Guestimation of large angle scattering

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- **Limited data and knowledge about large angle scattering**
  - Discrepancy between data about test mass mirrors and the arm loss
  - Uncertainty about the prediction of stray lights
- **Loss = mirror surface aberration disturbance in a cavity**
  - More data of uncoated surface and limited data of coated surface
  - How to connect uncoated surface data to coated surface information
  - How to properly include necessary effects, like source size effect, diffraction effect …
- **Limited in situe measurements**
  - OpLev BRDF : BRDF(ITM@1.2°) ~ 10 x BRDF(ETM@7.7°)
  - ACB PD – proper handling of diffraction tail
  - Camera image
- **What are useful for further understanding**
  - Scattering with spatial wavelength of 0.05~1mm
  - Scattering in angle > 20°
  - Integrating sphere covering smaller angle
  - ???

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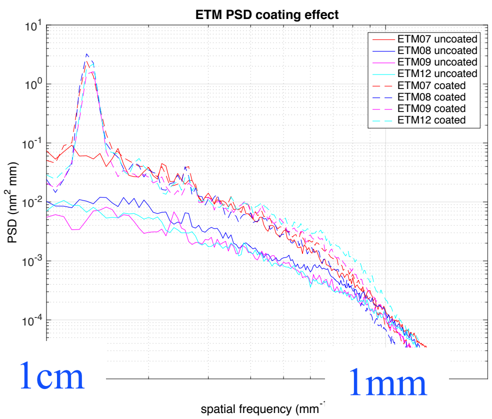
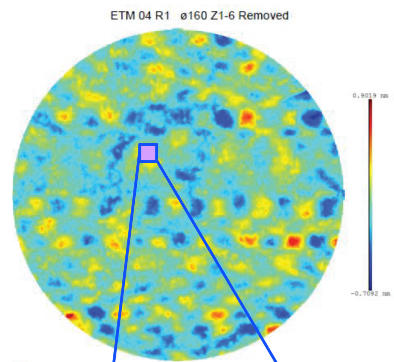
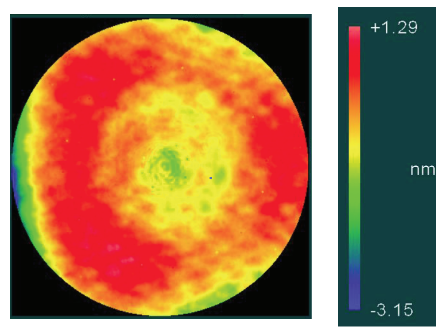
Different faces of mirror surface

Phasemap of coated and uncoated surface



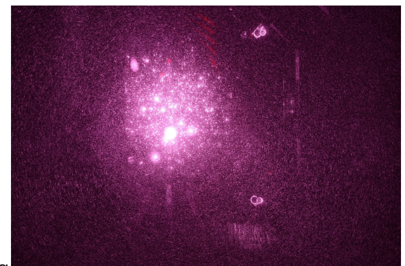


(1) Surface after polishing by ASML
Aperture size 160mm
RMS = 0.1732nm, PV=1.611nm

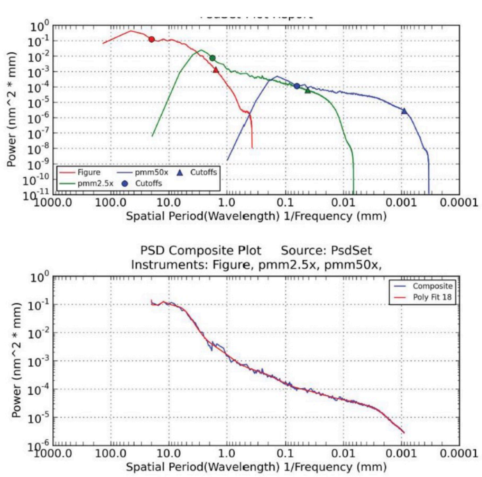


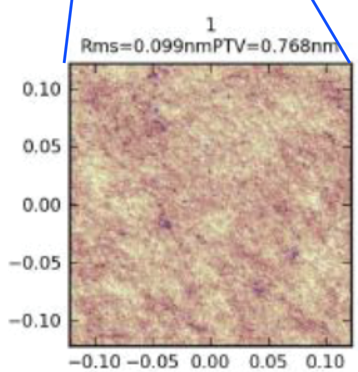
(2) Surface after multilayer coating by ison spattering
Aperture160mm
RMS = 0.563nm, PV=4.436nm

ETM Pcal Camera Image

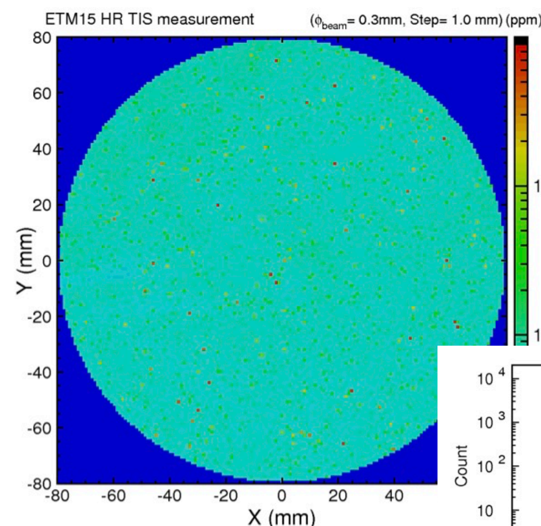


Phasemap and PMM

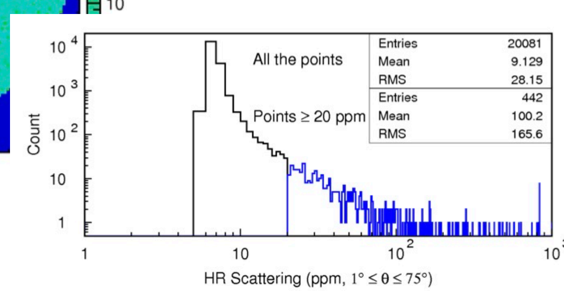




(3) Surface after polishing measured by PMM(phase measuring microscope) with magnification of 50.
0.25mm x 0.25mm square near center.
RMS = 0.099nm, PV=0.768nm



Integrating sphere loss histogram



IFO Geometry

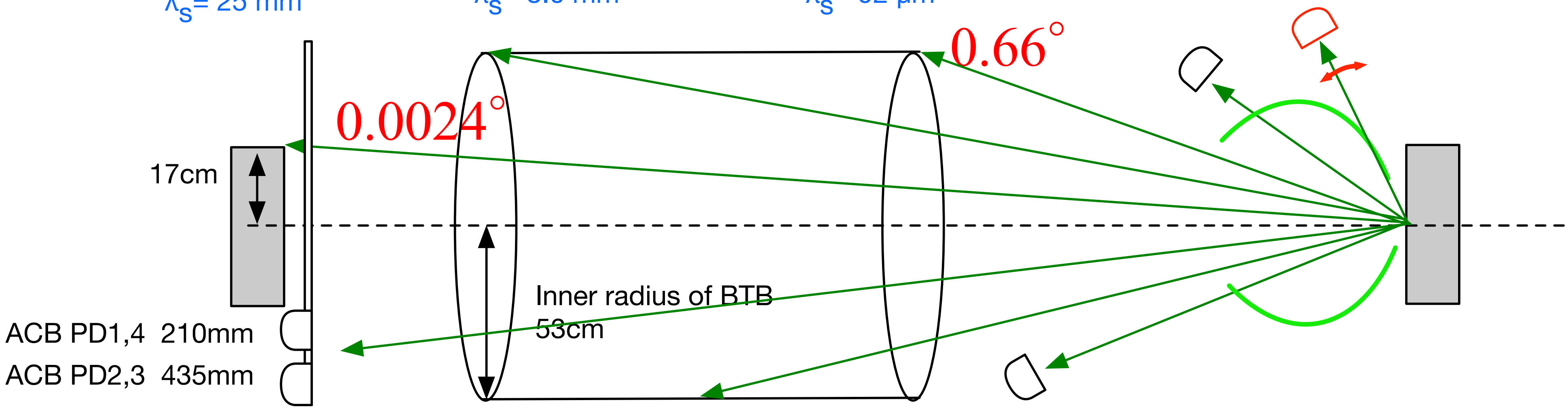
Test mass boundary
z = 3994.5 m
θ = 17cm/3994.5m
= 43 μrad
= 0.0024°
λ_s= 25 mm

