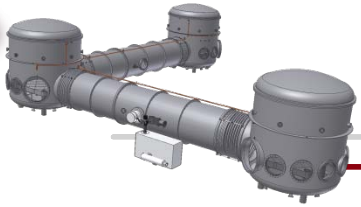
AEI 10m Prototype



Centre for Quantum Engineering and Space-Time Research

University of Glasgow

Leibniz Universität Hannover

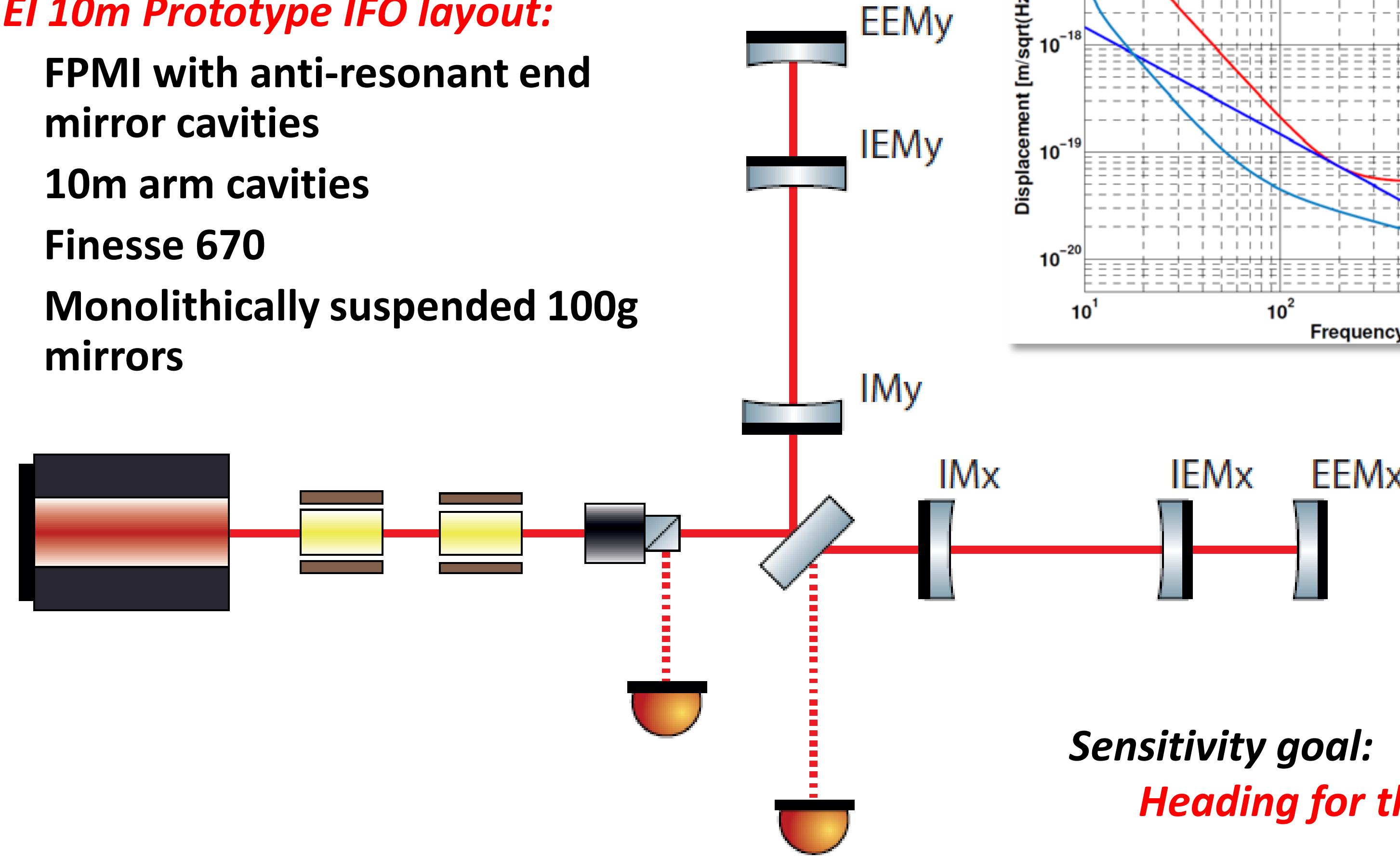
The AEI 10m SubSQL interferometer with tunable stability

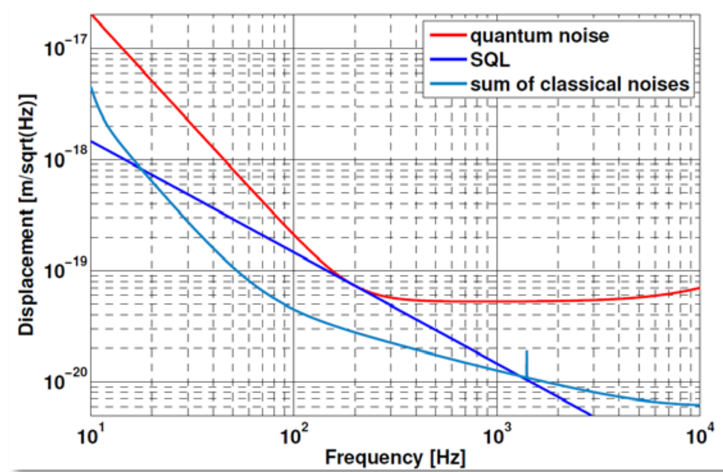
Christian Gräf for the AEI 10 m Prototype Team

The AEI 10m Prototype IFO

AEI 10m Prototype IFO layout:

- **FPMI with anti-resonant end mirror cavities**
- **10m arm cavities**
- **Finesse 670**
- **Monolithically suspended 100g mirrors**





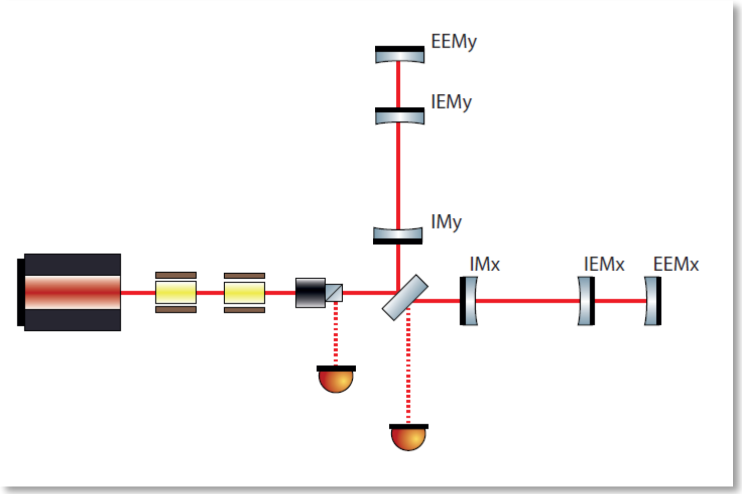
Sensitivity goal:

