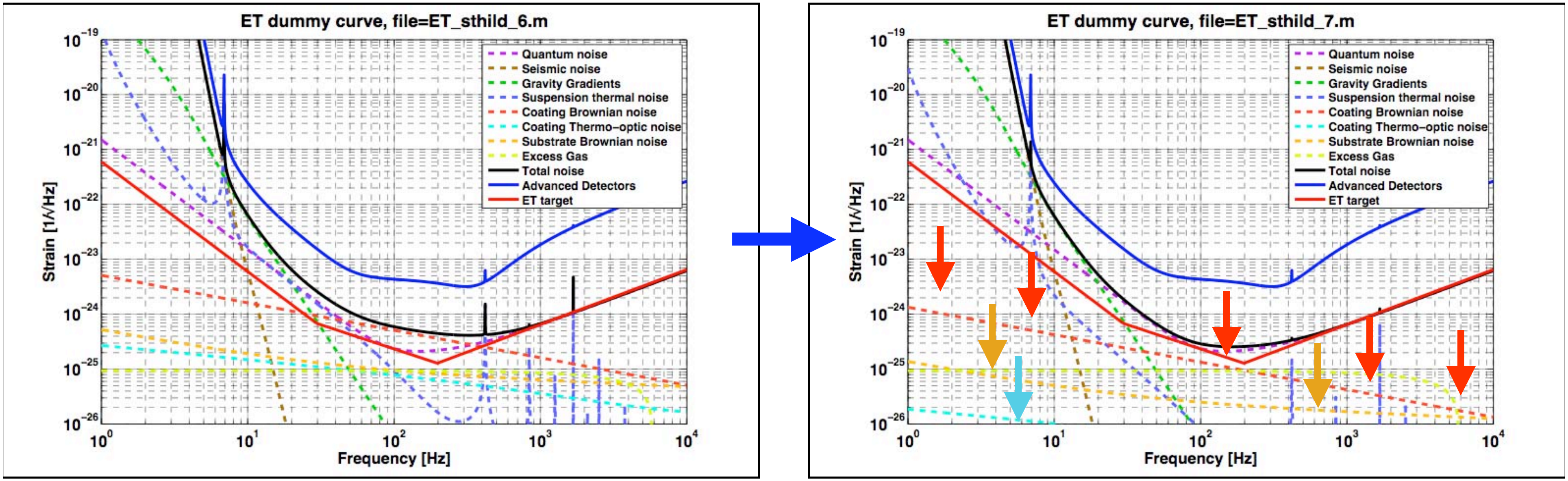
ACTION: Increase of beam radius from 6 to 12cm

EFFECT: Decrease of Coating Brownian by a factor 2

SIDE EFFECTS:

- Decrease of Substrate Brownian noise (~factor 2)
- Decrease of Thermo-optic noise (~factor 2)
- Decrease of residual gas pressure noise (~10-20%)

Step 6: Cooling the test masses

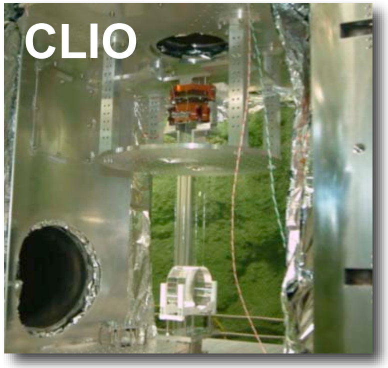


DRIVER: Coating Brownian noise

ACTION: Reduce the test mass temperature from 290K to 20K

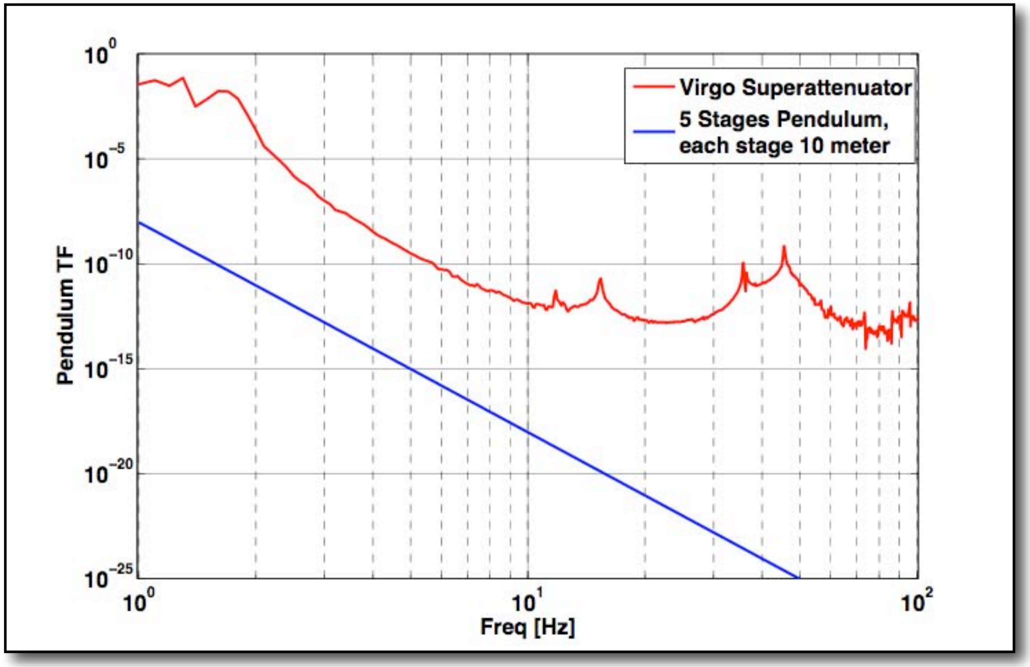
EFFECT: Decrease Brownian by ~ factor of 4

