

Part 1: FFT simulation of the back scattering by baffles

Based on work by Antonino CHIUMMO

Part 2: Modeling of full aLIGO using FOG

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I am developing a GW interferometer simulator called FOG :

Fast **F**ourier Transform **O**ptical Simulation of **G**ravitational Wave Interferometers

I have spent 3 weeks at Caltech working with Hiro the author of SIS

There were a number of goals for this visit:

- Cross-check simulation results between FOG and SIS.
- Compare notes on methods used.
- Develop in FOG configurations of power recycled and dual recycled interferometers for aLigo.
- Start looking at results of simulations with real aLigo mirror maps

Part 1: FFT simulation of the back scattering by baffles

Based on work by Antonino CHIUMMO

References: VIR-0188A-12, VIR-0272A-12, VIR-0055A-13, VIR-0137A-13

Part 2: Modeling of full aLIGO using FOG

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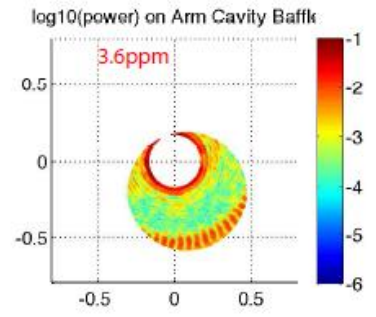
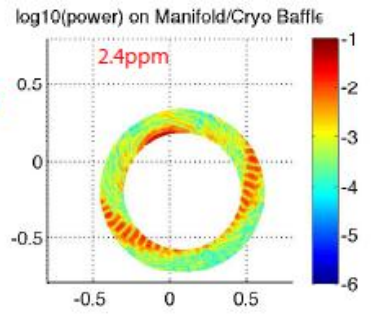
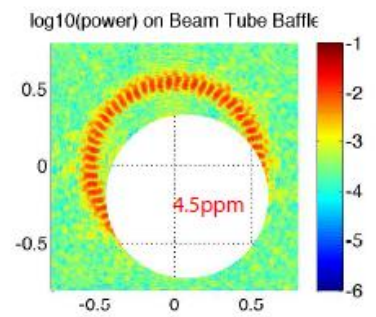
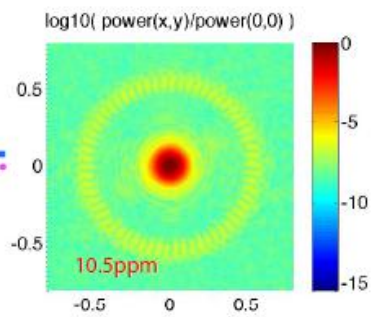
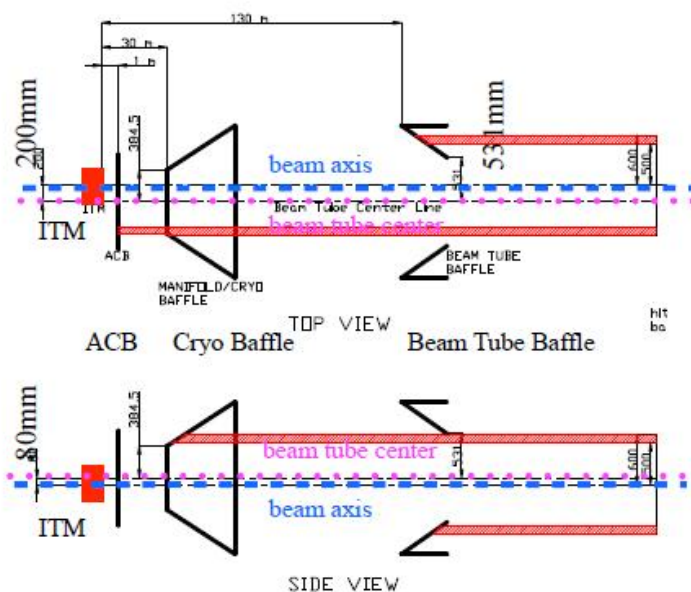
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- Reminder of different sources of backscattering.
- Reminder of coupling mechanism
- Step by step process to use FFT in backscatter calculation for one case.
- Discuss simulation results and compare with LIGO model.

Already described well by Hiro

LIGO

Already described well by Hiro
 How scattered ring hits baffles
 simple minded



LIGO-G1300398-v2

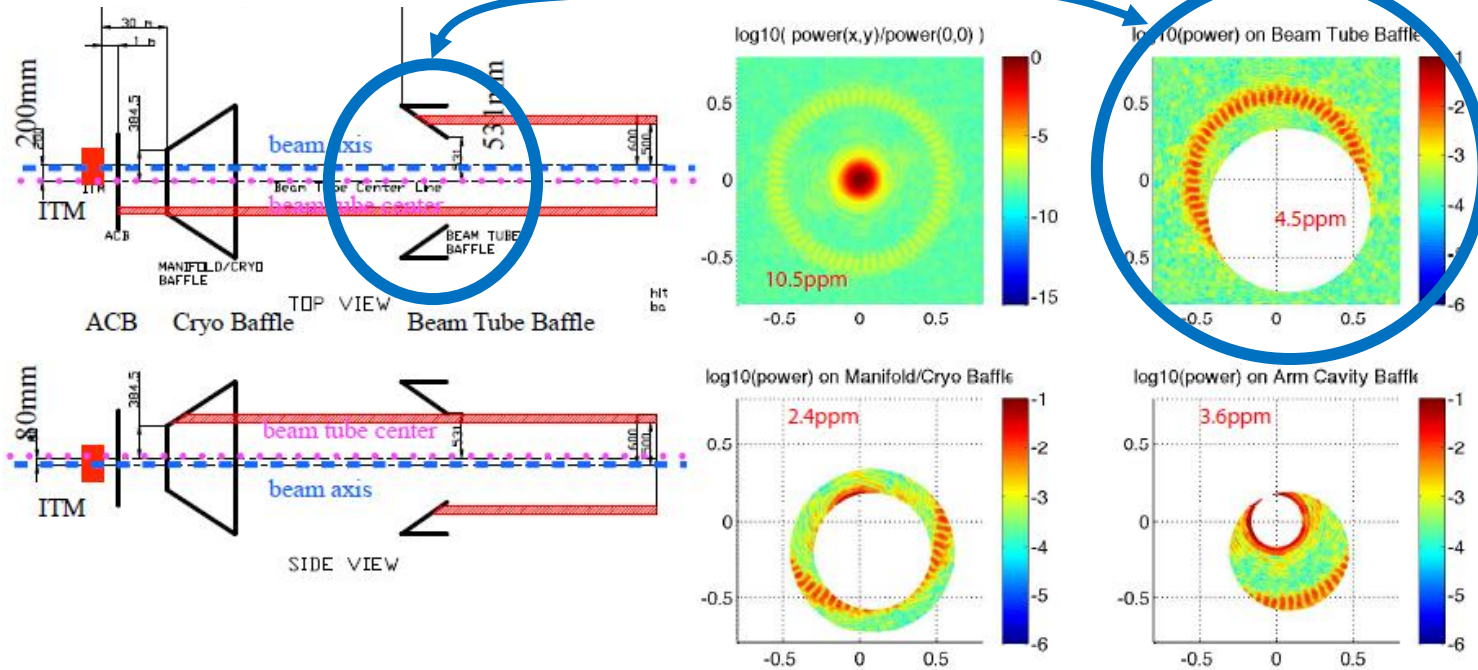
LIGO Seminar at Caltech April 16th, 2013

