# Negative ion drift in a low pressure OTPC

Dinesh Loomba, Alex Mills, Elizabeth Tilly
University of New Mexico
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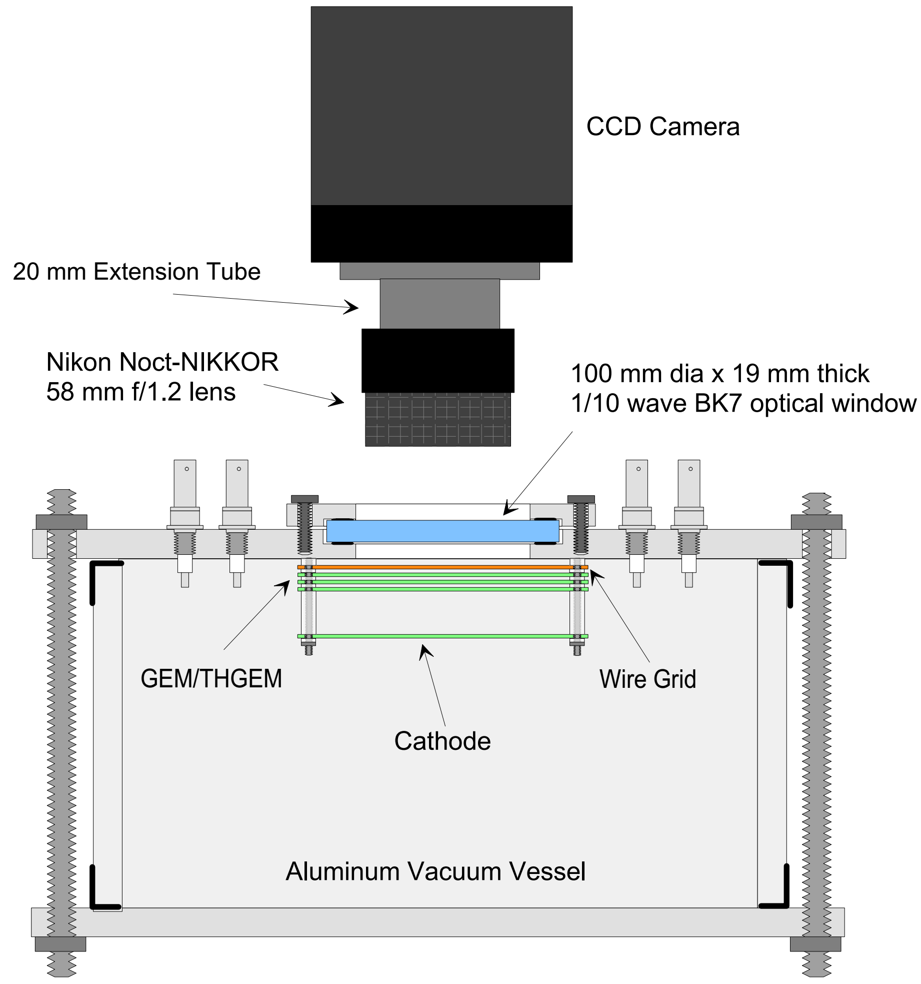
# OUTLINE

- OTPC Detector Setup:
  - Triple-thin GEMs for ~100-150 Torr
  - Double-THGEMs and Glass GEMs for ~50 Torr
  - CCD and CMOS cameras
- Optimizing CF4/NI mixtures for an OTPC:
  - Measuring/minimizing diffusion
  - Measuring/maximizing light and light yield
- Results
  - Proton, alpha and nuclear recoil tracks at ~150 Torr
  - Low energy electron tracks at ~50 Torr

# OTPC Detector

- 10 cm x 10 cm GEMs:
  - Standard thin GEMs
  - THGEMs ~ 0.45 mm pitch, 0.4 mm thick
  - Glass-GEMs 280 um pitch, 570 um thick
- 1.5-2 cm drift
- 1D wire grid anode
- Optical readout:
  - CCD/CMOS cameras
  - 58 mm f/1.2 Nikon lens

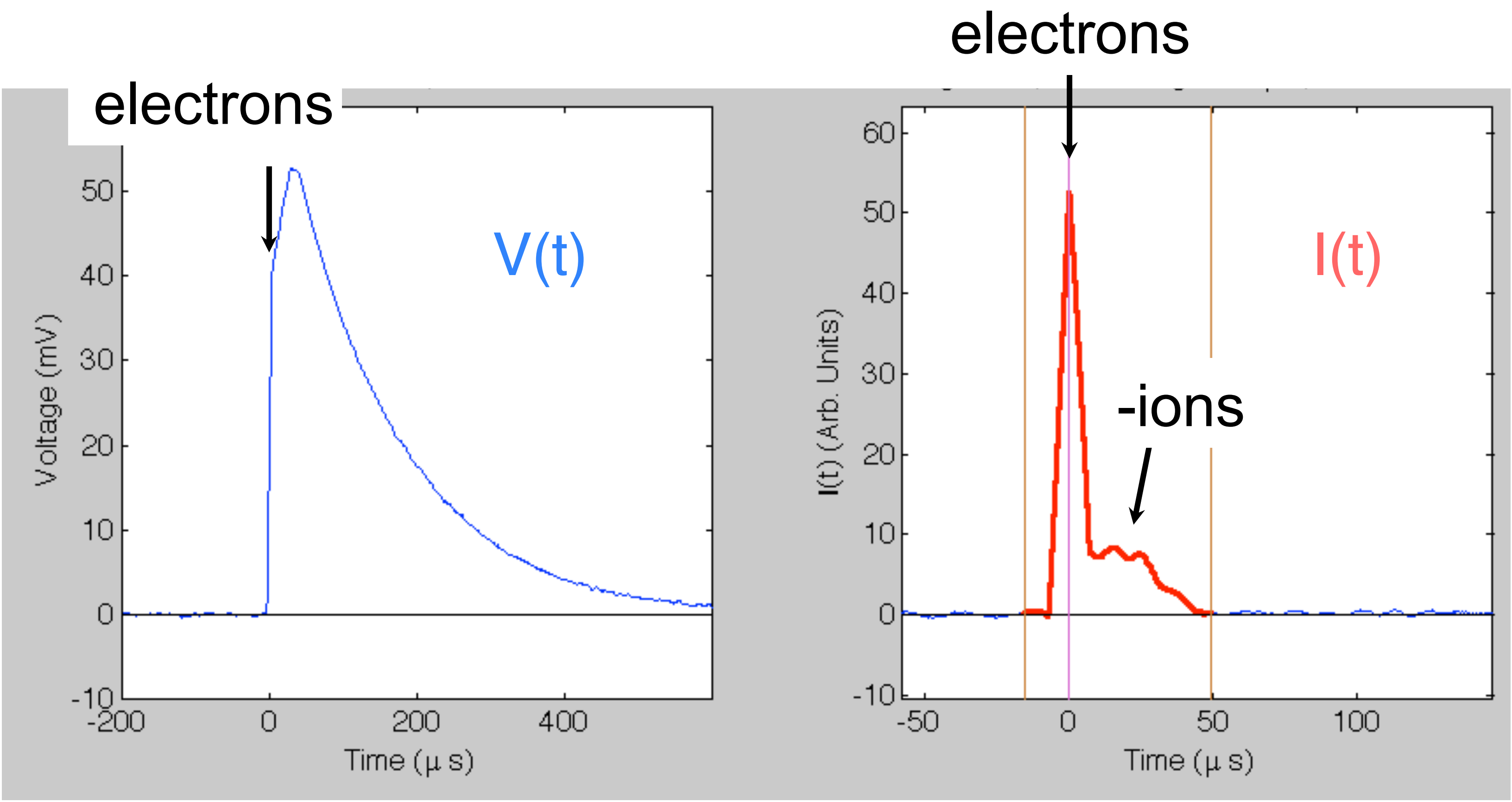


- Determine Optimal $CF_4$+NI Mixtures for NID

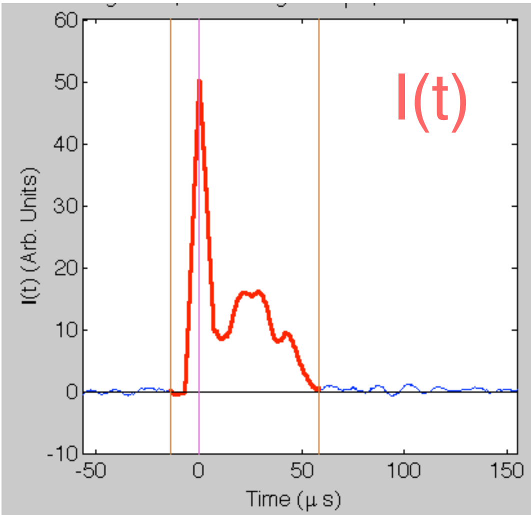
Doping $CF_4$ with small amount of NI gas and:

1. observe transition to negative ion drift (NID) in signal waveforms and alpha track images
2. quantify and optimize diffusion as a function of NI %:
   - Estimate $\sigma_L$ using 60 cm drift TPC with charge readout
   - Estimate $\sigma_T$ using width of Po-210 alpha tracks in optical readout
3. quantify effect of NI on light and light yield (LY):
   - Estimate light(charge) using optical(charge) Fe-55 spectrum
   - LY == light/charge using peaks in respective spectra

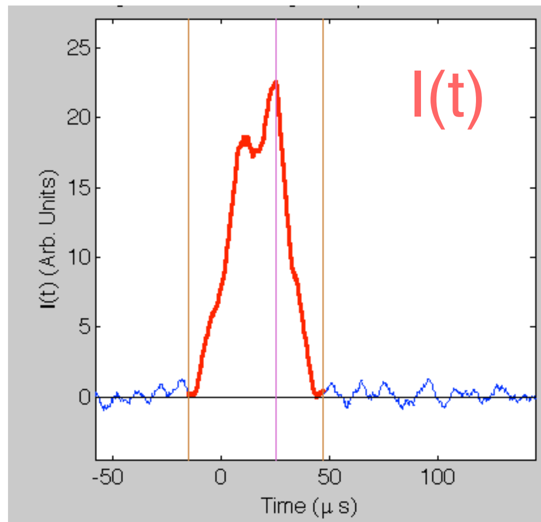
1. Transition to NID with increased NI content seen **qualitatively** in waveforms:




Small TPC with ~1.5 cm drift gap

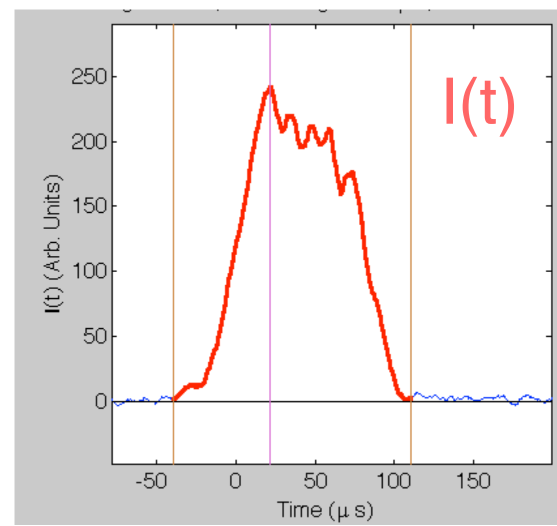



5.9 keV electron waveforms

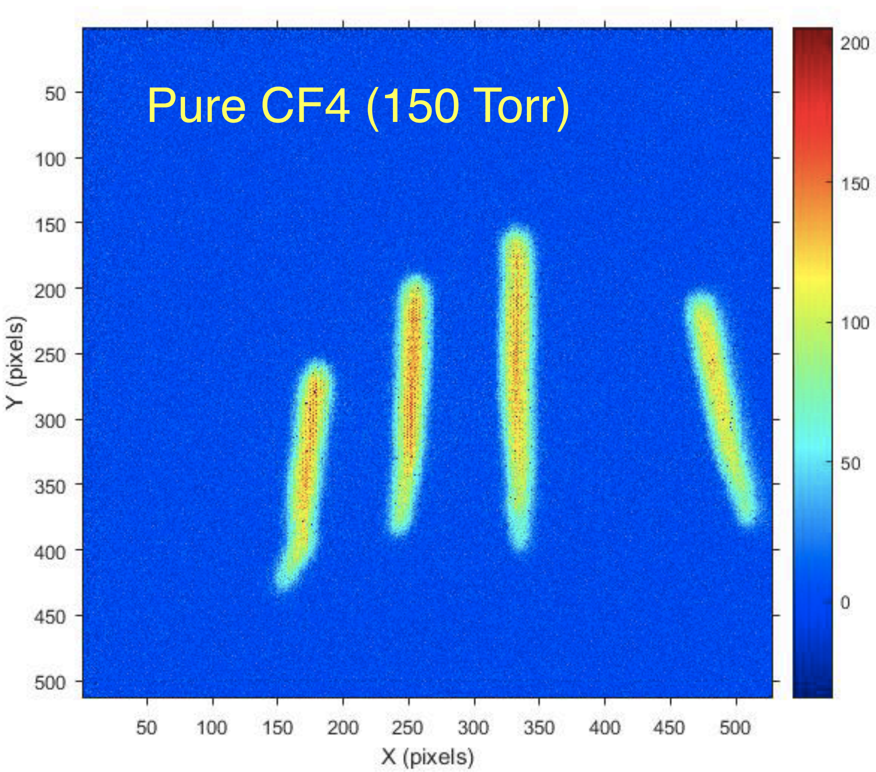


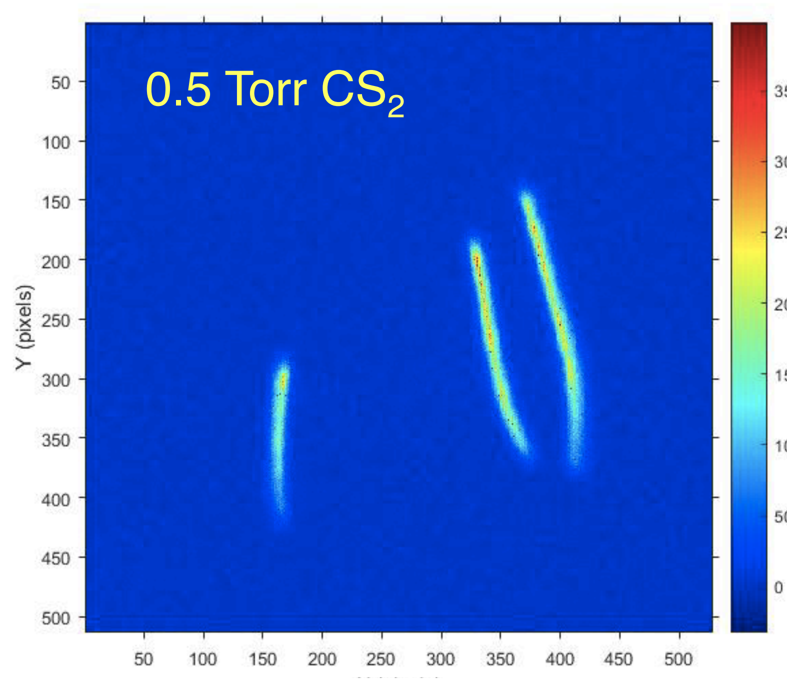

More $CS_2$

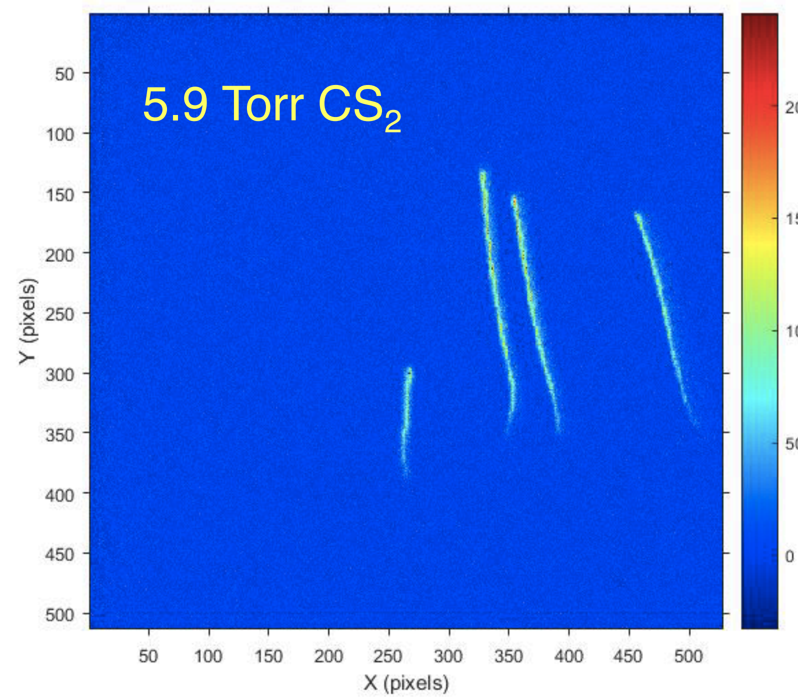
Nuclear Recoil waveform



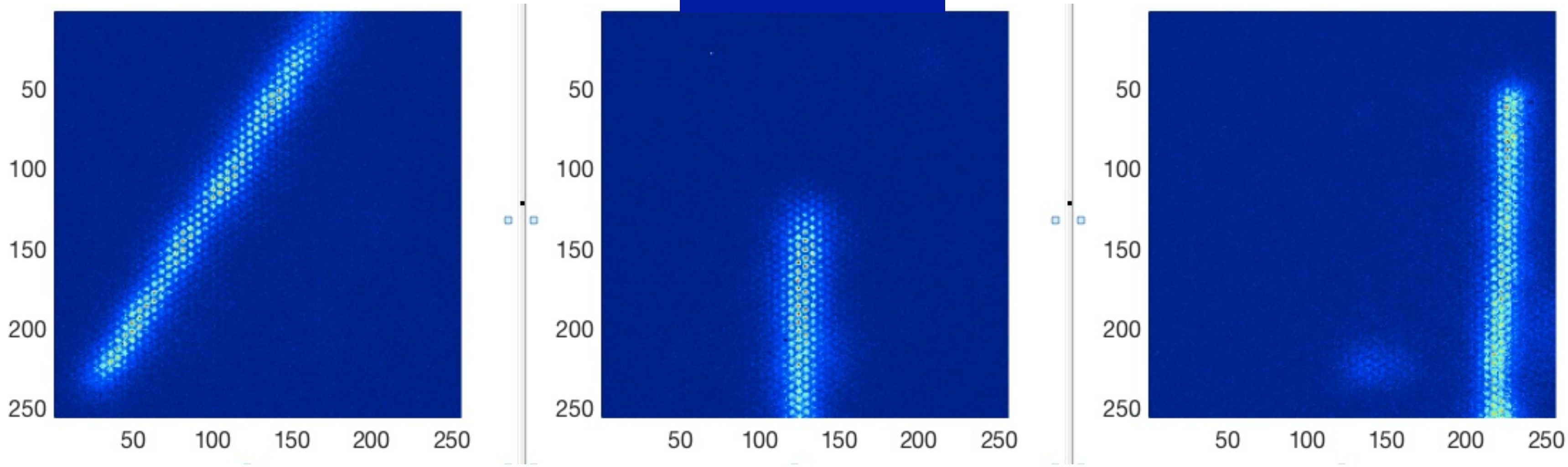
...and also in images of Po-210 alpha tracks:



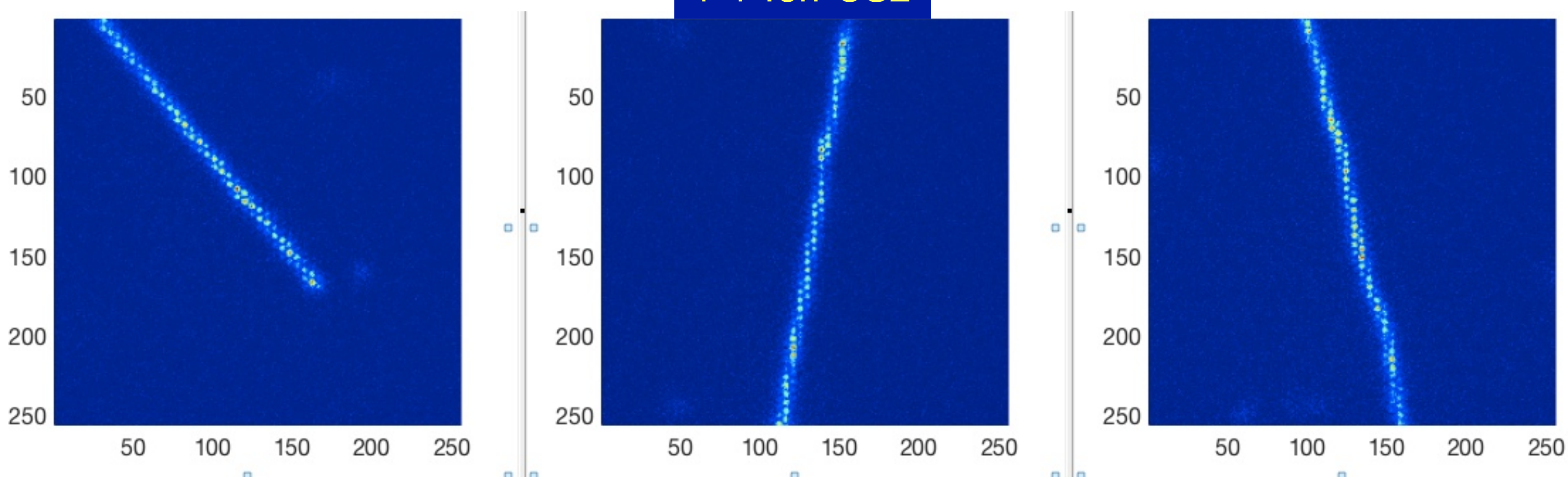



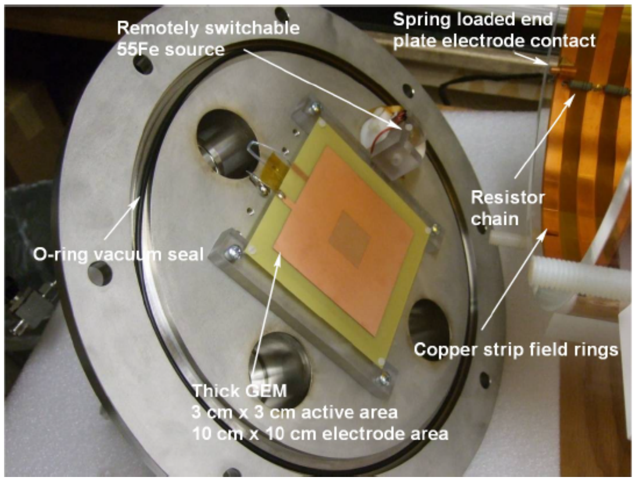
## ~40 Torr CF4

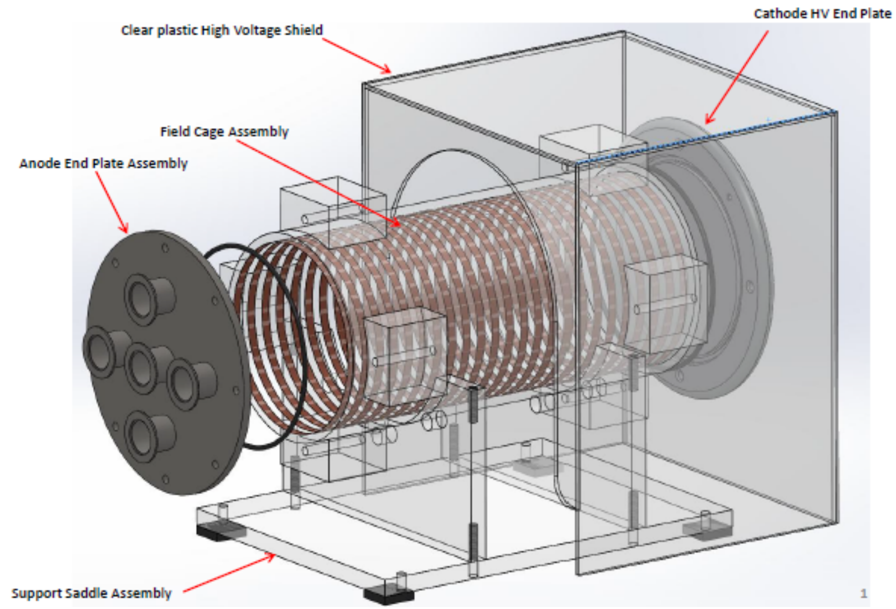


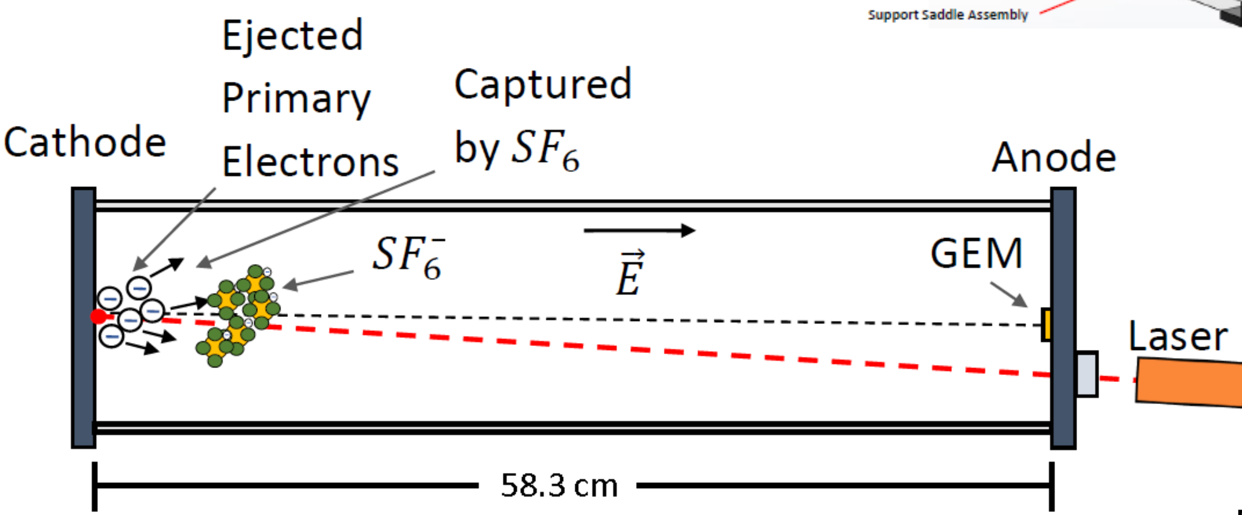

## + 4 Torr CS2



# 2a) Quantify diffusion ($\sigma_L$) and find optimal NI % using charge readout:



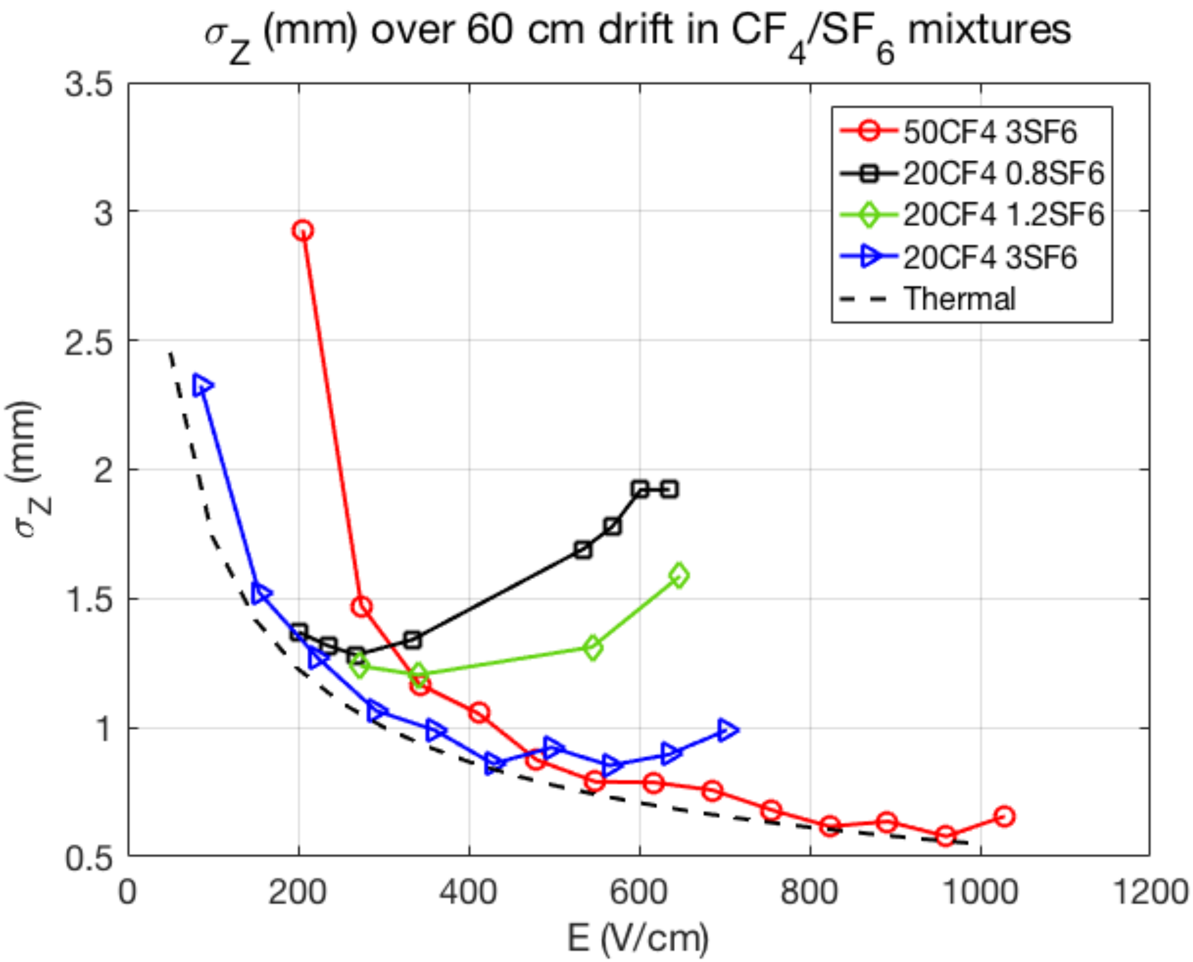

Used to measure:

- diffusion
- mobility
- waveforms

Phan et al 2017 *JINST*

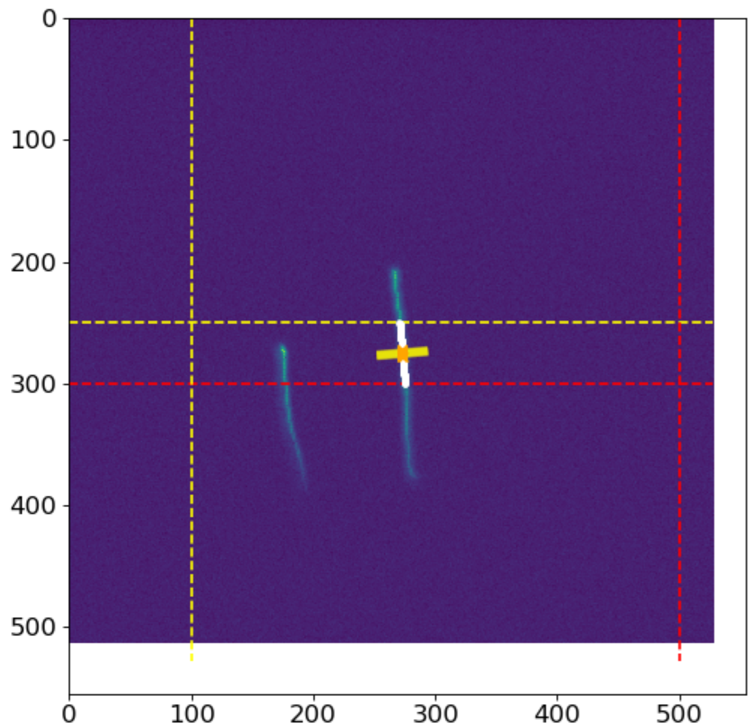
R. Lafler, PhD Thesis, UNM, 2019

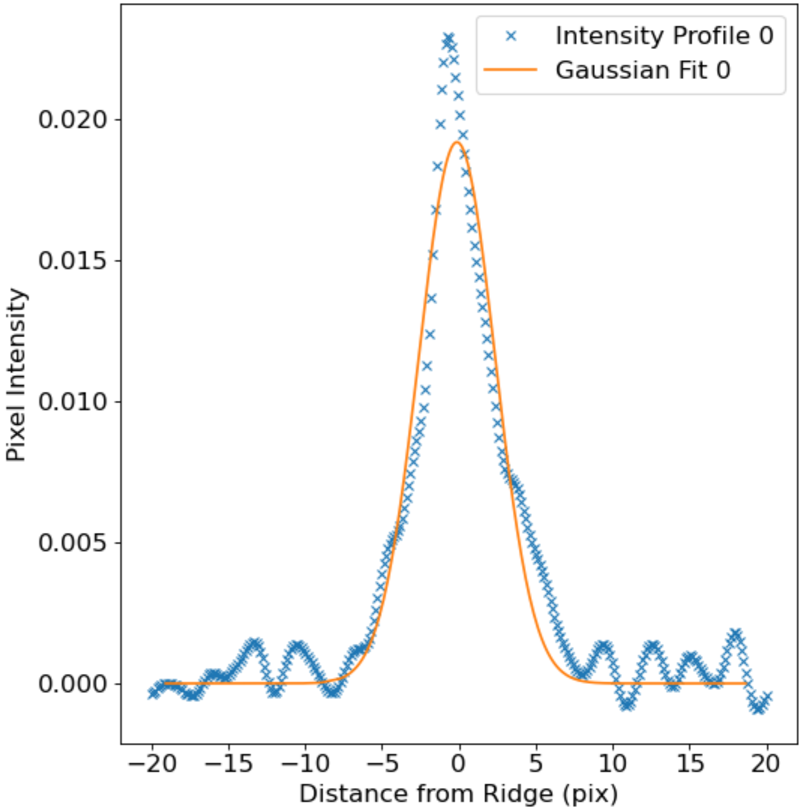
# Results for $\sigma_L$ in low pressure CF4/SF6 mixtures:




R. Lafler, PhD Thesis, UNM, 2019

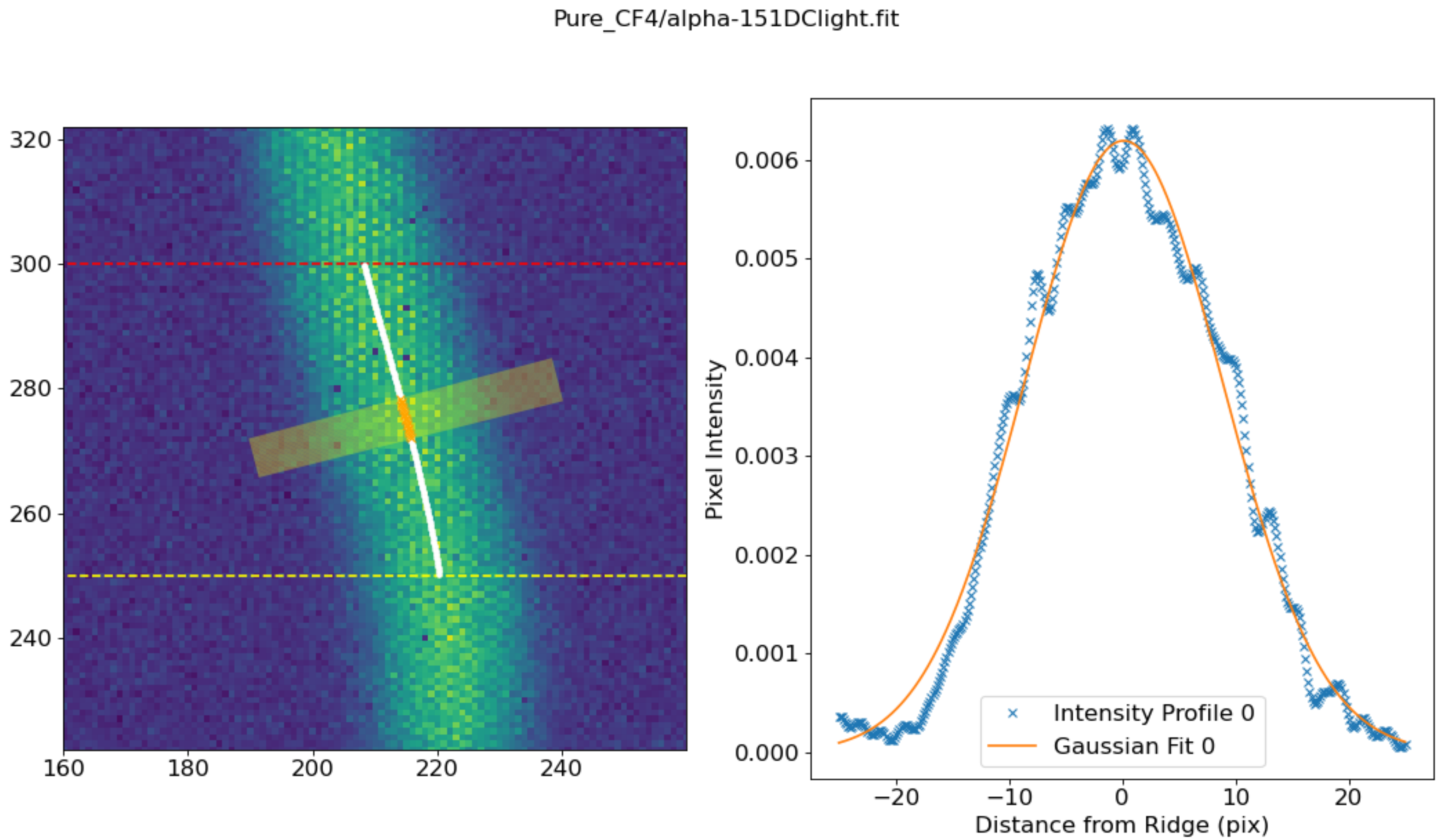
# 2b) Quantify diffusion ($\sigma_T$) and find optimal NI % using alpha tracks in an OTPC:




**The method**

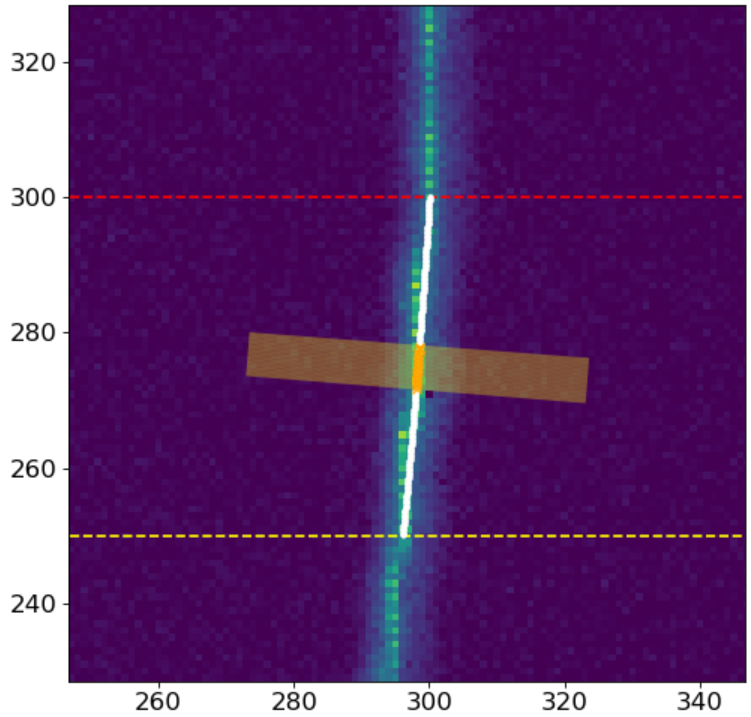
# 150 Torr $CF_4$

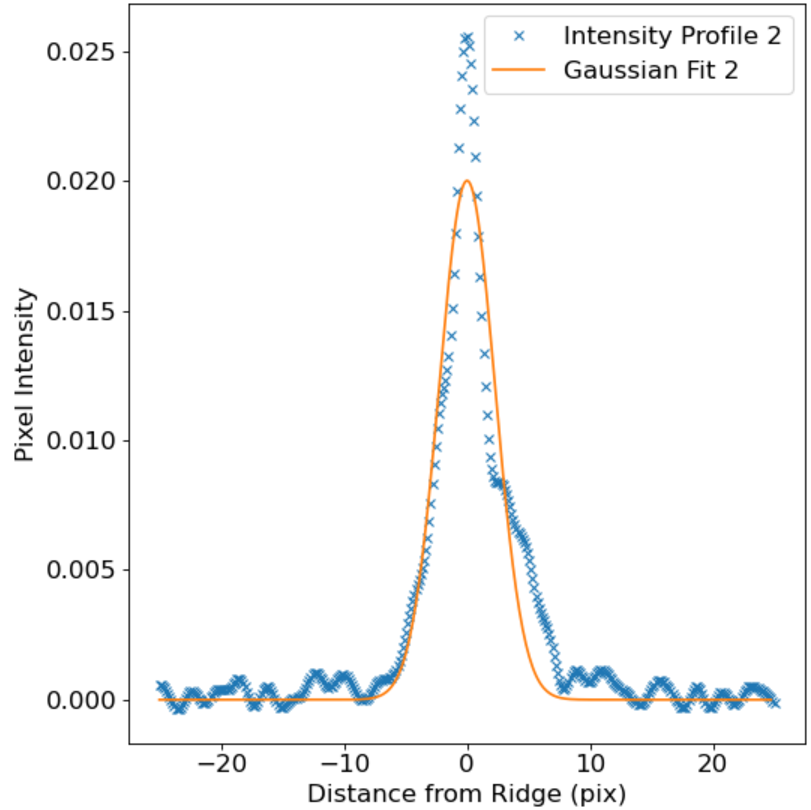


Pure_CF4/alpha-151DClight.fit
320
300
280
260
240
160
180
200
220
240
0.006
0.005
0.004
0.003
0.002
0.001
0.000
Pixel Intensity
−20
−10
0
10
20
Distance from Ridge (pix)
Intensity Profile 0
Gaussian Fit 0

