Resolving Accretion Disks Around Black-Holes

QUASARs are luminous (up to 10^4 L_{galaxy}) for $\dot{M} \sim \dot{M}_{Edd}$, when the dense gas is thermalised and emit in the visible

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Ceci n'est pas un disque d'accrétion .

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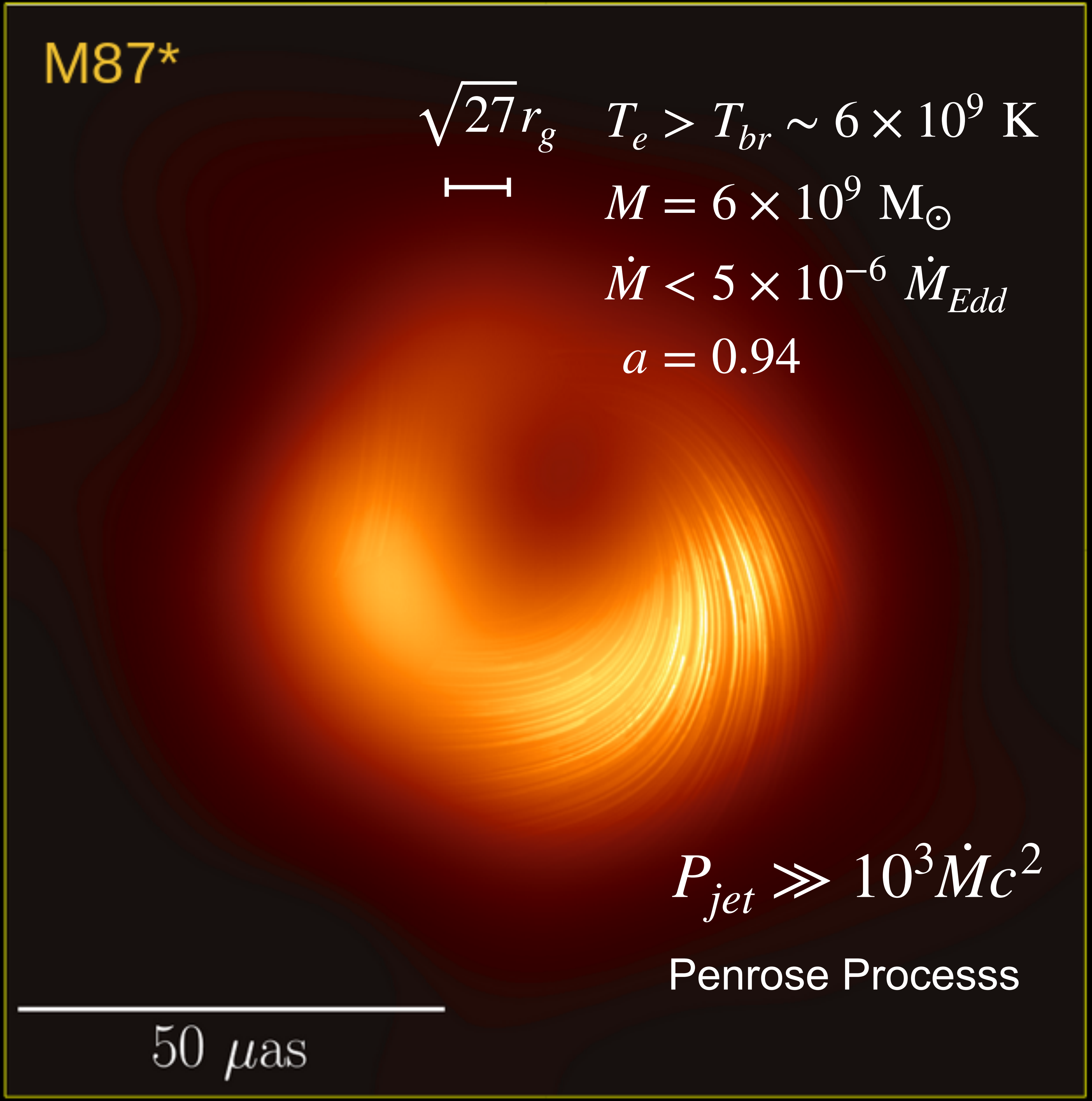
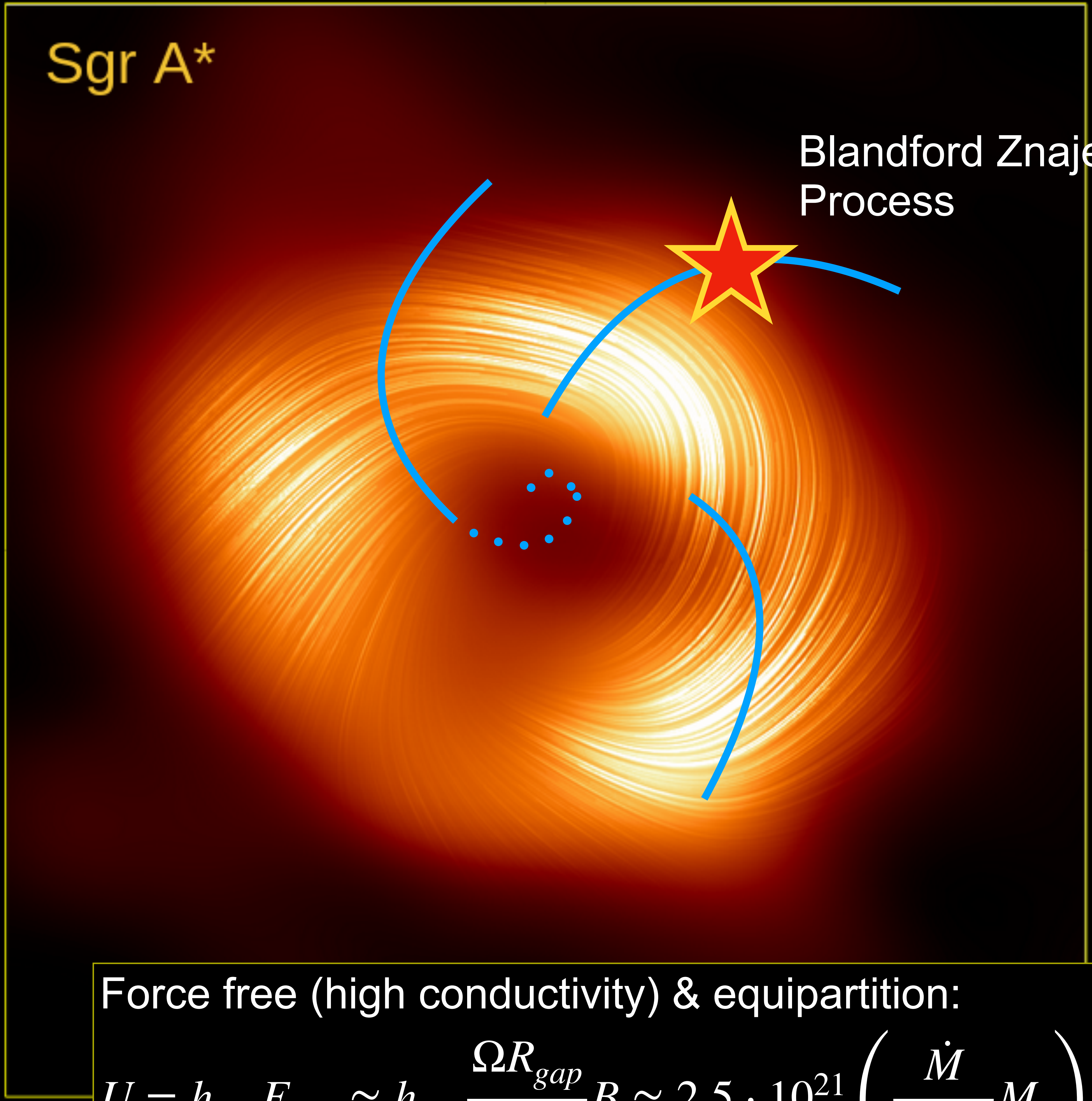
Most Super-Massive Black Holes ($\dot{M} \ll \dot{M}_{Edd}$) Look Like This

Polarized synchrotron images from the Event Horizon Telescope (EHT)





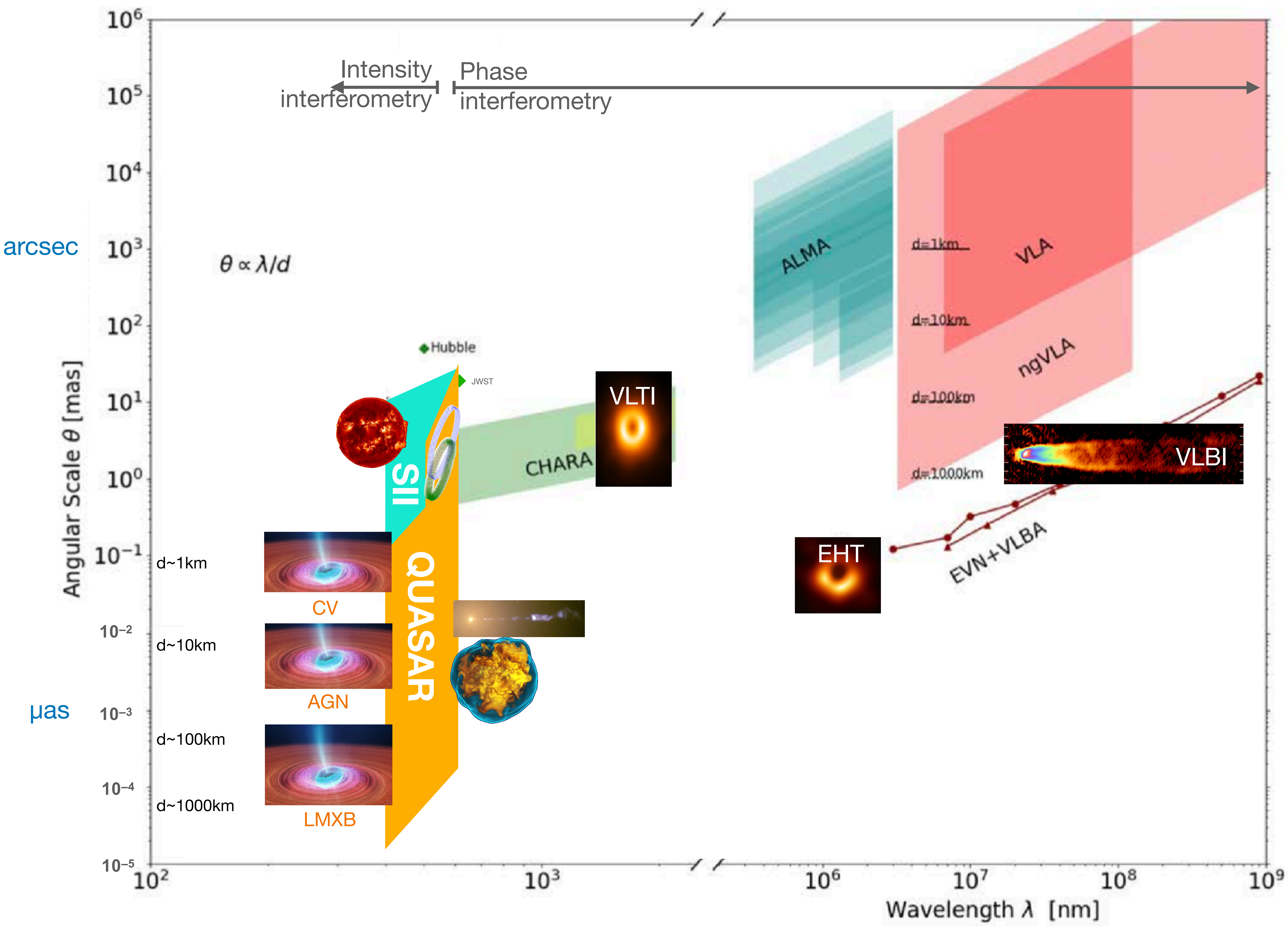
Force free (high conductivity) & equipartition:

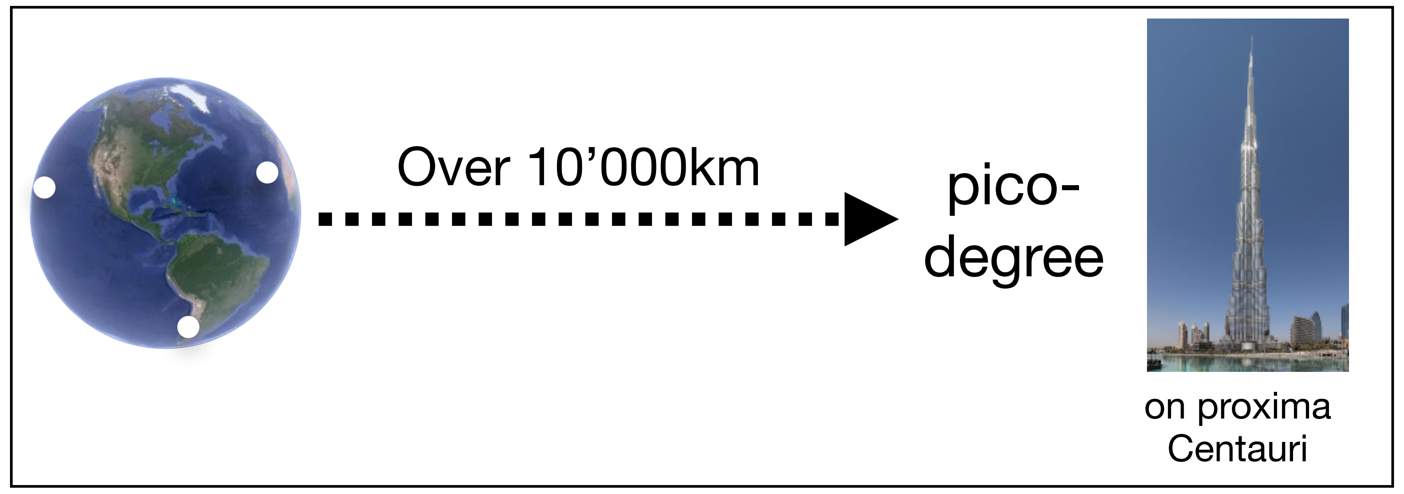
$$U = h_{gap} E_{gap} \approx h_{gap} \frac{\Omega R_{gap}}{c} B \approx 2.5 \cdot 10^{21} \left(\frac{\dot{M}}{\dot{M}_{Edd}} M_9 \right)^{1/2} \frac{h_{gap}}{R_g}\ \mathrm{V}\,.$$

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

Ceci n'est pas un disque d'accrétion.

