Advancements in Stellar Intensity Interferometry with PhotonPix Detectors

Verena Leopold, Sebastian Karl, Stefan Richter,
Yury Prokazov, Evgeny Turbin, Gennady Sintotskiy
and Joachim von Zanthier

Quantum Optics and Quantum Information

Friedrich-Alexander Universität Erlangen-Nürnberg

Stellar Intensity Interferometry Workshop 2025

16.10.25

Agenda

1. Why High Throughput?
2. Telescope Site
3. Setup and timing resolution
   a) Hybrid photon detectors
   b) PhotonPix detectors
4. Spatial Correlation Results
   a) The Problem of moving stars
   b) Spatial Correlations
   c) Hour angle binning
5. Future Applications of PhotonPix

JATIS Journal of Astronomical Telescopes, Instruments, and Systems

RESEARCH PAPER

On-sky demonstration of an ultra-fast intensity interferometry instrument utilizing hybrid single photon counting detectors

Verena G. Leopold,[a,*] Sebastian Karl,[a] Jean-Pierre Rivet,[b] and Joachim von Zanthier[a]

[a]Friedrich-Alexander-Universität Erlangen-Nürnberg, Quantum Optics and Quantum Information, Erlangen, Germany

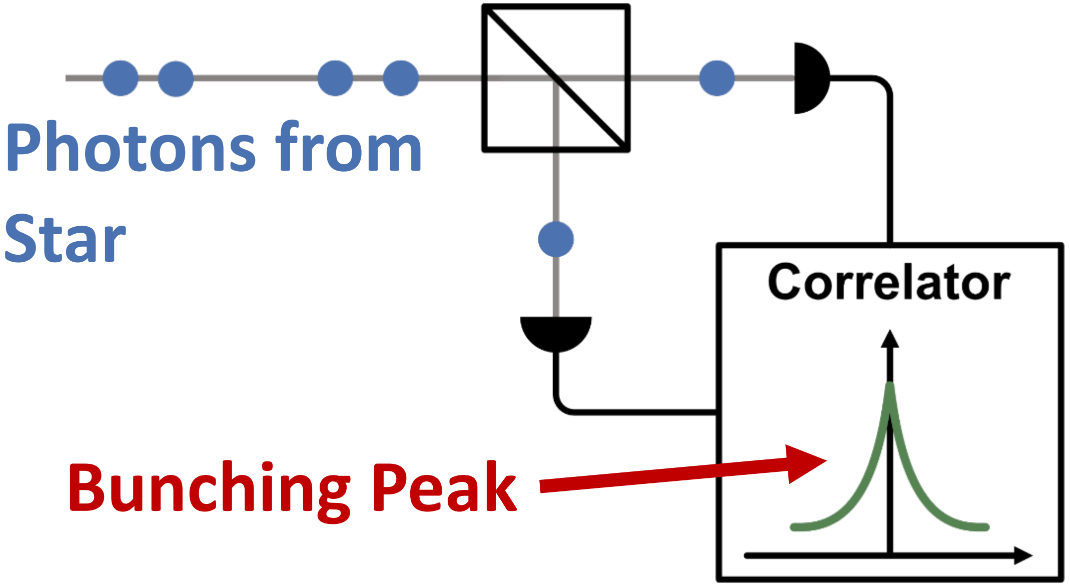
[b]Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, France

ABSTRACT. Intensity interferometry is a reemerging astronomical technique for performing high angular resolution studies at visible wavelengths, benefiting immensely from the recent improvements in (single) photon detection instrumentation. Contrary to direct imaging or amplitude interferometry, intensity interferometry correlates light intensities rather than light amplitudes, circumventing atmospheric seeing limitations at the cost of reduced sensitivity. We developed an ultra-fast, single photon counting and highly stable intensity interferometry instrument for 1 m class optical telescopes. The instrument records on sky the expected stellar photon rates and reaches the temporal coherence times as measured in the laboratory. In addition, all components, especially the photon detection hardware, of the instrument are easily upgradeable with custom hardware currently being developed. The collimated telescope output is spectrally filtered via an ultra-narrow band pass of 2 nm at a central wavelength of 405 nm. We use hybrid photon detectors (HPDs) for single photon detection and a constant fraction discriminator (CFD) for signal conditioning. A time-to-digital converter (TDC) is used for time stamping. The combination of HPDs and CFDs is optimized for a large active area and high timing resolution. We successfully measured photon bunching of three bright *A*-type stars—Vega, Altair, and Deneb at the 1.04 m Omicron telescope of C2PU (Centre Pédagogique Planète Univers) at the Calern Observatory in the south of France. In all cases, the observed coherence time, bunching peak amplitude, and S/N fit well to both the pre-calculated expect-

Why High Throughput?

+

Why High Throughput?



- Use single photon detectors and correlate signals using time-to-digital converter
- Larger telescopes increase signal to noise ratio

Problems:

- For bright stars: hybrid single photon detectors saturate @10MHz (>1m telescopes)
- High data rate

Solutions:

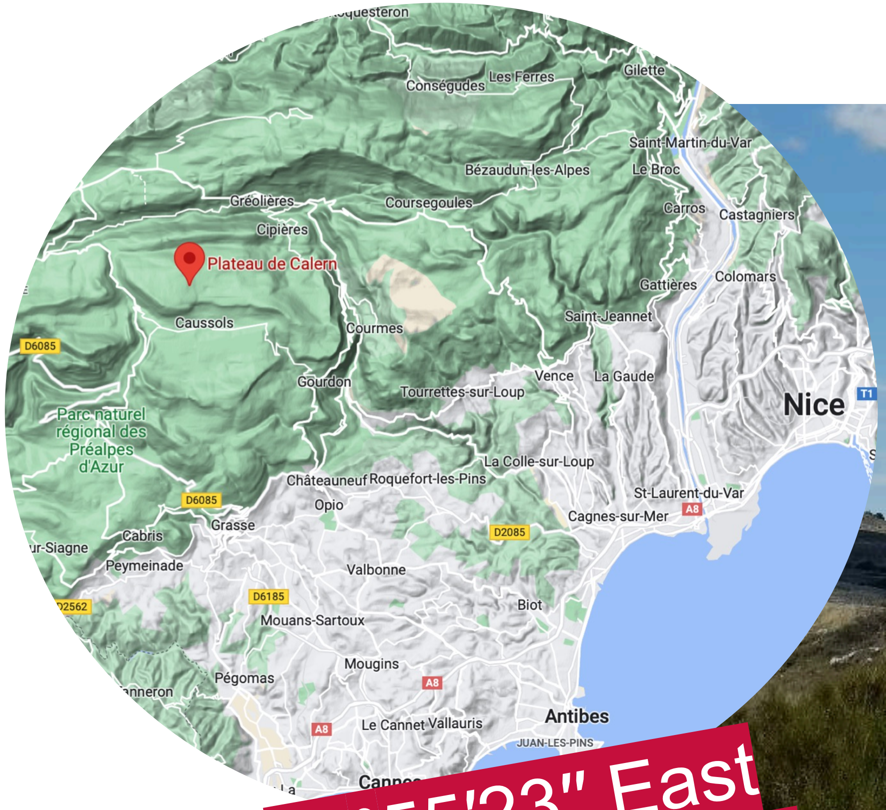
1) New kind of detector
2) High throughput TDC

Telescope Site

Telescope Site

The Calern observatory is located in the South of France close to Nice on a plateau with an altitude of 1270m. C2PU offers twin telescopes at a seperation of 15m.

- Primary mirror diameter of 1.04 m
- Equatorial yoke mount
- Cassegrain secondary focus
- Focal length of 13m and F/12.5



06°55'23" East
43°45'13" North

Telescope Site

The Calern observatory is located in the South of France close to Nice on a plateau with an altitude of 1270m. C2PU offers twin telescopes at a seperation of 15m.

- Primary mirror diameter of 1.04 m
- Equatorial yoke mount
- Cassegrain secondary focus
- Focal length of 13m and F/12.5

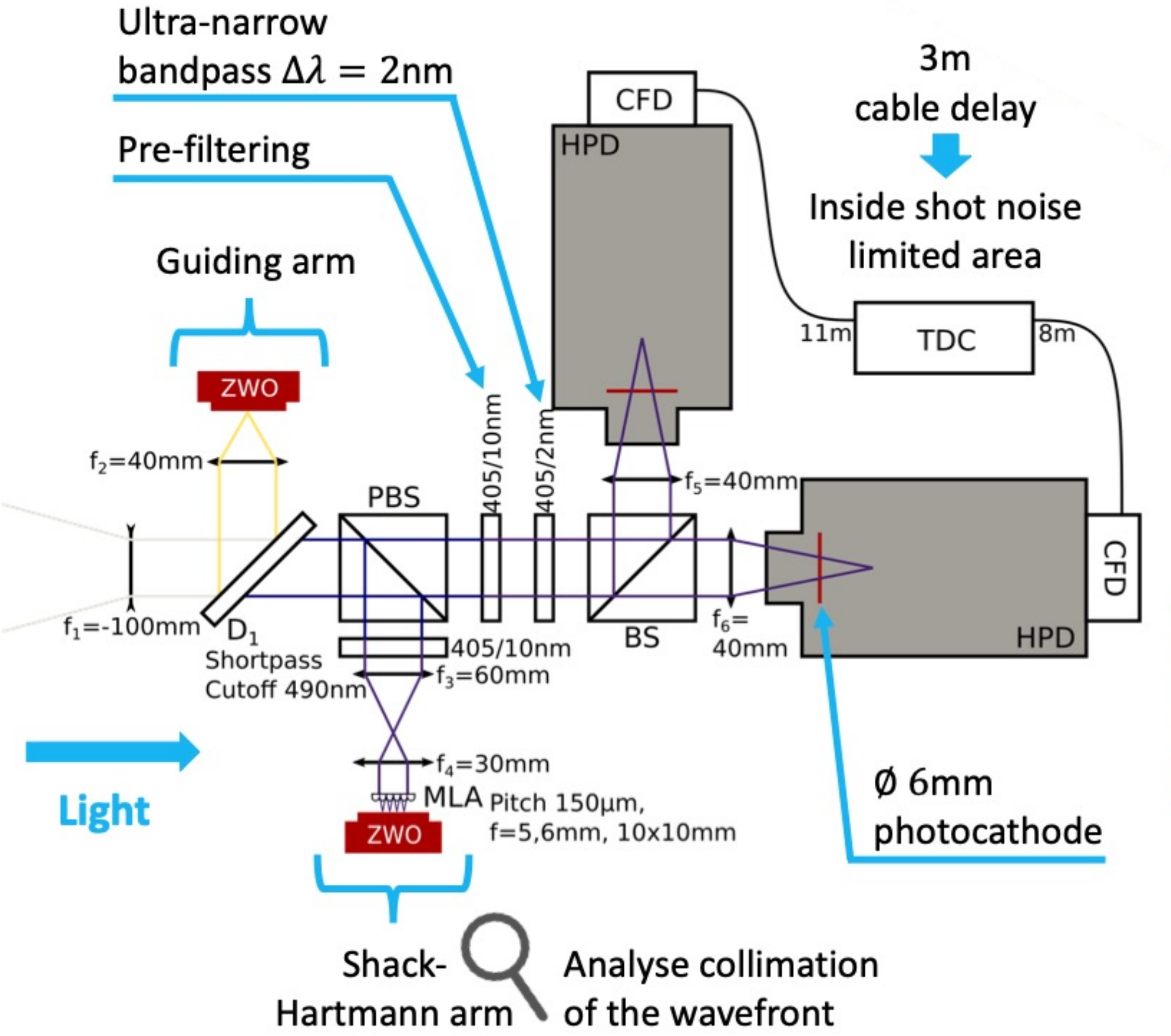
East Dome
Epsilon

Omicron
West Dome

Setup and timing resolution

a) Hybrid photon detectors
b) PhotonPix detectors

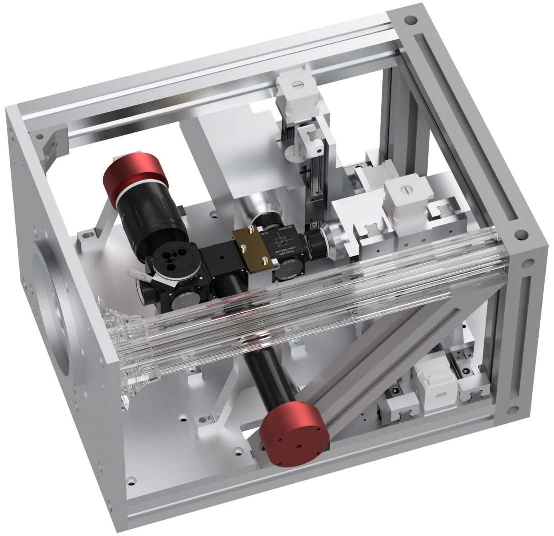
Optical Setup



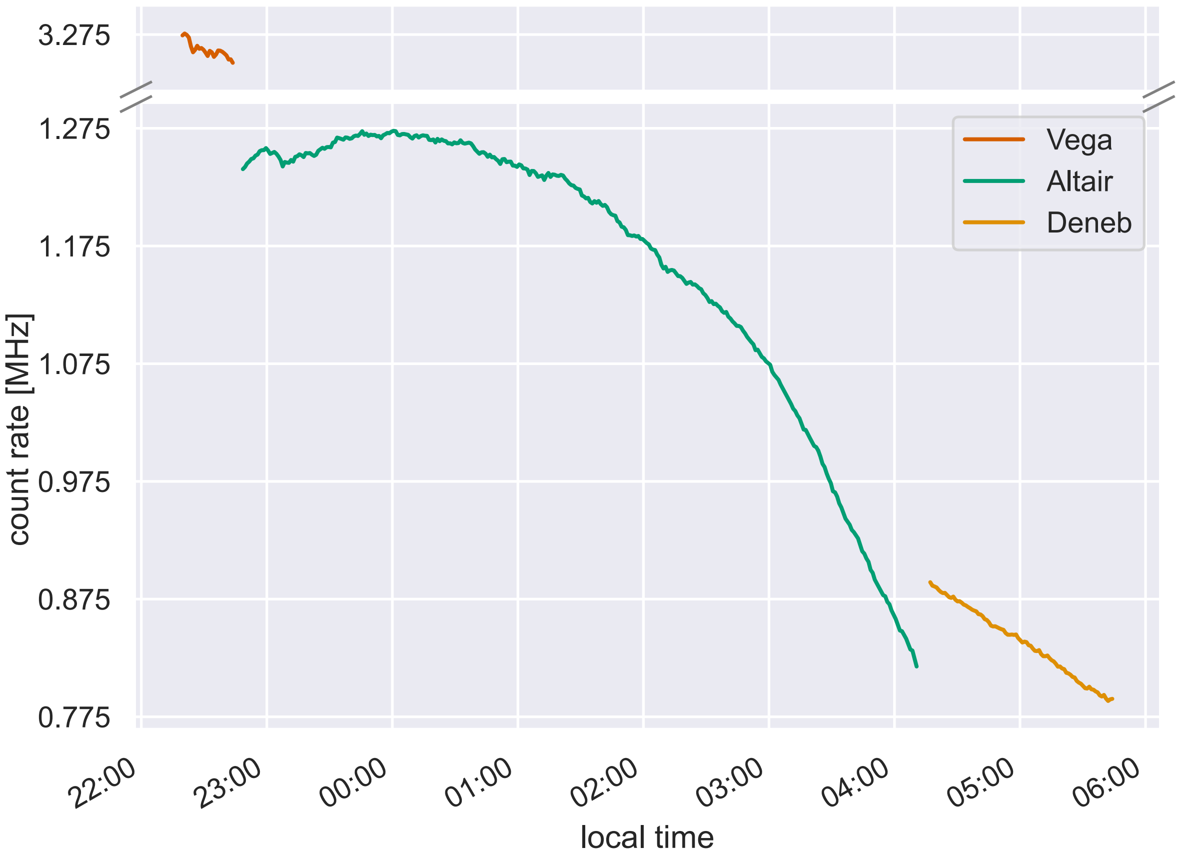
- 40/45mm lenses for beam compression (no focus)
- Cable delays will vary from 3 to 12m
- Used for all measurements
- Detectors will change

Advantages of the Setup

- Tracking of the star never lost
- Short optical path
- Observation in the blue at 405nm
- Easy to align at the telescope
- Movable detectors in x and y-direction



