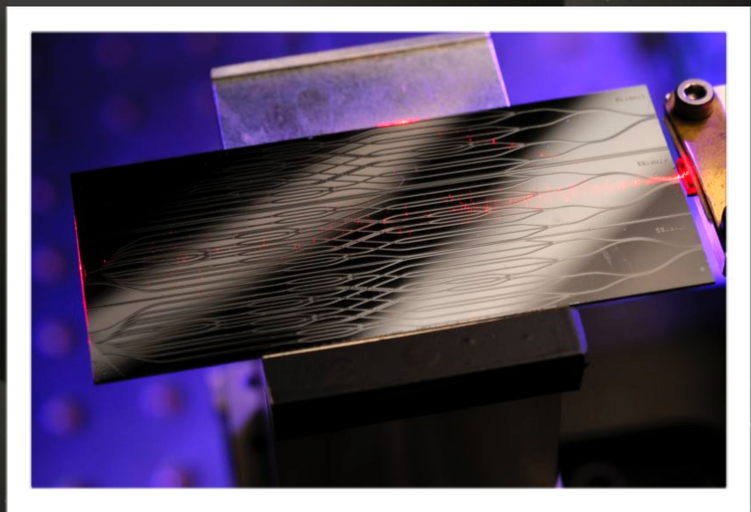
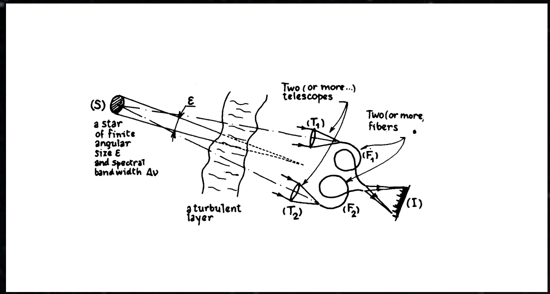
Photonics for long baseline interferometry

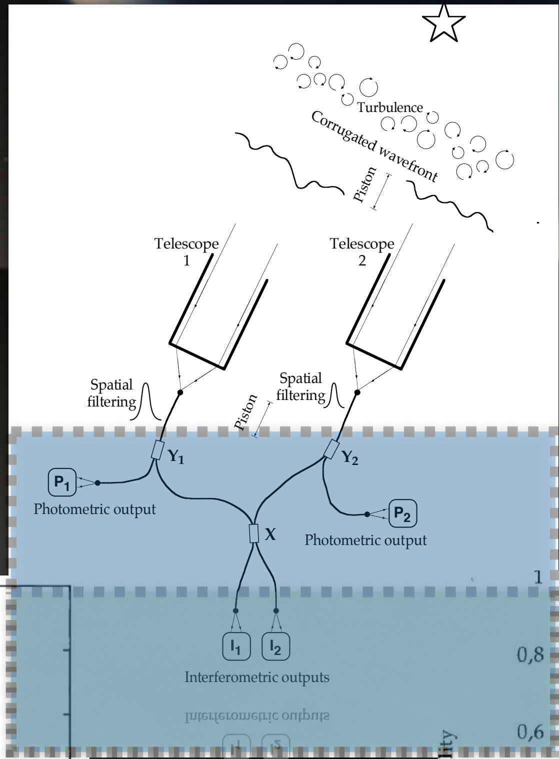
Jean-Philippe Berger
European Southern Observatory



The initial push

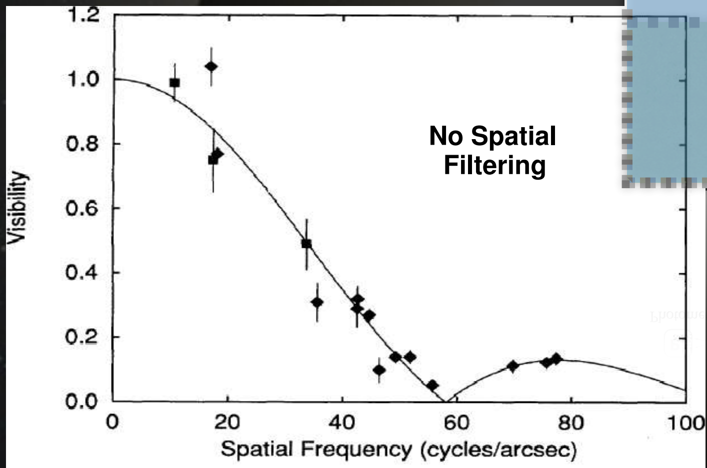


Froehly 1981

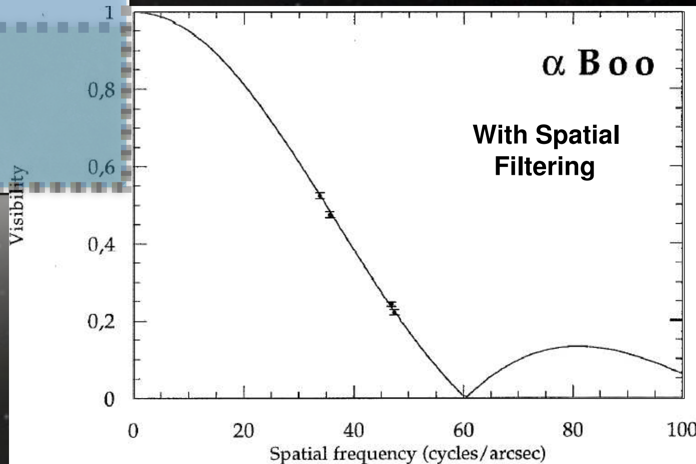


Coudé du Foresto 95
Perrin 98

Kern et al. 1996

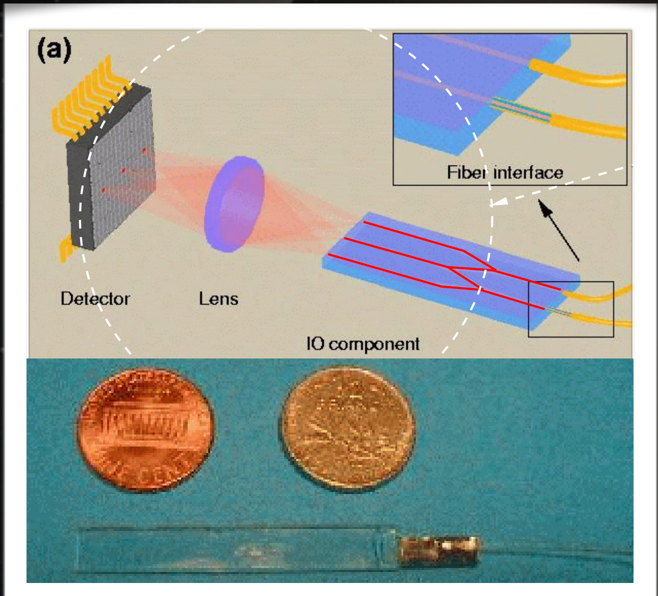


picture from Tuthill et al.

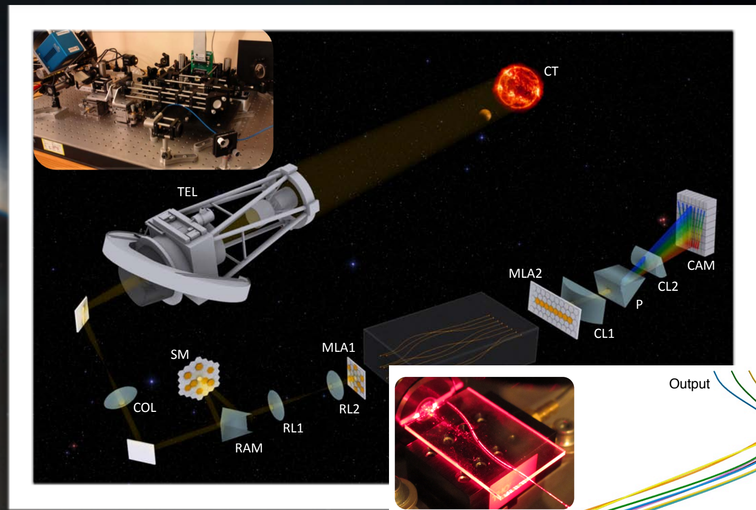


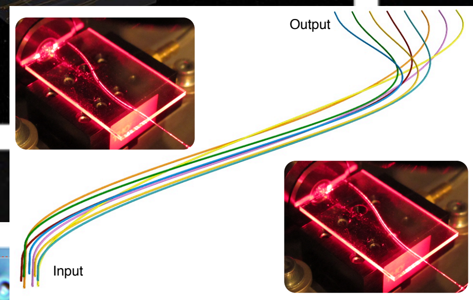
Coudé du Foresto et al. 1998

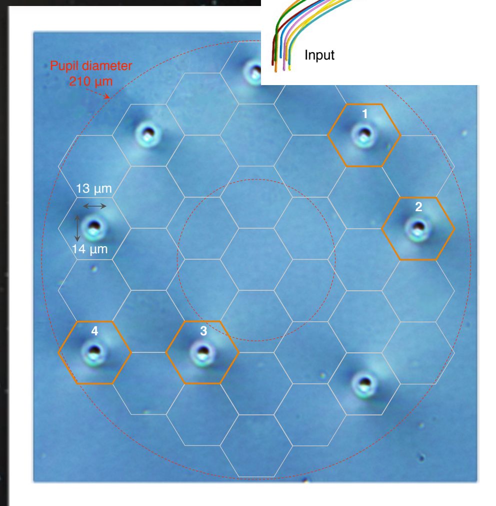
An obvious sense of progress (I)



Berger et al. ,1999, 2001

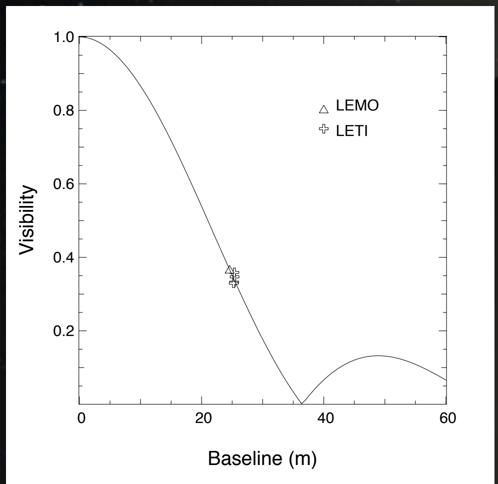




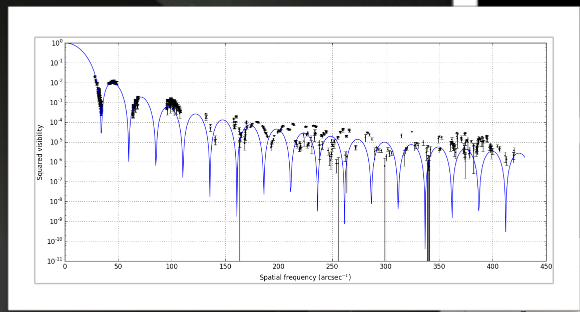


Jovanovic et al. 2012
Norris et al. 2014

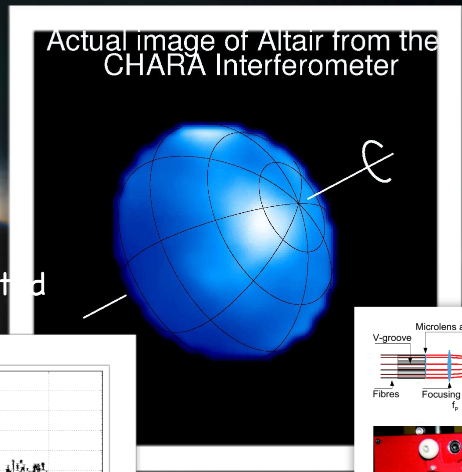
An obvious sense of progress (II)

