aLIGO test masses, revisited

- Scattering and loss by test mass
  - Discrepancy between the measured arm loss, 50ppm/mirror, and the loss based on optics data, 25ppm/mirror
  - Understand about the defects in coating
  - Integrating sphere measurement with extension (Liyuan Zhang)
    - Preliminary and proof of concept, but very interesting
    - Small angle ($\theta \leq 1^\circ$) and large angle ($\theta \geq 1^\circ$) scattering
      - Missing energy in the small angle scattering
      - Defect size/distribution information
- Excess PSD at $\lambda_{spatial} < 3mm$ (system meeting)
  - PSD of the coated mirror using the latest coating setup is larger than PSD using the original mask by more than 10 at λ_s=3mm~1/3mm
  - Effect on the aLIGO performance when ETM is replaced
    - Increase of arm loss and scattered light which hits beam tube baffles
    - PRG and scattering noise

Reflection and propagation of field

$$E[x,y,z] = \frac{i}{\lambda}\iint du\, dv\, E[u,v,w]\,\boxed{\frac{\mathrm{Exp}[-i\,k\,\rho]}{\rho}}\,\mathrm{Cos}[\theta]$$

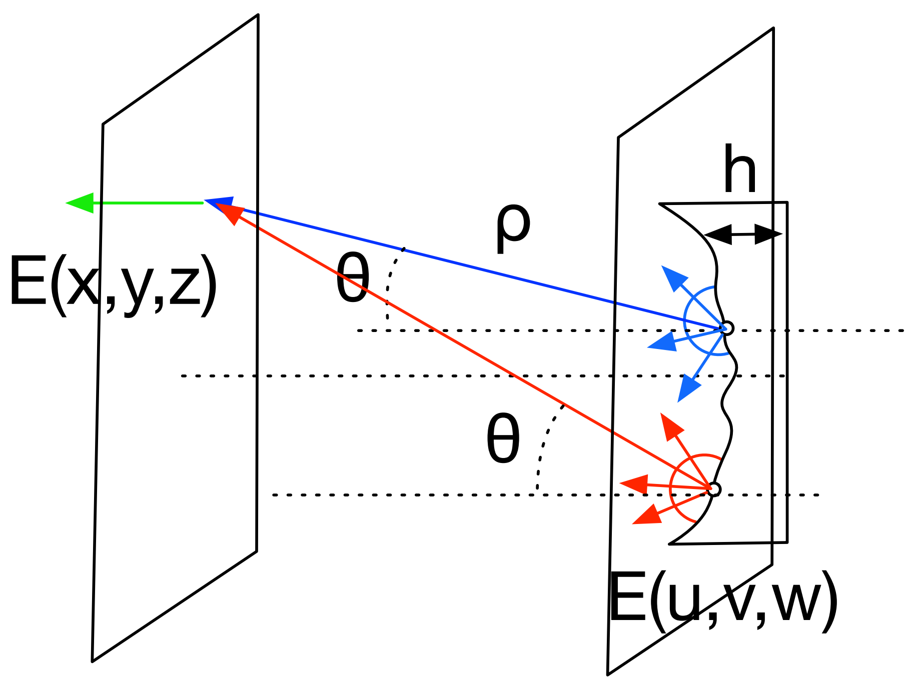
Spherical wave from source point

$$E[u,v,w] = (1 + A[u,v,\ \ldots])\ \mathrm{TEM}_{00}[u,v,w]$$

$$A = \mathrm{Exp}[i\,2\,k\,h] - 1 \simeq i\,2\,k\,h;$$

$$\iint |A|^2\, du\, dv = \left(\frac{4\pi}{\lambda}\right)^2 \iint |h|^2\, du\, dv = S\left(\frac{4\pi\sigma}{\lambda}\right)^2$$

far field near field



* total power of far field = total power of near field

* power distribution of far field = interference of near fields from various source points

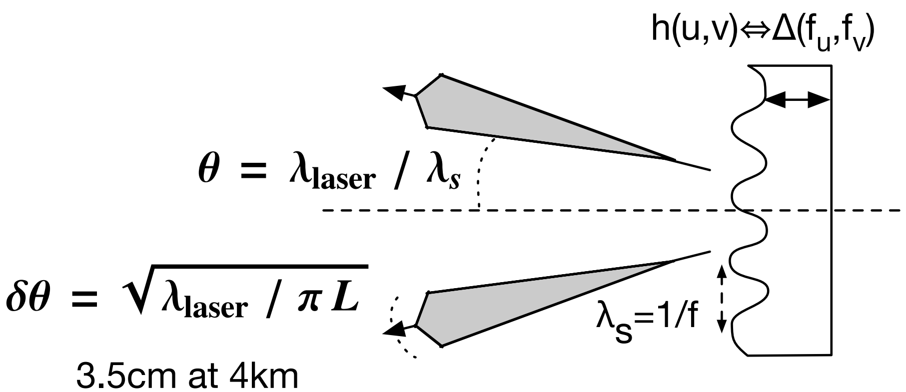
Far field and mirror ASD

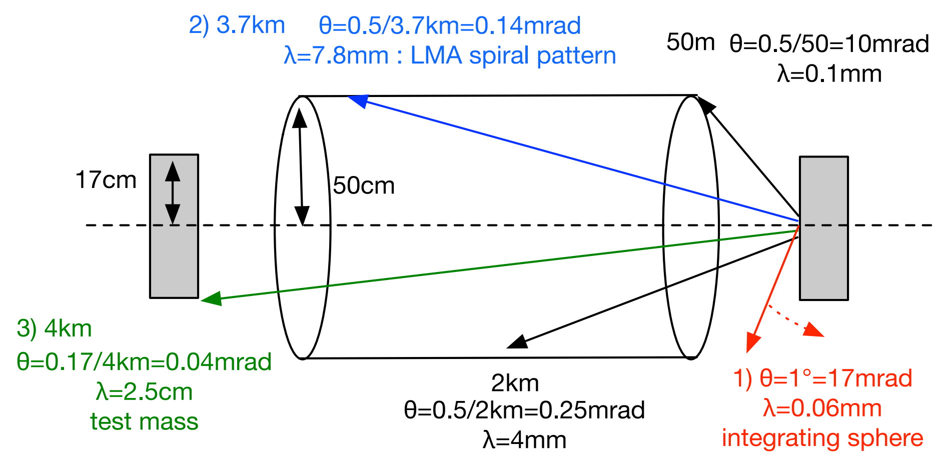
wide smooth surface characterized by ASD

$$\mathrm{dF}(x, y, z) = \sqrt{\frac{2}{\pi}}\ \frac{(-2\,k)}{\lambda\,L\,w(\mathrm{z1})}\ e^{-\frac{i\,k\left(x^2+y^2\right)}{2\,L} - i\,k\,L} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \Delta(f_u, f_v)\,\delta\!\left(f_u - \frac{\theta_x}{\lambda}, a\right)\delta\!\left(f_v - \frac{\theta_y}{\lambda}, a\right) d f_u\, d f_v;$$

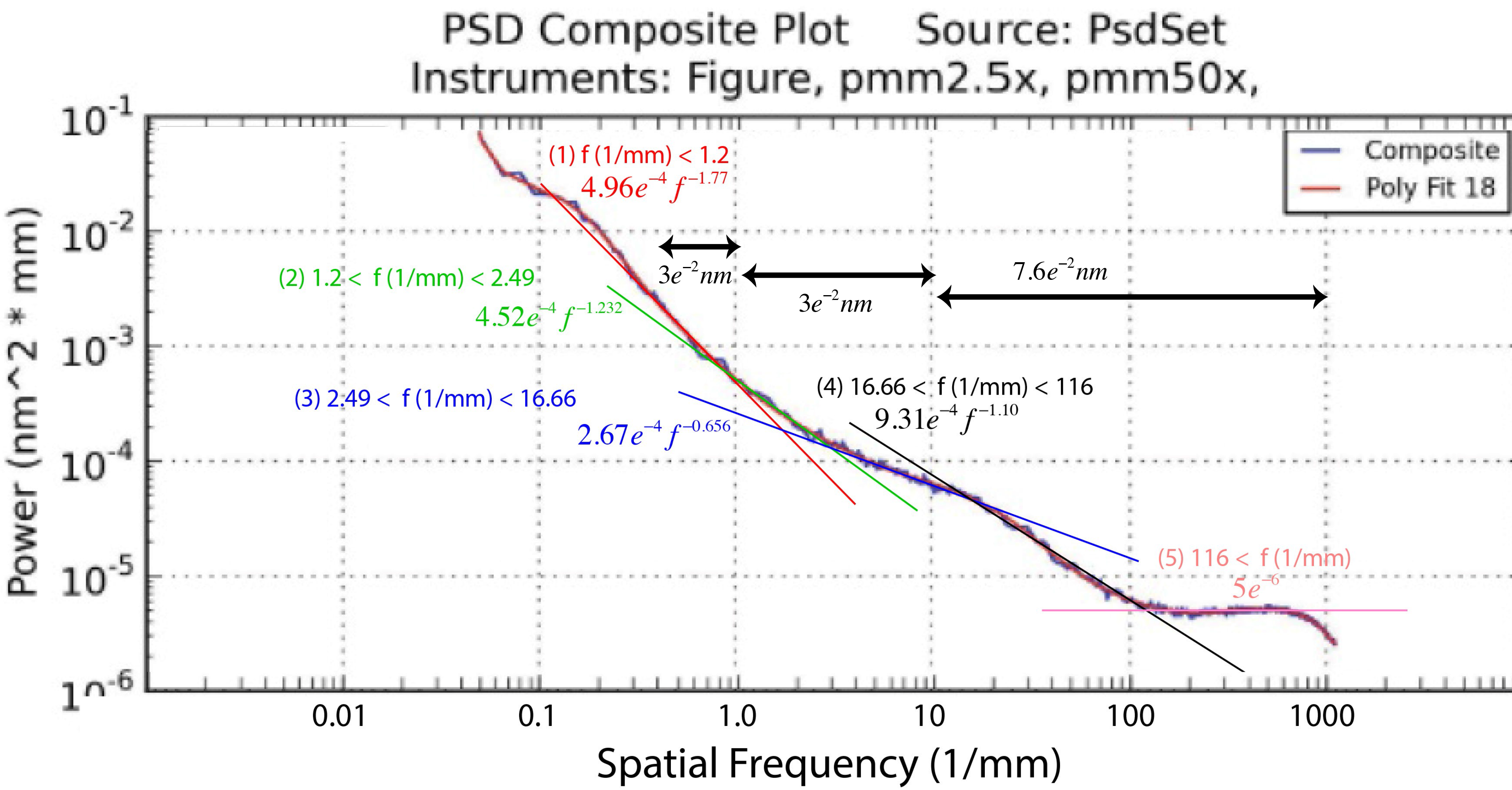
ASD: $$h[u, v] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \Delta[f_u, f_v]\, e^{-i\,2\,\pi\,(u\,f_u + v\,f_v)}\, d f_u\, d f_v;\quad \mathrm{Exp}[i\,2\,k\,h] \simeq 1 + i\,2\,k\,h;\quad A = i\,2\,k\,h;$$

