Computation of AdV arm-cavity baffle displacement noise projection

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on behalf of AdV SLC team

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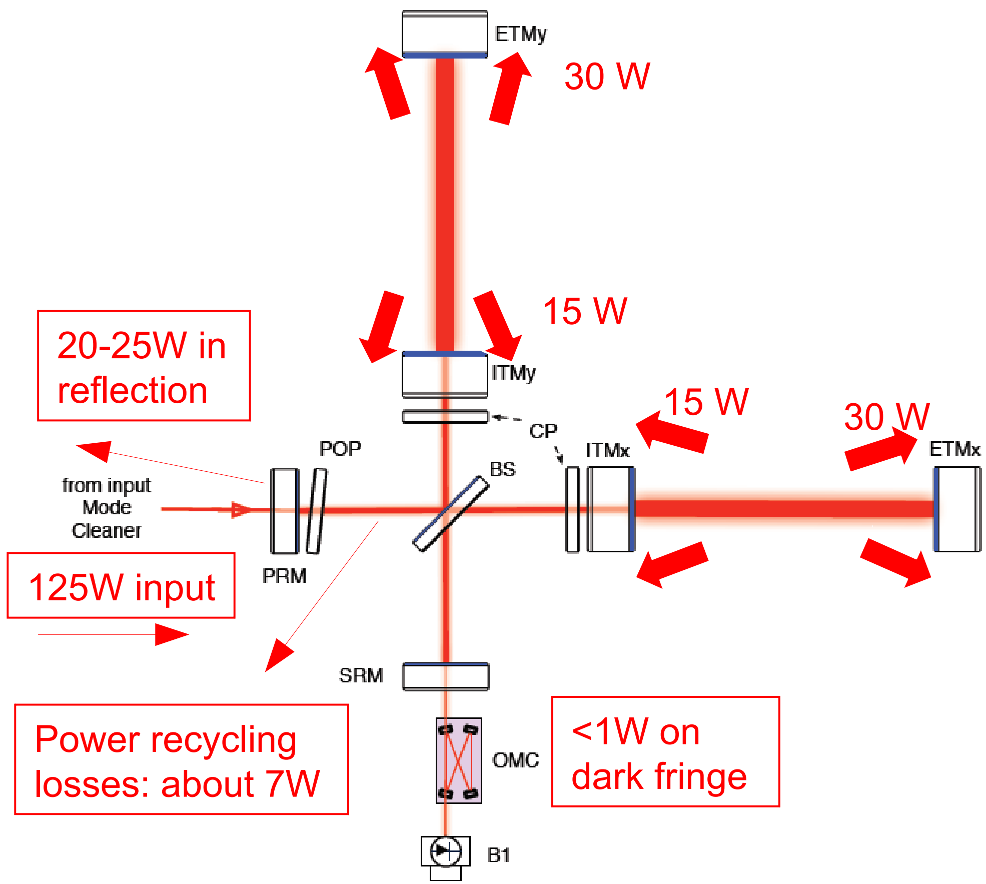
The problem:

- deal with all the light that goes out of the coating of the core optics.
- the recoupling of some of this light into the interferometer must induce a displacement noise 10 times lower than the sensitivity.



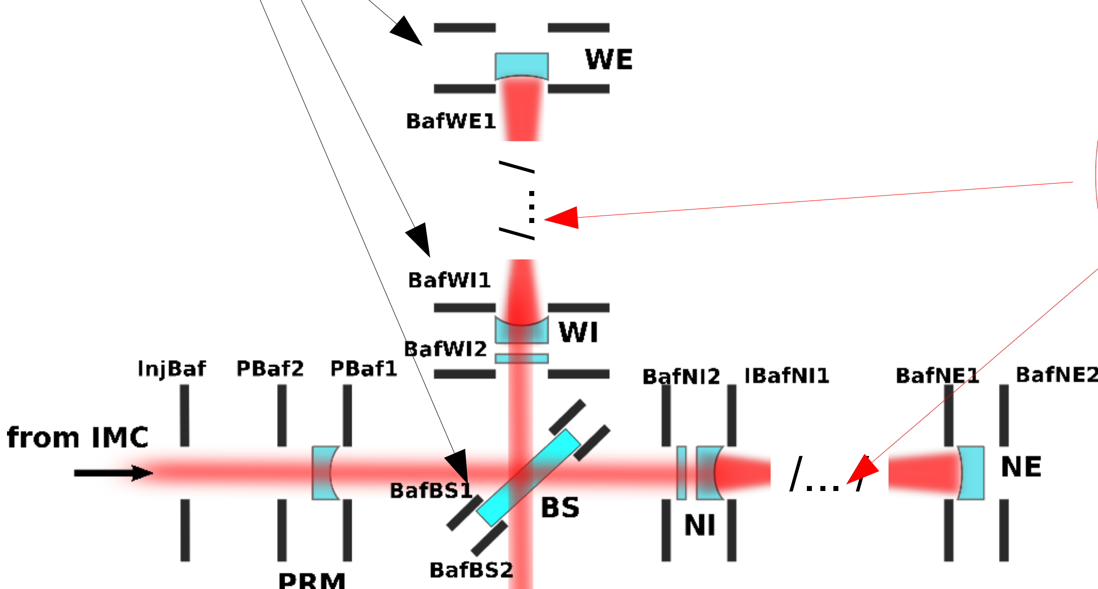
- *Stray Light* was an issue for Virgo-plus.
- If not properly managed, it would be even worse for second generation gw interferometric detectors (*enhanced sensitivity, increased power*)

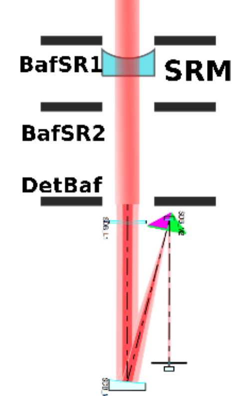
In AdV, ~100W will be lost by scattering/clipping around the core optics in the arm cavities

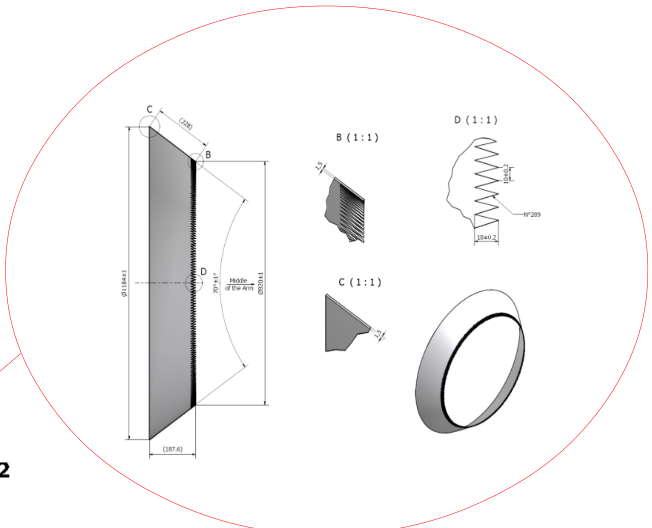
The envisaged solution:

New baffles and diaphragms will be installed in Advanced Virgo, around core optics and wherever stray light might be harmful.

Old arm-tube baffles will be kept in place (there are 160 baffles per arm)



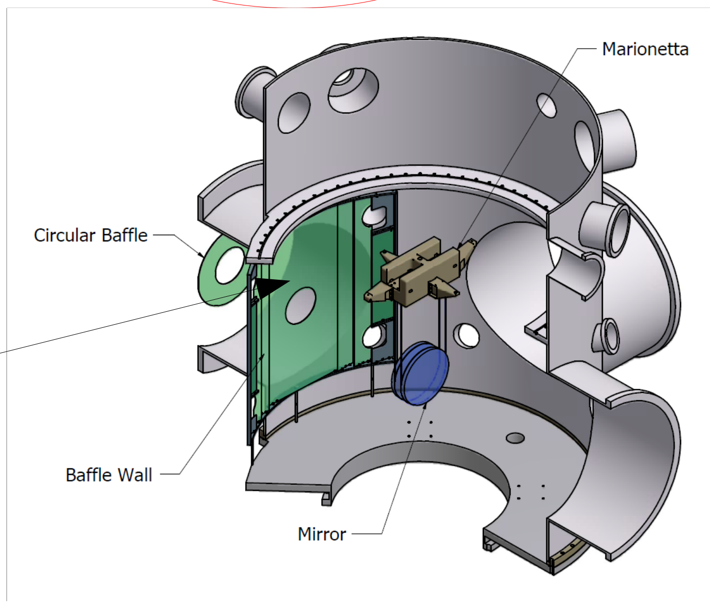




There will be baffles for tackling:

- *small angle scattering* caused by low spatial frequency figure errors of the mirrors

