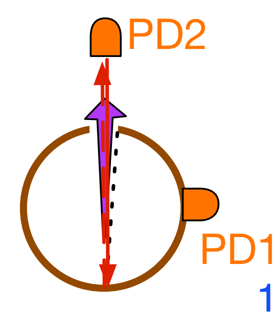
Mirror scattering loss analysis by integrating sphere measurement

- Scattering and loss by test mass
  - Discrepancy between the measured arm loss, 50ppm/mirror, and the loss based on optics measurement, 25ppm/mirror
  - Loss by mirror is estimated as
    - Loss by surface figure = 10ppm,
    - Larger angle scattering = 10ppm = 5ppm by micro roughness + 5ppm by point scattering,
    - Misc and uncertainty = sevetal ppm
- Large angle scattering measurement covers down to 1°. What if TIS(θ<1°) is comparable to TIS(θ≥1°)
- Integrating sphere measurement with extension to measure TIS in large and small angle (L. Zhang)
  - Preliminary and proof of concept
  - Small angle (θ≤1°) and large angle (θ≥1°) scattering
    - Missing energy in the small angle scattering
    - Information defect size/distribution
  - Micro roughness on coated surface is correlated to uncoated surface



Three scattering sources

Figure error, micro roughness and point scattering

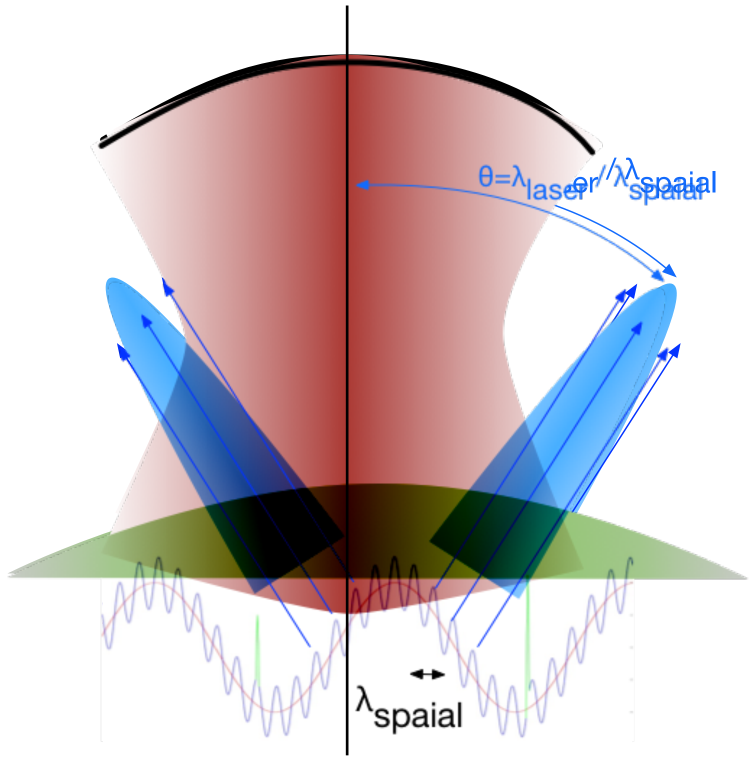
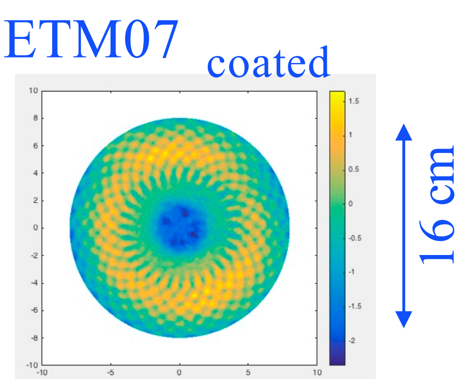
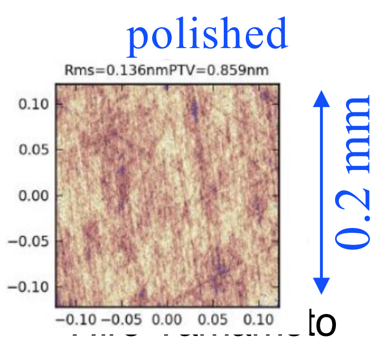
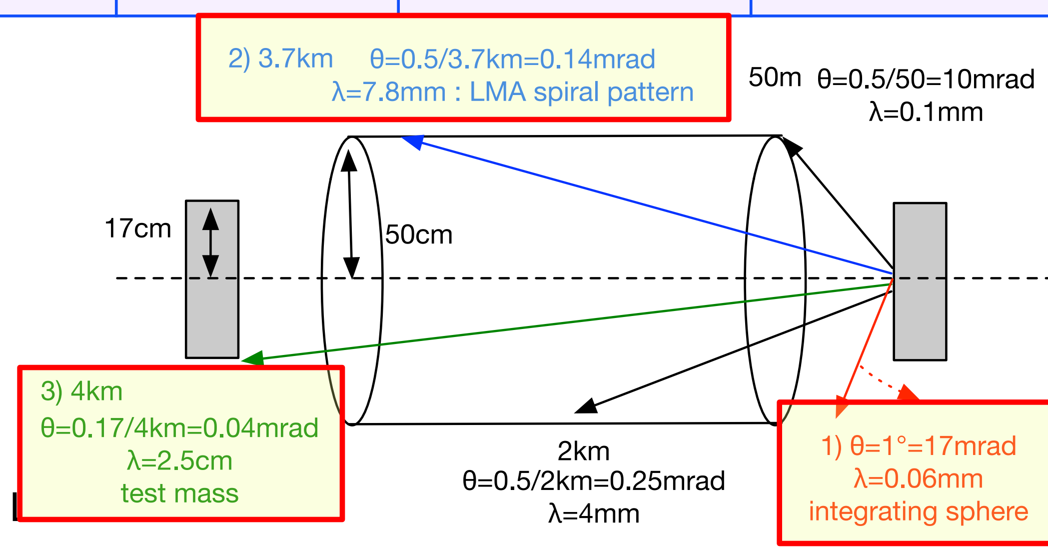


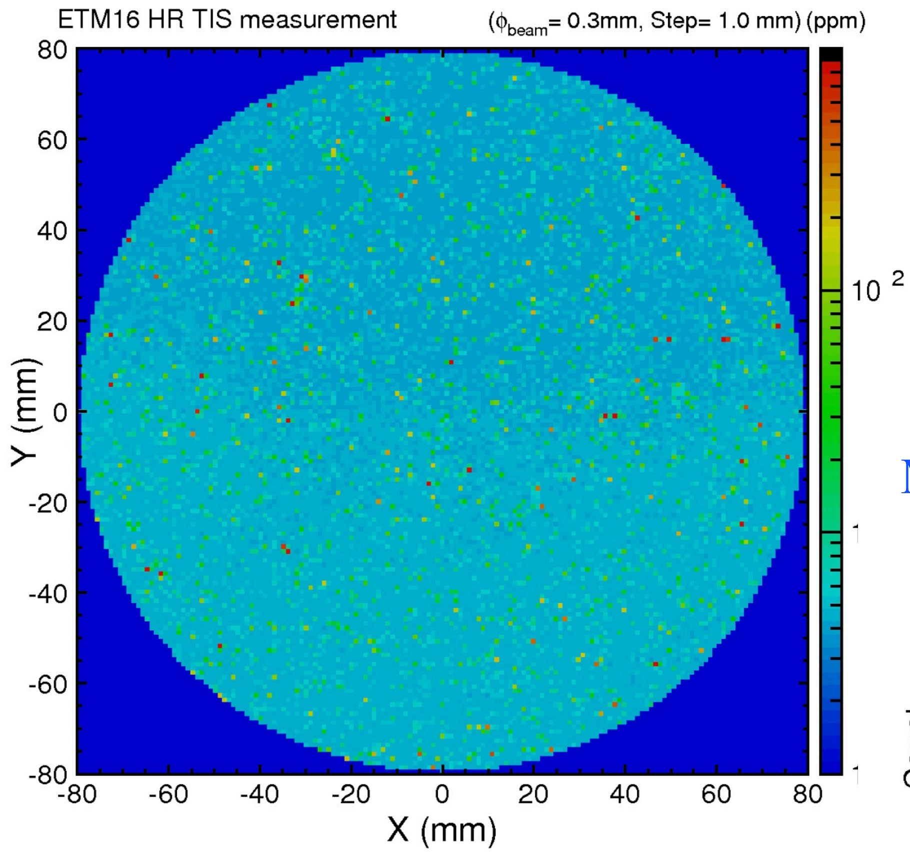
	Figure error	Micro roughness	Point scattering
$\lambda_{spatial}$	> 5mm	< 5mm	< 0.1mm
data	phasemap	PSD	data
cause	Reflect back into cavity	Reflect out of cavity to a fixed direction	Reflect uniformly, mostly out of cavity
effect	Change of resonating mode	Hit specific part of IFO, e.g., beam tube baffle.	Additional loss

