Design Choices for the Core Optics of Advanced Detectors

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GWADW, Florida, May 2009

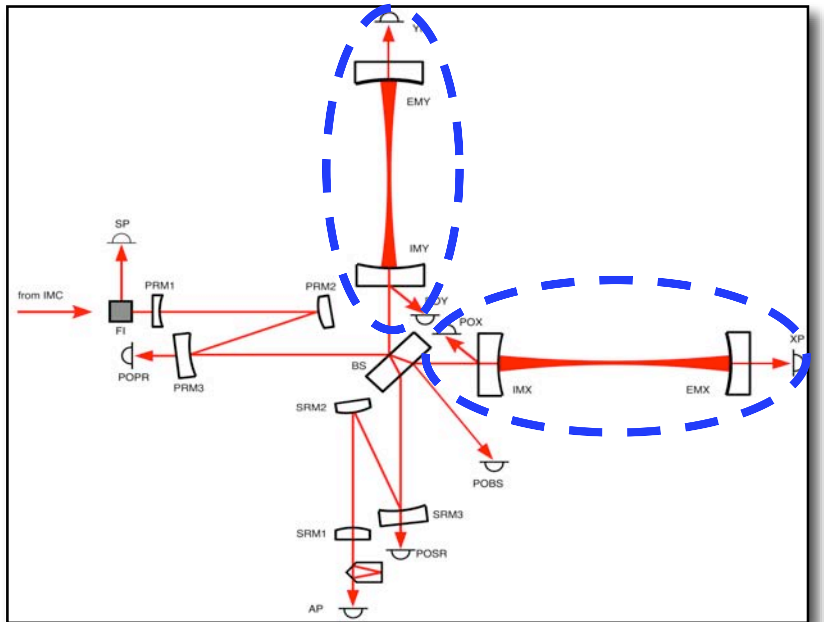
LIGO-G0900444-v1

Overview

- Arm cavity geometry (beam sizes, ROCs)
- Arm cavity finesse (high vs low)
- Mirror substrate geometry (etalon vs wedge)
- Recycling cavity design (NDRC vs MSRC)
- Signal Recycling configuration

Arm Cavities: The Core of a GWD

- In principle arm cavities are rather simple objects, consisting of just two mirrors and a space between them.
- In reality one has to carefully choose the characteristics of the arm cavities.
- Arm cavities are the 'heart' of the GW detector.
  - GW is here accumulated.



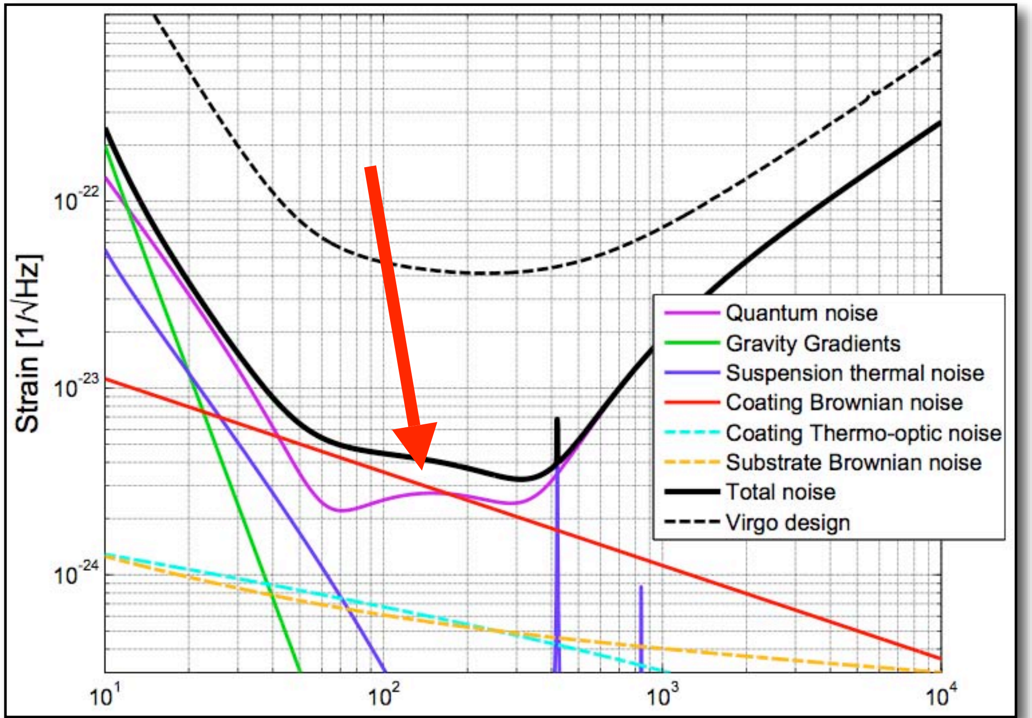
Arm cavity geometry

- Science driver: Coating Brownian noise

Coating Brownian noise of one mirror:

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

beam radius on mirror



→ Absolute beam size should be as large as possible.

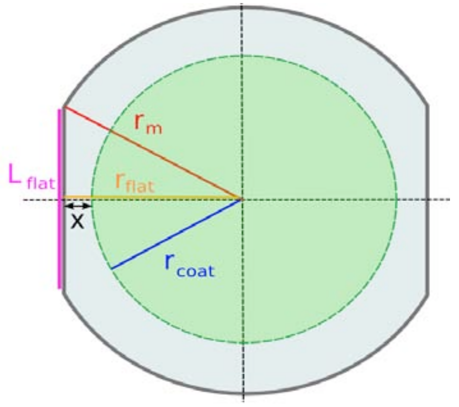
Beam Geometry

- Where to put the waist inside the arm cavity?
  - Initial detectors have the waist close/at the input mirrors

- Advanced detectors: Move waist towards the cavity center.
  - Larger beam at input mirror
  - Lower overall coating Brownian noise
  - BUT: much larger beams in the central interferometer
    - may need larger BS
    - much larger optics for input and output telescope
    - Non-degenerate recycling cavities might help

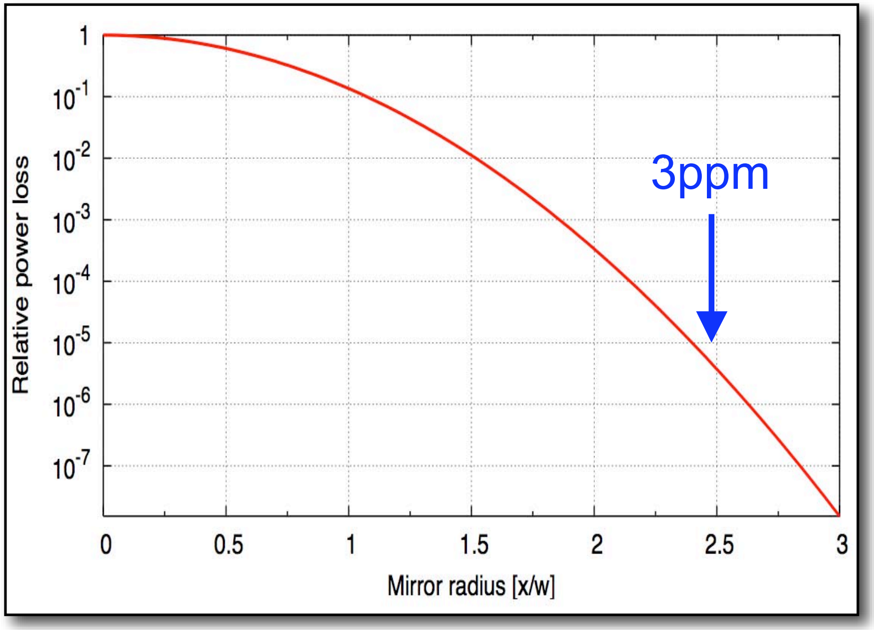
How to decide on Beam Size ?

- 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



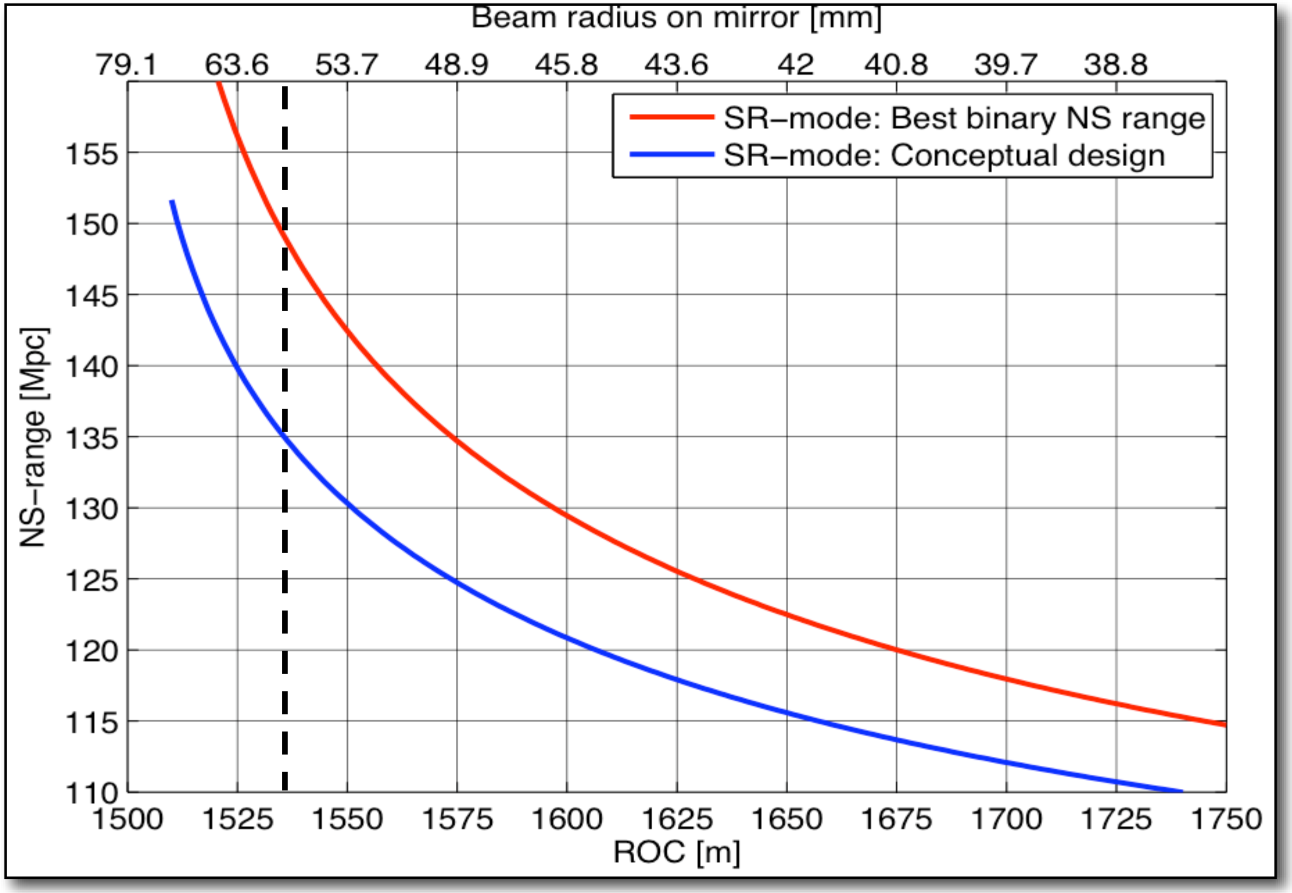
Advanced Virgo:

Mirror diameter 35cm

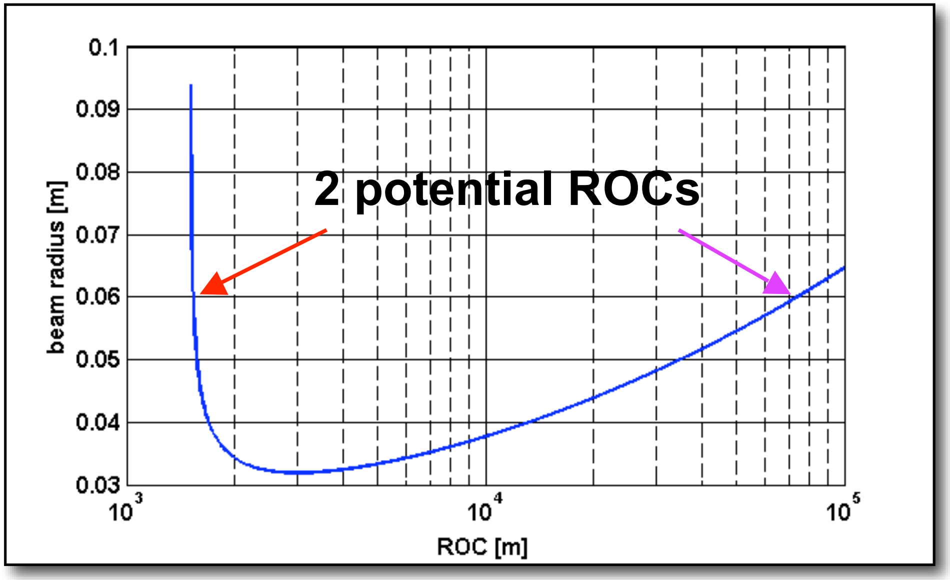
Maximal beam radius = 6.5cm

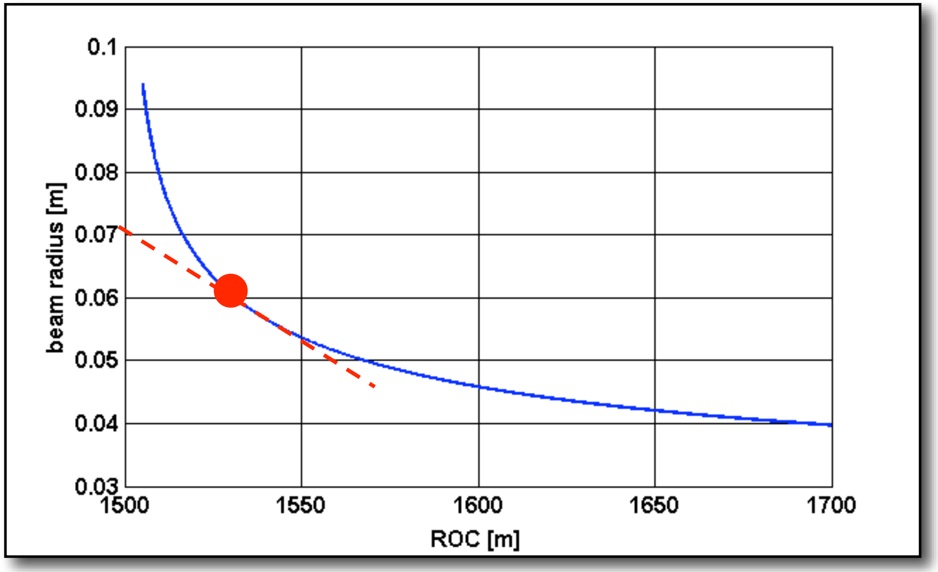
Sensitivity with symmetric ROCs

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



Choice of ROCs



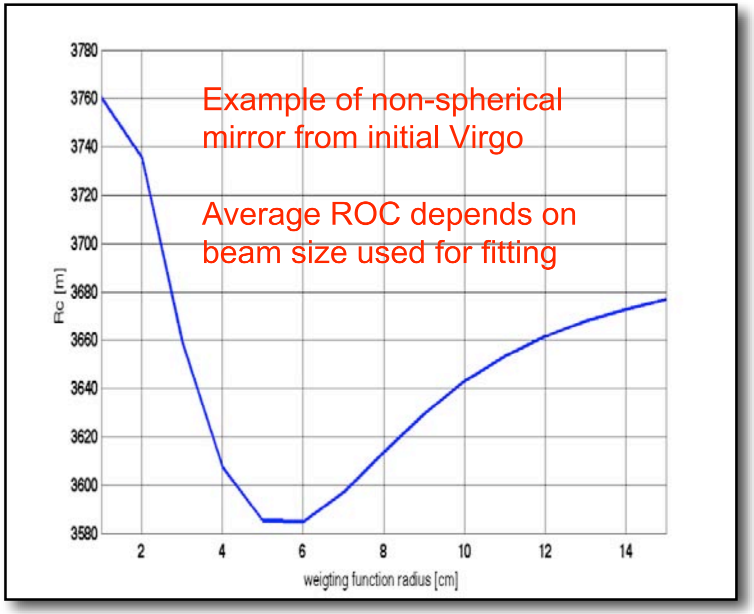


- 2 potential ways: either ROC close to L/2 or ROC>>L.
- Disadvantages of ROC close to L/2: beam size strongly depends on ROC.
- Disadvantages of ROC>>L: Tilt instability + hard to polish such a large ROC.
- 2nd Generation instruments go for ROC close to L/2

Cavity Stability and Choice of ROCs

- 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.
  - Additional problem: polished spheres are not spherical.

- Advanced Virgo: Believe that we can go for ROCs 2% of instability.
- Corrective coating as baseline.



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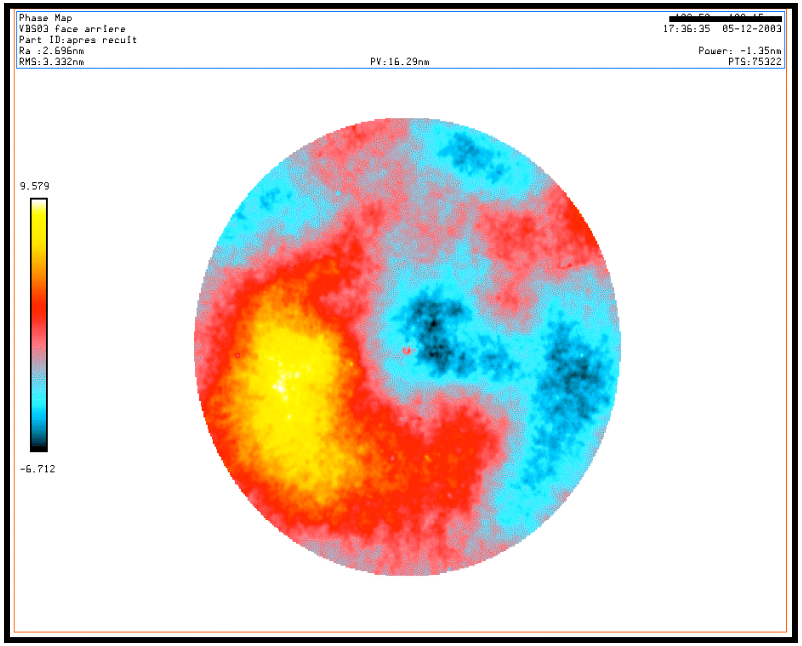
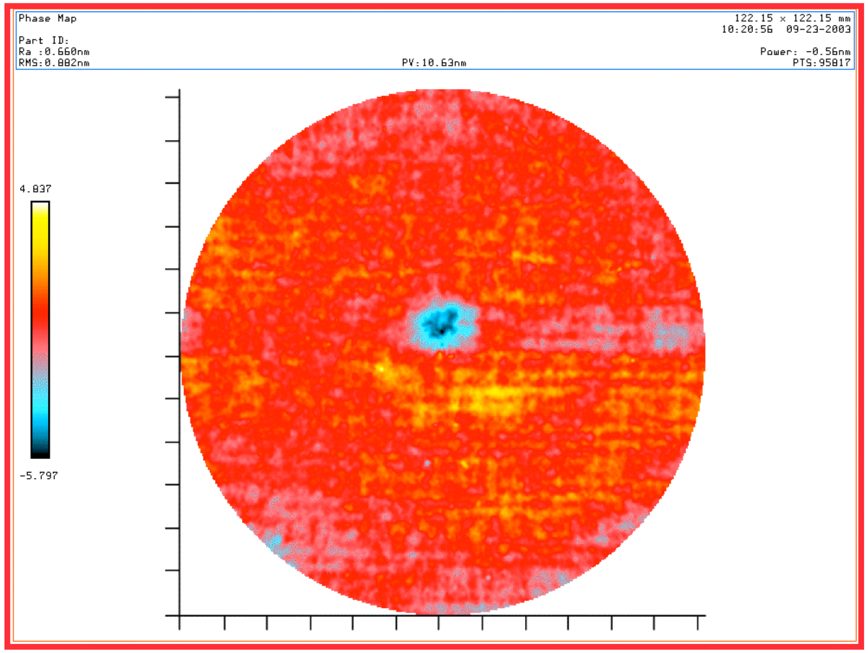
Corrective coating from LMA



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



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

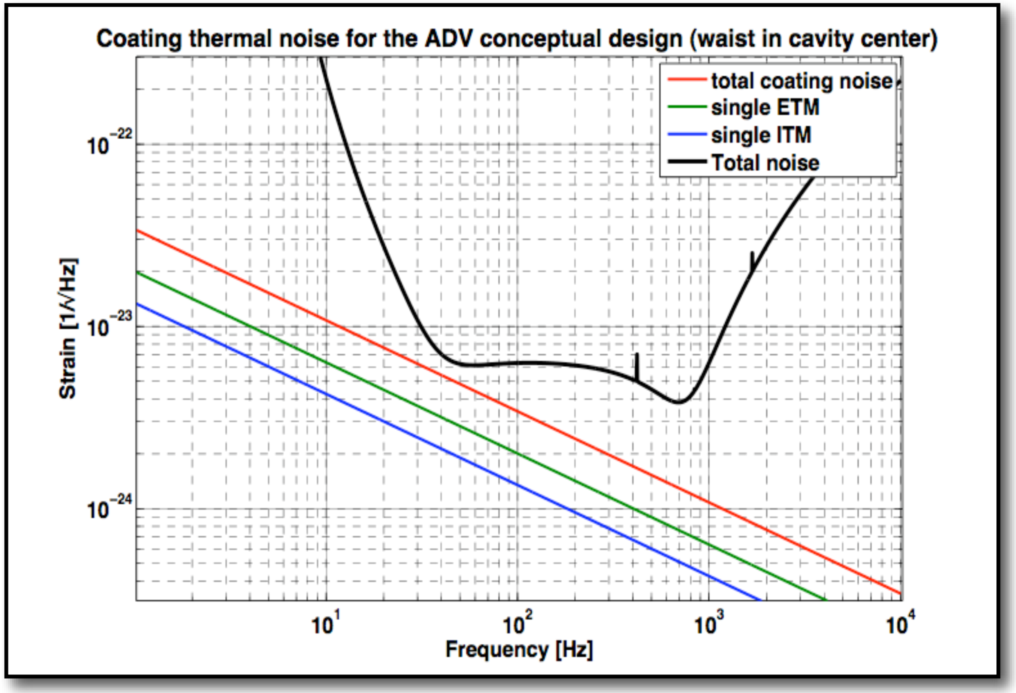
Symmetric ROCs of IM and EM ?