- *wide angle scattering* due to micro-roughness and defect points



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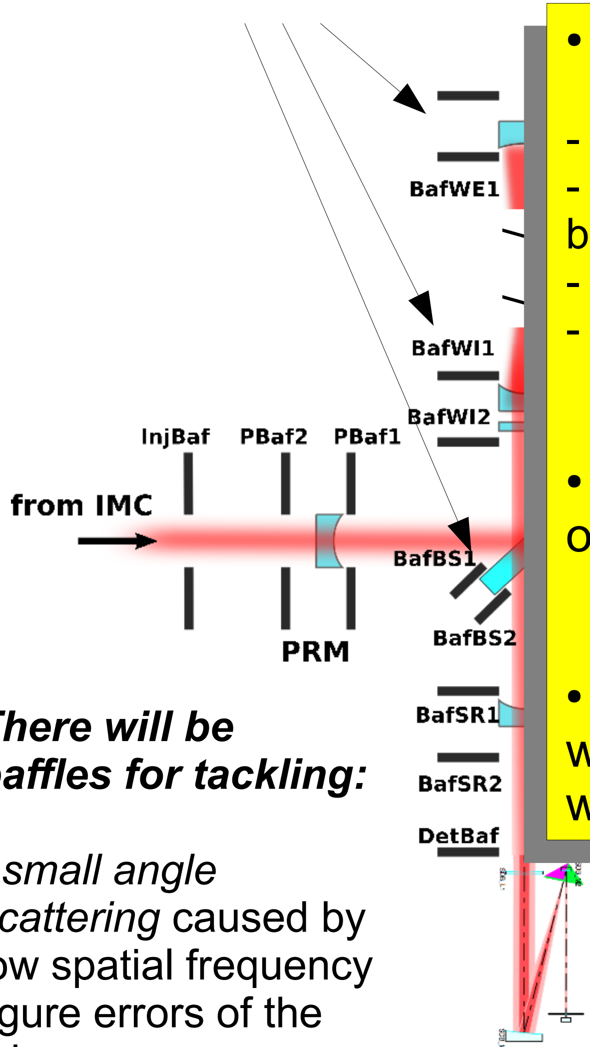
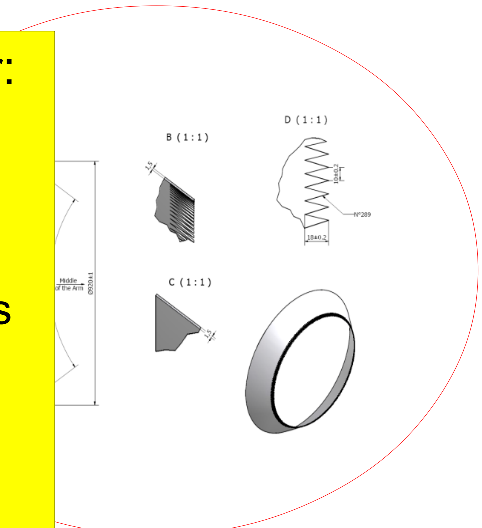


- **Requirements** are to be set for:
  - Damage threshold
  - External and internal diameters of baffles
  - Roughness and reflectivity of baffles
  - Edges geometry (sharp angles)
- Requirements will be a function of the position inside the ITF.
- In particular, some of the baffles will be suspended, some others will be ground-connected



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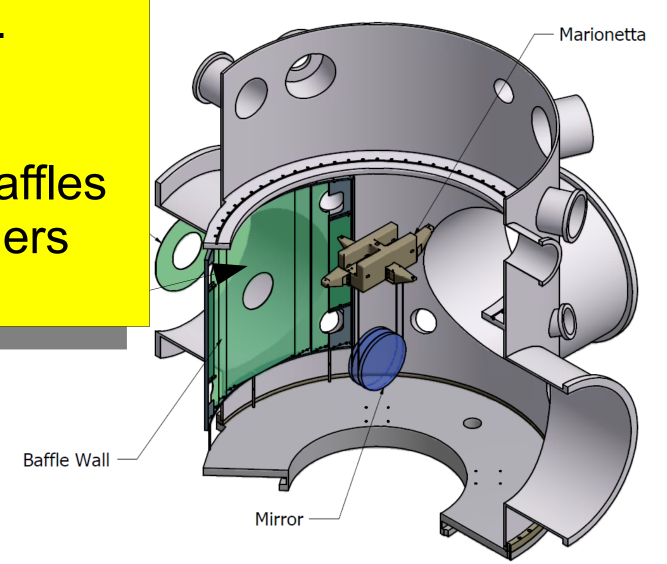
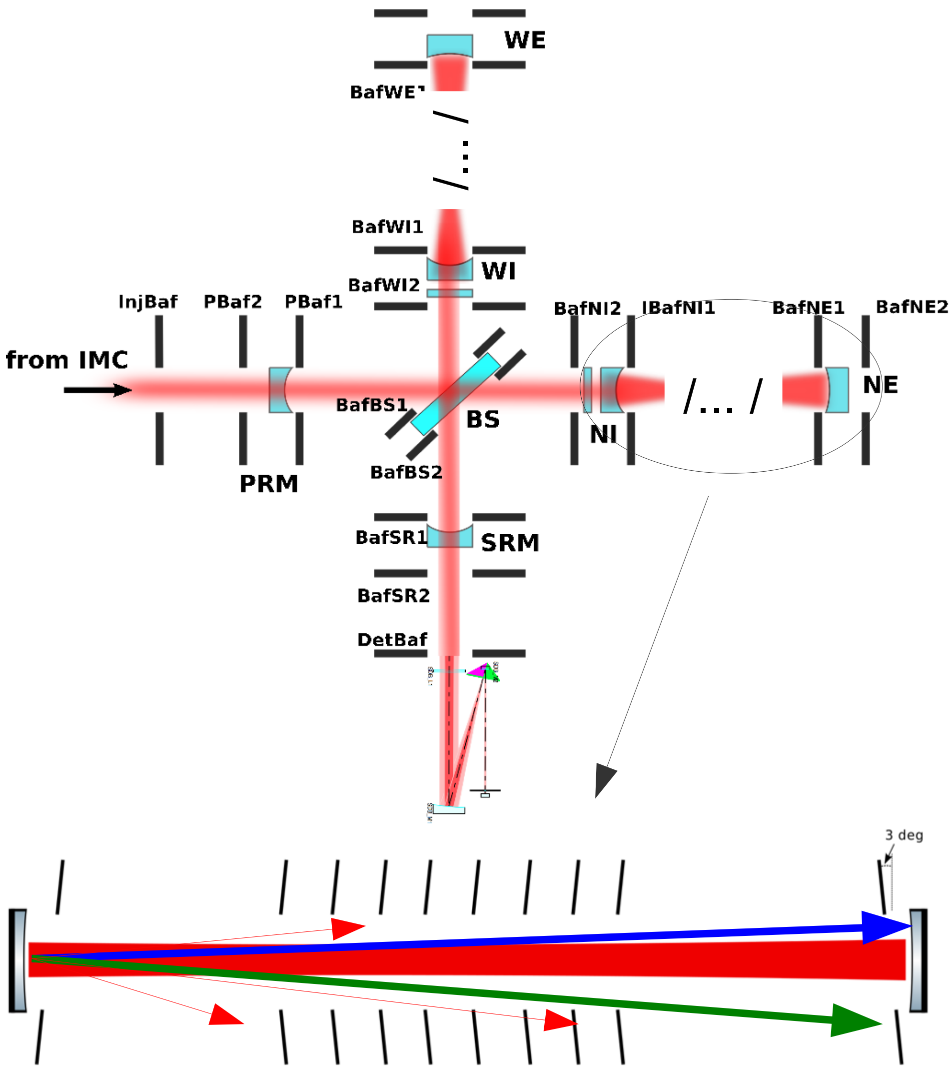
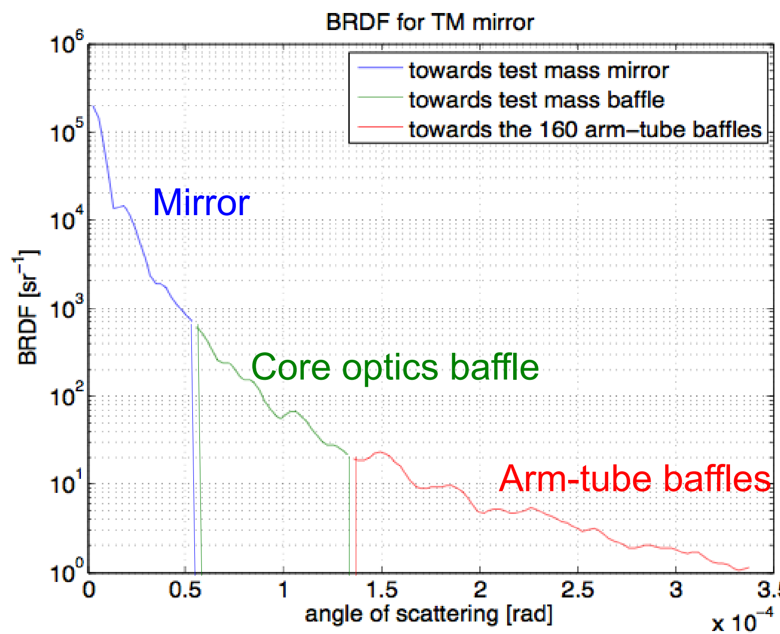


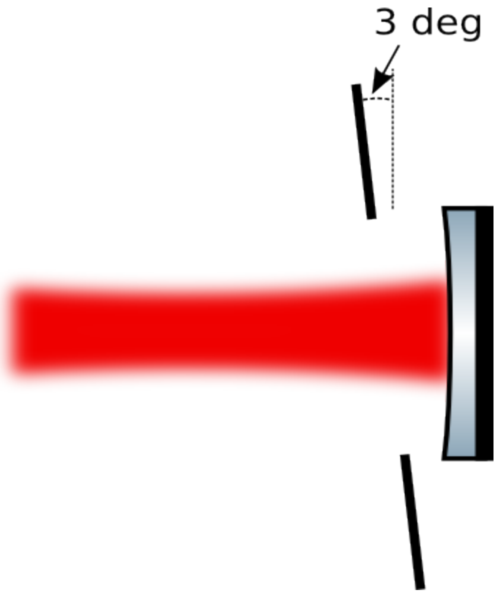
- *In the following we will focus on the baffles inside the arm cavities, around the core optics...*



... because they intercept order of magnitude more power than all the other arm baffles (all together) do!