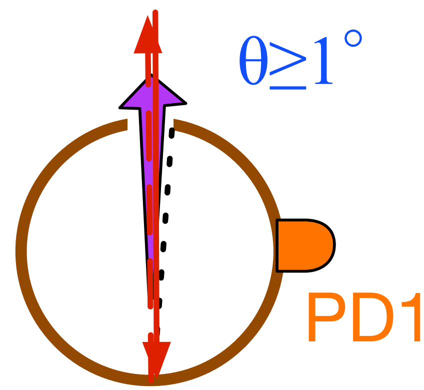


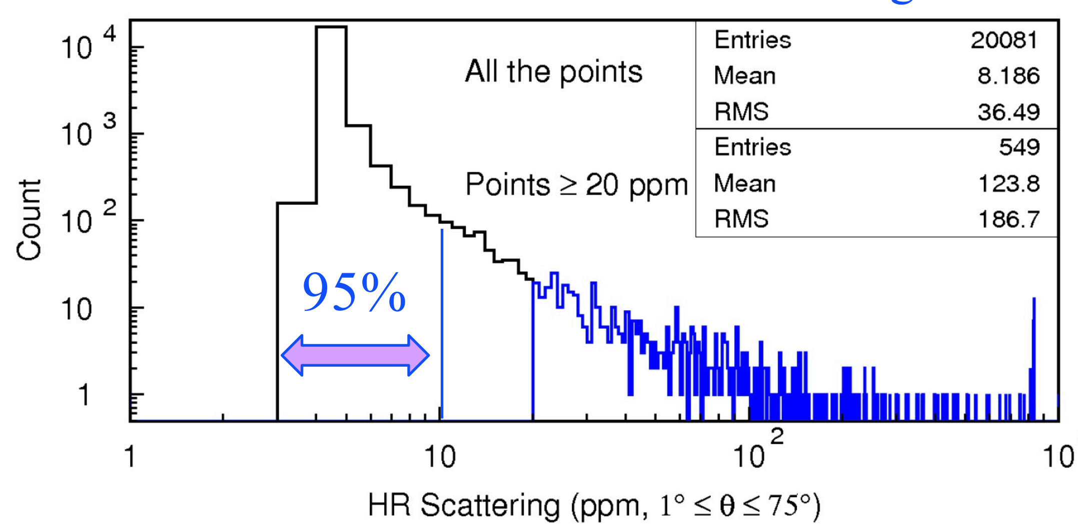




aLIGO ETM TIS(θ≥1°) using integrating sphere





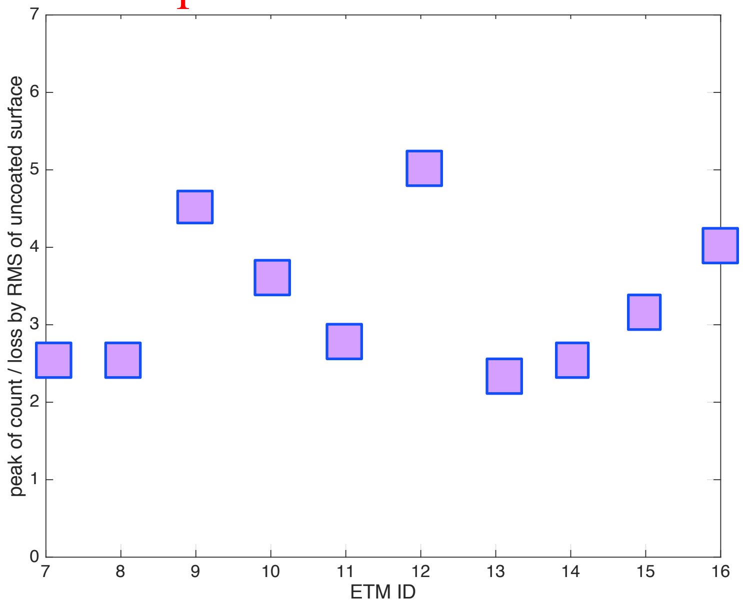


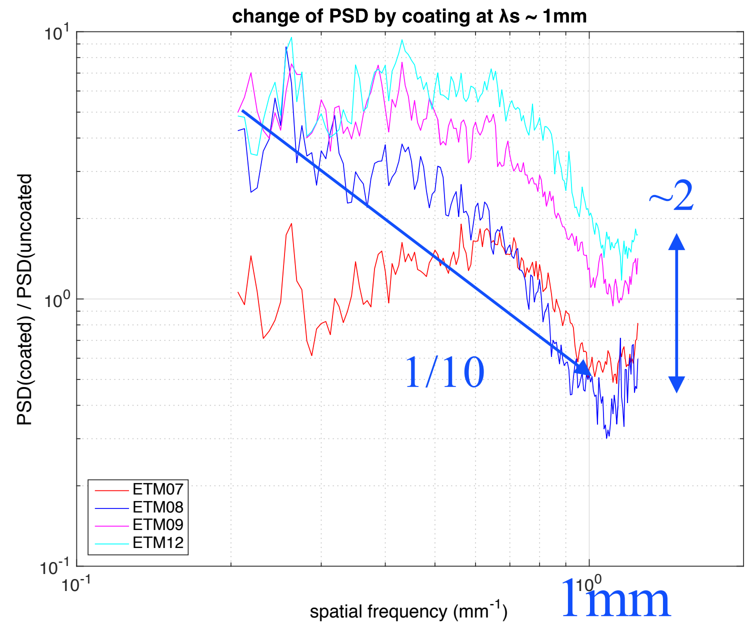
Micro roughness : coated ~ polished

low end of TIS(θ≥1°) ~ 3-4 x polished surface

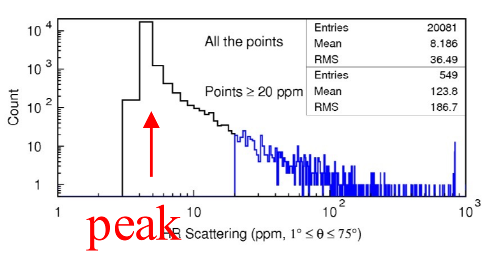
$TIS(\lambda_s<75\mu m) / (4\pi\, \sigma(\lambda_s<80\mu m)/\lambda_{laser})^2$

