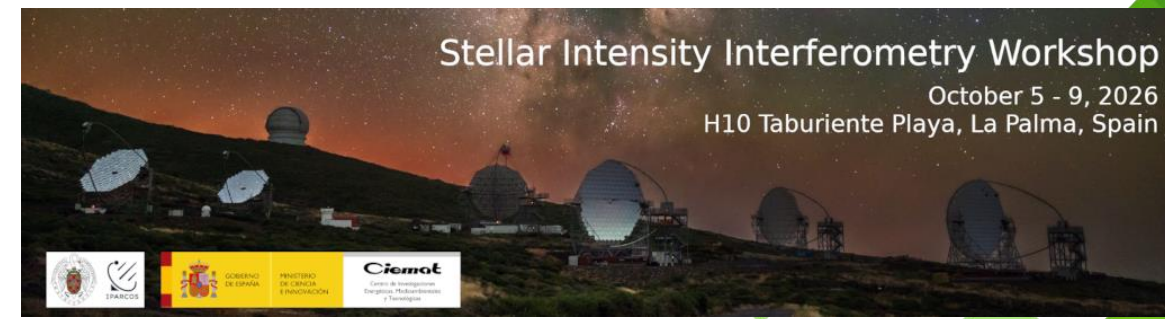
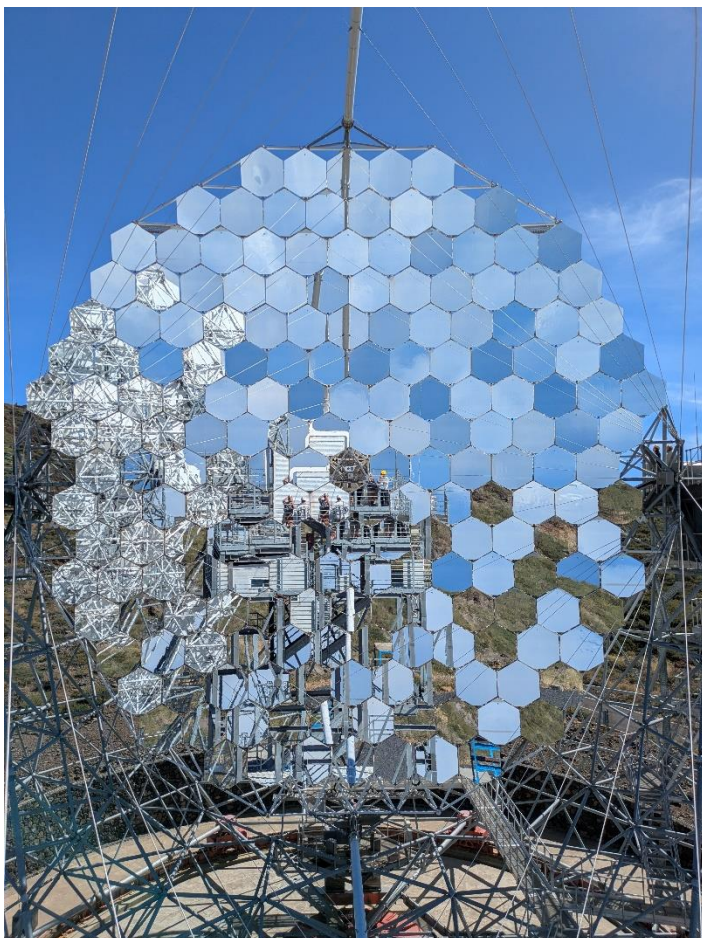




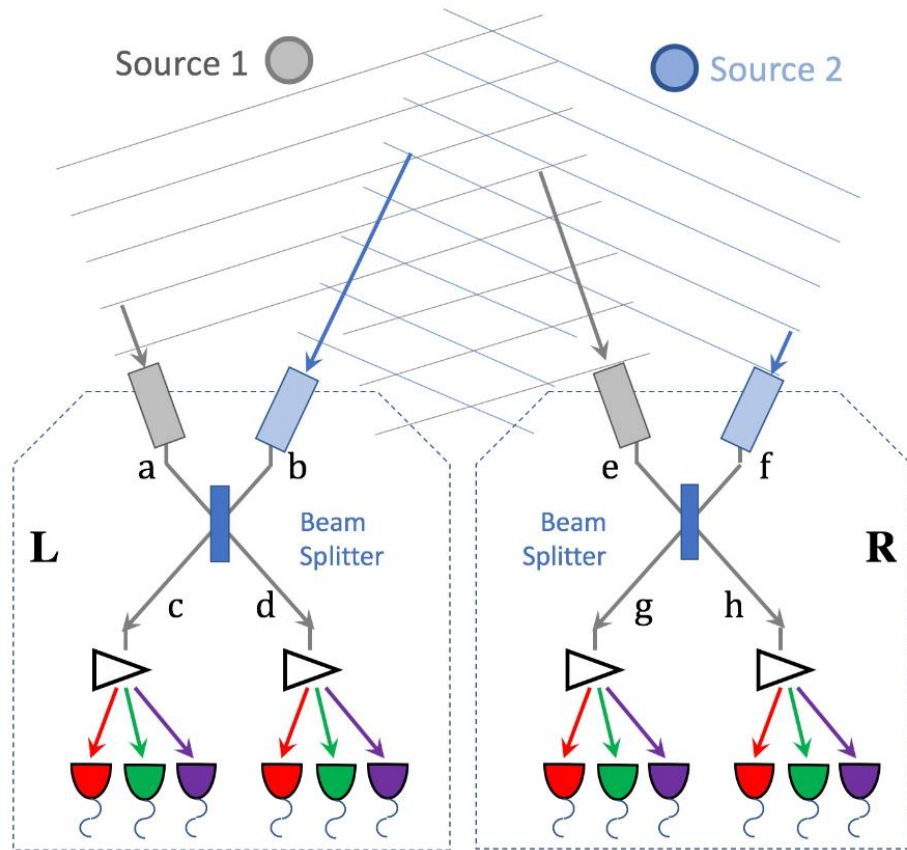
# Fast single-photon spectrometer near Heisenberg-Gabor limit for quantum-assisted astrometry

Sergei Kulkov, Andrei Nomerotski,  
Sarlotte Simsone, Peter Svihra



back to buisness...

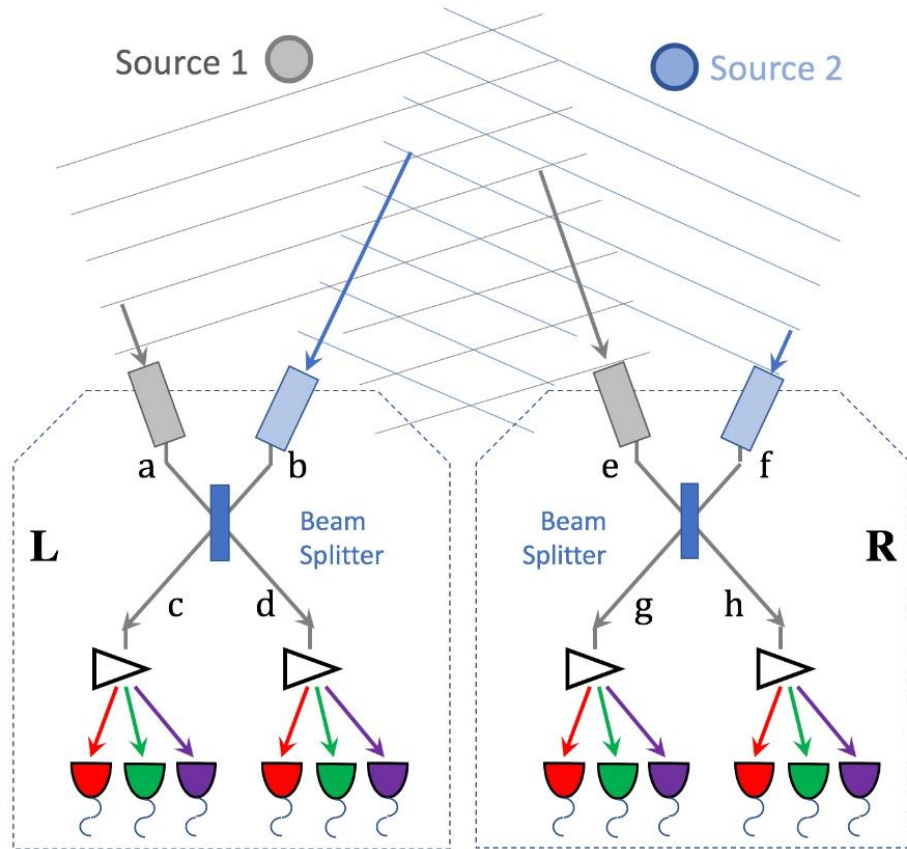
# Quantum-assisted astrometry



Stankus et al. (2022)  
*Open J. Astrophys.* **5**

“Two-photon amplitude interferometry”

# Quantum-assisted astrometry



Stankus et al. (2022)  
*Open J. Astrophys.* **5**

“Every reader will confirm...”

Full QFT calculation

$$N_c(xy) = \int_{-T_r/2}^{T_r/2} P_{L,R,\tau}^{\text{two photons}} d\tau =$$

$$= A^2 \eta_1 \eta_2 T_r \left[ \underbrace{(I_1 + I_2)^2}_{\text{rates}} + \underbrace{I_1^2 \frac{T_c g_{11}}{T_r} + I_2^2 \frac{T_c g_{22}}{T_r}}_{\text{HBT}} \pm \underbrace{2I_1 I_2 \frac{T_c g_{12}}{T_r} \cos \left( \frac{\omega_0 B (\sin \theta_1 - \sin \theta_2)}{c} + \frac{\omega_0 \Delta L}{c} \right)}_{\text{new oscillatory term}} \right] \quad (30)$$

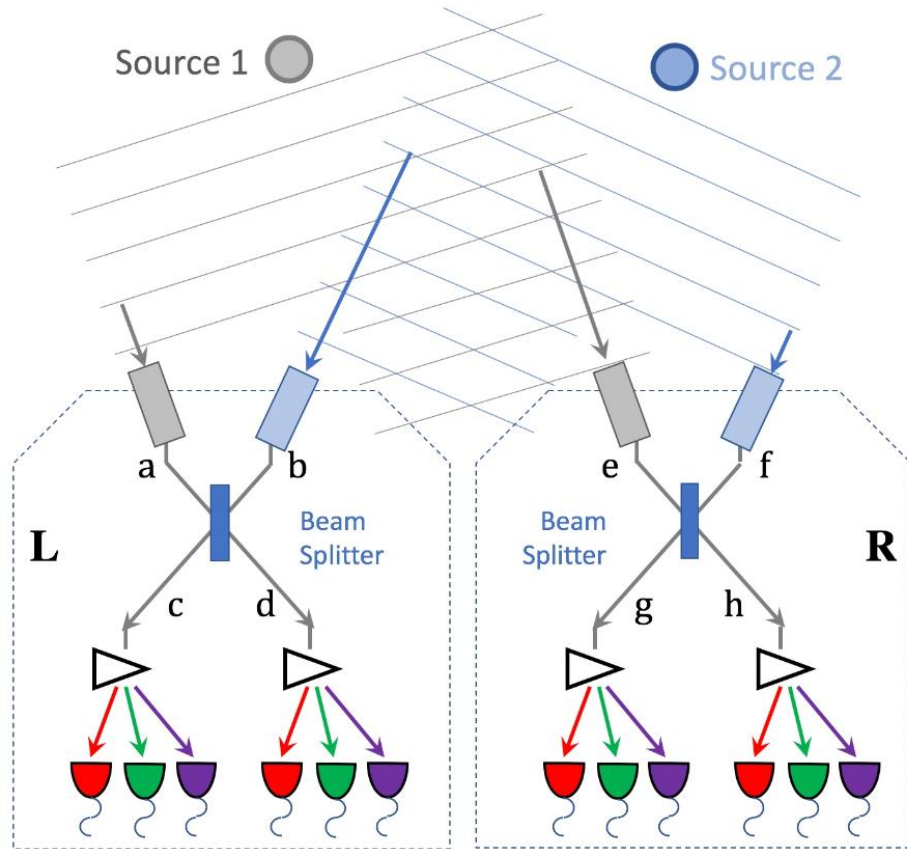
rates

HBT

new oscillatory term

“Two-photon amplitude interferometry”

# Quantum-assisted astrometry



Stankus et al. (2022)  
*Open J. Astrophys.* **5**

“Every reader will confirm...”

Full QFT calculation

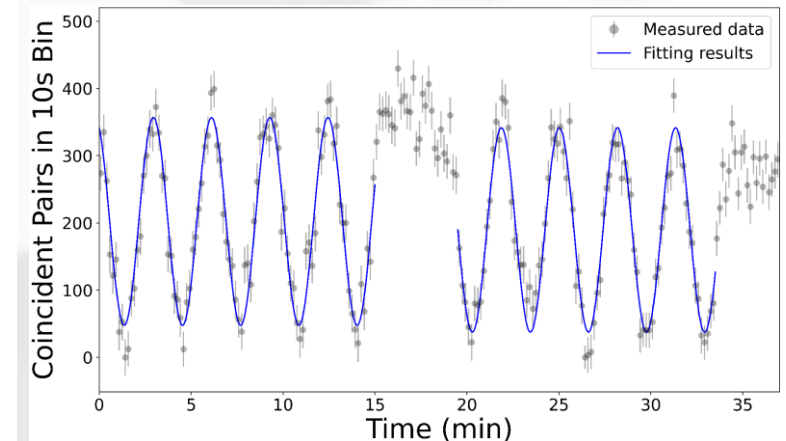
$$N_c(xy) = \int_{-T_r/2}^{T_r/2} P_{L,R,\tau}^{\text{two photons}} d\tau =$$

$$= A^2 \eta_1 \eta_2 T_r \left[ (I_1 + I_2)^2 + I_1^2 \frac{T_c g_{11}}{T_r} + I_2^2 \frac{T_c g_{22}}{T_r} \pm 2 I_1 I_2 \frac{T_c g_{12}}{T_r} \cos \left( \frac{\omega_0 B (\sin \theta_1 - \sin \theta_2)}{c} + \frac{\omega_0 \Delta L}{c} \right) \right] \quad (30)$$

rates

HBT

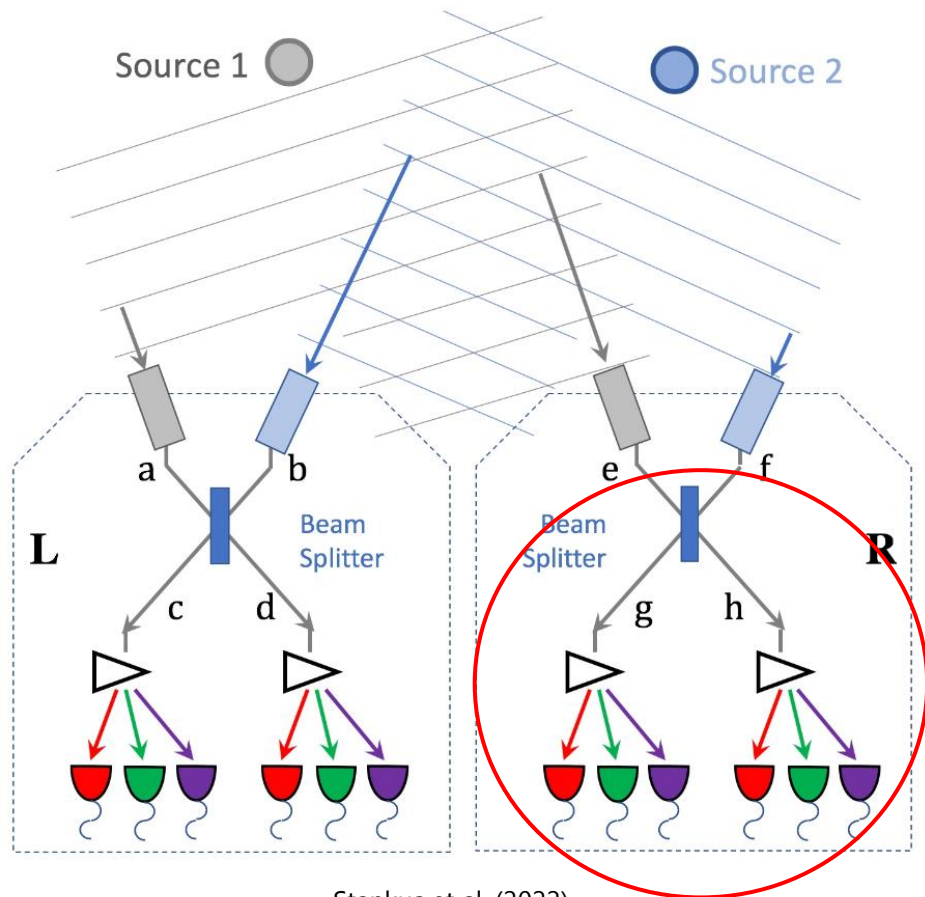
new oscillatory term



J Crawford, A Nomerotski et al, *Opt. Express* **31**, 44246-44258 (2023)

“Two-photon amplitude interferometry”

# Quantum-assisted astrometry



Stankus et al. (2022)  
*Open J. Astrophys.* 5

“Every reader will confirm...”

