Imaged Scattered light from LIGO Resonant Cavities:

Micro-roughness vs Point Scatter Loss

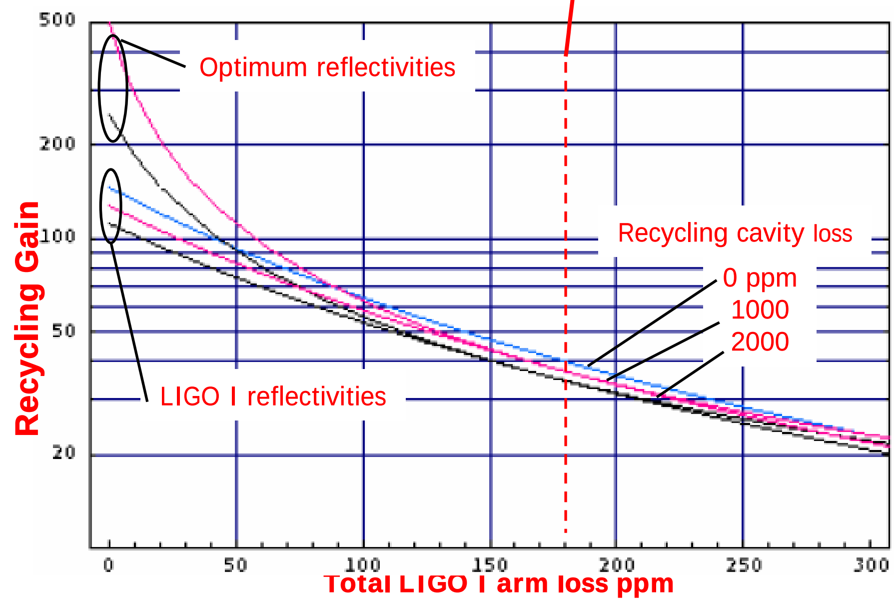
W. Kells
LIGO Laboratory, Caltech
C. Vorvick
LIGO Laboratory, Hanford

With acknowledgement of entire LIGO team for interferometer Optics development

Cavity Loss: Now → Future ?

- LIGO I cavities c. S5: net L_{RT} as much as 180 ppm (excludes $T_{coupler}$)
  - » Minor portion from absorption; finite mirror diffraction; R<1.

Strongly limits future recycling gains, or QND performance



- **Discrete cavity record: 2.7ppm**

  Rempe, Kimble, et al. Opt Lett **17,** 363 (*w*~30μm)

- **Disparity is scatter [Loss]**

Image of cavity beam TM foot print at non-specular Observation angle (coherent, 1064nm)

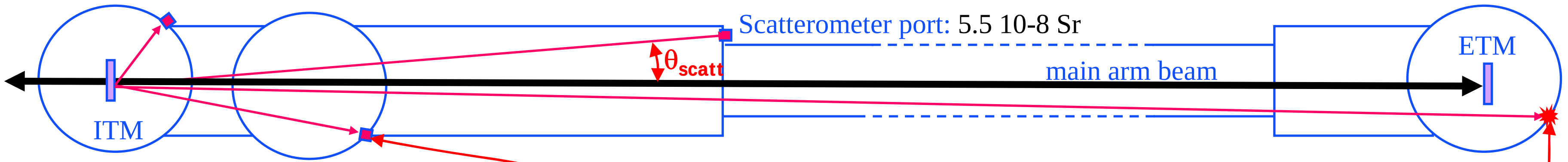
~ 10 cm (*w*= 4.5 cm)

Resonant arm, Gaussian illuminated ETM

Scatterometer studies

- Direct observation of the excess scatter (full operating interferom.)
  - Whence the 40-60ppm avg. additional loss per TM?

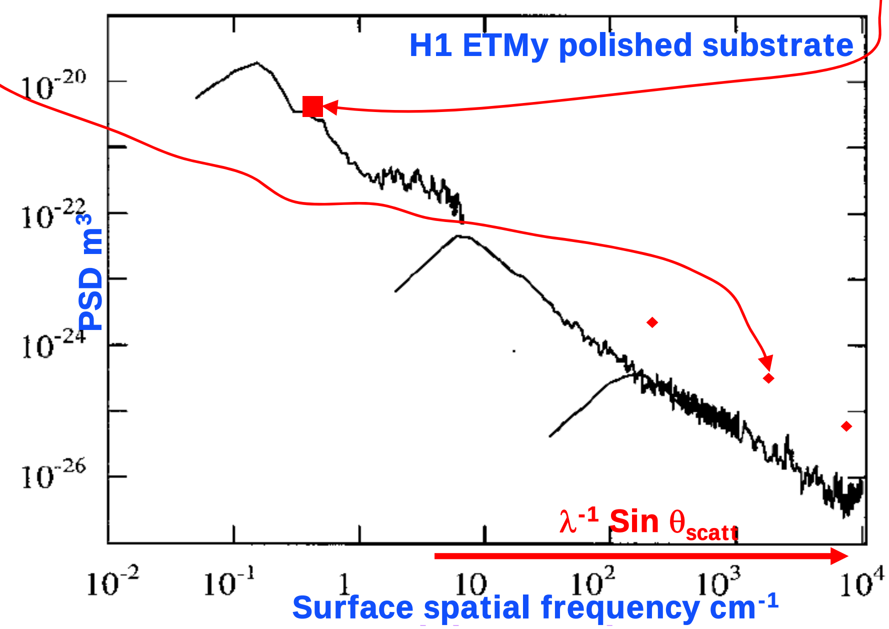
- In situ studies: Some HR surfaces viewable @ 3 angles:



- Angular dependence more isotropic, "point like" than metrology prediction
- Extrapolating to all angles consistent with net ~70 ppm/mirror loss

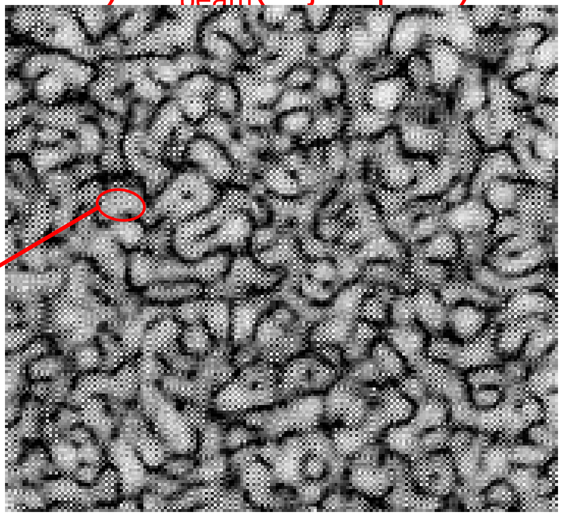
- ~same level, character for every TM independent of history/cleaning.

  Is "dust" contamination ruled out ?



HR surface beam spot imaging

- What do we expect imaged scatter to look like?
  - » Gaussian micro-roughness contribution: similar to coherent light "speckle"
    - – "standard" speckle theory: random (<Airy resolution), rough($\int PSD > \lambda^2$) surface.
    - – Strictly non-specular (Rayleigh << observation angle)
    - – Mean speckle pattern intensity $\propto$ PSD(θ, observation) x I_{beam}(object point)
    - – Detailed intensity pattern not invariant with respect to θ(observation)
    - – "Size" (correlation) scale of speckles ~ Airy resolution length of imaging optics



    - – Distribution of image intensities, $\boldsymbol{P}(I) \sim \exp(-I / I_{Mean})$: I=0 most likely
  - » Discrete point (defect) contribution: Same ~Mie scatter point location, all views

LIGO

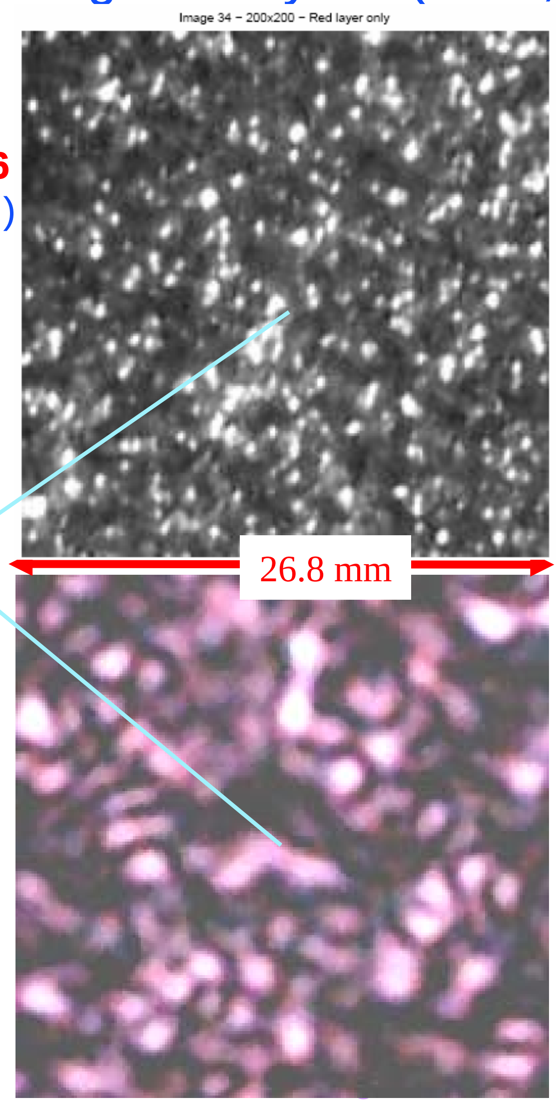
Image analysis of 4k ETMx, 7/04

Hi quality SLR CCD images analyzed (RAW, uncompressed pixel data)

f/5.6
(Airy resolution length ~ 0.4mm)