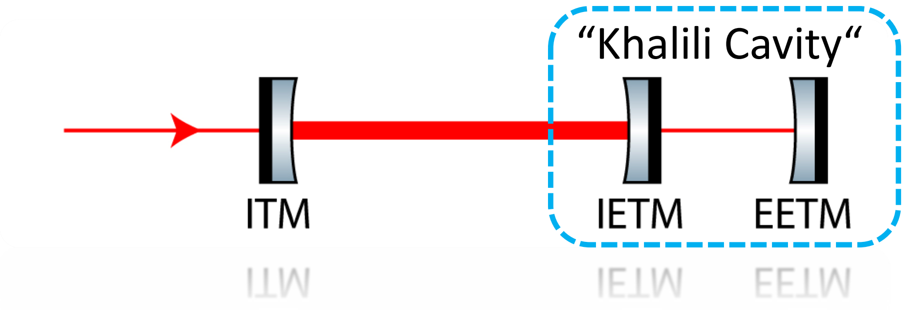
Heading for the SQL@200Hz

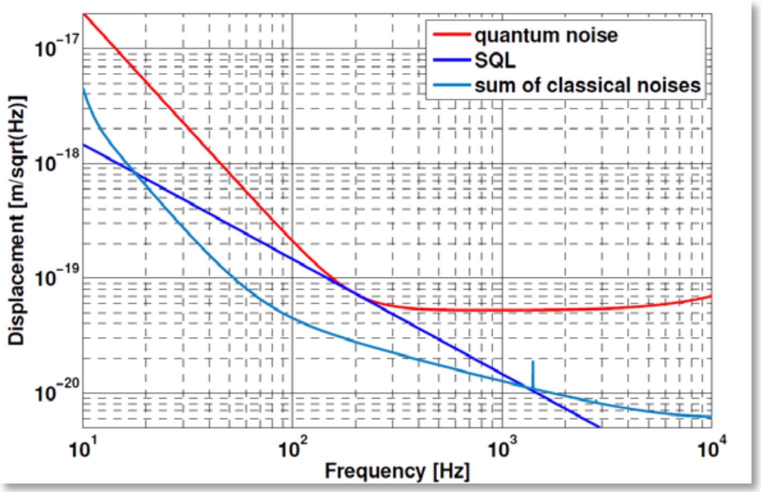
En route to the SQL

The “magic“ to bring down thermal noise:

- **Rigorous optimization** of all TN-relevant suspension and optics parameters
- **Extremely large beam spots** on HR coatings, balanced against diffraction loss
- **Khalili cavities,** strongly overcoupled, anti-resonant end mirror cavities with few coating layers on the input coupler







Drawback: poor stability

Implications of large spots:

- Large spots come at the expense of cavity g-factors of almost one
- As a consequence, cavities are to be operated near instability
- Another pitfall: low robustness w.r.t. fabrication error

Beam spot radius on cavity mirror:

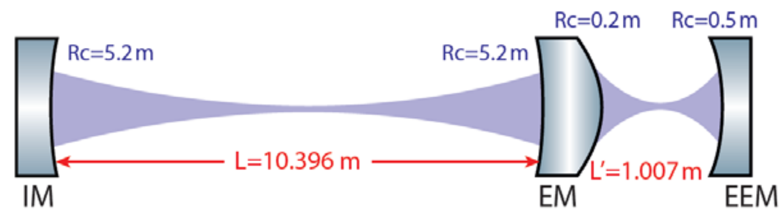
$$w_{1,2}^2 = \frac{\lambda L}{\pi} \times \sqrt{\frac{g_{2,1}}{g_{1,2}\left(1 - g_1 g_2\right)}}$$

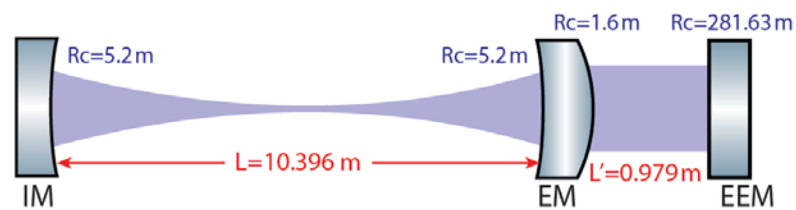
Stability criterion ($g := g_1 g_2$):

$$0 < g < 1$$

Typical stabilities:

- AC: L=10.4m with 9.7mm spots -> g ≈ 0.999
- KC: L ≈ 1m with 9.7mm spots -> g ≈ 0.99998





Conclusion:

- Configuration with KCs comes with a number of complications which strike simultaneously
- Better start simple, iterate towards full complexity configuration

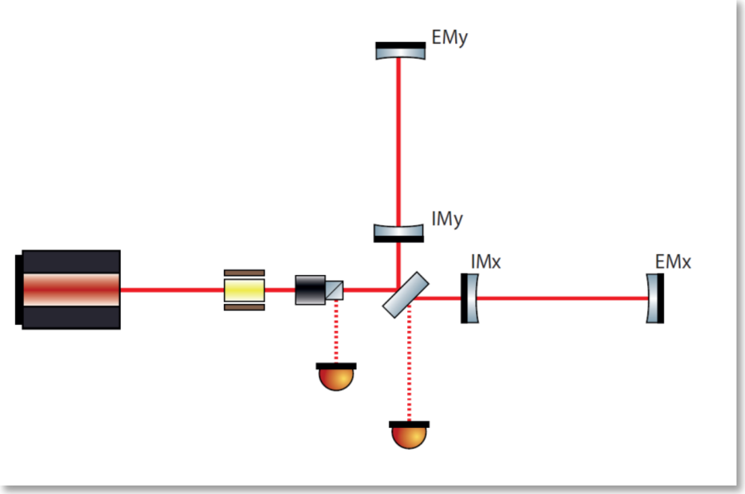
The starting configuration

1st simplification:

- Omit KCs in the first place but keep everything else
- Marginally stable, suspended FPMI with stability of 0.998, so far unprecedented!

Going one step further, 2nd simplification:

- Optimize IFO optics parameters for marginally stable operation BUT
- Start with shorter, more stable arm cavities
- Gradually increase cavity length
- What stability margin can we cope with?



	aLIGO	AdVirgo	ET-B
Arm cavity length	3996 m	3000 m	10000 m
RoC (ITM/ETM)	1934 m/2245 m	1420 m/1683 m	5070 m/5070 m
Cavity g-factor	0.832	0.871	0.945

Tunable arm cavity length FPMI

An example with numbers:

AC length reduction 11.4m -> 10.8m

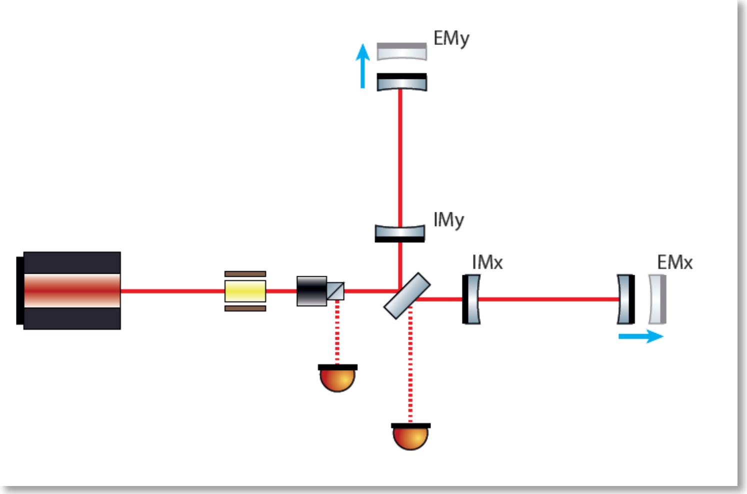
Cavity g-factor 0.998 -> 0.8

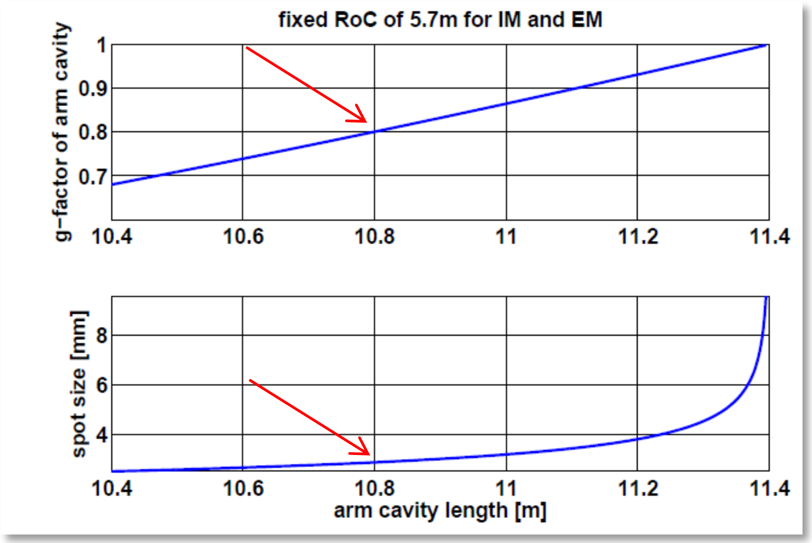
Beam radius@HR 9.72mm -> 2.86 mm

The crux: maintaining good mode matching for different arm cavity lengths!

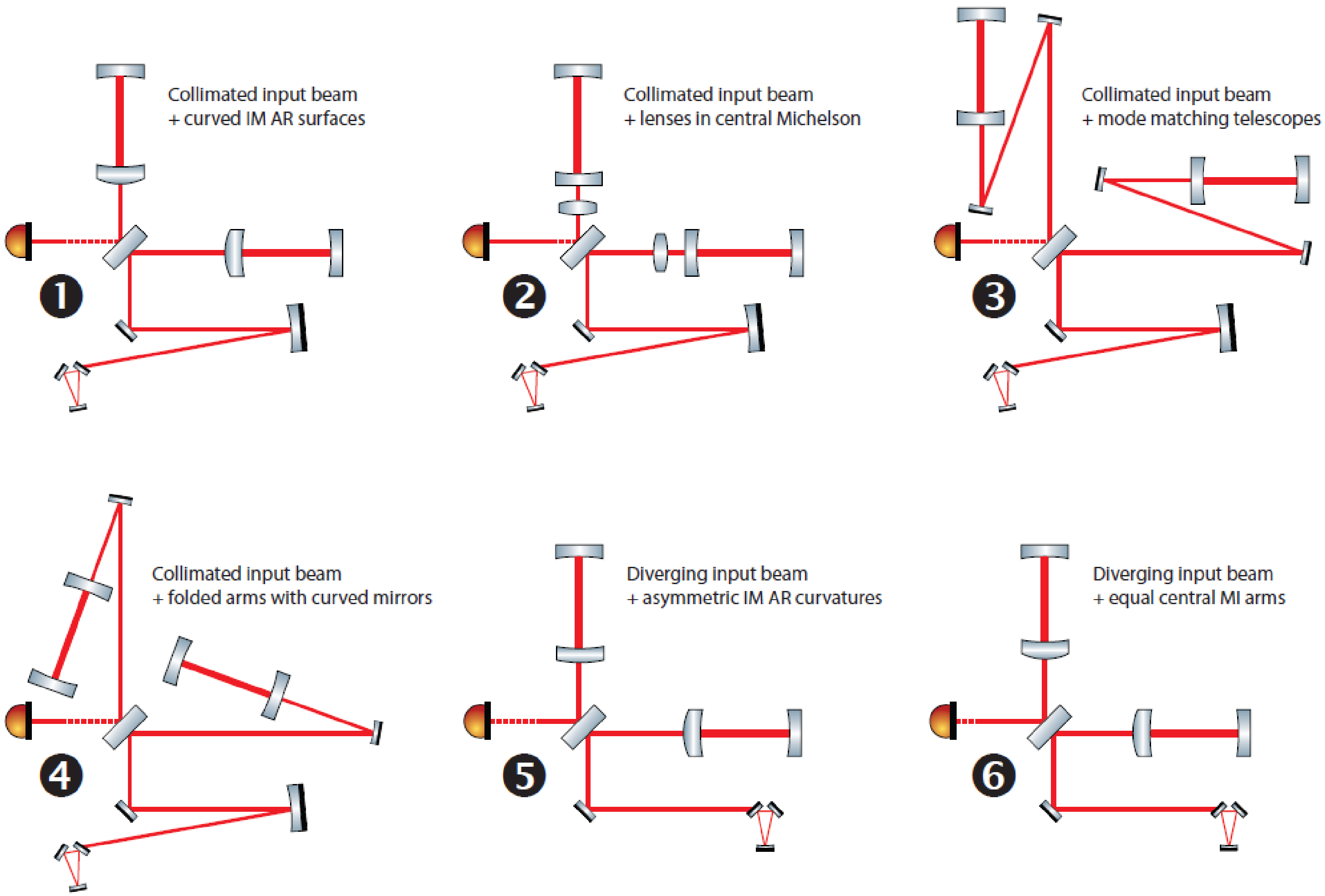
Further boundary conditions:

- Try not to introduce excessive astigmatism
- Maintain controllability of the IFO
- Keep the number of additional optical components at a minimum
- Keep it technically feasible





