Title: The QUASAR project : Resolving Accretion Disks with Quantum Optics

Speakers: Roland Walter

Collection/Series: Future Prospects of Intensity Interferometry

Subject: Cosmology

Date: October 31, 2024 - 2:00 PM

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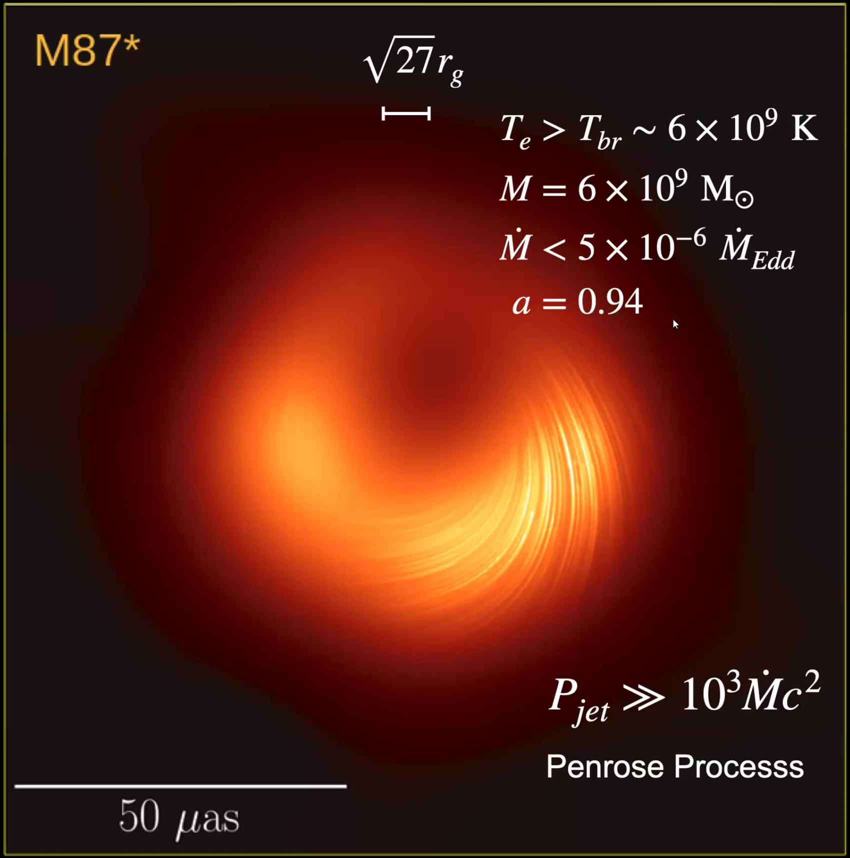
Abstract:

Accretion flows aroud black-holes, neutron stars or white dwarfs are studied since almost 60 years. Although they are ubiquitous and somewhat similar over scales reaching billions in mass and size, their study has been limited because they remain unresolved point like sources in the optical/ultraviolet and X-rays, where they emit. Two main modes of accretion have been identified in Active Galactic Nuclei. In most sources the accretion rate is low and a high pressure, low density, low collision rate, optically thin, radiatively inefficient, two temperature plasma can form (Shapiro 1976; Narayan & Yi 1994,1995). This solution is stable only for low luminosities (<1% LEDD). The Event Horizon Telescope has recently resolved such flows in Sgr A and M87, confirmed several aspects of the model and could detect particles accelerated close to the horizon of Sgr A (Wielgus, 2022) a likely signature of the Blandford-Znajek (1977) process. When the accretion rate is higher, momentum can be dissipated by viscosity and the flow proceeds via geometrically thin disk-shaped structures. These accretion disks provide feedback to their environment by accelerating winds and launching jets in their central regions. The apparent size of accretion disks are of the order of 1-40µarcsec in nearby quasars, Seyfert galaxies and galactic cataclysmic variables and of 0.1-1µarcsec in of low mass X-ray binaries in our Galaxy. Hanbury-Brown & Twiss (1954) invented intensity interferometry and measured the size of some bright stars by correlating the arrival times of photons detected by two optical telescopes. The physics has been explained as a quantum effect in the early 60s (Fano 1961) and has triggered the development of quantum optics (Glauber 1963). Its root is found in the quantum theory of statistical fluctuations in an ideal gas (Einstein 1925). The achievable signal-to-noise depends on the telescope size, the detector time resolution, and the number of spectral channels observed simultaneously. Extremely large telescope and 10ps resolution single photon detectors bring the key improvements to reach in the optical angular resolutions better than these achieved in the radio by the Event Horizon Telescope and to obtain the first images of accretion disks around galactic and extragalactic compact objects, a breakthrough.

I will present the goals and the status of the QUASAR project, which started one year ago, aiming at bringing a 10ps resolution optical spectrometer on very large telescope.

