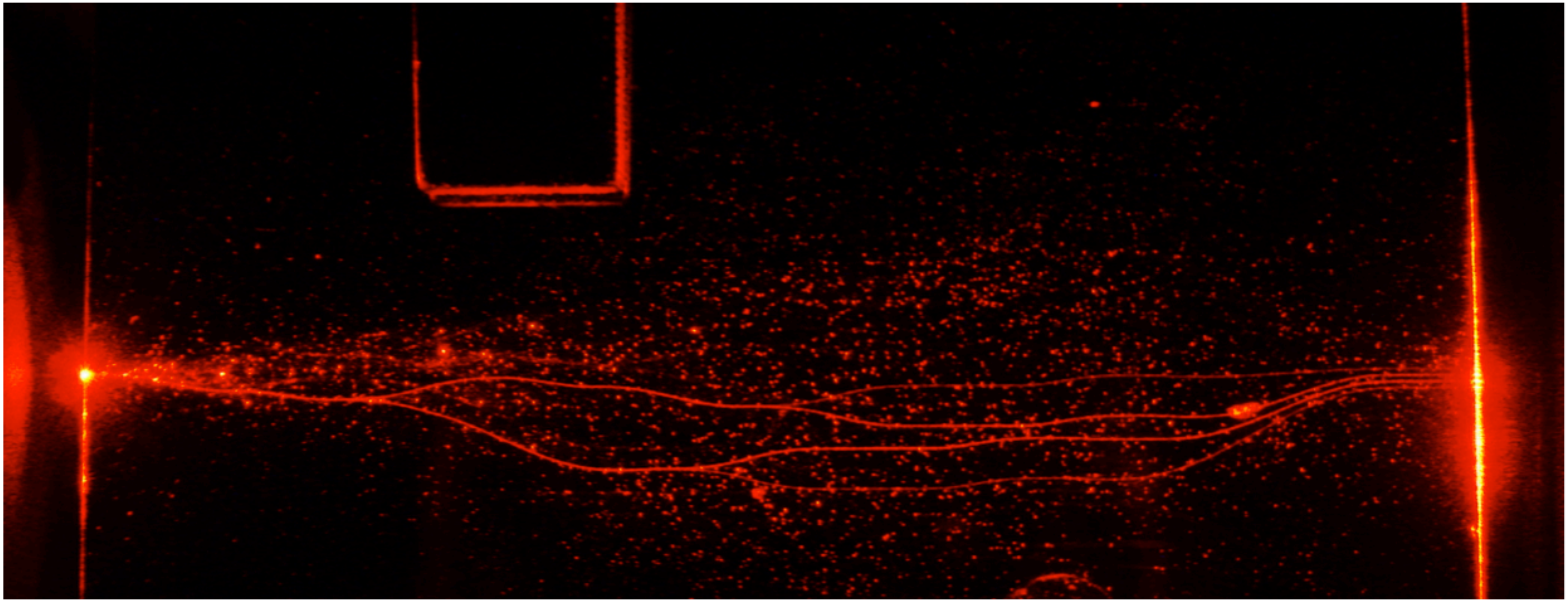
Photonics-based interferometry

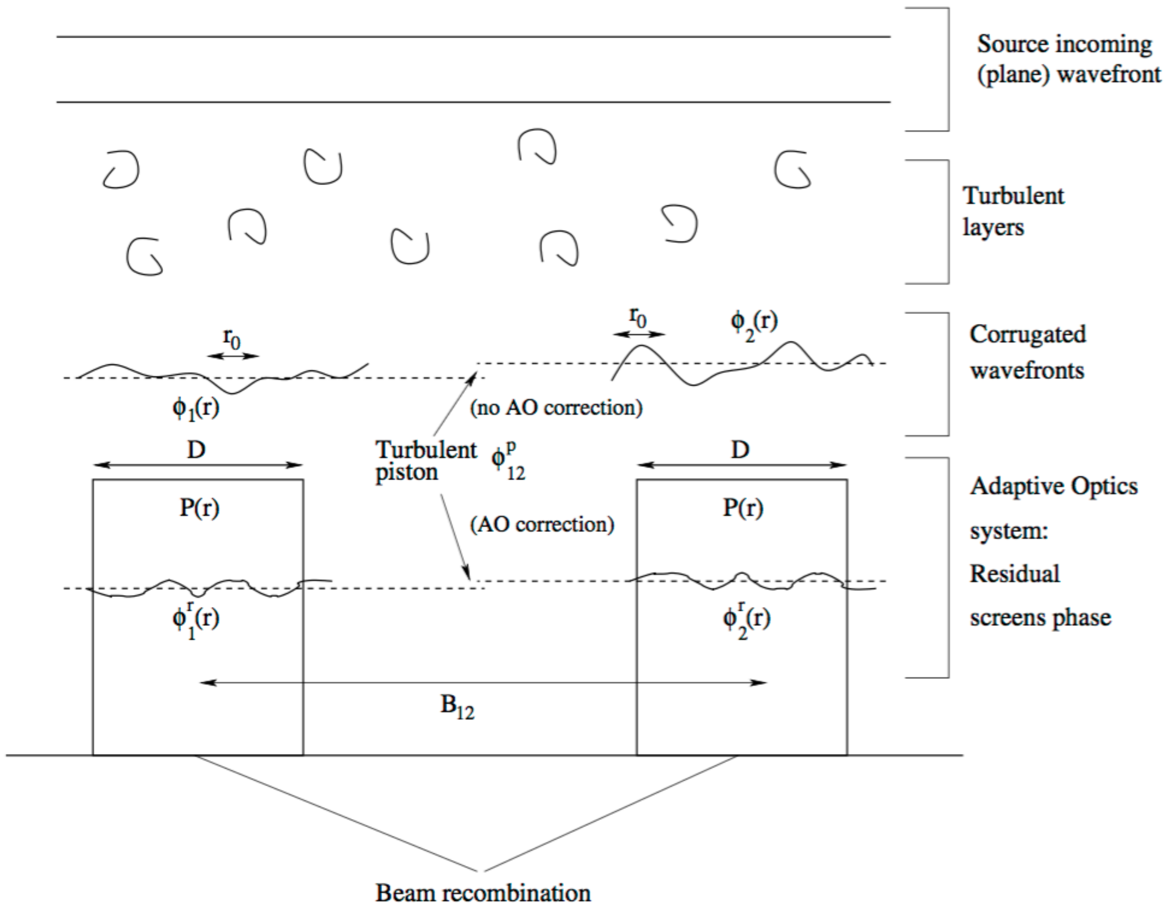


Nicolas Blind

Max-Planck Institut für Extraterrestrische Physik

The source of our problems: the atmospheric turbulence

- An interferometer measures the spatial coherence of the source
- Turbulence destroys this coherence



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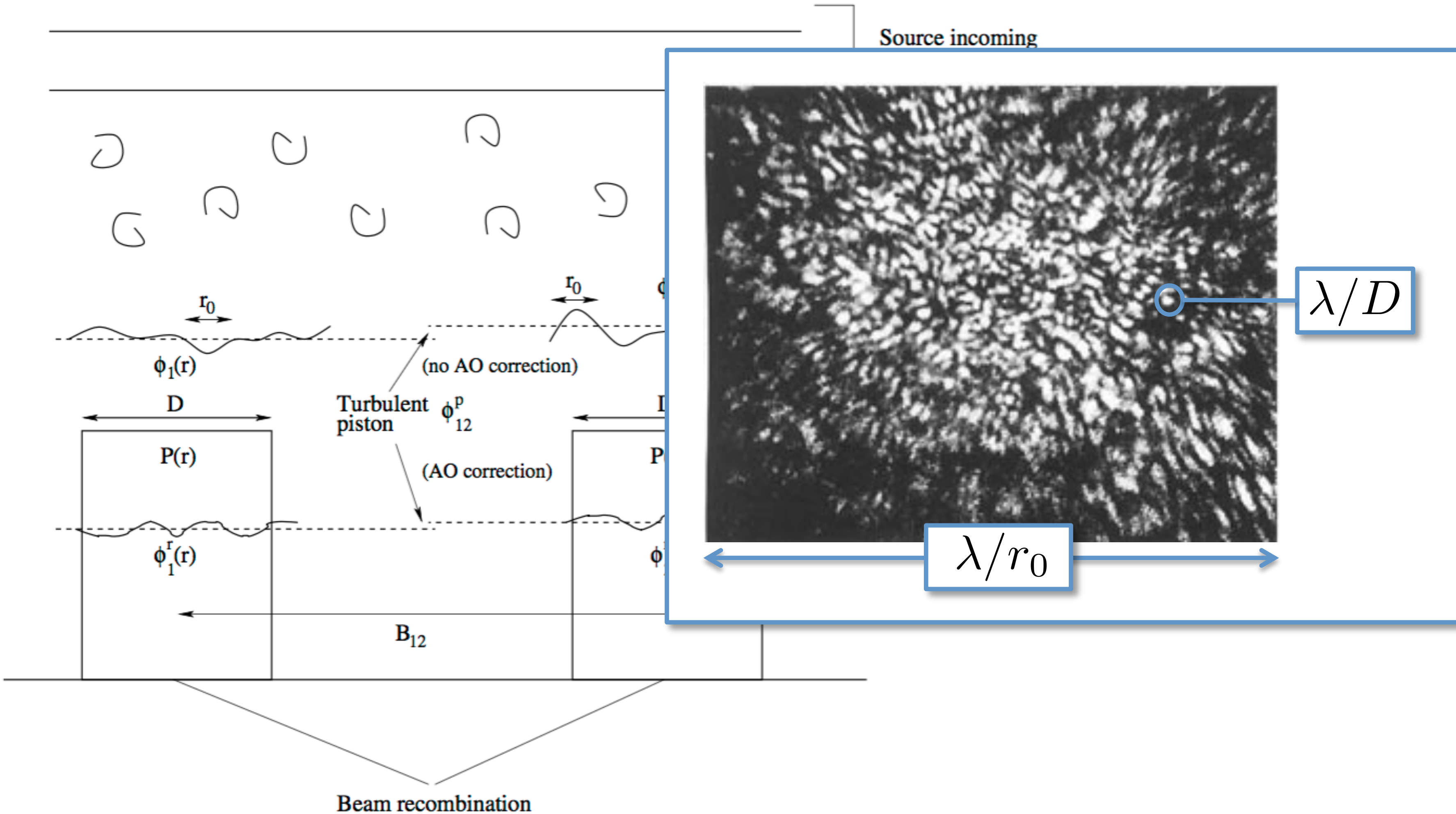

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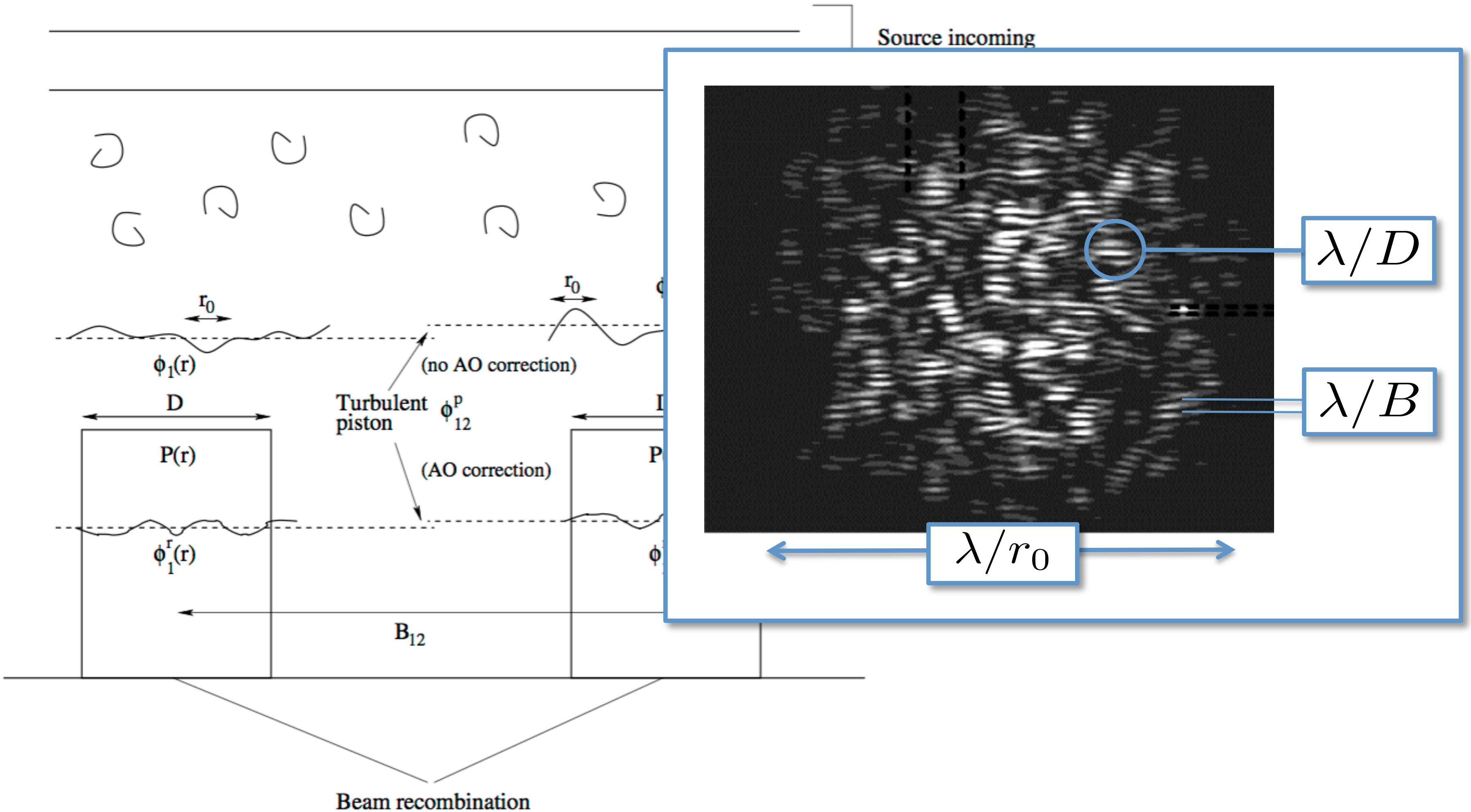

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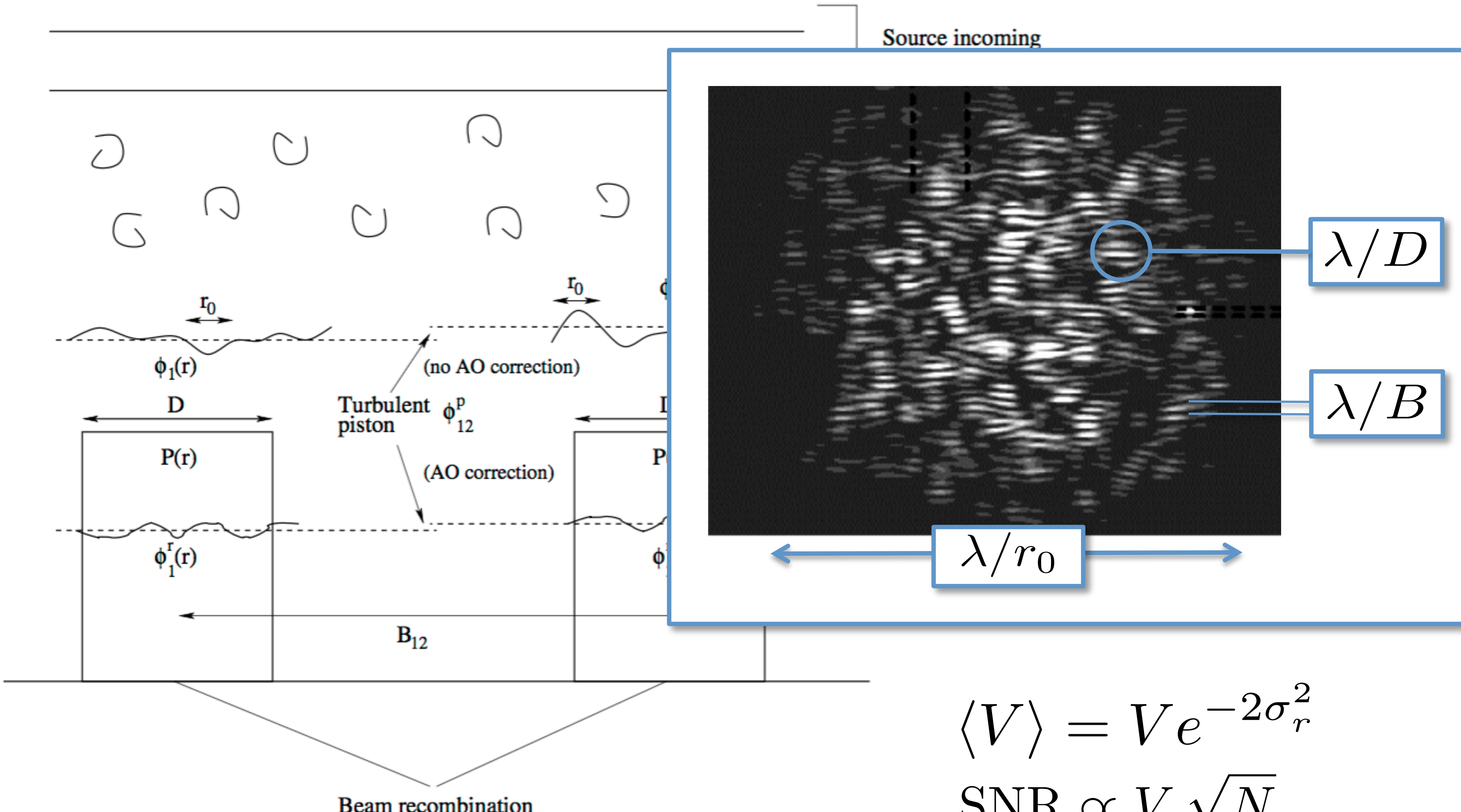