# 150 Torr $CF_4$ + 2.9 CS2

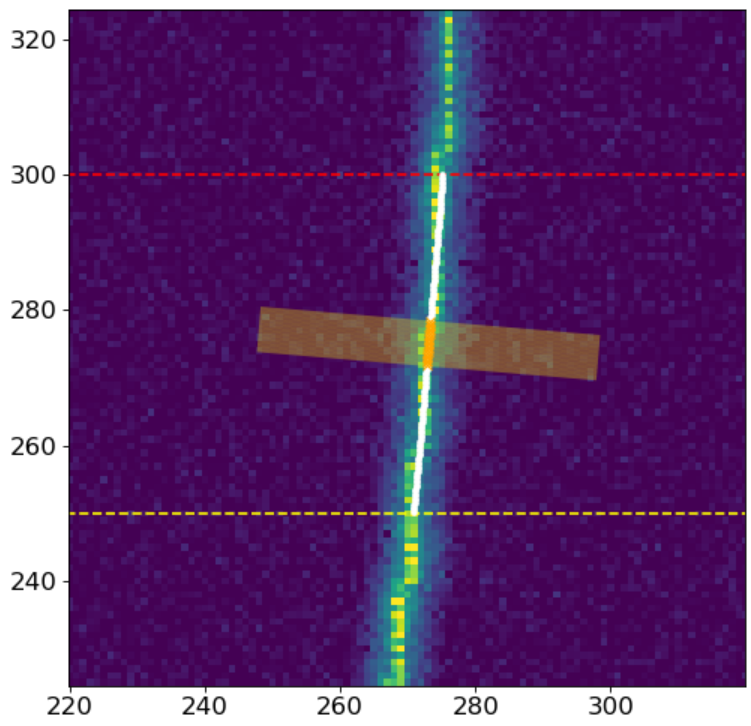
2.9Torr_CS2/alpha-002DClight.fits

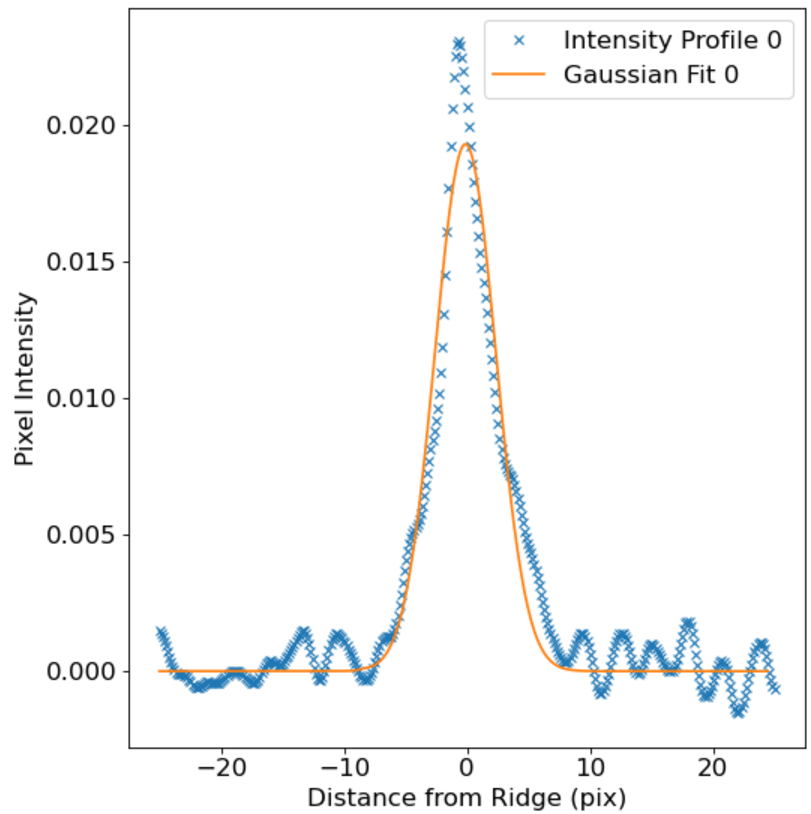


# 150 Torr $CF_4$ + 4.2 CS2

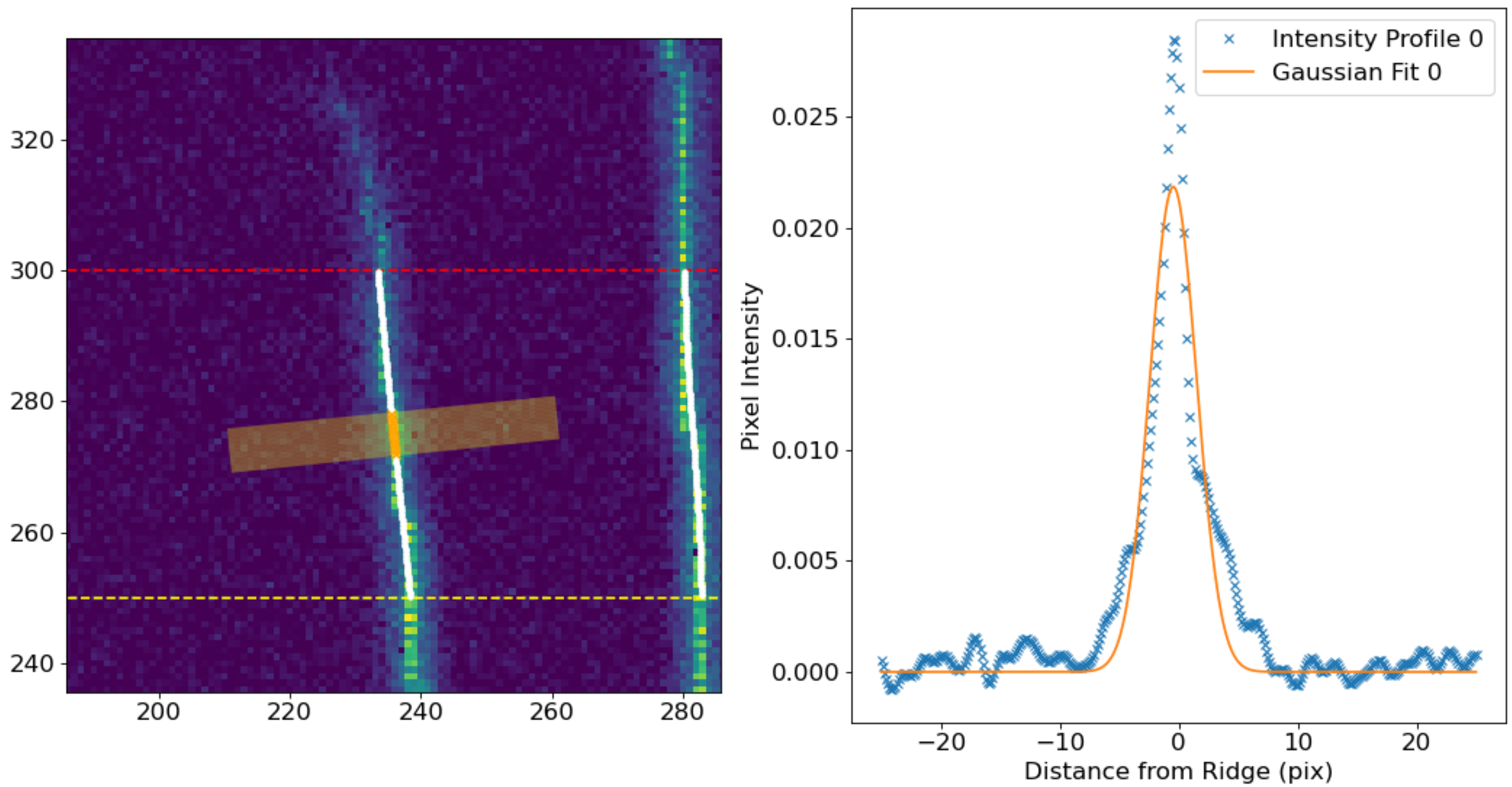
4.2Torr_CS2/alpha-003DClight.fits



# 150 Torr $CF_4$ + 5.4 CS2

5.4Torr_CS2/alpha-112DClight.fits



# Results for $\sigma_T$:

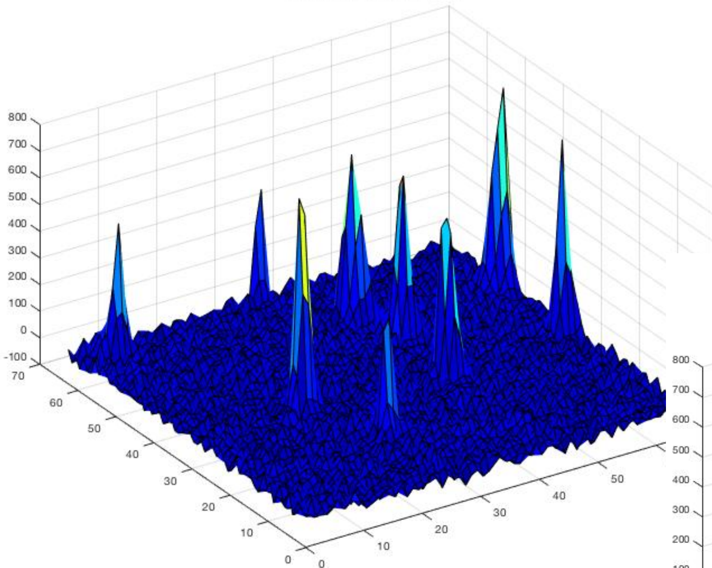
**150 Torr CF4 + x Torr CS2**

| $CS_2$ (Torr) | σ (pix) | σ(μm) |
|---|---|---|
| 0 | 9.21 | ~400 |
| 2.9 | 2.30 | 133.53 |
| 4.2 | 2.17 | 126.10 |
| 5.4 | 2.16 | 125.09 |

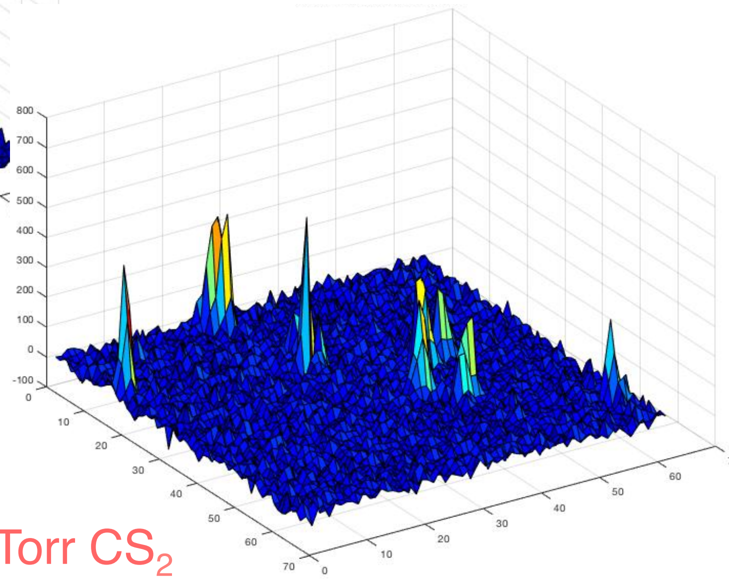
**~45 Torr CF4 + x Torr CS2**

| $CS_2$ (Torr) | σ(μm) |
|---|---|
| 0 | ~550 |
| 4 | ~150-200 |

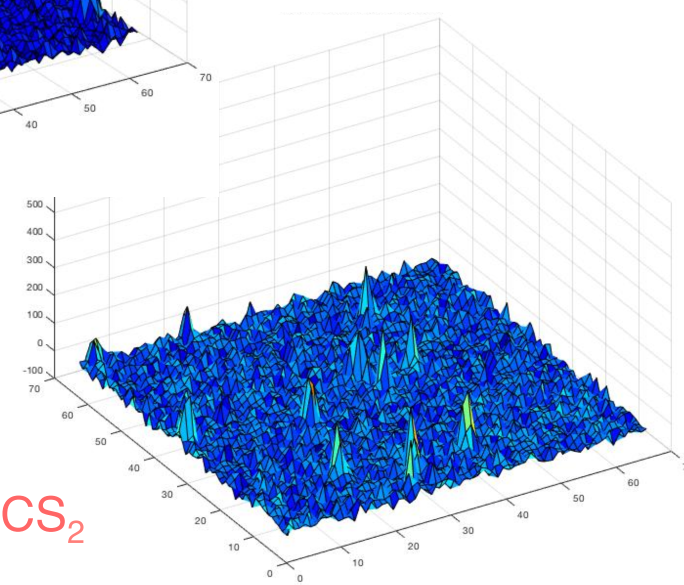
# 3. Fe-55 to quantify effect of NI on light and light yield (LY):