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

Coating thickness

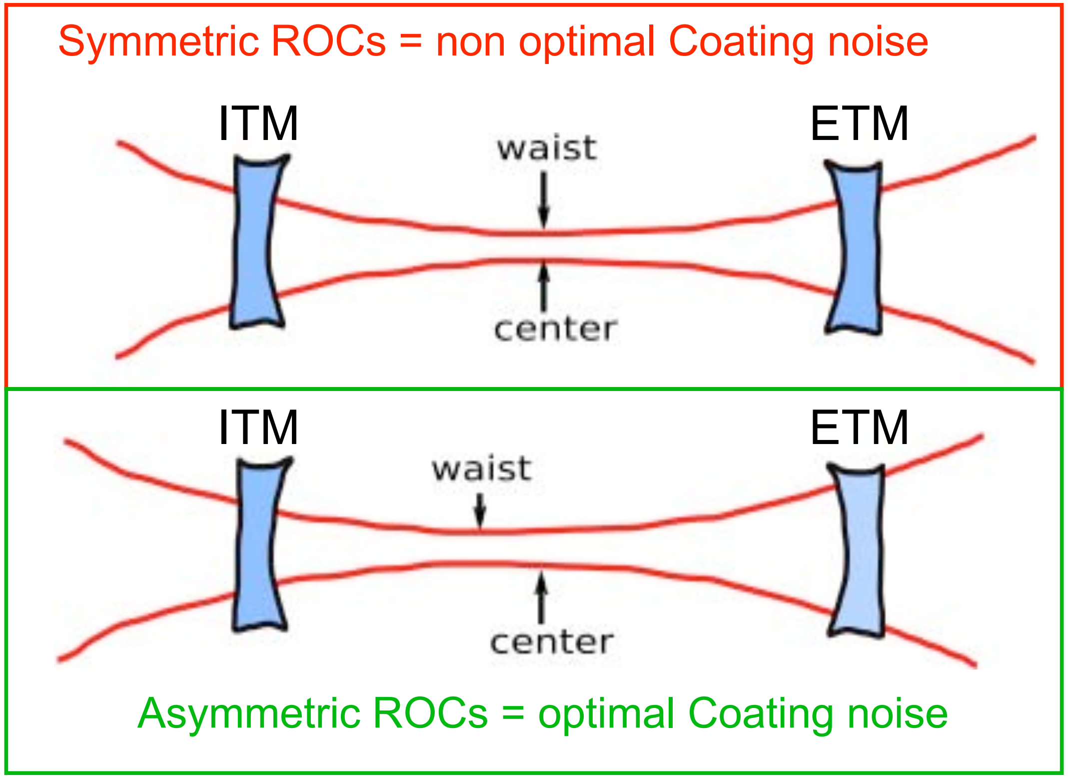
$$S_x(f) = \frac{4k_{\mathrm{B}}T}{\pi^2 f Y}\frac{d}{r_0^2}\left(\frac{Y'}{Y}\phi_{\|} + \frac{Y}{Y'}\phi_{\perp}\right)$$

- For equal beam size ETM has higher noise.



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.



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Cavity Stability and Choice of ROCs

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

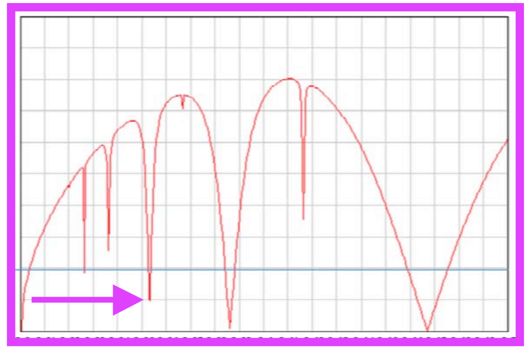
$$\phi_{l+m} = (l+m)\frac{1}{\pi}\arccos\sqrt{(1-\frac{L}{R_{c,i}})(1-\frac{L}{R_{c,e}})}.$$

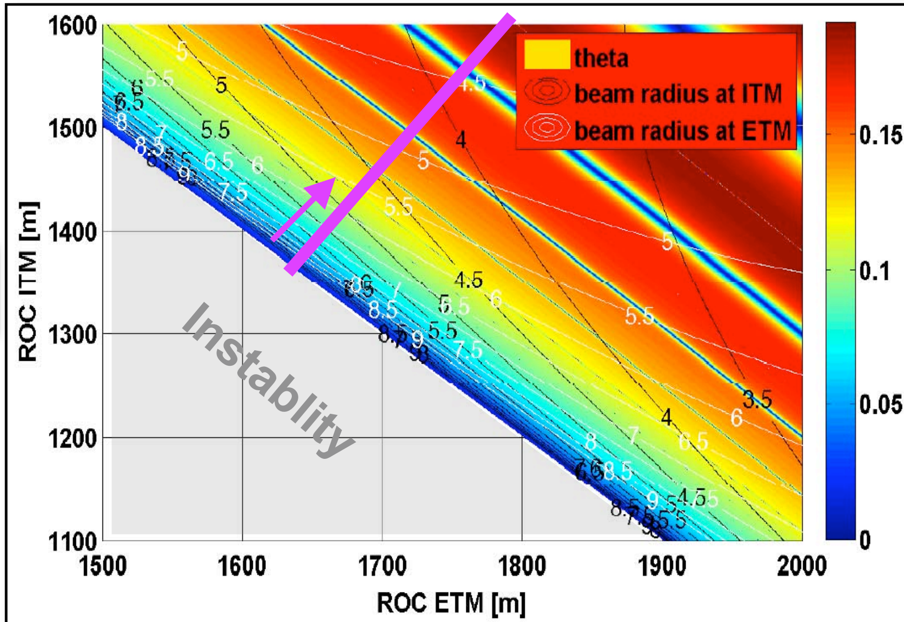
  - Mode-non-degeneracy for a single mode is:

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

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

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



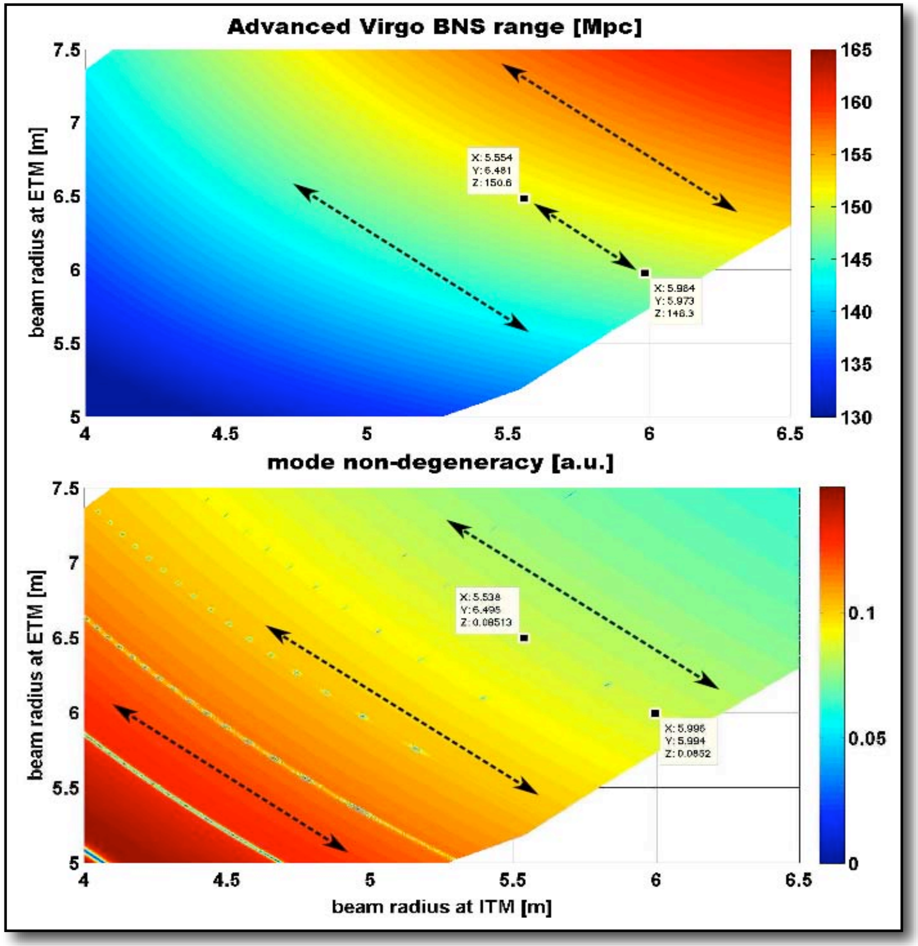


Choice of ROCs/beam size: Sensitivity vs Mode-non-degeneracy

- 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.

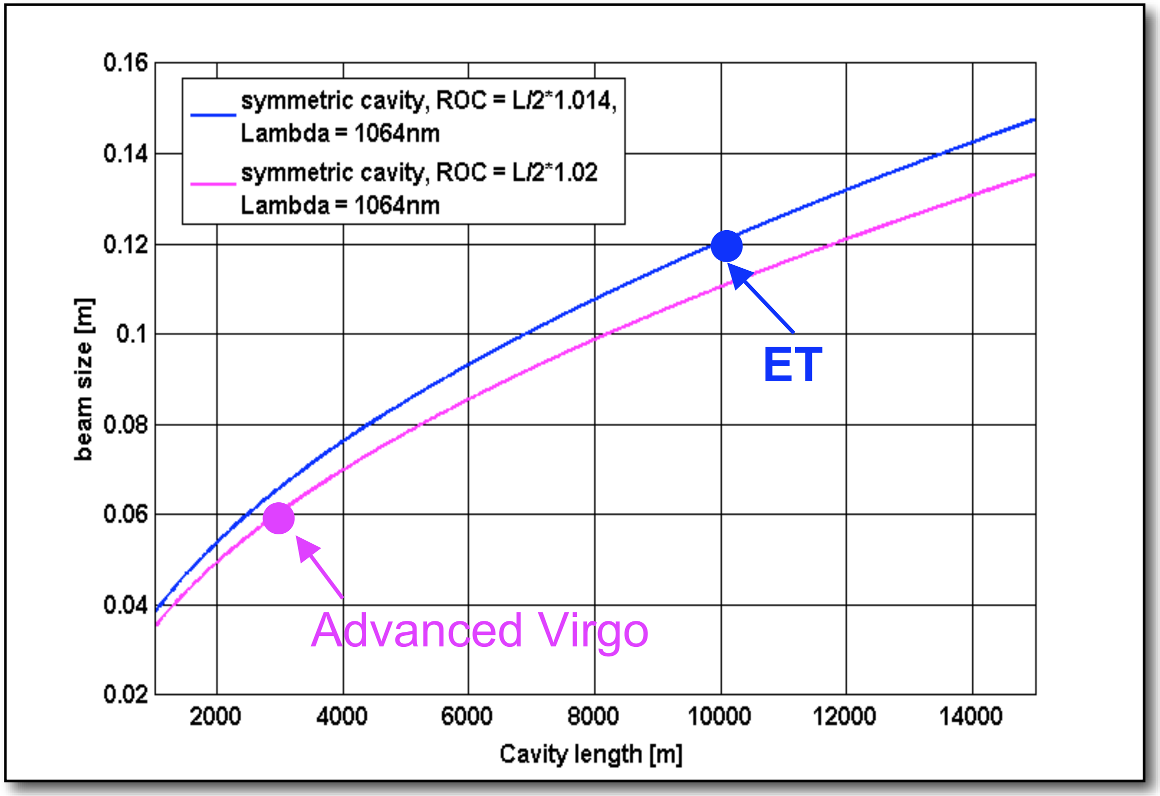
	input mirror	end mirror
beam radius [mm]	56	65
ROC [m]	1416	1646

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



Potential beam sizes for ET

- How large can we make the beam size for ET?
- Assuming we could go for a ROC 2% off instability.
- Assuming polishing improves we could think of going only 1.4% away from instability.
- For a 10km arm length we could increase the beam radius to 12cm.
- Minimal testmass dimension: 62cm diameter, 30cm thickness = about 200kg.

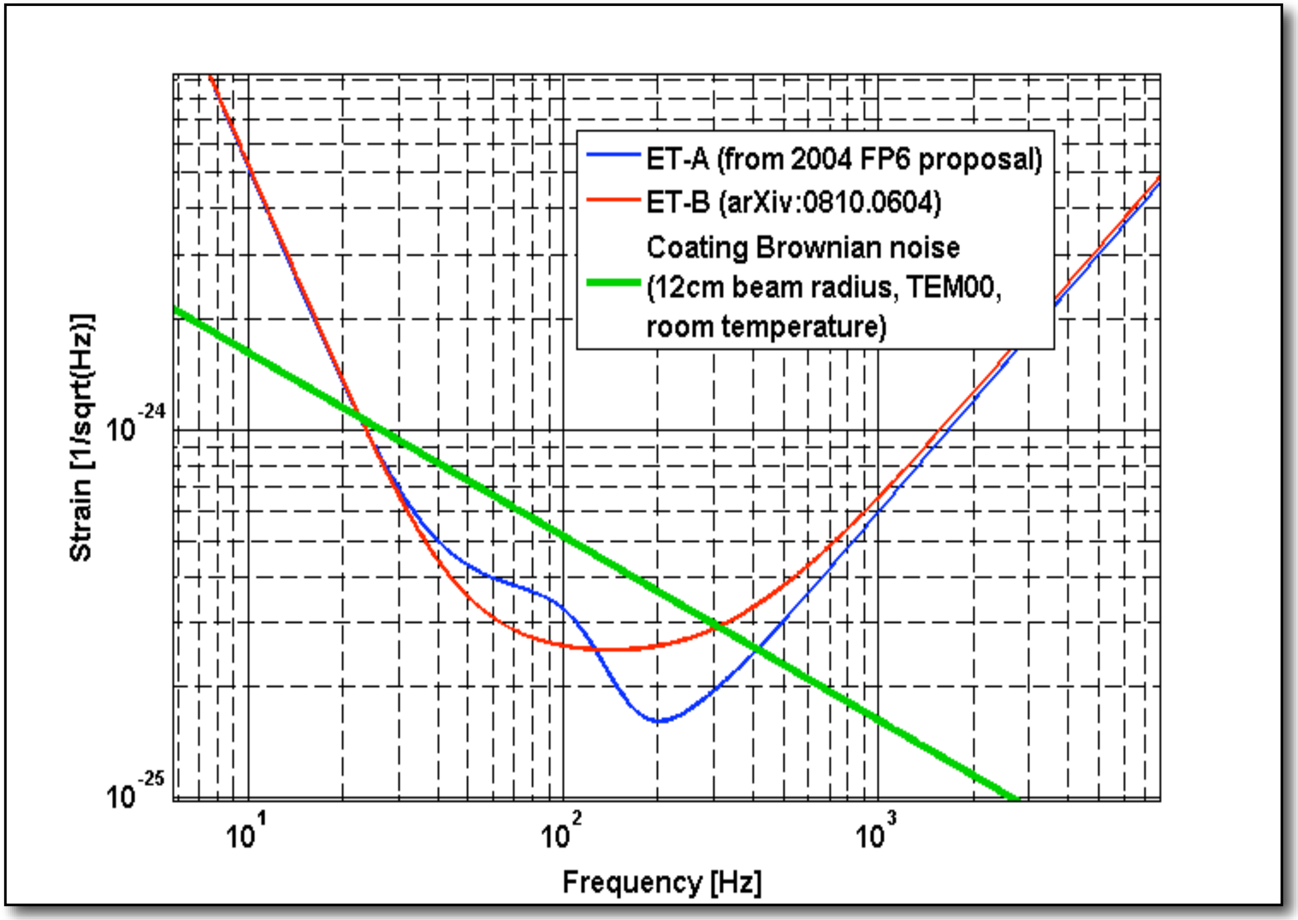


Will test masses (fused silica, silicon) with such dimensions become available in the next years ??

Coating noise: What factor is still missing?

- Assuming ET with 10km arms, TEM_{00}, room temperature and 12cm beam radius.

- To reach the ET target we need another factor 2 to 3.
  - Cryogenic ??
  - Better coatings ??
  - Different beam geometry?