SIDE EFFECTS:
- Decrease of substrate Brownian
- Decrease of thermo-optic noise

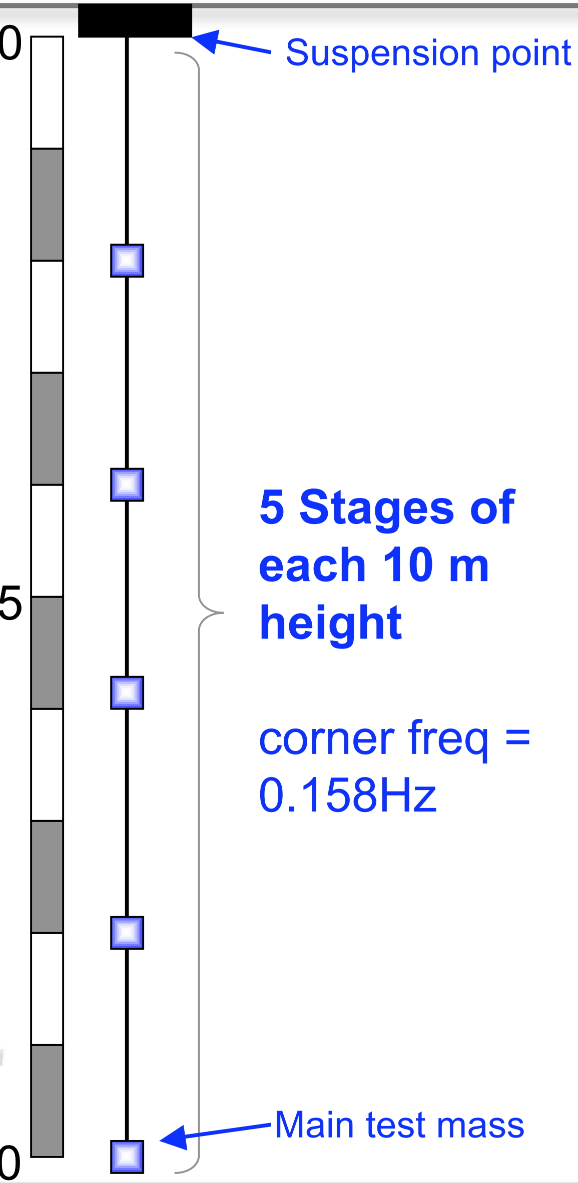


Kuroda 2008
LIGO-G080060

Seismic Isolation / Suspension



SA-data: G.Ballardin et al, Rev. Sci. Instrum., Vol.72, No.9 (2001)