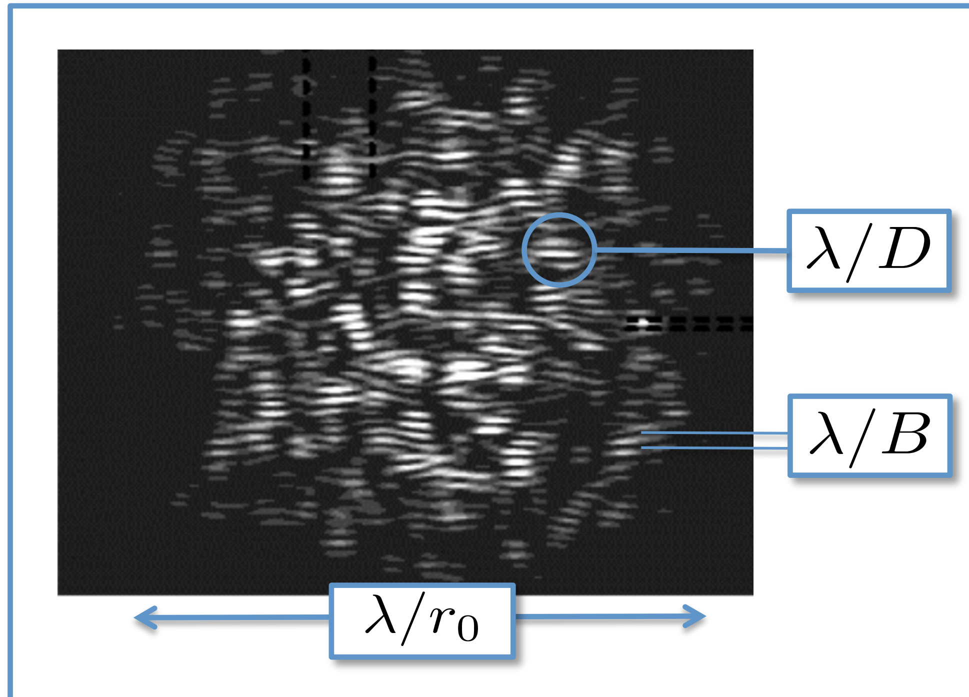
$$\langle V \rangle = V e^{-2\sigma_r^2}$$

$$\mathrm{SNR} \propto V\sqrt{N}$$

The source of our problems: the atmospheric turbulence

Options to preserve coherence:

1. Limit telescope size to ~ r_0
2. Pupil sampling
3. Spatial filtering with field stop
   - e.g. MIDI [Leinert+ 2003]
4. Modal filtering with SM waveguide



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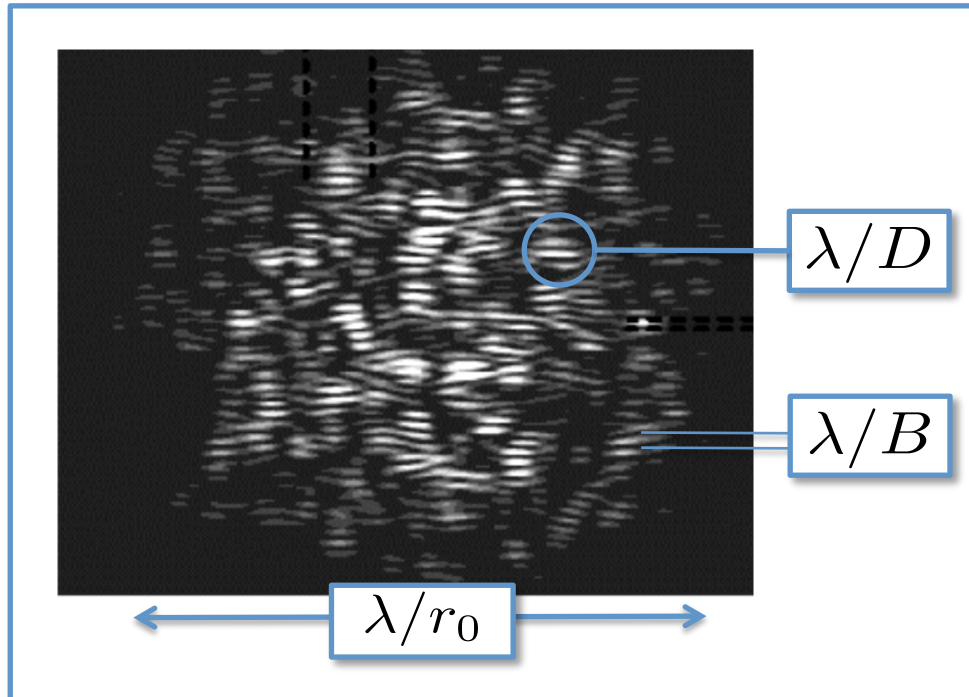
3. Spatial filtering with field stop
   - e.g. MIDI [Leinert+ 2003]
4. **Modal filtering with SM waveguide**
   - Keep coherence instead of flux [Tatulli+ 2004 & 2010, A&A]
   - <1% visibility precision [Kervella+ 2004, A&A]



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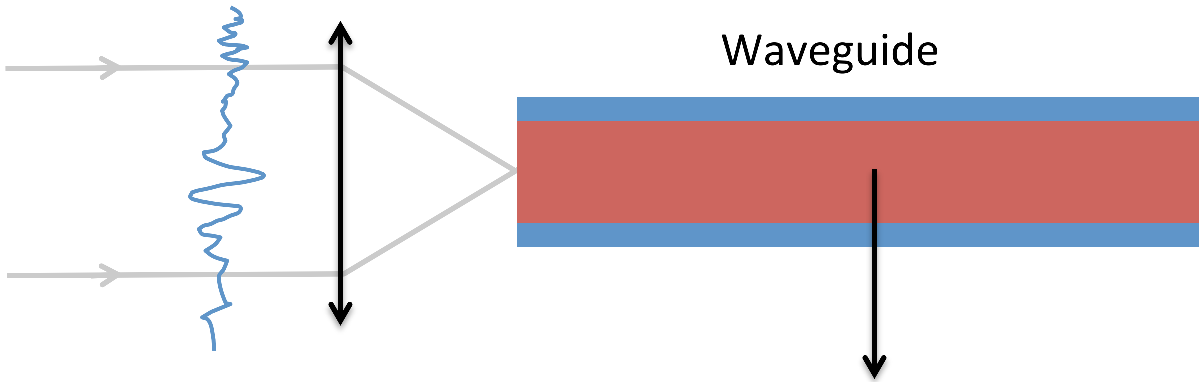
Interferometry with waveguides

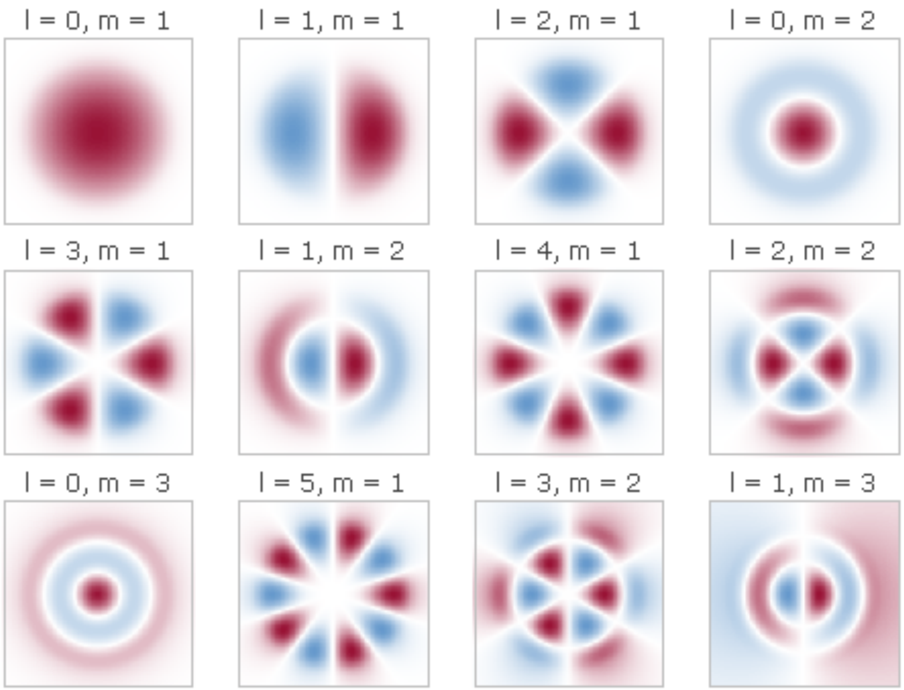


V parameter: $V = \frac{2\pi}{\lambda} a \cdot \mathrm{NA}$

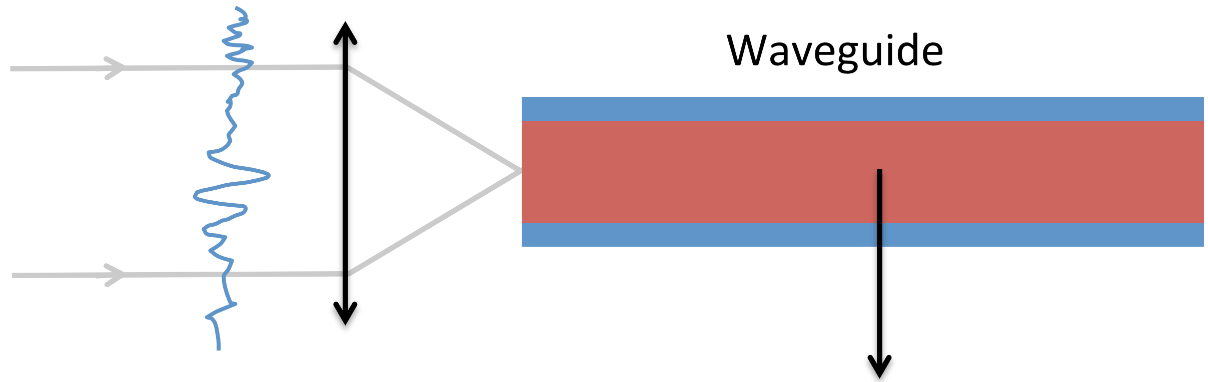
$$\mathrm{NA} = \sqrt{n_{core}^2 - n_{cladding}^2}$$

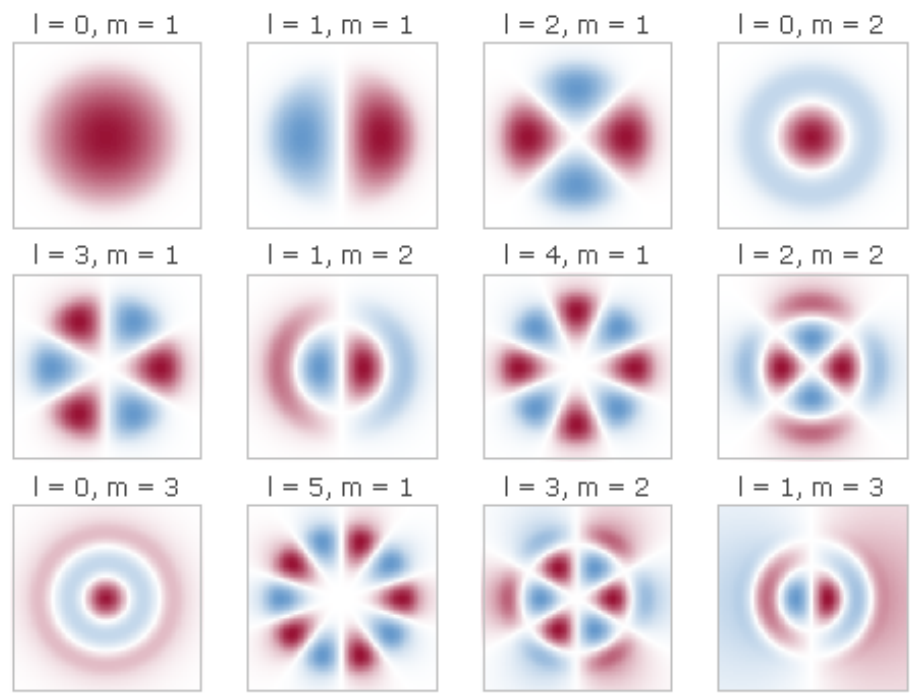
Number of modes

$$\mathrm{M} \sim V^2/2$$



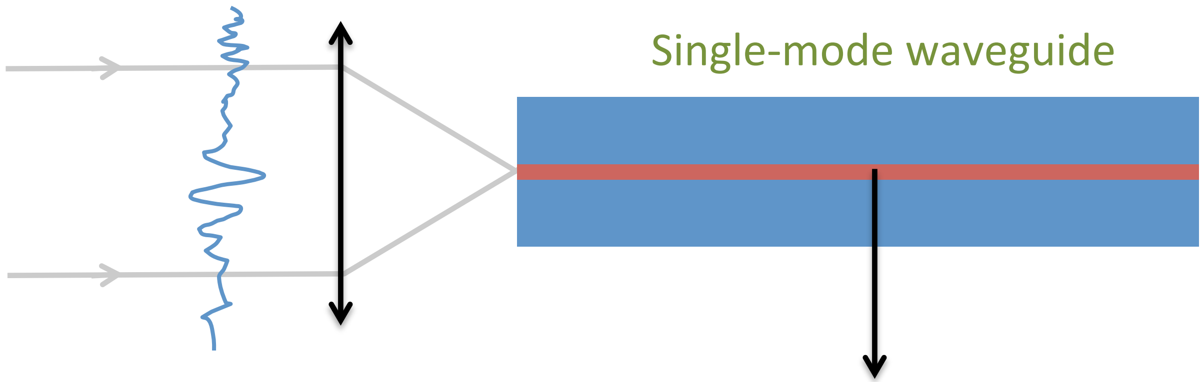
Interferometry with waveguides





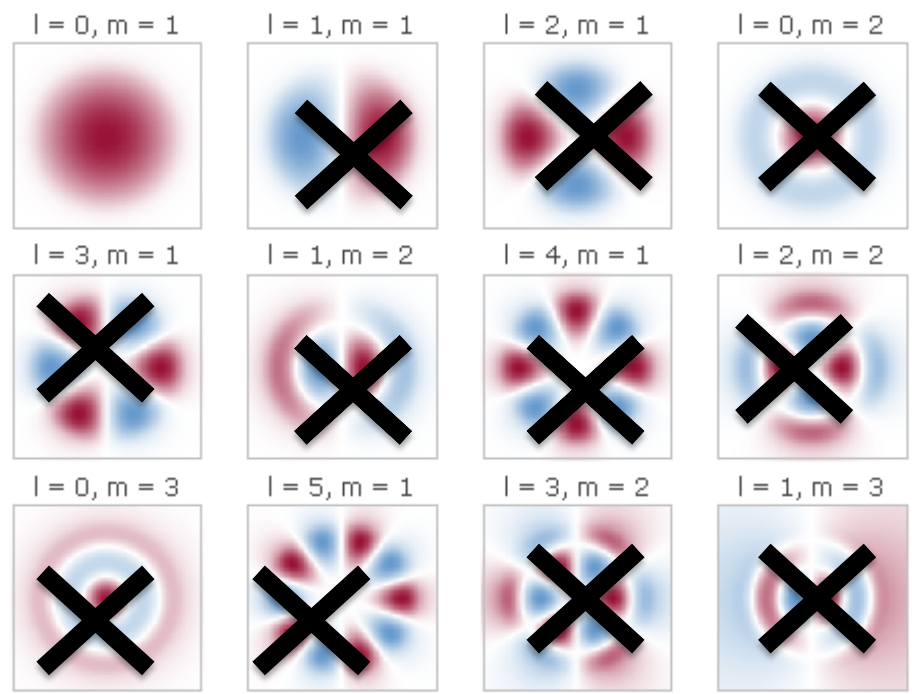
BUT modal dispersion: each mode has its own propagation speed

Interferometry with waveguides

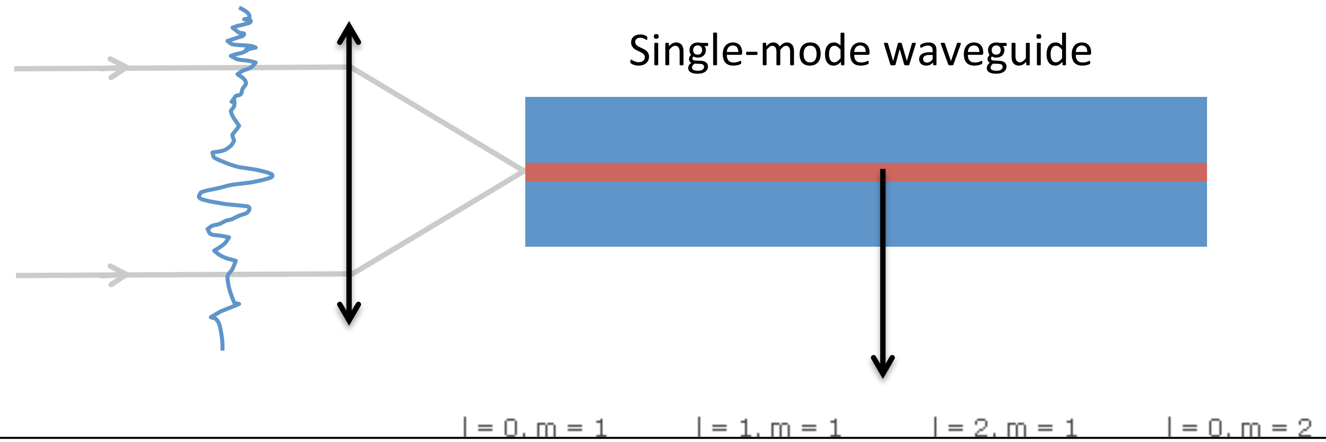


BUT modal dispersion: each mode has its own propagation constant

Interferometry needs single-mode waveguides: M=1, V<2.405

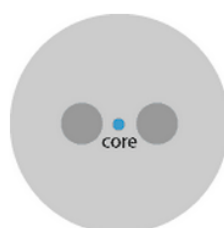


Interferometry with waveguides



BUT again:

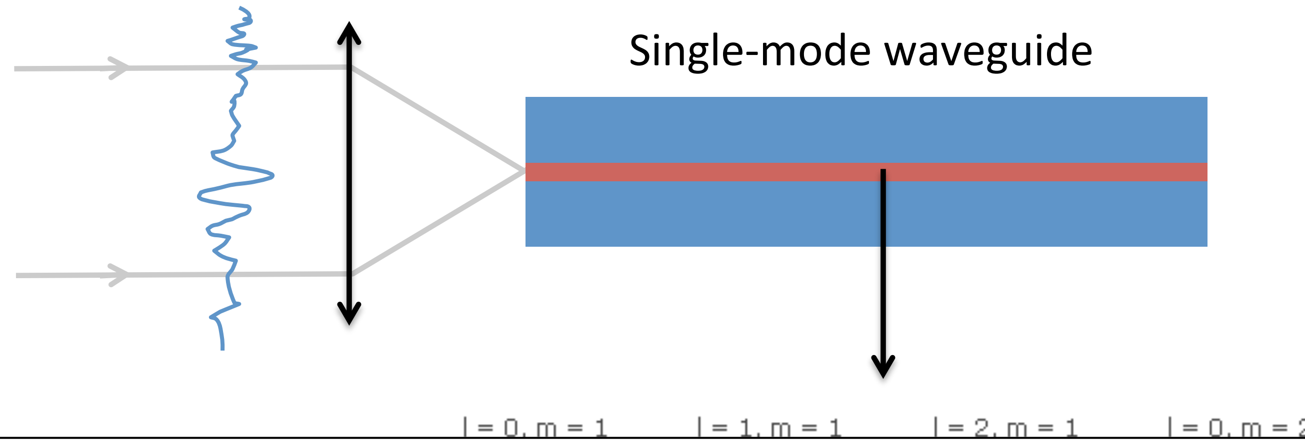
- Birefringence: each polarisation has a mode
  - Low via bending, twisting, etc. stress
  - High via build-in stress: Polarisation Maintaining fibers (PMF)



PANDA PMF

Bow-tie PMF

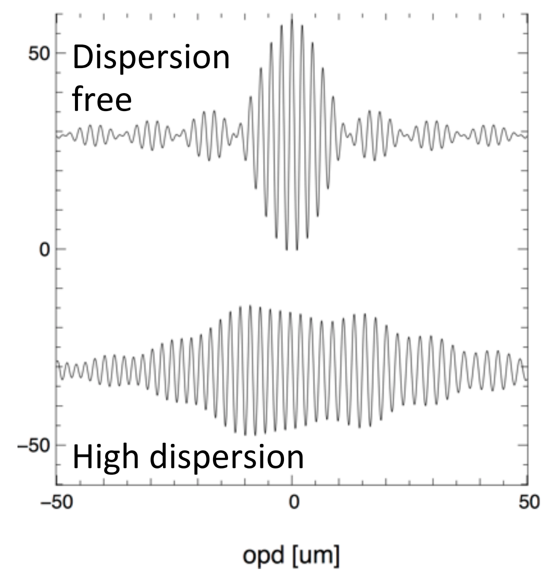
Interferometry with waveguides



BUT again:

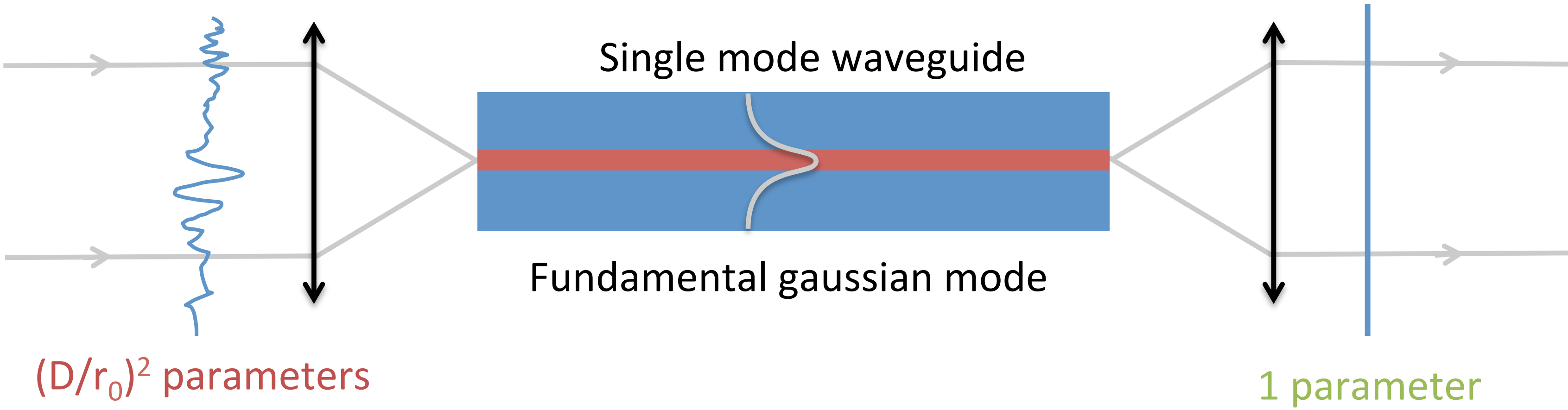
- Birefringence: each polarisation has a mode
    - Low via bending, twisting, etc. stress
    - High via build-in stress: PMF

- Chromatic dispersion in glass
    - Fiber lengths must be equal to +/- 10mm for instrumental contrast > 90% (broadband)



Benefit of single-mode interferometer

1. Single-mode instrument: M = 1, V < 2.405



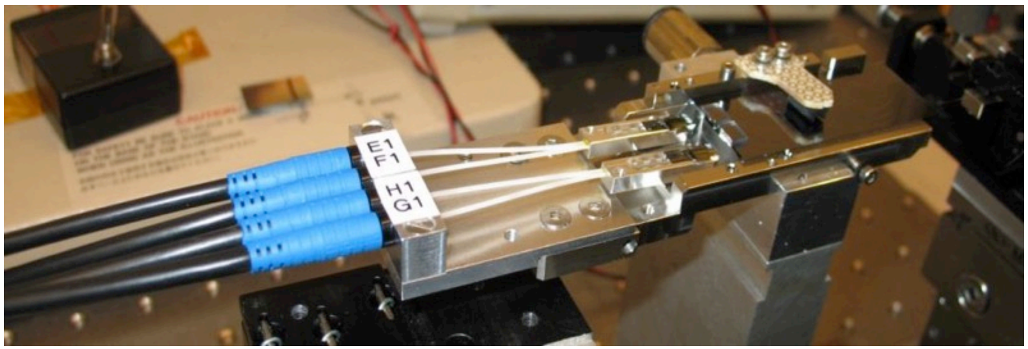
- From a theoretical point of view, it is better to keep coherence rather than all the photons, especially at low Strehl and with big telescopes [Tatulli+ 2004, 2010 A&A]

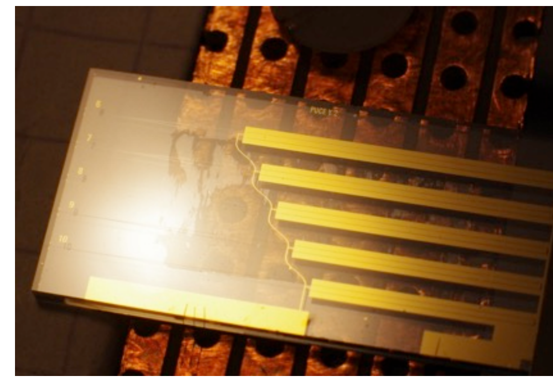
- Modal filtering transforms wavefront fluctuations into power fluctuations leading to very high instrumental contrast

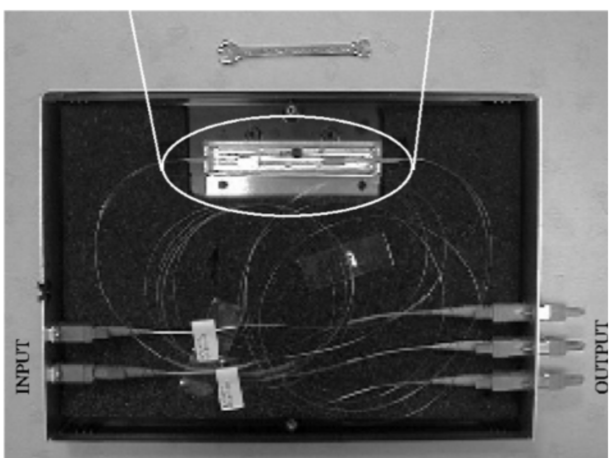
Modal filtering preserves the coherence
and
Allow much more precise calibrations

Benefit of single-mode interferometer

1. Single-mode instrument for modal filtering of the wavefront
2. Transporting light
3. Replacing bulk functions in fully integrated components
   - Ease the alignment by decreasing the number of mirrors

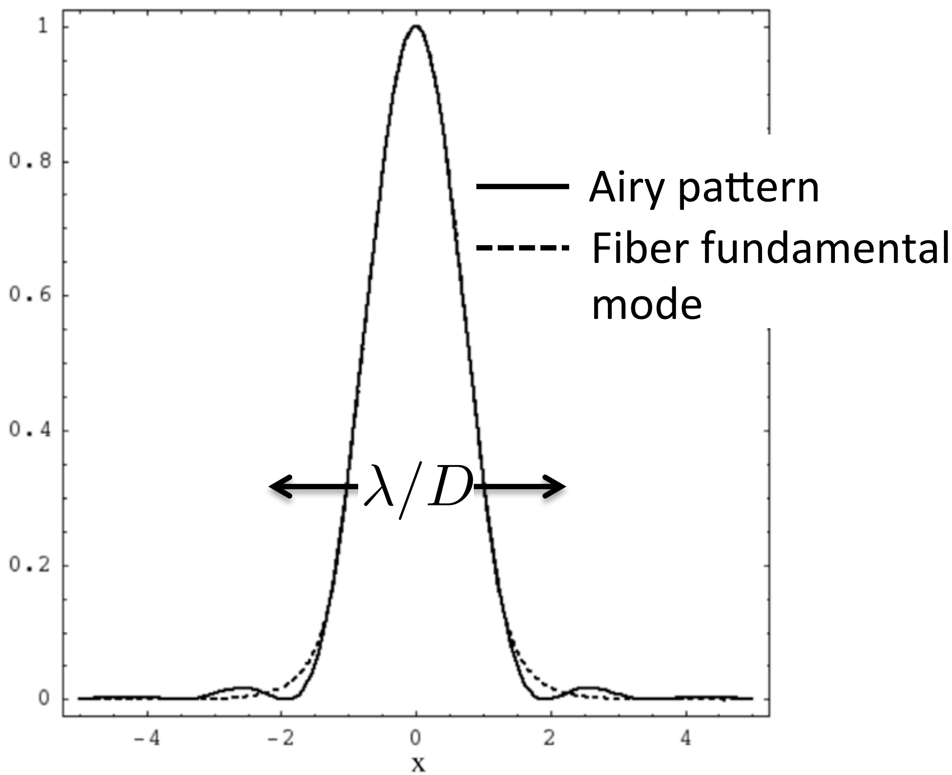






In practice: coupling light into SM fibers

Coupling efficiency in SM fiber: $\rho = \left| E_{field} \star E_{01,fiber} \right|^2$



- The fiber NA is scaled to the telescope diffraction for optimum coupling
- For a perfect Airy pattern:

$$\rho = 0.8$$

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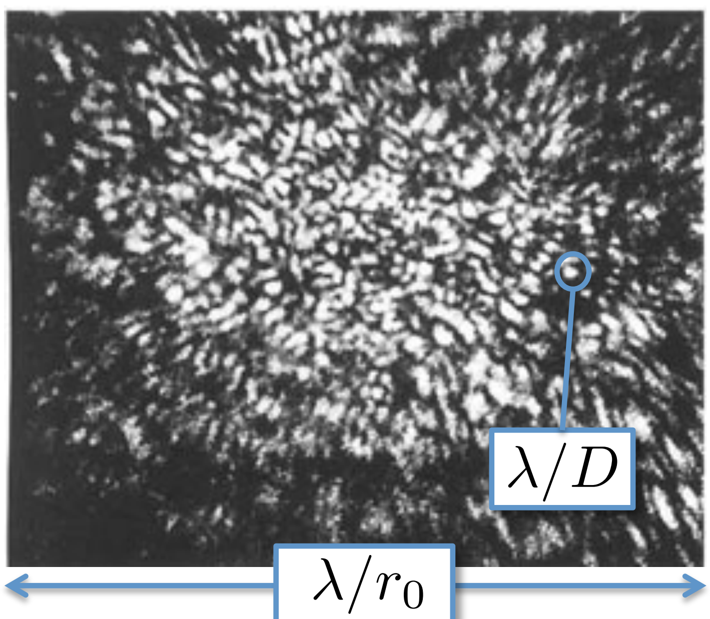

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- For a real telescope:

$$\rho \sim 0.8\,\mathcal{S}$$

$\mathcal{S}$ being the instantaneous Strehl ratio

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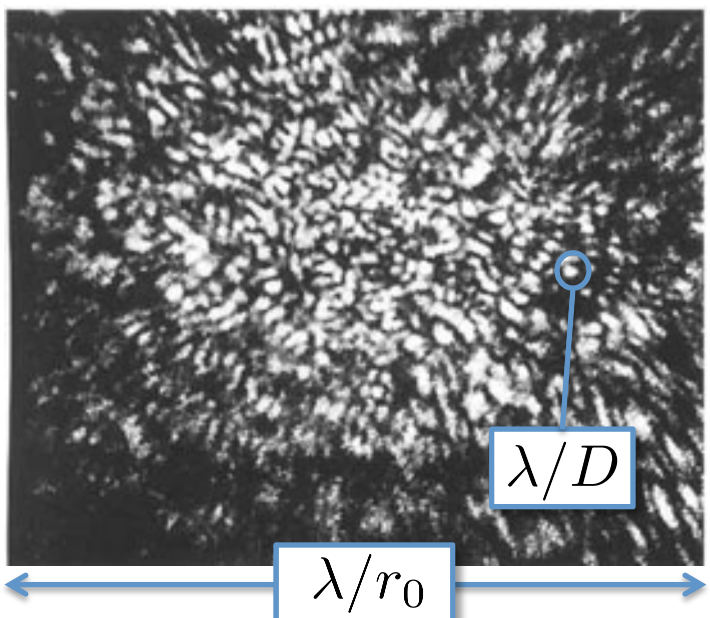
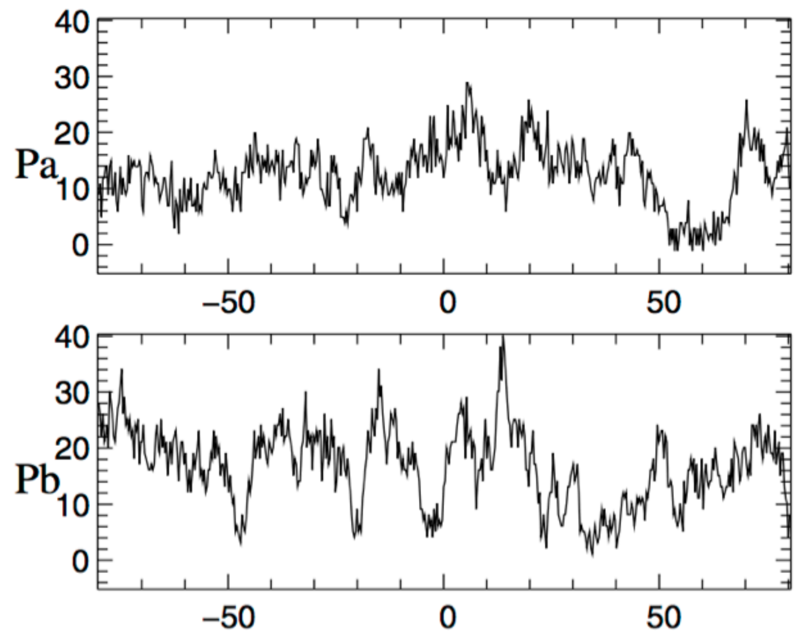


Flux in VINCI-2TH with
0.35m siderostats



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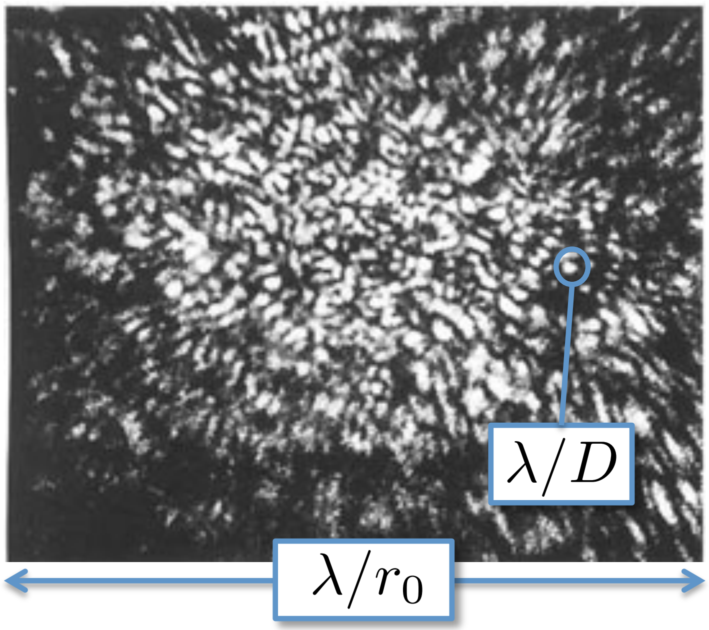

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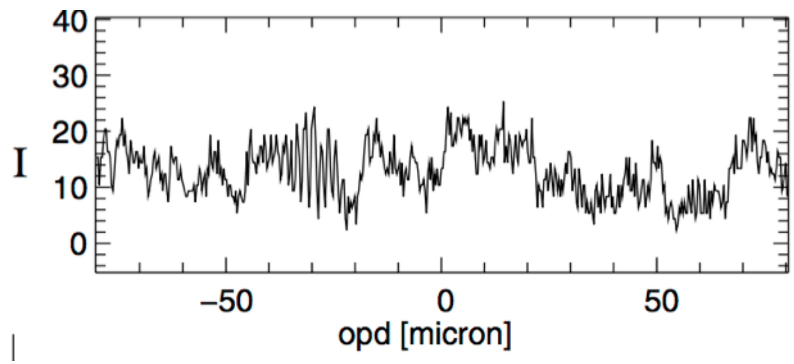


