OHANA NUI: Intensity correlations on a White Dwarf

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Introduction (1): Intensity correlations, the basics

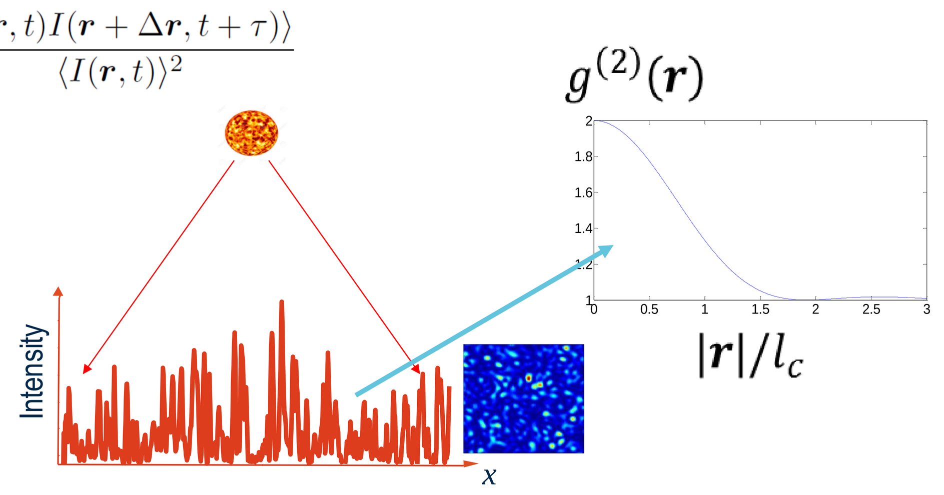
Intensity correlation function: $g^{(2)}(\Delta \mathbf{r},\tau)=\frac{\langle I(\mathbf{r},t)I(\mathbf{r}+\Delta\mathbf{r},t+\tau)\rangle}{\langle I(\mathbf{r},t)\rangle^2}$

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

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.

$l_c = \lambda L/D$

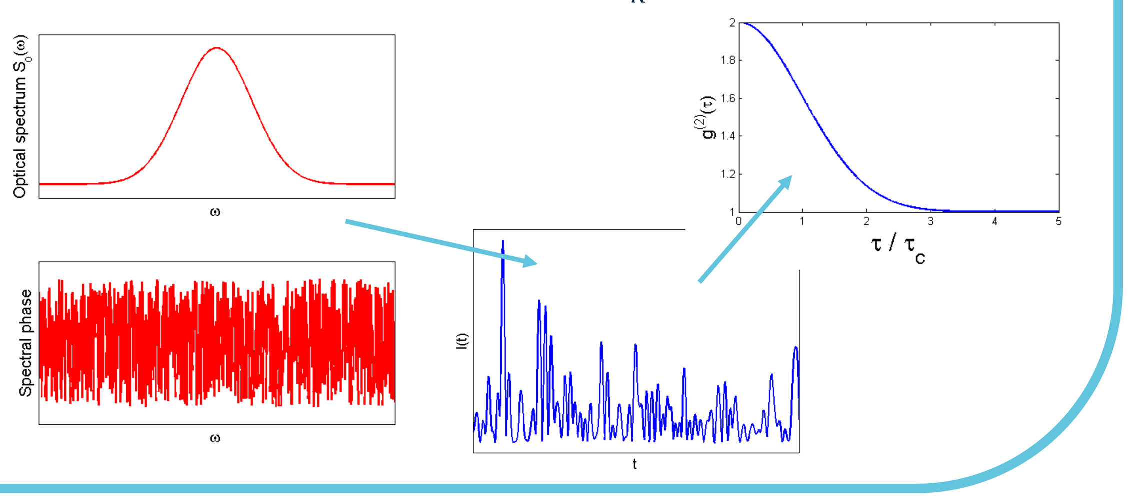


In the time domain: $g^{(2)}(\mathbf{r}=0,\tau)$

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.