Most SMBH ($\dot{M} \ll \dot{M}_{Edd}$) Should Look Like This



$T_e > T_{br} \sim 6 \times 10^9$ K

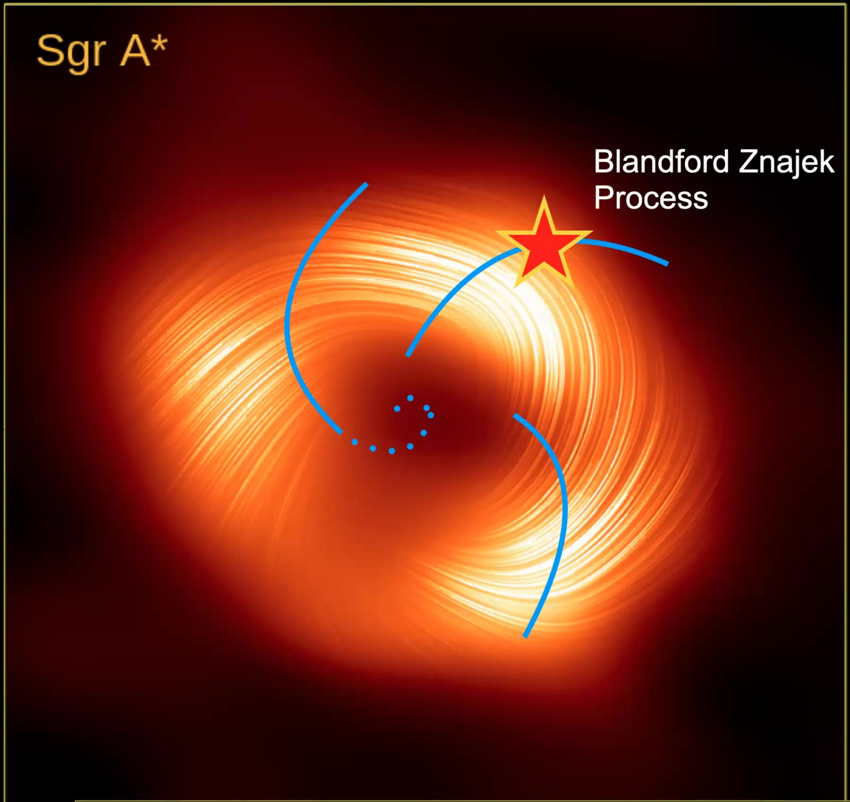
$M = 6 \times 10^9\ \mathrm{M}_\odot$

$\dot{M} < 5 \times 10^{-6}\ \dot{M}_{Edd}$

$a = 0.94$

$P_{jet} \gg 10^3 \dot{M} c^2$

Penrose Processs



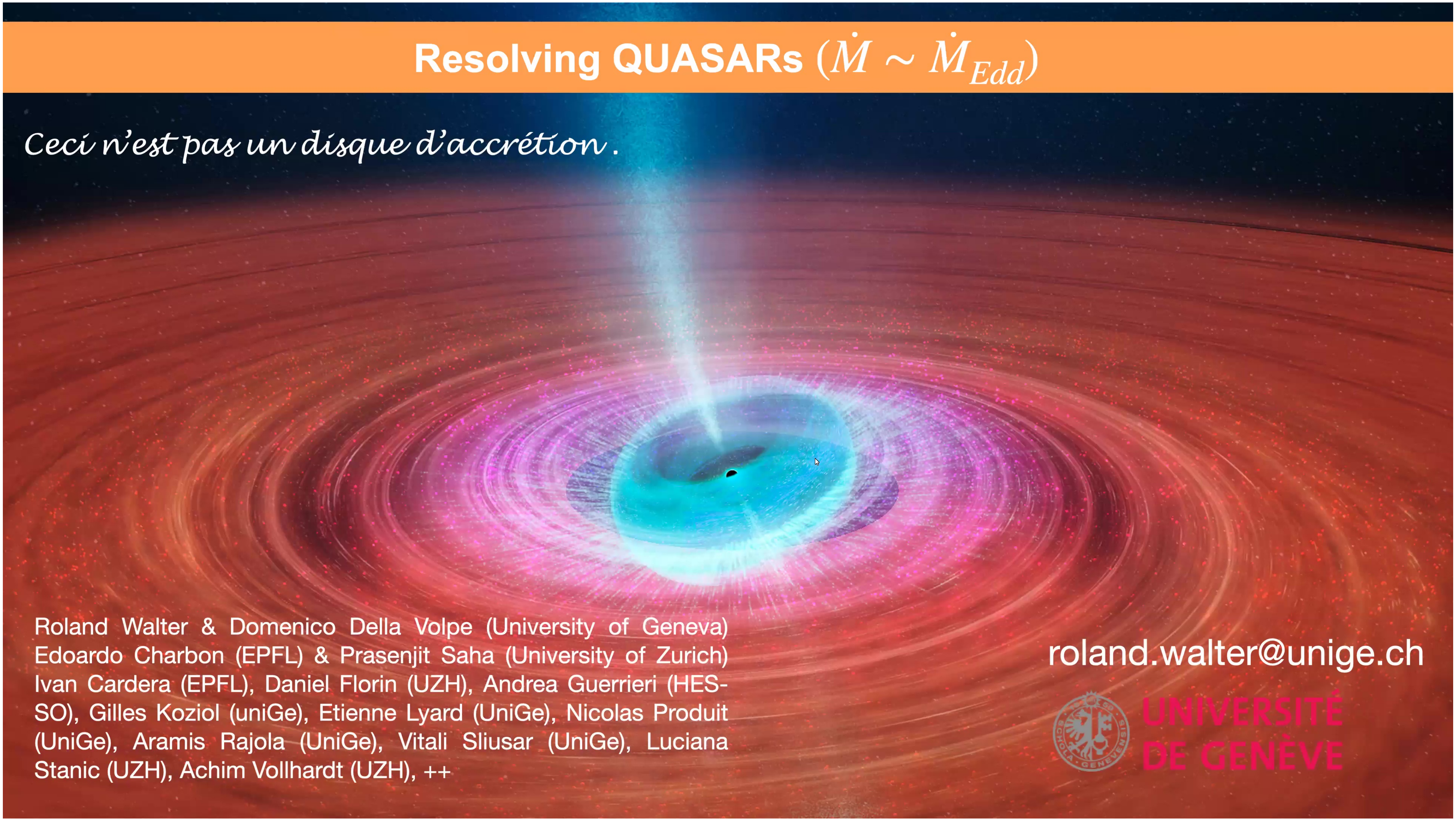
Force free (high conductivity) & equipartition:

$$U = h_{gap}E_{gap} \approx h_{gap}\frac{\Omega R_{gap}}{c}B \approx 2.5 \cdot 10^{21}\left(\frac{\dot{M}}{\dot{M}_{Edd}}M_9\right)^{1/2}\frac{h_{gap}}{R_g}\ \mathrm{V}\,.$$

i.e. 10^{18}V for $10^{-6}\dot{M}_{Edd}$

Ceci n'est pas un disque d'accrétion.

Resolving QUASARs ($\dot{M} \sim \dot{M}_{Edd}$)



Ceci n'est pas un disque d'accrétion .

Roland Walter & Domenico Della Volpe (University of Geneva) Edoardo Charbon (EPFL) & Prasenjit Saha (University of Zurich) Ivan Cardera (EPFL), Daniel Florin (UZH), Andrea Guerrieri (HES-SO), Gilles Koziol (uniGe), Etienne Lyard (UniGe), Nicolas Produit (UniGe), Aramis Rajola (UniGe), Vitali Sliusar (UniGe), Luciana Stanic (UZH), Achim Vollhardt (UZH), ++

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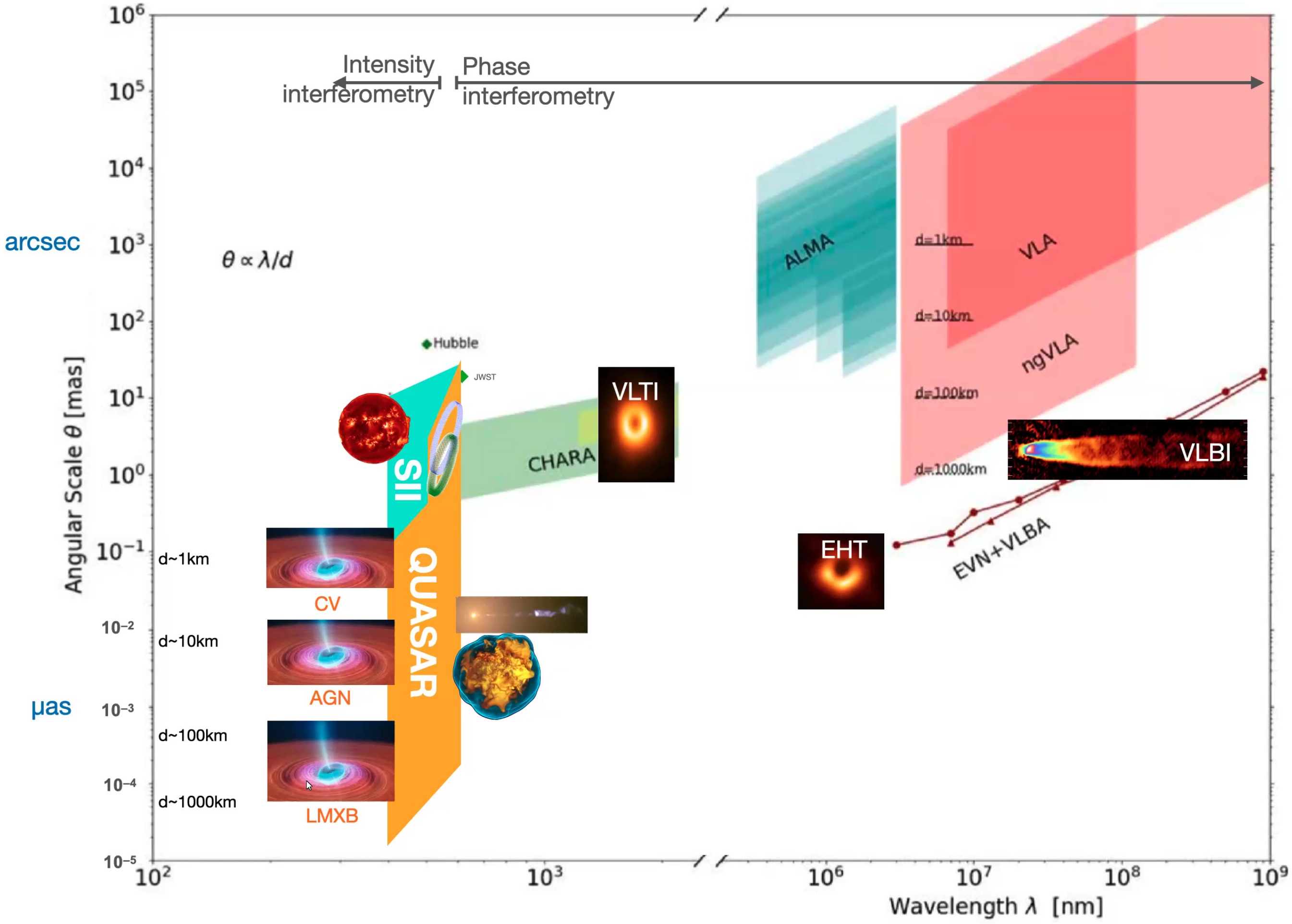
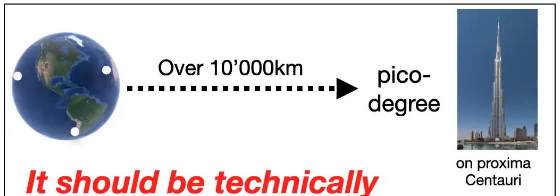
In the optical, a baseline of 4km provides the same resolution as the EHT





It should be technically possible and would be a fun discussion for panel #2...

