

OHANA NUI: Direct measurement of the size of a White Dwarf using intensity interferometry

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Introduction: Intensity correlations

Intensity Interferometry was first developed and used by Hanbury Brown & Twiss between 1954 and 1974 [1, 2, 3]. It differs from amplitude interferometry [4] in that it is a 2-photon process, which makes it less sensitive, but only requires measuring the time of arrival of individual photons [5].

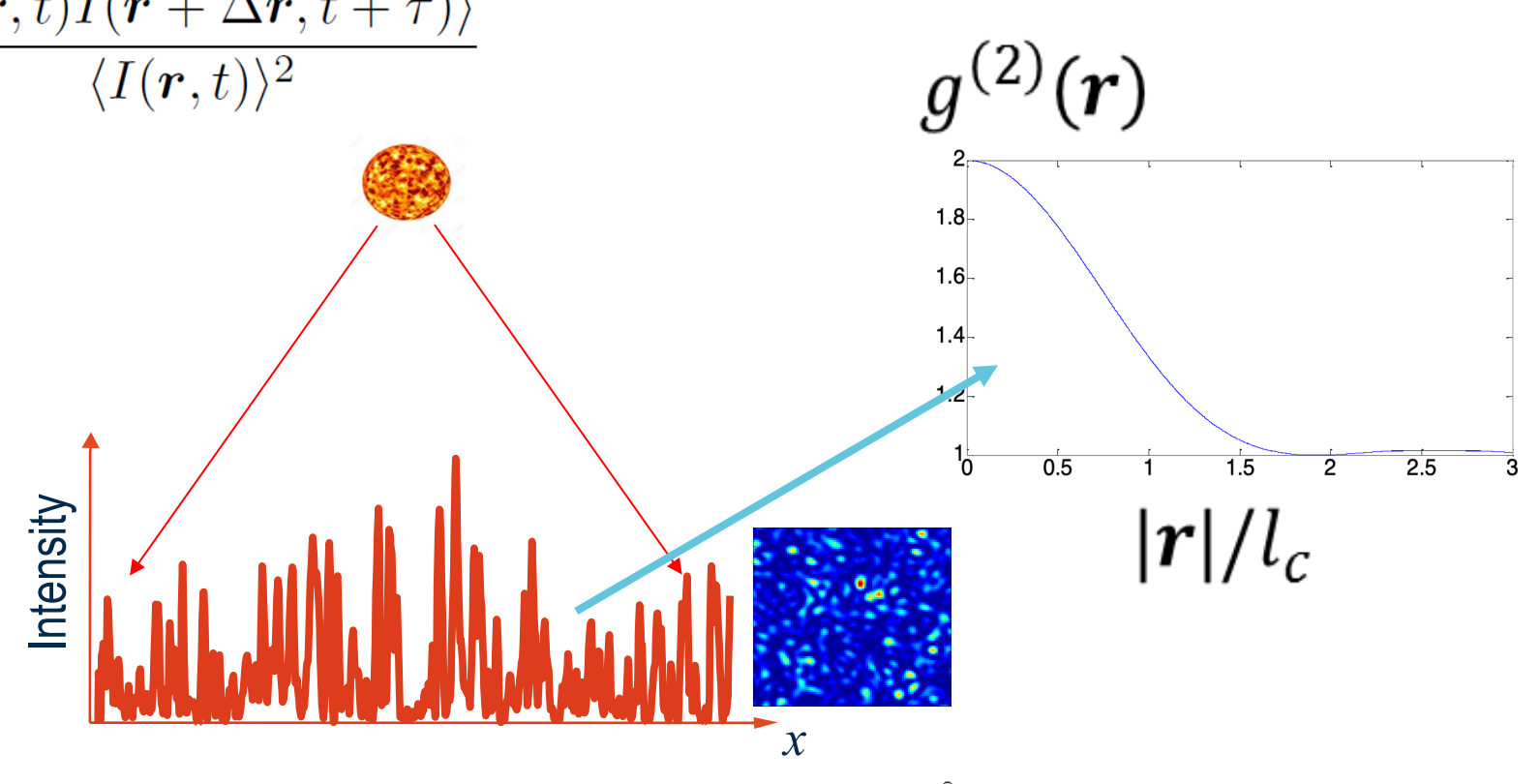
$$\text{Intensity correlation function: } g^{(2)}(\Delta r, \tau) = \frac{\langle I(r, t)I(r + \Delta r, t + \tau) \rangle}{\langle I(r, t) \rangle^2}$$