last BT baffle
z = 3989m
θ = 53cm/3989m
= 0.13 mrad
= 0.0076°
λ_s= 8.0 mm

first BT baffle
z = 46m
θ = 53cm/46m
=11.5 mrad
= 0.66°
λ_s= 92 μm

ETM OpLev
z = 5.6m
θ =0.13 rad
= 7.7°
λ_s= 8 μm

BRDF measurements
θ = 10°~76°
λ_s= 0.8 ~ 6.1 μm



ACB PD
θ = 210,435 mm/4000m
= 53, 109 μrad
= 0.003°, 0.006°
λ_s= 20, 9.8 mm

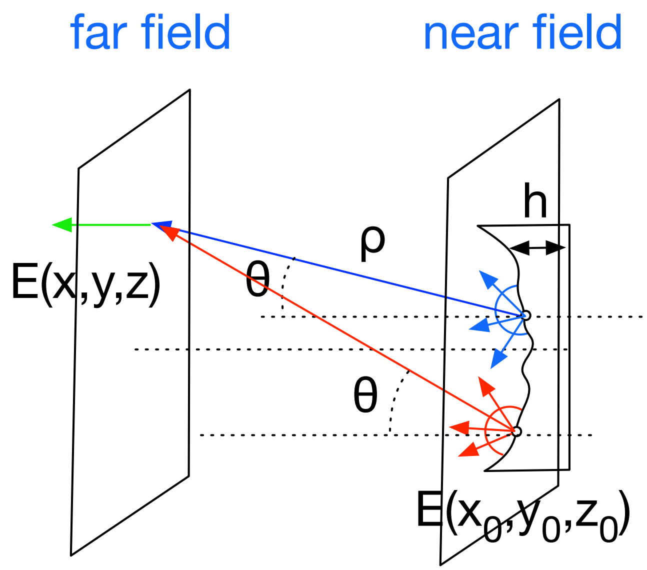
Middle of arm
z = 2000 m
θ = 53cm/2000m
= 0.265 mrad
= 0.015°
λ_s= 4.0 mm

ITM OpLev
z = 33 m
θ = 0.021 rad
= 1.2°
λ_s= 51 μm

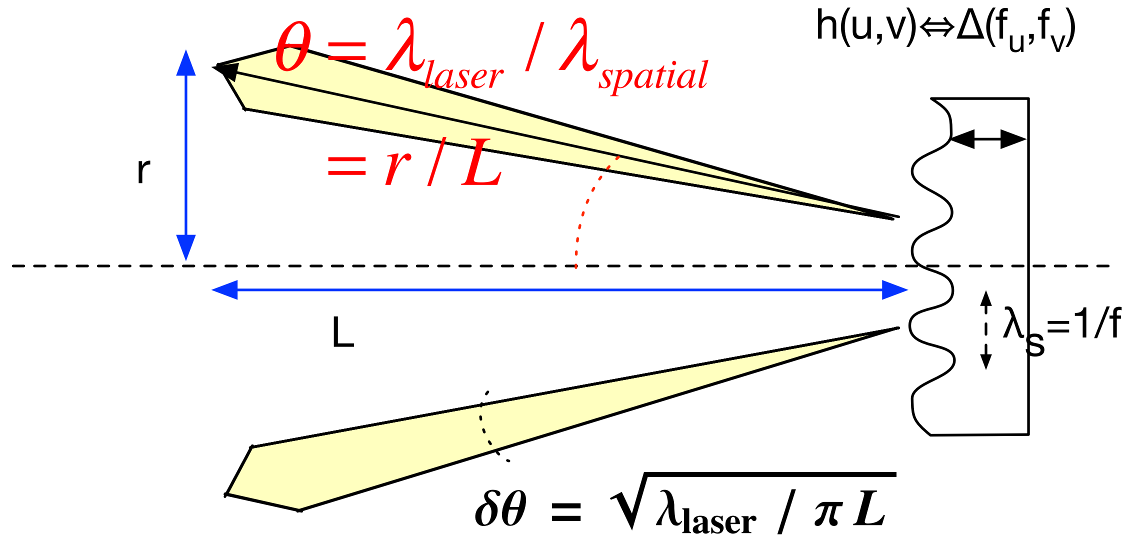
Integrating Sphere
Sphere size = 10.8 cm
θ = 0.017 ~ 1.3 rad
= 1°~75°
λ_s= 0.8 ~ 61 μm

mirror surface aberration and scattered fields

Huygen's integral



Far field distribution & ASD/PSD



$$dP = |E_0|^2 \cdot \Delta S \cdot \left(\frac{4\pi\sigma}{\lambda_{laser}}\right)^2 \qquad \sigma^2 = \frac{\iint dx_0\, dy_0\, |h(x_0, y_0)|^2}{\Delta S}$$

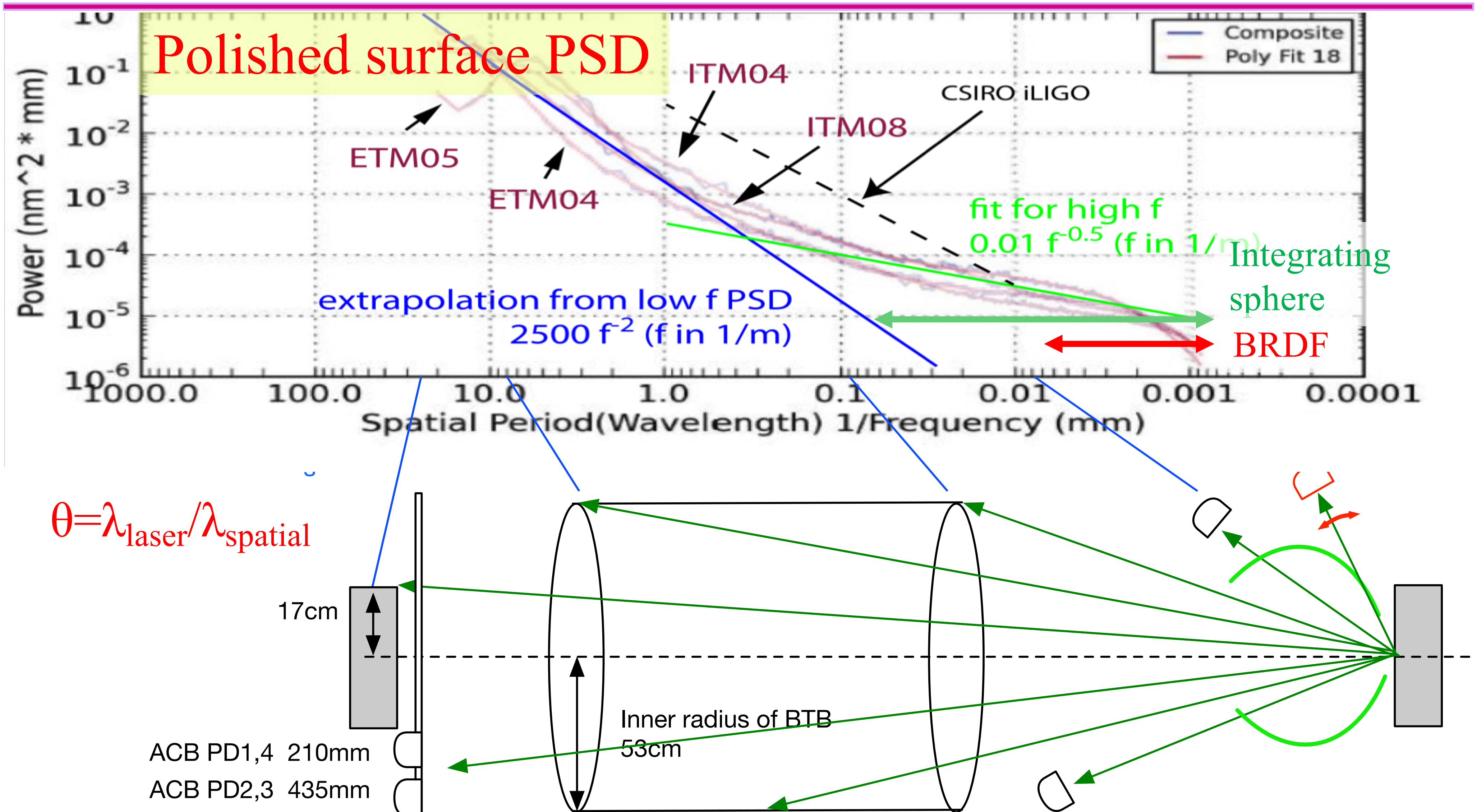
$$BRDF(\theta) = \left(\frac{4\pi}{\lambda^2}\right)^2 PSD_{2d}(f)$$