Full QFT calculation

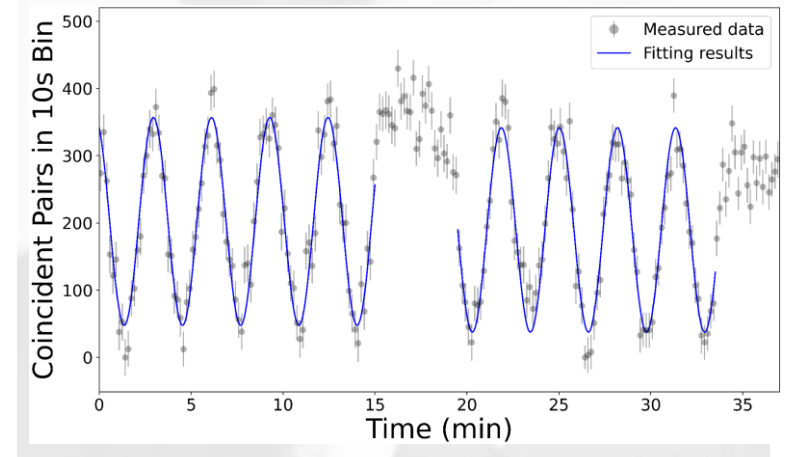
$$N_c(xy) = \int_{-T_r/2}^{T_r/2} P_{L,R,\tau}^{\text{two photons}} d\tau =$$

$$= A^2 \eta_1 \eta_2 T_r \left[ \underbrace{(I_1 + I_2)^2}_{\text{rates}} + \underbrace{I_1^2 \frac{T_c g_{11}}{T_r} + I_2^2 \frac{T_c g_{22}}{T_r}}_{\text{HBT}} + \underbrace{2I_1 I_2 \frac{T_c g_{12}}{T_r} \cos \left( \frac{\omega_0 B (\sin \theta_1 - \sin \theta_2)}{c} + \frac{\omega_0 \Delta L}{c} \right)}_{\text{new oscillatory term}} \right] \quad (30)$$

rates

HBT

new oscillatory term



~10 uas

Binary orbits

Cosmic distance ladder

Microlensing events

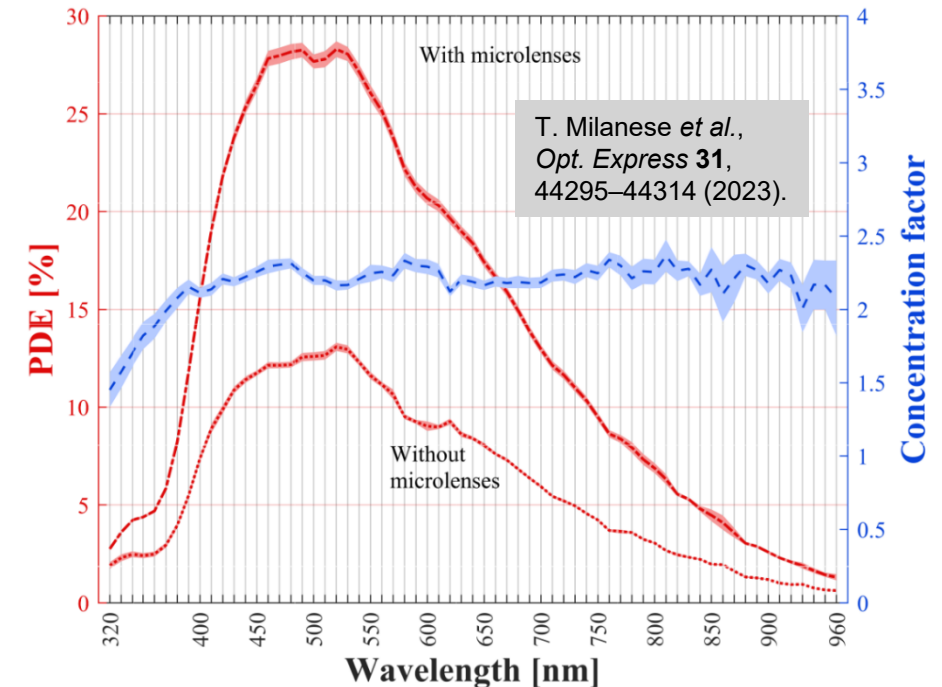
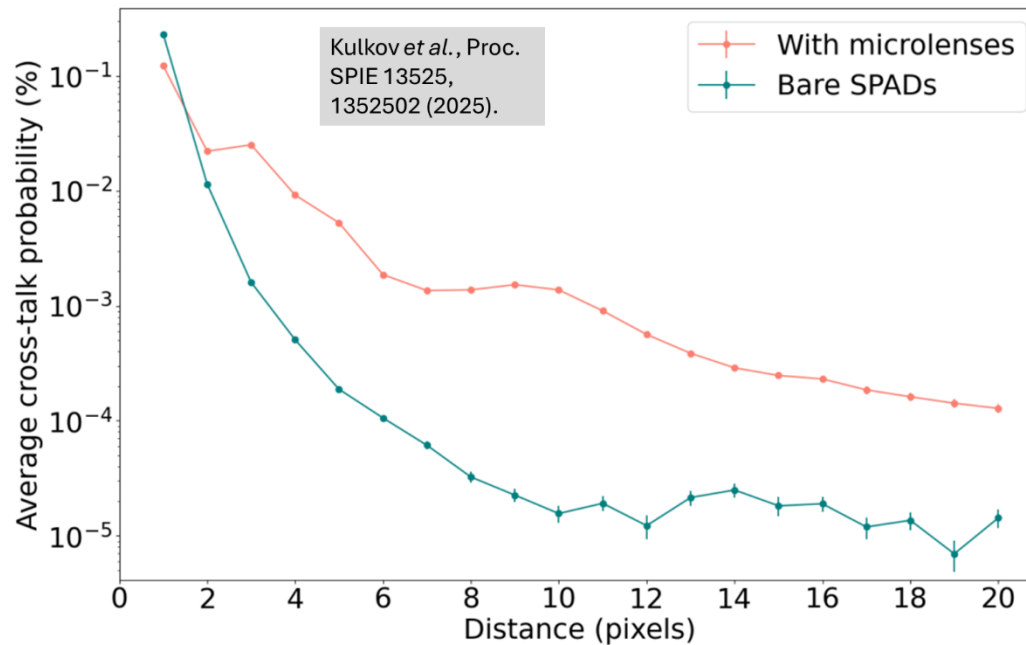
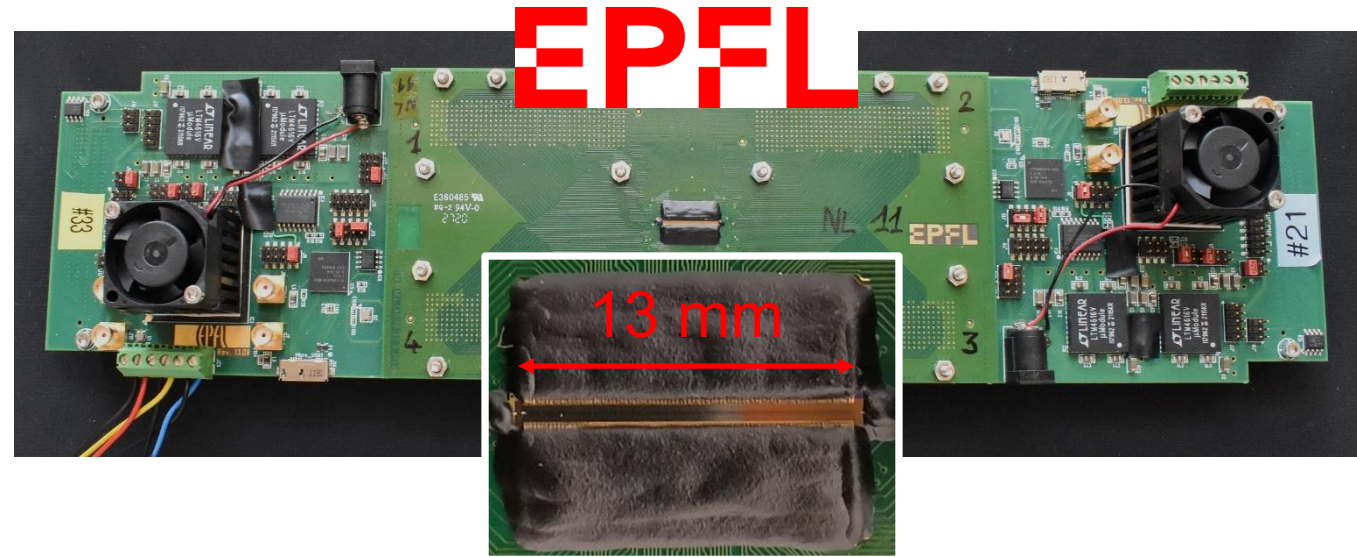
Gravitational waves in uHz range

“Two-photon amplitude interferometry”

J Crawford, A Nomerotski et al, Opt.  
Express **31**, 44246-44258 (2023)

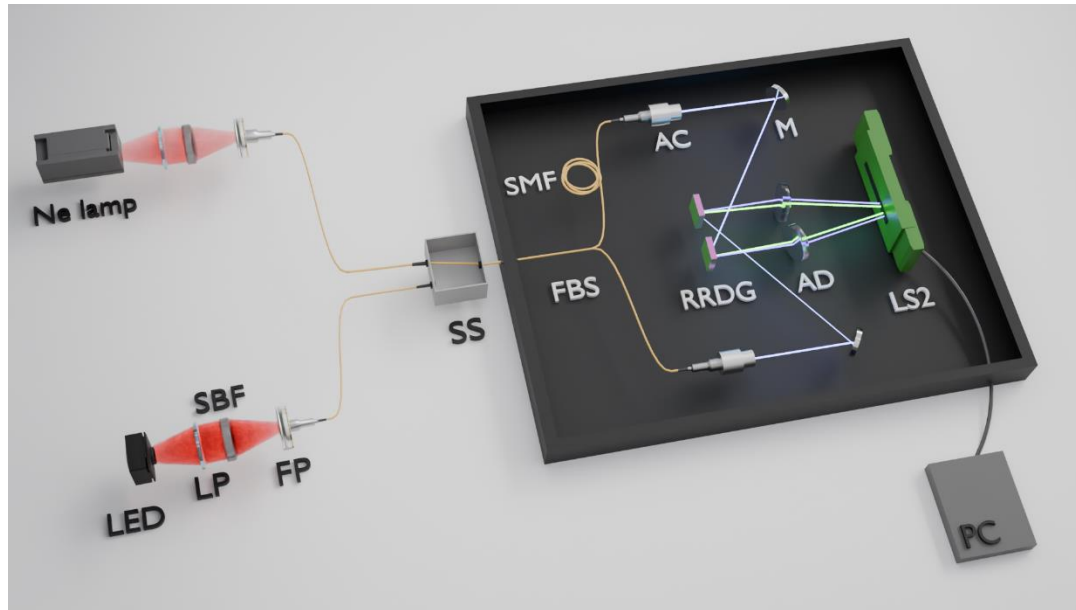
# Camera: LinoSPAD2

- 256 pixels (out of 512 total)  
26.2×26.2  $\mu\text{m}^2$
- 40 ps rms resolution
- DCR: 125 cps/pixel @ 28 °C
- **Room temperature!**

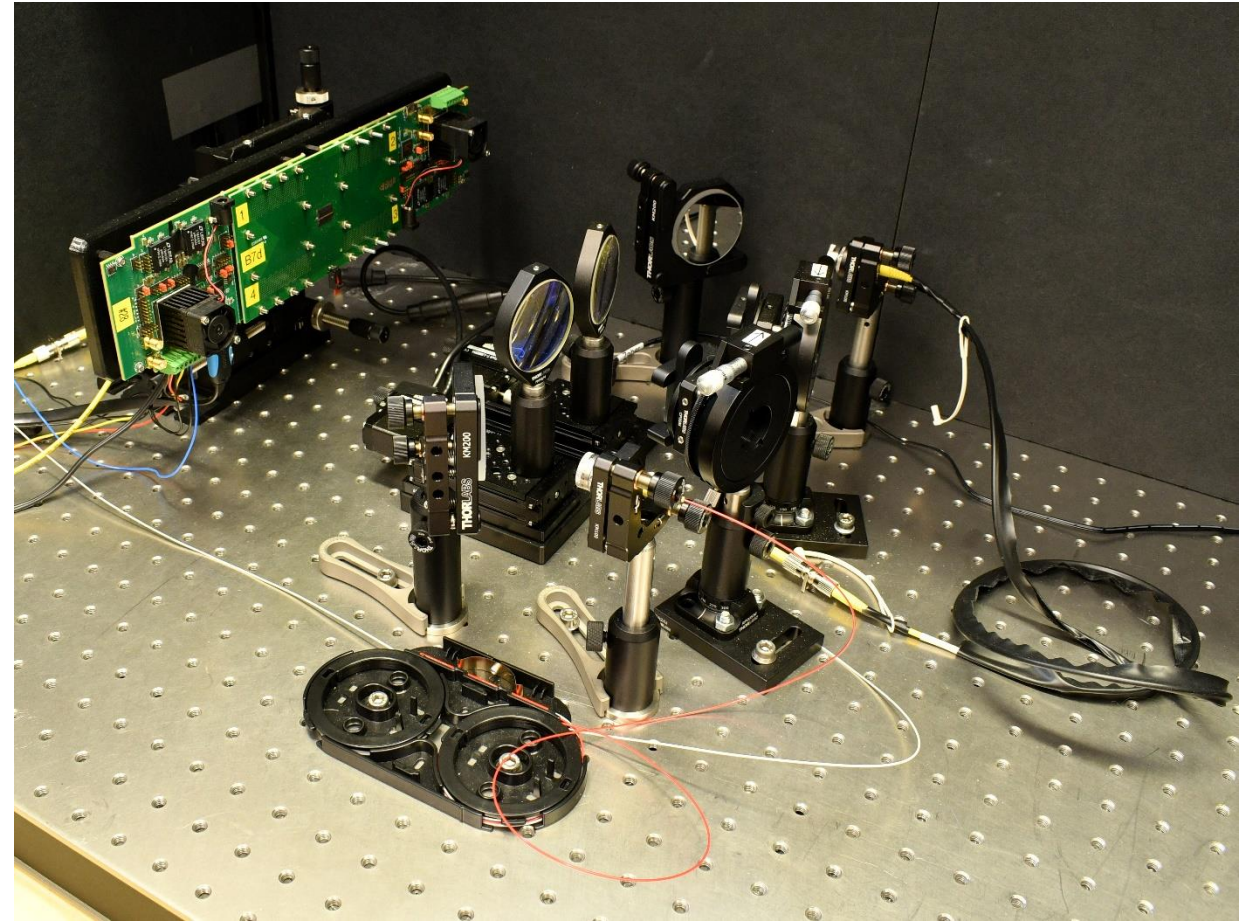


# Best published so far: ~70 HBT peaks

Publication

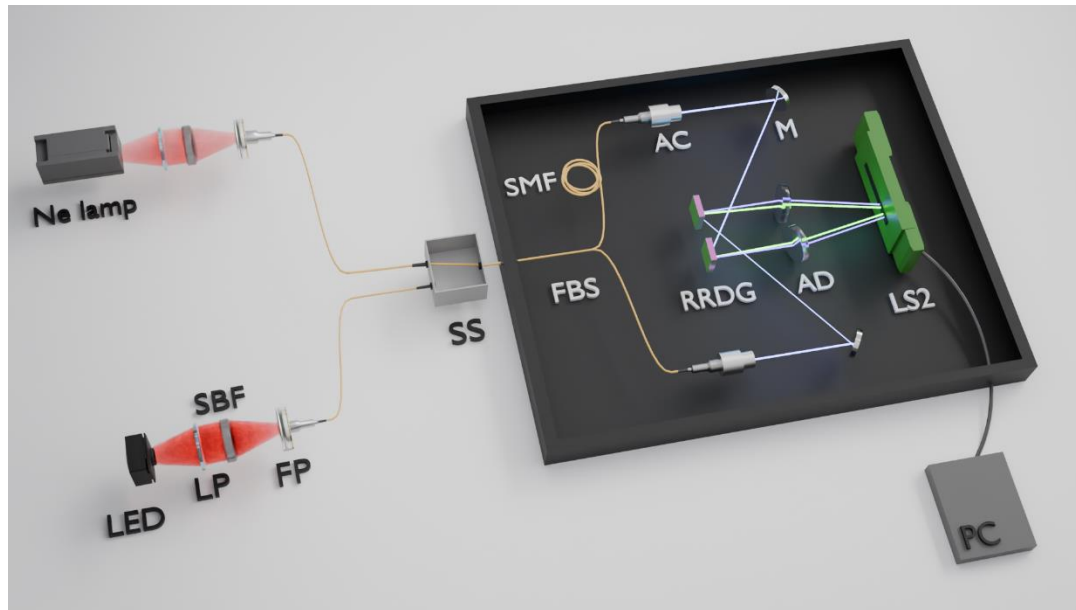


- 1200 gr/mm
- 200 mm
- CWL ~640 nm (10 nm FWHM)
- 0.11 nm/pixel
- ~28 nm range
- ~48 pm resolution