In the spatial domain: $g^{(2)}(r, \tau = 0)$

Classical picture: speckle from an extended disordered source.

The size of the speckle grain (= spatial correlation l_c) is related to the size of the source.

$$l_c = \lambda \cdot L/D$$

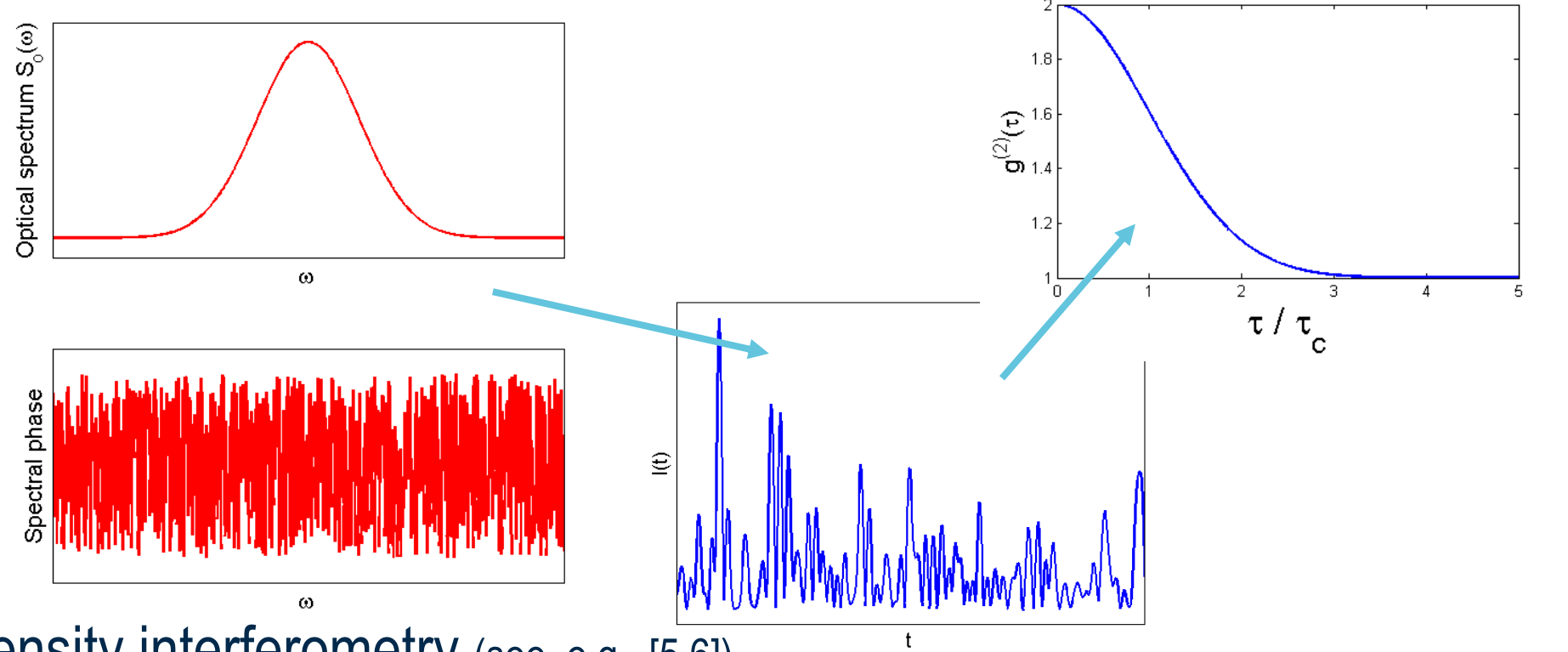


In the time domain: $g^{(2)}(r = 0, \tau)$

Similar explanation: an incoherent (thermal) spectrum creates intensity noise (beating of the different frequency components).