$$= \left(\frac{4\pi}{\lambda^2}\right)^2 D \cdot PSD(f)_{1d} / f$$

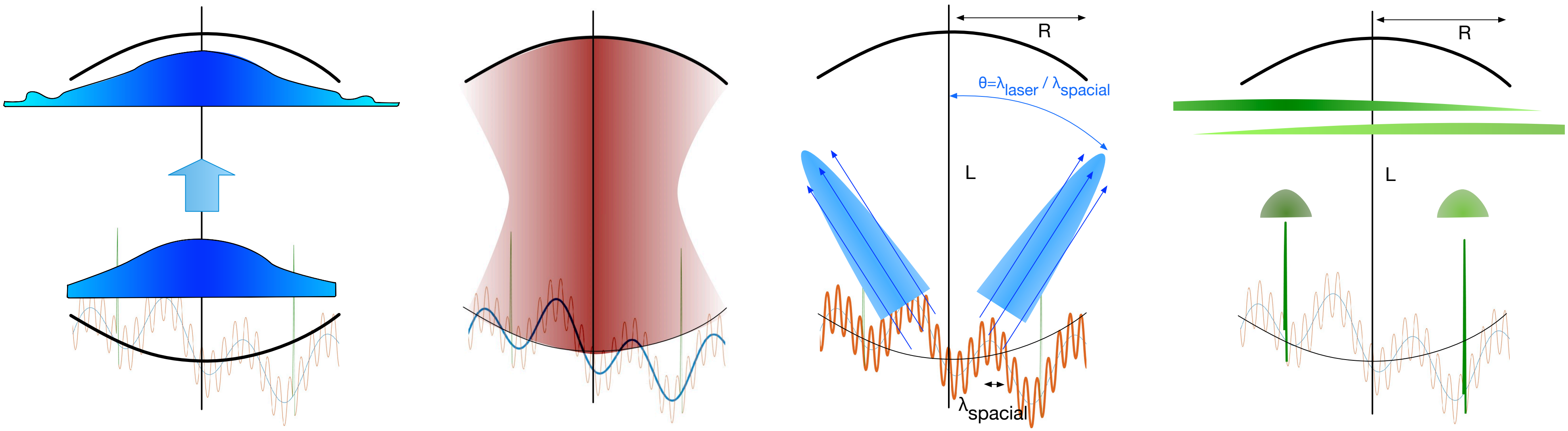
(D~1/2π)

- No far field interference effect on dP
- $dP/P \sim (a/w)^2 = (0.5\mu/5cm)^2 = 10^{-10}$

IFO geometry and mirror surface wavelength

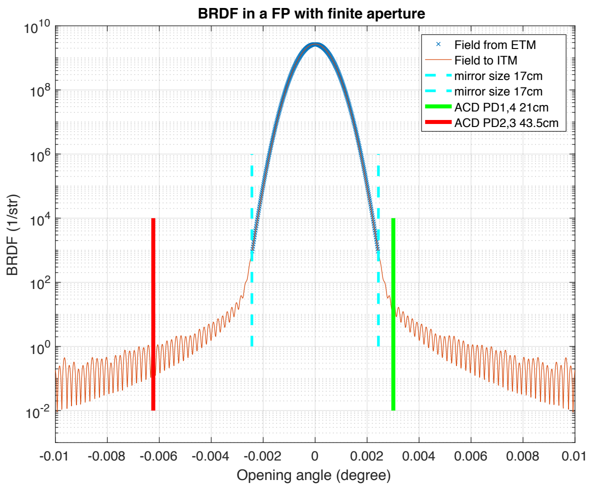


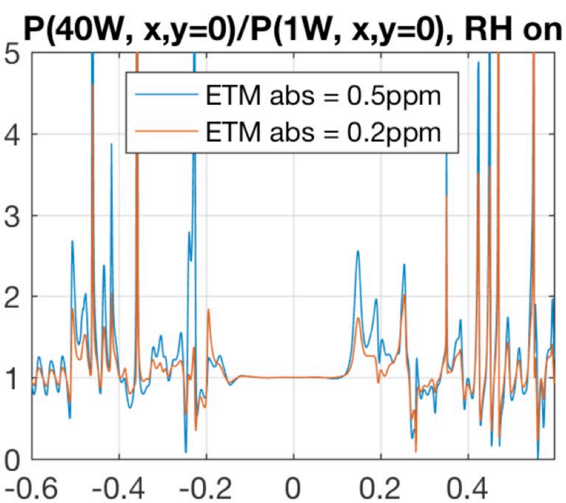
Distrubance of field in a cavity



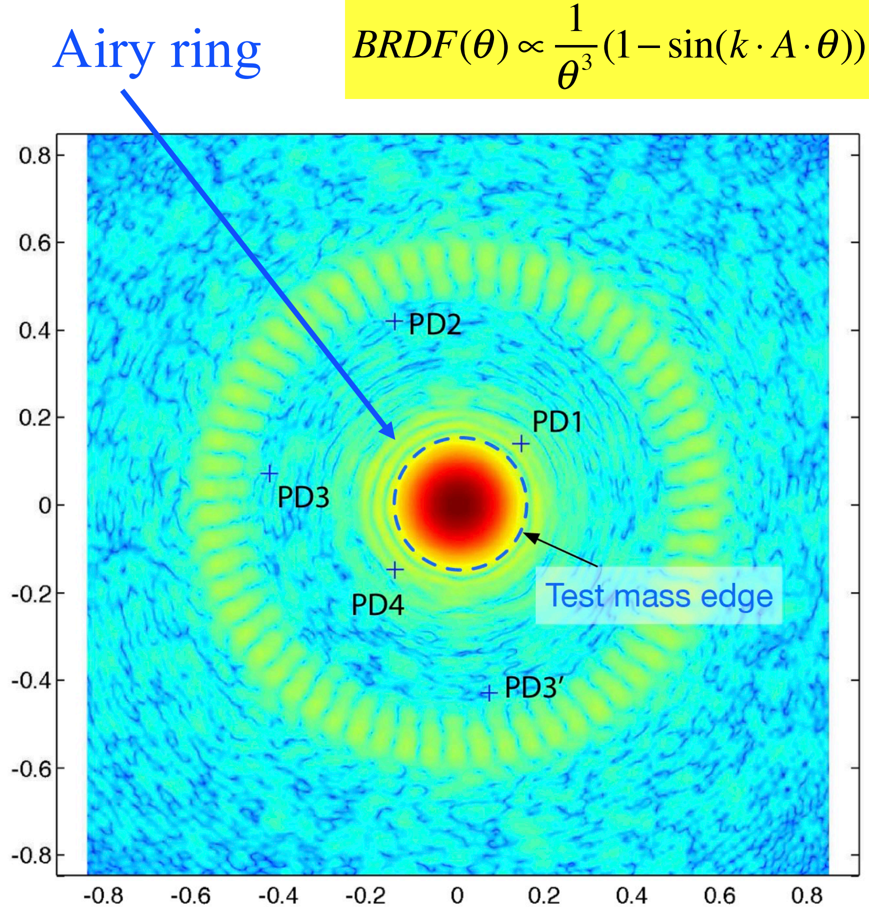
Mirror finite aperture	Surface figure error	Microroughness - PSD	Point defects
Non-gaussian diffraction tail ~ θ^{-3}	Change of resonating field and larger tail	Fixed angle scattering by interference of far field	Scattering by small sources located randomly
1.9ppm for A=32.6cm	H1x:20ppm,H1y=16ppm L1x:18ppm,L1y=15ppm	10~20ppm ?	10~30ppm ?
Airy ring outside of mirror $\theta < 0.003^\circ$	$\lambda s > 5$mm or $\theta < 0.01^\circ$	$\lambda s < 1$mm or $\theta > 0.06^\circ$, BRDF~$1/\theta^n$, n~1.5-3	All angle, measurable at large angle ?