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





Resolving accretion disks: how to make it work ?

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

Large telescopes
500 m²

Many narrow wave bands
1000 channels

High time resolution
12 ps

Problems to be solved :

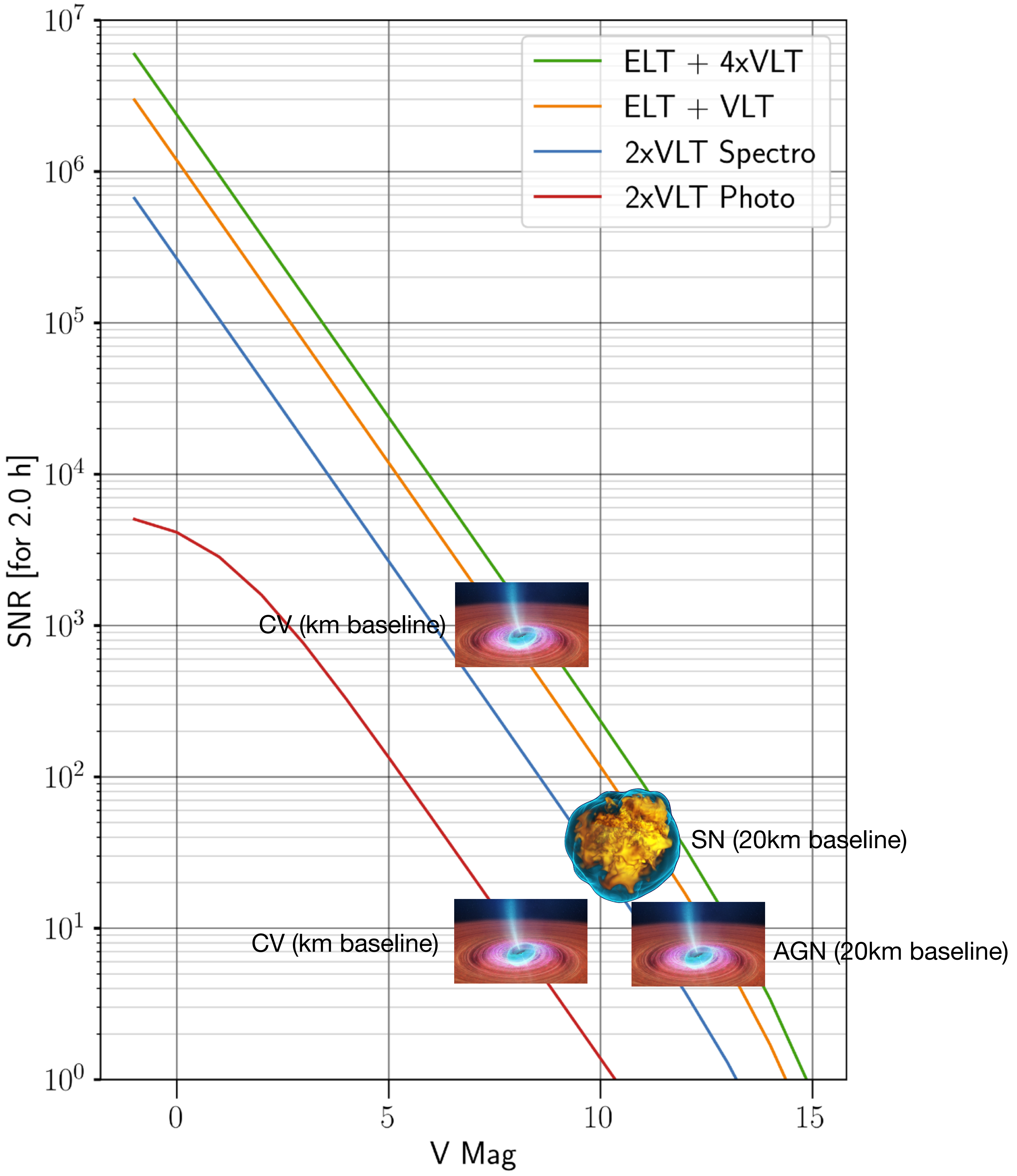
- ✓ High resolution detector & TDC
- ✓ Low systematic noise
- ✓ Clock synchronisation over many km
- ✓ High performance time tag correlator
- ✓ Sub-mm position of telescopes

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

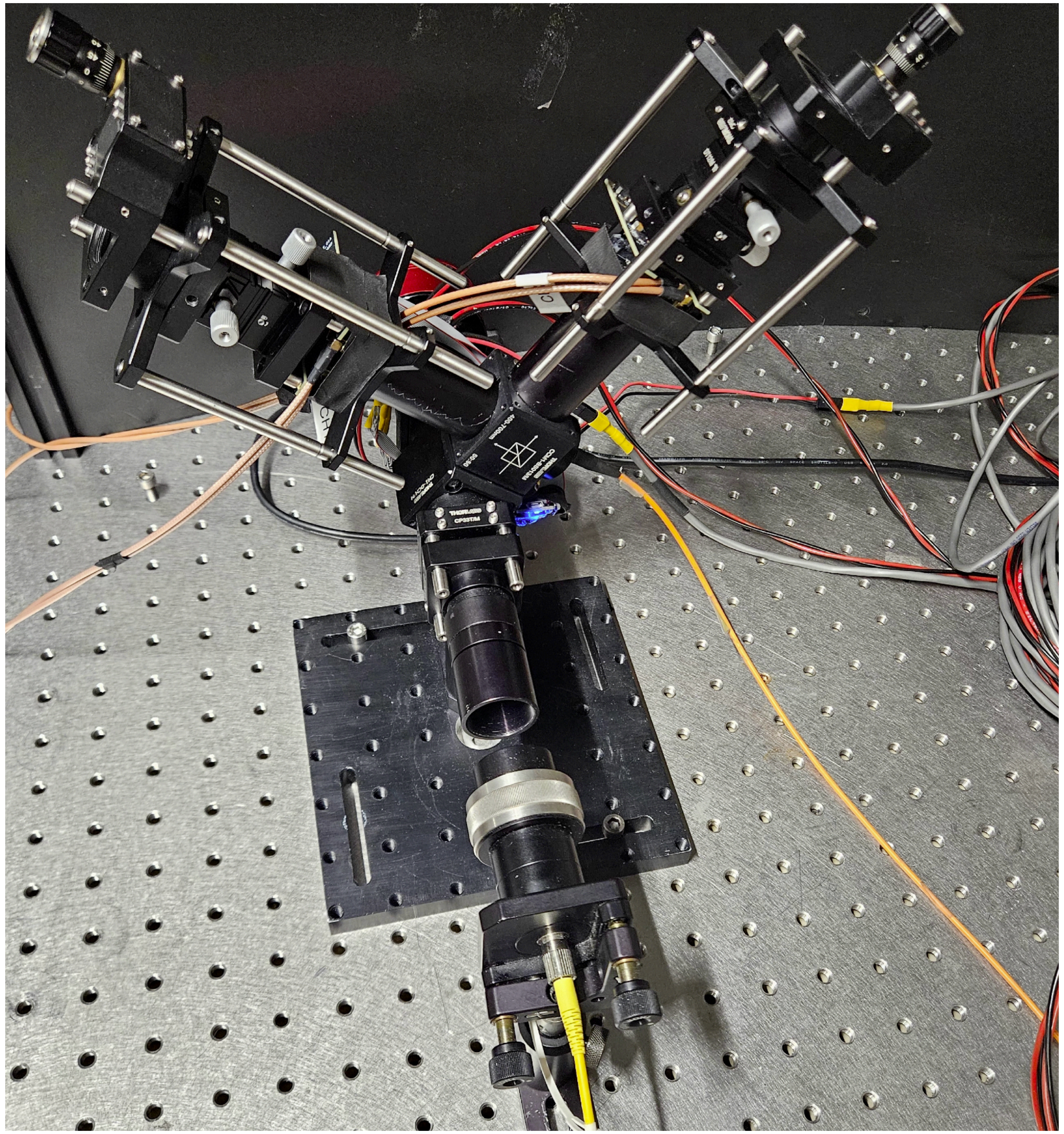
Simulations includes source spectra, dispersion, slit, optical and quantum efficiencies, dead-time, fill factor, dark noise, cross-talk

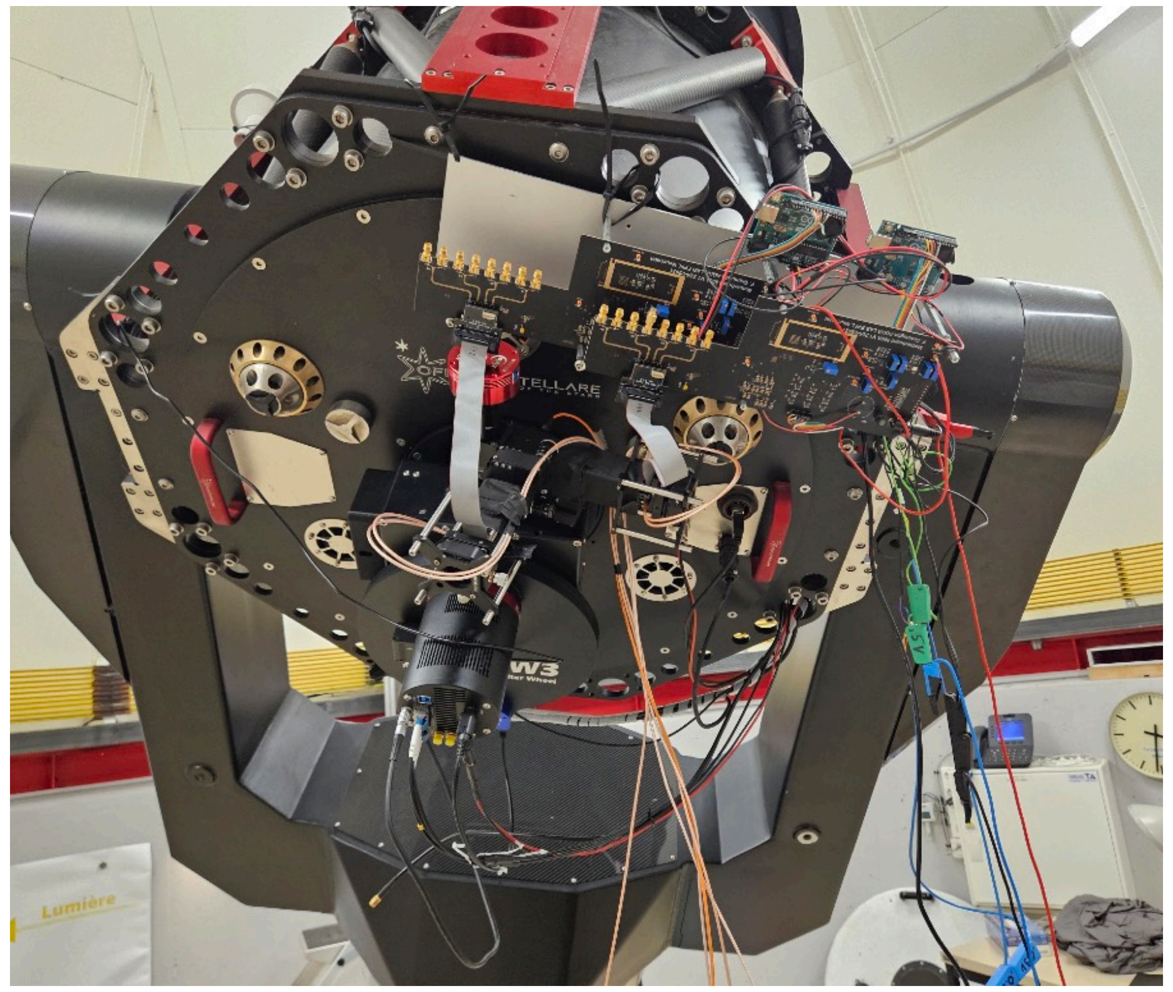


Improvements since the original Hanbury Brown & Twiss experiment:
- 10^3 in mirror area
- 10^3 in spectral channels
- 10^3 in timing resolution