The correlation time τ_c is related to the width of the spectrum.

$$\tau_c = 1/\Delta\omega$$



The future: towards a revival of intensity interferometry (see, e.g., [5,6])

Limitations of direct interferometry:

- Complicated and expensive
- Fringe tracking limits the accessible magnitude
- How to increase the baselines to km-scale ?

Intensity interferometry:

- Much simpler: no recombination, no delay line, insensitive to turbulence
- Separations can be increased to km or more
- Large array of many collectors possible (e.g. CTA) -> high resolution imaging
- Need large collectors and very long integration times @ but detectors and electronics made a lot of progress since the 1970s !!! -> can be useful again

SNR = $\sqrt{N_{\text{channel}}} A \eta F(\nu) |V(r)|^2 \sqrt{\frac{T_{\text{obs}}}{2\pi\tau_{el}}}$

Wasatch Photonics, Berkshire Photonics, Keck/CFHT 10m/4m, Multiplexing N=16, Fast SPD $\tau_{el}=20\text{ps}$

SNR : $\times 4 \times 40 \times 4 \Rightarrow \times 640$

$T_{\text{obs}} \div 400\,000$

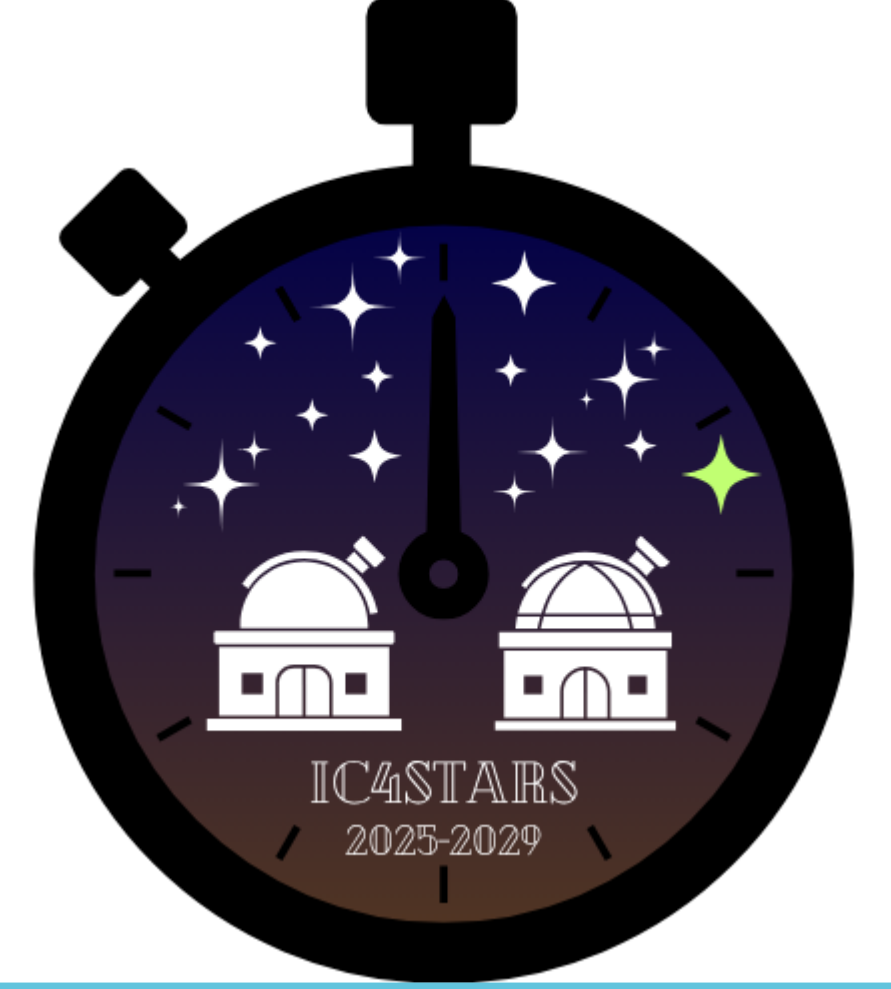
OHANA NUI team structure:

Université Côte d'Azur:

- Institut de Physique de Nice: Robin Kaiser (PI), William Guerin (Project Scientist), Guillaume Labeyrie, Mathilde Hugbart, Federico Izraelevitch, Sarah Tolila, Andreas Zmija, Ilian Ellafi.
- Observatoire de la Côte d'Azur: Olivier Lai (chairman of OHANA committee), Jean-Pierre Rivet.

MaunaKea:

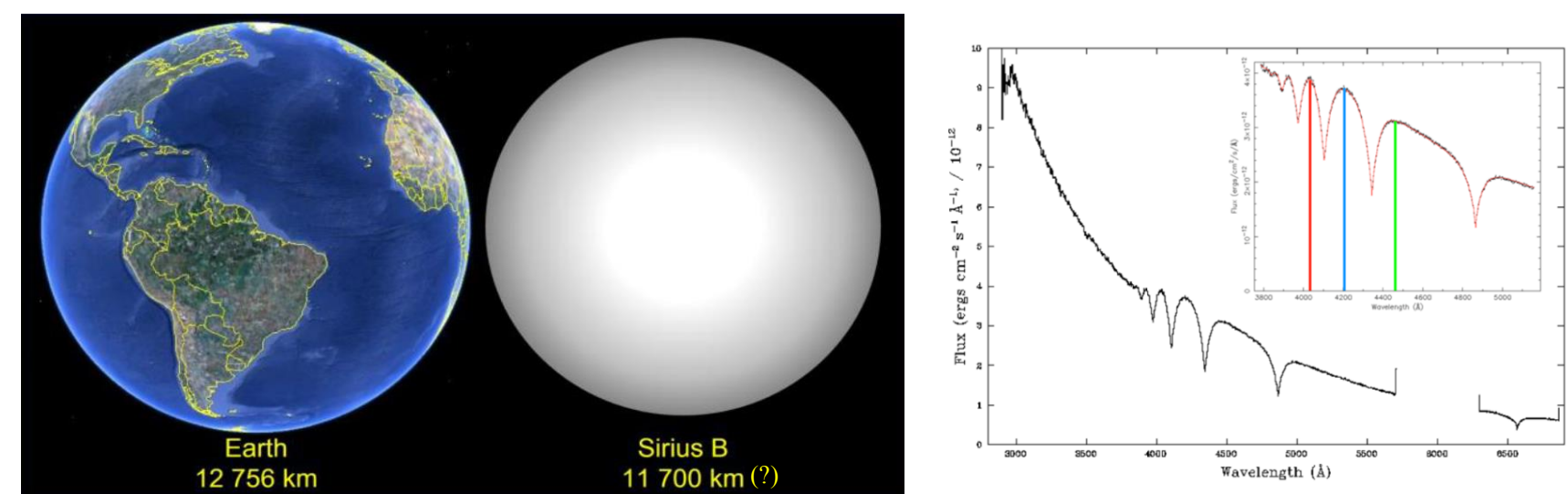
- IfA, University of Hawaii: Mark Chun, Curt Dodds, Branden Allen, Sebastien Vievard, Doug Simons.
- CFHT: Jean Gabriel Cuby, Marc Baril, Gregory Barrick.
- W.M. Keck Observatory: Antonin Bouchez, John O'Meara, Peter Wizinowich.
- Gemini Observatory: Andy Adamson, John White, Eduardo Tapia.
- Subaru Telescope: Naoyuki Tamura, Olivier Guyon, Julien Lozi.