• In order to compute requirements, simulations have been performed with different tools and in steps:



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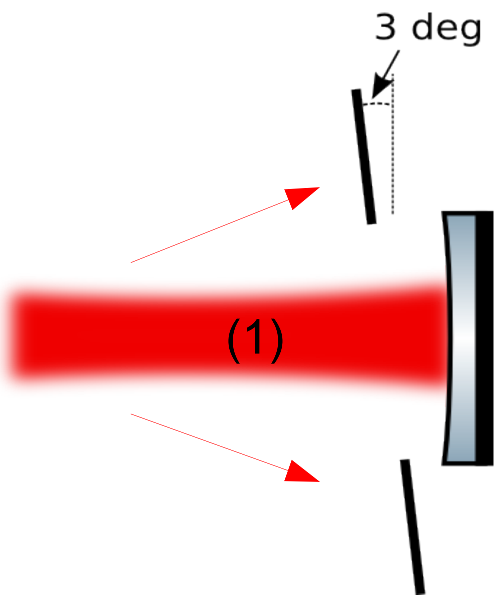

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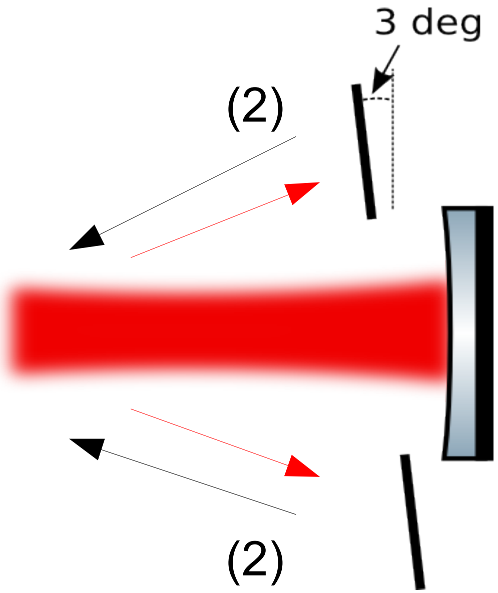

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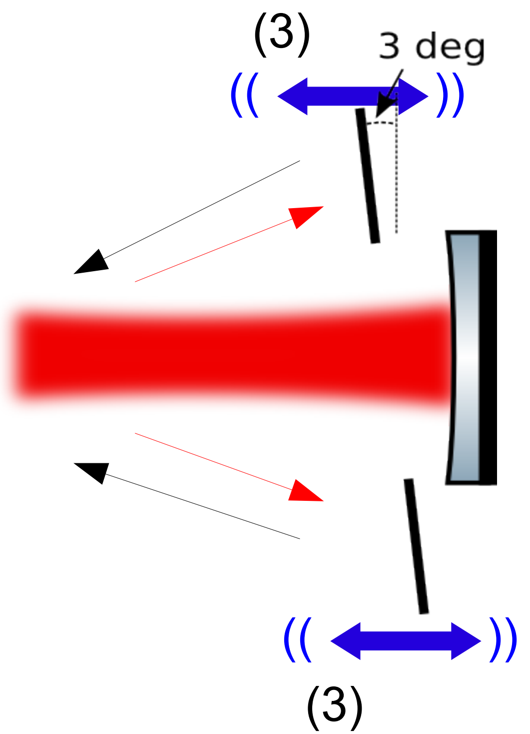

(*) Optickle by M.Evans
Frequency domain Matlab methods for doing interferometer simulation.
Features: only TEM00 mode, includes radiation pressure, mechanical TFs and quantum noise.
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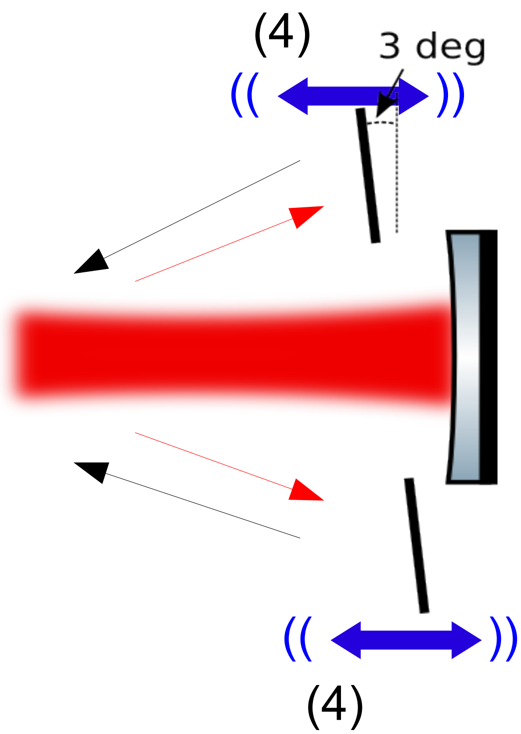
(4) Project noise to the strain sensitivity assuming the specified motion for the various baffles as input



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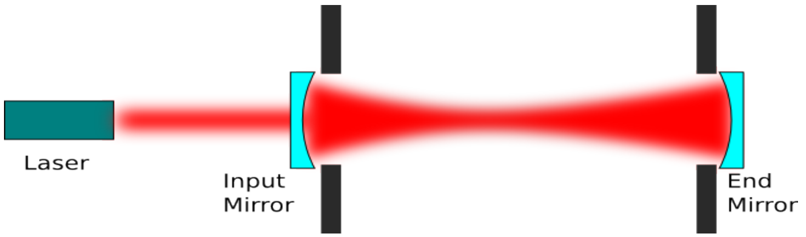
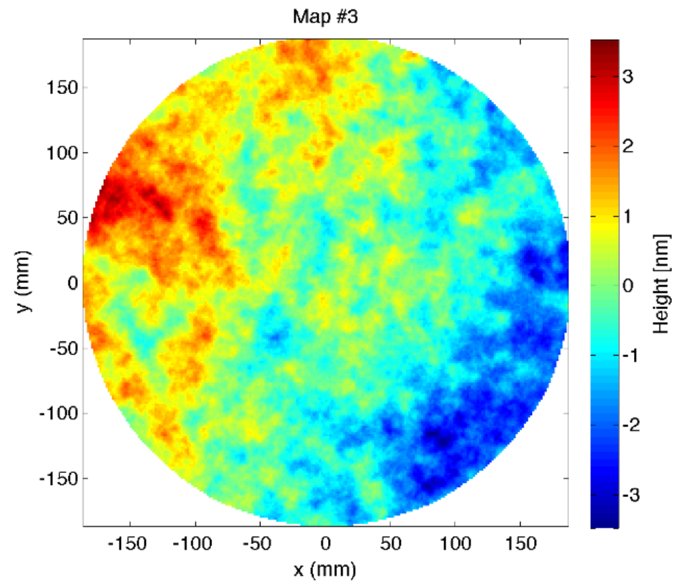
(1) Use optical FFT propagation simulation (FOG) to compute the distribution of light out of the coatings

FOG simulation of one arm cavity, with different mirror maps





AdV arm cavity parameters:

Input mirror RoC	=	1420m
End mirror RoC	=	1683m
Cavity length	=	2999.8m
T_IM	=	0.014
T_EM	=	1ppm

8 LMA maps available for the simulation, used with all combinations (fake maps fulfilling AdV requirements) after removing piston and tilt with a gaussian weight