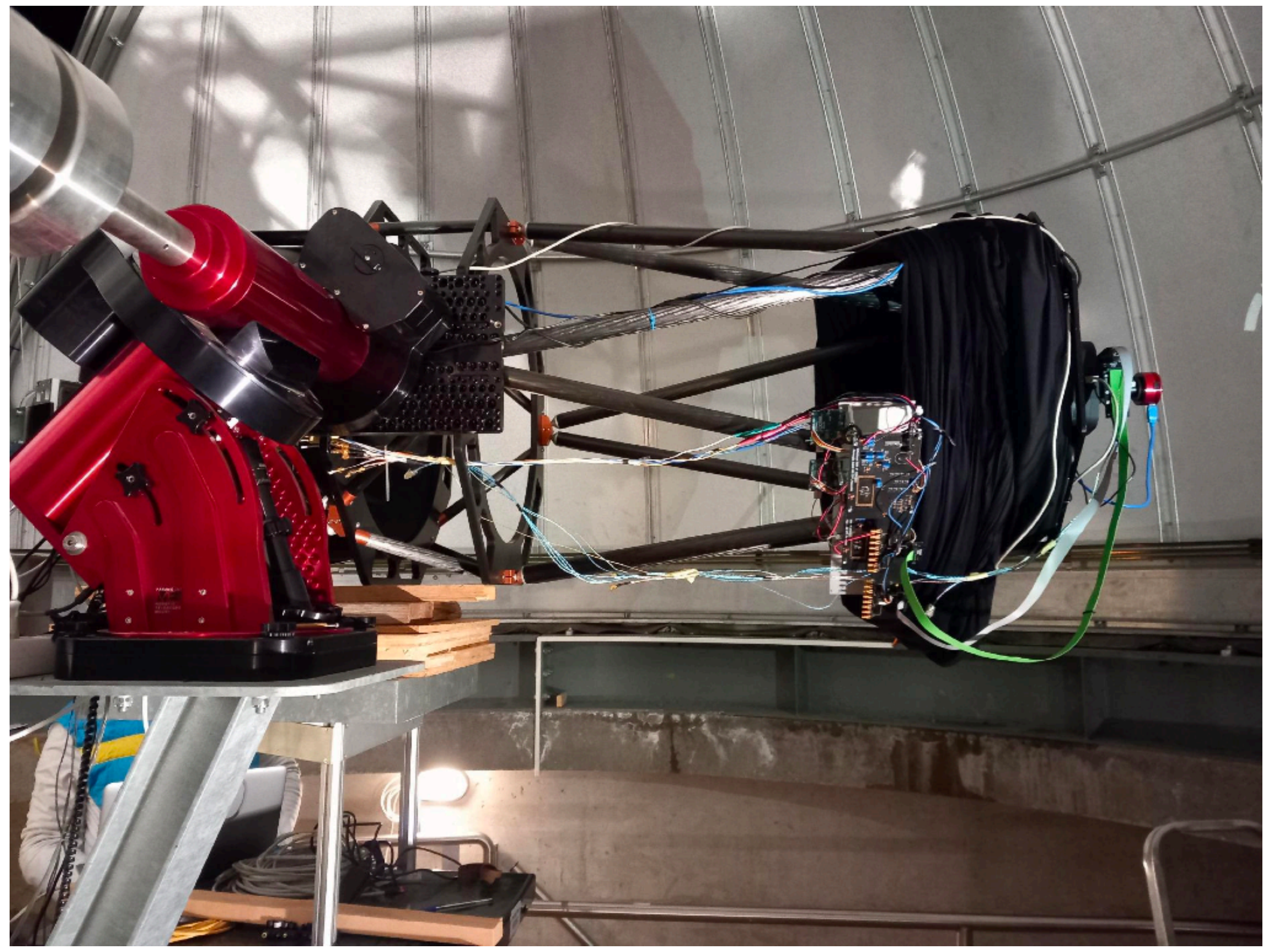
→ 10^6 in SNR compared to HBT

Photometer

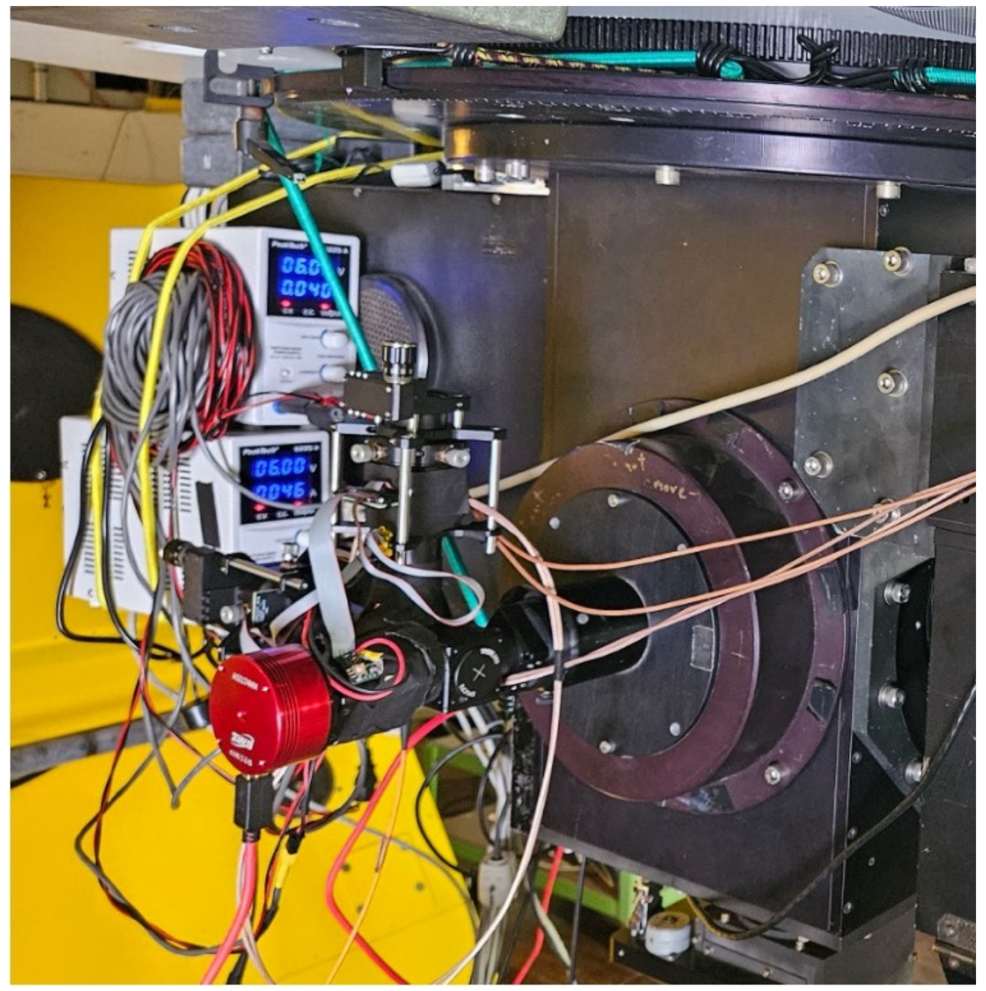




Geneva



St-Luc (Swiss alps)



Skinakas (Crete)

C2PU Calern (France)

High Resolution Detector & TDC

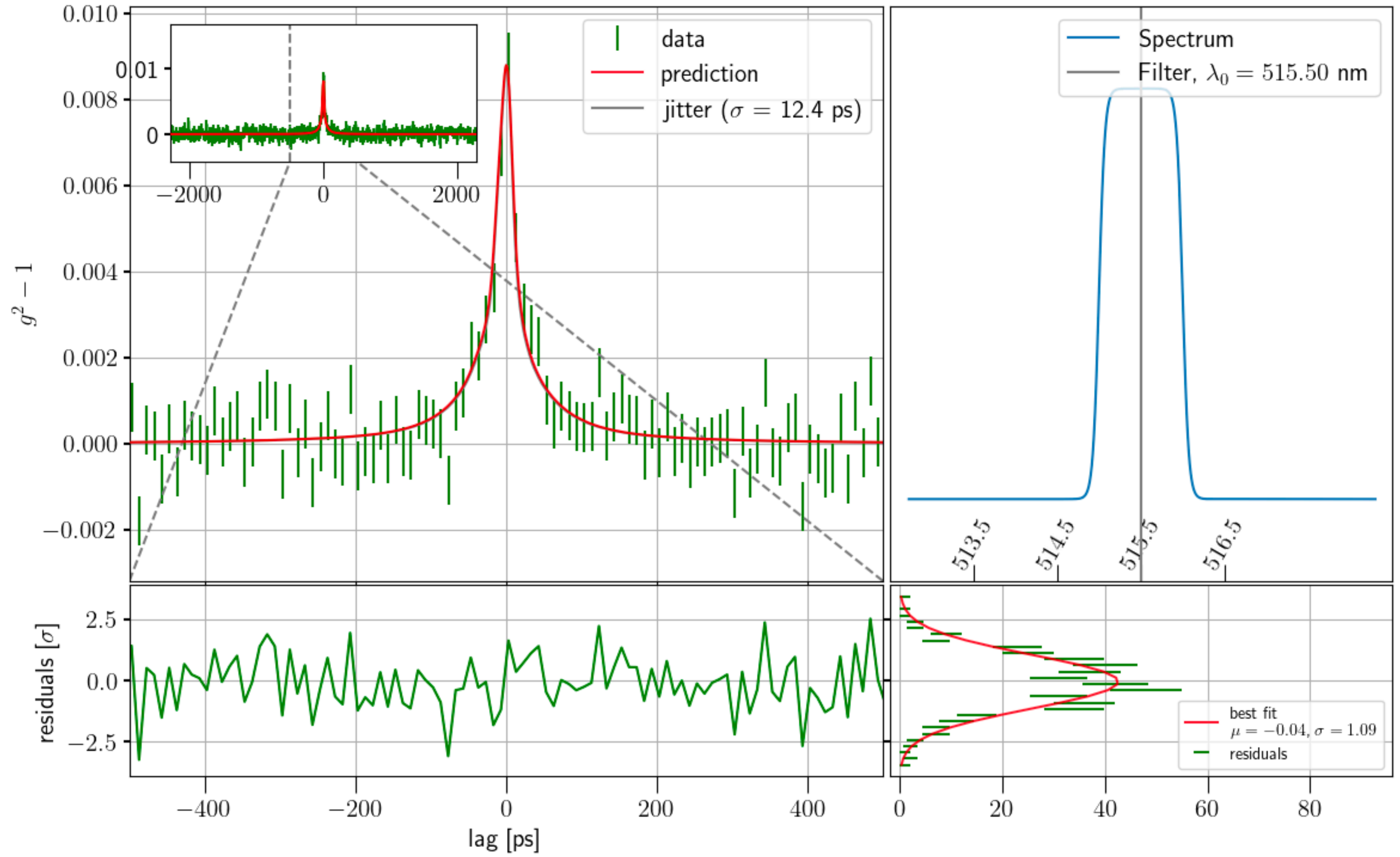
- Fast detectors: EPFL SPADs
  - 3ns dead-time (configurable)
  - ~55% PDP @ 5V/500nm
  - 20Hz DCR @ 5V/20°C
  - Time jitter ~5.1ps RMS
- TDC: IDQuantique ID1000
  - resolution 1ps
  - Inter-channel σ <3.6ps
  - 300MHz / channel correlation
  - 10MHz total timestamp readout

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

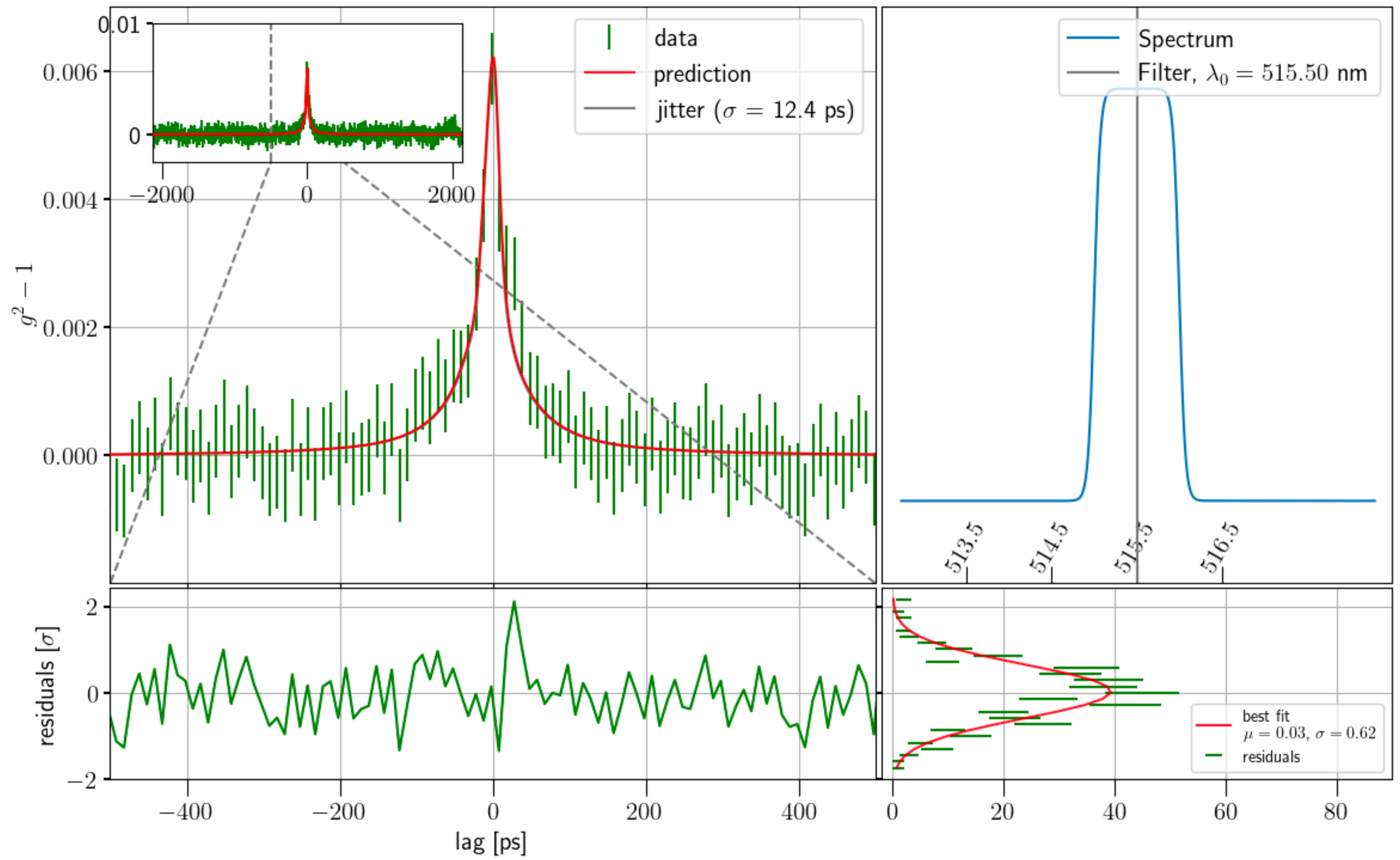
1. Broad-Spectrum from chaotic sources

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

Xenon lamp



LED (3 mm², 70W, blue converted to green)

