Lock-in Imaging Below Diffraction Limit

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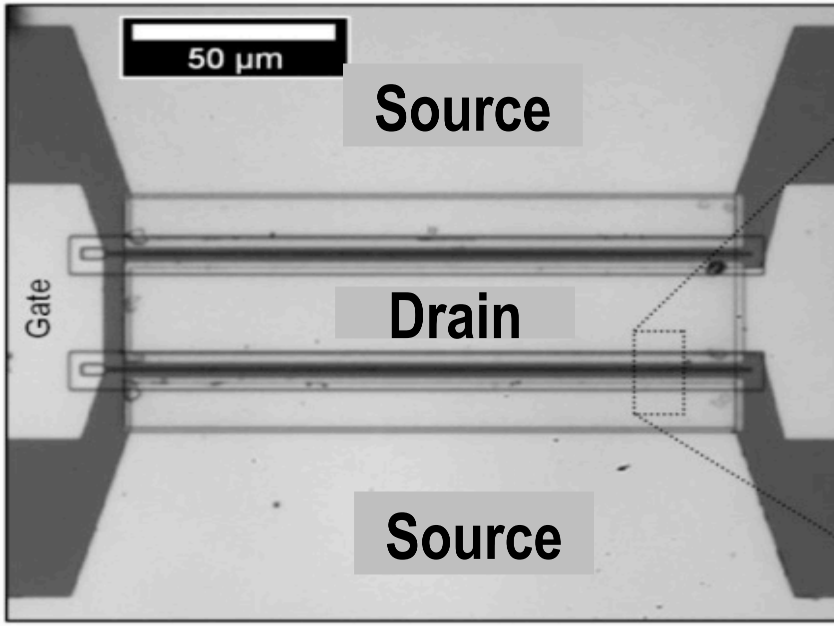
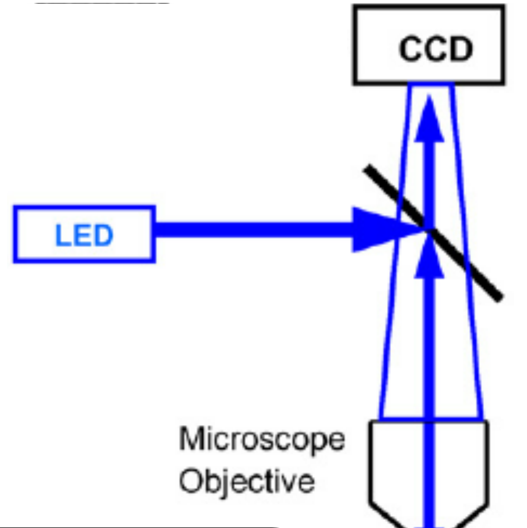
High resolution thermoreflectance imaging

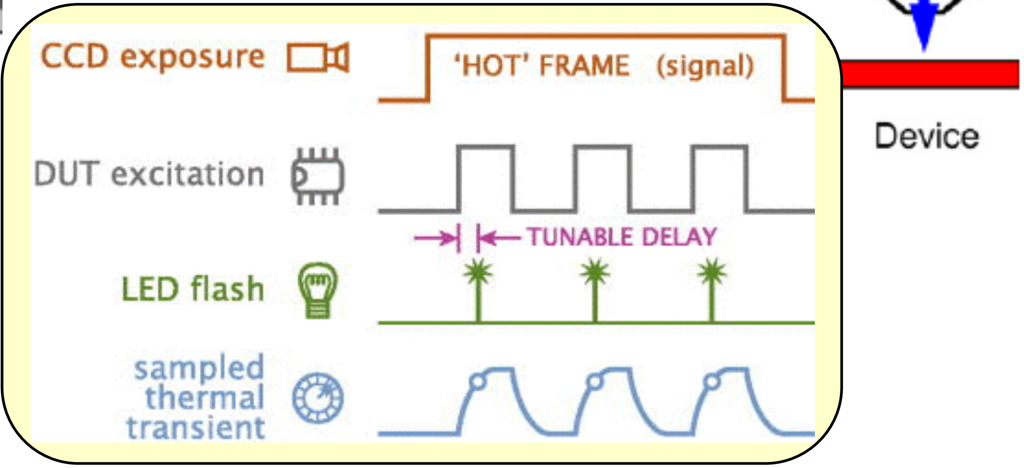


Optical Image of GaN HEMT

$(\Delta R/R)/\Delta T$
$\sim 10^{-4}$ /C

Mega Pixel Lock-in Camera





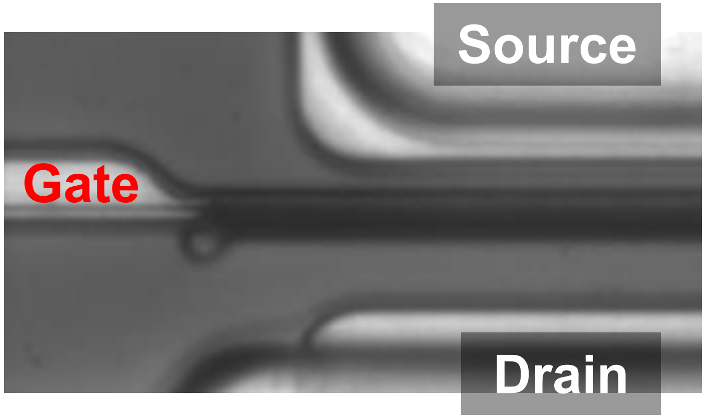
- Temp. resolution: 0.01°C
- Spatial: 100's nm
- Time: 50ns (800ps)

J. Christofferson, A. Shakouri, ***Rev. of Scientific Instruments***, 2005
K. Yazawa, A. Shakouri, ***Electronics Cooling Magazine***, Vol. 3, p.10, March 2011

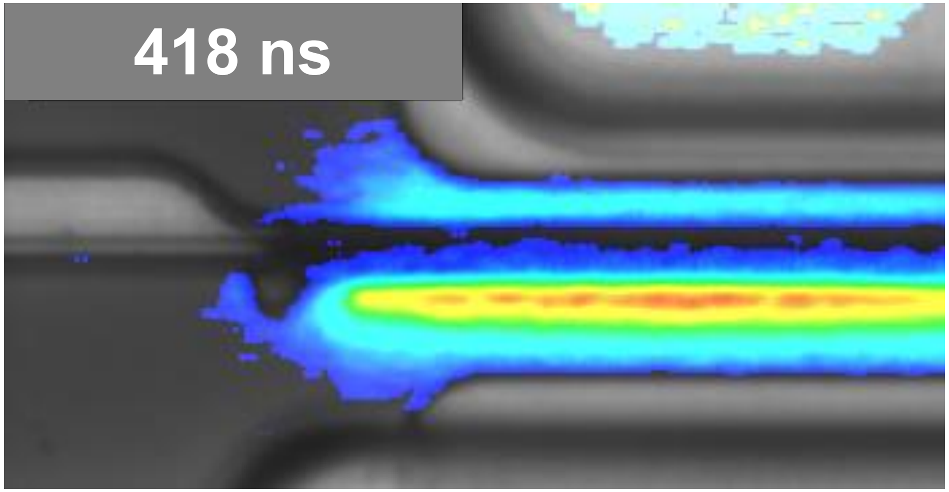
Disclosure: Commercialization by Microsanj.com