$\lambda_S \rightarrow \theta_{\text{far field}}$: $$\theta_x = \frac{x}{L};\quad a = \sqrt{i\,\frac{1}{\pi\,\lambda\,L}\,\frac{\mathrm{w2}}{\mathrm{w1}}\,\exp(-(\eta(\mathrm{z2}) - \eta(\mathrm{z1})))};\quad \delta\!\left(f_u - \frac{\theta}{\lambda}, a\right) = \frac{\exp\left(-\frac{\left(f_u - \frac{\theta}{\lambda}\right)^2}{a^2}\right)}{\sqrt{\pi}\,a};\quad \int_{-\infty}^{\infty} \delta(f, a)\, d f = 1;$$





Uncoated surface PSD
not simple, pretty complex



Far field and small size defects

small defects cannot be characterized by PSD

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

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

small

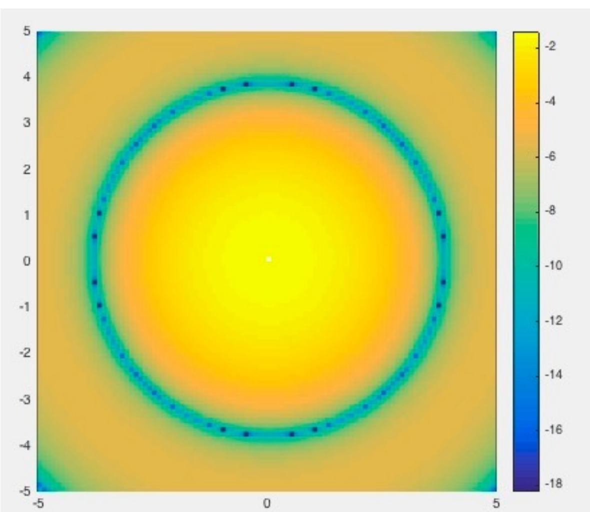
circle with radius a

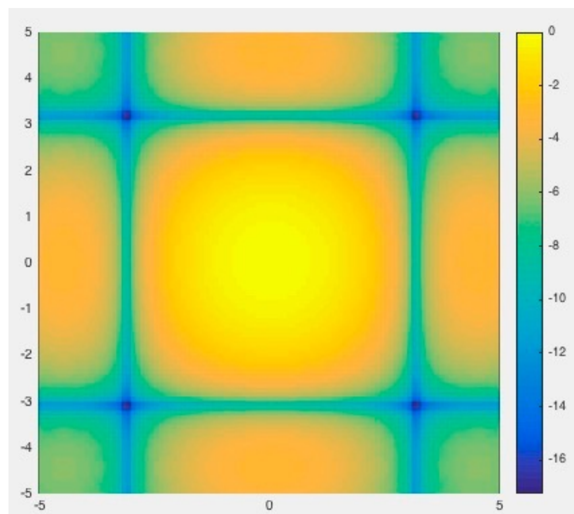
$$P(\theta) \sim \left(\frac{J_1(k\, a\, \theta)}{k\, a\, \theta}\right)^2;$$

rectangle size of du x dv

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

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



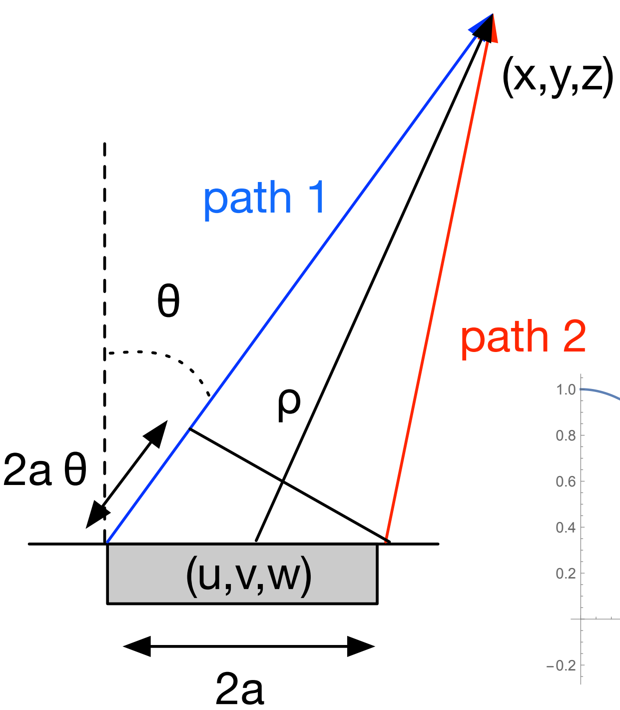


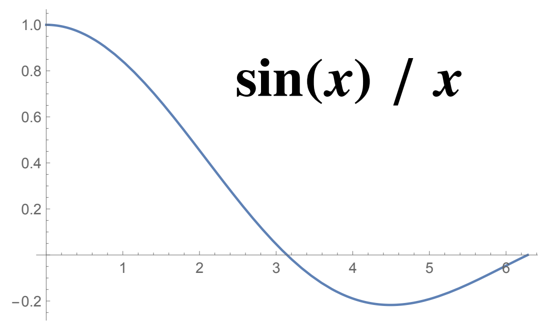
k a θ =1 when
a = 1μm, θ=10°
or
a=10μm, θ=1°

Defect size looks different seen at different angle

interference and angle dependence of far field

Small defect



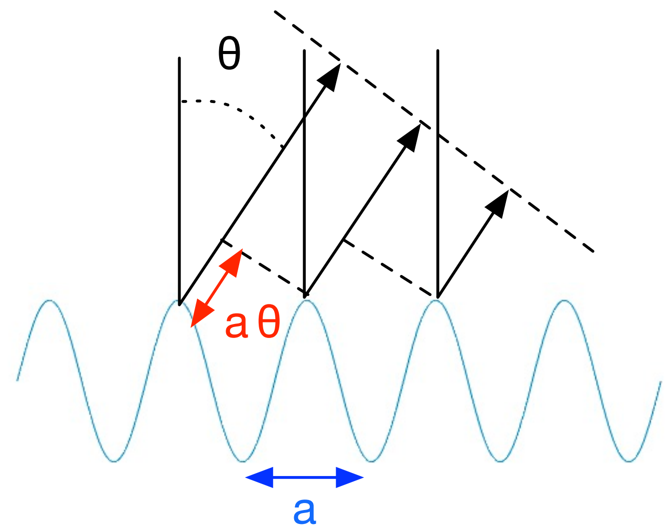


$\sin(x)\ /\ x$

$$\text{Exp}[-i\,k\,\rho] = \text{Exp}[\,i\,k\,(x\,u + y\,v)\,/\,L\,] = \text{Exp}[i\,k\,(\theta_x\,u + \theta_y\,v)];$$

$$\int_{-a}^{a} \text{Exp}[i\,k\,\theta_x\,u]\,du = 2\,a\,\frac{\text{Sin}[\,k\,\theta_x\,a]}{k\,\theta_x\,a}$$