View point: ~9º from normal
5.8 m from HR surface

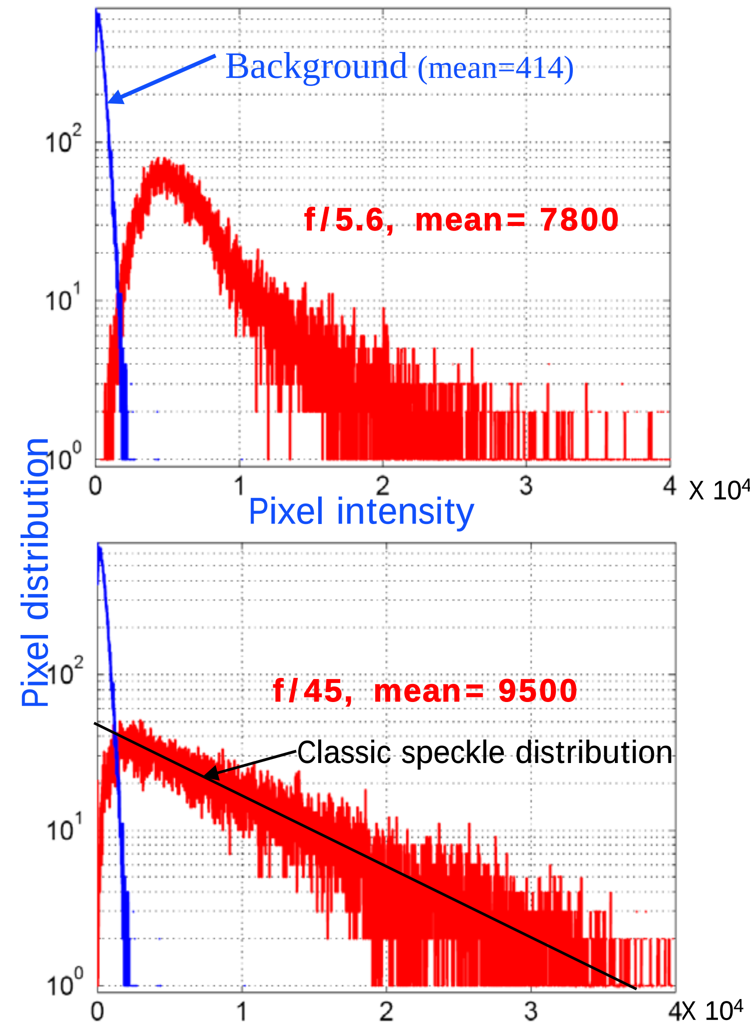
Beam center



f/45

Expect:
(mean $I_{speckle}$)/($I_{Defect\ Pts}$) = $(f/\#)^2$

Thus “defect points” disappear
Into speckle background

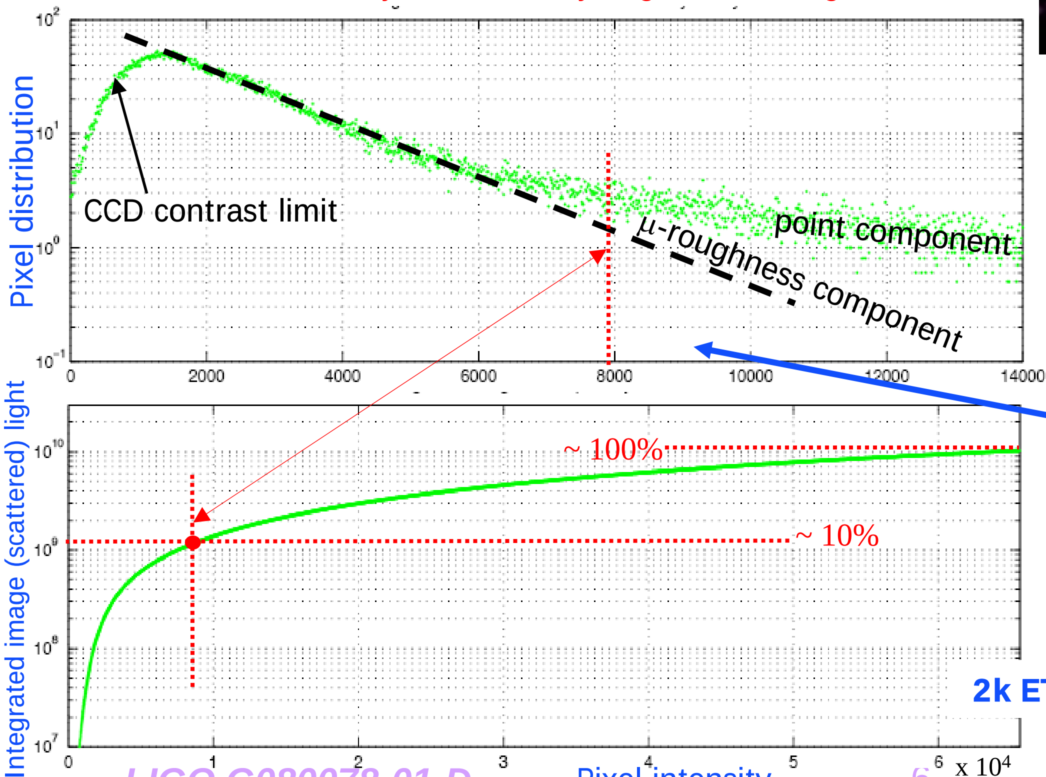


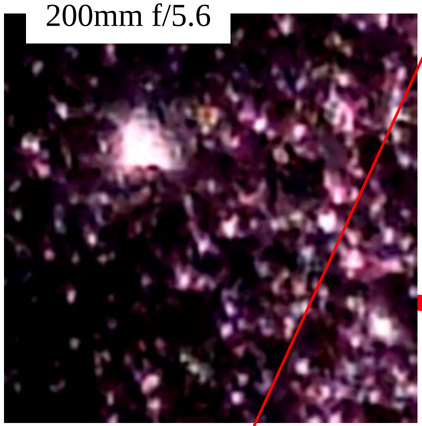
Improved resolution brings out "point" defects

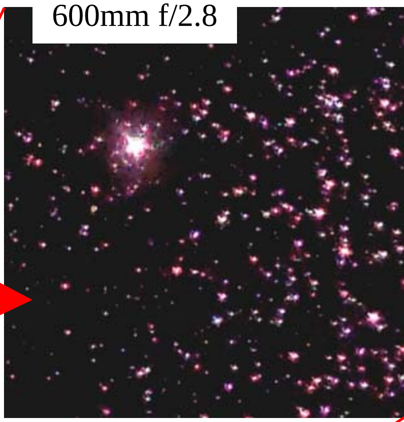
Post S5 LHO scatterometer survey included
a few updated photo sessions with even higher resolution
to conclusively distinguish localized point component.