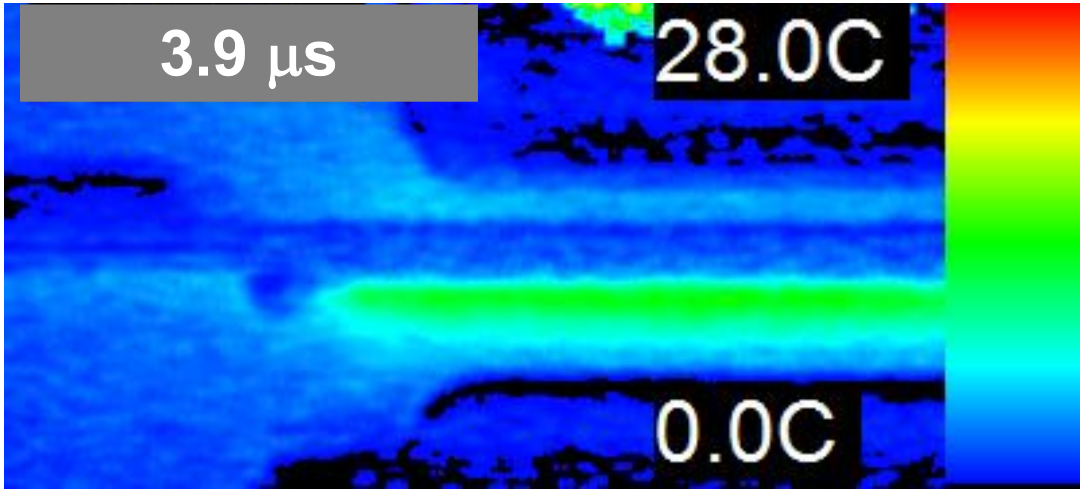
Transient Thermal Imaging of HEMT

28V,
300mA,
2.19W/mm



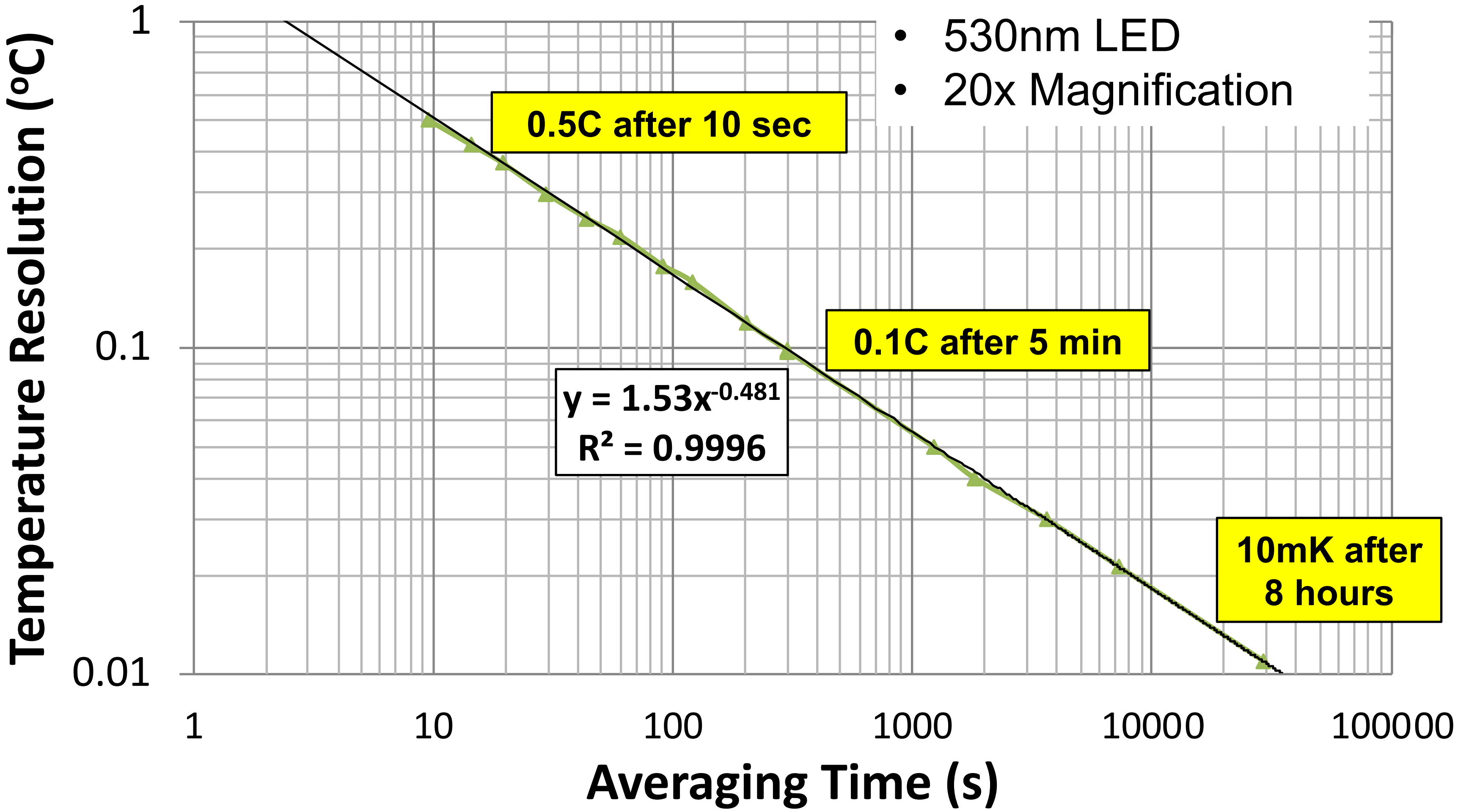
GaN High Electron Mobility Transistor (HEMT)





Kerry Maize et al., IEEE IRPS 2013, …

Temperature Resolution



- 530nm LED
- 20x Magnification

0.5C after 10 sec

0.1C after 5 min

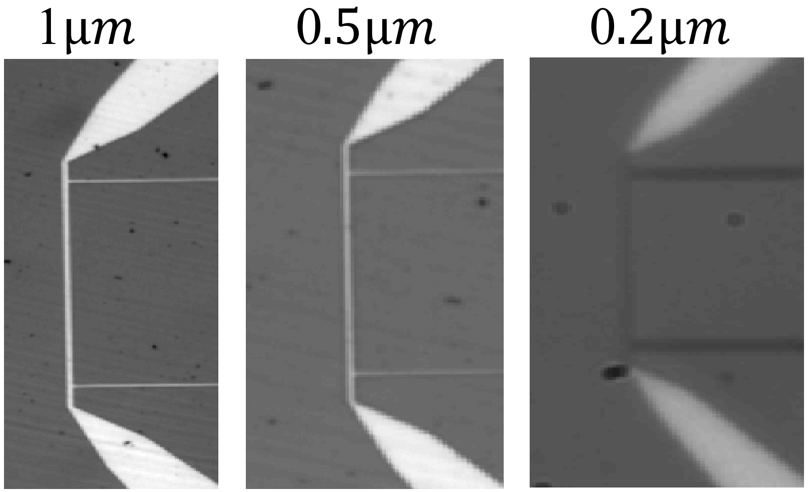
10mK after 8 hours

$y = 1.53x^{-0.481}$
$R^2 = 0.9996$

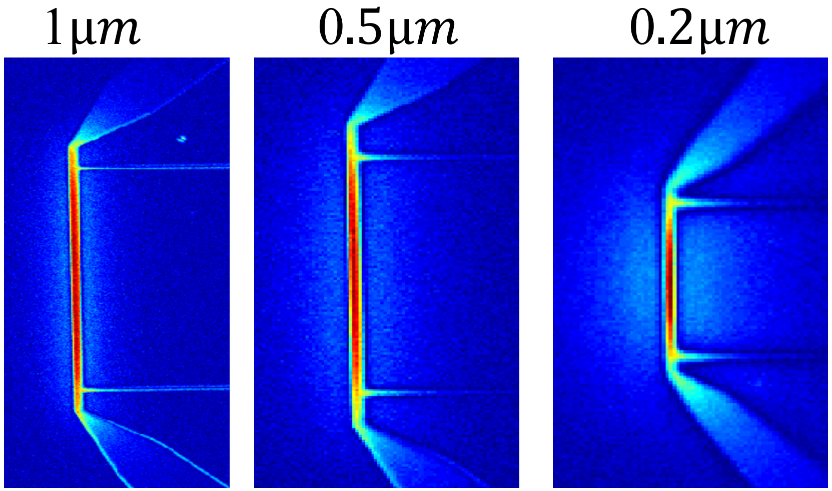
- **Temperature resolution on gold region with 8x8 pixels**
- **Resolution can be improved by 1/√t (t is the averaging time)**

Temperature profile near nanoheater sources

Sub-Diffraction Thermoreflectance Imaging

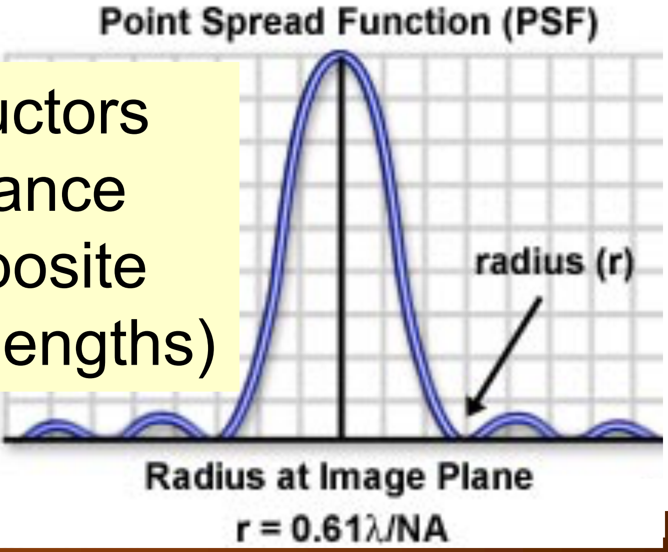


Optical Images



Thermal Images

Metals & semiconductors have thermoreflectance coefficients with opposite signs (at certain wavelengths)