150 Torr $CF_4$

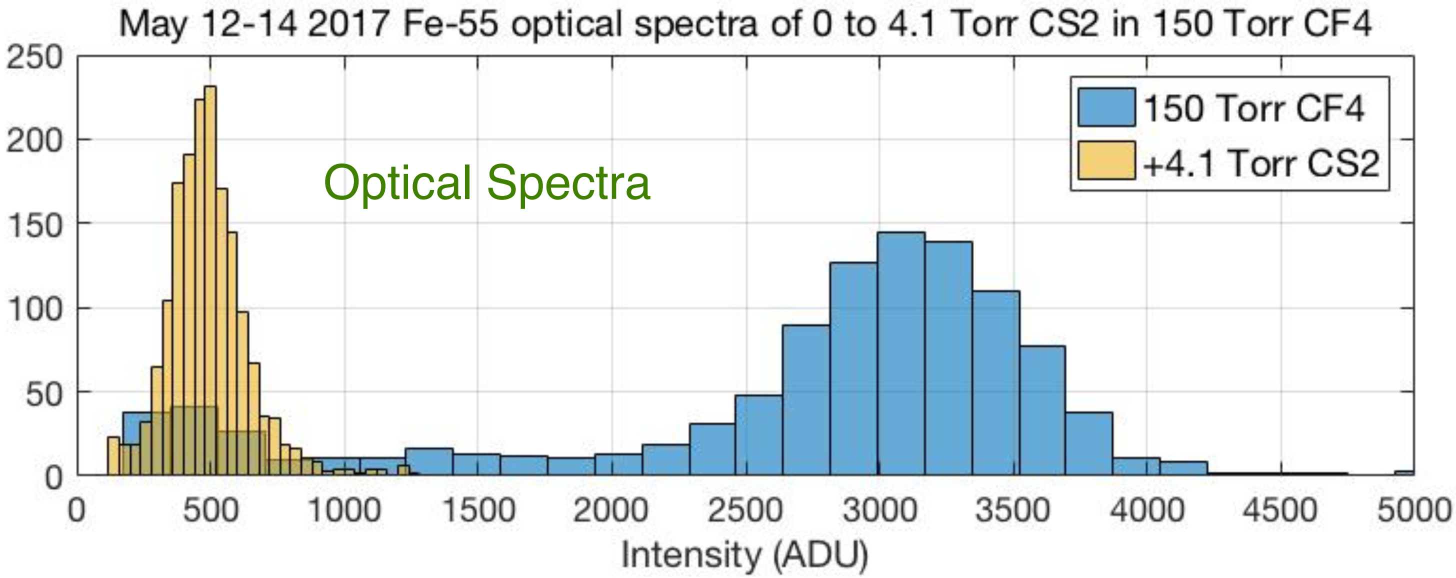


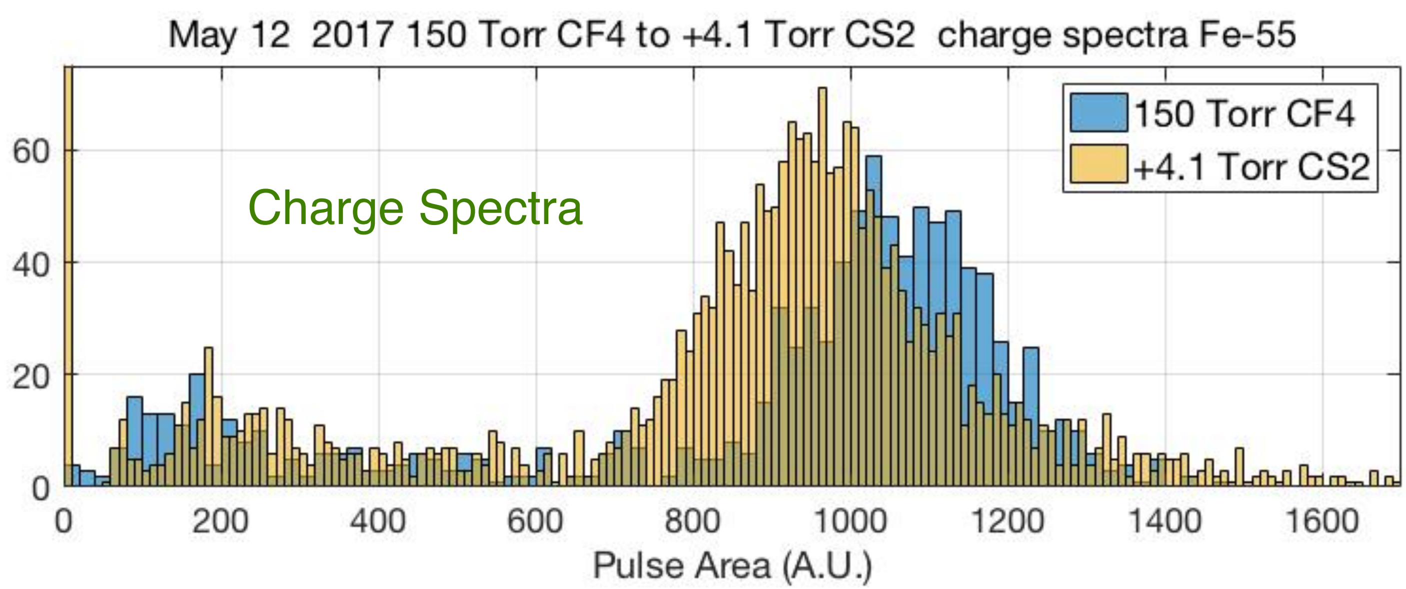

+0.5 Torr $CS_2$



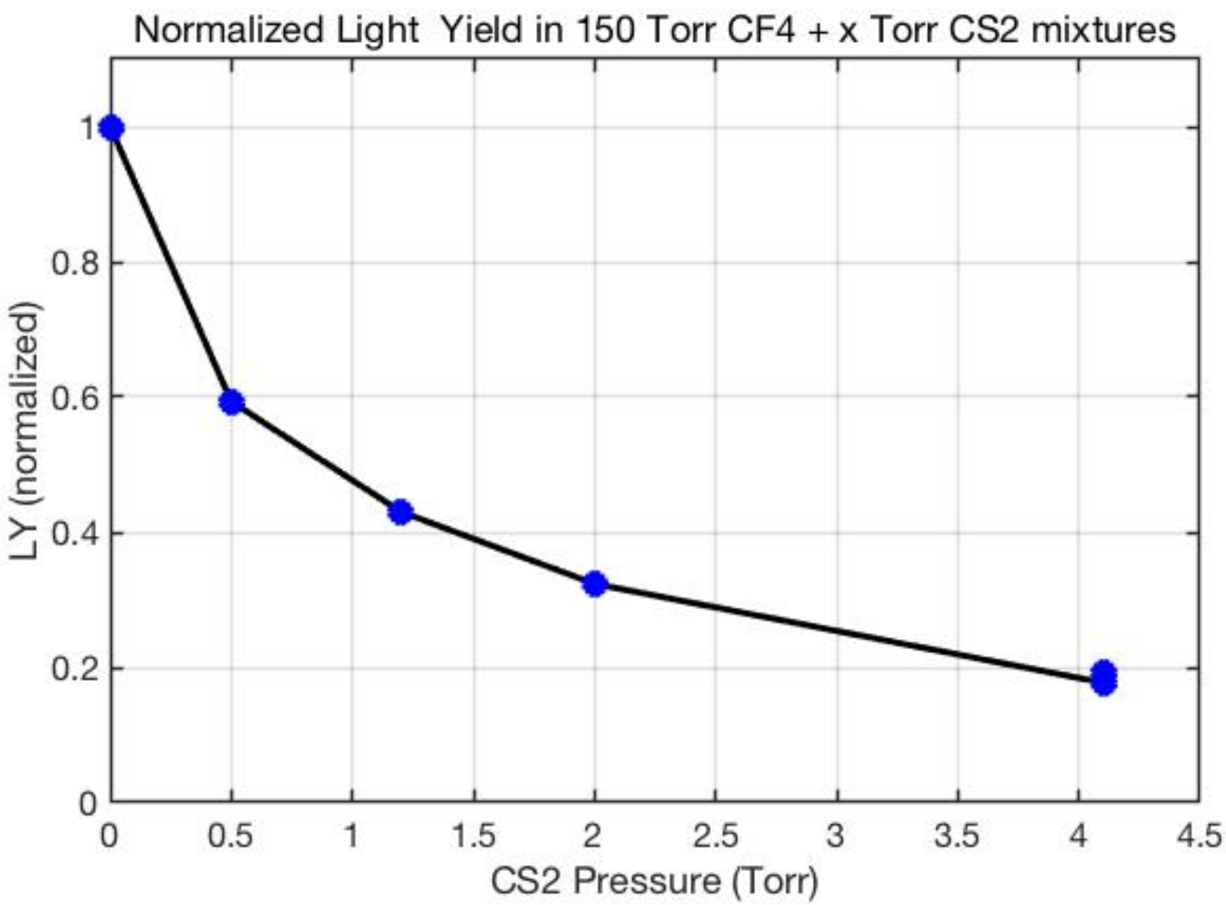

+4.1 Torr $CS_2$

D. Loomba, UNM

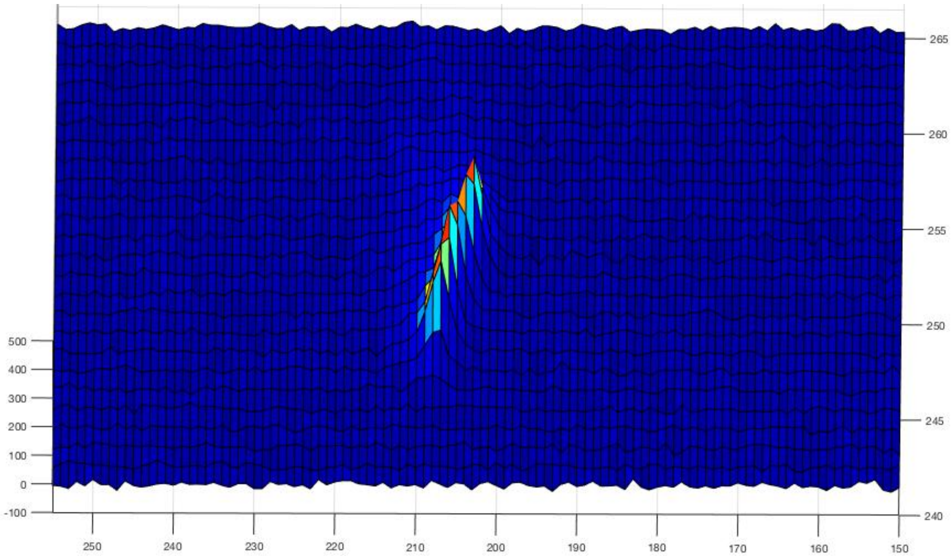

May 12-14 2017 Fe-55 optical spectra of 0 to 4.1 Torr CS2 in 150 Torr CF4
150 Torr CF4
+4.1 Torr CS2
Optical Spectra
0
50
100
150
200
250
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Intensity (ADU)

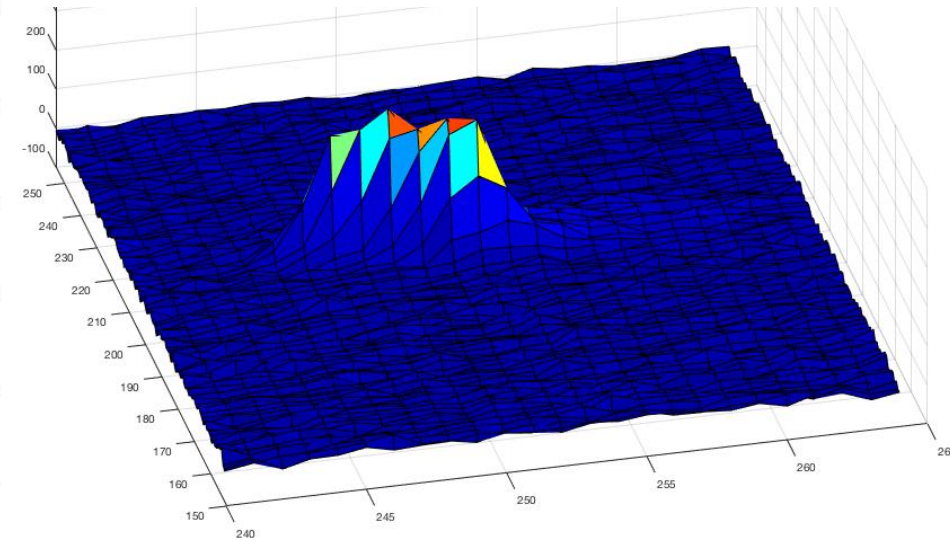

May 12 2017 150 Torr CF4 to +4.1 Torr CS2 charge spectra Fe-55
150 Torr CF4
+4.1 Torr CS2
Charge Spectra
0
20
40
60
0
200
400
600
800
1000
1200
1400
1600
Pulse Area (A.U.)

# Light Yield (LY) in **150 Torr CF4 + x Torr CS2**

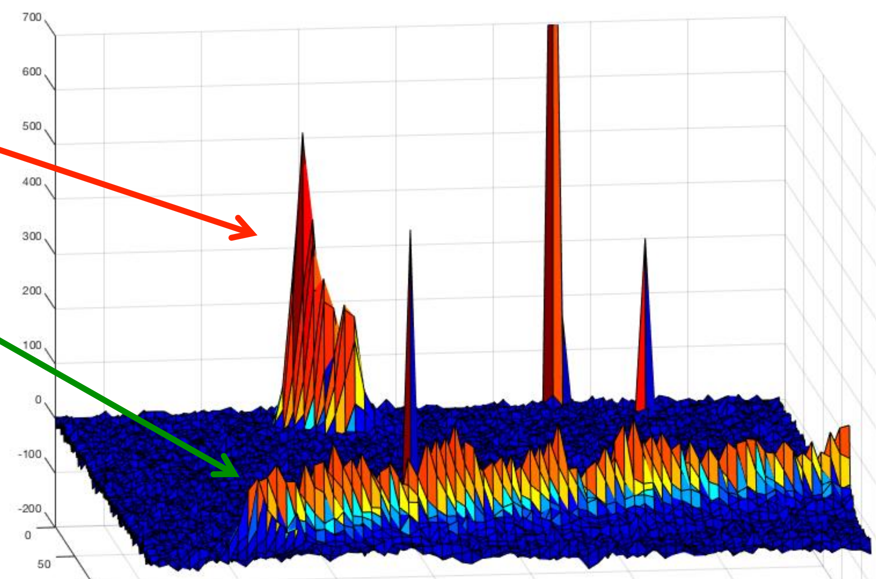


# Nuclear recoils in 150 Torr CF4 + 5 Torr CS2




**Fluorine recoils**, **proton** and CRs in $CF_4$+$CS_2$



# What about low energy electrons and NRs?

- Need to go to lower pressures, ~50 Torr
- Higher signal-to-noise for low dE/dx particles

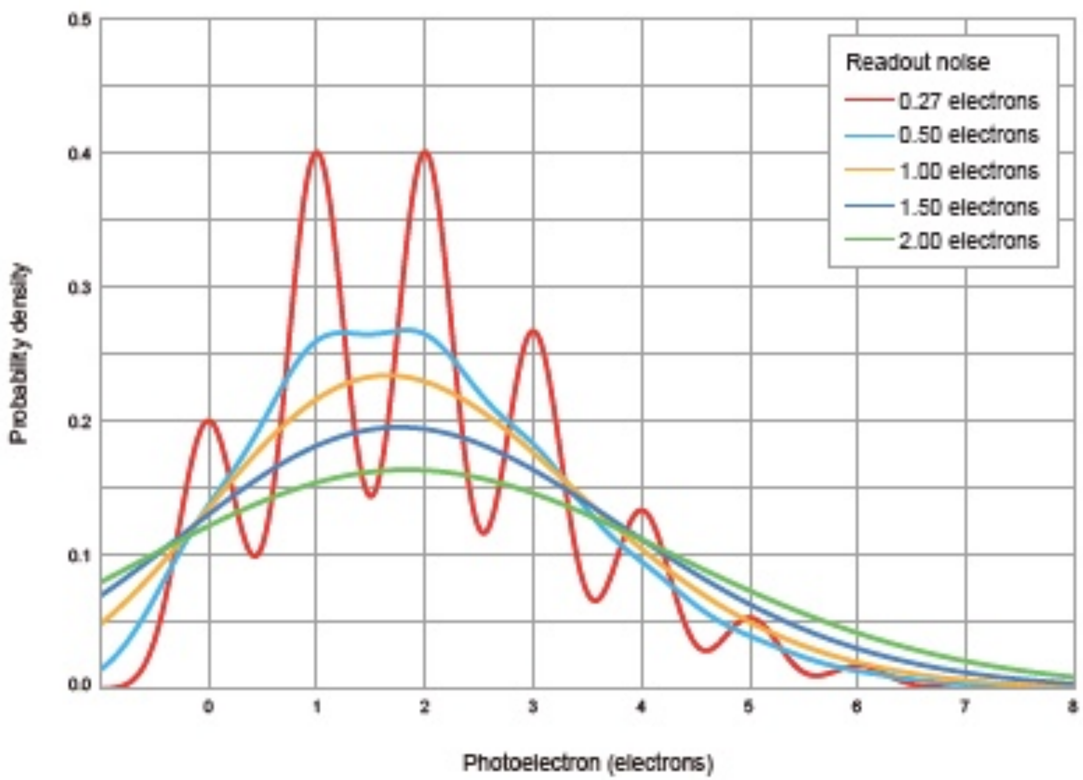
➢ Double Glass-GEMs for high (>$10^5$) gas gain at low P
  - 10 cm x 10 cm
  - 280 μm pitch, 570 μm thick

➢ Hamamatsu ORCA-Quest CMOS camera:

# 2. Realization of photon number resolving (PNR) output

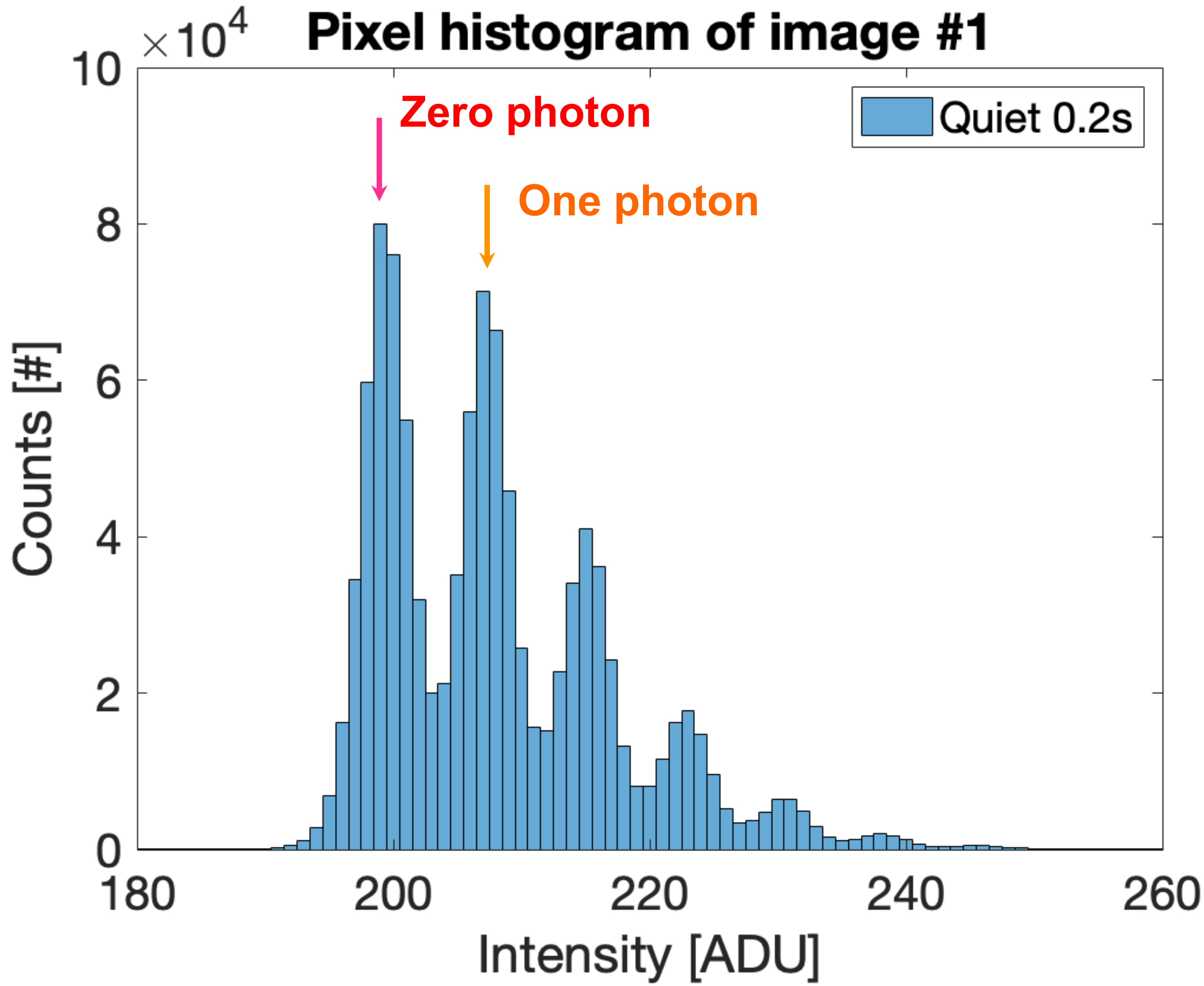
## Realization of photon number resolving by low-readout noise

**Simulation data of photoelectron probability distribution** (Average number of photoelectrons generated per pixel: 2 electrons)

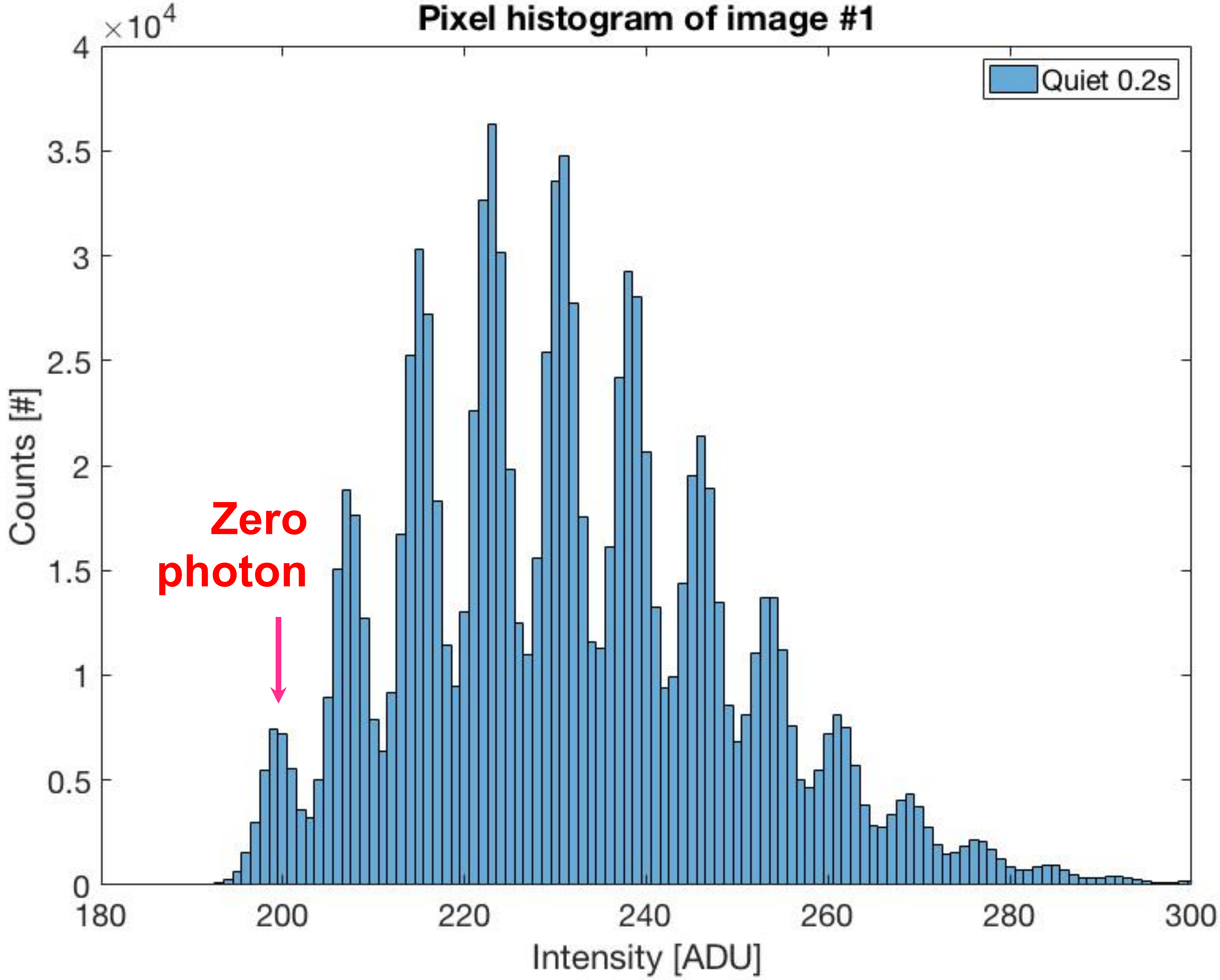



* Photon number resolving is unique and quite different from photon counting (More precisely the method resolves the number of photoelectrons. However, since single photon counting instead of single photoelectron counting has been used for a comparable method in this field, we will use the term "photon number resolving" in this brochure).

