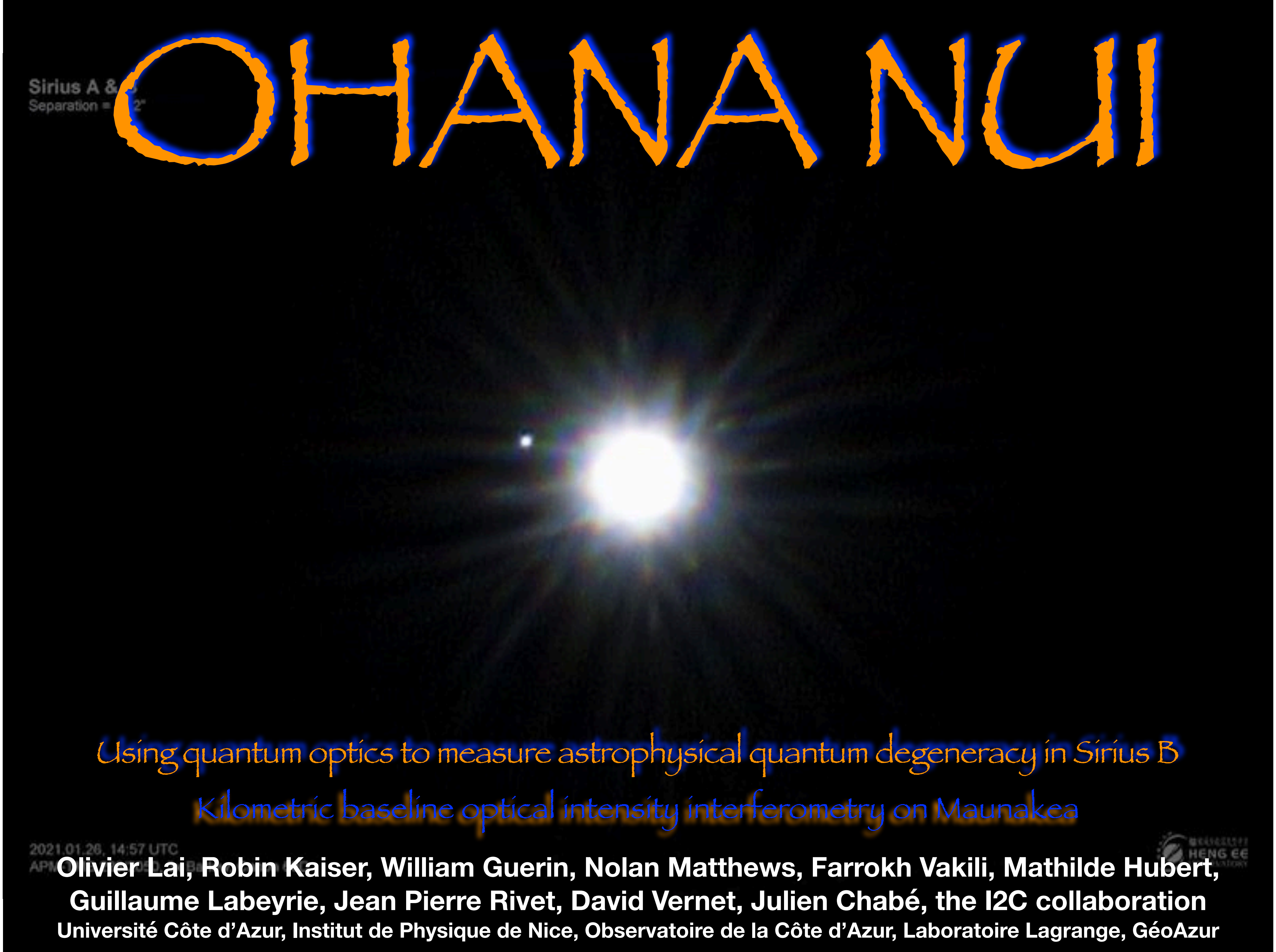
OHANA NUI



Using quantum optics to measure astrophysical quantum degeneracy in Sirius B

Kilometric baseline optical intensity interferometry on Maunakea

Olivier Lai, Robin Kaiser, William Guerin, Nolan Matthews, Farrokh Vakili, Mathilde Hubert, Guillaume Labeyrie, Jean Pierre Rivet, David Vernet, Julien Chabé, the I2C collaboration

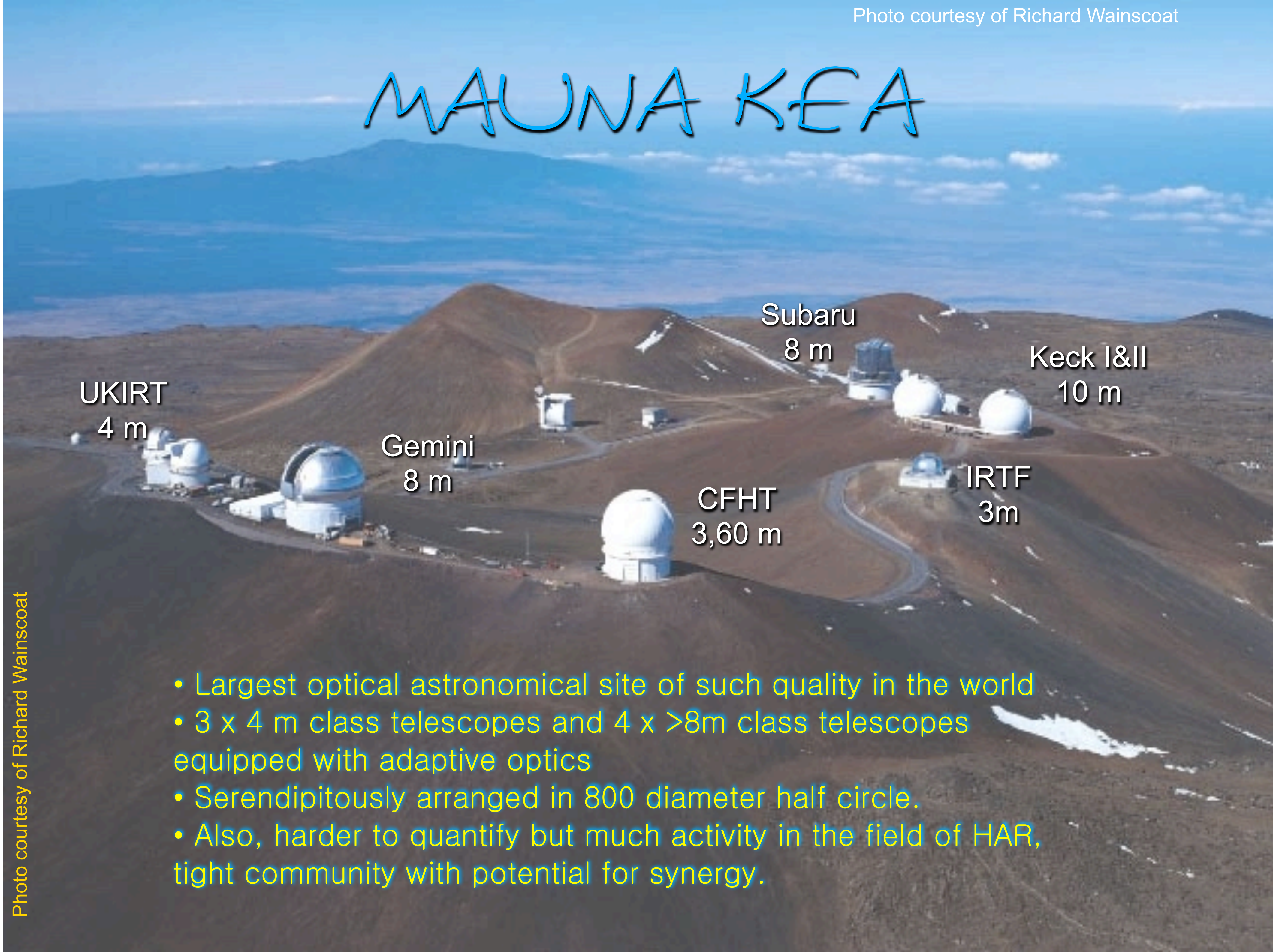
Université Côte d’Azur, Institut de Physique de Nice, Observatoire de la Côte d’Azur, Laboratoire Lagrange, GéoAzur