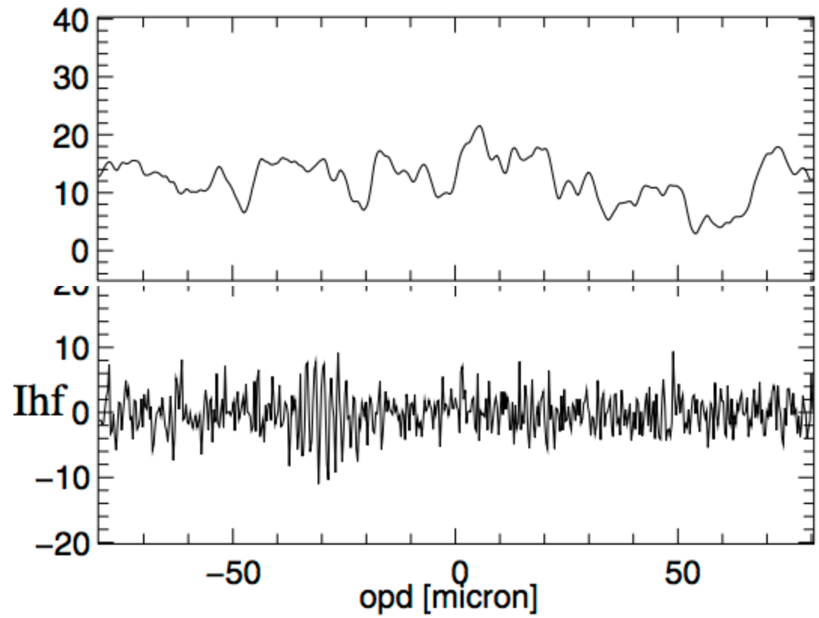
In practice: coupling light into SM fibers

- Fringes with VINCI-2TH and 0.35m siderostats
  - P_A and P_B are easy to monitor with dedicated channels
  - Geometric photometry

$$\sqrt{P_a P_b}$$

  - Corrected fringes

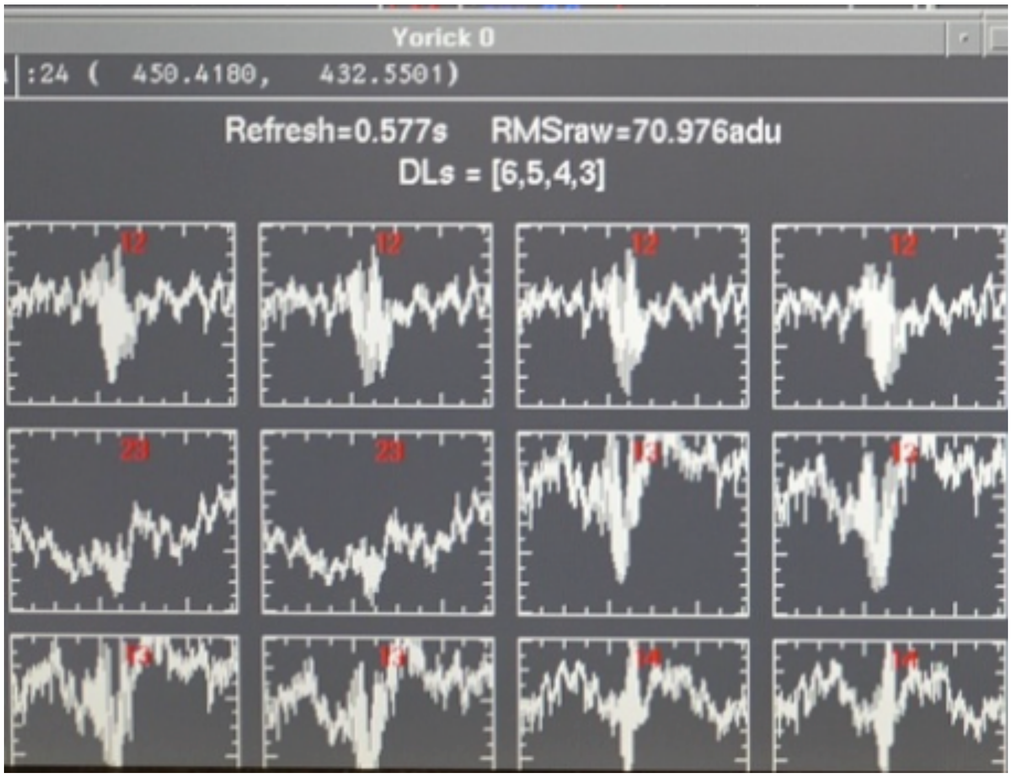
$$\frac{I - \kappa_a P_a - \kappa_b P_b}{2\sqrt{\kappa_a \kappa_b}\,\sqrt{P_a P_b}}$$

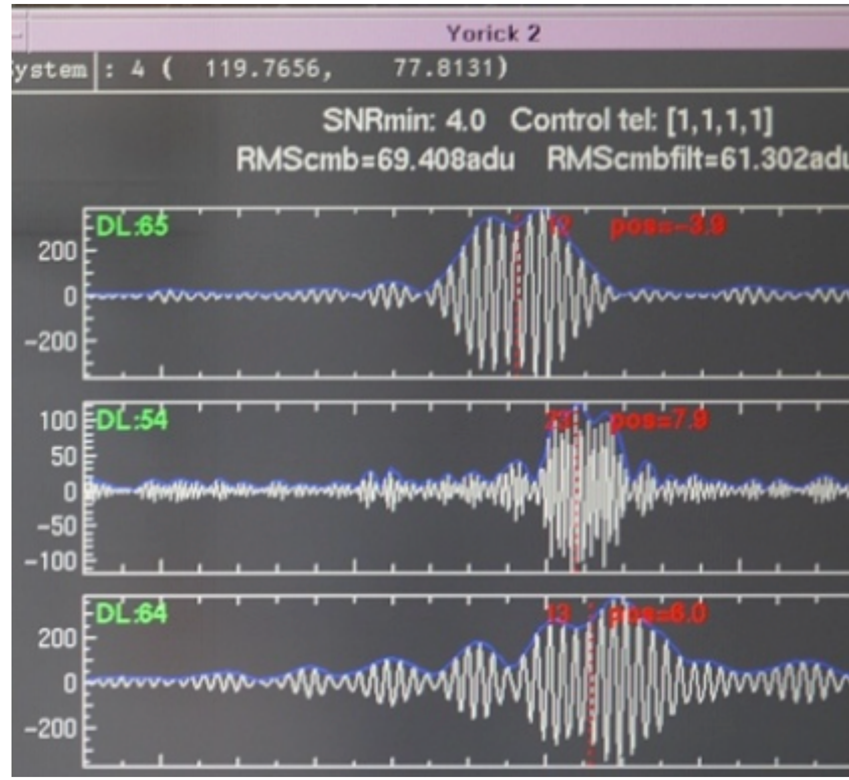


The monitoring of the "instantaneous" transfer function allows reaching better than 1% precision on V^2

In practice: coupling light into SM fibers

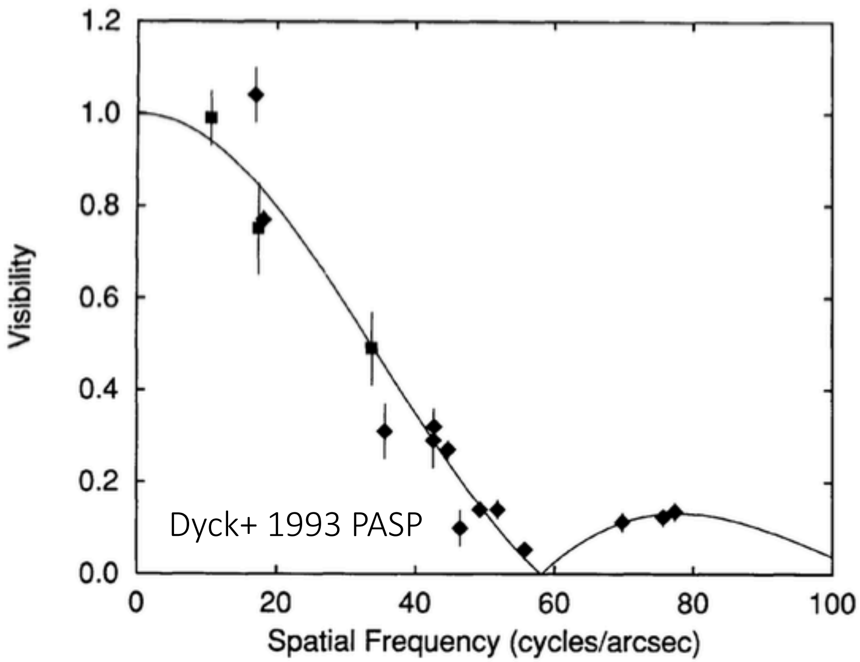
- Fringes with PIONIER (H) on ATs (2 m)



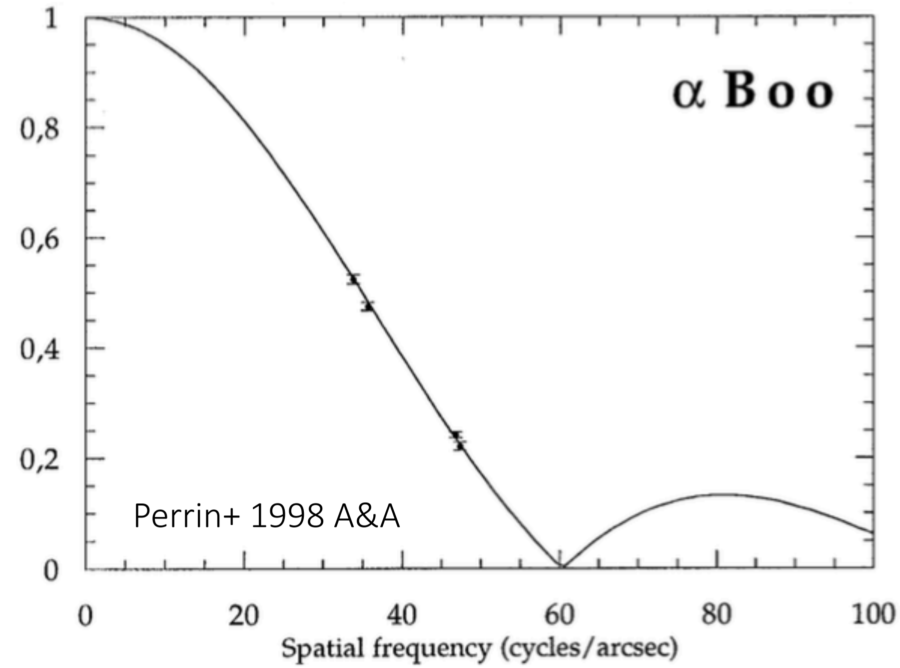


An example of increased precisions on visibilities

Classical interferometry (IRMA+I2T):

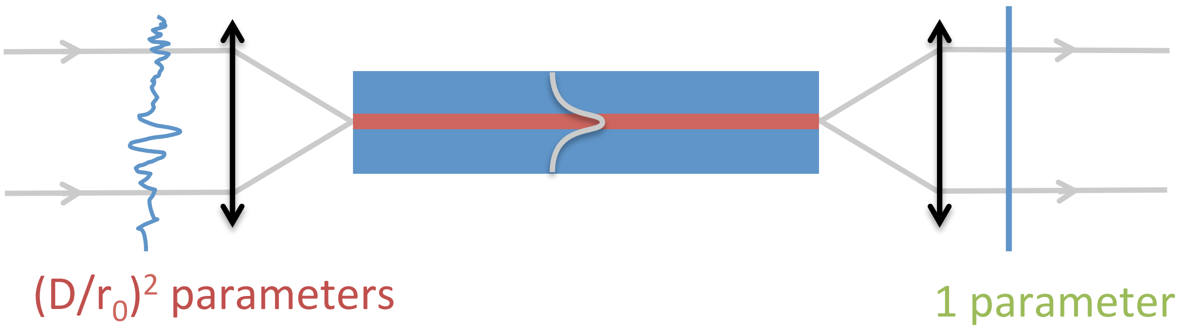


Single-mode interferometry (FLUOR/IOTA):



Closure phase precision

- In SM interferometry, phase is defined in a unique way



- Closure phases up to 0.25 degrees precision with PIONIER
  - Imaging dynamic range:

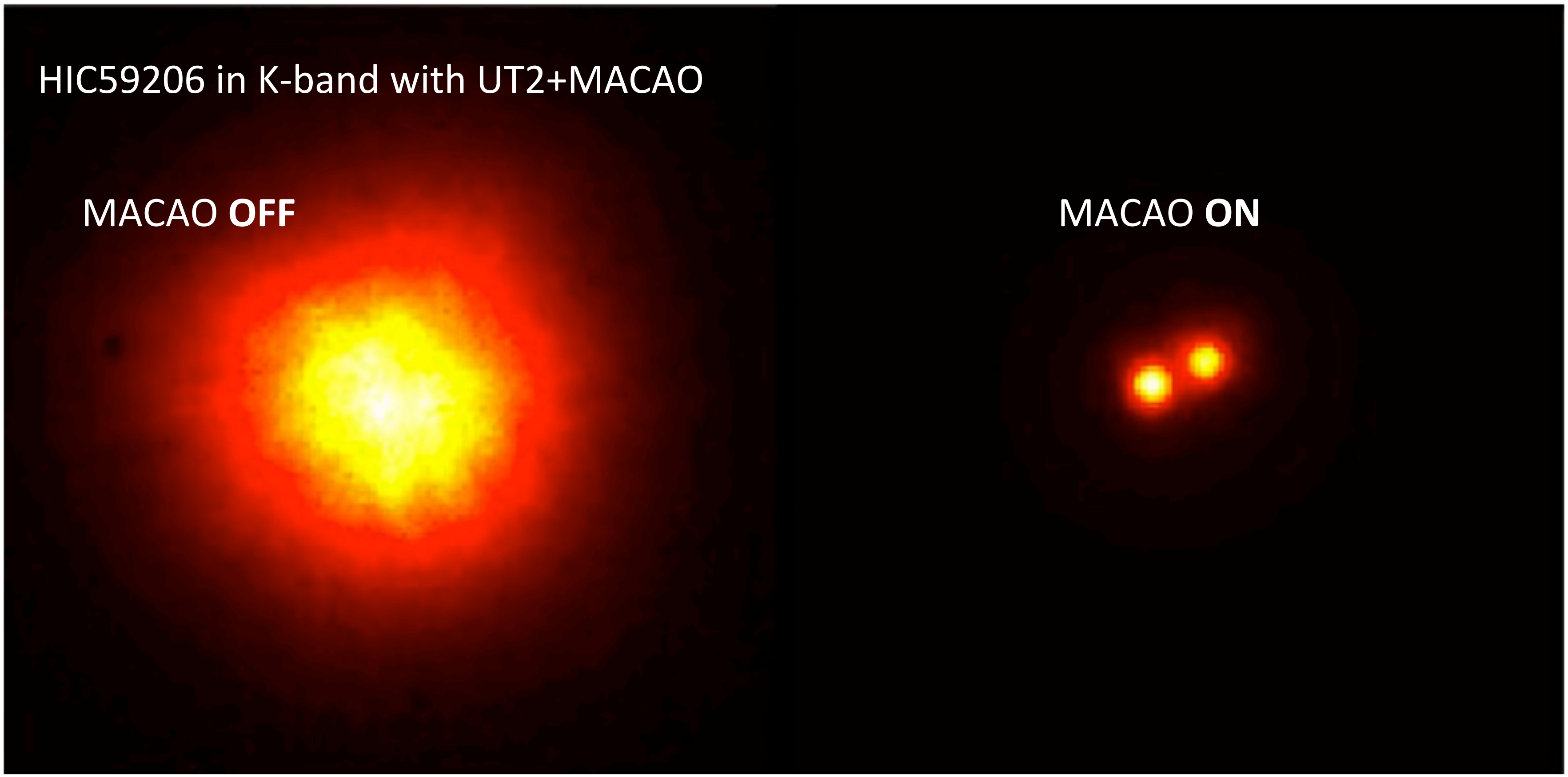
$$DR = \sqrt{\frac{N_{\mathrm{data}}}{(\sigma_V/V)^2 + \sigma_\phi^2}}$$

[Baldwin & Haniff 2002]

  - Companion detection up to contrast level of 200 (~6 mag)
    Up to 500 expected for deep integration

[Absil & Le Bouquin 2011 A&A]

Benefits of AO



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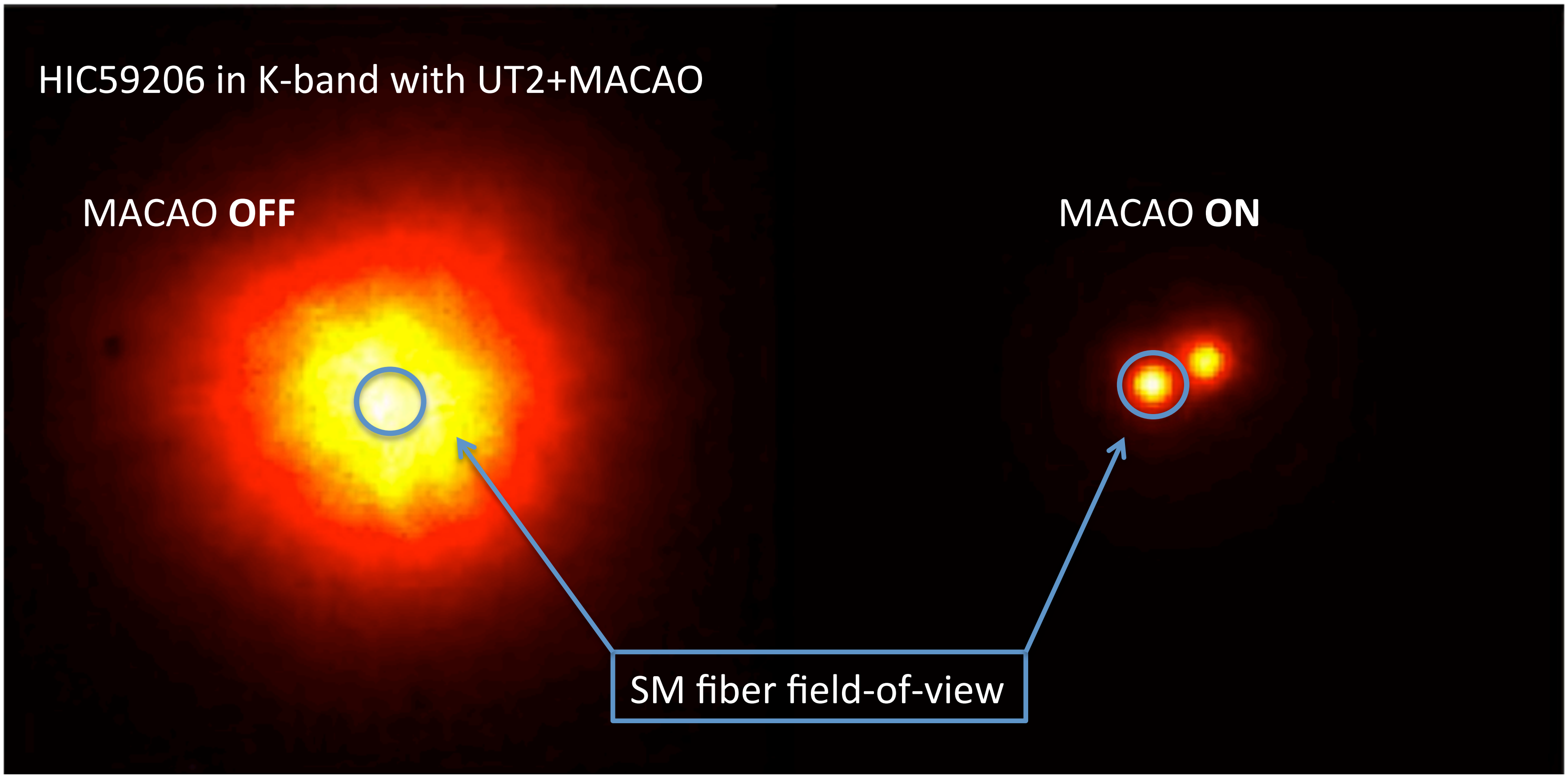