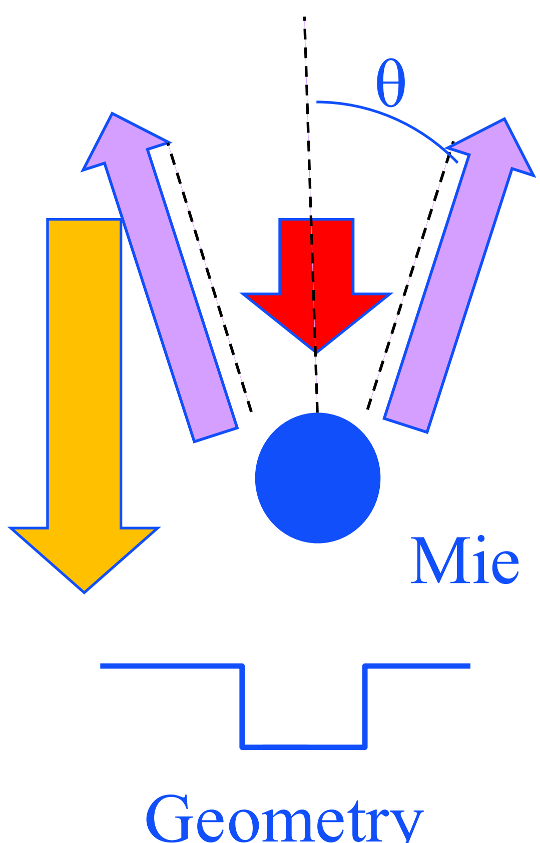
Periodic defect

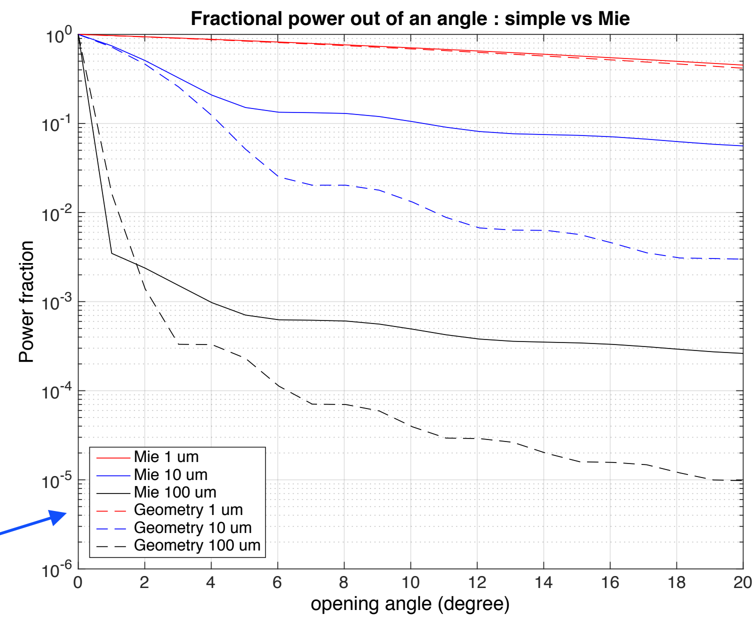


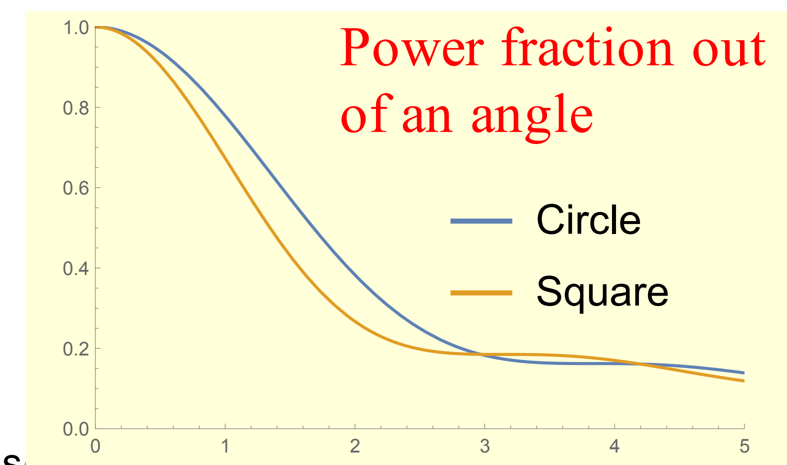
$$a\,\theta = \lambda$$

Power distribution depends on the defect size

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

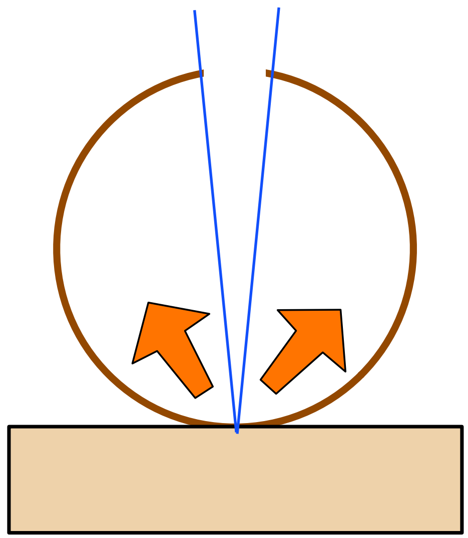


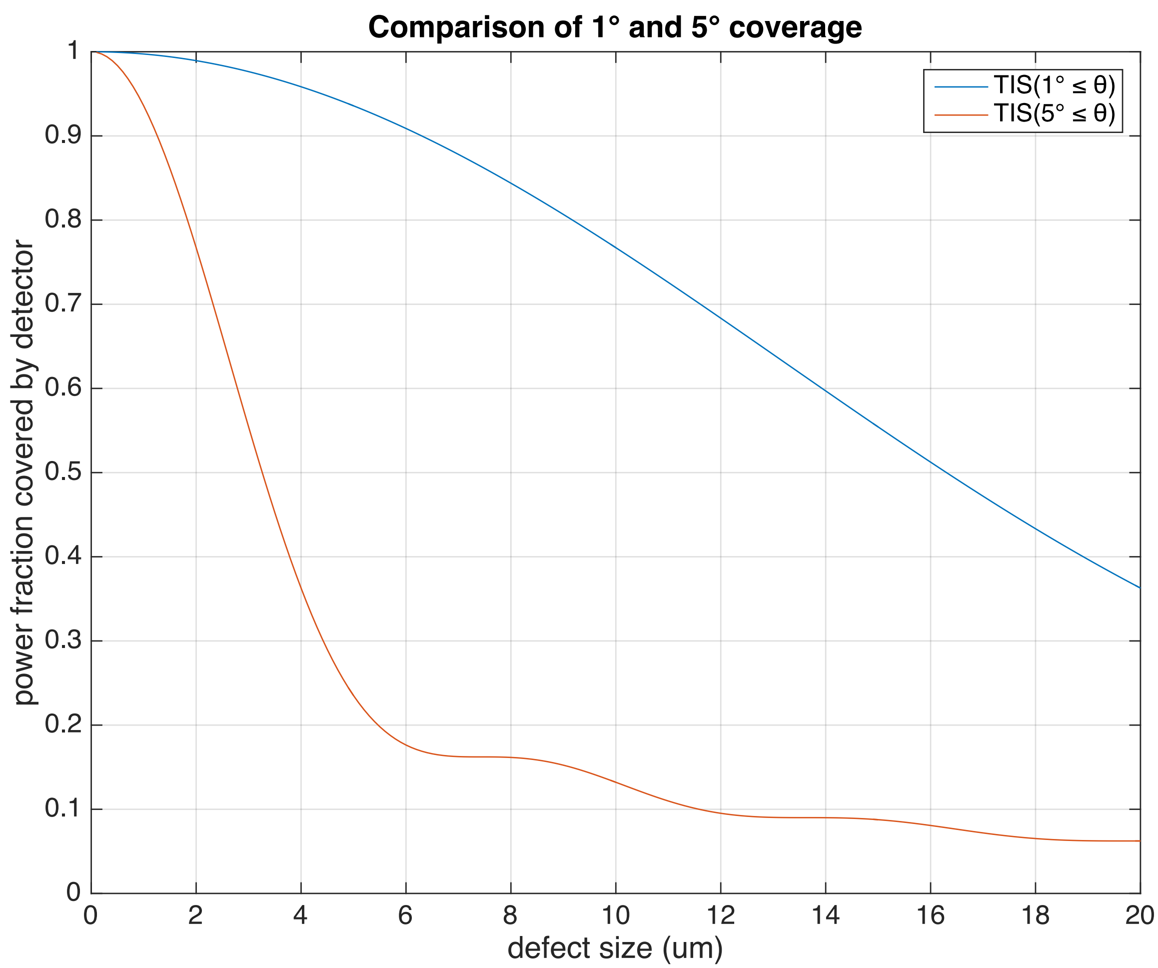




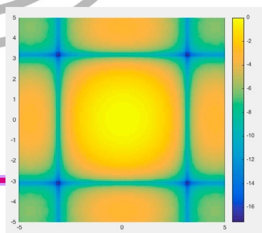
axis : k a θ = 0.1 a(μm) θ(degree)