# Low light – Photon # Resolving

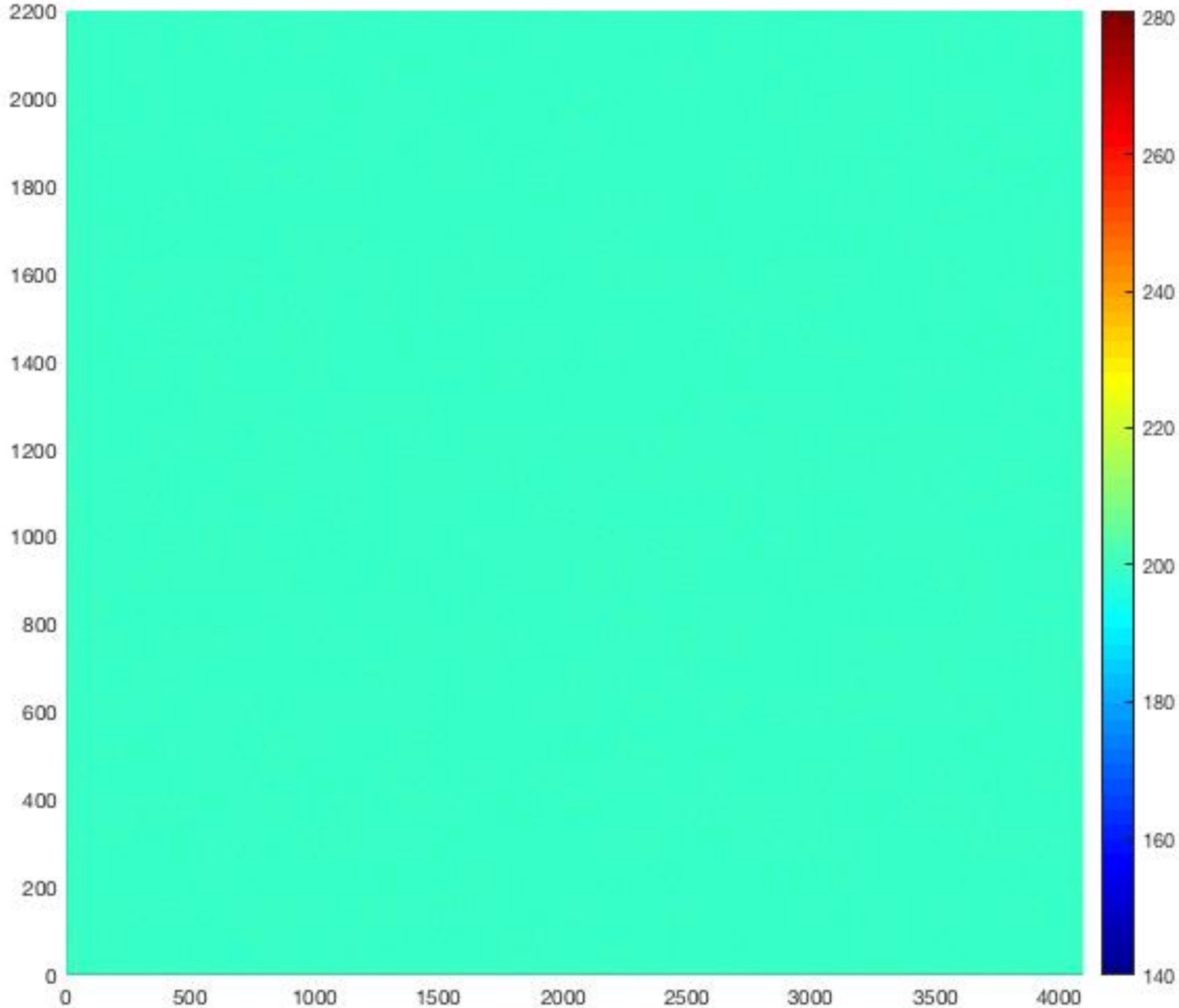


# More light



Pixel histogram of image #1
Quiet 0.2s
Counts [#]
Intensity [ADU]
×10^4
4
3.5
3
2.5
2
1.5
1
0.5
0
180
200
220
240
260
280
300
Zero photon

# Darks – 0.2s, ultra-quiet
# 1x1 binning, full chip

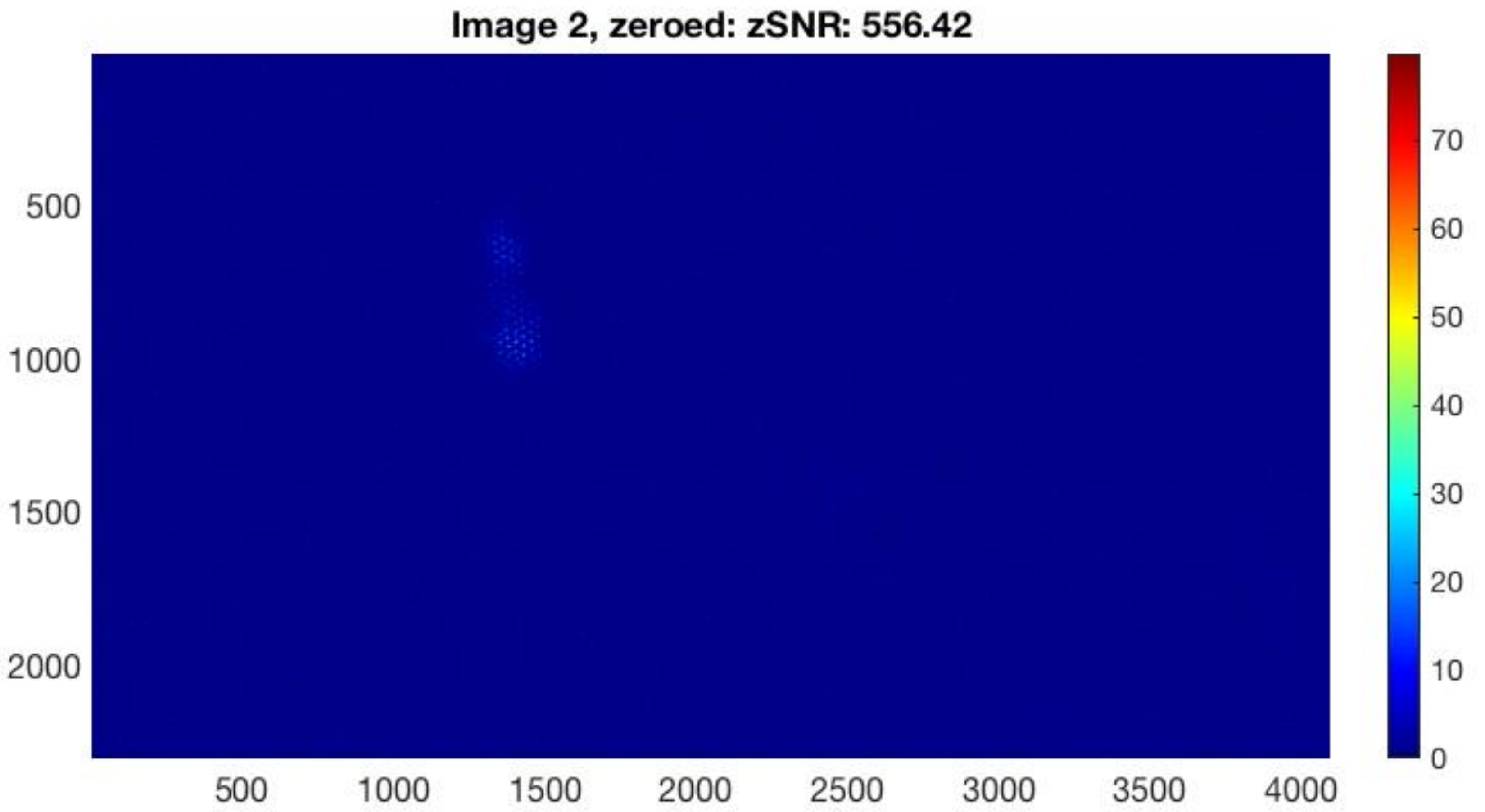


# Imaging low-energy Fe-55 electron tracks in a NI-OTPC

QUEST + G-GEMs:

- **50 Torr CF4**
- **45 Torr CF4 + 4.3 Torr $CS_2$**

# 5.9 keV electron tracks in 50 Torr $CF_4$



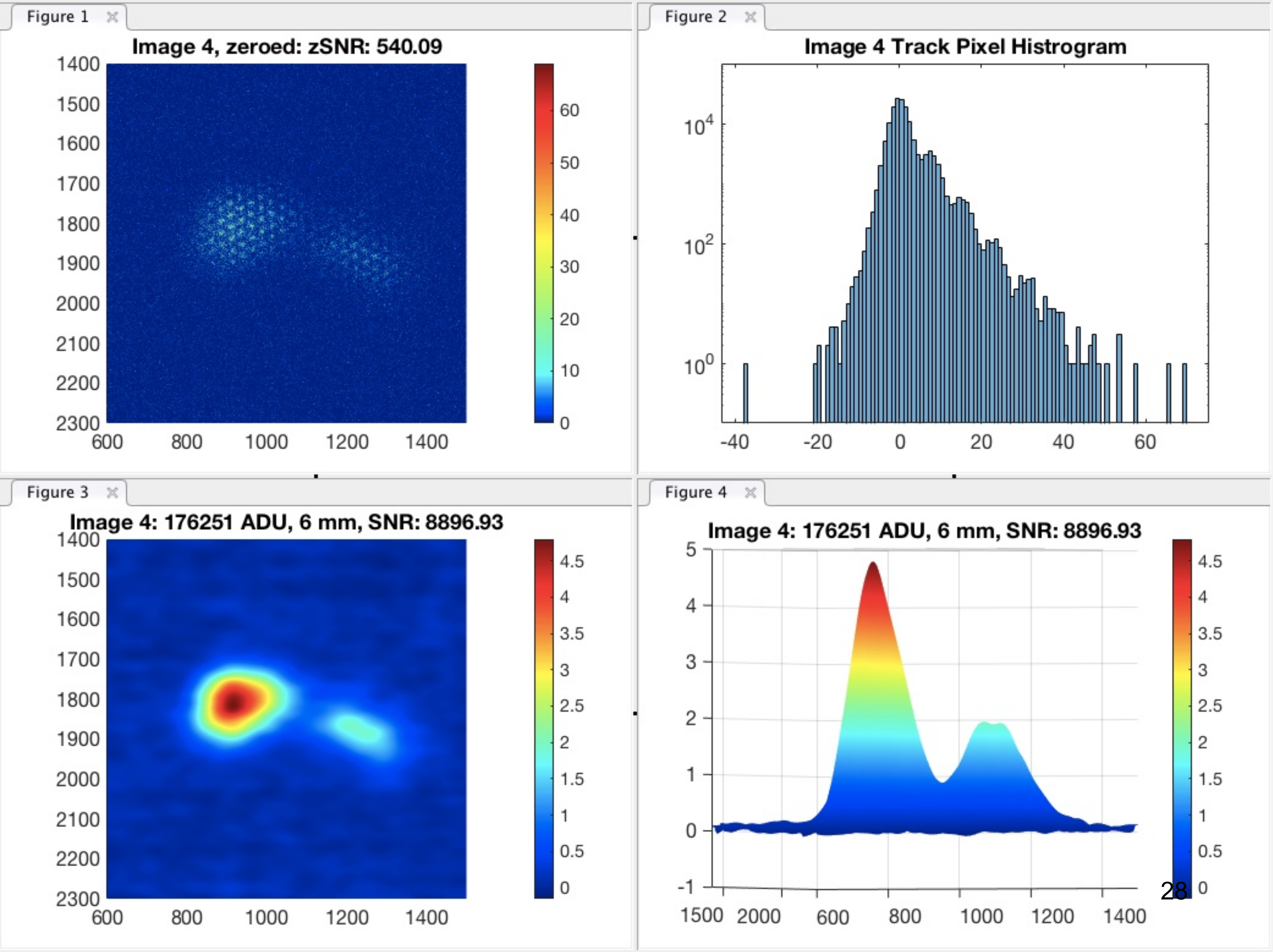
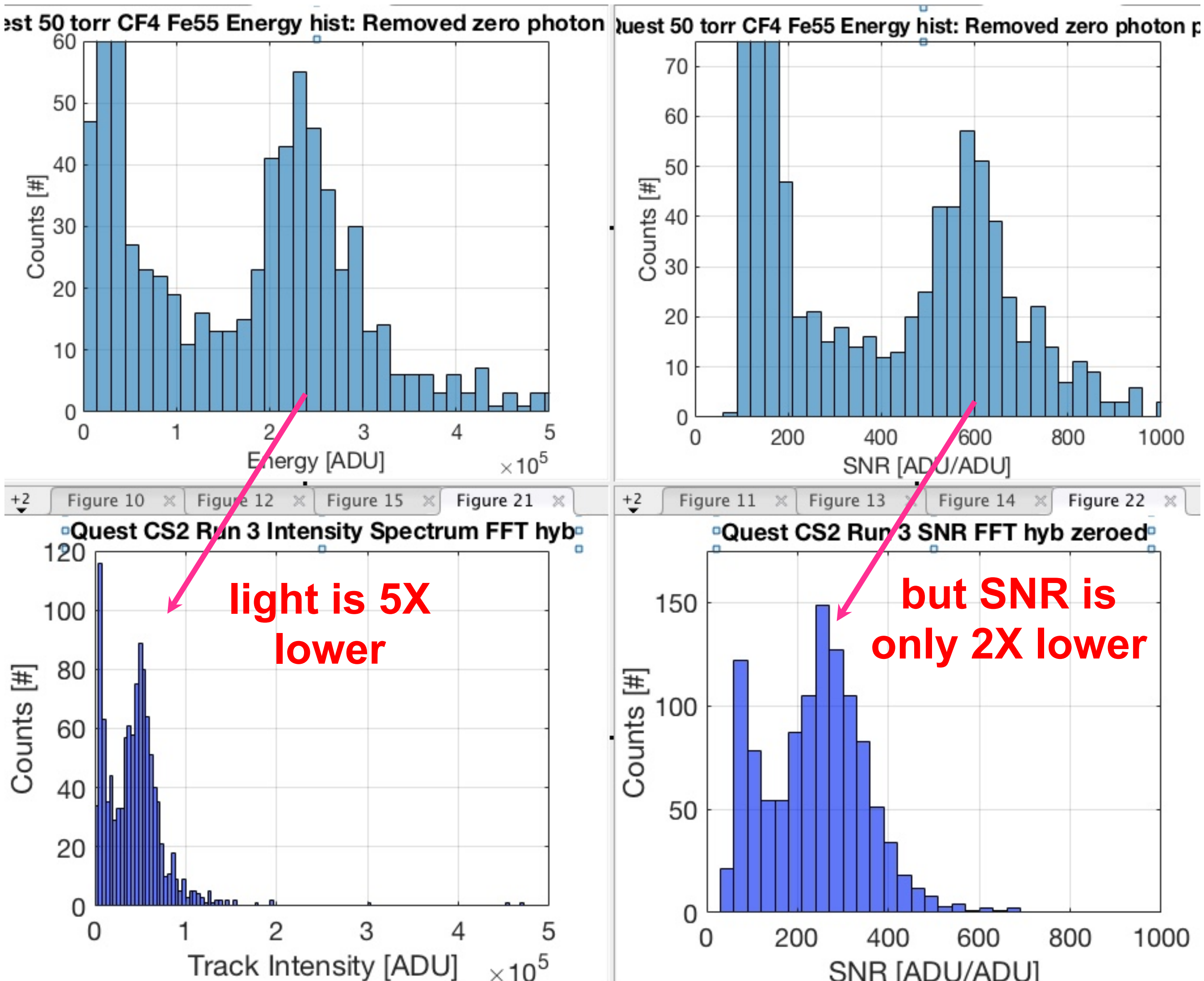


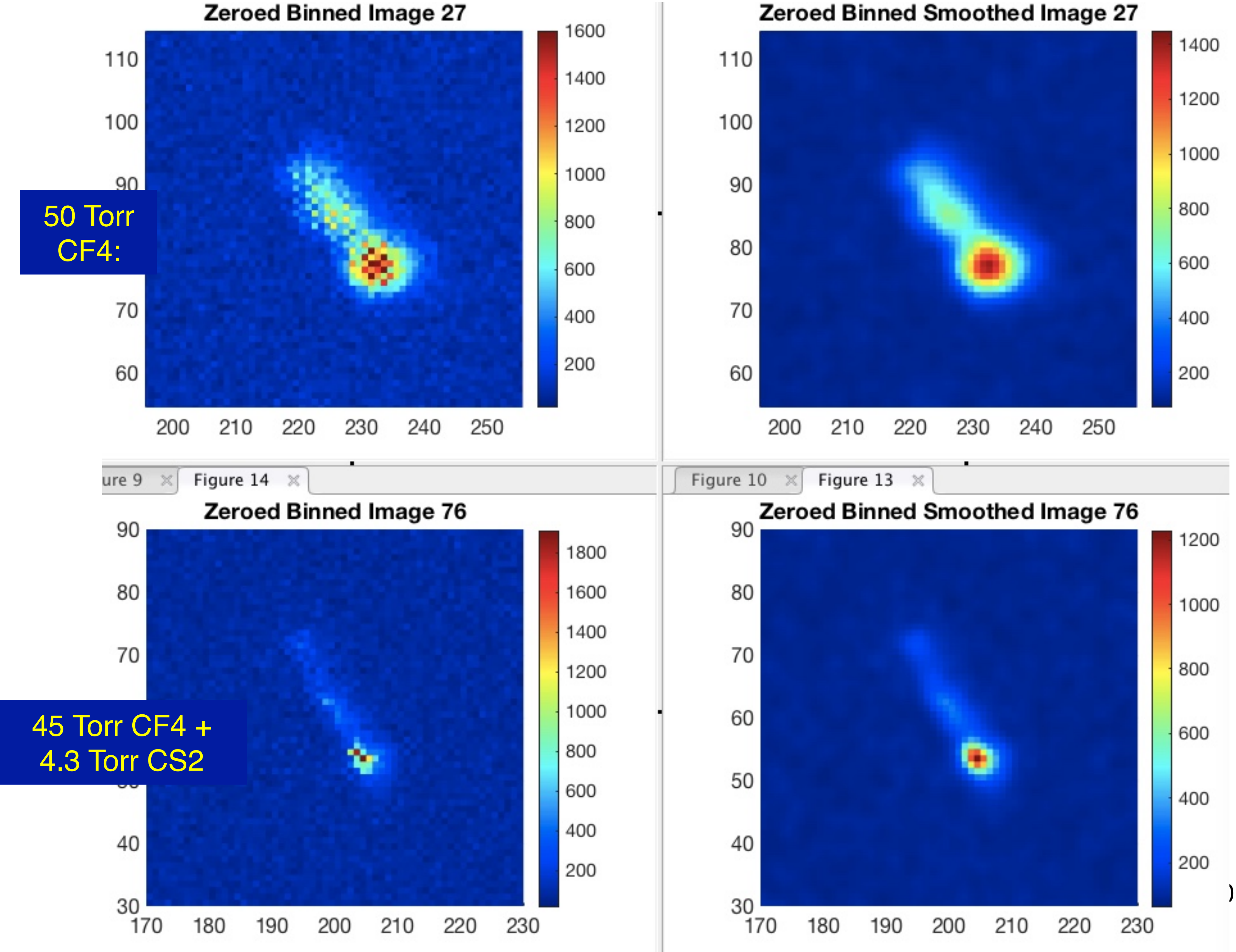
Figure 1
Image 4, zeroed: zSNR: 540.09
Figure 2
Image 4 Track Pixel Histrogram
Figure 3
Image 4: 176251 ADU, 6 mm, SNR: 8896.93
Figure 4
Image 4: 176251 ADU, 6 mm, SNR: 8896.93