Resolving accretion disks: how to make it work ?

$$\mathrm{SNR} = \sqrt{2}\sqrt{\epsilon_1\epsilon_2}\sqrt{\frac{A_1A_2}{(1+B_{\nu1}/F_\nu)(1+B_{\nu2}/F_\nu)}}\frac{F_\nu}{h\nu}V_{12}^2\sqrt{N_{chan}}\sqrt{\frac{T_O}{\sigma_t}}$$

Large telescopes
500 m²

Many narrow wave bands
1000 channels

High time resolution
12 ps

Problems to be solved (1ps/c = 0.3mm) :

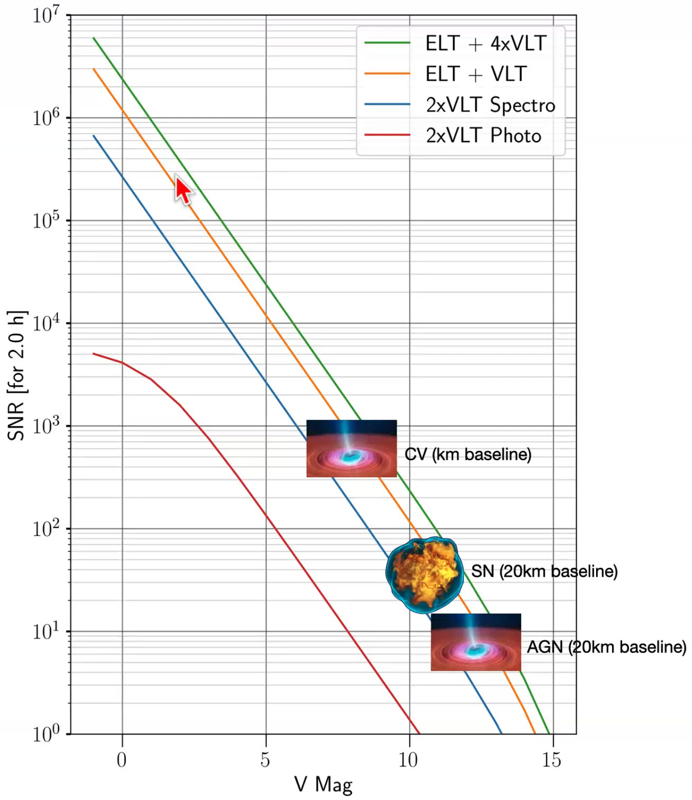
✓ Detector & TDC at high resolution
✓ Low systematic noise
✓ Clock synchronisation over many km
✓ High performance time tag correlator
✓ Sub-mm position of telescopes

Photometer is tested and can be adapted on telescopes now

➡ Detector array with low crosstalk
➡ Dewar & FPGA
➡ Synchronous optical spectrometer

Spectrometer hopefully to reach telescopes in late 2026
→ quasars in 2030

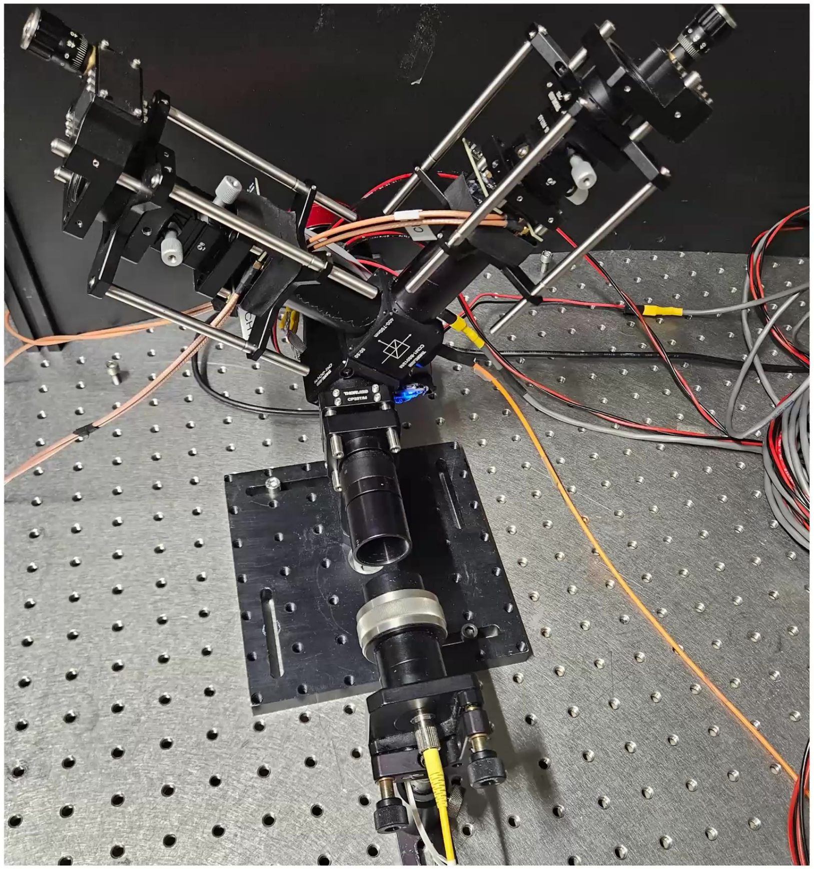
Simulations includes source spectra, dispersion, slit, optical and quantum efficiencies, dead-time, fill factor, dark noise, cross-talk

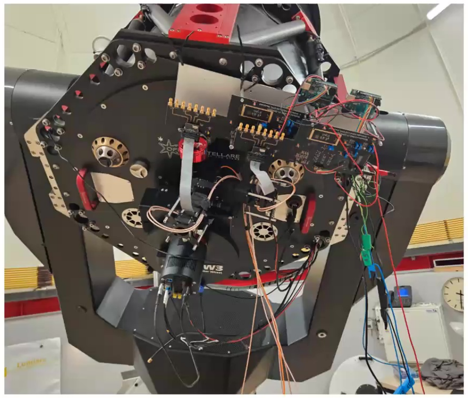


Improvements since the original Hanbury Brown & Twiss experiment:
- 10^3 in mirror area
- 10^3 in spectral channels
- 10^3 in timing resolution

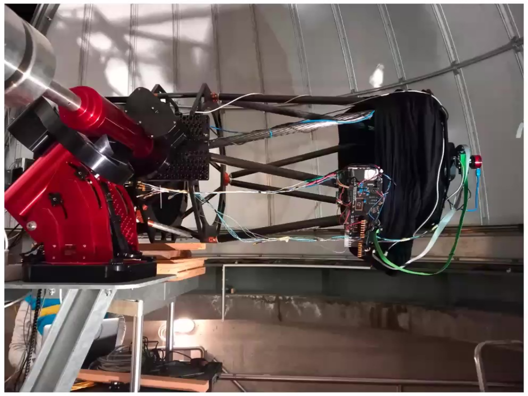
→ 10^6 in SNR compared to HBT

Photometer

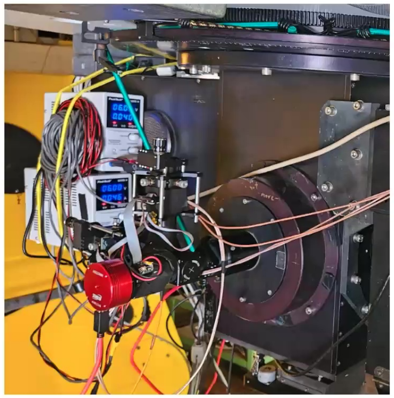




Geneva



St-Luc (Swiss alps)



Skinakas (Crete)

C2PU Calern (France)