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And hence the sensitivity and sky coverage

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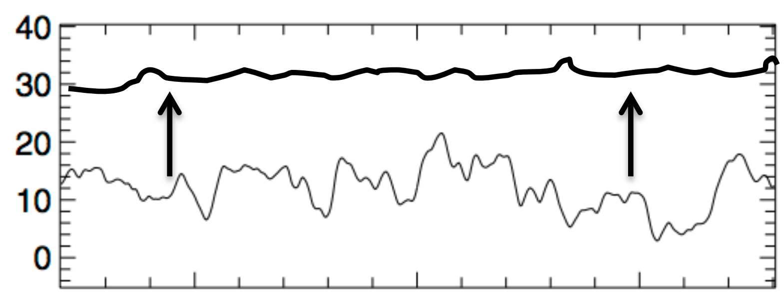
And hence the sensitivity

$$\langle V \rangle \propto \sqrt{P_a P_b} \cdot V$$

$$\mathrm{SNR} \propto V\,\sqrt{N}$$



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  → improve fringe tracking efficiency

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  [Ridgway+ 2008 SPIE, Tatulli+ 2010 A&A]
- Will soon allow SM interferometry in the visible @CHARA
  - Strehl going from <0.5% to "few" %

Some limitations of SM interferometry

- Field of view limited to the telescope diffraction pattern, i.e. in K-band:
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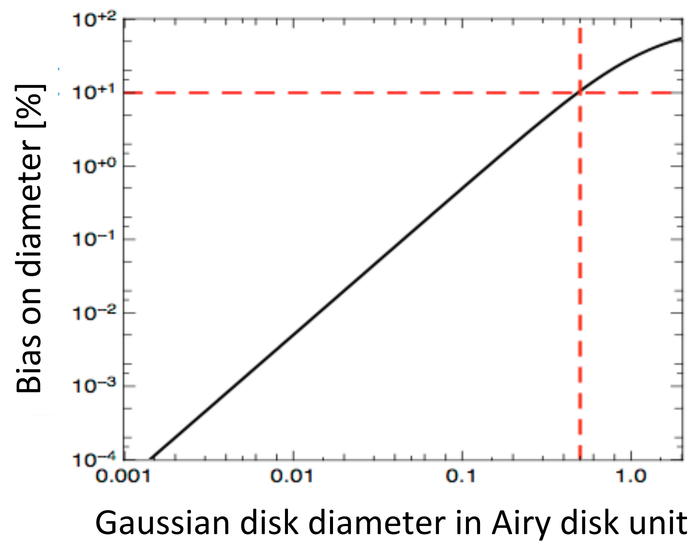


[Tatulli 2004+, PhD thesis, p.52]

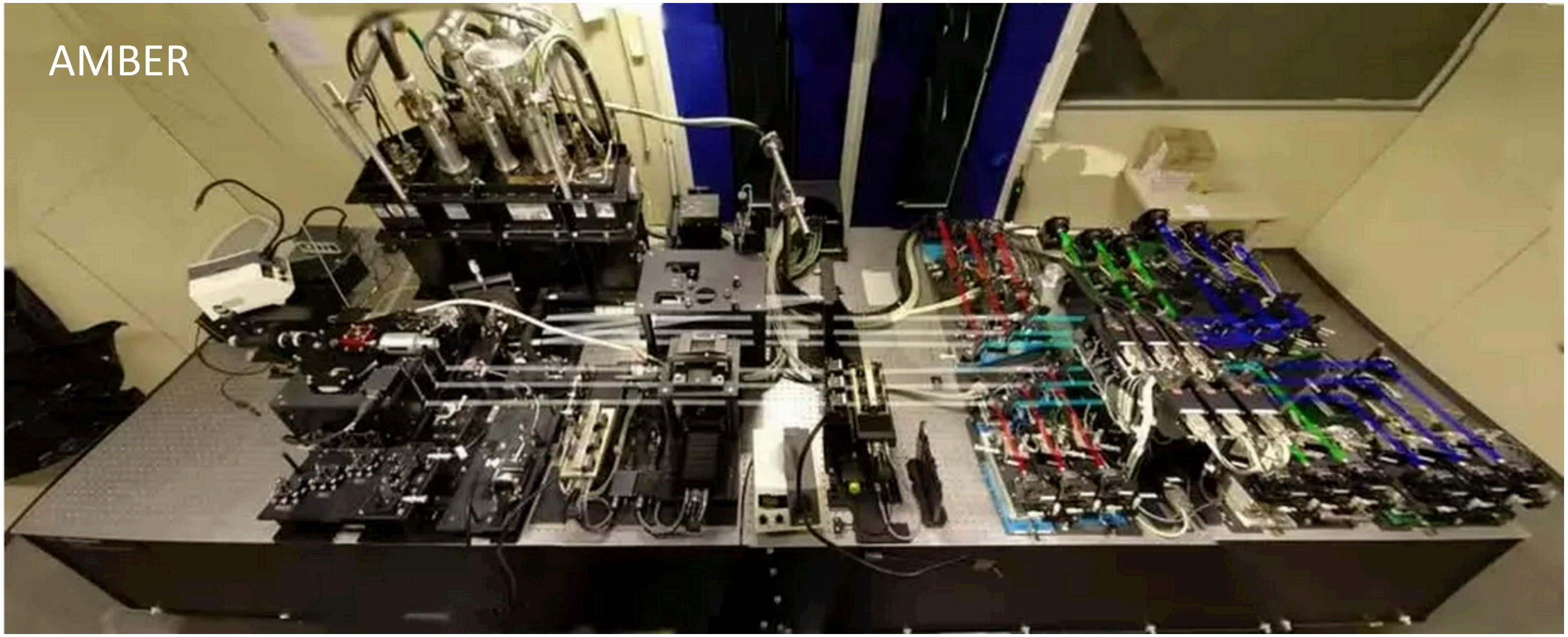
Bias of 10% for a disk diameter of ½ the Airy disk
Bias < 1% for a disk diameter < 20% Airy disk

Some limitations of SM interferometry

- Field of view limited to the telescope diffraction pattern, i.e. in K-band
  - 60 mas with UTs
  - 250 mas with ATs
- Lobe effect: modal visibility bias
- Bandwidth limitations
  - Limited to few 100nm bandwidth (~1 astronomical band)
    - SM waveguide stops guiding at longer wavelength
    - SM waveguide becomes bi-mode at shorter wavelength
  - U, V, B, I needs AO, but feasible
  - H, K bands with fibers and (short) integrated optics
  - L, M bands with some fibers only
    - Development of IOBC in LiNbO3 & Chalcogenide materials

Single-mode beam combiners

- Sole use of SM fibers for spatial filtering:
  - MIRC @ CHARA [Monnier+, 2004]
  - CLASSIC, CLIMB @ CHARA [Sturmann+ 2010 SPIE, ten Brummelaar+ 2010 SPIE]
  - AMBER @ VLTI [Petrov+ 2007 A&A]



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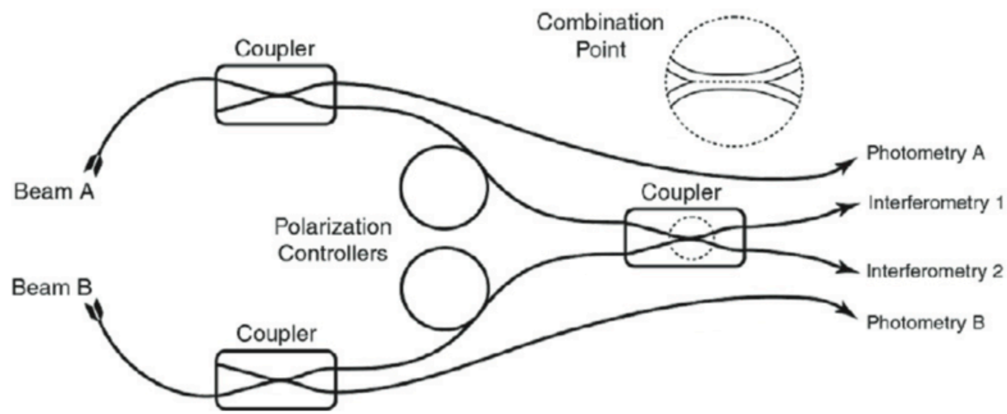

  - GRAVITY @ VLTI : polarisation and delay control

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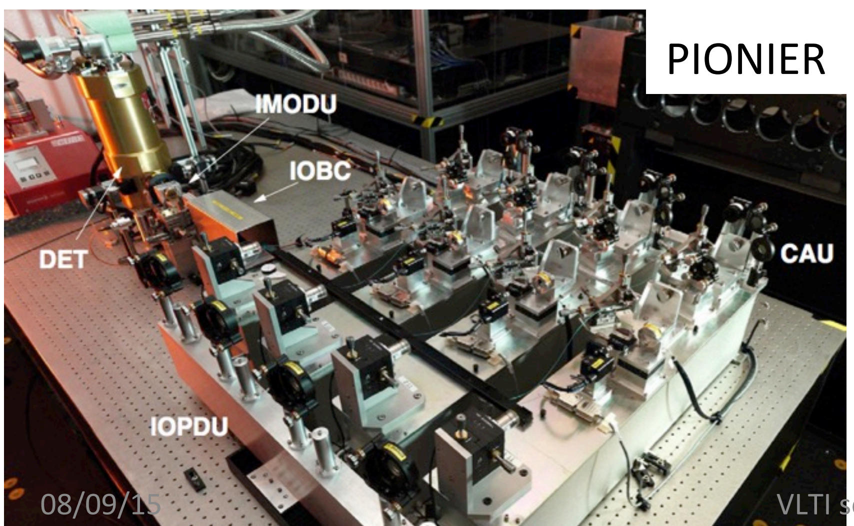
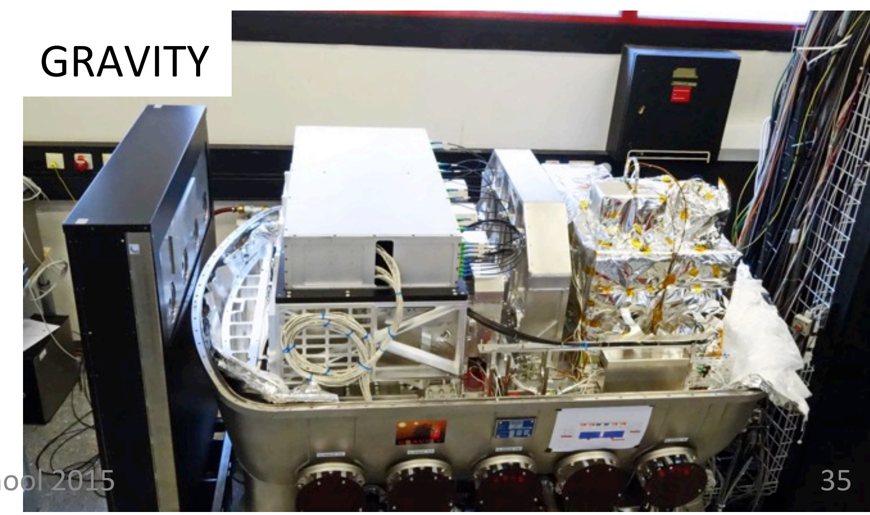
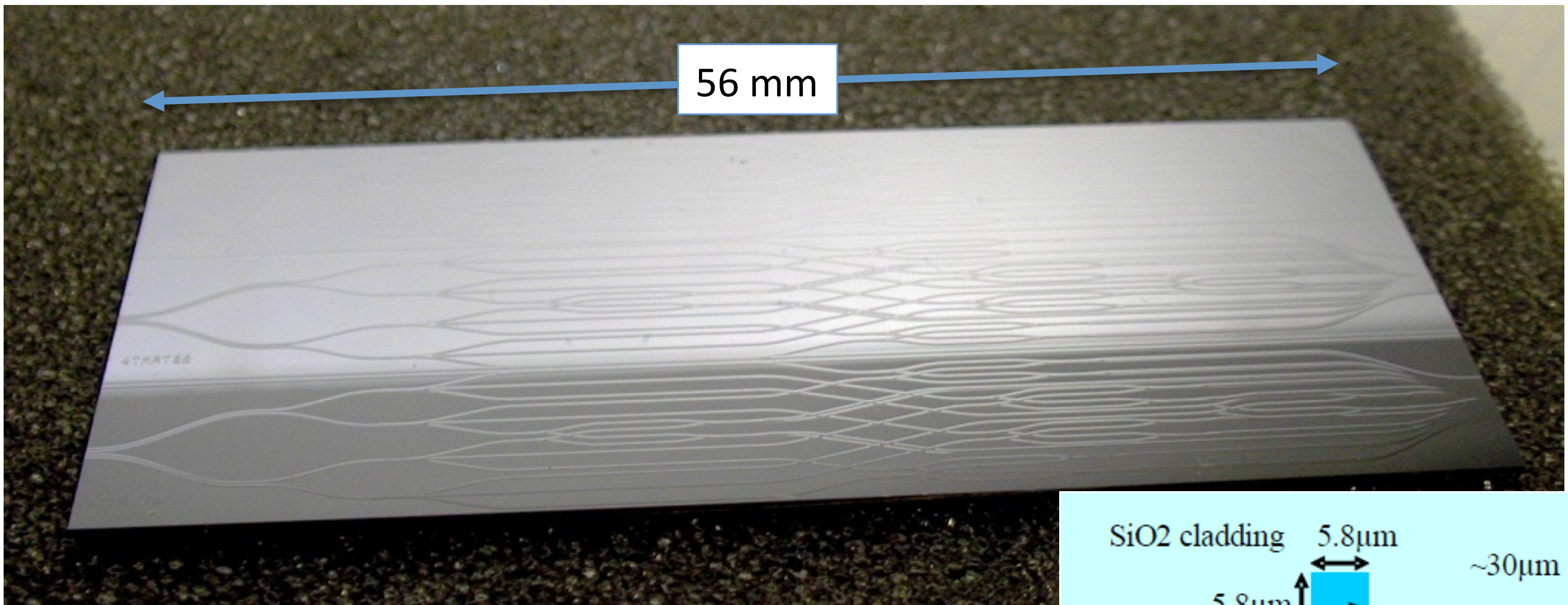
- Use of fibered functions
  - FLUOR @ CHARA : splitters/couplers
  - GRAVITY @ VLTI : polarisation and delay control
- Integrated optics: complex beam combination in stable & compact SM device
  - PIONIER @ VLTI
  - GRAVITY @ VLTI

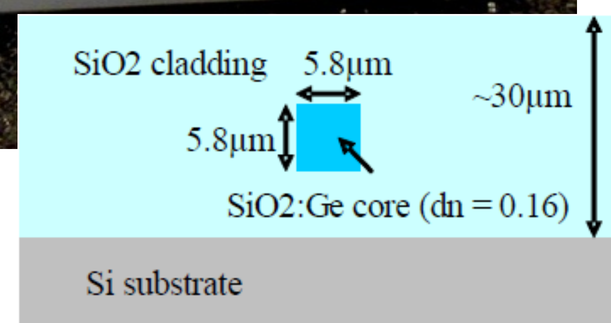




The integrated beam combiners of GRAVITY and PIONIER

- Planar integrated optics beam combiners (IOBC)
- Combine 4 VLTI beams (6 baselines) by pair with an ABCD coding
- Average throughput ~60-70%