Typical Measurement Night

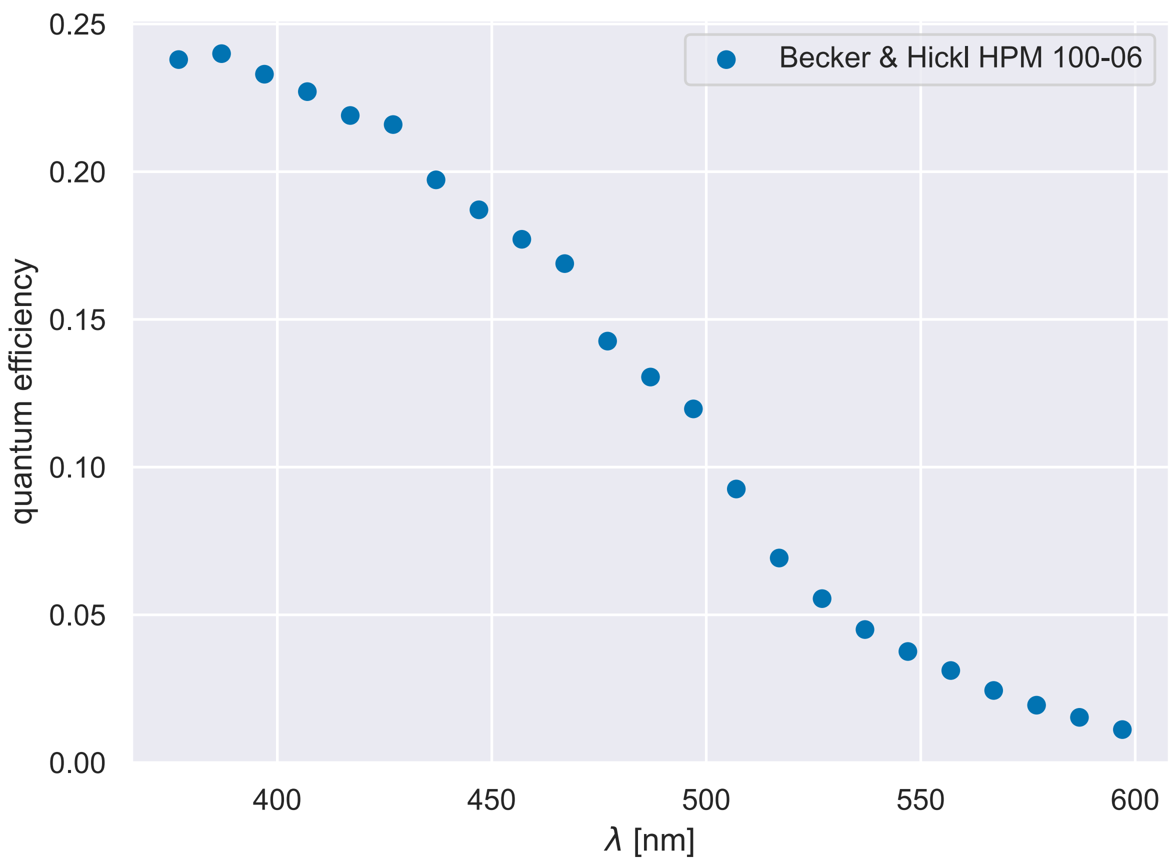


Hybrid Photon Detectors

Hybrid Photon Detectors (HPDs)

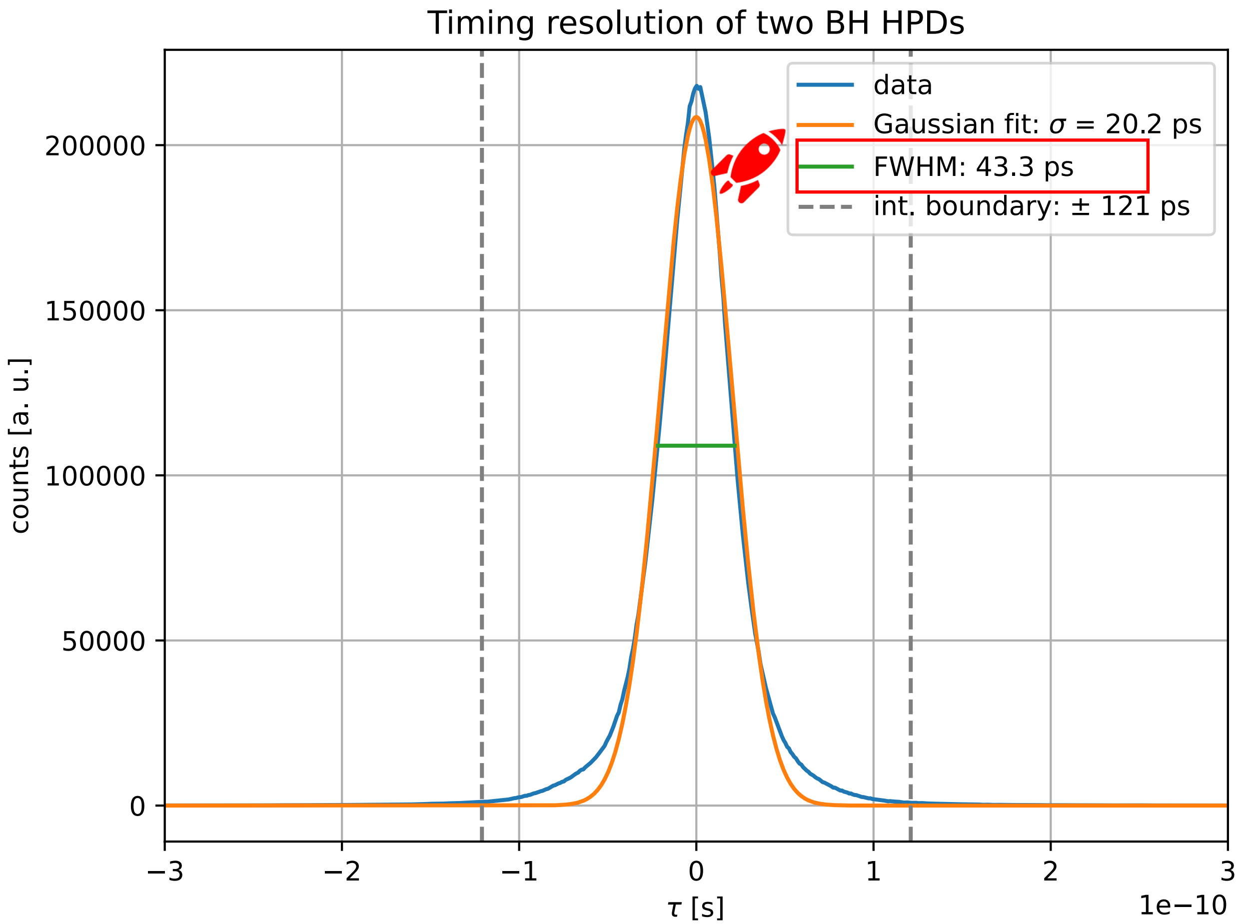
- Ø6mm active area
- Max. continuous countrate 10MHz
- 15Hz dark counts (data sheet)
- Quantum efficiency of 22.7% at 405nm
- Output is not discriminated, pulse height varies (need CFD for TDC)

Becker & Hickl



Timing resolution with HPDs

Timing jitter @2MHz

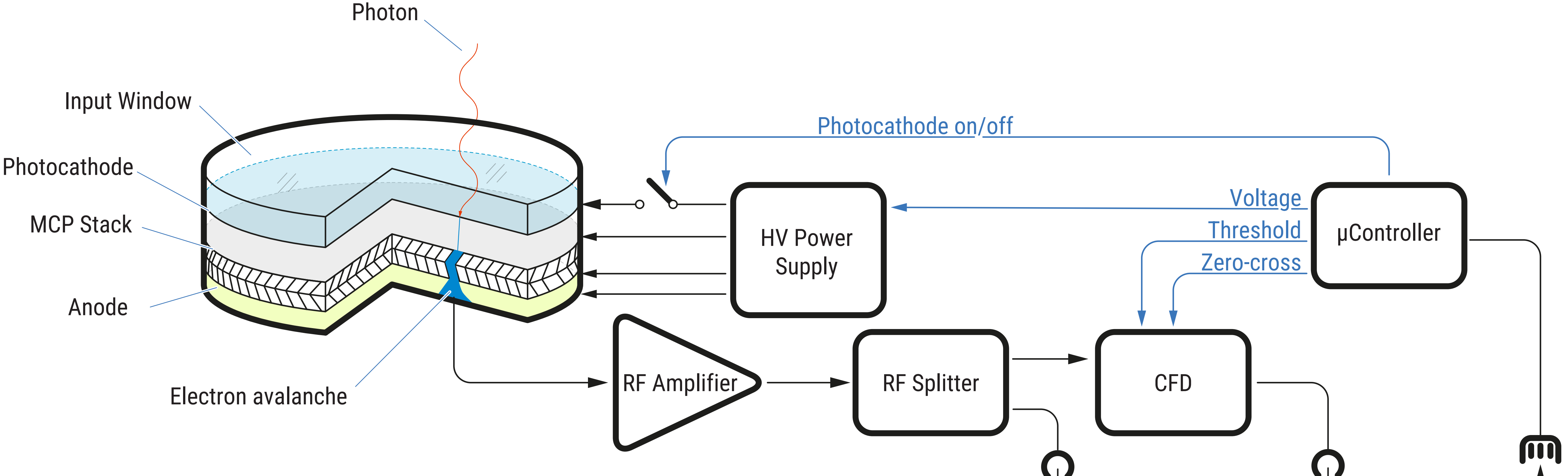


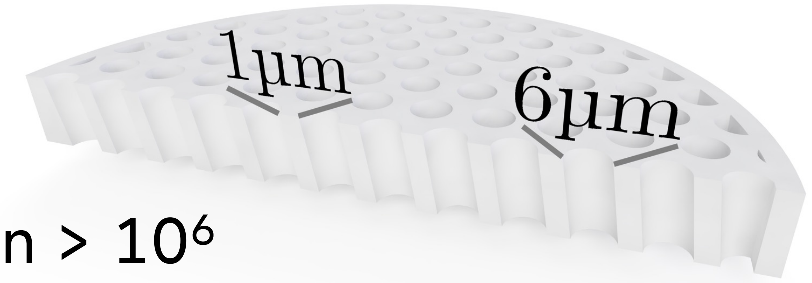
- 43.3ps timing jitter of the system using a fs-pulsed laser
- Full photo detection system of 2 HPDs, 2 CFDs and the TDC, as well as one 50:50 non-polarizing beam splitter
- Result will be used to define integration bounds for evaluation

PhotonPix Detectors

PhotonPix from Photonscore.

PHOTON COUNTING MADE EASY





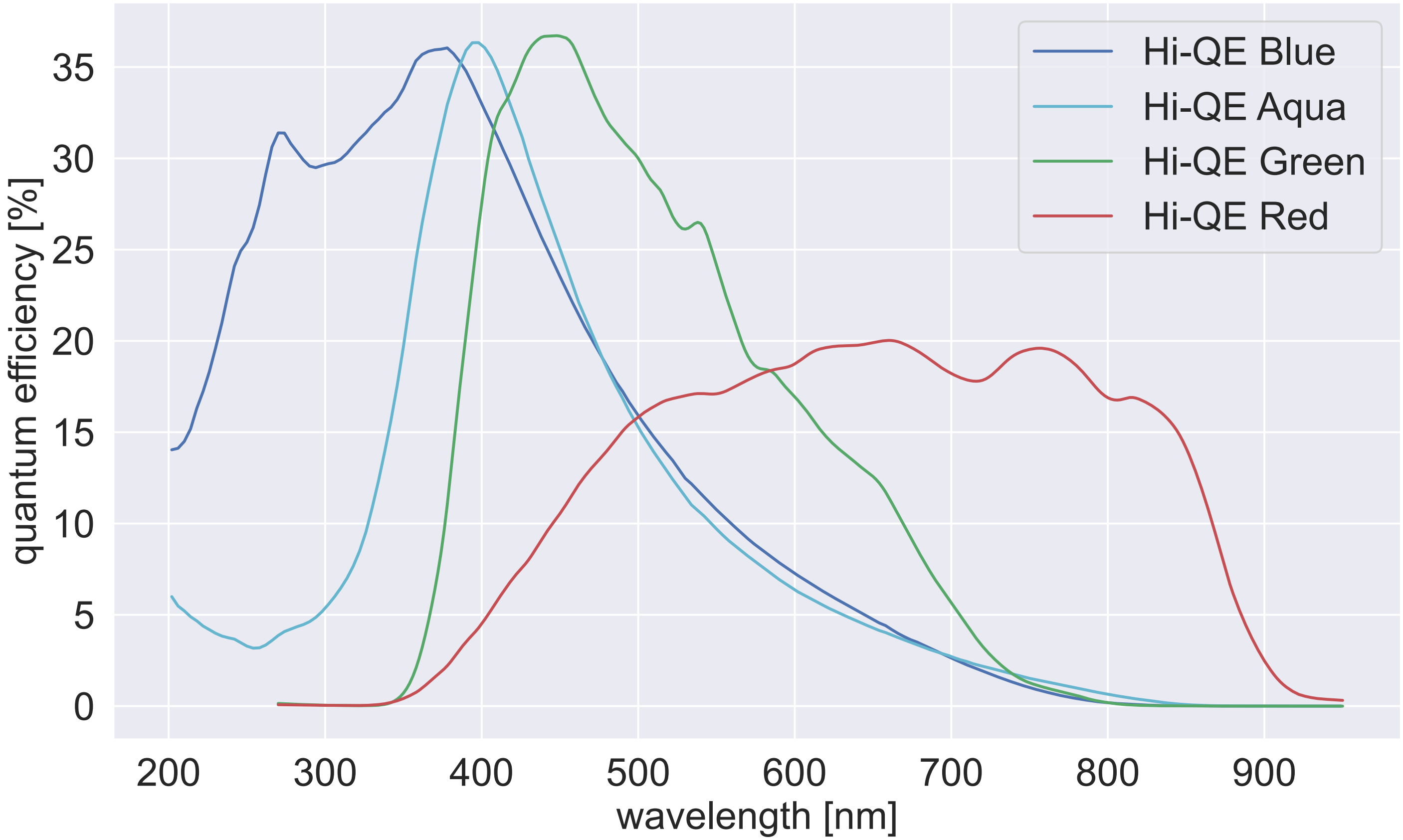
Multi cannel plate:

- ➢Amplify signal
- ➢Chevron stack → Gain > 10^6
- ➢Channel tilt = 5° – 10°

Photocathodes from PHOTONIS

Reveal the invisible

FAU

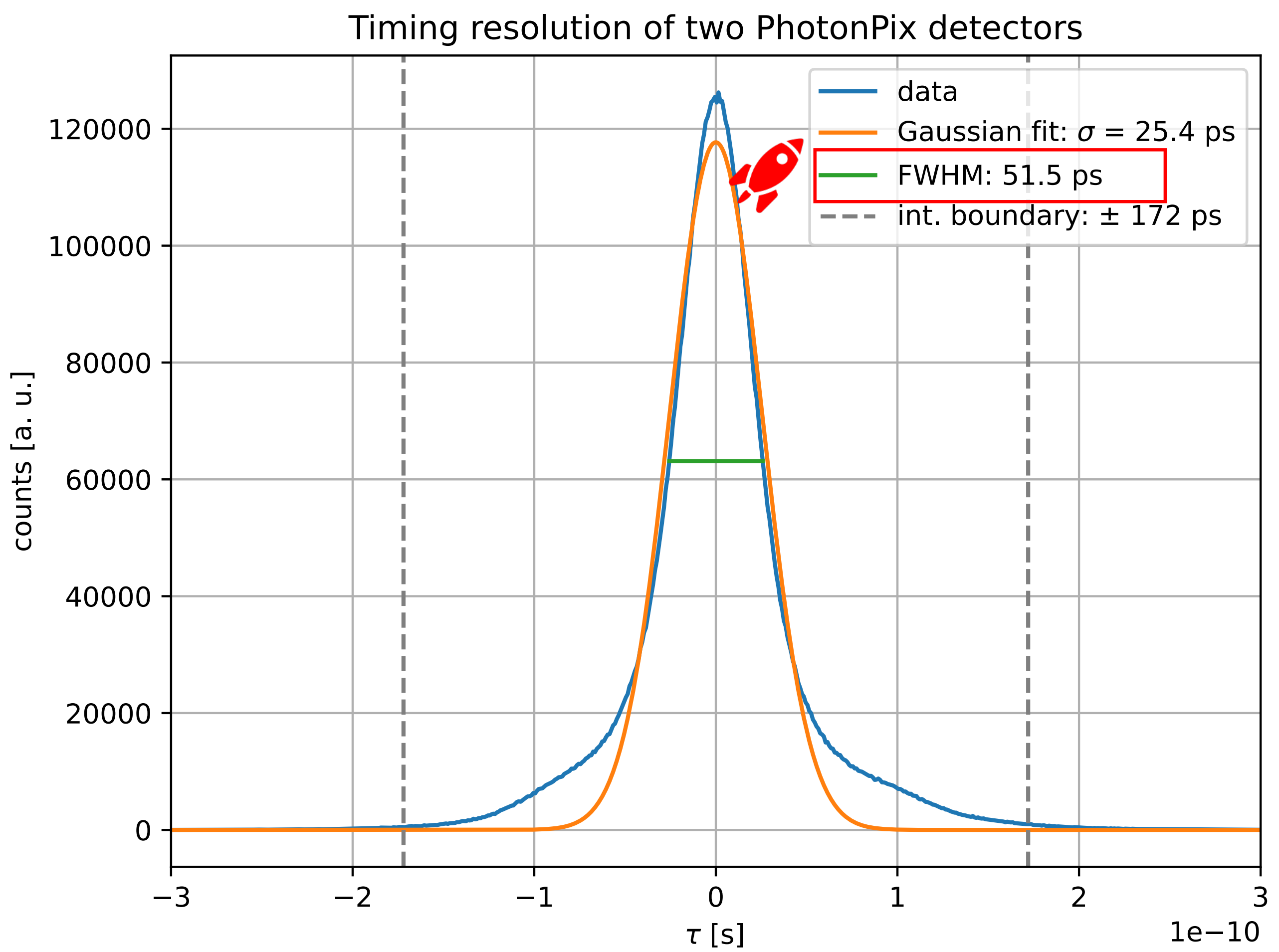


Photonscore.