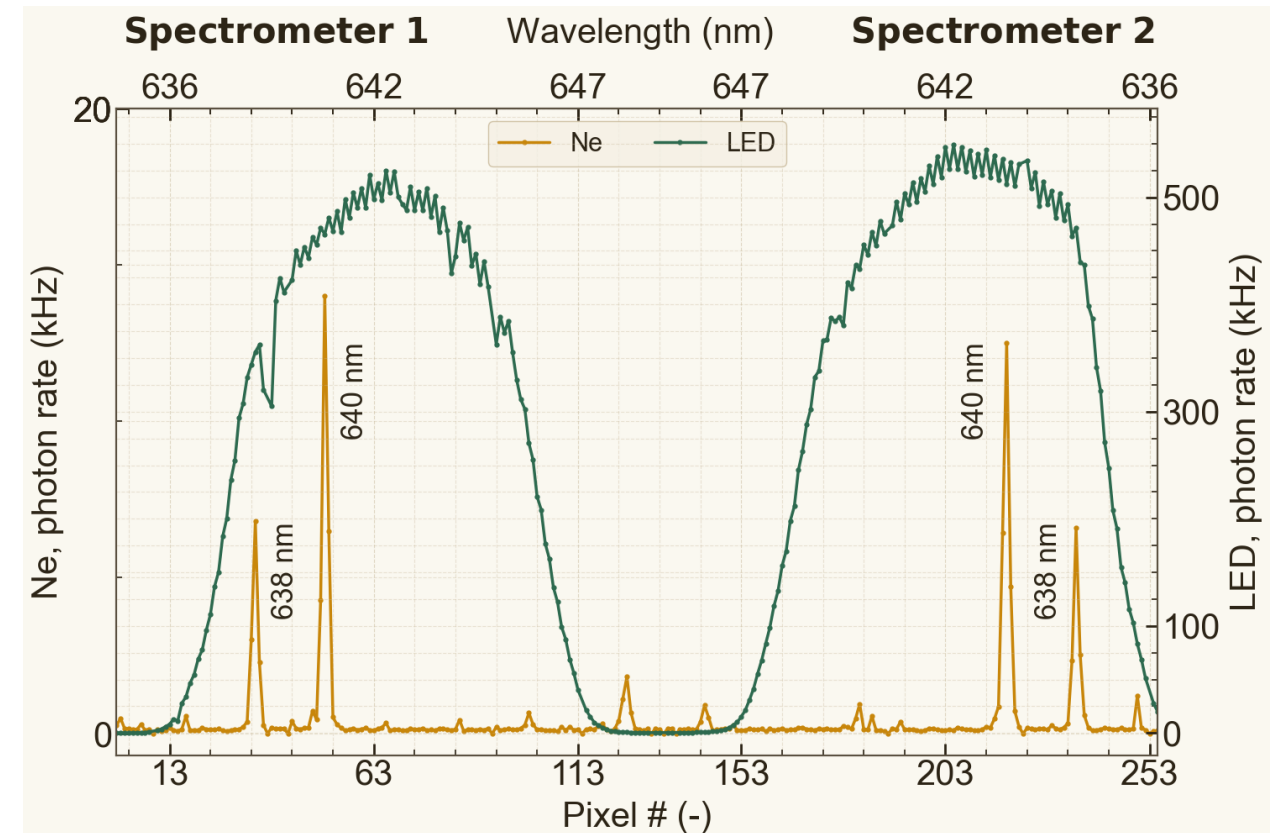


# Best published so far: ~70 HBT peaks

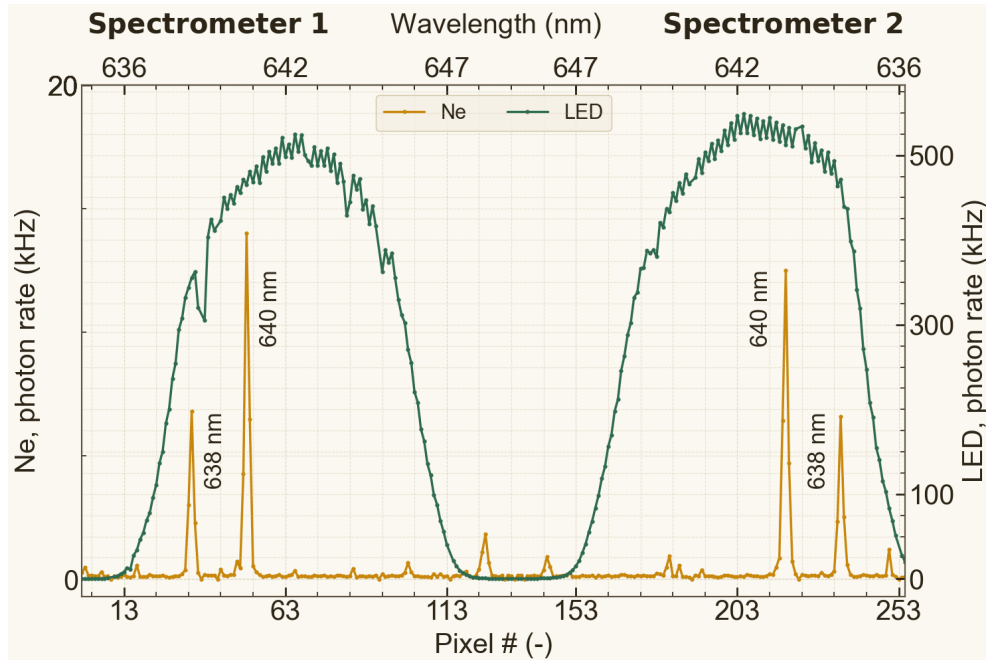
Publication



- 1200 gr/mm
- 200 mm
- CWL ~640 nm (10 nm FWHM)
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- ~28 nm range
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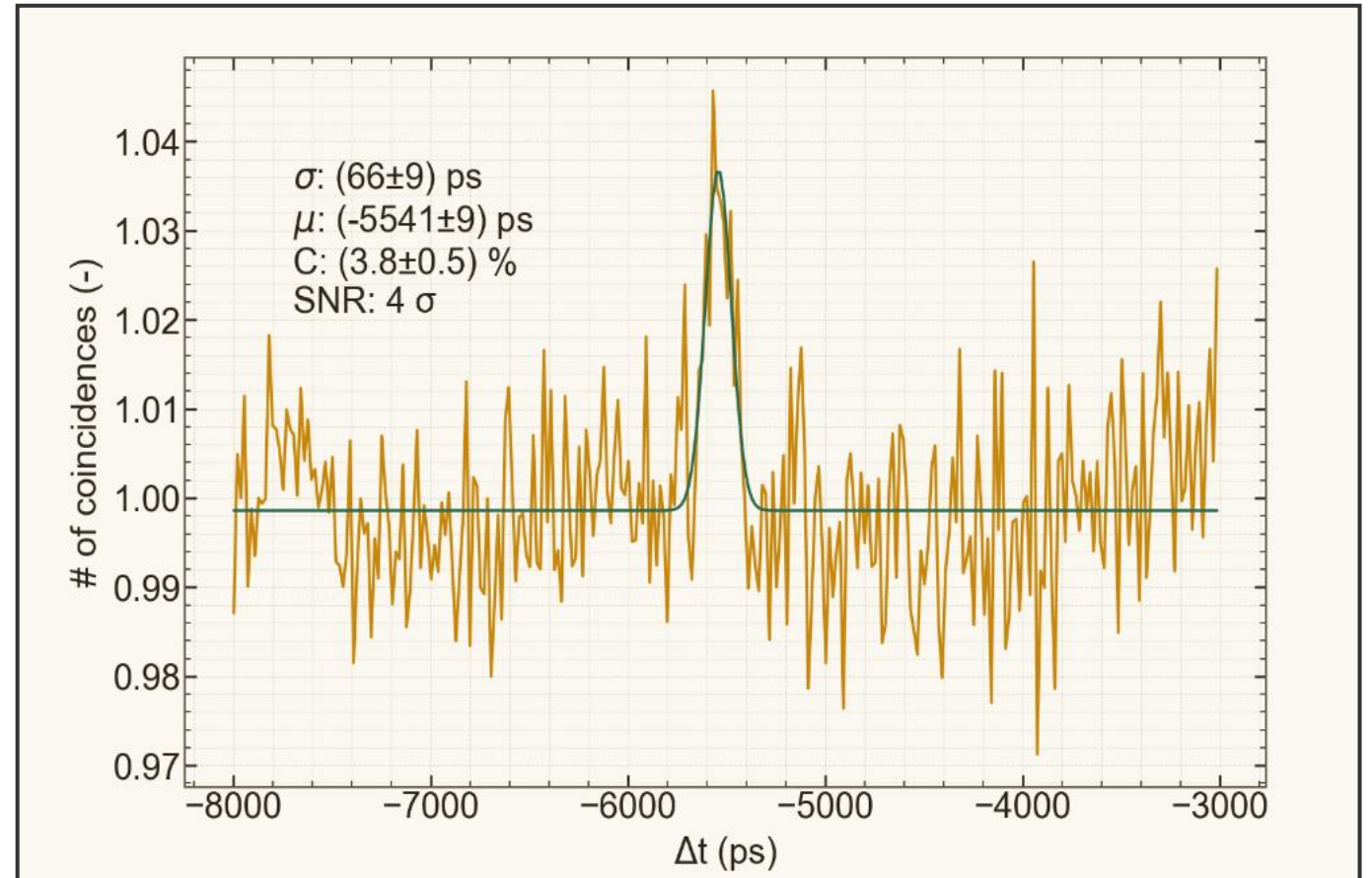


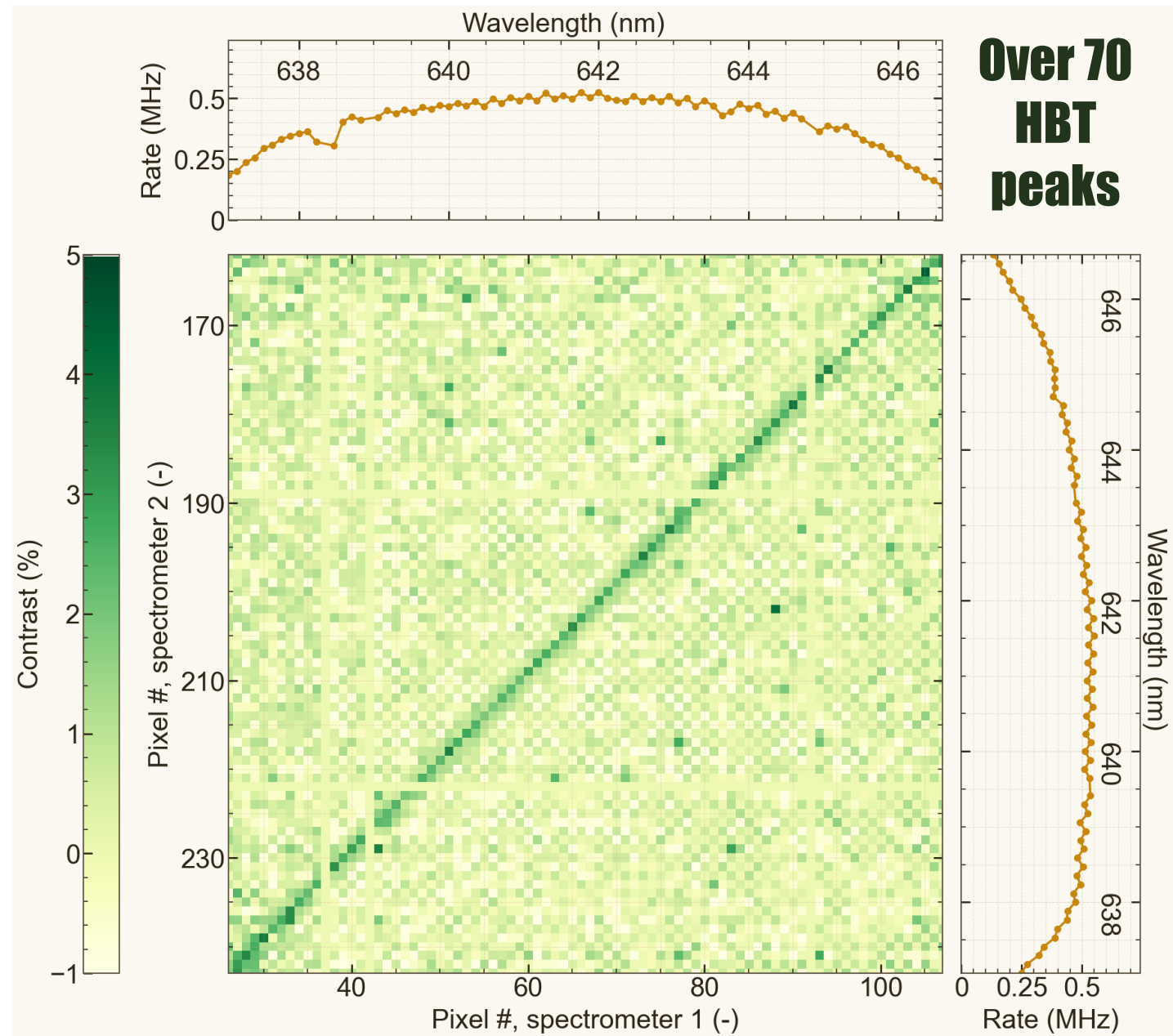
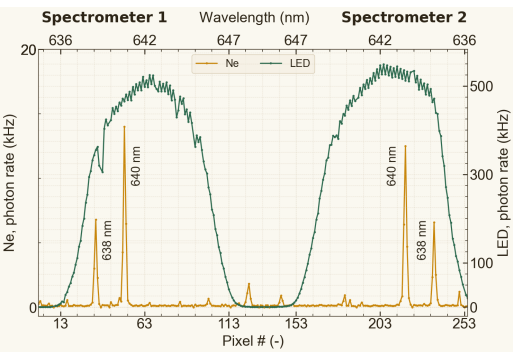
# Coincidences



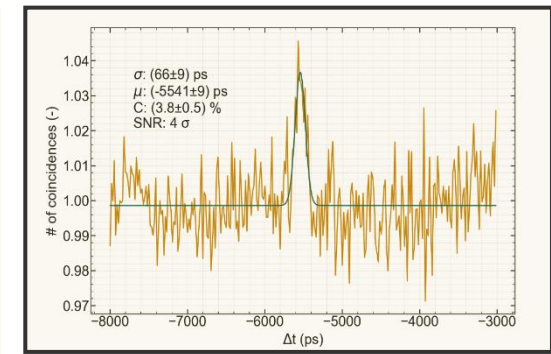
- 9 hours of data collection
- 2 TB of data
- 10000 pairs of pixels