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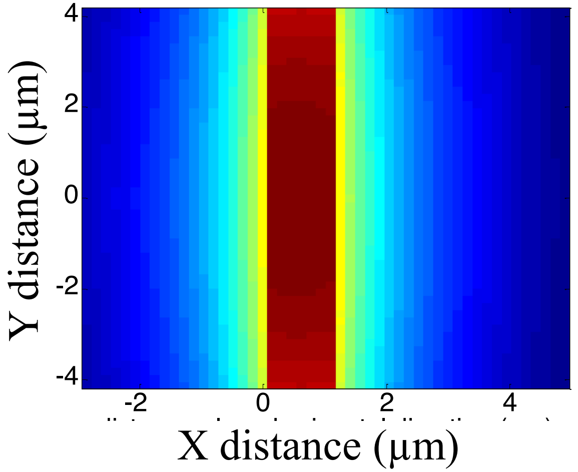
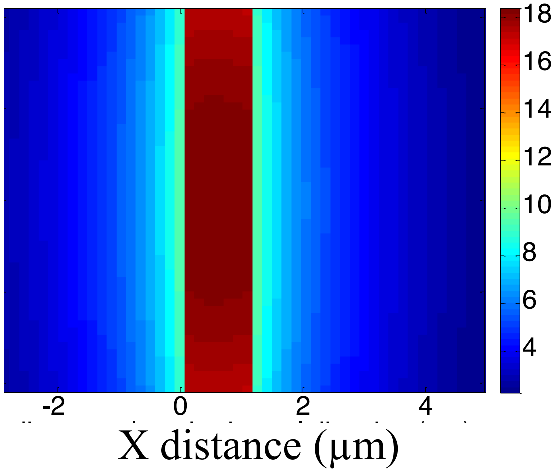
http://www.olympusmicro.com/primer/java/mtf/airydisksize/

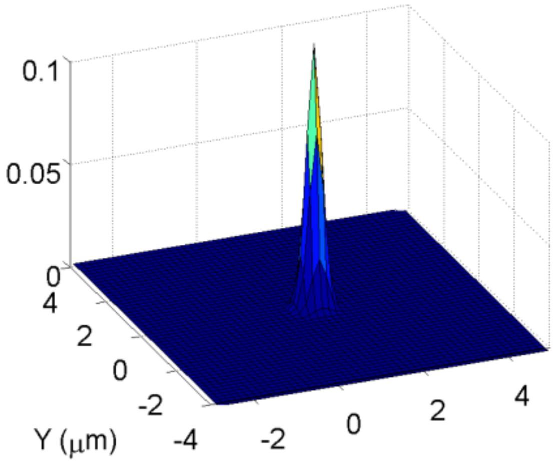
Diffraction (Forward Model) –part I



1. ANSYS Temperature Profile for **1μm device**



2. Temperature profile Normalized by Au C_{TR}

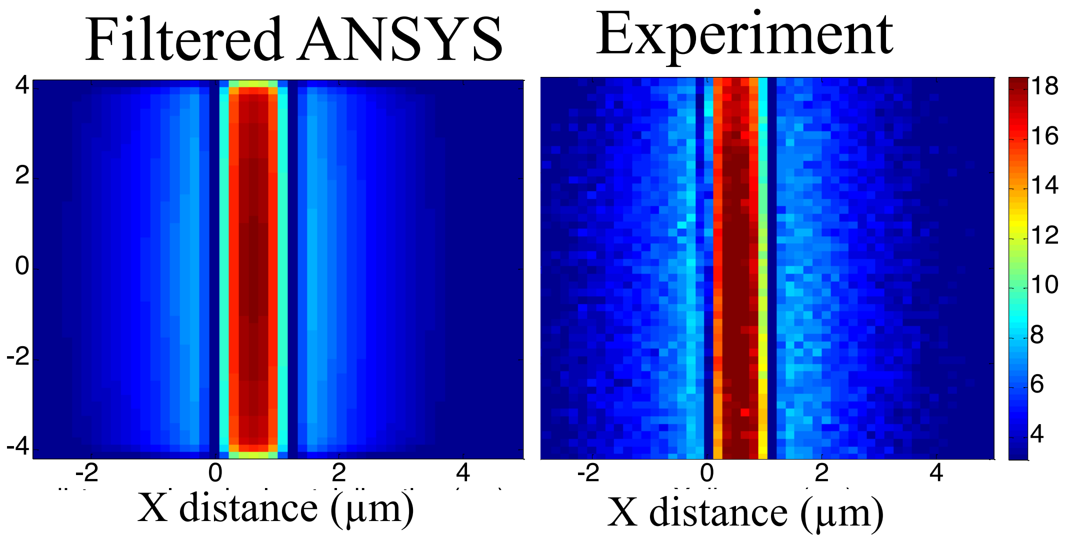


3. Filtered by Gaussian (Approx. diffraction function)

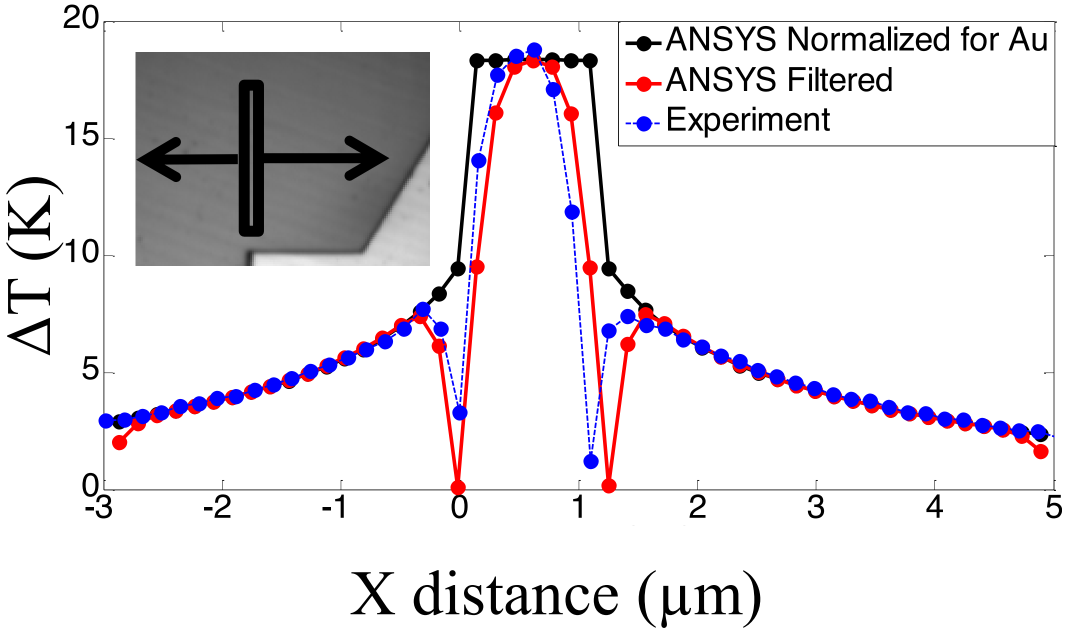
Diffraction can be modelled using image convolution (point spread function)