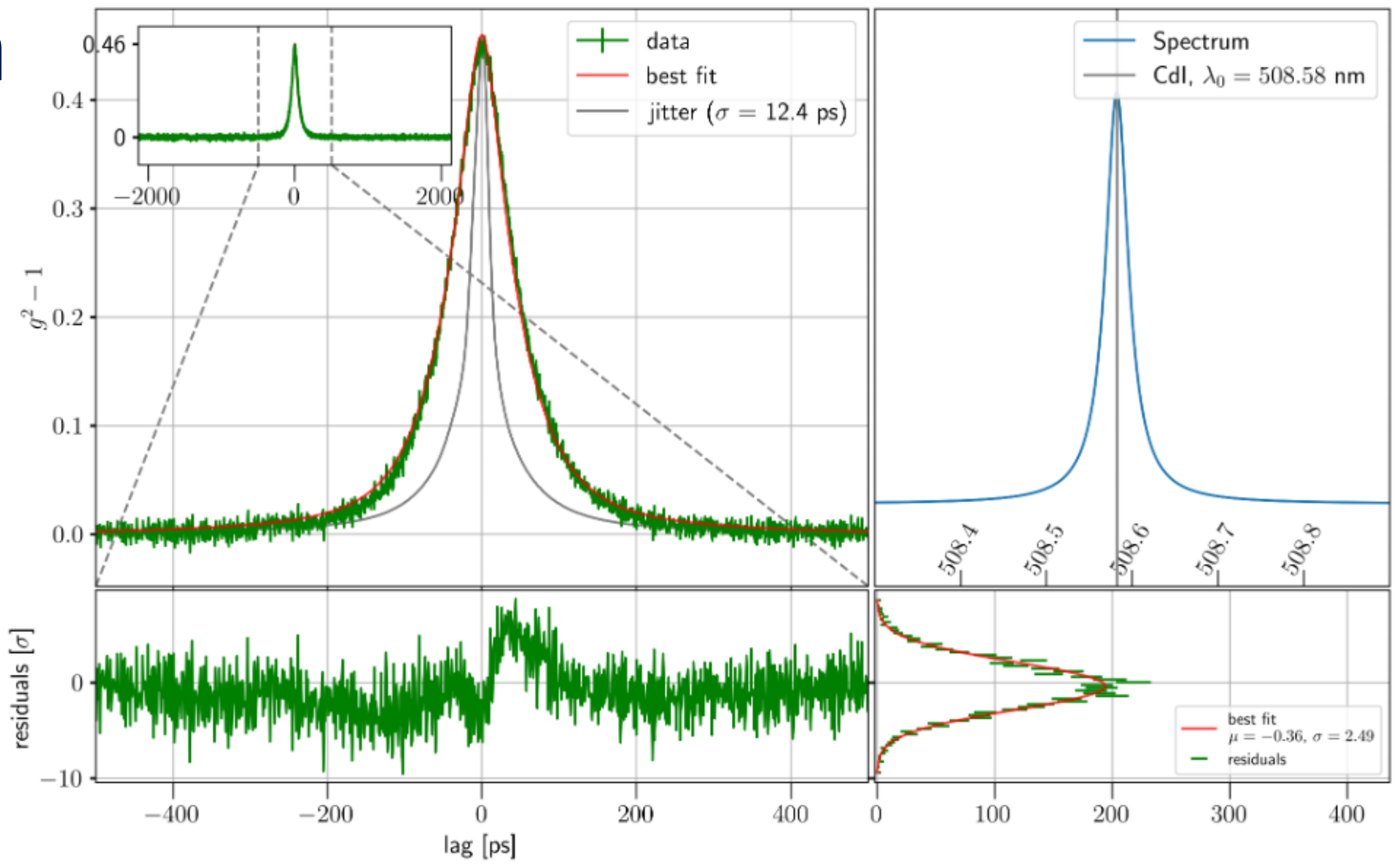


High Resolution Detector & TDC

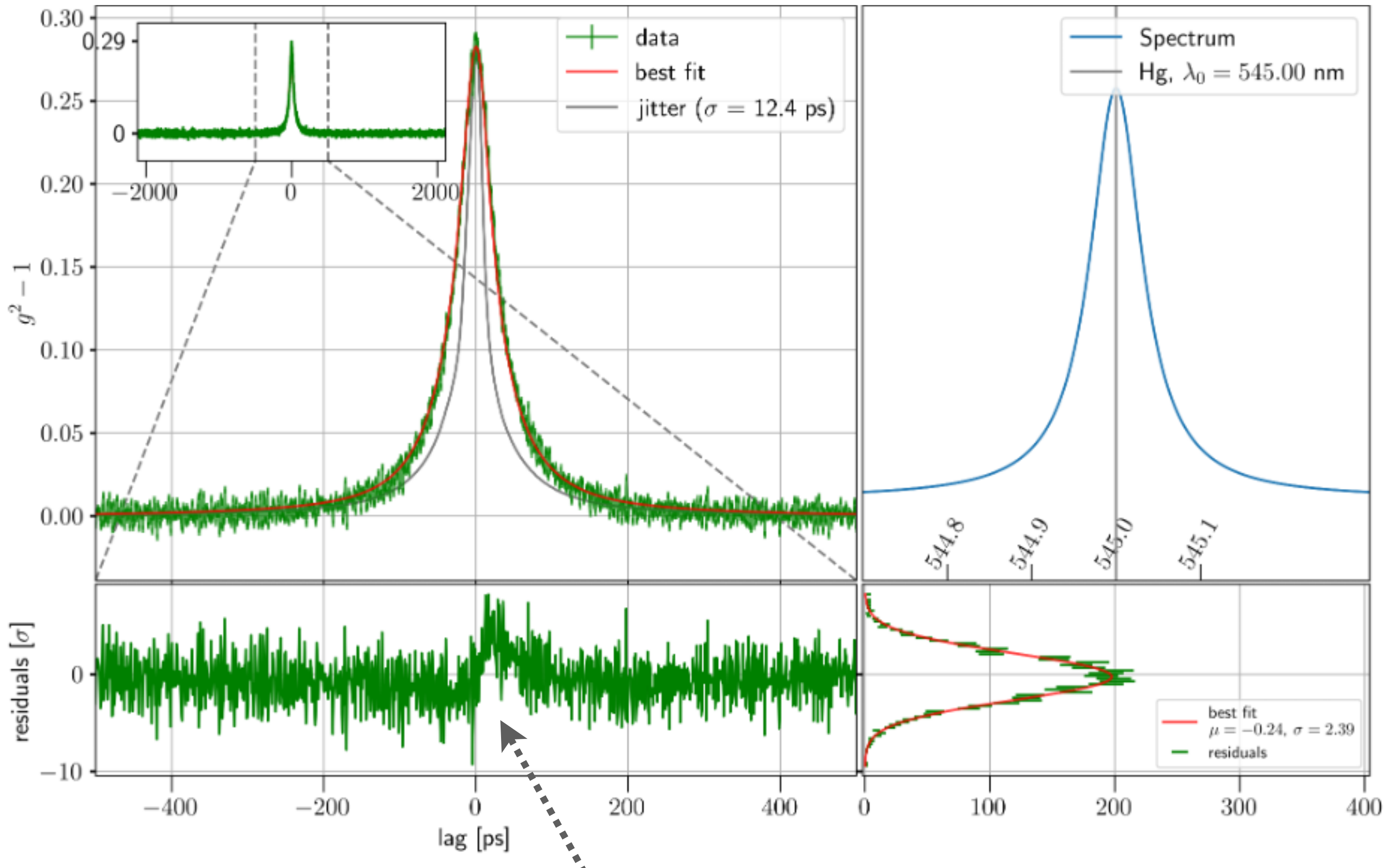
2. Spectral lines: the g² peak is resolved

polariser & single mode filter, 10MHz/channel

Cd 508 nm

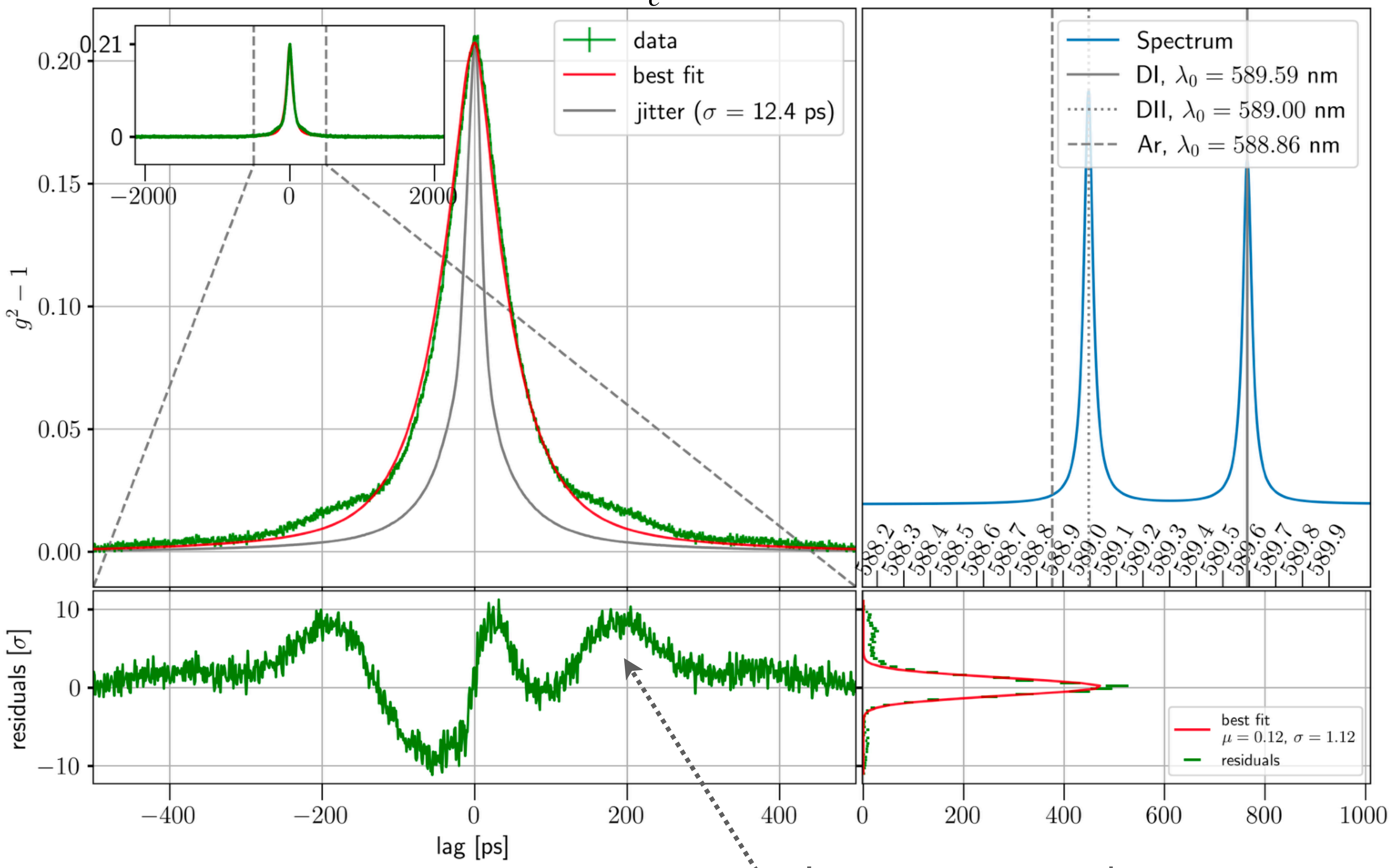


Hg 545nm



TDC response is slightly assymetric

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

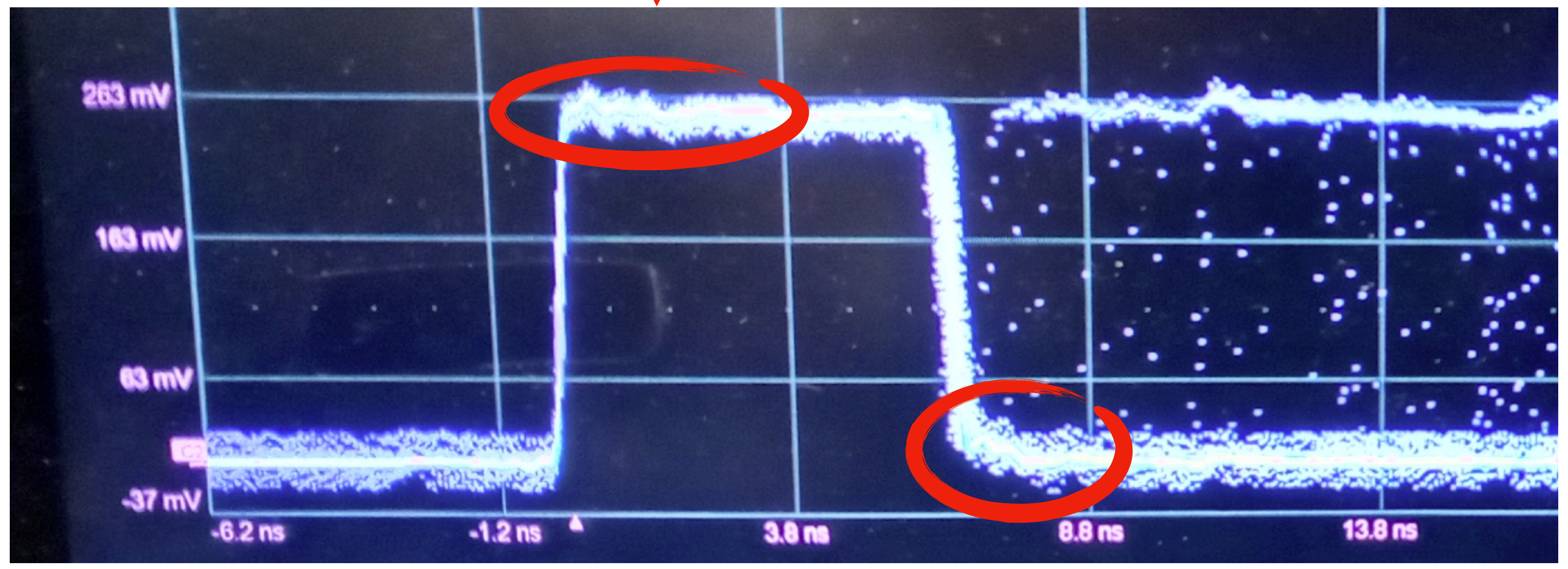


Lamp spectrum is more complex (e.g. traces of Argon)

