Ultra-High Resolution Astronomical Imaging Using Quantum Properties of Light

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ANGULAR SCALES IN OPTICAL ASTRONOMY

Rayleigh Criteria

$\Theta = 1.22\ \lambda/D$ (Single lens dia. D)

$R = 1.22\ \lambda/B$ (Telescope baseline B)


Sun, Moon ~30 arcmin

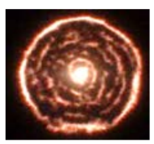
Human Eye limit (D= 1 cm)




Planets ~30 arcsec

Optical Telescope limit (D= 10 m)



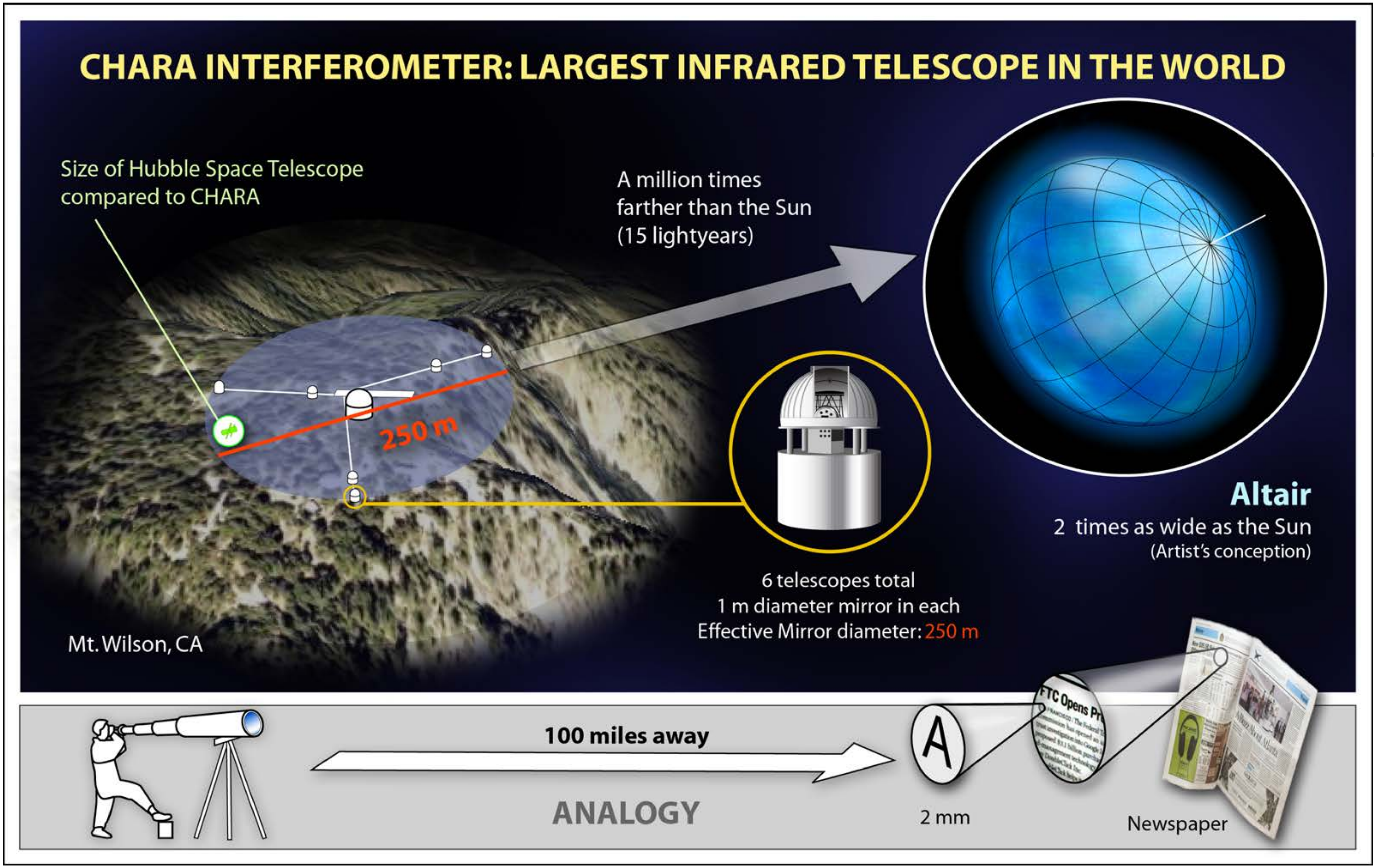


Largest stars ~30 mas

Interferometer limit (B= 300m, IR)

Typical bright stars ~1 mas

Radio images—VLBA (B>1000 km)



CHARA INTERFEROMETER: LARGEST INFRARED TELESCOPE IN THE WORLD
Size of Hubble Space Telescope compared to CHARA
A million times farther than the Sun (15 lightyears)
250 m
Altair
2 times as wide as the Sun
(Artist's conception)
6 telescopes total
1 m diameter mirror in each
Effective Mirror diameter: 250 m
Mt. Wilson, CA
100 miles away
ANALOGY
A
2 mm
FTC Opens Pr
Newspaper

Present optical resolution

~ 1 mas (JHK band, VLTI, NPOI, CHARA)

How to much better resolution possible?

Shorter λ ---- JHK -> UV band (factor of 3)
Longer B ---- 300 m -> 2 km -> 10 km (factor of 7->30)

Potential optical resolution

~ 10-100 μas (UV band, 2 km distance)

Rayleigh Criteria

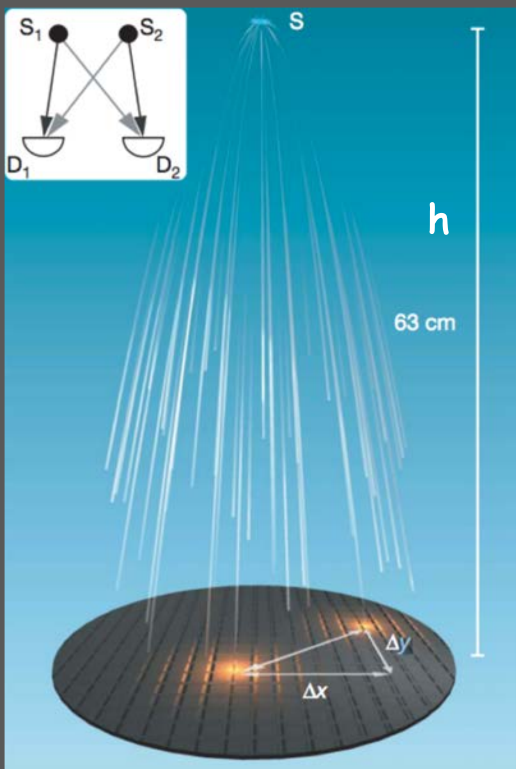
$\Theta = 1.22\,\lambda/D$ (Single lens dia. D)

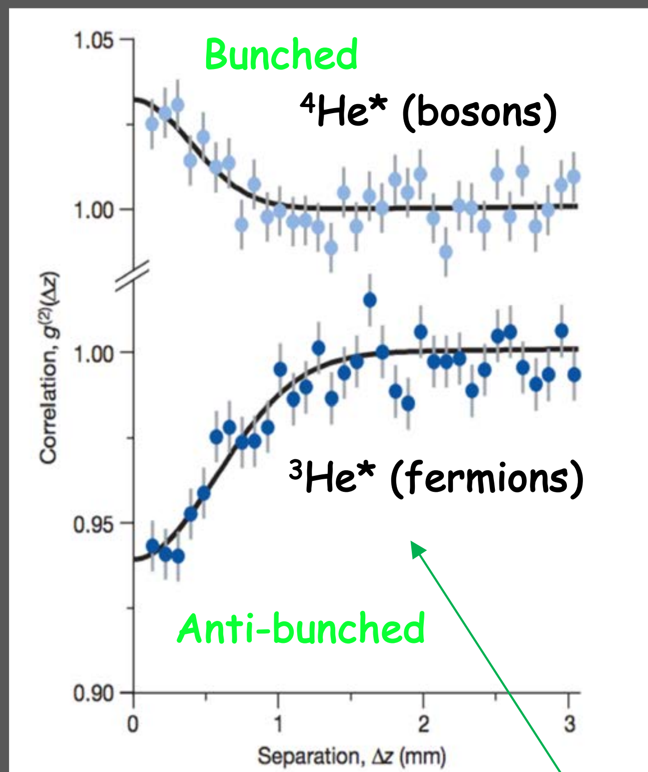
$R = 1.22\,\lambda/B$ (Telescope baseline B)

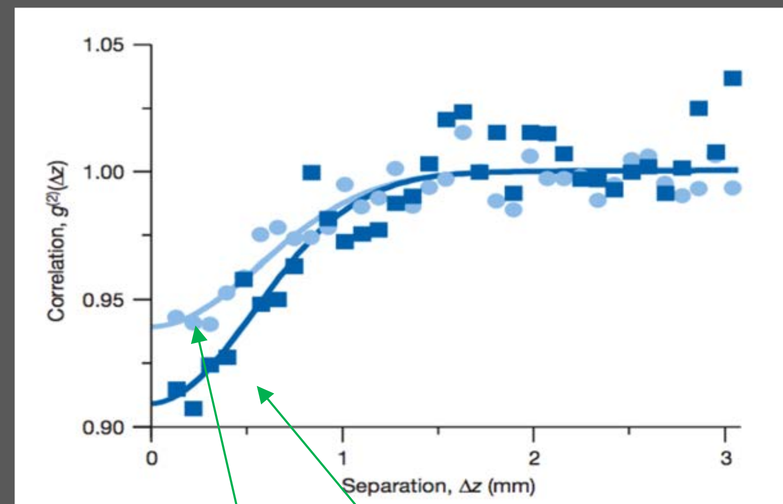
Technical Issues

- Atmospheric turbulence
- Pathlength compansation
- Source characteristics (spectral density, feature contrast)