Zoo of candidate configurations



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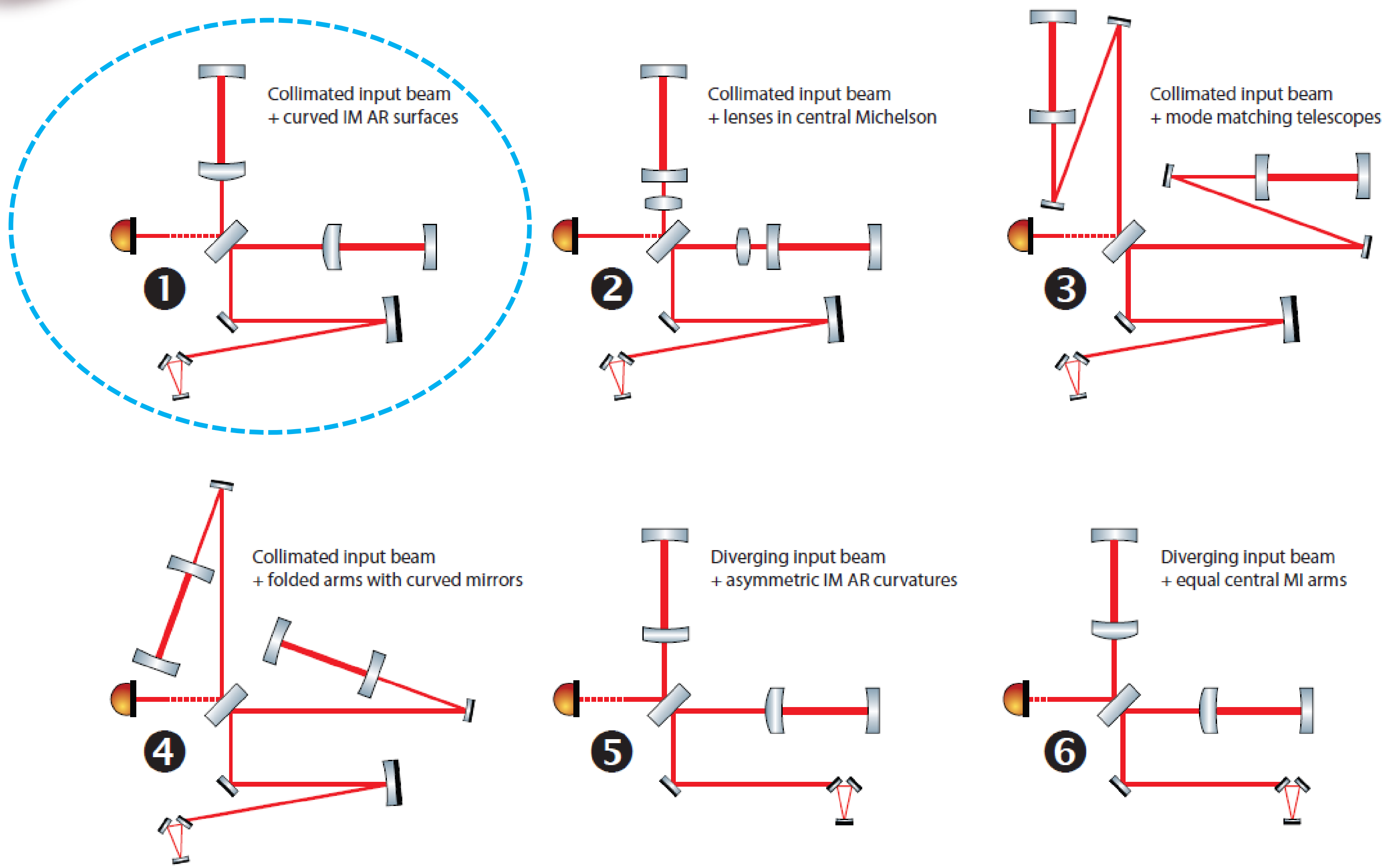


Taking a closer look

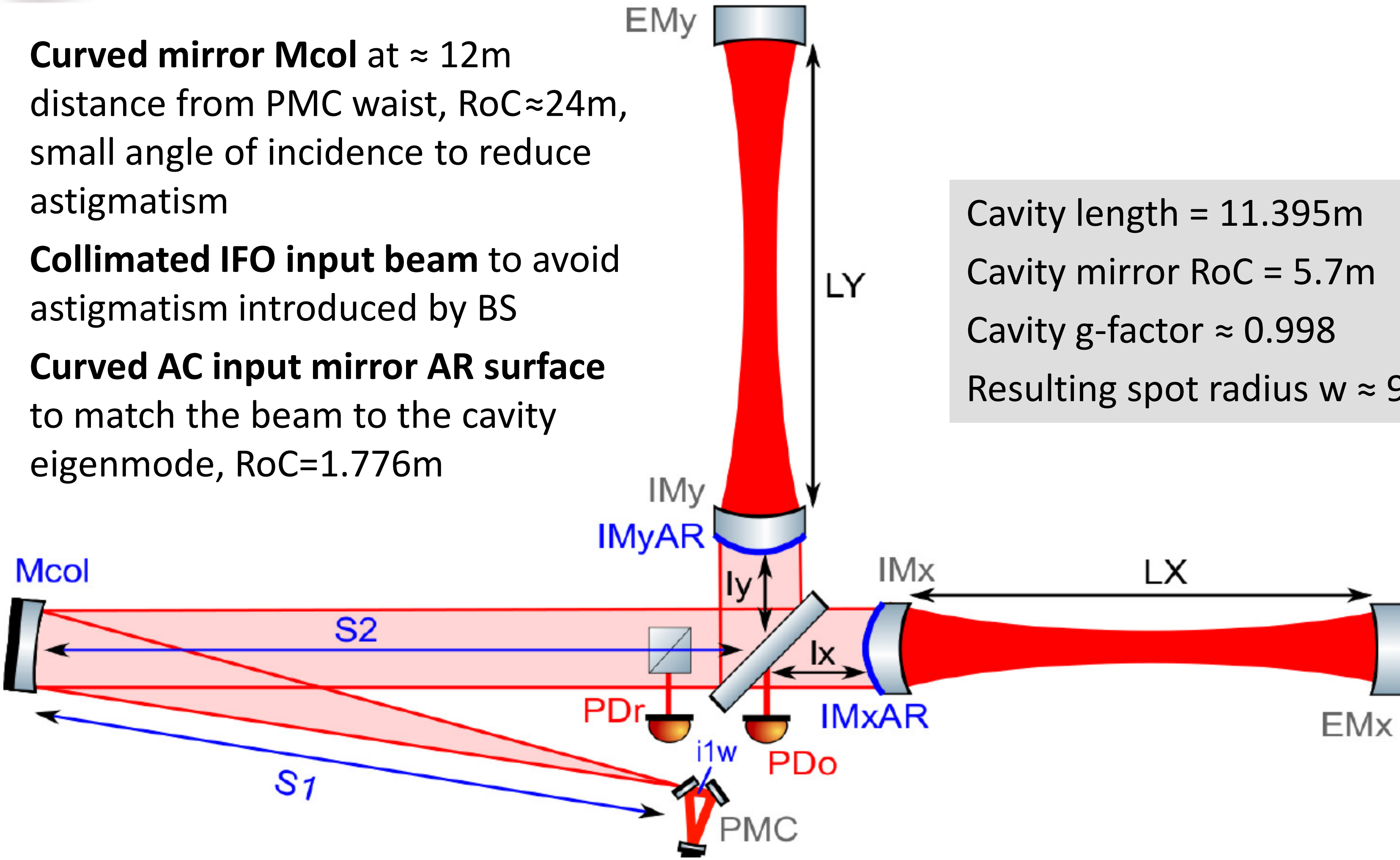
- **Curved mirror Mcol** at ≈ 12m distance from PMC waist, RoC≈24m, small angle of incidence to reduce astigmatism
- **Collimated IFO input beam** to avoid astigmatism introduced by BS
- **Curved AC input mirror AR surface** to match the beam to the cavity eigenmode, RoC=1.776m