A. Ziabari, et al., IEEE SemiTherm, 2015

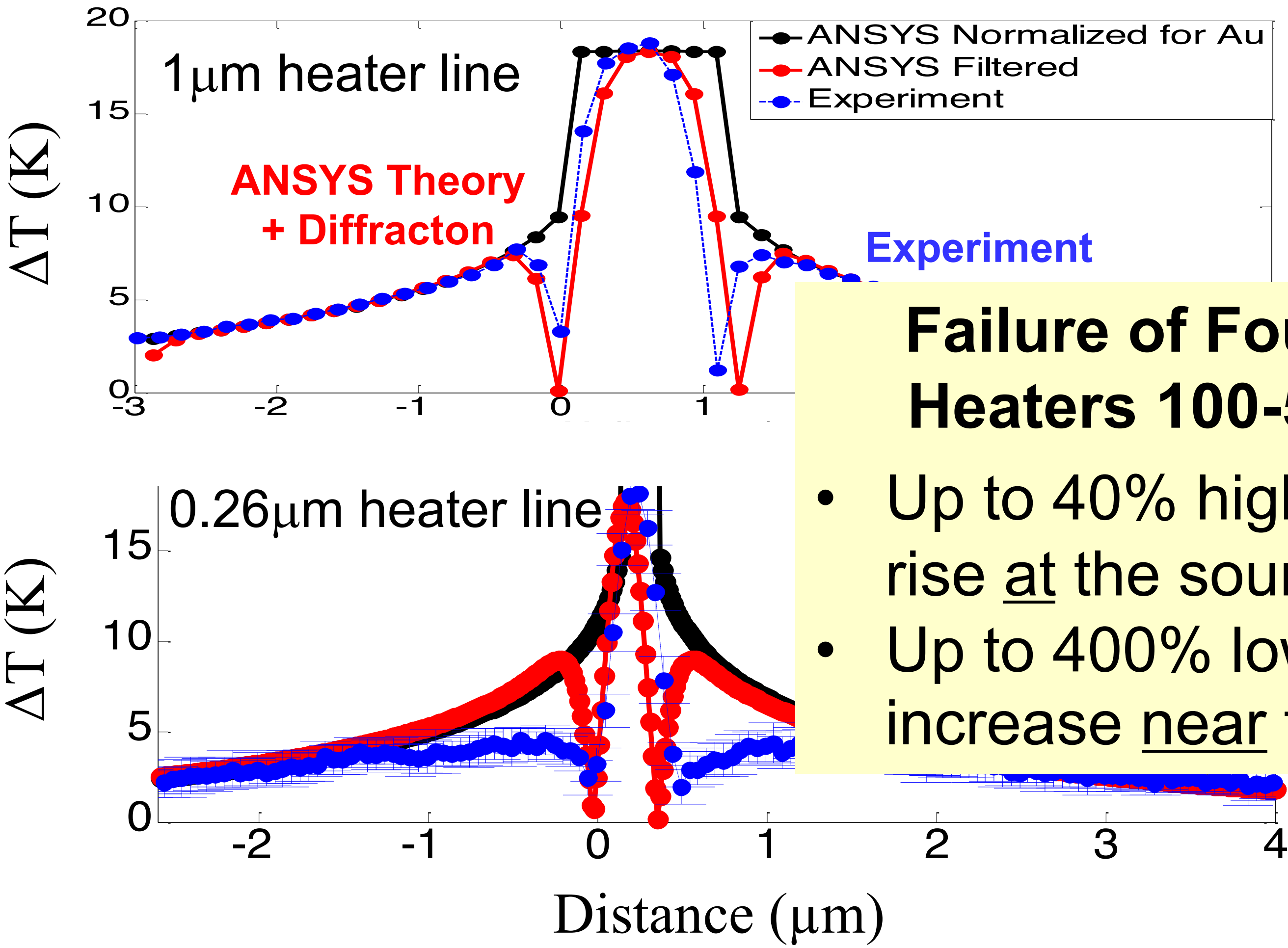
Diffraction (Forward Model) –part II



Theory (Fourier heat equation) vs. Experiment for 1µm wide Heater Line on InGaAs Substrate



Sub-Diffraction Thermoreflectance Imaging



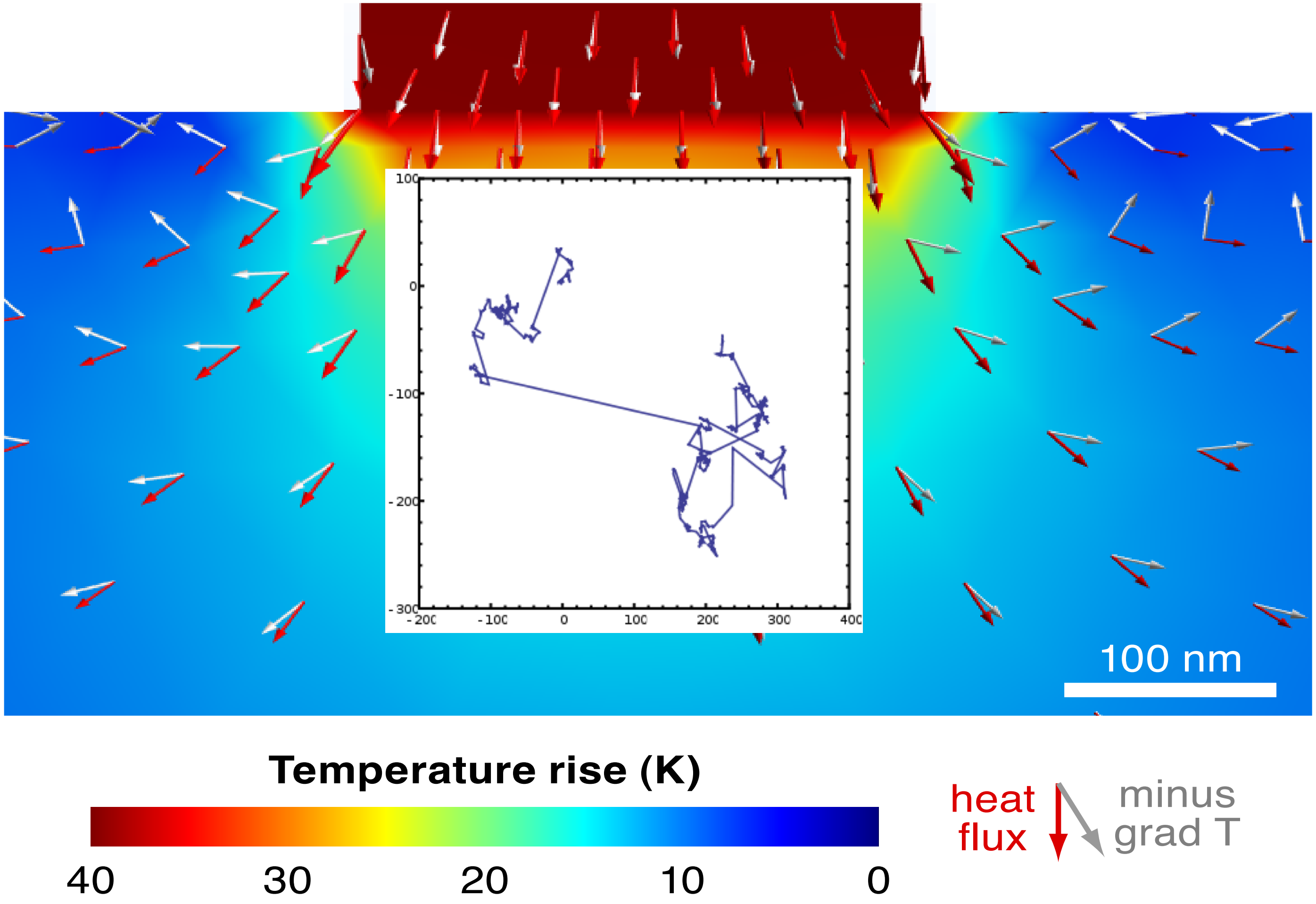
Failure of Fourier Law for Heaters 100-500nm wide:

- Up to 40% higher temperature rise at the source
- Up to 400% lower temperature increase near the source

A. Ziabari (ITherm 2017)

Nanoscale Heat Flow at room T

“small” device (W = 265nm)