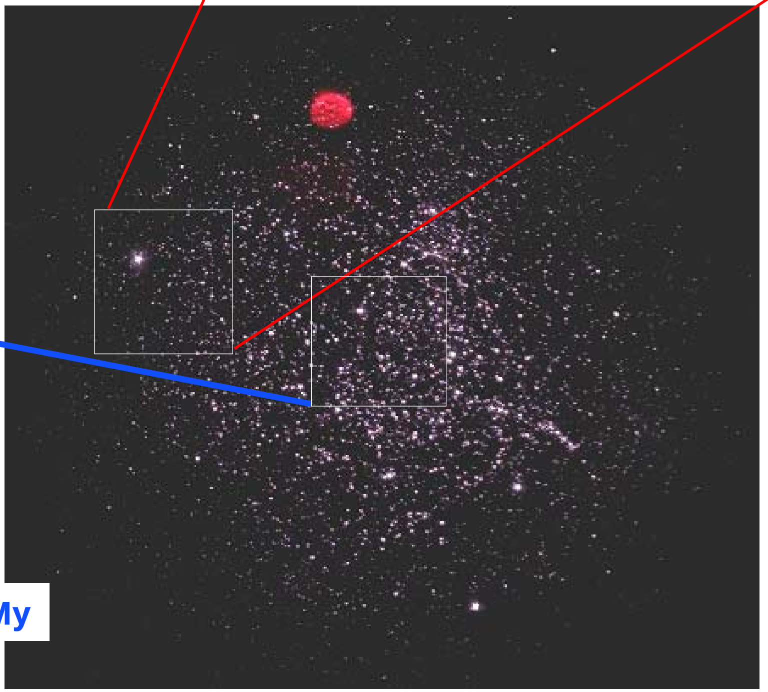
Re-imaged 4k ETMx showed same points, >3 years later.

Preliminary quantitative result: point component loss ~90%
not inconsistent with scatterometer (slide 3) inference
However this at only one relatively large scatter angle !









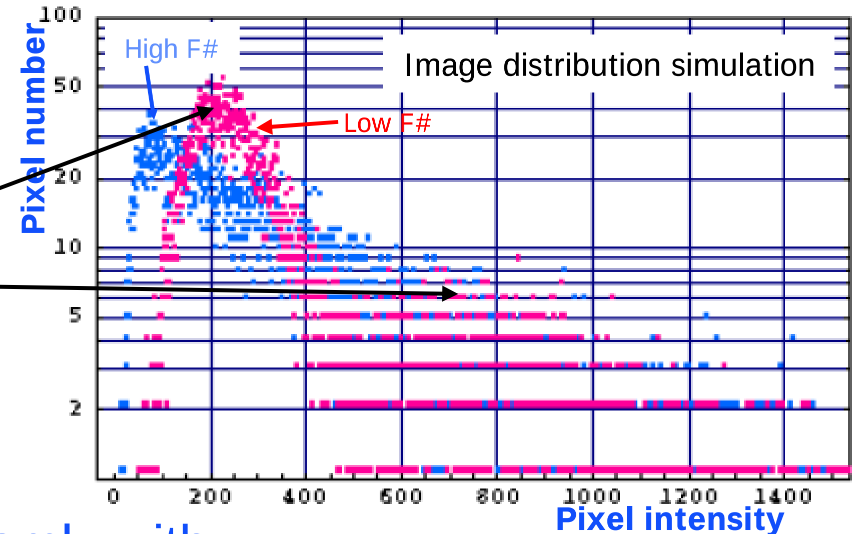
Background Speckle vs defects

- Distinguish "bright defect" tail of distribution via contrasting f/#.

Model of image distribution:

Background speckle component

Sporadic "point component"



- Speckle image pattern changes randomly with:
  - » Airy patch sample (∝ f/#)
  - » Different field solid angle patch (Δ camera view angle >.005 rad, LHO ETMs)
- Distinct (*within single Airy patch*) "point" defects remain fixed.
  - » Find: most bright points fixed (LIGO, 40m)

w~ 4 mm beam spot image in air.
Single pass reflection (no cavity)