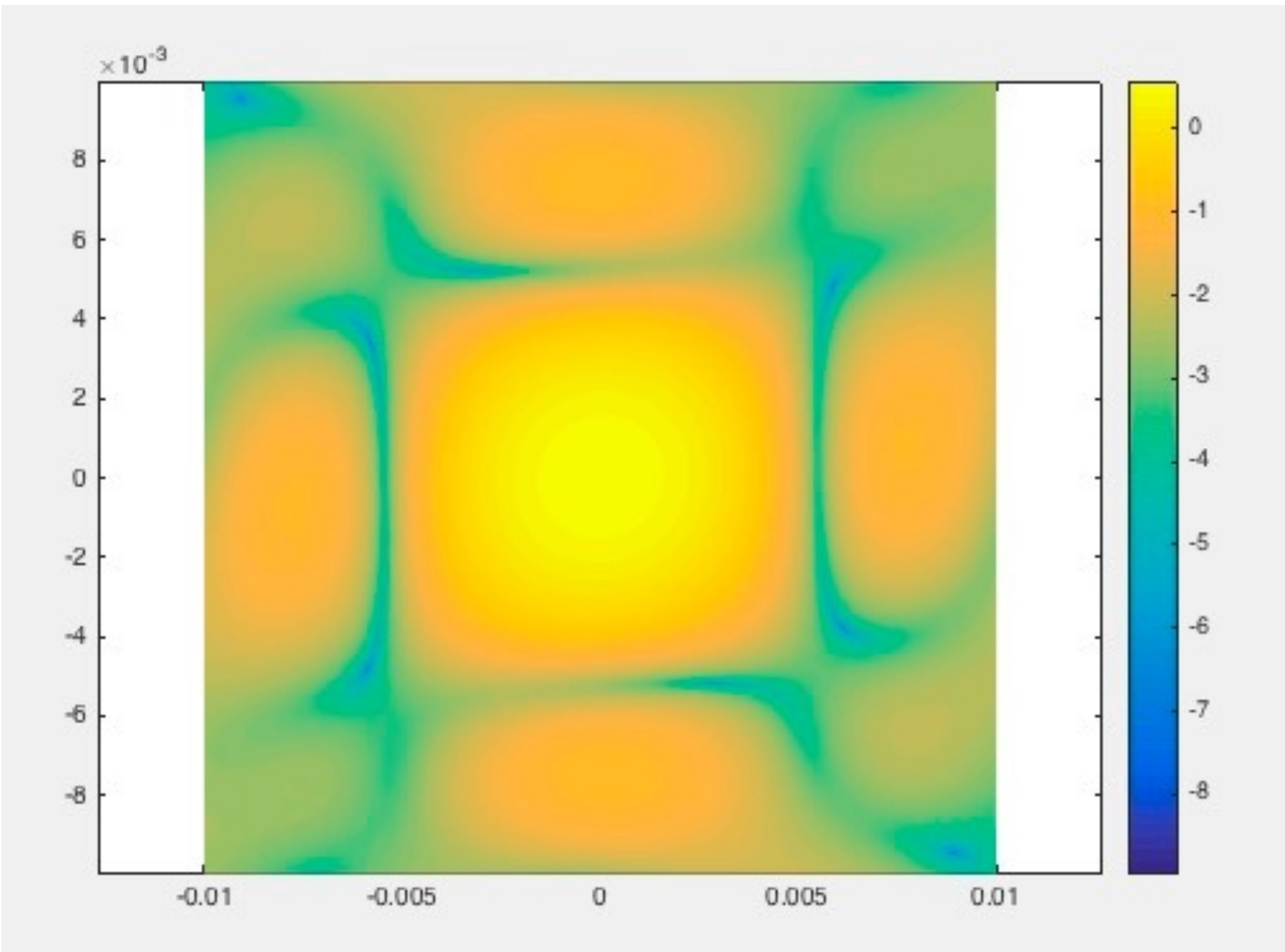
Comparison of 1° vs 5° dead region



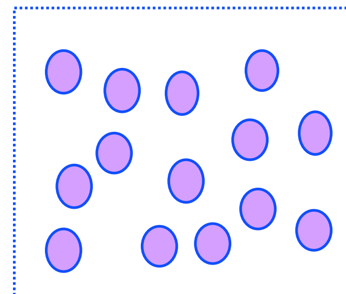


Clustered defects behave like a single defect





Power distribution generated by small defects in a square



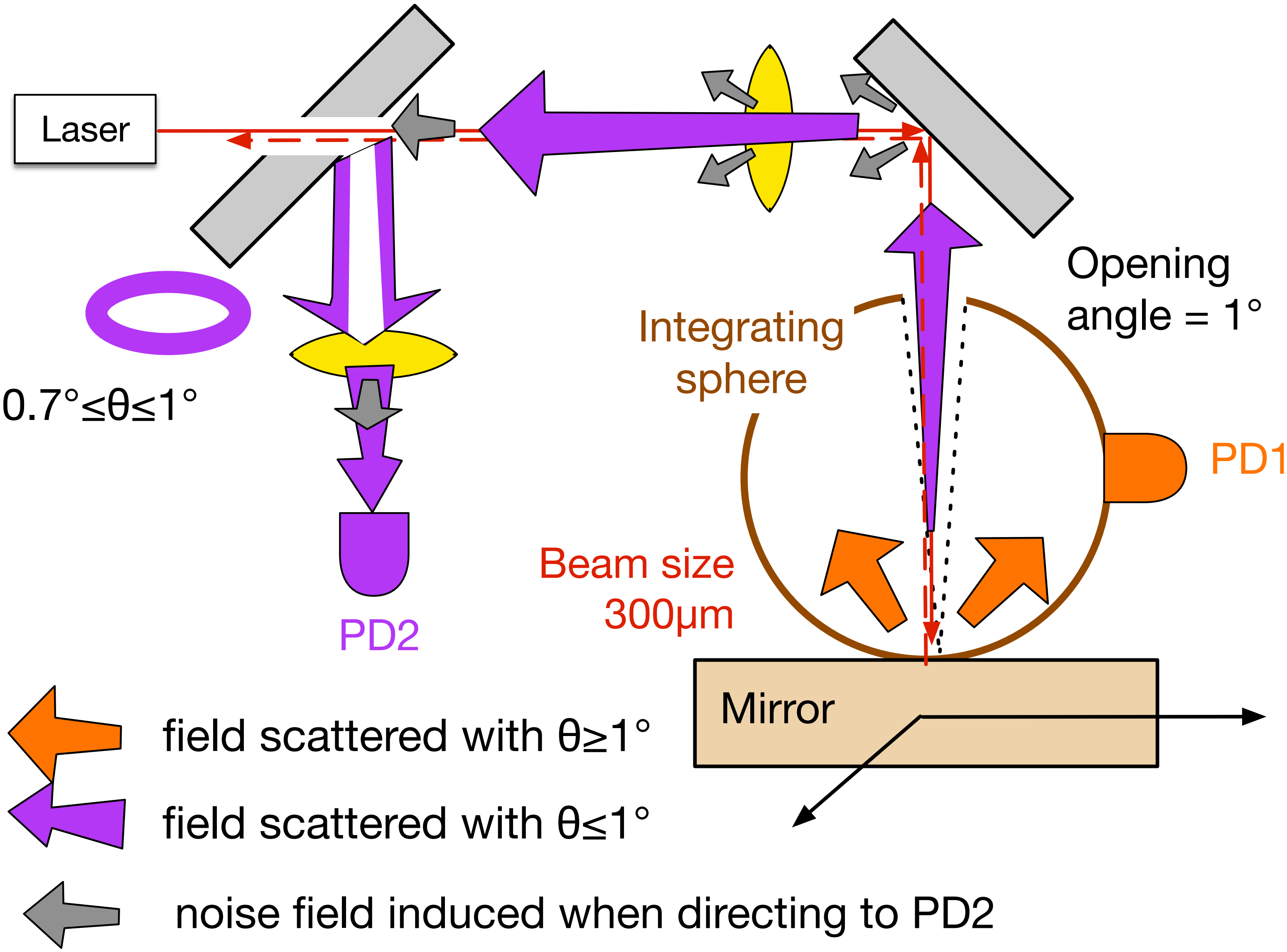
Same distribution generated by

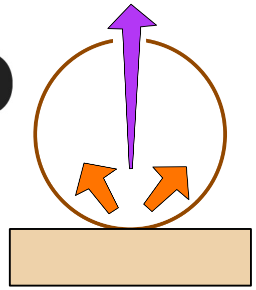
TIS measurement in small angle using integrating sphere

by Liyuan Zhang

- Scattering loss of mirrors
  - Total loss in the arm cavity vs mirror data
  - Understanding the defects in the coating
- Integrating sphere covering $\theta \geq 1^\circ$ predicts scattering loss / mirror ~ 10ppm
  - Solid angle of the hole in $\theta \leq 1^\circ$ is $(\pi/180)^2 = 3 \times 10^{-4}$, so correction should be negligible.
- If there are defects with size > 1μ, this may cause something unexpected
- Integrating sphere + pickoff to measure TIS in the small angle region $\theta \leq 1^\circ$ in addition to large angle $\theta \geq 1^\circ$

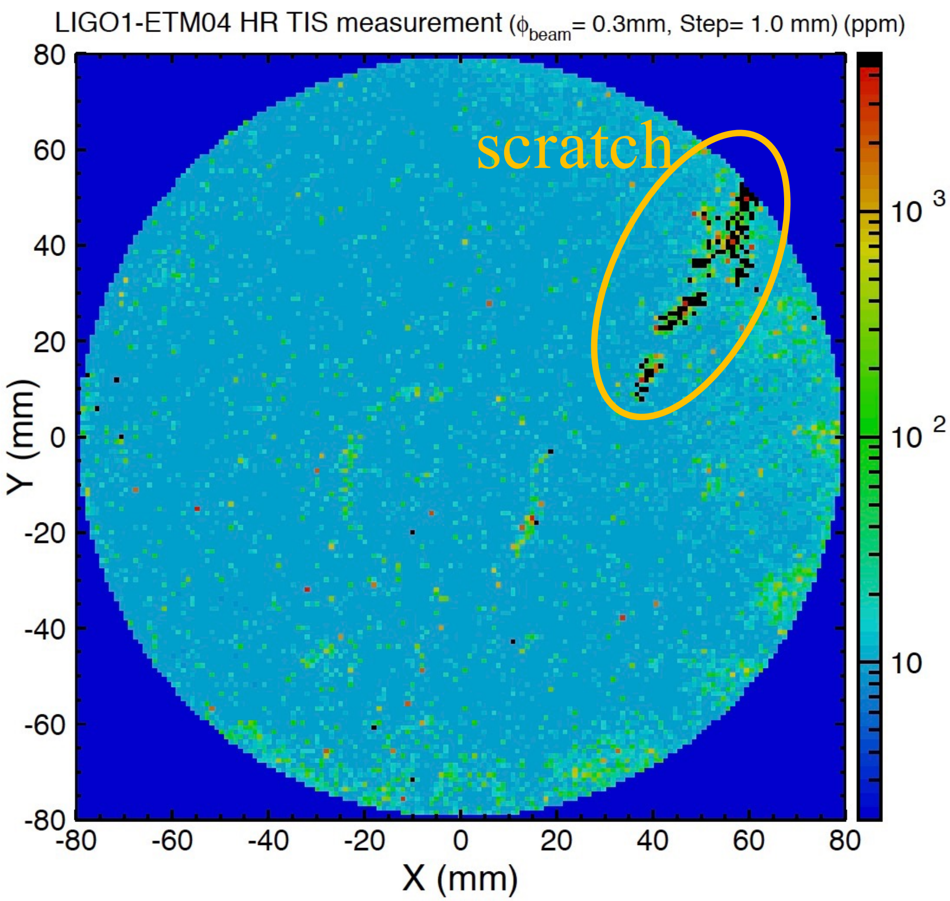
Setup for measuring TIS(θ≤1°) and TIS(θ≥1°)



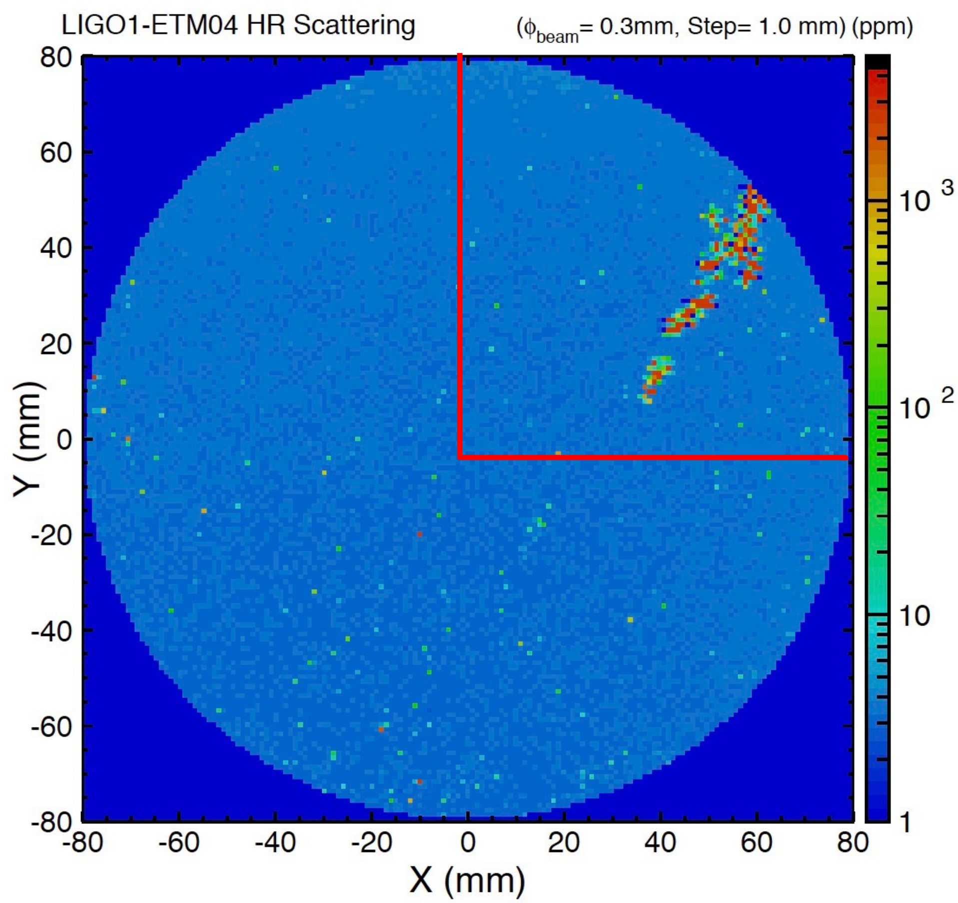


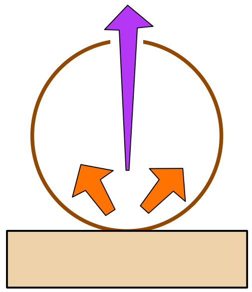
Very preliminary results
mirror : initial LIGO ETM04