Cavity length = 11.395m

Cavity mirror RoC = 5.7m

Cavity g-factor ≈ 0.998

Resulting spot radius w ≈ 9.7mm



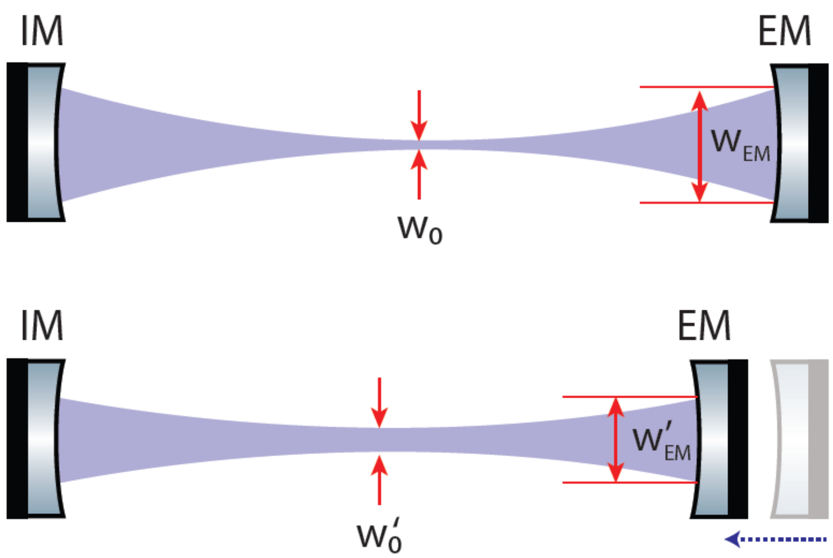
Matching the cavity eigenmode

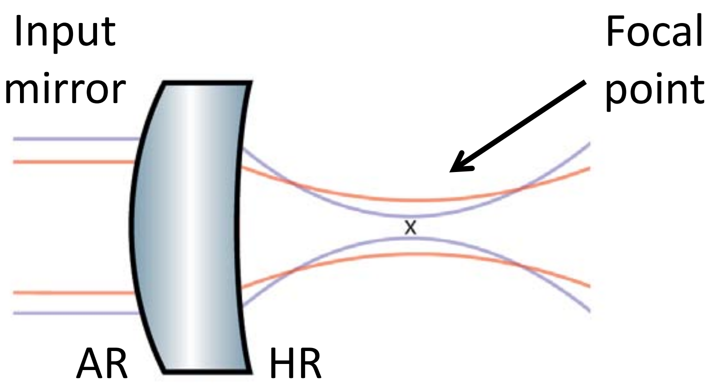
From the cavity's perspective:

- Desired to shift as few optics as possible when changing the AC length
- Shifting only the end mirrors changes the eigenmode waist radius and position

From the input beam's perspective:

- Curved input mirror AR surfaces to match collimated input beam to cavity eigenmode
- IM AR RoC can only be optimized for one cavity length -> beam waist position mismatch for shortened arm cavities

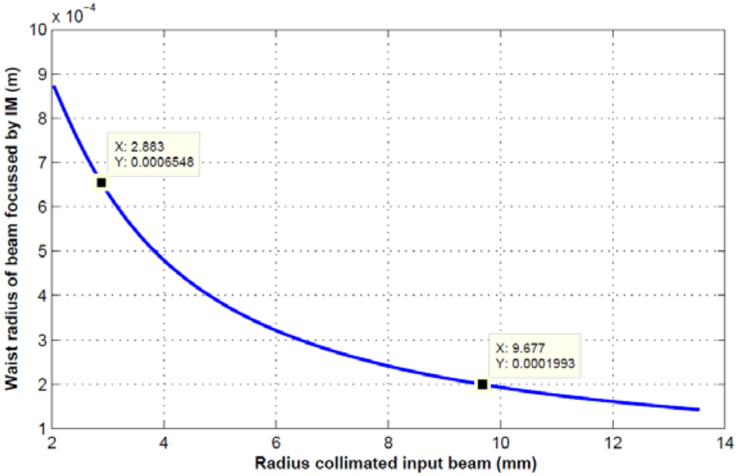




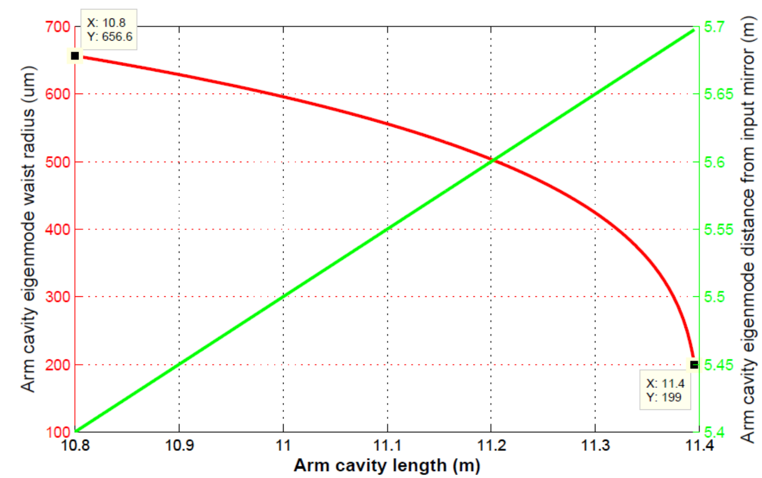
Fixed IM AR RoC sets upper limit to achievable mode matching visibility.

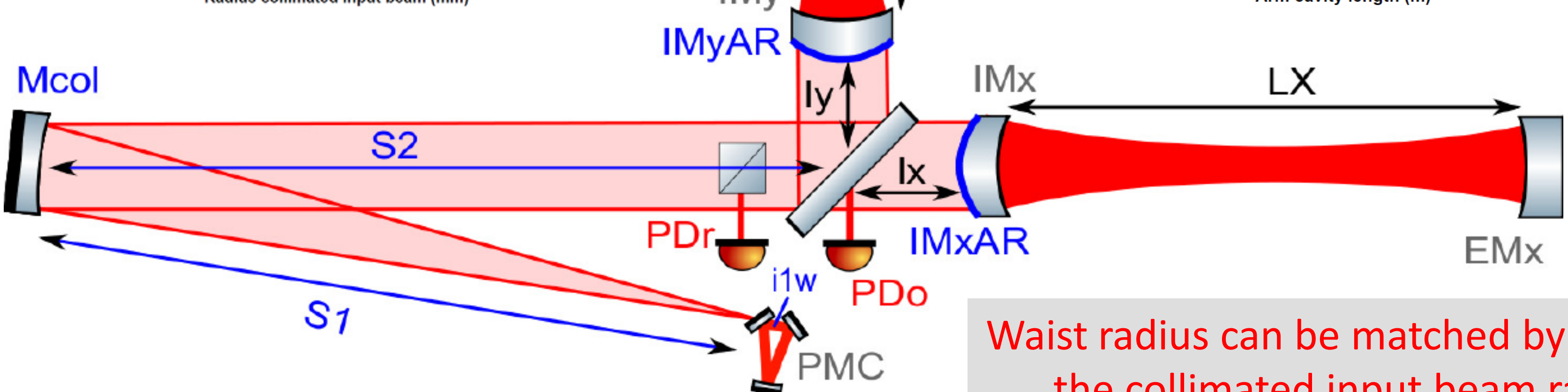
Matching the waist radius

Seen from the collimated input beam...



Seen from the AC eigenmode...