# Fe-55 optical spectra and SNR:

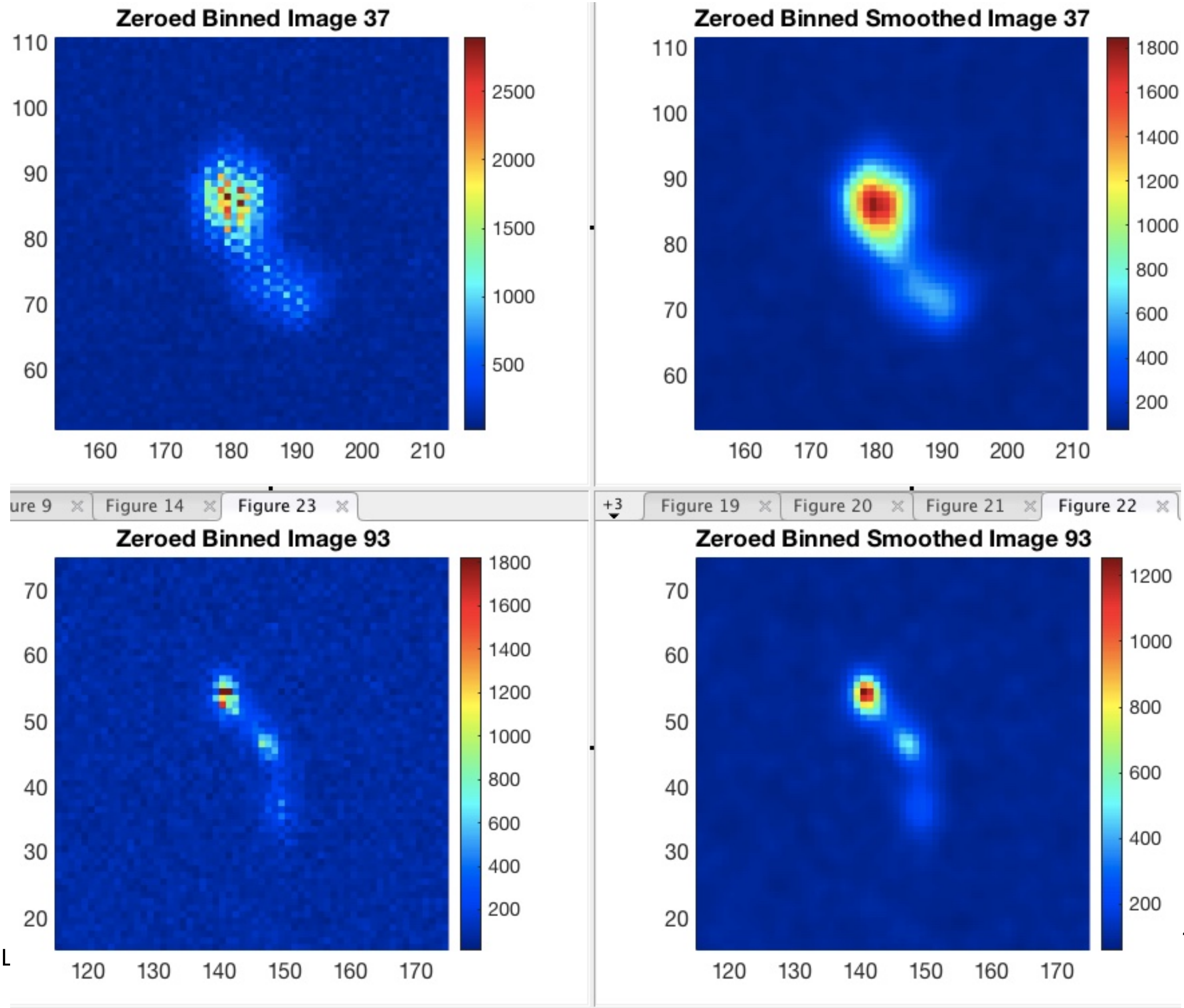
**50 Torr CF4:**

**45 Torr CF4 + 4.3 Torr CS2**

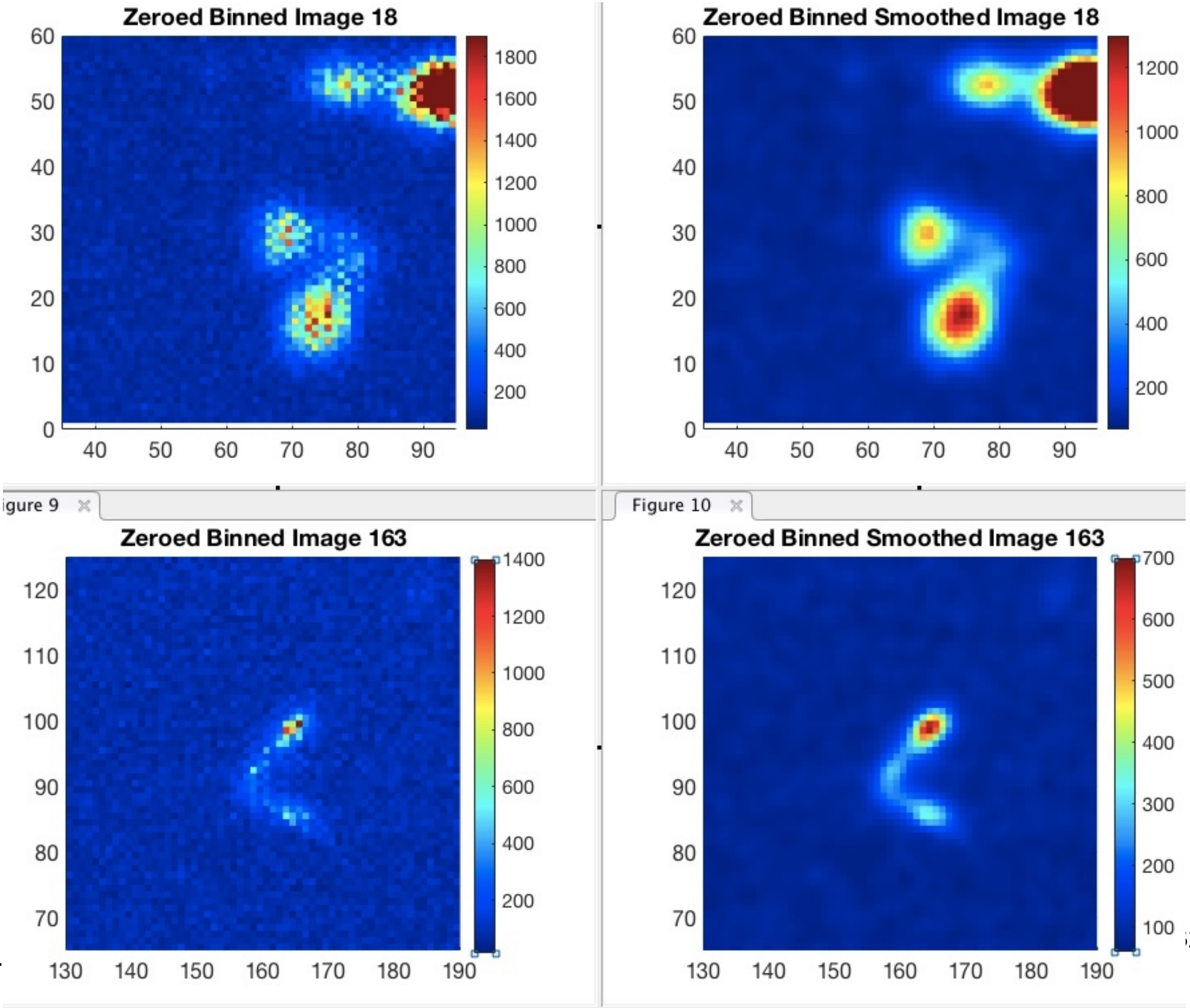




Zoered Binned Image 27
Zeroed Binned Smoothed Image 27
50 Torr
CF4:
ure 9
Figure 14
Figure 10
Figure 13
Zeroed Binned Image 76
Zeroed Binned Smoothed Image 76
45 Torr CF4 +
4.3 Torr CS2

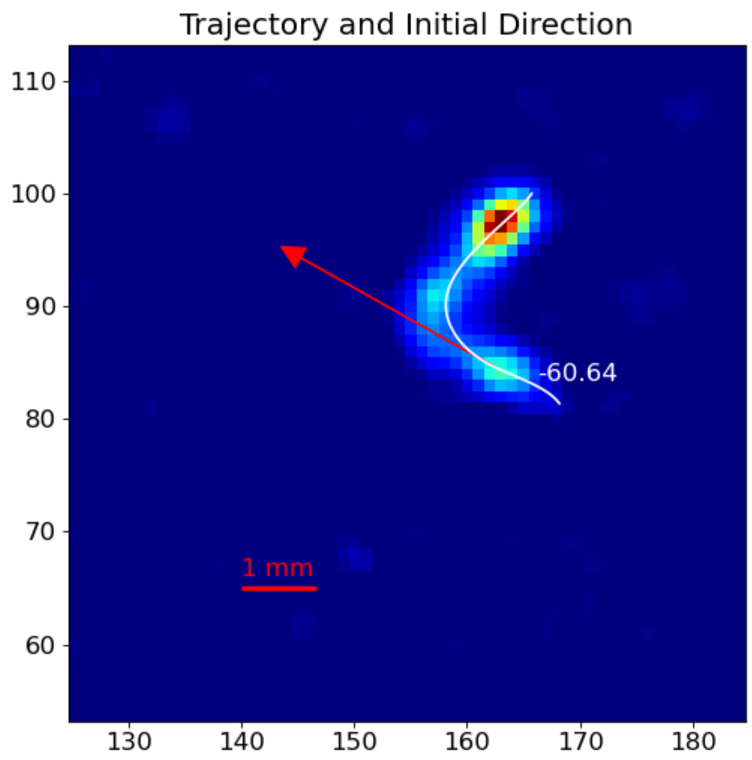

Zeroed Binned Image 37
110
100
90
80
70
60
160 170 180 190 200 210
2500
2000
1500
1000
500
Zeroed Binned Smoothed Image 37
110
100
90
80
70
60
160 170 180 190 200 210
1800
1600
1400
1200
1000
800
600
400
200
ure 9
Figure 14
Figure 23
+3
Figure 19
Figure 20
Figure 21
Figure 22
Zeroed Binned Image 93
70
60
50
40
30
20
120 130 140 150 160 170
1800
1600
1400
1200
1000
800
600
400
200
Zeroed Binned Smoothed Image 93
70
60
50
40
30
20
120 130 140 150 160 170
1200
1000
800
600
400
200

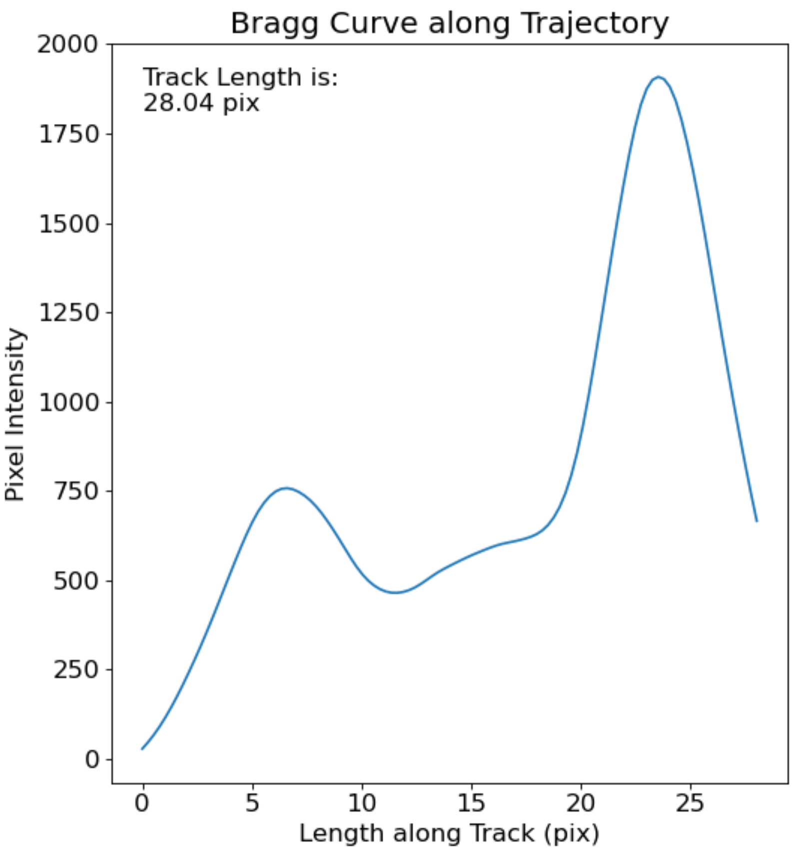
D.

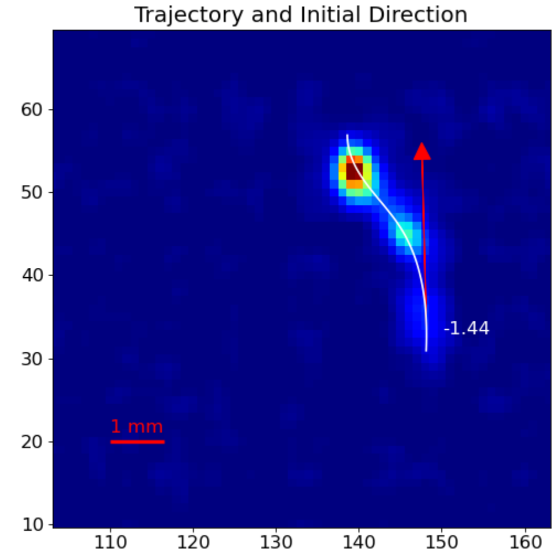

Zeroed Binned Image 18
Zeroed Binned Smoothed Image 18
igure 9
Figure 10
Zeroed Binned Image 163
Zeroed Binned Smoothed Image 163

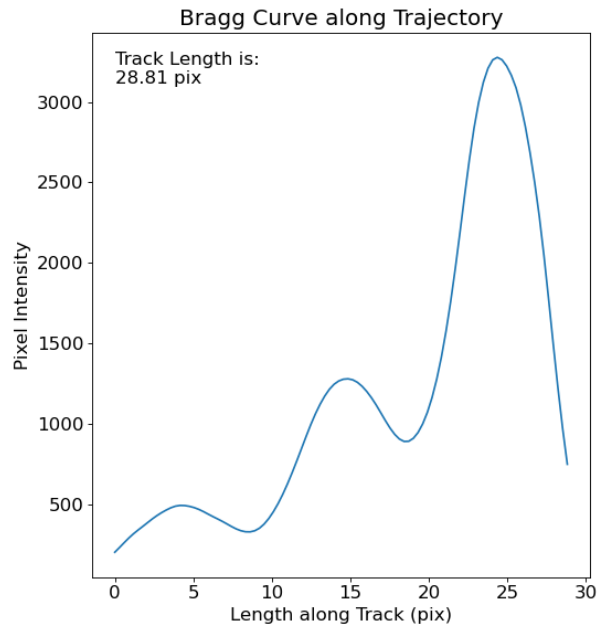
# Conclusions

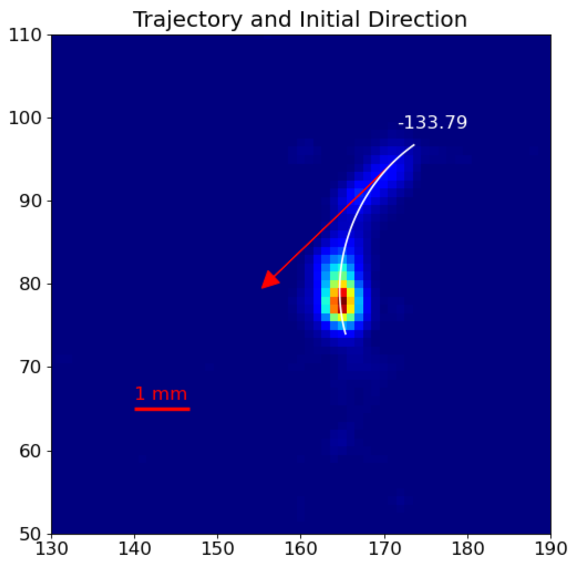
- With with G-GEMs and Quest camera high SNR we have shown at a negative ion OTPC can image particle tracks with the very high resolution
- This enables:
  - detailed reconstruction of the particle's trajectory
  - mapping of the ionization loss
  - particle ID, from NRs to low energy electrons
  - reconstructing the interaction vertex and initial direction
  - etc
- Applications include
  - directional DM and ν searches (CYGNO, CYGNUS)
  - Migdal effect (MIGDAL)
  - X-ray polarimetry
  - rare nuclear decays, and many others

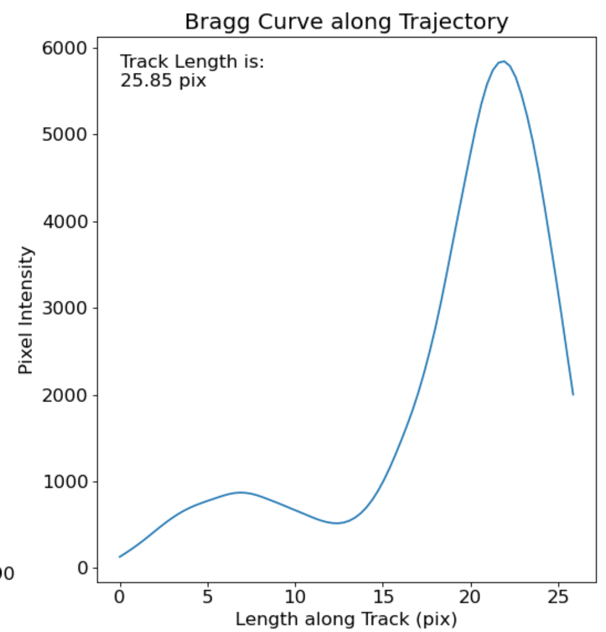

Trajectory and Initial Direction
110
100
90
80
70
60
130
140
150
160
170
180
-60.64
1 mm


Bragg Curve along Trajectory
Track Length is:
28.04 pix
2000
1750
1500
1250
1000
750
500
250
0
Pixel Intensity
0
5
10
15
20
25
Length along Track (pix)


Trajectory and Initial Direction
-1.44
1 mm
60
50
40
30
20
10
110
120
130
140
150
160


Bragg Curve along Trajectory
Track Length is:
28.81 pix
Pixel Intensity
Length along Track (pix)
3000
2500
2000
1500
1000
500
0
5
10
15
20
25
30


Trajectory and Initial Direction
-133.79
1 mm
110
100
90
80
70
60
50
130
140
150
160
170
180
190


Bragg Curve along Trajectory
Track Length is:
25.85 pix
Pixel Intensity
Length along Track (pix)
6000
5000
4000
3000
2000
1000
0
5
10
15
20
25

# BACKUP SLIDES

# Specification

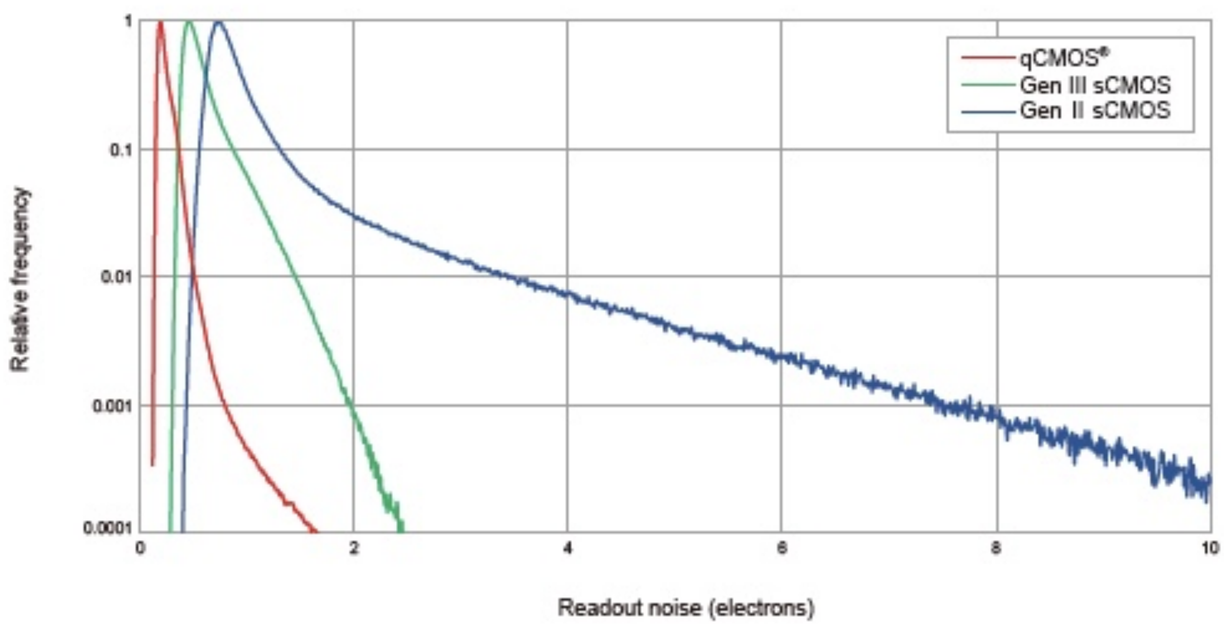
| | | |
|---|---|---|
| Product number | | C15550-20UP |
| Imaging device | | qCMOS® image sensor |
| Effective number of pixels | | 4096 (H) × 2304 (V) |
| Pixel size | | 4.6 μm (H) × 4.6 μm (V) |
| Effective area | | 18.841 mm (H) × 10.598 mm (V) |
| Quantum efficiency (typ.) | | 90 % (peak QE) |
| Full well capacity (typ.) | | 7000 electrons |
| Readout noise (typ.) | Standard scan | 0.43 electrons rms |
| | Ultra quiet scan | 0.27 electrons rms |
| Dynamic range (typ.) *1 | | 25 900: 1 |
| Dark signal non-uniformity (DSNU) (typ.) *2 | | 0.06 electrons rms |
| Photoresponse non-uniformity (PRNU) (typ.) *2*3 | | 0.1 % rms |
| Linearity error | EMVA 1288 standard (typ.) | 0.5 % |

| Cooling | Sensor temperature | Dark current (typ.) |
|---|---|---|
| Forced-air cooled (Ambient temperature: +25 °C) | −20 °C | 0.016 electrons/pixels/s |
| Water cooled (Water temperature: +25 °C) | −20 °C | 0.016 electrons/pixels/s |
| Water cooled (max cooling) (typ.) *4 | −35 °C | 0.006 electrons/pixels/s |

# Four key features
that enable the ORCA®-Quest
to achieve ultimate quantitative imaging

## 1. Ultra-low readout noise 0.27 electrons rms
**at Ultra quiet scan**

In order to detect weak light with high signal-to-noise, ORCA®-Quest has been designed and optimized to ev
structure to its electronics. Not only the camera development but also the custom sensor development ha
technology, an extremely low noise performance of 0.27 electrons has been achieved.