Atomic Spatial Correlations







Different source diameters S

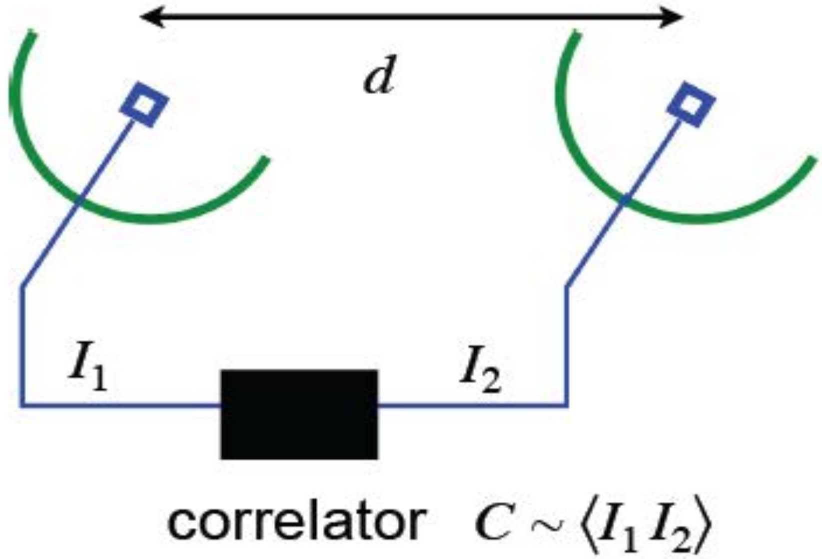
$\Delta z = 1.22\ \lambda_D\ h/S$

Unexplainable in classical mechanics

T. Jeltes et al., *Nature* 445, 25 (402) 2007

Intensity interferometry

Robert Hanbury Brown
1916-2002



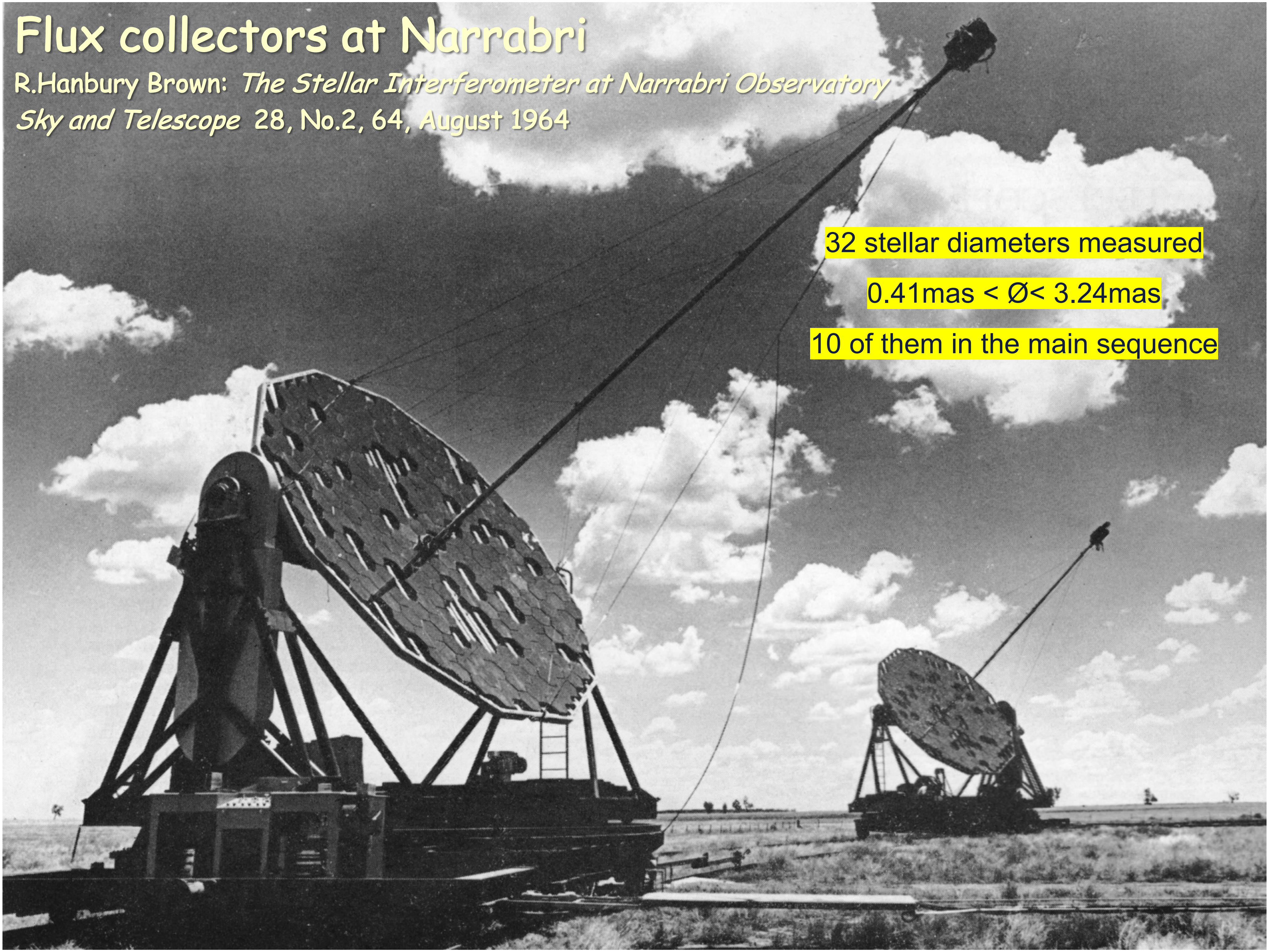
The current noise in two optical (or radio) telescopes should be correlated for sufficiently small separations d. Reminiscent of Michelson's interferometer to measure stellar diameters, but less sensitive to vibrations or atmospheric fluctuation.
The correlation implies photon "bunching".

40 Mhz electronic bandwidth- atmospheric turbulence ok
V--band observations
Correlation time >> correlation time: Requires large mirror area (10 m diameter)