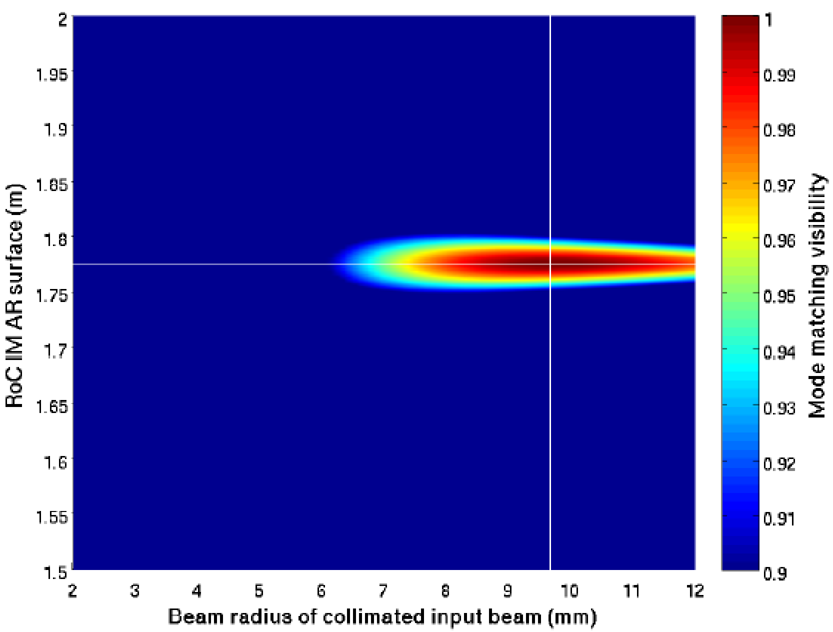




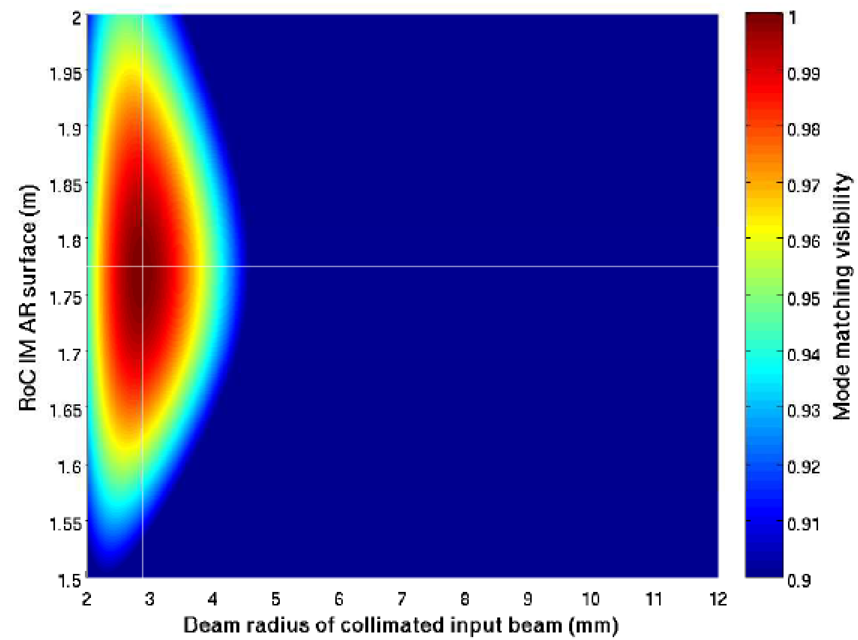
Waist radius can be matched by tuning the collimated input beam radius.

Max. mode matching visibilities

AC length L=11.39m



AC length L=10.8m

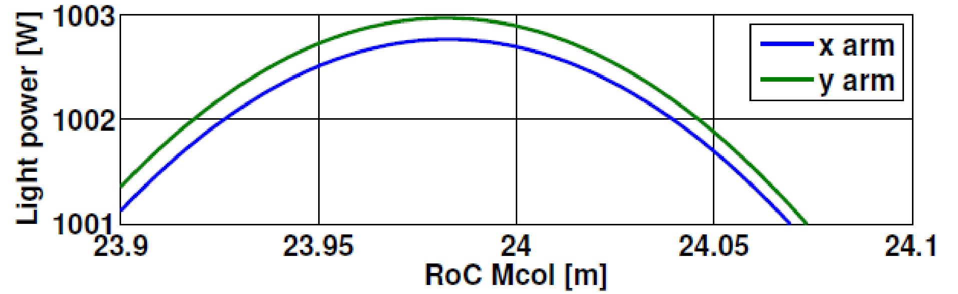


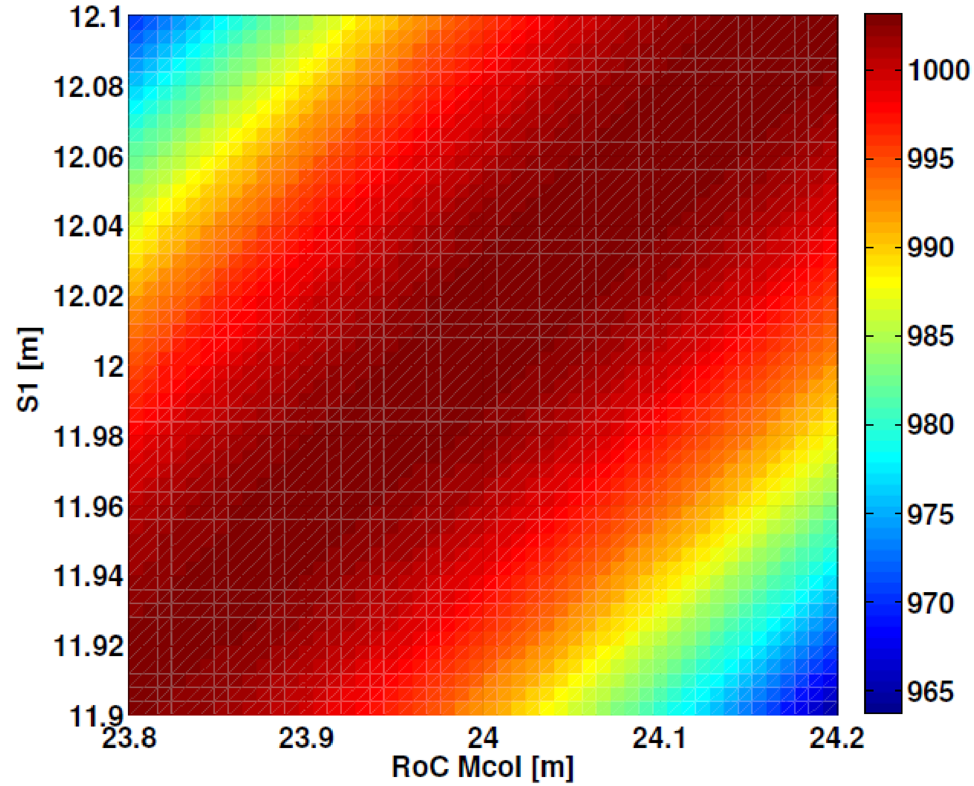
Mode matching visibility > 99% for L=10.8m arm cavities, for shifting end mirrors only