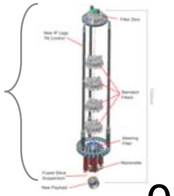


Suspension point

5 Stages of each 10 m height

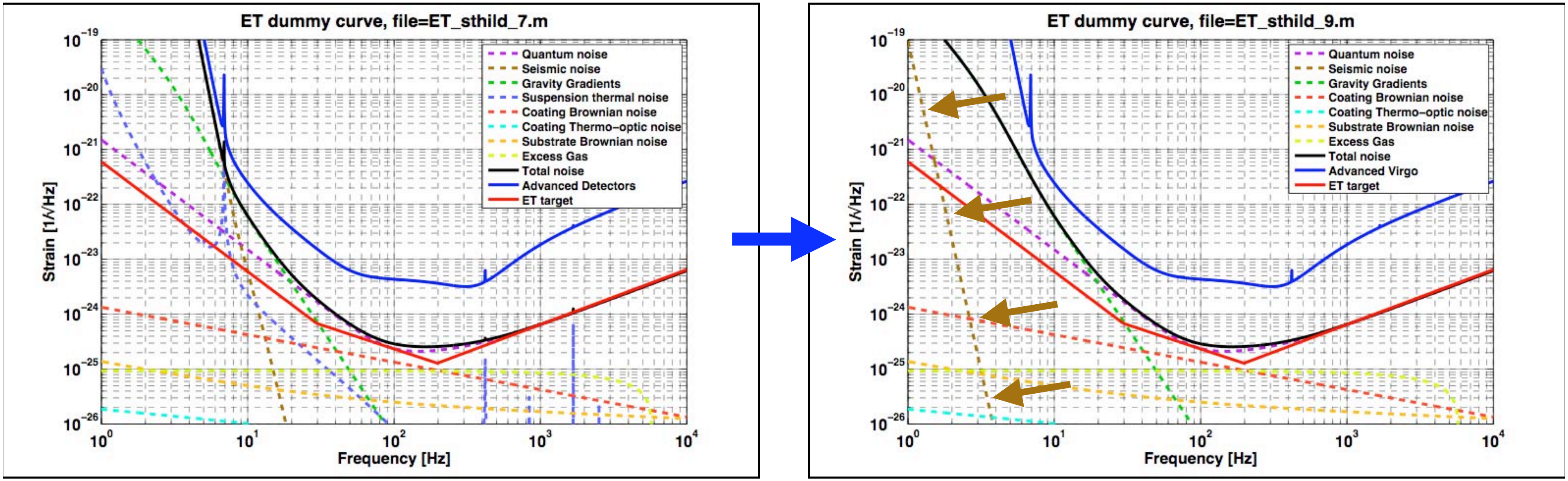
corner freq = 0.158Hz

Main test mass



Virgo Superattenuator (height ~ 8 meter)

Step 7: Longer Suspensions

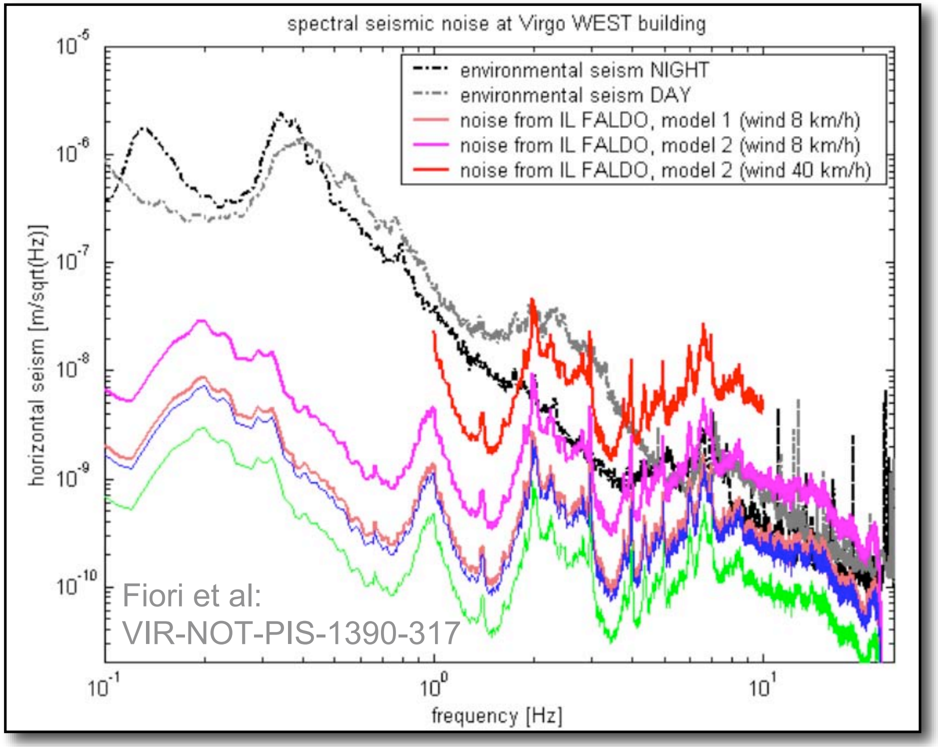


DRIVER: Seismic noise

ACTION: Build 50m tall 5 stage suspension (corner freq = 0.158 Hz)

EFFECT: Decrease seismic noise by many orders of magnitude
or pushes the seismic wall from 10 Hz to about 1.5 Hz