f/5.6 at 82 cm, VP Δ= 6.3°

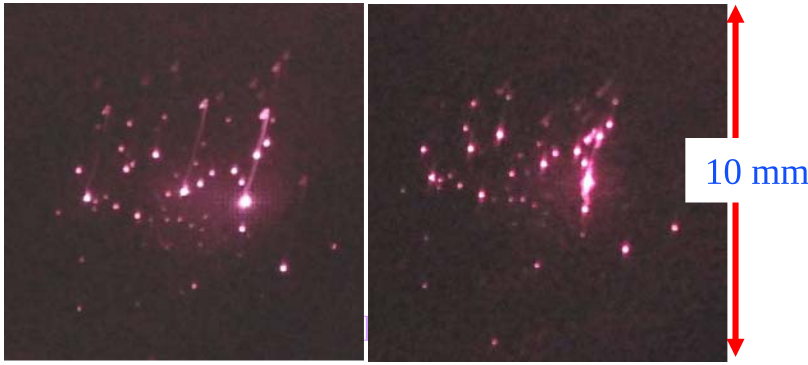
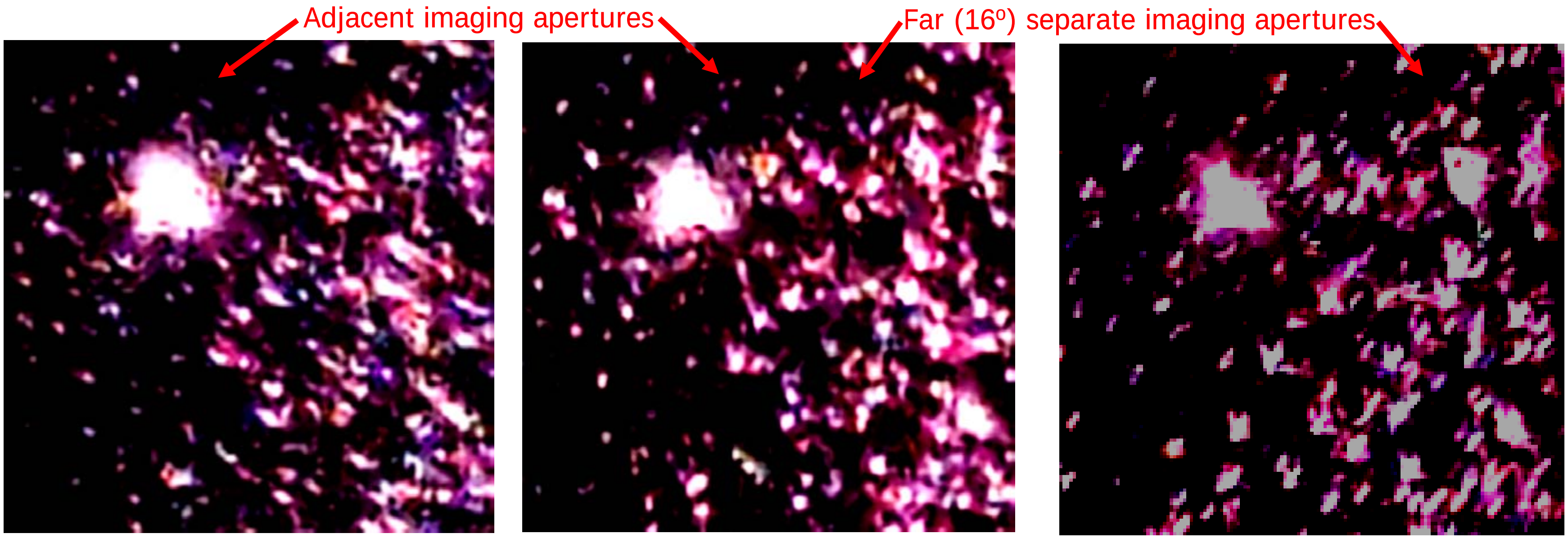


Image view point correlation

- For diffraction limited imaging, non-overlapping apertures image random μ-roughness speckle randomly differently.
- Brightest points in images (selected by contrast and f/# optimization) remain fixed for non-overlapping apertures.
- 2^D image overlay correlation software will make quantitative.

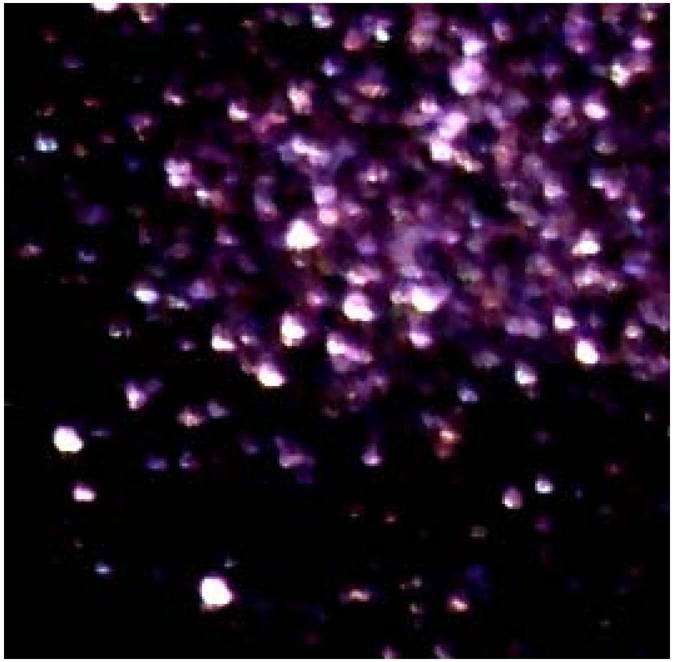
2k ETMy extreme contrast enhancement



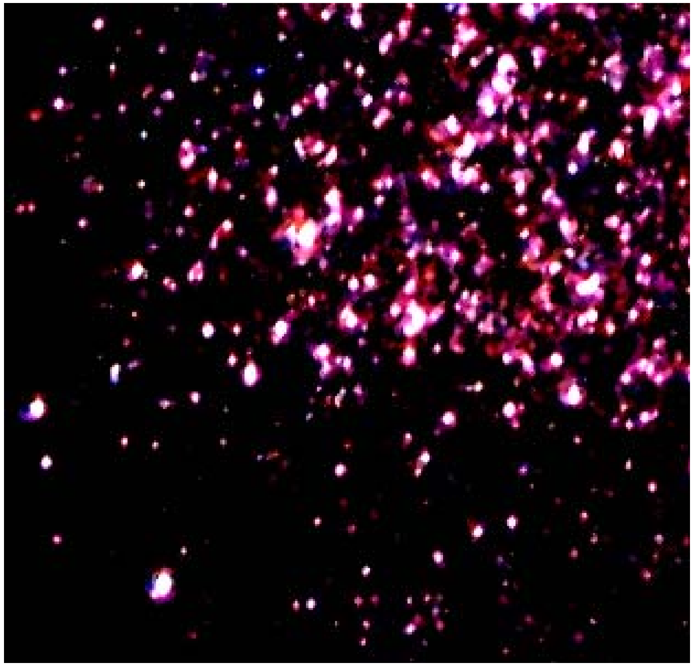
Ease of long term monitor

(see talk of J.R. Smith, Friday ~3:30)