TIS (θ≥1°)



TIS (0.7°≤ θ≤1°)

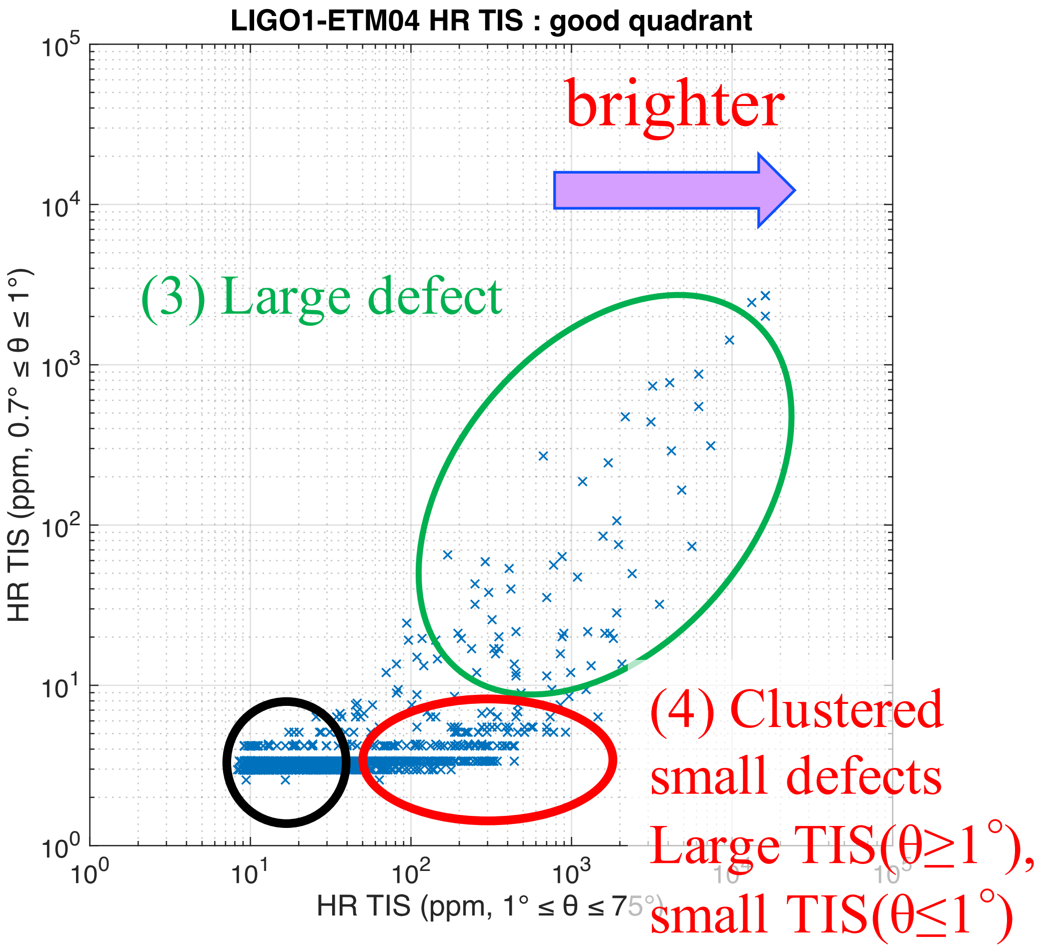




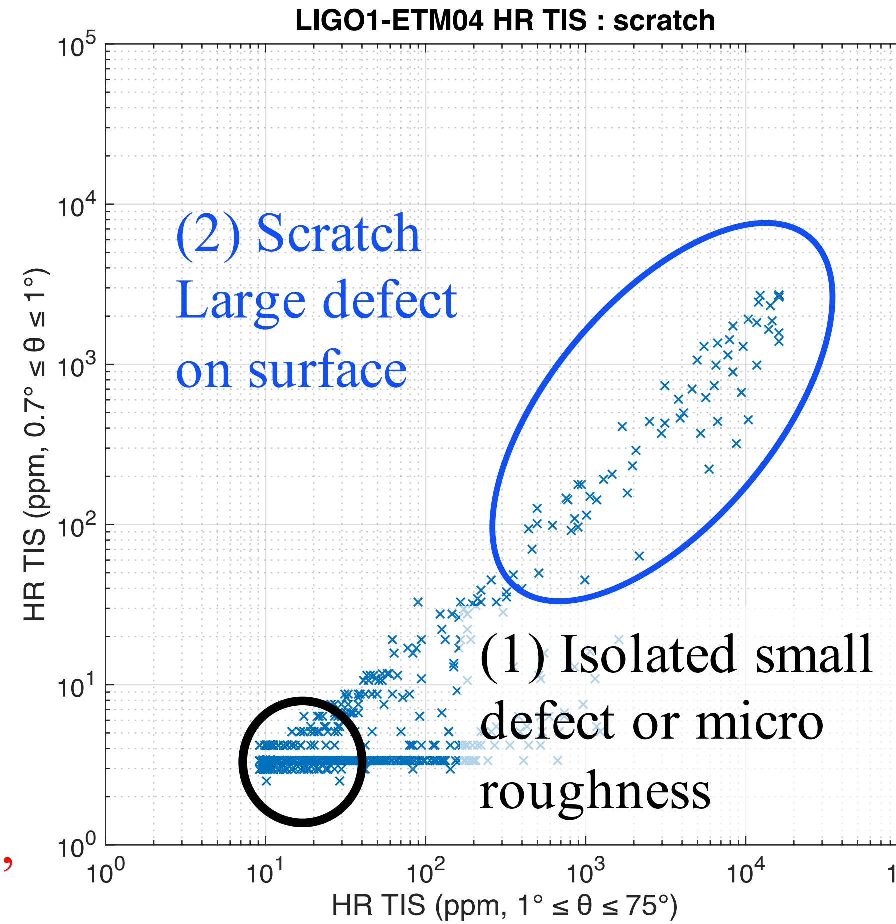
TIS(θ≤1°) vs TIS(θ≥1°)