Tackling Gravity Gradient noise: going underground



Fiori et al: VIR-NOT-PIS-1390-317

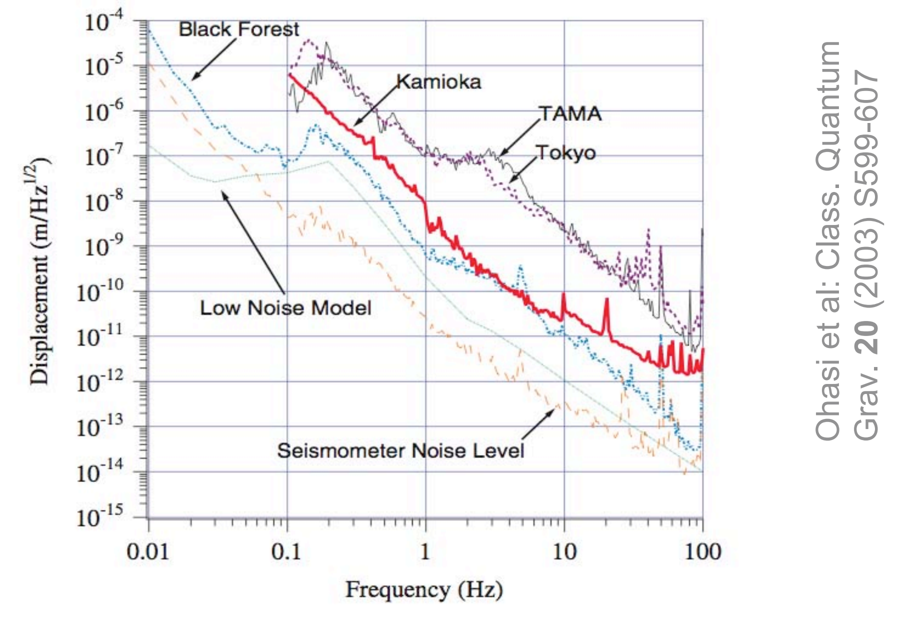


Figure 7. Low seismic noise environment at the Kamioka site. Displacement noises at Kamioka, TAMA site, Tokyo, Black Forest Geophysical Observatory (Germany) and a low noise model (a hybrid spectrum of quiet sites in the world) are described.

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

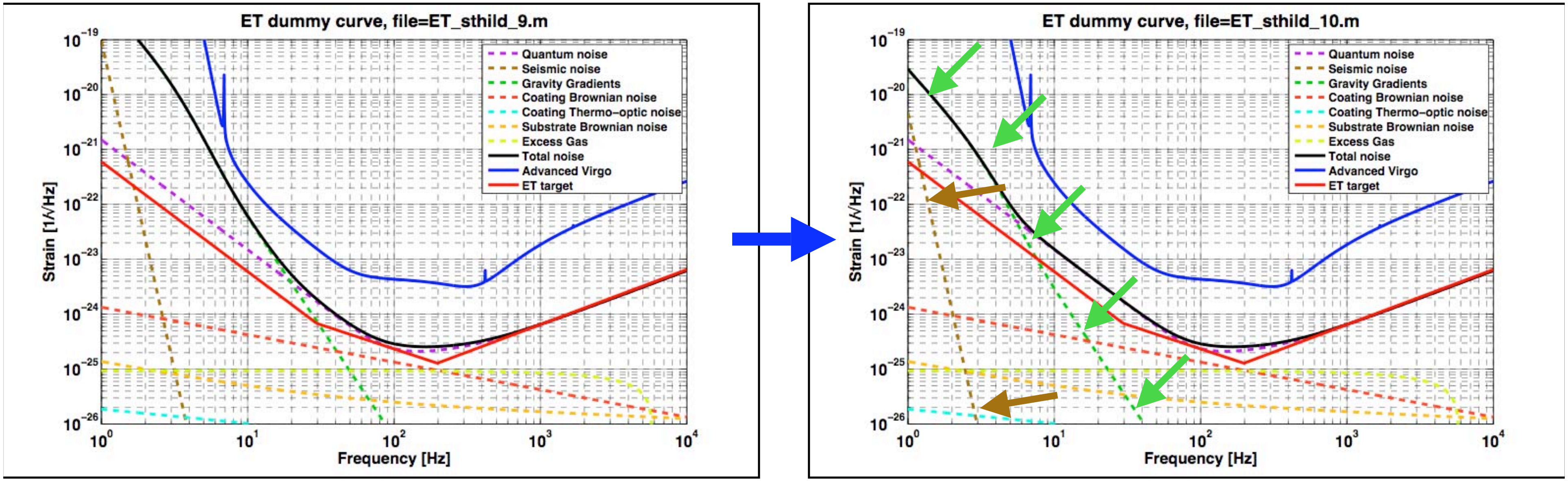
Surface (Cascina)