Overview

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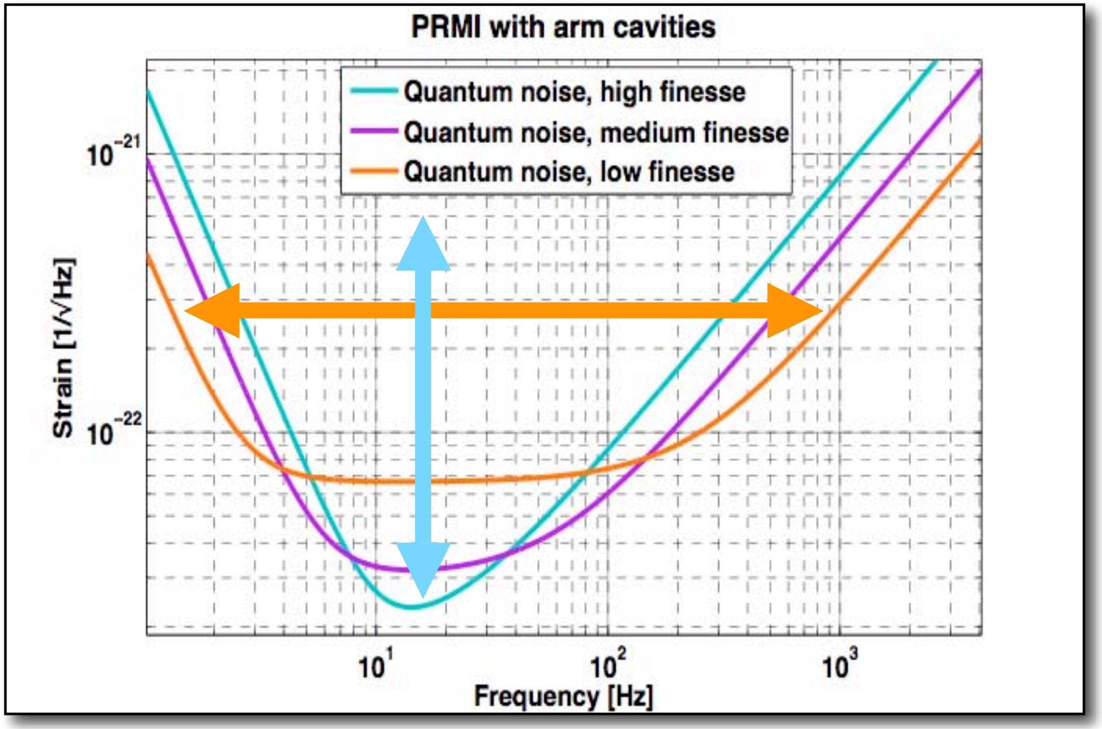
Michelson sensitivity versus arm cavity finesse

- In the initial detectors the arm cavity finesse determines the detector bandwidth:
  - Low finesse = large bandwidth
  - High finesse = best peak sensitivity

- Is this also true for an interferometer with Signal Recycling?



How to compare different arm cavity finesse values?

- A change of arm cavity finesse goes hand in hand with a change of the optical power inside the arm cavities.
- If we decrease the arm cavity finesse, the stored optical power will go down as well. => stronger shot noise contribution. => not a fair comparison.
- One can compensate for the lower finesse by increasing the power recycling gain.
- Our approach for a fair comparison: If we change the arm cavity finesse we will always restore the intra cavity power by increasing the power recycling gain, thus we always compare configurations with ~750kW per arm.

Sensitivity for finesse 888 and 444

➲ Let's see how the ADV sensitivity changes if we lower the arm cavity finesse by a factor of 2.

Step 1:
- double ITM transmission
- double PR factor

ITM transmission:	0.0070
PRM transmission:	0.0464
Finesse:	888.08
Power Recycling Factor:	21.53
Arm power:	760.78 kW

↓

ITM transmission:	0.0141
PRM transmission:	0.0240
Finesse:	444.04
Power Recycling Factor:	41.19
Arm power:	727.69 kW

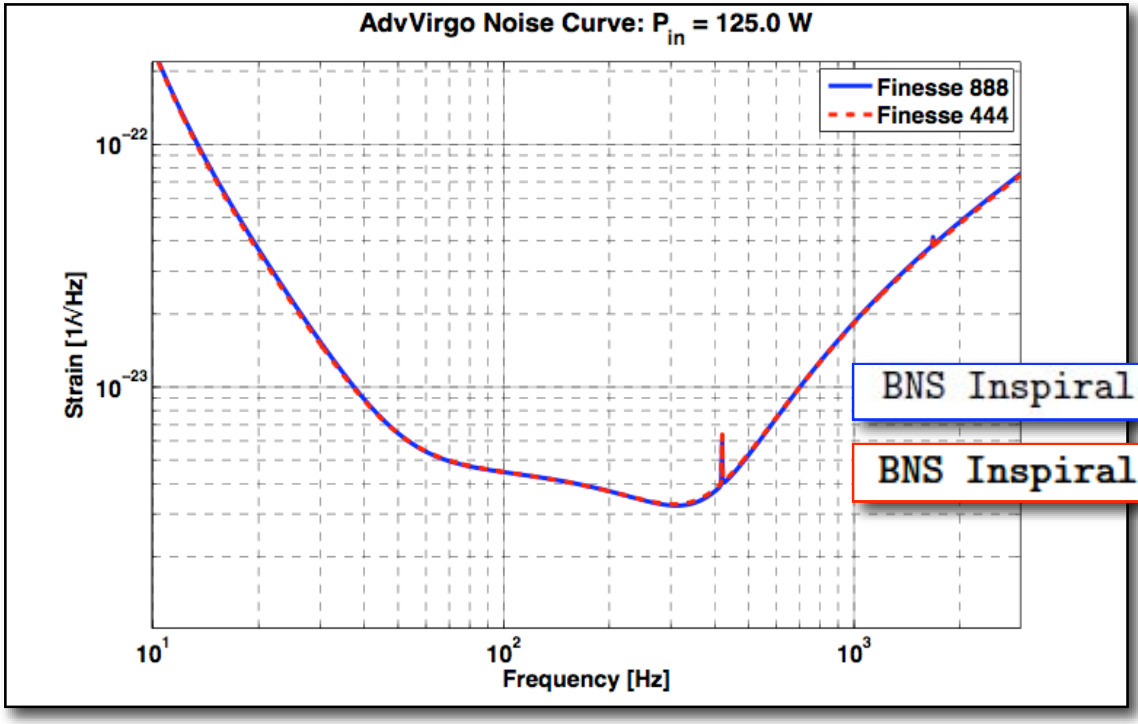
Step 2:
If we half the arm cavity finesse we also have to compensate the Signal Recycling parameters:
- double Signal Recycling detuning
- double SRM transmittance

SRM Detuning:	8.59 degree
SRM transmission:	0.1100

↓

SRM Detuning:	17.19 degree
SRM transmission:	0.2200

Sensitivity for finesse 888 and 444



Please note: in this analysis coating Brownian of the ITM was considered to be constant. See slide 23 for the influence of the coating layer number.

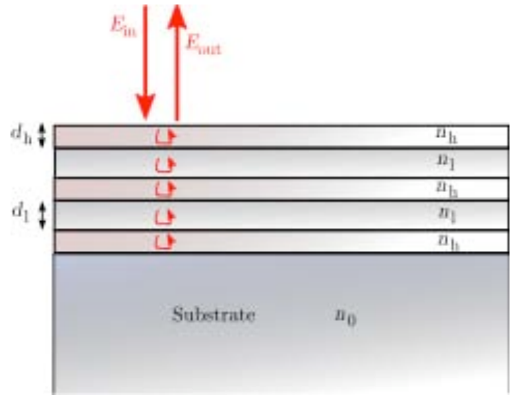
BNS Inspiral Range: 148.58 Mpc

BNS Inspiral Range: 148.75 Mpc

- The Advanced Virgo sensitivity is (within a certain) range independent of the arm cavity finesse !!

Coating Brownian and finesse (I)

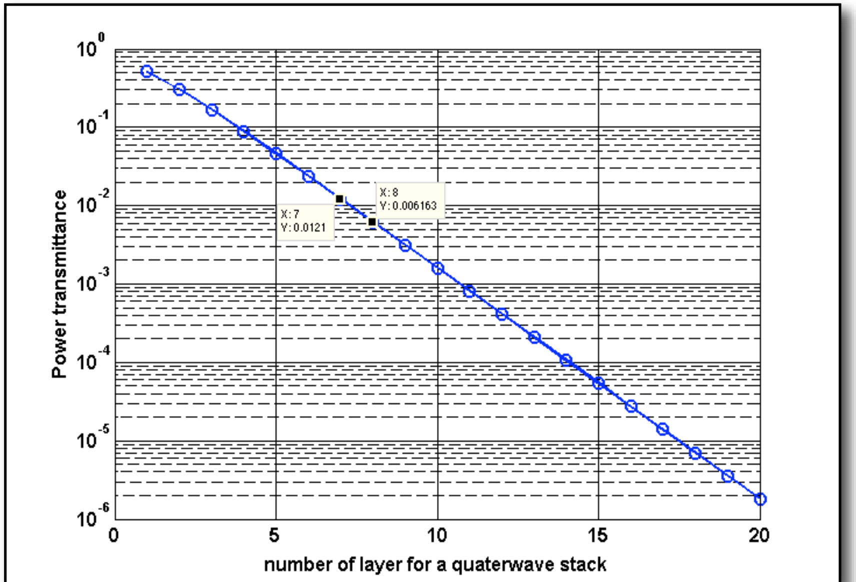
- Lower finesse => higher transmittance of the ITM HR coating.
- Lowering arm cavity finesse from 888 to 444:
  - increasing ITM transmittance from 0.007 to 0.014
  - might be able to get rid of one coating layer on ITM
  - Reduce coating Brownian of ITM

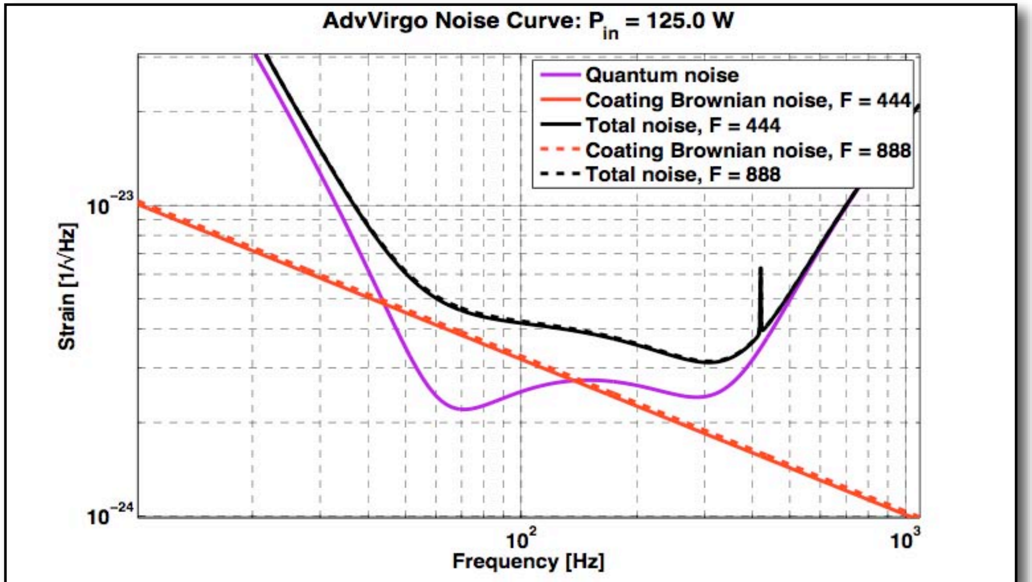


Coating Brownian noise of one mirror:

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

Coating Brownian and finesse (II)





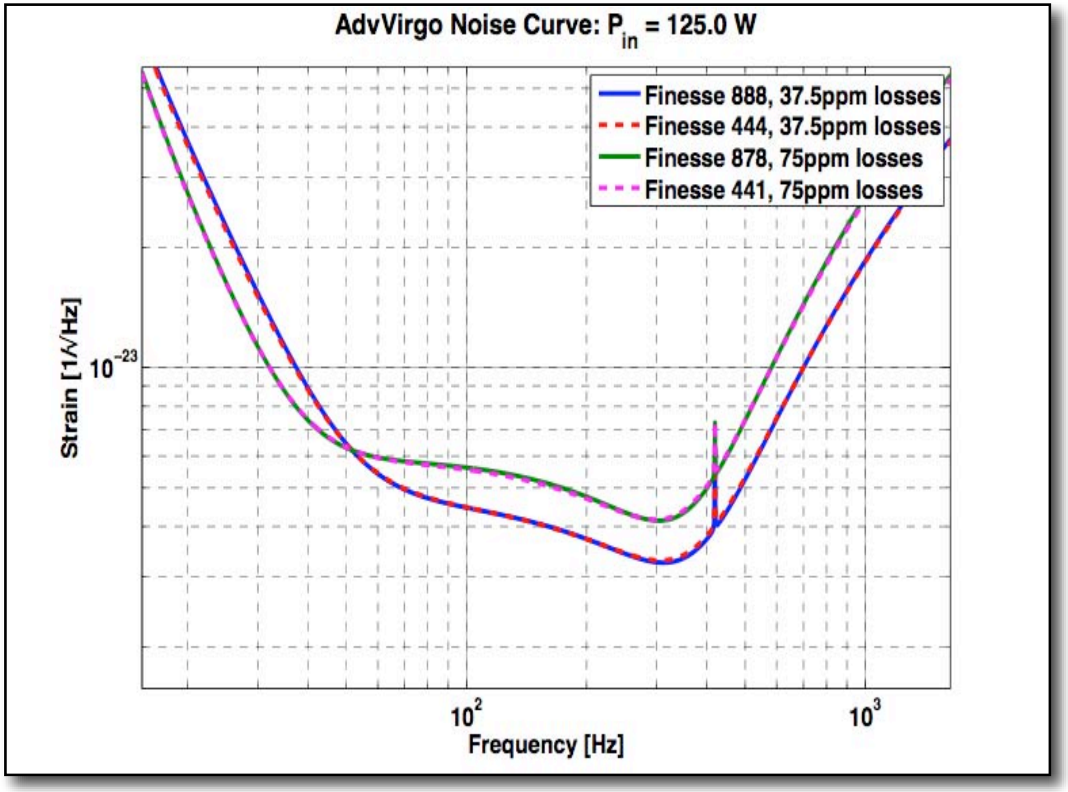
Optic	Number of HLL	Thickness of low index material [m]	Thickness of high index material [m]
ITM, Fin = 888	8	1.83e-6	1.05e-6
ITM, Fin = 444	7	1.65e-6	0.92e-6
ETM	16	3.30e-6	2.09e-6

- When going from 888 to 444 in arm cavity Finesse the BNS inspiral increases by only 1.3%.
- We do not consider this small influence as significant.

Finesse and mirror losses

- Advanced Virgo preliminary design assumes 37.5ppm loss per surface.
- This is an ambitious goal. What happens if the losses turn out to be twice as much (75ppm)? Any influence of arm cavity finesse?

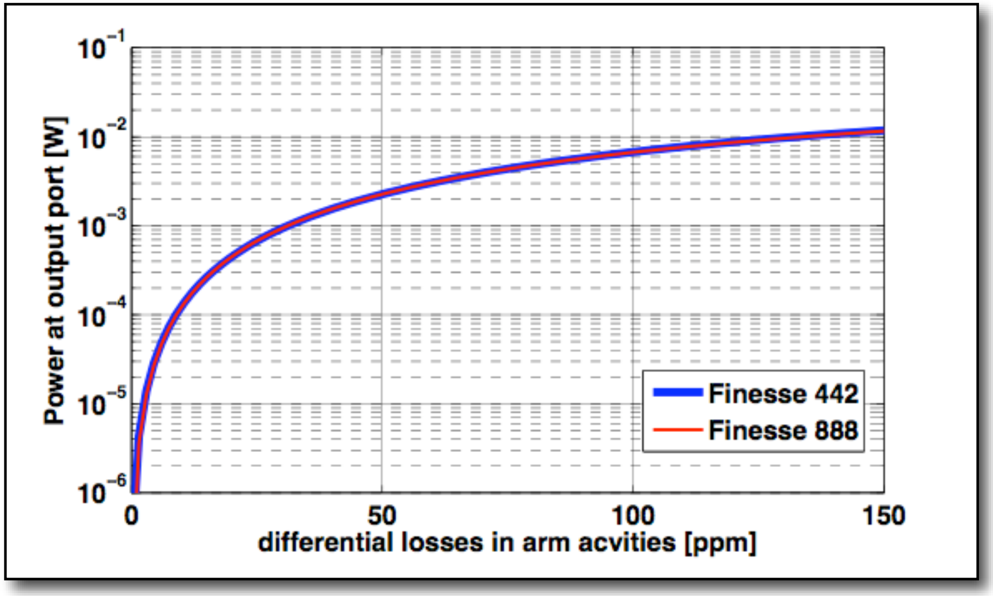
- The sensitivity changes with the actual mirror losses, BUT is independent of the arm cavity finesse.



Dark fringe offset and arm cavity finesse

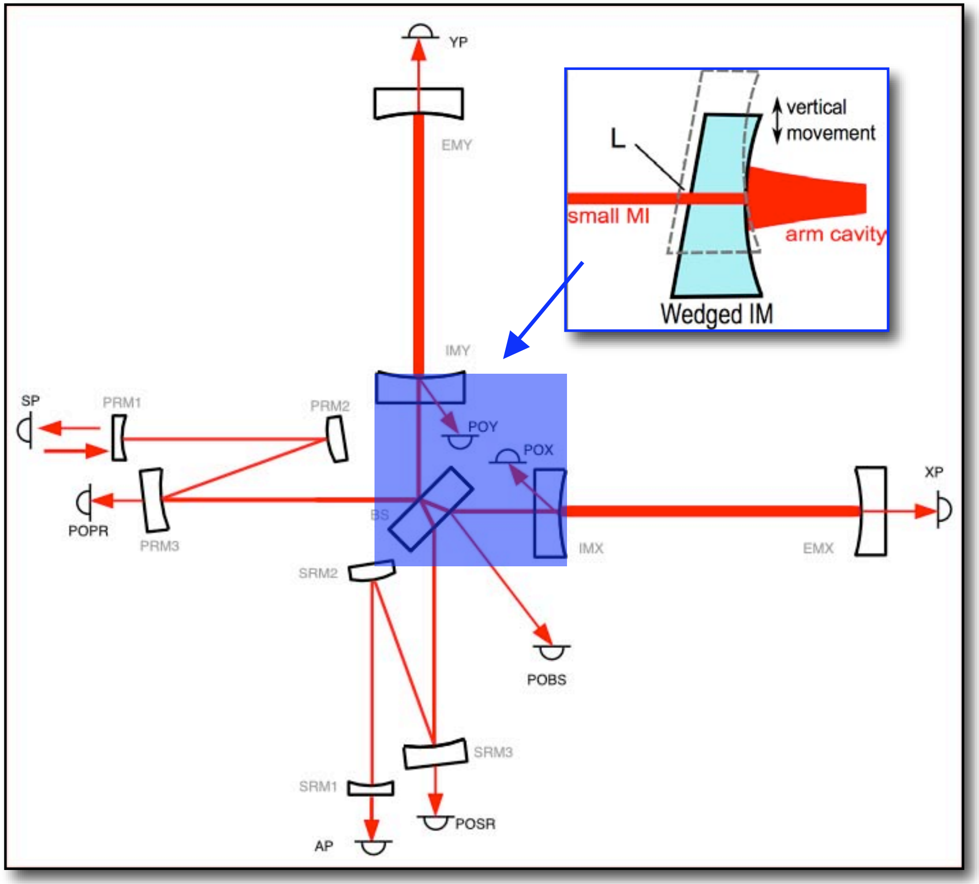
- Consider imbalanced losses in the two arm cavities. => Does the coupling of differential losses to dark port power depend on the arm cavity Finesse?
- Performed a simple numerical simulation using Finesse software:

- The coupling of differential losses to the dark port power is independent of the arm cavity finesse.



Noise coupling from the small Michelson

- All differential arm length noise inside the small Michel-son (MICH) gets suppressed by the arm cavity finesse.
- Lower finesse => stricter requirements for:
  - Thermo refractive noise inside ITMs, CPs, BS.
  - Quietness of wedged optics (CPs? ITMs? BS?)
  - … etc …



Thermal load of BS, CP and ITM substrates

- Optical power inside the power recycling cavity is proportional to inverse of the arm cavity finesse.
- Lowering the arm cavity finesse from 888 to 444 increases optical power in BS, CP and ITM substrates from 2.6kW to 5.1kW.