OHANA

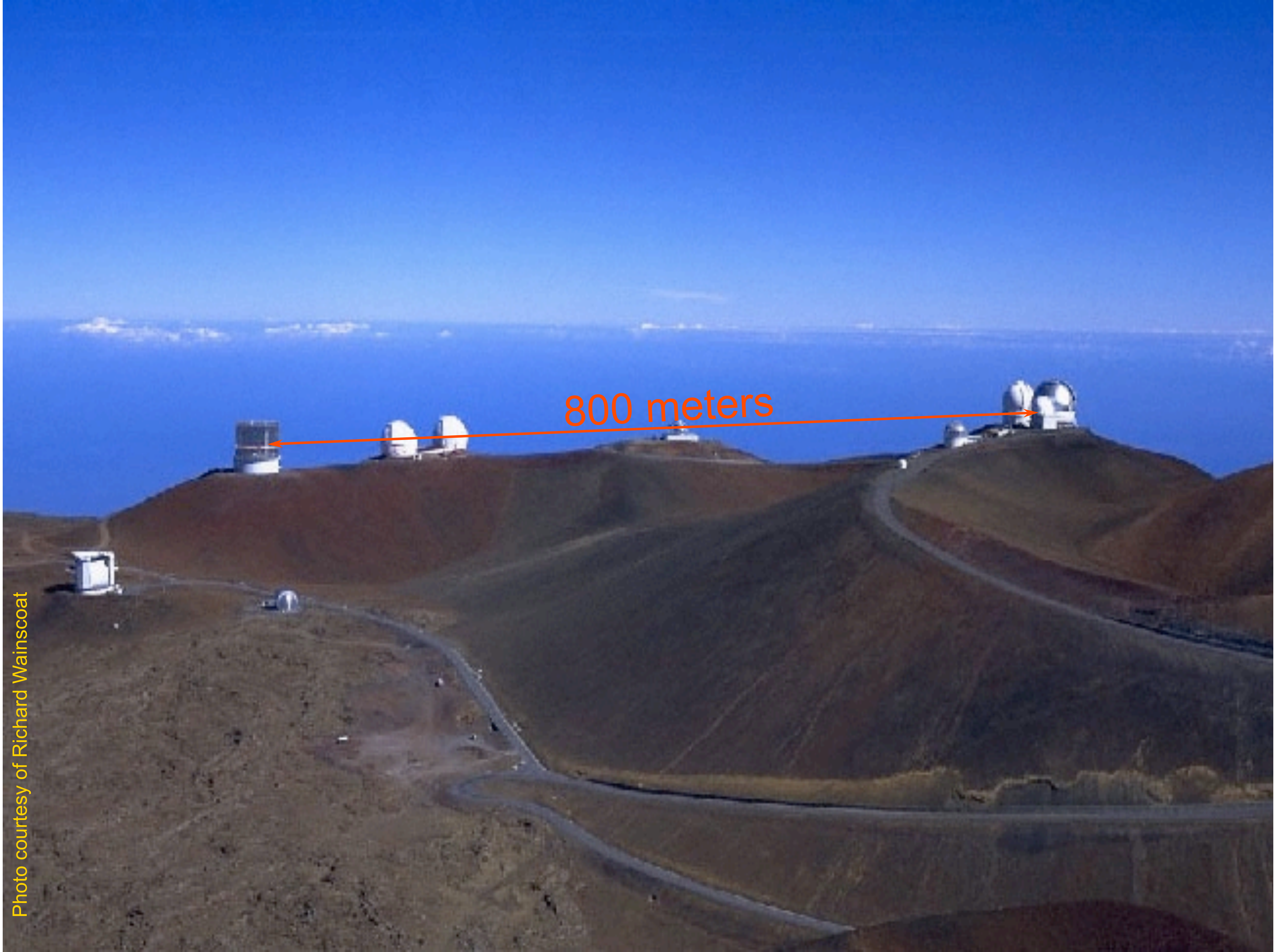
A crazy idea!

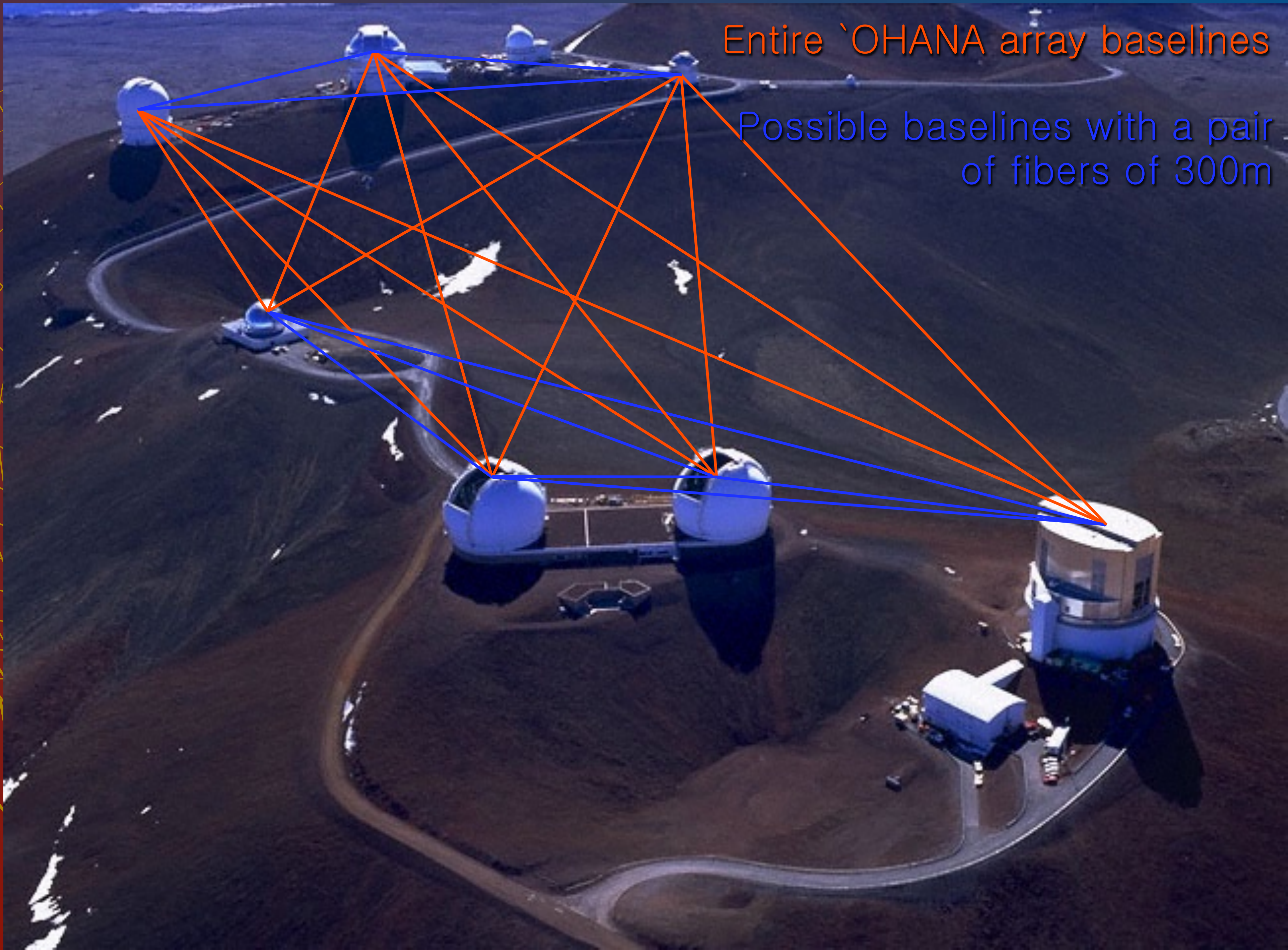
- Ambitious project: interferometric connection of Maunakea observatories for equivalent 800m diameter telescope in terms of resolution (λ/B ~ 2,75 nanoradians ~ 500 μarcseconds at K band)
- Original paper exposing this idea: Mariotti et al., 1995.
  Started project with Guy Perrin in Jean-Marie's memory in 1999.
- Two key technological enablers: adaptive optics and single mode fibres.
  - AO allows to restore coherence to light after crossing atmosphere.
  - Single mode fibres only transmit coherent light; but preserve phase.
- Thus it seemed possible to generate interference fringes (and measure their contrast) from light from distant telescopes on a site never originally planned for it.