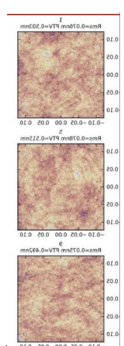
Around the peak





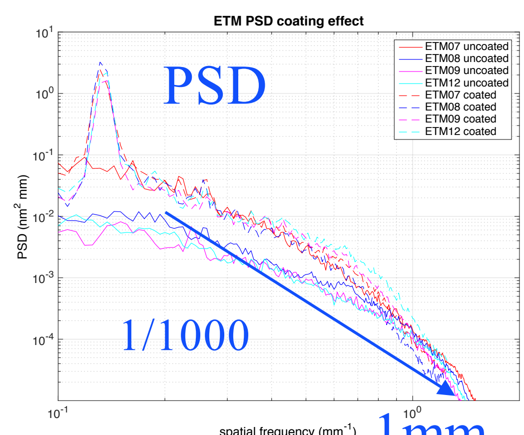
ETM16 case





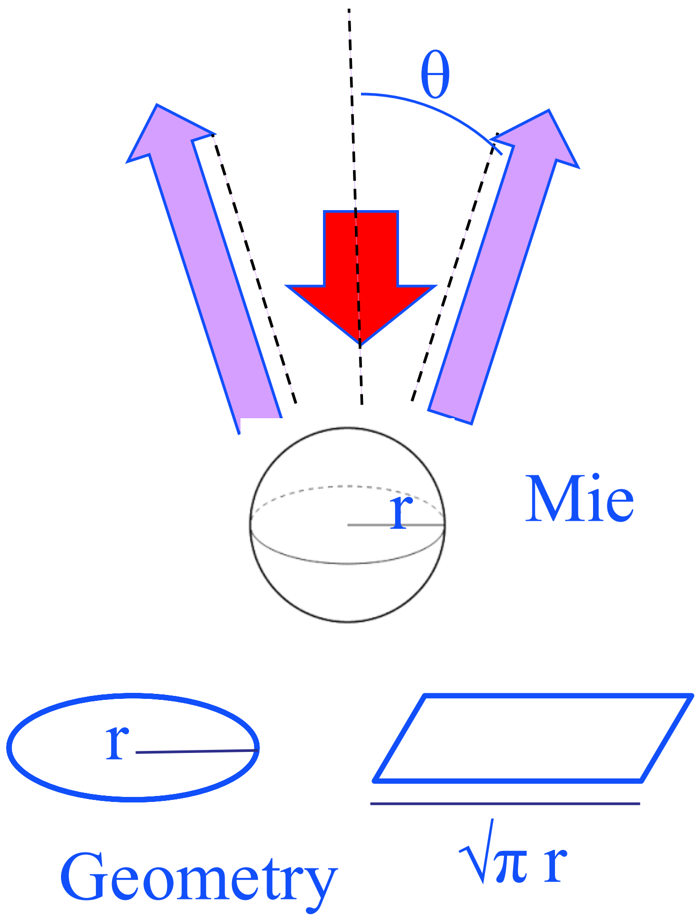
Zygo 50x PMM

$80\mu m > \lambda_s > 0.9\mu m$

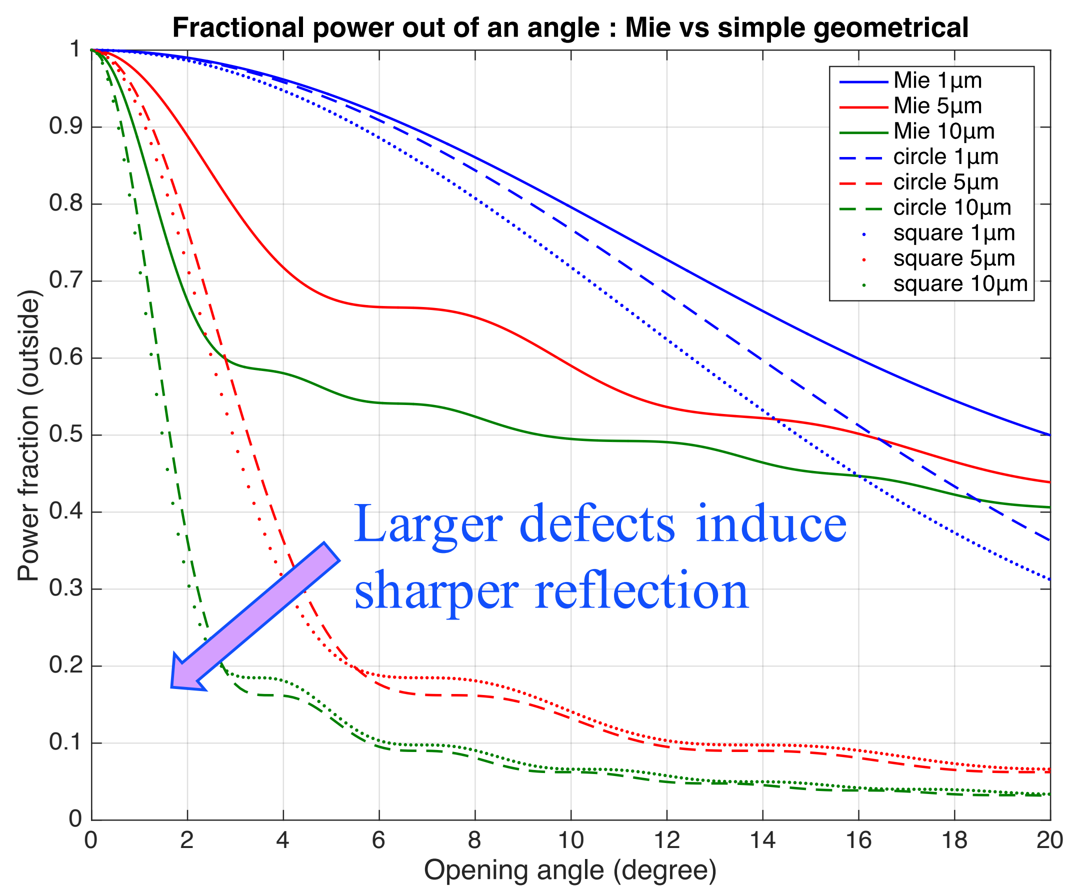


Angular distribution of reflected field depends on the defect size

$$\textbf{Power Frac}(\theta) \equiv \int_{L\theta}^{\infty} P(r)\, r\, dr \Big/ \int_{0}^{\infty} P(r)\, r\, dr$$