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LIGO

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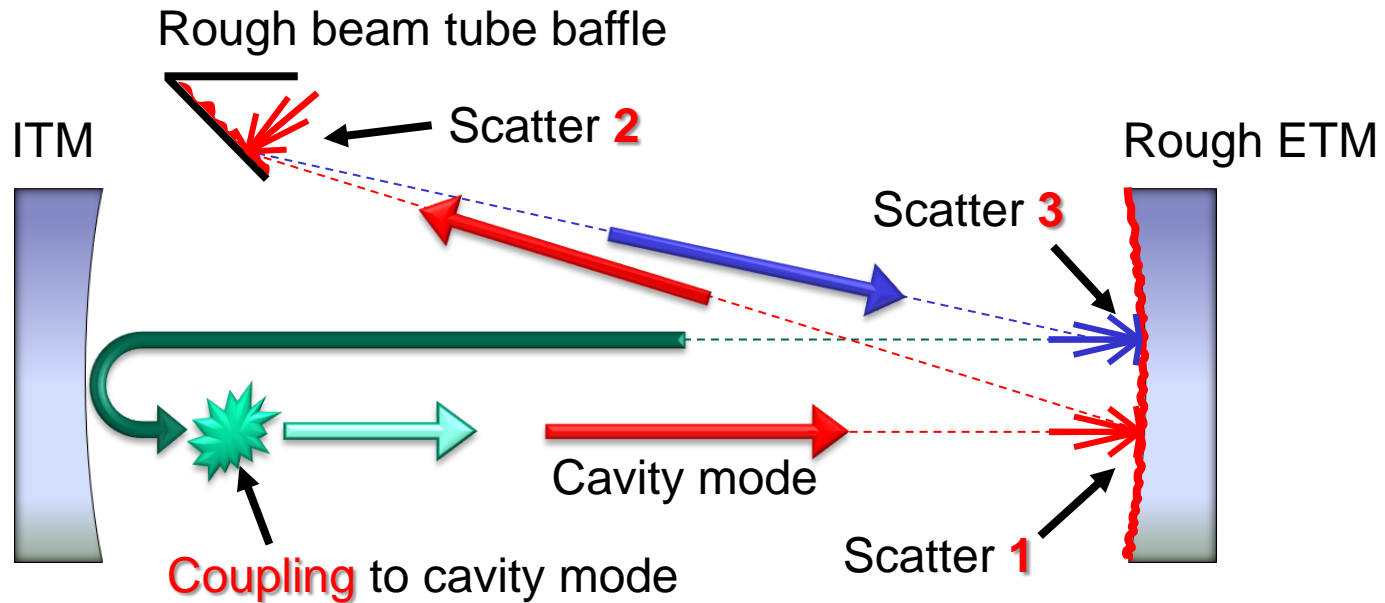
We will focus on this one







LIGO-G1300398-v2

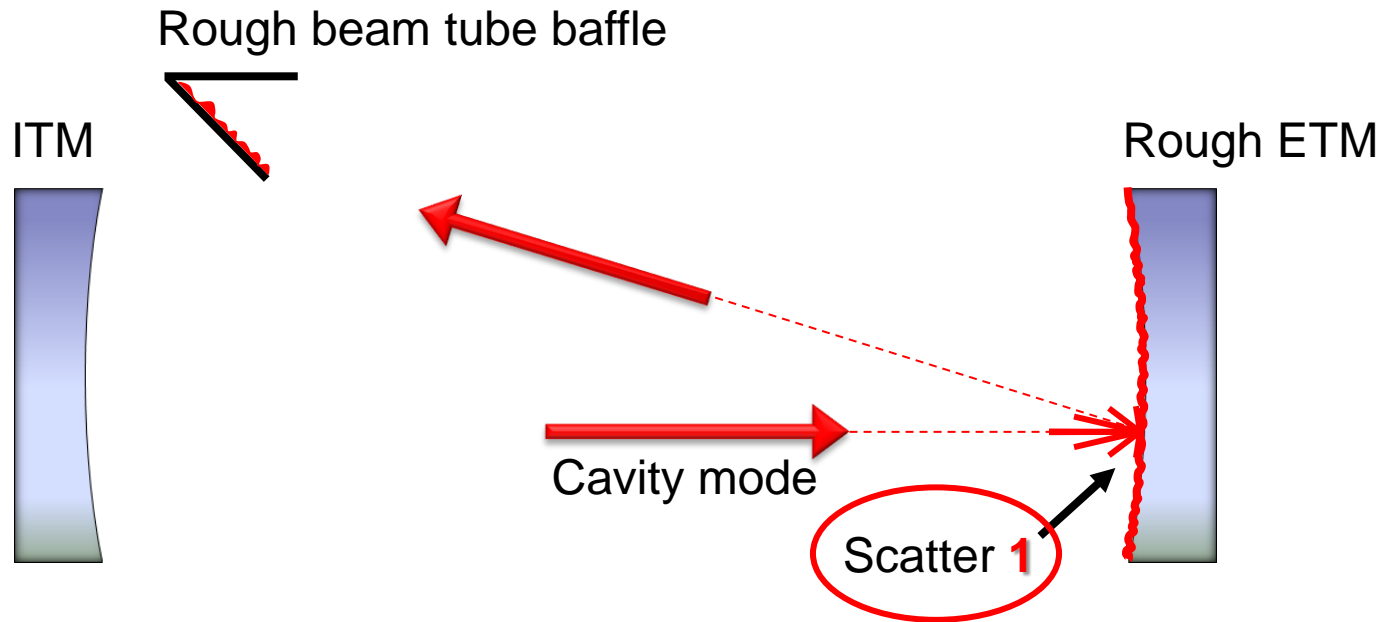
LIGO Seminar at Caltech April 16th, 2013

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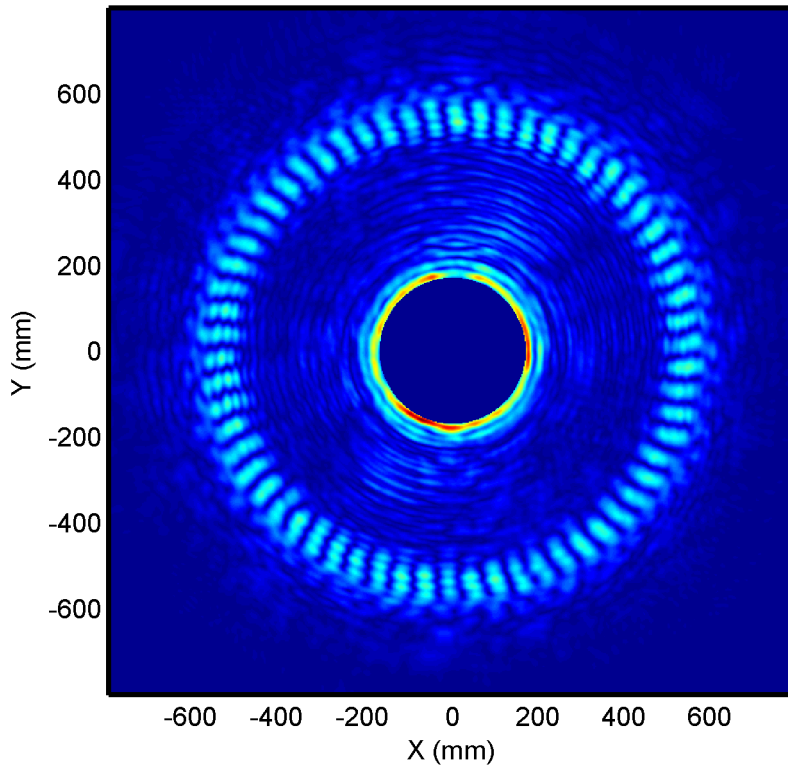
How much scattered light coupled into cavity mode?

- Scatter **1**  **Ok** : Use FFT & mirror maps
- Scatter **2**  **Tricky** : Use BRDF to estimate
- Scatter **3**  **Ok?**: Use FFT & mirror map (but what field?)
- Coupling**  **?**: How exactly does it couple?