MAUNA KEA



- Largest optical astronomical site of such quality in the world
- 3 x 4 m class telescopes and 4 x >8m class telescopes equipped with adaptive optics
- Serendipitously arranged in 800 diameter half circle.
- Also, harder to quantify but much activity in the field of HAR, tight community with potential for synergy.


800 meters
Photo courtesy of Richard Wainscoat

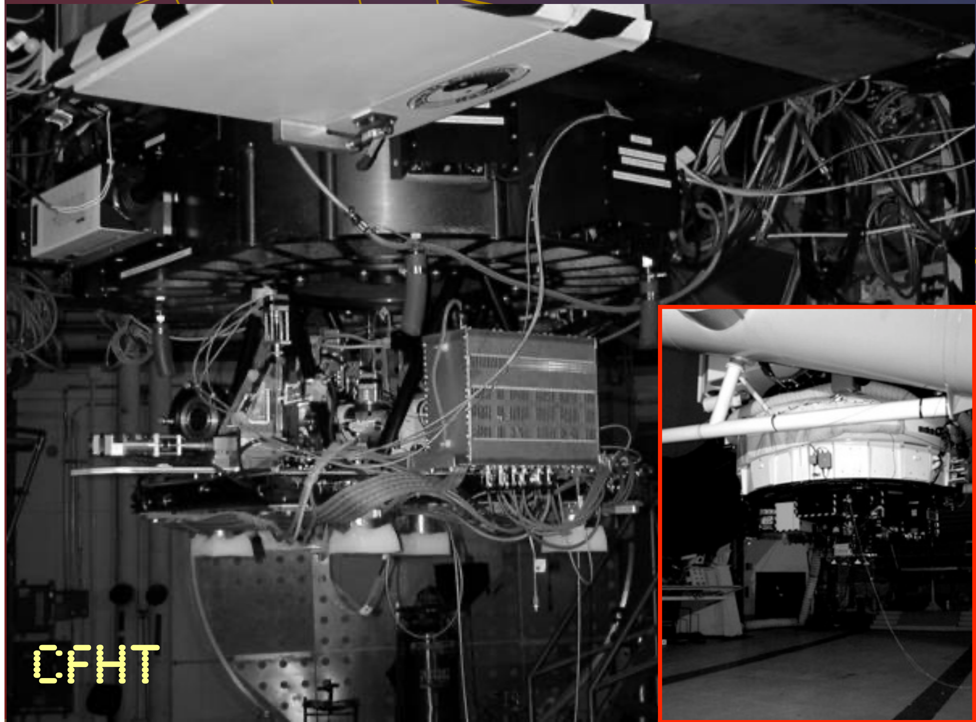

Entire `OHANA array baselines
Possible baselines with a pair of fibers of 300m

CONSTRUCTIVE INTERFERENCES ON MAUNA KEA

- `OHANA was a multi national collaboration whose goal was optical/IR interferometry on hectometric baselines
  - Mauna Kea Master Plan lays out strict rules for impact of further development on Mountain.
    - Use of optical fibers ideally suited to address this issue.
      - Fibers seemed in many ways ideal, but turned out to be great vibration sensors.

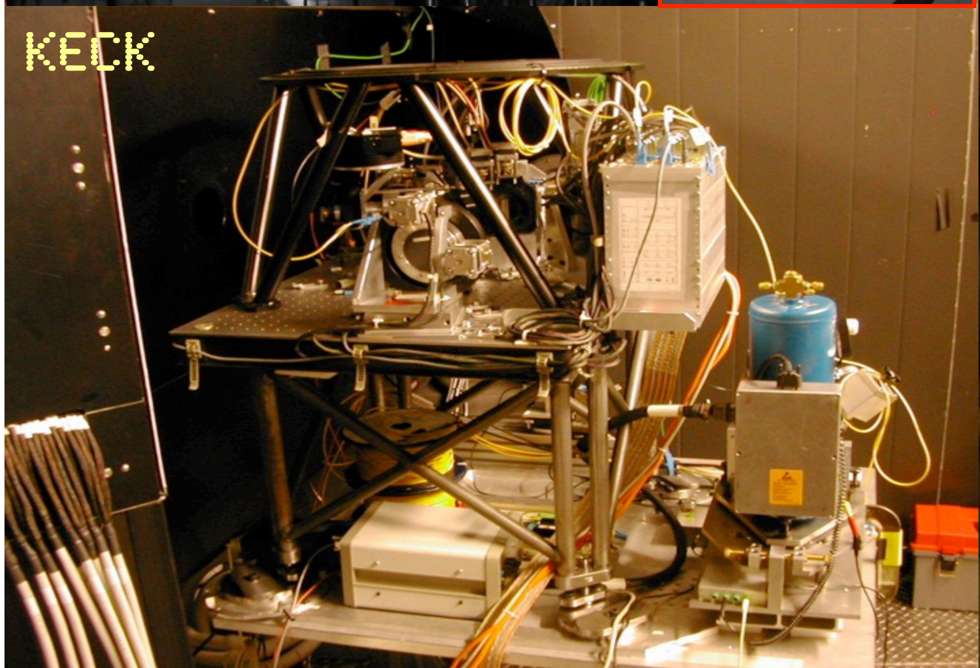
- Achievable angular resolution of 500μas (K band, 300μas in J), with goal of K limiting magnitude of 12.
- Main astrophysical drivers were Young Stellar object accretion, AGN BLR and quasars, as well as Cepheid direct diameter measurement.

SOME EARLY SUCCESSES



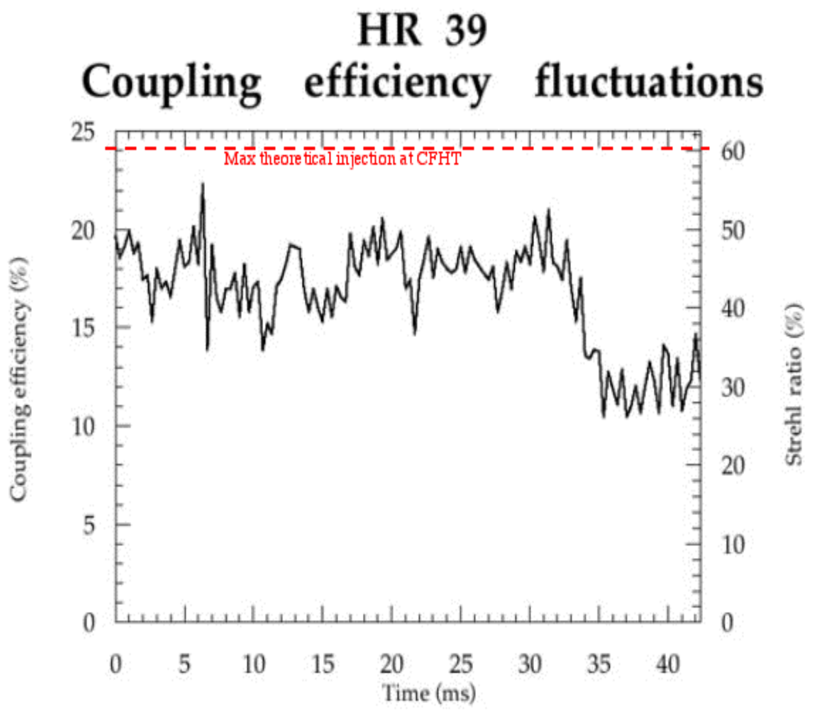
INJECTION TESTS (FIBER/AO COUPLING)