3% of solid angle



Far field and small size defects

small defects cannot be characterized by PSD

reflected power = power density at defect · defect size · $|A|^2$

$A = \text{Exp}[i\, 2\, k\, h] - 1;\quad |A|^2 = \left(\frac{4\pi h}{\lambda}\right)^2$ when $h \ll \lambda$; $= 0 \sim 4$ when $h \sim \lambda$;

small

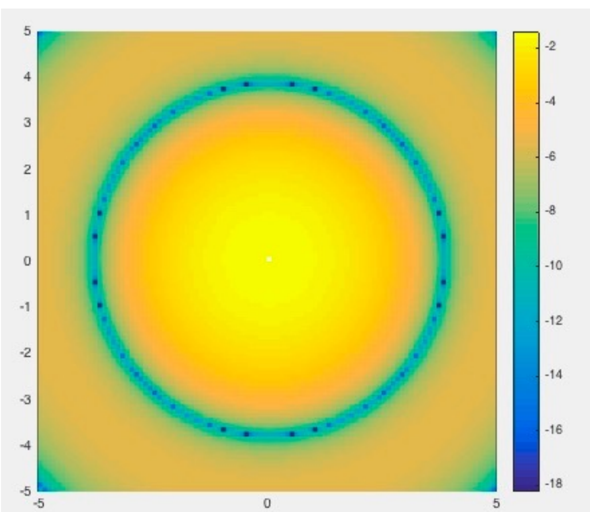
circle with radius a

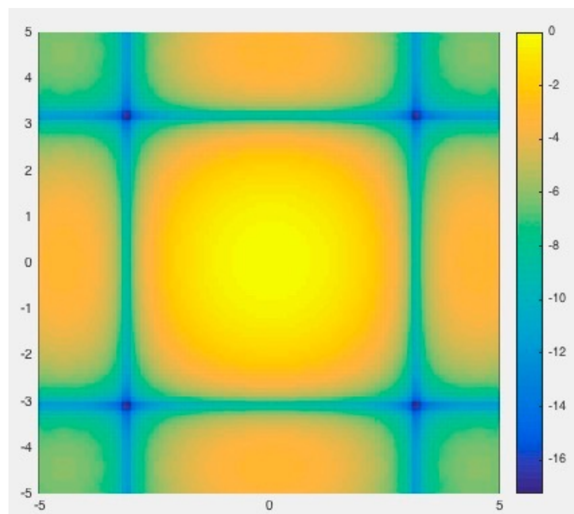
$$P(\theta) \sim \left(\frac{J_1(k\, a\, \theta)}{k\, a\, \theta}\right)^2;$$

rectangle size of du x dv

$$P(\theta_x, \theta_y) \sim \left(\frac{\text{Sin}[k\, \text{du}\, \theta_x]}{k\, \text{du}\, \theta_x}\, \frac{\text{Sin}[k\, \text{du}\, \theta_y]}{k\, \text{du}\, \theta_y}\right)^2$$

log(power) axis : k a θ = 0.1 a(μm) θ(degree)

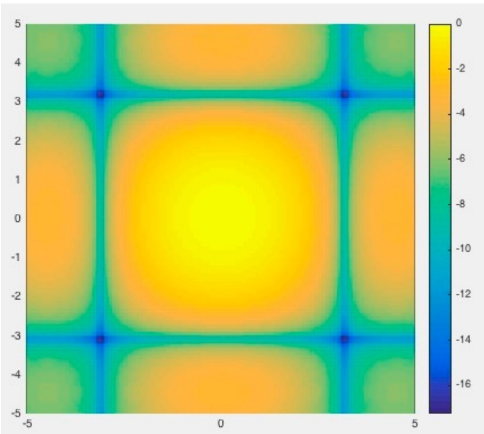




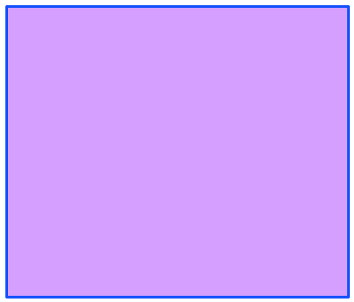
k a θ =1 when
a = 1μm, θ=10°
or
a=10μm, θ=1°

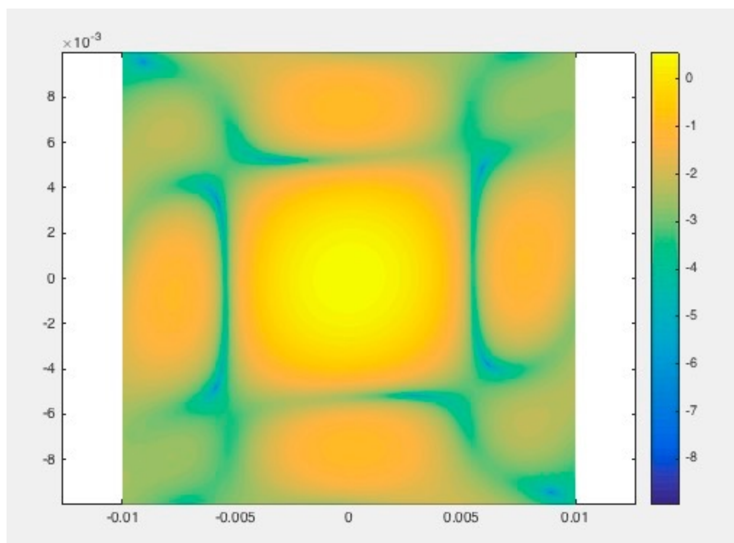
Defect size looks different seen at different angle