PHOTON COUNTING MADE EASY

Timing resolution with PhotonPix

Timing jitter @3MHz



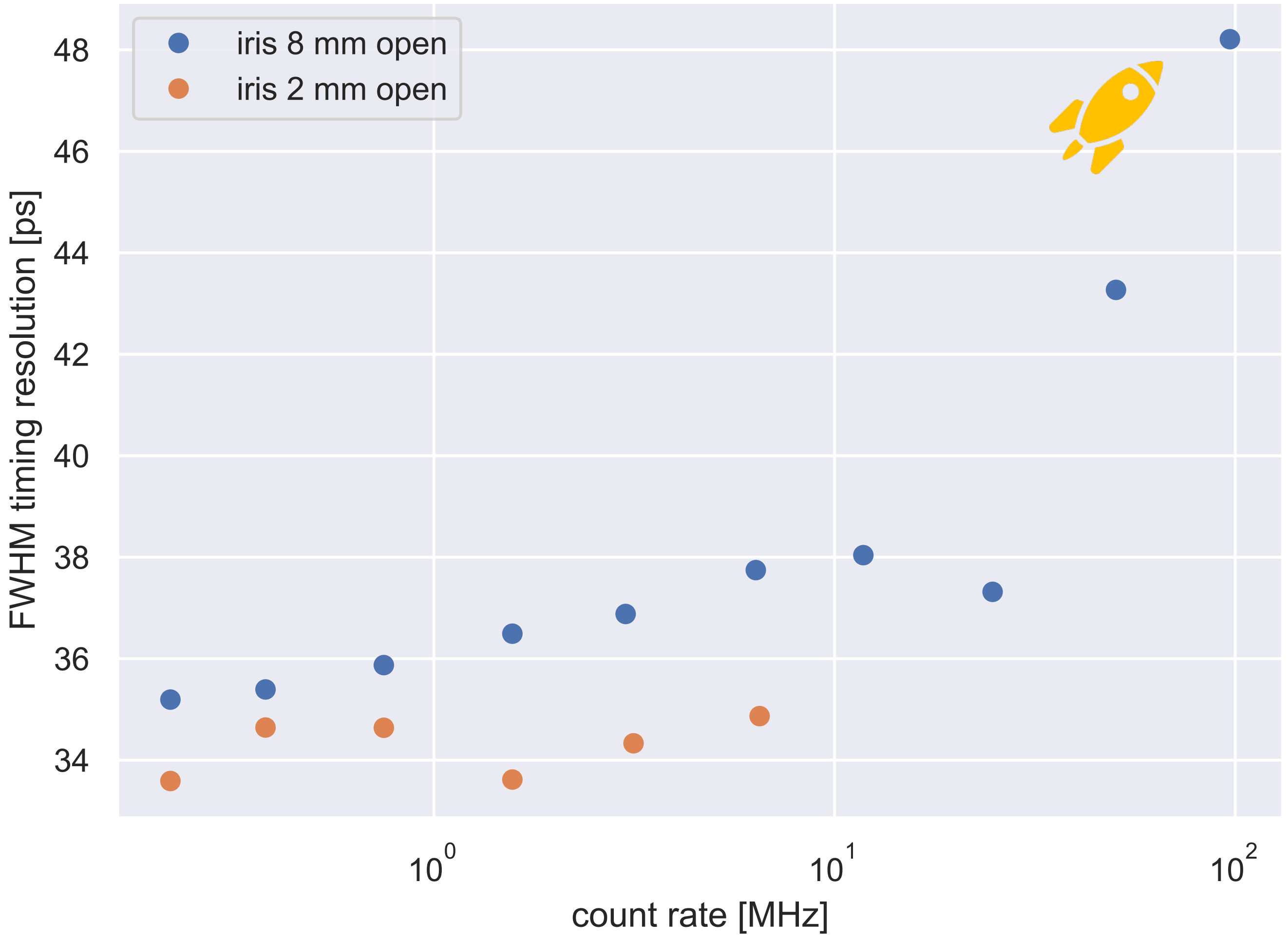
- 51.5ps timing jitter of the system using a fs-pulsed laser (actually measured for all 6 detector combinations)
- Full photo detection system of 2 PhotonPix and the TDC, as well as one 50:50 non-polarizing beam splitter
- Result will be used to define integration bounds for evaluation

Timing resolution of PhotonPix

Varying the illuminated area:

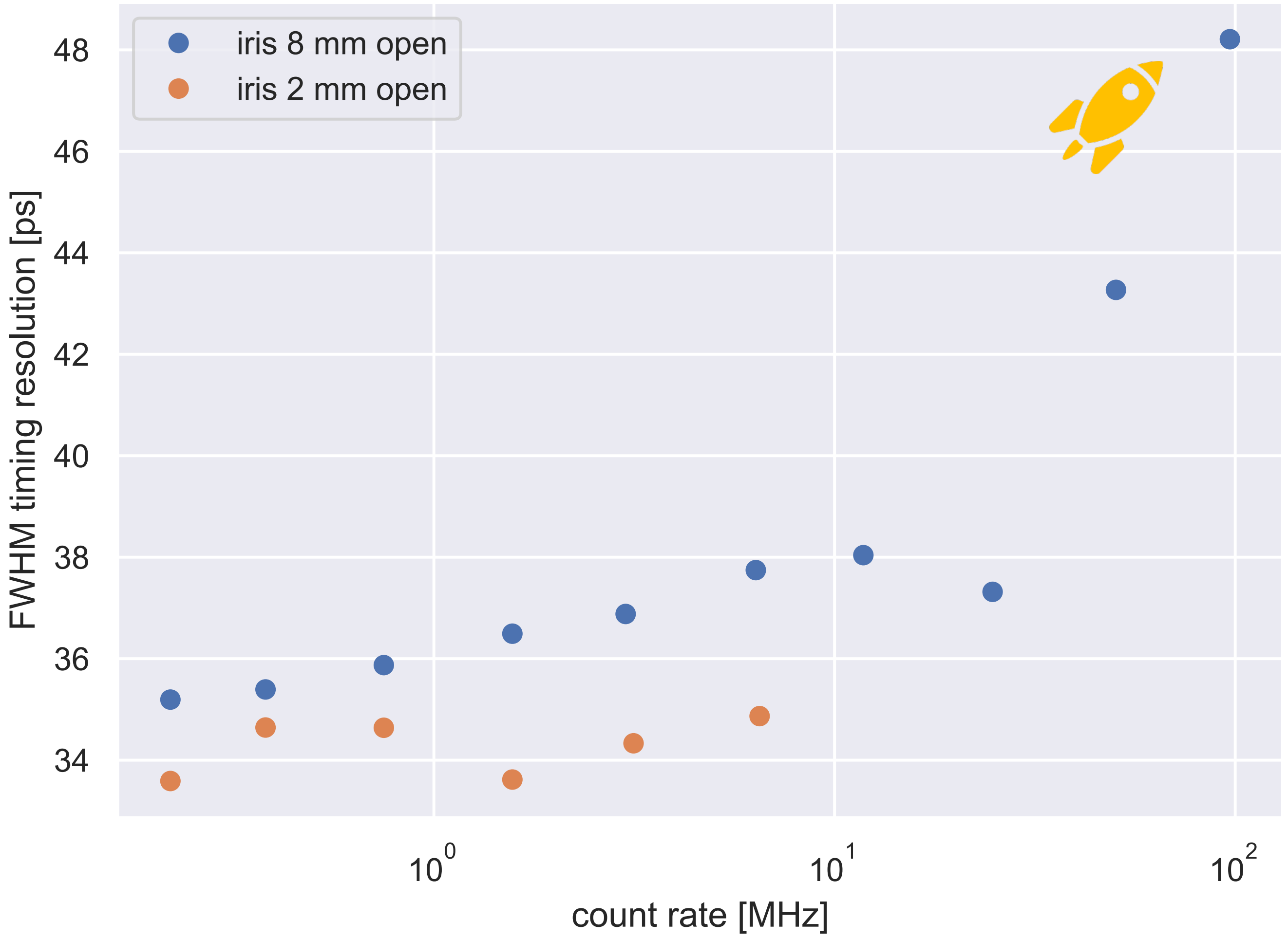
- Tune iris to 2mm opening diameter
- Smaller active area → similar timing resolution
- Full area increases jitter by < 5 ps

Iris closed and open



Timing resolution of PhotonPix

For more information check out our paper in the SPIE library



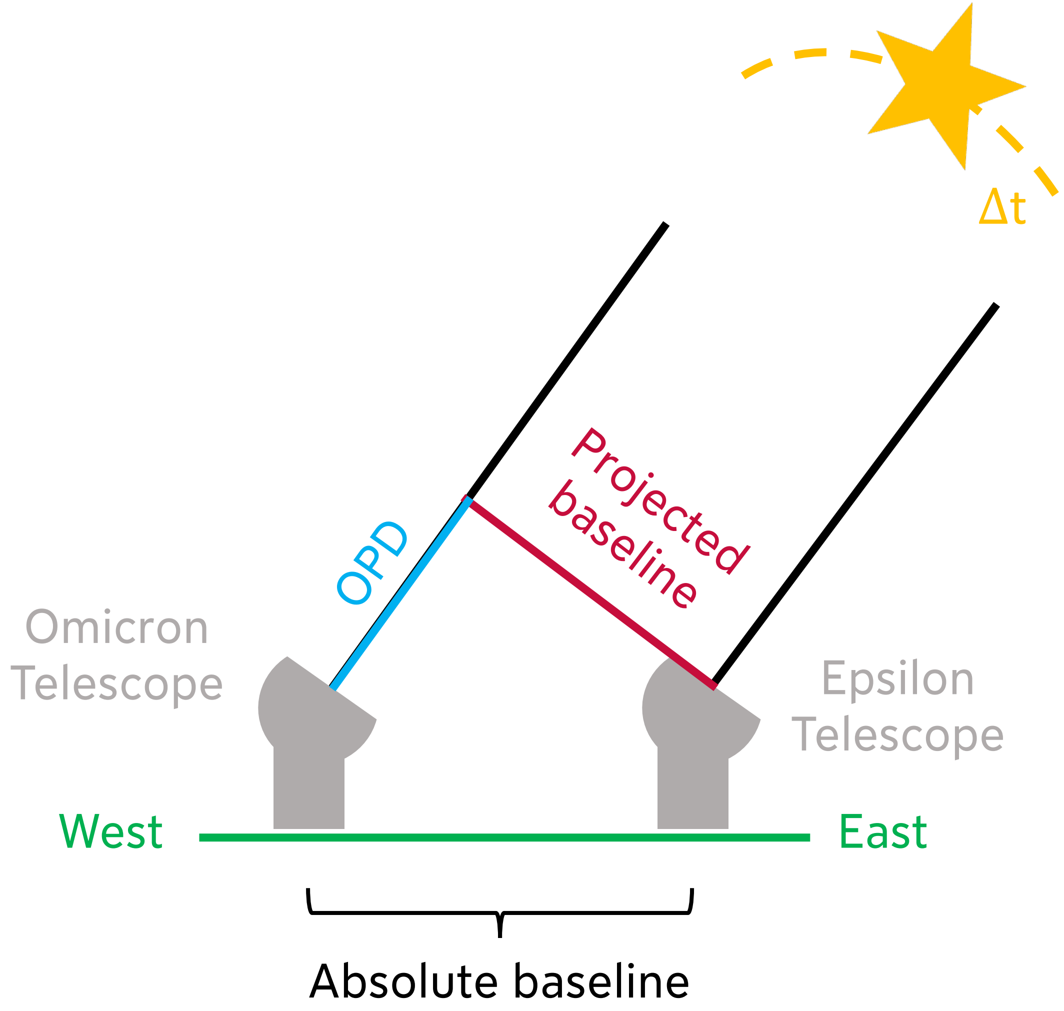
Spatial Correlation Results

a) The Problem of moving stars
b) Spatial Correlations
c) Hour angle binning

The Problem of moving Stars

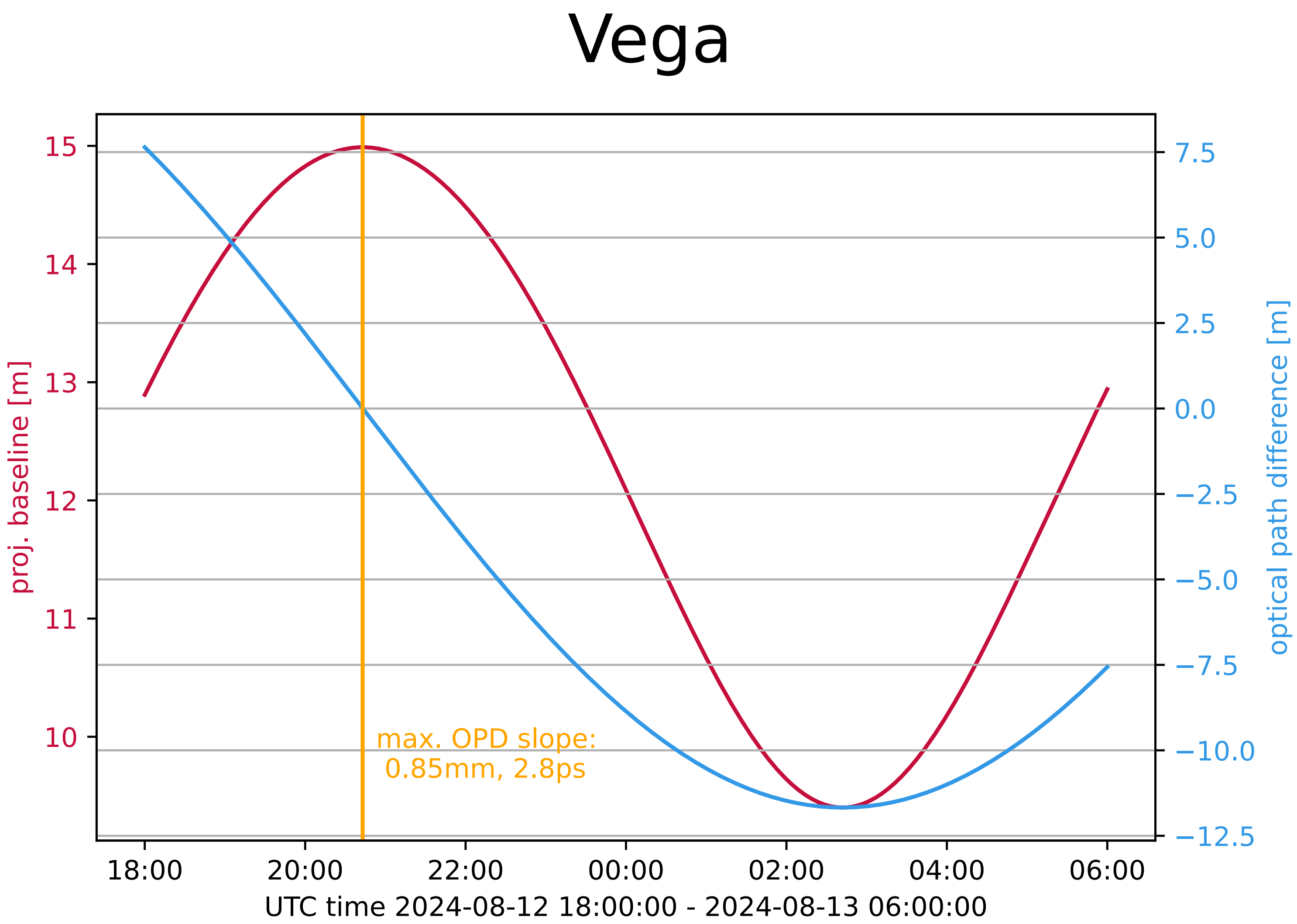
Calculation of baselines

- Absolute baseline of C2PU is 15m
- Baseline changes as star moves over the sky
- Calculate projected baseline for Δt
- Calculate optical path difference (OPD) for Δt
- Shift each histogram accordingly

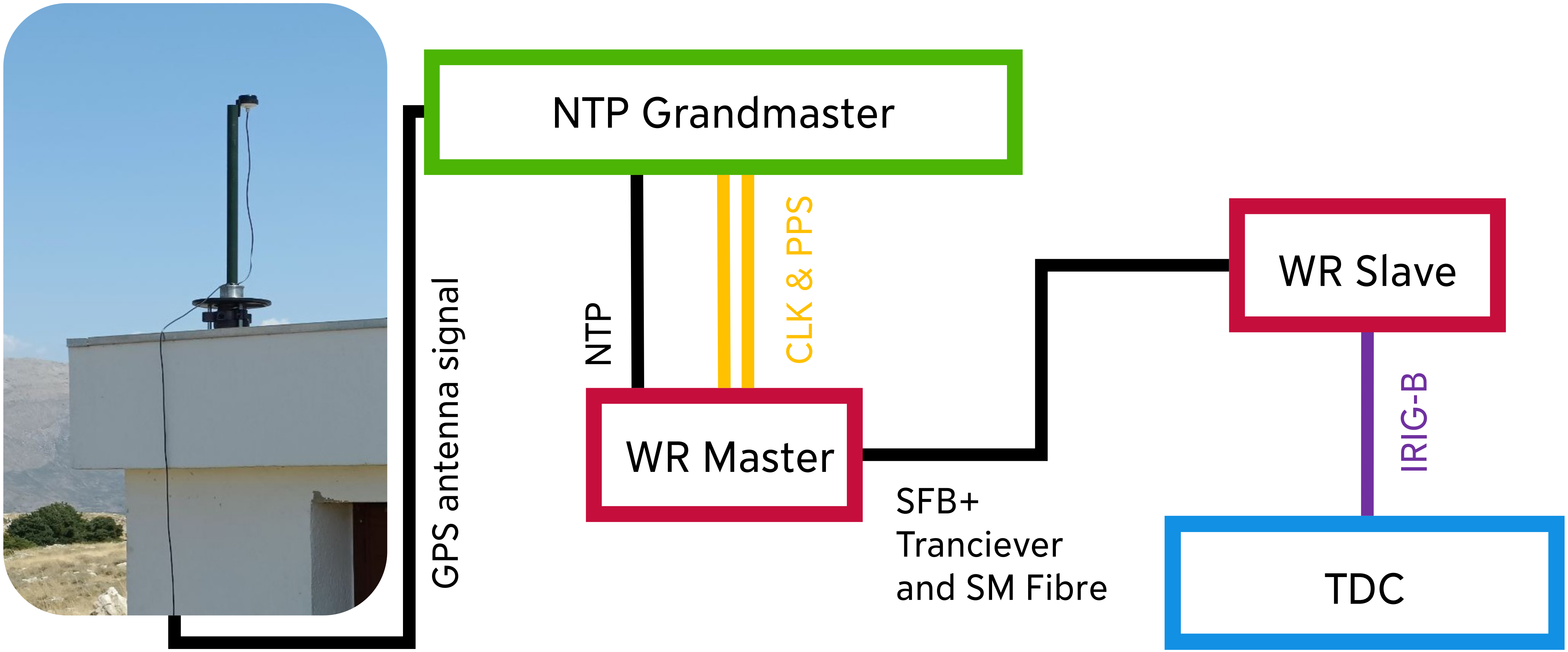


Optical path difference (OPD)