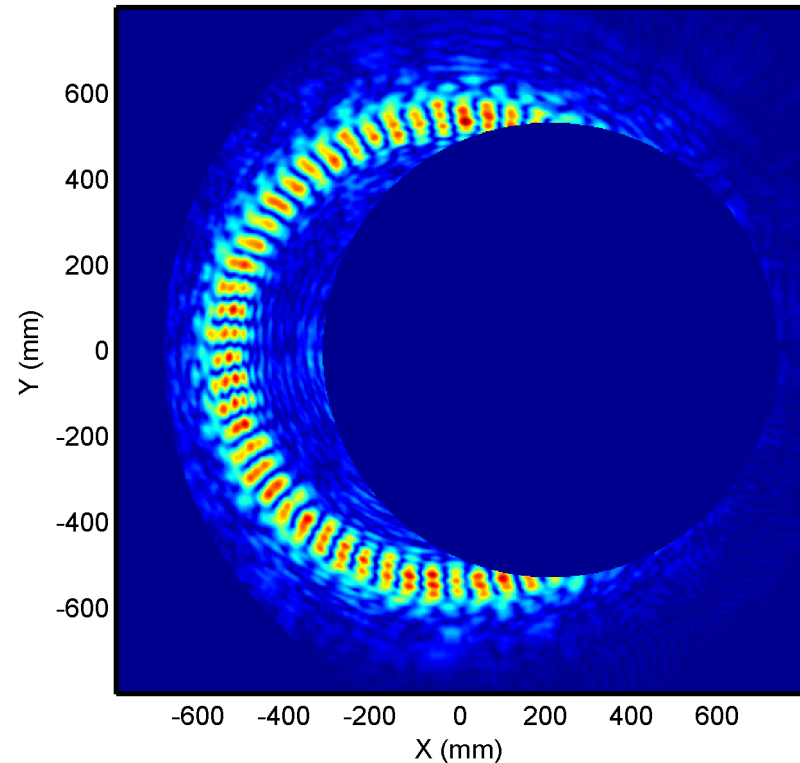


- Use FFT to find cavity field of FP using real ETM map
- Reflect cavity field off rough ETM and propagate to ITM

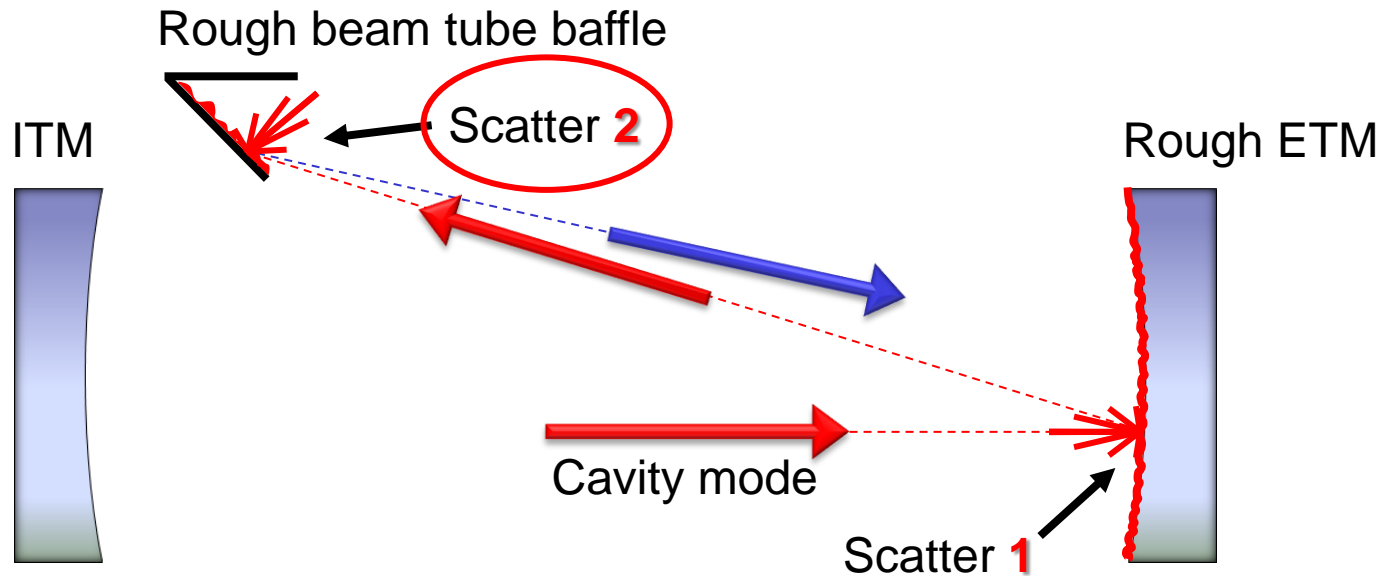
We observe the amplitude distribution at the ITM
 Results agree well with SIS simulation by Hiro



What we see outside ITM if
 no baffles are clipping



We assume that field impinges
 beam tube baffle like this



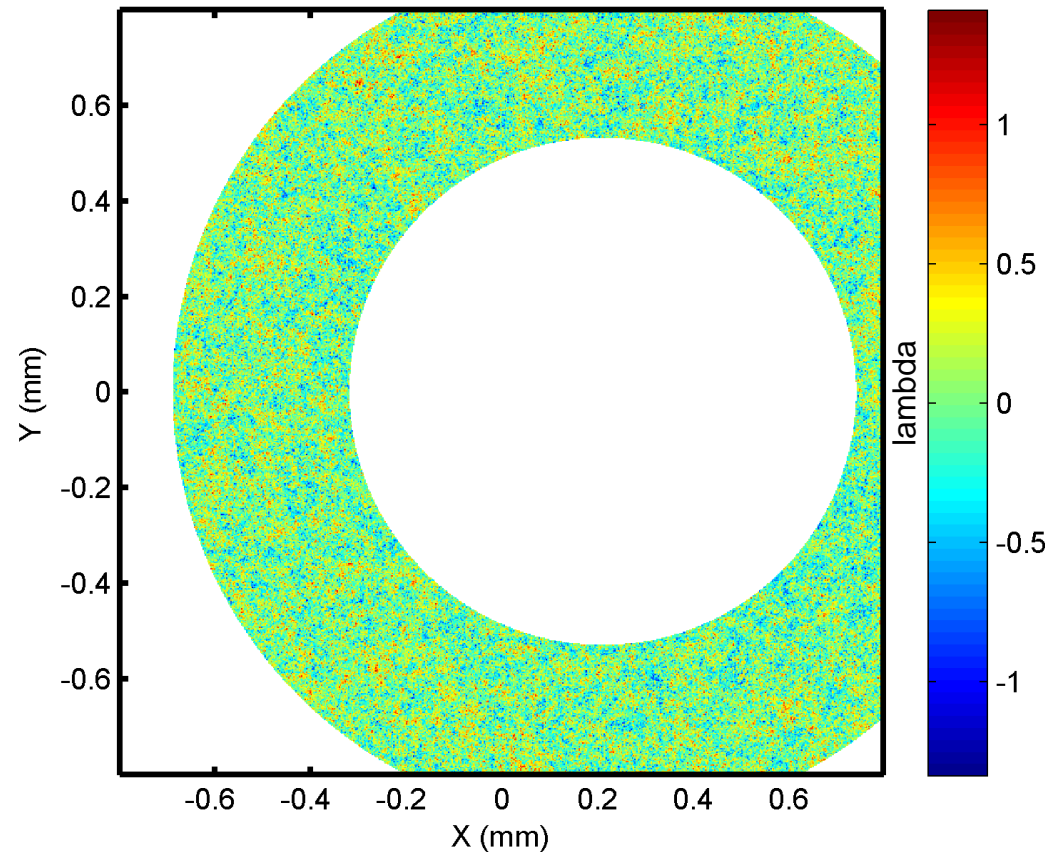
Trickier: baffle at 55 degrees angle of incidence

→ Cannot use random map and FFT in conventional manner

But we do have BRDF that tells us how much power will be sent back to ETM

→ We try to build a “mirror” map that imitates baffle backscatter

Finding “effective” baffle map which scatters according to known BRDF of baffle.