Flux collectors at Narrabri

R.Hanbury Brown: *The Stellar Interferometer at Narrabri Observatory*

Sky and Telescope 28, No.2, 64, August 1964



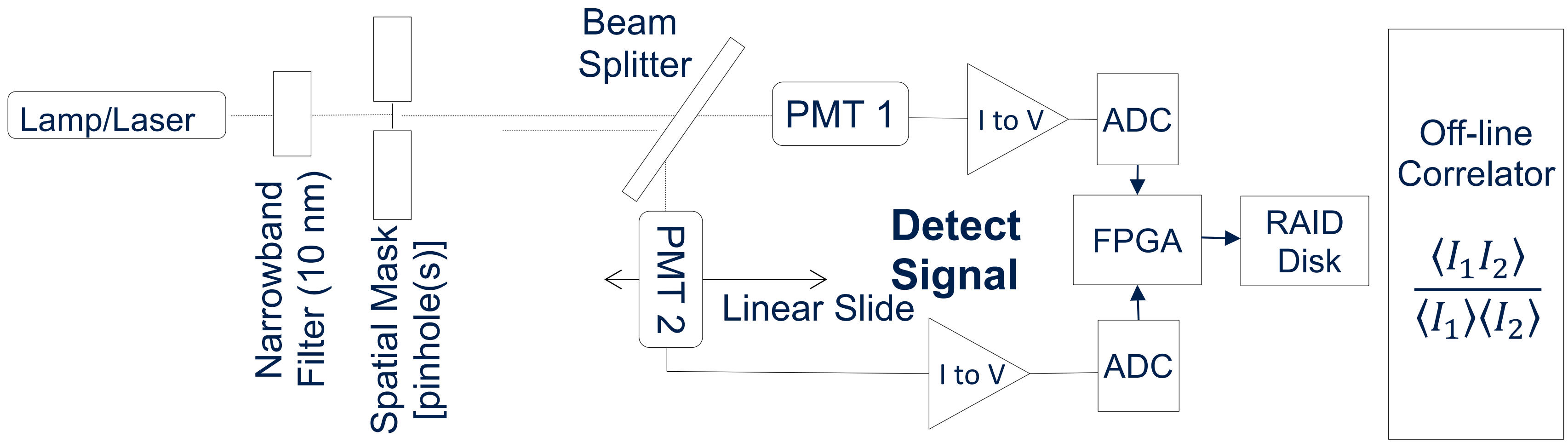
32 stellar diameters measured

0.41mas < Ø< 3.24mas

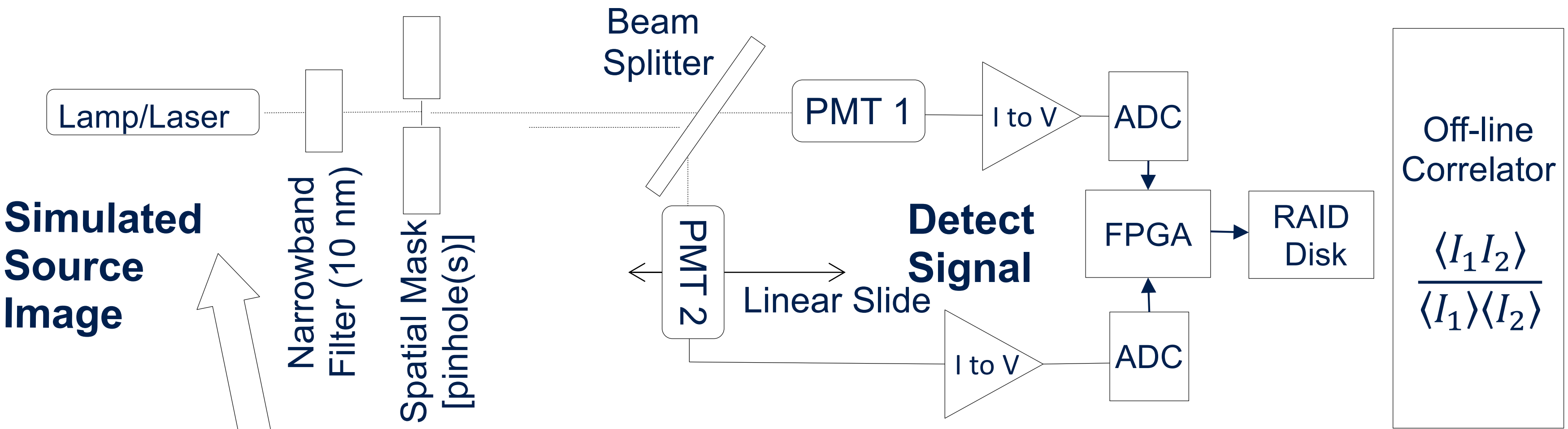
10 of them in the main sequence

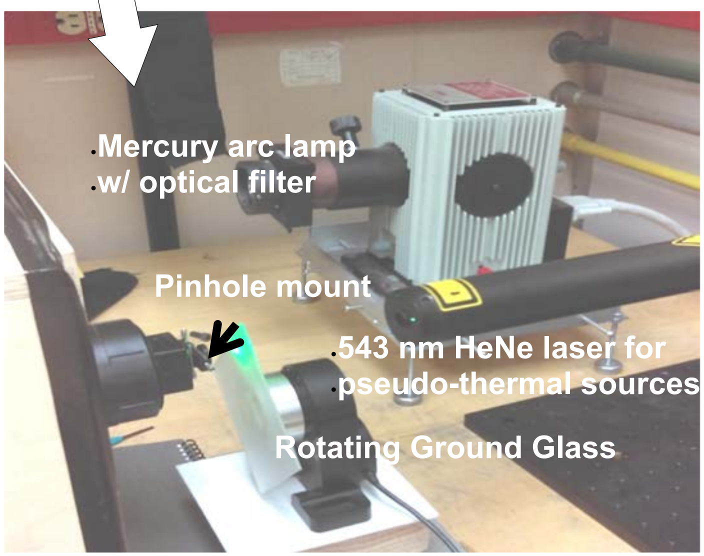
Laboratory Tests of Photon bunching

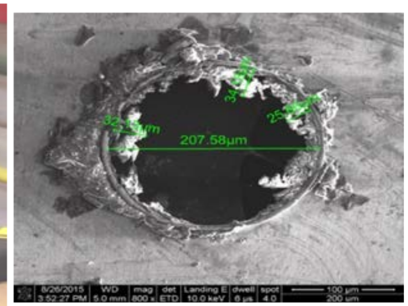
HBT Interferometry: U of Utah Lab



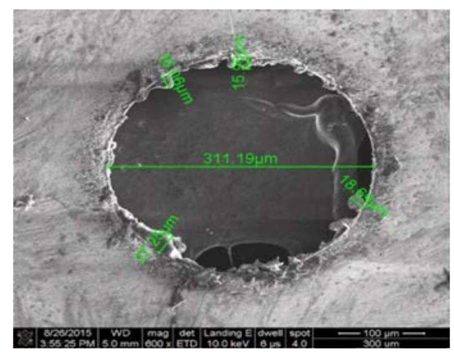
HBT Interferometry: U of Utah Lab



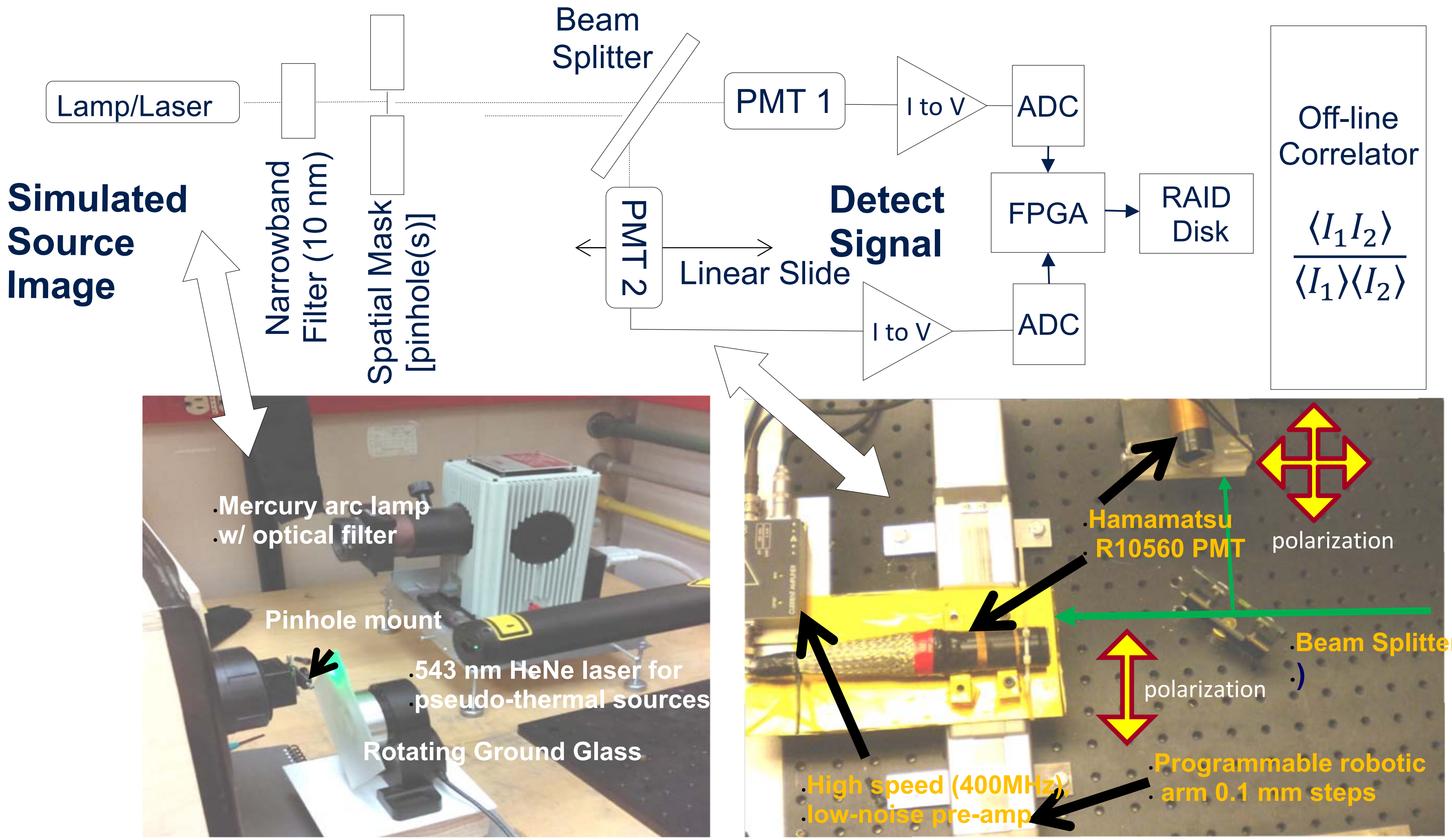




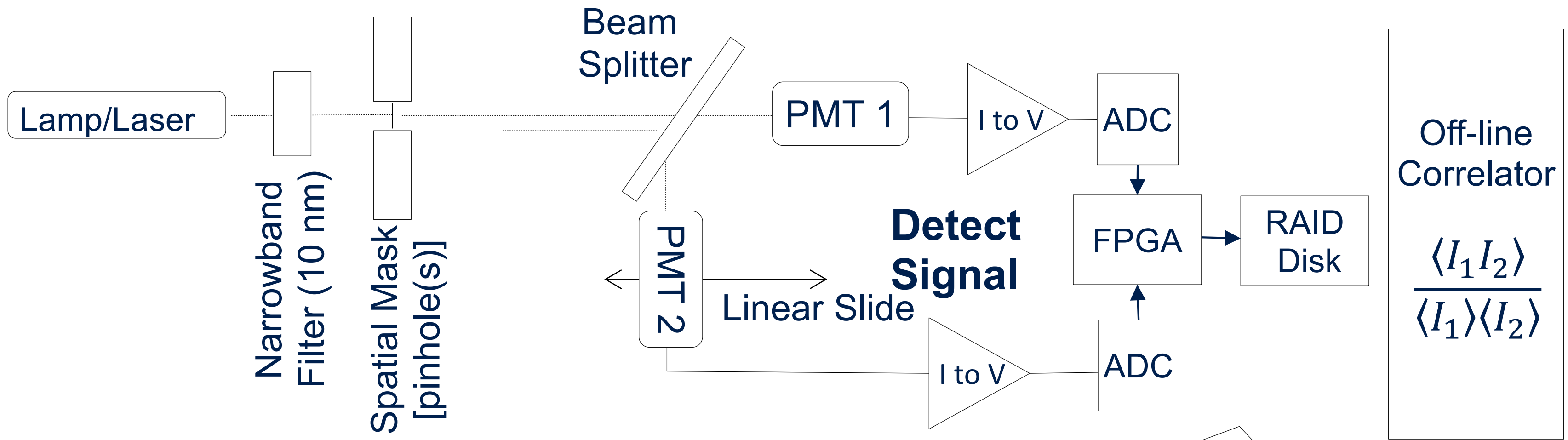
Laser drilled pinholes
On metal mask