High Resolution Detector & TDC

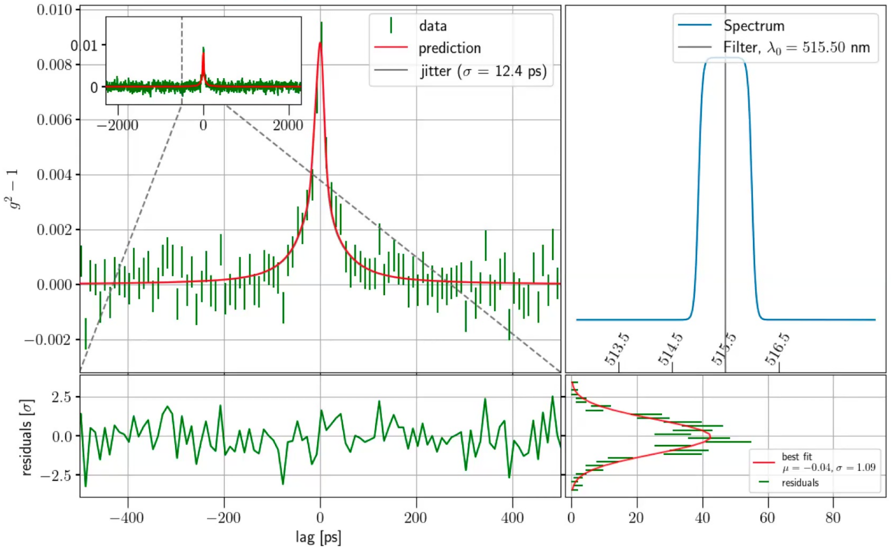
- Fast detectors: EPFL SPADs
  - 3ns dead-time (configurable)
  - ~55% PDP @ 5V/500nm
  - 20Hz DCR @ 5V/20°C
  - Time jitter ~5.1ps RMS
- TDC: IDQuantique ID1000
  - resolution 1ps
  - Inter-channel σ <3.6ps
  - 300MHz / channel correlation
  - 10MHz total timestamp readout

➡ Measured full jitter [TDC + two SPADs]: 12.4 ps RMS

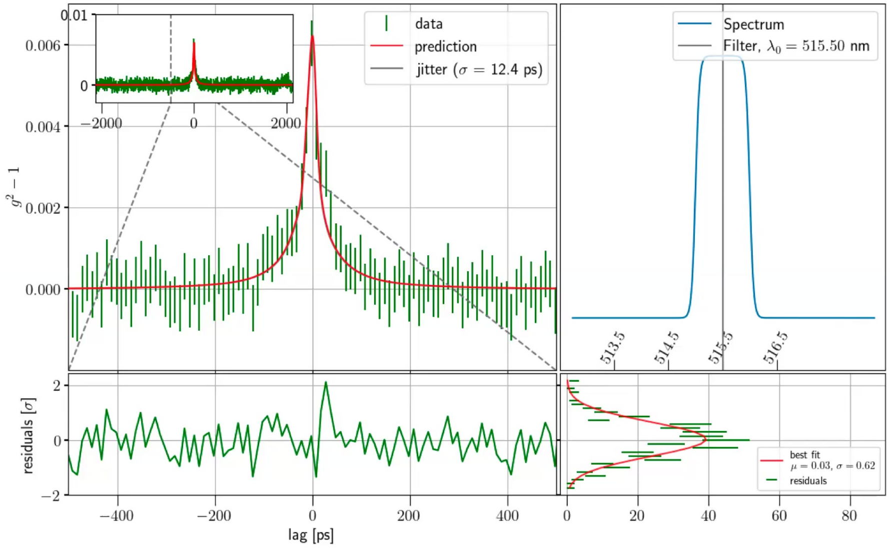
1. Broad-Spectrum from chaotic sources

515/1nm filter (~0.8ps coherence time), correlation peak width dominated by experimental jitter

Xenon lamp



LED (3 mm^2, 70W, blue converted to green)

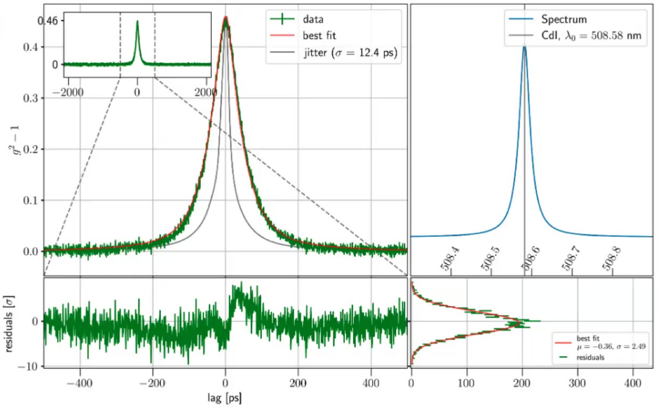


High Resolution Detector & TDC

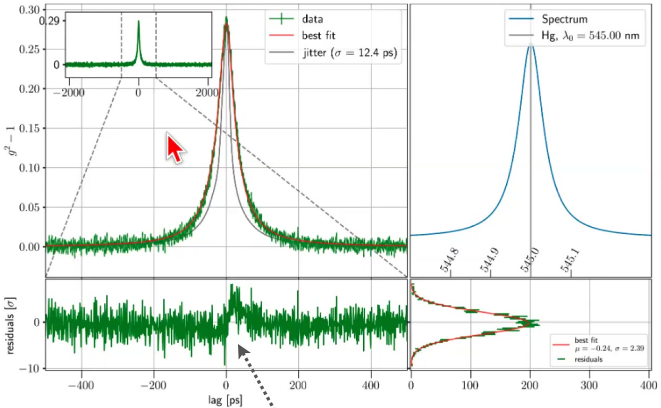
2. Spectral lines: the g^2 peak is resolved