1) Generate random map from “white” PSD → lambertian diffuser

2) Make map into baffle shape

3) Scale so that $\text{rms} > \lambda/\pi$
→ specular reflection “scrambled”

4) Adjust reflectivity such that fraction of power scattered off baffle and, after propagation, hitting ETM is same as BRDF calculation
→ $\text{BRDF} = 0.2 \text{ sr}^{-1}$

- Reflect scatter **1** field off rough baffle and propagate to ETM

Warning !

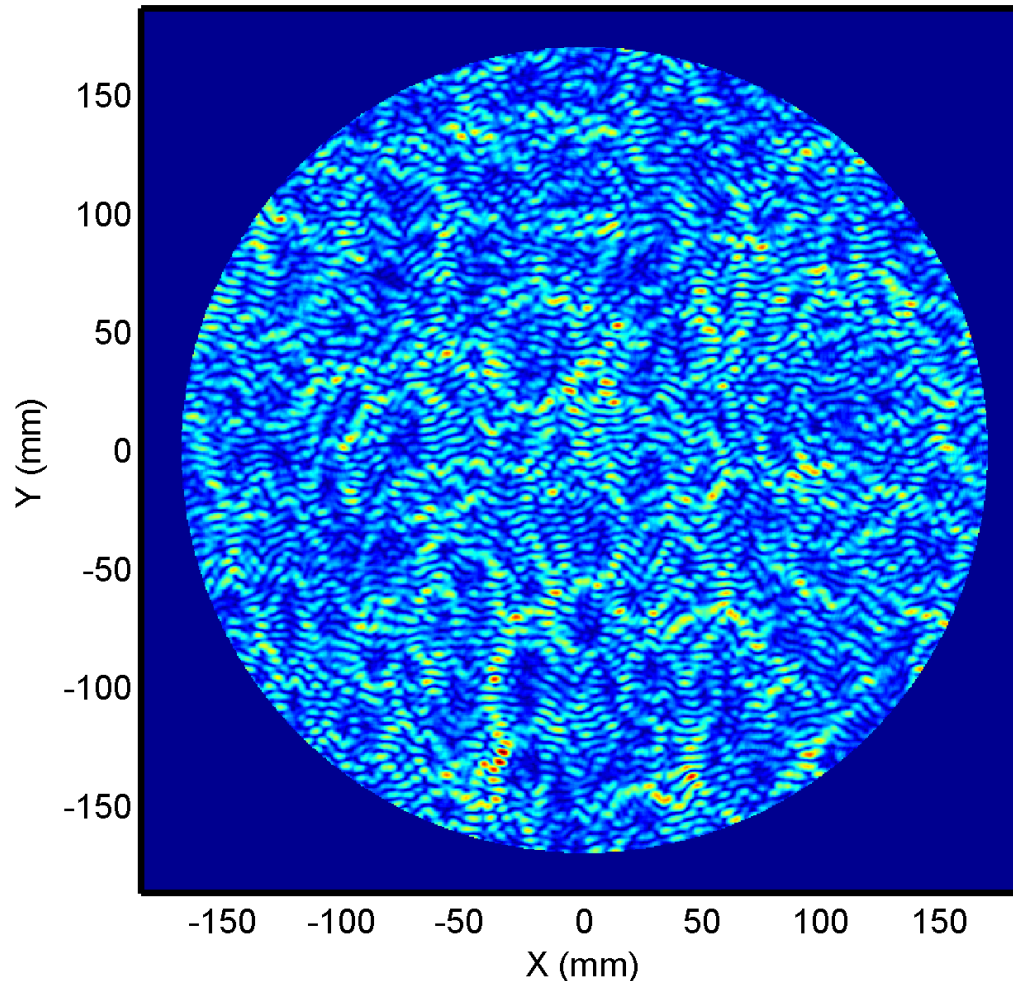
Throughout this study I have used a BRDF of 0.2 sr^{-1}

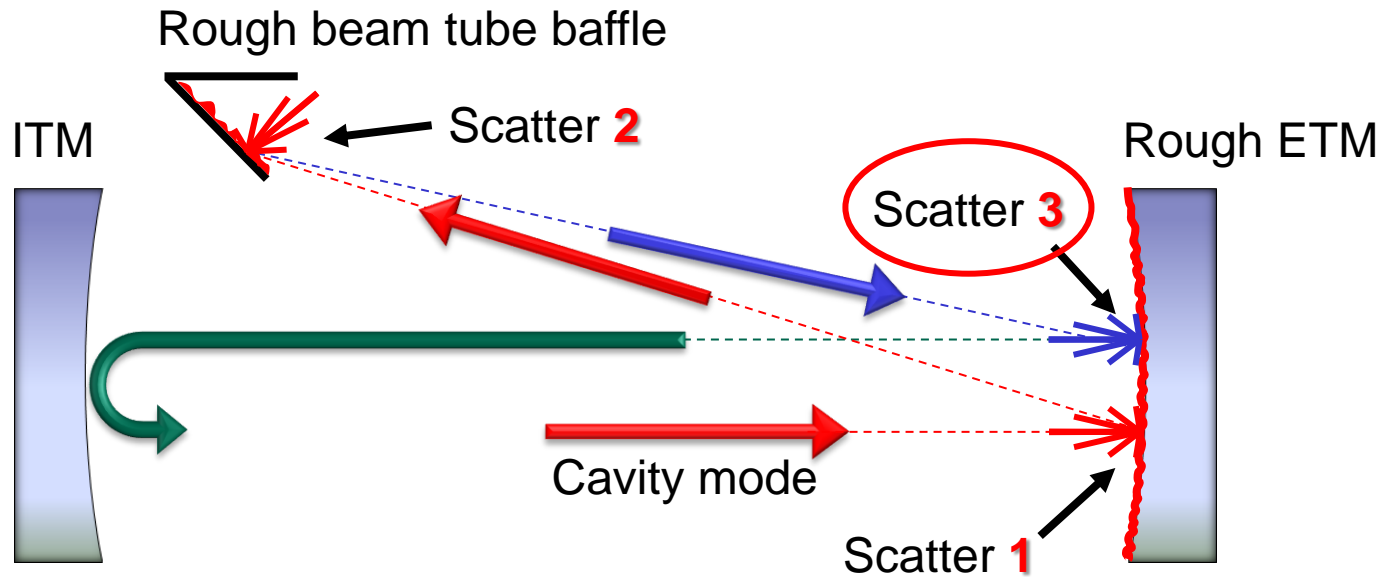
This is an error on my part.

The BRDF should be 0.02 sr^{-1}

The reader should therefore divide all final coupling factors by 10 in order to have a fair evaluation of coupling in aLigo