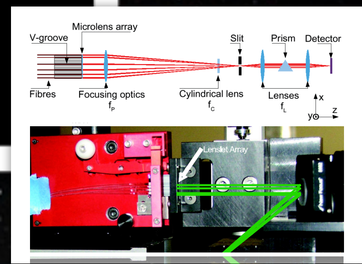


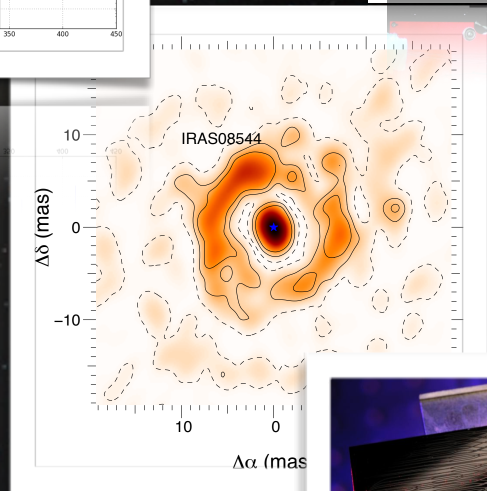
Montarges et al. 2015 accepted



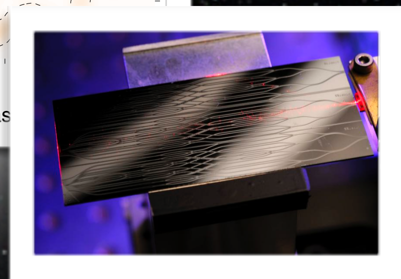
Monnier et al. 2015

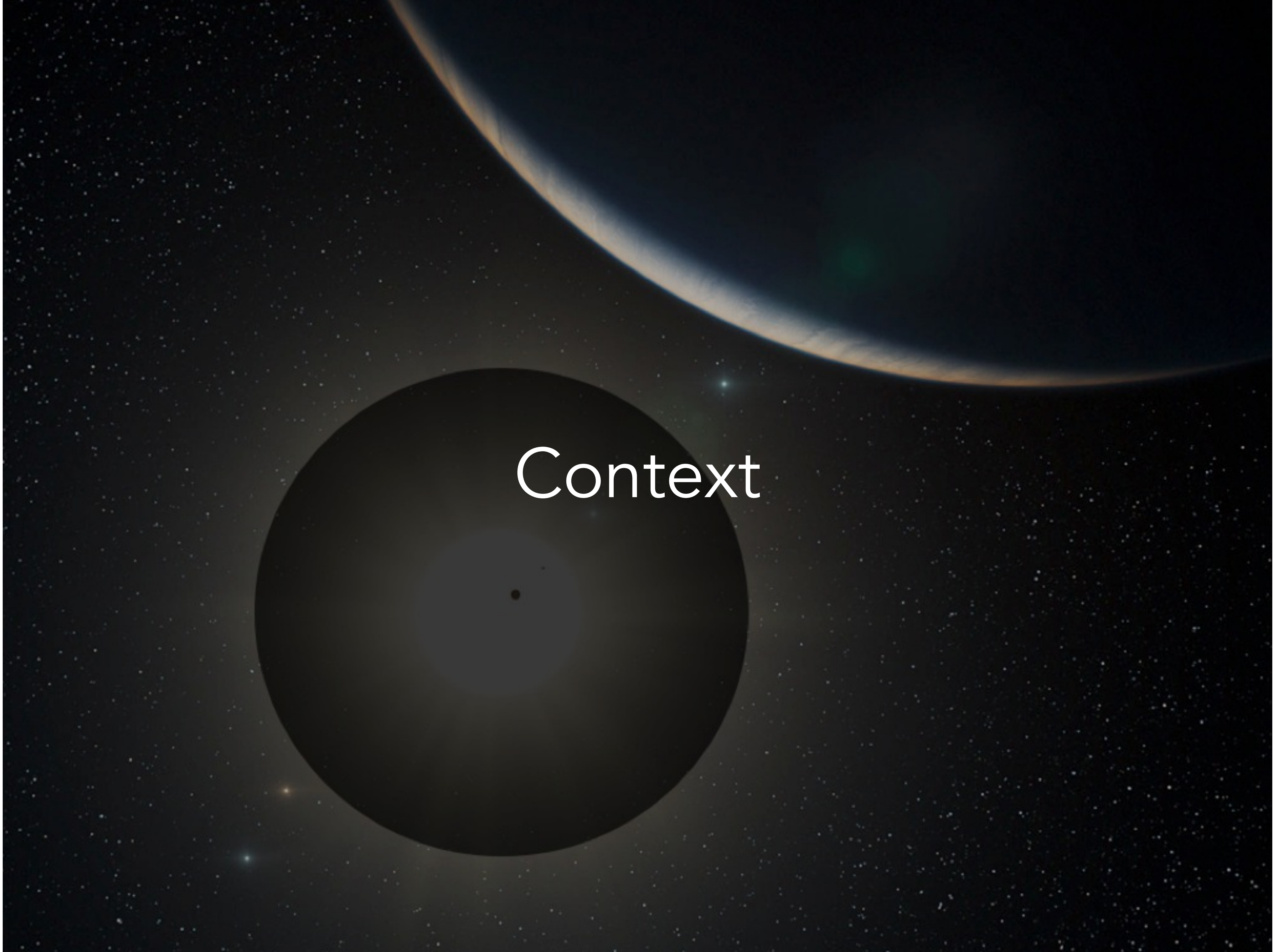






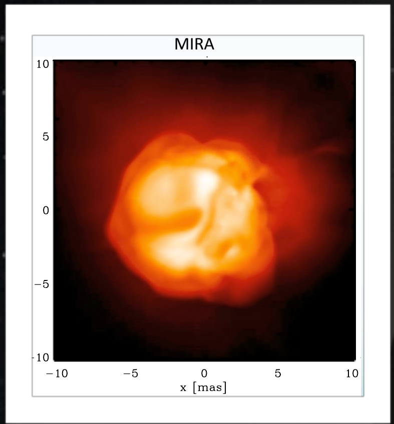
Hillen et al. 2015




Context

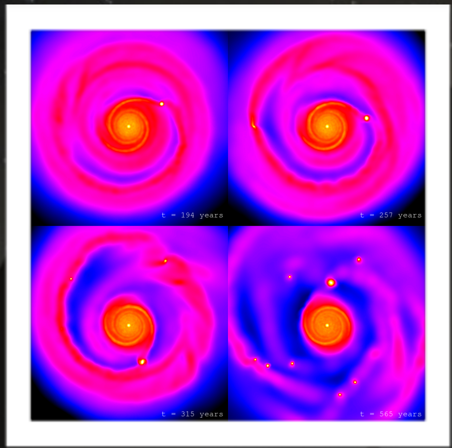
Scientific drivers turn into technical requirements

Stellar and circumstellar environments +AGN



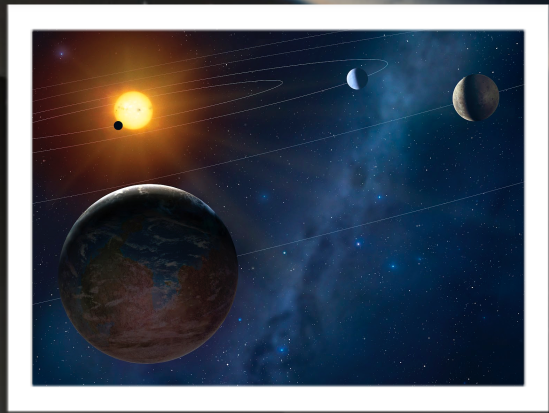
- Imaging (NT)
- High resolution spectroscopy
- Visible to mid IR

Planet formation



- Sensivity
- Imaging (NT)
- High contrast
- Mid infrared

Exoplanet detection and characterisation



- High contrast
- NIR-MIR

Understand GRAVITY in the strong regime

- Sensivity
- Imaging
- High contrast
- Phase reference imaging/astrometry

Opportunities driving R&D

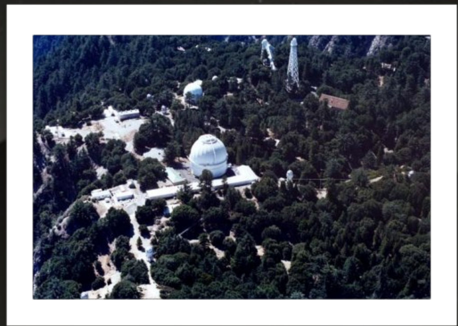
VLTI

4 x 8 m UT
4 x 1.m AT
Bmax = 160m

Instruments:

PIONIER: 4T (H, R~40)
AMBER: 3T (H,K, R ~12000)
MIDI: 2T (N R~ 300)

CHARA



6 x 1 m
Telescopes
Bmax = 330m

Instruments:

CLIMB: 3T (H, K, R~5)
MIRC: 4-6T (H,K, R ~40)
PAVO: 3T (R R~ 100)
VEGA: 3T (B,V,R ~1500 - 30000)

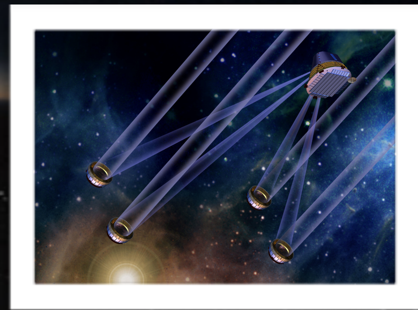
NPOI

6 x 0.12 Siderostats
(+ 4 1x1.8 Keck O?)
Bmax = 79m (437m)

Instruments:

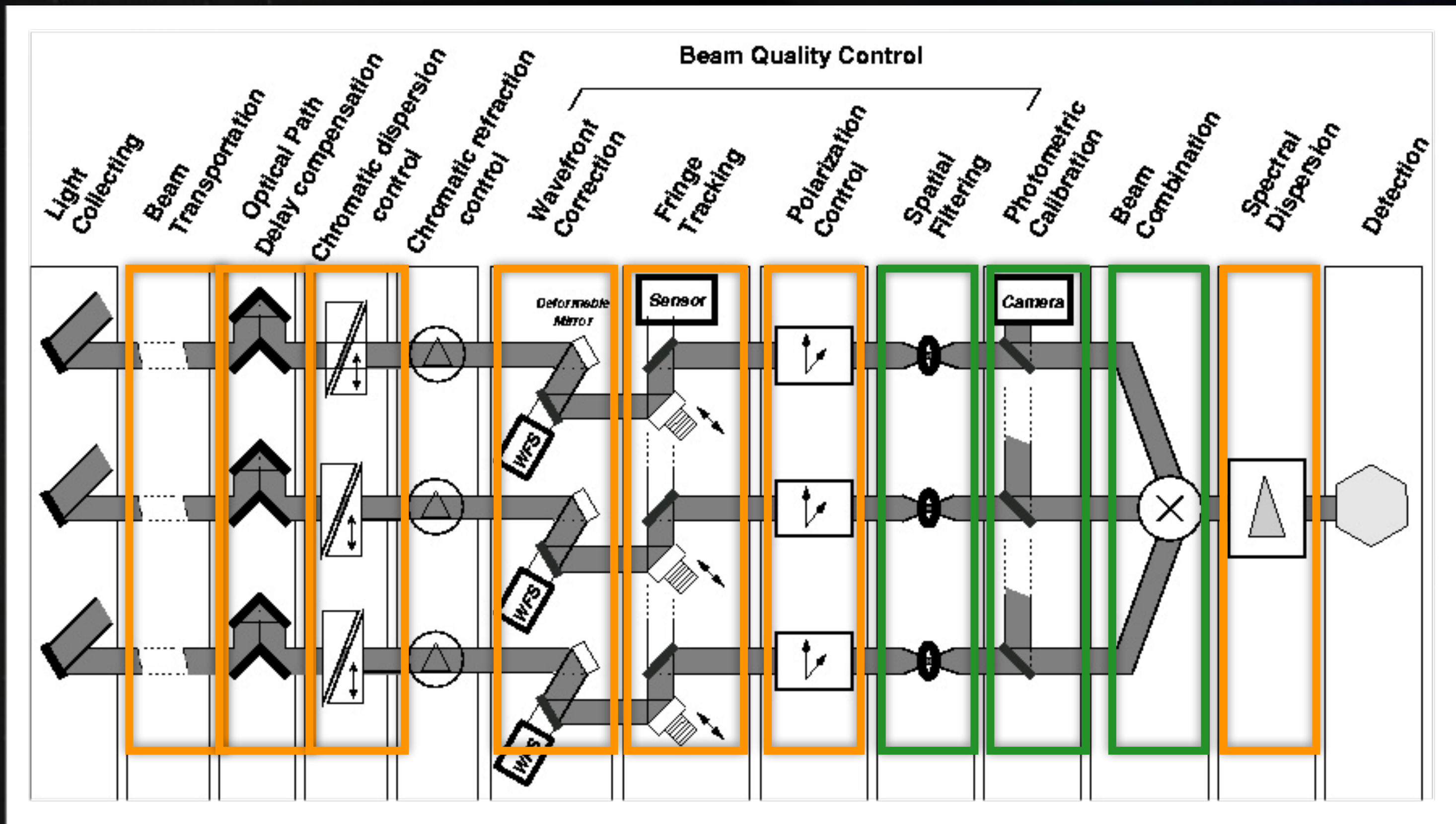
V,R: 4-6T, R ~ 80

DARWIN- TPF



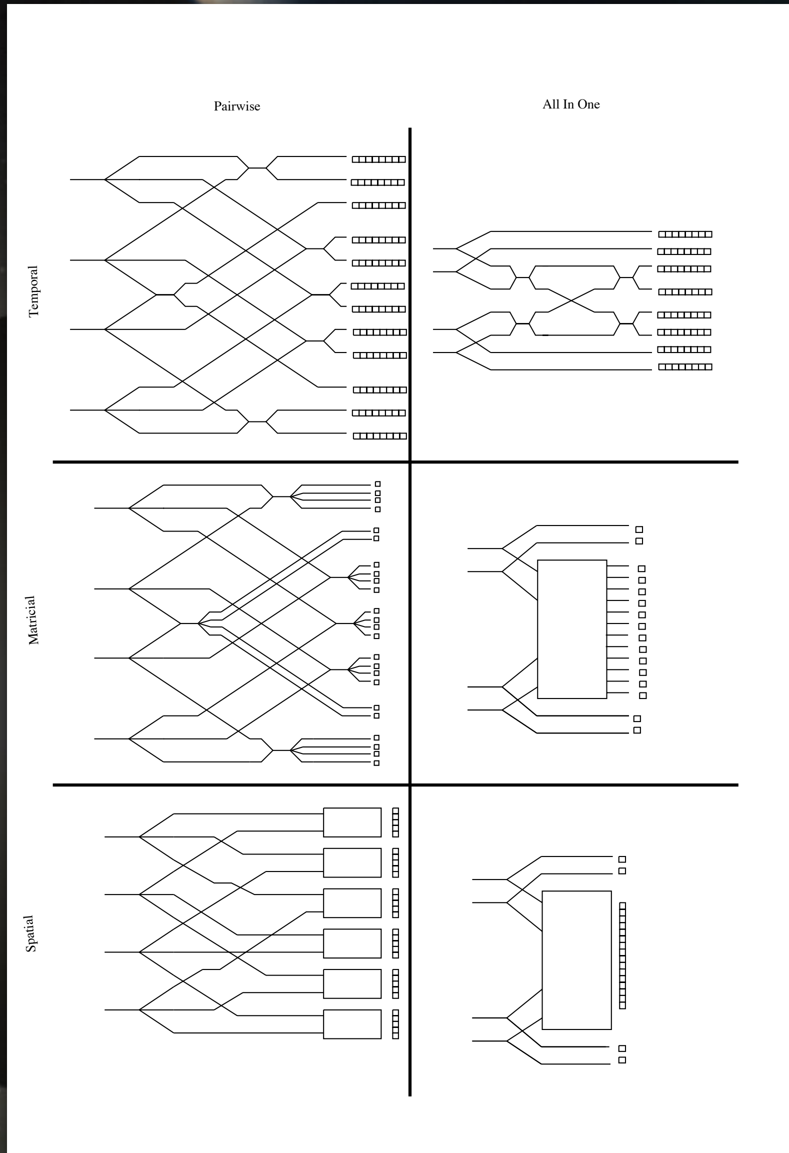
8-10m class
AO corrected
telescopes

Functional diagram of an optical interferometer



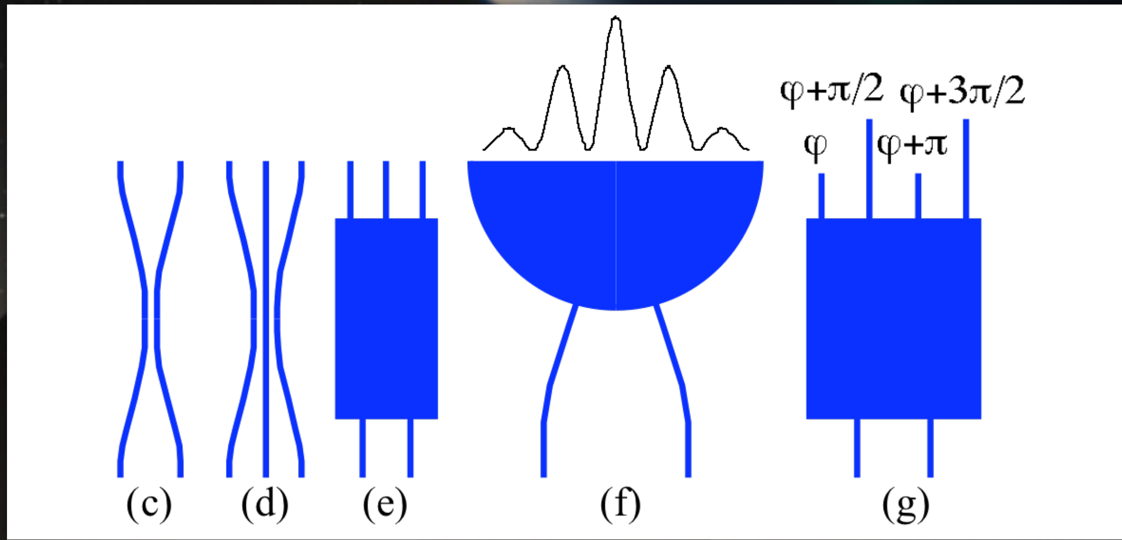
Beam routing strategies

- Minimising losses
- Minimising # of pixels
- Minimising crosstalk
- Minimising chromaticity
- Ensuring photometric calibration