- OPD slope needs to be < timing jitter of system
- Max. OPD slope: 0.85mm, 2.8ps per second
- Need UTC timestamps every second for OPD calculation



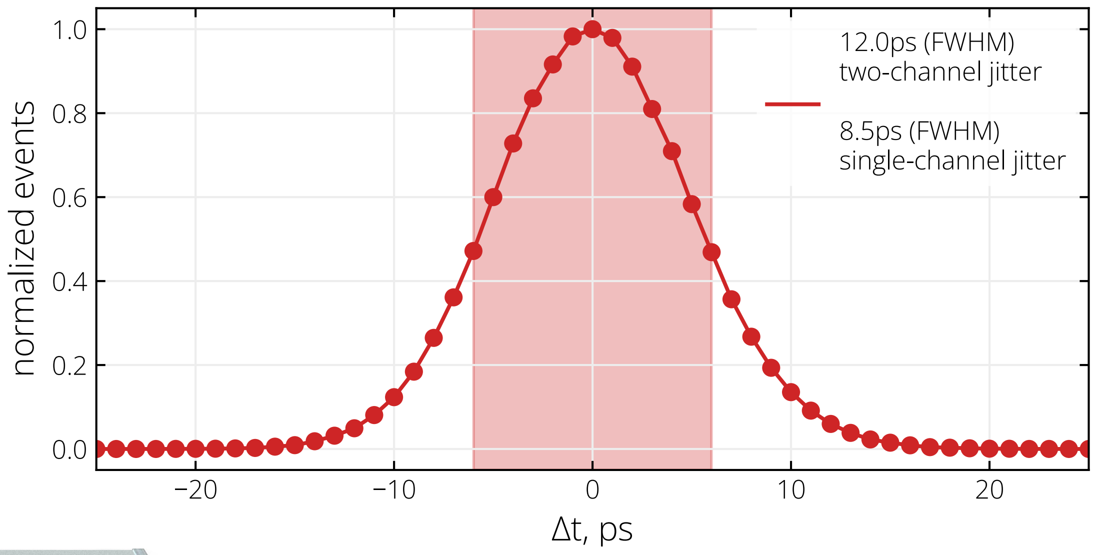
Obtaining UTC timestamps



LINTag from Photonscore

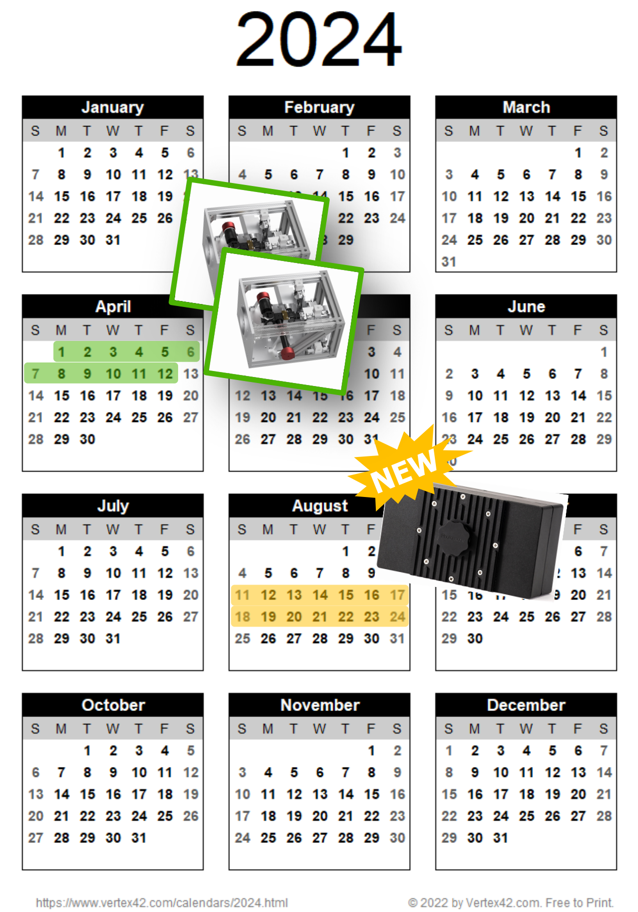
- time-tagger system developed for ultra-fast data acquisition
- Temporal accuracy of 8.5ps (FWHM) / 3.6ps (RMS)
- 10G Ethernet SFB+ connection
- full-stack TCP/IP interface
- Transfer up to 400 MEvents/s
- Multi-Start Multi-Stop correlation