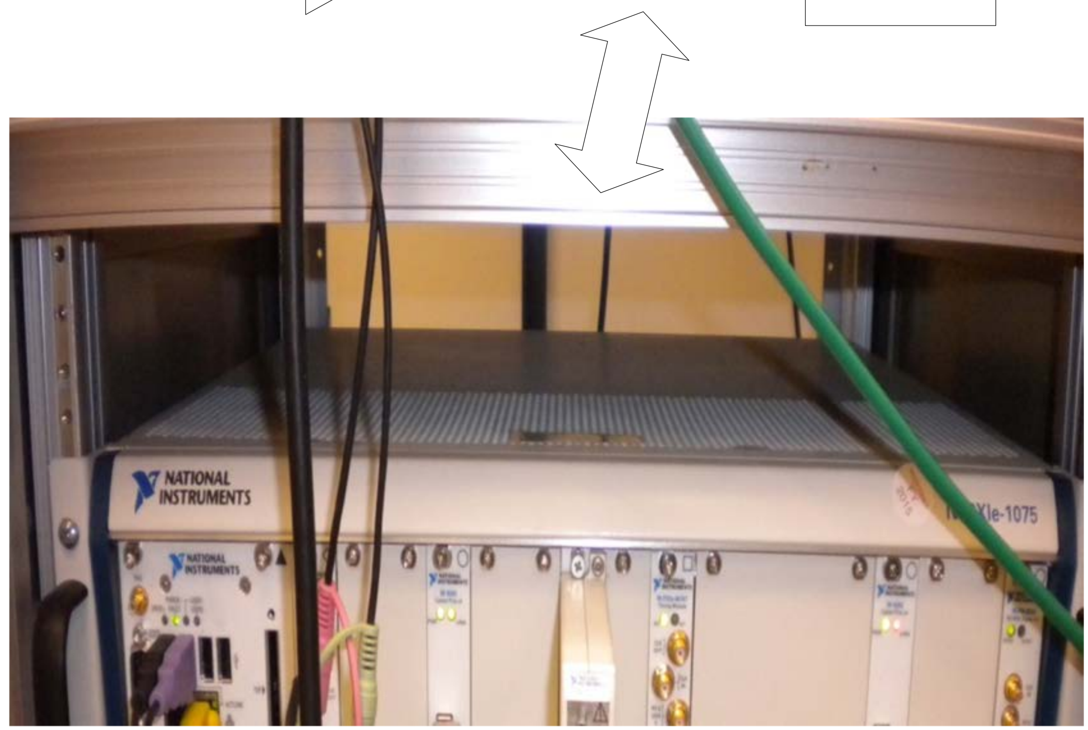
HBT Interferometry: Photon Sensors



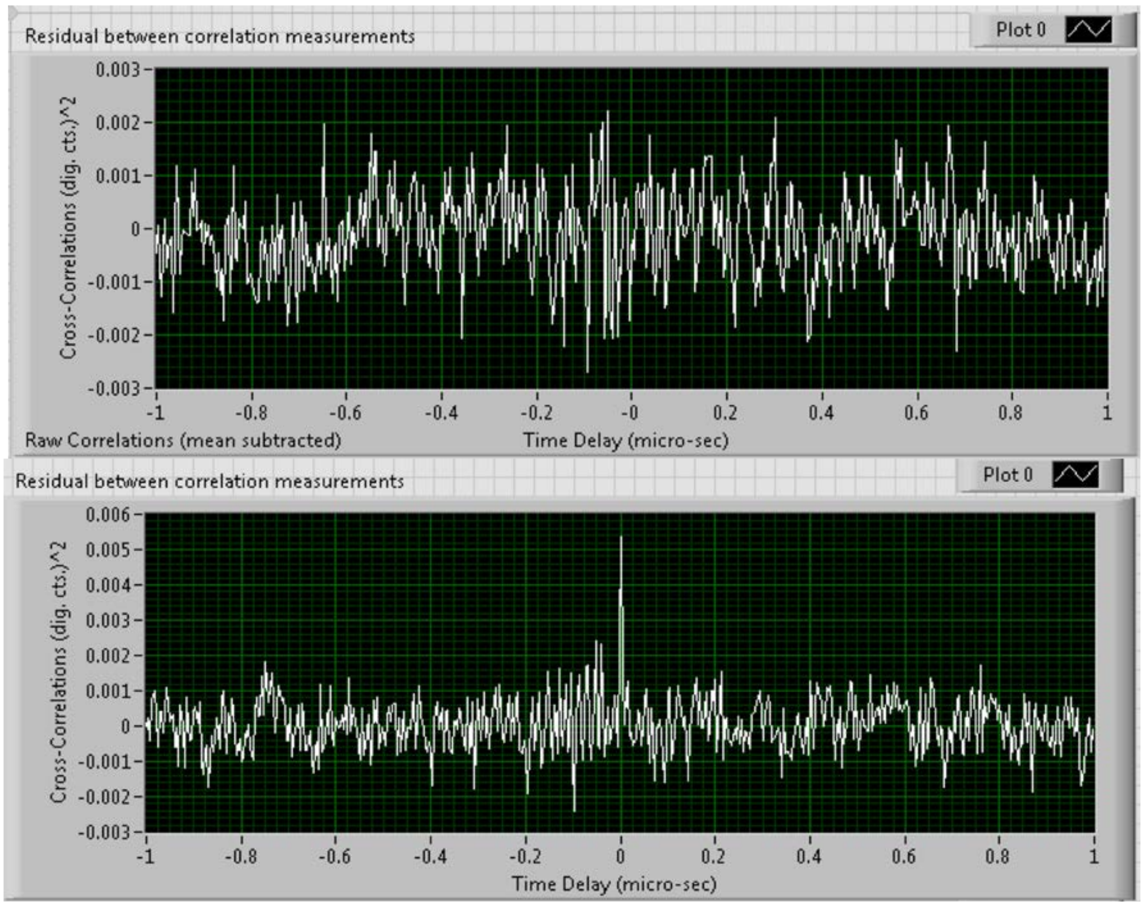
HBT Interferometry: DAQ& processing

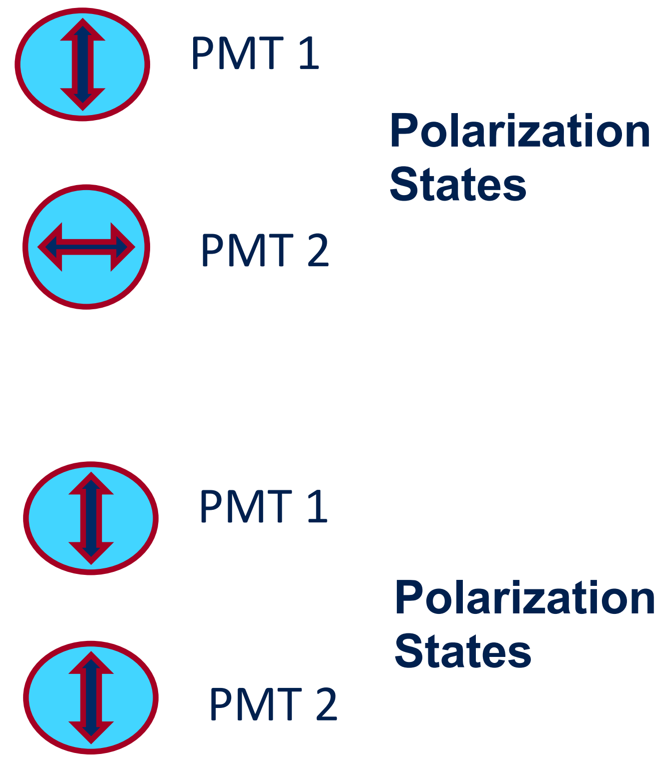


- Digitize data at 250MHz (4ns/sample).
- Virtex-5 or Kintex-7 FPGA pipeline processing
- Data streamed continuous to 12 TB disk at 500MB/sec.
- Online Software Correlation analysis performed using FPGA
- Offline correlation uses large computer farm



HBT Interferometry: Simulated Stars



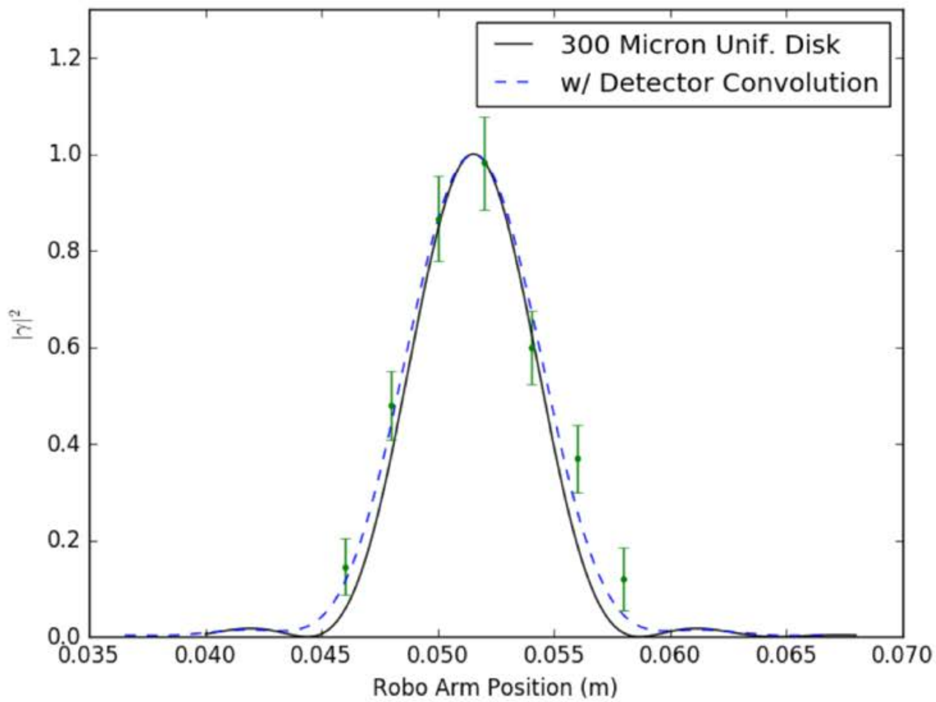


- 10 minutes observation, 10 nm optical filter
- Correlation signal only observed in identical polarization state
- Statistical significance ~ 7σ