At the ETM we get a rather finely structured speckle pattern

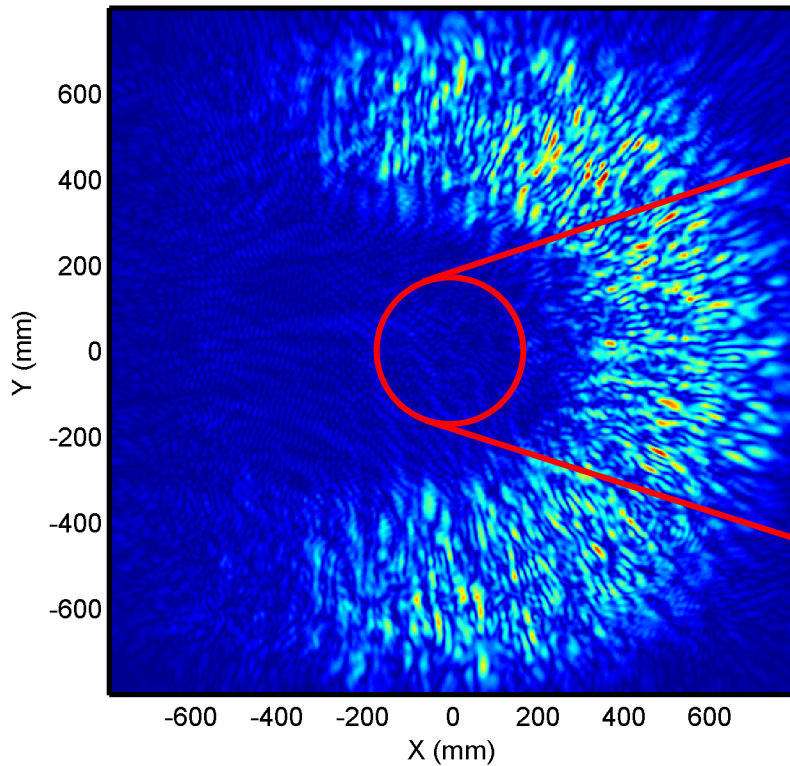




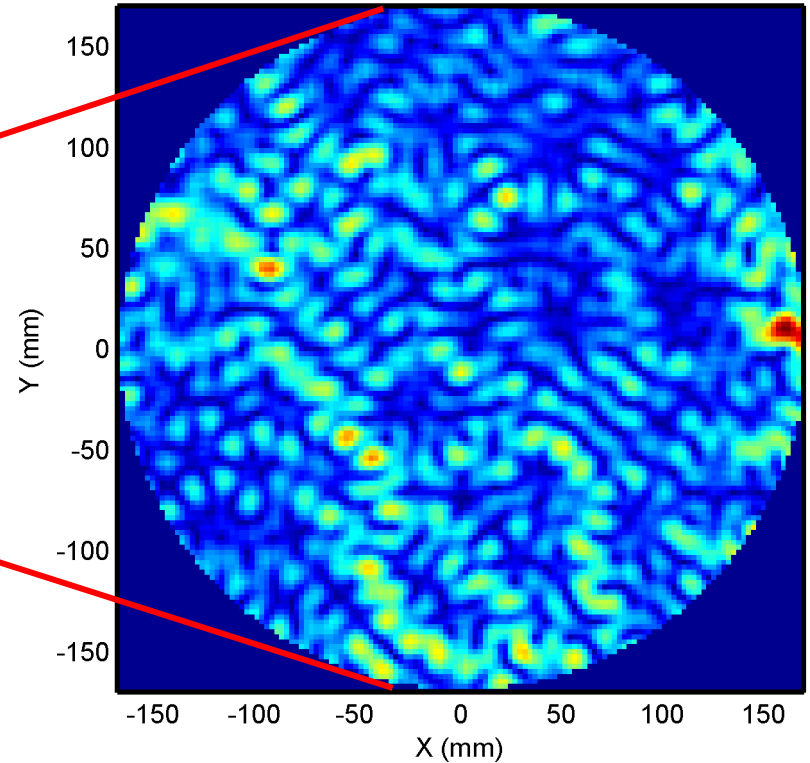
Almost there!

- Reflect scatter **2** field off rough ETM and propagate to ITM

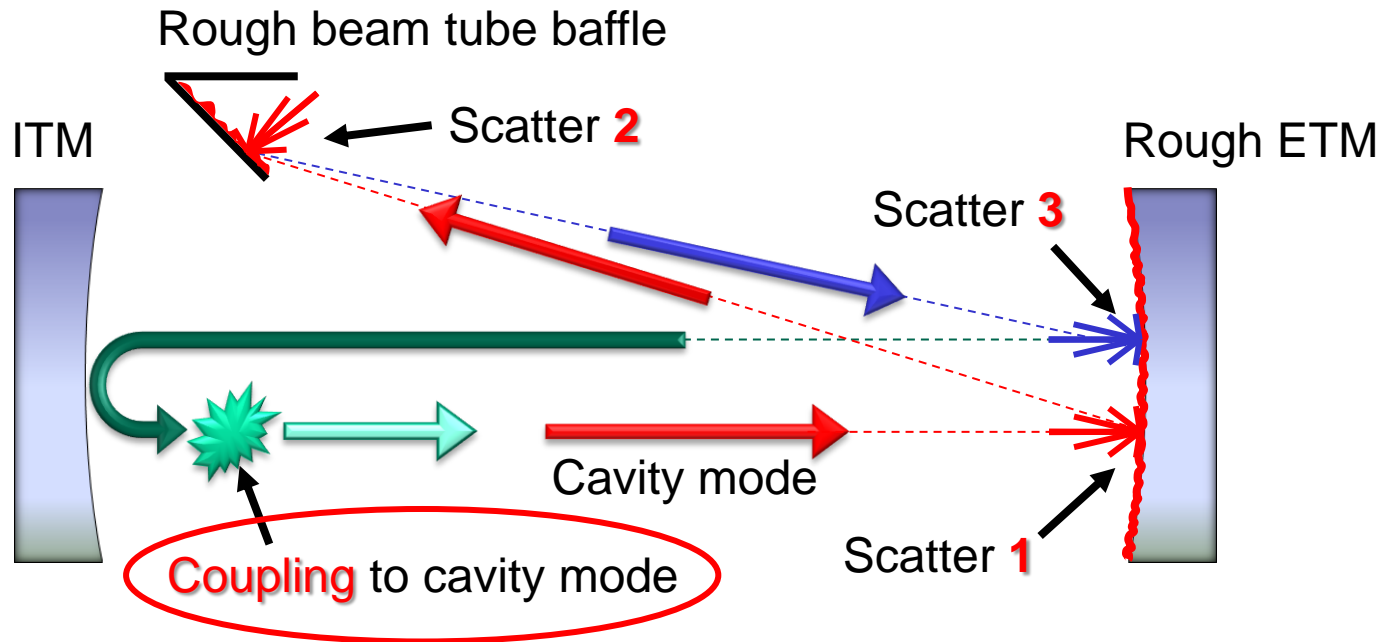
Scatter 3 field at ITM



Out-of-focus image of baffle due to ETM “imaging lens”



Final field hitting ITM



Finally reflect scatter **3** field off ITM and find **Coupling** to cavity mode

Two methods considered:

Maybe good enough: Find directly component of field in the cavity mode.

Slow but “sure”: Use field as if the external source, and find component of converged field in the cavity mode.

We need to find $\delta I_{mb} \rightarrow$ Power scattered into cavity mode.

Maybe good enough:

$$\delta I_{mb} = \frac{\left| \int E_c^* E_s dx dy \right|^2}{\int |E_c|^2 dx dy} \quad \begin{array}{l} E_s \rightarrow \text{Scatter field} \\ E_c \rightarrow \text{Cavity field} \end{array}$$

Slow but “sure”:

Find steady state cavity field E_{sst} using E_s as source

$$\delta I_{mb} = \frac{T}{G} \frac{\left| \int E_c^* E_{sst} dx dy \right|^2}{\int |E_c|^2 dx dy} \quad \begin{array}{l} T \rightarrow \text{ITM transmission} \\ G \rightarrow \text{Cavity gain} \end{array}$$