One pair of pixels,  
matching wavelength

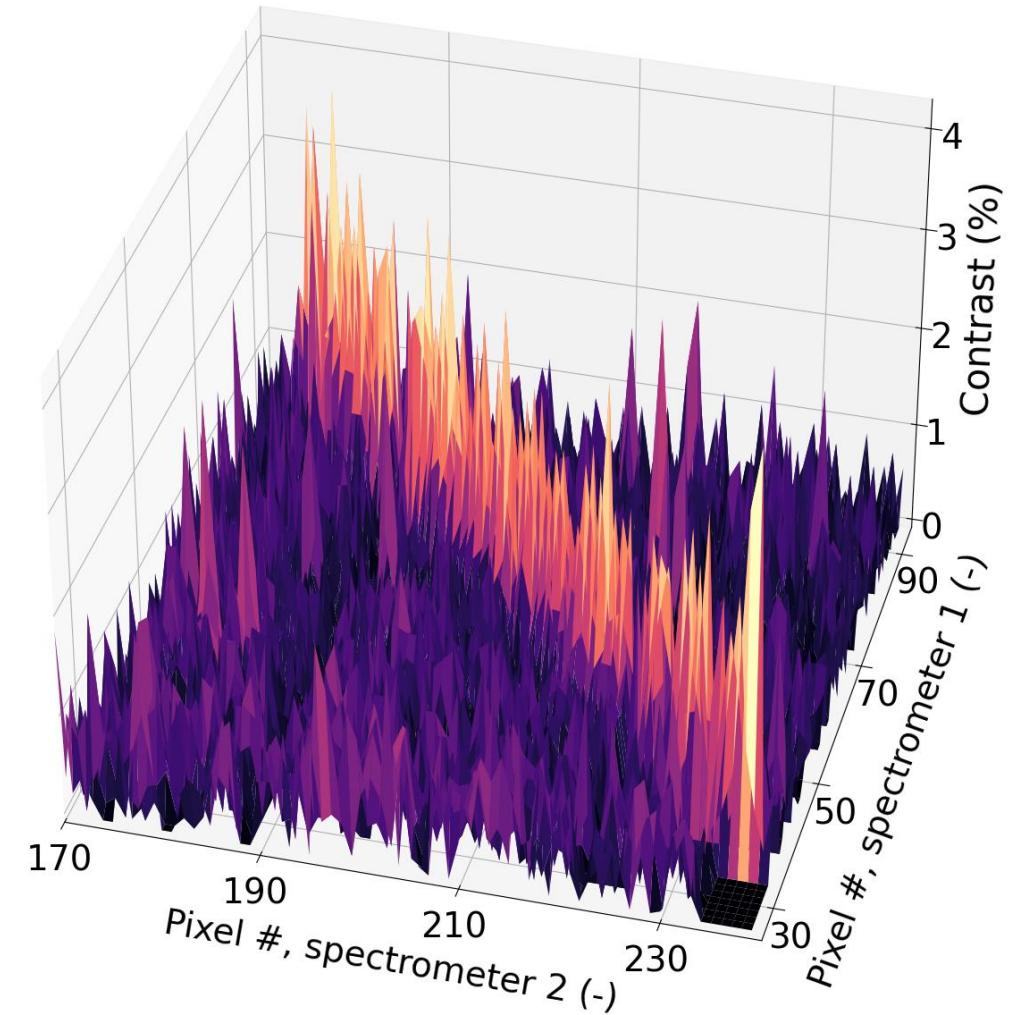
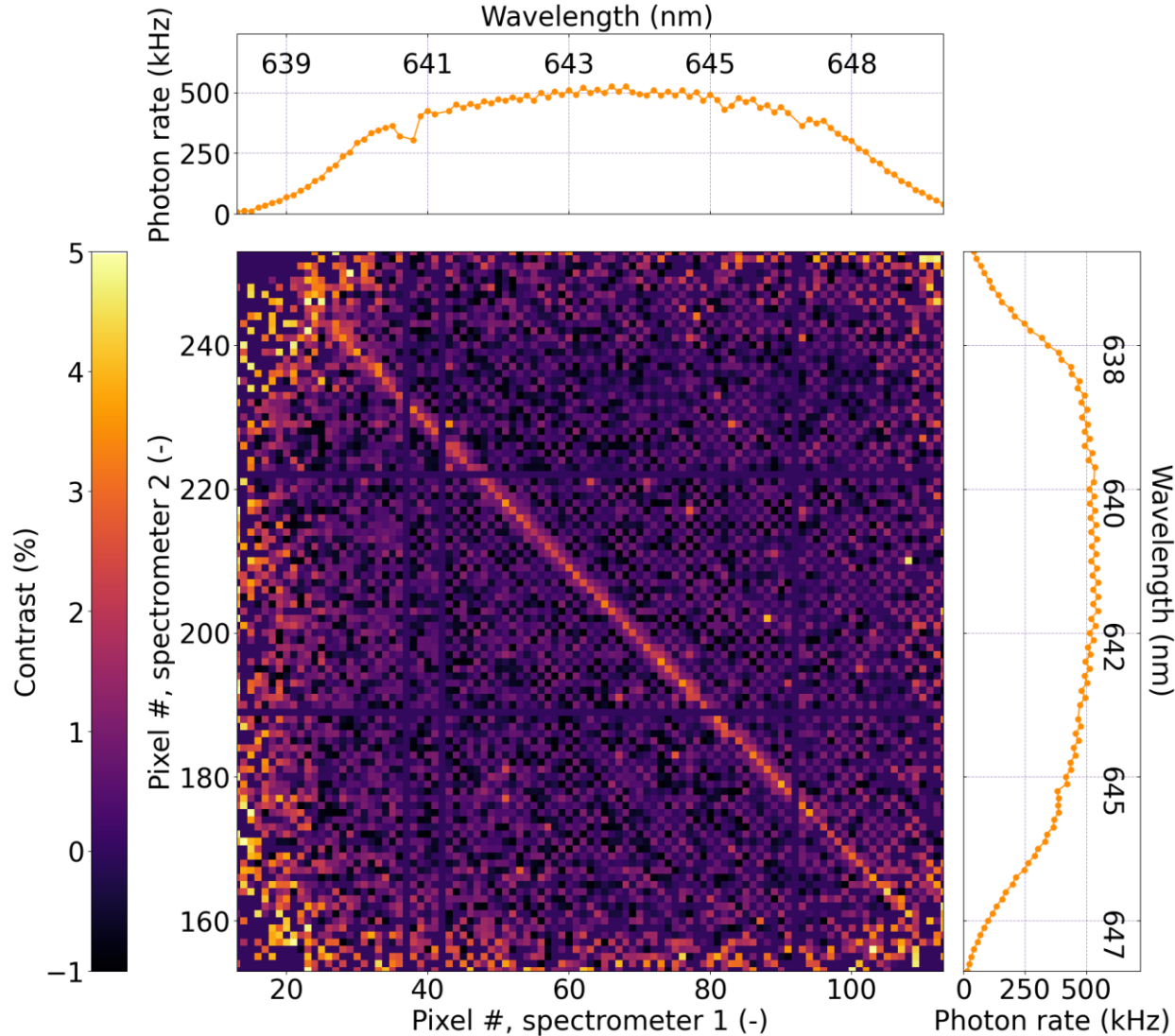




**Over 70  
HBT  
peaks**

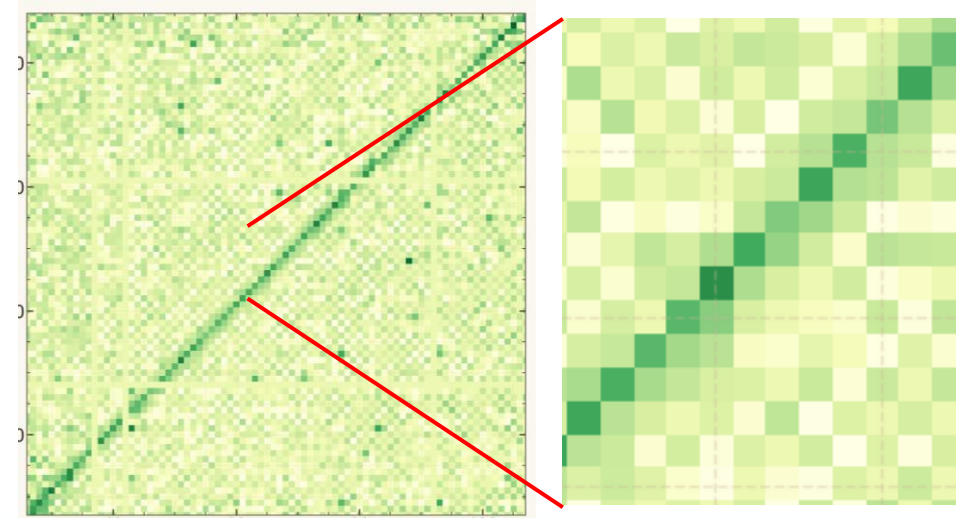


# Hundreds of HBT peaks



# Why spectral multiplexing?

SNR of sky HBT observations



$$\text{SNR} = \sqrt{2} \sqrt{\epsilon_1 \epsilon_2} \sqrt{\frac{A_1 A_2}{(1 + B_{\nu 1}/F_\nu)(1 + B_{\nu 2}/F_\nu)}} \frac{F_\nu}{h\nu} V_{12}^2 \sqrt{N_{chan}} \sqrt{\frac{T_O}{\sigma_t}}$$

Interferometer/telescope parameters

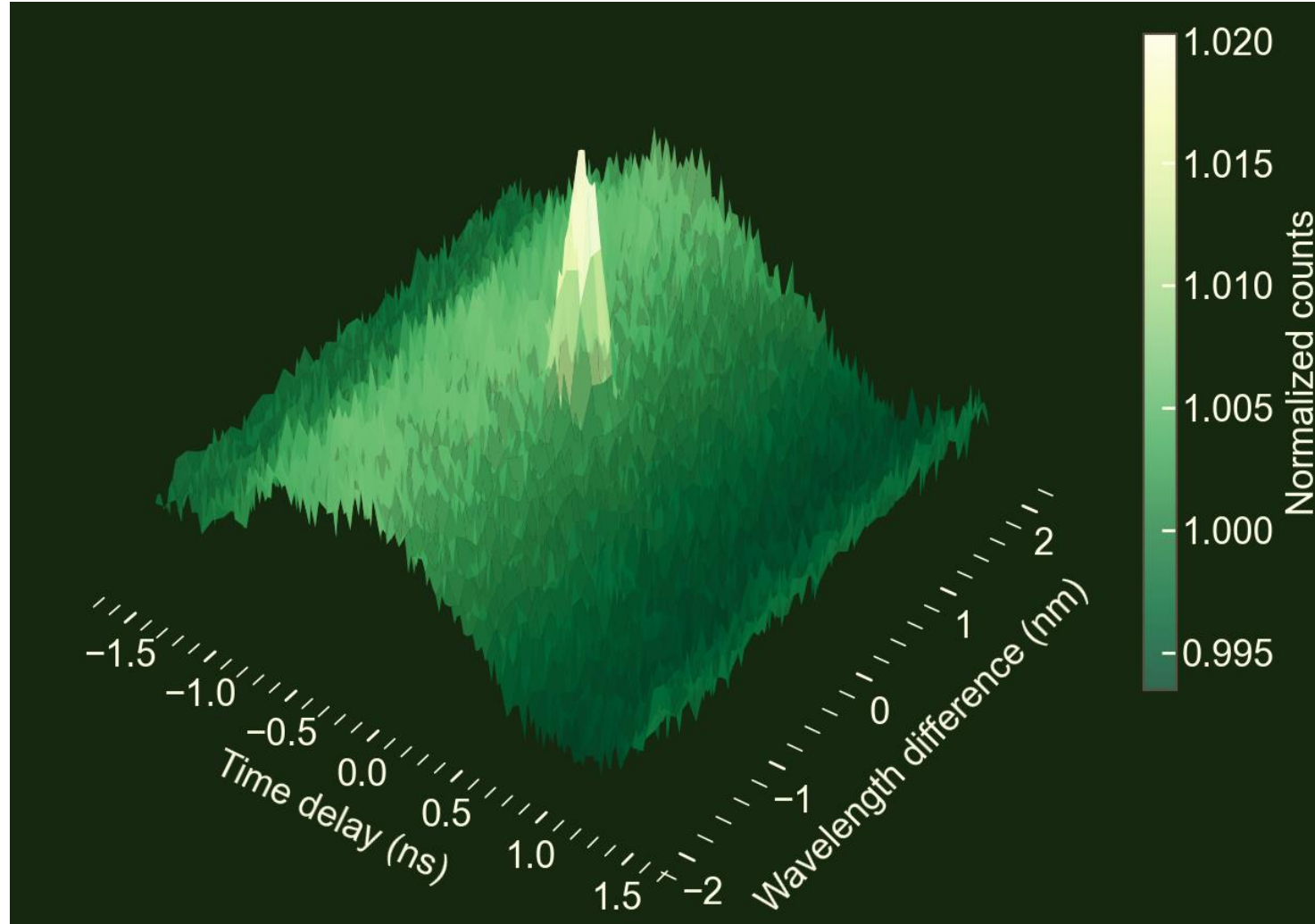
Contrast **Camera**

Time

**~10x higher SNR  
with current spectrometer**

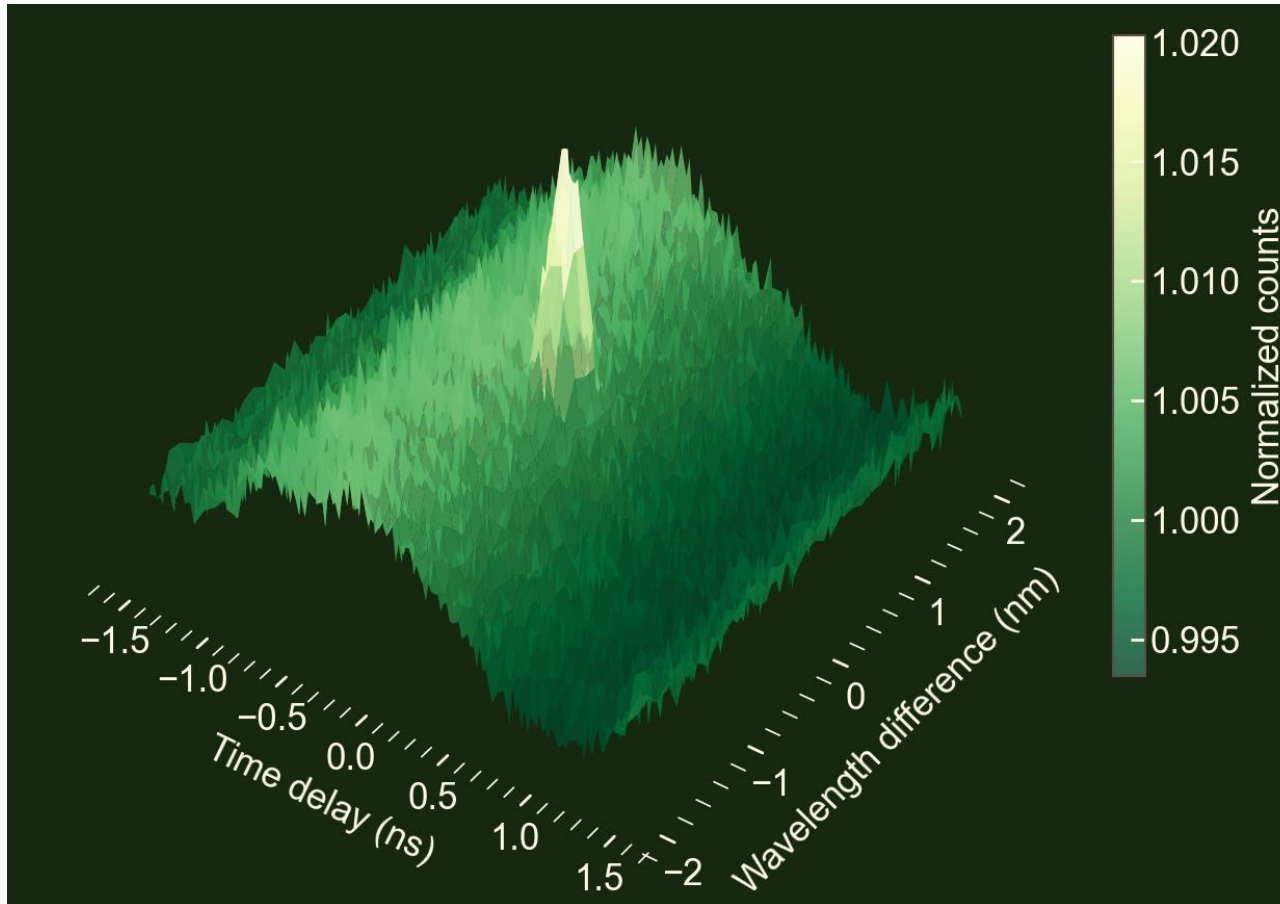
# Heisenberg-Gabor Limit (HGL)