Clustered defects behave like a single defect

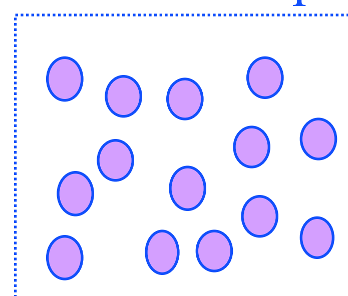


Same distribution generated by

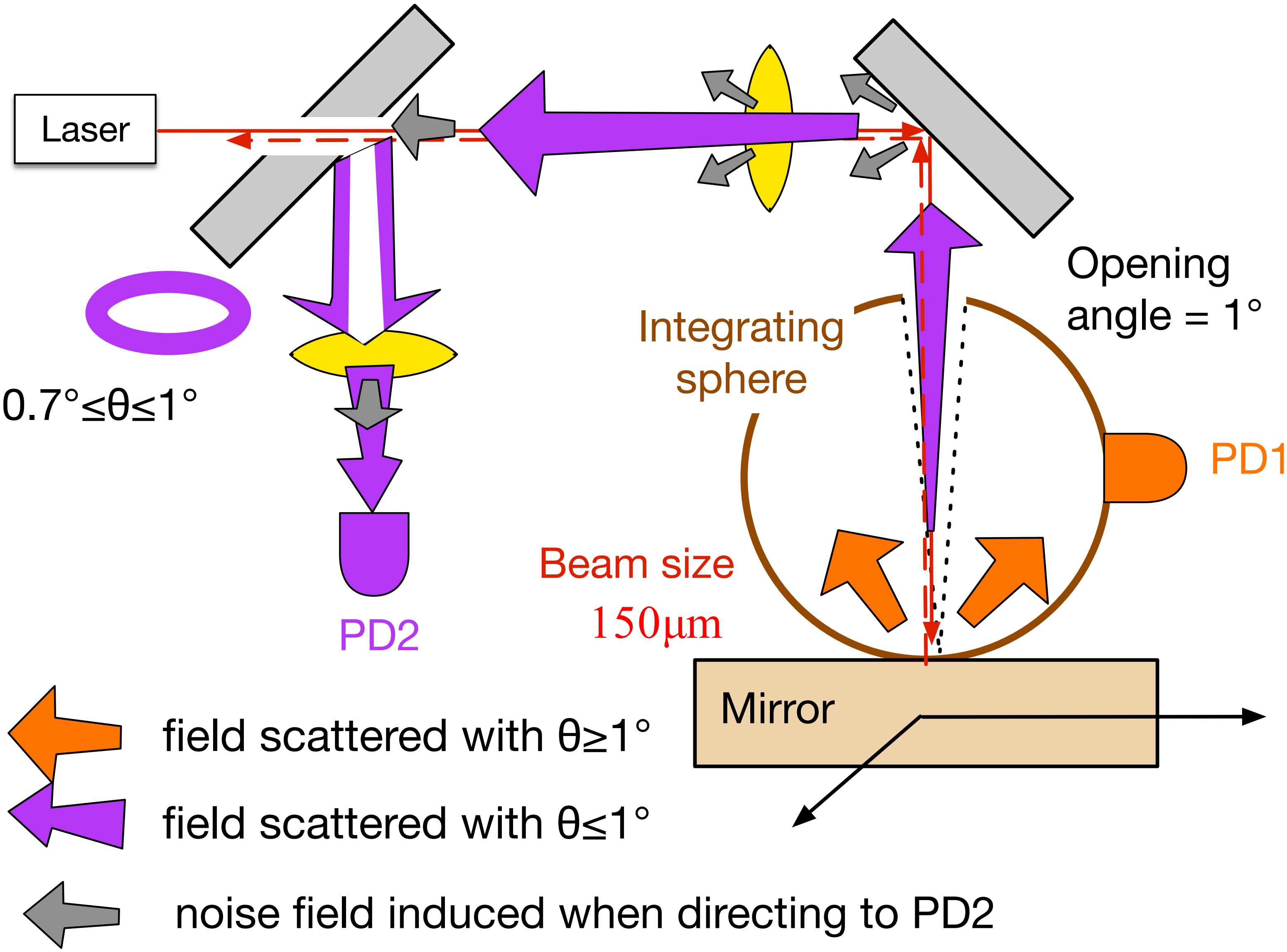




Power distribution generated by small defects in a square

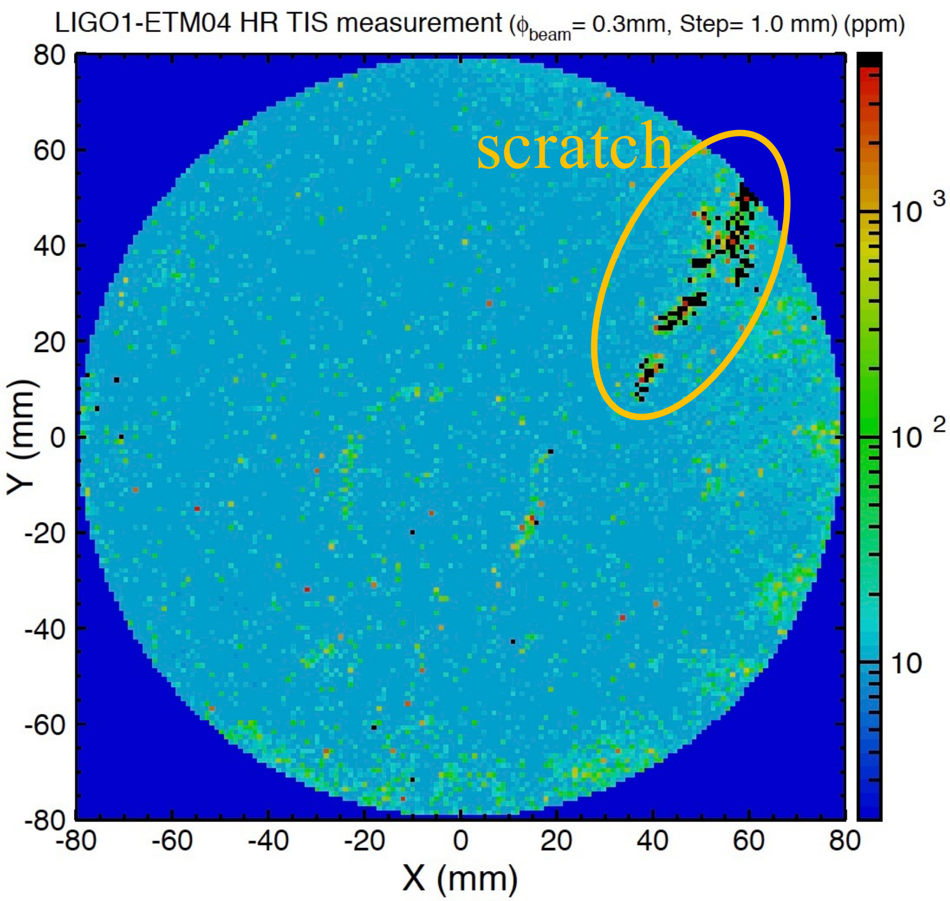


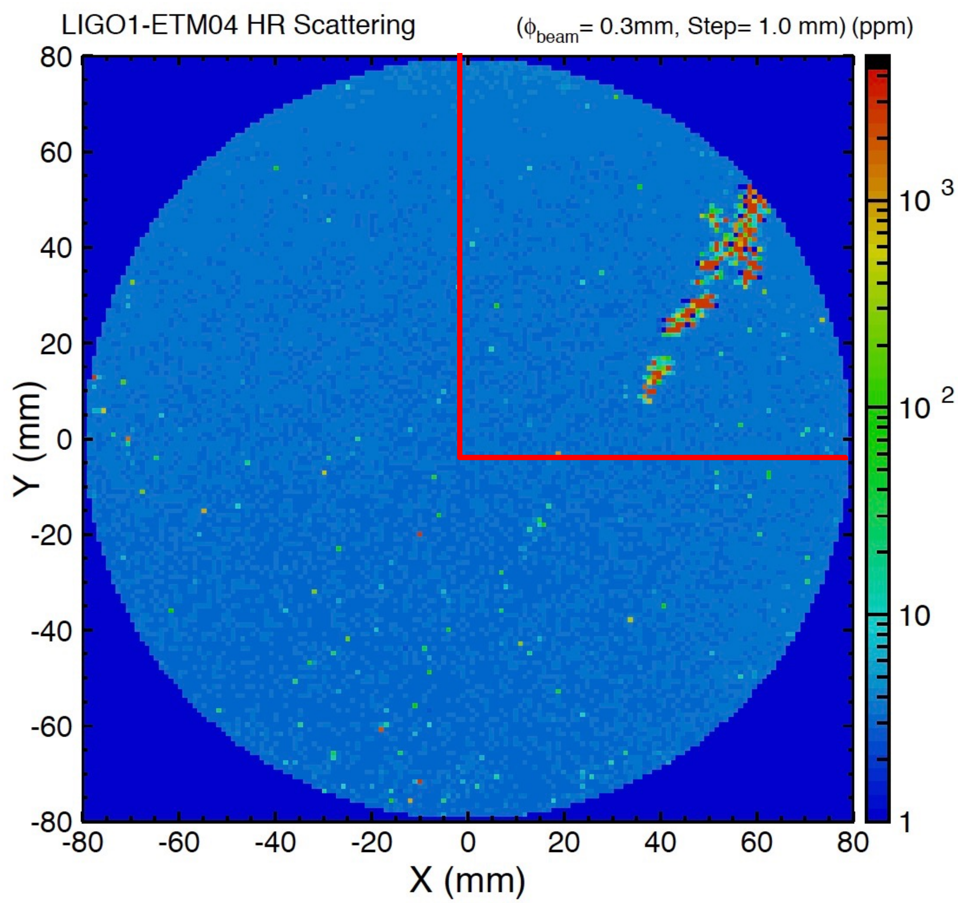
Setup for measuring TIS(θ≤1°) and TIS(θ≥1°)