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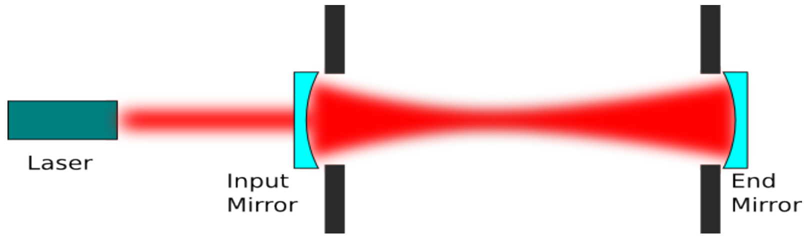
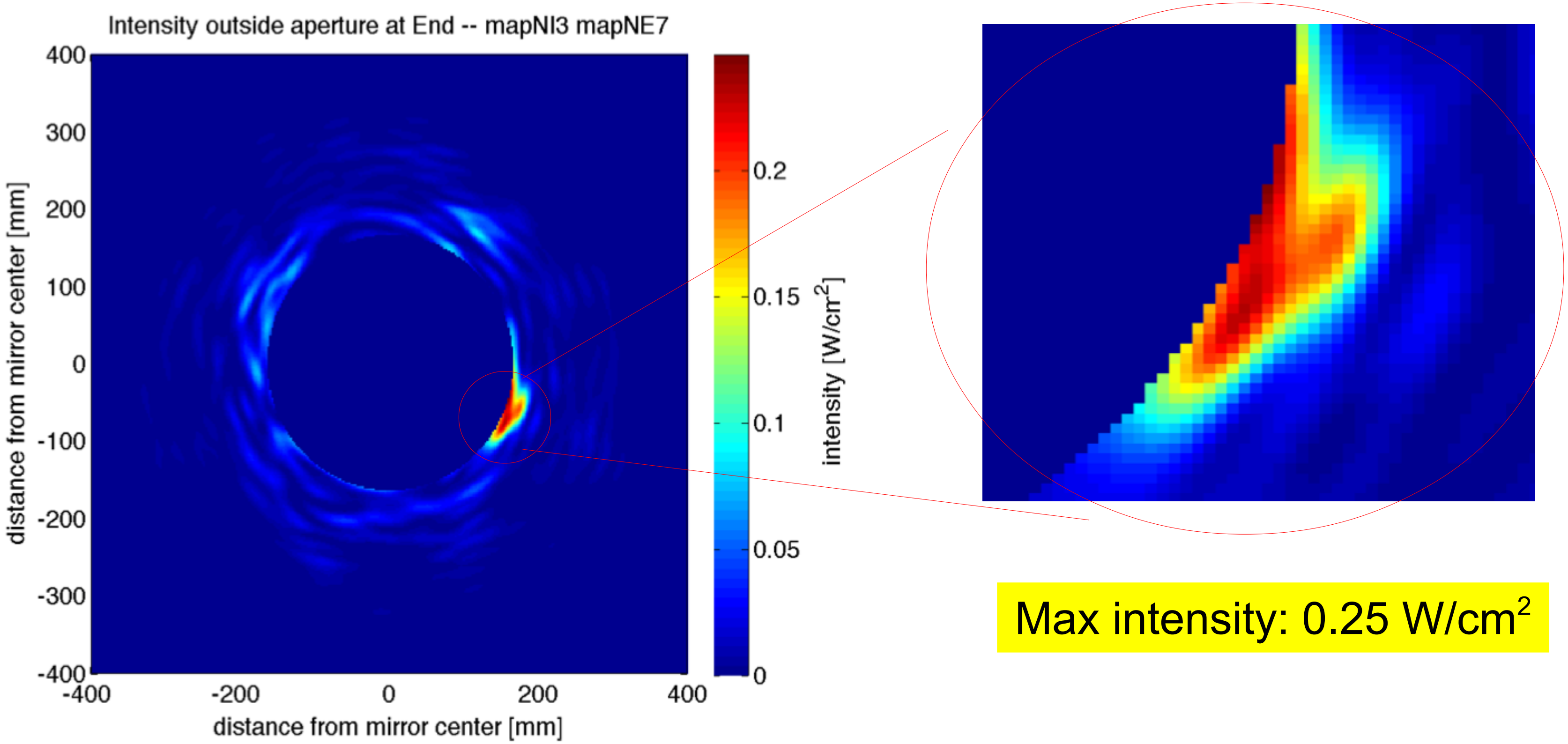




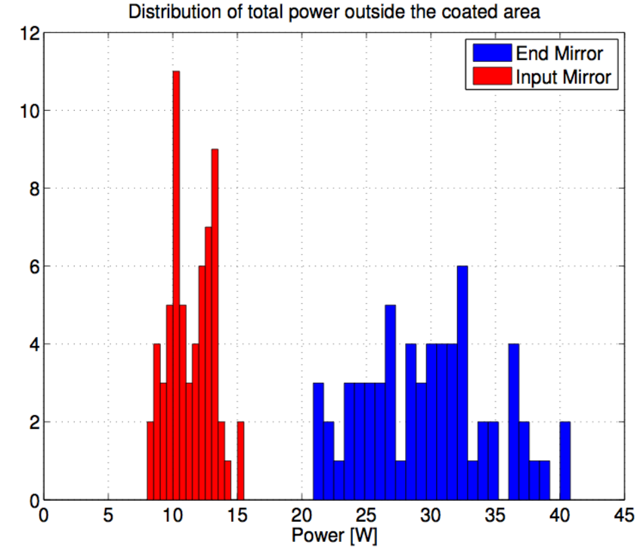
Max intensity: 0.25 W/cm^2

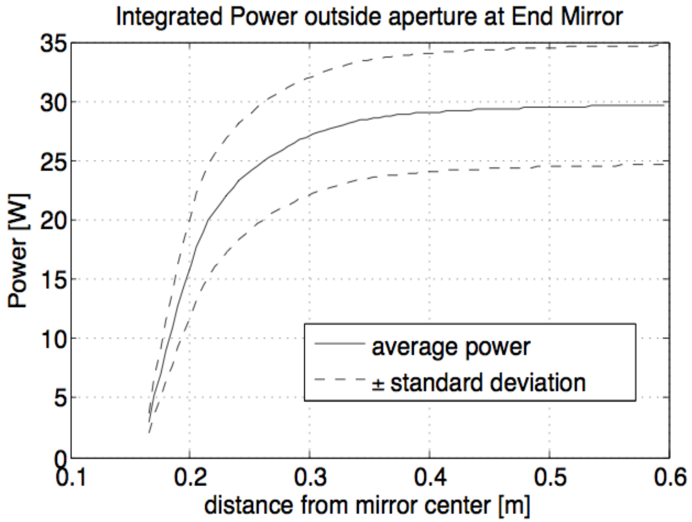
(1) Use optical FFT propagation simulation (FOG) to compute the distribution of light out of the coatings

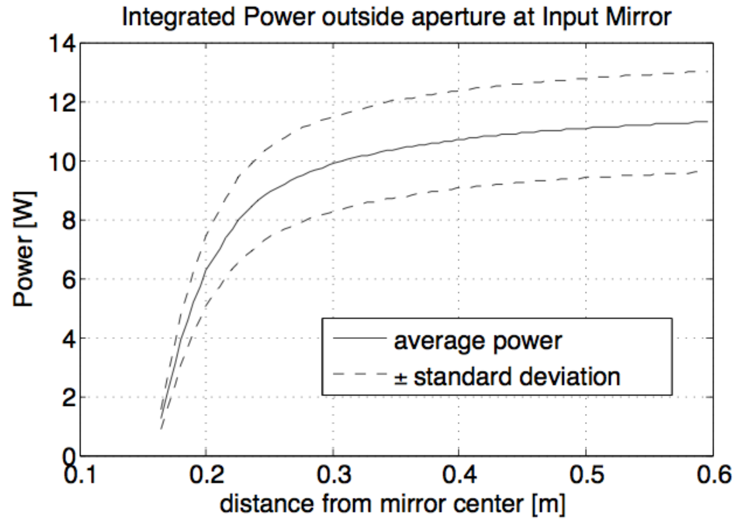
FOG simulation of one arm cavity, with different mirror maps

Baffle radius:
Inner = 16.5cm
Outer= 40.0cm

→ This catches 95% of scattered light inside the cavity (in 95% of cases)





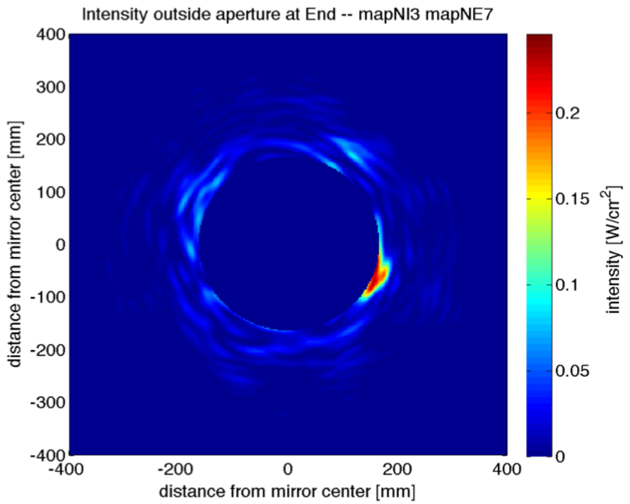


(2) Use optical FFT propagation simulation (FOG) to compute how much light from the baffles is then re-coupled to the main interferometer beam

- insert an “effective” baffle map to simulate the actual scattering,

- use scattering from baffles as an intracavity “source” to distinguish the field coming from the baffles wrt the main cavity mode

- evaluate the coupling efficiency of the scattered light to the main cavity mode



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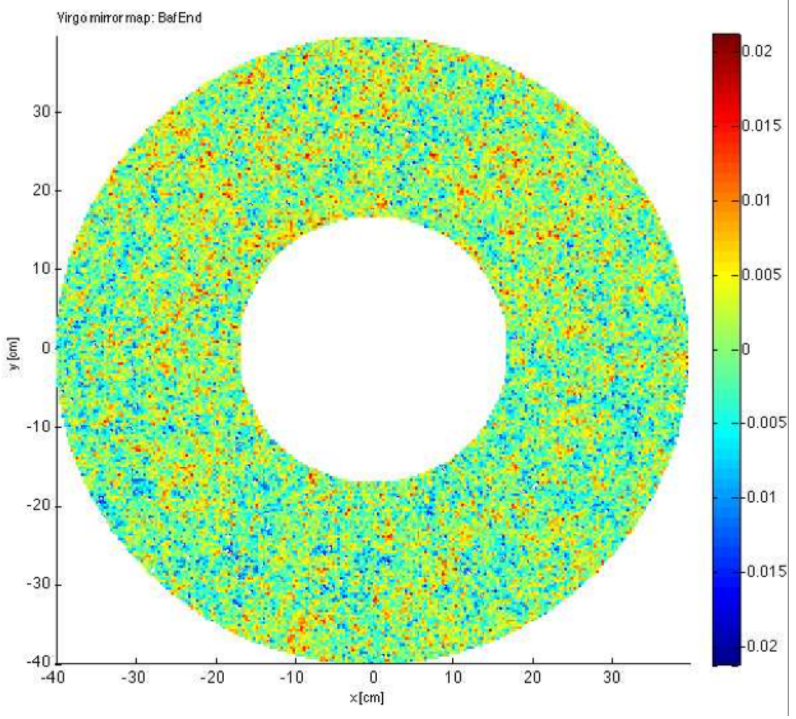
- the actual arm baffles will be tilted by ~3deg to avoid small angle scattering.
For this angle of incidence, the involved spatial frequency for back scattering is $\sim 10^5\ m^{-1}$ (!)