polariser & single mode filter, 10MHz/channel

Cd 508 nm

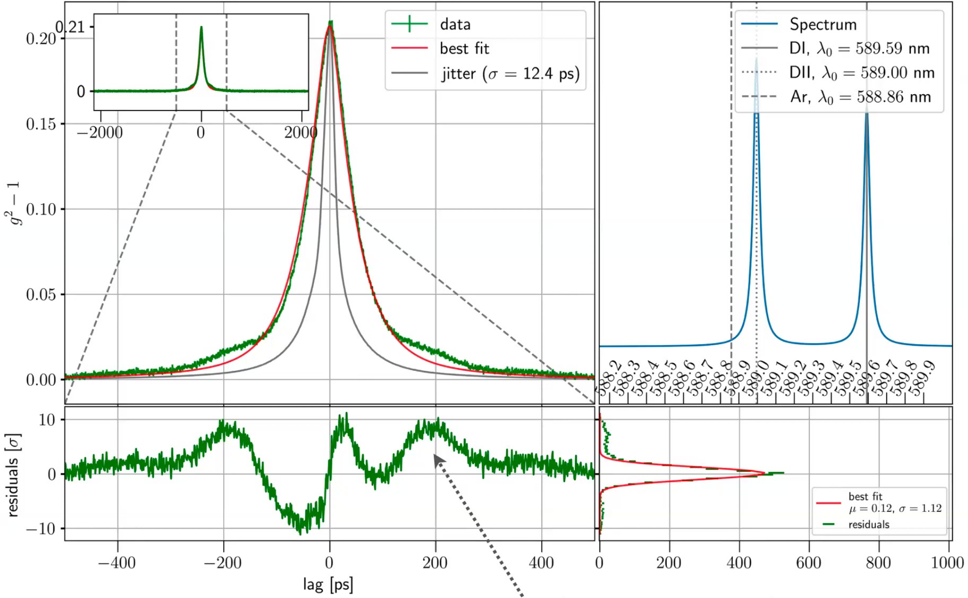


Hg 545nm



TDC response is slightly assymetric

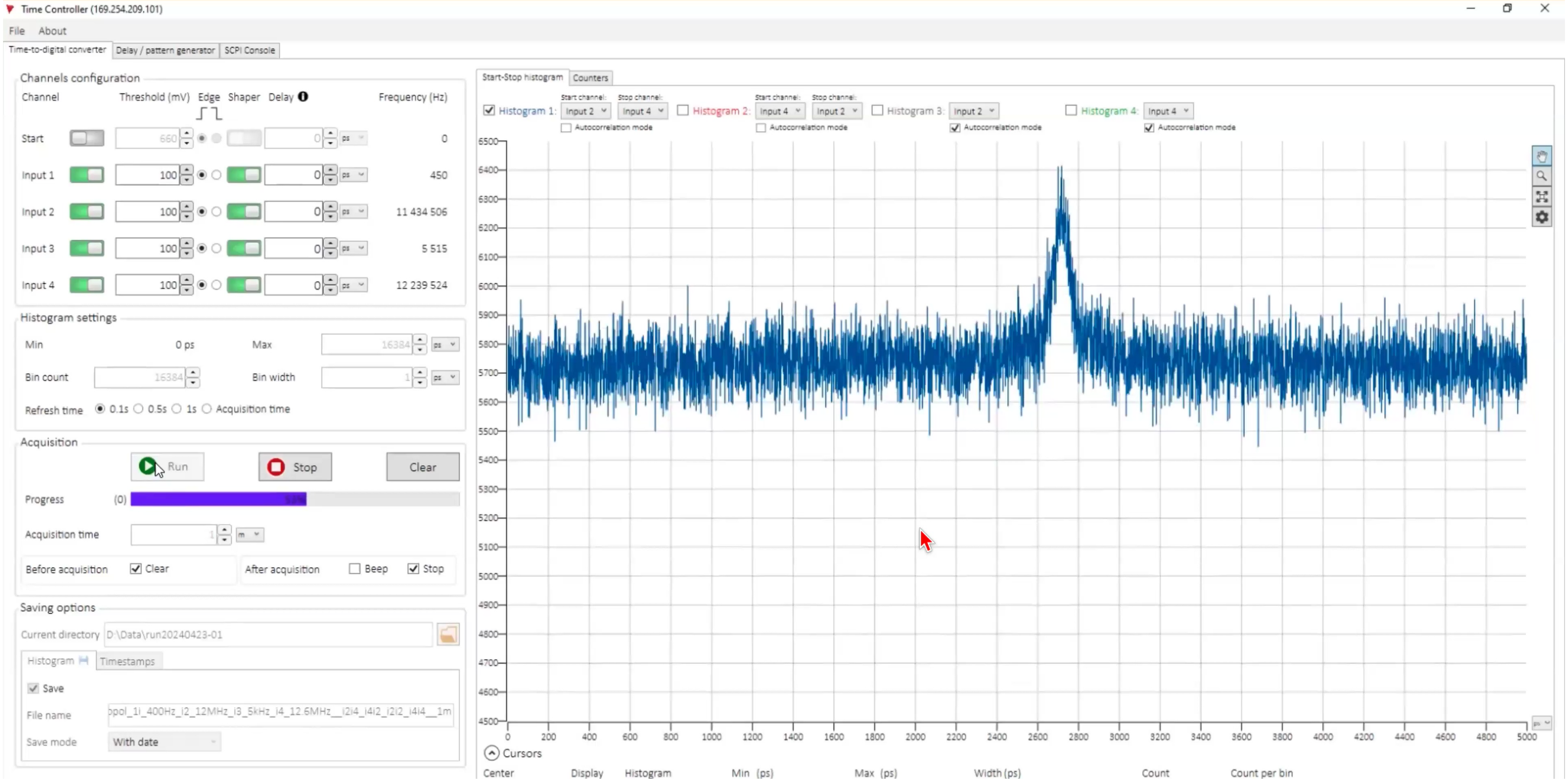
Na D-lines $\rightarrow \Delta\lambda = \dfrac{\lambda^2}{4\pi\tau_c} \approx 0.03\text{Å}$



Lamp spectrum is more complex (e.g. traces of Argon)

Perfect Poisson Noise !!!

HBT acquisition, Na lamp, real-time, 1ps sampling



Channels configuration

Channel	Threshold (mV)	Edge	Shaper	Delay	Frequency (Hz)
Start	660	●		0 ps	0
Input 1	100	● ○		0 ps	450
Input 2	100	● ○		0 ps	11 434 506
Input 3	100	● ○		0 ps	5 515
Input 4	100	● ○		0 ps	12 239 524

Histogram settings

Min 0 ps
Max 16384 ps
Bin count 16384
Bin width 1 ps
Refresh time ● 0.1s ○ 0.5s ○ 1s ○ Acquisition time

Acquisition

Progress (0)
Acquisition time 1 m
Before acquisition ☑ Clear
After acquisition ☐ Beep ☑ Stop

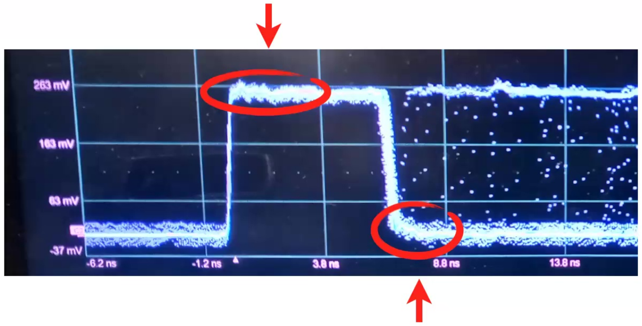
Saving options

Current directory D:\Data\run20240423-01
Histogram | Timestamps
☑ Save
File name ɔpol_1i_400Hz_i2_12MHz_i3_5kHz_i4_12.6MHz__i2i4_i4i2_i2i2_i4i4__1m
Save mode With date

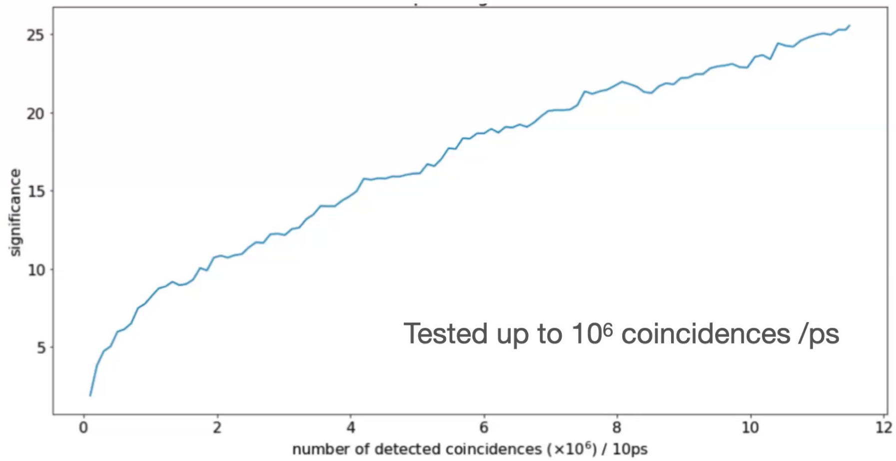
☑ Histogram 1: Start channel: Input 2 Stop channel: Input 4 ☐ Autocorrelation mode
☐ Histogram 2: Start channel: Input 4 Stop channel: Input 2 ☐ Autocorrelation mode
☐ Histogram 3: Input 2 ☑ Autocorrelation mode
☐ Histogram 4: Input 4 ☑ Autocorrelation mode

Stable Systematics can be Subtracted

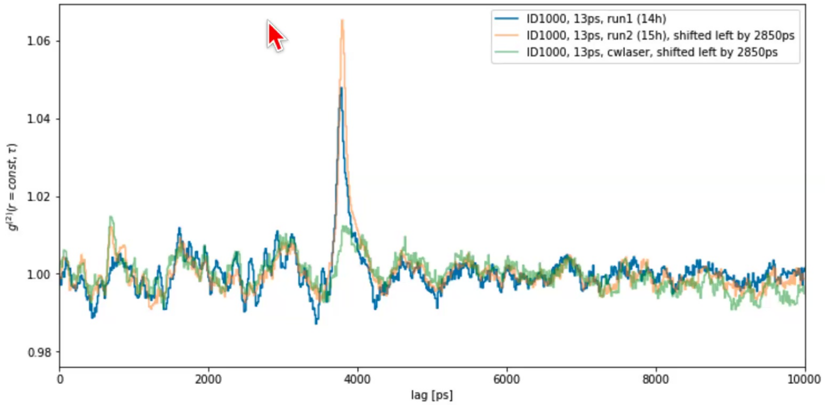
wiggles are stable so the correlated noise can be subtracted (TDC discriminator also involved)