- AT CFHT IN JANUARY AND AUGUST 2002
- KECK IN DECEMBER 2002
- GEMINI IN JULY 2003

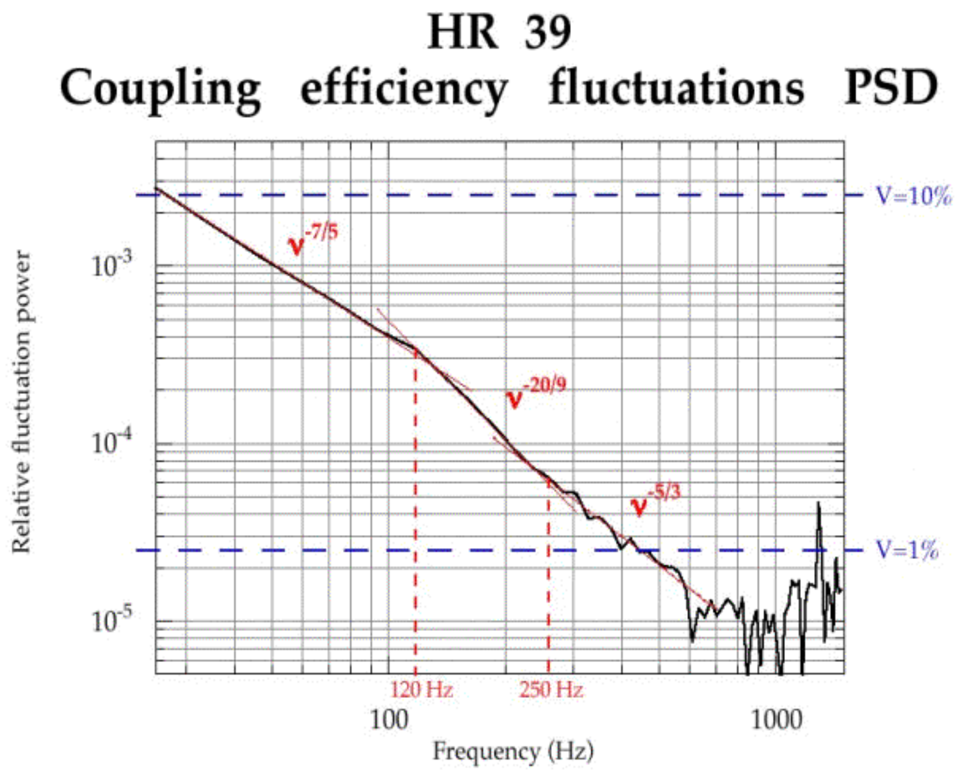


Injection Module

- At CFHT in January and August 2002



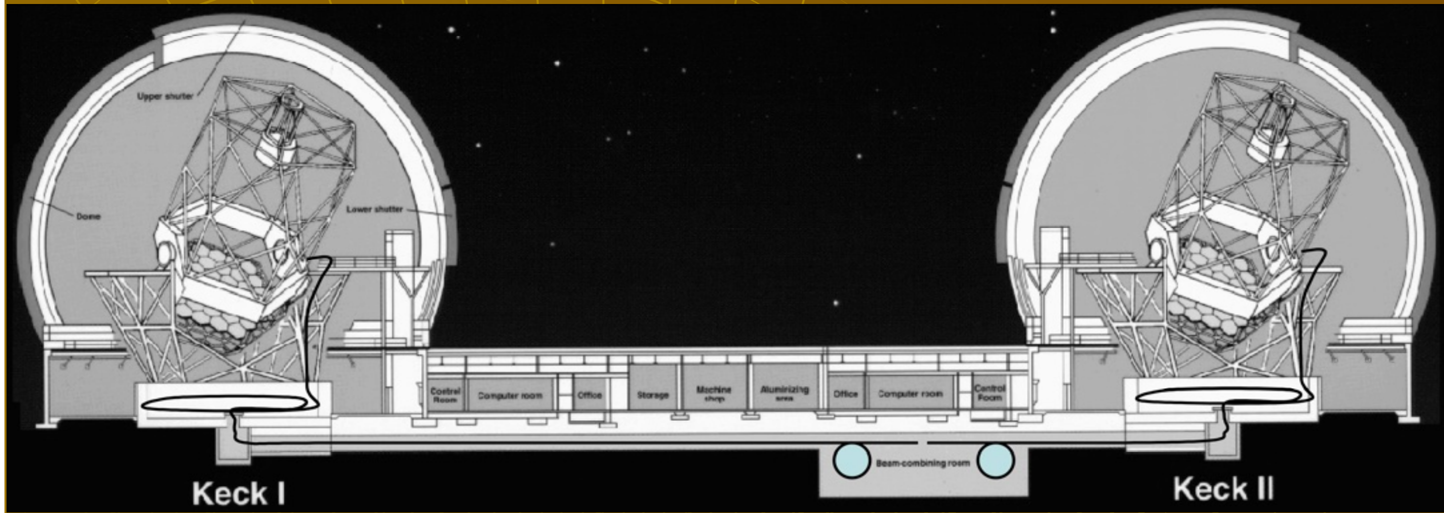
42 ms scan



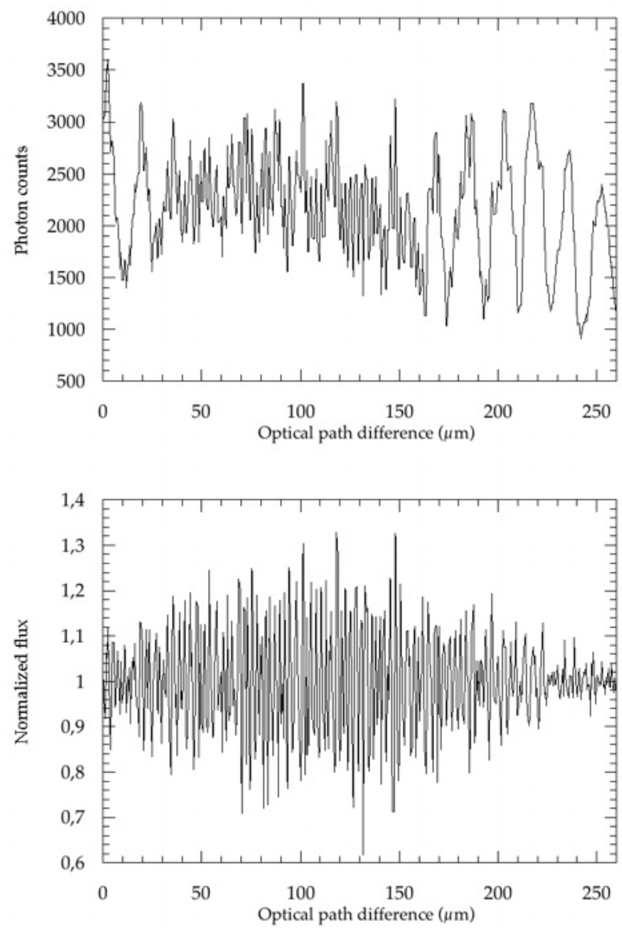
Based on 200x42 ms scans

'OHANA @ KECK EXPERIMENT

Goal: Attempt to duplicate Keck interferometer using fibers to bring light to common focus:

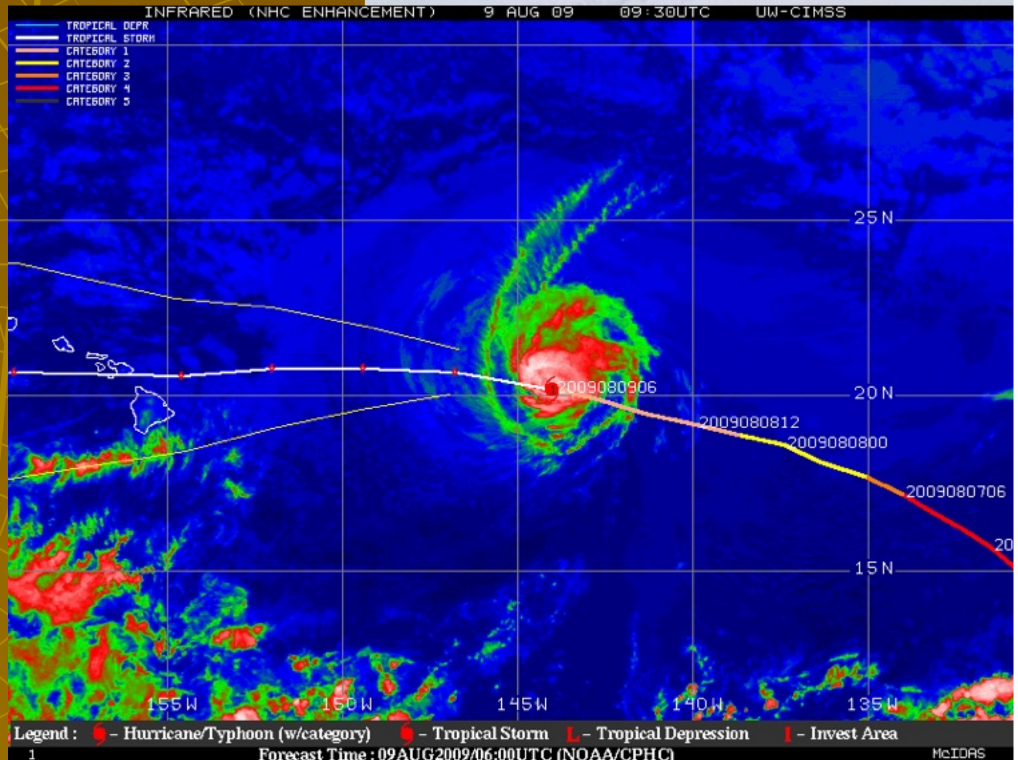


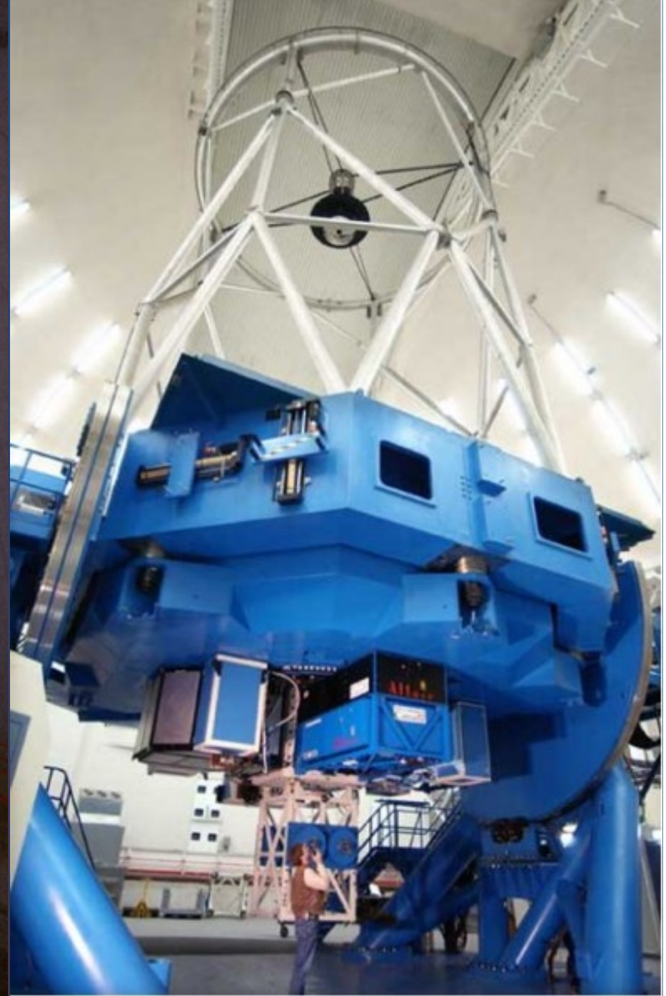
- December 1st 2004
  - Lost to weather
- January 31st 2005
  - Lost to weather
- June 17th 2005
  - Clouds, varying photometry. Found dispersed fringes at 12:26 on Hercules (contrast ~25%) on 107 Her, K=4.6. Problem with dispersion
  - Obtained data and calibrator on giant star, but Archiver failure.



'OHANA @ KECK EXPERIMENT

- A pattern was starting to emerge…
  - May 2006
    - Snow… In May!
    - Never found the fringes on the sky
  - November 2007
    - Clear night, but humidity went to 100% at 8pm and never came down.
  - August 2008
    - Hurricane Felicia
  - March 2009
    - AO failure
- Defeated by weather?
  - No!
    - Young and foolish?
    - Maybe: persevered with CFHT-Gemini baseline

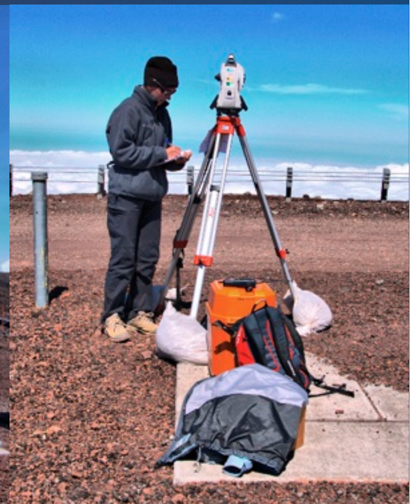


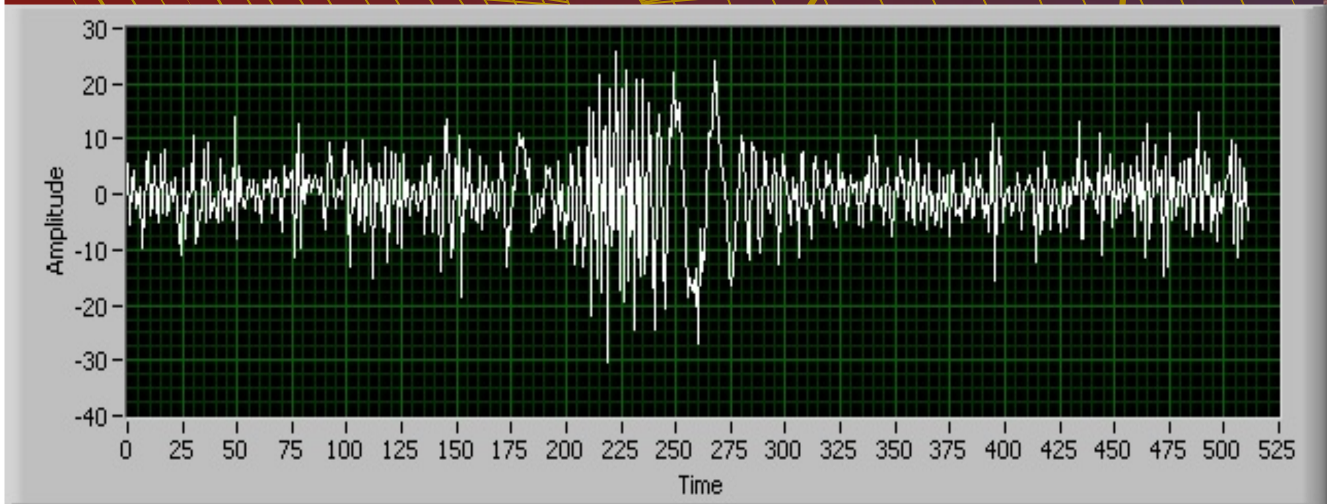


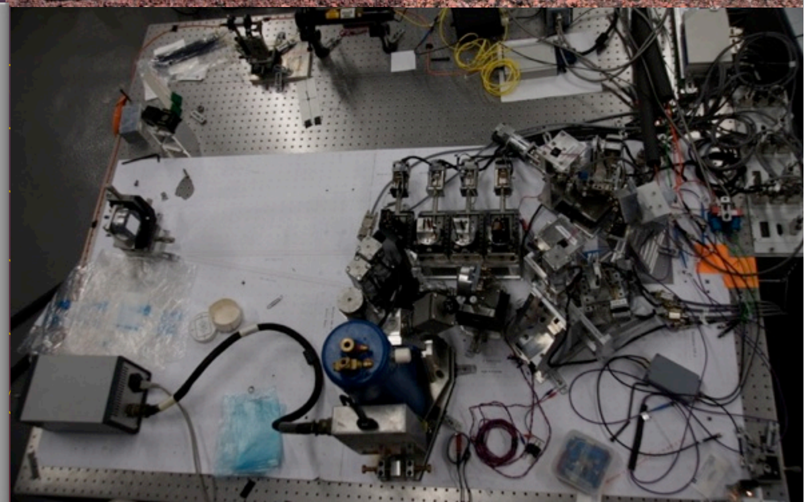
- Attempted to link CFHT with Gemini (2006-2012).
  - Two (very different) telescopes never designed to be coupled interferometrically.
    - Gemini 8m alt-az with SH AO system, field rotator and pupil rotation
    - CFHT is a 3.6m equatorial mount with a curvature AO system
  - Baseline is 160m long, aligned almost perfectly North South.