- this would be very difficult to simulate with FFT!

- the trick: find an “effective” baffle map to simulate the actual scattering, starting from the expected BRDF of the baffle.

(2) Use optical FFT propagation simulation (FOG) to compute how much light from the baffles is then re-coupled to the main interferometer beam

- the trick: find an “effective” baffle map to simulate the actual scattering, starting from the expected BRDF of the baffle.



• Start from the PSD of a TM map → produce random annulus-shaped map

• Roughness x 10^6 (rms > lambda/2 to have a speckle pattern in reflection)

• Adjust “reflectivity” to match expected BRDF

BRDF(theta = 3deg) = ~$3x10^{-3}$ sr^{-1}
for micro-roughness = 10A @10^5m^{-1}

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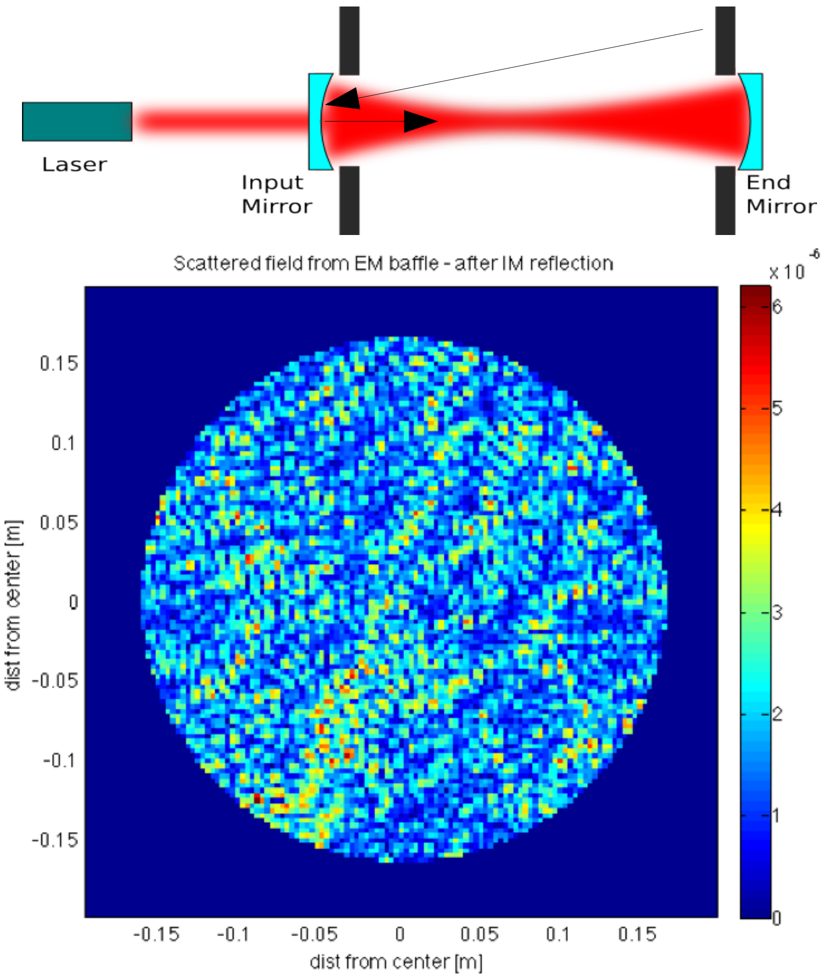
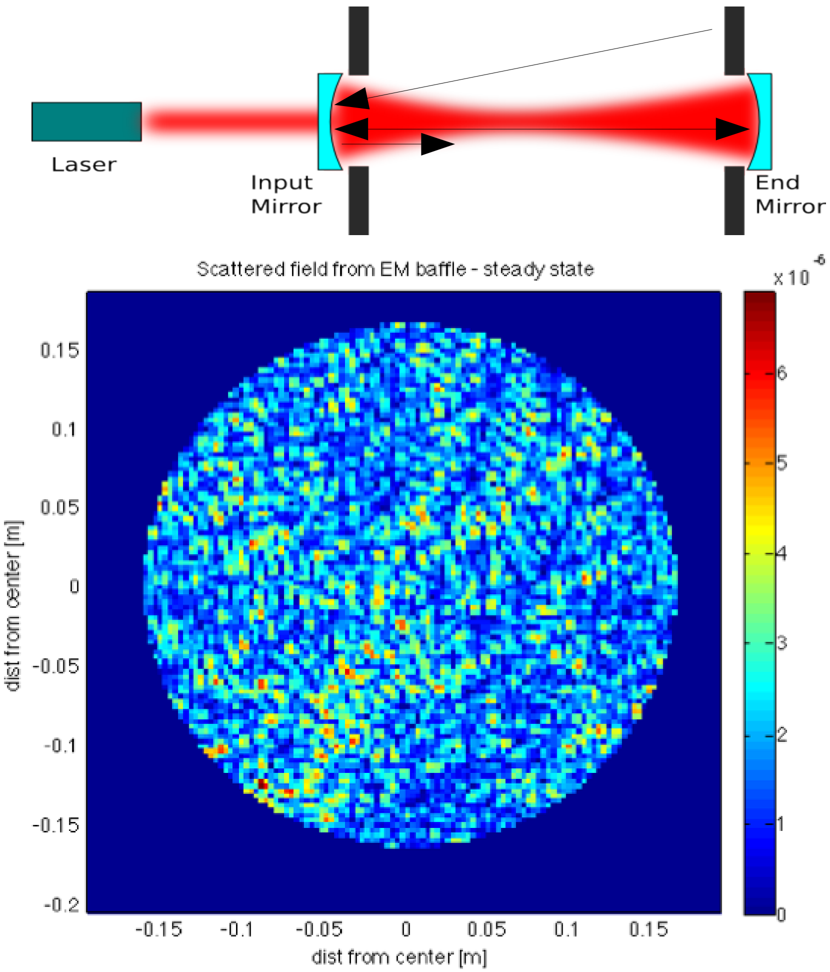
Prompt scattering



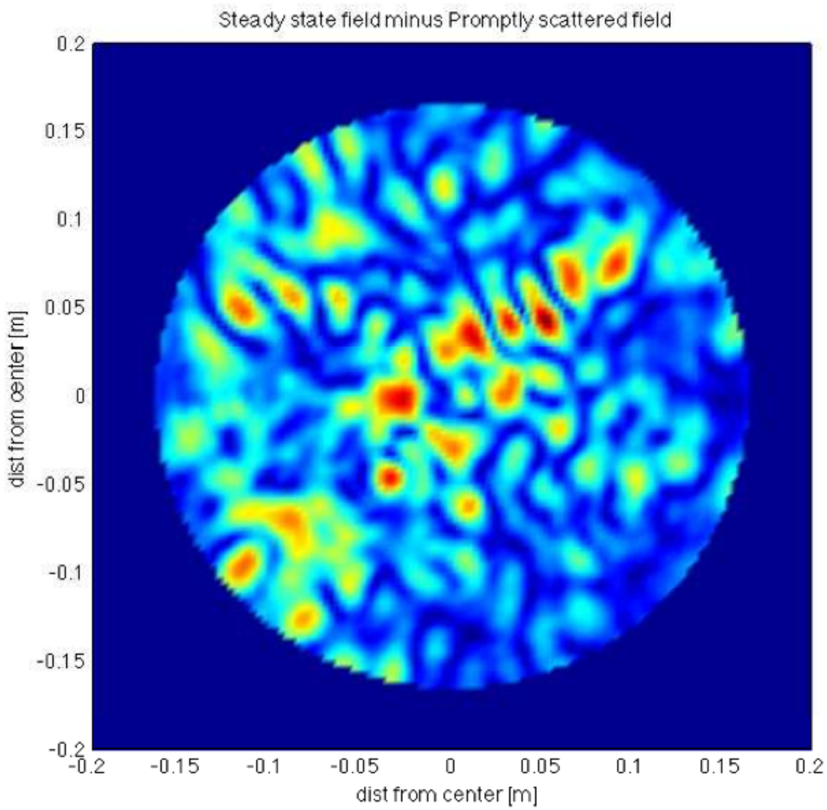
Recycled scattering



Speckle size ~1cm; roughly in agreement with size = lambda./dist .* width_source

(2) Use optical FFT propagation simulation (FOG) to compute how much light from the baffles is then re-coupled to the main interferometer beam

Difference between PS and RS field



- The two fields look like the same, but they are really different wrt TEM00 projection:

$$c_{00}^{xx} = < E_{00} | E_{xx} > = \frac{\int E_{00}^{*} E_{xx} dxdy}{\int |E_{00}|^2 dxdy \int |E_{xx}|^2 dxdy}$$

$$|c_{00}^{PS}|^2 = 1.66 \times 10^{-7} [W/W]$$
$$|c_{00}^{RS}|^2 = 5.04 \times 10^{-3} [W/W]$$

- By taking into account the cavity mode power Pcav and power carried by the RS field, we can compute the coupling C of the scattered power to the cavity mode:

$$C = |c_{00}^{RS}|^2 \times P_{NI}^{RS} / (P_{cav}\ G^{intra}) = 3.61 \times 10^{-22}\ W/W$$