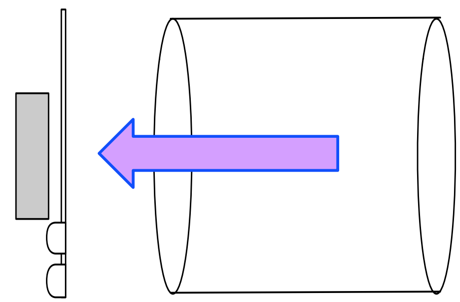
Field around mirror with airy ring



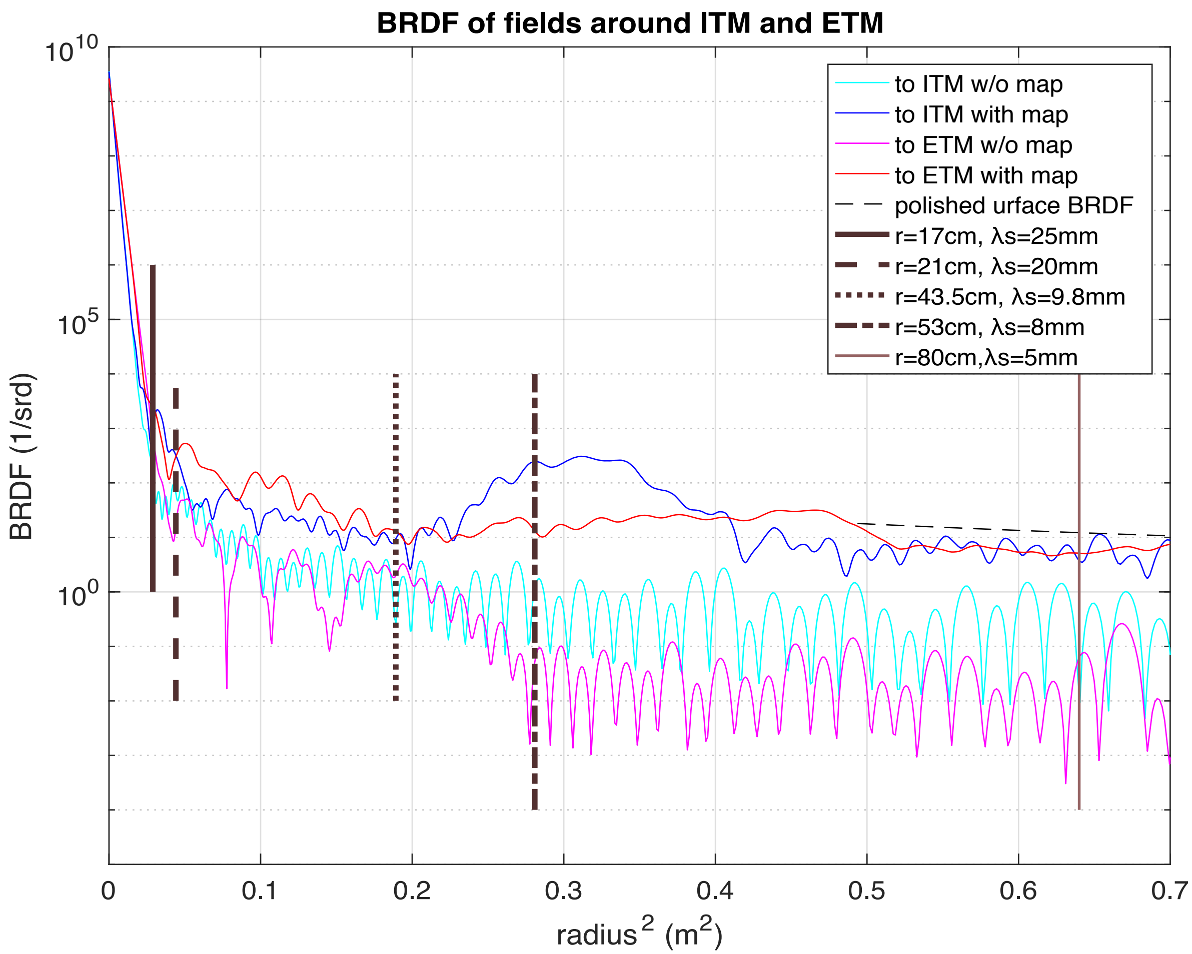


$$BRDF(\theta) \propto \frac{1}{\theta^3}(1 - \sin(k \cdot A \cdot \theta))$$

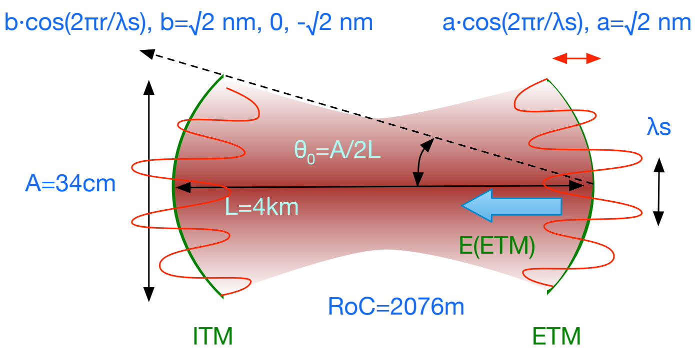


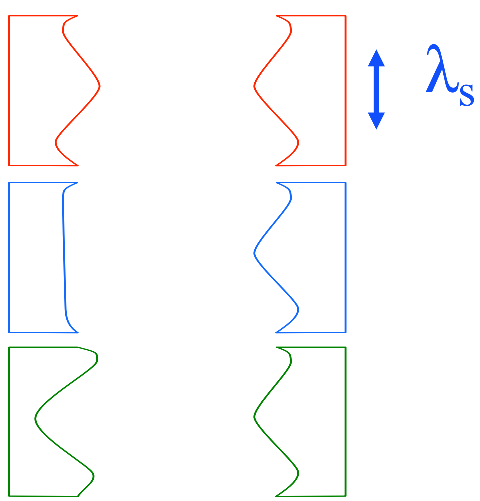


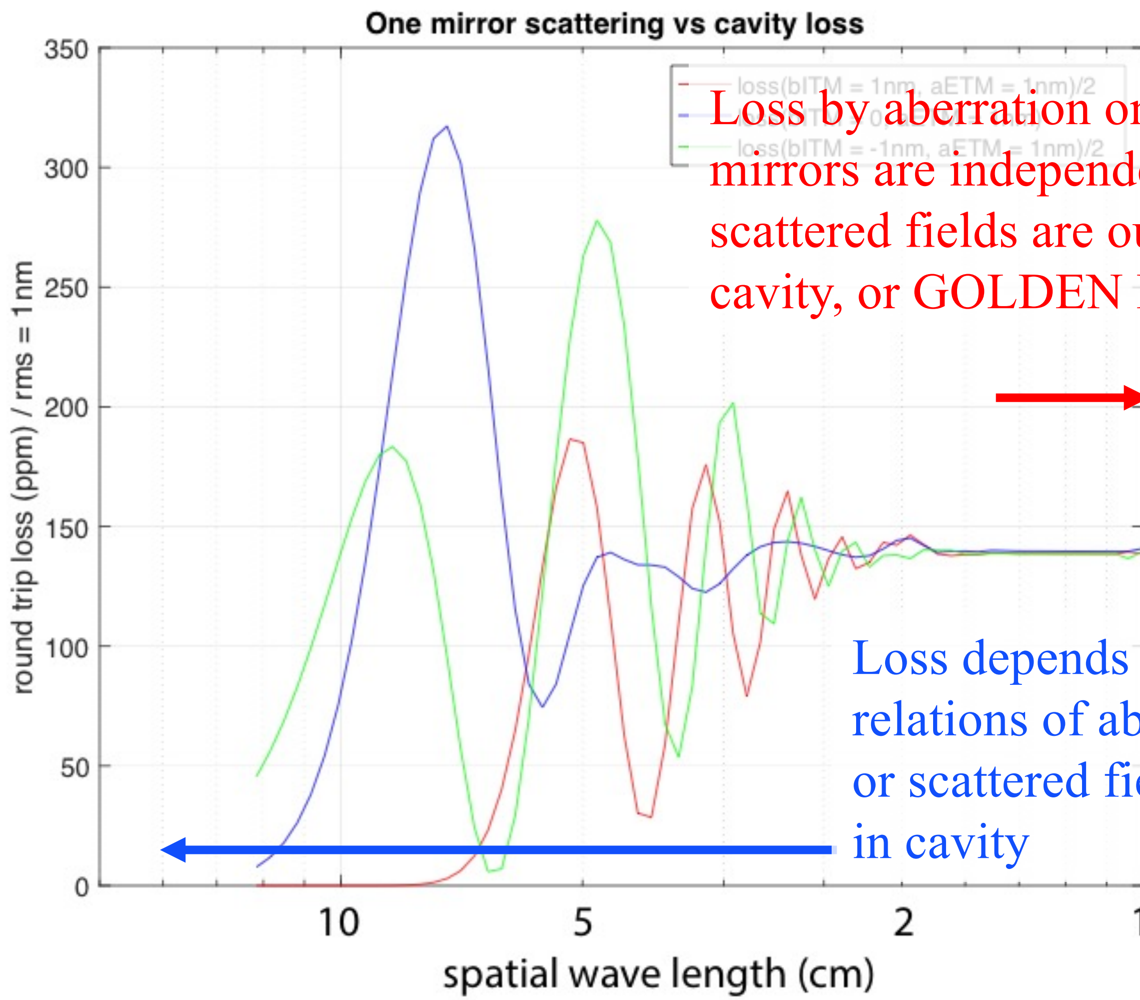
Field tail by figure error



Surface aberration and cavity loss or when golden rule applies





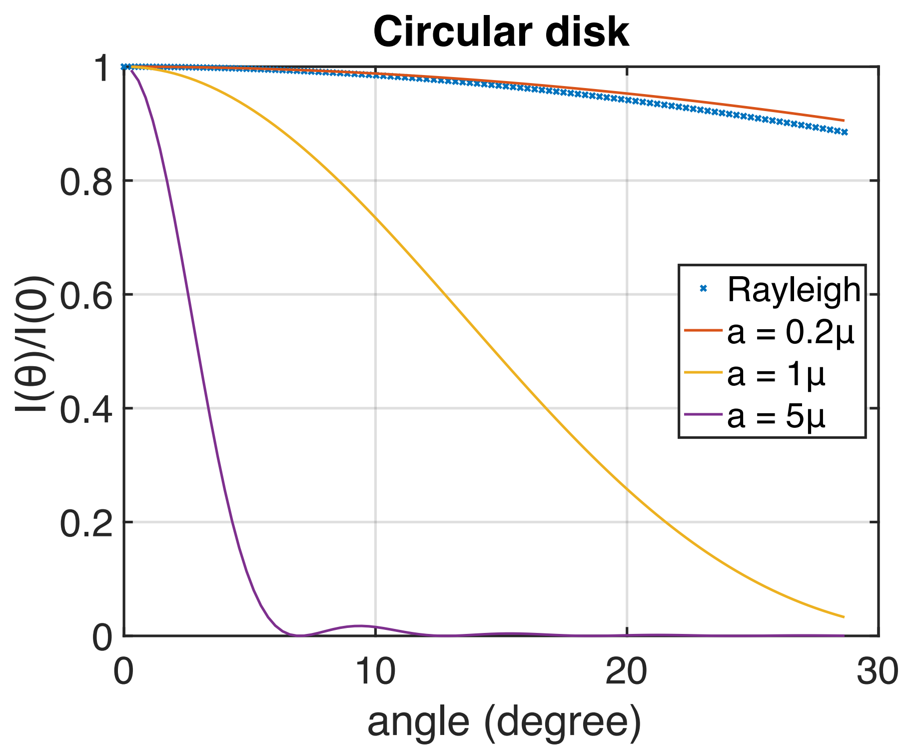


Loss by aberration on two mirrors are independent, or scattered fields are out of cavity, or GOLDEN RULE

Loss depends on relations of aberrations, or scattered fields stay in cavity