Matthews, Kieda & LeBohec , J Mod Opt (2017)

HBT Spatial Correlations: Disk source

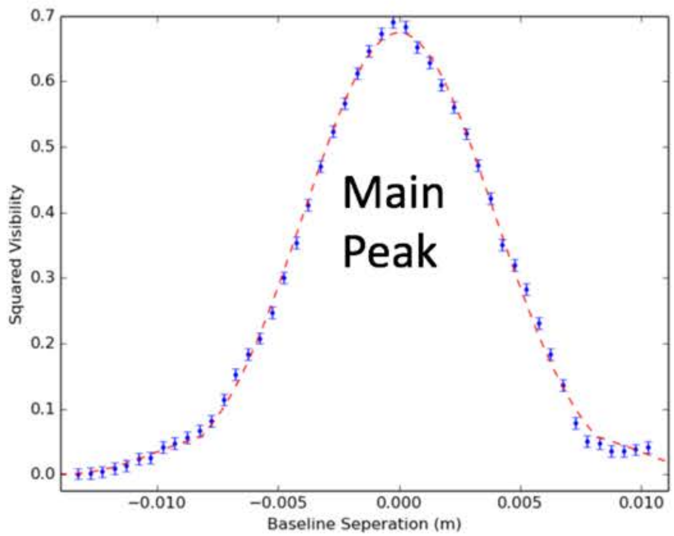
Spatial decoherence: blackbody source (Hg arc lamp), 300 Micron pinhole

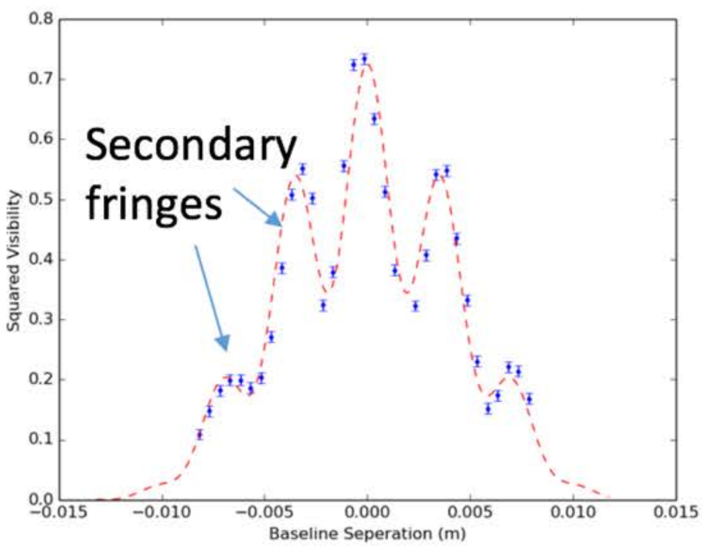


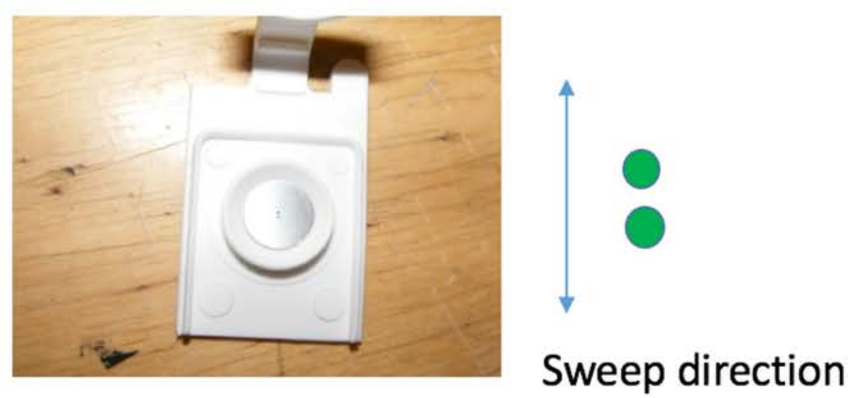
- Individual Data Points typically require 5-10 minutes observation
- Each observation point requires 150-300 Gbyte
- Correlations are calculated the the following day after the data has been recorded.
- New: First II observation on true Quantum Source using Software correlation
- New: Software correlation will allow n-fold correlation measurements (n >2)

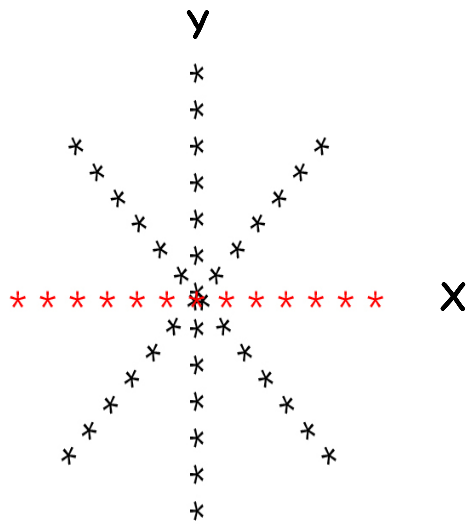
Matthews, Kieda & Lebohec, J. Mod Opt.(2017).

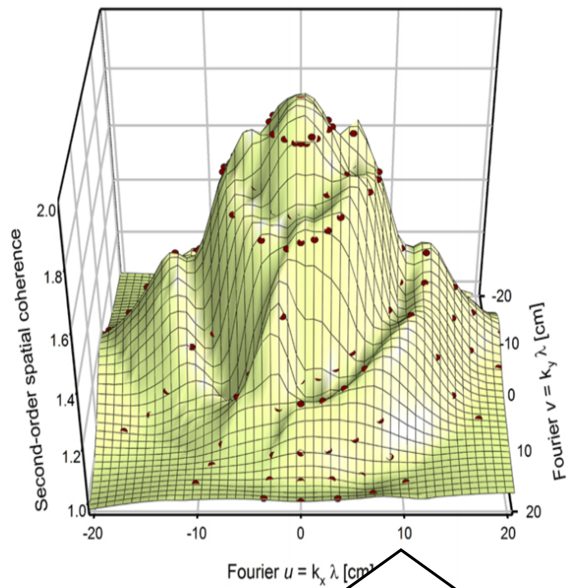
Lab Tests: Simulated Binary Star

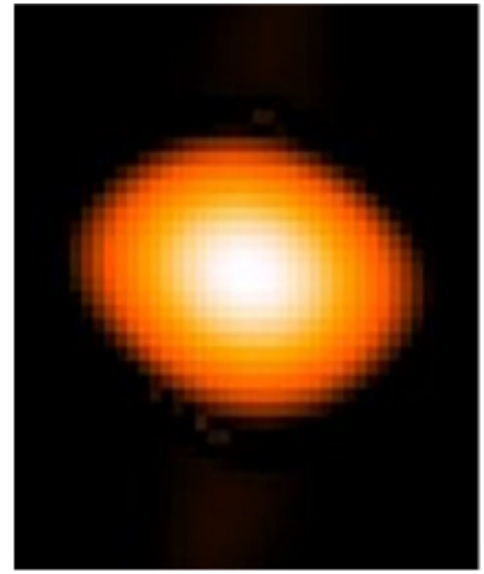












$$\frac{< I_A I_B >}{< I_A >< I_B >} = 1 + |\Gamma(B)|^2$$

Measure Second order coherence normalized

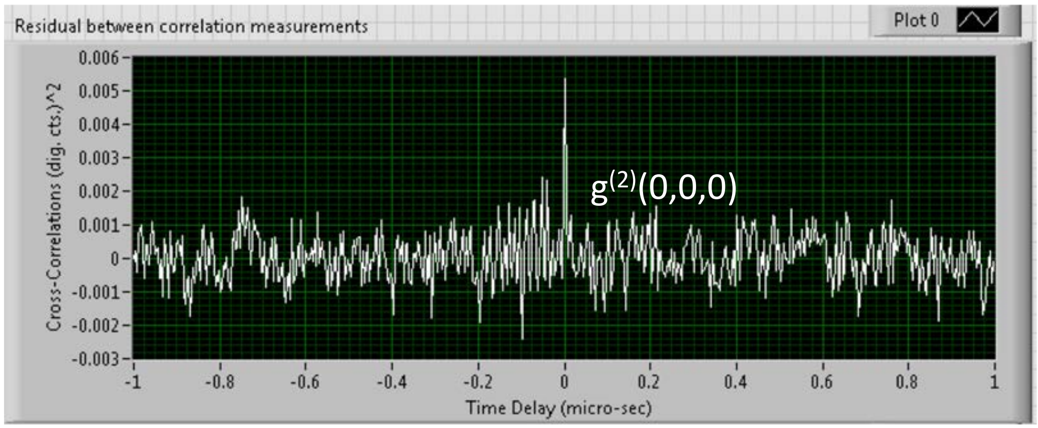
Complex visibility the Fourier transform of the source

$$\Gamma(B)\ \alpha\ \int F(\theta) e^{ikB\theta} d\theta$$

$F(\theta)$ describes the angular size of source and brightness distribution

Dravins, Dainis, Tiphaine Lagadec, and Paul D. Nuñez. “Long-baseline optical intensity interferometry: Laboratory demonstration of diffraction-limited imaging.” 18 Jun 2015. arXiv:1506.05804.