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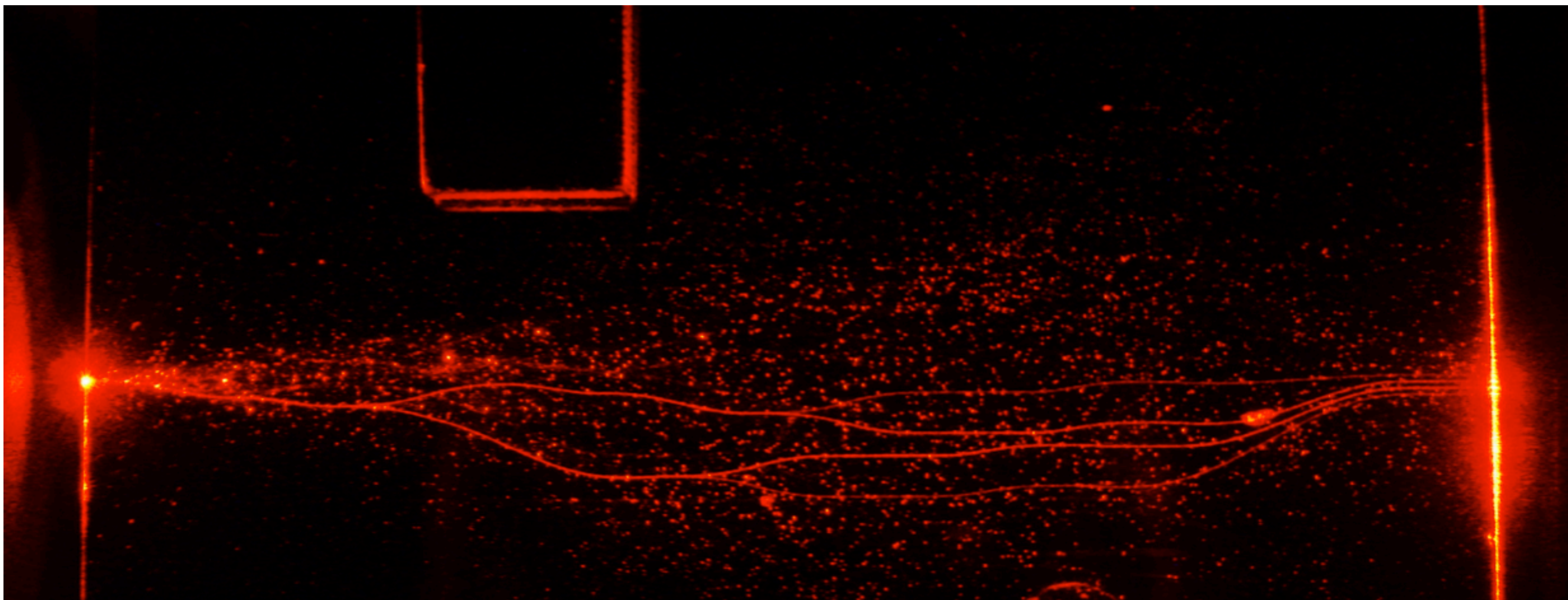

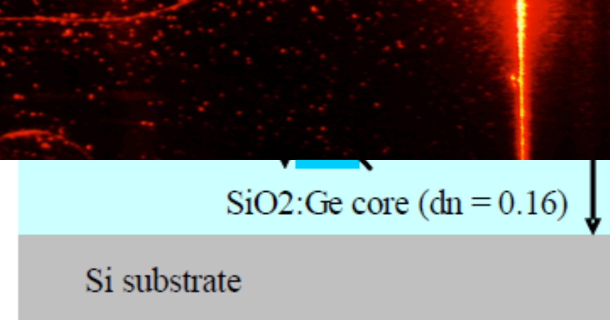

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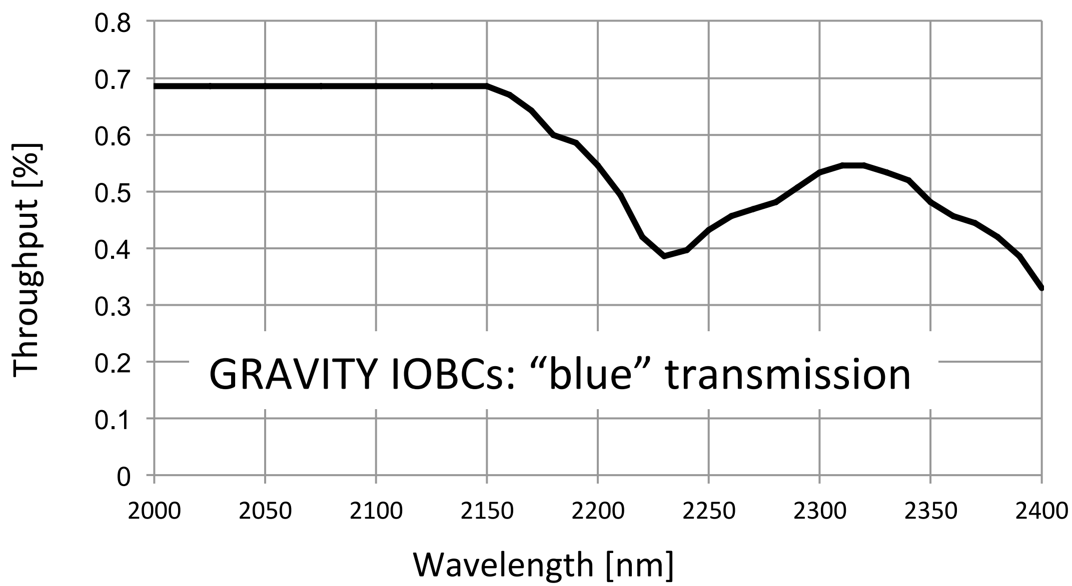
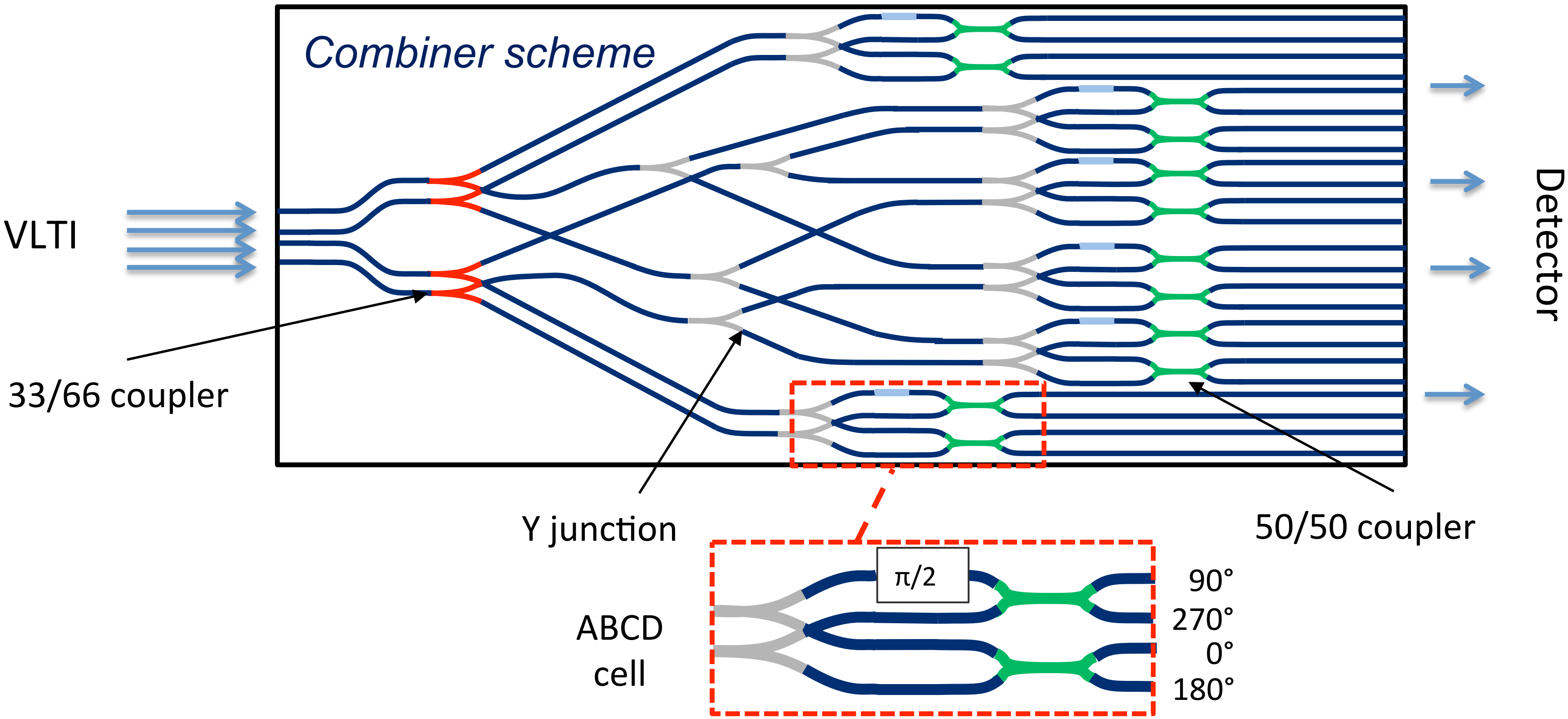


- Interferometric contrast >90% in broadband
  - Low differential effects (chromatism & birefringence)

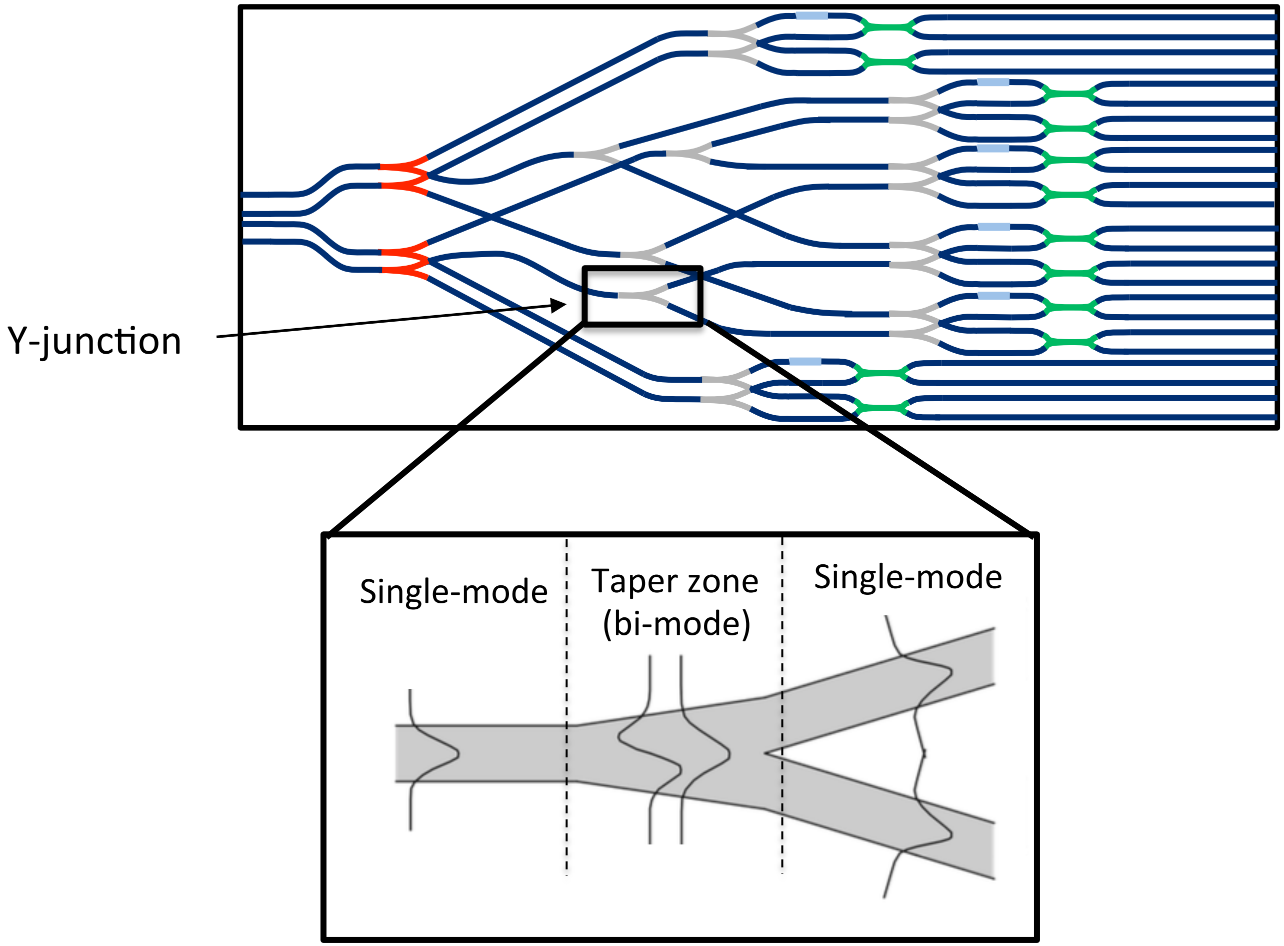
IOBCs of GRAVITY and PIONIER

- Planar integrated optics beam combiners (IOBC)
- 6 baselines combined by pair with an ABCD sampling: 24 outputs



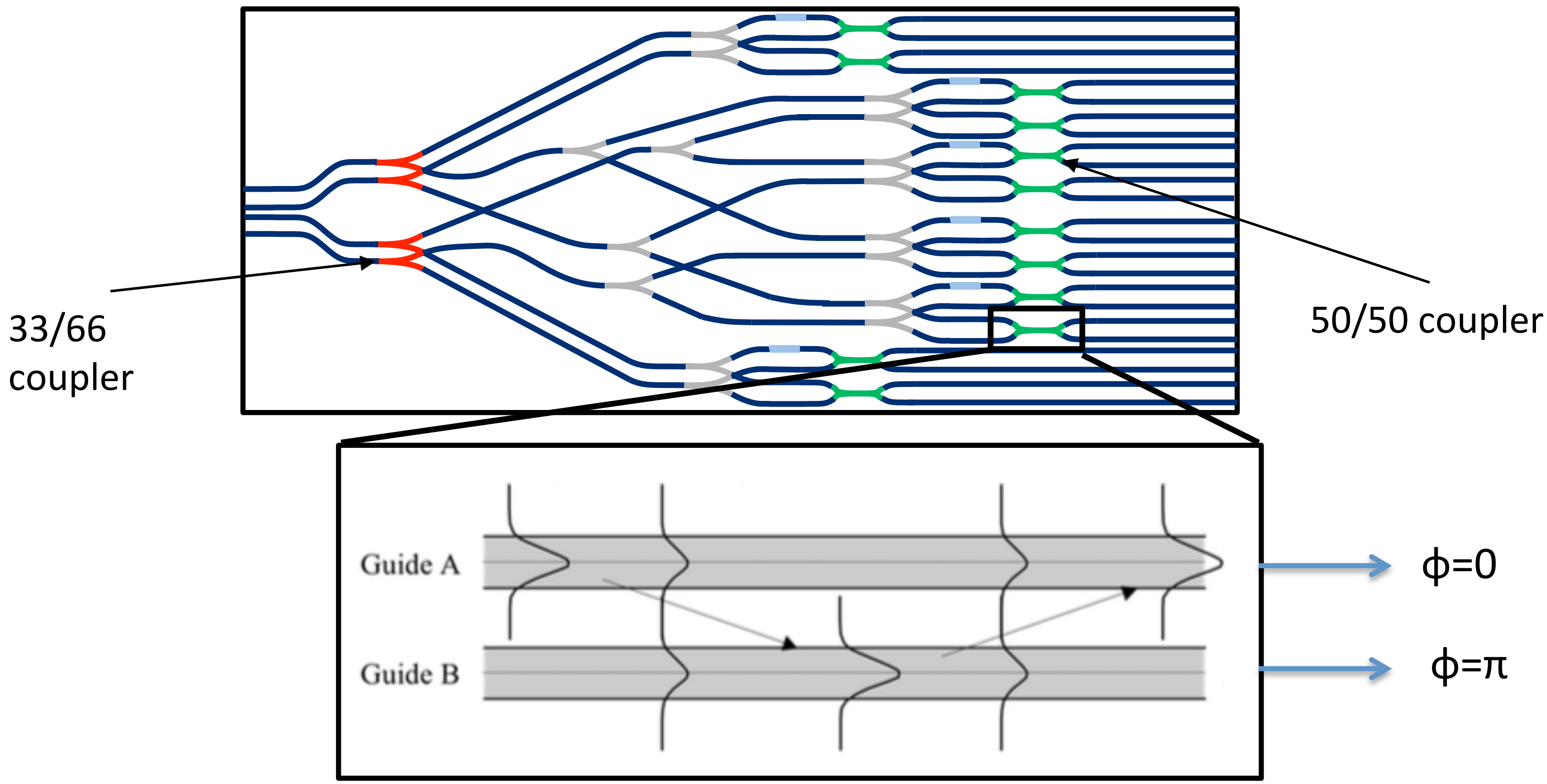
Jocou+ 2014 [SPIE]

IOBCs of GRAVITY and PIONIER: Y-junctions



- Y-junctions well balanced and achromatic

IOBCs of GRAVITY and PIONIER: couplers



- Couple evanescent field to a neighbor waveguide
- Phase shift of π = AC cell
- 50/50 couplers splitting ratio varies typically from 40/60 to 60/40 across a band

[Benisty+ 2009 A&A]

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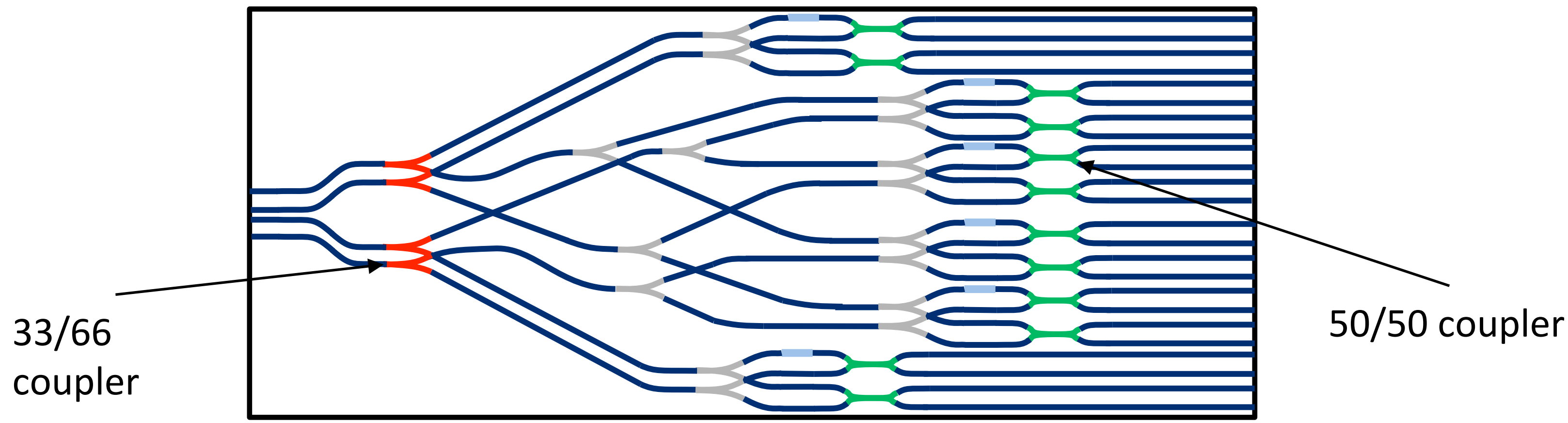