- '04 → '07 comparison: 4k ETMx



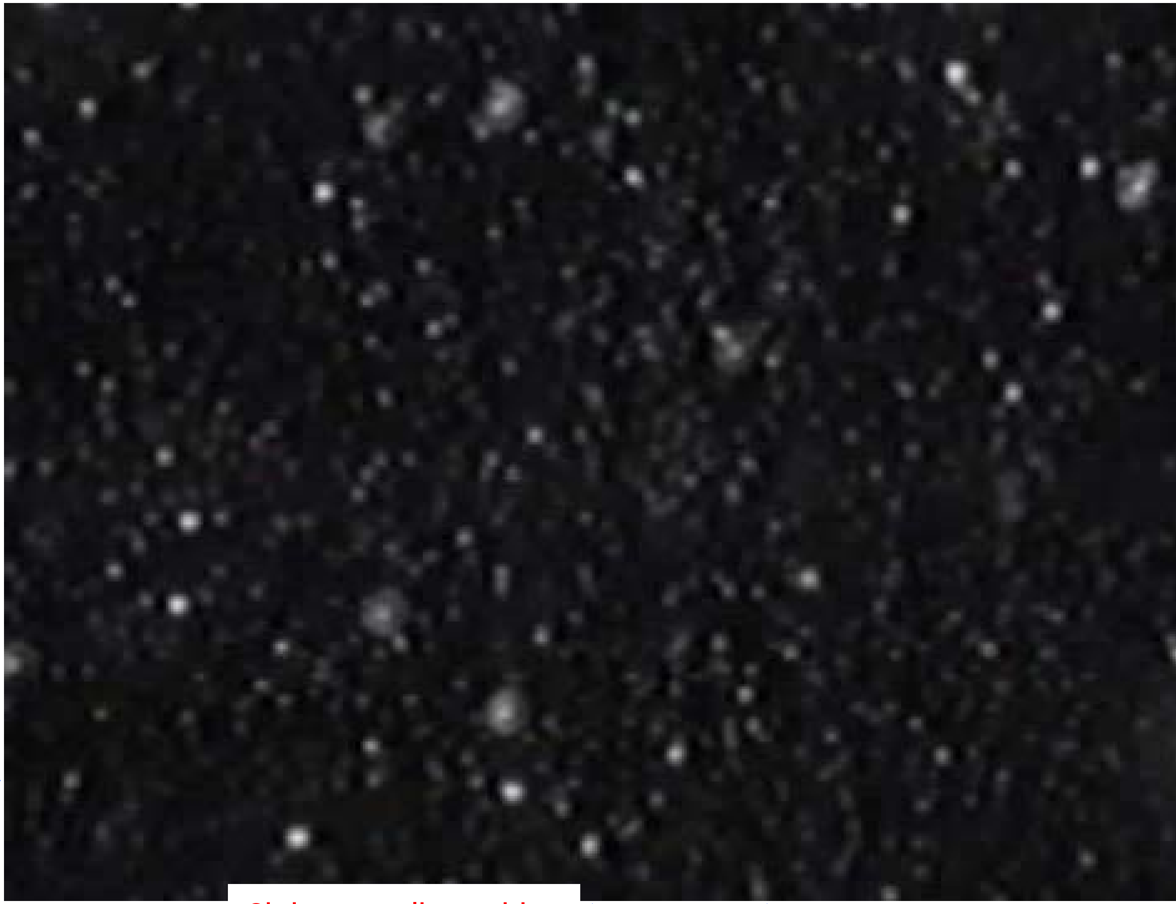
~ 6/07 (bad focus !)



~ xx/04 (original shots)

Defects vs Speckle: Twinkling Images

- Cavity field illuminating HR surface: a **standing wave**
  - » For cavity end mirrors SW nodes locked to TM position: **stationary surface illumination**