Timing jitter

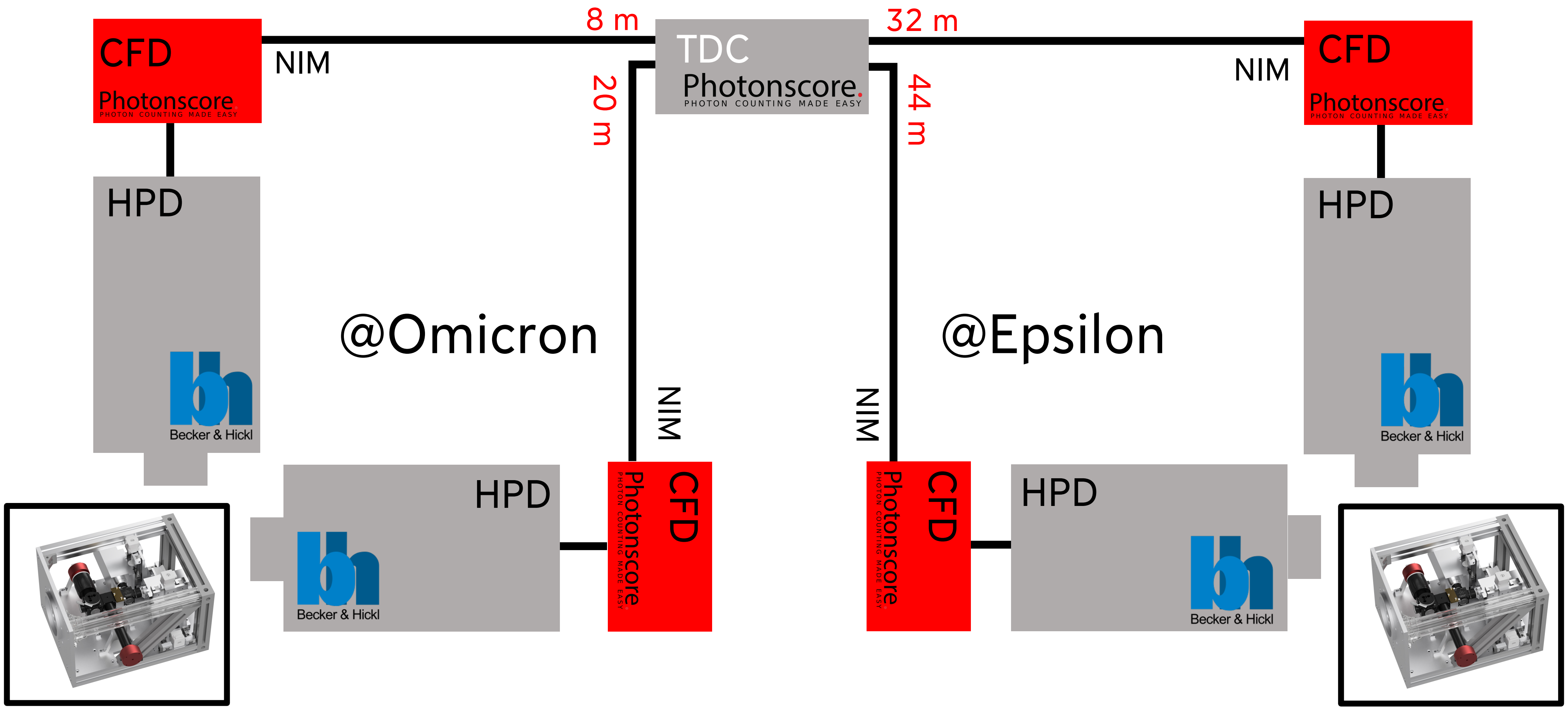


Photonscore.
PHOTON COUNTING MADE EASY

Spatial Correlations

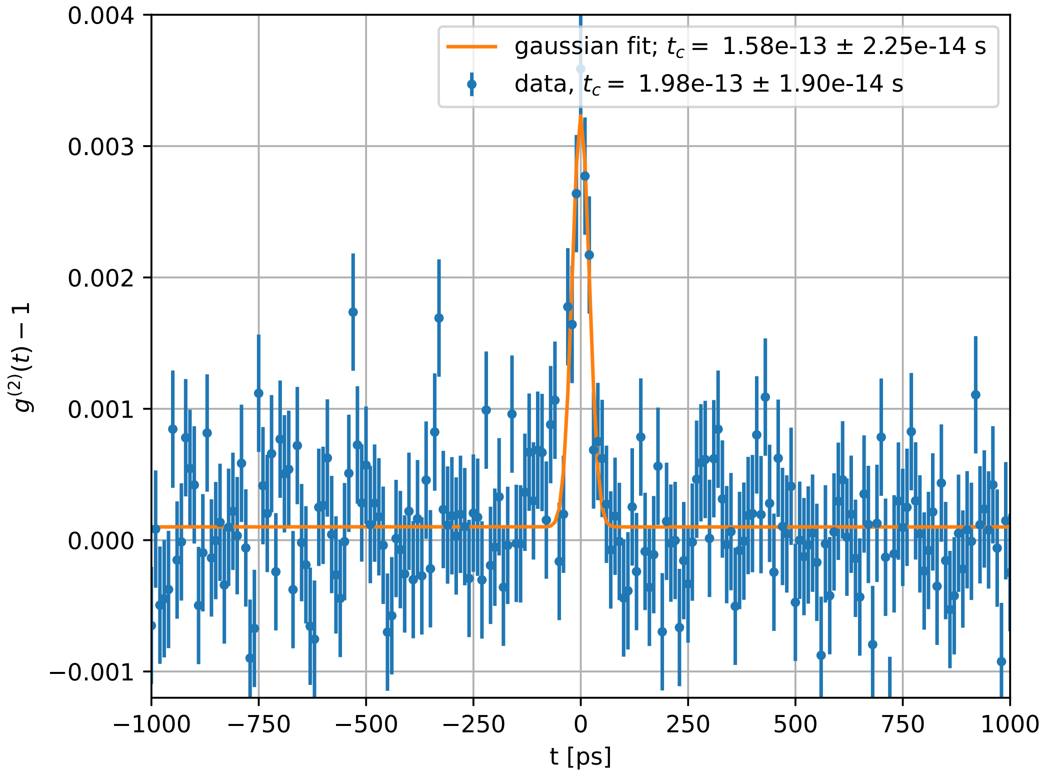


Configuration using HPDs

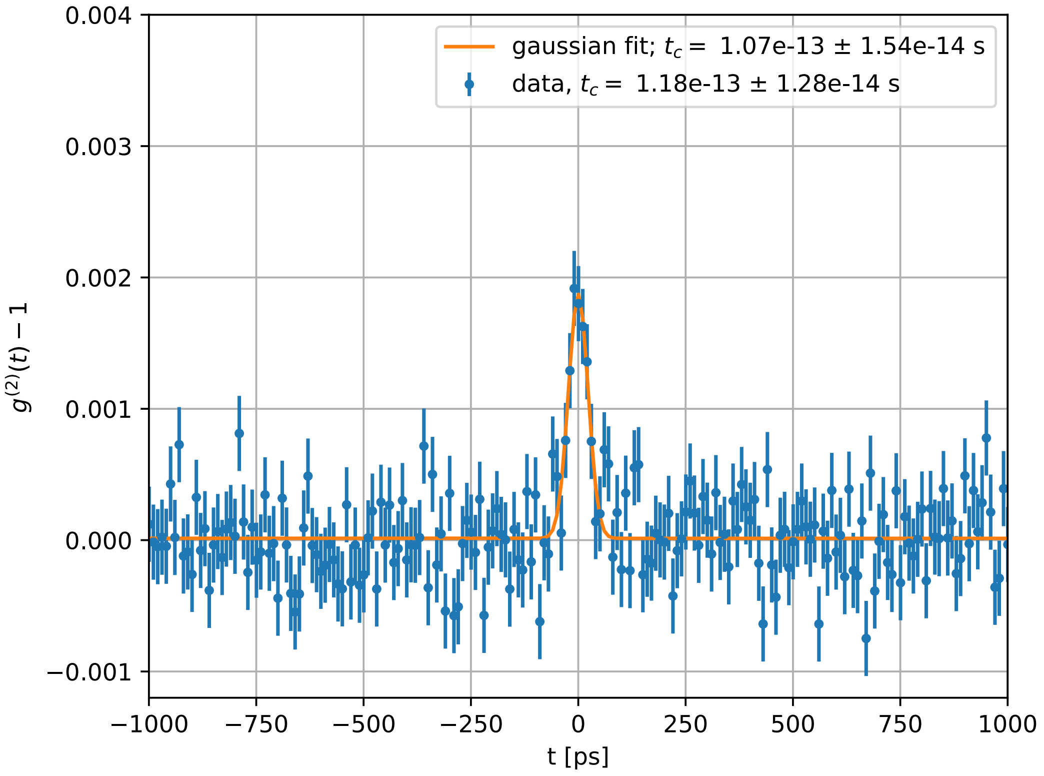


Results for Vega using HPDs

Zero Baseline

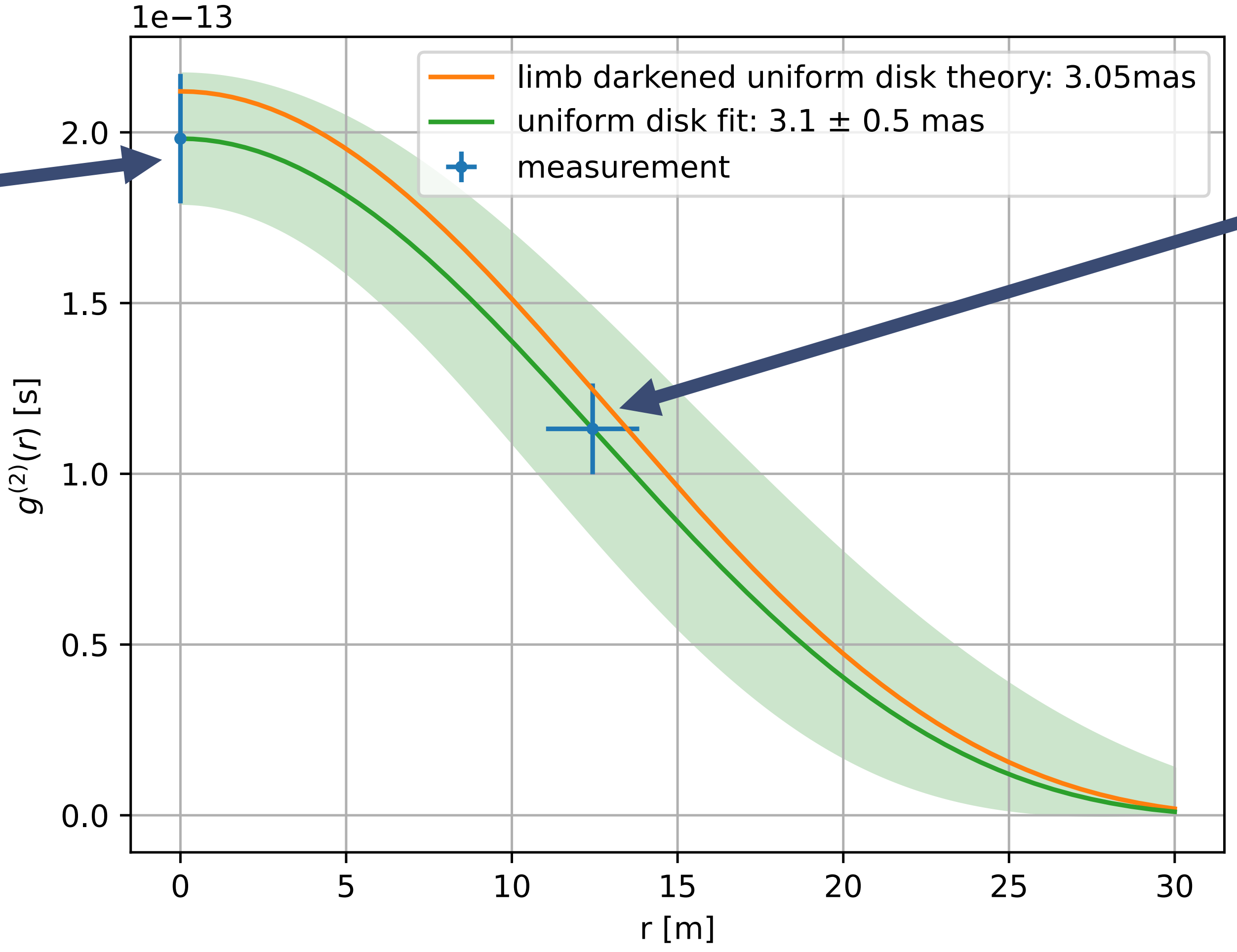


Cross-Correlation



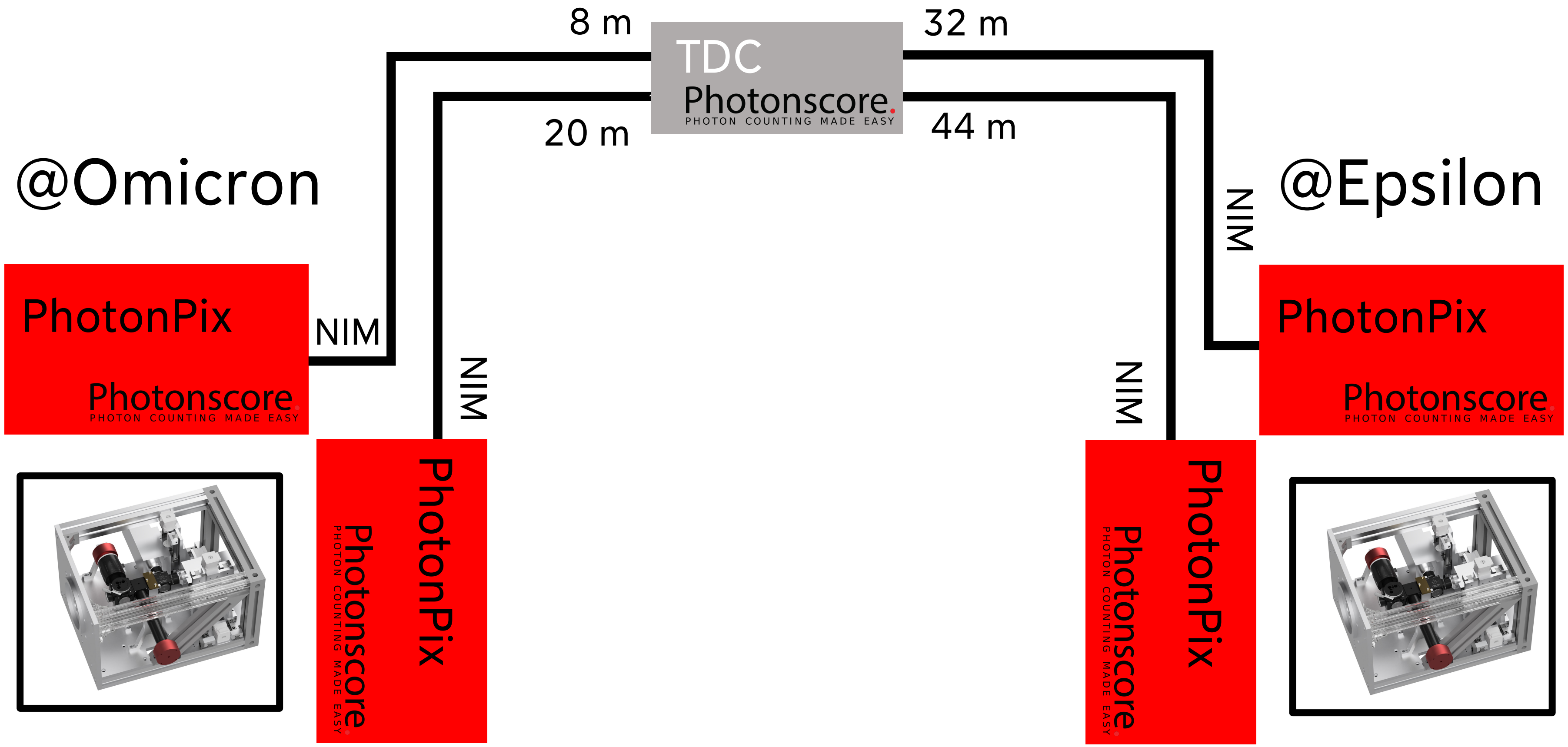
Visibility curve using HPDs

Bunching

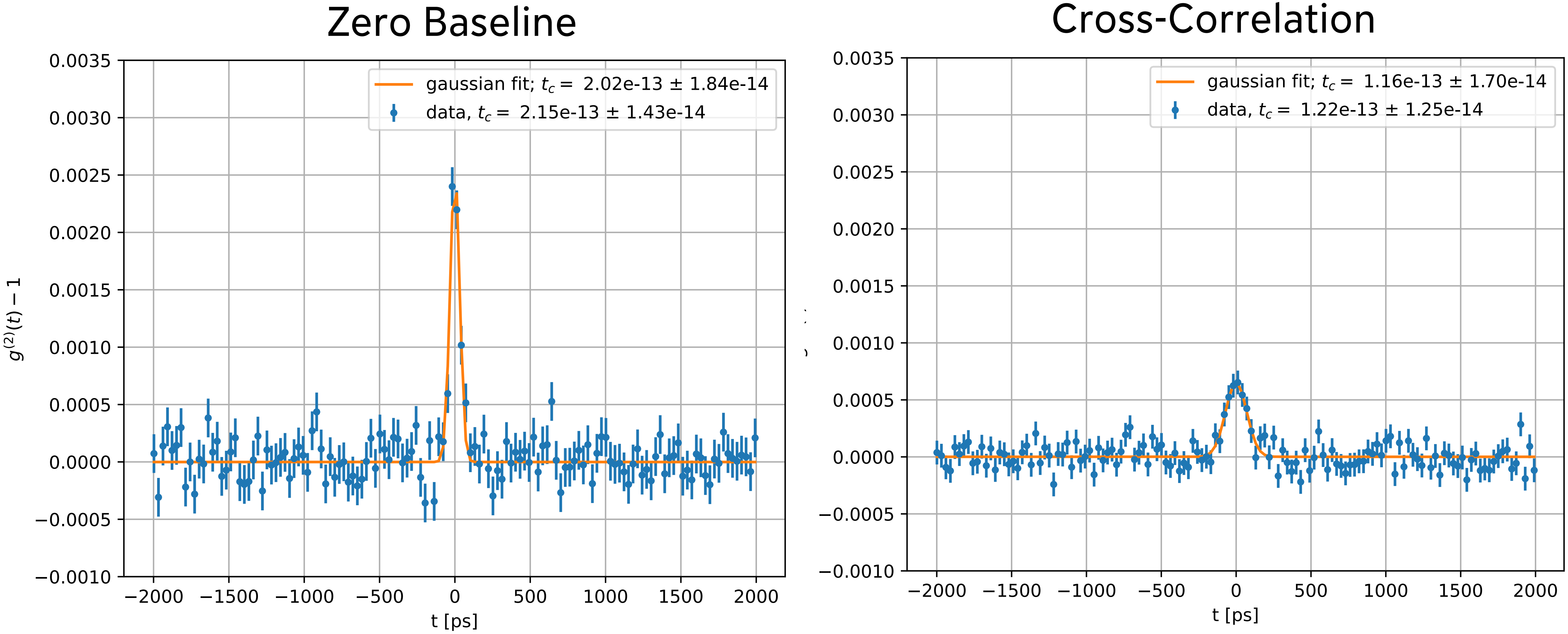


Cross-correlations averaged over all baselines put into one single data point

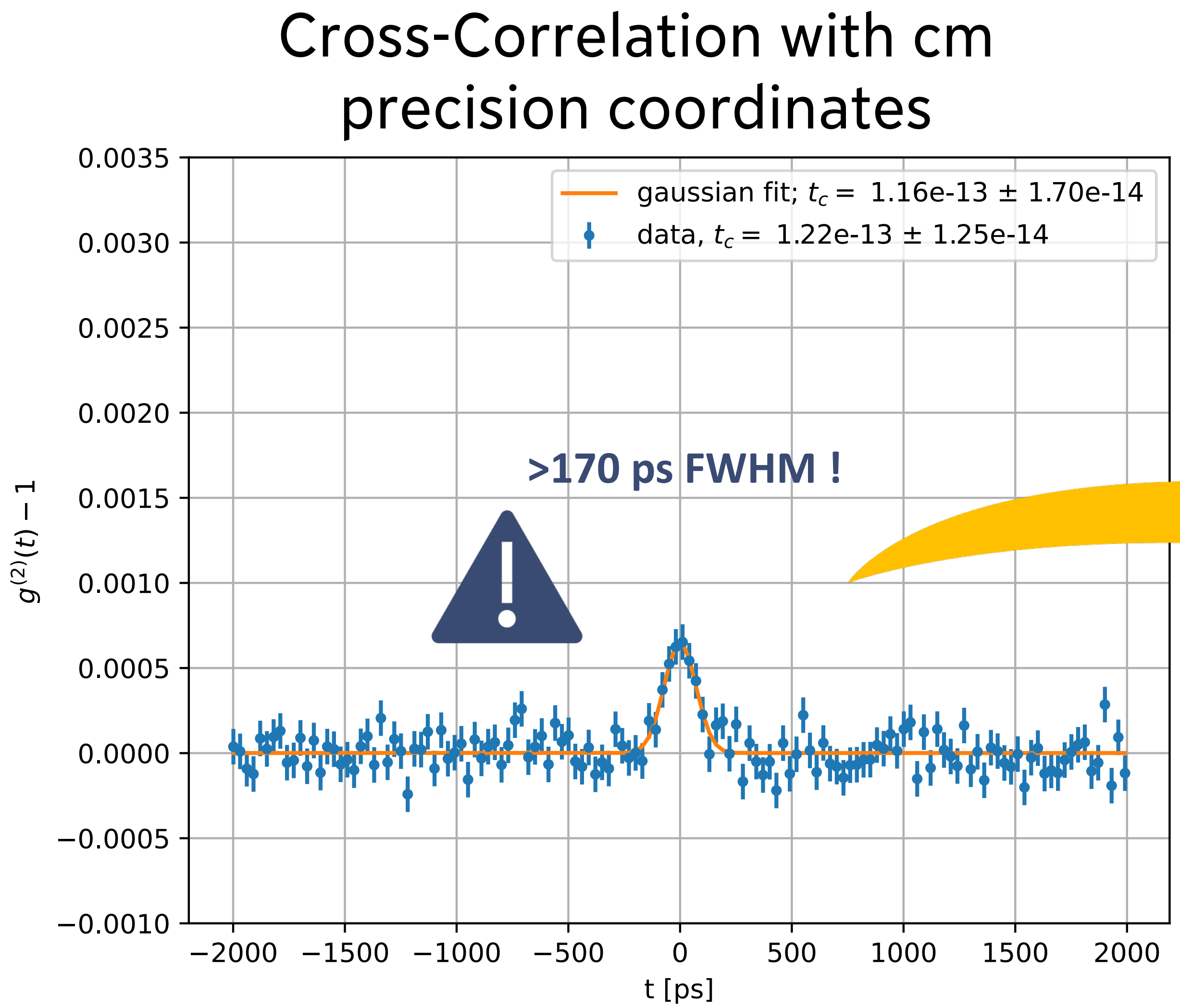
Configuration using PhotonPix