OHANA CFHT-GEMINI

- For CFHT-Gemini, we had to build an interferometer from scratch.
  - October 2006: Magnitude 6.5 earthquake
  - October 2006-March 2007: delay line installation
  - Summer 07: Beam combiner installation
  - Winter 07: pipe installation
  - Summer 08: Baseline determination
  - Internal fringes in Spring 2010

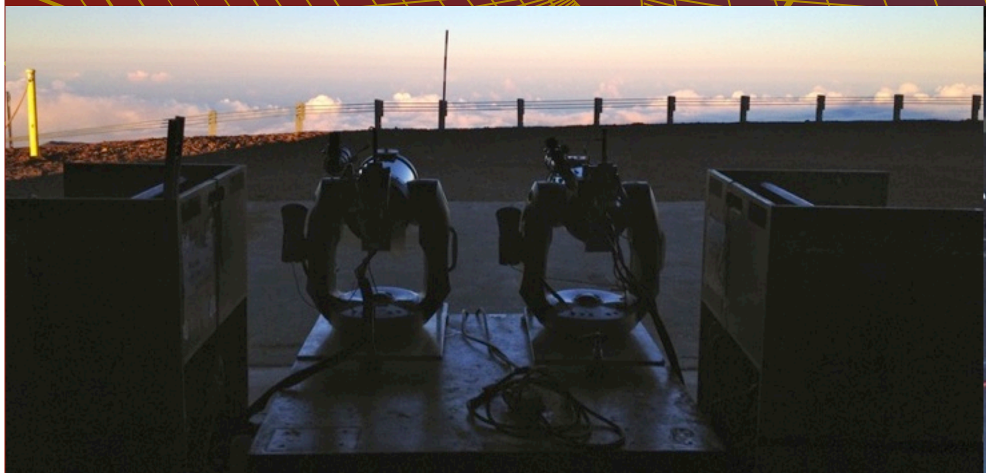


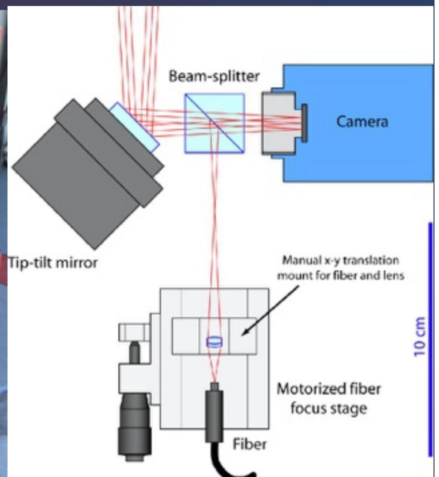




OHANA IKI

- Before using large telescopes, wanted to validate entire chain (from acquisition to calibrated fringes) using small telescopes.
  - Developed Ohana iki (iki means small in Hawaiian) project, mostly carried by students.
  - Two Celestron C8 ($r_0(J)$~0.3m) with image stabilisation and fiber injection.
  - Built a kind of amateur interferometer!

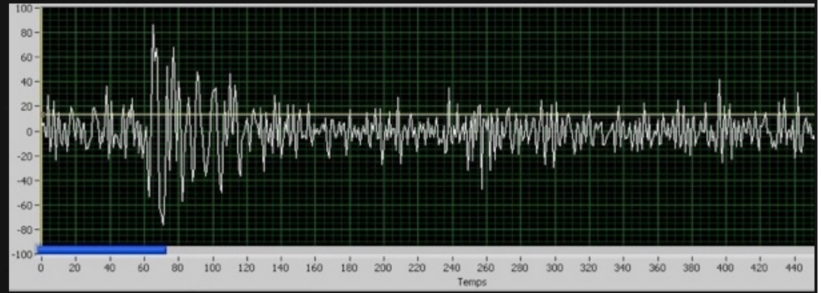


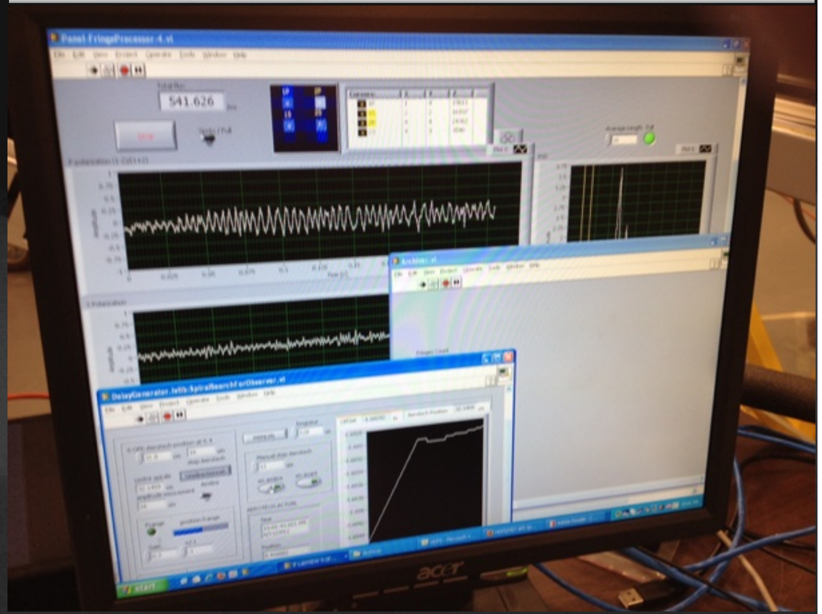


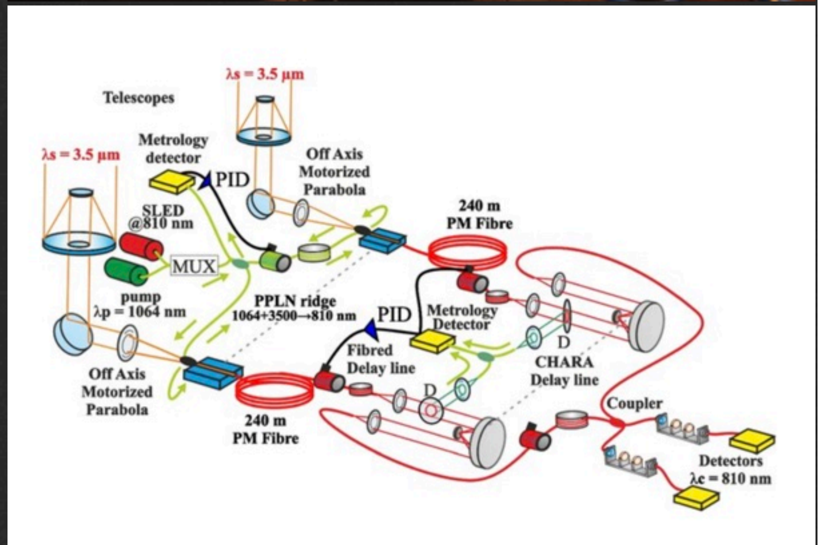

TWO INTERFEROMETERS ON MAUNAKEA

OHANA IKI

- Interference fringes
    - In J band in July 2010 (Arcturus) ->
        - In H band in June 2012 (internal) ->
    - But vibration environment much worse than originally measured.
    - Not attributable to a single source, it may have been that delay line amplified ambient vibrations, and/or the fibers themselves!
        - Real problem as many microns of longitudinal vibrations (> 1 fringe) at high frequency: Unable to measure spectrum, calibrate visibilities.
    - Would have had to develop fibered metrology, e.g. ALOHA@CHARA ->







End of an Era

- In 2012, Guy Perrin was co-PI of Gravity on VLTI (and vice president of Paris Observatory), Julien Woillez was leaving Keck, and my appointment at CFHT was terminated, so OHANA stopped.
  - OHANA project had many offshoots:
    - Extension of CHARA for km baselines using fibres at H band (CHARA Michelson Array Pathfinder project, Ligon et al, 2022),
    - Progress on fluoride glass fibres enabled GRAVITY instrument on VLTI (with spectacular results on SgrA*),
    - Ohana iki -> AGILIS concept -> STELLIM (Stellar imager using VLTI delay line and 13 small telescopes), Haubois et al 2022.
- We were young and ambitious then, we put a lot of effort into these experiments…
  - But when told we could do astronomical interferometry without delay lines, without worrying about atmospheric turbulence, vibrations or matching the opd to a few nm? But with caveat: using quantum optics/intensity interferometry…
  - Well, despite being older, apparently not any wiser…!