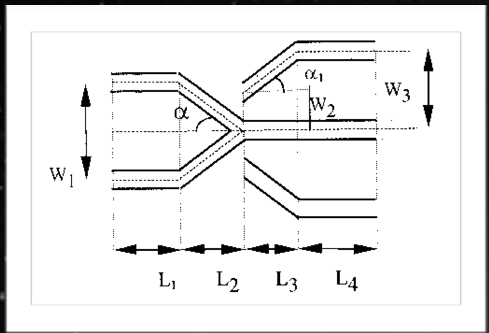


Le bouquin++ 2014

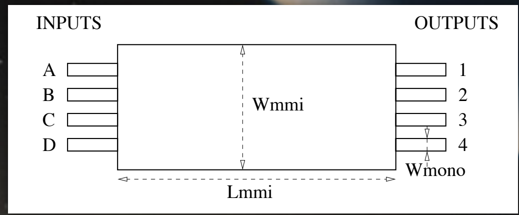
Beam combining functions



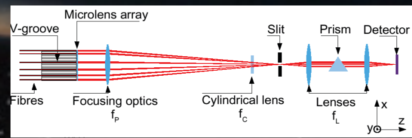
Beam combining functions

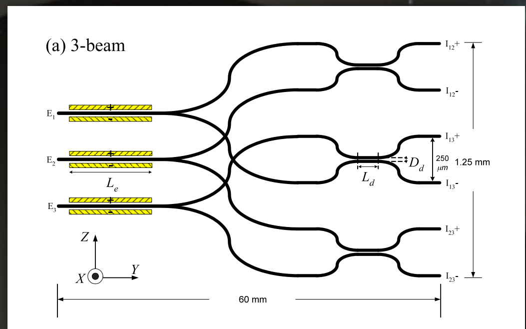


El Sabban 2000

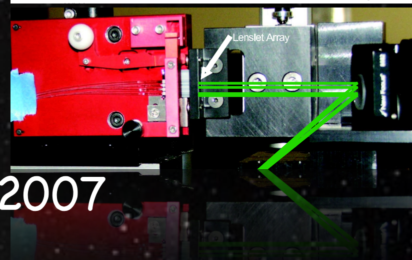


Rooms et al. 2003

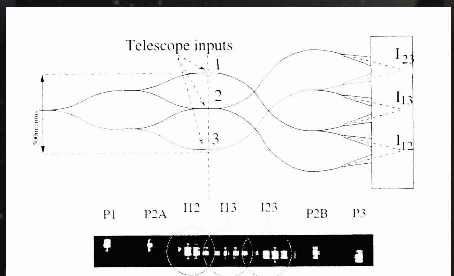




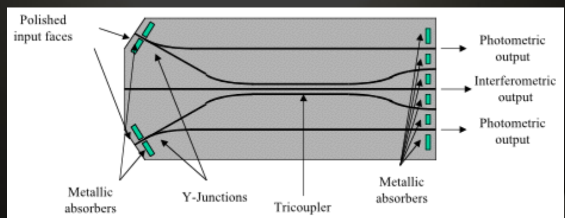
Hsiao++ 2009



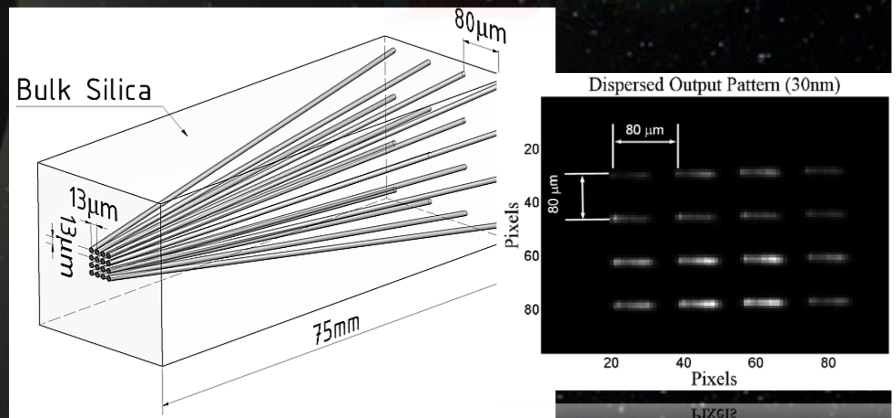
Monnier et al. 2007



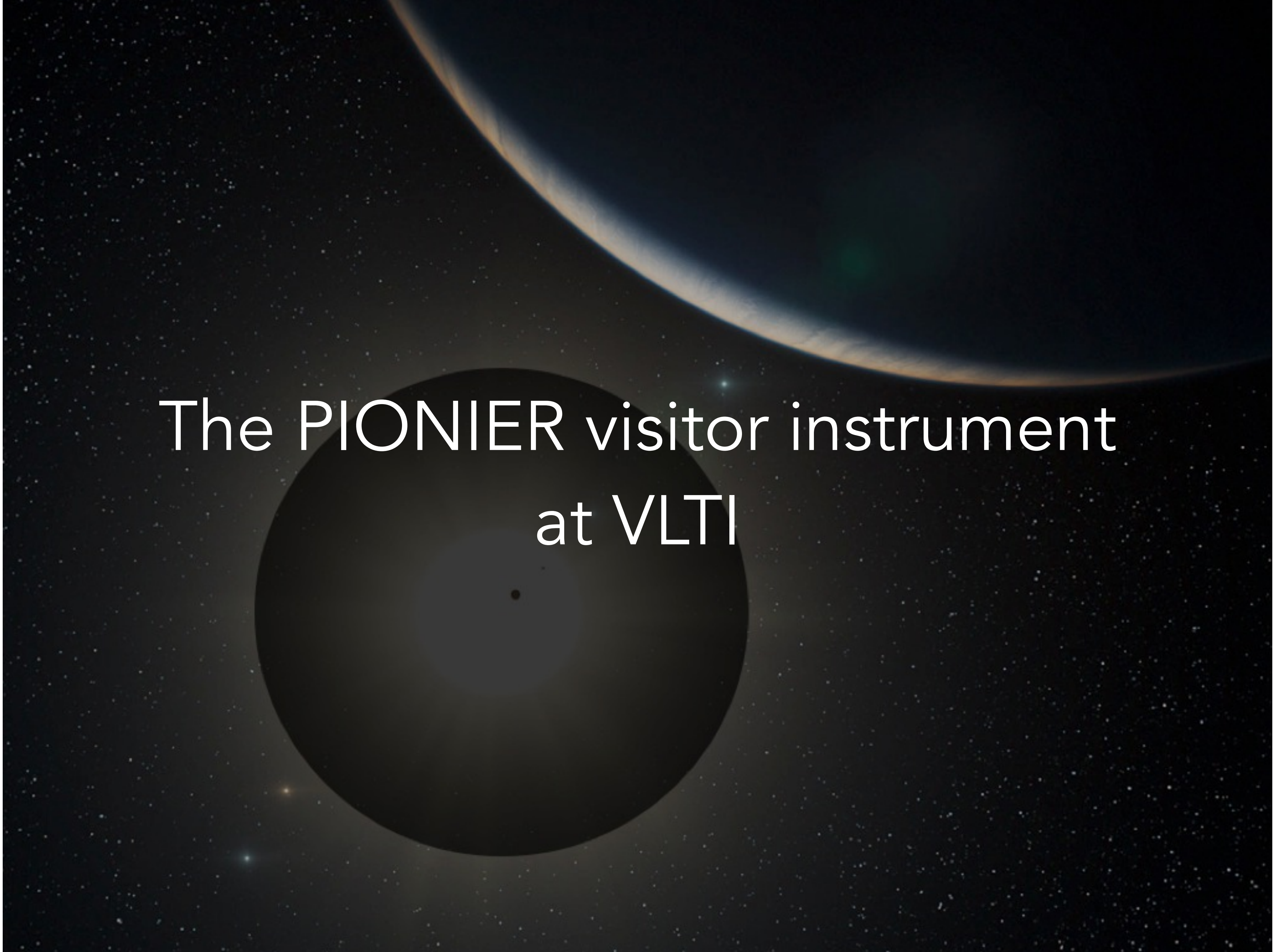
Berger ++ 2000



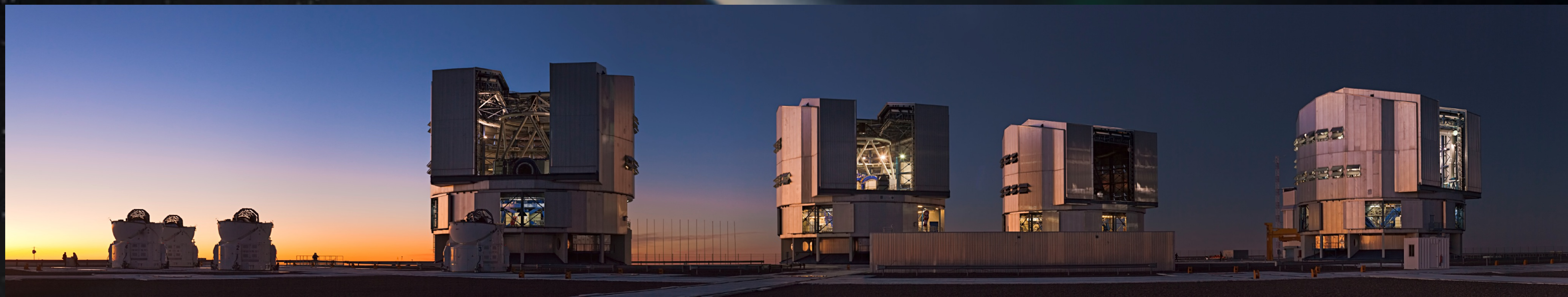
Haguenauer ++ 2003

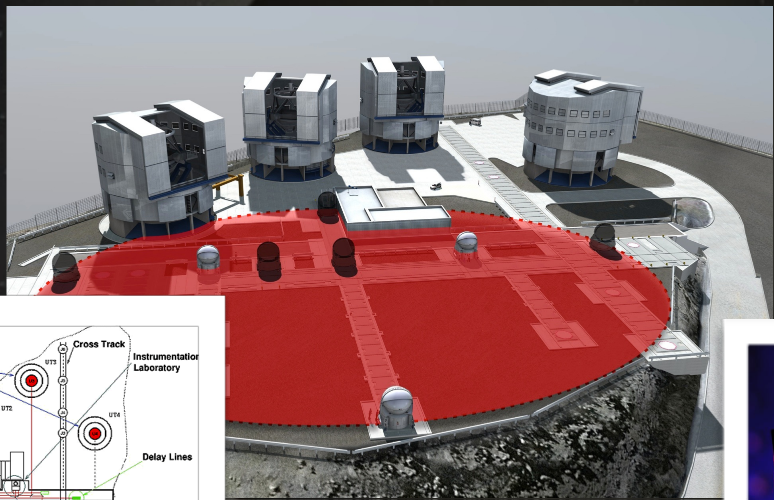


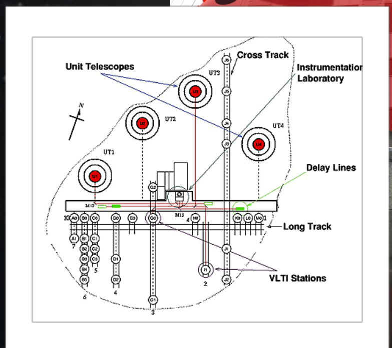
Minardi 2014

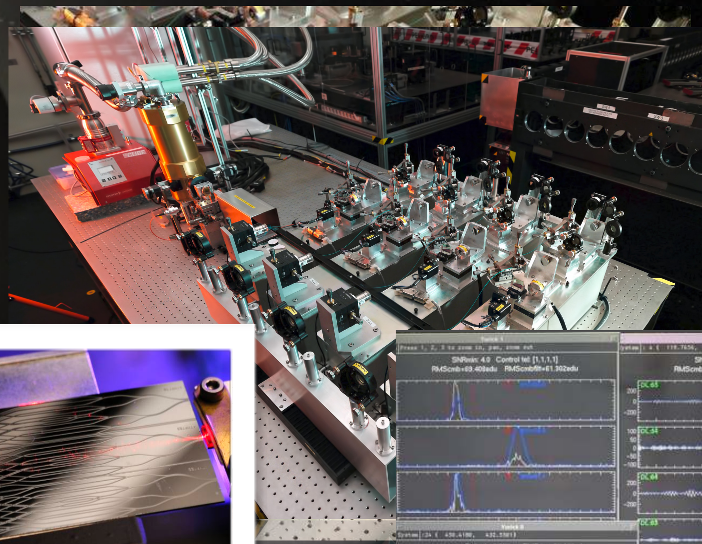

The PIONIER visitor instrument
at VLTI

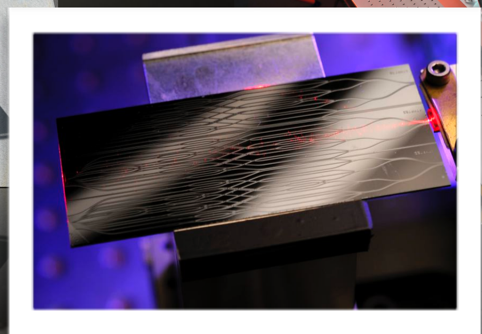
PIONIER at VLTI

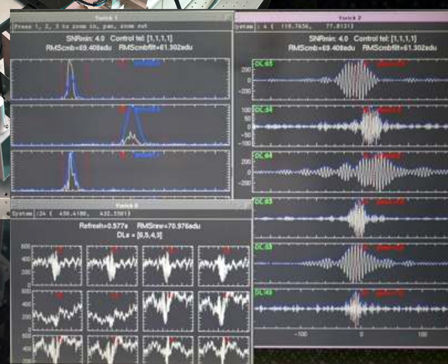






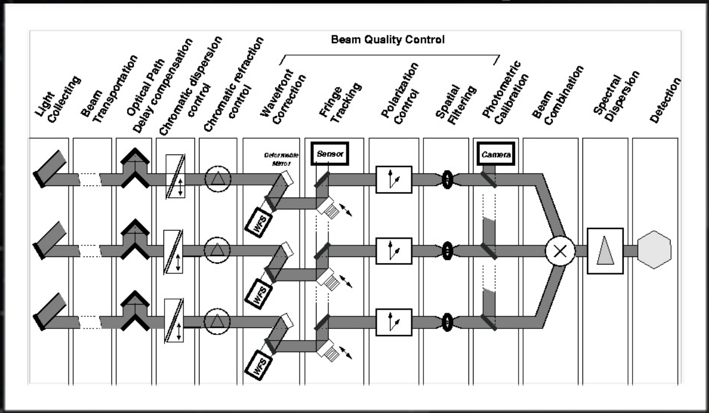


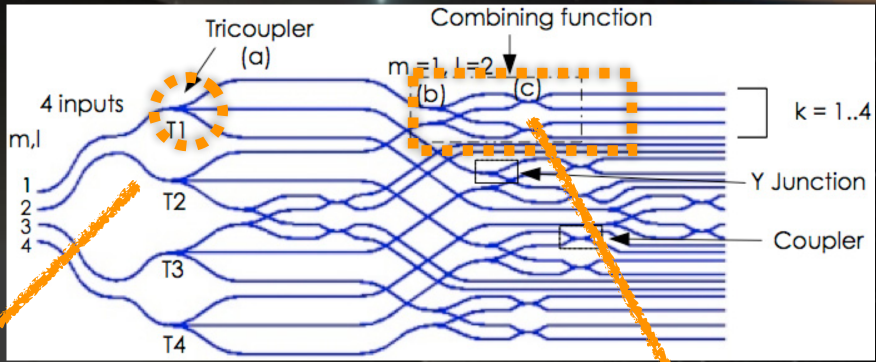


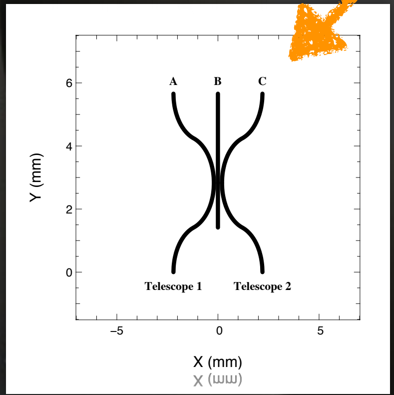


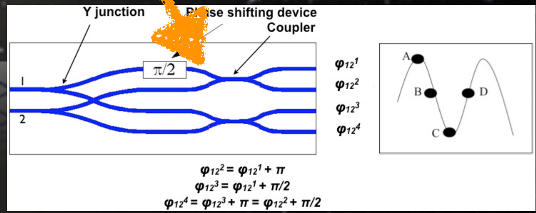
Berger et al. 2010, Lebouquin et al. 2011

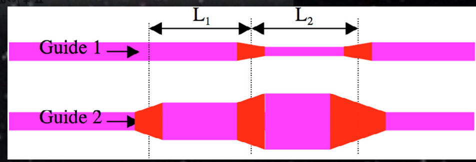
Functions in a long baseline optical interferometer