very preliminary

Quadrants no scratch

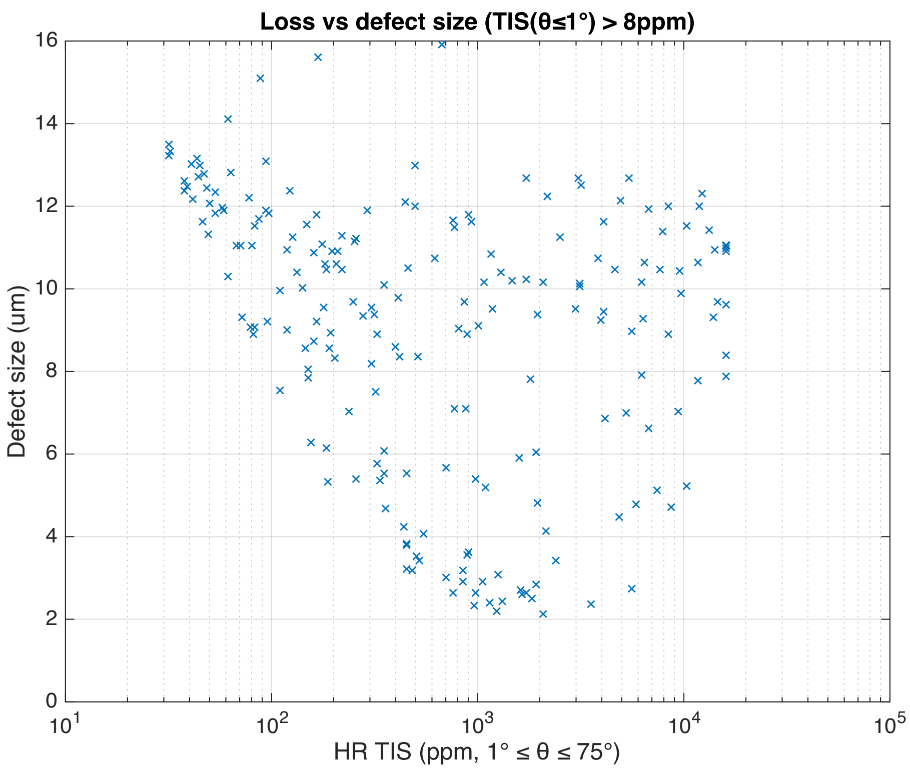


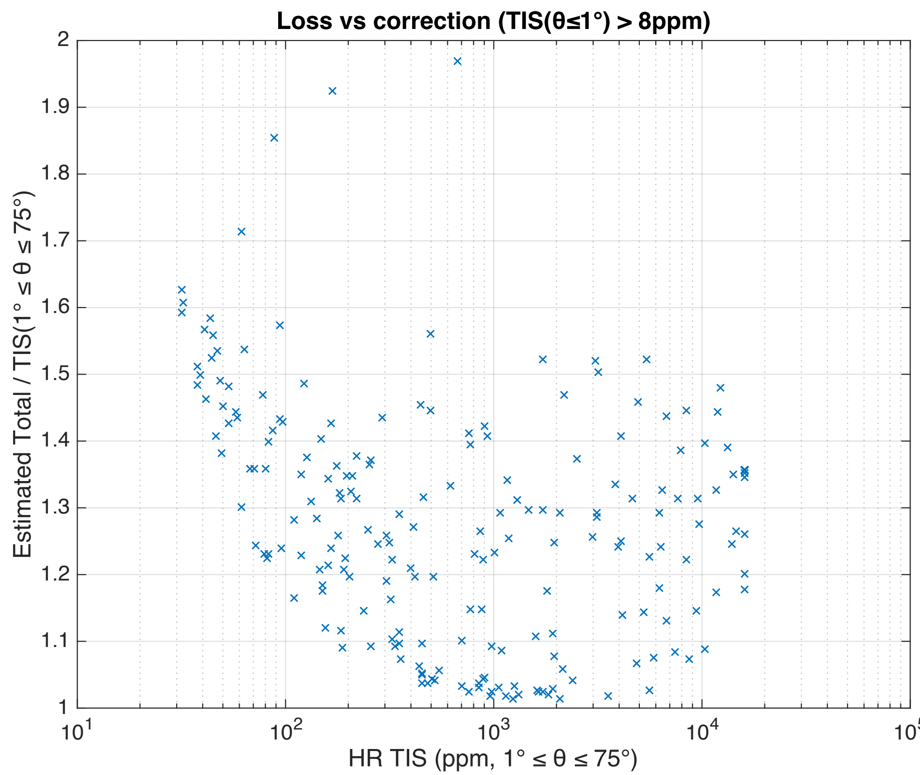
Quadrant with scratch



Defect size and total loss

assuming defect shape is circle

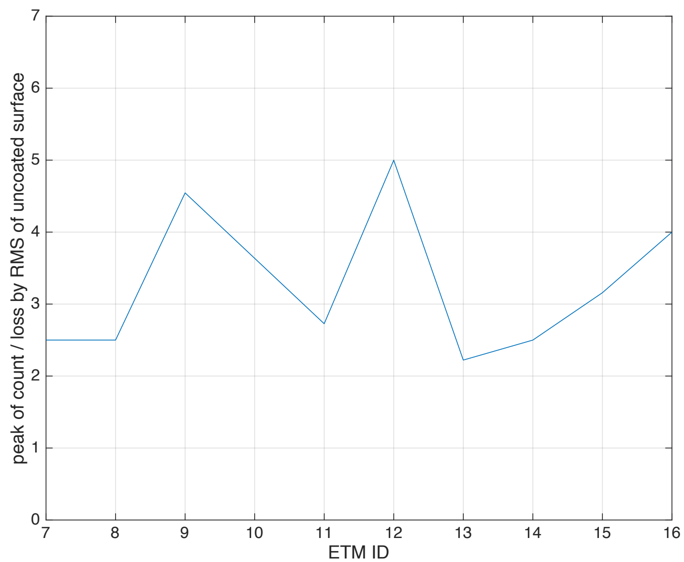




Defect size vs TIS(θ≥1°)   Total / TIS(θ≥1°) vs TIS(θ≥1°)

aLIGO ETM TIS(θ≥1˚)

low end of TIS(θ≥1˚) by continuous roughness

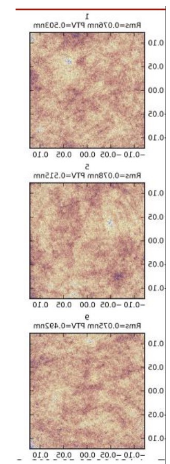


Ratio of teak of measured TIS and loss using uncoated surface RMS of 10 aLIGO ETMs

Majority of the scattered data are by continuous roughness

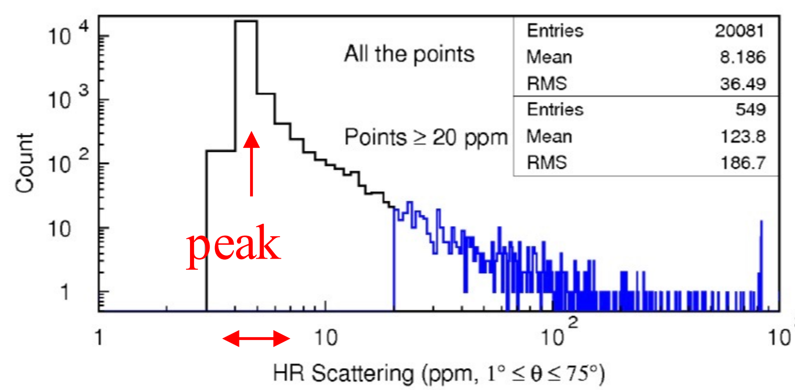
ETM16 case

Zygo 50x PMM
rms → loss



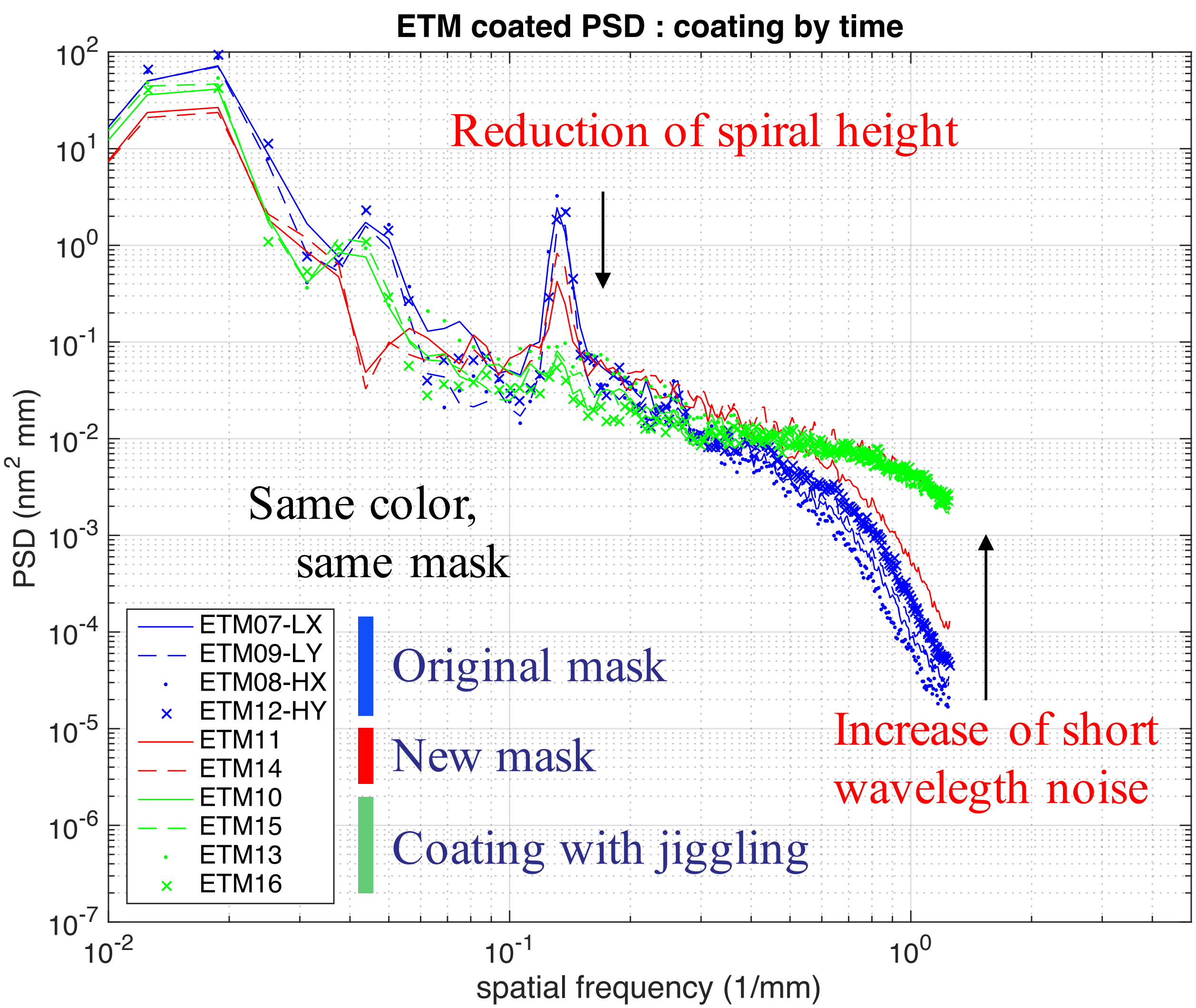
Location	RMS (nm)
1	0.079
2	0.086
3	0.077
4	0.081
5	0.081
6	0.115
7	0.079
8	0.094
9	0.077
Average	**0.085**