Expected timeline:

- 2026: Multiplex instrument design, White Rabbit synchronisation & write-to-disk demonstration.
- 2027: On-sky validation (Nice, Maunakea) using small telescopes.
- 2028: First Sirius B observations, 2 telescopes
- 2029: Longer baselines, multiple telescopes.

Angular resolution of a white dwarf



Count rates : Sirius B
Quantum efficiency : 90%
Throughput : 20%

Keck: 110 000 cps
CFHT : 18 000 cps

D=11700km
L=8.6 light years= 8 10^16m
 $\Delta\theta=30\mu''$

The best direct test of stellar degeneracy is the determination of radii for white dwarfs in visual binaries (Table 1). In these cases, white dwarf masses are well determined from their orbital parameters, and stellar radii are derived from knowledge of effective temperatures and distances. Since

These exotic objects are supported by Fermi electron degeneracy, and their diameter is estimated from their luminosity; such a measurement would uniquely constrain the diameter and demonstrate quantum mechanics at work on an astrophysical size object!



Between 1999 and 2012, a collaboration of Observatories strived to connect telescopes at the summit of Maunakea with single mode optical fibres into a kilometric baseline interferometer to operate at near infrared wavelengths; it was the OHANA project, (Optical Hawaiian Array for Nanoradian Astronomy, with all the telescopes operating as a family) [9, 10, 11]. Unfortunately, luck was not with us and adverse weather conditions prevented us from performing astronomical observations of YSOs and AGNs. The project came to an end in 2012. We propose to revive the idea of interferometric connection of the Maunakea telescopes, but this time in the visible and using quantum optics and the technique of intensity interferometry.

Path-opening on Sirius B (white dwarf) : quantum degenerate Fermi gas of electrons

SNR ≈ 6 in 1 hour observation time !!!!