YOUNG AND FOOLISH

Older, and apparently not any wiser

- Difficulties offset (but hopefully also reduced):
  - Baseline determination needs to be carried over larger baselines than CFHT-Gemini, but precision relaxed (<cm, but not <mm).
  - No need to lay fibres between observatories: use existing telecom dark fibres to distribute time using White Rabbit, SigmaWorks or other protocol.
  - Can carry out preliminary experiments on smaller baselines with smaller telescopes (e.g. CFHT-IRTF-UH88) or single telescope (e.g. Subaru SCExAO single mode fibre feed in the near IR) for $g^2(\tau)$.
- OHANA network rekindled, support from CFHT, W.M. Keck Observatory, Gemini Observatory, Subaru Telescope and University of Hawaii.
- Maunakea is ideal for an experiment to directly measure the diameter of closest known White Dwarf, Sirius B (Magnitude 8, ~40µas).

Sirius B, Radical Scientific Goal!

- So why Sirius B?
- Sirius A was first star observed by II (1956).

A TEST OF A NEW TYPE OF STELLAR INTERFEROMETER ON SIRIUS

By R. HANBURY BROWN

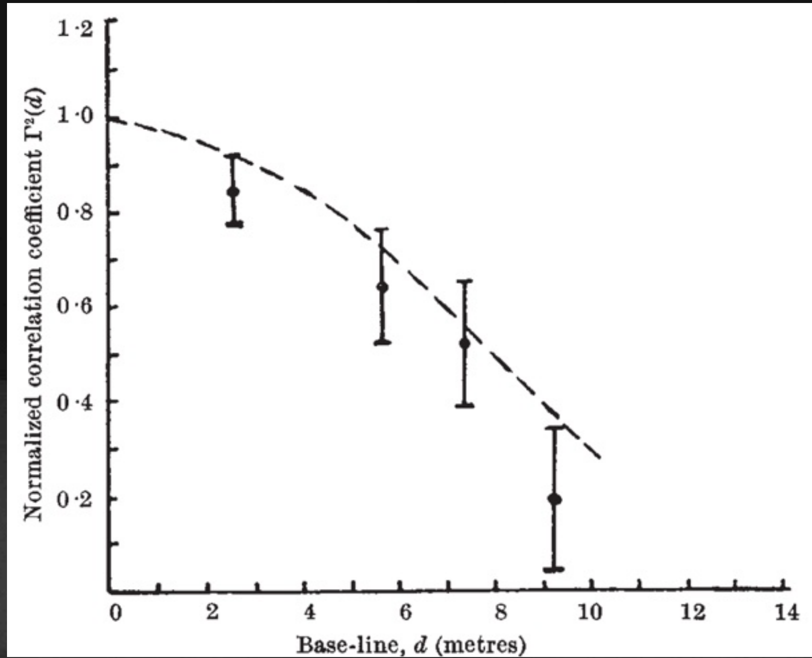
Jodrell Bank Experimental Station, University of Manchester

AND

Dr. R. Q. TWISS

Services Electronics Research Laboratory, Baldock

$g^{(2)}(r)$ measured on Sirius (A!) from Manchester, brightest star in visible. Two telescopes made from searchlights with 1.56m diameter and separation up to 9m. First direct measurement of the angular diameter, 6.8 ± 0.5mas



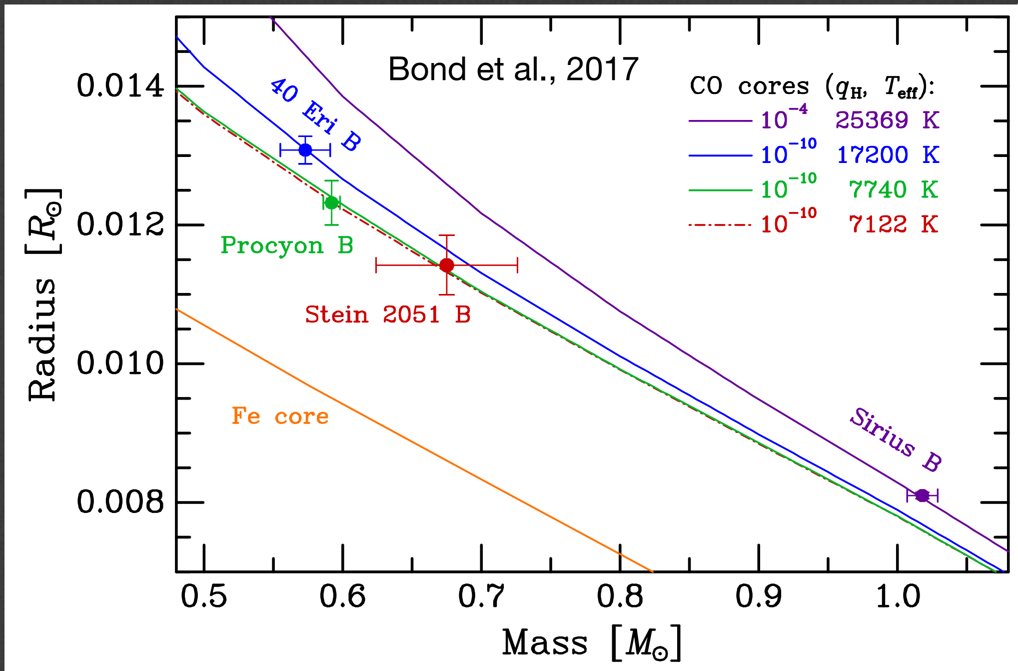
- 70 years later propose to observe and resolve Sirius B, closest known white dwarf.
- White Dwarfs, though well known, are very exotic objects.
  - Usually produced after nuclear fusion stops and outer shells ejected in planetary nebula. Electrons in core become a degenerate gas, all energy levels are filled due to Pauli exclusion principle, preventing further gravitational collapse. Young WD temperature $>10^5$K, slowly cool down over billions of years (temperature of e^- gas in core 10^7~10^8K!)
- Direct diameter measurement to confirm models, constrain mass-radius discrepancy & study relativistic corrections of equation of state of degenerate state of matter.