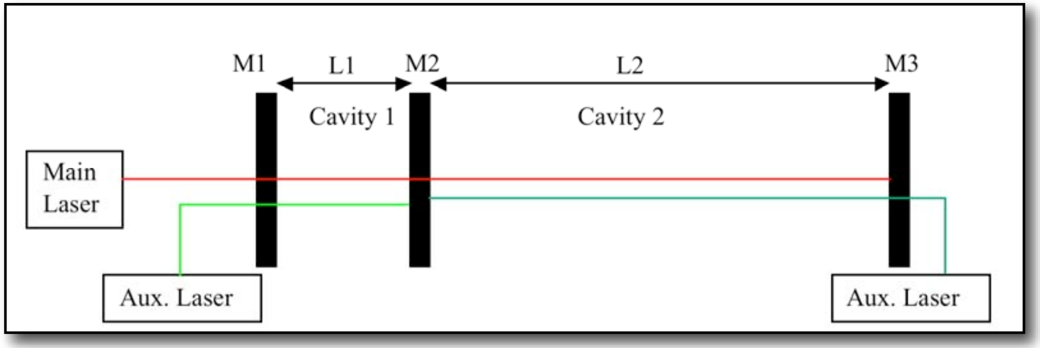
ITM transmission:	0.0070
PRM transmission:	0.0464
Finesse:	888.08
Power Recycling Factor:	21.53
Arm power:	760.78 kW
Power on beam splitter:	2691.27 W

ITM transmission:	0.0141
PRM transmission:	0.0240
Finesse:	444.04
Power Recycling Factor:	41.19
Arm power:	727.69 kW
Power on beam splitter:	5148.41 W

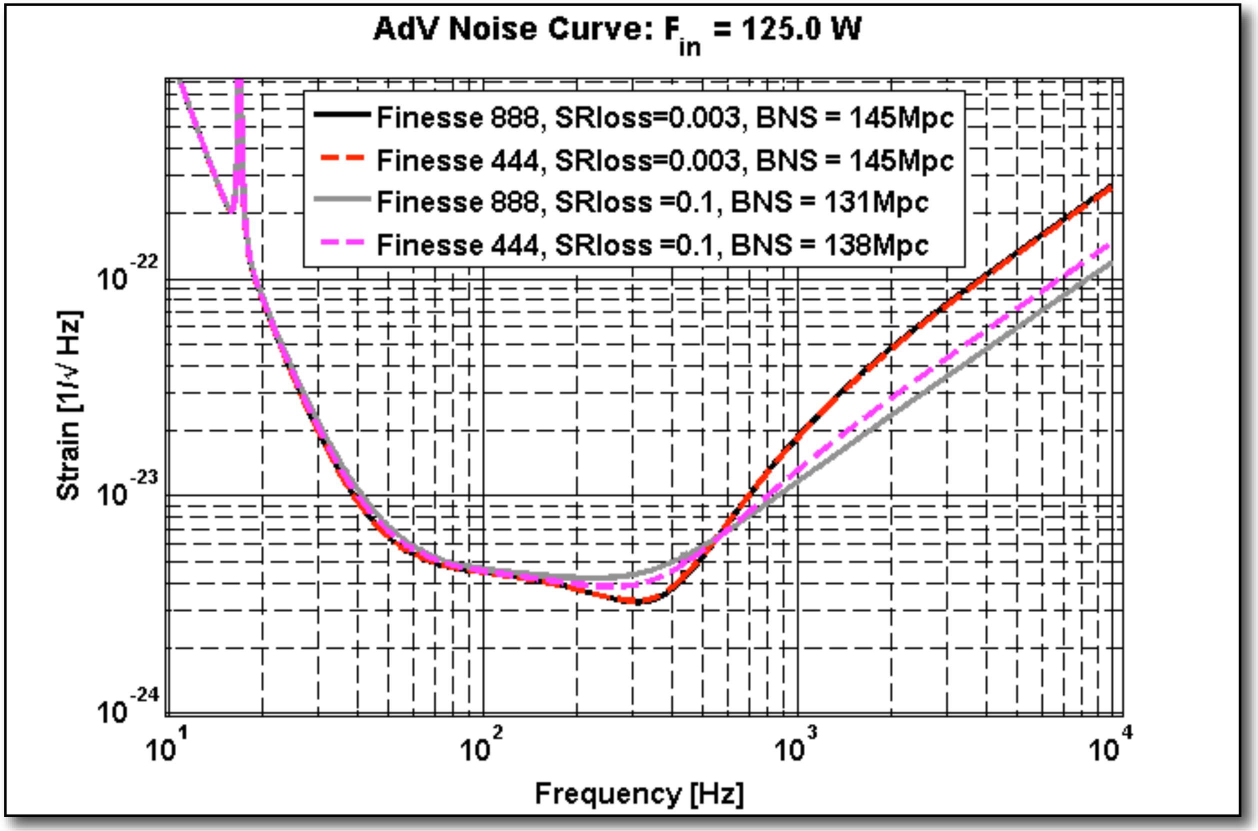
- The lower the arm cavity finesse the more optical power is inside the substrates of the CITF.
- As long as the finesse is not too low (<100) should be no serious problem.

Lock-acquisition and finesse

- The capture range of arm cavities inverse proportional to the Finesse.
- Would lowering the arm cavity finesse makes lock acquisition easier.
- However, advanced detectors might use auxiliary systems for lock acquisition.
- Baseline for Advanced Virgo: lock acquisition with auxiliary lasers (different wavelength)



Losses inside the SRC



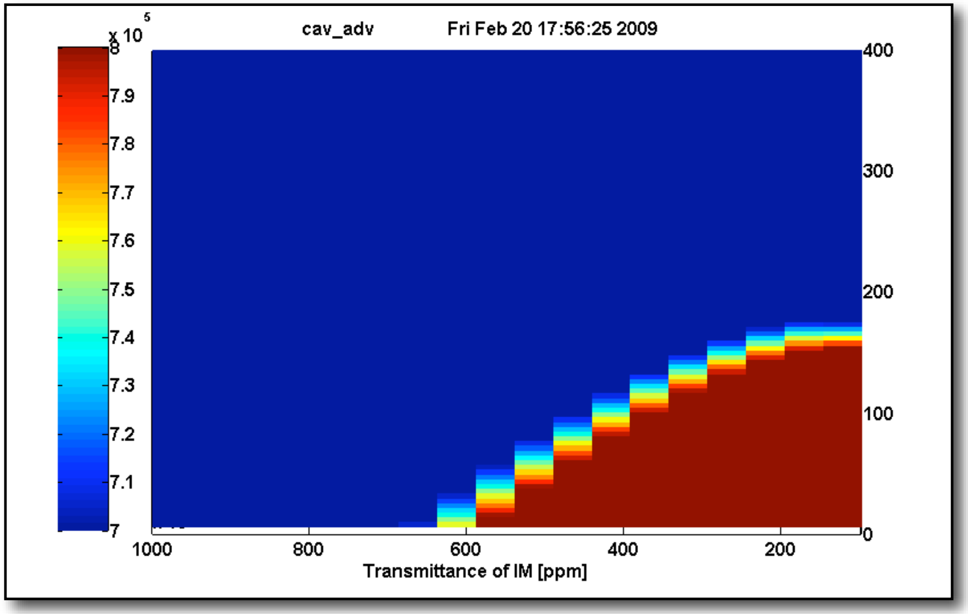
- If there are unexpectedly high losses inside the SRC, then a low arm cavity finesse would be better.

Potential reasons for lowering the finesse?

- Sensitivity ……………………………………………….*independent*
- Coating Brownian from ITMs ……………………….. *independent*
- Mirror losses ………………………………………..*independent*
- Coupling of diff losses to dark port power ………*independent*
- Noise couplings from small Michelson ……………..**NO**
- Thermal load of BS, ITM and CPs ………………….**NO**
- Lock acquisition ……………………………………**YES,** ***not in AdVirgo***
- Losses inside the recycling cavities ………………….**YES**

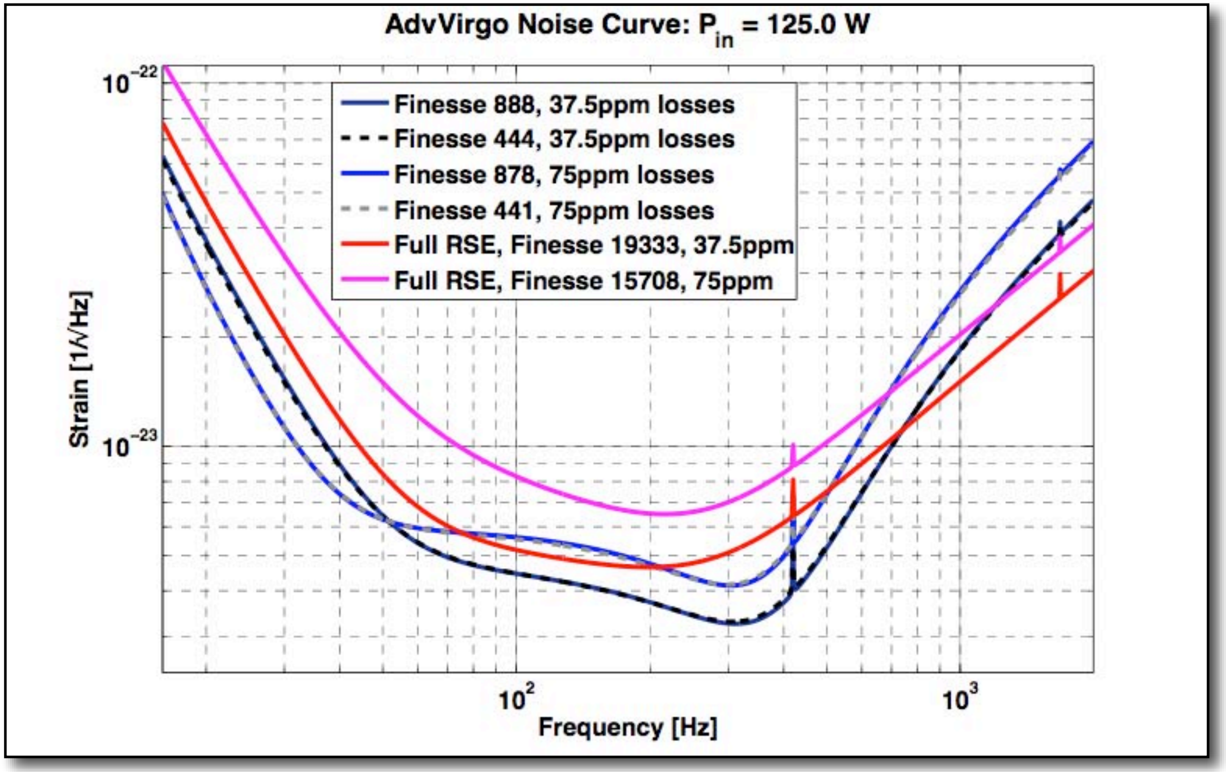
Full RSE (I)

- Recently the question rose, why not to use full RSE? This would mean:
  - Get rid of power recycling
  - Increase arm cavity finesse to restore high optical power.
  - Increase SRM reflectivity.



- To get 750 kW:
  - ITM transmittance = 300ppm
  - Arm cavity Finesse = 19333
- Adjusting RSE again:
  - SRM transmittance = 0.005

Full RSE (II)



- High Finesse ‘amplifies’ the influence of losses inside the signal recycling cavity. With 37.5ppm loss per surface Full RSE cannot achieve a sensitivity compatible with dual-recyling.

Arm cavity finesse of ET

- Arm cavity finesse seems to be rather flexible.
- As long as one does not go 'too' low or 'too' high there should be no problem.

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- Arm cavity geometry (beam sizes, ROCs)
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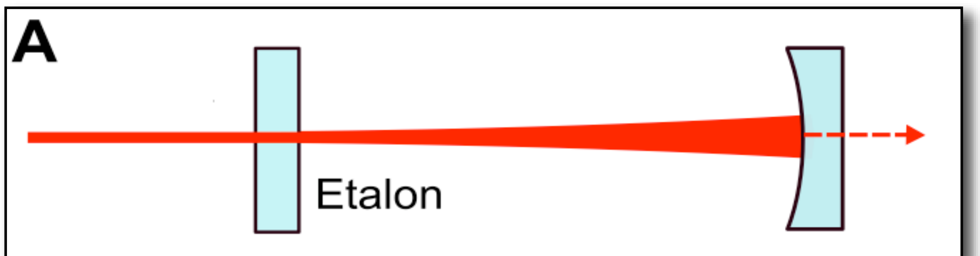
Wedges vs Etalon

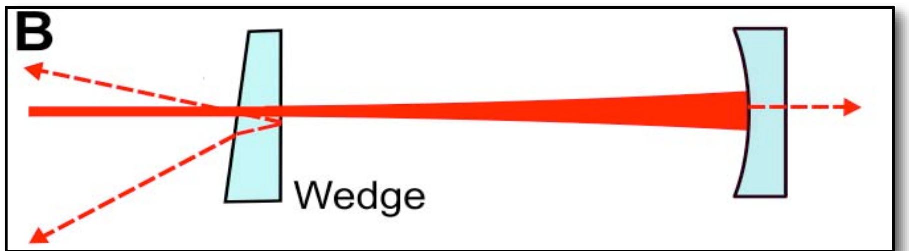
Input mirror etalon:

- Initial Virgo has no wedges in the input mirrors
- The etalon effect could be used for adjusting the cavity finesse (compensating for differential losses)
- If etalon effect is not controlled it might cause problems

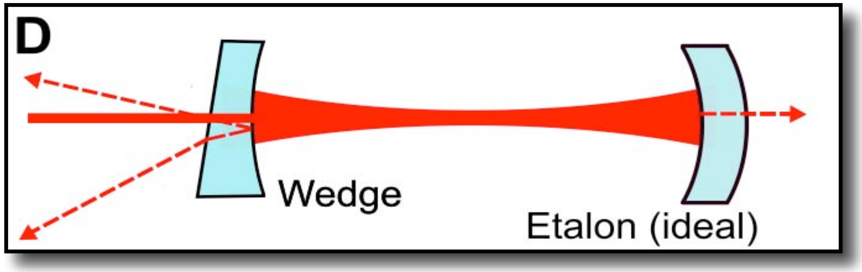
Input mirror with wedge:

- Used by initial LIGO
- Reflected beams from AR coating can be separated from main beam => pick-off beams provide additional ports for generation of control signals.
- No etalon effect available.





Possible design option: Wedges at input mirrors and etalon effect at end mirrors

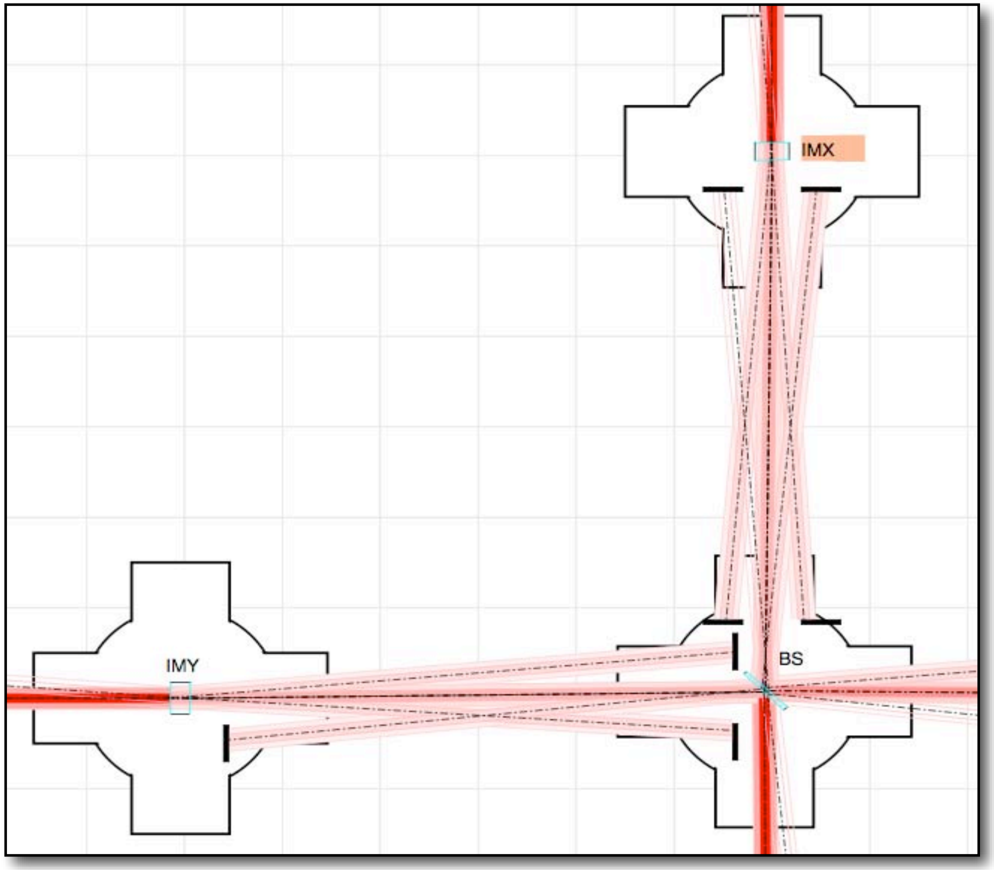


- Wedge at input mirrors:
  - Allows for additional pick-off beams

- Use etalon effect at end test mass
  - Tune etalon to balance arms => reduce noise couplings => might speed up commissioning
  - Tune etalon to change readout quadrature in DC-readout.
  - Replace AR-coating by a coating of about 10% reflectivity.
  - Ideally use a curved back surface (same curvature as front).

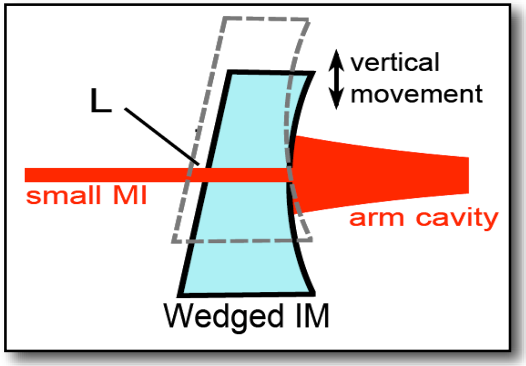
Wegdes at Input Mirrors

- Need a wedge large enough to separate beams within about 5 meter (distance ITM to BS).
- For 6cm beam radius a wedge of about 1.5 deg is required.
- High hardware impact (larger vacuum tube in centeral IFO, more optical elements)



Differential Arm Length Noise from vertical Movement of wedged Input Mirrors

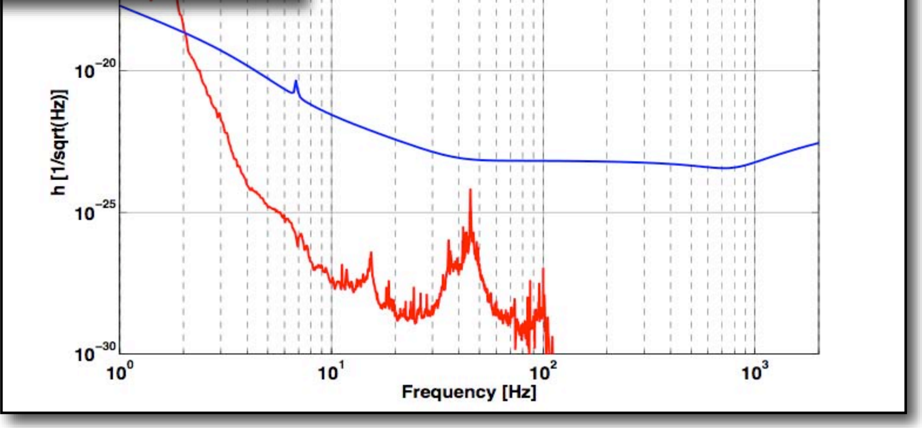
- Lateral movement of a wedged mirror cause length sensing noise.