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

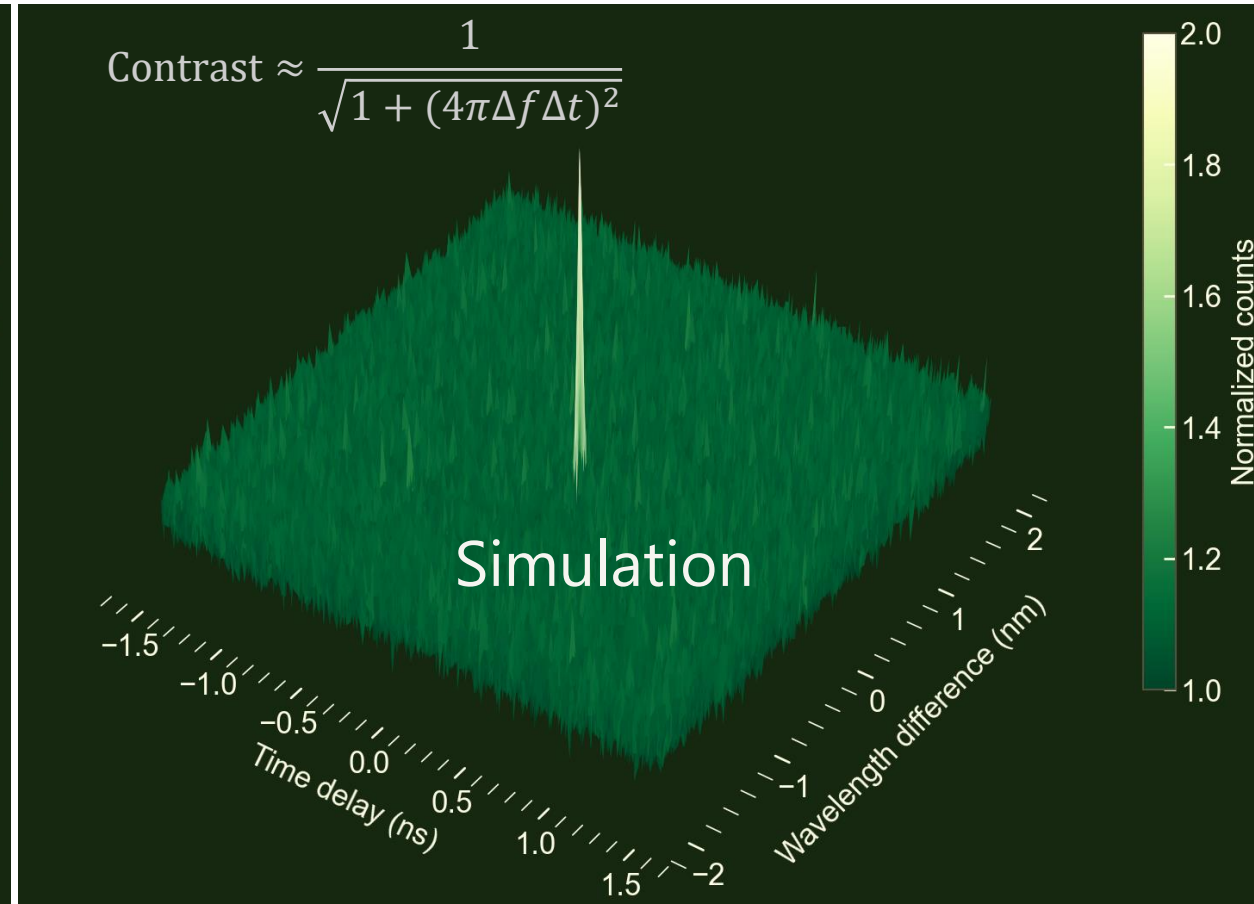


$$\Delta f \Delta t \geq \frac{1}{4\pi}$$

# Heisenberg-Gabor Limit (HGL)



~48 ps, ~48 pm (rms) => 21x above HGL



~10 ps, ~10 pm (rms) => at HGL

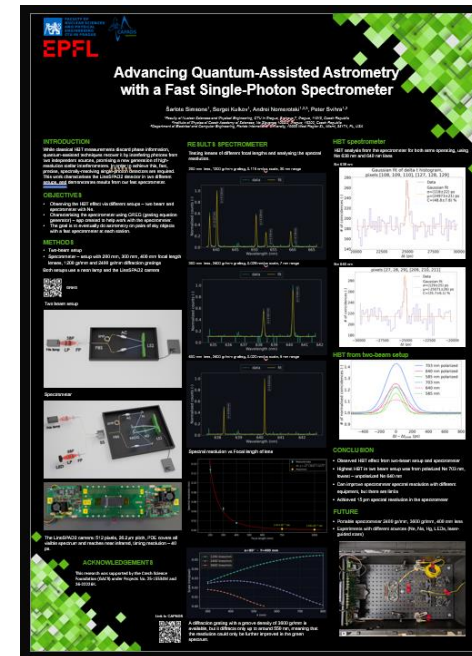
# New developments

# Improving the setup

- Testing different gratings (2400 gr/mm, 3600 gr/mm)
- Testing different lenses ( $f=300$  mm, 400 mm, and higher)
- Top-tier collimators (Thorlabs Polaris) = amazing stability



- See Sarlote Simsone's poster



# Improved setup

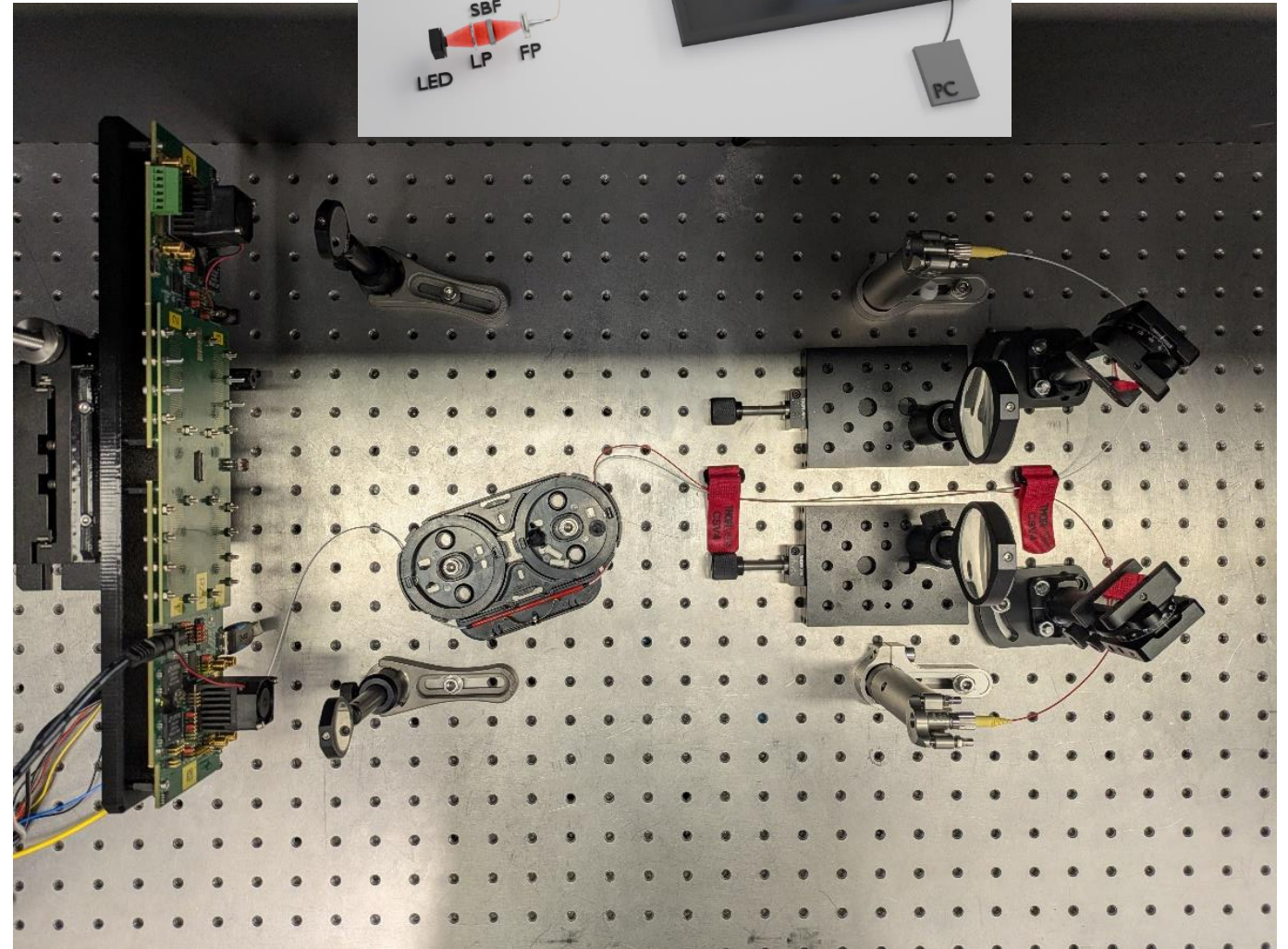
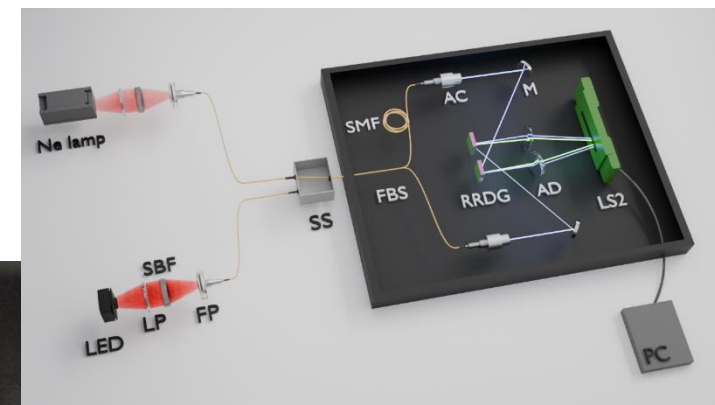
## Was