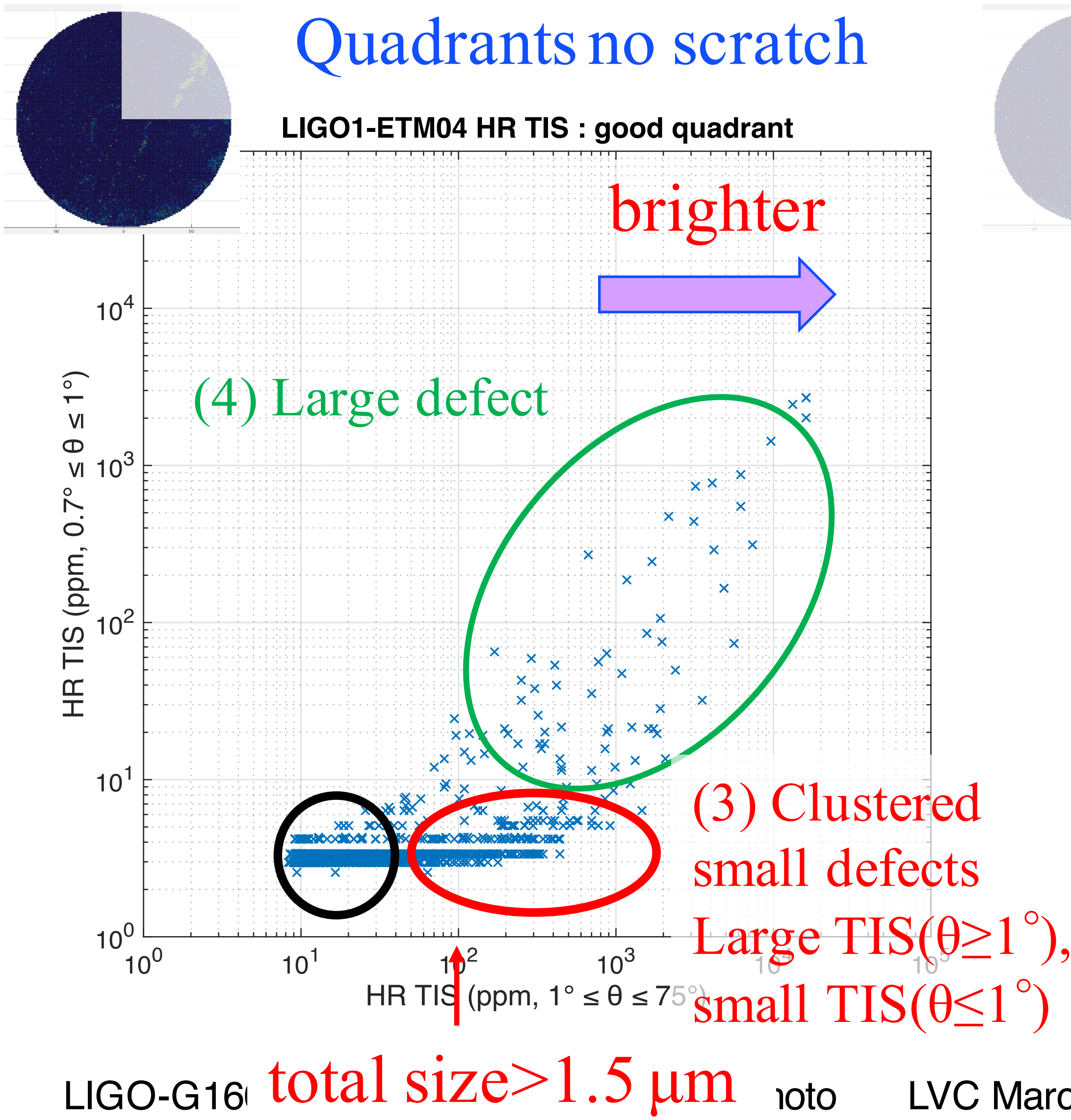
Very preliminary results mirror : initial LIGO ETM04