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

Step 8: Going underground



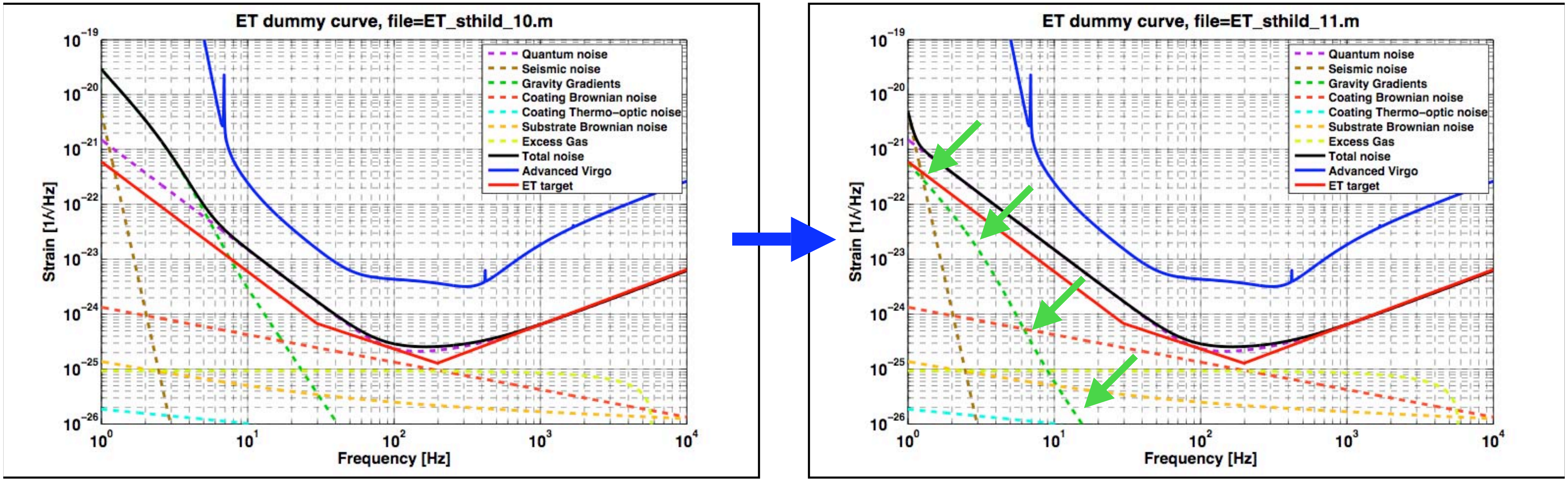
DRIVER: Gravity gradient noise

ACTION: Go from the surface to underground location

EFFECT: Decrease gravity gradients by a factor 20

SIDE EFFECTS: Decrease in seismic noise by a factor 20

Step 9: Gravity gradient suppression

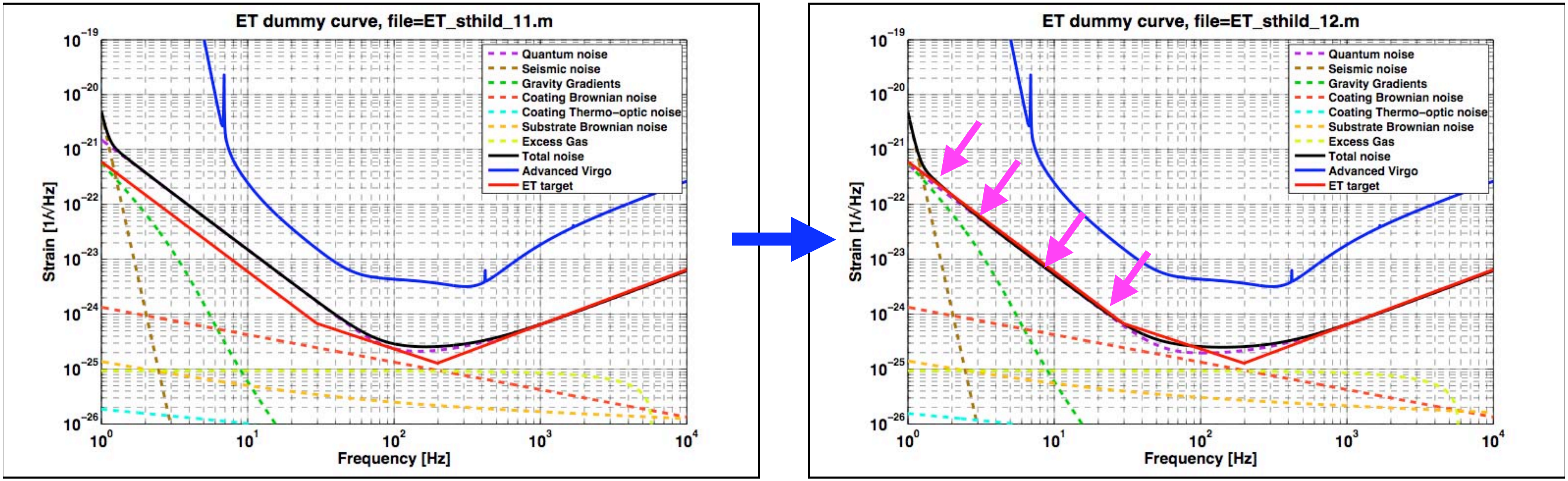