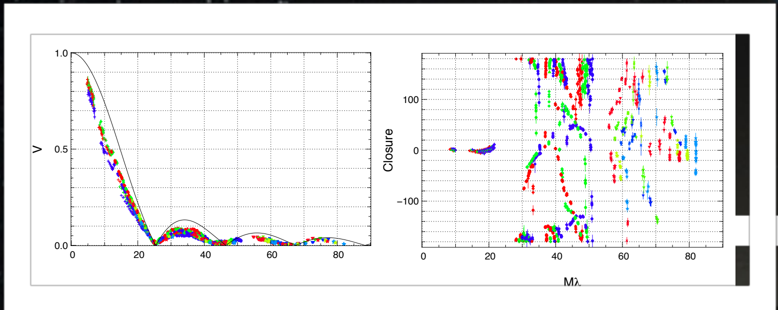


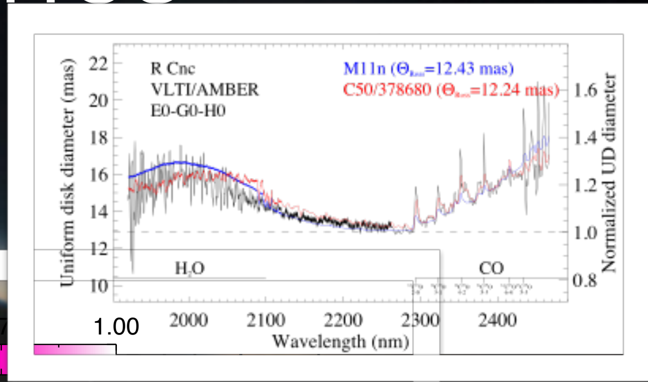


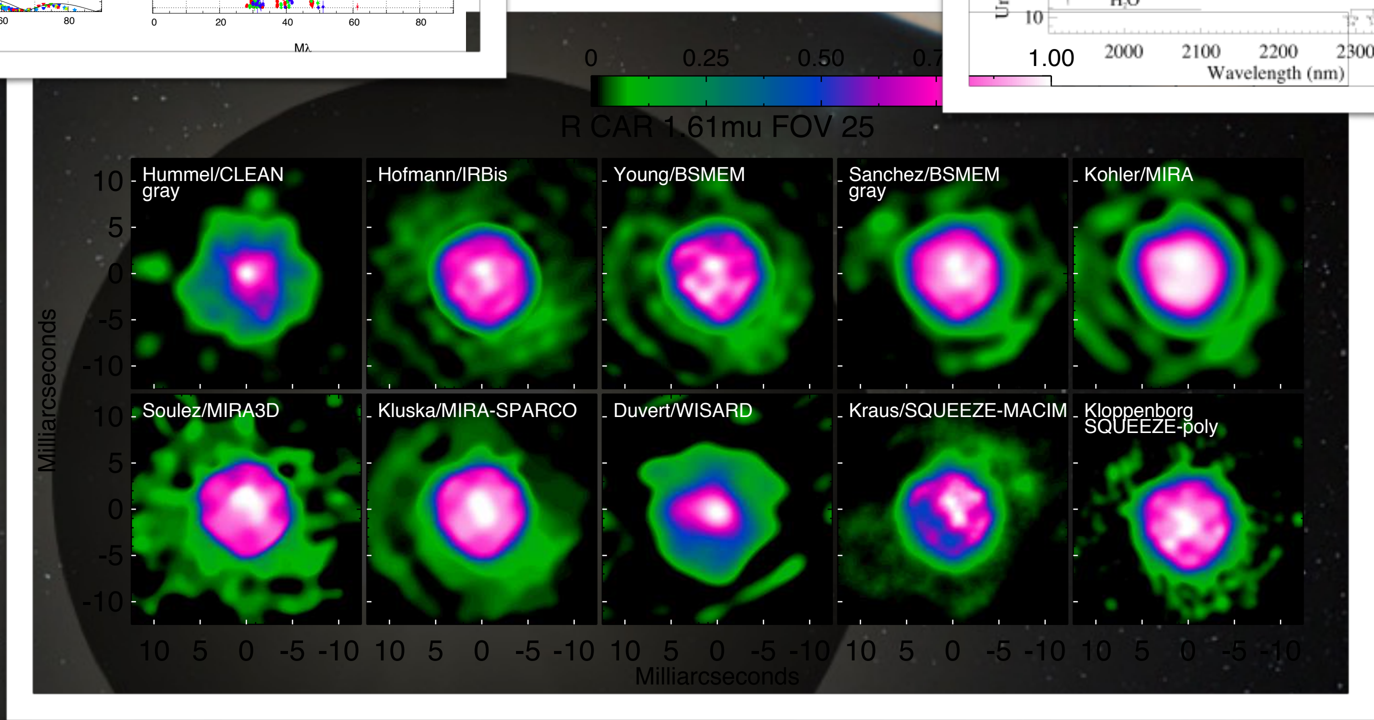


Benisty et al. 2007

Imaging science





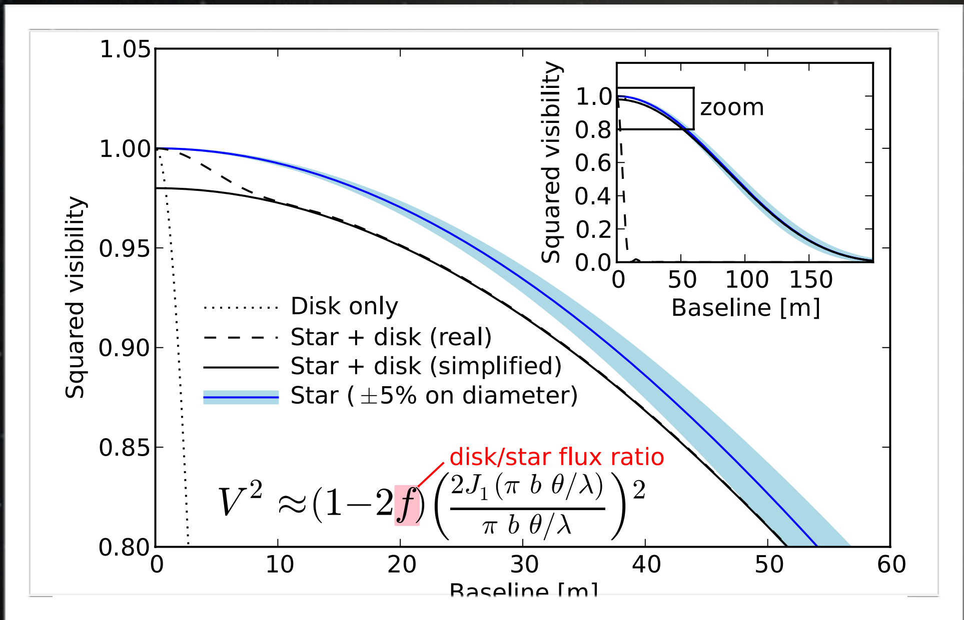


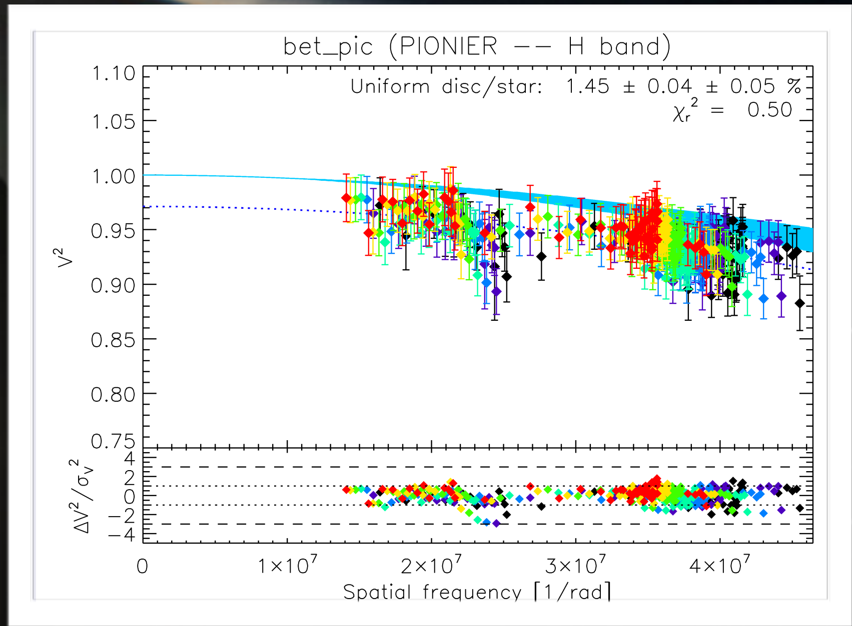
Monnier++ 2014

More telescopes needed + spectral resolution

Débris disk science: high precision visibilities

xxx: figure debris disk

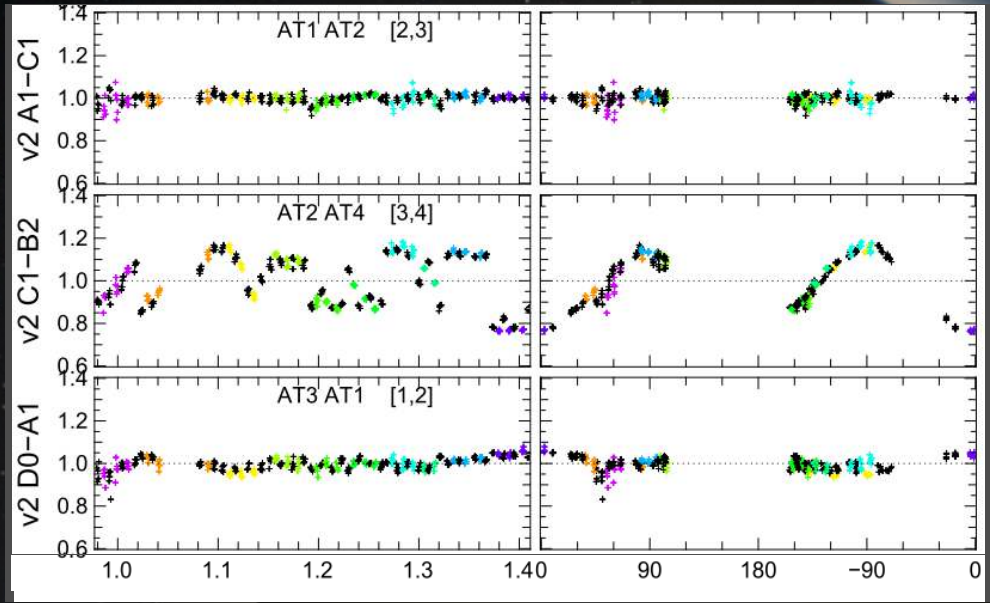


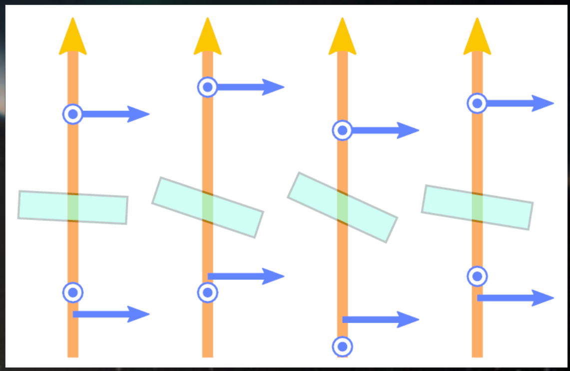


Ertel et al. 2014

Calibration is key

Understanding polarisation propagation



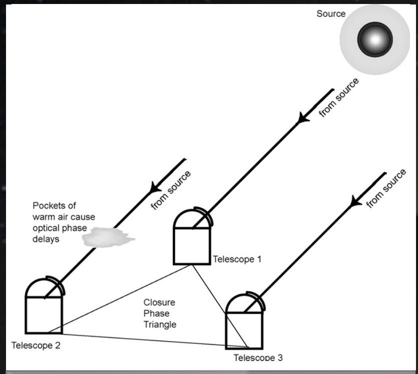


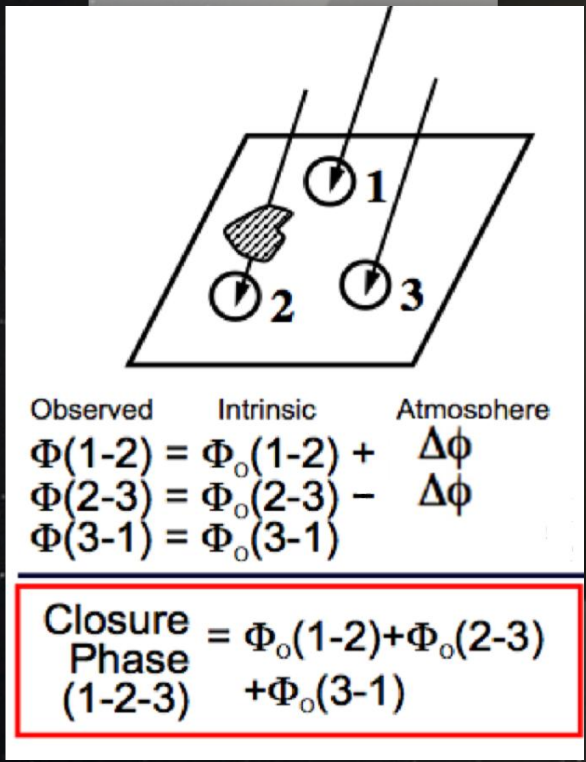
- Angularly close calibrators (< 1deg)
- Important margin for progress.
- Scientific polarisation measurements

Lazareff et al. 2012

Exoplanet science: precision closure phase

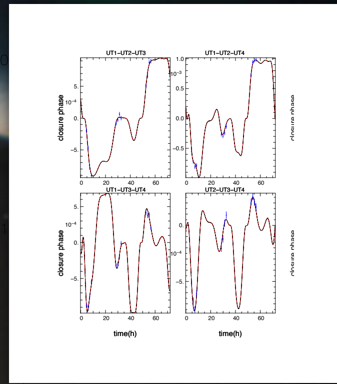
Monnier 2007



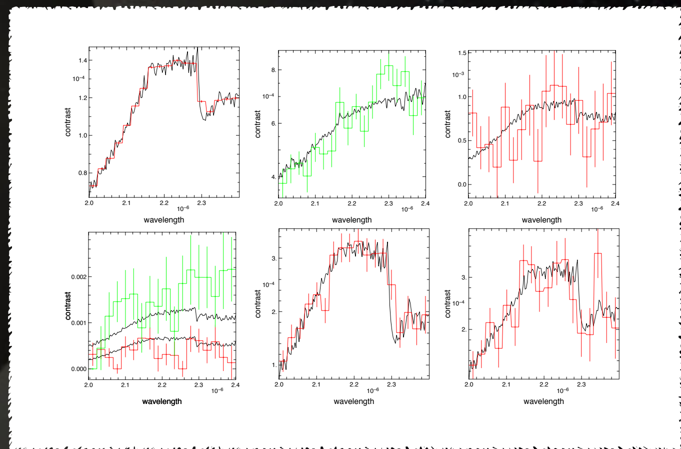


Predicted CP signal

Renard et al. 2008



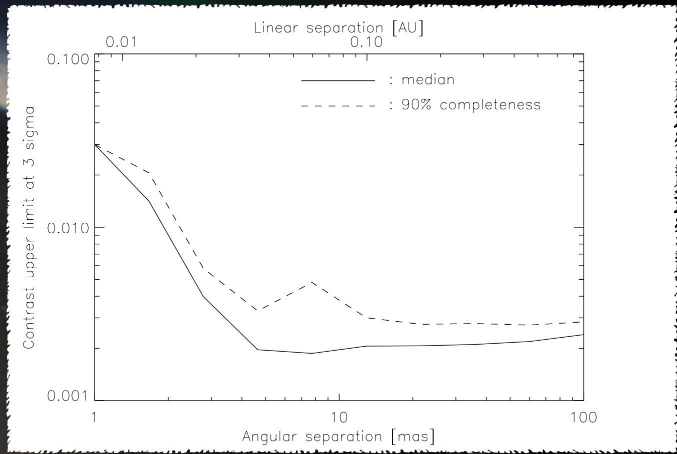
Reconstructed spectra



Requested CP precision ~ 0.01 deg

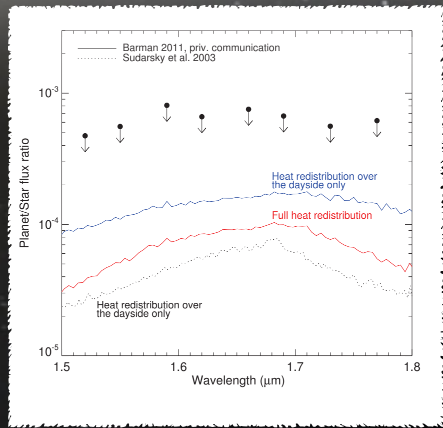
Exoplanet science: precision closure phase

Absil et al. 2012



Systematics not entirely understood

- Residual atmospheric fluctuation phase effects
- Chromatic effects dominating (atmosphere, finer dispersion)
- Mitigation with multiple calibrator strategy and medium resolution
- Increase photon efficiency
- Crosstalk, polarisation