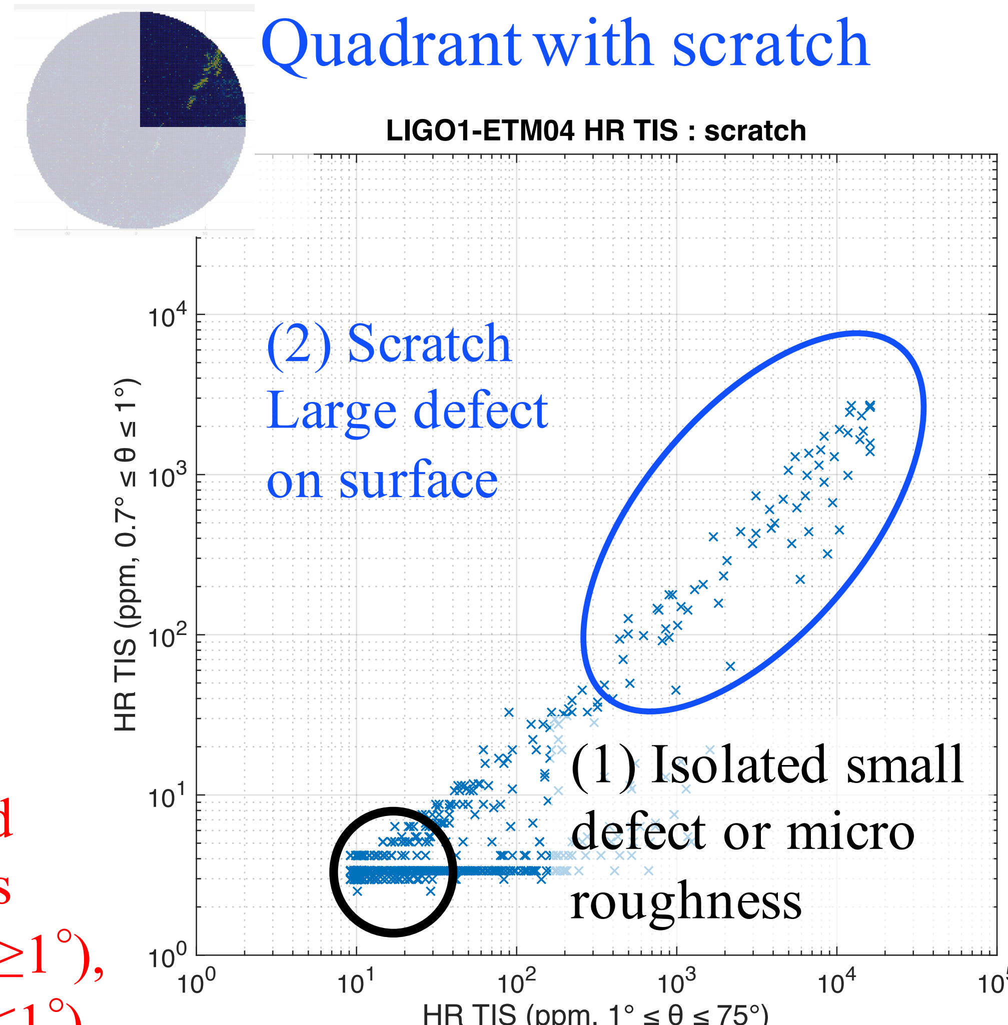
TIS (θ≥1°) TIS (0.7°≤θ≤1°) dΩ=1.5e^{-4}





TIS(θ≤1˚) vs TIS(θ≥1˚)
very preliminary

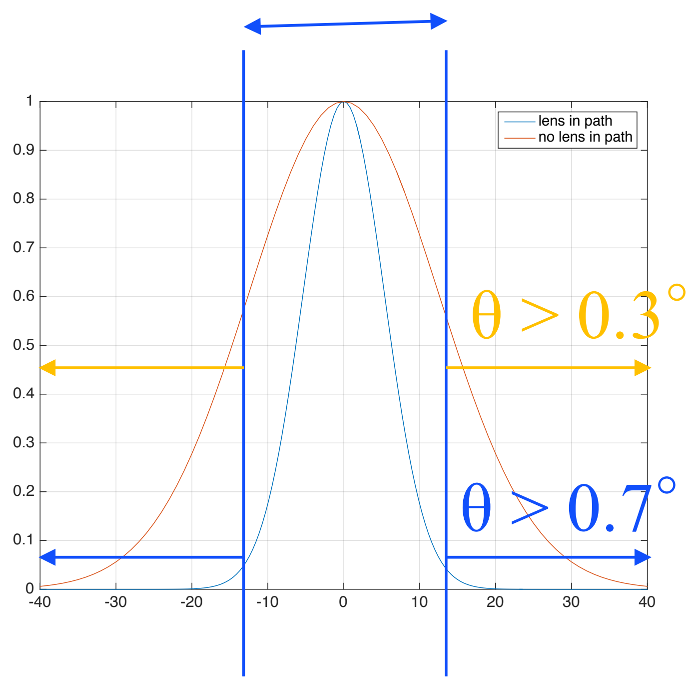


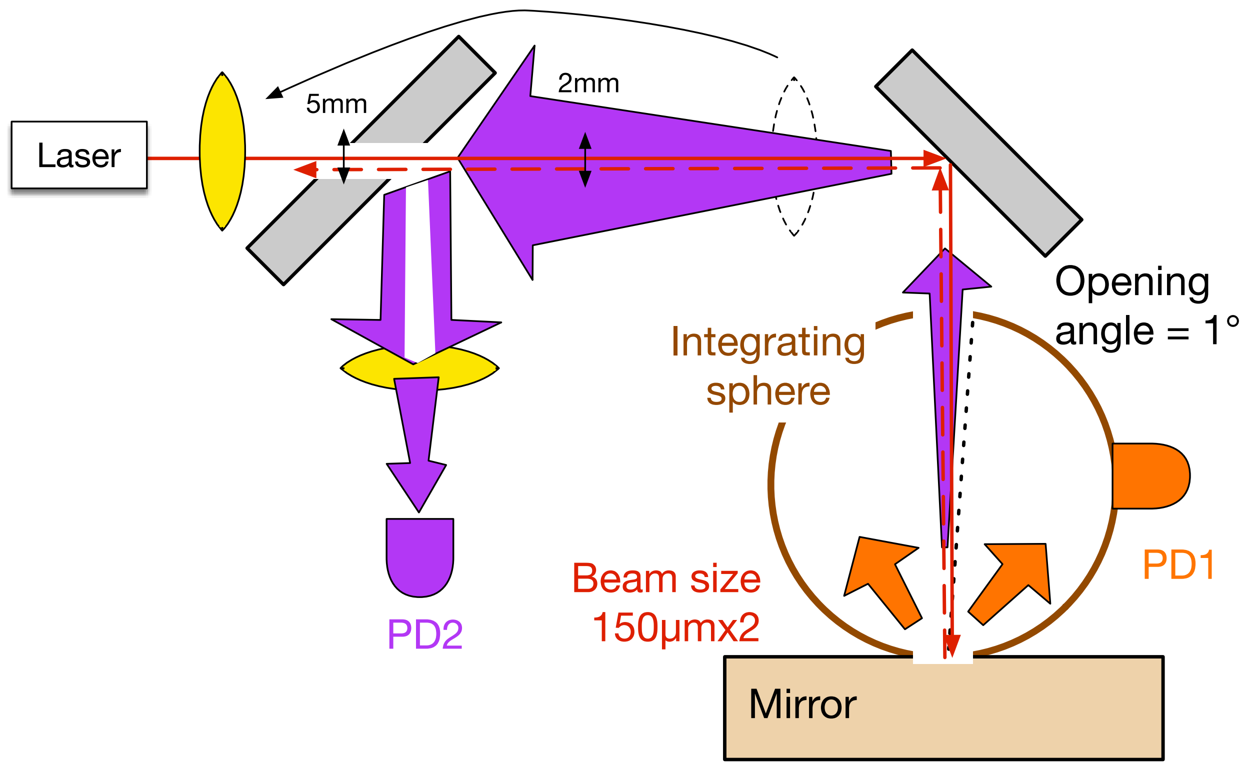


Revised setup

Hole in the mirror

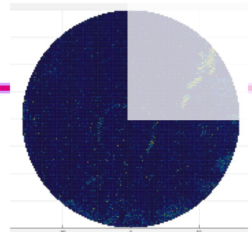
Lens moved out of the path to reduce noise
Beam diverging toward the second mirror,
which induces larger tail noise of the undisturbed beam.

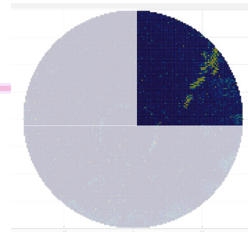




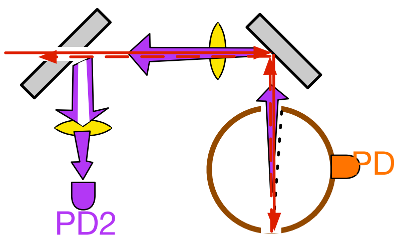
iLIGO
ETM04

Comparison of results :
PD2(0.7°≤ θ≤ 1°) vs PD2(0.3°≤ θ≤ 1°)