More detail in
Hild et al: VIR-037A-08

- Need to do a projection of seismic noise to DARM:

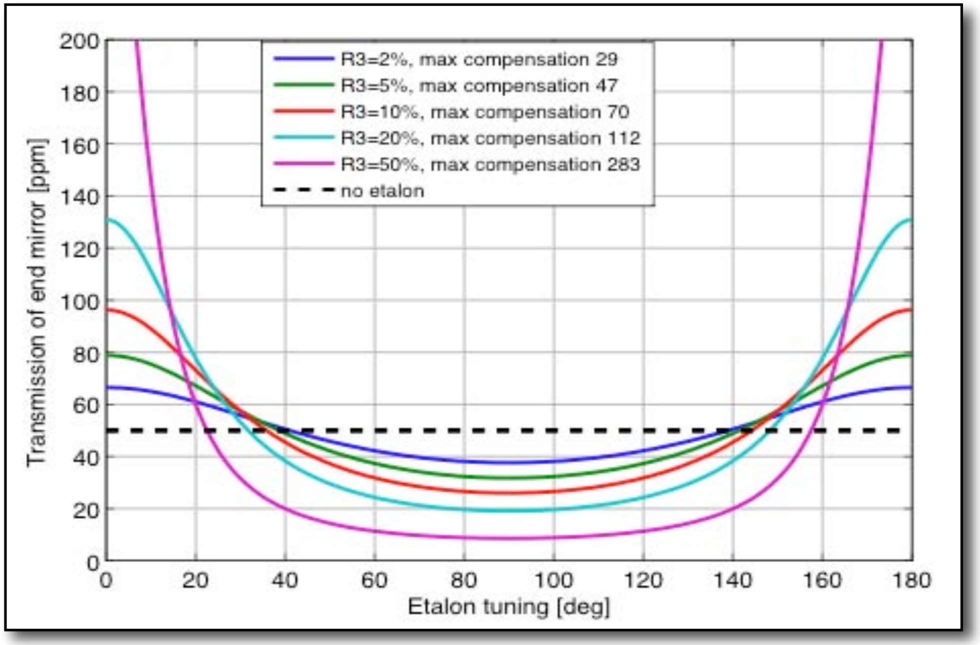
$$h_{\mathrm{wedge}} = 2 \cdot \tilde{V}_{\mathrm{sei}} \cdot TF_{\mathrm{SA}} \cdot \tan(\alpha) \cdot (n_{\mathrm{sub}} - 1) \cdot \frac{\pi}{2F} \cdot \frac{1}{3000\,\mathrm{m}}$$

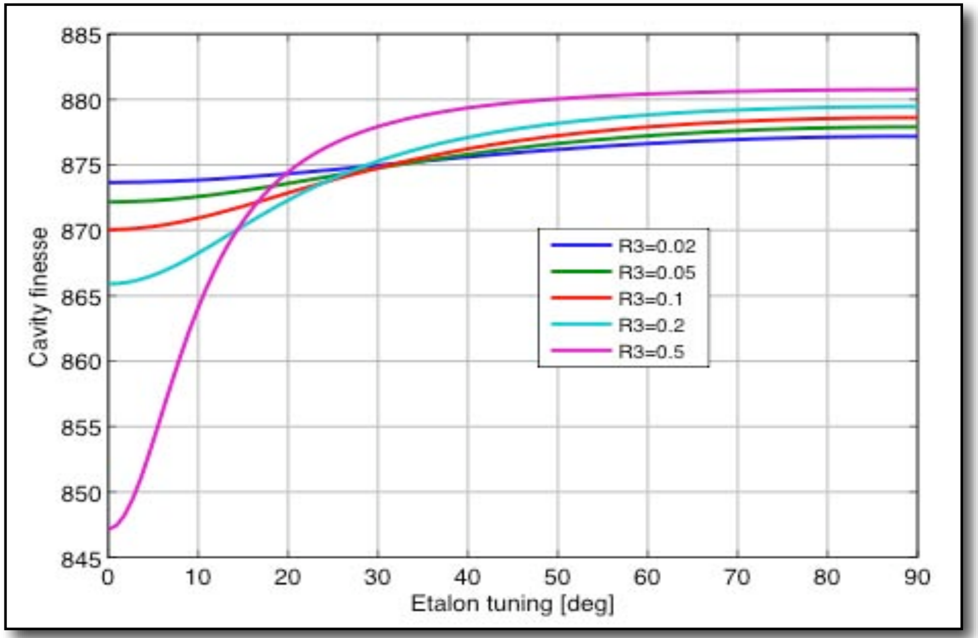


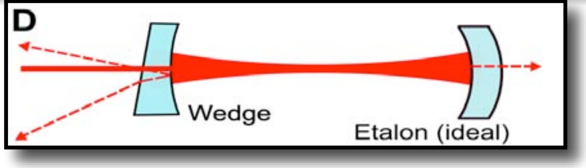
- **RESULT: Not limiting within the detection band.**

- Please note: No actuation noise considered.

Balancing Range due to Etalon Effekt

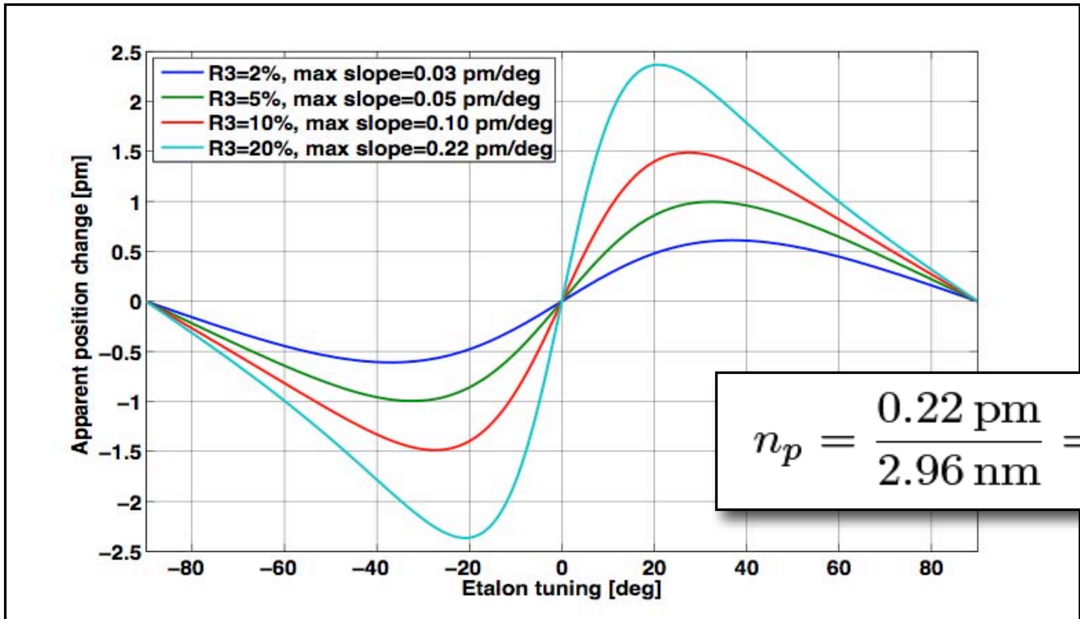






- Examples of figures of merit:
  - Transmittance of end mirror (etalon)
  - Finesse of arm cavity

Etalon changes Optical Phase



$$n_p = \frac{0.22\,\mathrm{pm}}{2.96\,\mathrm{nm}} = 7.4 \times 10^{-5}$$

- When changing the etalon tuning the optical-phase changes as well. (noise!)
- The two etalon surfaces build a compound mirror, whose apparent position depends on the etalon tuning.

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Requirement for Temperature Stability of Etalon Substrate

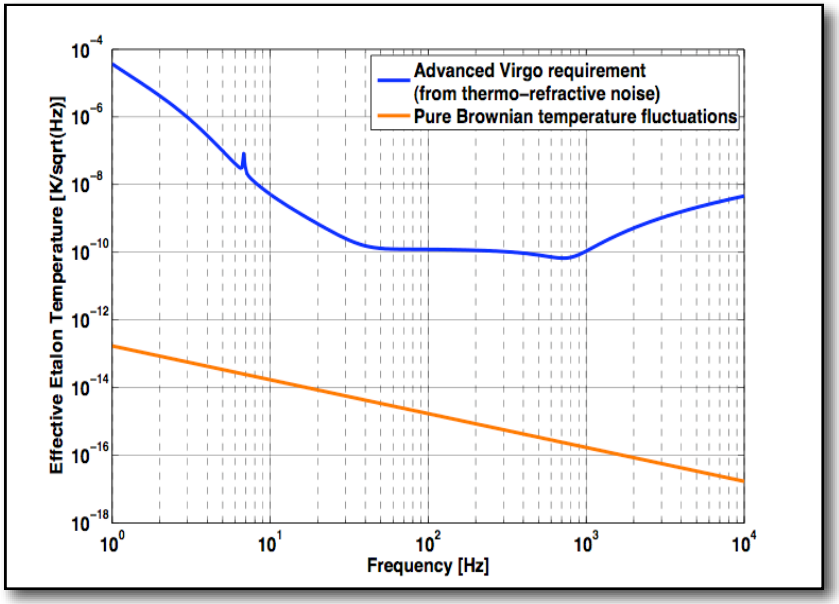
- Certain temperature stability of Etalon substrate required to not spoil AdV sensitivity

$$\tilde{h}_{\mathrm{adv}}(f) = \tilde{T}_{\mathrm{req}}(f) \cdot \frac{dn}{dT} \cdot l_{\mathrm{eta}} \cdot n_p \cdot \frac{1}{L},$$

- Can compare this requirement to substrate thermal noise

$$\tilde{T}_{\mathrm{mirror}}(f) = \sqrt{\frac{4 k_b T^2 \kappa}{(\rho C)^2 l_{\mathrm{eta}}} \frac{1}{\pi R_b^4 (2\pi f)^2}},$$

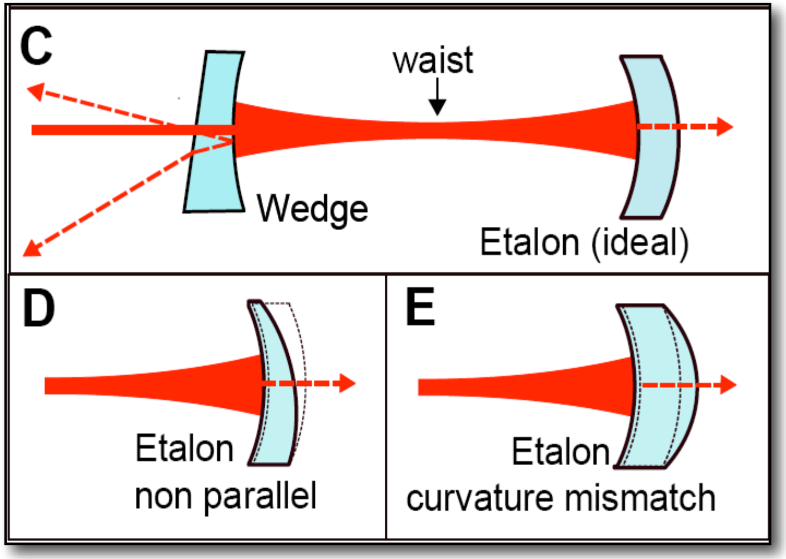
- **RESULT: Not limiting.**
- Please note: Did not consider technically driven temperature fluctuations.



More detail in
Hild et al: VIR-058A-08

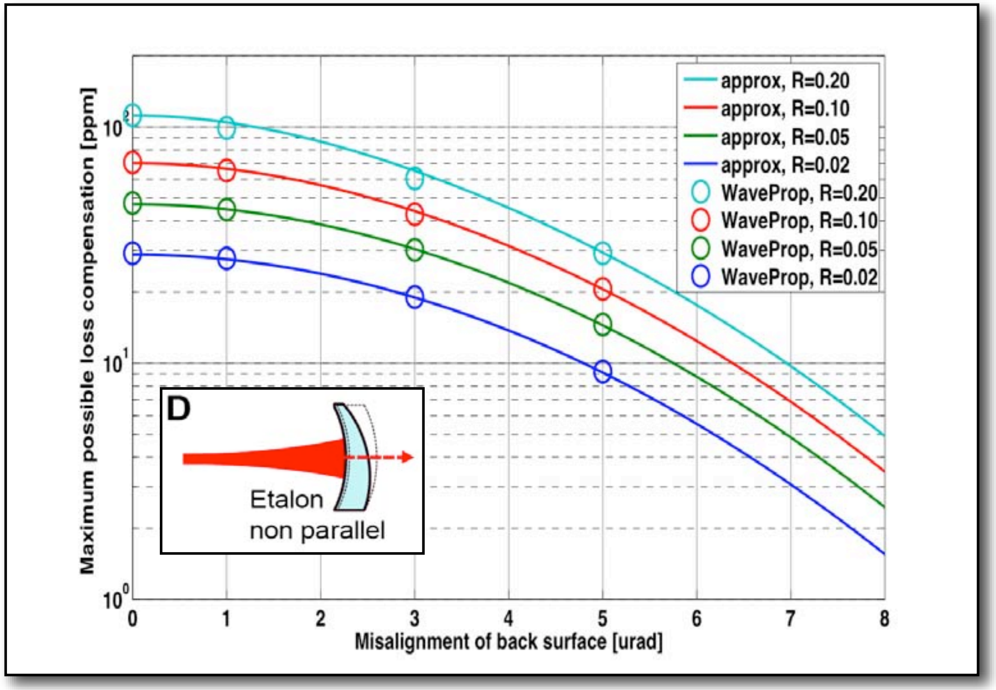
Optical Design: Check System Integrity for Deviations from Specs

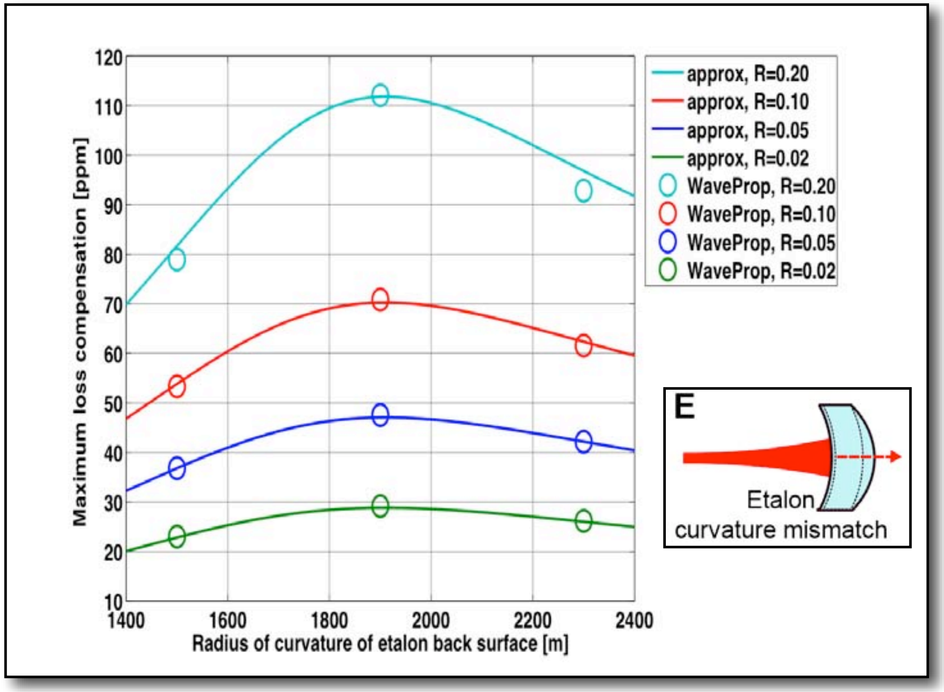
- A deviation in the relative misalignment (parallelism) and relative curvature of the two etalon surfaces:
  - Imperfect wave front overlap…
  - Reduces tuning range …
  - Beam shape distortions …



- Two methods for analysis:
  - FFT based code (Waveprop)
  - Coupling coefficients

Tuning Range of imperfect Etalon





- Requirements for Etalon manufacturing accuracy:
  - Parallelism better than a few urad.
  - ROC deviation: uncritical

Mirror geometry of ET

- If it turns out that ET might run into problems originating from imbalanced arm cavities:
  - different finesse
  - different losses
- ... then using etalons (EM and/or IM) can help.

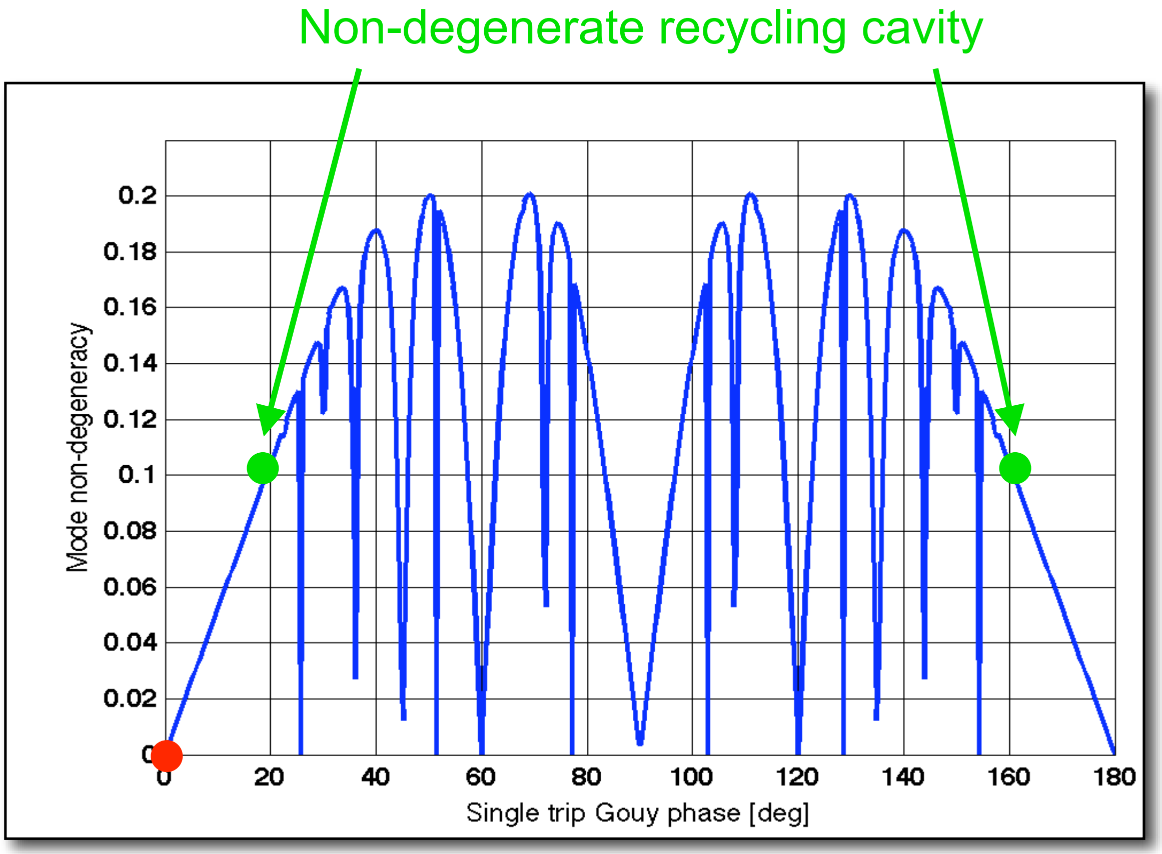
Overview

- Arm cavity geometry (beam sizes, ROCs)
- Arm cavity finesse (high vs low)
- Mirror substrate geometry (etalon vs wedge)
- Recycling cavity design (NDRC vs MSRC)
- Signal Recycling configuration

Non-degenerate Recycling cavities

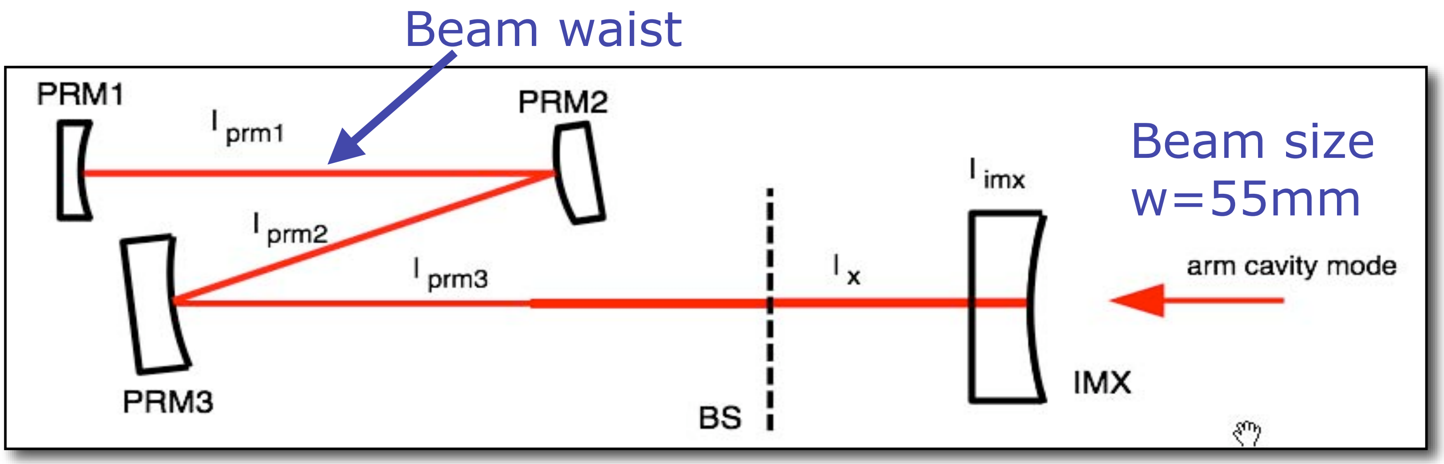
- Motivation: Thermal effects or misalignments scatter light into higher-order modes so that optical signal is lost. Non-degenerate cavities reduce this effect.