A. Ziabari et al. (Nat. Comm. 2018)

Hydrodynamic Model for Heat Flow

Heat
Flux

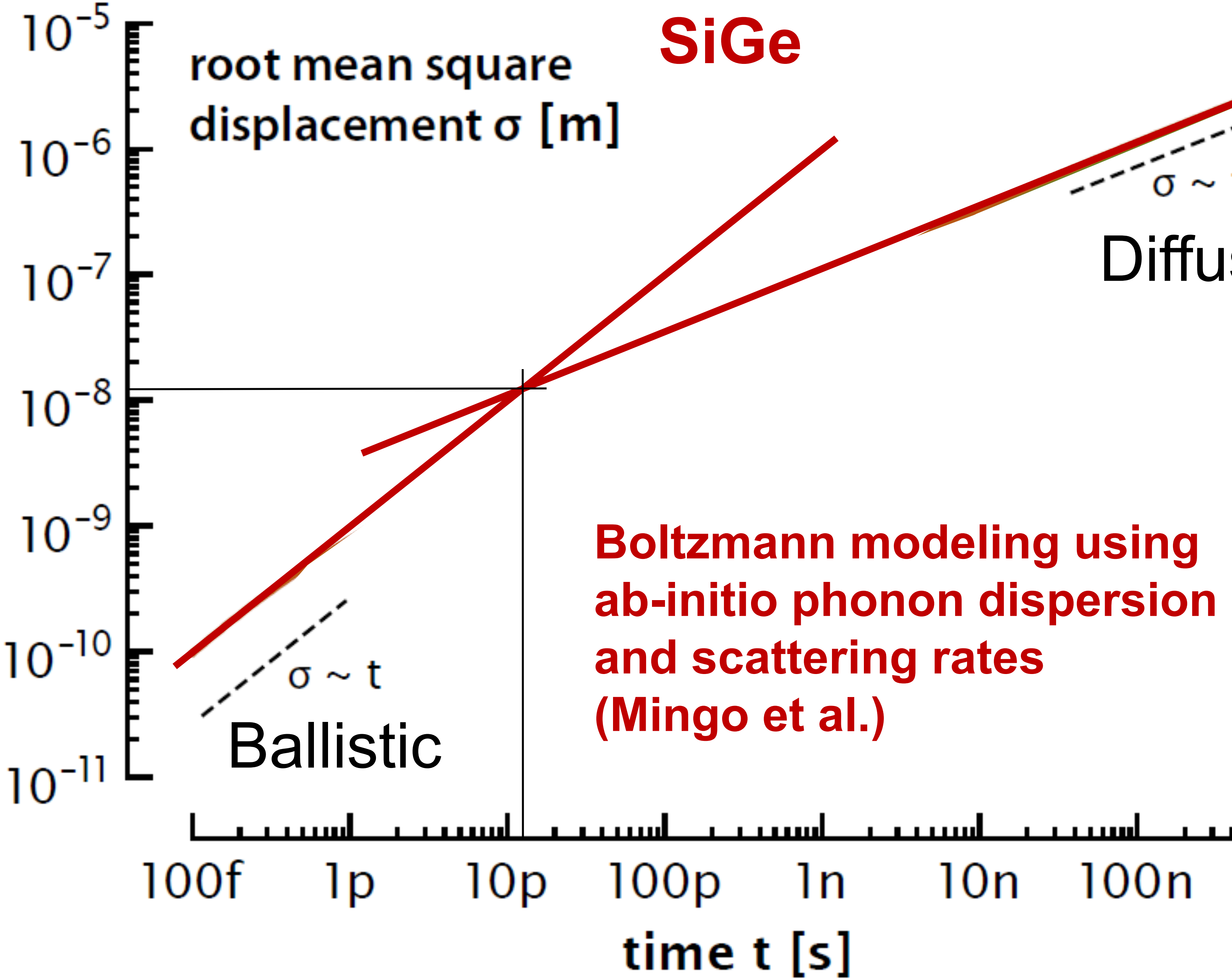
Temperature
Gradient

$$\vec{q} - \underbrace{[l^2(\nabla^2\vec{q} + 2\nabla\nabla.\vec{q})]} = -\kappa\nabla \mathrm{T}$$

Nonlocality induced by normal phonon scattering and gives rise to hydrodynamic effects over characteristic length *l*

Xavier Alvarez: Univ. Autonoma de Barcelona

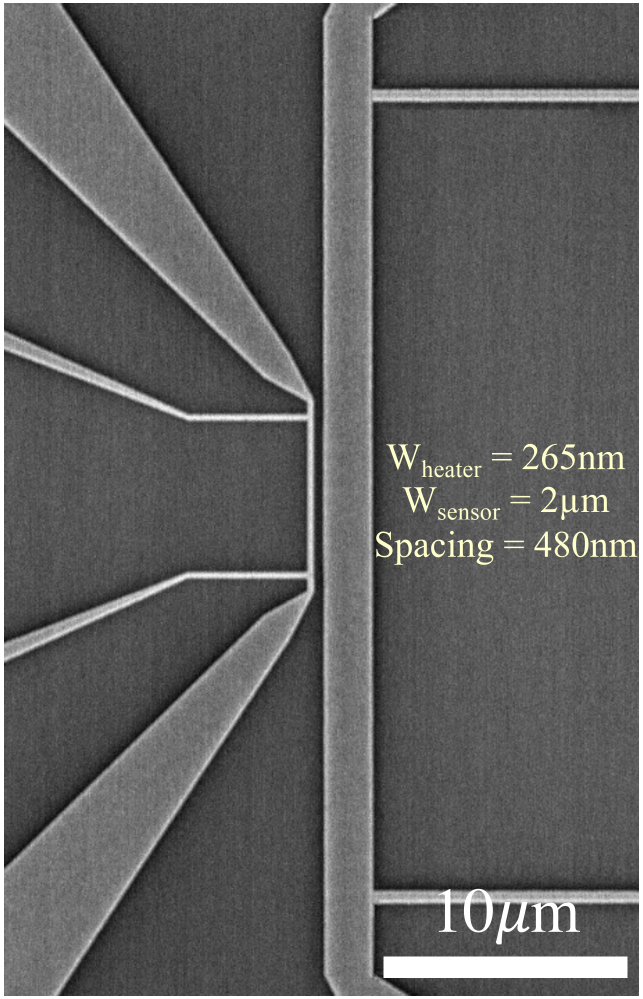
SiGe

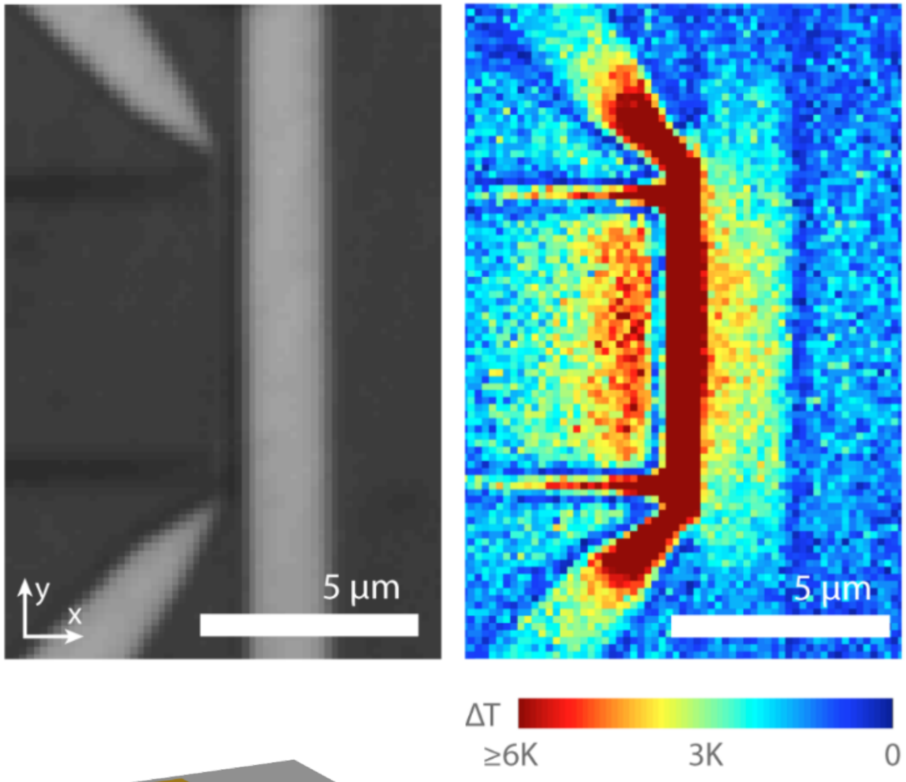


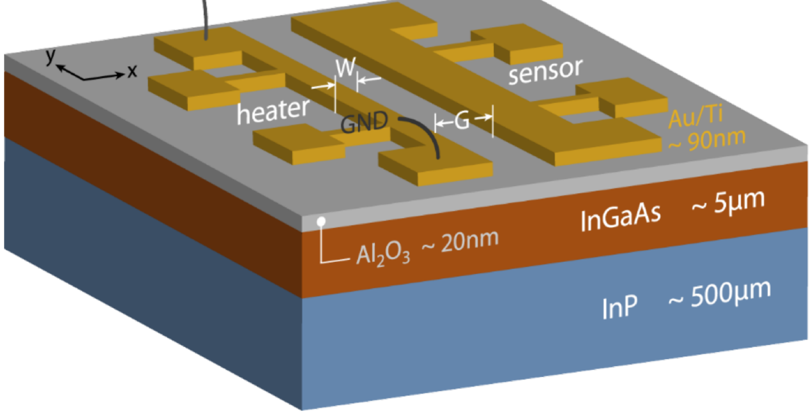
Boltzmann modeling using ab-initio phonon dispersion and scattering rates (Mingo et al.)