2^{nd}-order time coherence $g^{(2)}$ & Fourier Image plane



Lab measurement of $g^{(2)}(0, 0, t)$ of simulated star/thermal light
Matthews, Kieda & LeBohec , to be published in J Mod Opt (2017)

$$\frac{\langle I_A I_B \rangle}{\langle I_A \rangle \langle I_B \rangle} = g^{(2)}(u, v, t) = 1 + \left| g^{(1)}(u, v, t) \right|^2$$

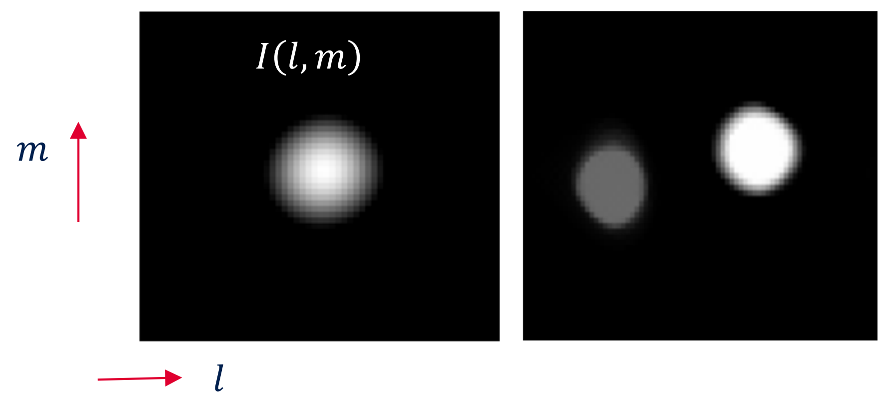
For II: experimental time resolution $\Delta t \sim$ 1 nsec
blackbody coherence time $t_c \sim {}^1/_{\Delta\nu} \sim 10$ psec

$g^{(2)}(0,0,0) = 1 + \epsilon \sim 1 + 10^{-4}$ small non-Gaussian fluctuations
=> Need large photon counts: 10+ m mirrors

$g^{(1)}$ (u, v, t) : first-order coherence
=1 for [u, v, t=0]

$$g^{(1)}(u, v, 0) = \iint I(l, m)\, e^{-2\pi i(lu+mv)} dl\, dm$$

$I(l, m)$ describes the image size and brightness distribution
(Van Cittert-Zernike Theorem 1934,1938)



Reconstructed simulated stellar images
stellar disk (left) & binary system (right)
Matthews, Kieda & LeBohec , ato be published in J Mod Opt (2017)

Potential SII at Optical Telescope Arrays

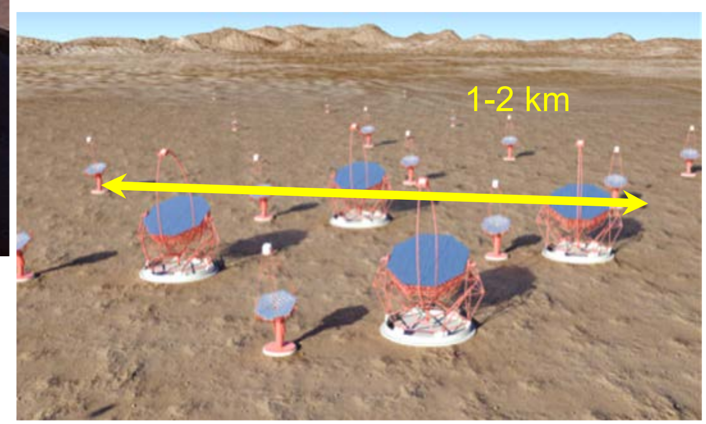
VERITAS IACT Array

- Excellent instruments for SII:
- -Large photon collection area (~10 m diameter mirrors)
- -Optically isochronous (< 5 ns)

VLTI- Paranal

100 m to km baselines
(milli-arcsec resolution)

Future CTA/pSCT Array

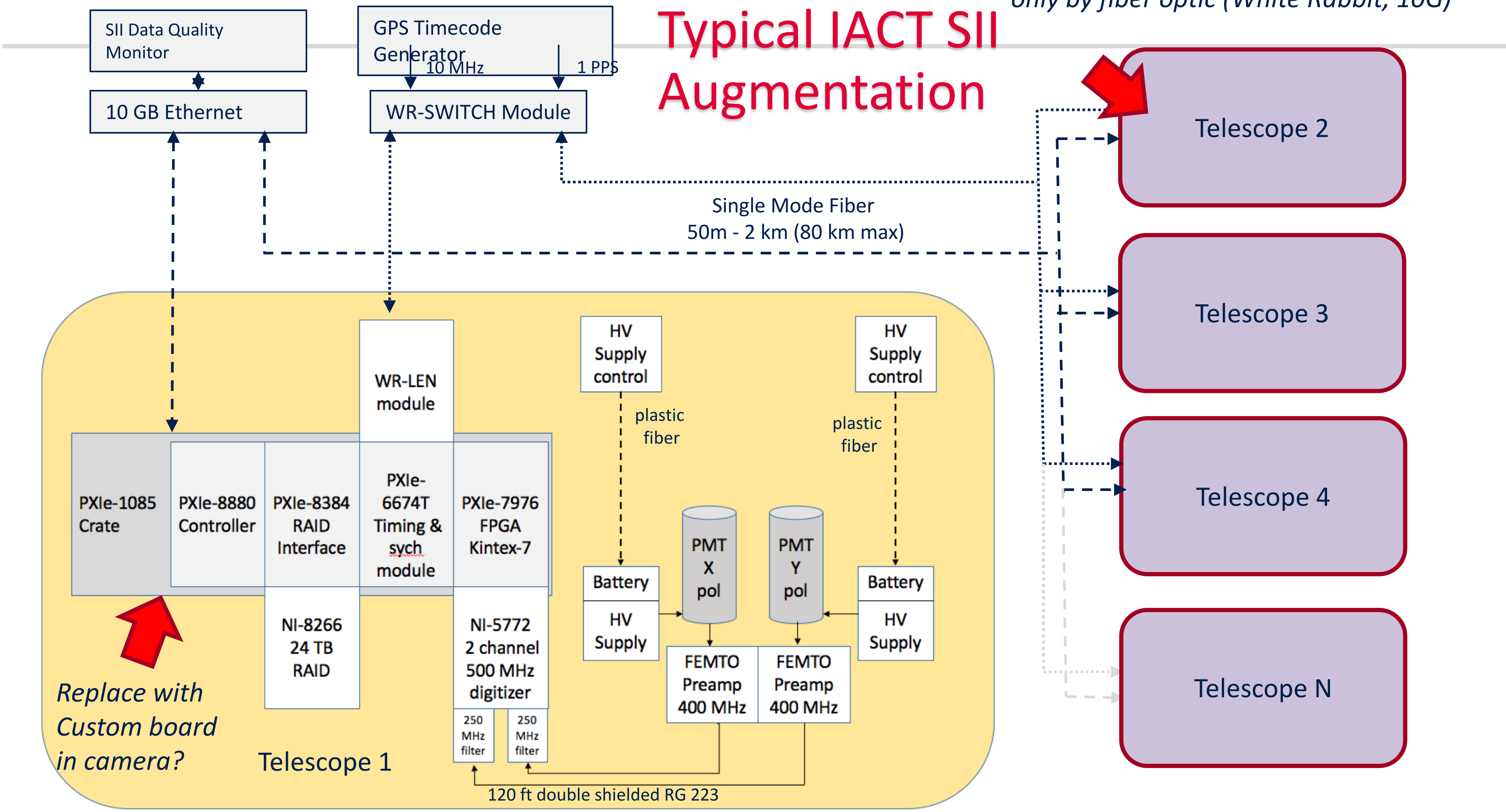


J. Holder and S. LeBohec, *Ap. J.* **649** (2006) 399

D. Dravins *et al., New Astronomy Reviews* **56**, 5 (2012) 143

Typical IACT SII Augmentation

Standalone telescope connected only by fiber optic (White Rabbit, 10G)

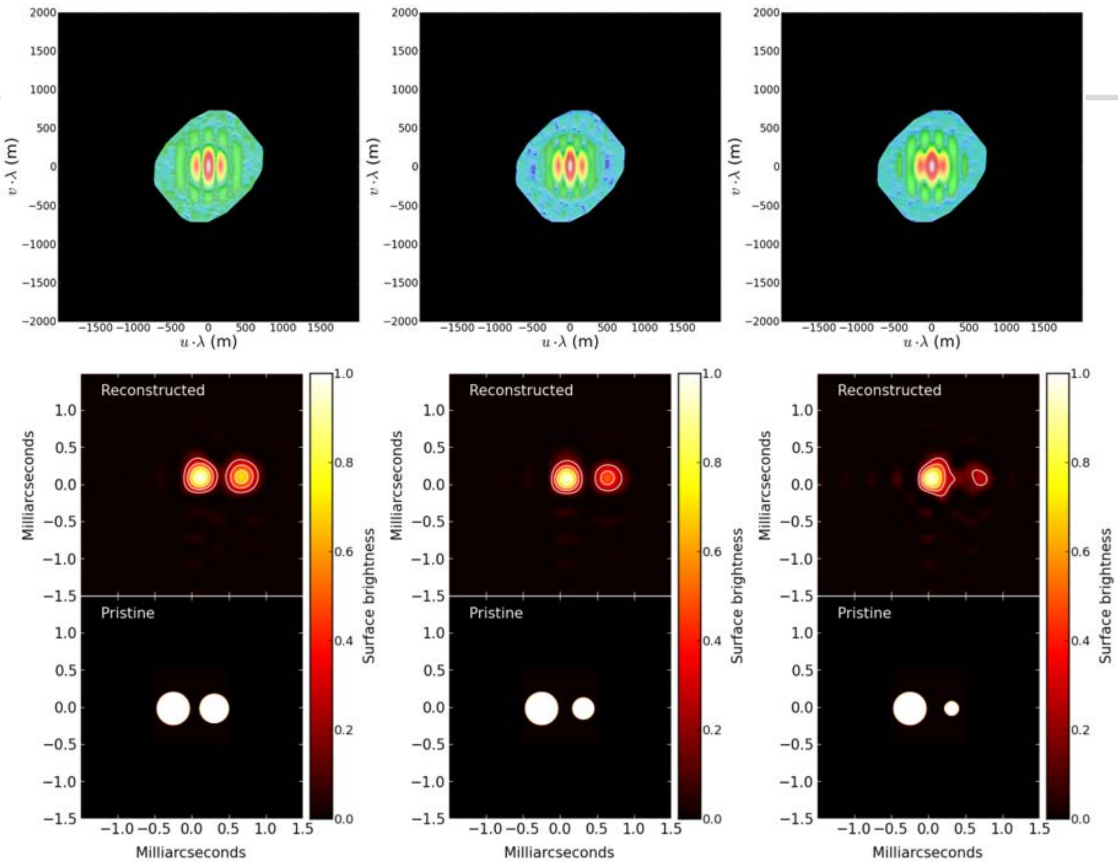


VERITAS SII augmentation of VERITAS funded by National Science Foundation (January 2018)