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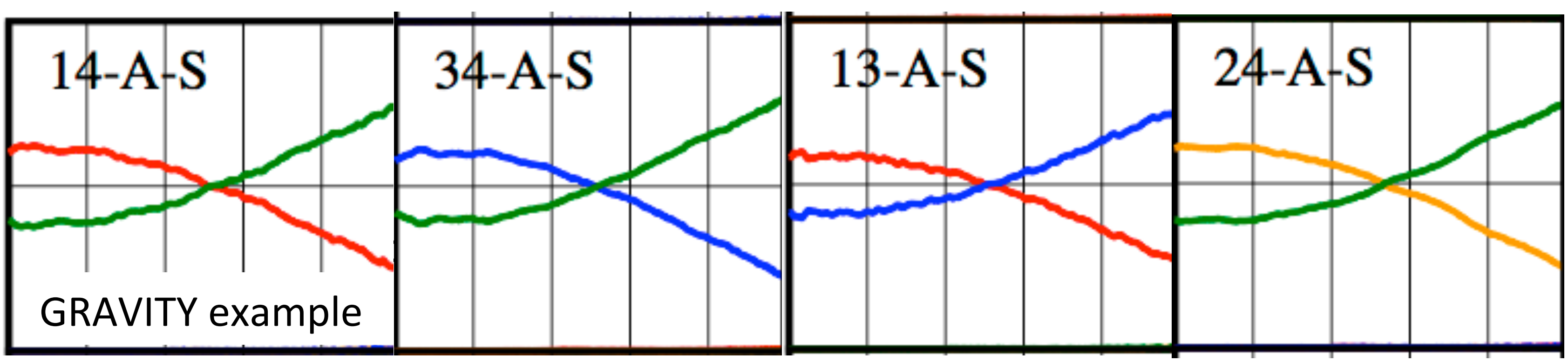
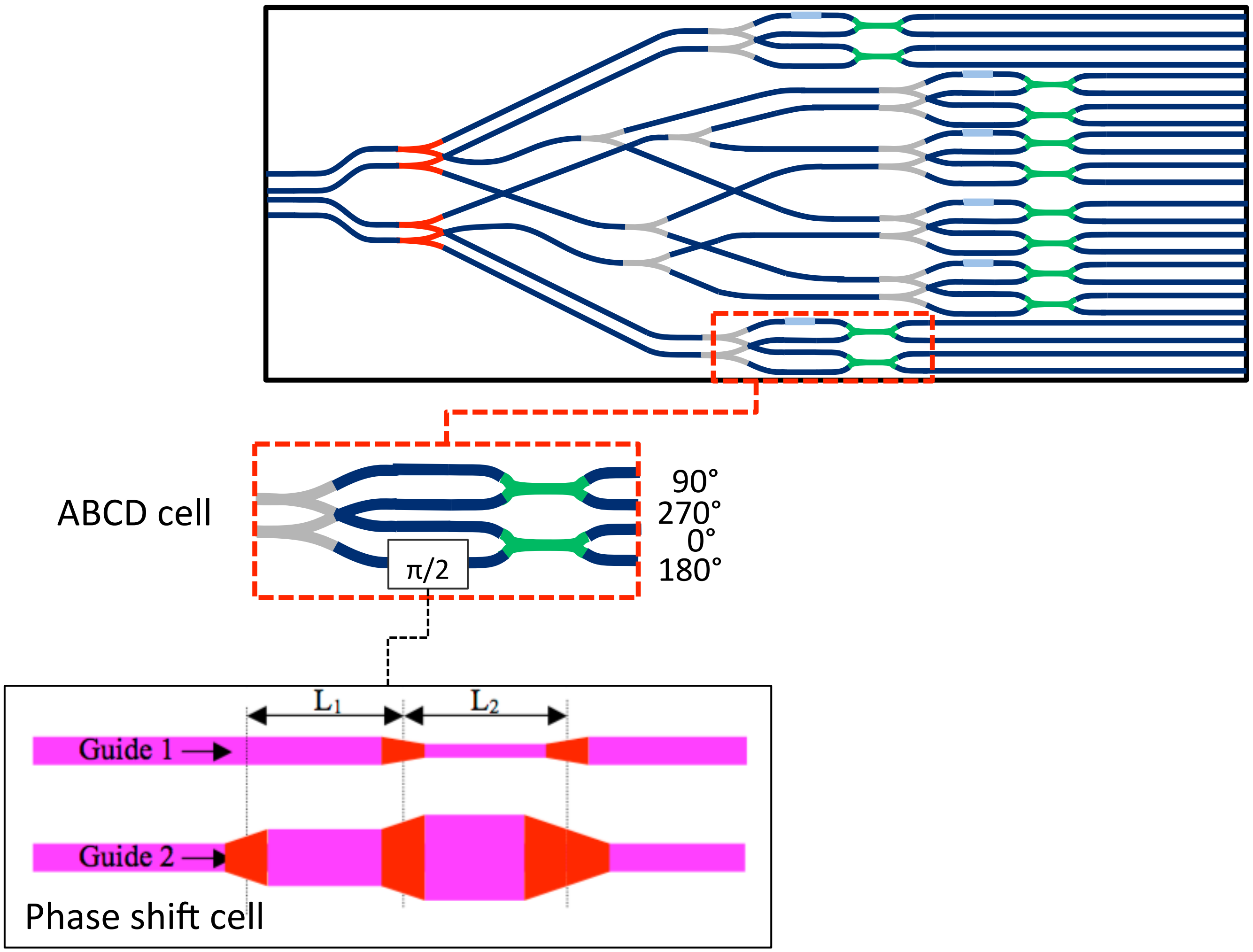


IOBCs of GRAVITY and PIONIER: ABCD cells



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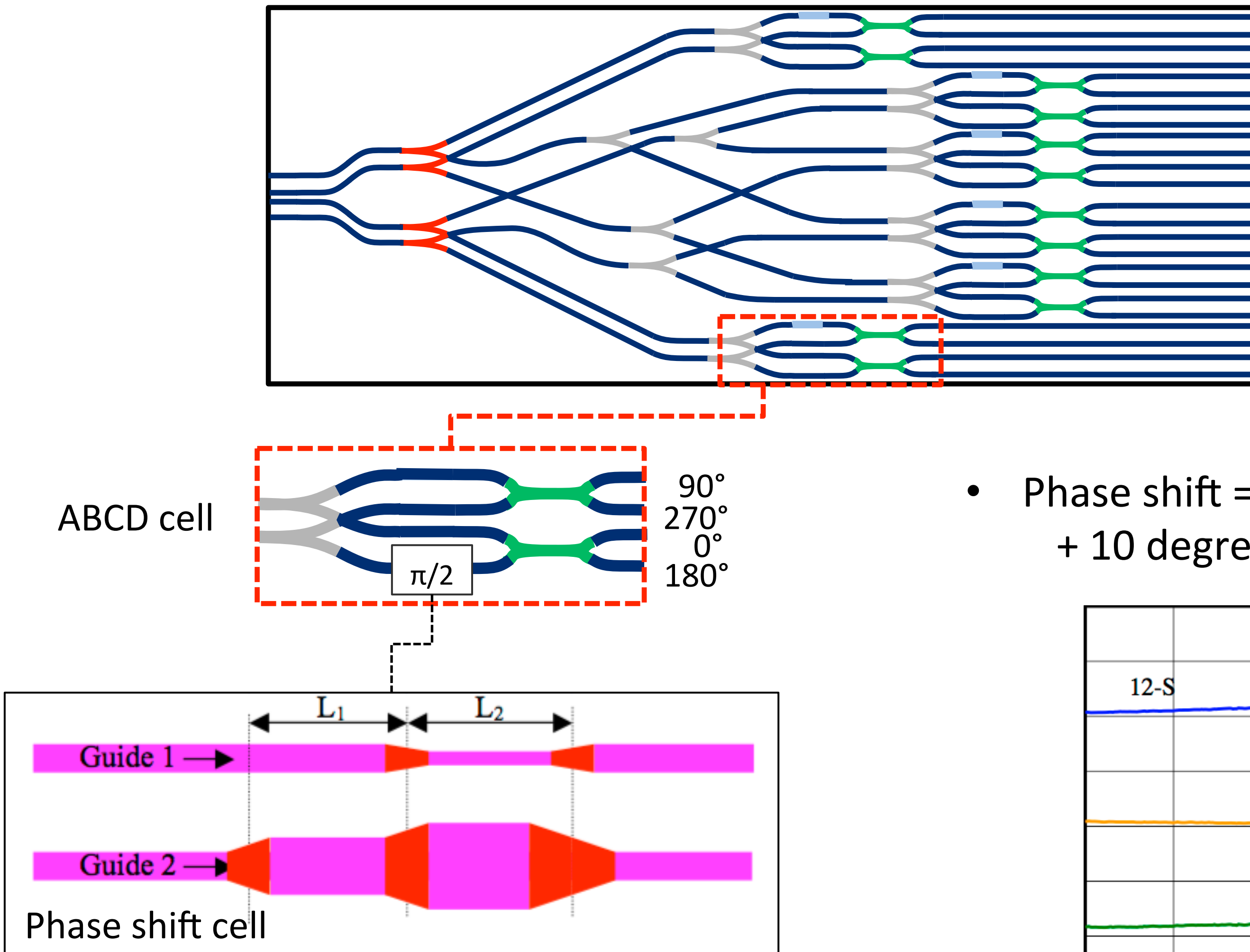
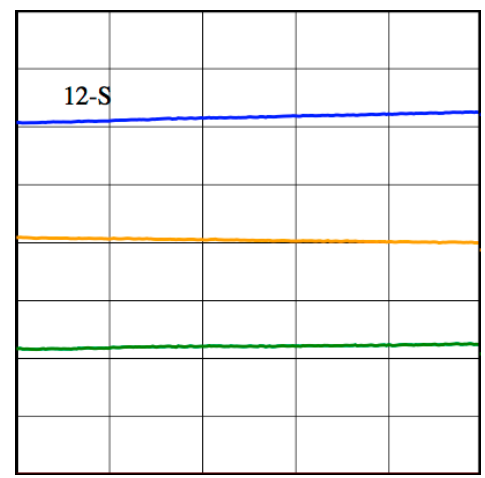
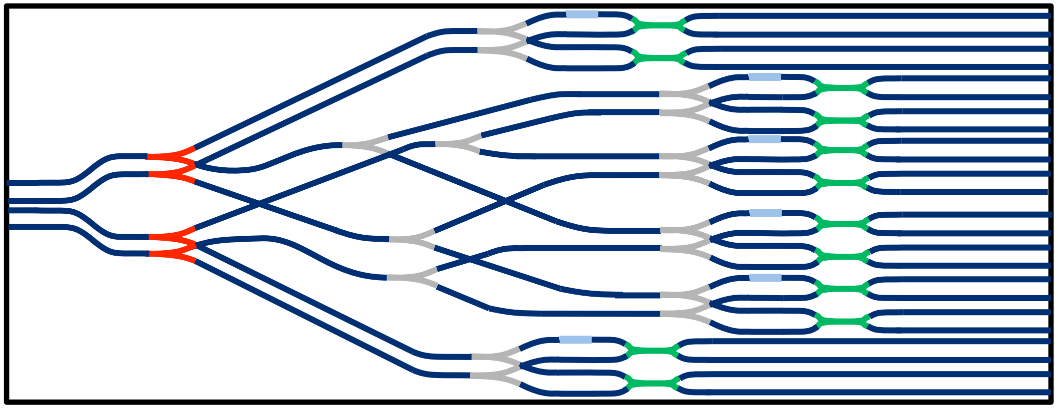


- Phase shift = 90+/-10 degrees + 10 degrees chromaticity



IOBCs of GRAVITY and PIONIER: cross-talks



- Light from telescope A leaking/recoupling into waveguide of telescope B
- Various origins:
  - X-crossing
  - Leaks in curves
  - Leaks from waveguide imperfections

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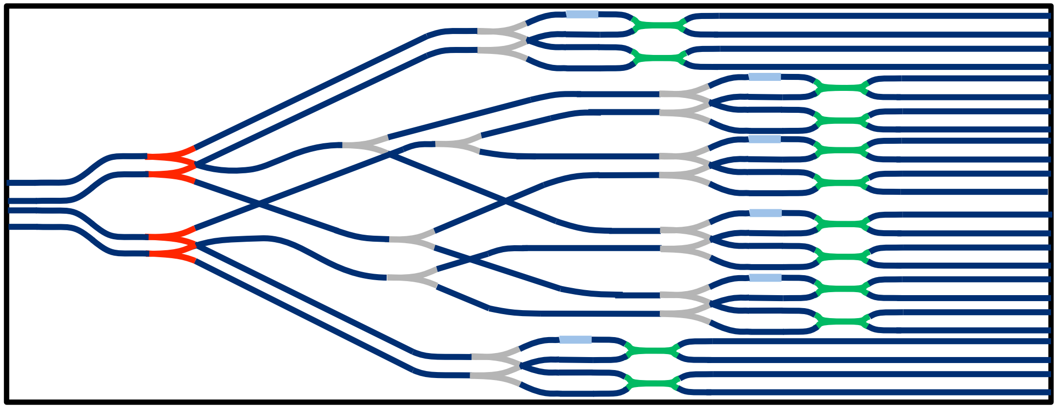

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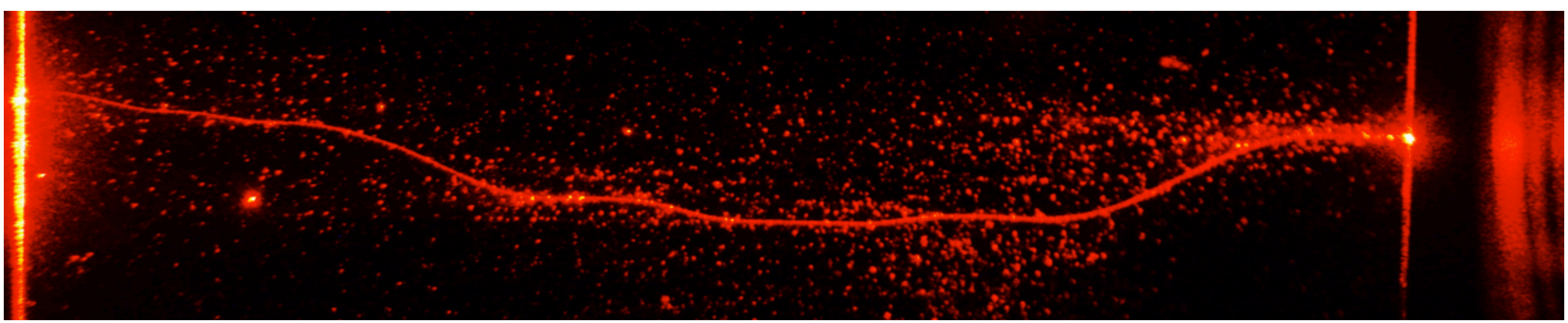

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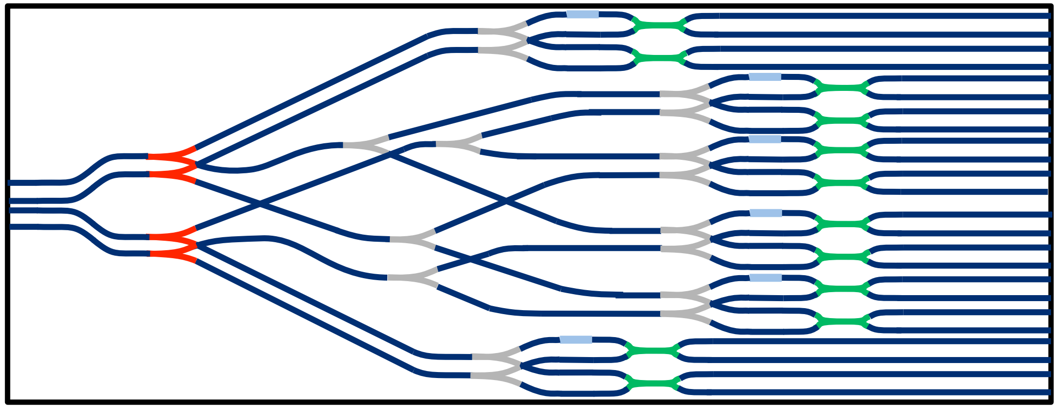

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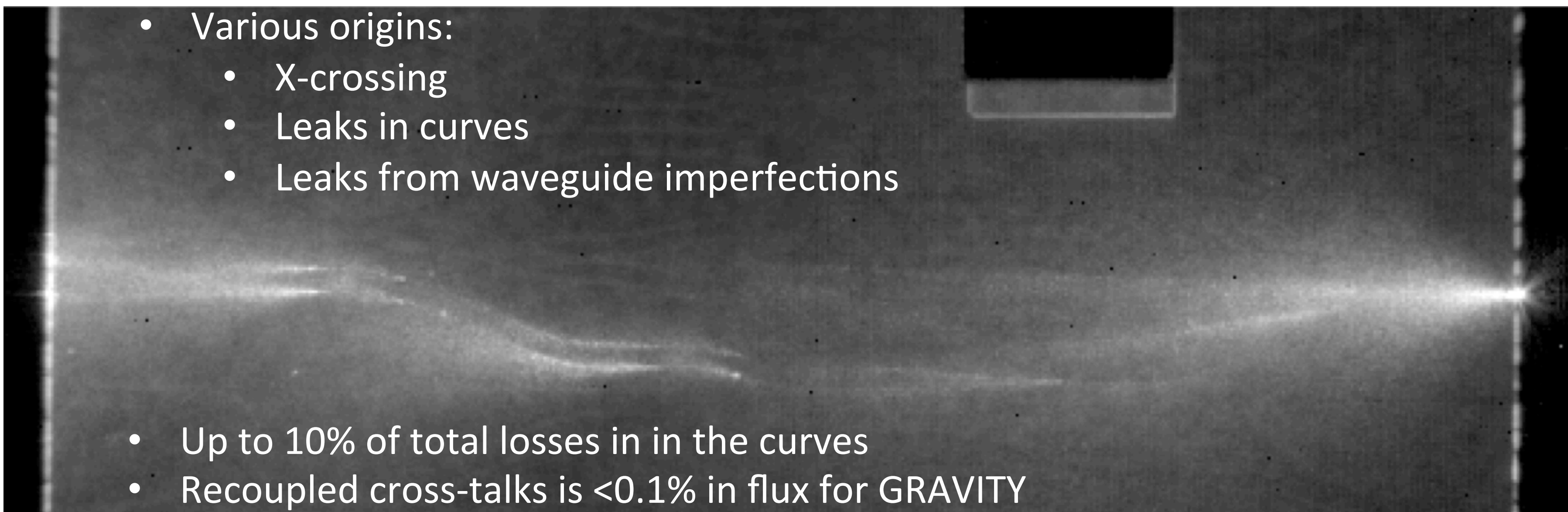
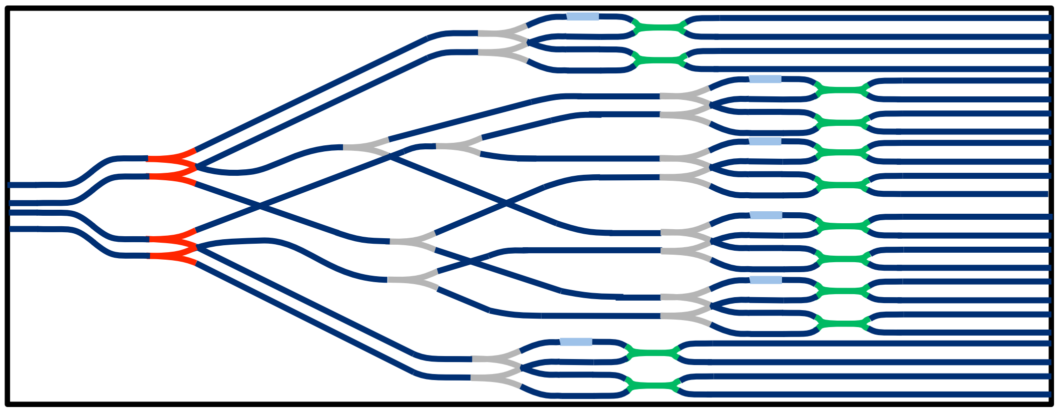