Beyond reach of present instruments

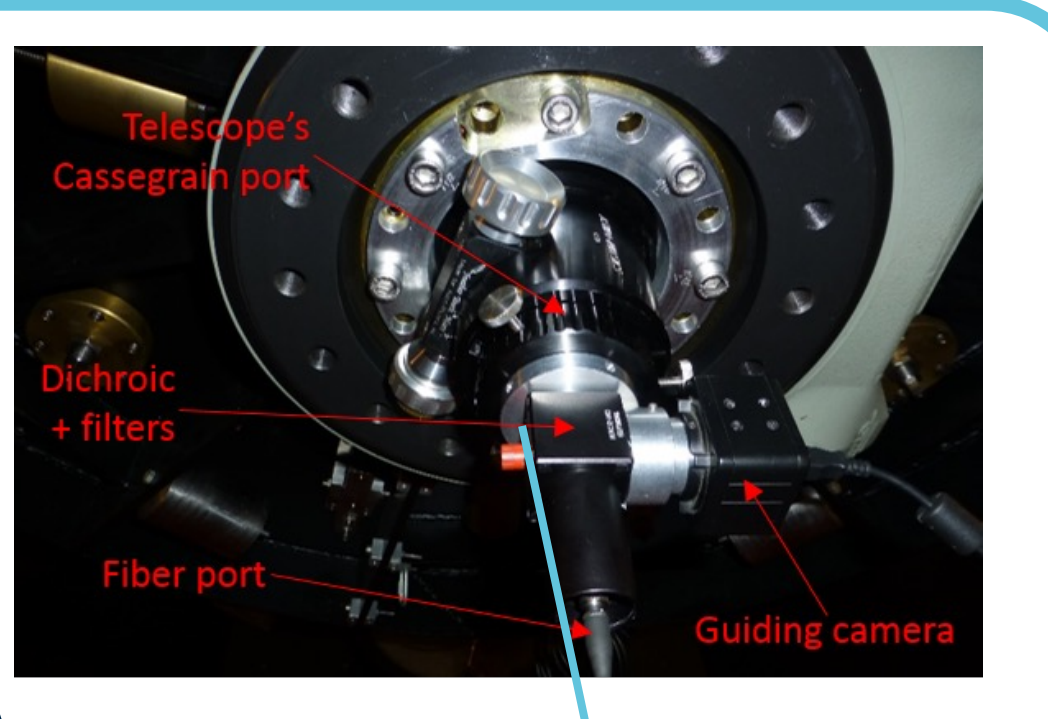
Photon Bunching

- @ $\lambda = 420\text{nm}$
- D=630m