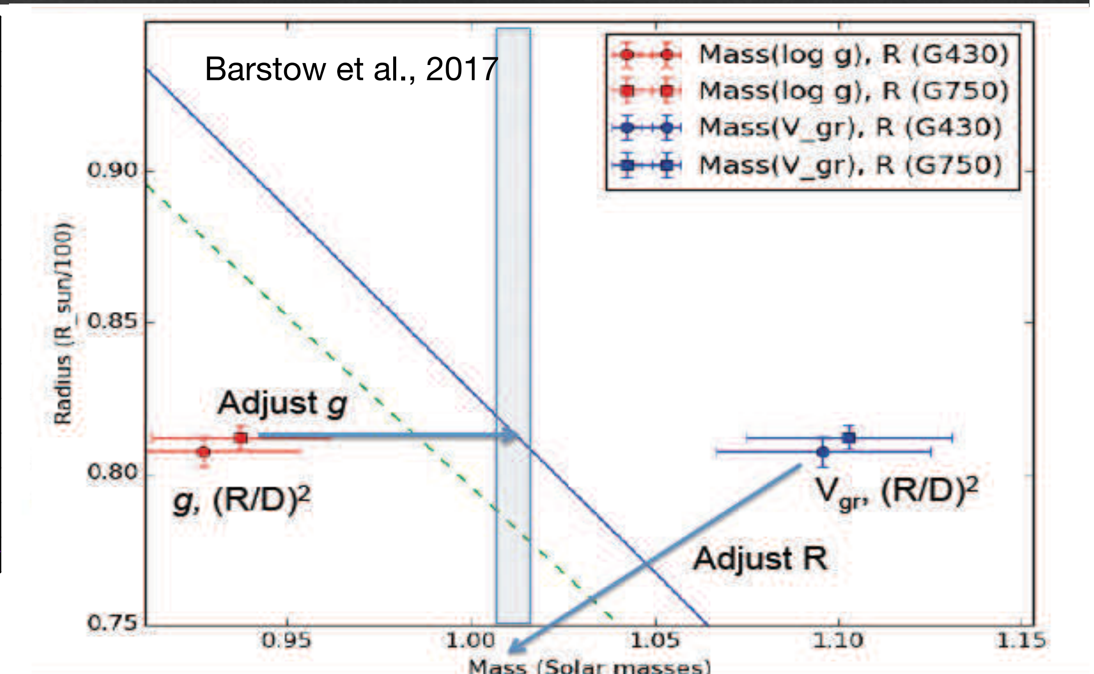
MASS-RADIUS OF WHITE DWARF

- Non-relativistic equation of state gives Mass-radius relationship: $R \simeq \frac{N^{5/3}\hbar^2}{2m_e G M^{1/3}}$, with *R* radius, *M* mass of star, *N* the number of electrons/unit mass (dependent only on composition), m_e electron mass and *G* the gravitational constant.

- Dynamic mass in binary systems (e.g. Sirius, 40 Eridani)

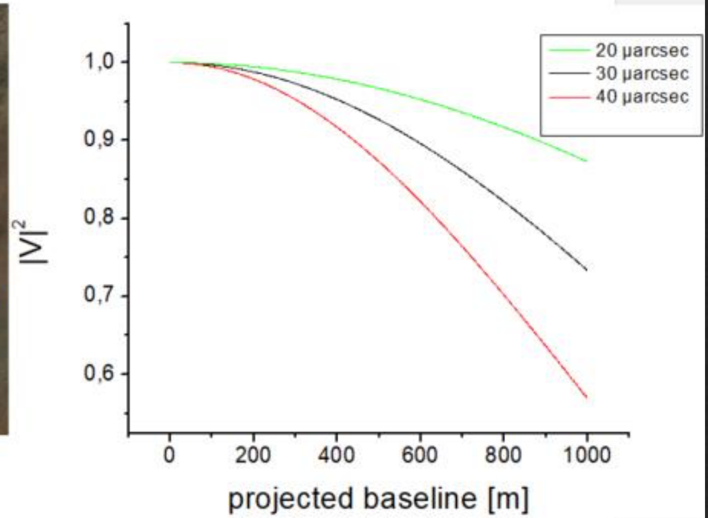
- Radius from normalised flux. But Mass-Radius discrepancy.

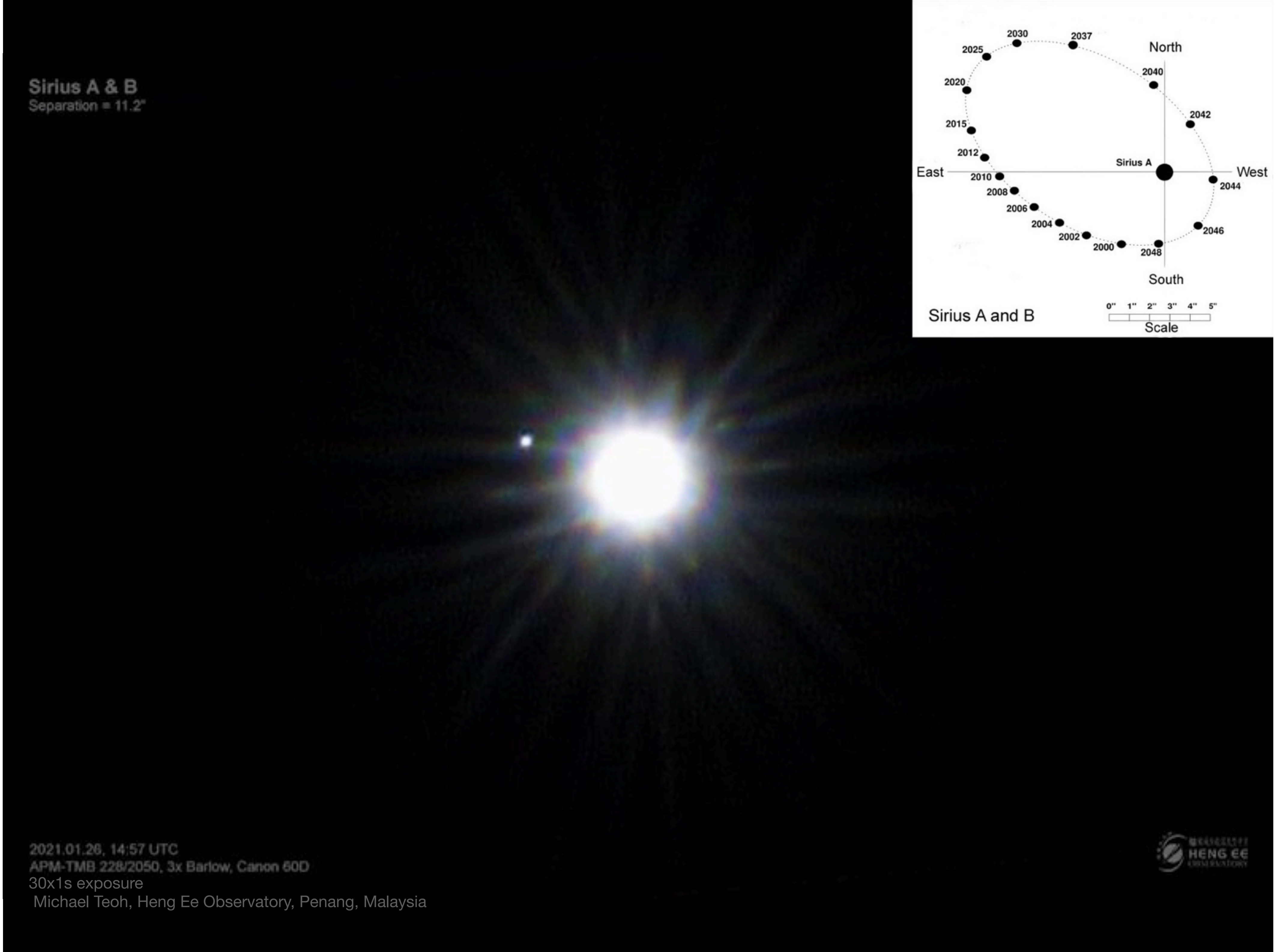




OHANA NUI

- Sirius B expected apparent diameter: 40µas
- At 440nm, with longest baseline on Maunakea (800m), λ/B=115µas
- So at 40µas, which is 1/3, we can still expect V^2~70%, good contrast for detection, but still sufficiently ≠ 1 to fit uniform disk and obtain diameter..
- Keck, CFHT, Gemini, Subaru, University of Hawaii (UH88, IRTF, UKIRT) signed letters of support…
- “We’re putting the band back together…!”




Sirius A & B
Separation = 11.2"
2021.01.26, 14:57 UTC
APM-TMB 228/2050, 3x Barlow, Canon 60D
30x1s exposure
Michael Teoh, Heng Ee Observatory, Penang, Malaysia
North
South
East
West
Sirius A
2030
2037
2025
2040
2020
2042
2015
2012
2010
2044
2008
2006
2004
2046
2002
2000
2048
Sirius A and B
0" 1" 2" 3" 4" 5"
Scale