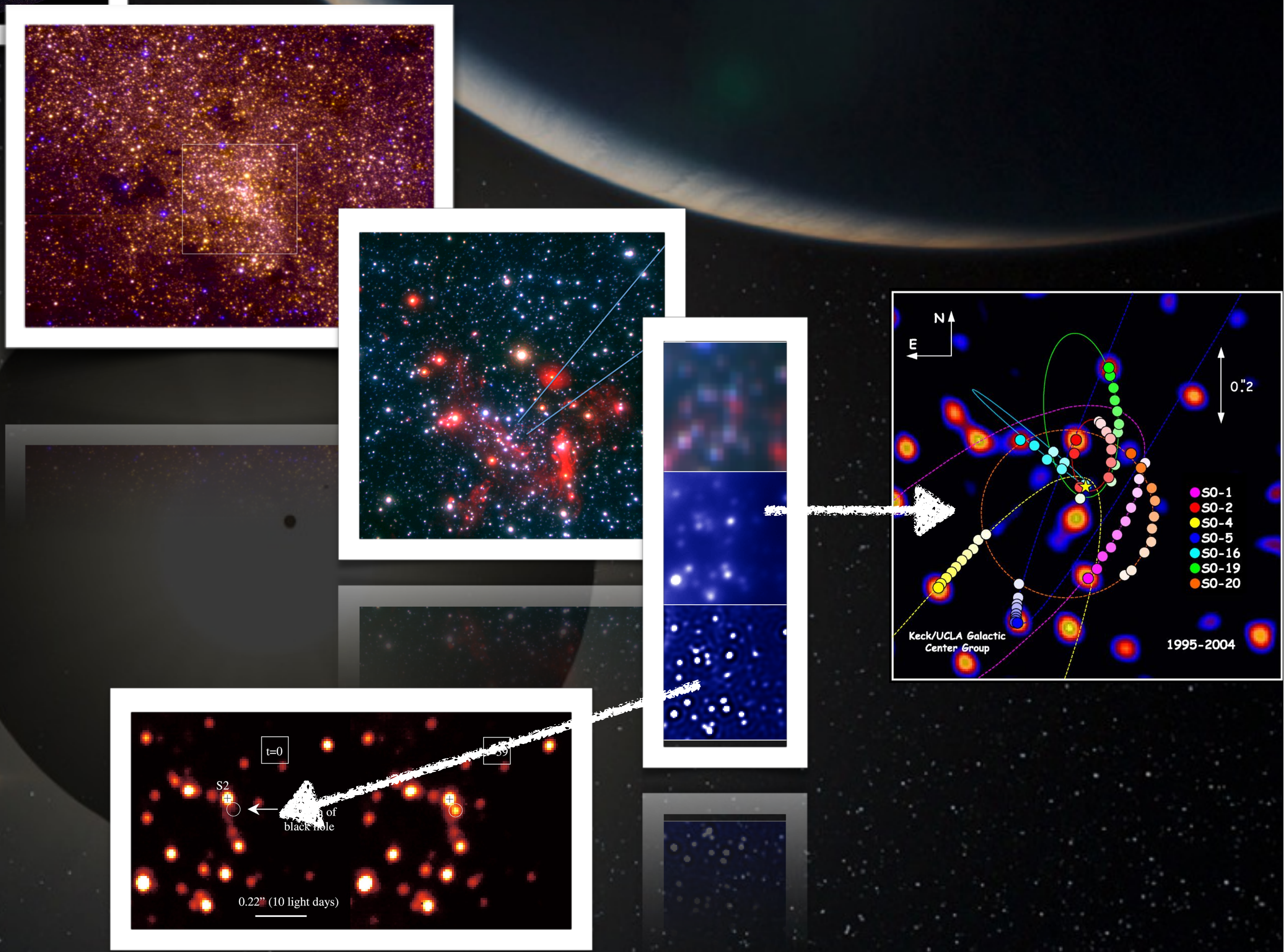


Zhao et al. 2014

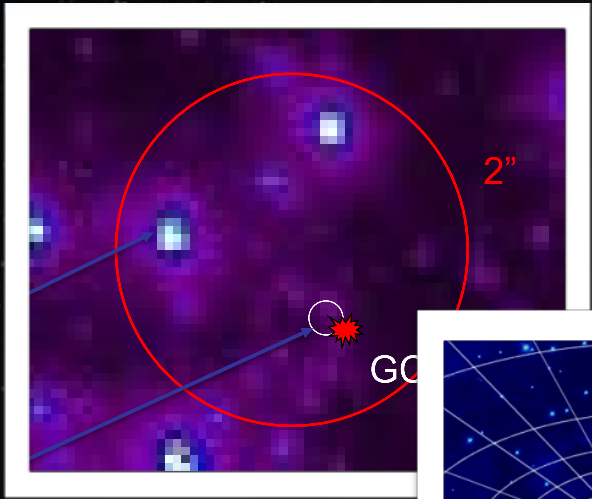
Best CP precision ~ 0.1 deg

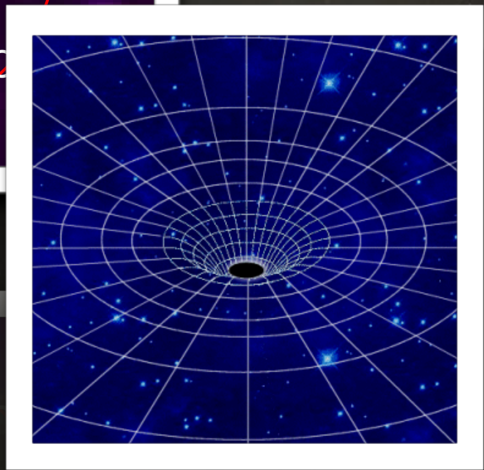

GRAVITY: Hunting for the
Galactic Center black-hole

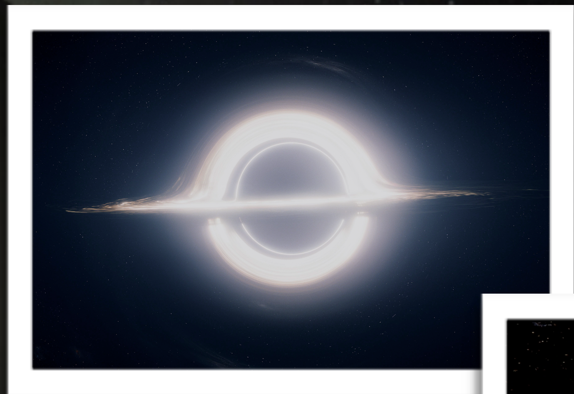
Galactic Center

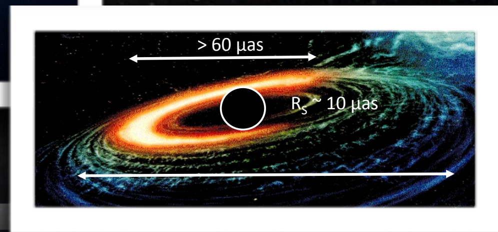


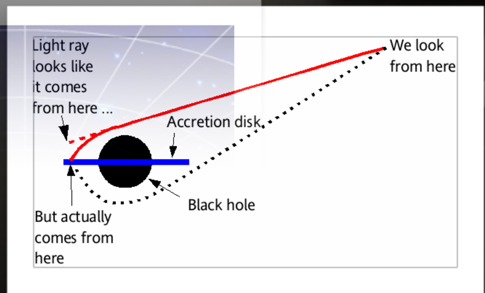
GRAVITY: science case





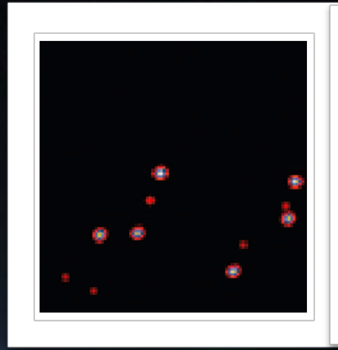


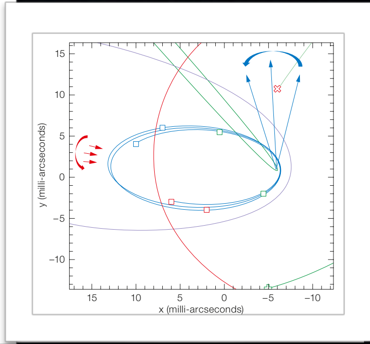


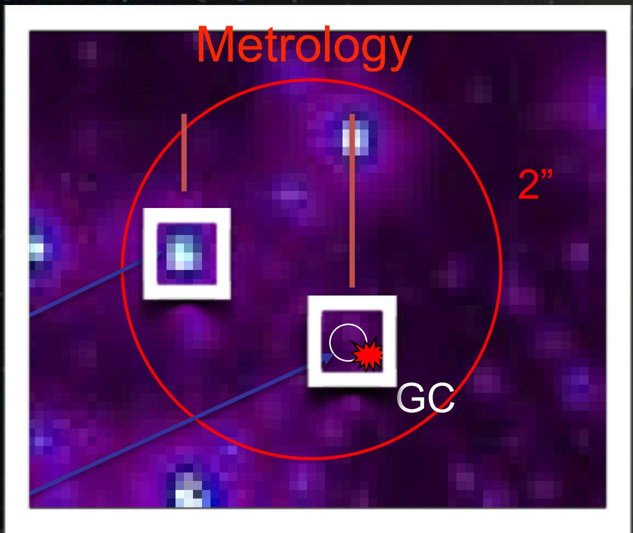


GRAVITY core science case

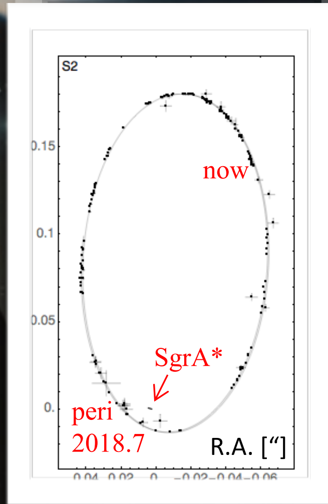
The young stars paradox

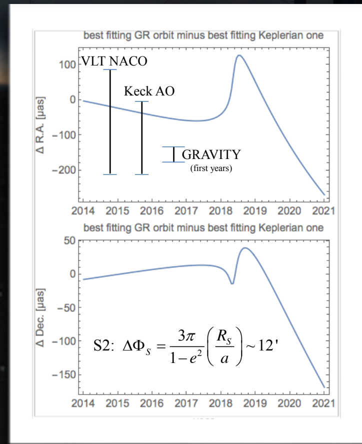




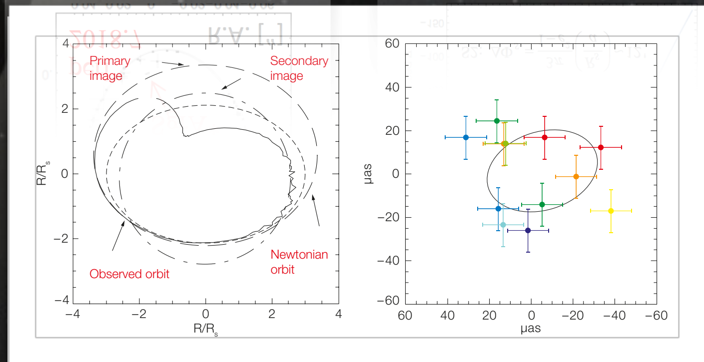


The S2 - pericenter passage

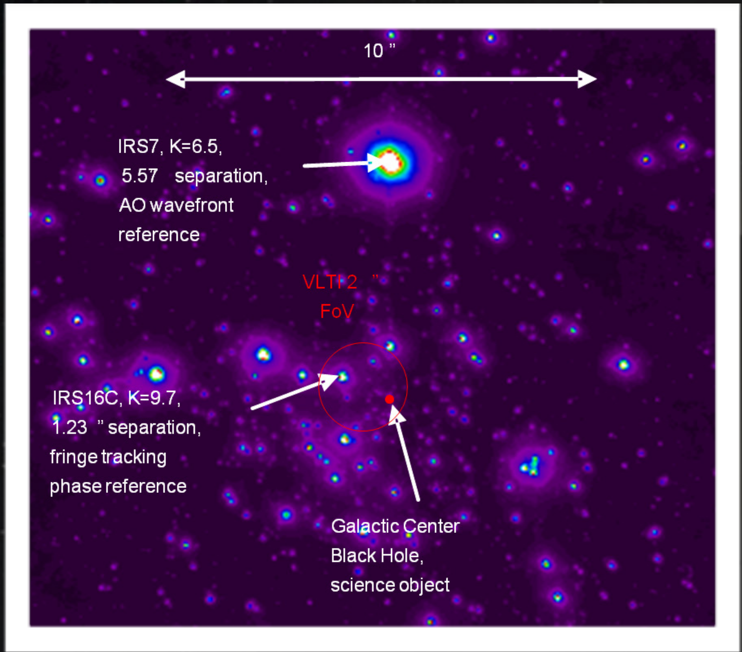


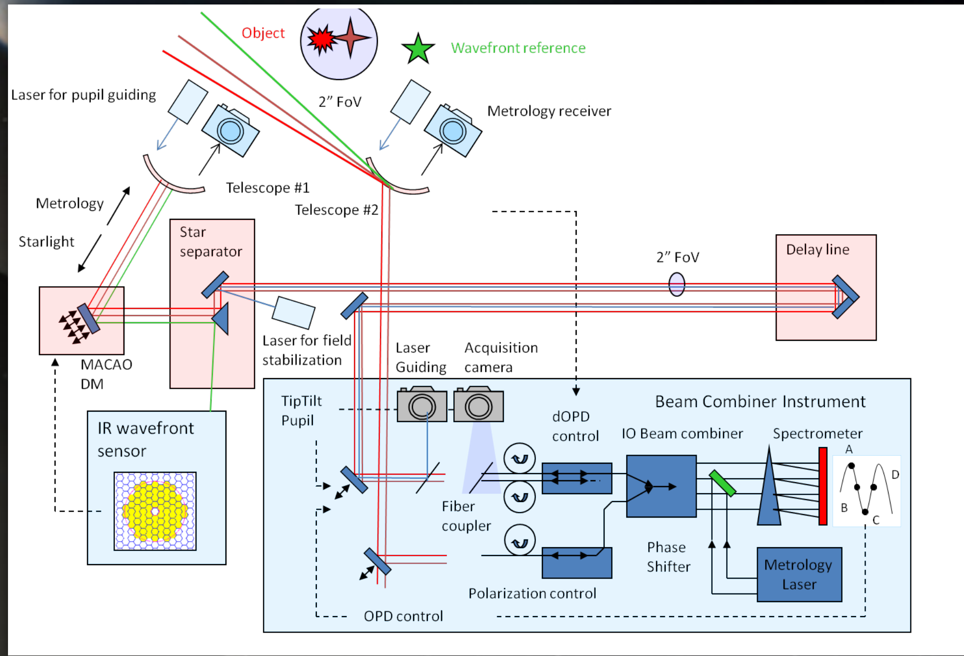


Probing the BH last stable orbit



GRAVITY concept





Key Photonics developments

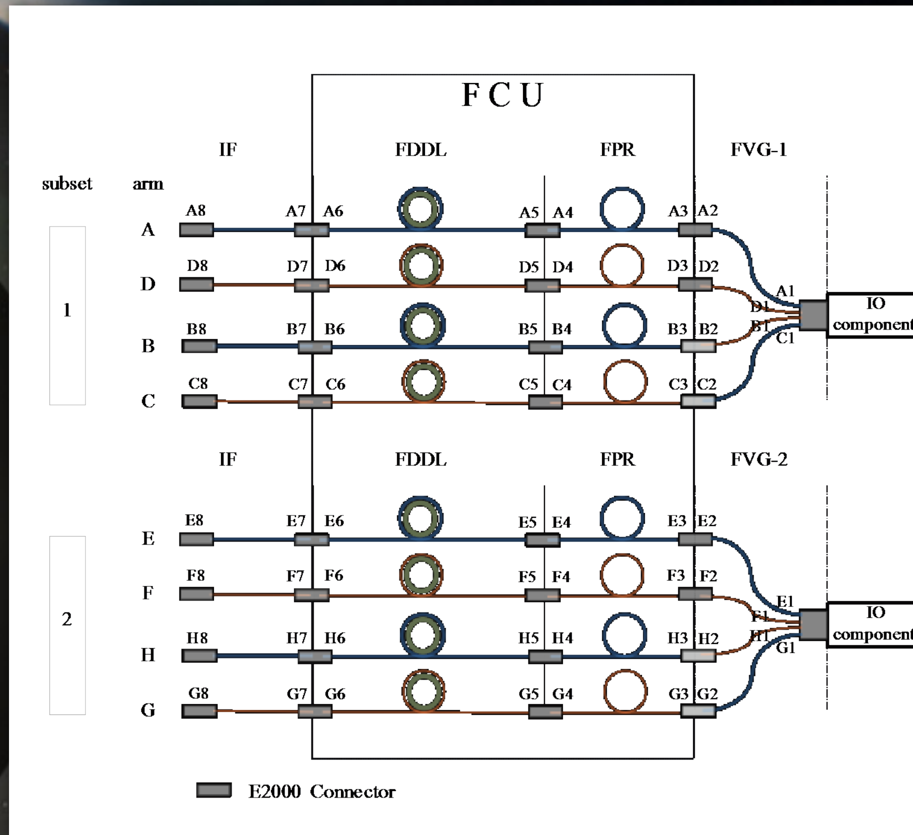
- K band (2-2.4 micron) cryogenic integrated optics
- Metrology compatible IO
- Fluoride fibers polarisation control
- Fluoride fibers differential delay lines

GRAVITY at Paranal

Fiber Control Unit
Acquisition Camera
Metrology injection
4 Fiber Couplers
4 Guiding receivers
2 Spectrometers
Calibration Unit
16 mm
54 mm
33/66 coupler
Y junction
50/50 coupler
Phase shifting
Phase shifting
Coupler
π/2
φ+3π/2
φ+π/2
φ+π
φ
Phase shifting cell
A1
D1
B1
C1