Simulated
Fourier image
Planes

Reconstructed
Binary images

Input
Binary images

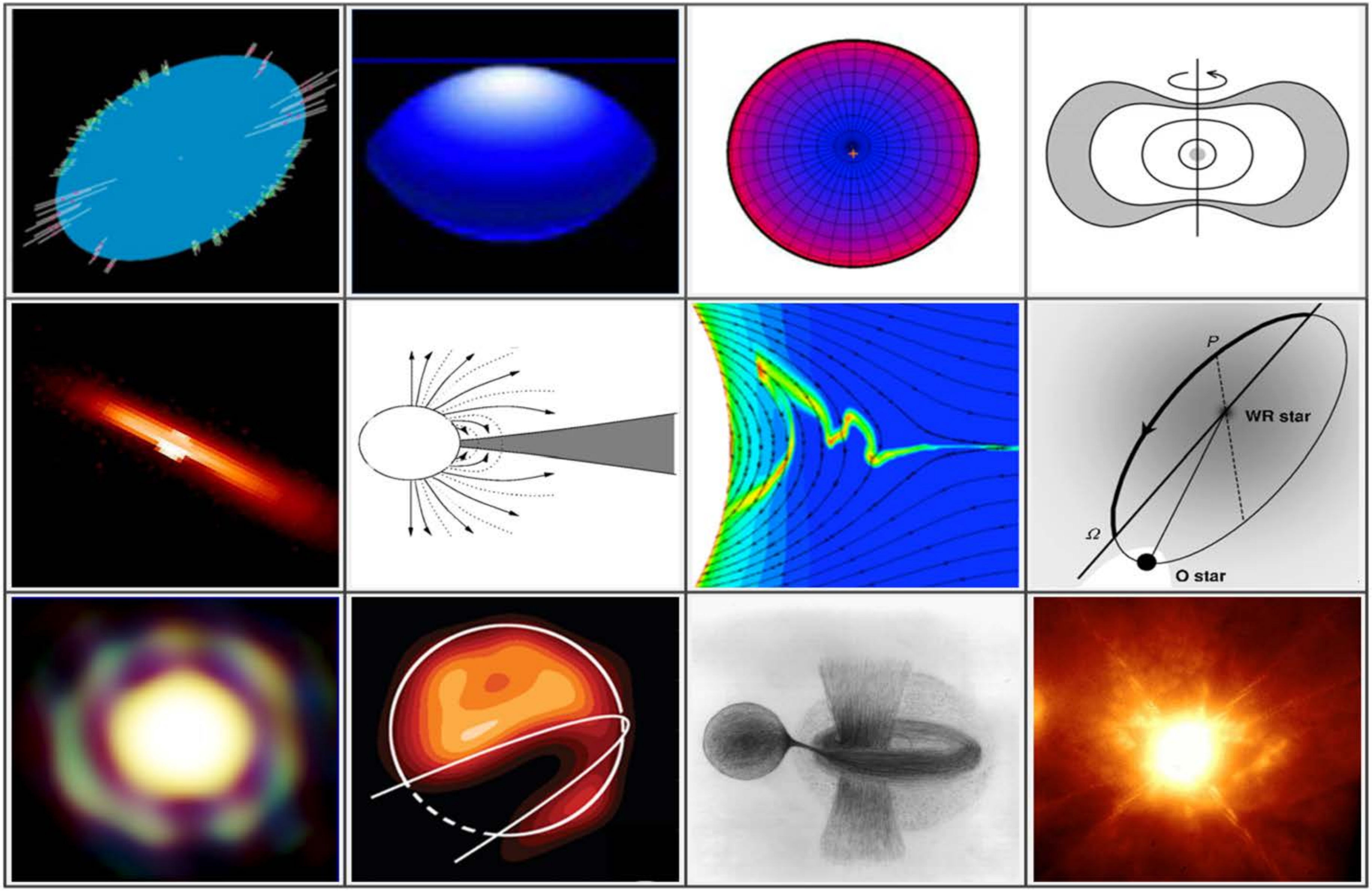


Simulated observations of binary stars with different sizes.
($m_V = 3$; $T_{eff} = 7000$ K; $T = 10$ h; $\Delta t = 1$ ns; $\lambda = 500$ nm; $\Delta\lambda = 1$ nm; QE = 70%)

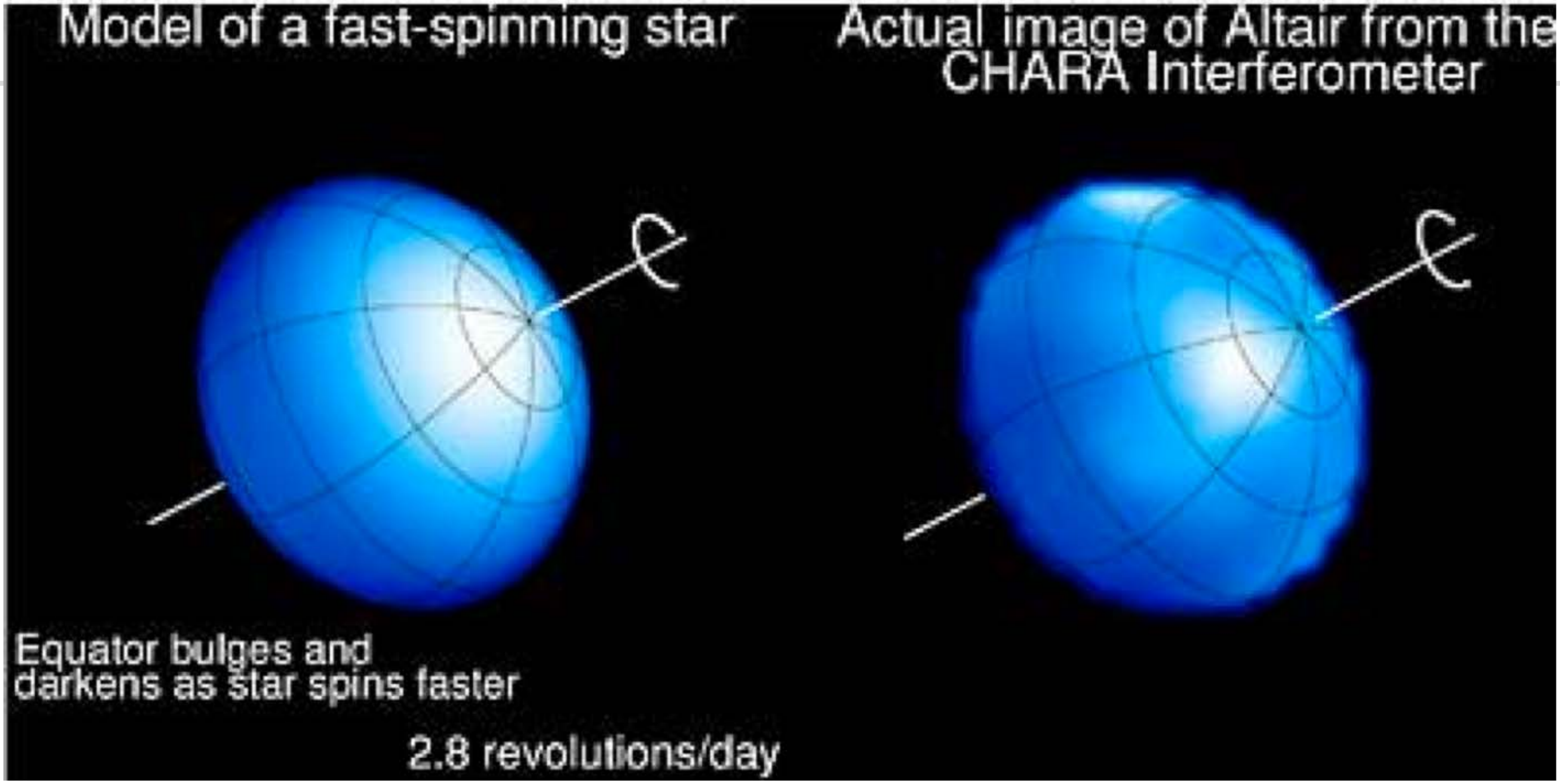
Already changes in stellar radii by only a few micro-arcseconds are well resolved.
Better sampling of Fourier image plane-> no ghost images

D.Dravins, S.LeBohec, H.Jensen, P.D.Nuñez:, CTA Consortium
Optical intensity interferometry with the Cherenkov Telescope Array, Astropart. Phys. 43, 331 (2013)

Astrophysical targets for km-scale interferometry



D.Dravins, S.LeBohec, H.Jensen, P.D.Nuñez:, CTA Consortium
Optical intensity interferometry with the Cherenkov Telescope Array, Astropart. Phys. 43, 331-347 (2013)