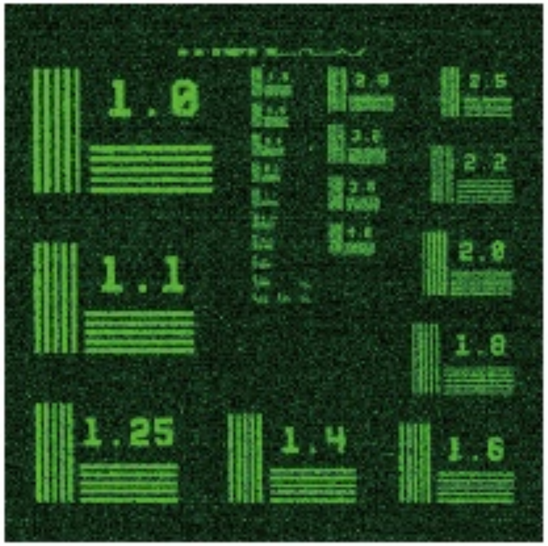
1.

## Low-dark current 0.006 electrons/pixel/s at −35 °C

In the field of single photon counting and photon number resolving, even dark currents as low as 0.5 electrons/pixel/s can affect photon detection. The 0.006 electrons/pixel/s @−35 °C value achieved by ORCA®-Quest is an extremely low probabilistic value of only 1 electron of dark current generated in approximately 167 pixels when exposed for 1 second.

Thus, the ORCA®-Quest, which is less affected by dark current, is ideal for quantitative imaging and analysis.

**ORCA®-Quest**




**Gen II sCMOS camera**

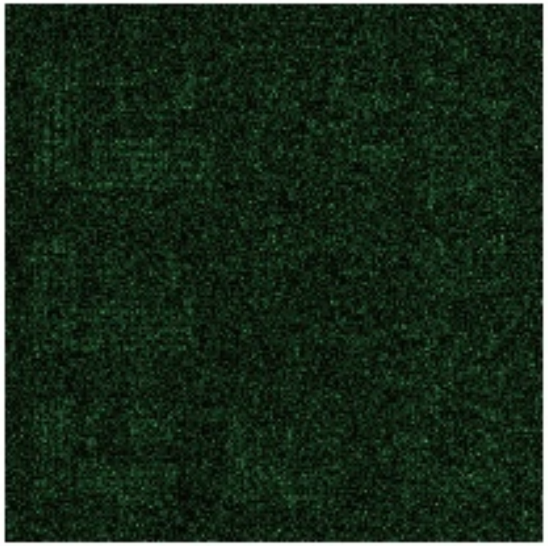
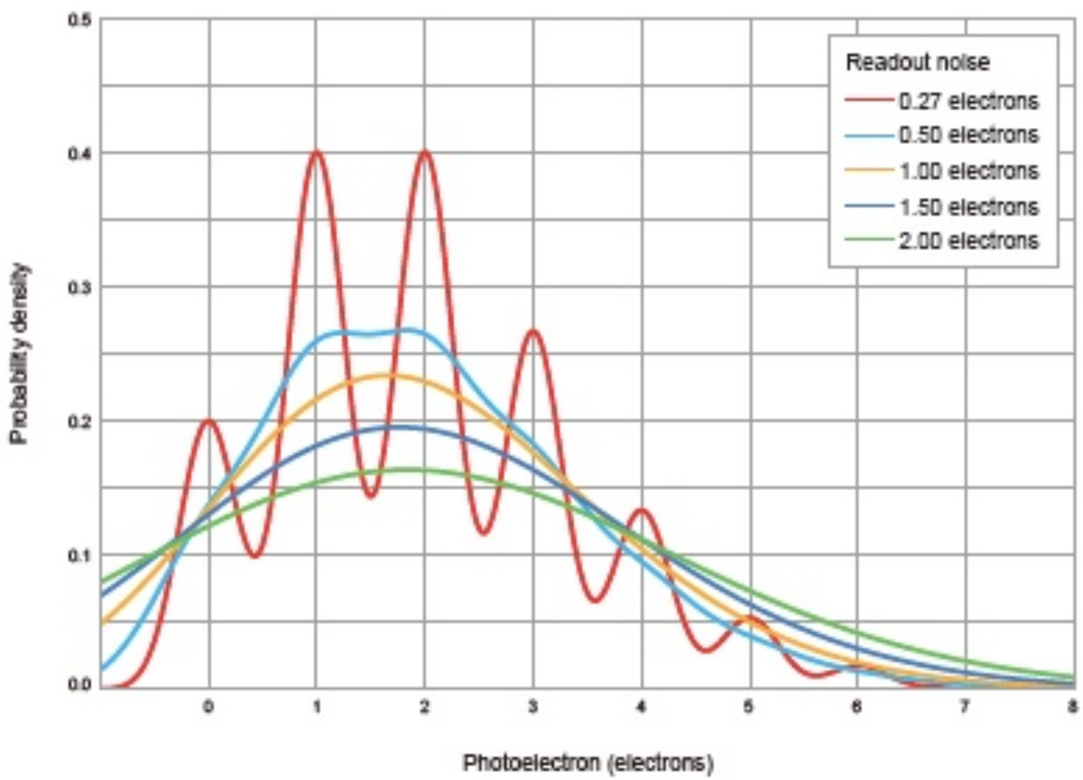


Image quality comparison at long exposure time (pseudo-color)
Incident light intensity: 0.05 photons/pixel/s Exposure time: 15 min (10 s × 90 times integration)

# 2. Realization of photon number resolving (PNR) output

## Realization of photon number resolving by low-readout noise

**Simulation data of photoelectron probability distribution** (Average number of photoelectrons generated per pixel: 2 electrons)




* Photon number resolving is unique and quite different from photon counting (More precisely the method resolves the number of photoelectrons. However, since single photon counting instead of single photoelectron counting has been used for a comparable method in this field, we will use the term "photon number resolving" in this brochure).

# 3. Back-illuminated structure and high resolution

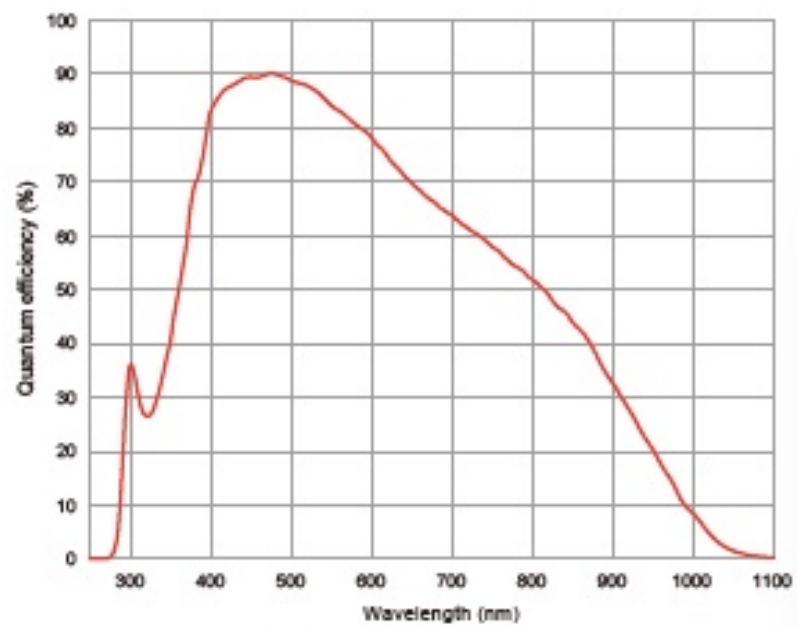
## Trench structure to suppress crosstalk

High QE is essential for high efficiency of detecting photons and achieved by back-illuminated structure.

## High QE 90 % at 475 nm   33 % at 900 nm

It also has high quantum efficiency in the near-infrared region because of its thicker layer of the charge detection region.

Normally, there is a trade-off between the thickness of the layer of the photon detection region and the resolution, but the trench structure suppresses the degradation of the resolution.



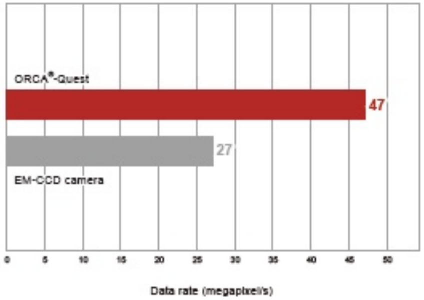
# 4. Realization of a large number of pixels and high speed readout

## Realization of PC/PNR with a large number of pixels and high speed
**at Ultra quiet scan**

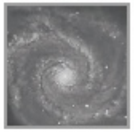
Photon counting (PC) level images have typically been acquired using electron multiplication camera such as EM-CCD camera with about 0.3 megapixels. However, ORCA®-Quest can acquire not only PC level images but also photon number resolving images with 9.4 megapixels.

In addition, it is not fair to compare readout speeds of cameras with different pixel number by frame rate. In such a case the pixel rate (number of pixels × frame rate), which is the number of pixels read out per second, is used.
Until now, the fastest camera capable of SPC readout was the EM-CCD camera with about 27 megapixel/s, but the ORCA®-Quest enables photon number resolving imaging at about 47 megapixel/s, nearly twice as fast.

ORCA®-Quest (4096 × 2304)

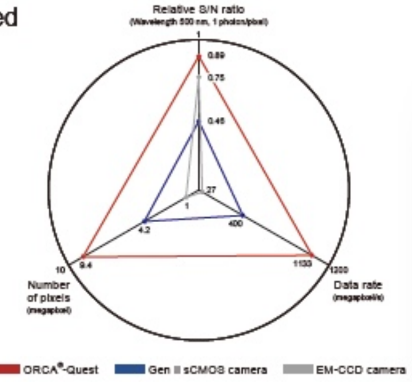



EM-CCD camera (1024 × 1024)



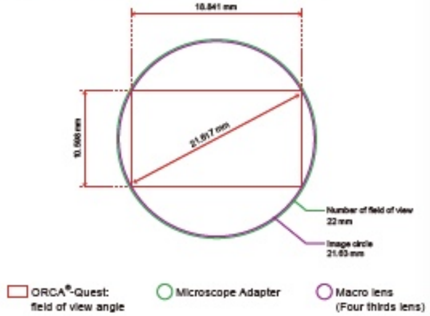
## Excellent pixel count and readout speed
**at Standard scan**

ORCA®-Quest delivers low noise and it has 4096 (H) × 2304 (V) pixels, about 2.2 times larger than a conventional Gen II sCMOS camera, allowing for the simultaneous capture of a large number of objects. Standard scan delivers less readout noise (0.43 electron), and 2.8 times faster speed than a conventional Gen II sCMOS camera, which enables high-speed low light imaging.

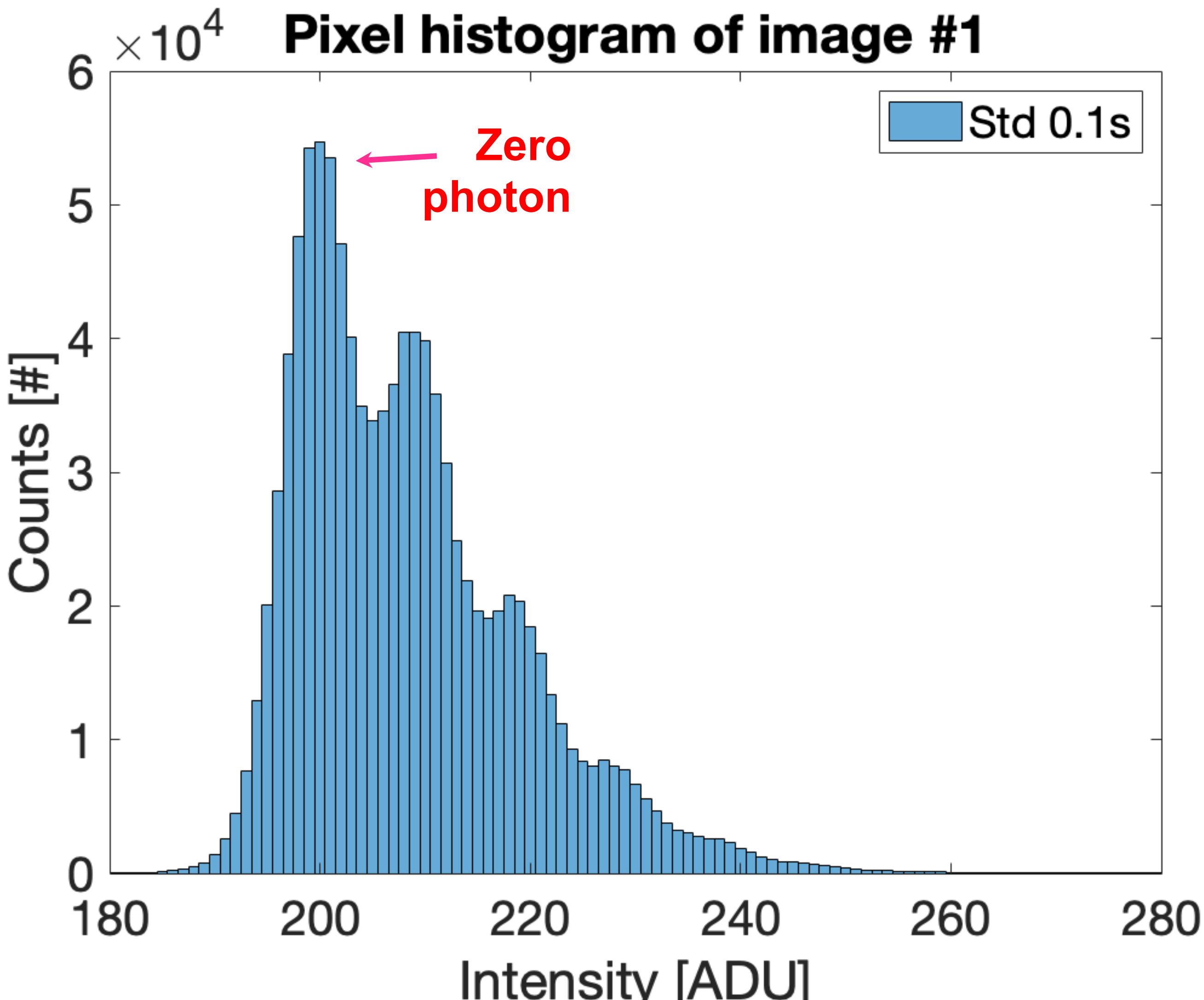



## Sensor sizes that can be used with general-purpose optical systems

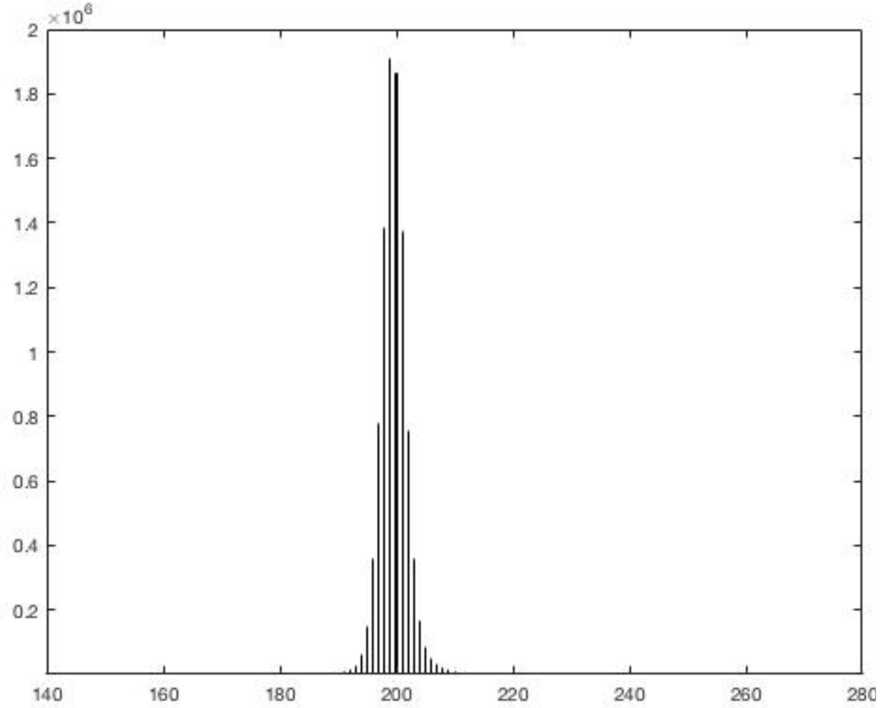
As the number of pixels increases, the size of the sensor also increases, resulting in cases where the peripheral field of view is missing when using optics such as under a microscope. The ORCA®-Quest has 18.841 mm (H) × 10.598 mm (V) by 9.4 megapixels, 4.6 μm px size, that fits in a C-mount of dia.25.4 mm, making it suitable for use with general-purpose optics.
* An F-mount option is also available.