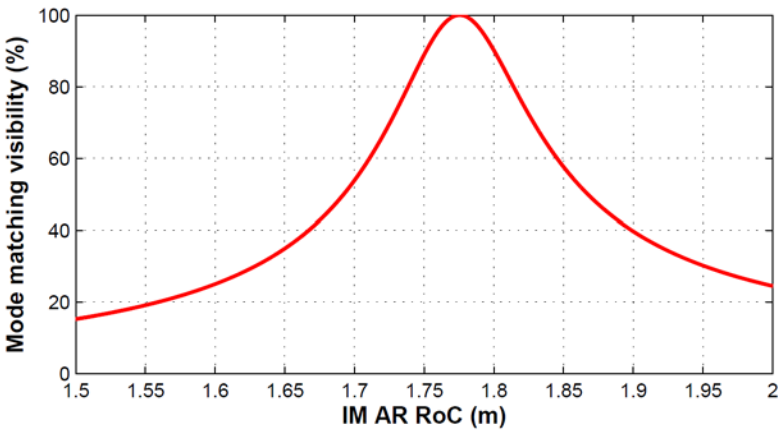
Robustness

Tolerancing of parameters with an effect on mode matching:

- Mcol RoC appears to be touchy but can be compensated for via position
- RoC of IM AR surface needs to be quite exact for marginally stable configuration







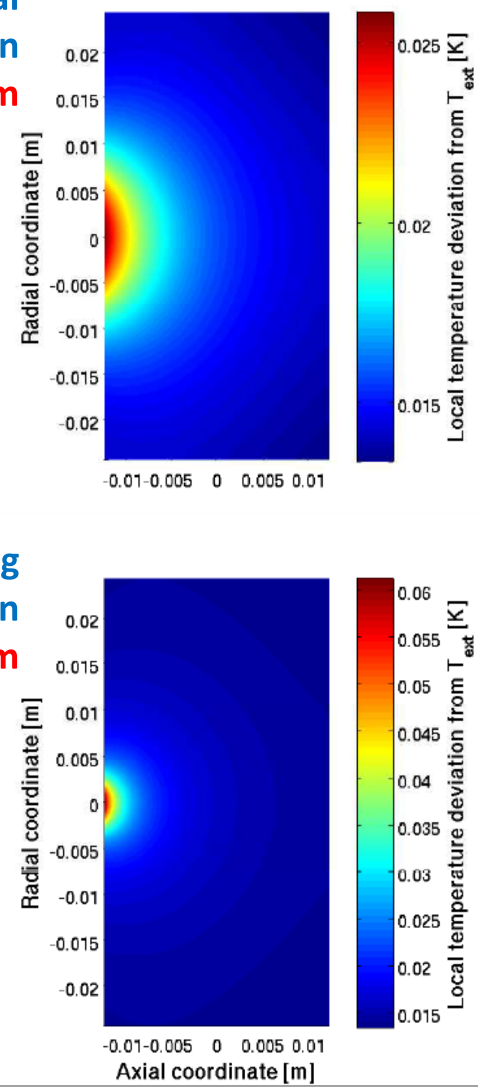
Thermal aberrations

Thermo-elastic and thermo-refractive effects driven by bulk and coating absorption:

- “Bulk effects“ degrade mode matching visibility, “coating effects“ additionally change the cavity eigenmode, stability, ...
- Assuming aLIGO like absorptions, 1ppm/cm bulk, 0.5ppm coating, for 2.5W transmitted and 1kW circulating power local heating (i.e. the “drive“) is fairly small
- Some first estimates:
  - Thermo-elastic mirror surface deformation, Δg≈-10^- 6 (stabilizing)
  - Coating+substrate TL-induced degradation of mode matching visibility ≈ 0.3%

Final configuration
w=9.72mm

Starting configuration
w=2.86mm



Based on Vinet et al., J. Phys. France 51 (1990) 1267-1282

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This is work in progress!

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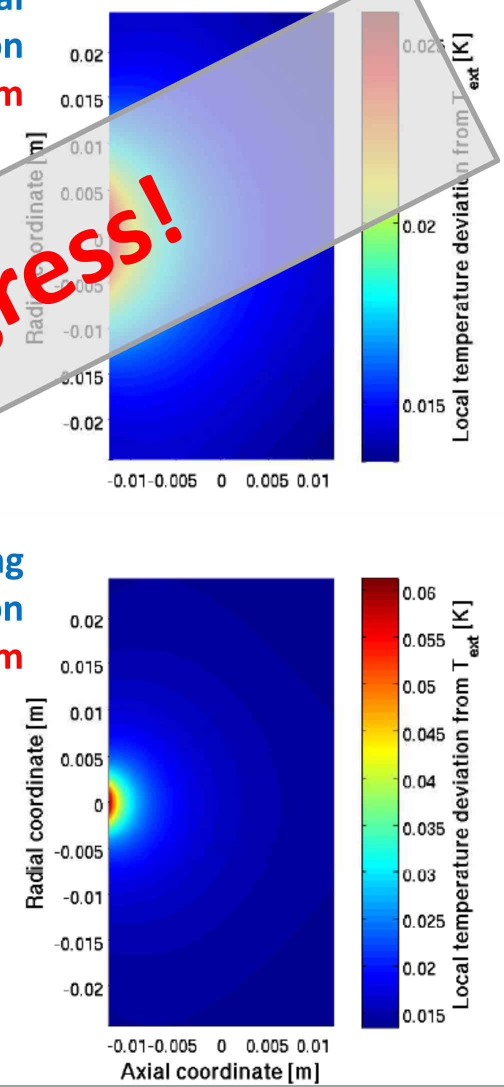