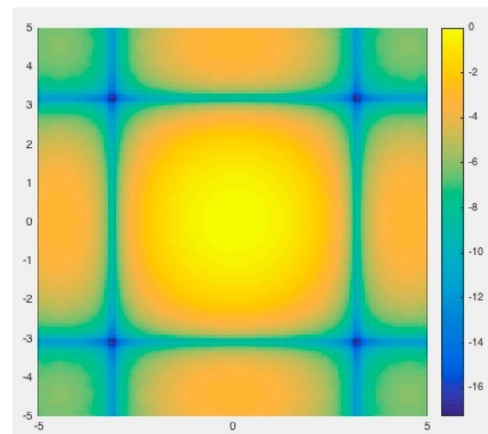
Angular distribution scattered by small anomalies

Power distribution depends on the size of source

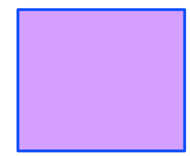


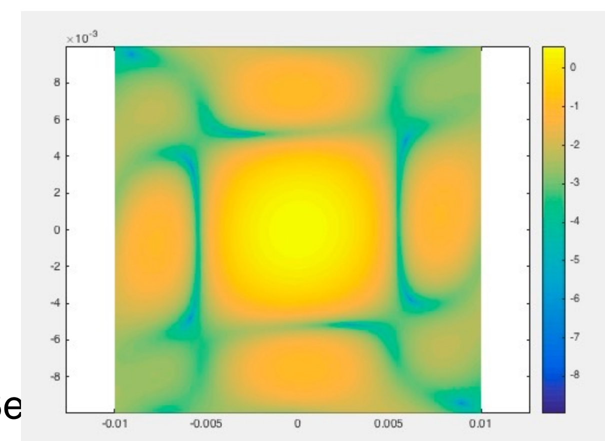
Clustered small sources scatter like a big source

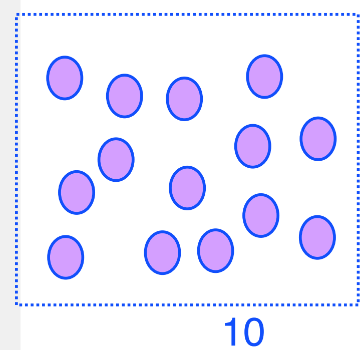
Far field



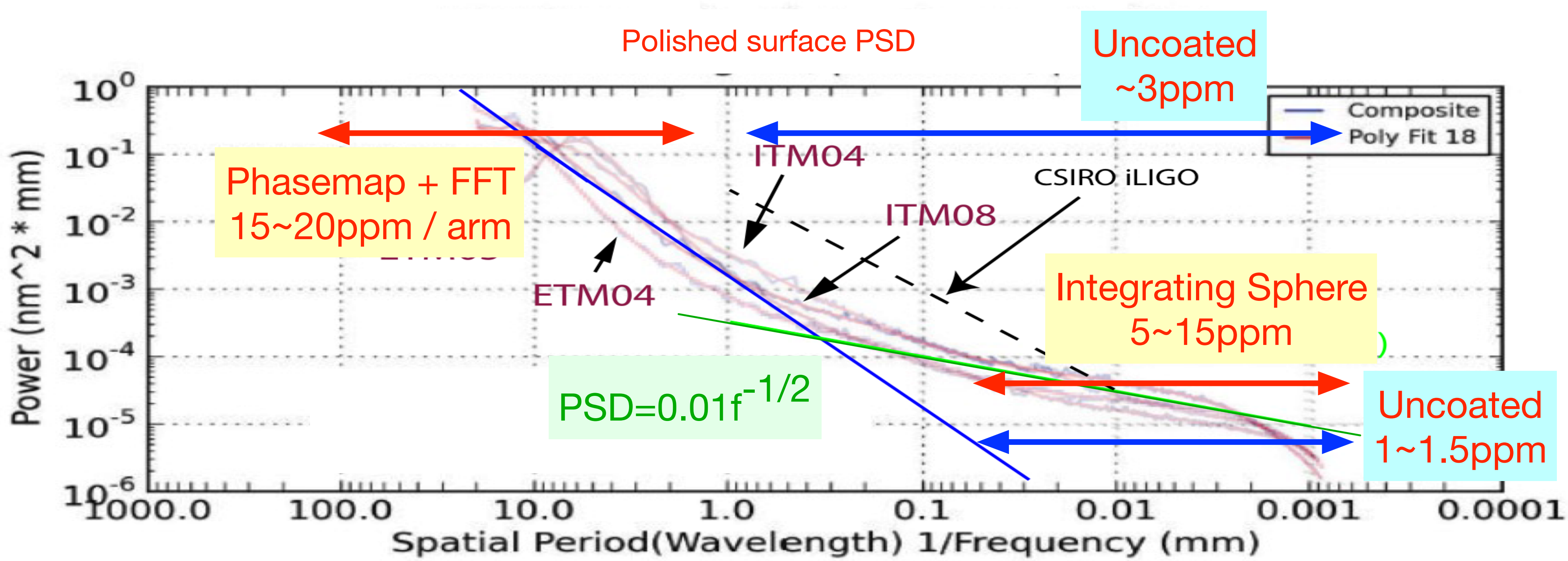
sources







Uncoated surface PSD and known losses



L1 alog 28668, H1 alog 30622

BRDF by OpLev for ITM and ETM

	ITMX	ITMY	ETMX	ETMy
	θ=1.2°		θ=7.7°	
L1	250ppm	500ppm	30ppm	43ppm
H1	260ppm	420ppm	37ppm	28ppm