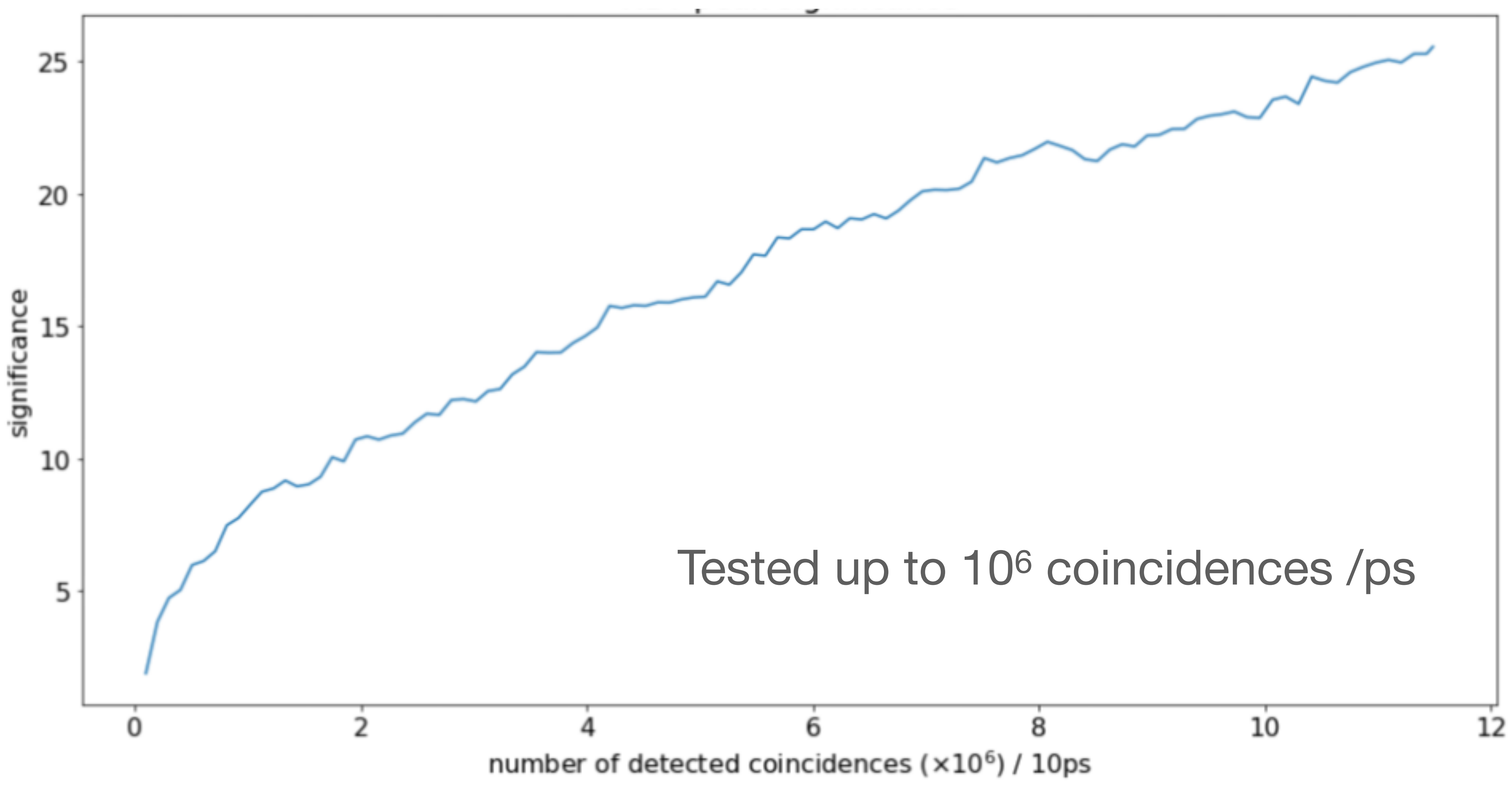
Perfect Poisson Noise !!!

Stable Systematics can be Subtracted

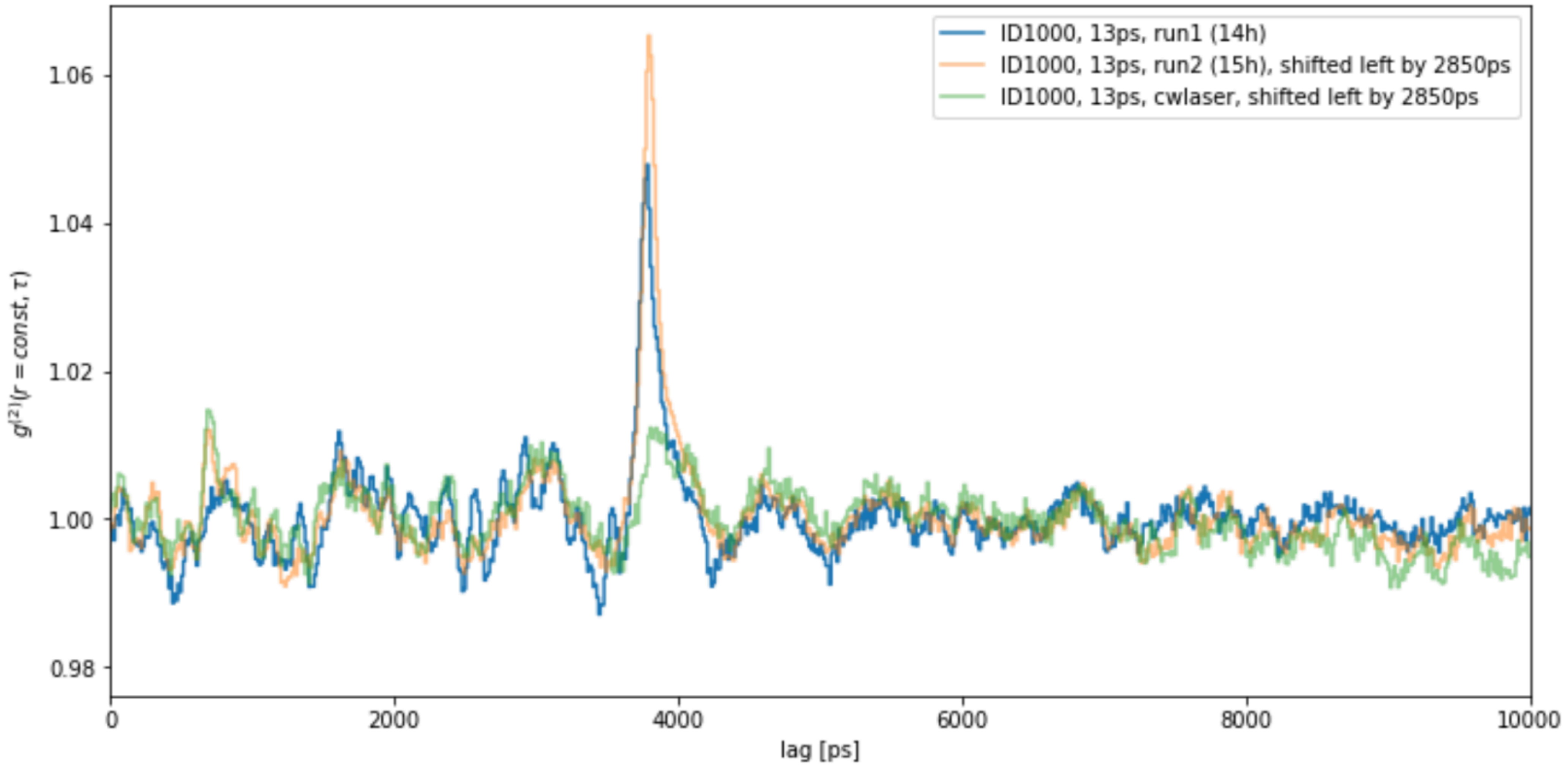
wiggles are stable so the correlated noise can be subtracted (TDC discriminator also involved)



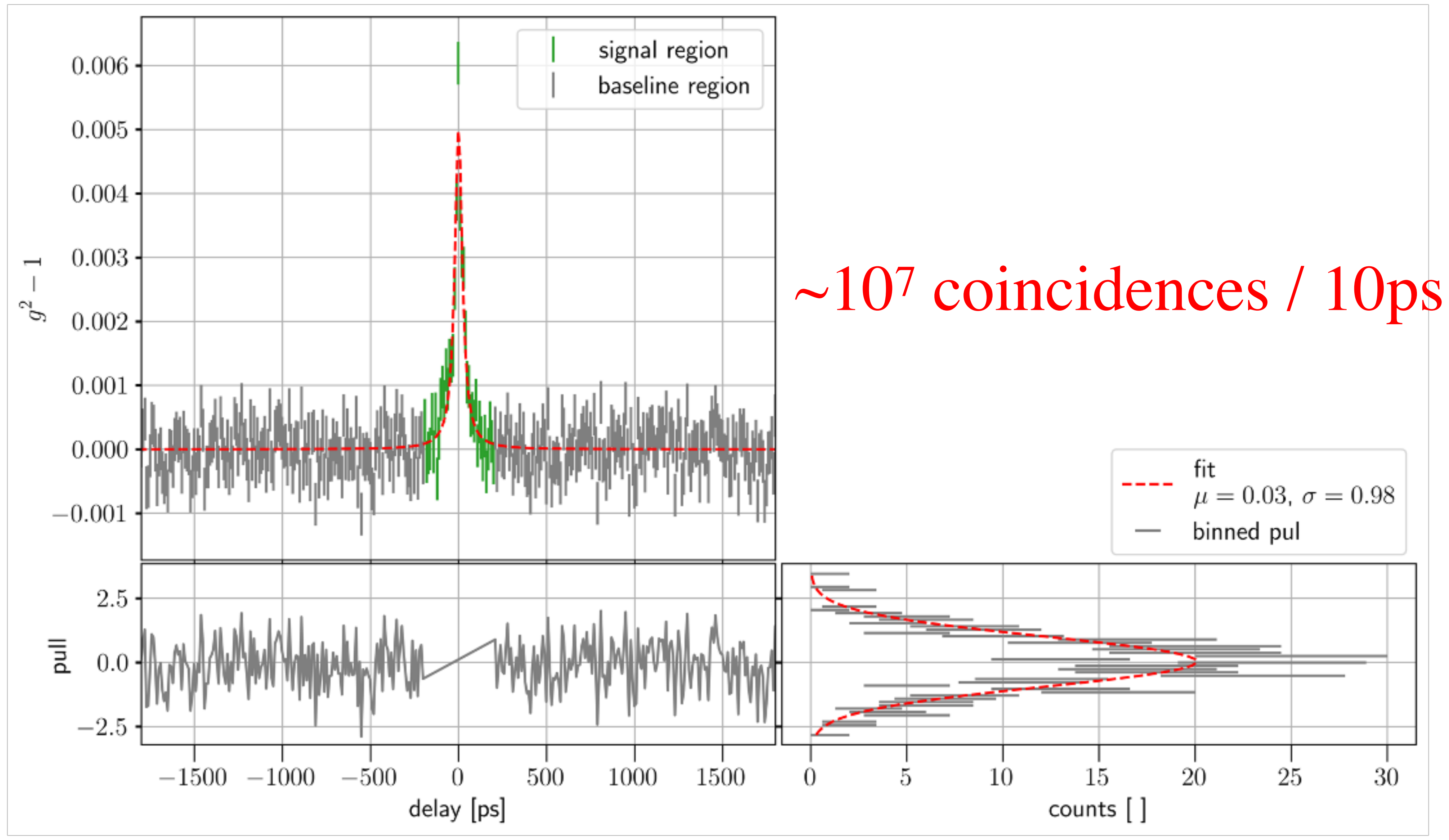
widens the timing response at very high rate → do not exceed tens of MHz