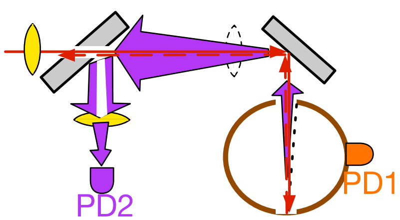


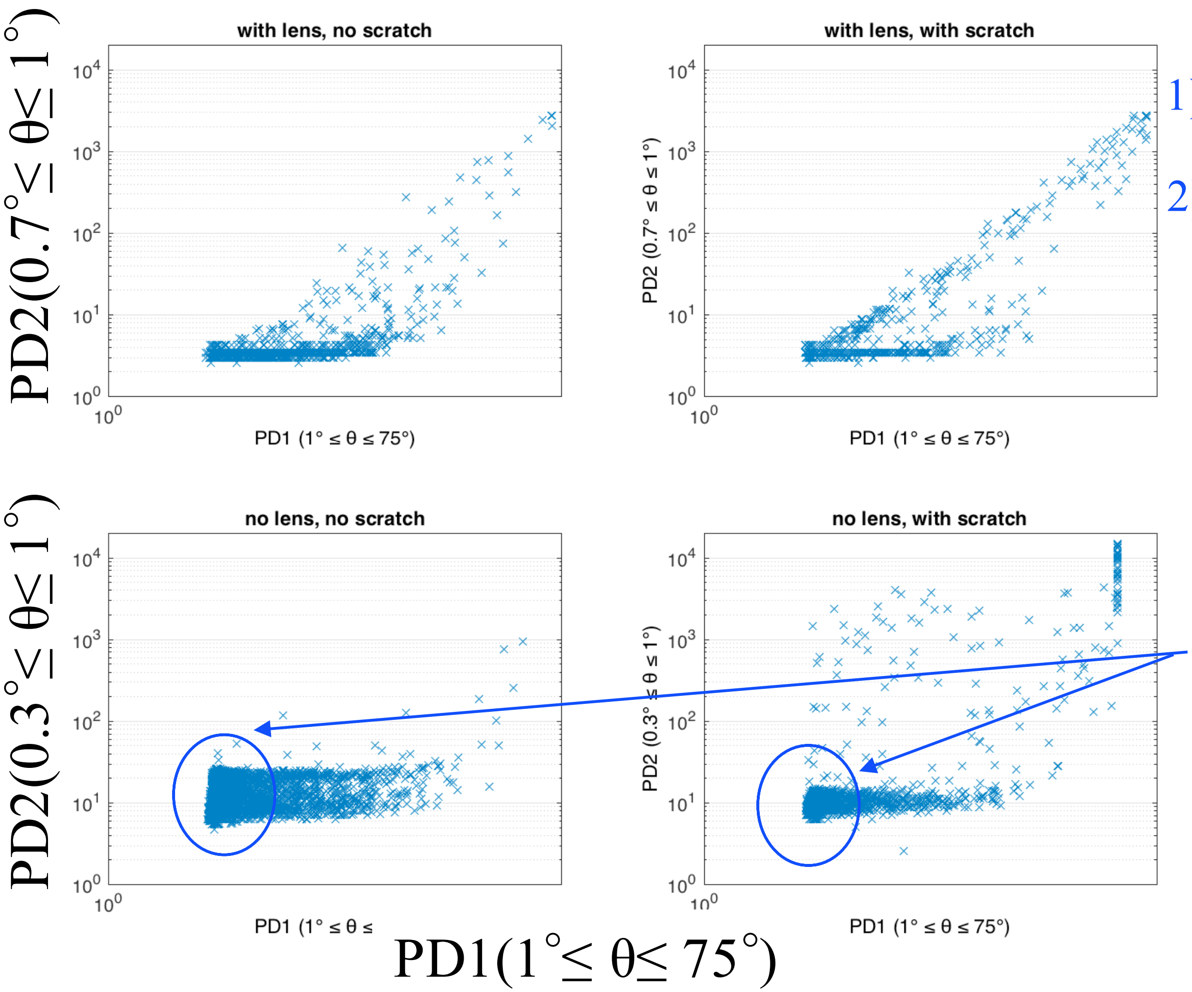


lens in path



lens out path

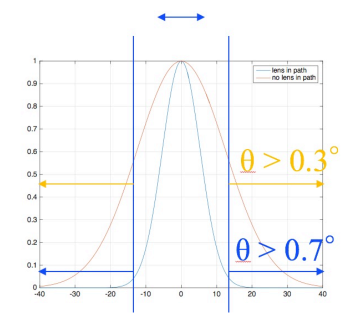




Why different?

1) Cleaning issue?

2) Efficiency difference?



3) Tail of gaussian Beam (1mm beam going thr 2.5mmx2 hole)

Mirror with larger hole being prepared

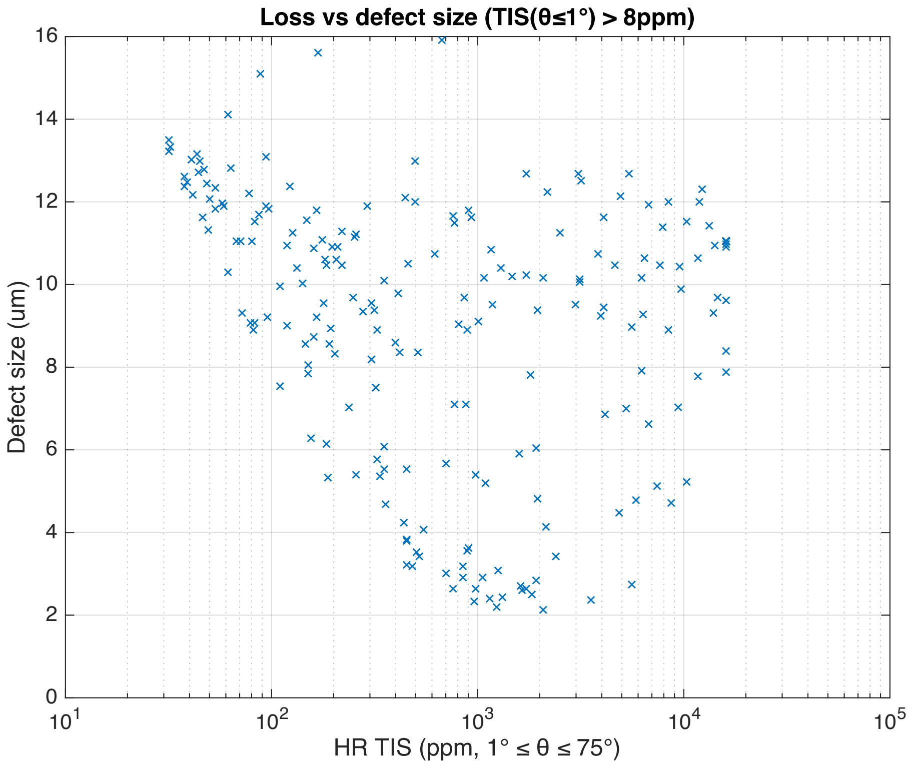
Summary

- Extended Integrating Sphere measurement
  - Preliminary result – proof of concept
  - In the small solid angle (10^{-4} , $\theta<1^{\circ}$), comparable energy observed as in the large solid angle($\theta\geq1^{\circ}$)
  - Improvement of measurement setup and understanding of systematic uncertainties are necessary to quantify the conclusion
- Large angle ($\theta\geq1^{\circ}$) TIS may underestimate the loss
- Measurement of aLIGO test masses coated by LMA
  - Necessary to quantify the loss contribution from defects
- Quantitative comparison of larger and small angle TIS may provide further information of defects
  - Size, clustering, …

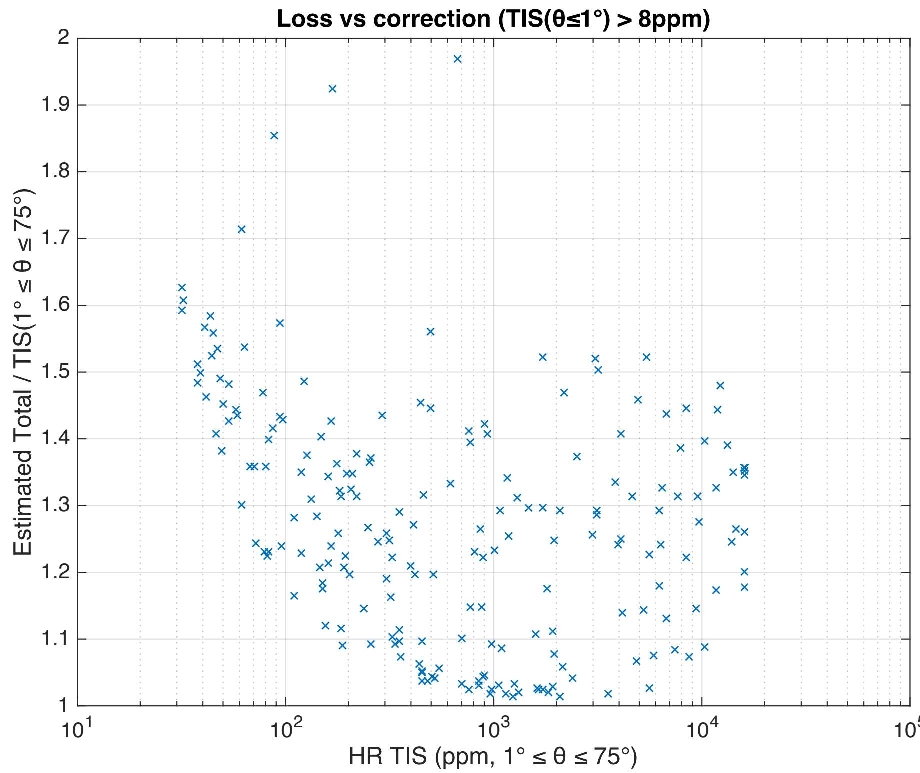
End of slides

Defect size and total loss

assuming defect shape is circle



Defect size vs TIS(θ≥1°)



Total / TIS(θ≥1°) vs TIS(θ≥1°)

Loss function