Polished surface PSD to BRDF

$$BRDF(\theta) = (\frac{4\pi}{\lambda^2})^2 PSD_{2d}(f) = (\frac{4\pi}{\lambda^2})^2 D \cdot PSD(f)_{1d} / f$$

$$PSD_{1d}(f) \sim f^{-C}$$

$$D = \Gamma(\frac{C+1}{2}) / 2\sqrt{\pi}\Gamma(\frac{C}{2})$$

D=1/4 for C=2, D=1/2π for C=1

$$PSD(f)_{1d} = 0.01 f^{-0.5} (nm^2 mm) \text{ for } \lambda_s < 0.5\text{mm}$$

$$\Rightarrow BRDF(\theta) = 1.3\theta^{-1.5}$$

OpLev BRDF : reflection by coated surface from all sources

BRDF(θ)=A x polished surface BRDF + total point scatter / 2π

A = 8, total point scatter = 30ppm

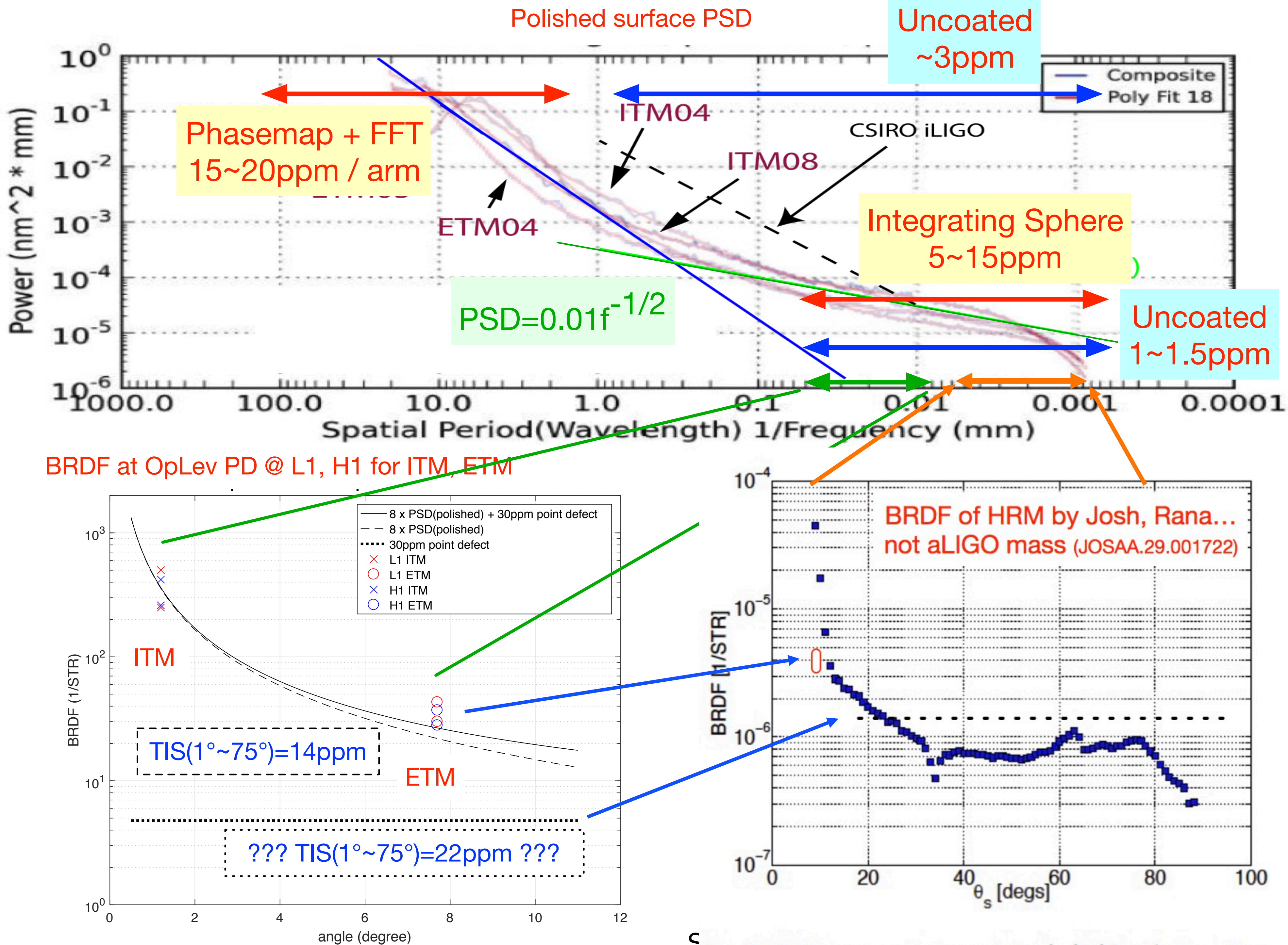


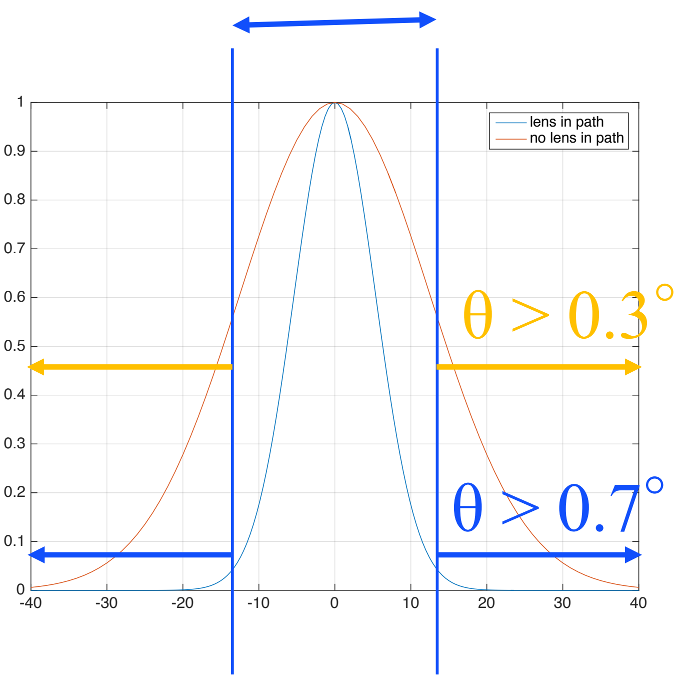
Fig. 9. BRDF versus scattering angle for the highly-reflecting mirror.

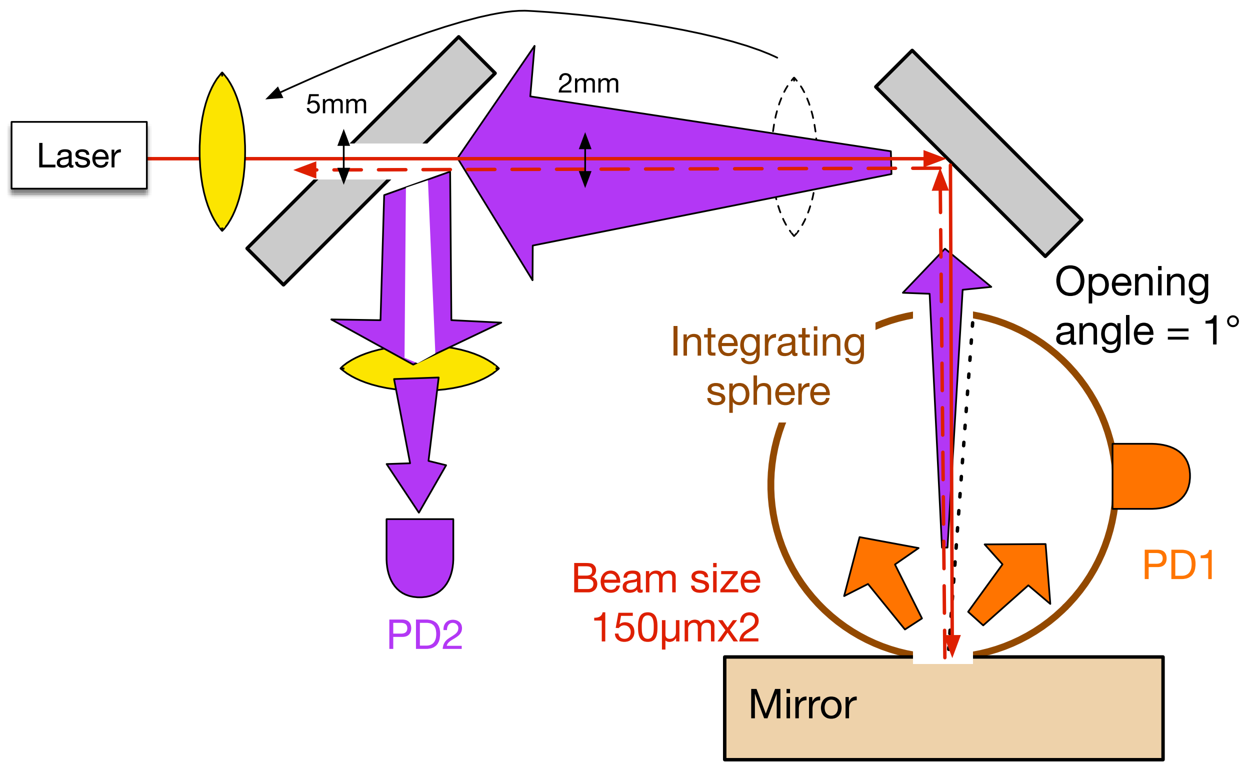
Integrating sphere

large (θ > 1°) and small(θ < 1°) angle

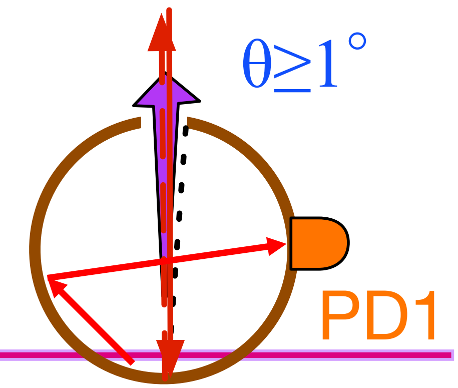
Lens moved out of the path to reduce noise
Beam diverging toward the second mirror,
which induces larger tail noise of the undisturbed beam.