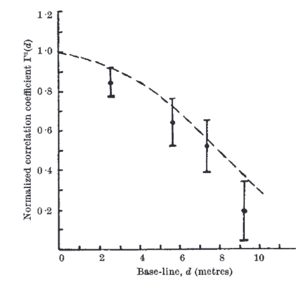
$\tau_c = 1/\Delta\omega$



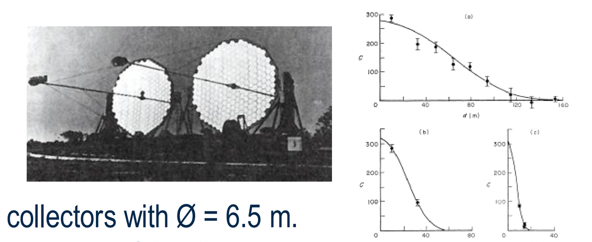
Introduction (2): Intensity correlations in astronomy

The past: the historical Hanbury Brown & Twiss experiments

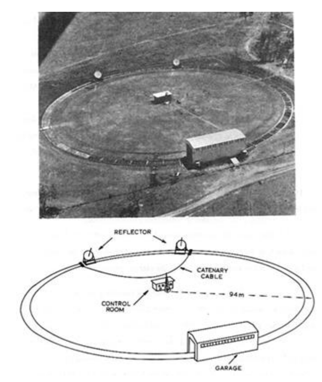
HBT 1956: First demonstration of $g^{(2)}(r)$ with 2 telescopes (measurement on Sirius) [1]



HB 1963-1974: The Narrabri stellar interferometer (Australia) [2,3]



Two collectors with Ø = 6.5 m. Measurement of the diameter of 32 stars with baselines between 10 and 188 m.



After 1975: the development of "direct interferometry" [4] put a halt to intensity interferometry. At the cost of combining the optical paths (with very precise and active delay lines), direct interferometry is much more efficient for the signal-to-noise ratio.

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**

What are the performances and limitations of intensity interferometry with today's photonic technologies ?

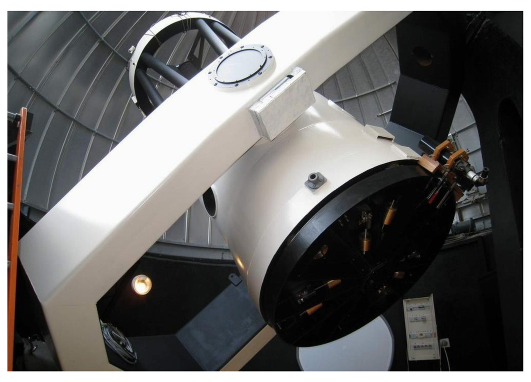
$$SNR = \alpha N_{\rm ph}(\lambda) A \sqrt{\frac{T_{\rm obs}}{2\tau_{\rm el}}}$$

α : detection efficiency → significant gain
N_{ph} : photon spectral flux
A : collection area
τ_{el} : electronic timing resolution → huge gain !
T : integration time

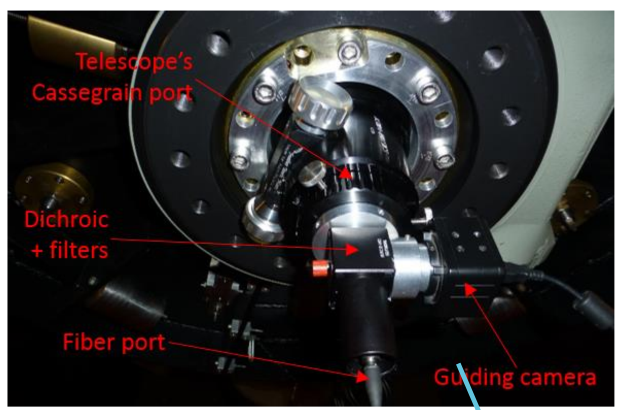
+ fiber technologies, digital electronics, time distribution at large distances…
And spectral multiplexing, SNR ~√N, where N is the number of spectral channels;

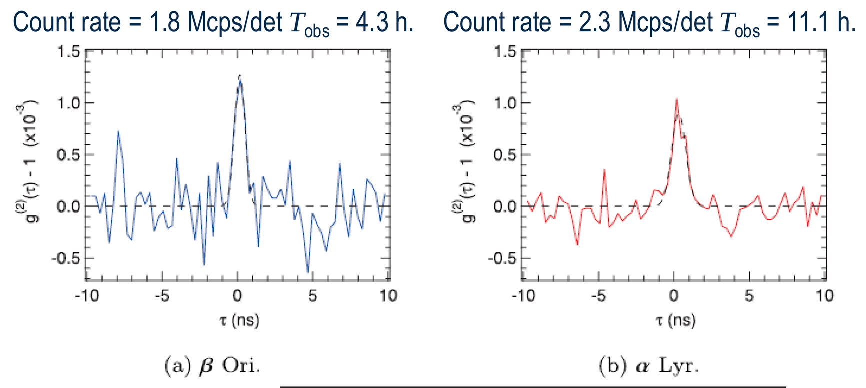
C2PU at Calern, OCA

Cassegrain telescopes:
- Ø = 1 m
- Focal reducer → f = 5.6 m
- NA = 0.09 ; f/5.6
- PSF = 42 µm for seeing = 1.5"