Tested up to 10^6 coincidences /ps



subtracting correlated noise



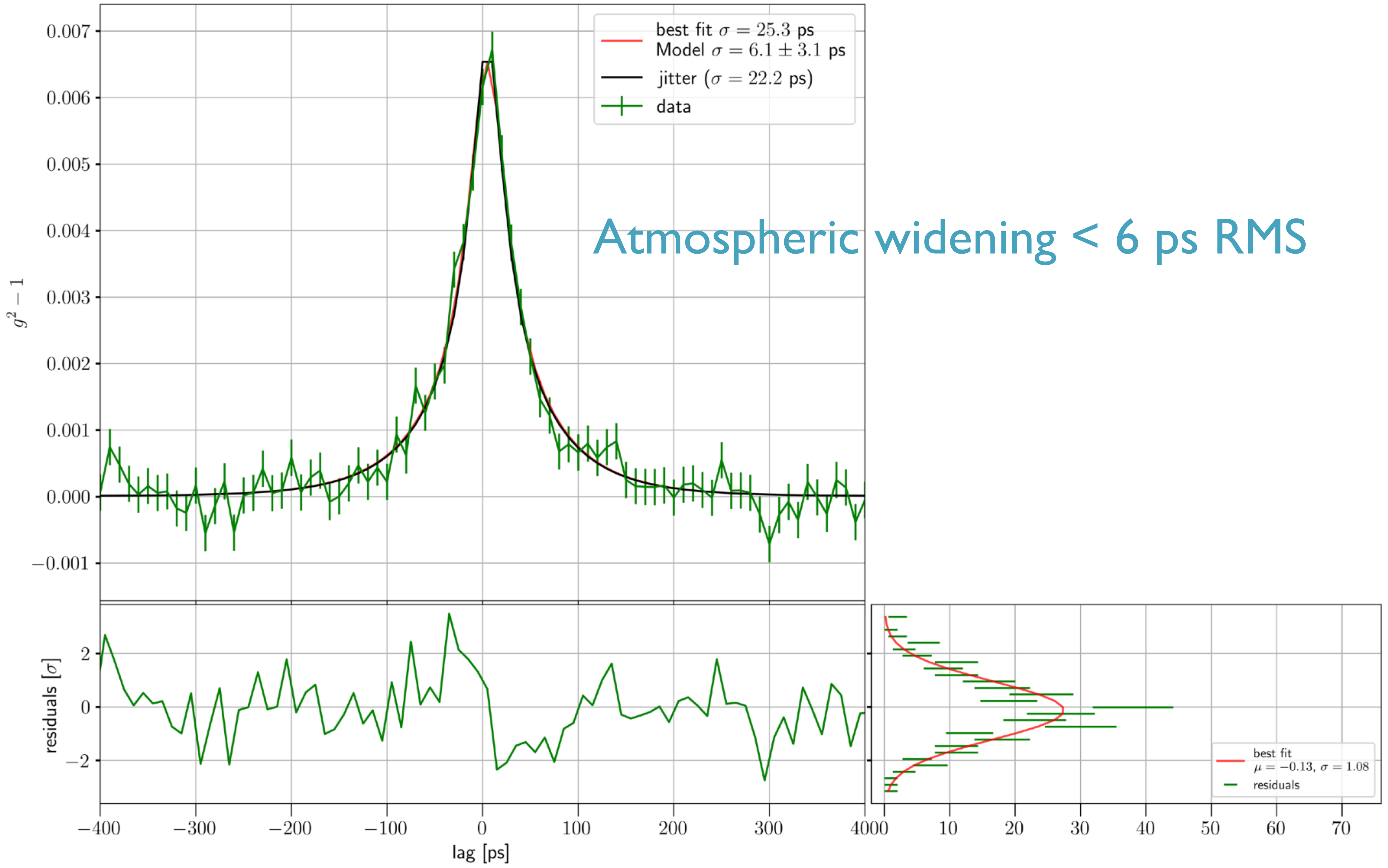
~10^7 coincidences / 10ps

On Telescopes

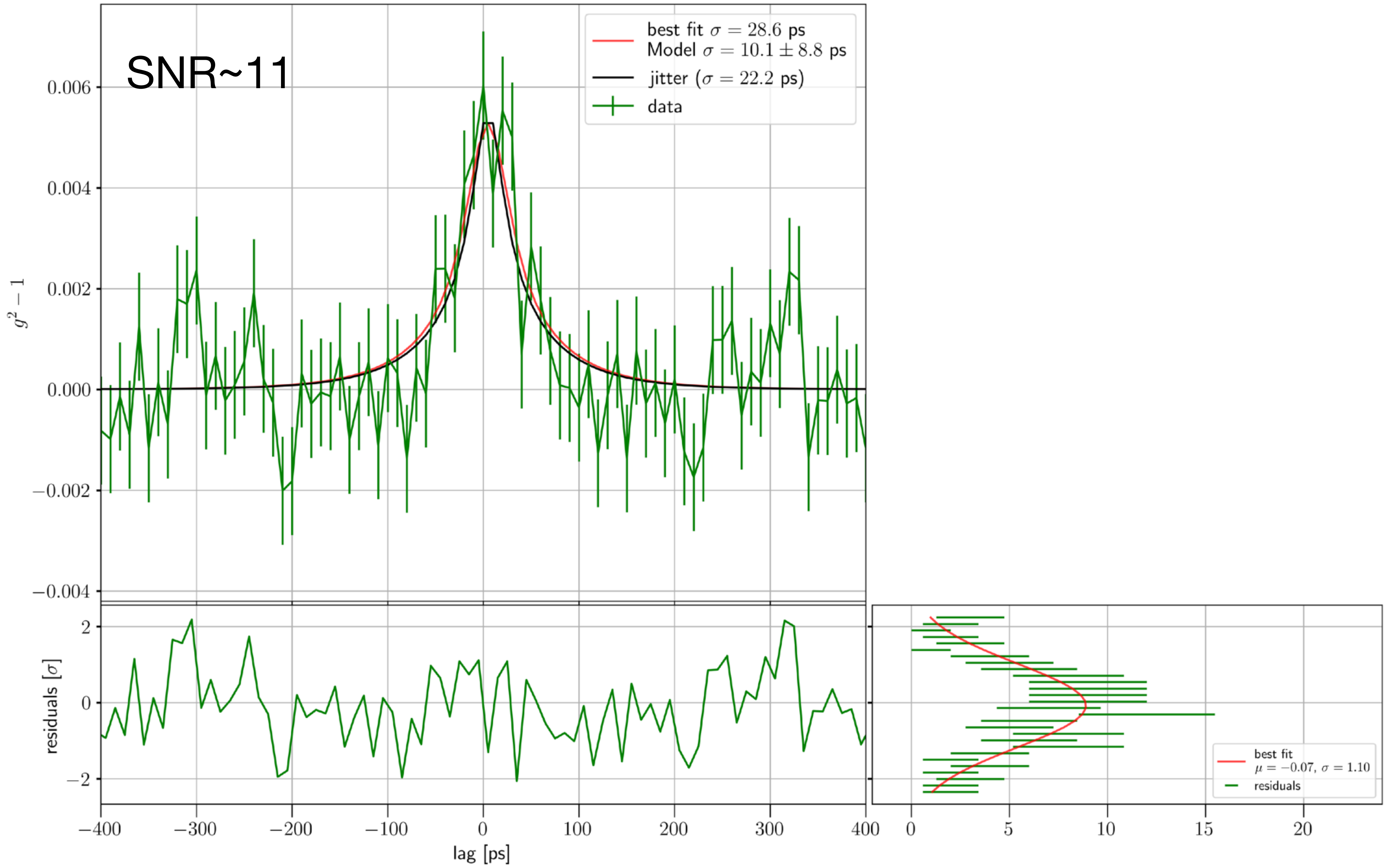
3. Stars

515/1nm filter & polarizer

The Sun (30 min, 25MHz/channel)



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



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

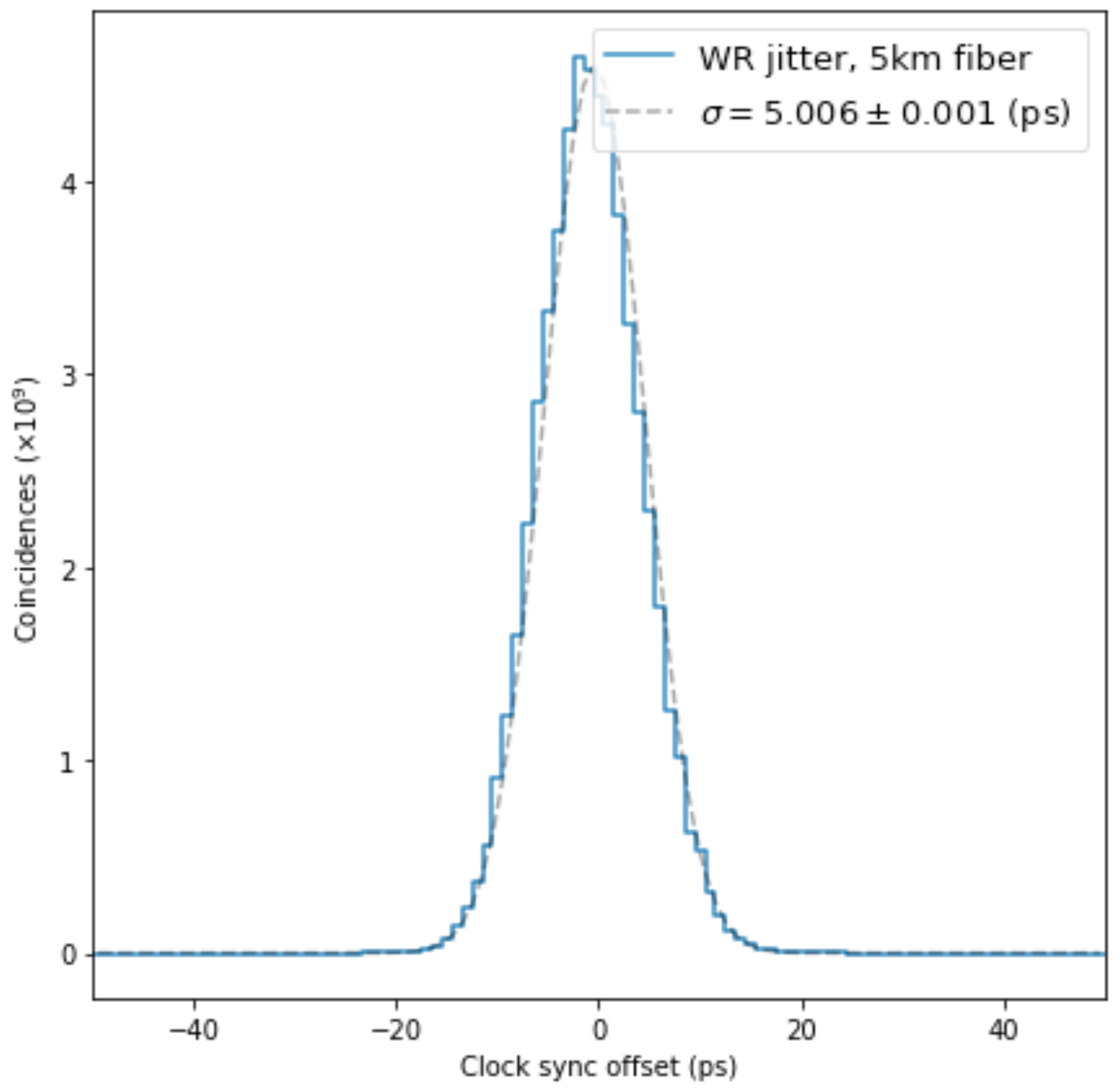
Up to 30+ km

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

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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

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

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Clock Synchronization with Correlated Photons