Integrating sphere counts

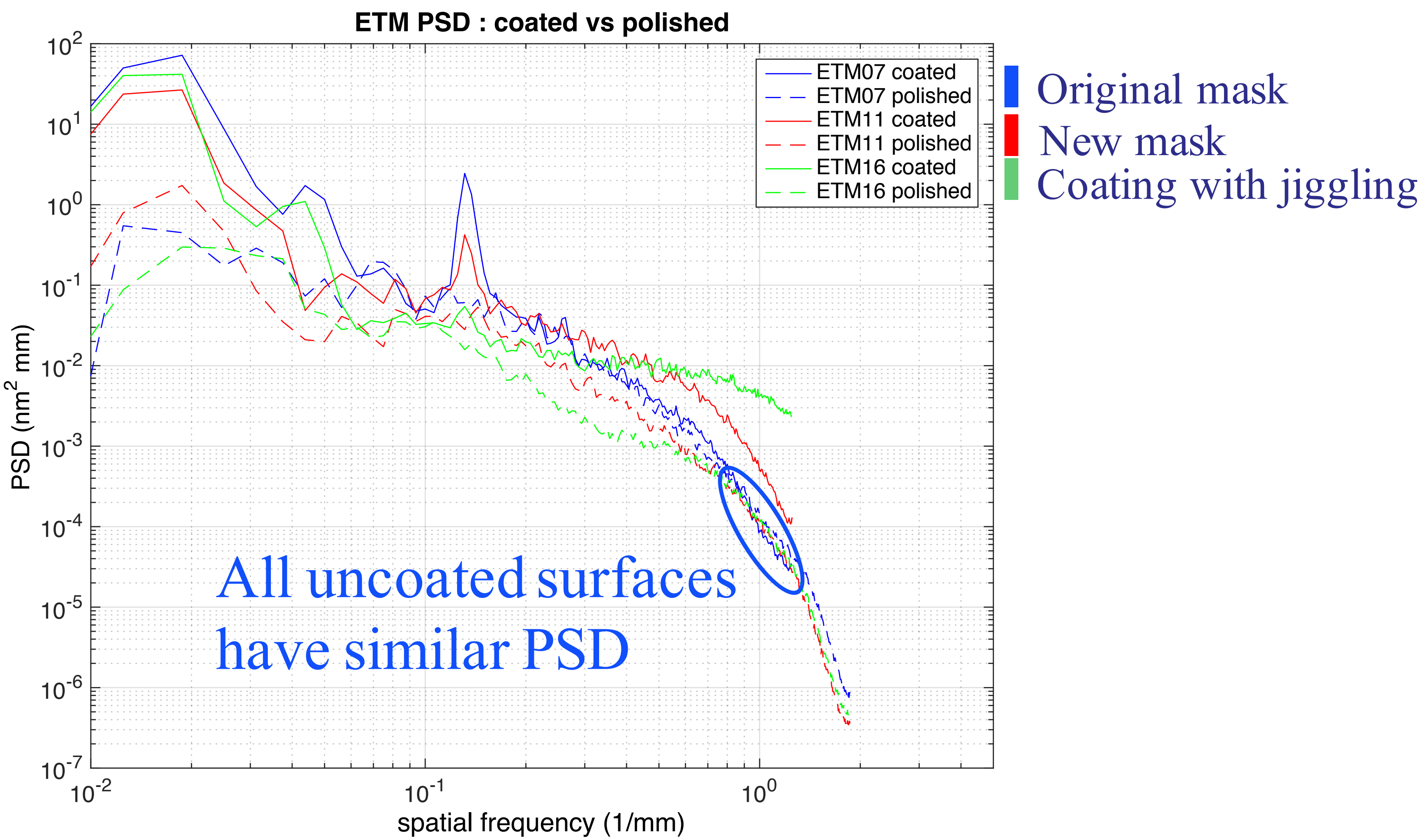


ETM PSDs with different coating

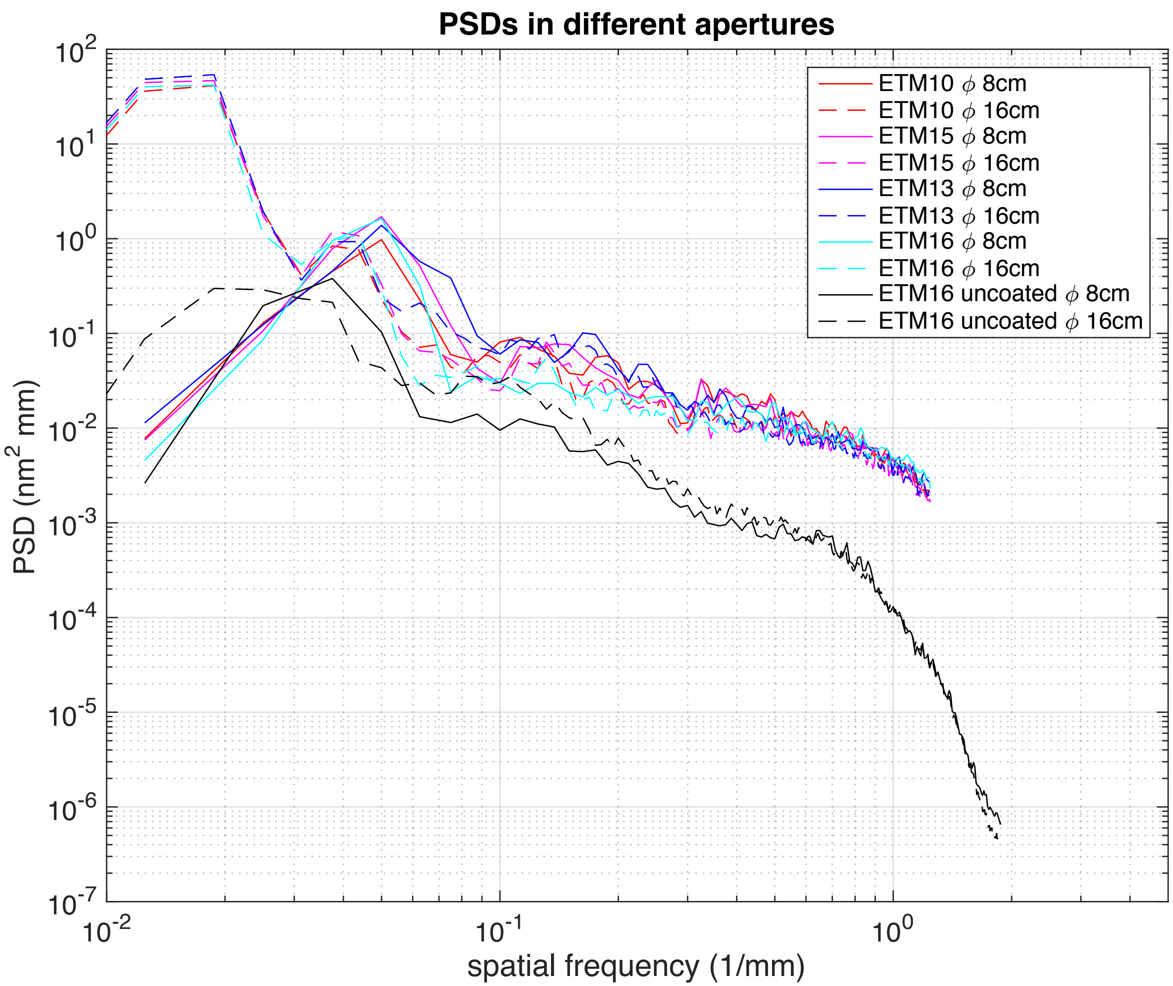
Does it cause any problems?



PSDs with and without coating



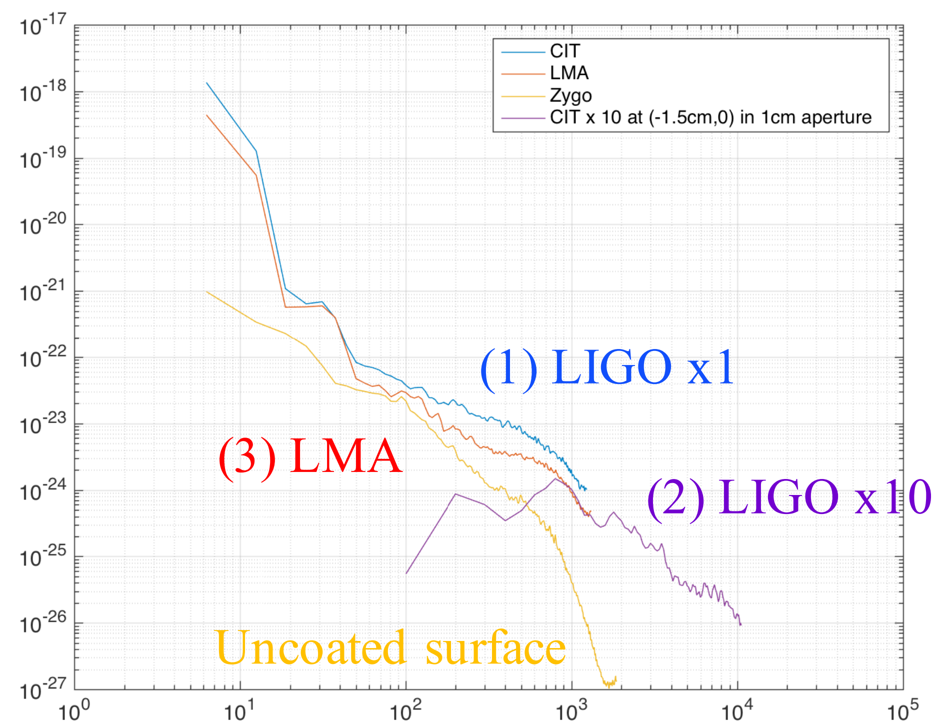
Same high PSD in the central region as well



PSD(coated)/PSD(uncoated) > 10: Is this increase real?

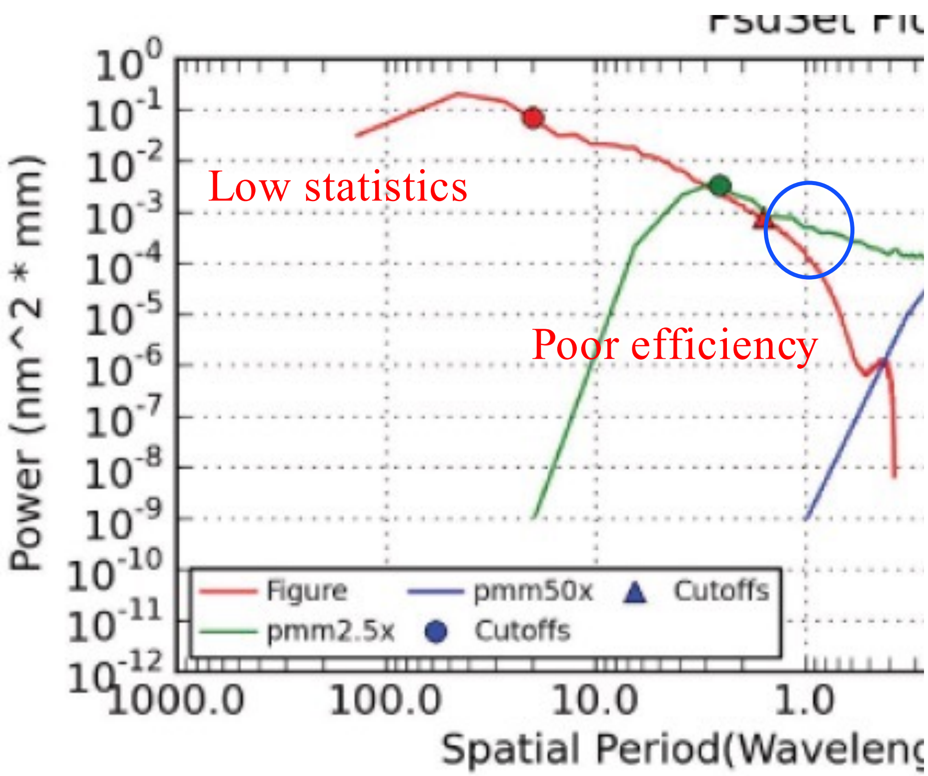
- Three independent measurements of phasemaps of the coated ETM16 are consistent
  - (1) Measured by LIGO Fizeau IFO without magnification
  - (2) Measured by LIGO Fizeau IFO with x10 magnification
  - (3) Measured by LMA Fizeau IFO without magnification