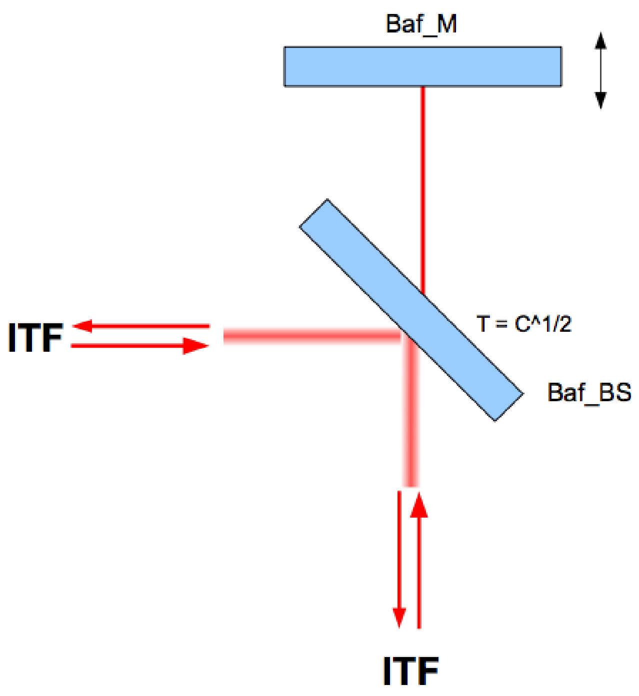
To use in simulations with Optickle

(3) Use Optickle to compute the Transfer Function between baffle motion and dark fringe

Optickle cannot deal with annulus-shaped optics such as baffles, nor it can handle defect maps (no HOMs).
But it can be used to evaluate the effect of a moving element coupling an assigned amount of power (derived from the previous step) to the ITF mode.

- *The problem* is that the “scattered” light from the mock baffle should go only towards the farthest optics, not directly to the optic element being “baffled”.

- *The trick*: fold the ITF with an almost perfectly reflecting beam sampler, add a moving mirror with unity reflectivity in transmission to the beam sampler.



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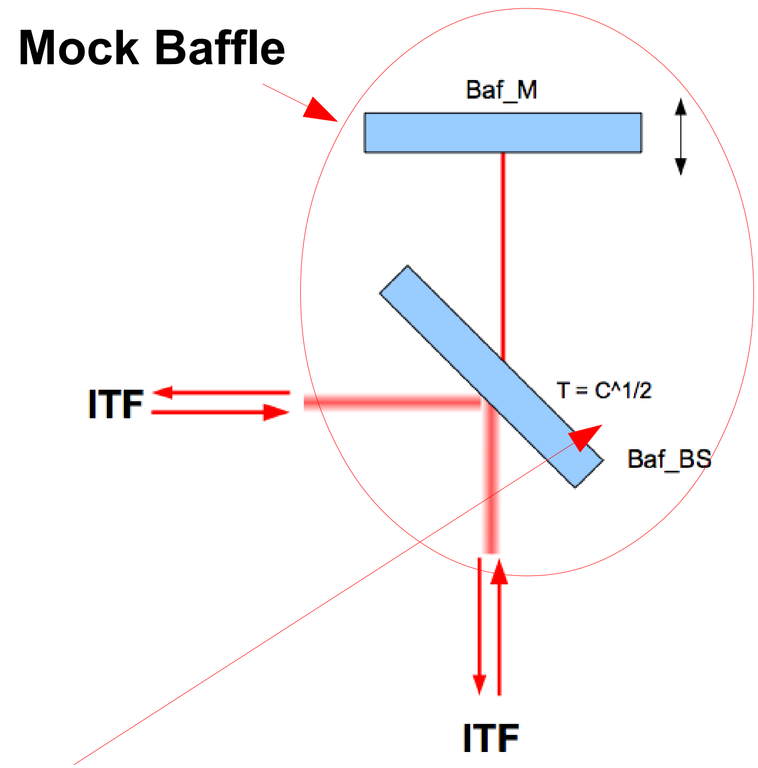

$T = C^{1/2}$ to account for the double passage through the BS

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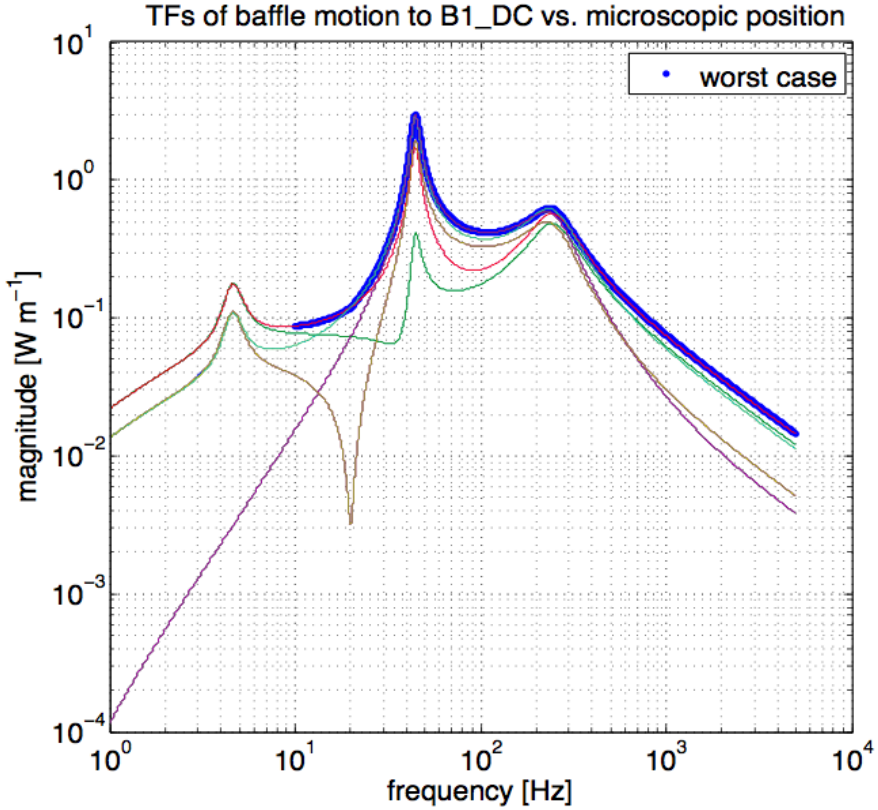

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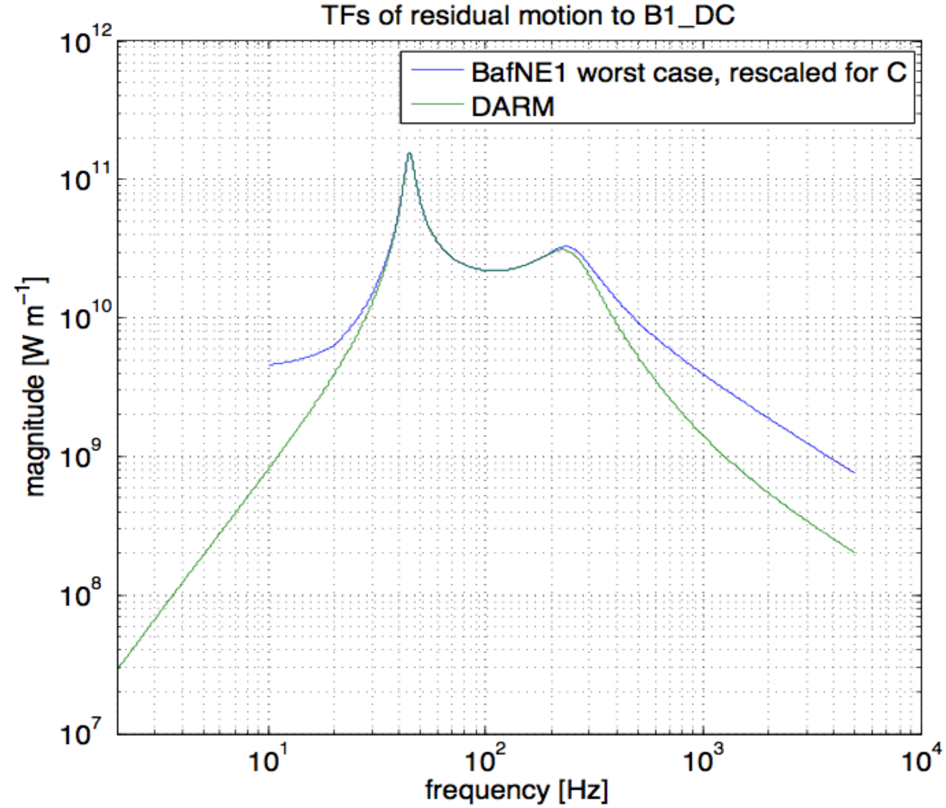


(2)

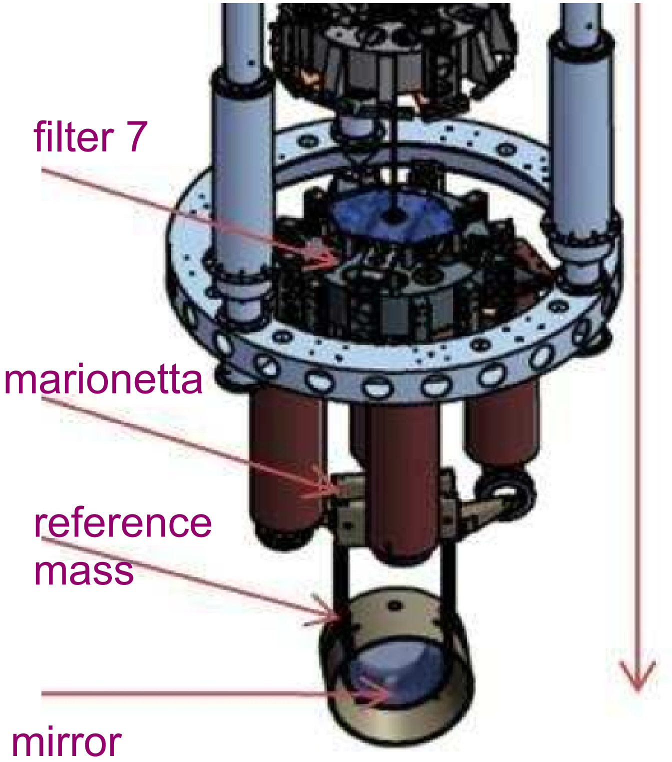
(1) The TF of BafNE1 residual motion to B1_DC depends on its microscopic position (different colors: different positions)

(2) When rescaled for the coupling efficiency, it matches very closely DARM.