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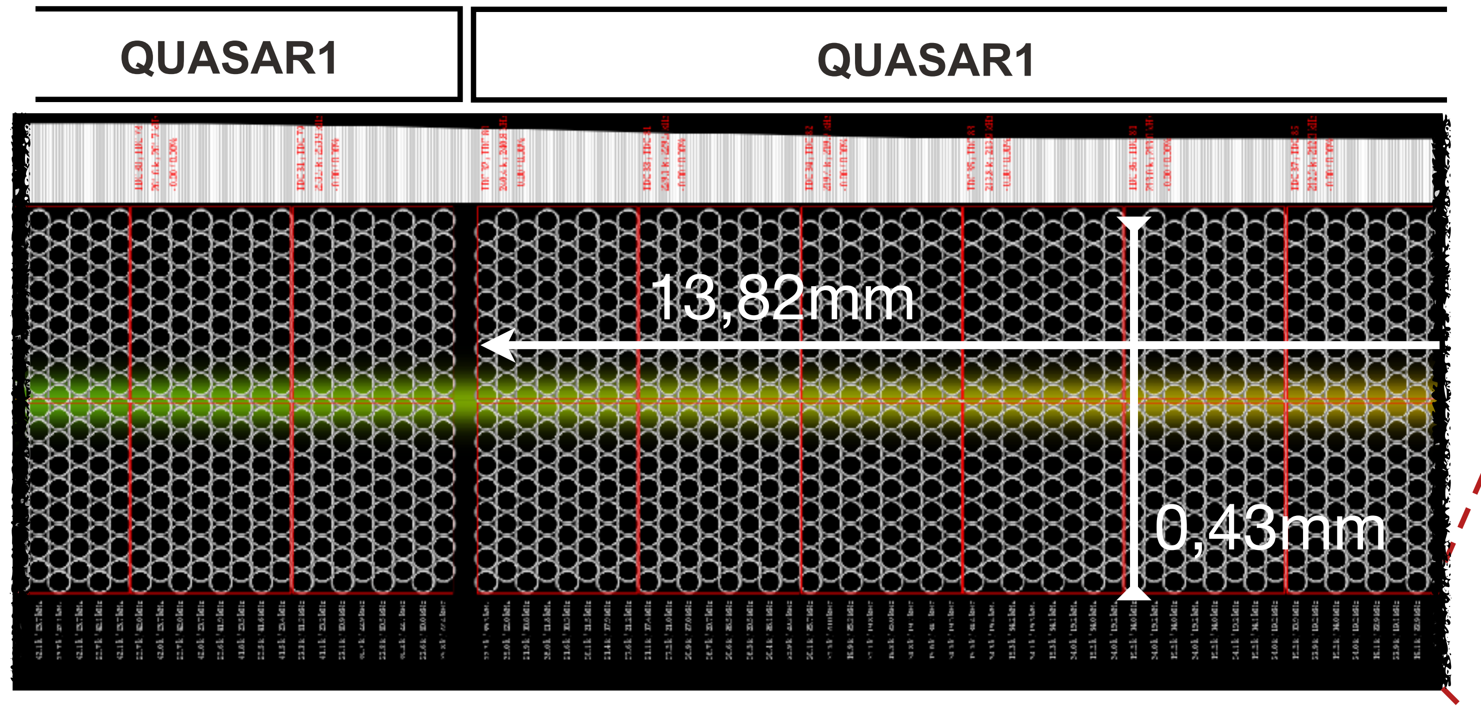
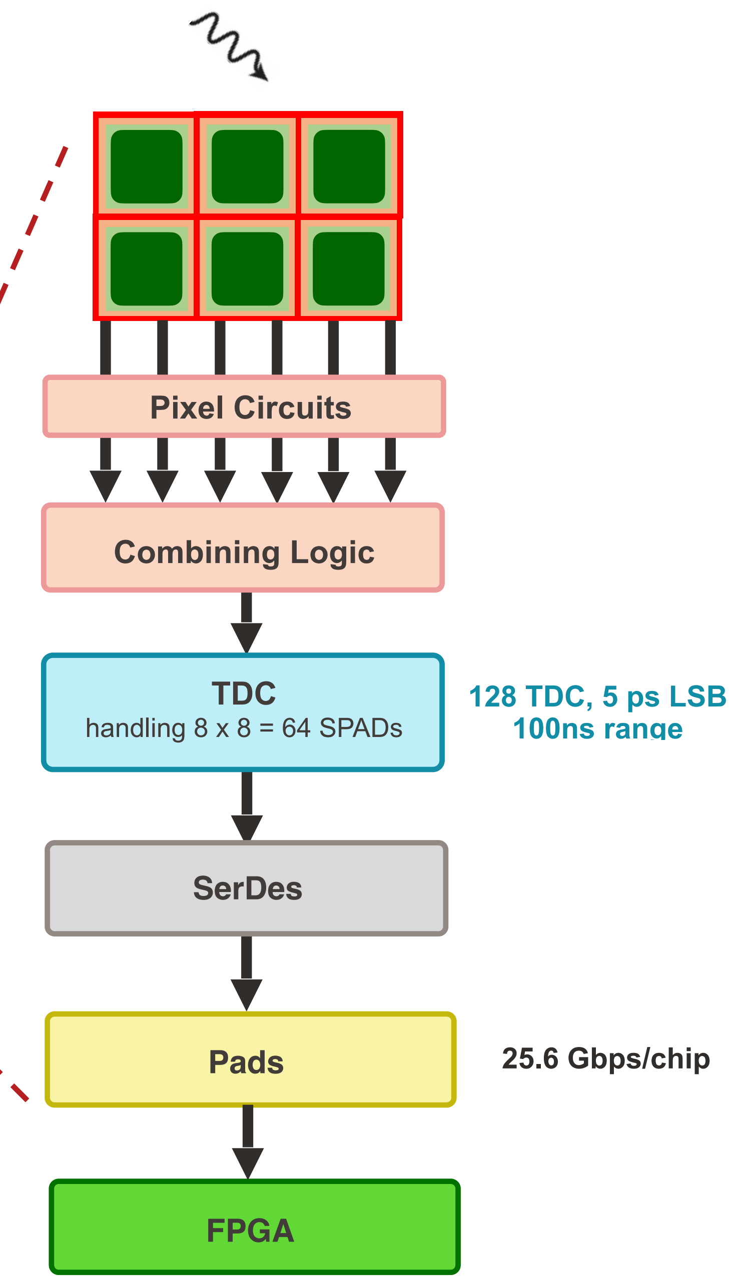
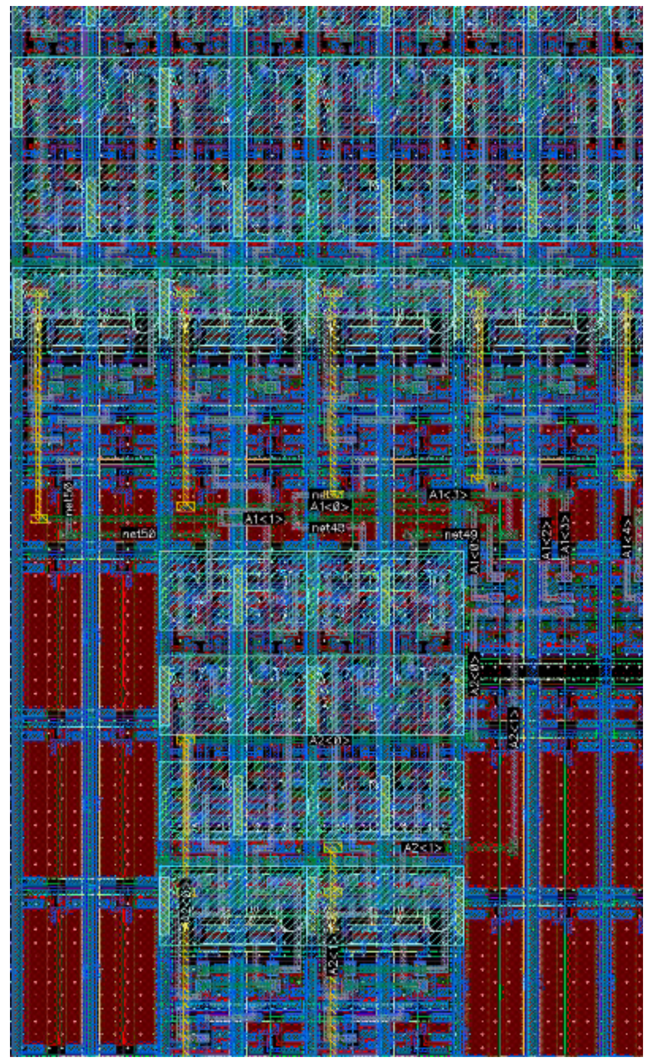
Spectrometer Development

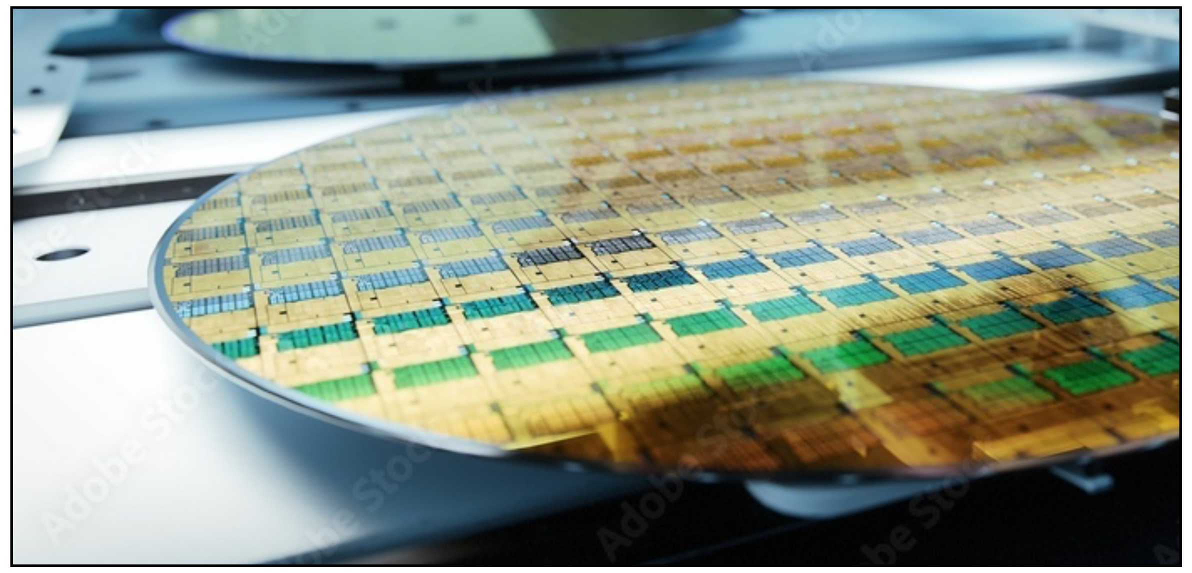
QUASAR1 chip

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.





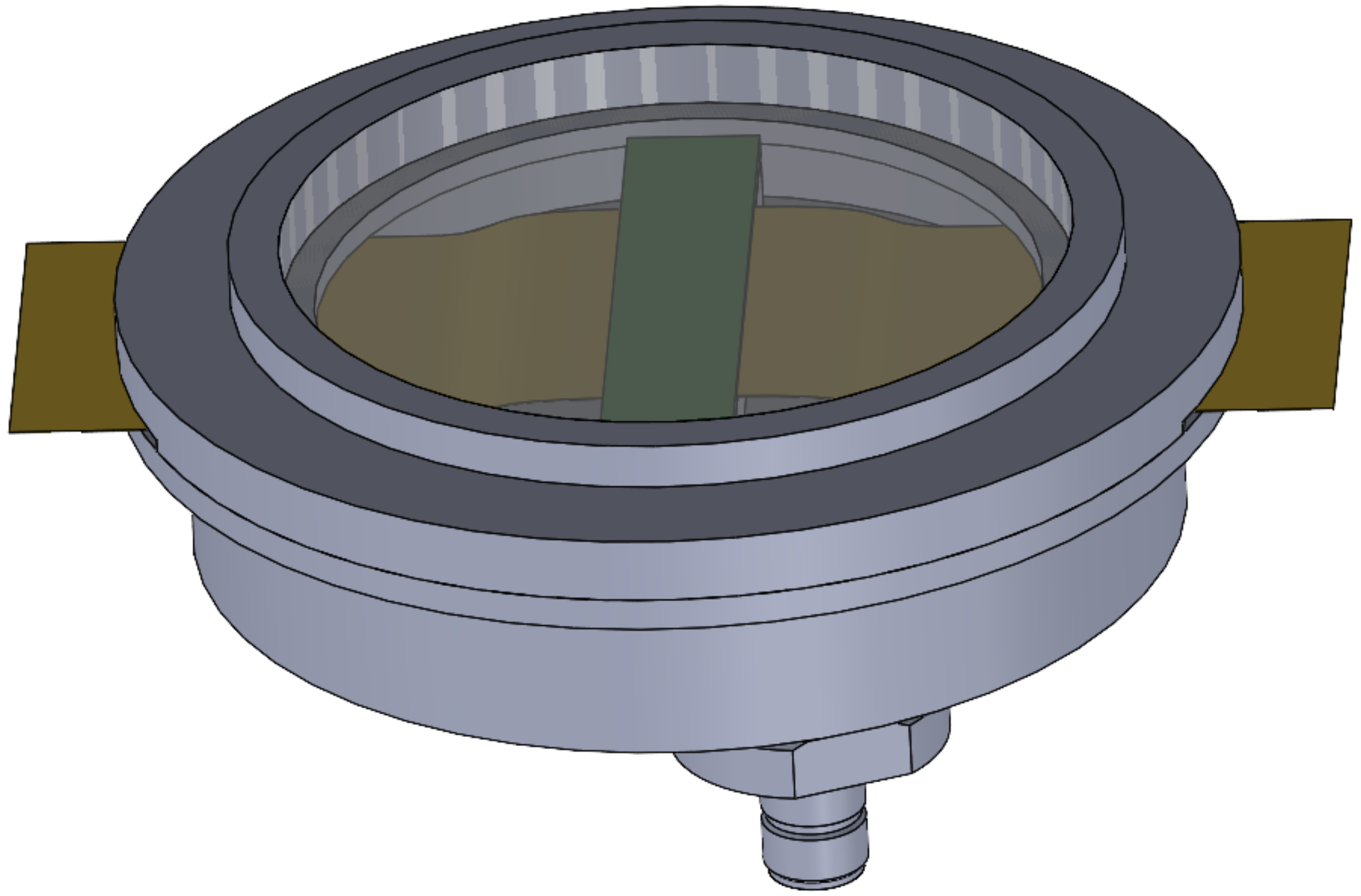




1000 QUASAR1 chips in May 2025

Dewar

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

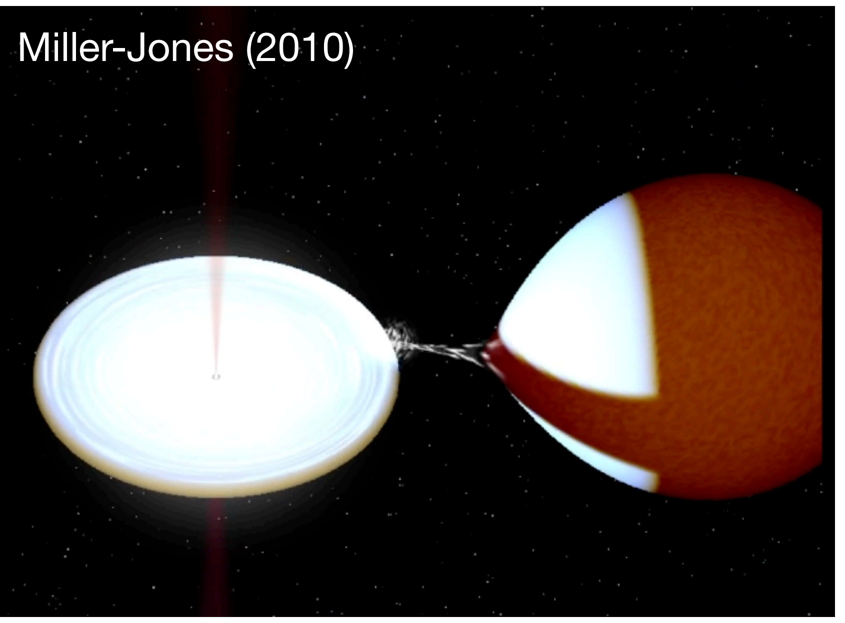


FPGA Board

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

Resolving Cataclysmic Variables (1 night)