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



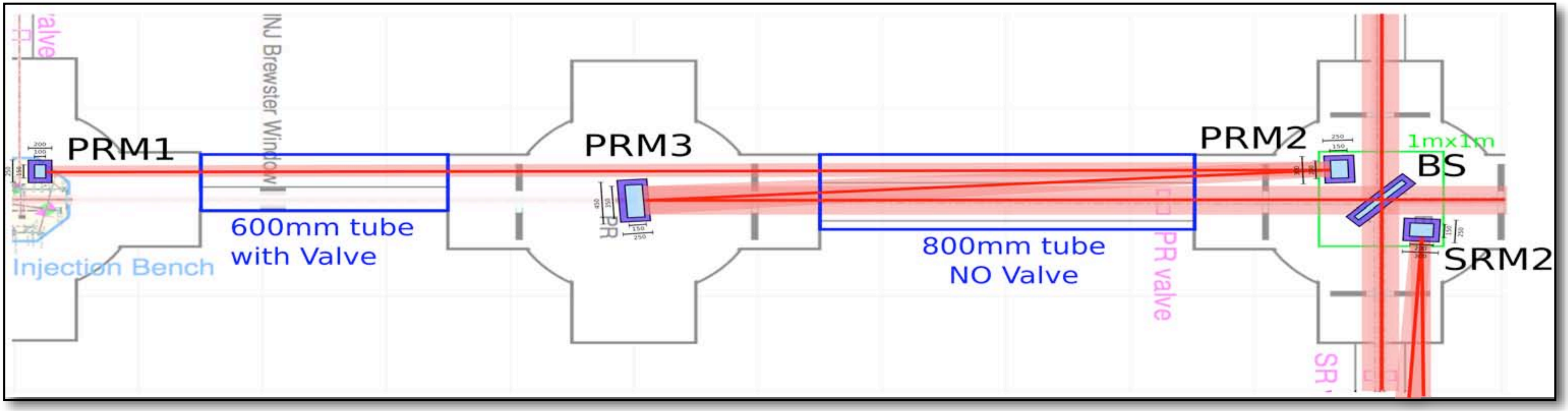
A possible optical layout

- Design of Non-degenerate Recycling Cavity



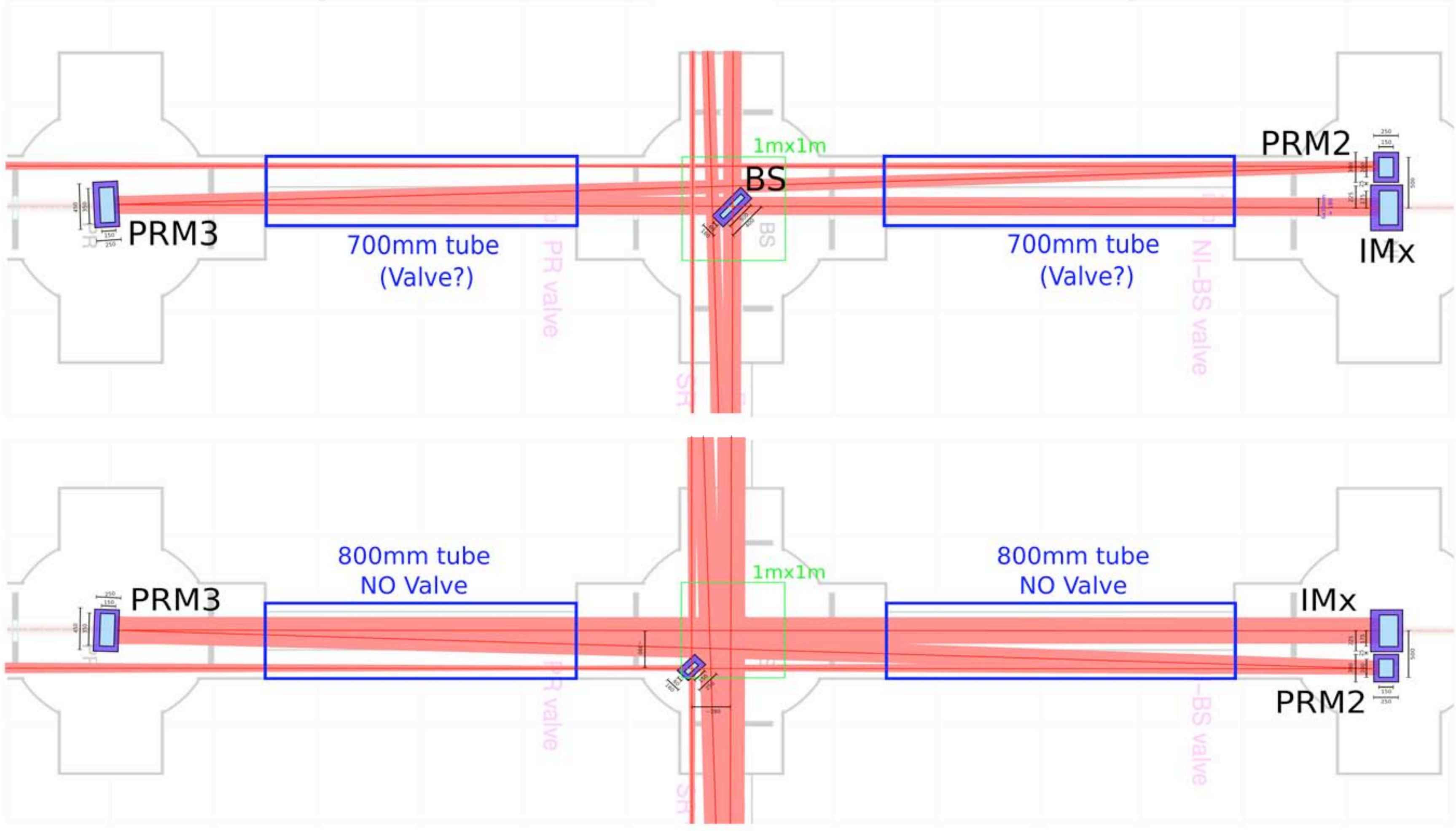
- Proper design of the non-degenerate Recycling Cavity is rather complicated …
- Here I concentrate on a single aspect: Infrastructure

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

Examples of other NDRC layouts



NDRC and ET?

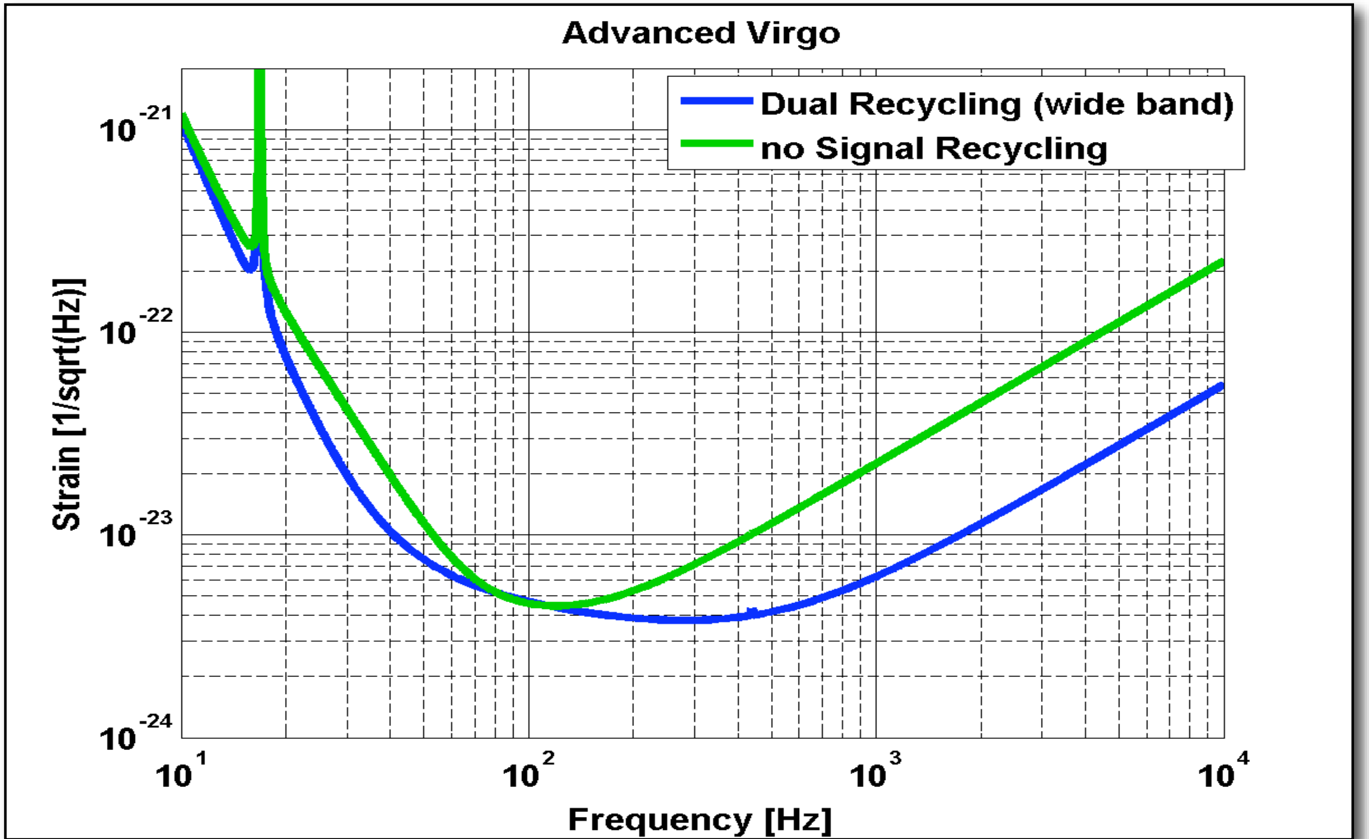
- If non-degenerate RC perform like we think (we will find out in 2G), then for sure ET will have them.

- ET should ideally have:
  - Lots of space (large CITF, many vacuum tanks, large vacuum links etc)
  - Lots of flexibility (more than 1 optic per vacuum vessel, platforms etc)

Overview

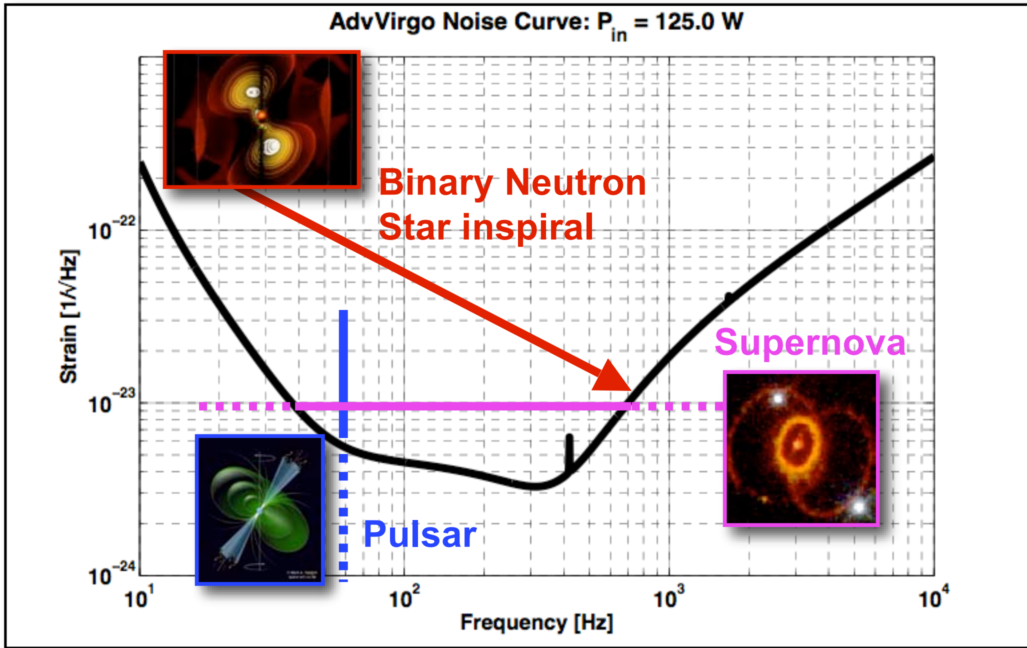
- Arm cavity geometry (beam sizes, ROCs)
- Arm cavity finesse (high vs low)
- Mirror substrate geometry (etalon vs wedge)
- Recycling cavity design (NDRC vs MSRC)
- Signal Recycling configuration

Signal Recycling / RSE helps!



- Signal Recycling / RSE significantly improves 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.

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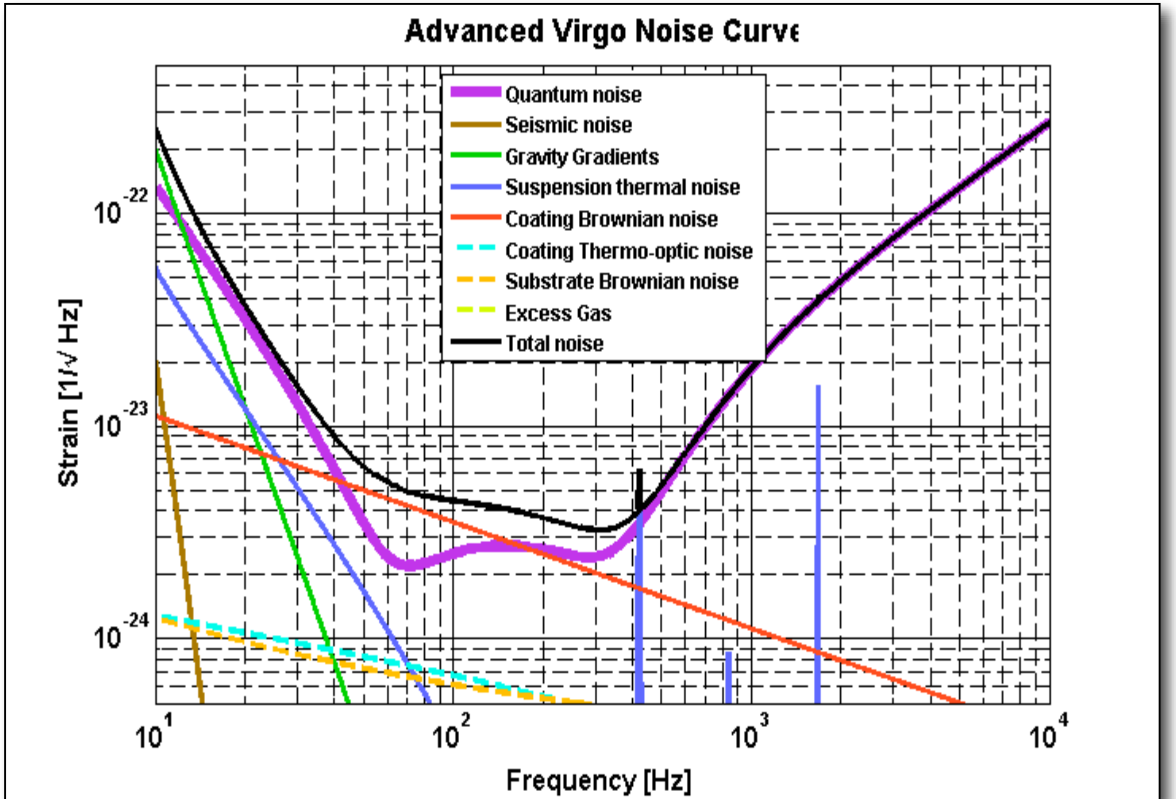
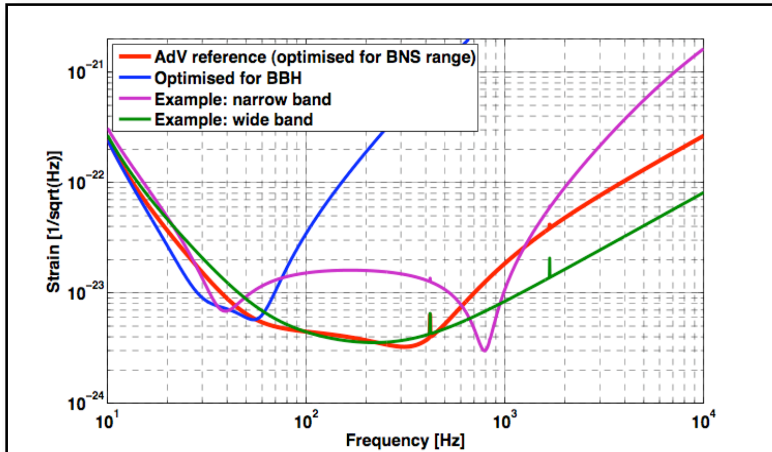
Fundamental noise limits for Advanced Virgo



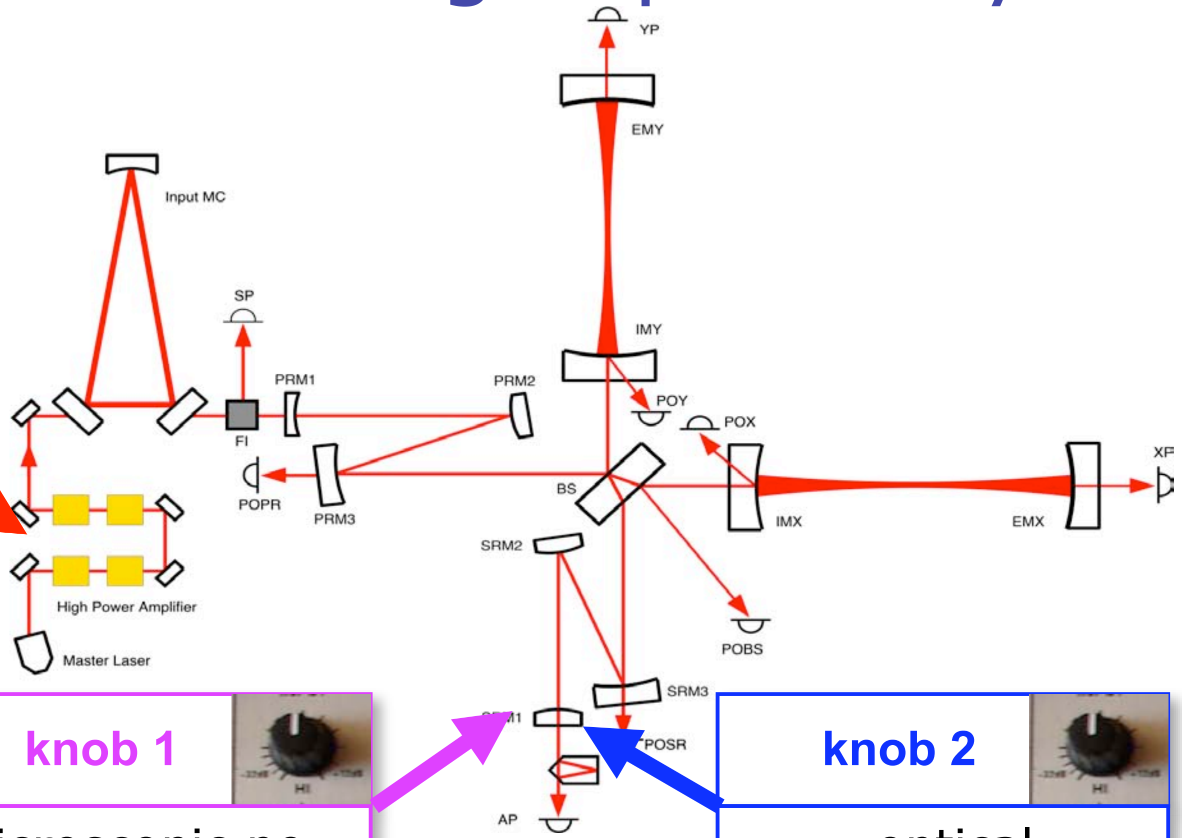
- Advanced Virgo will be limited by **quantum noise** at nearly all frequencies of interest.