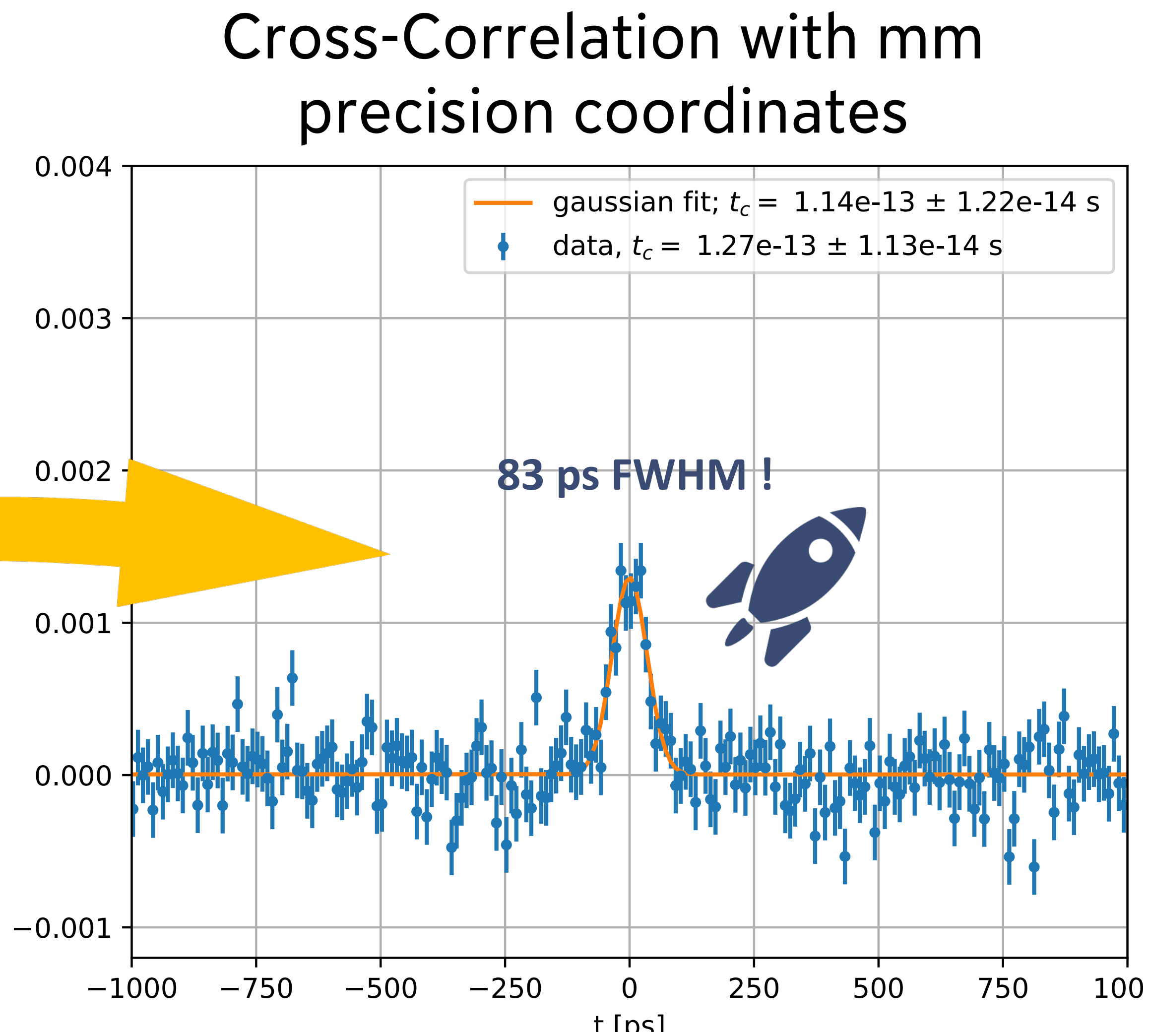


Results for Vega using PhotonPix



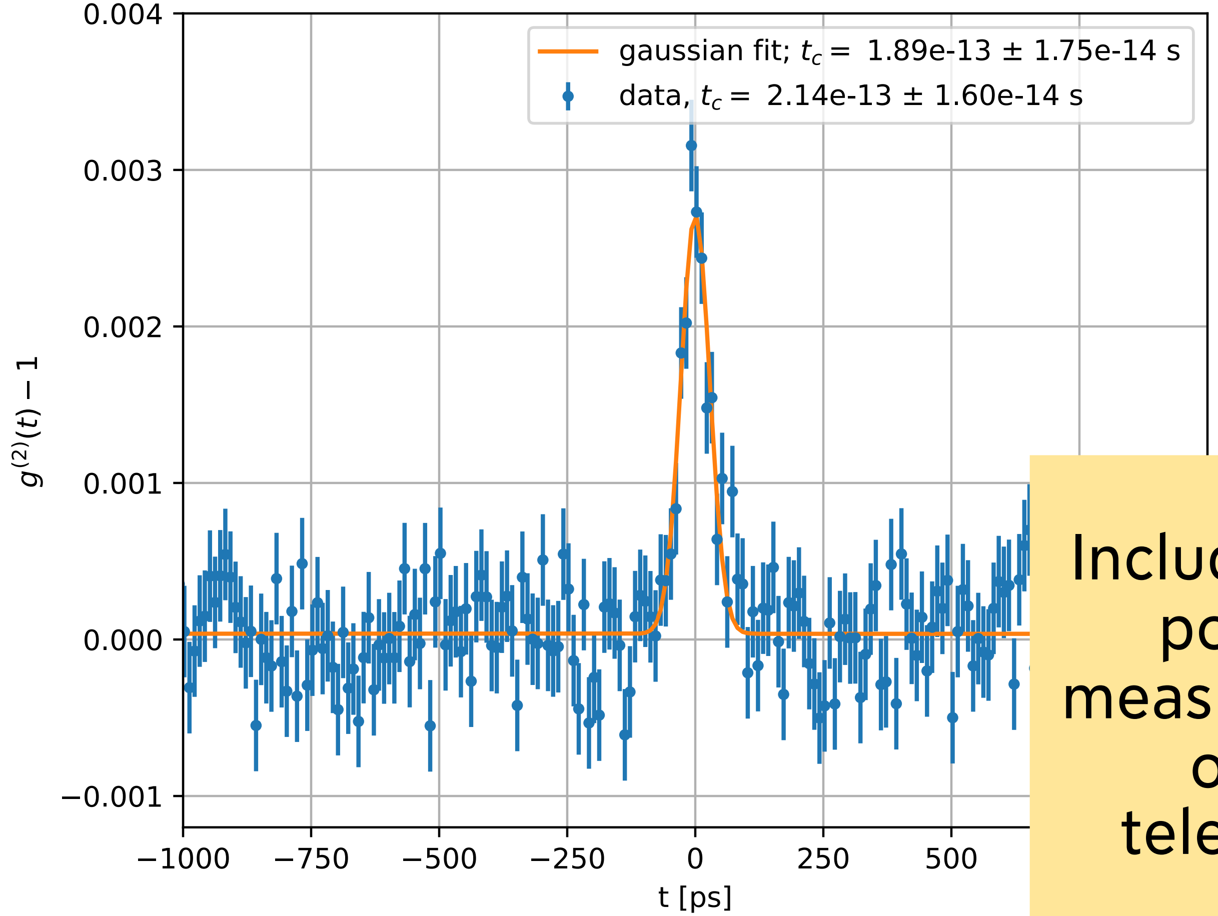
Effect of precise telescope positions



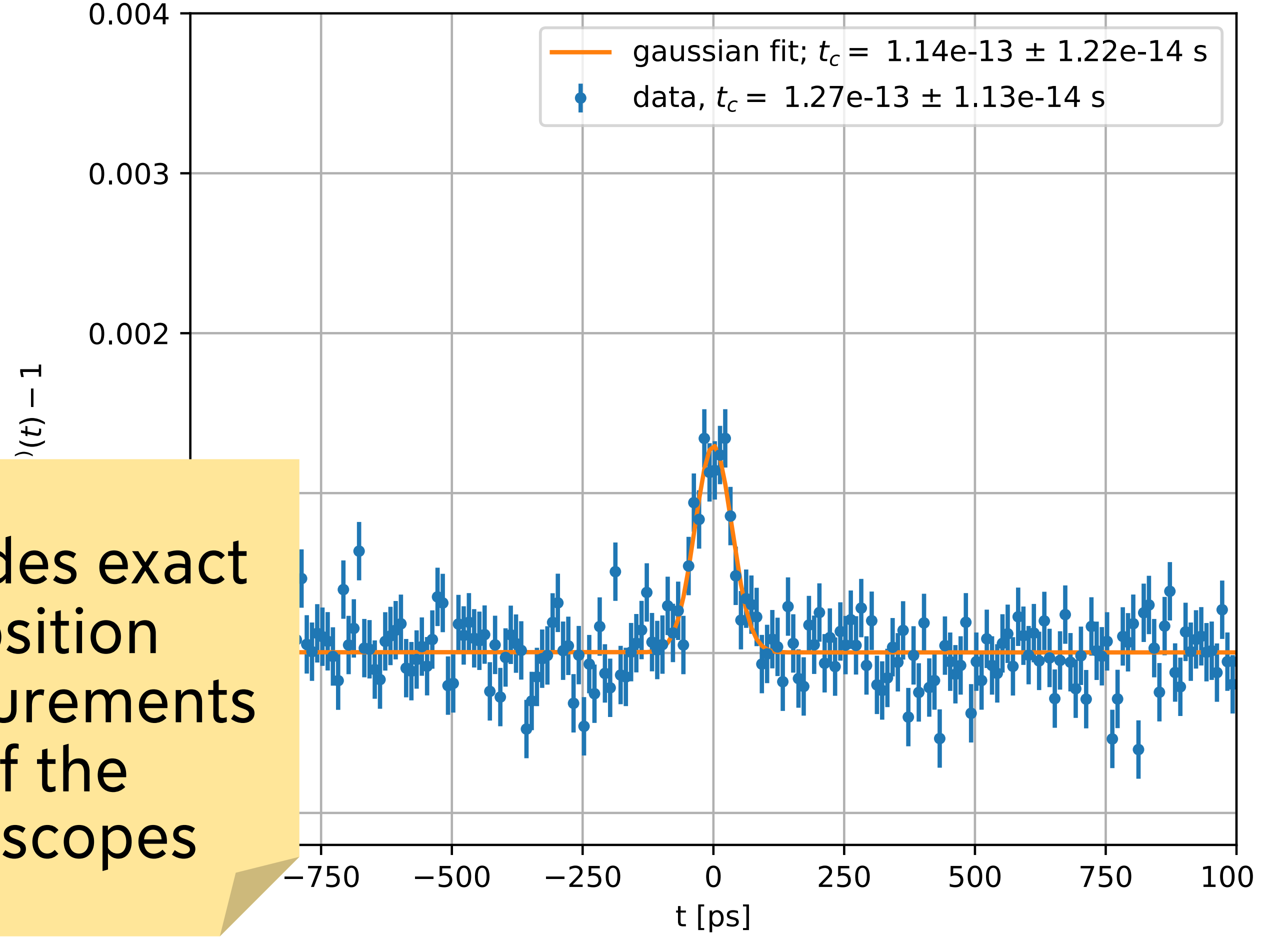


Results using exact Positions

Zero Baseline



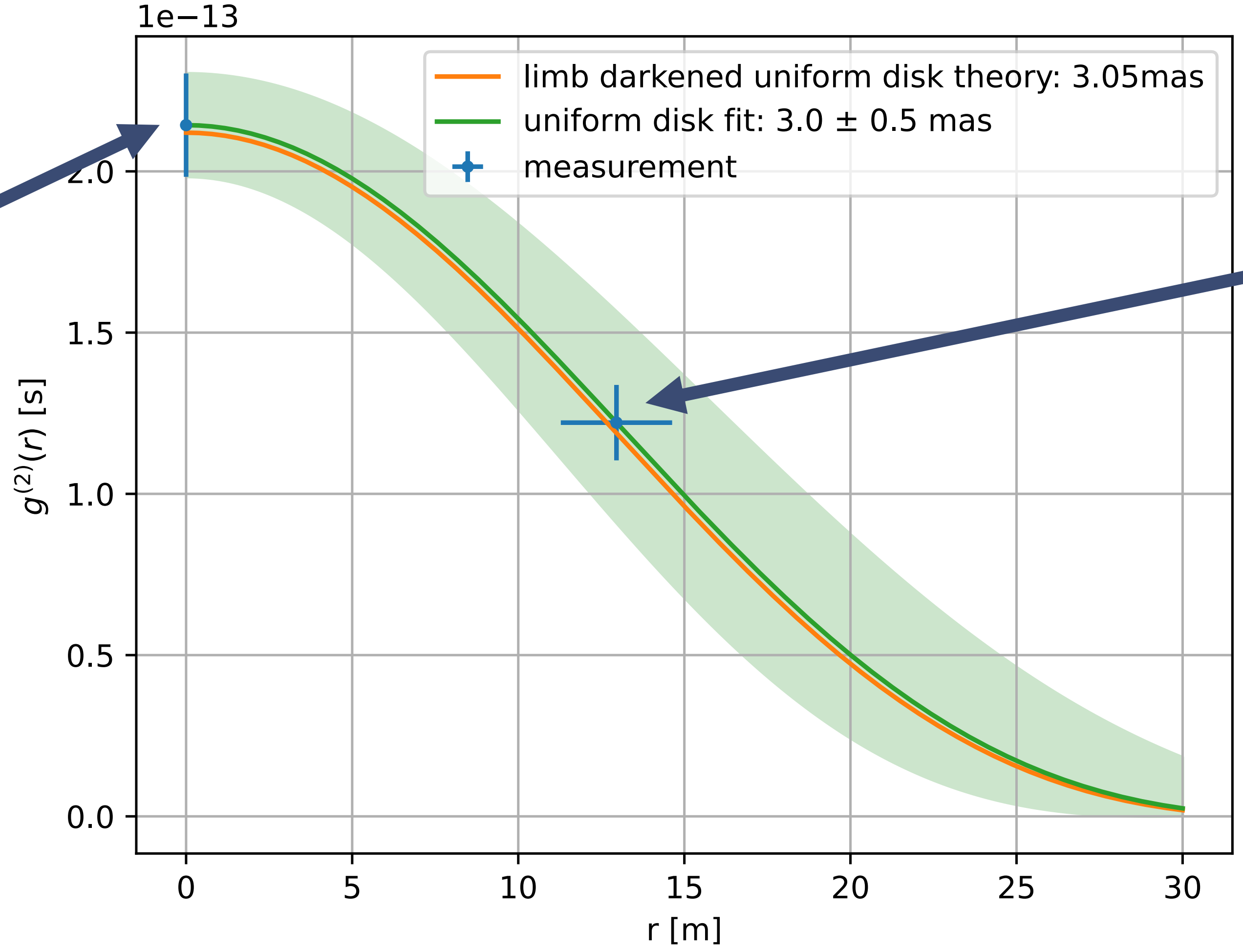
Cross-Correlations



Includes exact position measurements of the telescopes

Visibility curve using PhotonPix

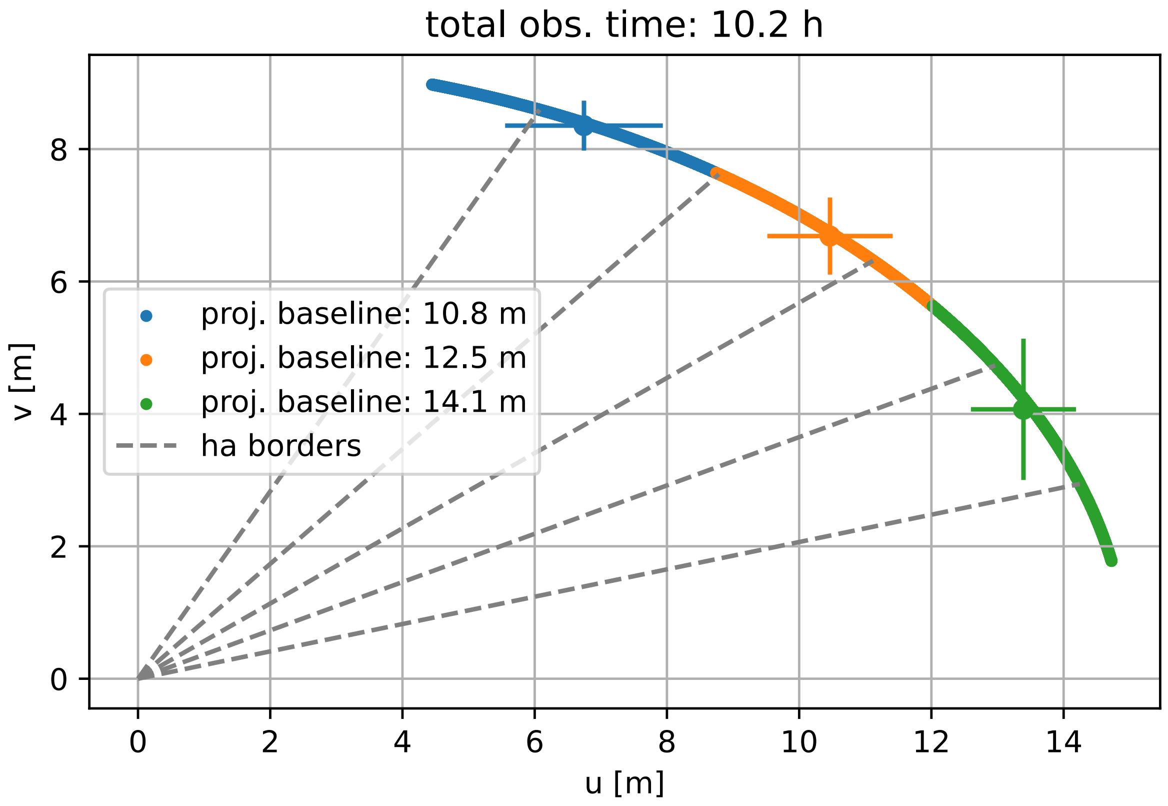
Bunching

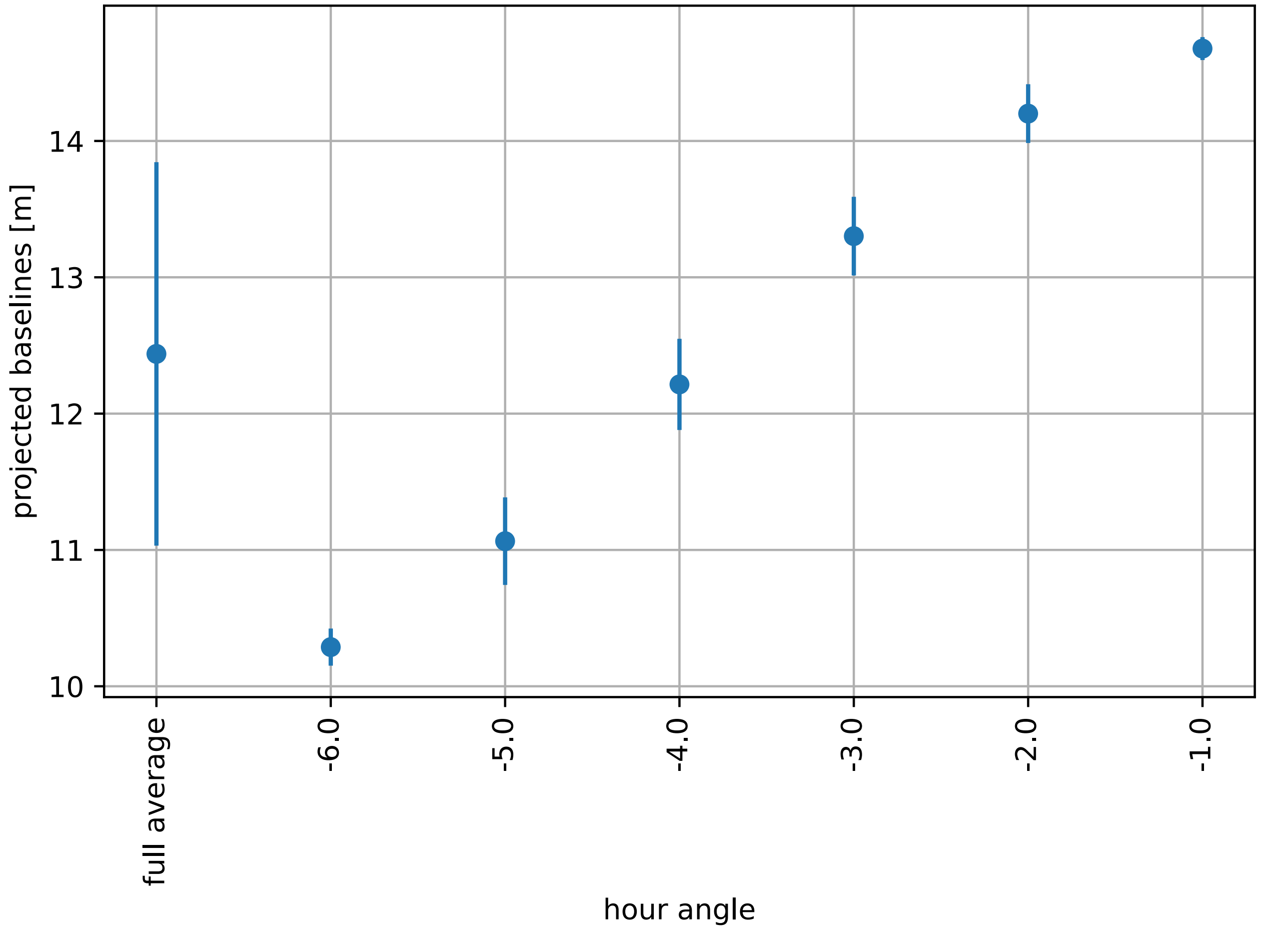


Cross-correlations averaged over all baselines put into one single data point

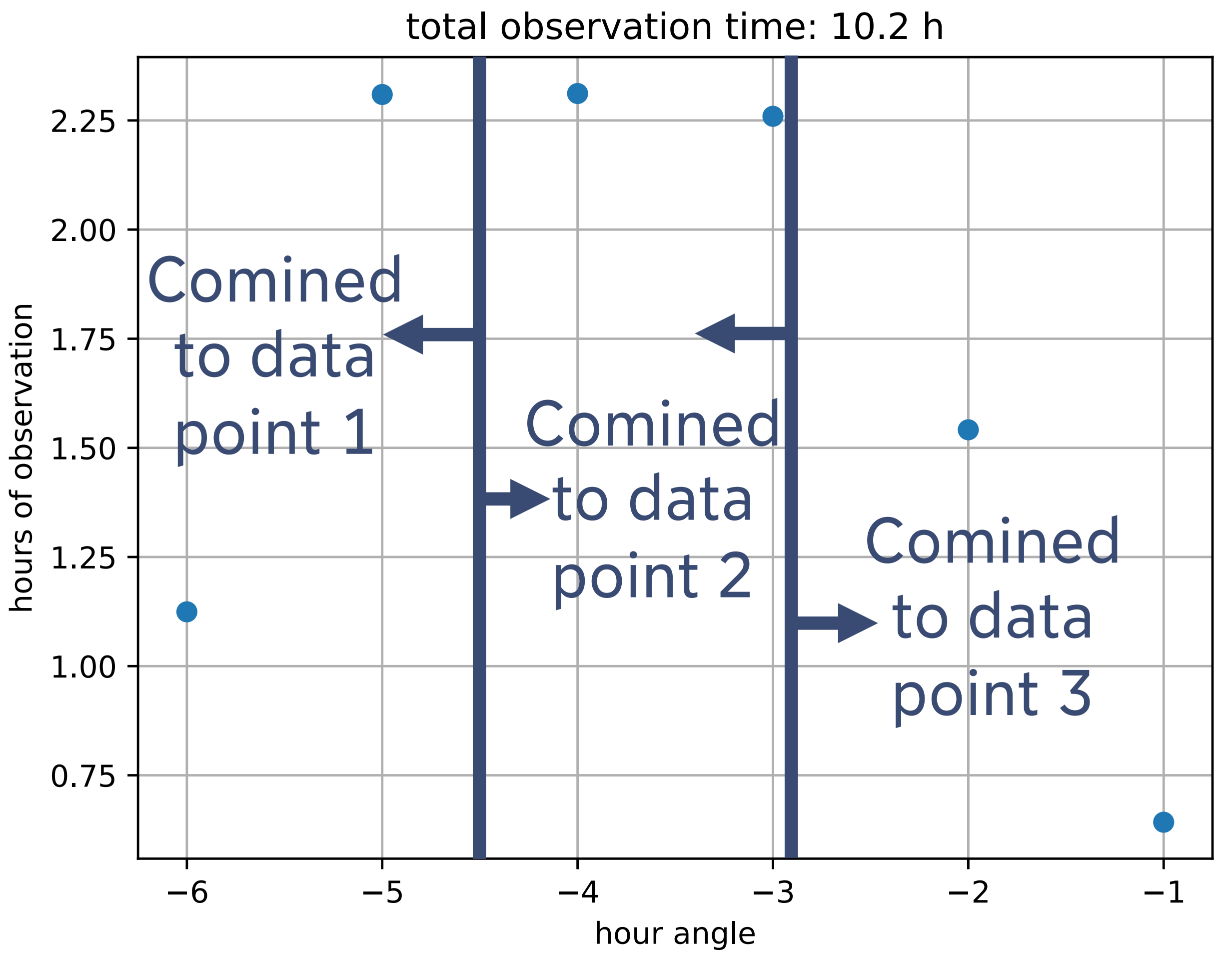