2k beam splitter video

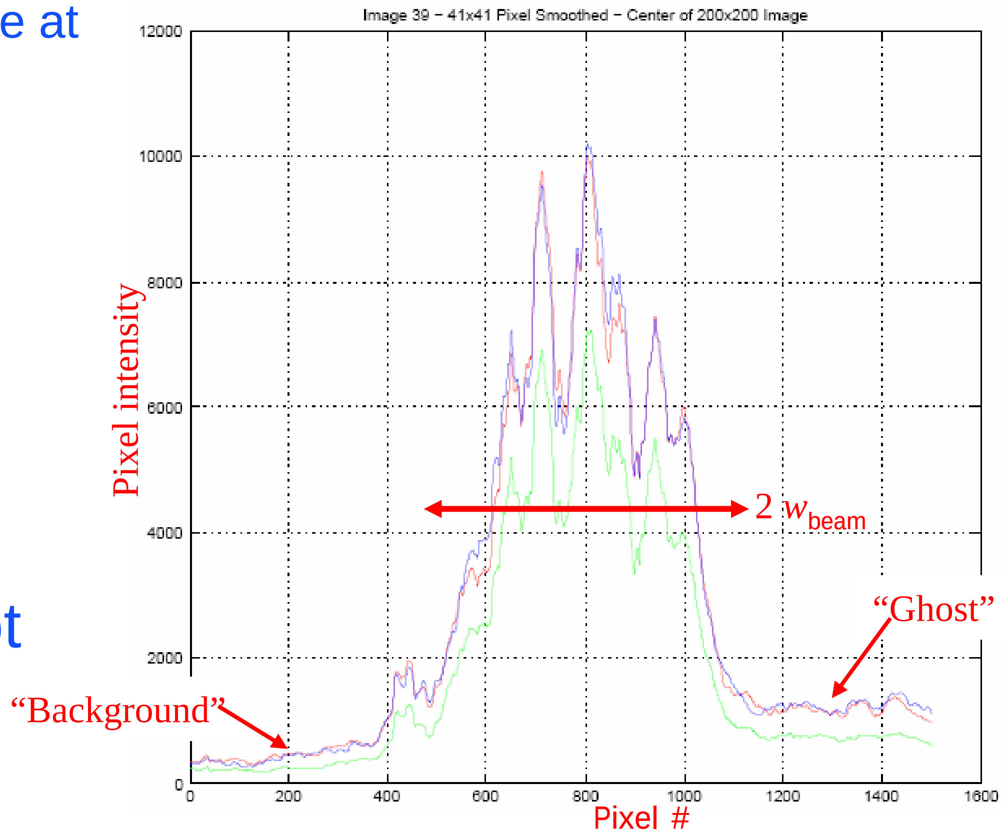
- Folding or splitter mirrors can (and do!) move *w.r.t.* SW nodes: *image twinkling*
  - ~ half pendulum period.
  - ~ Full extinction twinkling "resolves" $\lambda/2$ scale defects, while maintaining their apparent fixed position in image.
- Roughness speckle comes from random Avg. over Airy patch (>10^2 nodes wide):

Expect random morphing as diagonal sliced SW slews across surface.

Irregularity of images investigated

- Attempt to "smooth" image: reveal Gaussian profile
  - » Single pixel line through beam center
  - » Irregular on all scales
  - » Anomalous ghost [speckle] image at RH edge of beam spot
- Indicates in situ images have complex "dark" background dependence
- Camera (Fuji S5) biases not fully understood.

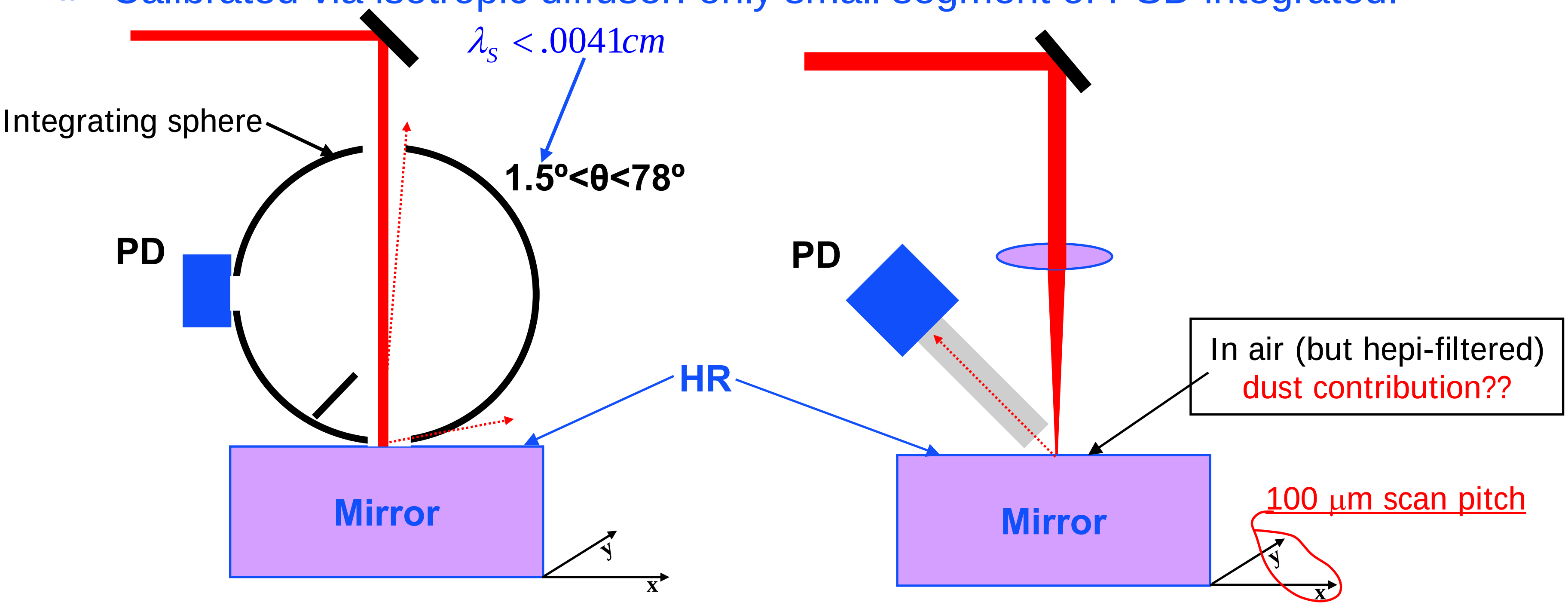
  E.G: Image contrast is strongly local brightness dependent



Bench scatter mapping

(see L. Zhang talk, Friday, ~3pm)

- In air scanning of HR surfaces: scatter & absorb.
  - » Calibrated via isotropic diffuser: only small segment of PSD integrated.