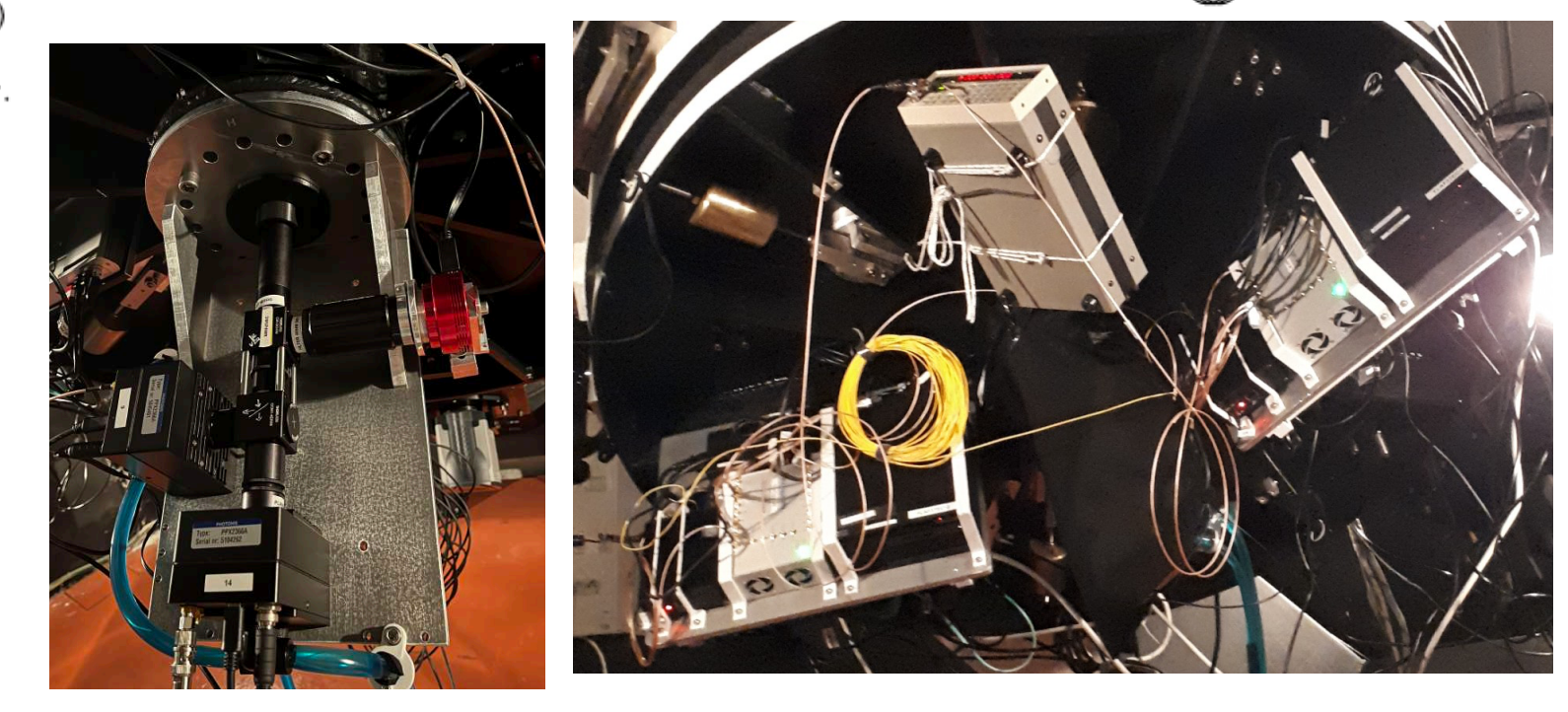
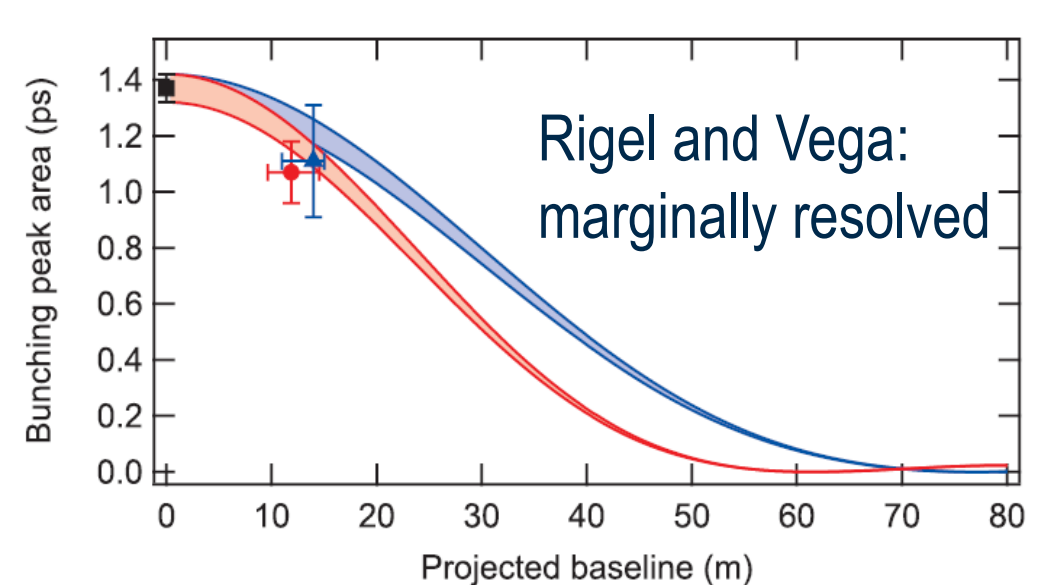
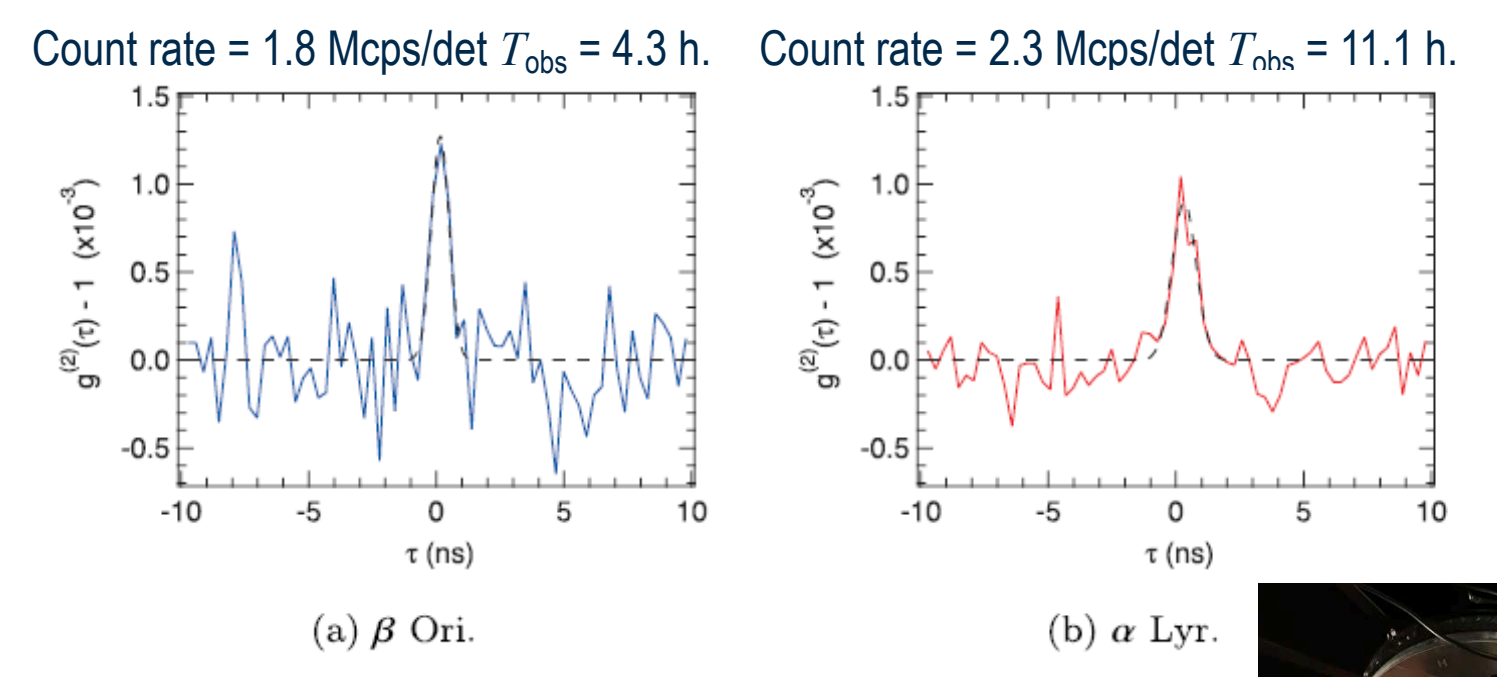
Mauna Kea @ Hawaii