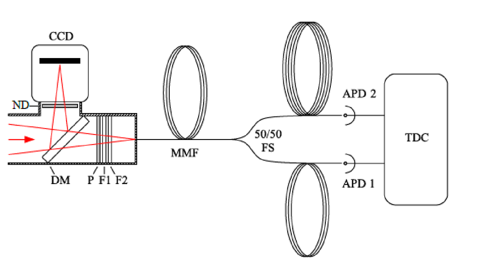


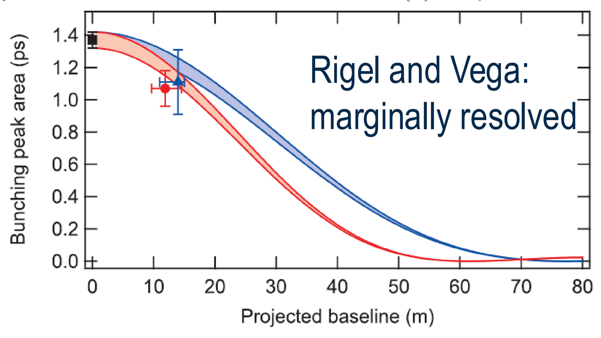
Results with starlight



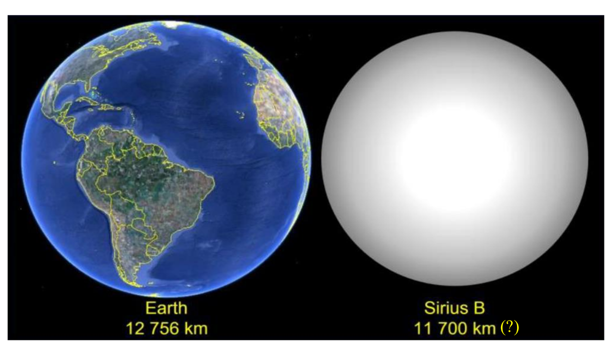


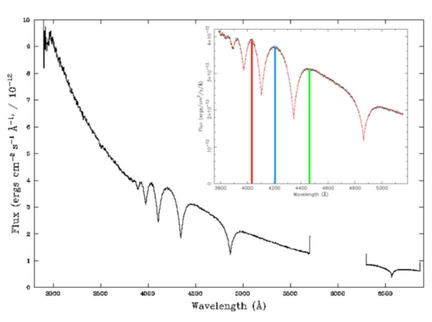
We have developed a collaboration between quantum optics physicist and astronomers at Université Côte d'Azur since 2016 and have demonstrated the promise of the technique using our 1m telescopes to achieve original and meaningful astrophysical measurements [7, 8].





Angular resolution of a white dwarf





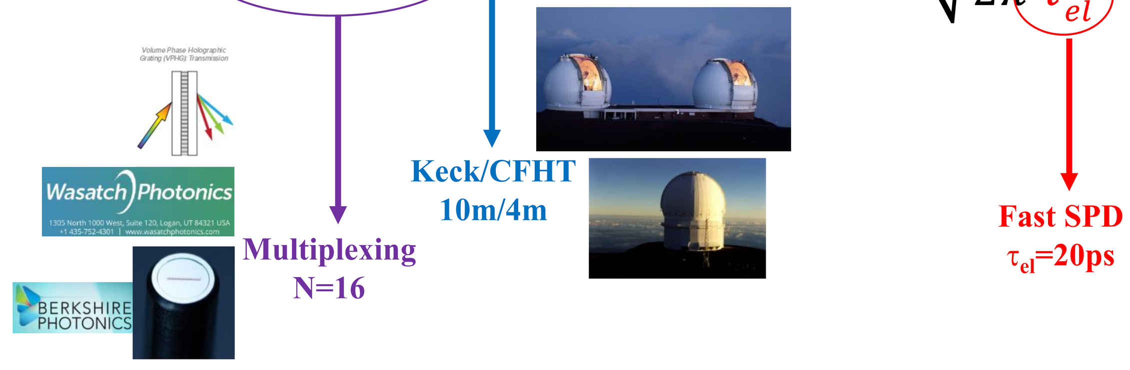
Count rates :
Sirius B
Quantum efficiency : 90%
Throughput : 20%

Keck: 110 000 cps
CHFT : 18 000 cps

D=11700km
L=8.6 light years= 8 10^16m
Δθ=30µ″

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!