...as expected

(4) Project noise assuming the specified motion for the baffles

- The suspended baffles for the core optics will be attached to the filter 7 of the super-attenuator.
- The core optic is suspended to the marionetta that is suspended to the F7.
- This means an attenuation roughly 10^4 less than the core optics



Assume that a suspended baffle for the test masses moves as:

$$x_{Baf}(f) \sim 10^4 \times h_{strain}(f)\ L_{cav}$$

(4) Project noise assuming the specified motion for the baffles

- The projection Nbaf of the noise due to the residual baff e motion (xBaf(f)) to the strain sensitivity is obtained by:

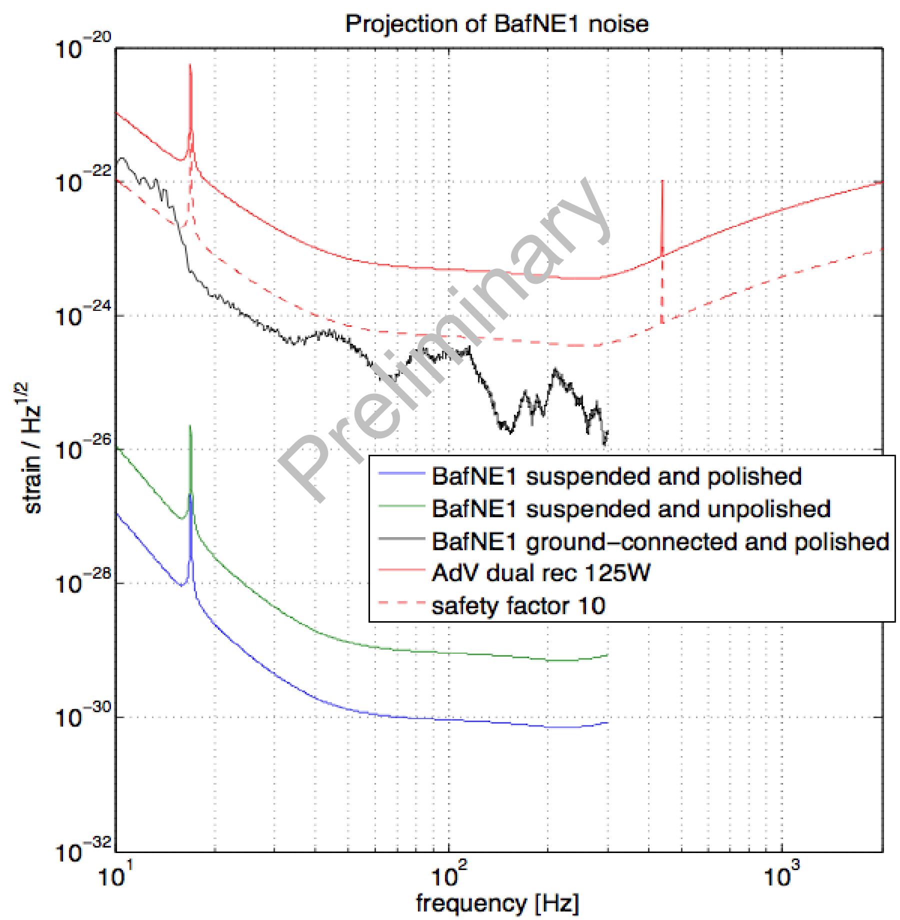
$$N_{Baf} = \frac{1}{TF_{DARM->B1\_DC}} \frac{1}{Lcav} TF_{x_{Baf}->B1\_DC}\, x_{Baf}(f)$$

- *noise projection for three cases:*

- **Blue**: suspended and polished baffle (BRDF = 3.10^{-3} sr^{-1})

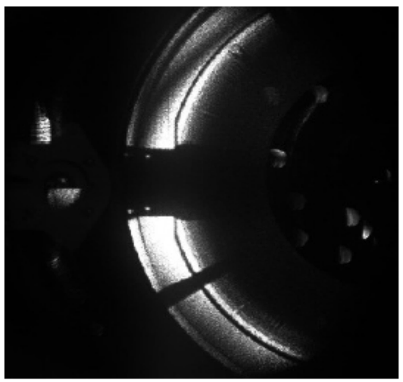
- **Green** : suspended and unpolished (BRDF = 0.3 sr^{-1})

- **Black**: ground-connected polished baffle (res. motion as measured by seismometers)

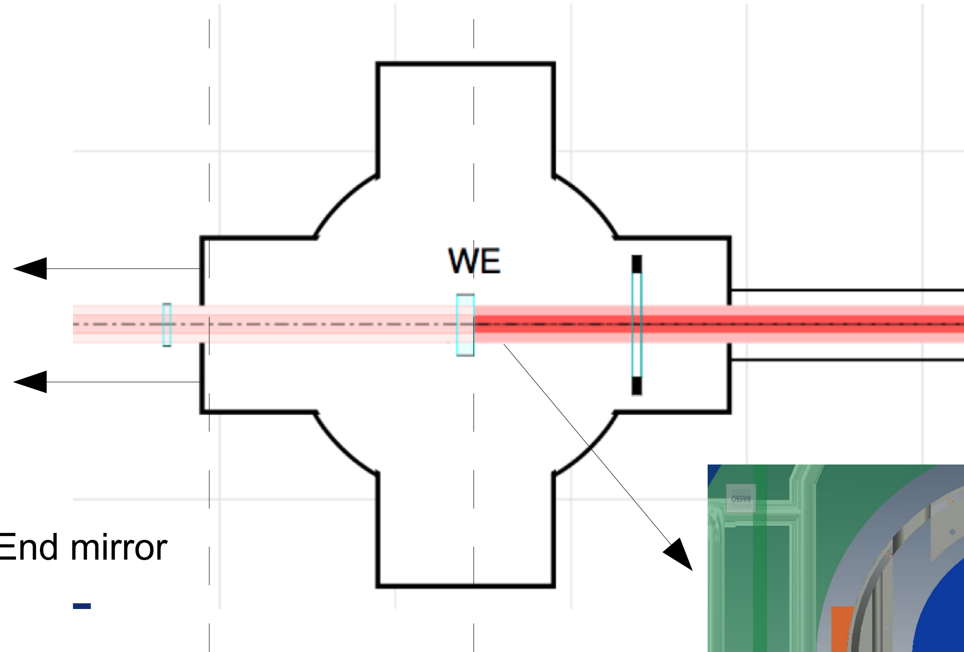


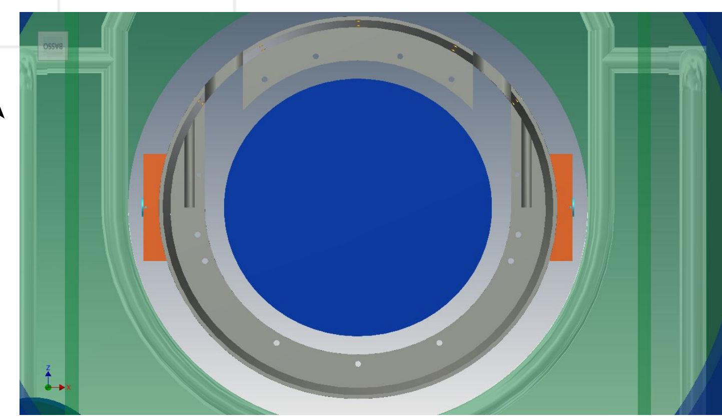
- How to validate this procedure?