DRIVER: Gravity gradient noise

ACTION: Active subtraction of the gravity gradients

EFFECT: Decrease gravity gradient noise by a factor 50.

Step 10: Heavier mirrors

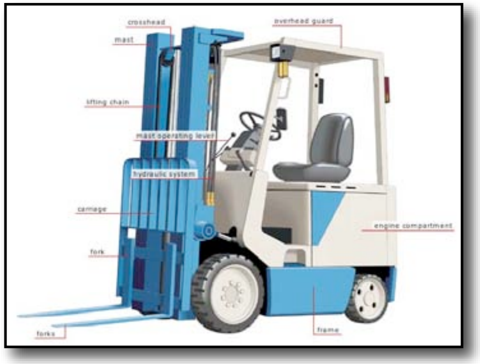

ET dummy curve, file=ET_sthild_11.m

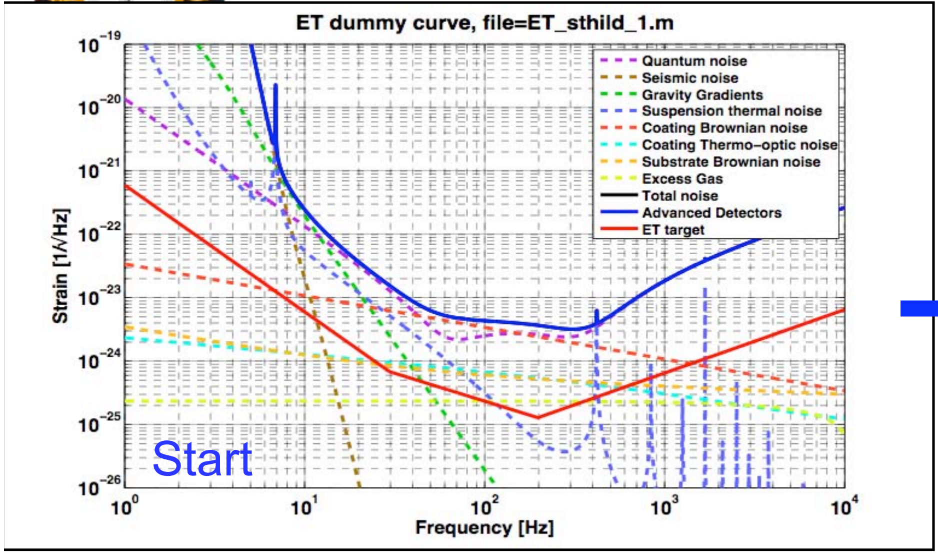
ET dummy curve, file=ET_sthild_12.m

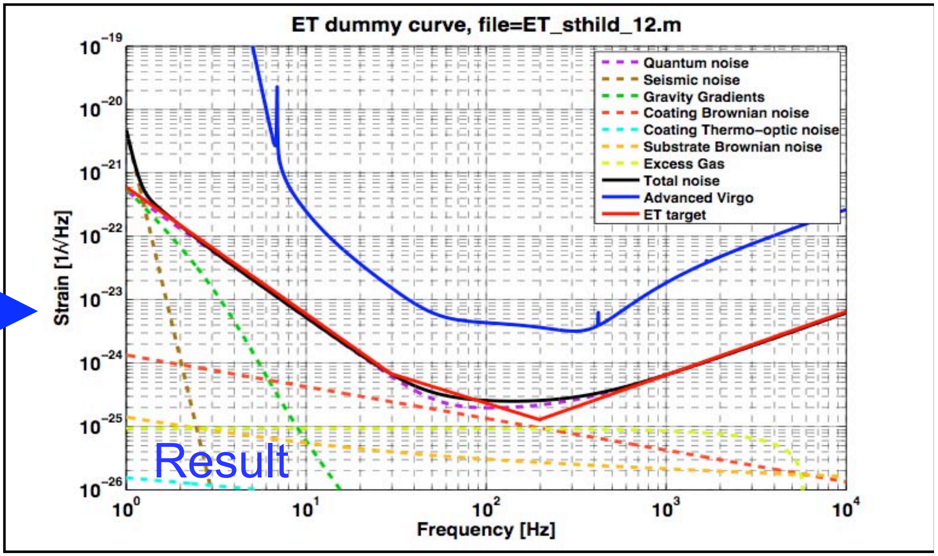
DRIVER: Quantum noise at low frequencies