B. Vermeersch, et al., Superdiffusive… I & II, PRB. 2015 (ArXiv)

Heater and sensor lines







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A. Ziabari et al. (Nat. Comm. 2018)

Sub-Diffraction (Inverse Problem)

$$\hat{f} \leftarrow argmin_f \left\{ \frac{1}{2\sigma_w^2} \parallel g - \mathbf{H}f \parallel^2 + \frac{1}{p\sigma_x^p} \sum_{\{i,j\}\in C} B_{i,j}|f_i - f_j|^p \right\}$$

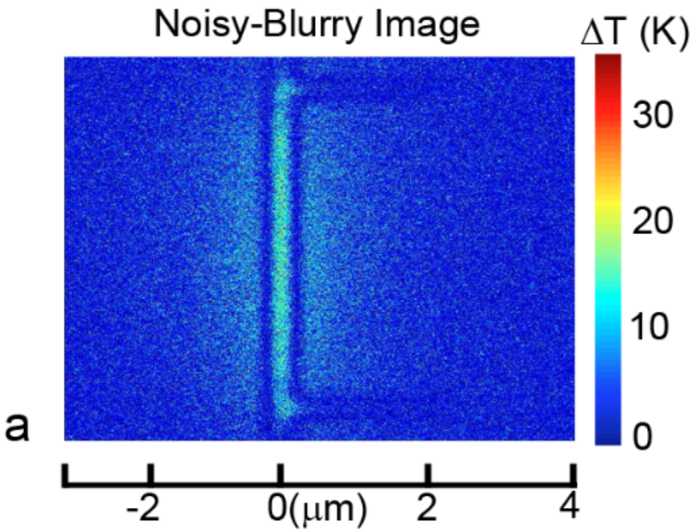
g: $measured\ image$ $(Blurred\ and\ noisy)$
$\mathbf{H}$: $matrix\ representaion\ of\ the\ blurring\ kernel$
σ_w^2: $Noise\ variance$
f: $reconstructed\ image$

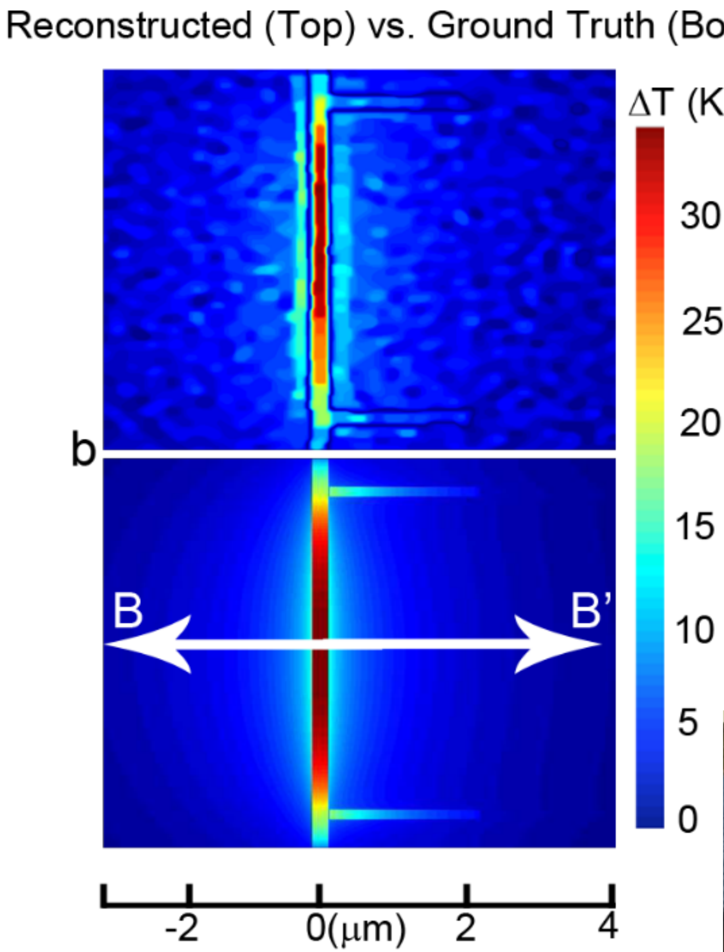
B: $Weight\ matrix\ for\ the\ neighborhood\ pixels$
σ_x: $Regularization$
$p \in [1,2]$
C: $Neighborhoood\ Clicks$

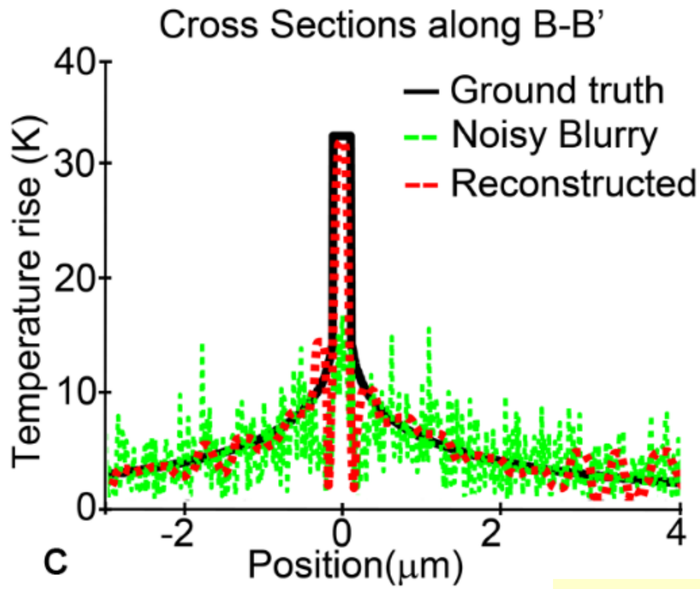
Maximum A-Posteriori (MAP) with non-Gaussian Markov Random Field

Ziabari et al. (InterPACK 2017, To be published)

Sub-Diffraction (Inverse Problem)