$\frac{T}{G}$ is needed to factor out “amplification” of field

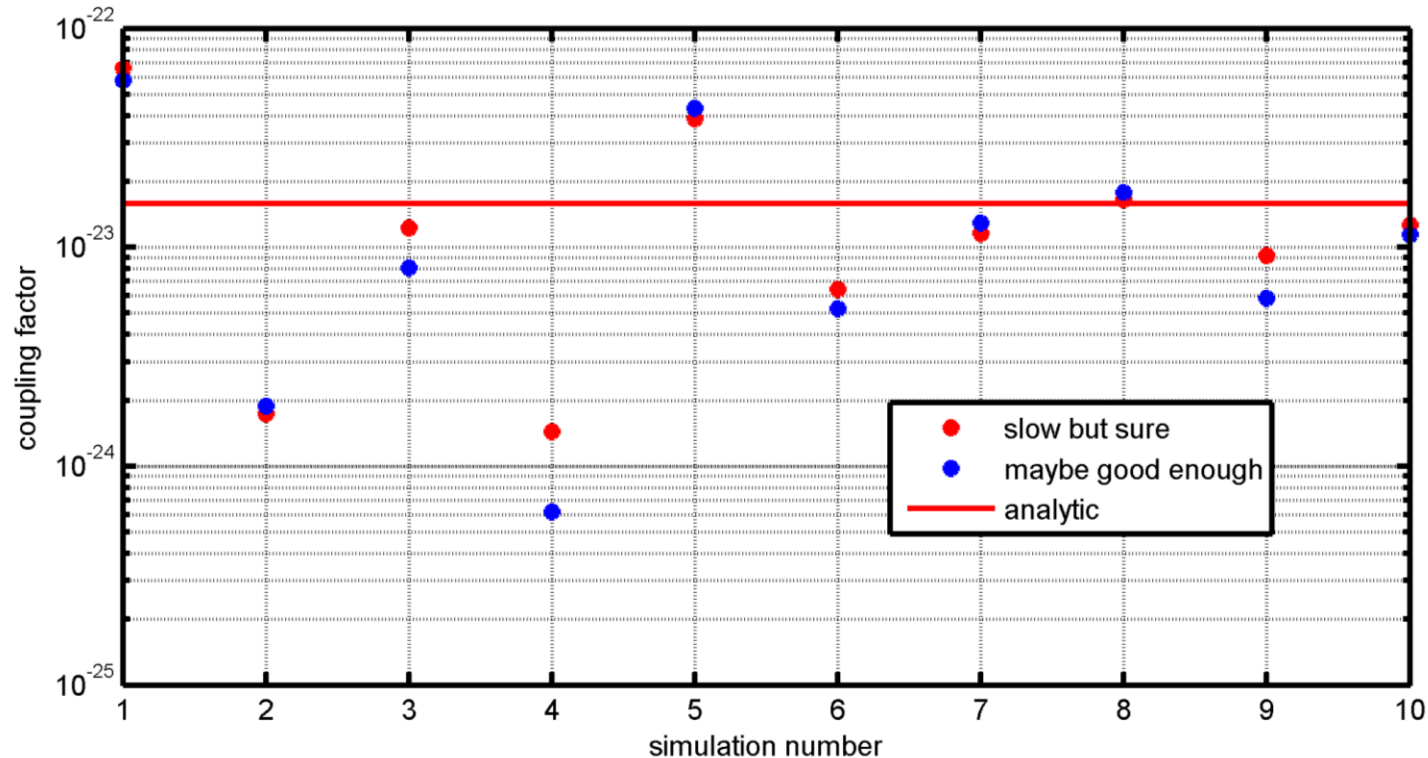
And we’re done ! Now let’s see the LIGO approach ...

$$\frac{\delta I_{mb}}{I_{mb}} = \frac{\lambda^2}{r^2} \left(\frac{dP}{d\Omega_{ms}} \right)^2 \frac{dP}{d\Omega_{bs}} \delta\Omega_{ms}$$

Calculate for usual aLigo parameters and BRDF = 0.2 sr⁻¹

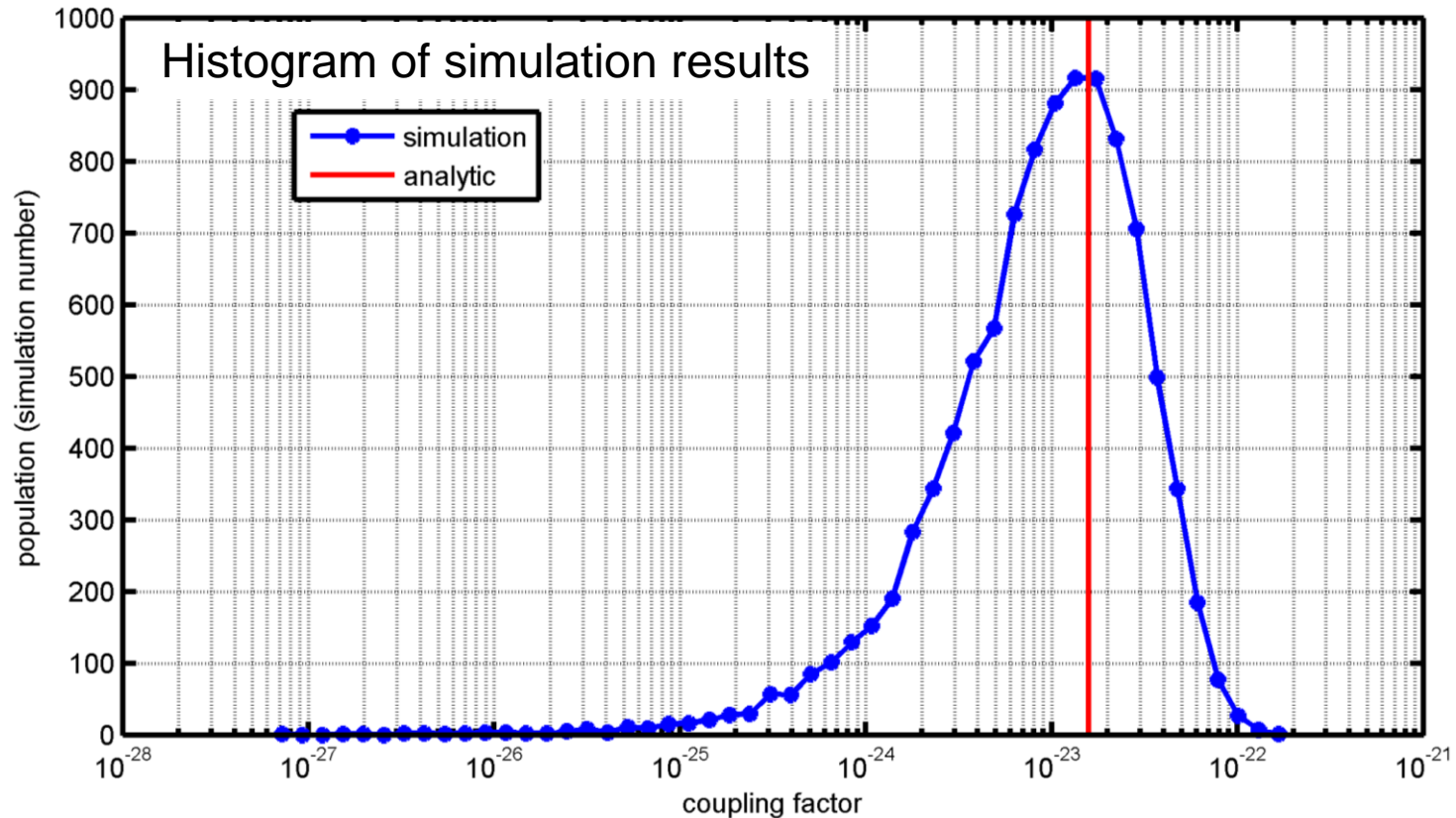
$$\frac{\delta I_{mb}}{I_{mb}} = \frac{\lambda^2}{r^2} \left(\frac{dP}{d\Omega_{ms}} \right)^2 \frac{dP}{d\Omega_{bs}} \delta\Omega_{ms} = 1.58 \times 10^{-23}$$

Carry out 10 simulations. Each using a different random baffle map



- Results in same ball park as analytic result.
- Large dispersion in results.
- Both coupling methods give similar results
→ use “maybe good enough” method from now on (much faster)