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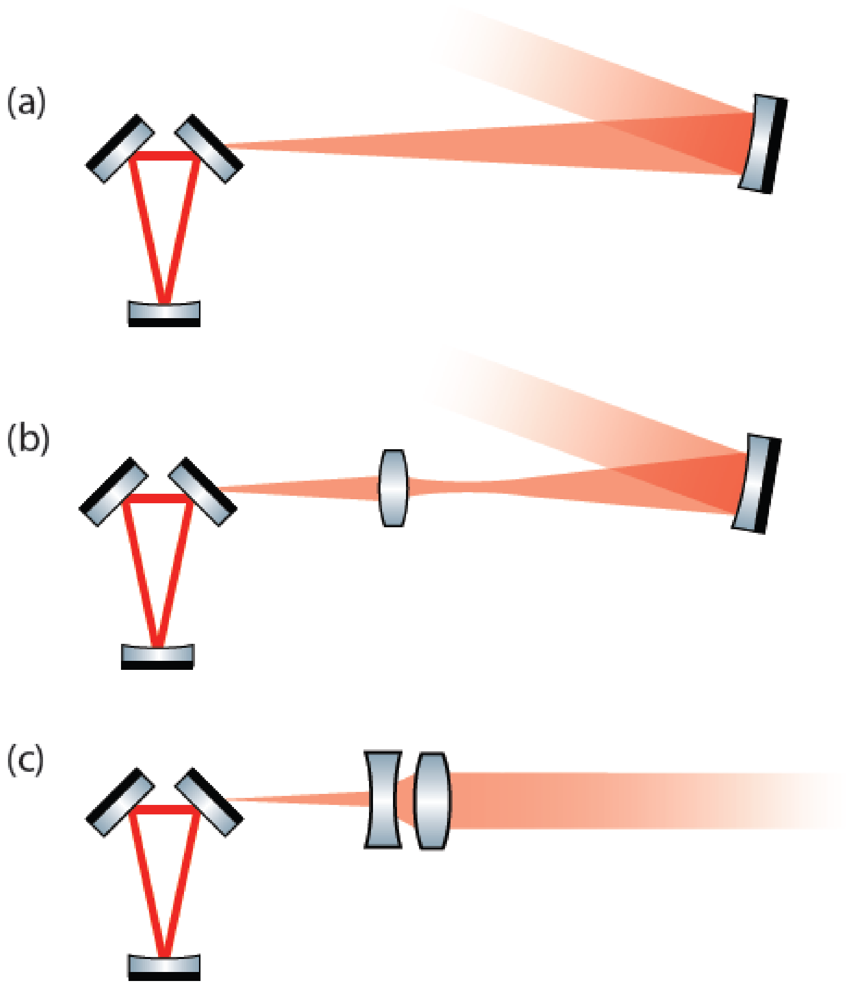
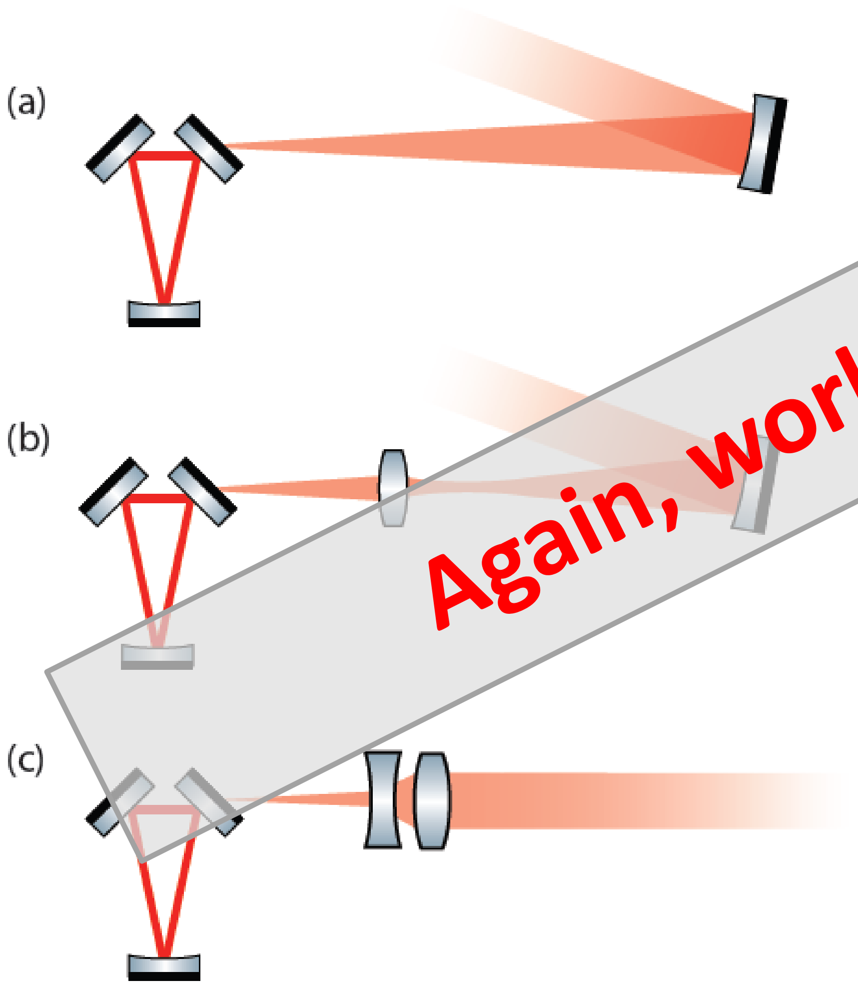
Adapting the input beam



Requirement: collimated input beam radius needs to be tunable

- Theoretically, (a) is fine for the marginally stable configuration
- Additional optics required when shortening ACs , to adapt collimated beam radius
- Combination of a lens and a collimating mirror (b) or two mirrors is probably the way to go
- Mirrors preferred over lenses as there is in this position no isolator foreseen to attenuate back reflected light in the beam path, tilting lenses induces astigmatism

Adapting the input beam



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Again, work in progress!

New opportunities

Learn more about operating arm cavities near instability:

- Potentially interesting upgrade for 2nd generation GW observatories to reduce thermal noise
- Considered a "standard" feature in 3rd generation observatory designs

Exciting measurements:

- Thermal noise limiting for short arm length/small spot size
- Long arm cavity configuration theoretically limited by QN

Foundation for testing advanced technologies:

- Khalili cavities/etalons, Ti doped coatings, waveguides...

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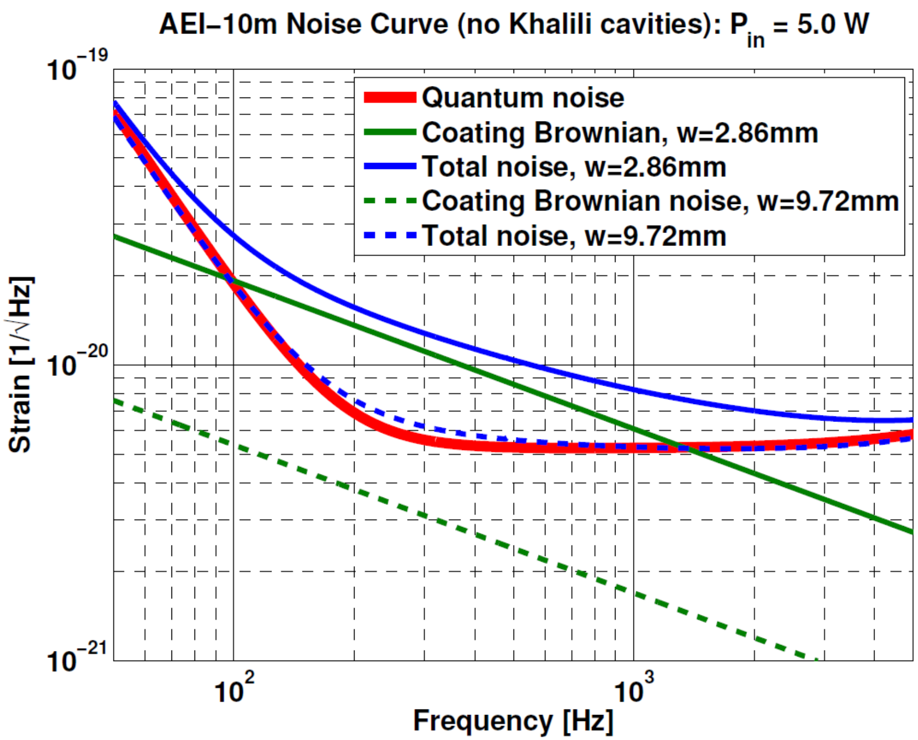

Thank you for your attention.