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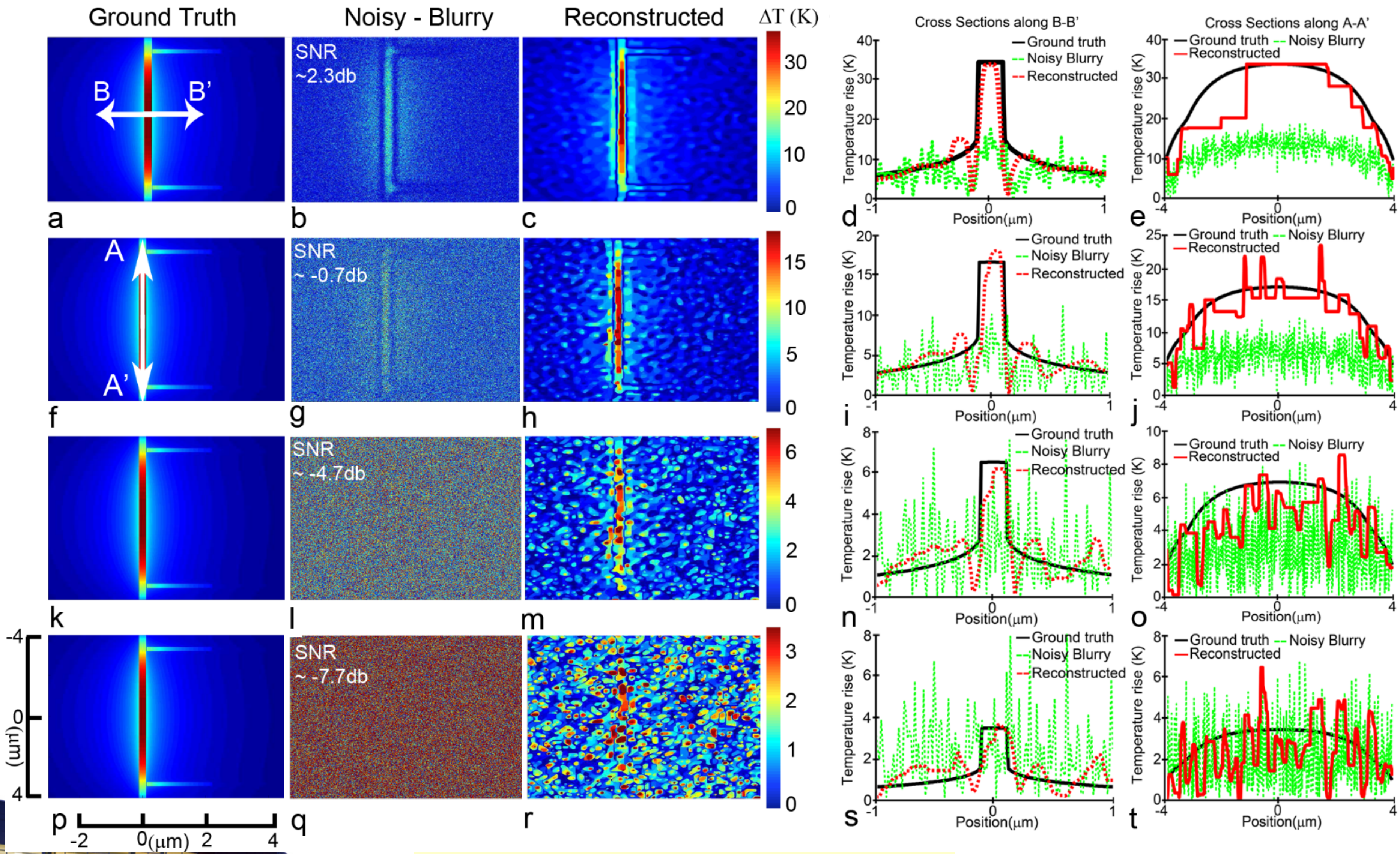
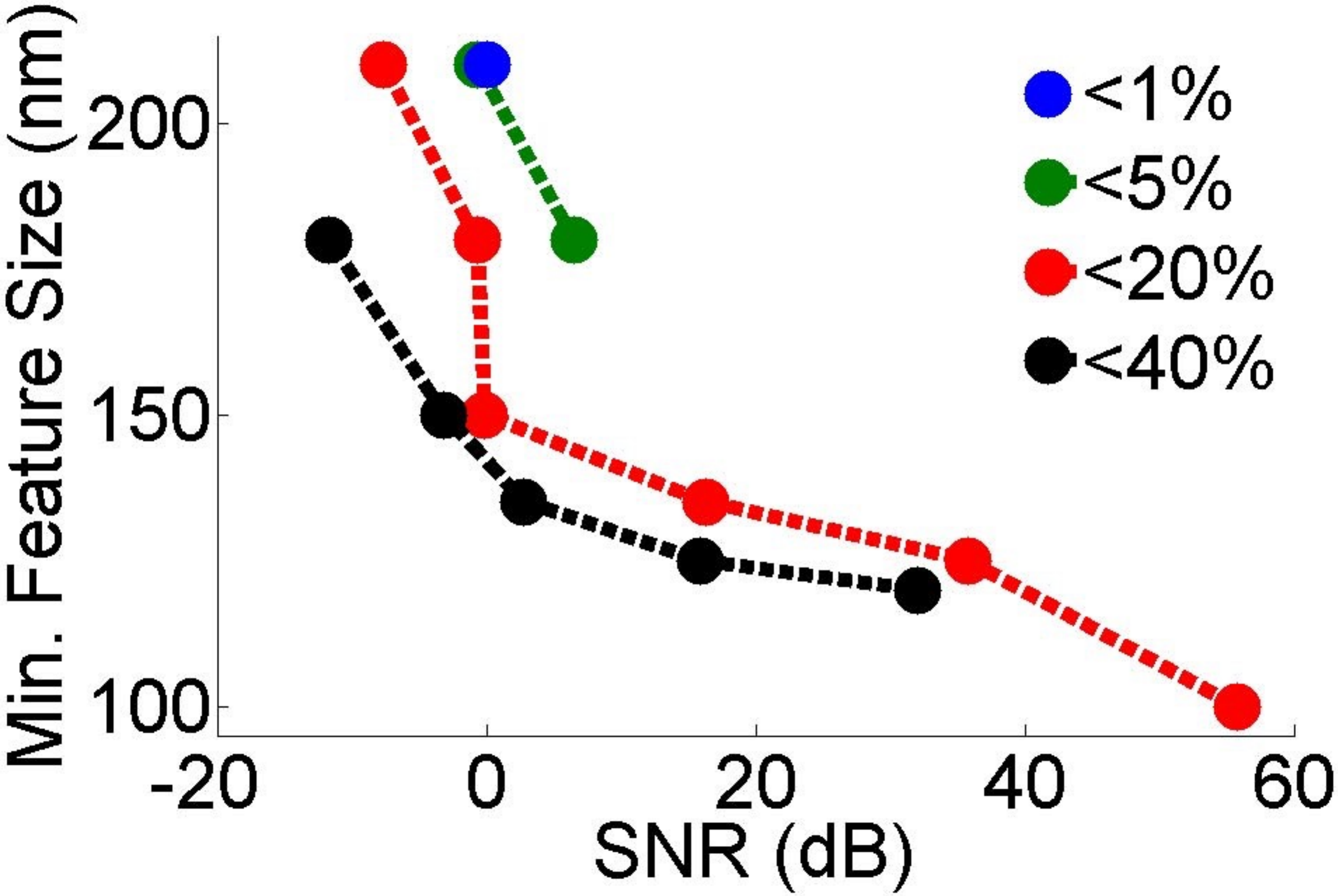
Numerical Experiments