- 1200 gr/mm
- 200 mm
- 0.11 nm/pixel
- ~28 nm range
- ~48 pm rms

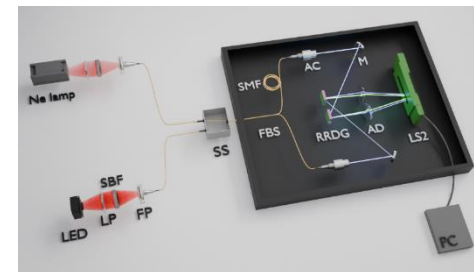
## Now

- 2400 gr/mm
- 400 mm
- 0.02 nm/pixel
- ~4.8 nm range
- ~16 pm rms

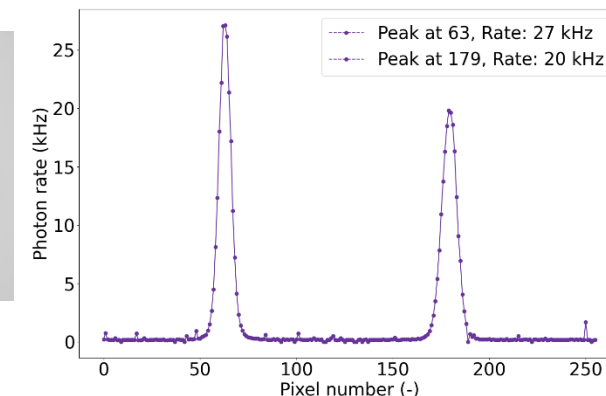
Not the limit – see Sarlote's poster



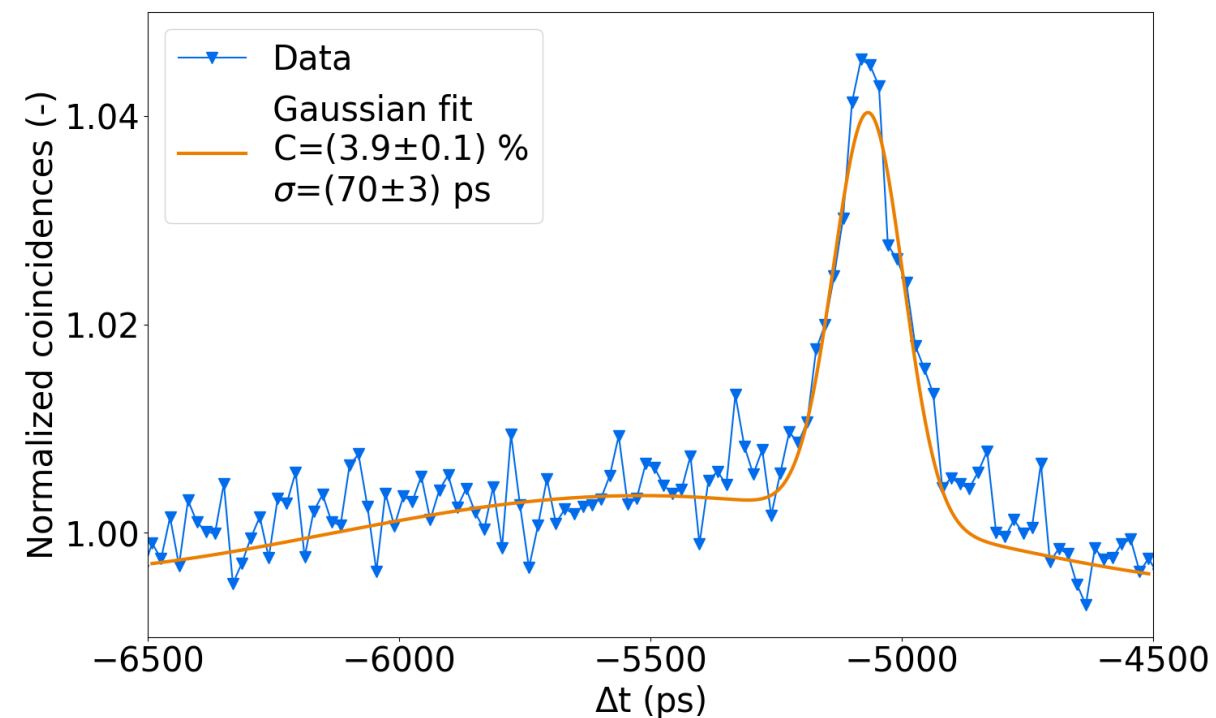
# HBT with higher contrast



LED with Alluxa  
656.4+/-0.05 nm

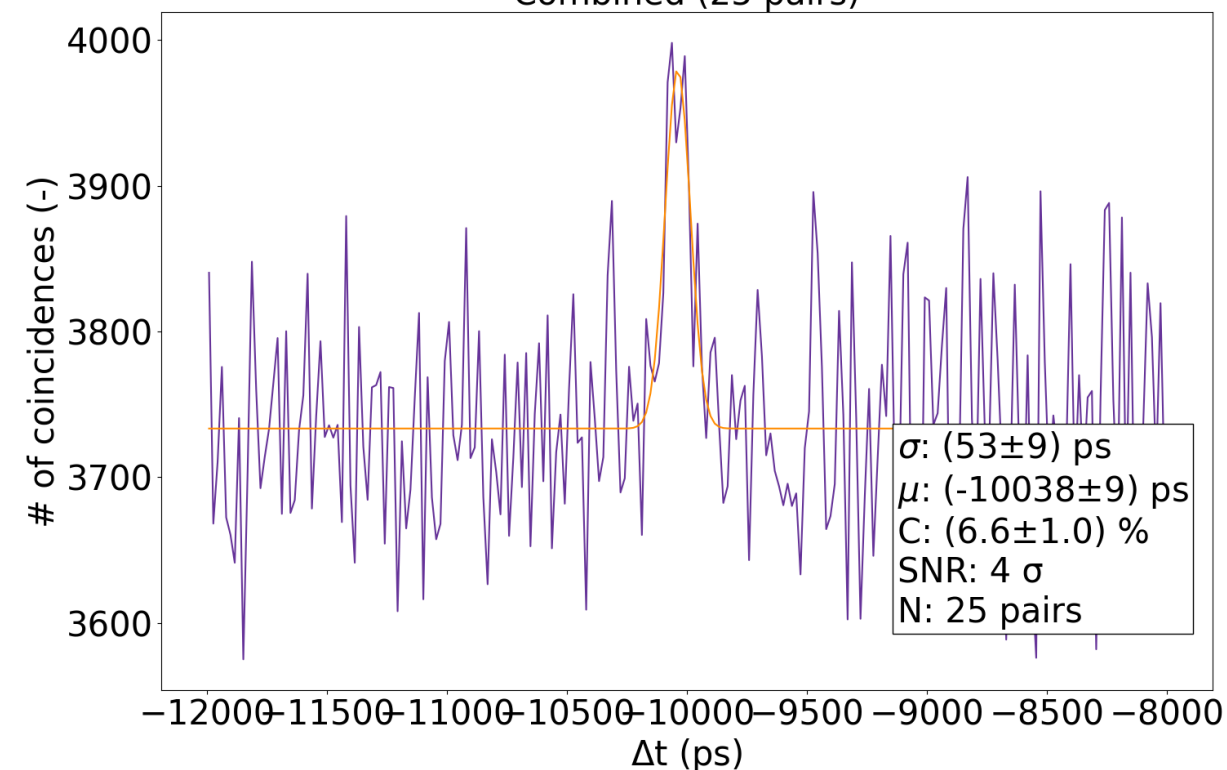


# Was

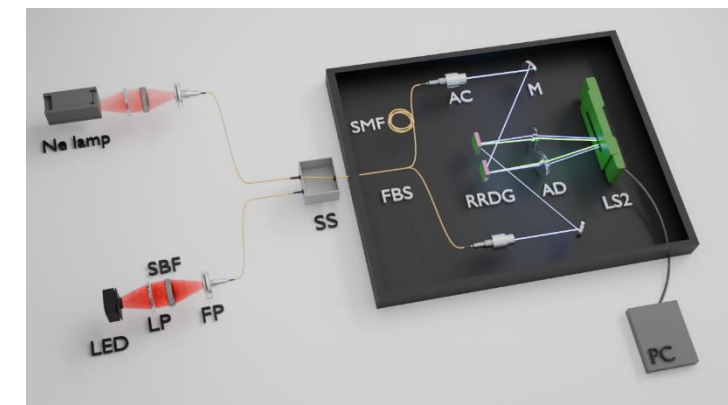
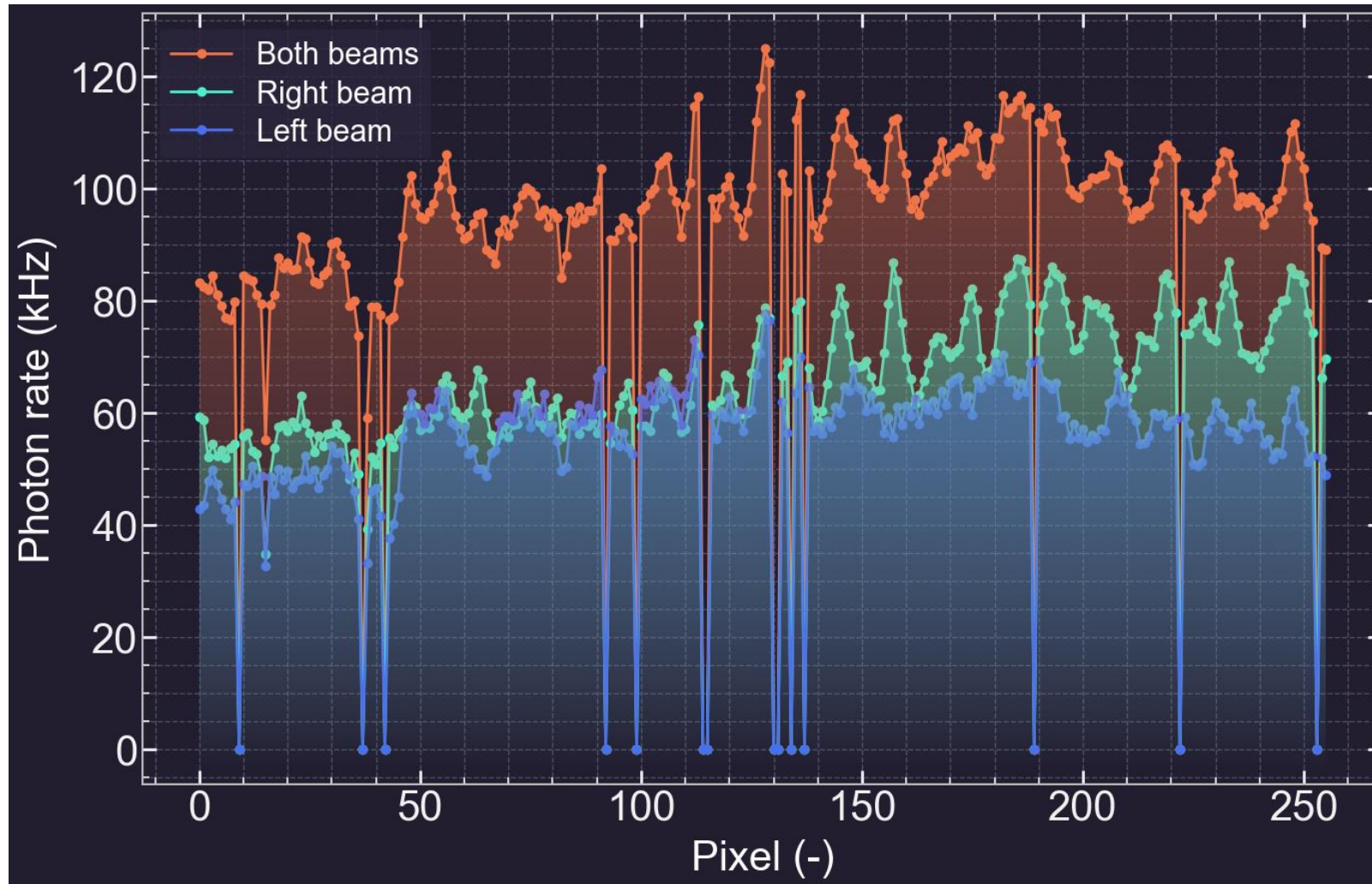


## Now

Combined (25 pairs)



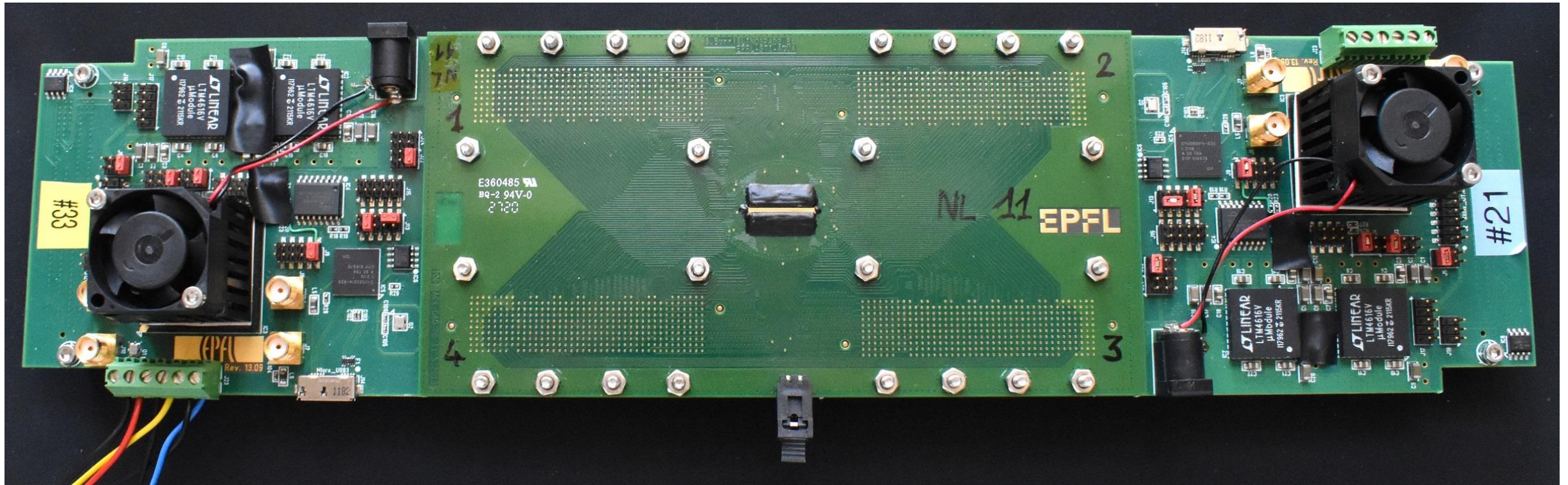
# Looking for HBT w/o filter



- More channels
- Better resolution => better contrast
- But ½ because of the wvl overlap
- 3 TBs of data, running analysis...

# Doubled spectral range

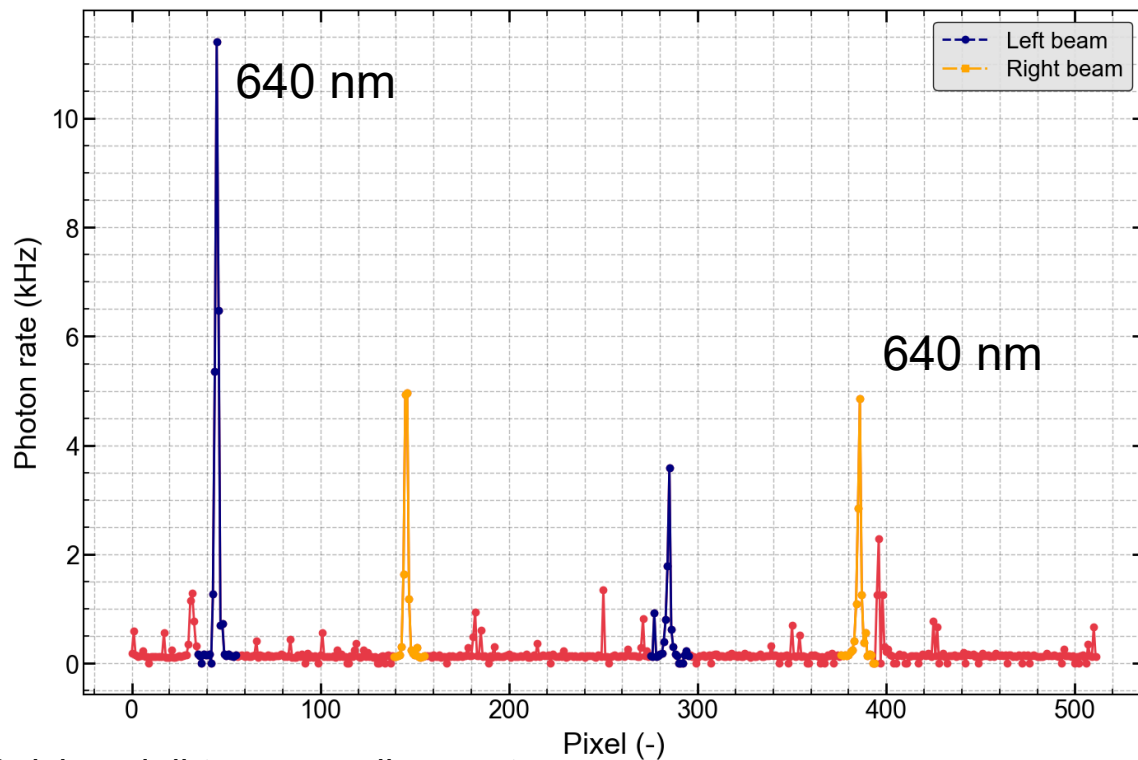
# Doubled the spectral range...



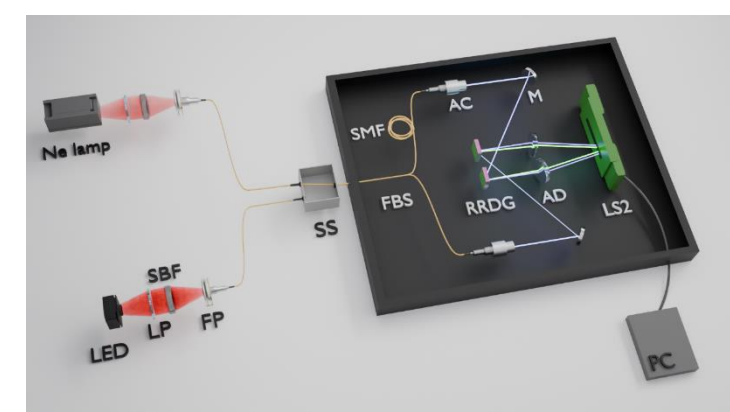
...synchronizing the two halves

# HBT between two halves

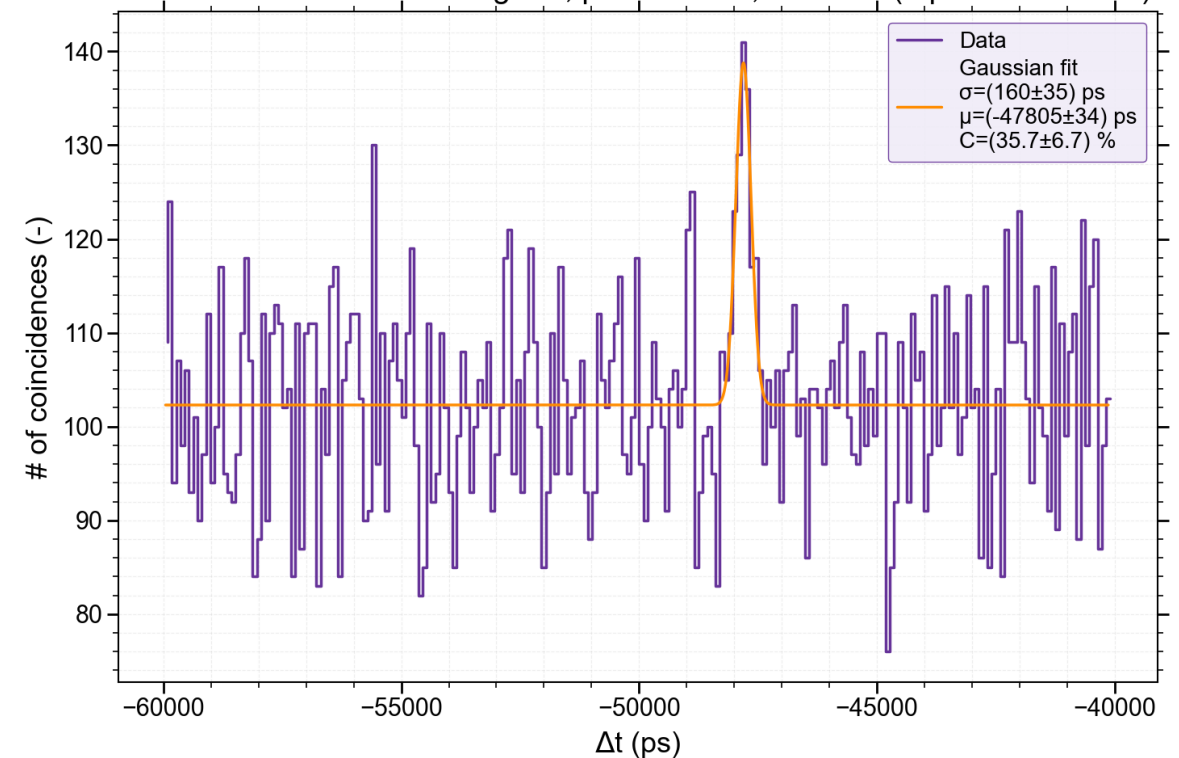
Ne lamp, spectrometer (2400 gr/mm, 400 mm)



Quick and dirty – poor alignment...  
But in time for the conference!