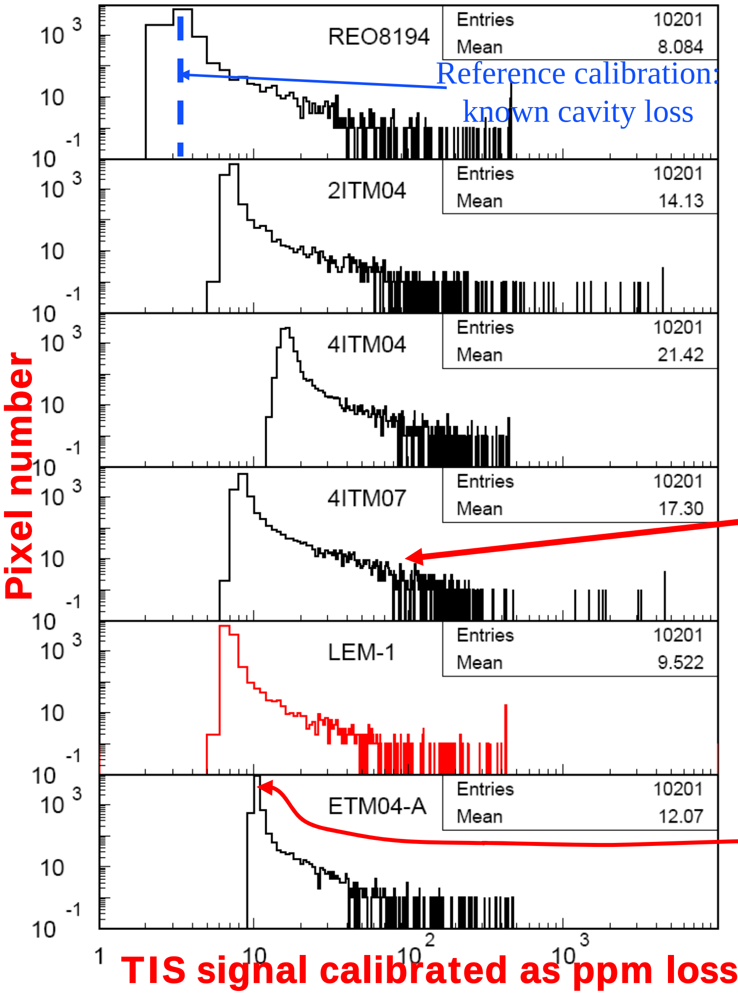


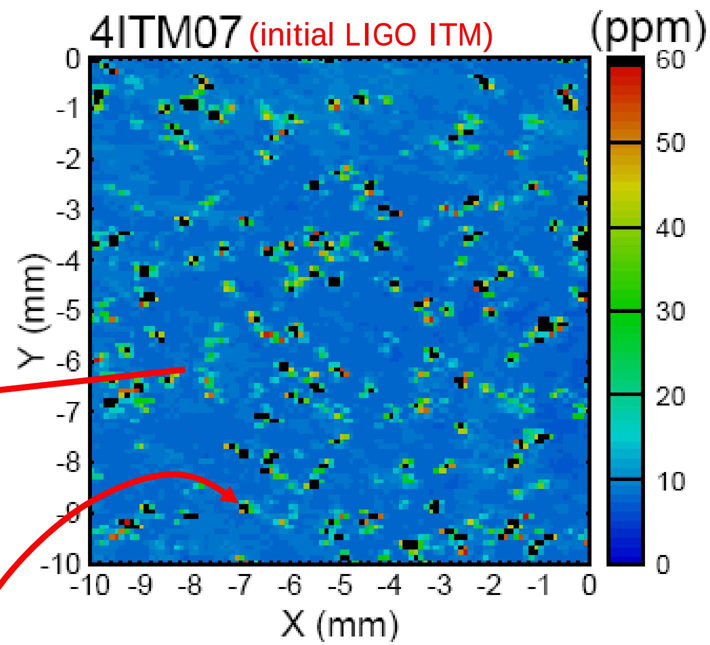
TIS: collimated beam, Dia.~.25 mm, modest spatial resolution, more collected scattering light.

BRDF @ 45 degrees: focused beam, Dia. 0.1 ~ 0.5 mm, high spatial resolution, less collected scattering light.

Further evidence of fixed defects

- Non-imaged scatter: many localized high scatter pixels
  - » Min. background “micro-roughness” larger than PSD prediction.





Surface resolution ≤ that of best in-situ camera scatter images

Distribution of pure μ-roughness ≈ δ function at this resolution

Future outlook

- Higher than anticipated “point defect scatter”
  - » Post fabrication contamination? Is it dust (becoming clear mostly not)
    - – Invariant, large, point defect component in all investigations *w.r.t* cleaning
  - » Better [coating] process control likely can impact defect density (fabrication contamination ?)
  - » Can contribute 10-20 ppm excess loss/mirror

- Dedicated imaging system will do far better (J. R. Smith talk, Friday pm)
  - » Contiguous B/W pixels. High contrast (CCD). No rate compromise (cooled, ~~fast exposures~~).
  - » Long, thermal noise free, exposures $\Rightarrow$in-situ arm power not required: optimal Lab. Imaging.

- Substrate polish finish
  - » Full use of “superpolish” technology: micro-roughness component < 1ppm
  - » Can substrates be polished significantly smoother on mm – cm scales?
    - – This regime currently costs > 20ppm loss/mirror
  - » Possible goal HR mirrors with net loss (LIGO regime: long cavity, wide beam) <10ppm ???