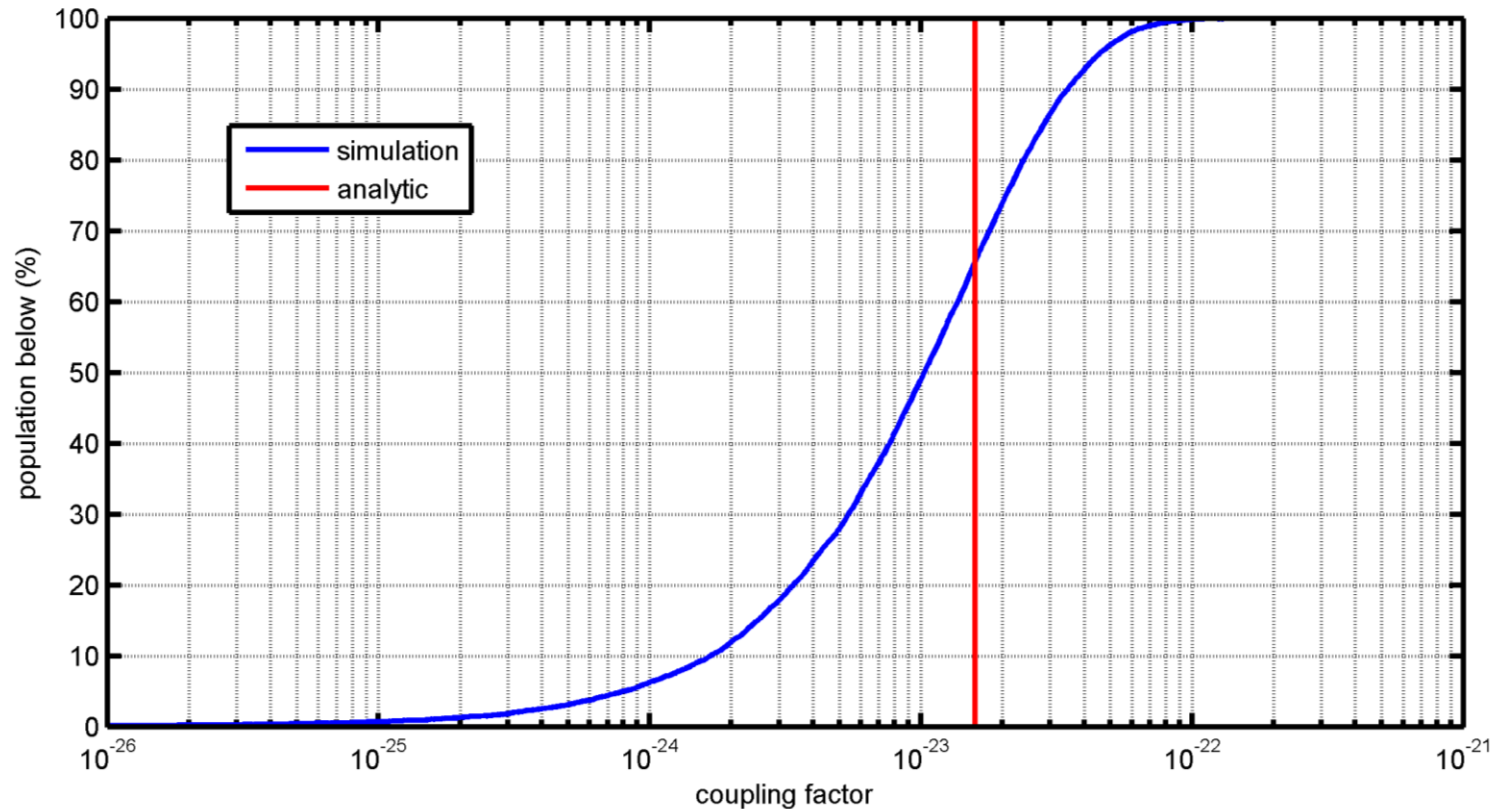
Carry out 10000 simulations. Each using a different random baffle map



Analytic result corresponds to most probable coupling factor.

Distribution over orders of magnitude for just one single BRDF

Another way to look at data: population below a given coupling factor



65% chance that baffle with BRDF = 0.2 sr^{-1} has coupling factor lower than 1.58×10^{-23}

99% chance that coupling factor lower than 7×10^{-23} → better upper limit ?

- We presented a novel approach for the FFT simulation of backscatter coupling from tilted baffles.
- The results show good agreement with the analytic calculations.
- For any given BRDF we may expect a dispersion in coupling factor that varies by orders of magnitude.
- The simulations indicate that 7×10^{-23} is a suitable upper limit.
- The approach presented here may be applied to all wide angle scattering needs; baffles, steering mirrors, off-axis RC mirrors etc...

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FOG was conceived when polishing requirements were needed for the Advanced Virgo (AdV) IMC

It is a Matlab code that was inspired by Oscar and DarkF

It was later used intensively during the design phase of AdV

In its current state, its most interesting features are:

- Optimized accelerated convergence algorithms making it relatively fast despite it running in Matlab
- Handles seamlessly the infamous problem of aliasing known so well in FFT simulators.
- Capable of running full interferometer configurations

FOG was designed for Virgo; Adaptive grid size method for handling big and small beams had never been implemented.

→ This was a challenge for such a short visit. But now we have something that works.

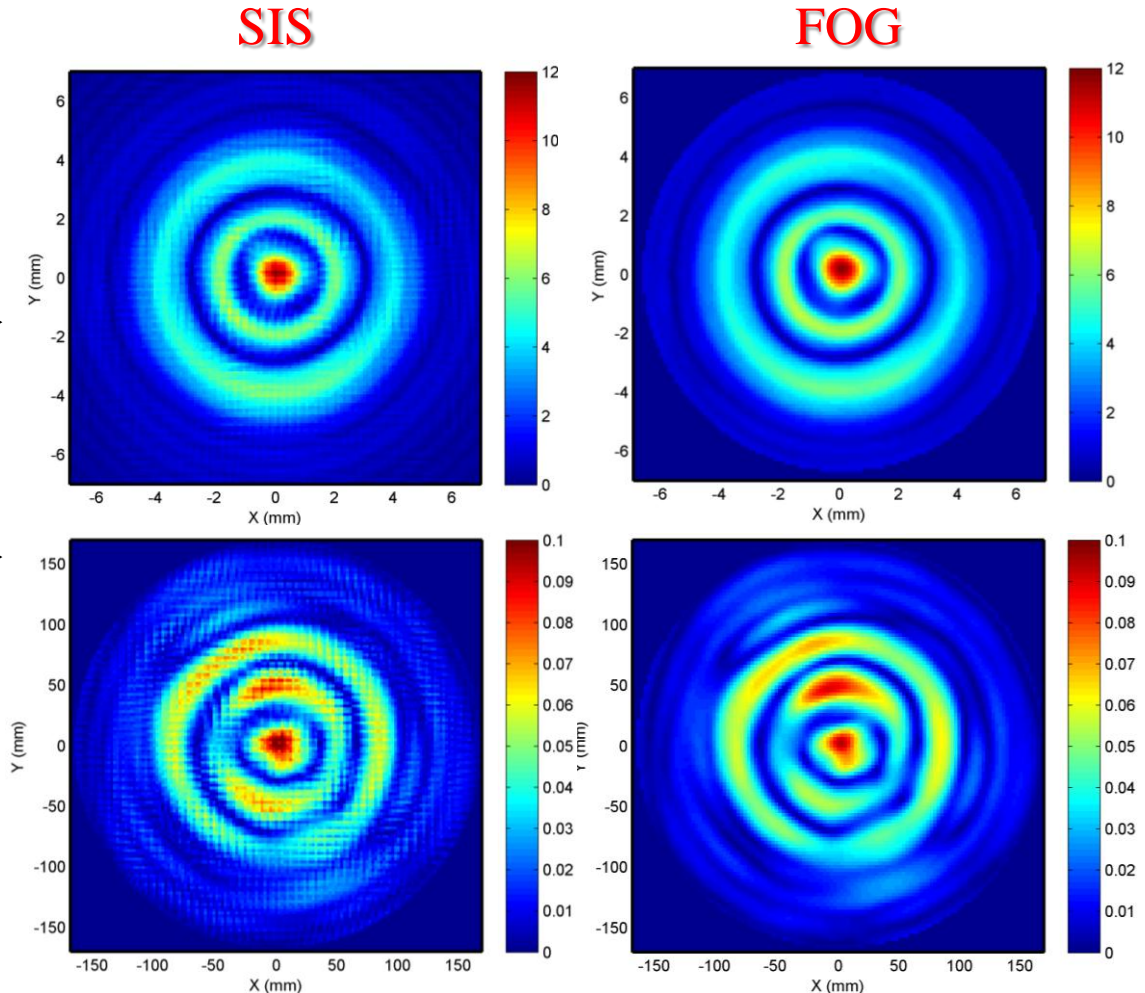
A few minor errors found (in FOG). Now all results agree within about 1%

Example: Y arm PR coupled cavity with ETM07 map.