ETM16 PSDs

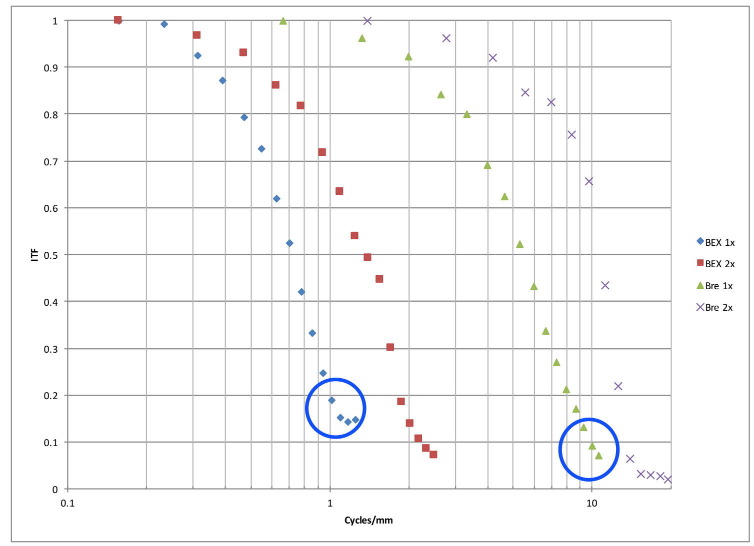


One complication we don't/can't handle/understand properly

Zygo PSDs by different devices



LIGO Fizeou IFO
Instrument transfer function

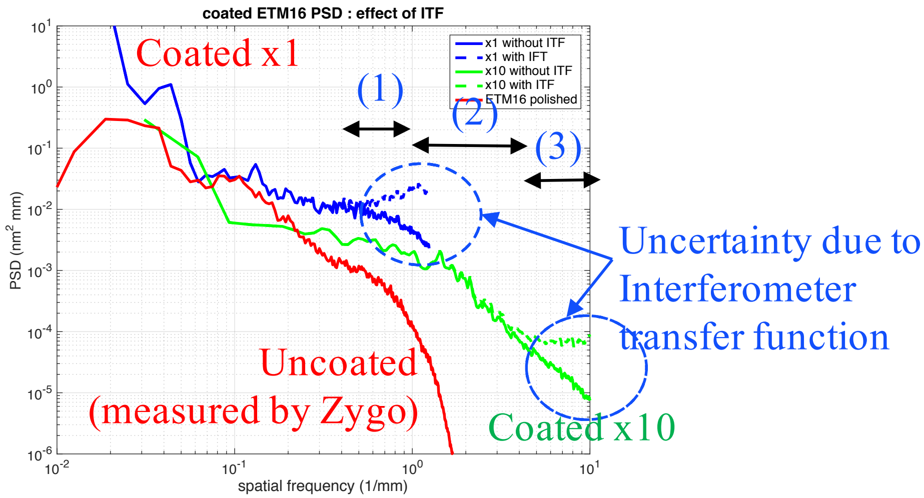


x1 @1mm 0.2

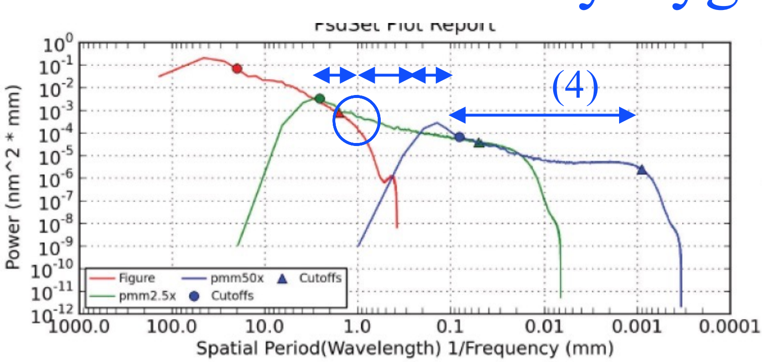
x10 @0.1mm 0.1

Change of rms and loss
loss=1.3~2ppm @ λ_s =3~1/3mm

Coated ETM16 PSD by LIGO

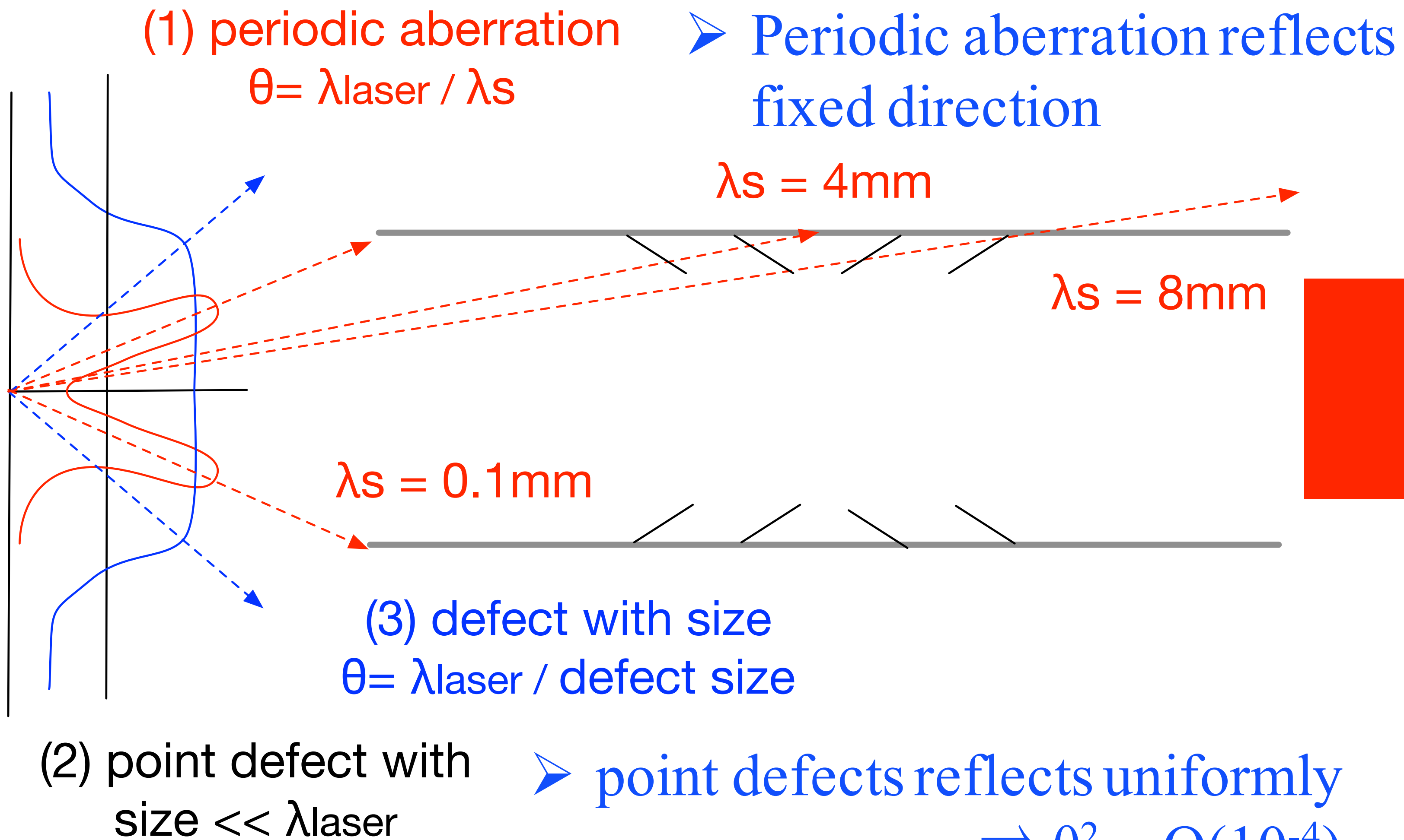


Uncoated ETM16 by Zygo



	Uncoated rms / loss	Coated rms / loss
(1) 3mm ~1mm	0.03nm 0.1ppm	0.08nm ~ 0.1nm 1.0ppm ~ 1.5ppm
(2)1mm ~0.3mm	0.02nm 0.06ppm	0.06nm ~ 0.07nm 0.50ppm ~ 0.75ppm
(3)0.3mm ~ 0.1mm	0.02nm 0.08ppm	same as uncoated -assumed
(4)0.1mm~ 1μm	0.076nm 0.83ppm	same as uncoated -assumed
Total loss λ_s < 3mm	1.1ppm	2.4ppm ~ 3.2ppm

Scattering by periodic aberration vs point defects

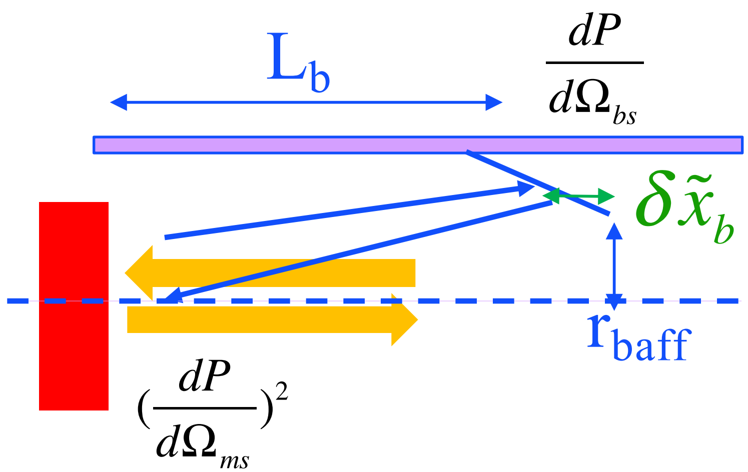


- Periodic aberration reflects to a fixed direction
- point defects reflects uniformly
  $\Rightarrow \theta^2 \sim O(10^{-4})$

Noise by sparial on ETM07 vs periodical aberration ~1mm on ETM16

$$\delta\tilde{x}_{TM}^2(f) = \frac{1}{2}\left(\frac{\lambda}{L_b}\right)^2 \left(\frac{dP}{d\Omega_{ms}}\right)^2 d\Omega_{ms} \frac{dP}{d\Omega_{bs}} \delta\tilde{x}_b^2(f)$$

$$= \frac{(4\pi)^3}{(\lambda \cdot r_{baff})^2} \int_{f_1}^{f_2} PSD(f_s)^2 f_s df_s \frac{dP}{d\Omega_{bs}} \delta\tilde{x}_b^2(f)$$



Scattering by mirror = 4.5ppm by spiral in a narrow region
= 1.5ppm by $\lambda_s \sim 3\sim1/3$mm in wide spread

Scattering by baffle $\frac{dP}{d\Omega_{bs}}$ = 0.02 for forward (spiral)
= 0.005 for backward ($\lambda_s < 4$mm)

$$\frac{\delta\tilde{x}_b(\lambda_s = 3 \sim 1/3mm)}{\delta\tilde{x}_b(spiral\ on\ ETM07)} = 0.02 \sim 0.04$$

Summary

- Extended Integrating Sphere measurement
  - » Preliminary result – proof of concept
  - » Comparison of large angle TIS ($\theta \geq 1^\circ$) and small angle TIS($\theta \leqq 1^\circ$) provides information about the defect size and uncovered scattering
  - » Measurement of aLIGO test masses coated by LMA using better setup and detector.
- Large PSD at short wavelength region
  - » Looks real, cause unknown
  - » PRG loss and back scattered noise by beam tube baffle, OK
  - » Any other issue by higher roughness in the short wavelength region which tends to scatter light to wider angle?