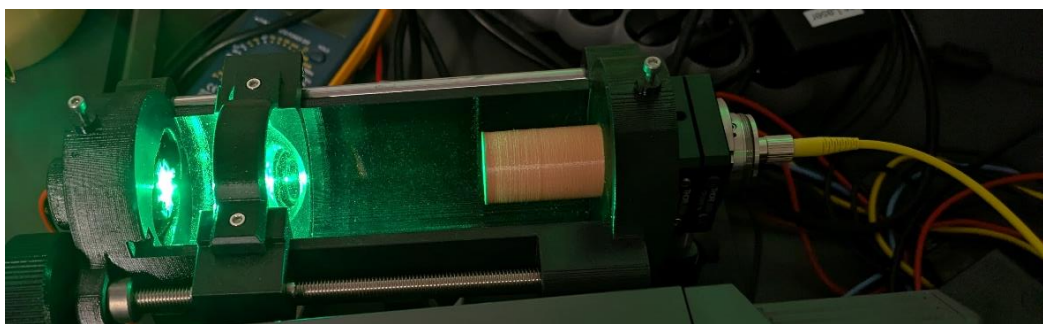
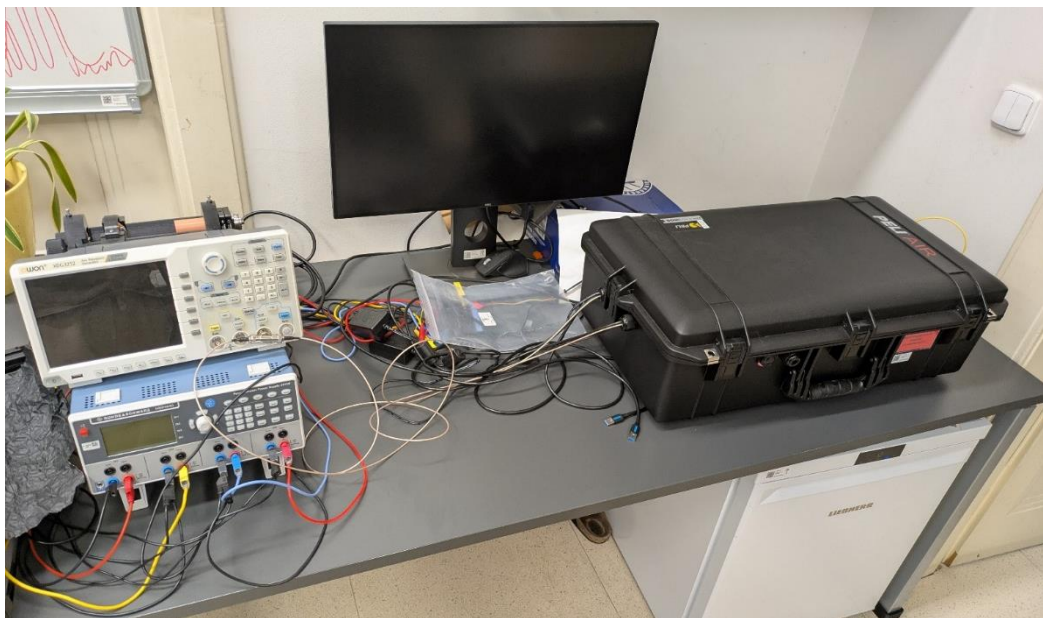
Gaussian fit of delta t histogram, pixels 44-46, 385-387 (9 pairs combined)



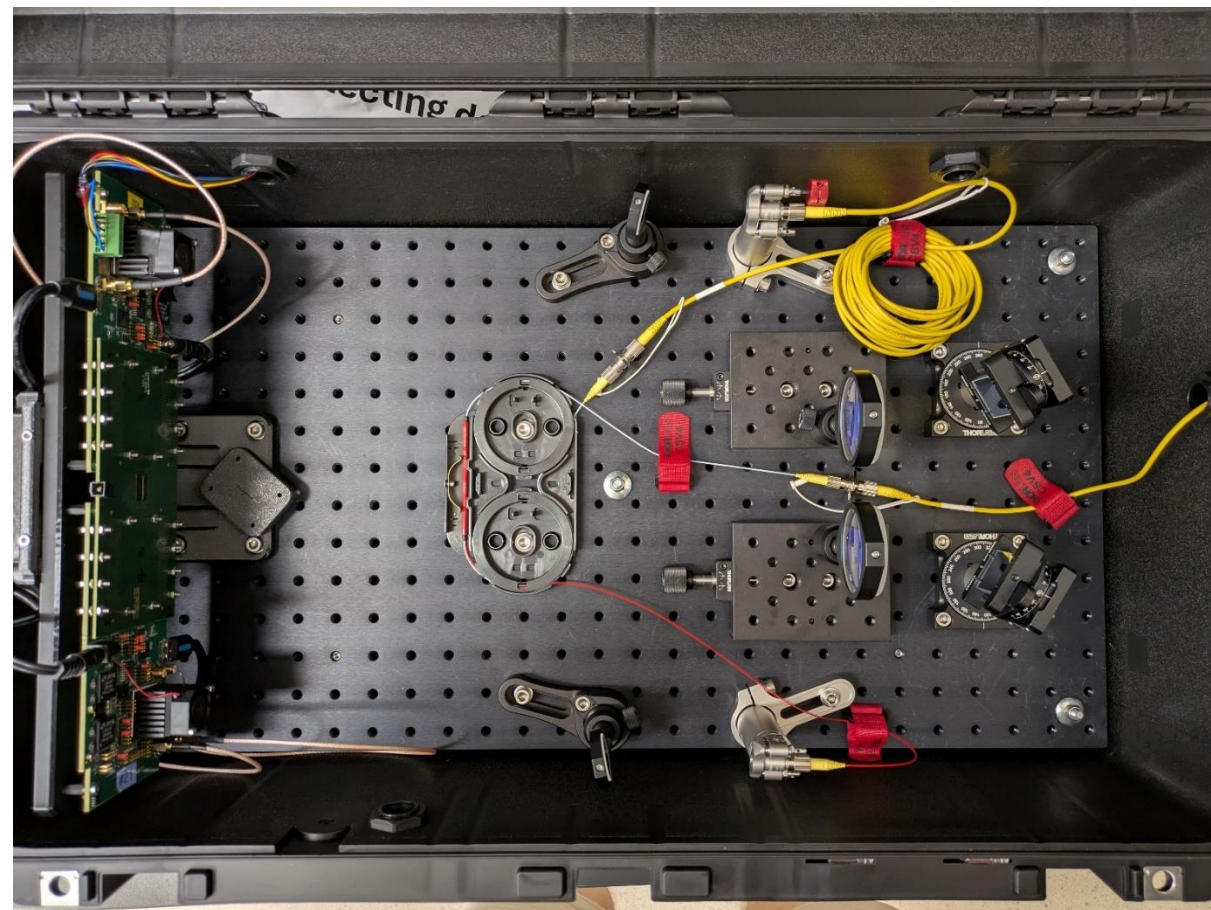
640 nm lines

# Portable spectrometer

# Portable spectrometer (in a Peli box)



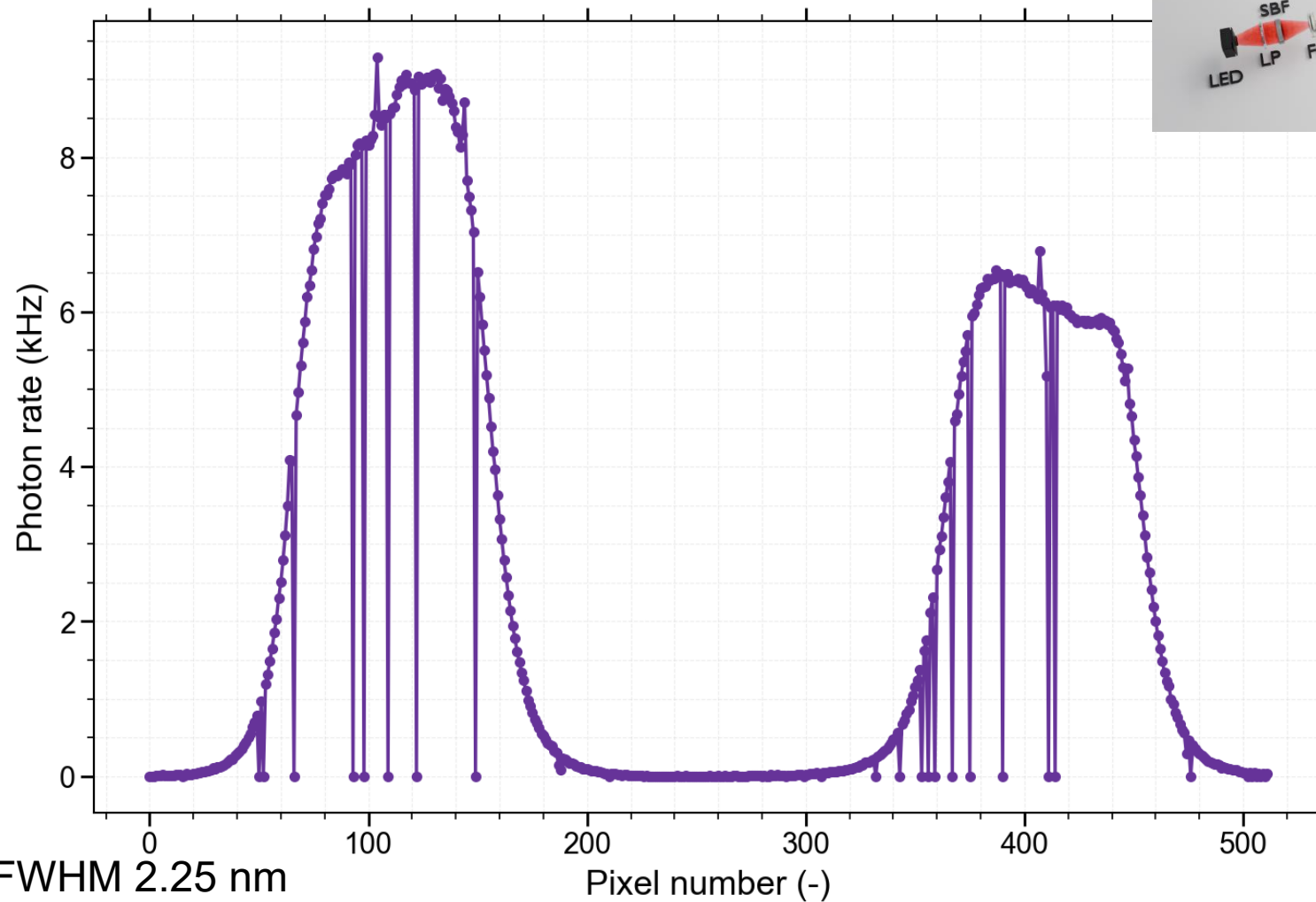
Alluxa CWL 532 nm, FWHM 2.25 nm



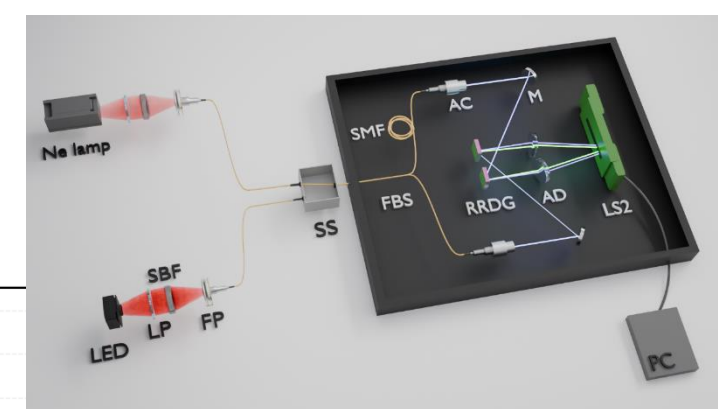
~10 kg

# Camera's output

2400 gr/mm  
400 mm  
~15 pm rms



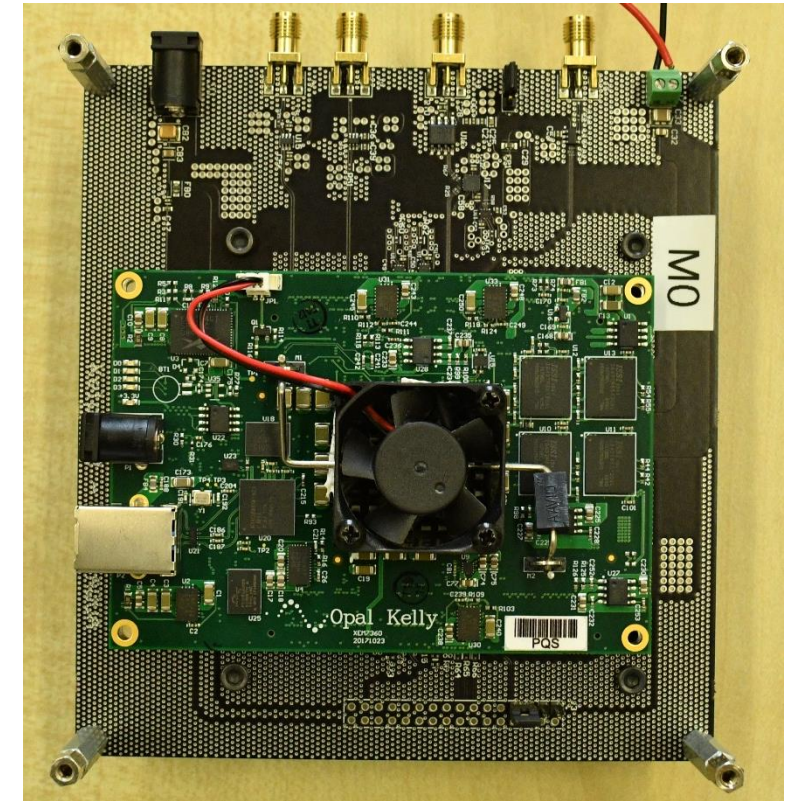
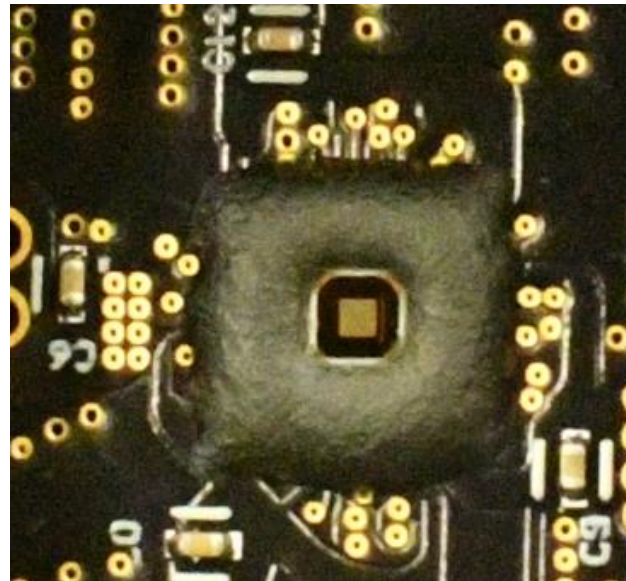
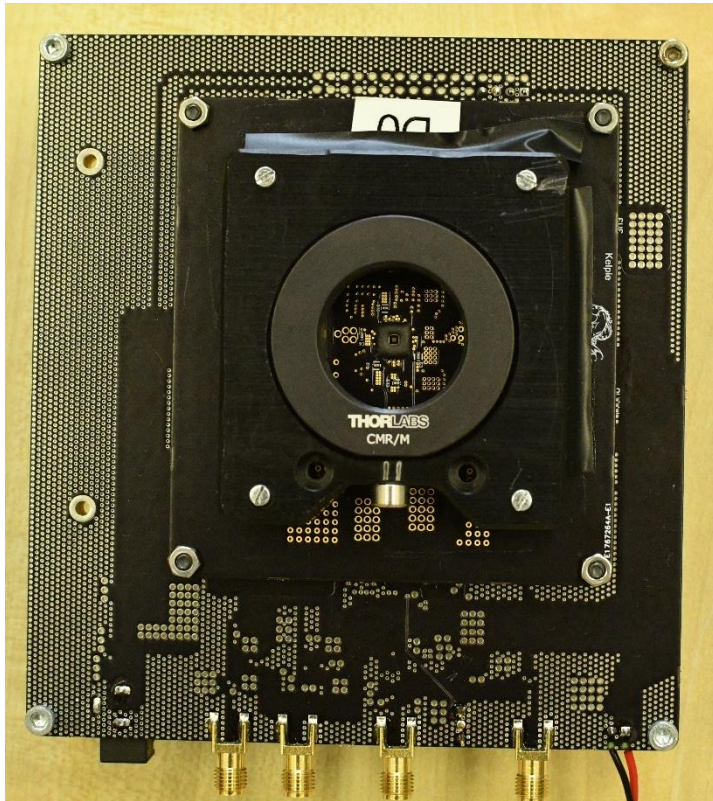
Alluxa CWL 532 nm, FWHM 2.25 nm