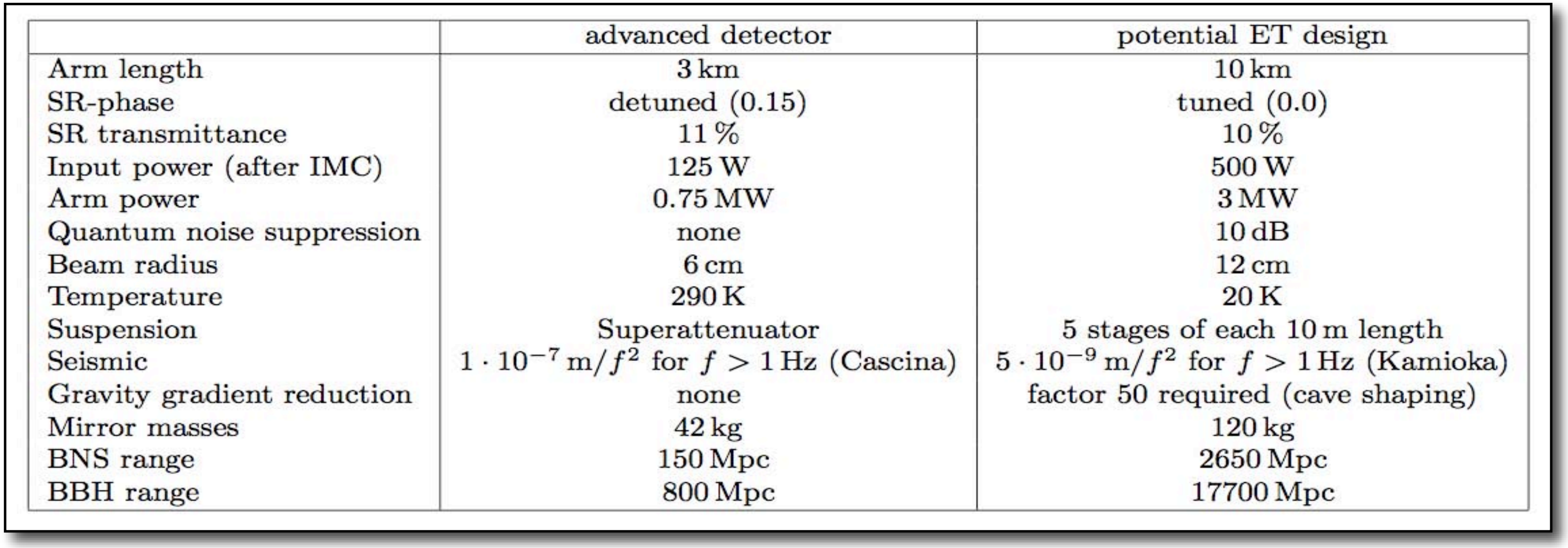
ACTION: Increase test mass weight from 42 kg to 120 kg