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

Advanced Virgo optical layout

- We have three knobs available for optimisation:



knob 3 

Input
Light power

knob 1

microscopic position of SRM1 (nm scale)

Signal Recycling resonance frequency

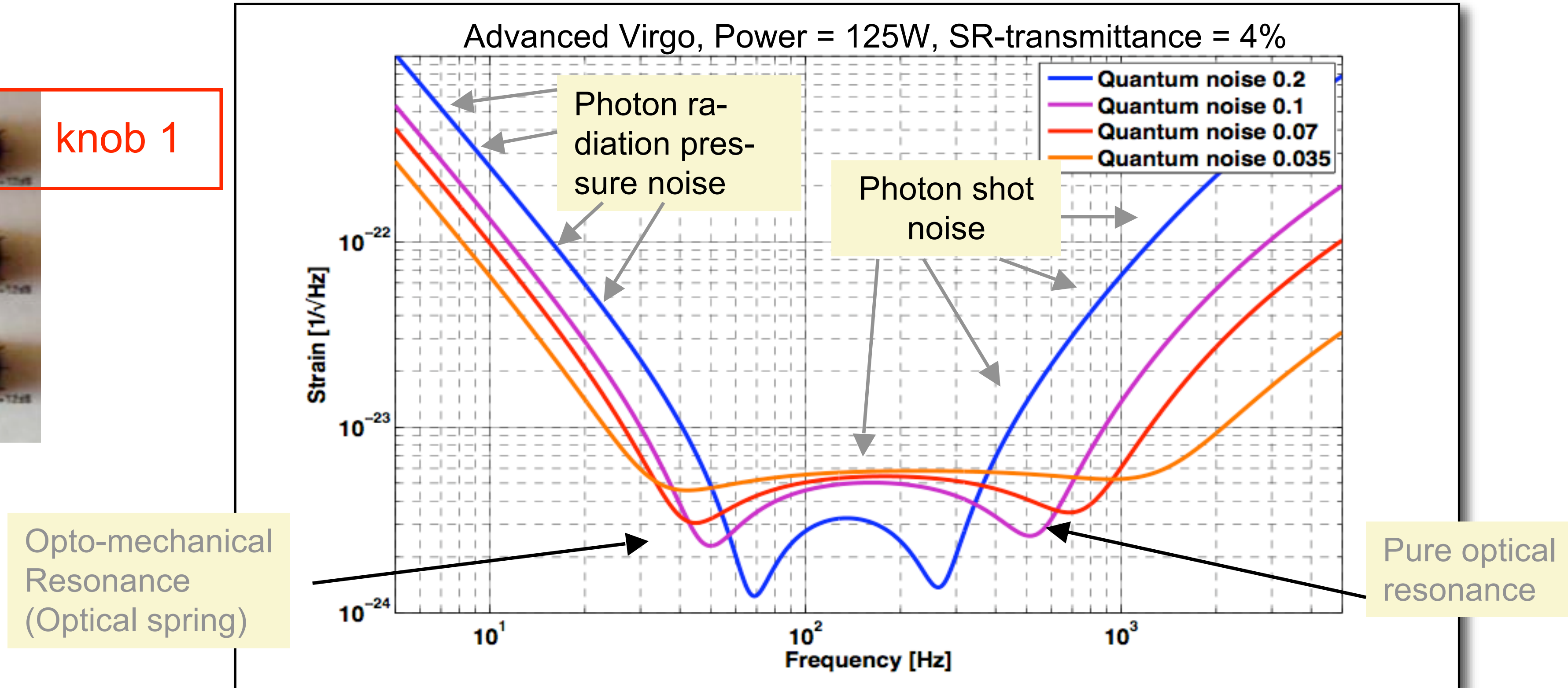
knob 2

optical transmittance of SRM1

Signal Recycling bandwidth

Optimization Parameter 1: Signal-Recycling (de)tuning

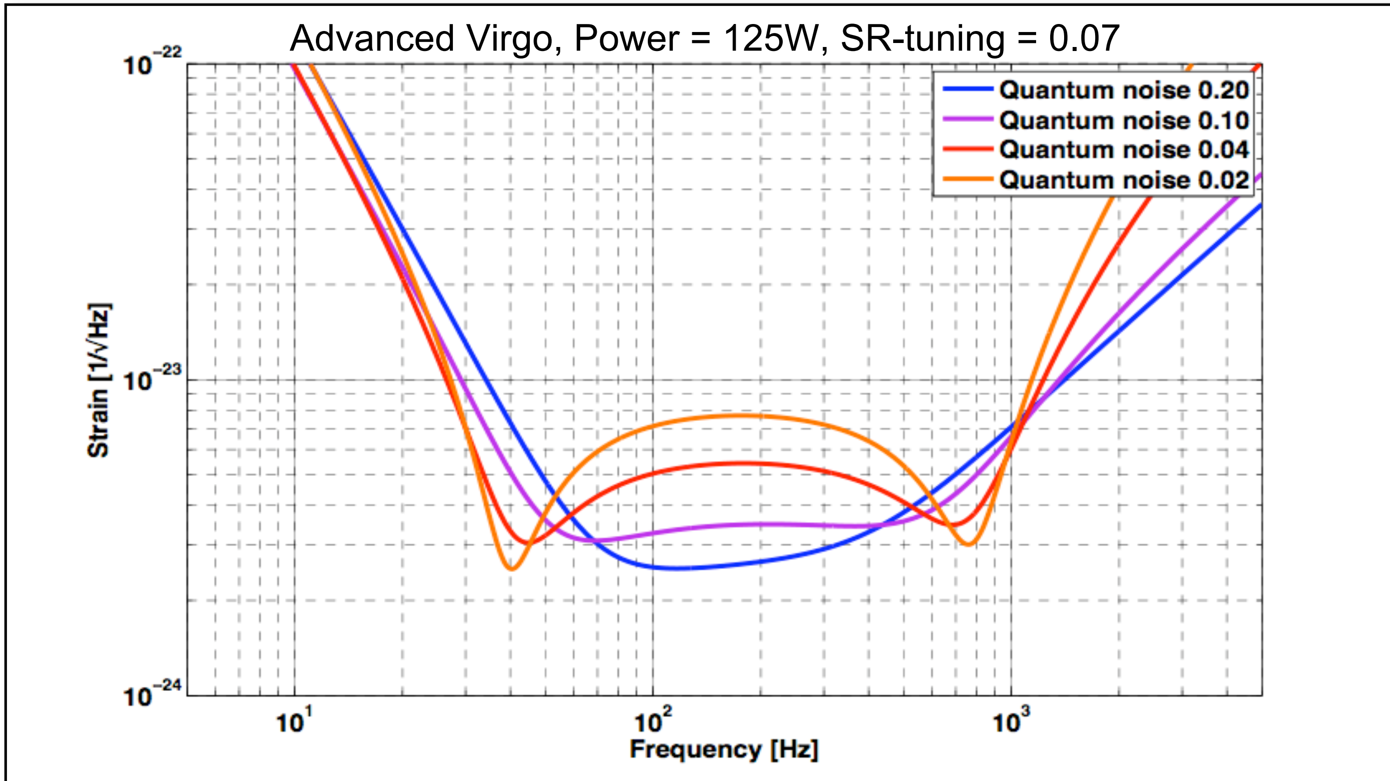
knob 1



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

Optimization Parameter 2: Signal-Recycling mirror transmittance

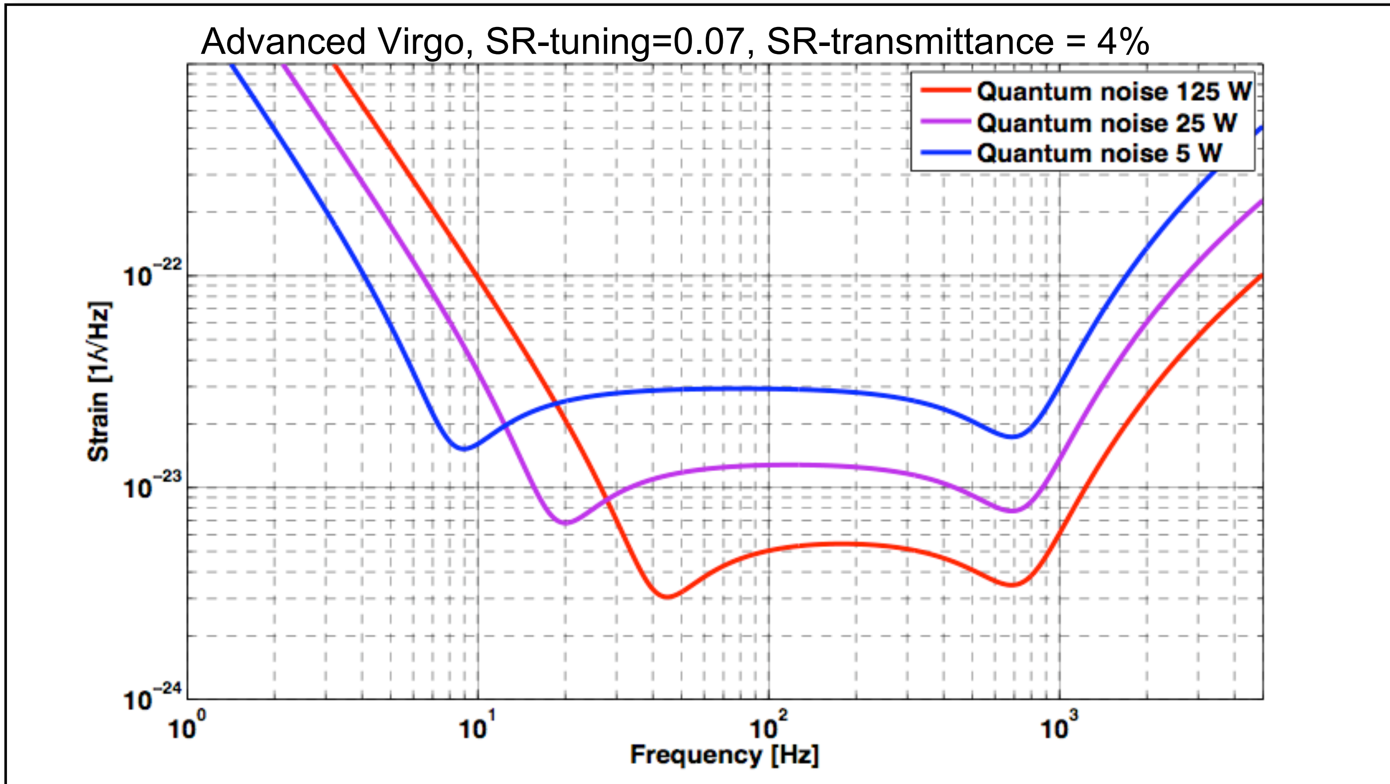
knob 2



- Resonances are less developed for larger SR transmittance.

Optimization Parameter 3: Laser-Input-Power

knob 3



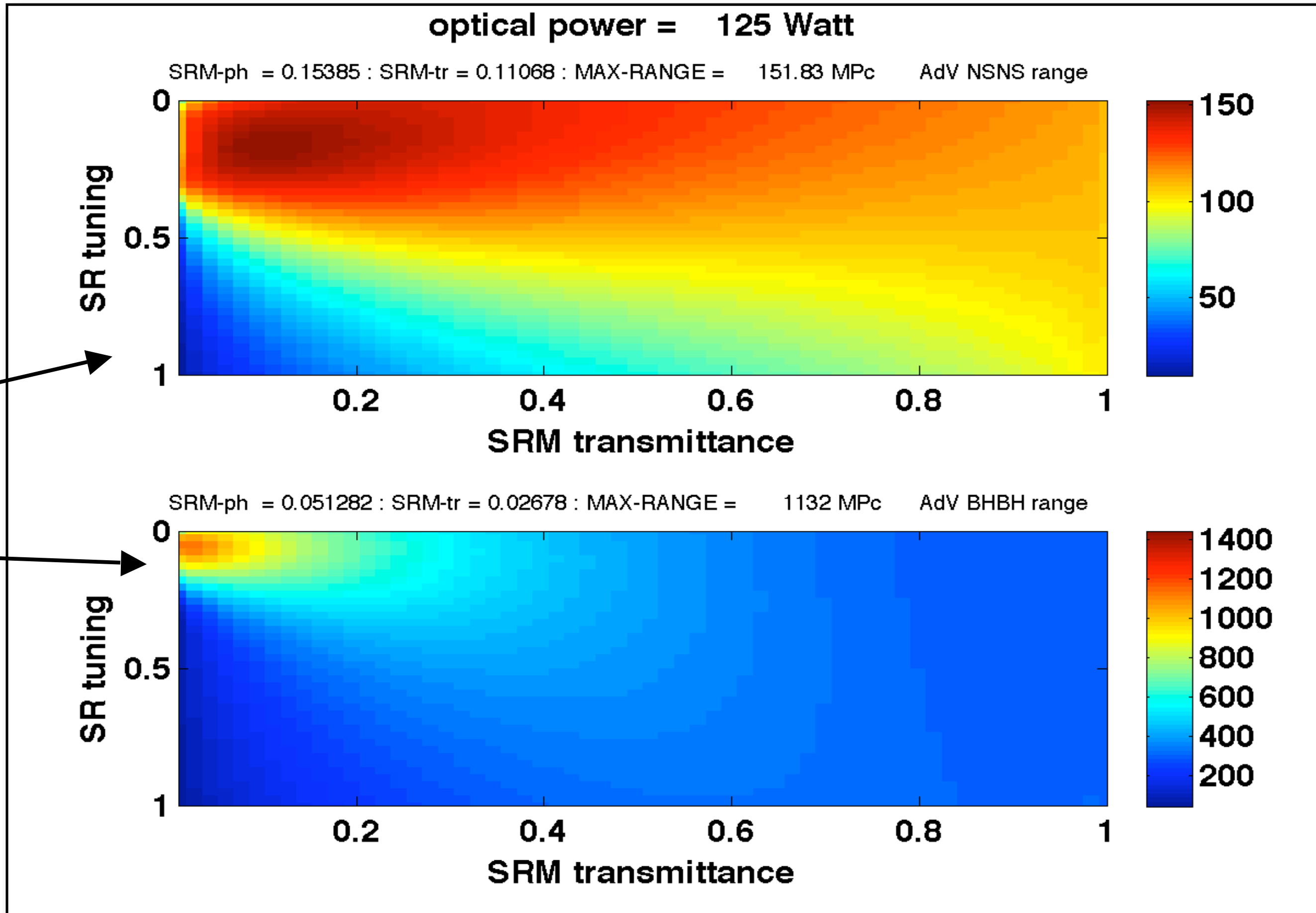
- High frequency sensitivity improves with higher power (Shotnoise)
- Low frequency sensitivity decreases with higher power (Radiation pressure noise)

Example: Optimizing 2 Parameters

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

NSNS-range

BHBH-range



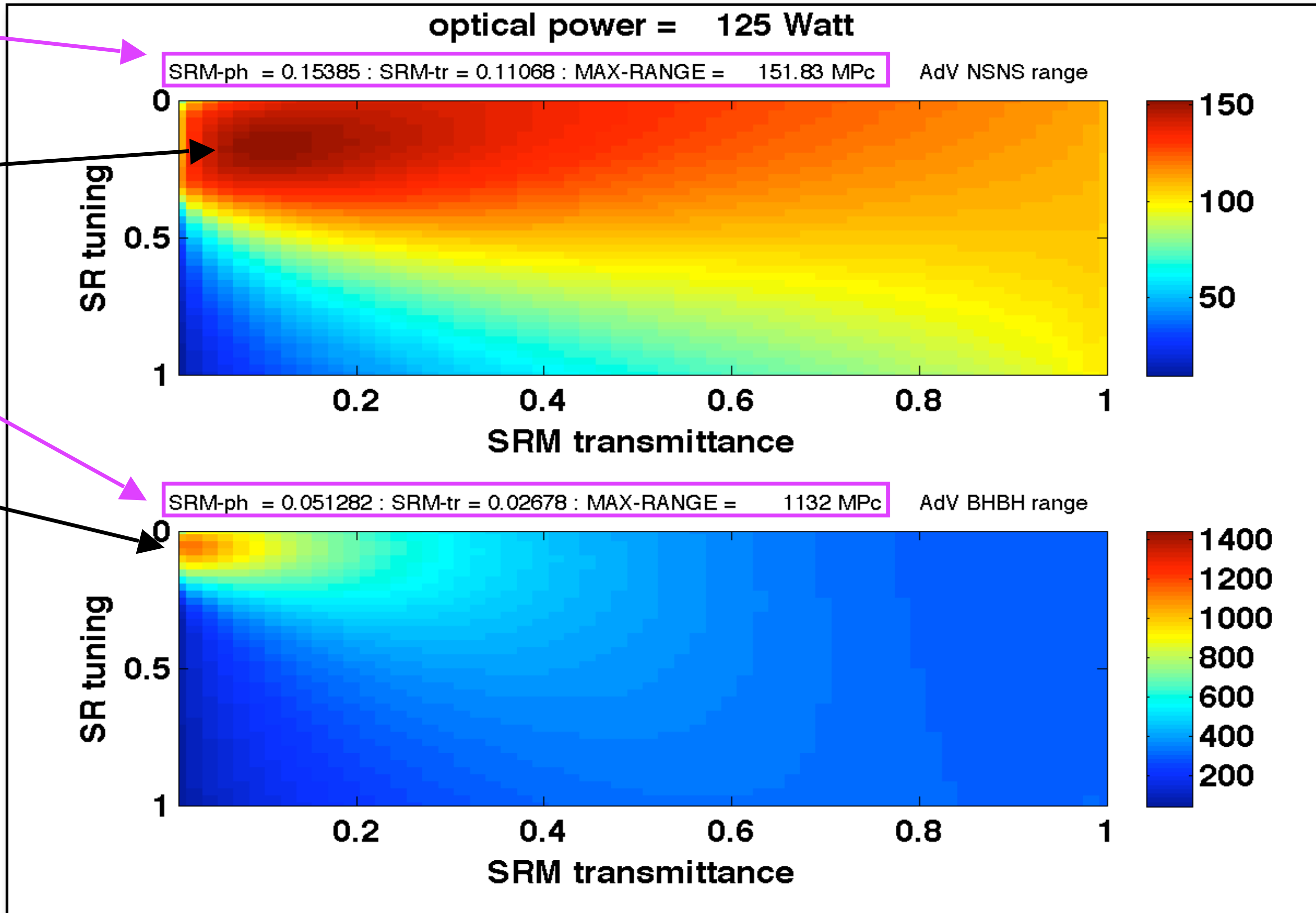
Example: Optimizing 2 Parameters

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 !