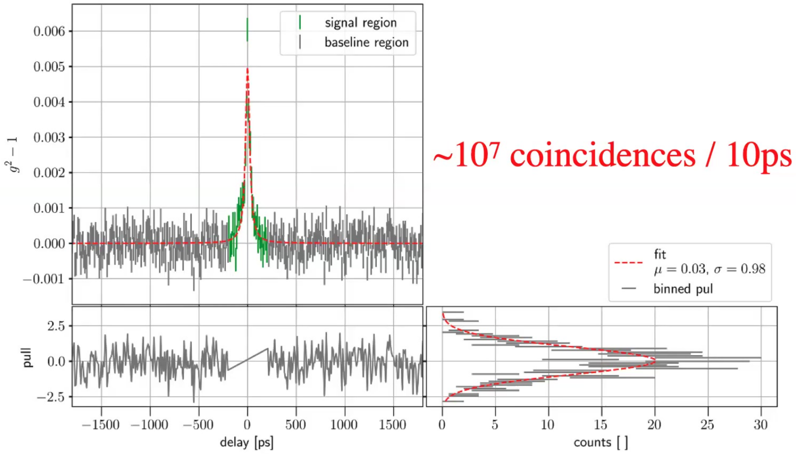
widens the timing response at very high rate → do not exceed tens of MHz



Tested up to 10^6 coincidences /ps



subtracting correlated noise



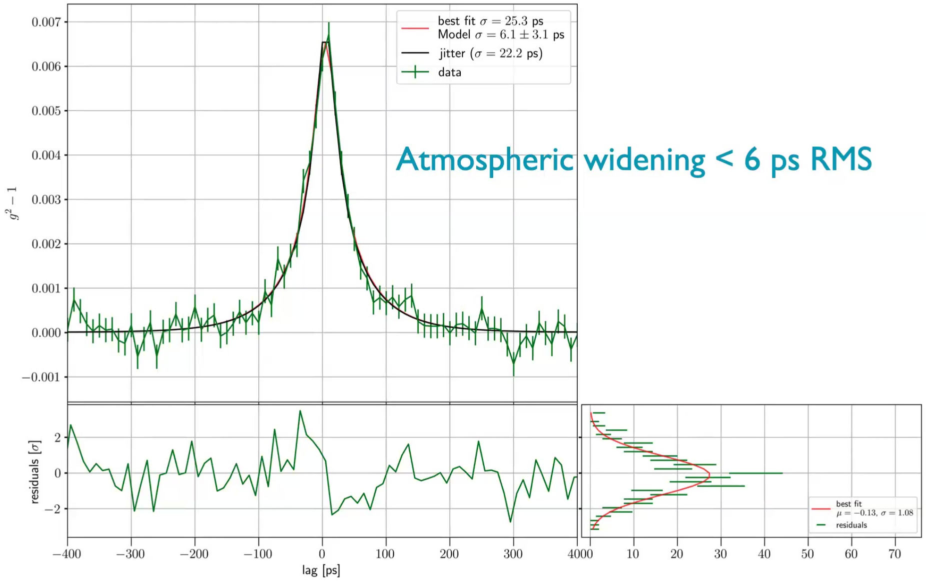
~10^7 coincidences / 10ps

On Telescopes

3. Stars

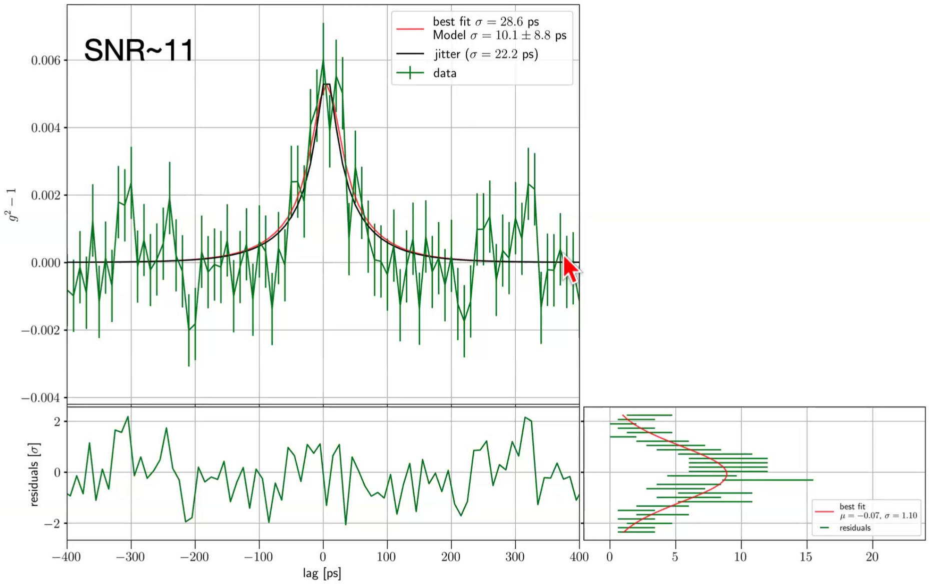
515/1nm filter & polarizer

The Sun (30 min, 25MHz/channel)



Atmospheric widening < 6 ps RMS

Vega & Capella (6.5h, 2MHz/channel)



SNR~11

The jitter at the telescope was 22ps rather than 12ps because of a wrong setting of the voltage

Exposure time is 50x less than with ns detectors

Time Distribution & Synchronistion

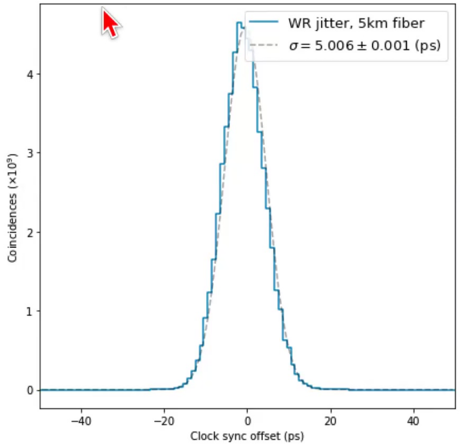
Up to 30+ km

White Rabbit sub ns ~ 100ps

Low jitter White Rabbit ~ 20ps

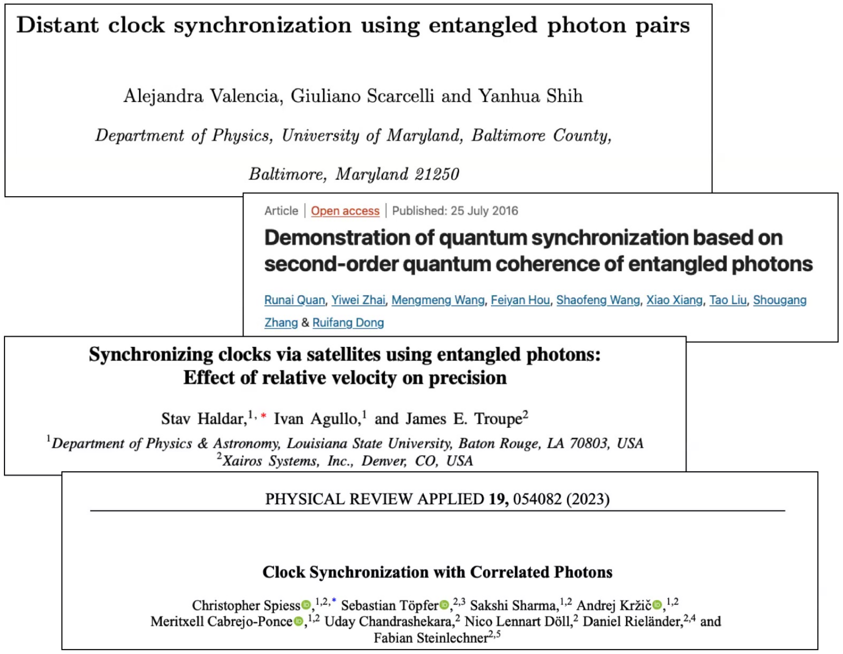
Improved low Jitter White Rabbit < 5ps

- Fiber temperature (changes of alpha-value)
- Internal electronics temperature



Earth scale ?