Changes in Stellar Evolution:

- Equitorial Bulge
- Large Temperature Gradient (von Zeipel effect)

J.CHARA/MIRC

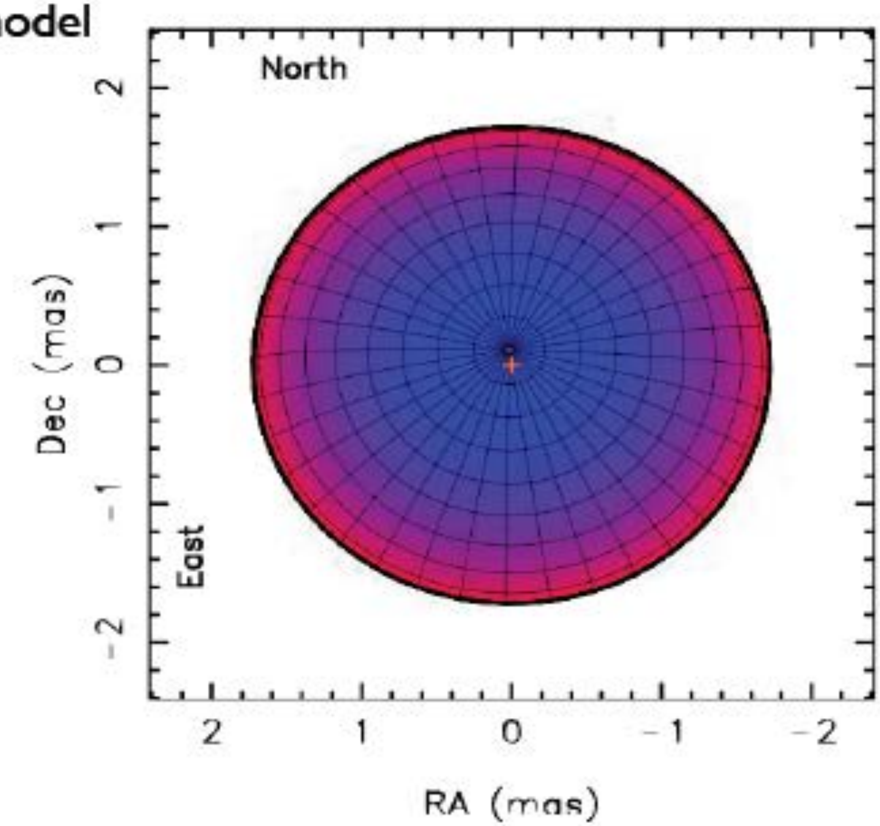
Vega (A0 V)

T_{eff}	9 000 K
V [mag]	0.03
$v \sin i$	15 km/s
θ	3.2 mas

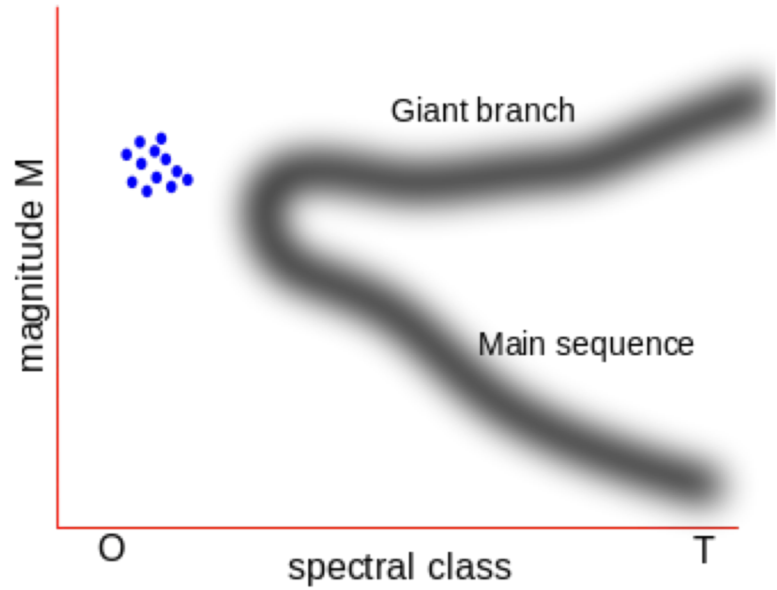
- Widely studied standard star. "Arguably the second most important star in the sky after the Sun" [Gulliver et al., 94, ApJ429]
- Realized to be a rapidly rotating pole-on star
- Center-limb intensities: 18x drop at 500 nm, compared to 5x drop for non-rotating model [Peterson et al., 2006, Nature 440, 896]

Chara Baseline ~ 100-200 m

Ang resolution ~ 0.5 mas



Blue Stragglers in Globular clusters



Generally thought to be the result of Binary collision/mergers

- Fast Rotations > 75x sun
- Angular momentum loss to disk?
- Convective dredge-up?
- Spectral misclassifications?

Cherenkov Telescope Array as an Intensity Interferometer

Expected resolution for assumed exoplanet transit across the disk of Sirius

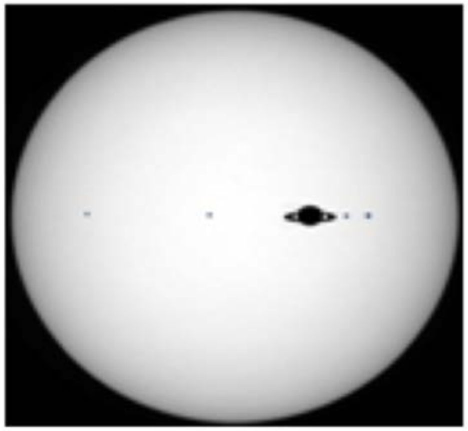
Stellar diameter = 1.7 solar
Distance = 2.6 pc
Angular diameter = 6 mas

Assumed Jupiter-size planet with rings;
four Earth-size moons;
equatorial diameter = 350 μas.

CTA array spanning 2 km;
Resolution 50 μas at λ 400 nm provides more than 100 pixels across the stellar diameter

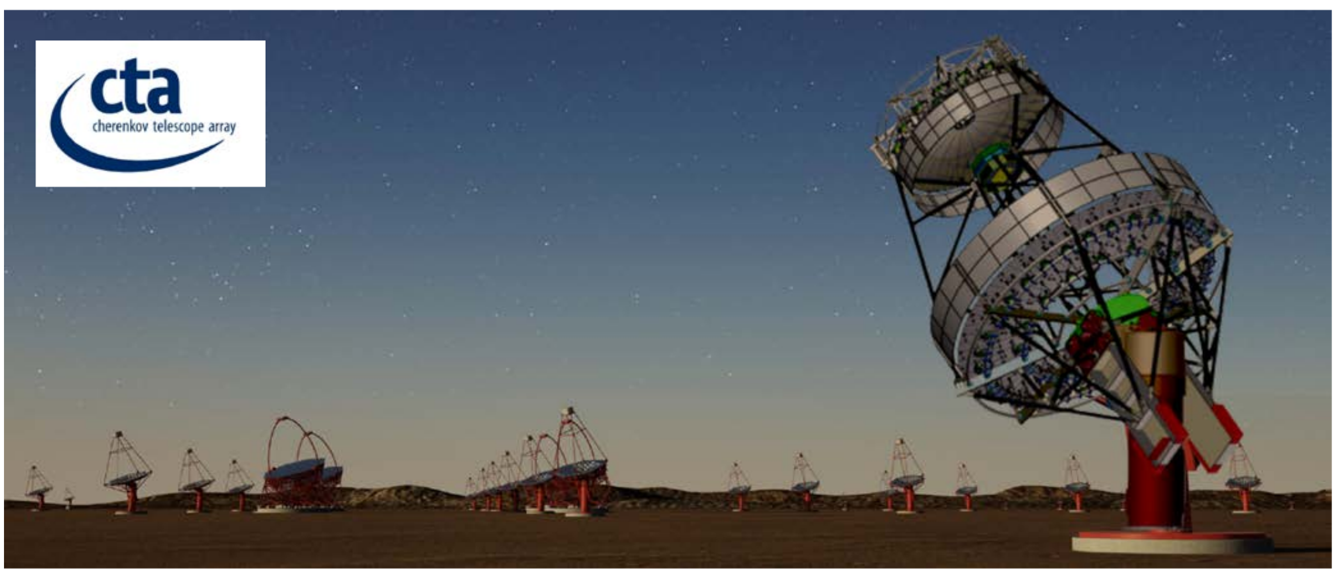
(D. Dravis, NICE SII workshop 2014)

SII Imaging → Summary



100 micro-arc second resolution of Jupiter & rins/moon @ 8 light year distance (Dravins 2013)

- Clear demonstration of spatial/time coherence on true quantum source (Blackbody)
- First successful demonstration of a simulated Binary system with an software/FPGA correlator.
- Significant improvement in quantifying system gain, noise levels & measurement reliability.
- Spring 2018 : Stellar Observations using StarBase-Utah
- Fall 2018-Jan 2020:VERITAS/pSCT SII Imaging
- Longer Term: CTA implementation



References

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- N. Matthews, D. Kieda & S. LeBohec, J. Mod Optics (2017).
- Dravins, D., Lagadec T., Nunez P., “Long baseline optical interferometry – Laboratory demonstration of diffraction limited imaging”, A&A 580, A99 (2015), arXiv:1506.05804
- D. Dravins et al., “Optical Intensity Interferometry with the Cherenkov Telescope Array”, Astroparticle Physics, Vol. 43, March 2013. arXiv:1204.3624
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- Nunez, P. D. 2012, “Towards Optical Intensity Interferometry for High Resolution Stellar Astrophysics”. PhD thesis, The University of Utah, Salt Lake City