Hour angle rebinning

Hour angle binning HPDs



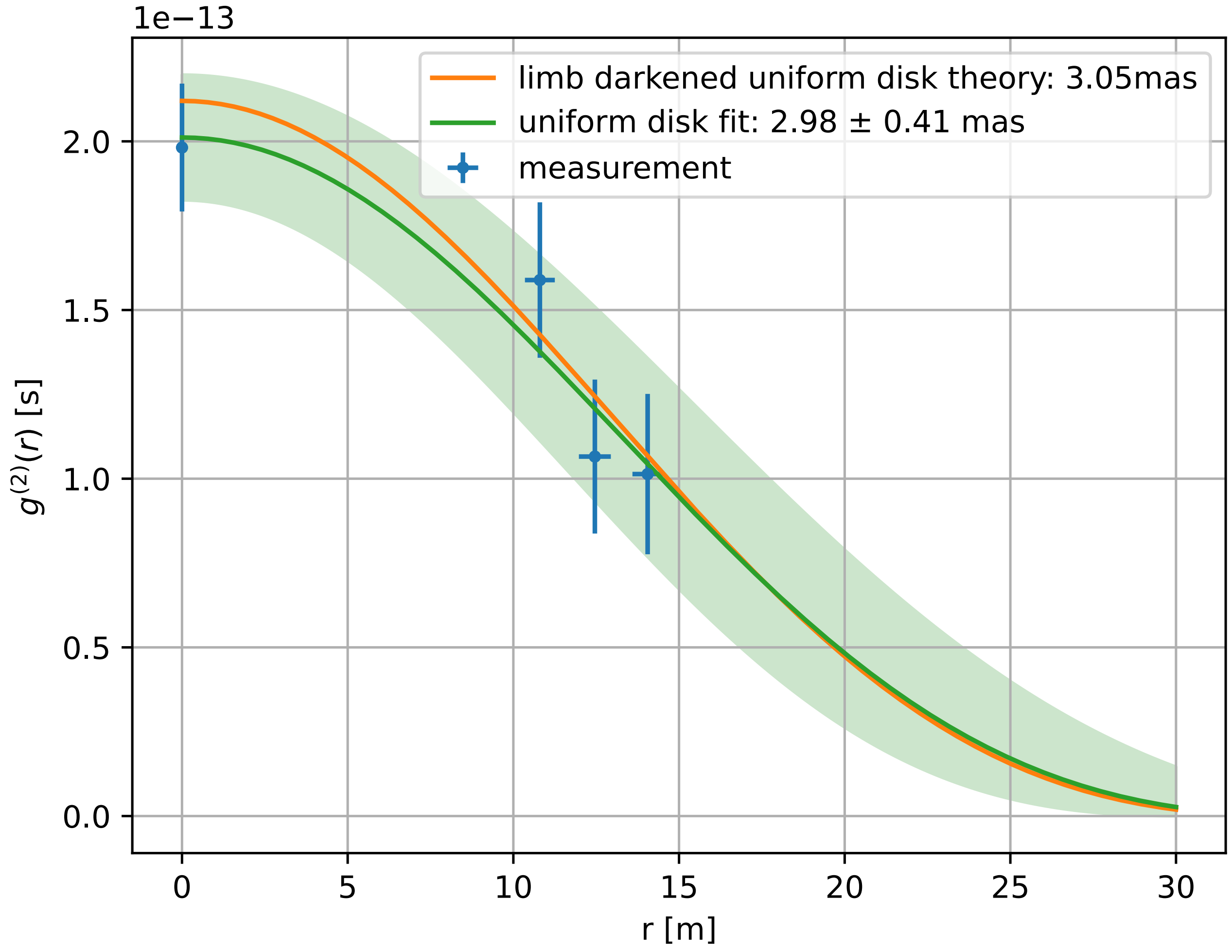


Hour angle binning HPDs



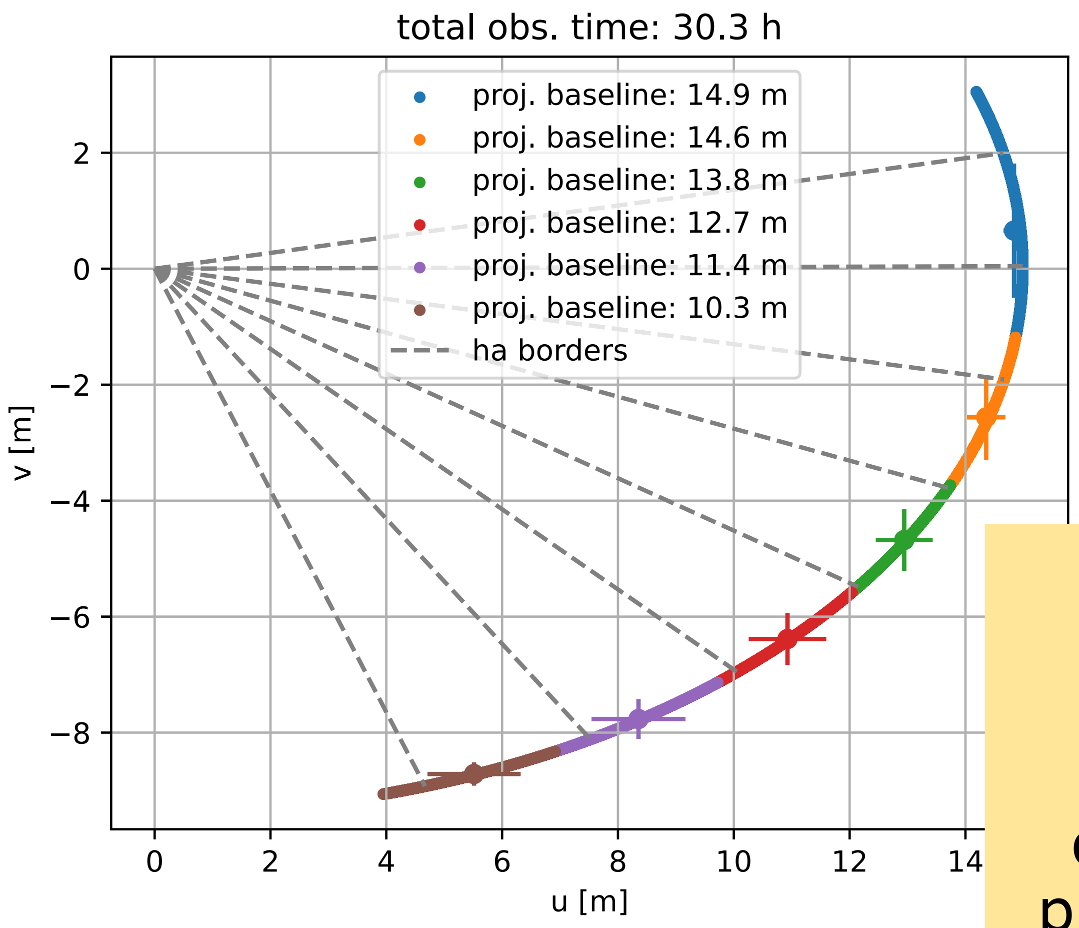
- The data from the cross correlation measurements is binned according to the hour angle
- Data is accumulated according to observation time. Threshold was set to 3h
- Produces 3 data points

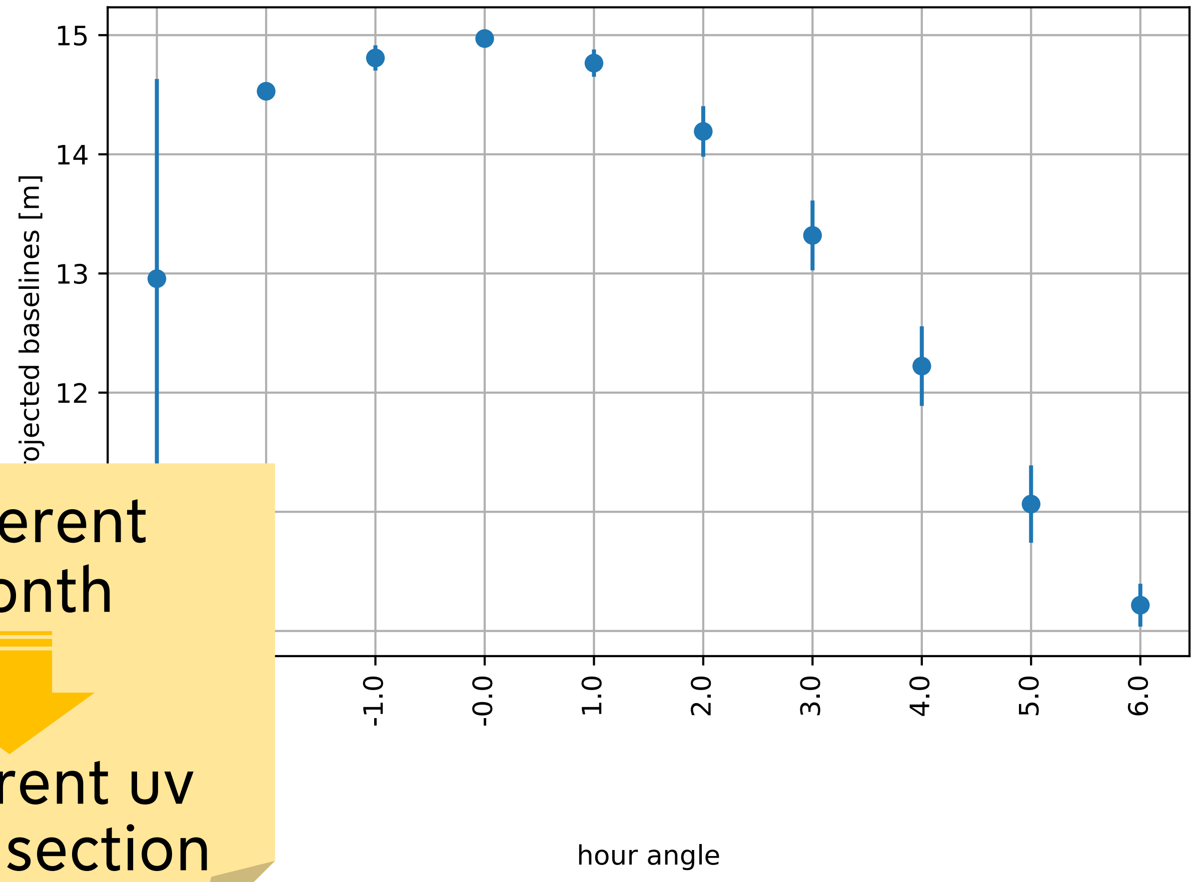
Hour angle binning HPDs



- The data from the cross correlation measurements is binned according to the hour angle
- Data is accumulated according to observation time. Threshold was set to 3h
- Produces 3 data points