Quantum clocks synchronised with entangled photons



Distant clock synchronization using entangled photon pairs

Alejandra Valencia, Giuliano Scarcelli and Yanhua Shih

Department of Physics, University of Maryland, Baltimore County,
Baltimore, Maryland 21250

Article | Open access | Published: 25 July 2016

Demonstration of quantum synchronization based on second-order quantum coherence of entangled photons

Runai Quan, Yiwei Zhai, Mengmeng Wang, Feiyan Hou, Shaofeng Wang, Xiao Xiang, Tao Liu, Shougang Zhang & Ruifang Dong

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Synchronizing clocks via satellites using entangled photons: Effect of relative velocity on precision

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[1]*Department of Physics & Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA*
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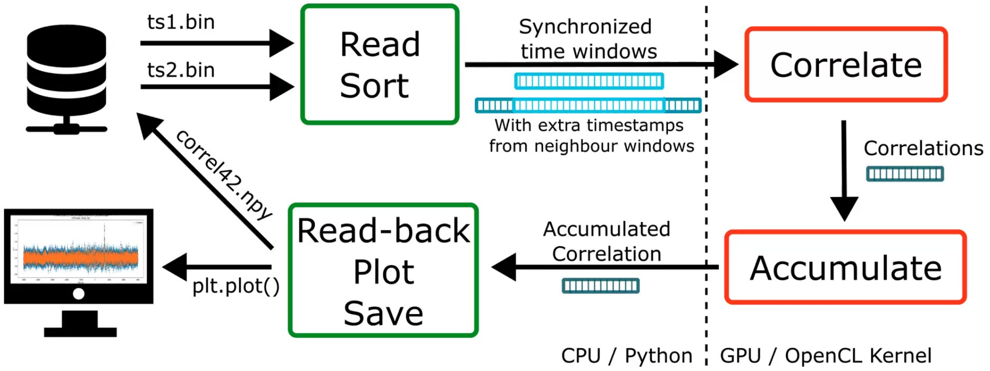
PHYSICAL REVIEW APPLIED **19,** 054082 (2023)

Clock Synchronization with Correlated Photons

Christopher Spiess,[1,2,*] Sebastian Töpfer,[2,3] Sakshi Sharma,[1,2] Andrej Kržič,[1,2] Meritxell Cabrejo-Ponce,[1,2] Uday Chandrashekara,[2] Nico Lennart Döll,[2] Daniel Rieländer,[2,4] and Fabian Steinlechner[2,5]

Real-Time Correlator

- Discrete correlation (no FFT)
- ‘True’ processing, also correlate timestamps at edge of time-windows
- Developped in python using an OpenCL kernel, single implementation runs in any GPU/OS



ts1.bin

ts2.bin

Read Sort

Synchronized time windows

With extra timestamps from neighbour windows

Correlate

Correlations

Accumulate

Accumulated Correlation

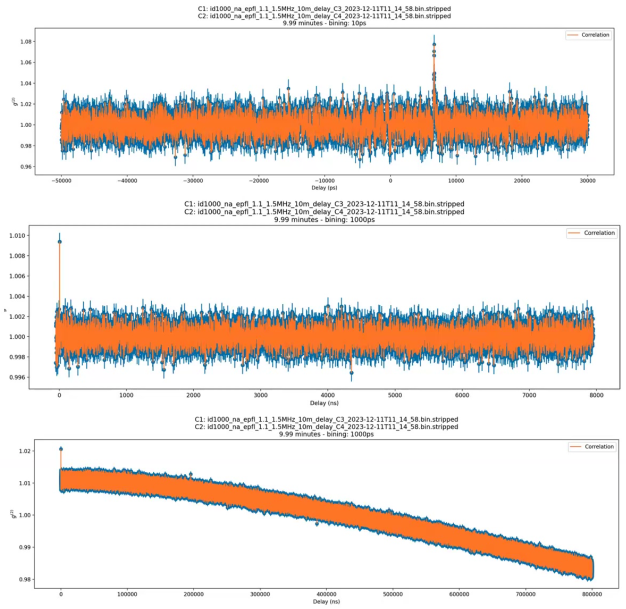
Read-back Plot Save

plt.plot()

correl42.npy

CPU / Python

GPU / OpenCL Kernel



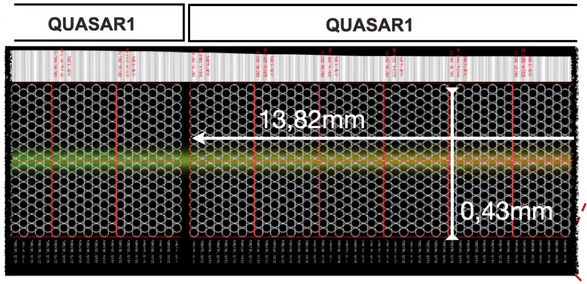
Device	Core i9 9880H	Radeon Pro 5500M	Quadro RTX 4000	M3 Pro 14 cores
Time to read/sort timestamps (s)	172,7	172,7	133	96,1
Time to transfer data to GPU (s)	0	4,1	4,5	1,4
Time to compute correlation (s)	1359	2,7	0,8	1,7
Max possible correlation rate in GPU for 2 Chans (scenario A . - MHz)	0,5	103,8	134,4	227,4

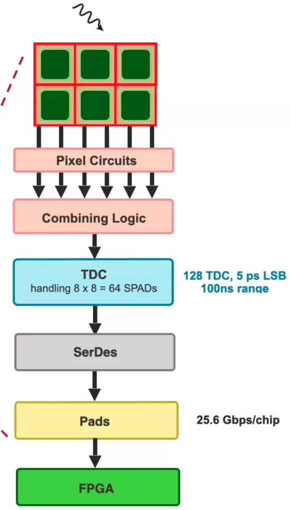
Enough for 2x 10m-class spectrometers

Spectrometer Development

QUASAR1 chip

512x16 spad array, ~1.4cm x 2mm, 600mW, 60%filling factor
DCR ~ 1cps/pix@-30C, dead time quenching, cross-talk filtering,
time to digital converter, time stamps via serial interface.





Pixel Circuits

Combining Logic

TDC
handling 8 x 8 = 64 SPADs

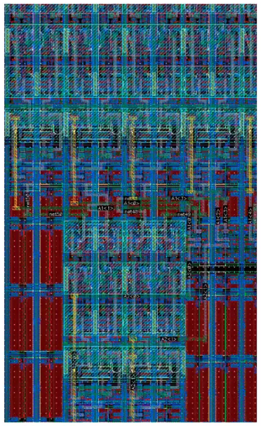
128 TDC, 5 ps LSB
100ns range

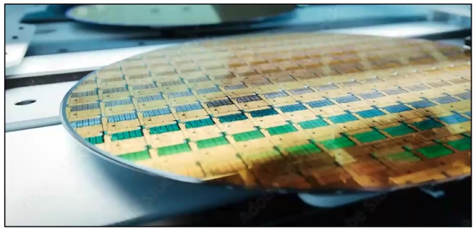
SerDes

Pads

25.6 Gbps/chip

FPGA

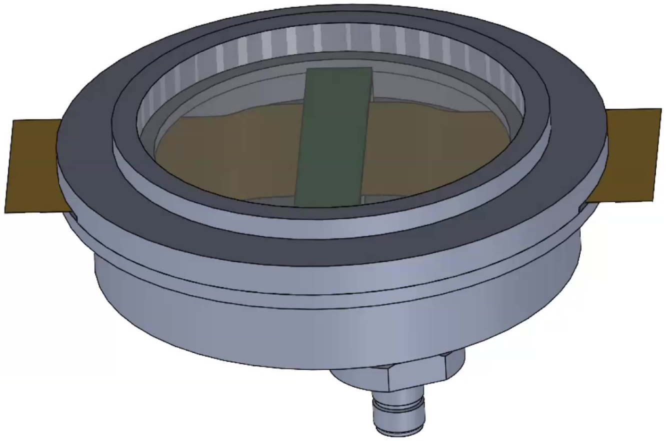




1000 QUASAR1 chips in May 2025

Dewar

6 QUASAR1 chips (3072x16 spads)
thermal sensors, power & timing distribution
cooling to -30C by Peltier, vacuum insulation

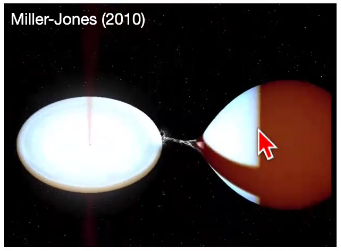


FPGA Board

3 SoC (to handle 6 QUASAR1 chips)
White Rabbit FPGA
Slow ctontrol
Optical & power i/f

Resolving Cataclysmic Variables (1 night)