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



SNR : × 4 × 40 × 4 ⇒ × 640

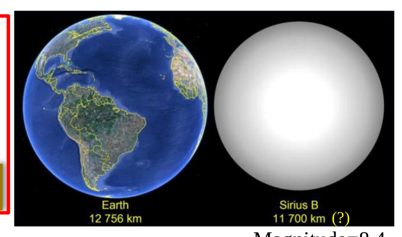
T_{obs} ÷ 400 000

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

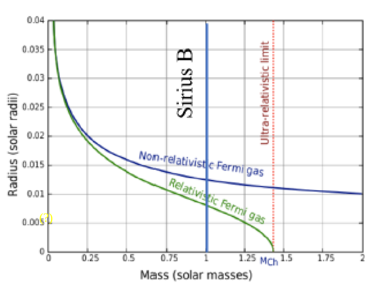
Between 1999 and 2012, a collaboration of Observatories strived to connect telescopes at the summit of Maunakea with single mode optical fibres into a kilometric baseline interferometer to operate at near infrared wavelengths; it was the OHANA project, (Optical Hawaiian Array for Nanoradian Astronomy, 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.

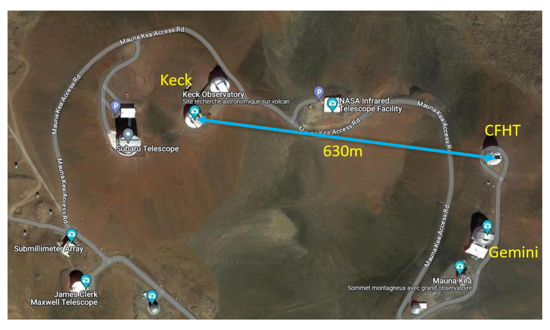
SNR ≈ 6
in 1 hour
observation time !!!!

Beyond reach of present instruments



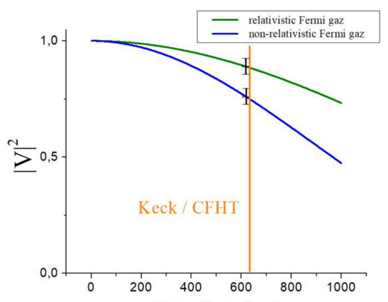
Magnitude=8.4



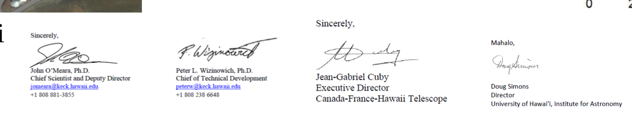


Mauna Kea @ Hawaii

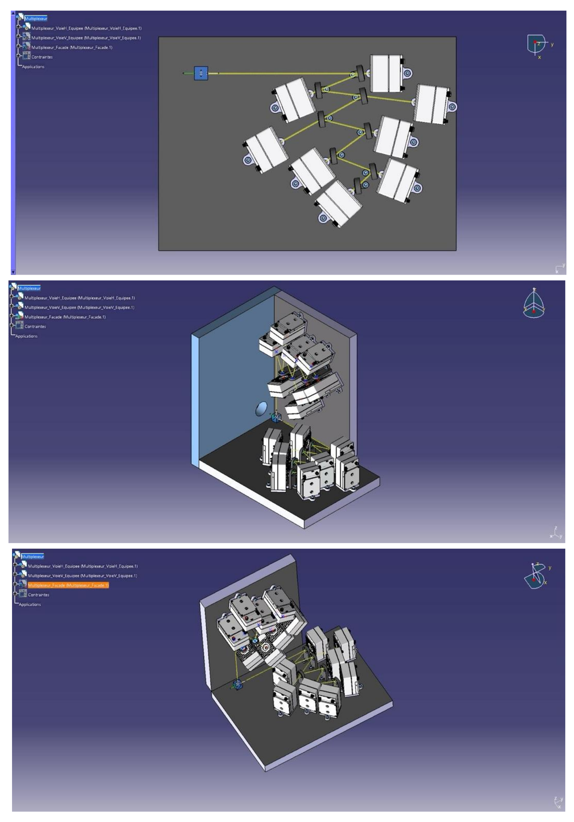
Photon Bunching
- @ λ = 420nm
- D=630m



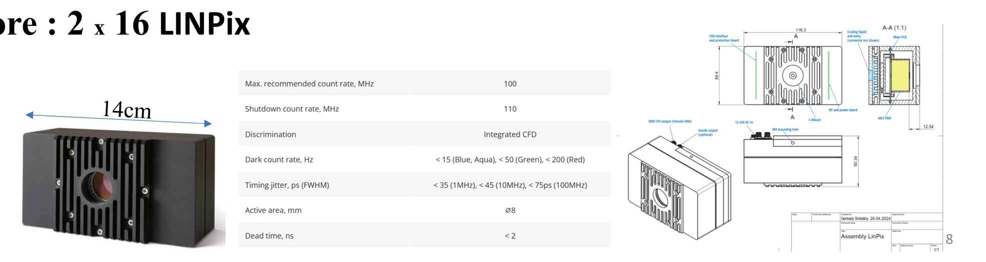
Baseline [m]