Hole in the mirror





aLIGO ITM07 TIS(θ≥1°) using integrating sphere



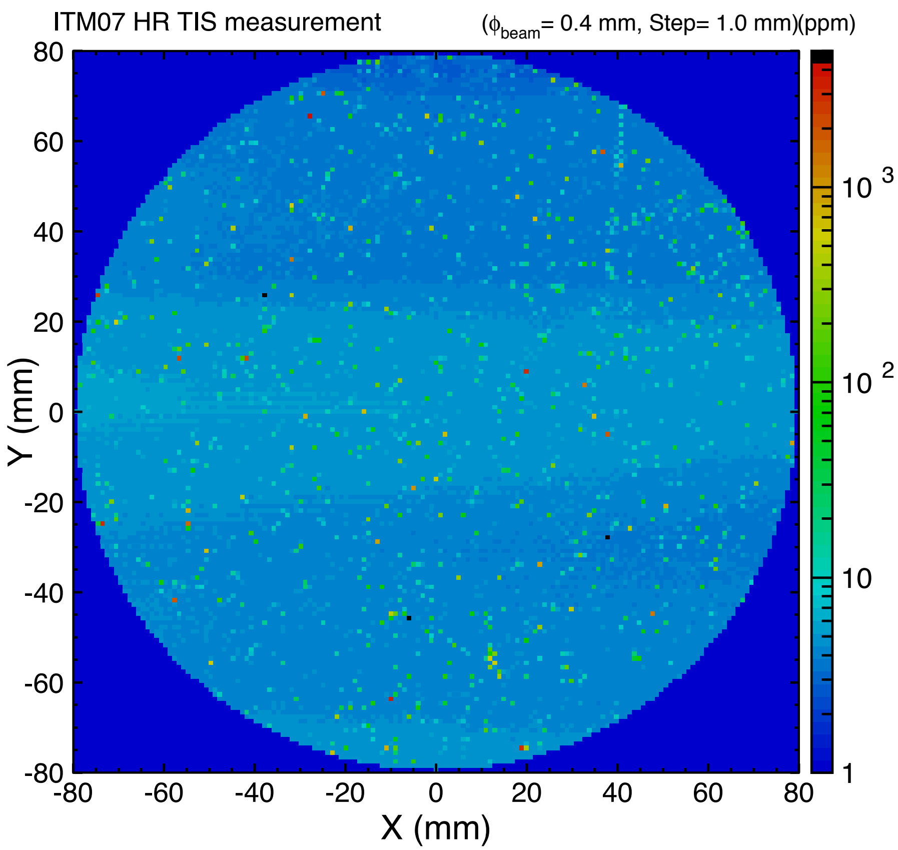
Scattering in the central 160mm by 0.4mm laser with 1mm step

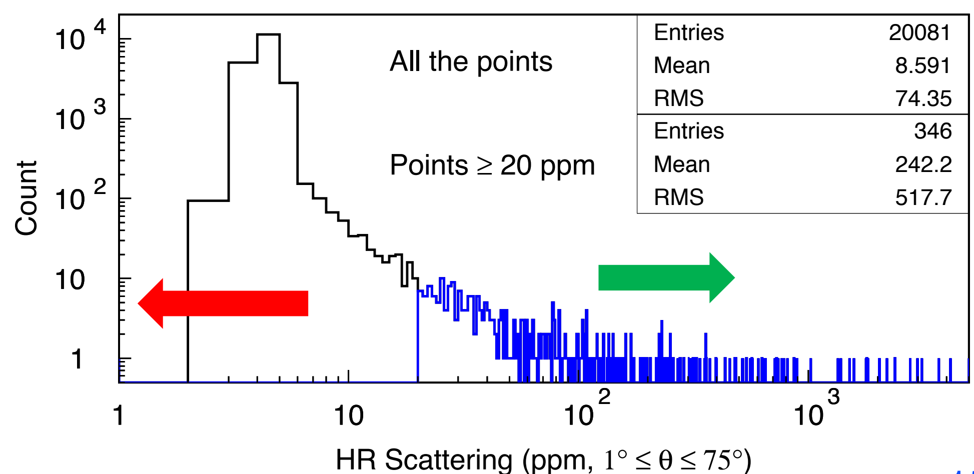
Continuous roughness

Point scattering

$$\frac{dP}{P_{in}} = \left(\frac{4\pi\sigma(w_0)}{\lambda}\right)^2 + \langle n \rangle\, dS \left(\frac{4\pi\Delta}{\lambda}\right)^2$$

- σ(w) : rms with f > 1/w
- <n> : density of point defects
- dS : size of point defect
- Δ : characteristics of point defect