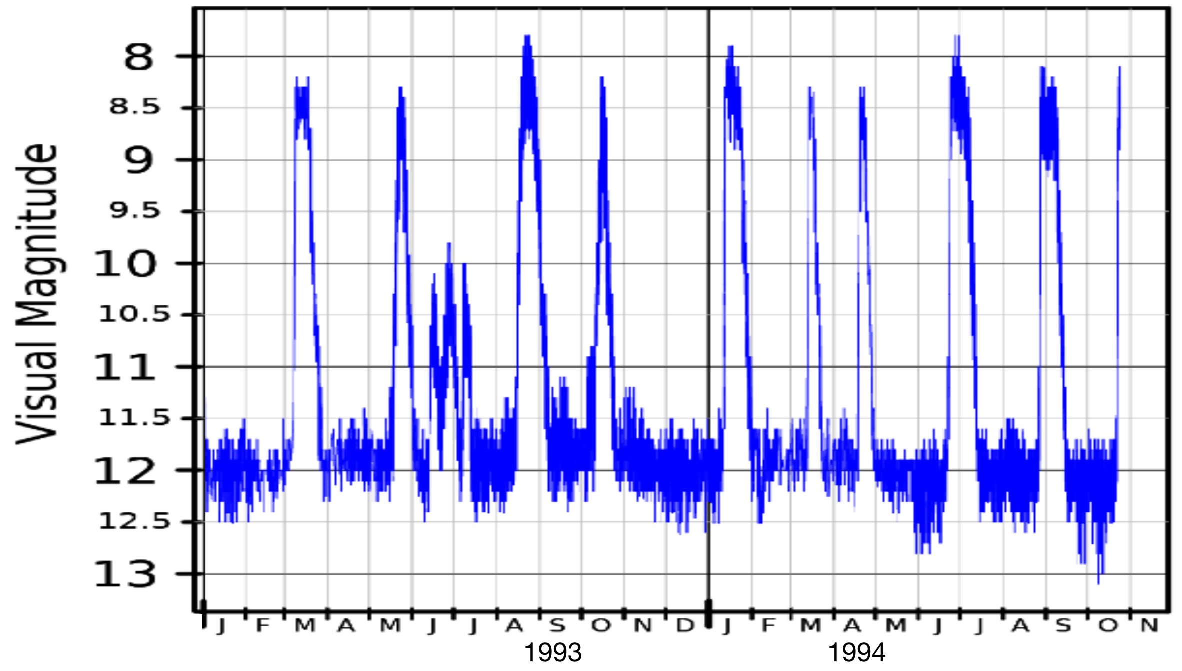
From 2026

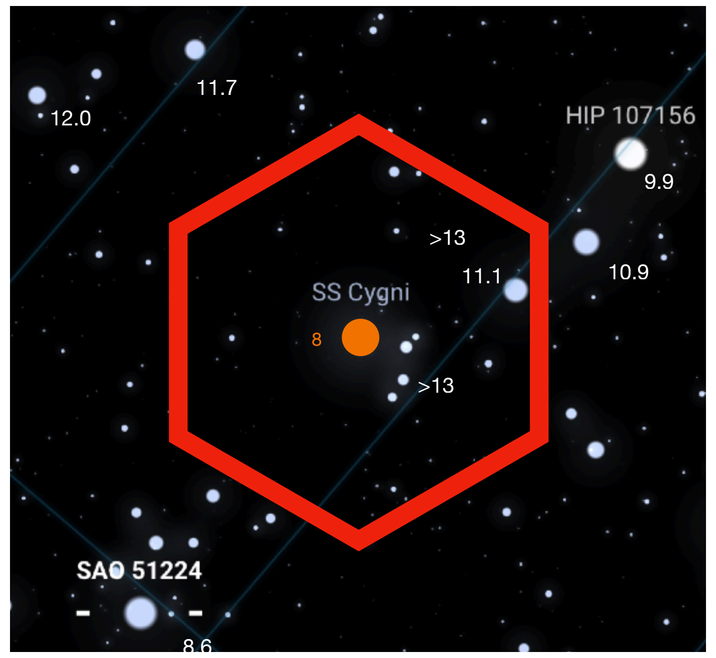


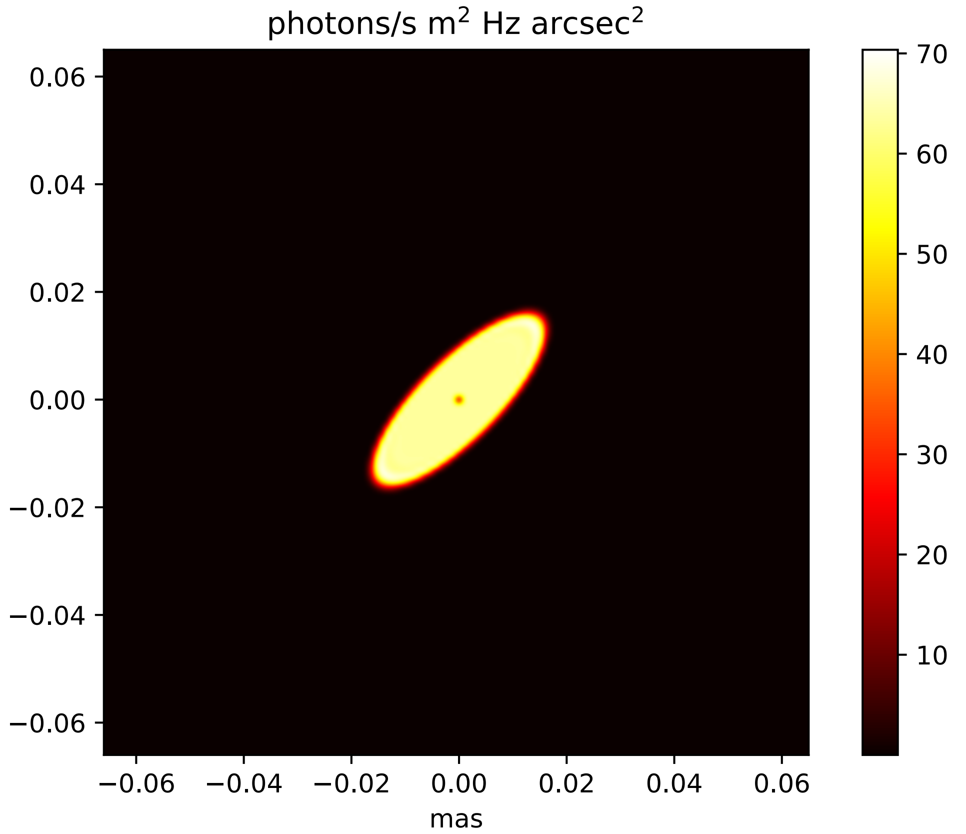
SS Cygni @ 115pc
P_{orb} = 6.6 h R_{orb} ~1.6 10^6 km
White dwarf: 0.8 $M_\odot$
Companion: K5V 0.5 $M_\odot$
R_{disk} = 0.4 10^6 km, 32 µarcsec

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

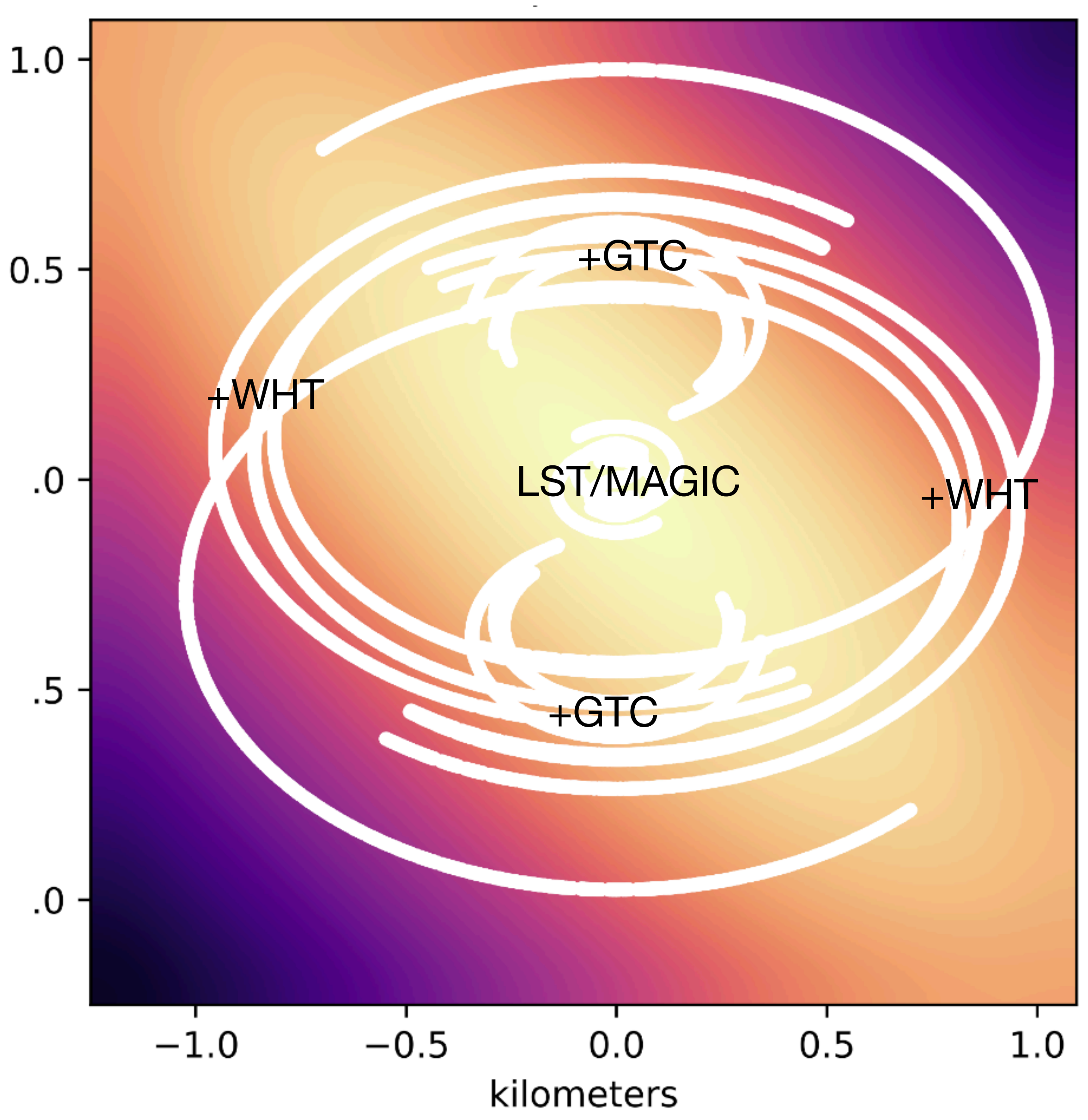
ν_{cold} : neutral gas, molecular viscosity
ν_{hot} : ionised gas, magneto-rotational instability



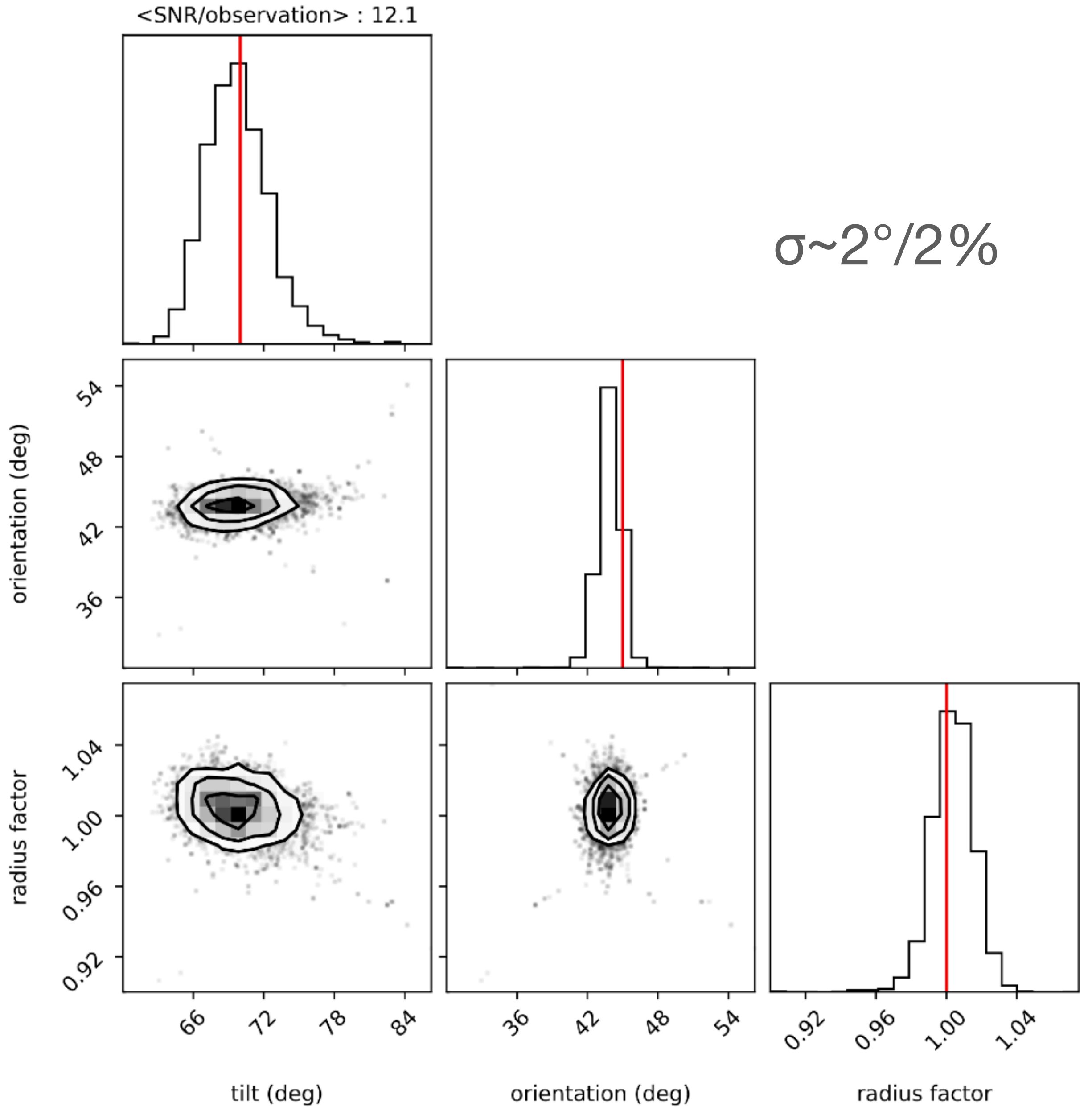




ORM 4 LST + 2 MAGIC:
Resolution : 400nm/309m = 333 µas
ORM GTC + WHT:
Resolution : 500nm/1273m = 80 µas



3 nights with GTC & WHT:



σ~2°/2%

Resolving Seyferts and QUASARS