At the beginning of V+MS commissioning, a ring of light scattered by the west flange of the west tower and passing between WE coating and the inner aperture of reference mass made a perfect noise injection to compare with our simulations



Around Virgo Plus West End mirror





Details in I.Fiori, et al. VIR-0493A-10; VIR-0513A-10 Virgo technical notes

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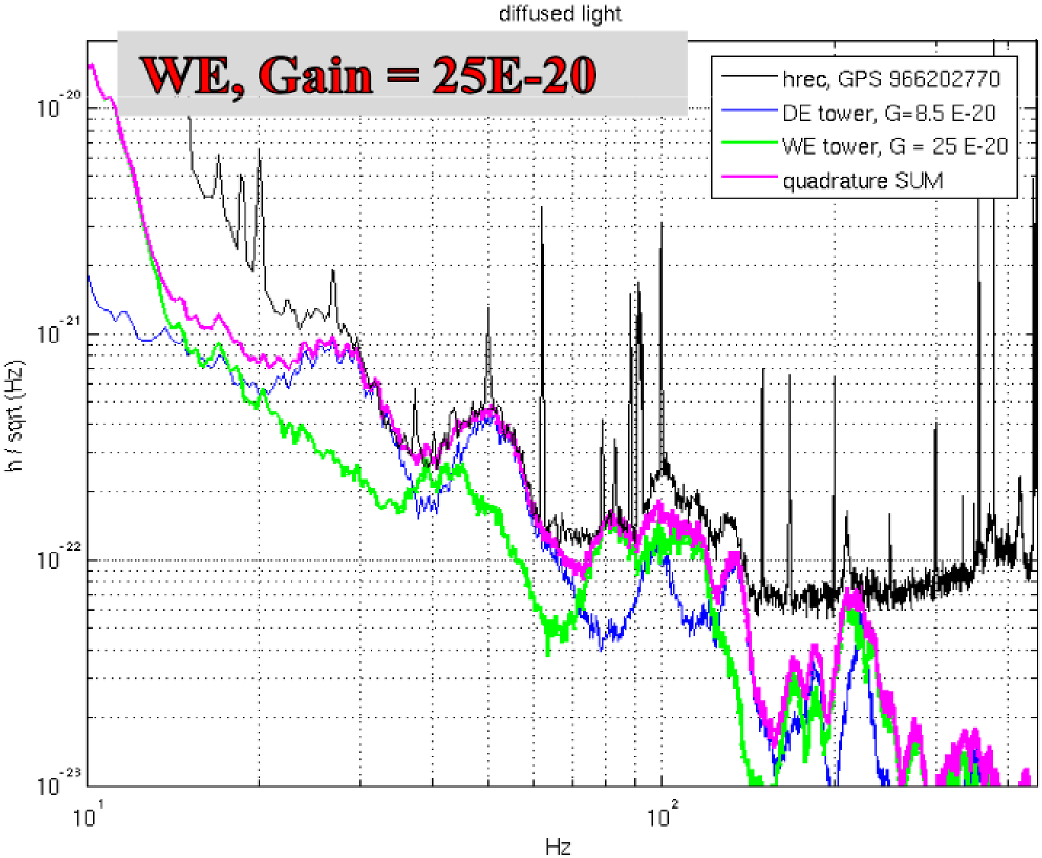

- Seismic noise injection to the walls of the WE tower allowed to derive a noise projection for this scattered light for normal seismic activity.

(**green** curve in the plot)

Details in I.Fiori, et al. VIR-0493A-10; VIR-0513A-10 Virgo technical notes

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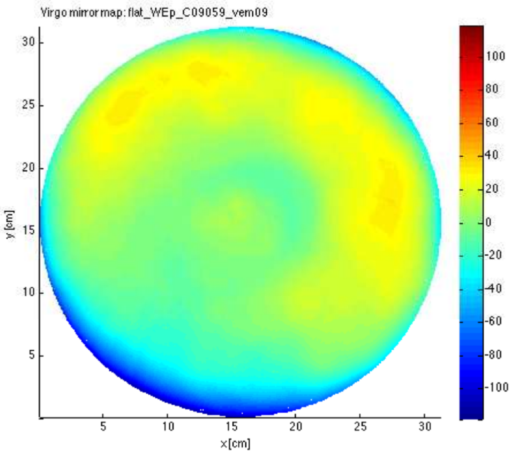
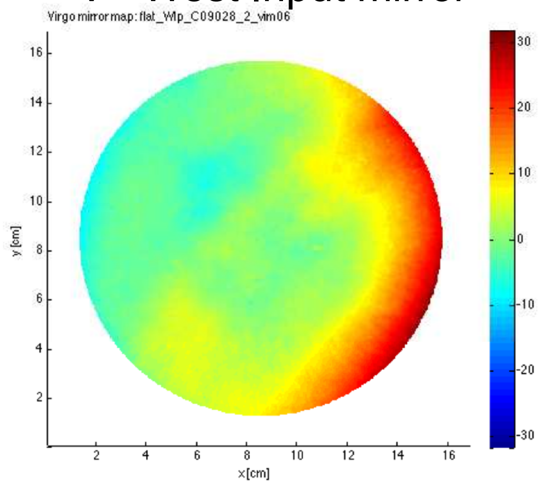
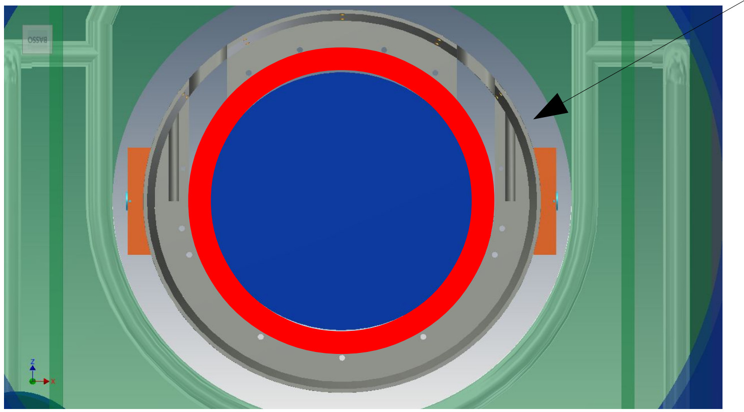
V+ West End mirror



V+ West Input mirror





Apply the procedure to Vp:

- measured maps for West Arm mirrors (LMA)
- "virtual baffle" of stainless steel around West End Mirror
- baffle outer diameter: inner aperture of the reference mass
- baffle BRDF = 2 sr^{-1} (assume same value measured for arm tube)
- baffle residual motion: as measured by seismometers on WE tower walls

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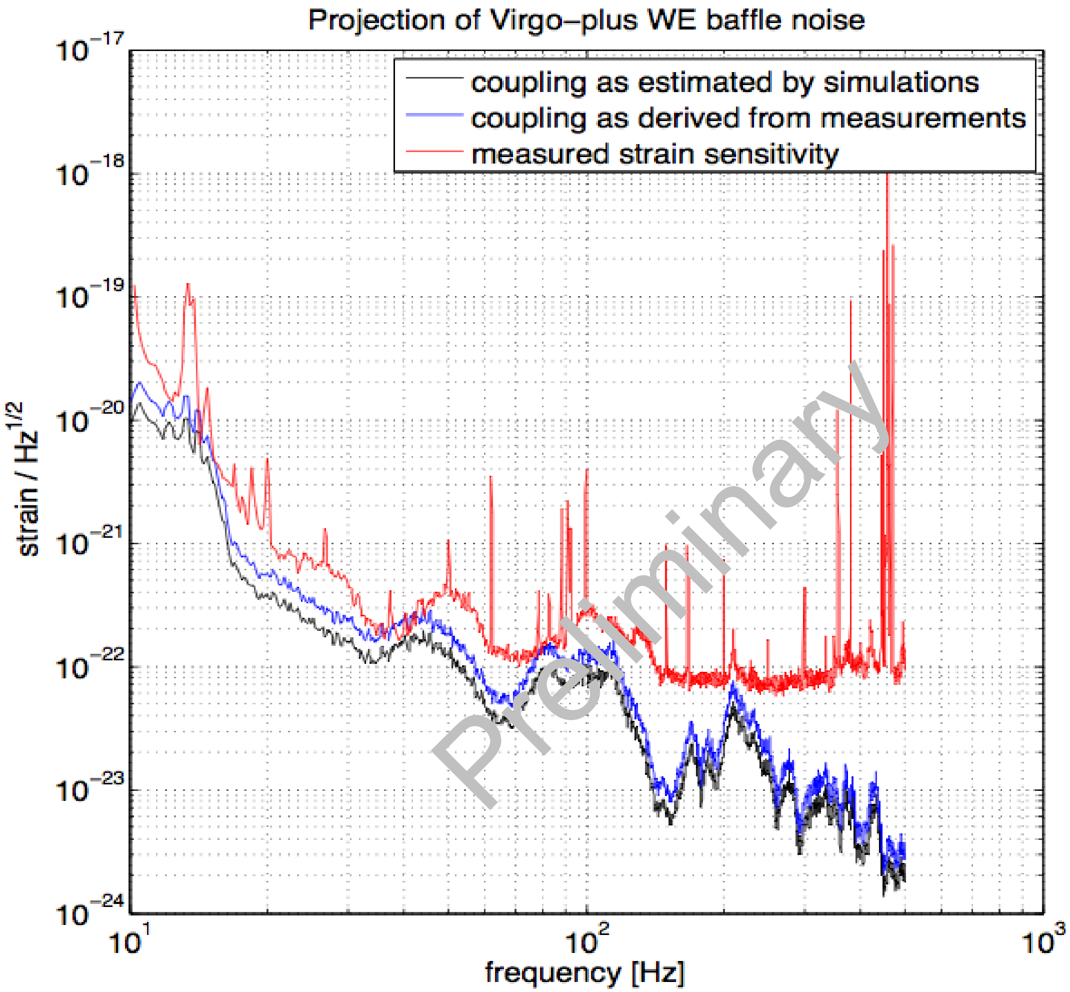

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Quite good agreement with experimental data

• Conclusions

- We presented a novel approach to simulations of effects of stray light due to small-angle scattering. We use:

  - *Optickle* frequency domain simulation with capability to estimate TFs taking into account radiation pressure and mechanical responses,
  - *FOG* simulation with FFT propagation that encompasses in a natural way the scattering off from a defect map.

- **The outcome of the simulations compares quite well with the experimental case we examined**

- Much more to be done before releasing actual requirements for baffles in AdV:

  - Study effect of diffraction by the edge of the baffles
  - Apply the procedure for all the suspended baffles
  - Apply the procedure for ground-connected baffles

- But the approach of making Optickle and FOG team up for stray-light simulation seems very promising.

Thank you!