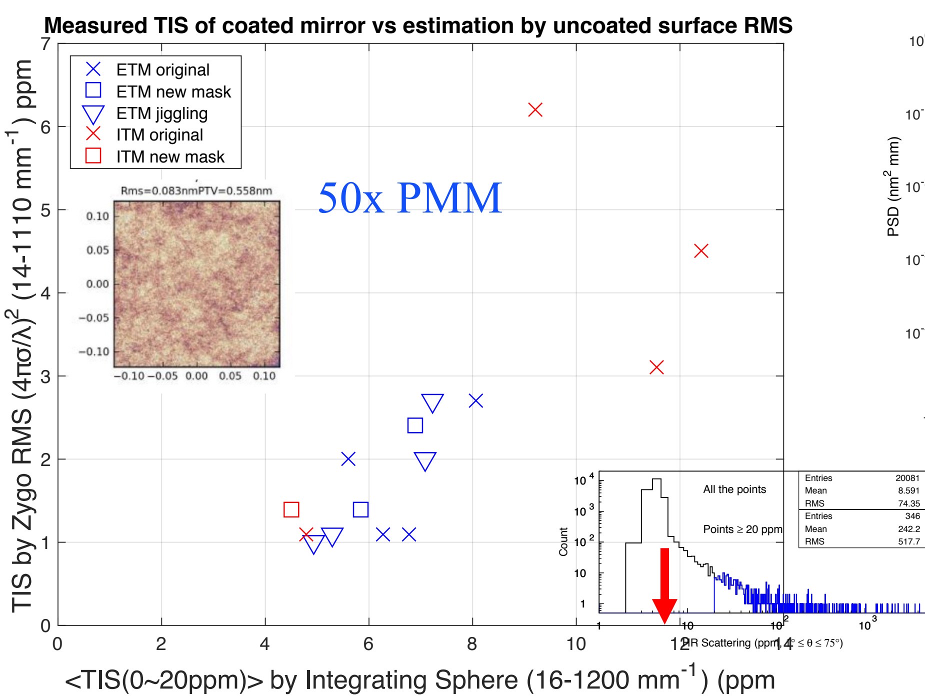


Roughness before and after coating

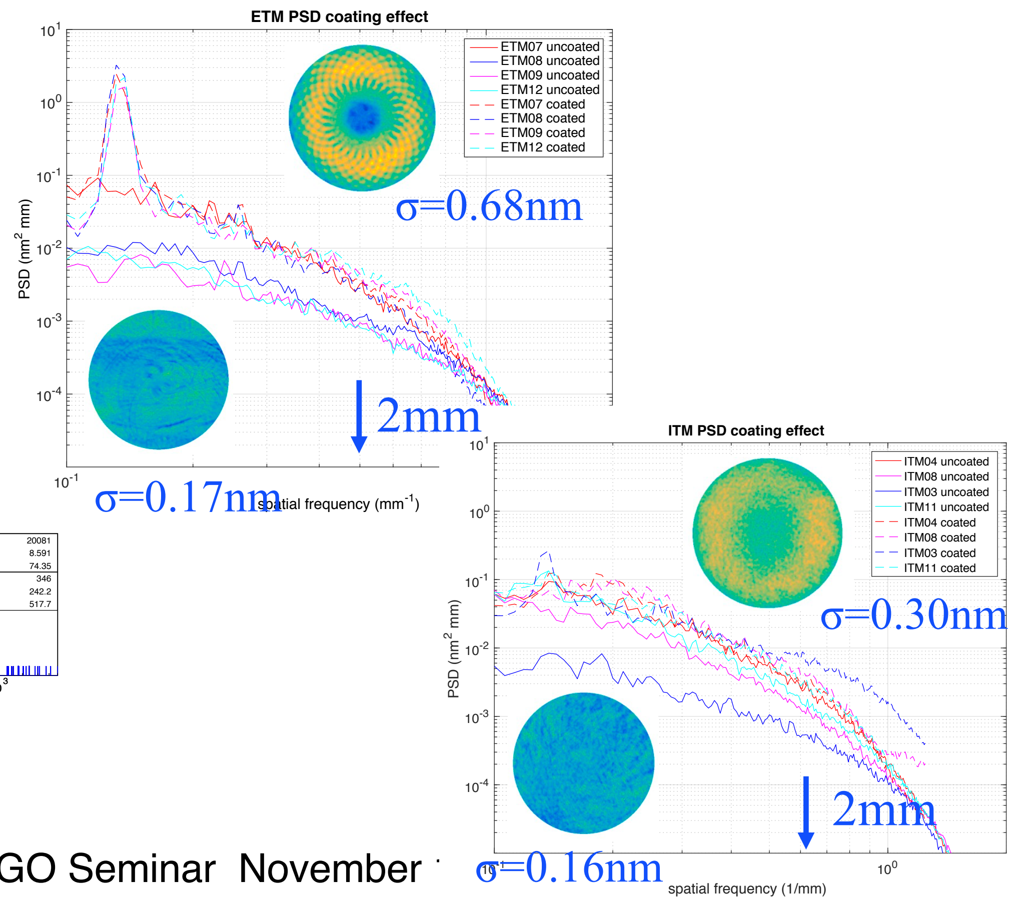
<TIS> data (w/ coating) vs Zygo rms (w/o coating) at λ_{space} = 70 ~1μm :
rms(w/ coat) ~ a few x rms(w/o)

PSDs with and without coating
λ_s > several mm : figured changed
λ_s ~ few mm : roughness amplified?

Unoated surface loss

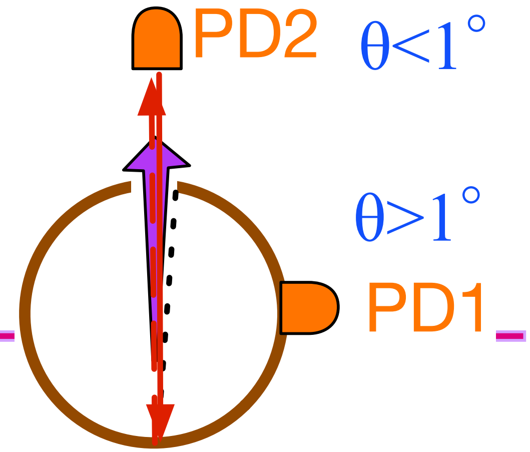


Coated surface loss

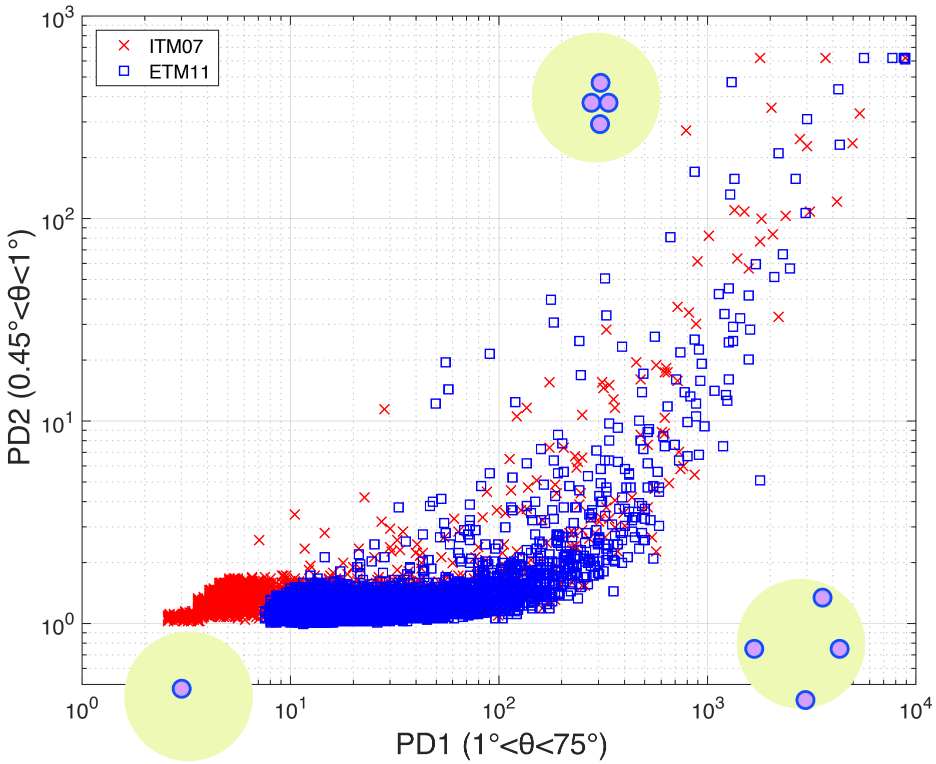


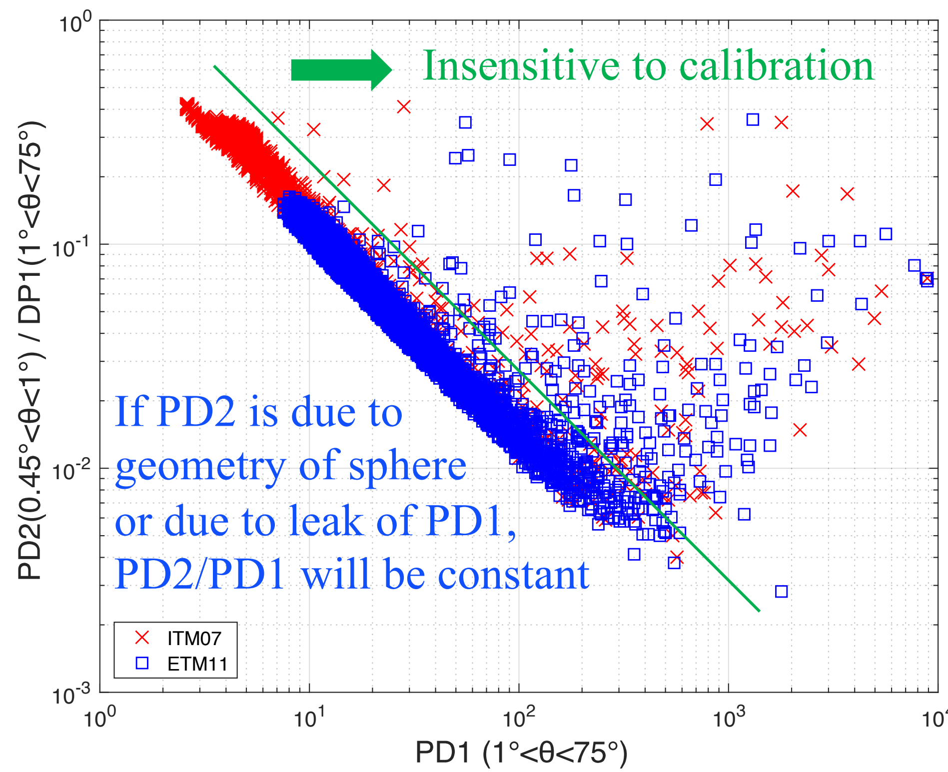
PD1 (1°<θ<75°) vs PD2 (0.45°<θ<1°)

very preliminary



larger PD2 ⇒ larger coherent scattering area (single or clustered)





larger PD1 ⇒ larger reflector area (100ppm PD1→ > 2μm defect)

(Total reflection < laser power x reflector area)

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Summary

- Guestimation error ~ factor of several
- Missing information
  - » Roughness at spatial wavelength ~ 0.05-1mm
  - » Coated surface vs uncoated surface qualities
  - » Total loss by random point defects
- Measurements
  - » Upgrade of integrating sphere to cover smaller angle
  - » More measurements by Fizeau IFO with magnification
  - » Camera image analysis
  - » ???