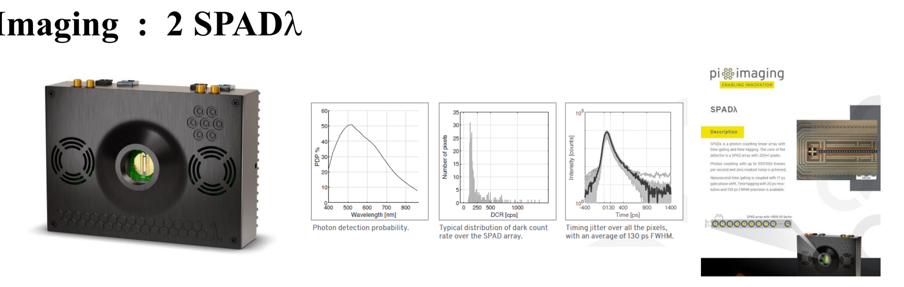
Technological progress driven by quantum optics and telecommunications has led to the development of new components (SPADs, SNSPDS) which have allowed to extend the sensitivity of the technique by orders of magnitude. We are developing various concepts for spectral multiplexing, such as an array of dichroic notch filters (right) to be used with LINPix detectors (below). We are also studying the possibility to use a linear SPAD array with a low time dispersion spectrograph

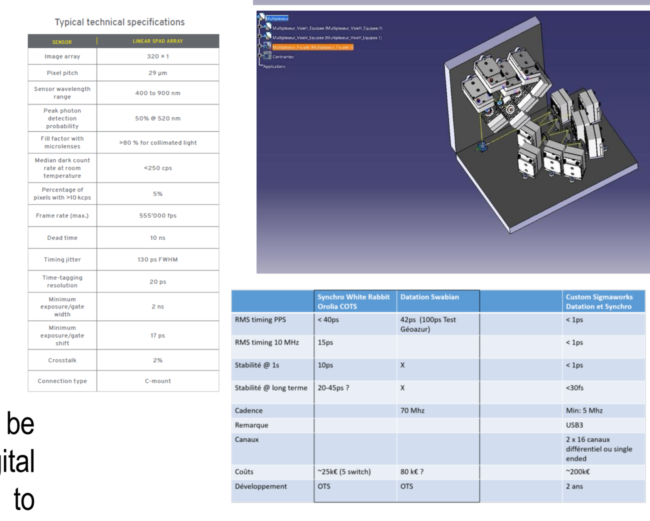


Photonscore : 2 x 16 LINPix

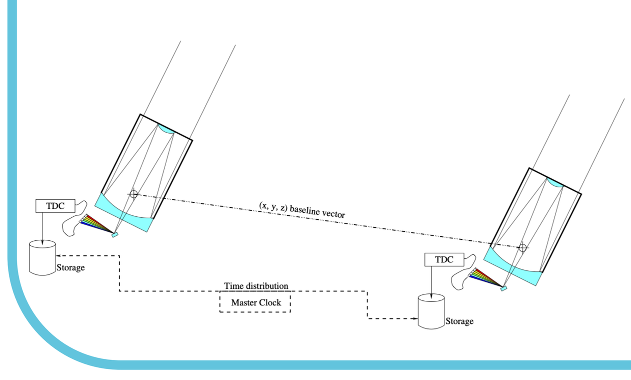


Pi Imaging : 2 SPADλ

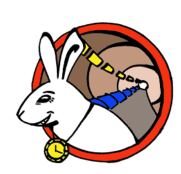


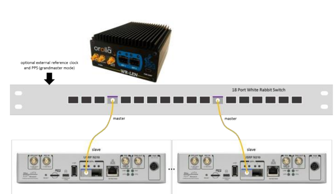


Photon arrival times will be recorded using a Time-to-Digital Converter (TDC) and written to disk for a posteriori correlations. However, clock at telescopes must be sybchronised to piscosecond level, and various solutions are available (below).



1 ps





16 ps

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