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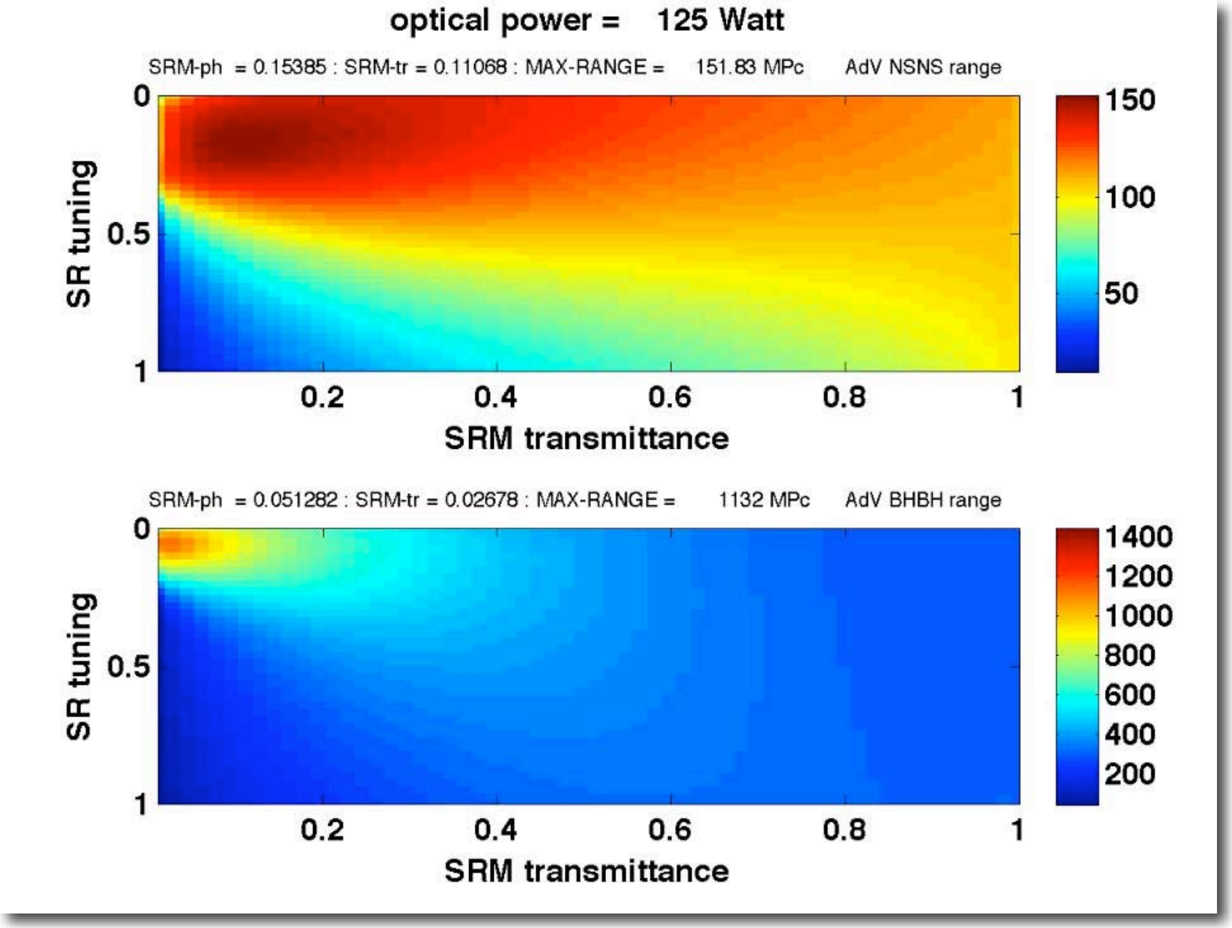
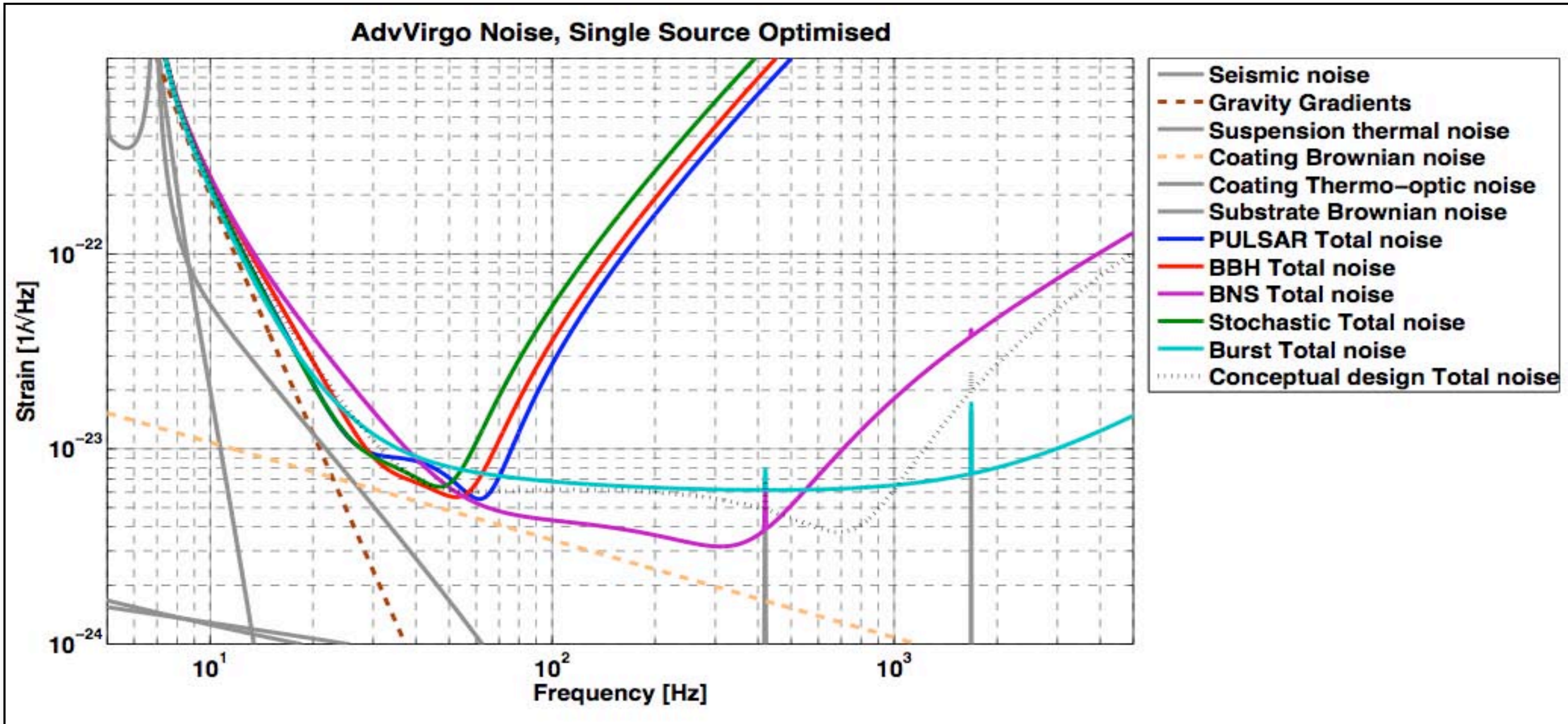
Example: Optimizing 3 Parameter for Inspiral range

- Scanning 3 parameter at the same time:
  - SR-tuning
  - SR-trans
  - Input Power

- Using a video to display 4th dimension.



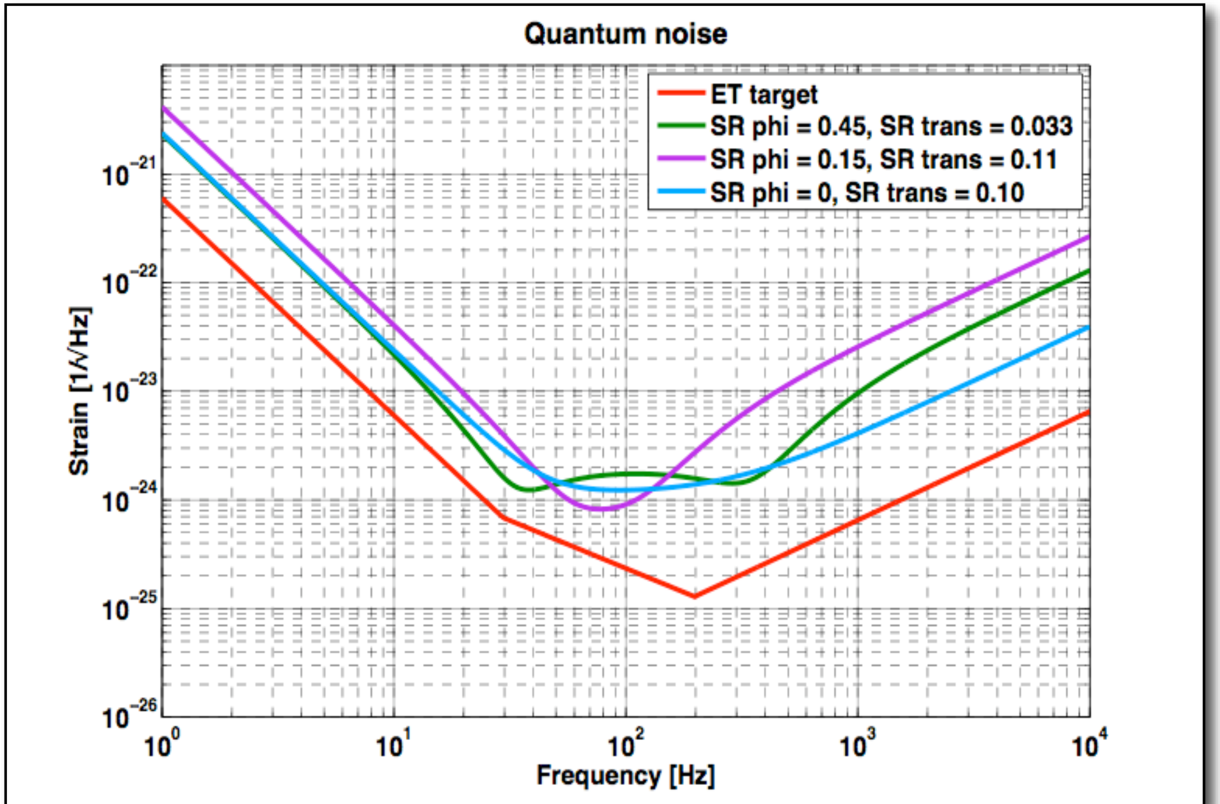
Optimal configurations



Curves show the optimal sensitivity for a single source type.

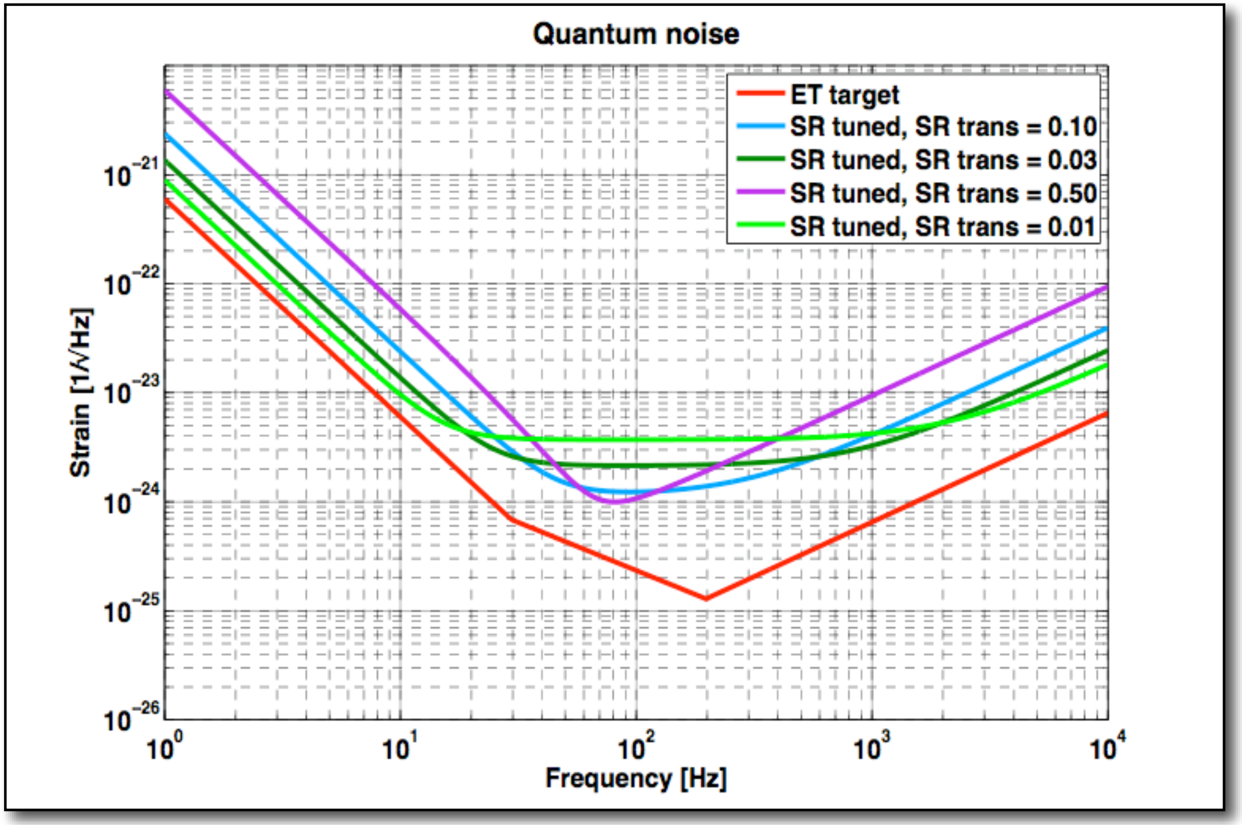
Optimising the signal recycling detuning

- Detuned SR is used in Advanced Virgo and Advanced LIGO
- For ET **tuned SR** seems to be more promising:
  - Optimal trade-off between peak sensitivity and bandwidth
  - Recycle both signal sidebands.

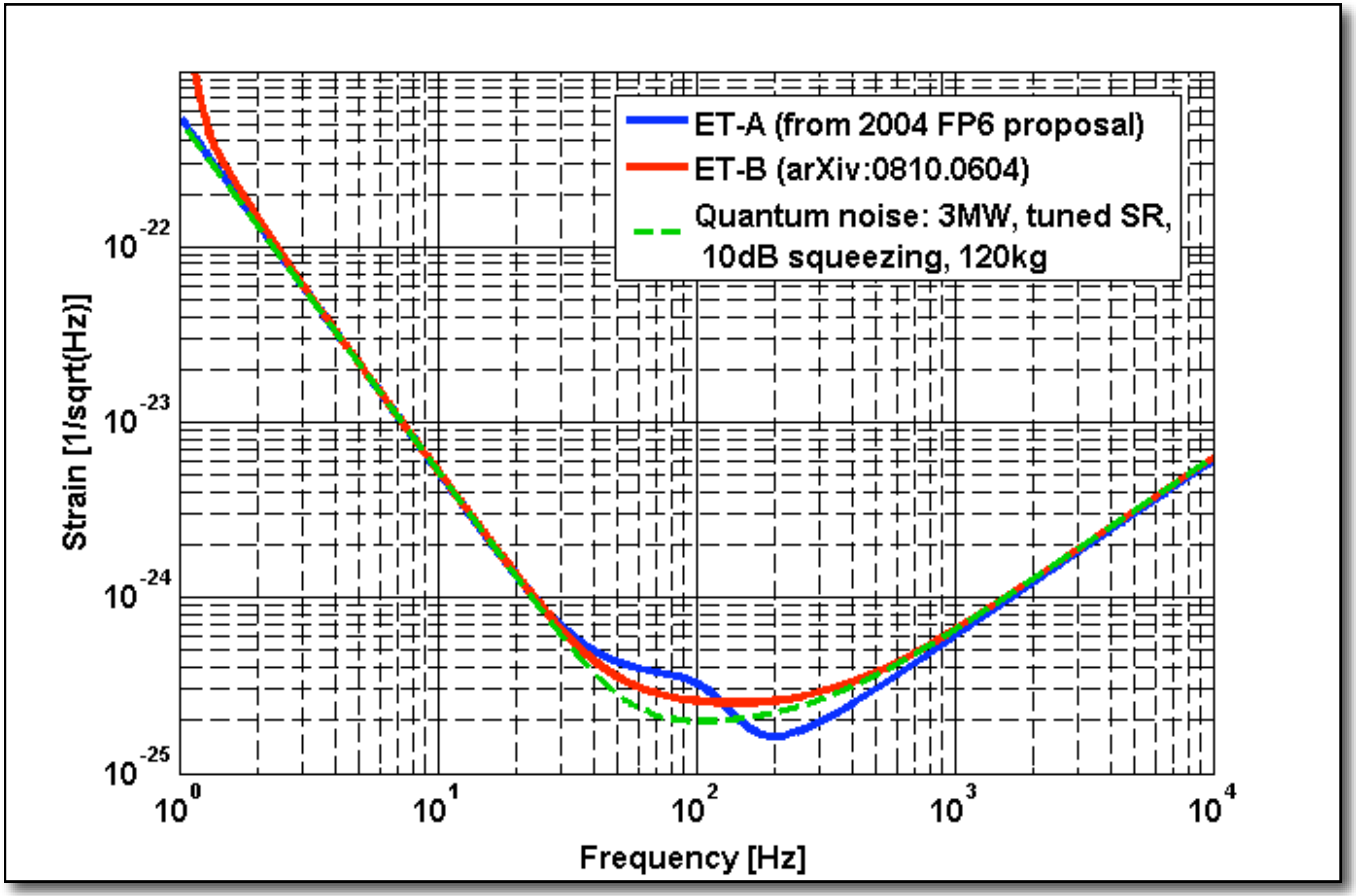


Optimising the signal recycling transmittance

- Optimal trade-off between peak sensitivity and bandwidth for 10% transmittance.

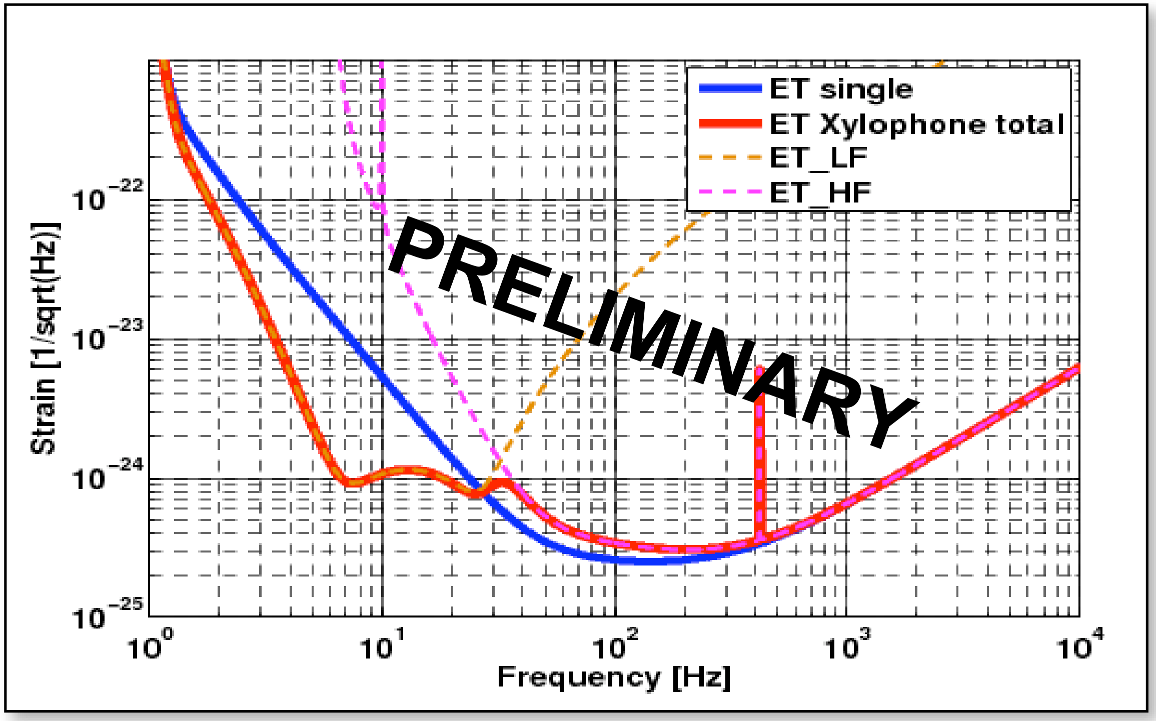


Quantum noise of ET-B



Xylophone interferometers

- HF-IFO:
  - Tuned SR
  - 3 megawatt
  - Room temperature
- LF-IFO:
  - Detuned SR
  - Only 18 kW
  - Cryogenic



A Xylophone Configuration for a third Generation Gravitational Wave Detector

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