# Kelpie: new frontier in SPAD technology

# Kelpie D0/M0

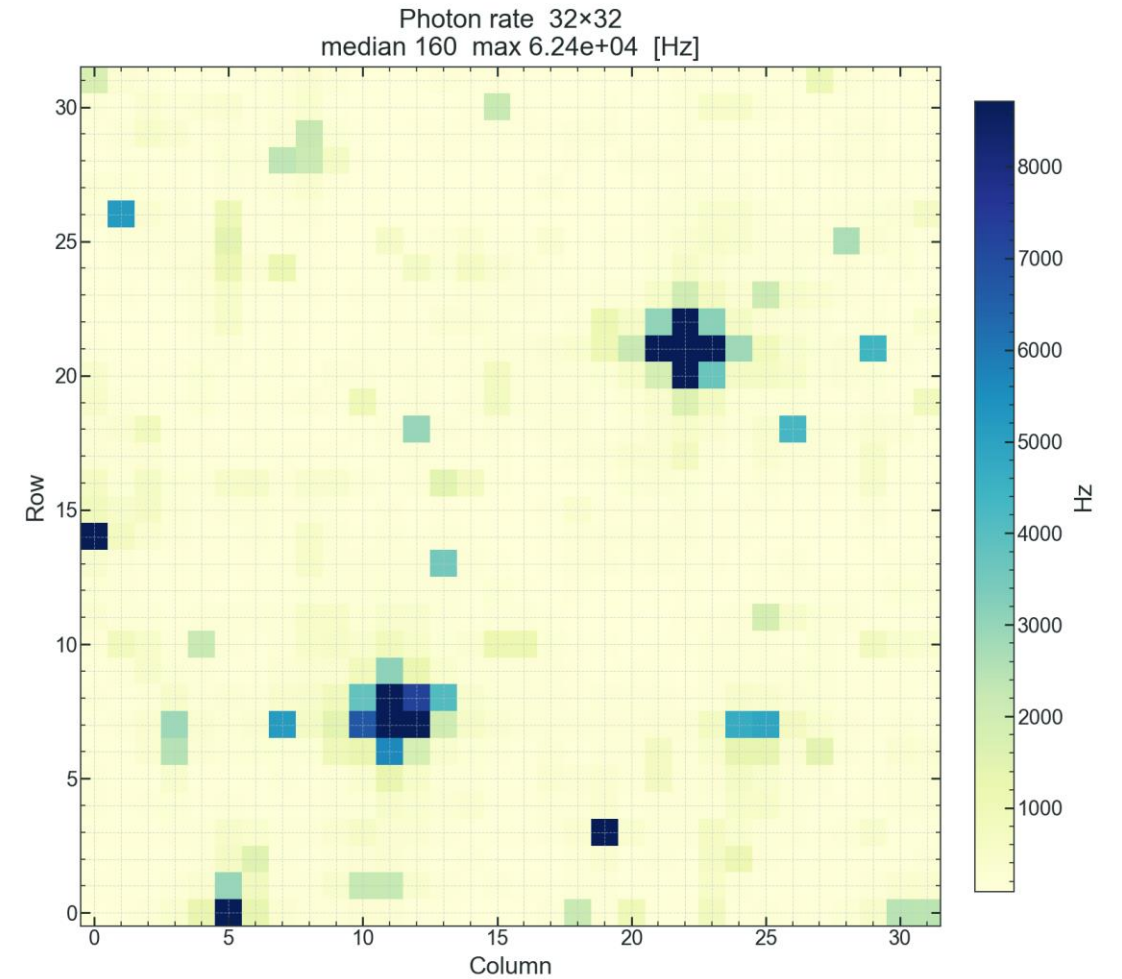
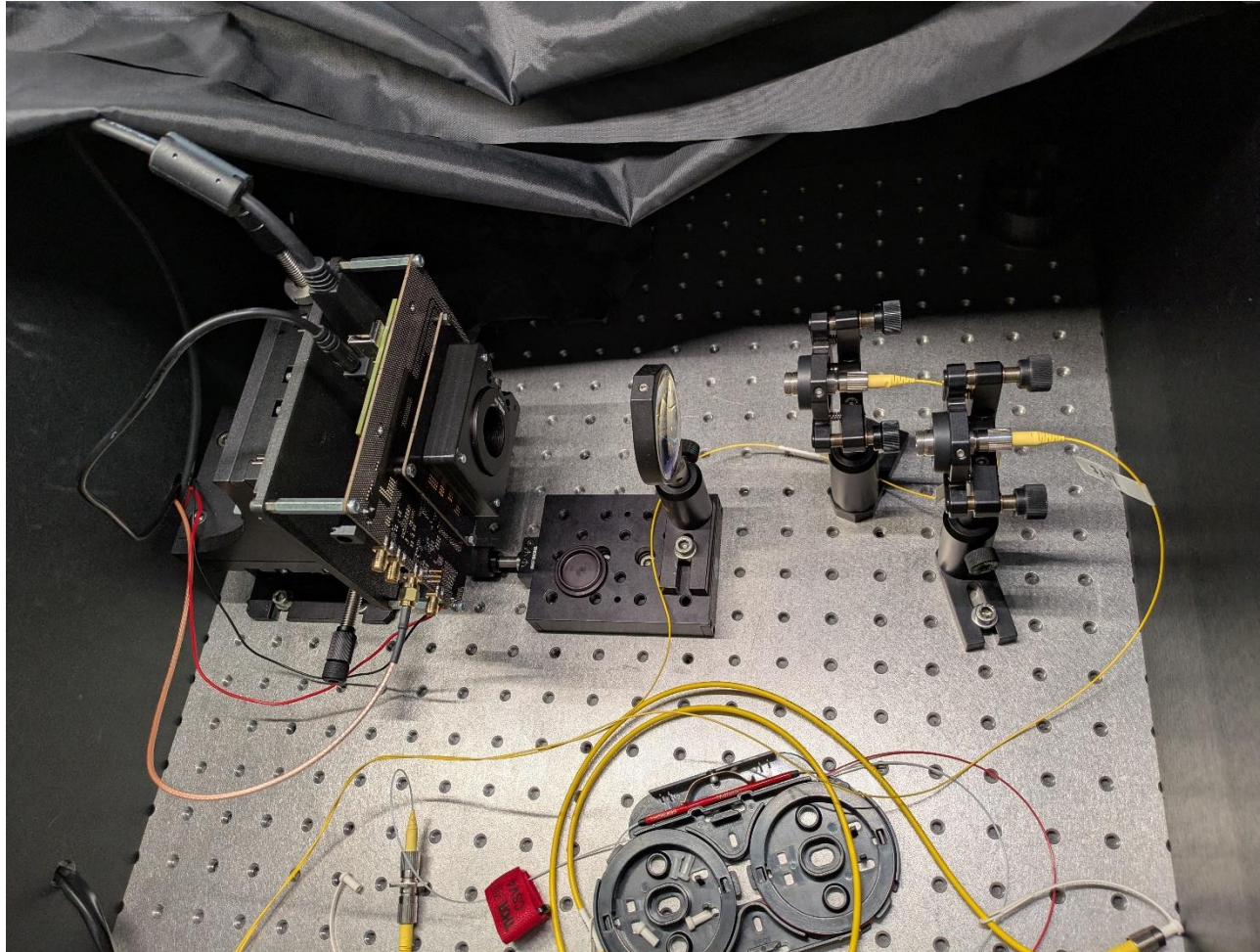
- 64x64
- 32x32 (2x2 macropixel)
- 2x2 mm<sup>2</sup> Si area
- 10.17  $\mu\text{m}$  pixel pitch
- QE best in NIR
- $\sim 40$  ps rms



- 2D sensor
- Fully reprogrammable (counting, timestamps)

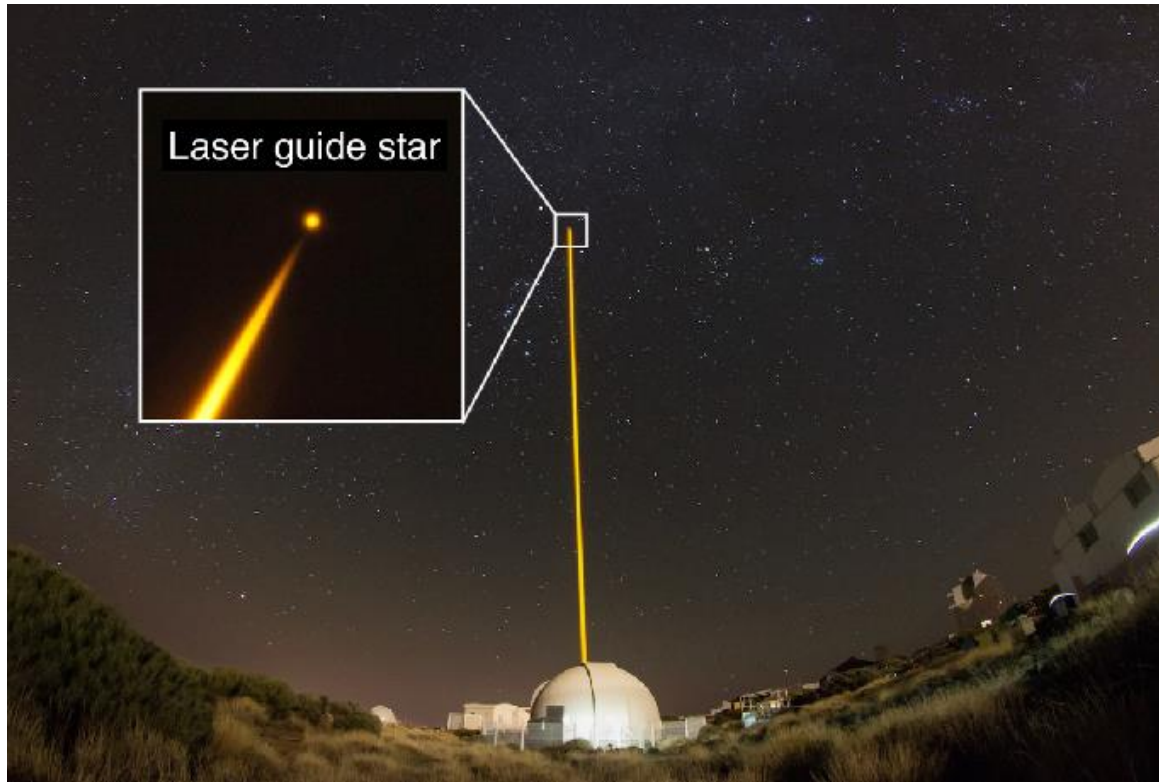
# Testing the camera, including HBT

Ar lamp w/ 794.9 nm filter

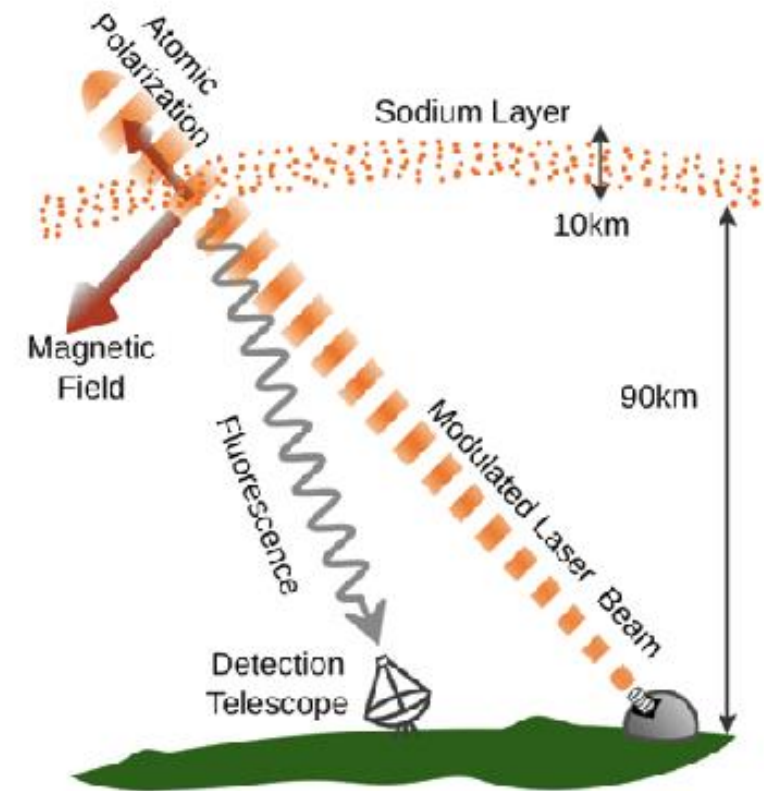


# Future plans: on-sky tests

# Laser guided stars: HBT from “stellar” Na



Courtesy of F. Pedreros/ESO [PedrerosBustos2018a].

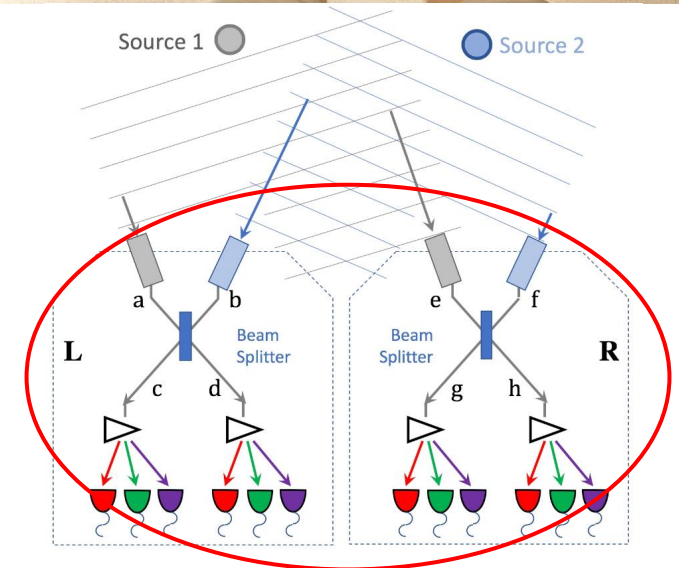
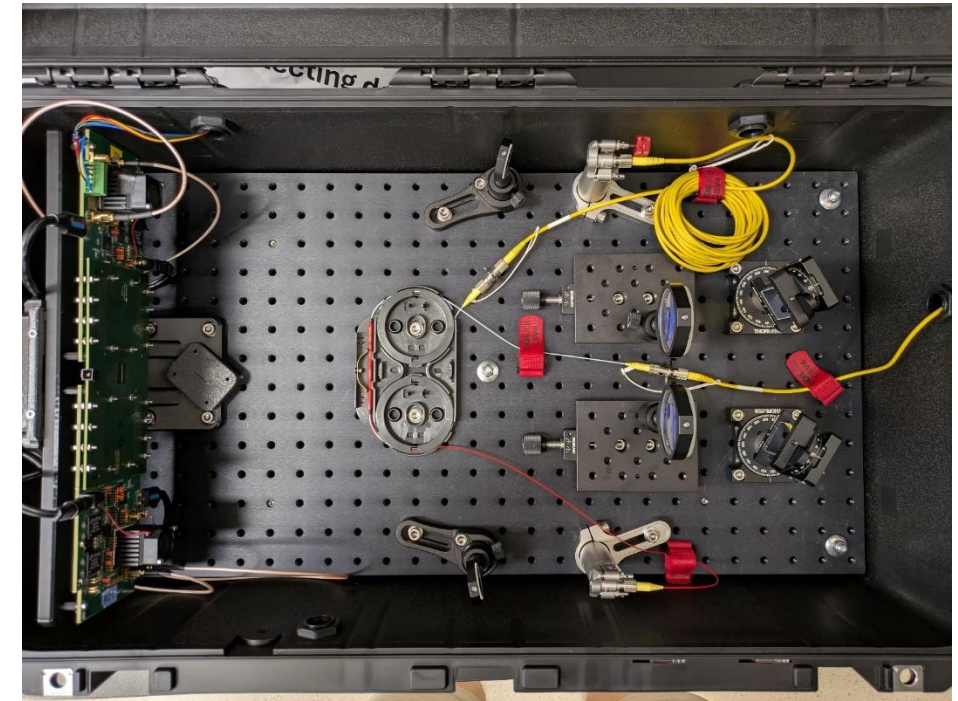


Source: Higbie 2011

Doublet 588.995 nm  
589.592 nm

# Summary

- Greatly improved the spectrometer setup:
  - Infinitely better stability
  - Better spectral resolution
- Portable spectrometer
- Plans:
  - SMF vs MMF
  - Echelle scheme
  - Tests with Na, preparing for...
  - ... HBT from LGS
  - In-fiber quantum-astrometry scheme in the lab



# Thank you for your attention!



CAPADS Web