EFFECT: Decrease of radiation pressure noise







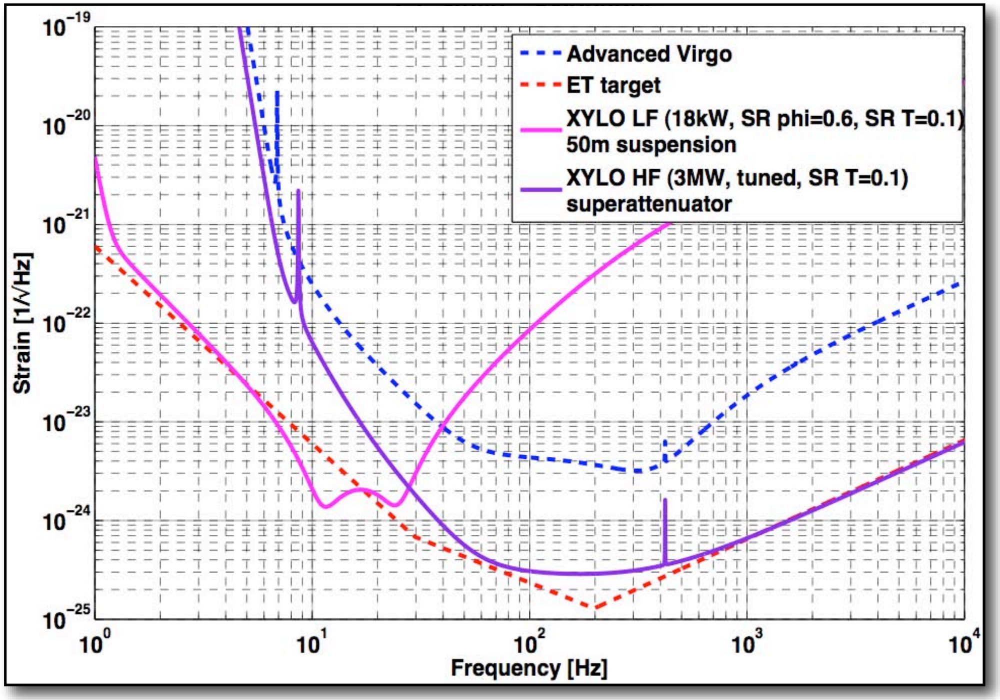


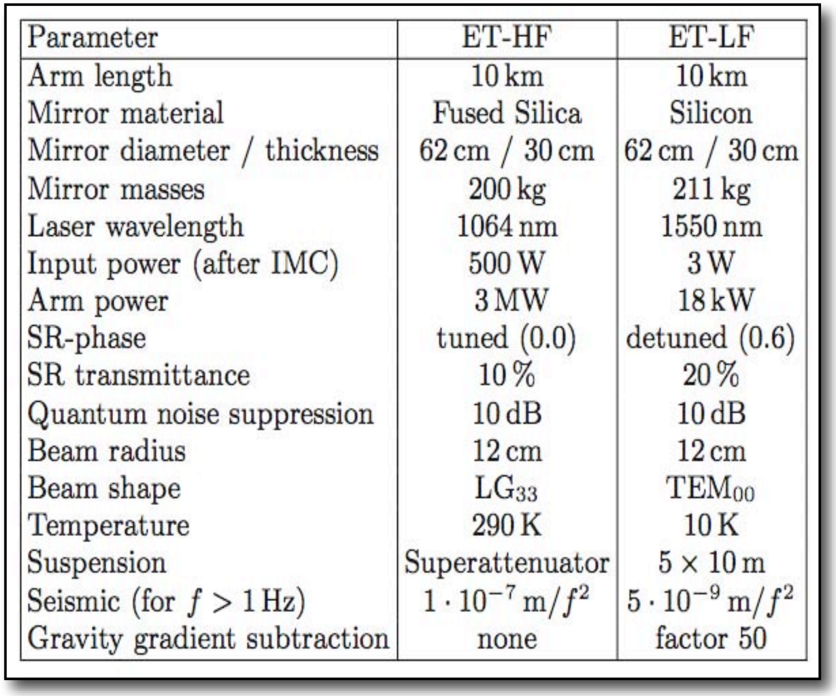
	advanced detector	potential ET design
Arm length	3 km	10 km
SR-phase	detuned (0.15)	tuned (0.0)
SR transmittance	11 %	10 %
Input power (after IMC)	125 W	500 W
Arm power	0.75 MW	3 MW
Quantum noise suppression	none	10 dB
Beam radius	6 cm	12 cm
Temperature	290 K	20 K
Suspension	Superattenuator	5 stages of each 10 m length
Seismic	$1 \cdot 10^{-7}\,\mathrm{m}/f^2$ for $f > 1\,\mathrm{Hz}$ (Cascina)	$5 \cdot 10^{-9}\,\mathrm{m}/f^2$ for $f > 1\,\mathrm{Hz}$ (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

Motivation for Xylophone observatories

- Due to residual absorption in substrates and coatings high optical power (3MW) and cryogenic test masses (20K) don’t go easily together.
- IDEA: Split the detection band into 2 or 3 instruments, each dedicated for a certain frequency range. All ‘xylophone’ interferometer together give the full sensitivity.
- Example of a 2-tone xylophone:
  - Low frequency: low power and cryogenic
  - High frequency: high power and room temperature

Xylophone: More than one detector to cover the full bandwidth





Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
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
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	10 dB	10 dB
Beam radius	12 cm	12 cm
Beam shape	LG$_{33}$	TEM$_{00}$
Temperature	290 K	10 K
Suspension	Superattenuator	5 × 10 m
Seismic (for $f > 1\,\mathrm{Hz}$)	$1 \cdot 10^{-7}\,\mathrm{m}/f^2$	$5 \cdot 10^{-9}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	factor 50

Low Frequency IFO: low optical power, cryogenic test masses, sophisticated low frequency suspension, underground, heavy test masses.

High Frquency IFO: high optical power, room temperature, surface location, squeezed light

E N D