- Observe HOM content of field at recycling mirror. →
- Observe HOM content of field at ITM. →

FOG and SIS appear to give equivalent results.

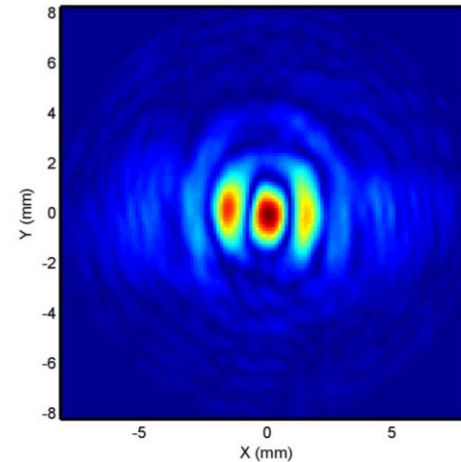
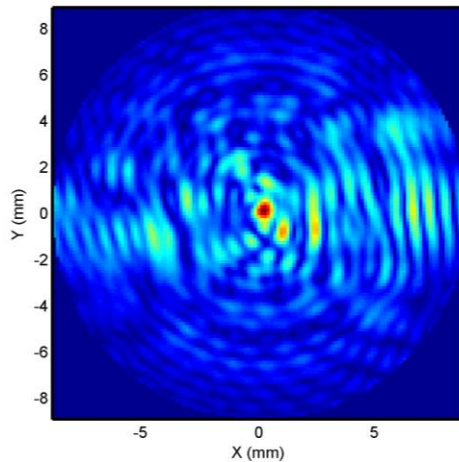
Note: Aliasing in SIS due to my bad choice of window size and apertures



From here on, **Preliminary**. No analysis. No warranty

With BS02 measured reflection & transmission maps

HOM content of field at RM.



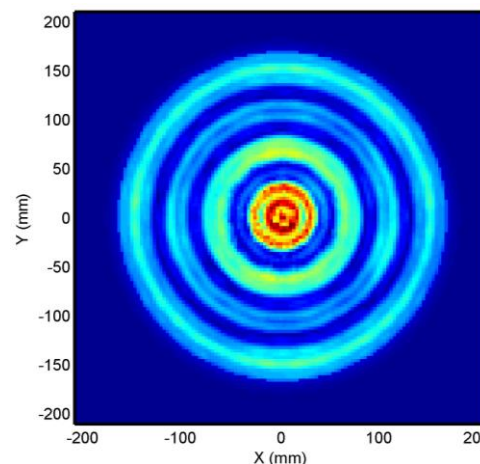
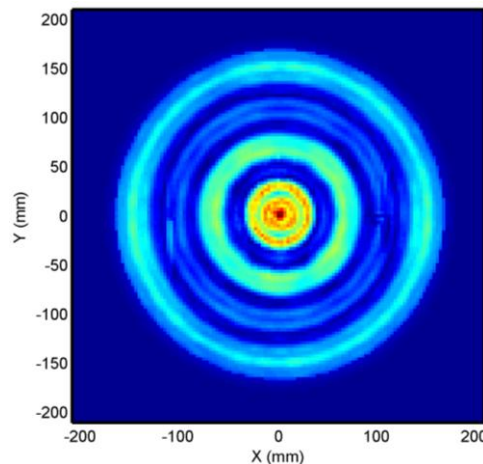
Field at dark port

Total power: 44.50W

HOM power: 1.40mW

Total power: 3.78mW

HOM content of field at ITM X.



HOM content of field at ITM Y.

Total power: 6247W

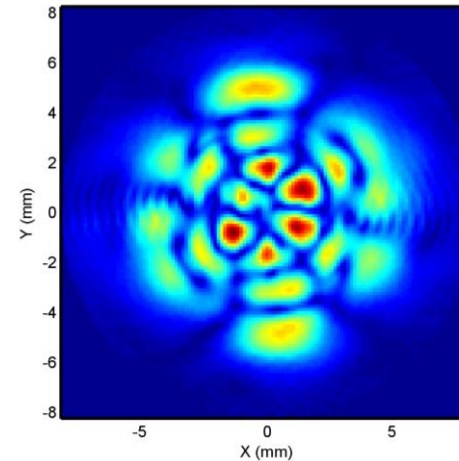
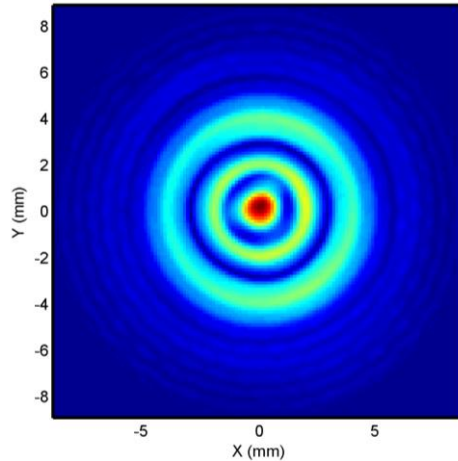
HOM power: 3.99mW

Total power: 6234W

HOM power: 3.84mW

ETM07 on X arm. ETM09 on Y arm (No BS map)

HOM content of field at RM.



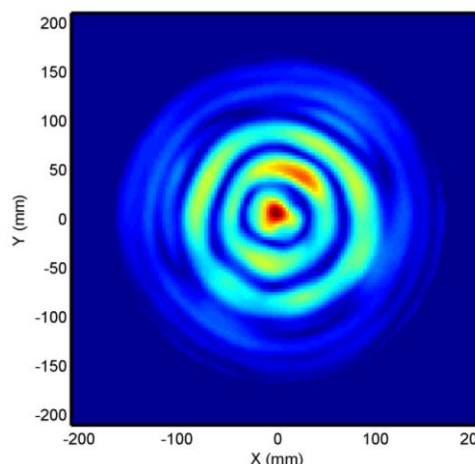
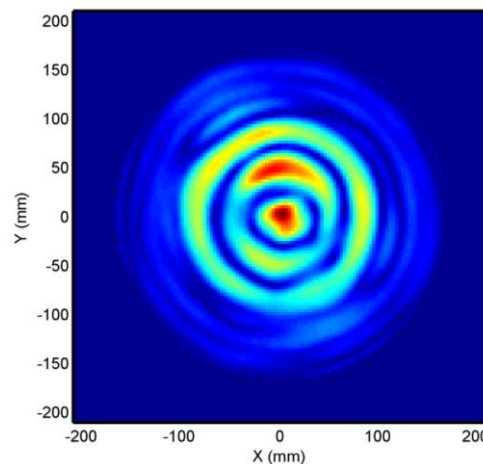
Field at dark port

Total power: 41.28W

Total power: 0.66mW

HOM power: 47mW

HOM content of field at ITM X.



HOM content of field at ITM Y.

Total power: 5777W

Total power: 5780W

HOM power: 358mW

HOM power: 357mW

- Cross-check simulation results between FOG and SIS.
 - After minor corrections (in FOG) they agree well.
- Developed different optical configurations for aLigo up to the full dual recycled interferometer. Run time is of the order of a few minutes.
- Initial simulations yield interesting results, but they have not yet been analyzed.
- Unfortunately time ran out before user interface could be completed.
 - Hiro has a copy of the code which is functional for an “expert user”.
 - I will continue on the user interface (rain check at Elba).
- My short stay at Caltech was both challenging and inspiring.
 - I thank those who made this visit possible.
 - And most especially, thank you to Hiro for making my visit so enjoyable.