- Polarisation control
- Fiber differential fiber delay line

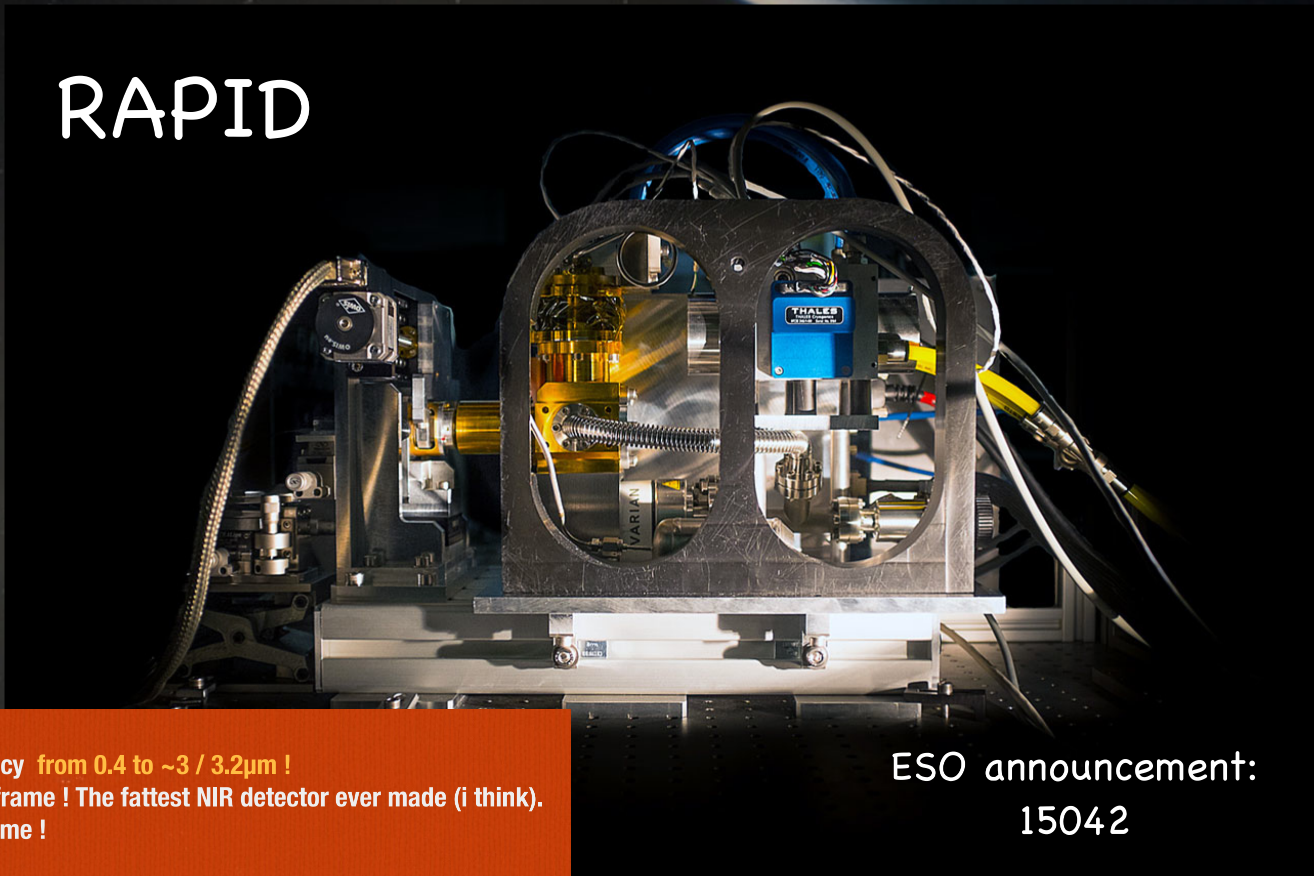
DDL: stroke 4mm, resolution 1micron



FPR: 180 deg amplitude accuracy 2 degree

The revolution of avalanche IR detector arrays

FUI-RAPID: SOFRADIR, IPAG, ONERA, LETI, LAM

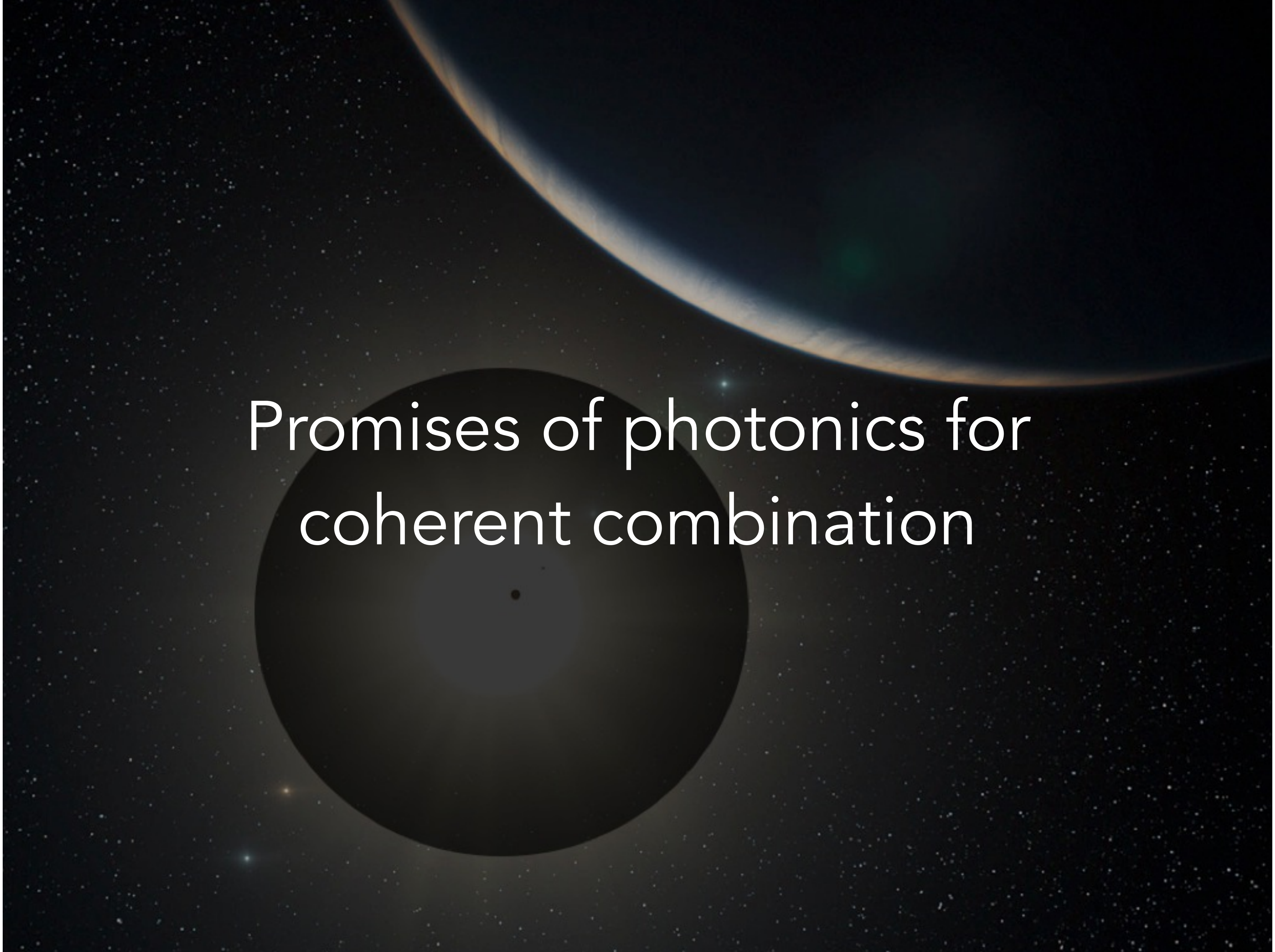


- Pixel size of 30µm
- Almost flat Quantum Efficiency from 0.4 to ~3 / 3.2µm !
- Frame rates of 1600 Hz, full frame ! The fattest NIR detector ever made (i think).
- Noise of ~2 electrons per frame !

Operated in a compact Pulse-Tube Cryo-cooler at ~80K (first one at Paranal) -> No nitrogen re-feeling.

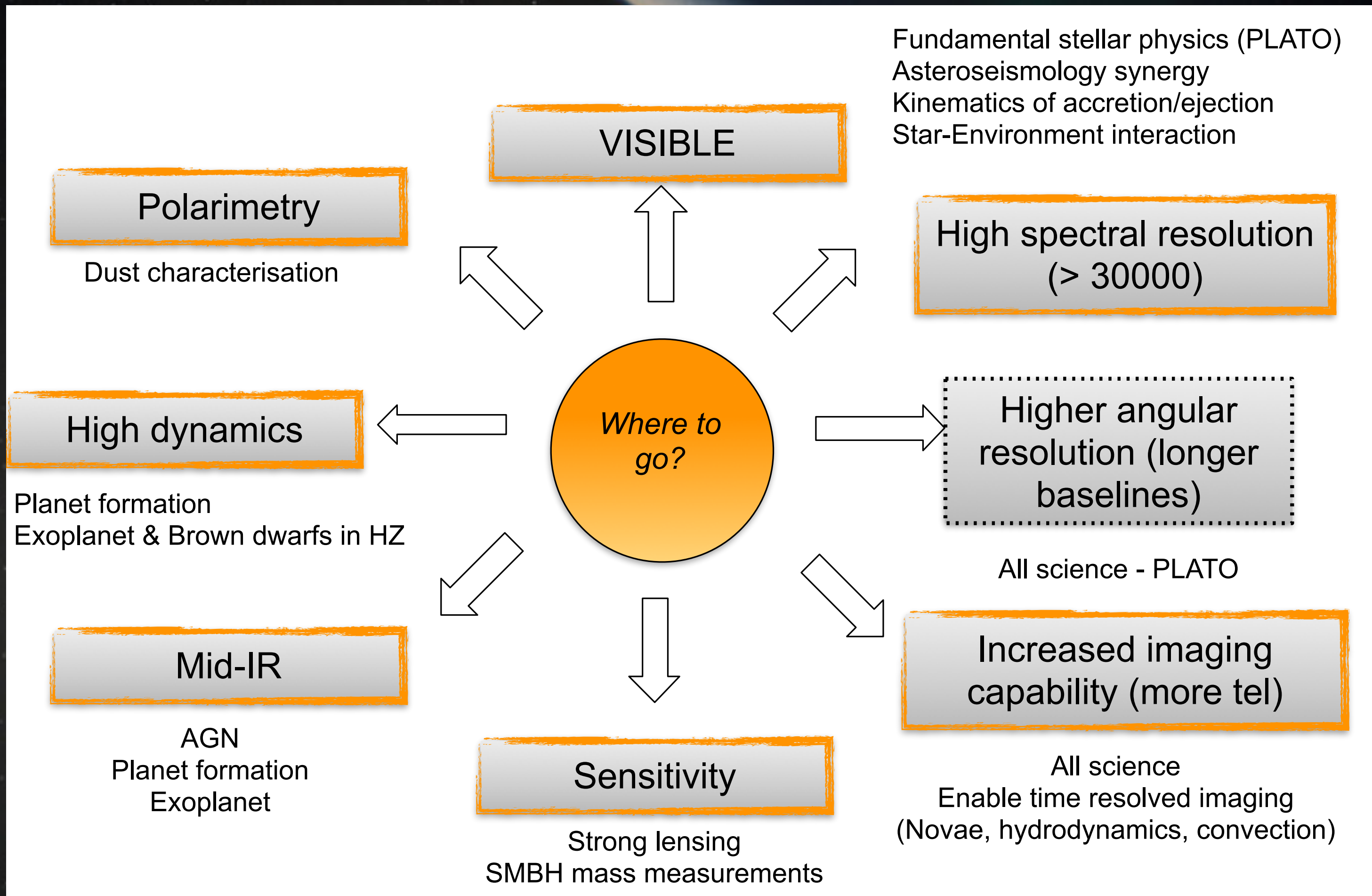
Also:

SELEX



Promises of photonics for coherent combination

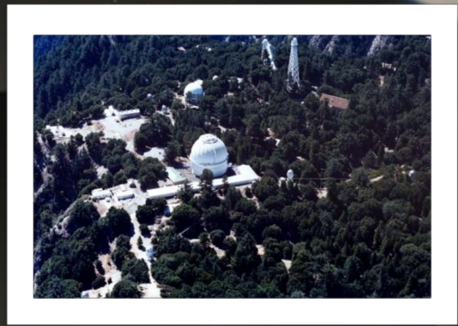
Science directions



The facility context

VLTI

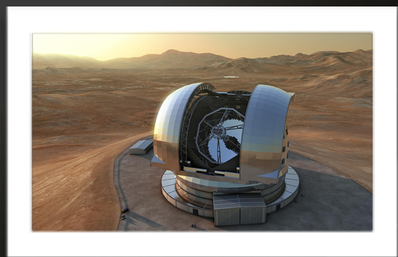
CHARA



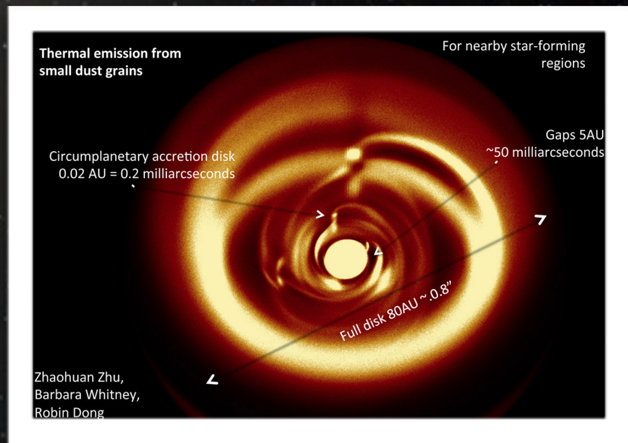
NPOI

MROI

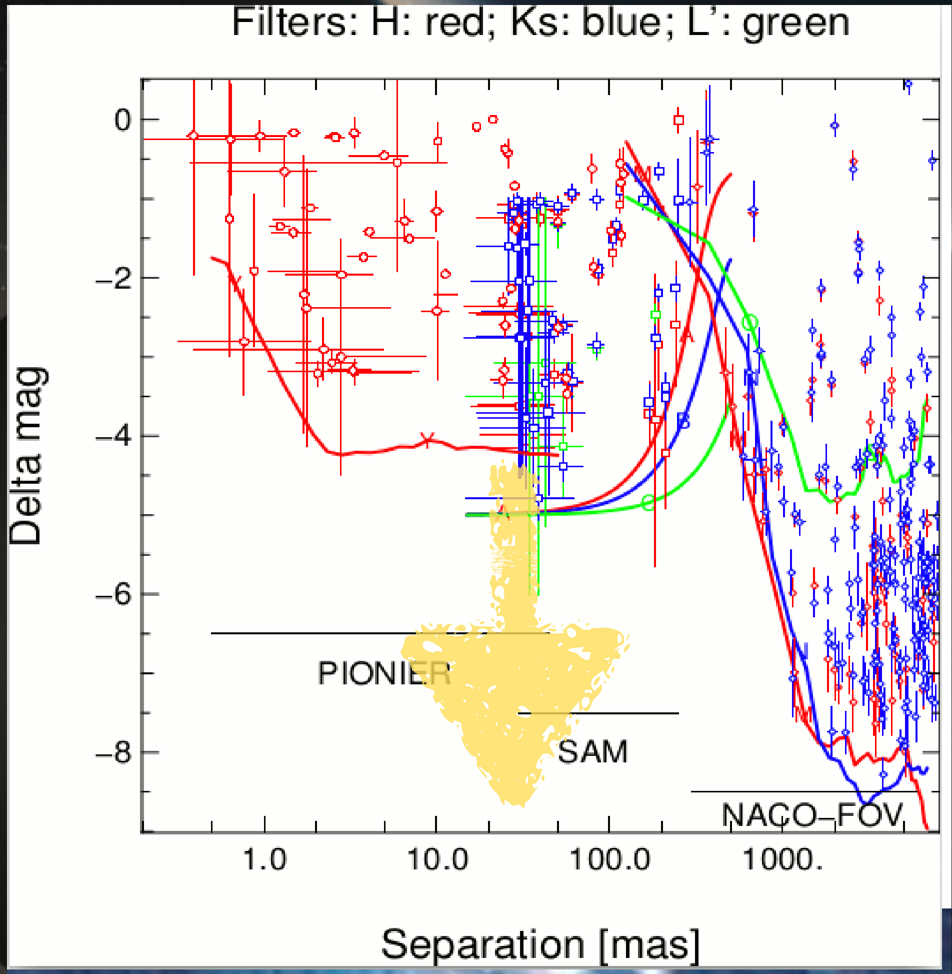
30-40 m class telescopes



PFI

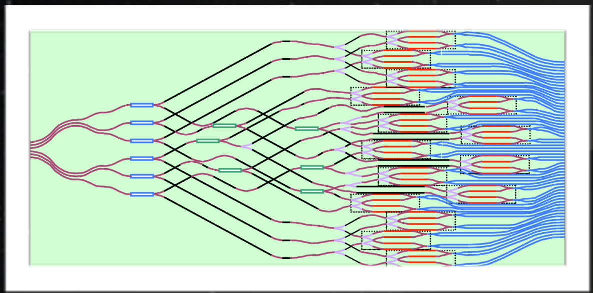


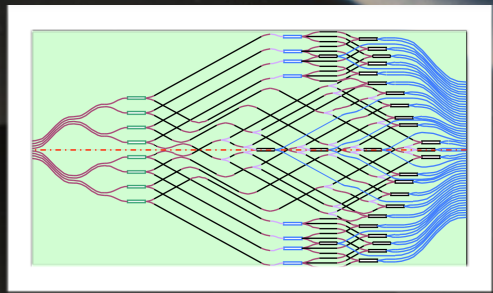
High dynamic range: nulling



Sana ++ 2014

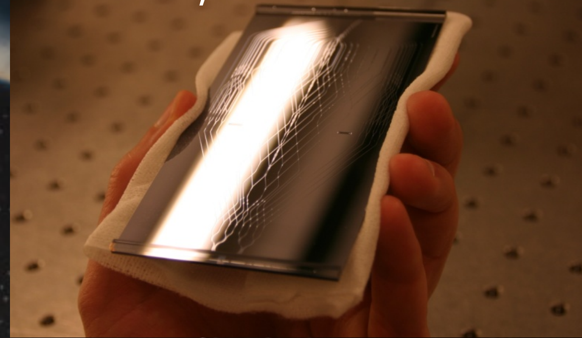
Imaging: the 10 telescopes ceiling?

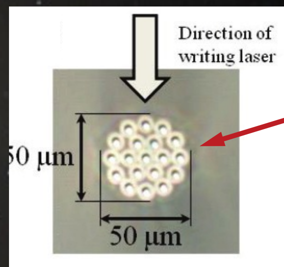


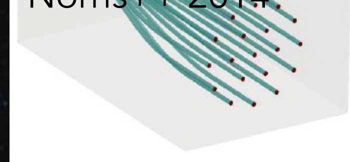


Labeye 2008 (LETI)

Lacour, Kotani

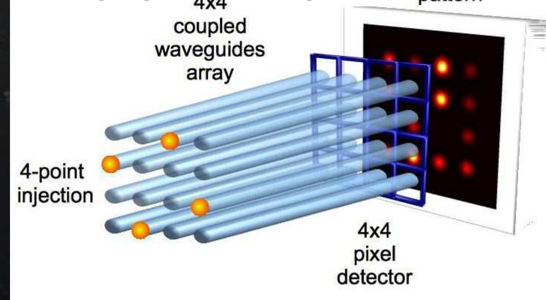






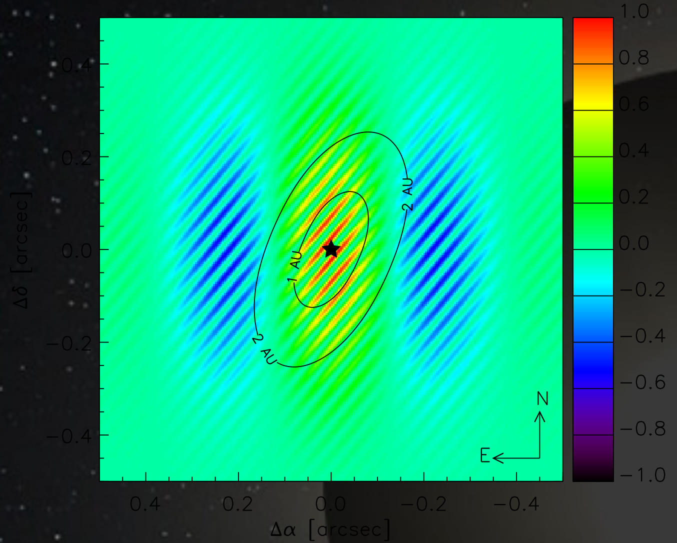
Jovanovic++ 2012
Gross++ 2013
Norris++ 2014

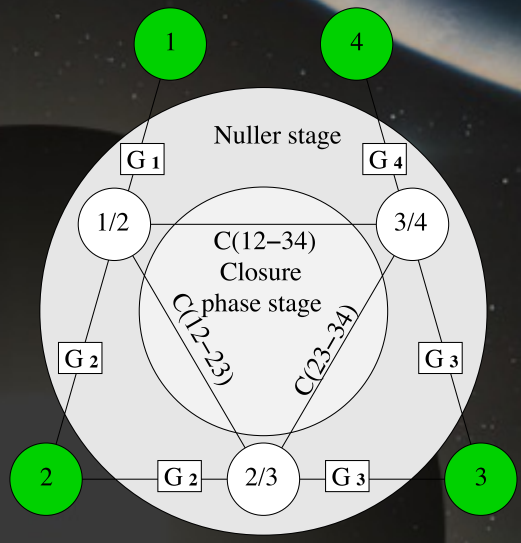
Minardi ++ 2014

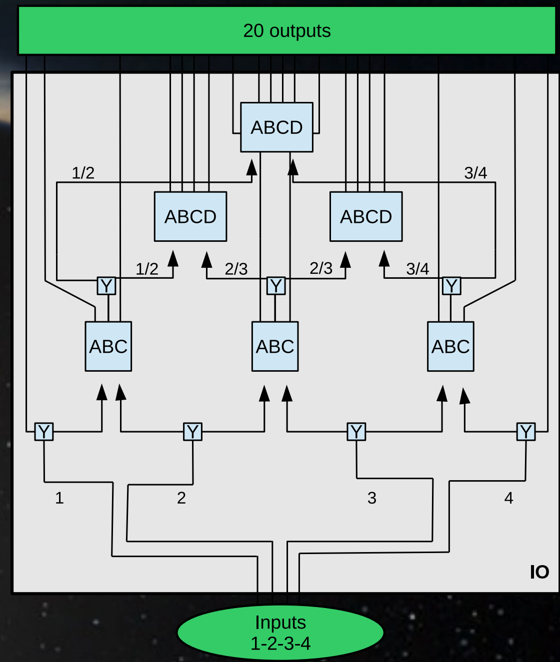


- Wafer size limitation: higher index
- Losses limitation
- Switchyards
- Hybridation 3D-2D
- Direct imaging
- Large format (512) low noise detectors

High dynamic range: nulling



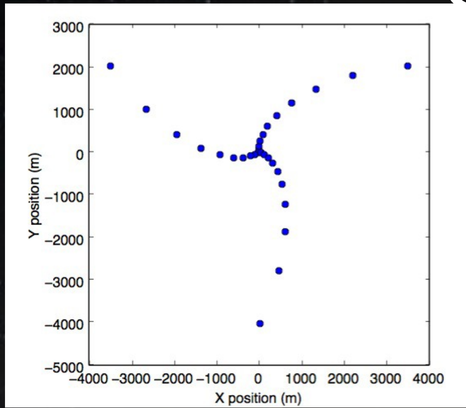


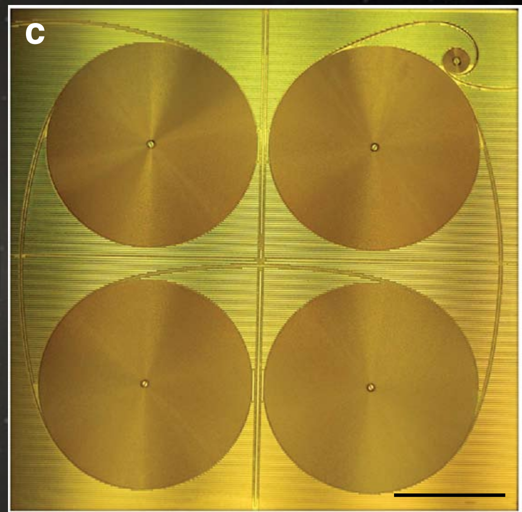


Chromatic and polarisation control

Lacour ++ 2013

Infrastructure photonics developments

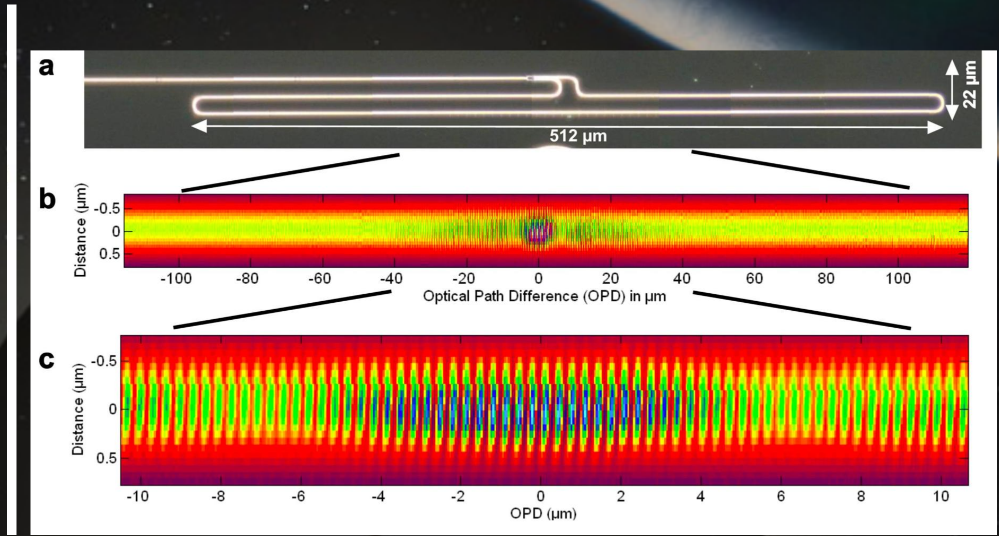




- Fiber beam transportation
- Delay lines

larger. Here we demonstrate a monolithic waveguide as long as 27 m (39 m optical path length), and featuring broadband loss rate values of (0.08 ± 0.01) dB m^{-1} measured over 7 m by optical

Integrated spectral dispersion



Lecoarer ++ 2009

- Efficiency
- Integration with combiners

More developments

- Polarisation control - Scientific polarisation
- Low-loss visible and MID-IR combiners
- Switchyards
- On-chip photonic modulation
- Hybridation
- APD matrices with higher number of pixels

Conclusion

- Gigantic progress of photonics detector technology enable combination of ~ 8T: we should be ok for existing facilities
- … but mostly in the near-infrared (good alternatives in visible e.g VISION)
- Breaking Limitations in dynamic range (closure phase, nulling) will require pushing technology and calibration strategy
- PFI sets new frontier in terms of imaging, phasing requirements
  - (re-)activate R&D (beam propagation, delay, coherent spectral resolution)
  - Prototyping facility needed (e.g not easy to use VLTI for R&D)