Results with starlight

We have developed a collaboration between quantum optics physicist and astronomers at Université Côte d'Azur since 2016 and have demonstrated the promise of the technique using our 1m telescopes to achieve original and meaningful astrophysical measurements [6, 7, 8].



C2PU at Calern, OCA



Recent result: Individual photon arrival times have been recorded and written to disk using two Time-to-Digital Converter (TDC), synchronised at few tens of picosecond level, using a White Rabbit link over a 500m telecom fiber.

Pulse generator time synchronisation at 15 picosecond level (bottom left), sky photons reach 35 picosecond jitter (below middle), limited by detector jitter; 3 nights of observing, SNR~9.

Pulse Generator - Fiber White Rabbit 500 m

Instrument concept

The instrument concept is shown on the diagram on the left: at the focus of each telescope, the light is separated in multiple spectral channels to benefit from the gain in SNR (\sqrt{N}). The individual photon arrival is digitized and written to disk locally by a Time-to-Digital Converter (TDC). These are synchronized across the summit telecommunications fibers using the White Rabbit protocol (see box at bottom left). The correlations are computed offline.

The size of these detectors makes spectral multiplexing more complicated. We studied two concepts, the first using a VPH, but this required an echelon to compensate for the temporal dispersion, as well as an image slicer to send the different parts of the spectrum to each detector. The second one uses narrow band notch filters at slightly different angles to transmit different wavelengths to each detector. The second solution was found to provide a slightly higher SNR for the same observing conditions. However, this concept requires splitting polarisations and precludes the use of an optical fiber to connect the detectors to the telescope, so the instrument will have to be mounted directly at the telescope's focus.

For the detector, we selected single photon detector by Photonics due to their excellent timing resolution and quantum efficiency. They are based on Micro Channel Plates, which contain millions of microscopic channels that amplify incoming electron signal via secondary emission.

Free space, big detection area : 8 mm diameter. Jitter FWHM : 35ps and 33% QE at 420nm. Require cooling system (peleter inside) with pump.

	Grating Instr.	Filters Instr.
Fibered ?	Yes	No
Spectral bandwidth per channel	0.90 nm	0.81-1.06 nm
Transmission	9%	15%
Temporal resolution (RMS)	43.6 ps	38.9 ps
Shape factor S	89%	86%
Multiplexing factor M	1.9	3.07
SNR (Sirius)	3.0	4.3

References

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