Extracted temperature profile for 200nm heater line at different noise levels



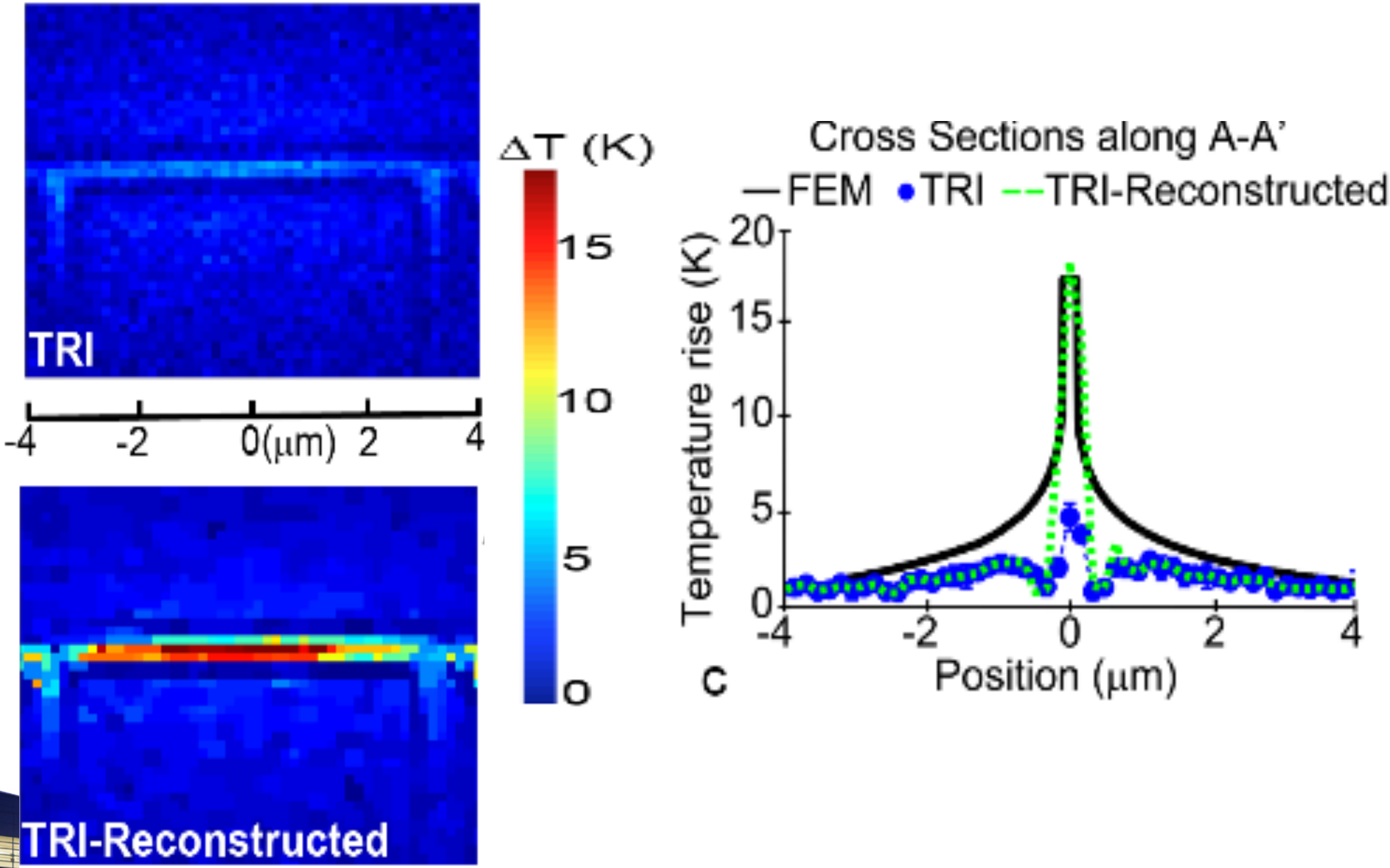
Numerical Experiments

Minimum feature size vs. SNR



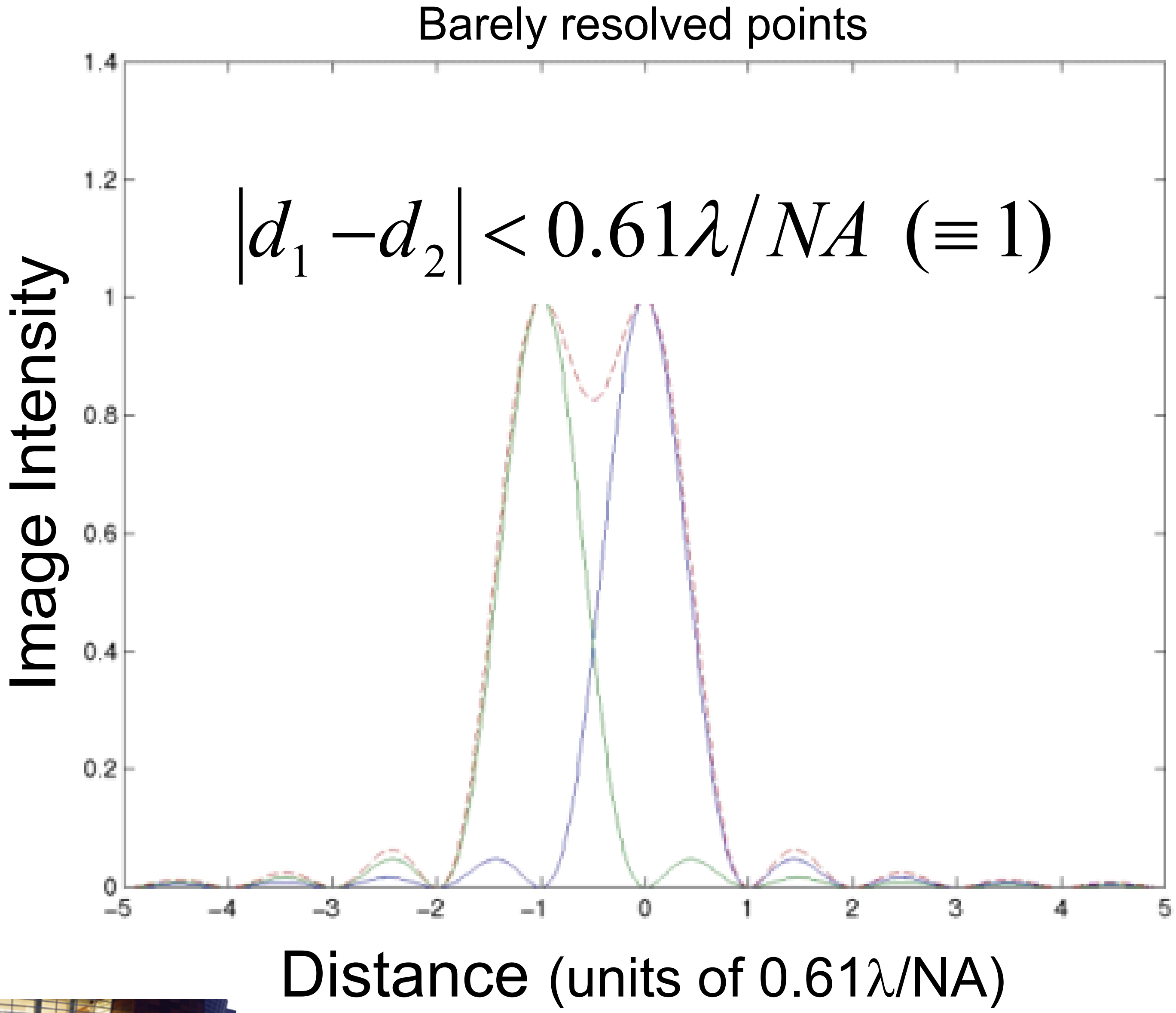
Temperature of features down to 100nm with errors less than 20% reconstructed

Experiment: **Thermal Image reconstruction** (200nm)



Ziabari et al. (InterPACK 2017, To be published 2019)

Diffraction Limited Imaging (point sources)



$$|d_1 - d_2| < 0.61\lambda / NA \;\; (\equiv 1)$$

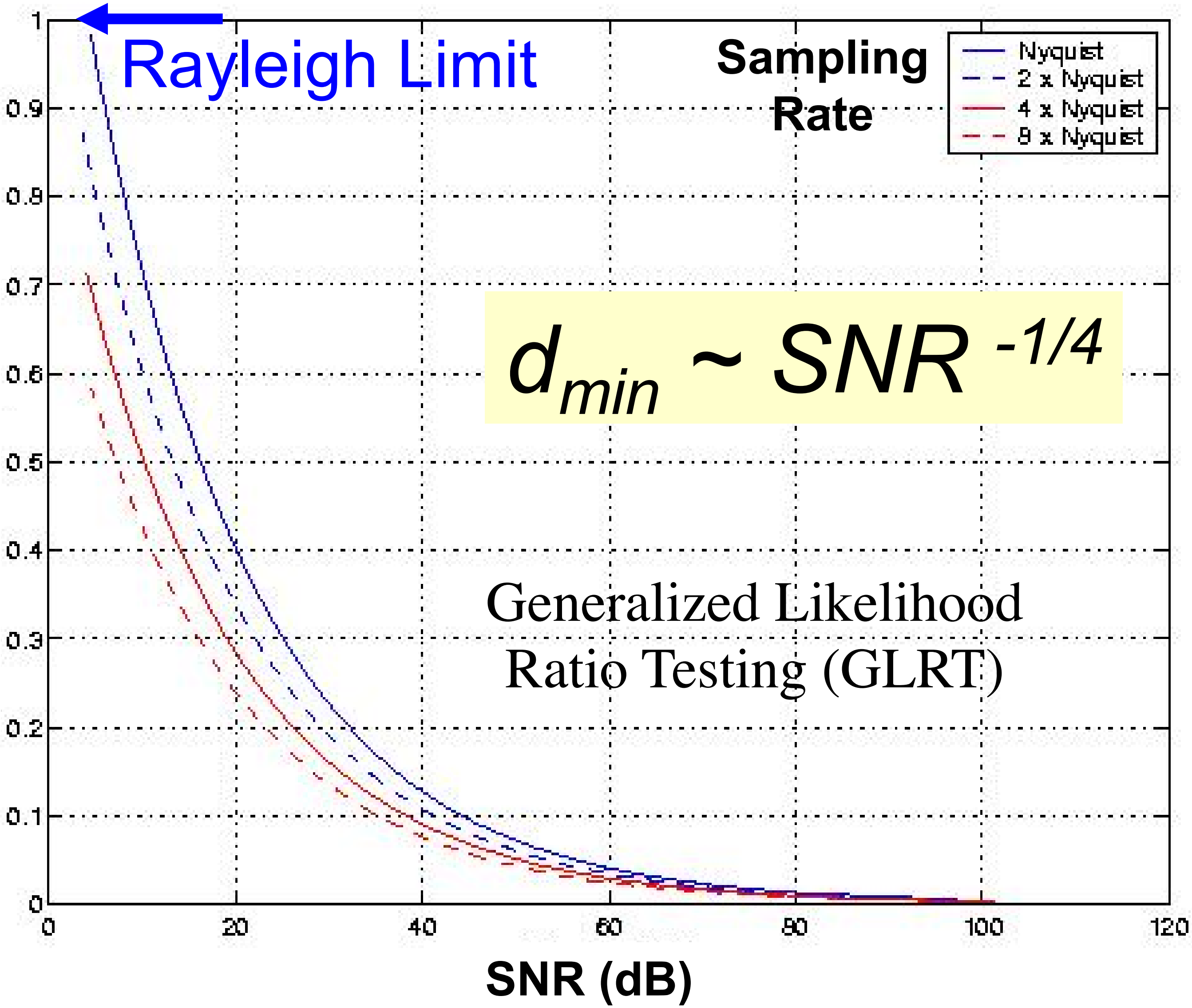
Peyman Milanfar

P. Milanfar, A. Shakouri ICIP 2002

Statistical Analysis of Diffraction Limited Imaging

Minimum Detectable Distance

$P_d = 0.99$
$P_F = 10^{-6}$



$$d_{min} \sim SNR^{-1/4}$$

Generalized Likelihood Ratio Testing (GLRT)

P. Milanfar, A. Shakouri, Int. Conf. on Image Proc., p.864, 2002

Summary

Far-field thermoreflectance imaging

- Lock-in imaging with mega-pixel CCD Camera (800ps time, 0.01C temperature resolution)
- Can detect temperature profile of 100-200nm devices
- Forward image blurring can give accurate temperature map
- Image reconstruction works for high SNR (need to know optical system parameters, device SEM, and bulk C_{TR})

Question: Can one improve temperature and/or spatial resolution using Quantum + Computations Imaging?

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