Hour angle binning PhotonPix

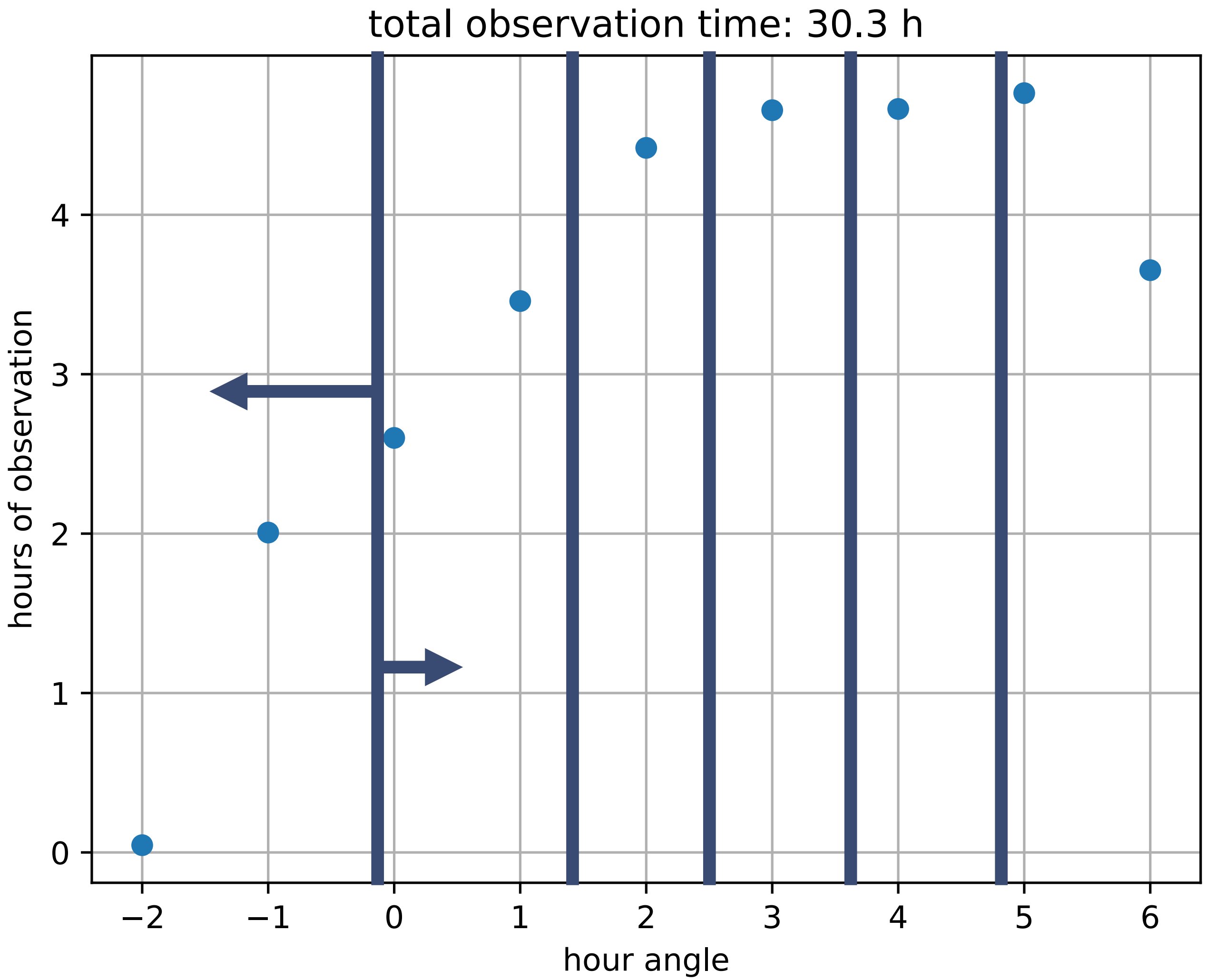




Different month

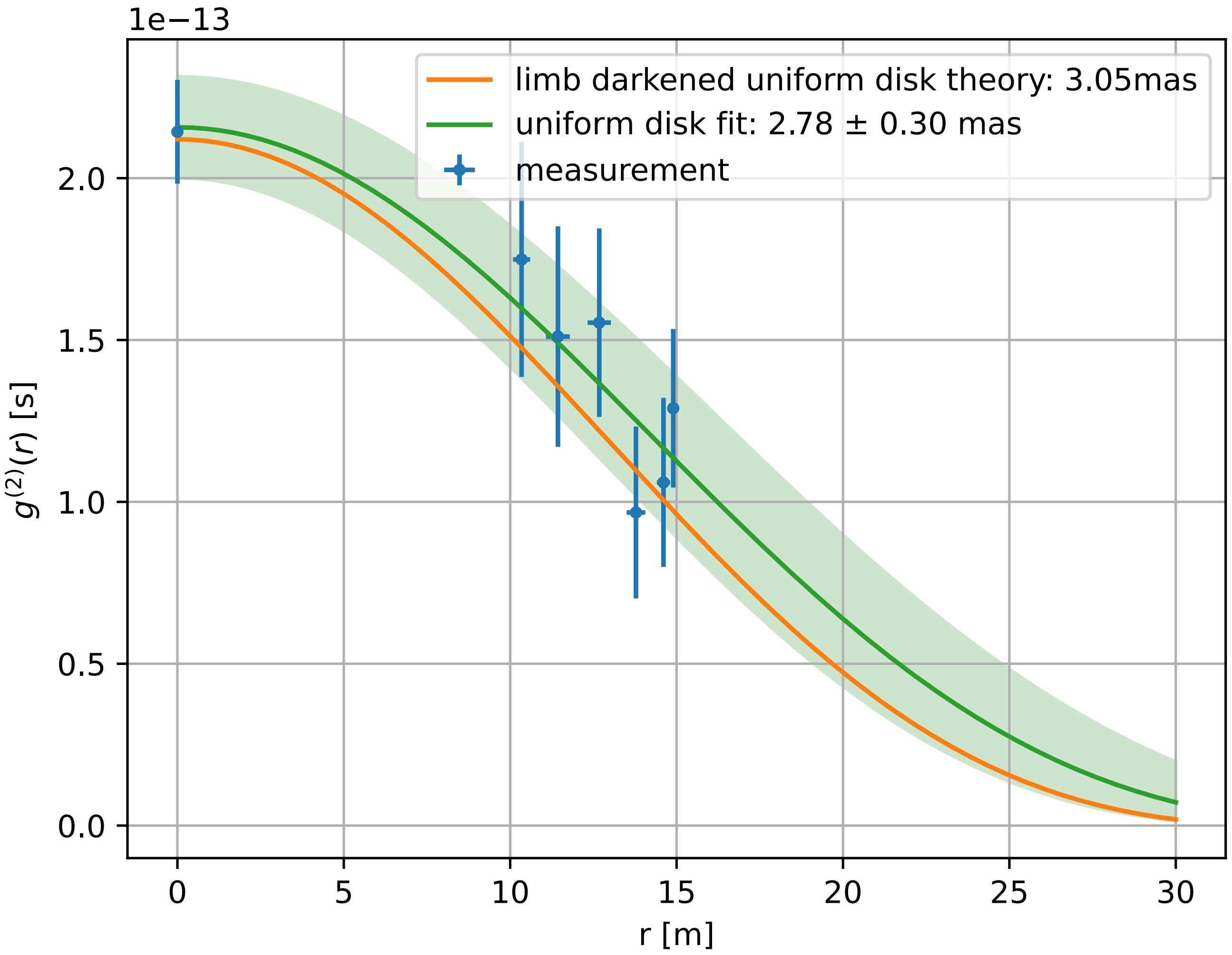
different uv plane section

Hour angle binning PhotonPix



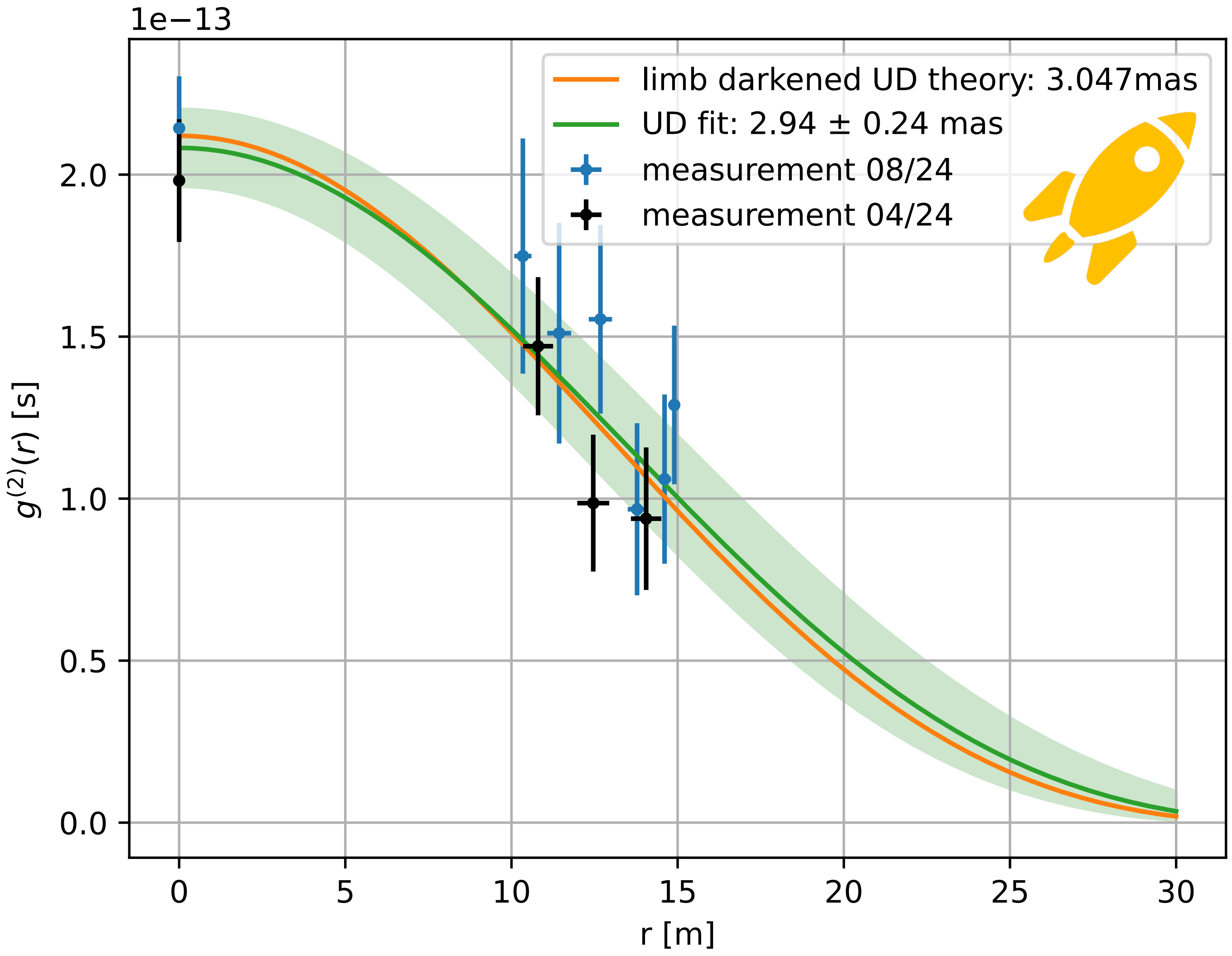
- The data from the cross correlation measurements is binned according to the hour angle
- Data is accumulated according to observation time. Threshold was set to 5h
- Produces 6 data points

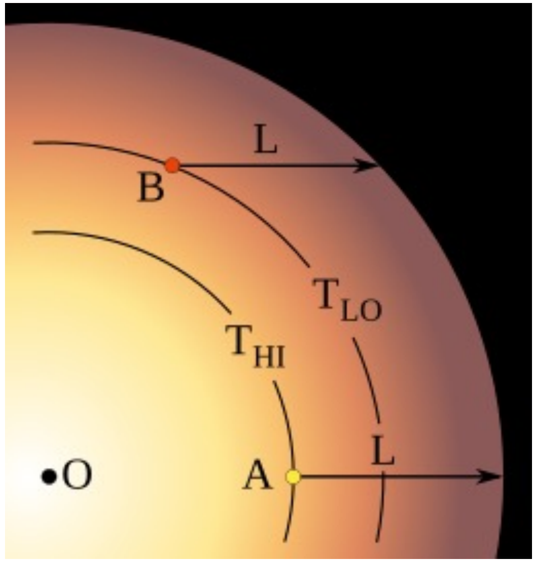
Hour angle binning PhotonPix



- The data from the cross correlation measurements is binned according to the hour angle
- Data is accumulated according to observation time. Threshold was set to 5h
- Produces 6 data points

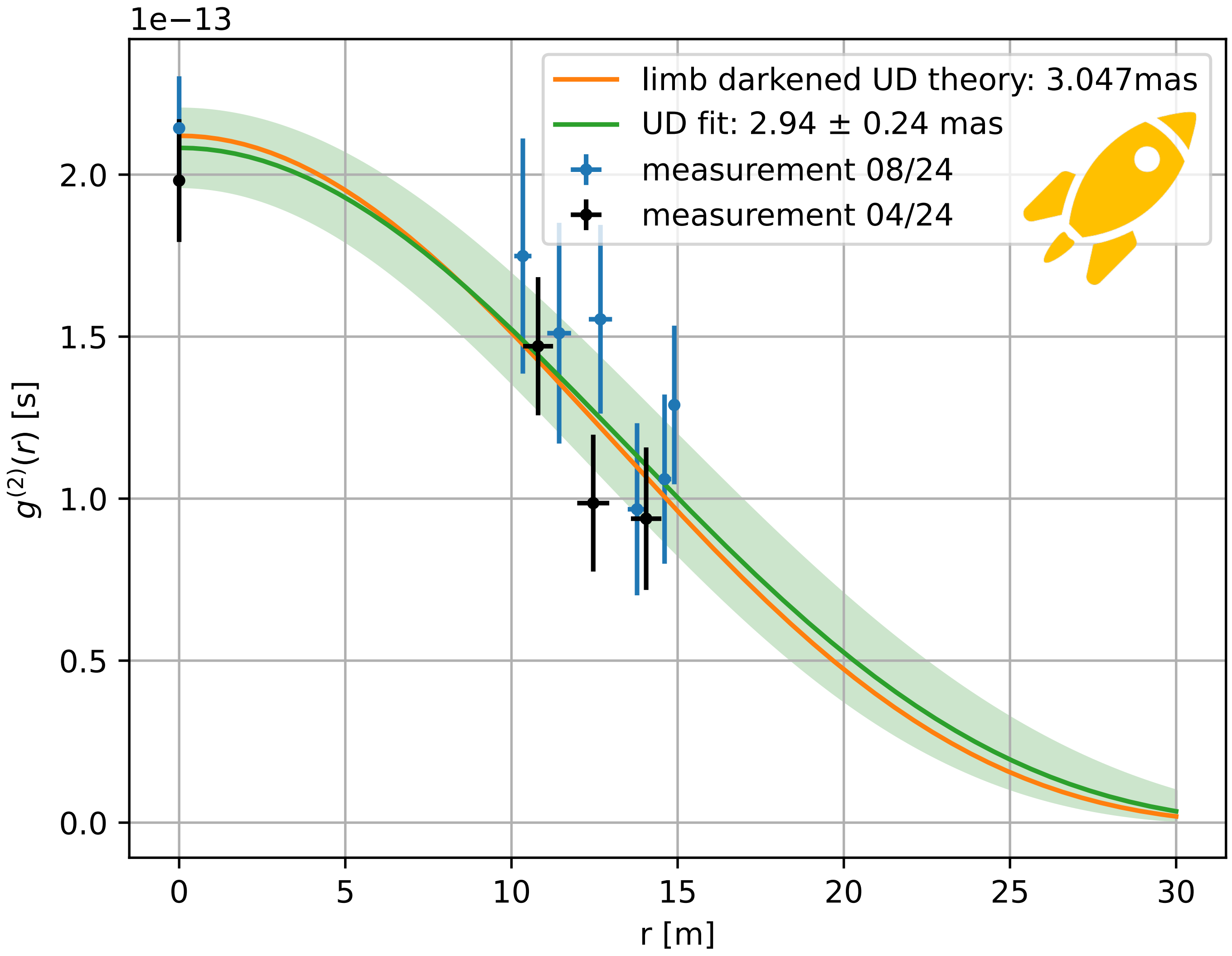
Combined visibility for Vega





Important: Limb of star appears darker

Combined visibility for Vega



- Measurement at CHARA MIRC beam combiner: 3.324 mas equatorial diameter
- Stellar atmosphere model (Jason Aufdenberg): 3.047 mas uniform disk diameter at 405 nm
- Fit to our data: 2.94 ± 0.24 mas uniform disk diameter

Future Applications of PhotonPix

Future Applications of PhotonPix

FAU

Benefits:

✓ high count rates up to 100 MHz

✓ great timing resolution

✓ large active area for easy alignment

Goal: Observe dimmer stars

Solution: Single photon counting

Future Applications

Observe star with mag 7 results in count rates >10MHz for 26 nm filter bandwidth

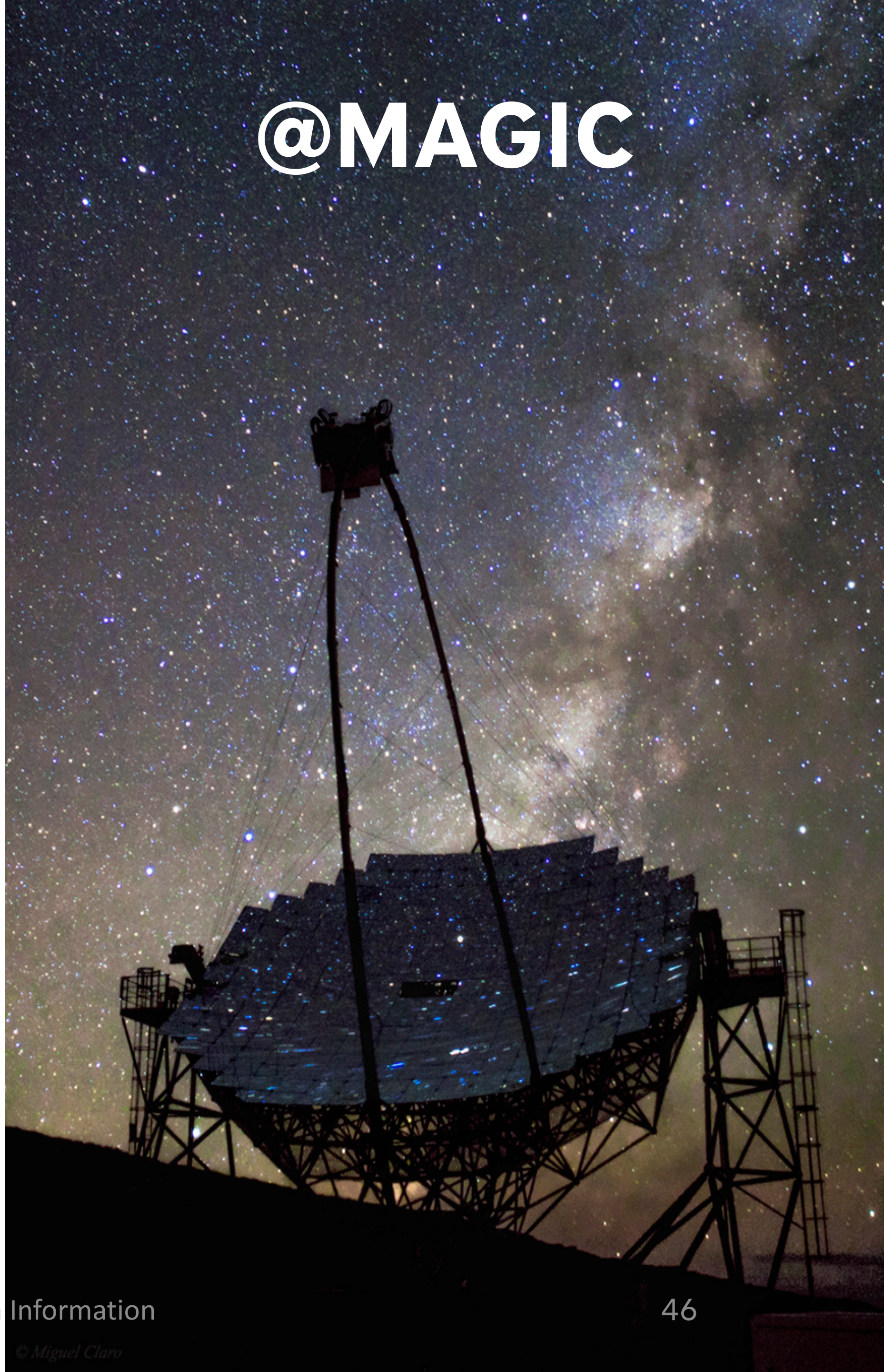
→ HPDs saturate

Active area of HPDs small compared to PSF

→ need larger detector

Solution: 18mm PhotonPix + LINTag

Single photon counting @IACTs



Thank you for your attention

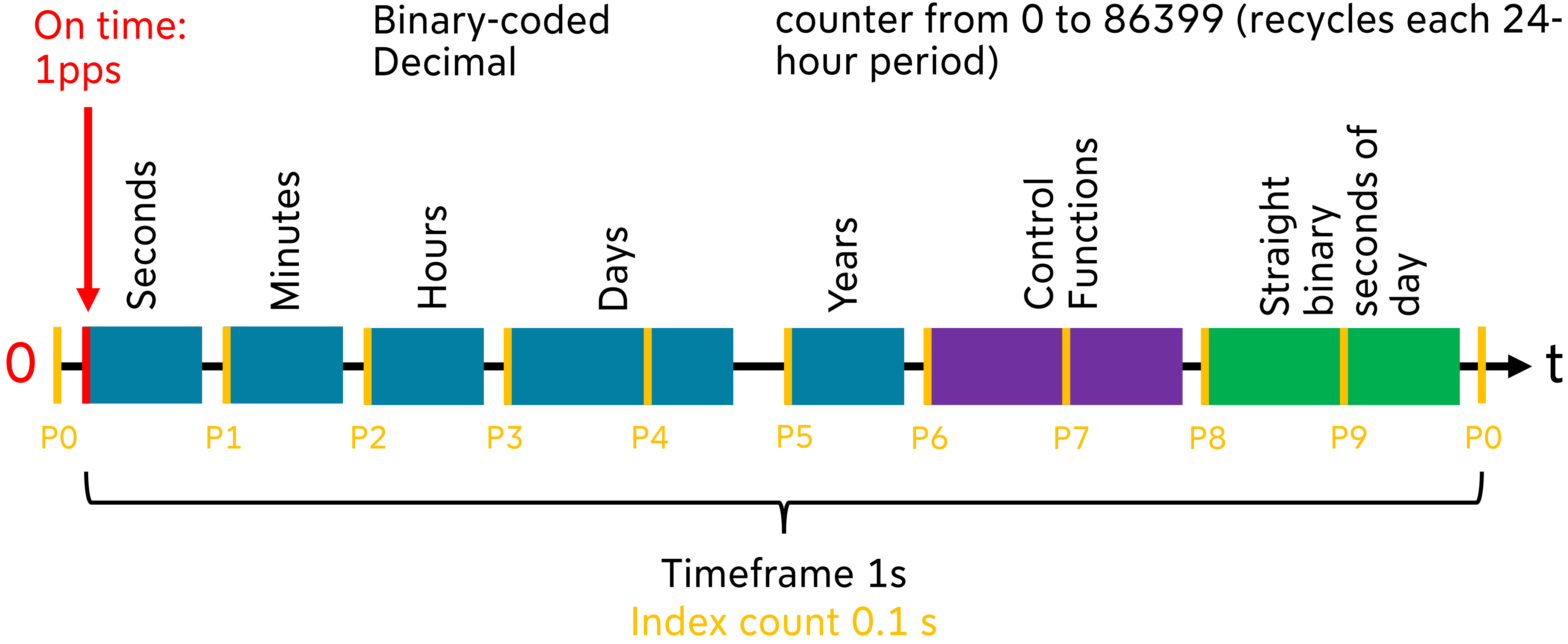
Image References

- Summer triangle: https://dq0hsqwjhea1.cloudfront.net/NHSC-Summer-Triangle.jpg
- Winter triangle: https://astrobackyard.com/wp-content/uploads/2020/12/winter-triangle.jpg
- HPD: taken from Becker&Hickl manual
- LINTag plot and image: taken from Photonscore manual and website
- Vacuum assembly: copyright Photonis
- MCP: copyright Stefan Richter
- MCP schematic: copyright Yury Prokazov
- PhotonPix: taken from Photonscore website
- Quantum efficiency: taken from LINPix Photonscore datasheet
- Limb Darkening: https://upload.wikimedia.org/wikipedia/commons/thumb/d/d4/Limb_darkening_layers.svg/256px-Limb_darkening_layers.svg.png
- MAGIC: https://www.miguelclaro.com/wp/wp-content/uploads/2013/10/MAGIC-MilkyWay_4766-net.jpg

IRIG-B timecode

- 100 Hz bit rate
- Encoding type: Binary-coded Decimal

- Years as number 00-99 (00=2000)
- Straight binary seconds: 17 bit binary counter from 0 to 86399 (recycles each 24-hour period)



IRIG-B timecode