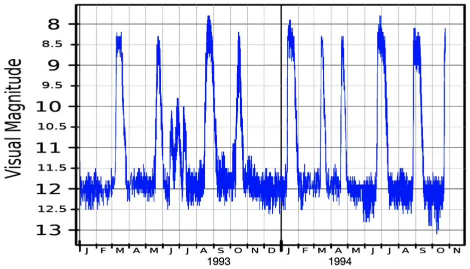
From 2026

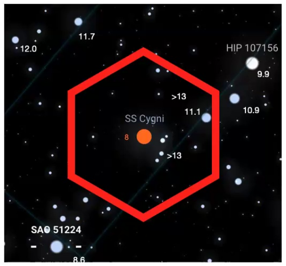


Miller-Jones (2010)

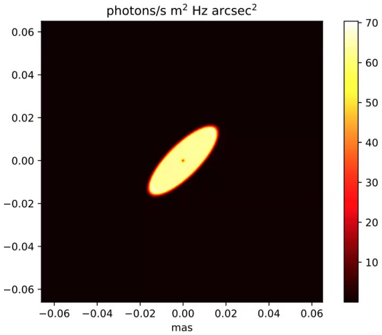
SS Cygni @ 115pc
P_{orb} = 6.6 h R_{orb} ~1.6 10^6 km
White dwarf: 0.8 $M_\odot$
Companion: K5V 0.5 $M_\odot$
R_{disk} = 0.4 10^6 km, 32 µarcsec

$$\dot{m} = \Sigma \cdot \left(3\pi\nu \left(1 - \sqrt{\frac{r_{in}}{r}} \right)^{-1} \right)$$

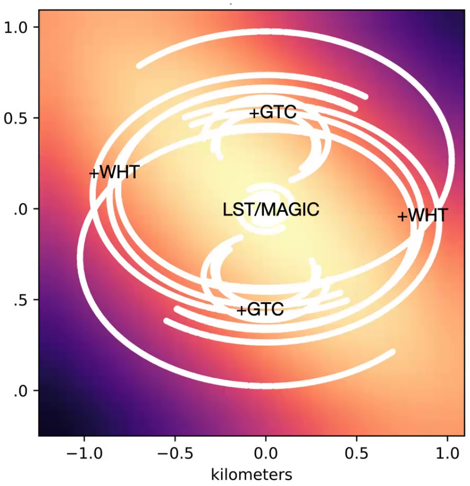
v_{cold} : neutral gas, molecular viscosity
v_{hot} : ionised gas, magneto-rotational instability



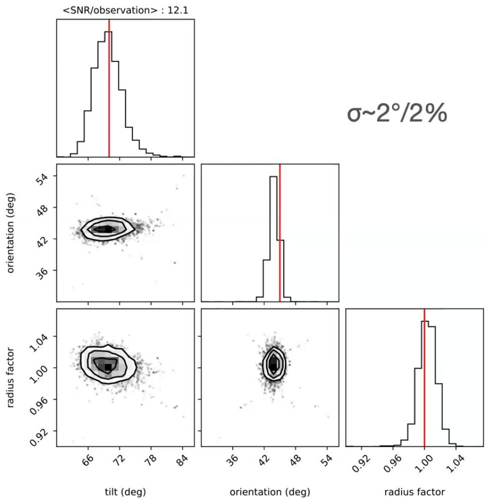




ORM 4 LST + 2 MAGIC:
Resolution : 400nm/309m = 333 µas
ORM GTC + WHT:
Resolution : 500nm/1273m = 80 µas



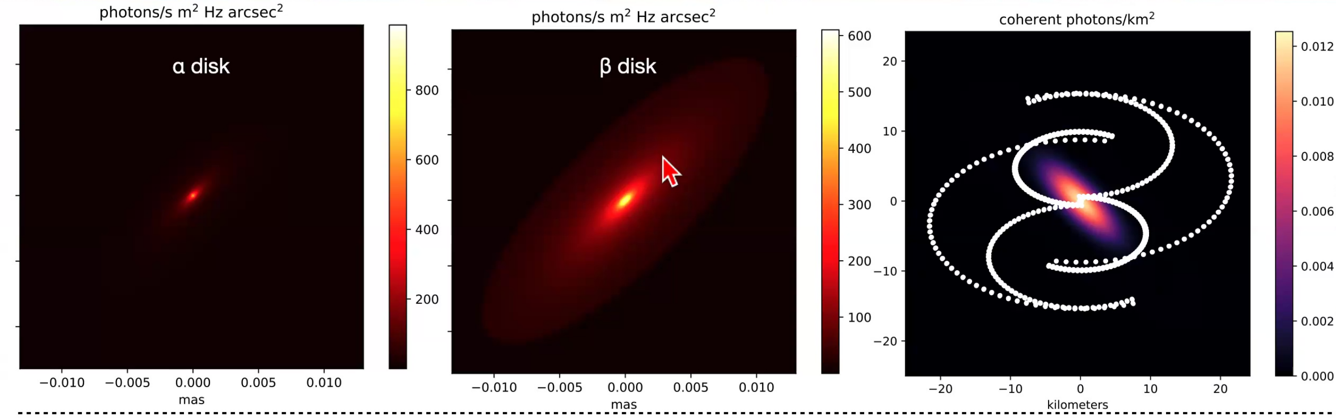
3 nights with GTC & WHT:

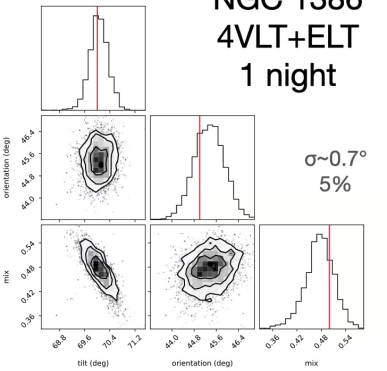


σ~2°/2%

Resolving Seyferts and quasars

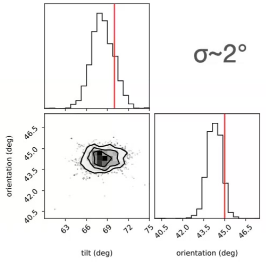

From 2030





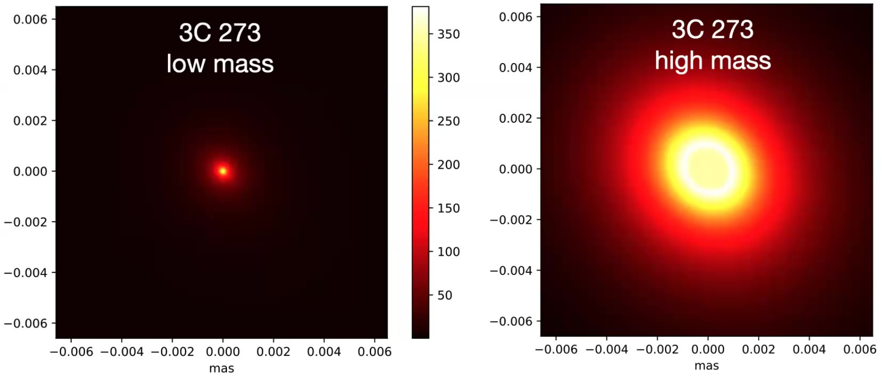
NGC 1386
4VLT+ELT
1 night

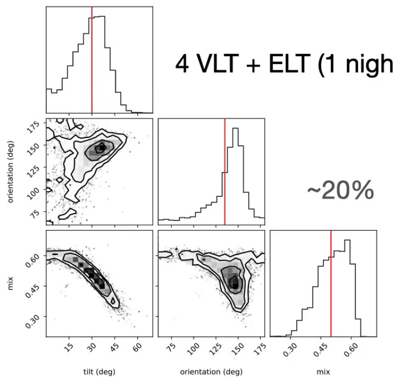
σ~0.7°
5%



NGC 5548
GTC+WHT
10 nights

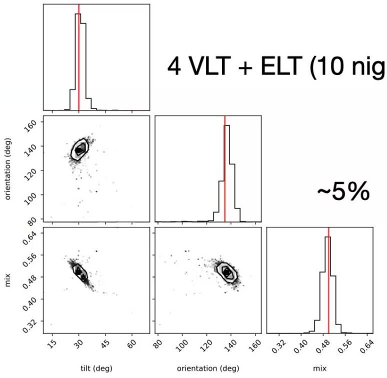
σ~2°





4 VLT + ELT (1 night)

~20%



4 VLT + ELT (10 nights)

~5%