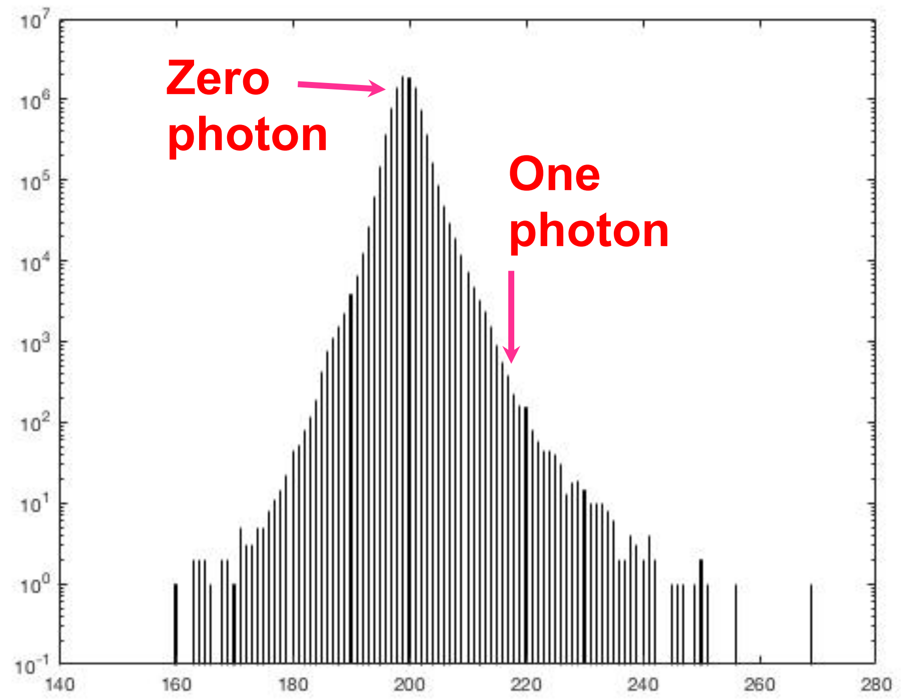


# More Noise – standard scan



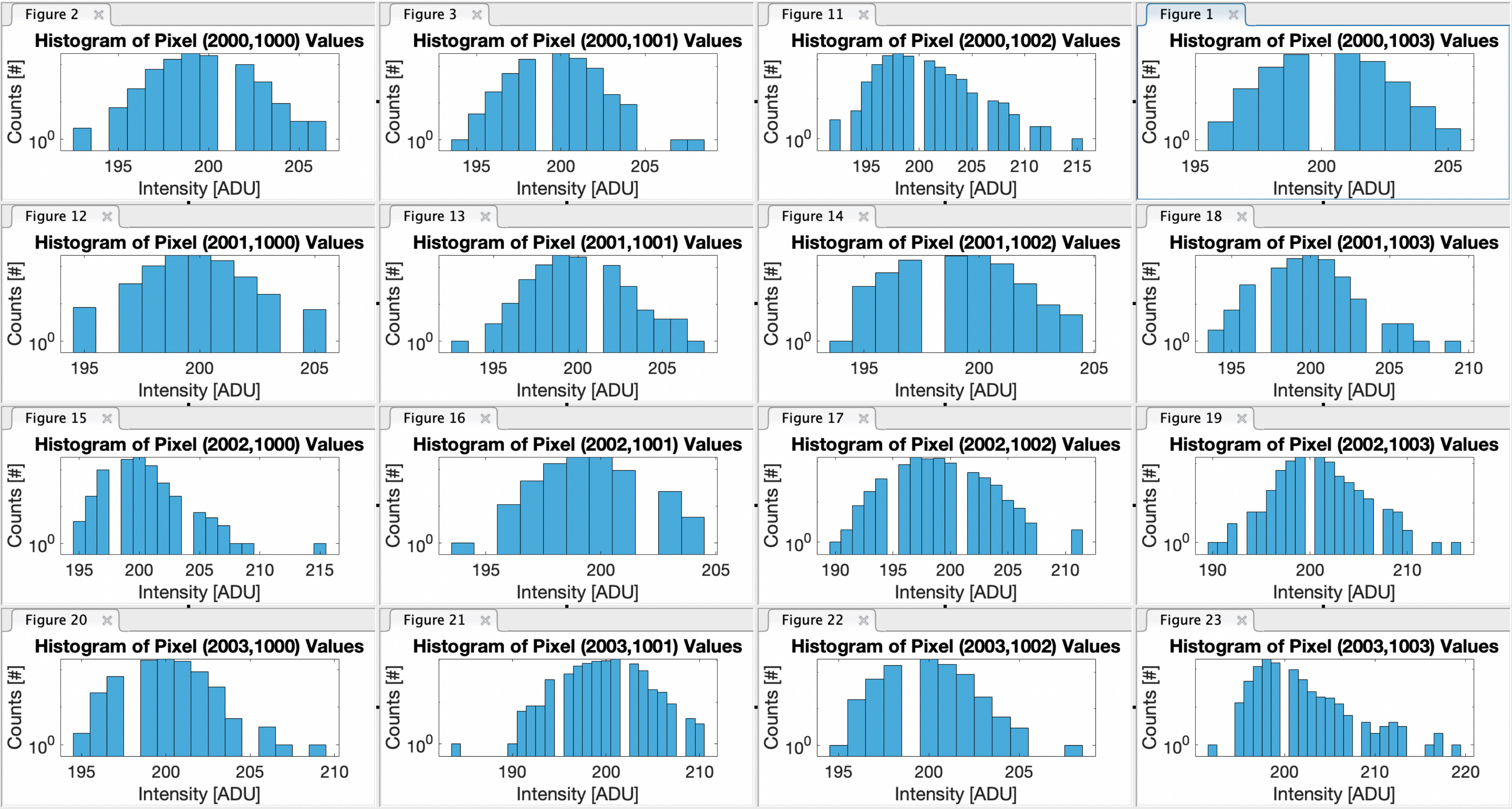
# Darks – 0.2s, ultra-quiet 1x1 binning, full chip (~9.4 Mpix)



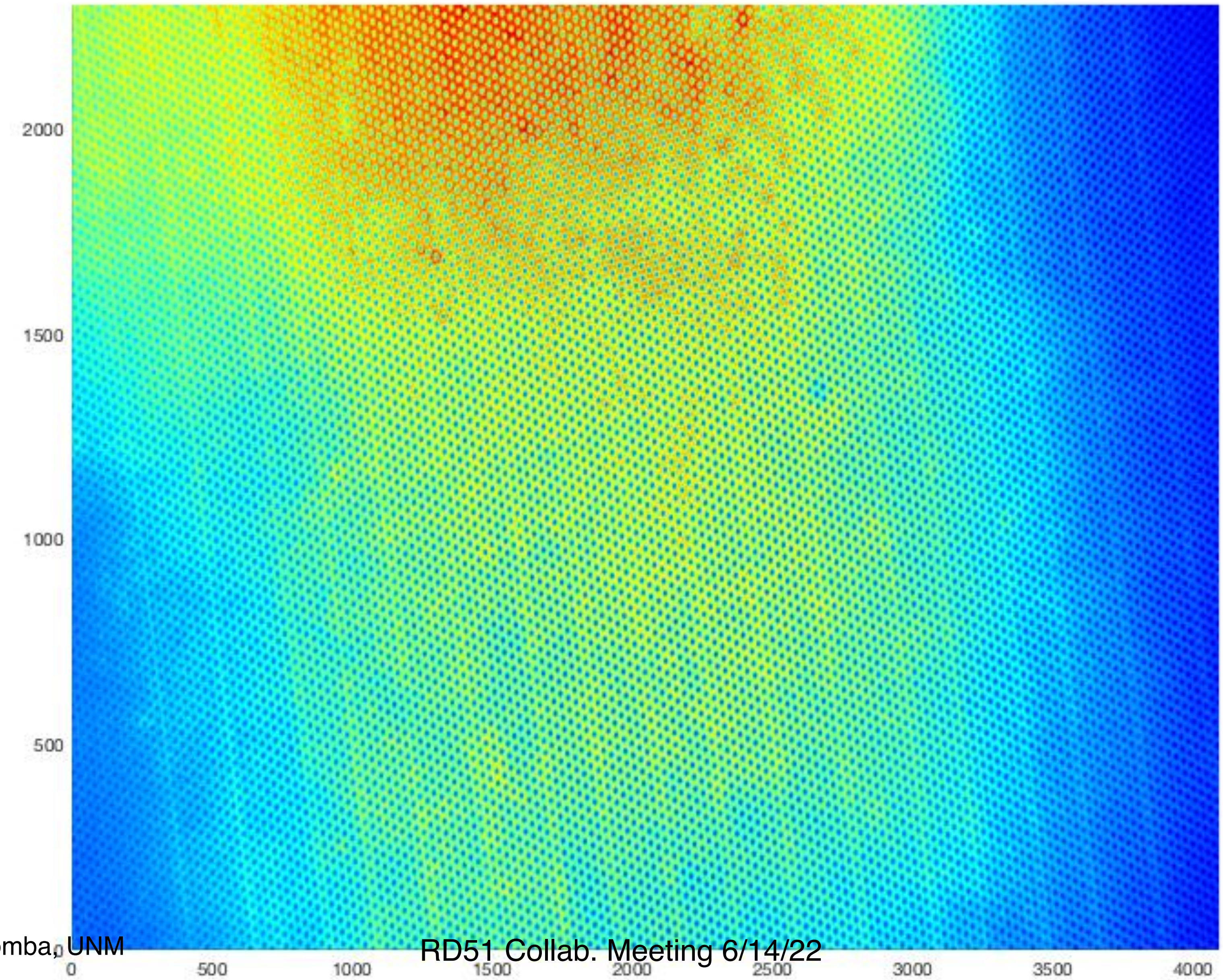




**Why not Gaussian?**

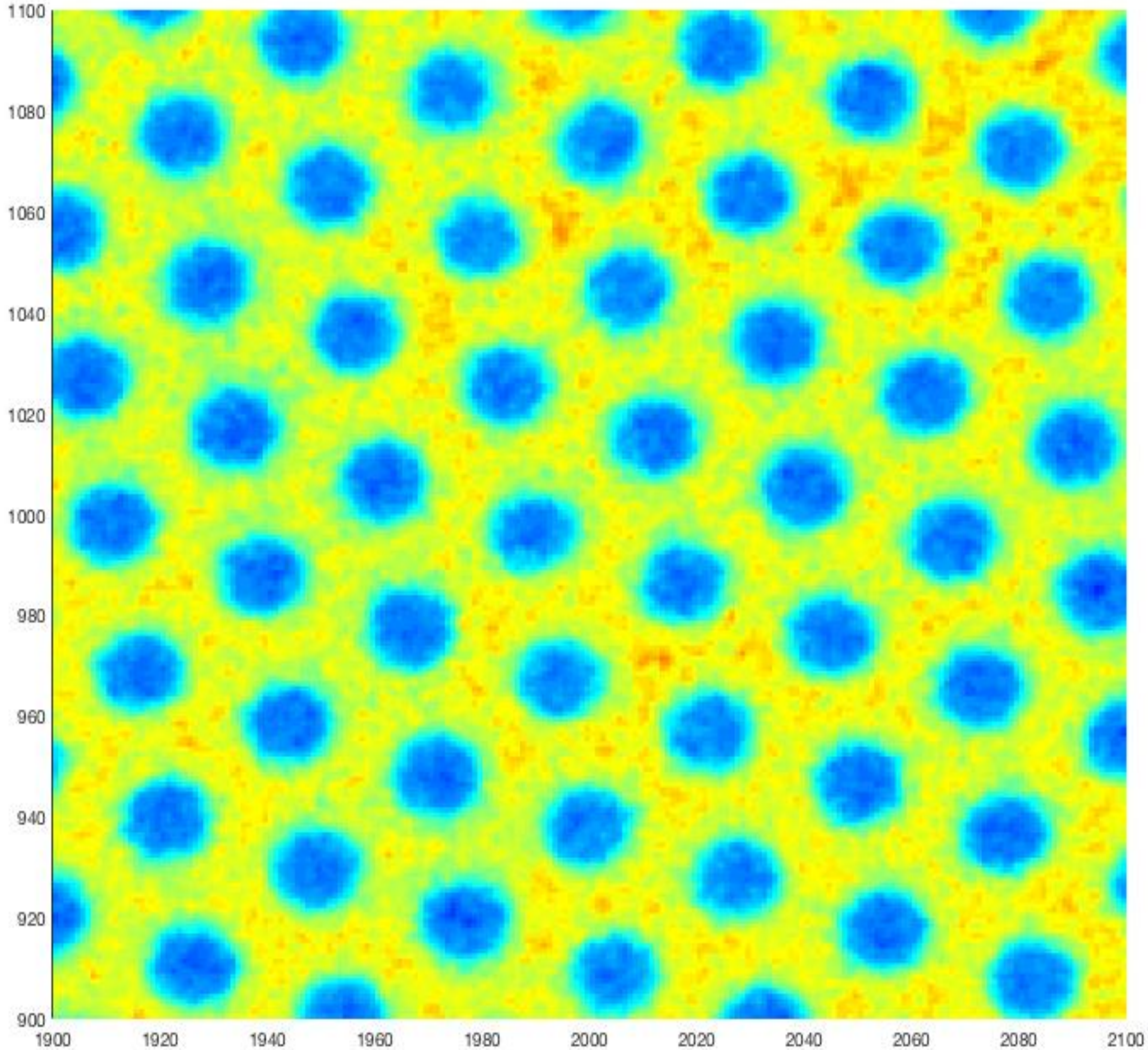
# Distribution of Darks for a sample of pixels



# Focus



# Focus



1100
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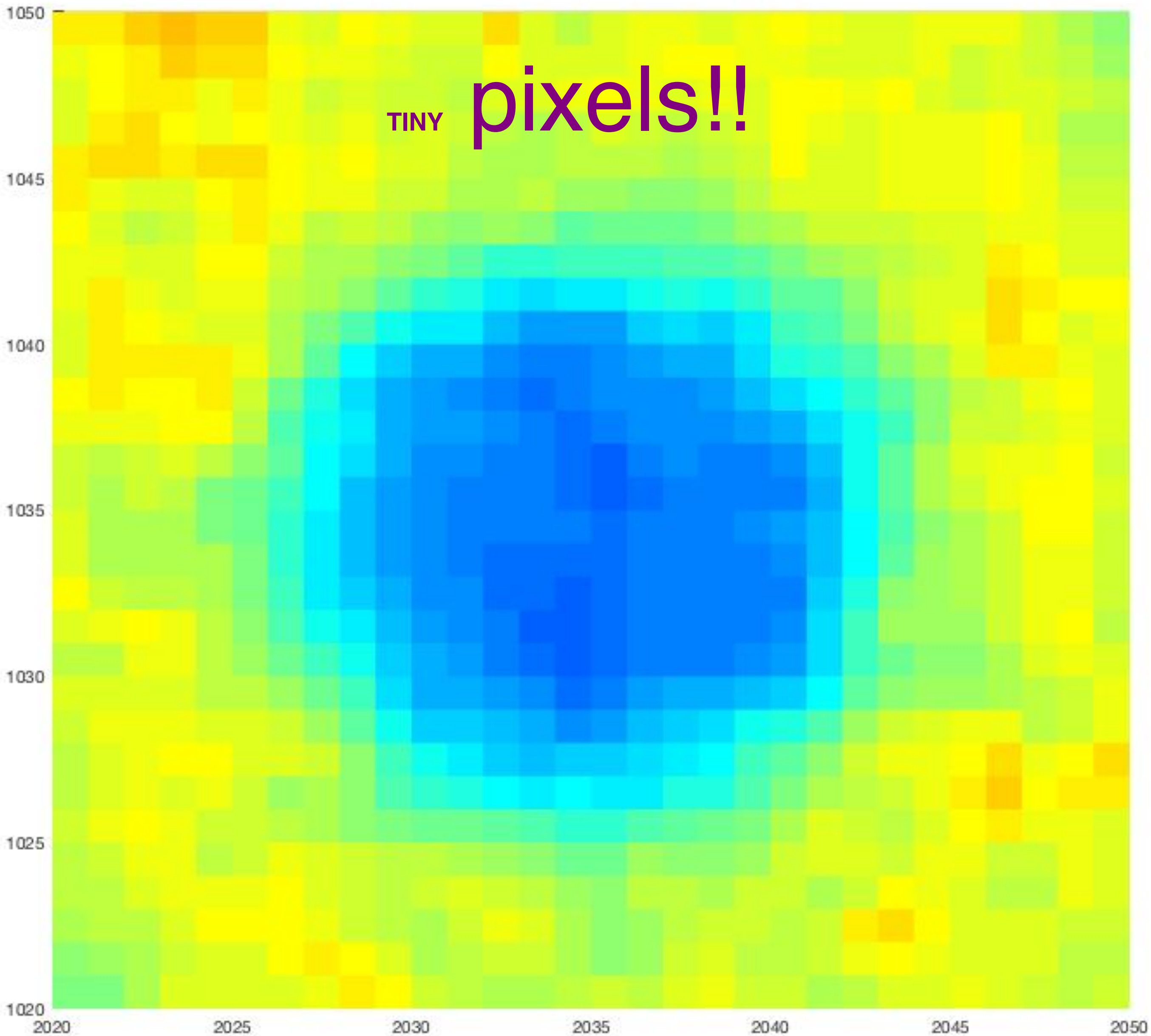
TINY pixels!!
1050
1045
1040
1035
1030
1025
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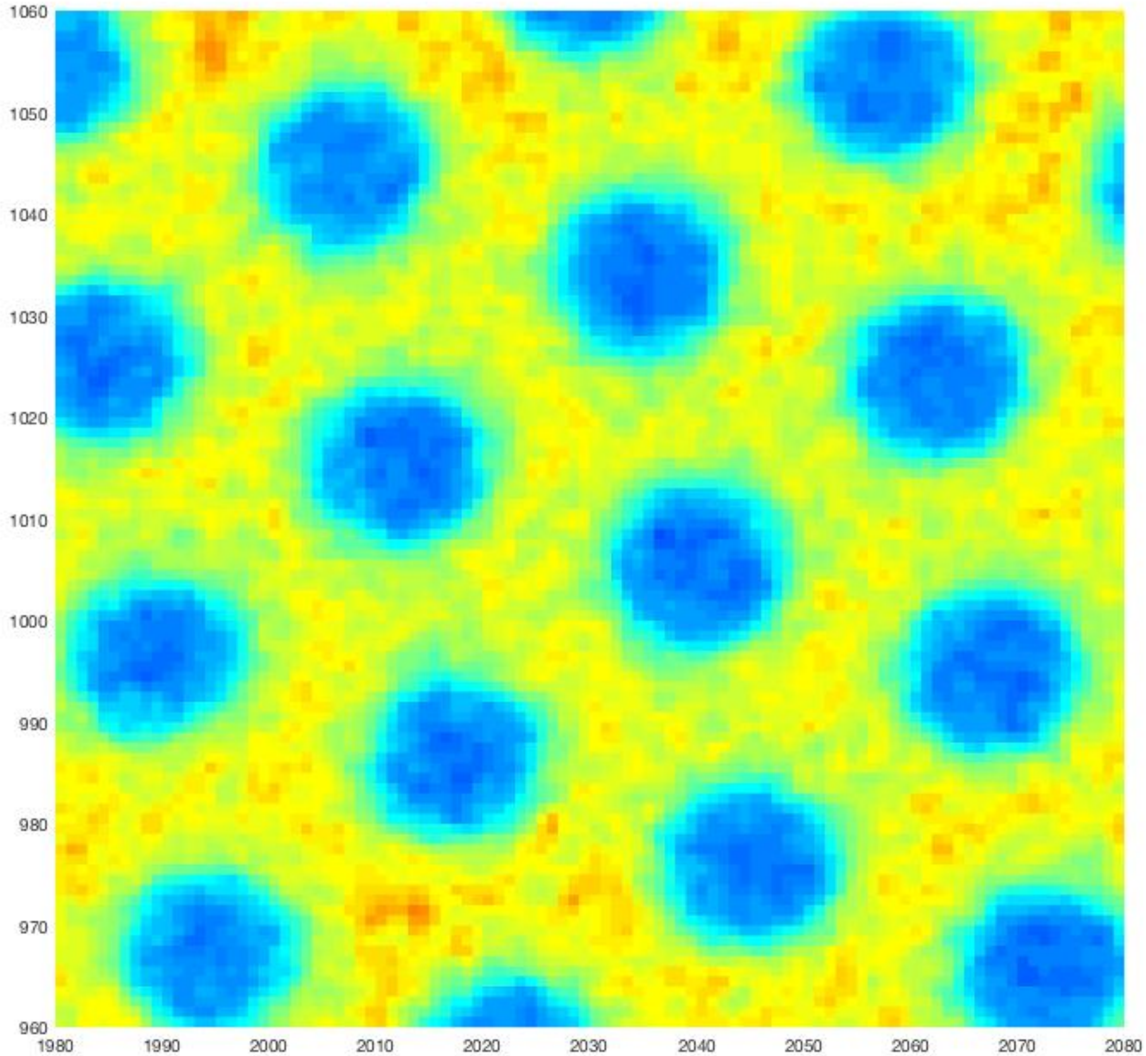
2020
2025
2030
2035
2040
2045
2050

# Focus


1060
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