- Up to 10% of total losses in in the curves
- Recoupled cross-talks is <0.1% in flux for GRAVITY

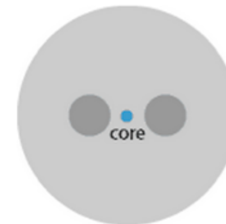
IOBCs of GRAVITY and PIONIER: estimating the 4 photometries



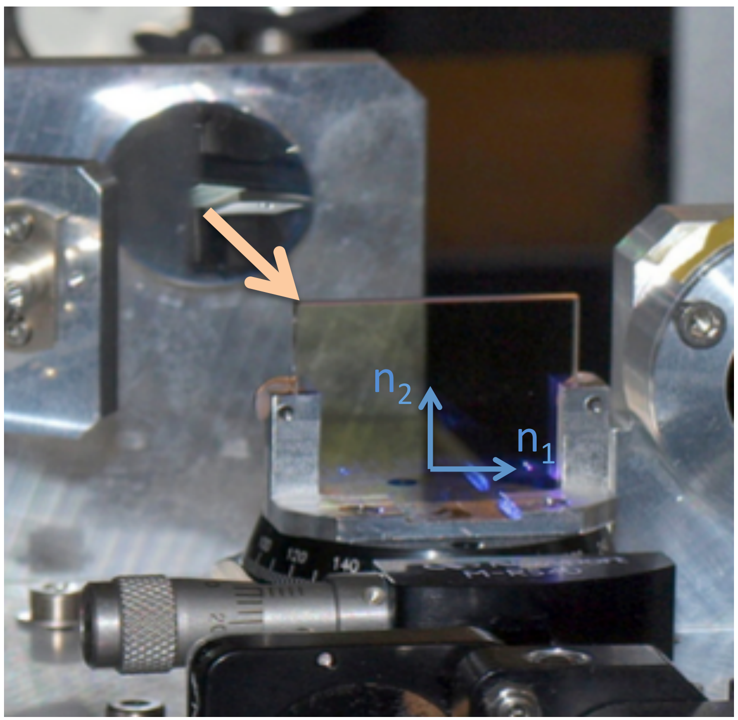
- Daily photometric and interferometric calibrations:
  → Pixel to Visibility Matrix (P2VM)
- No need for specific channels with 3T and more, and AC or ABCD fringe sampling
  → Can be extracted from the interferometric channels thanks to the P2VM

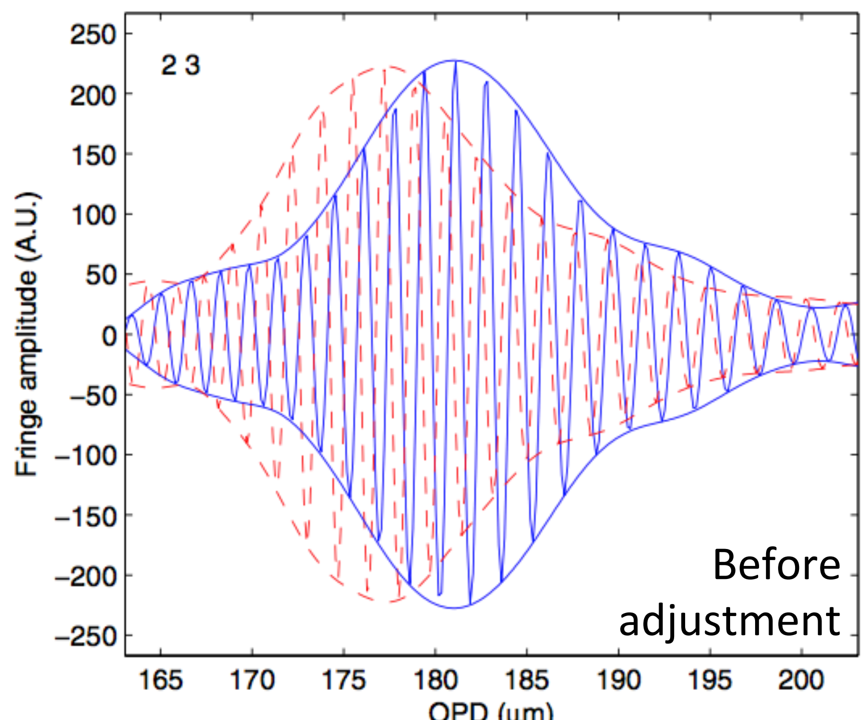
PIONIER polarisation management

- Light transported to IOBC with PM fibers
  Very birefringent stress-induced fibers



  Beating length = 3-5 mm → fiber of the same batch & equalized to 20 microns
- Need daily alignment of polarisations with birefringent $LiNbO_3$ plates





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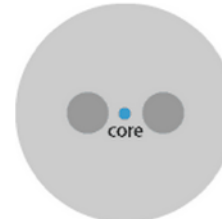

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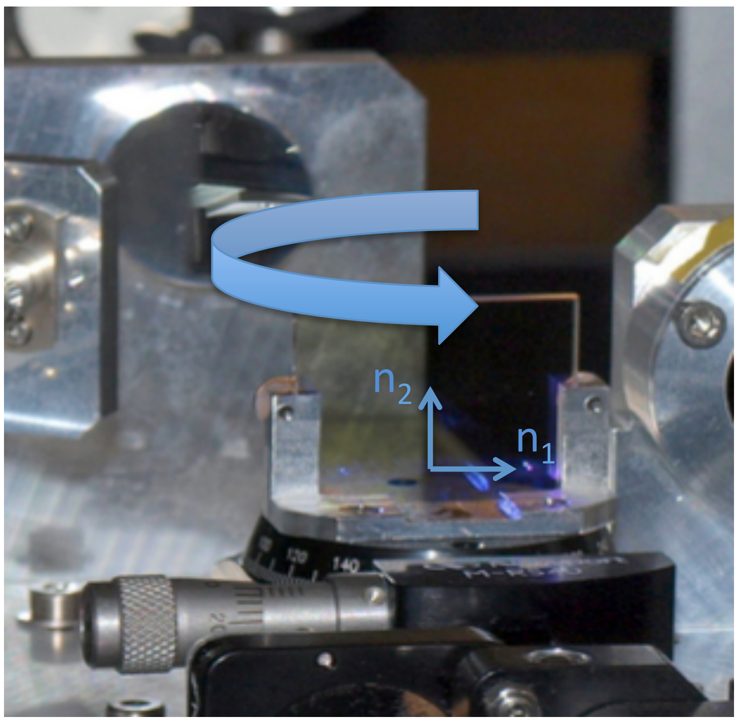
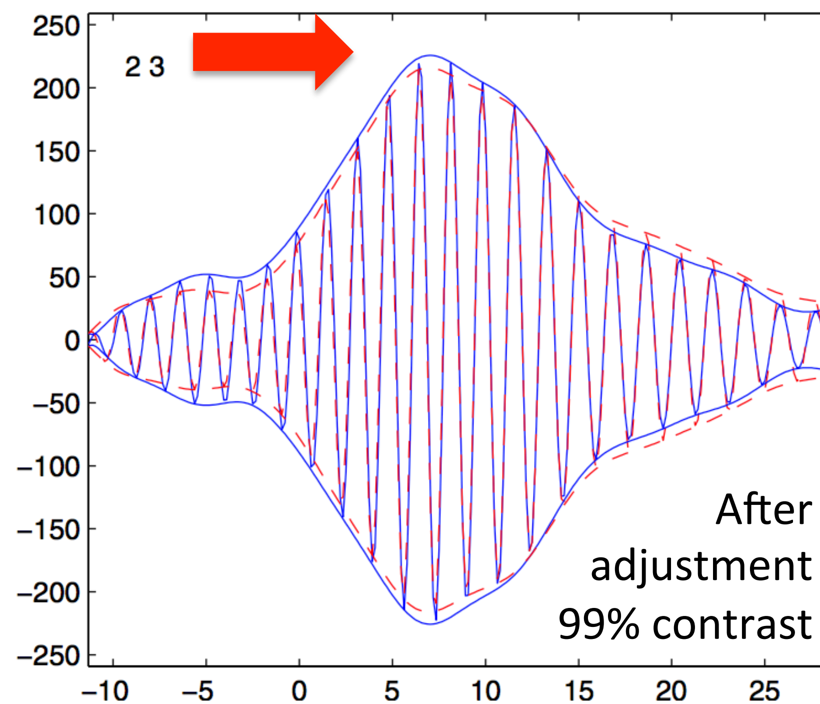
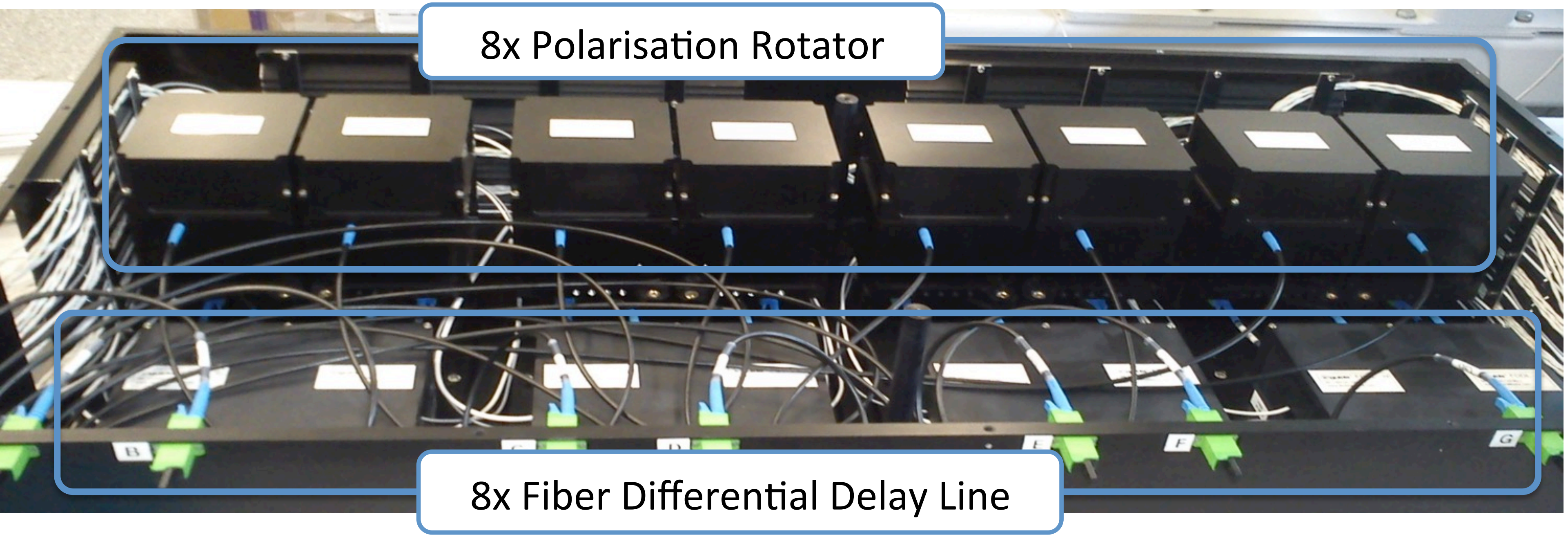




The fiber control unit of GRAVITY

Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

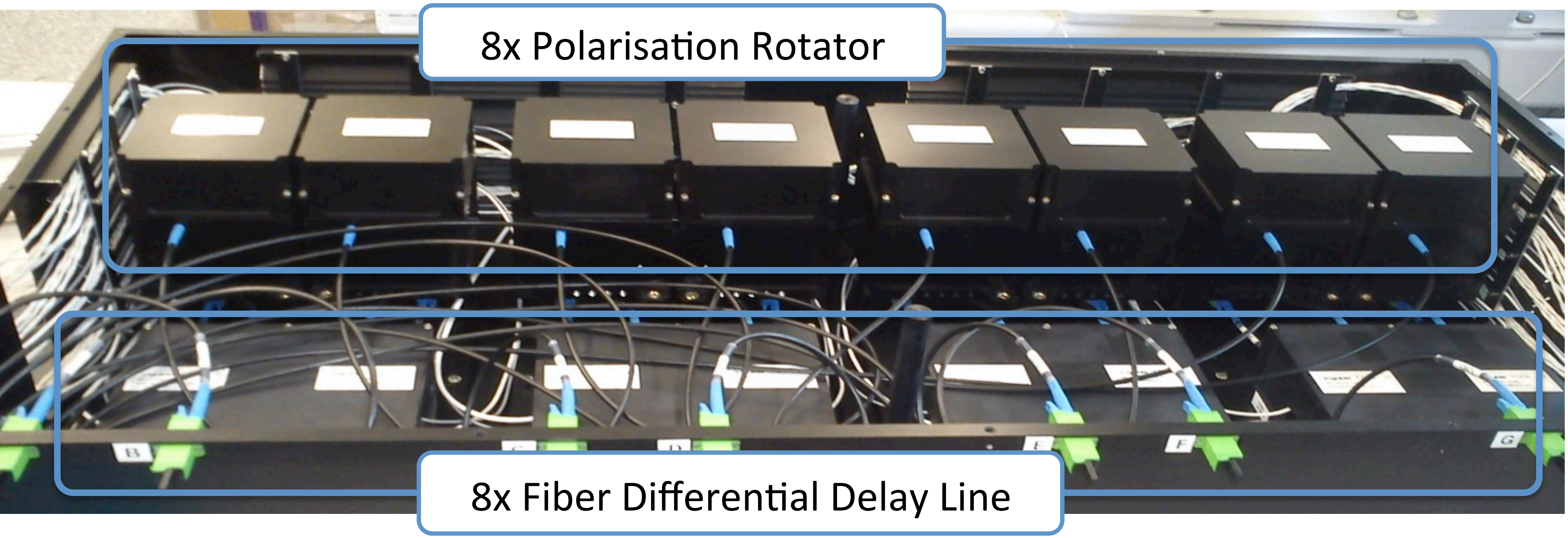
Perrin et al.



The fiber control unit of GRAVITY

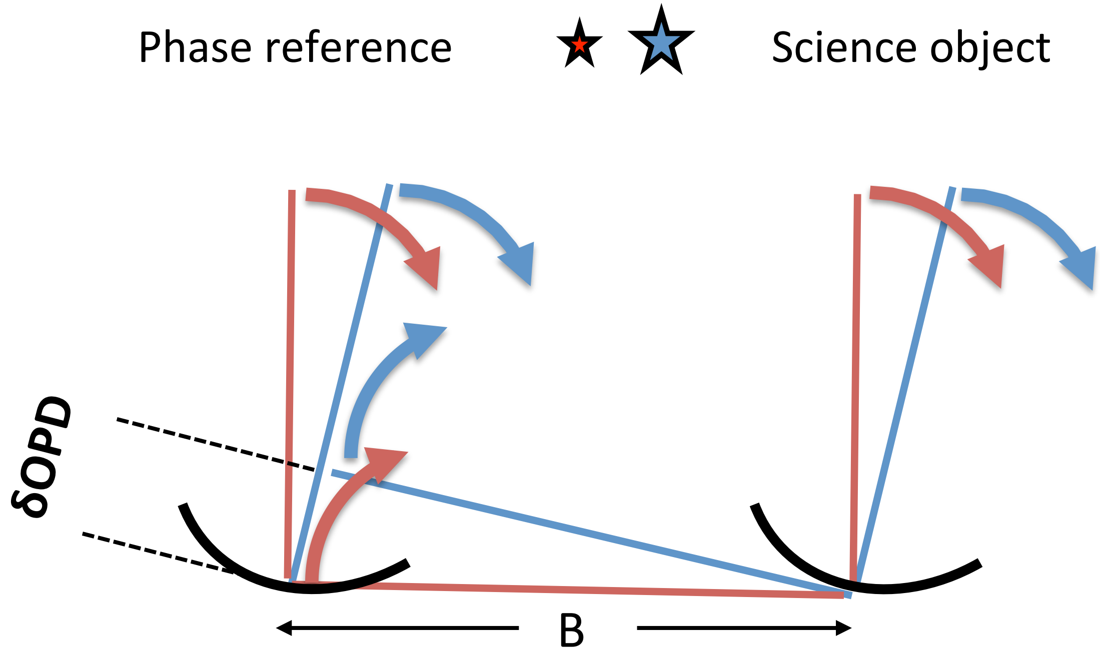
Perrin et al.

- Polarisation rotator: align VLTI polarisation axis to the IOBC ones



- FDDL: Compensate for the differential OPD between FT and SC, up to 4mm stretch
- ~20m of fluoride fiber per beam: T ~ 98%

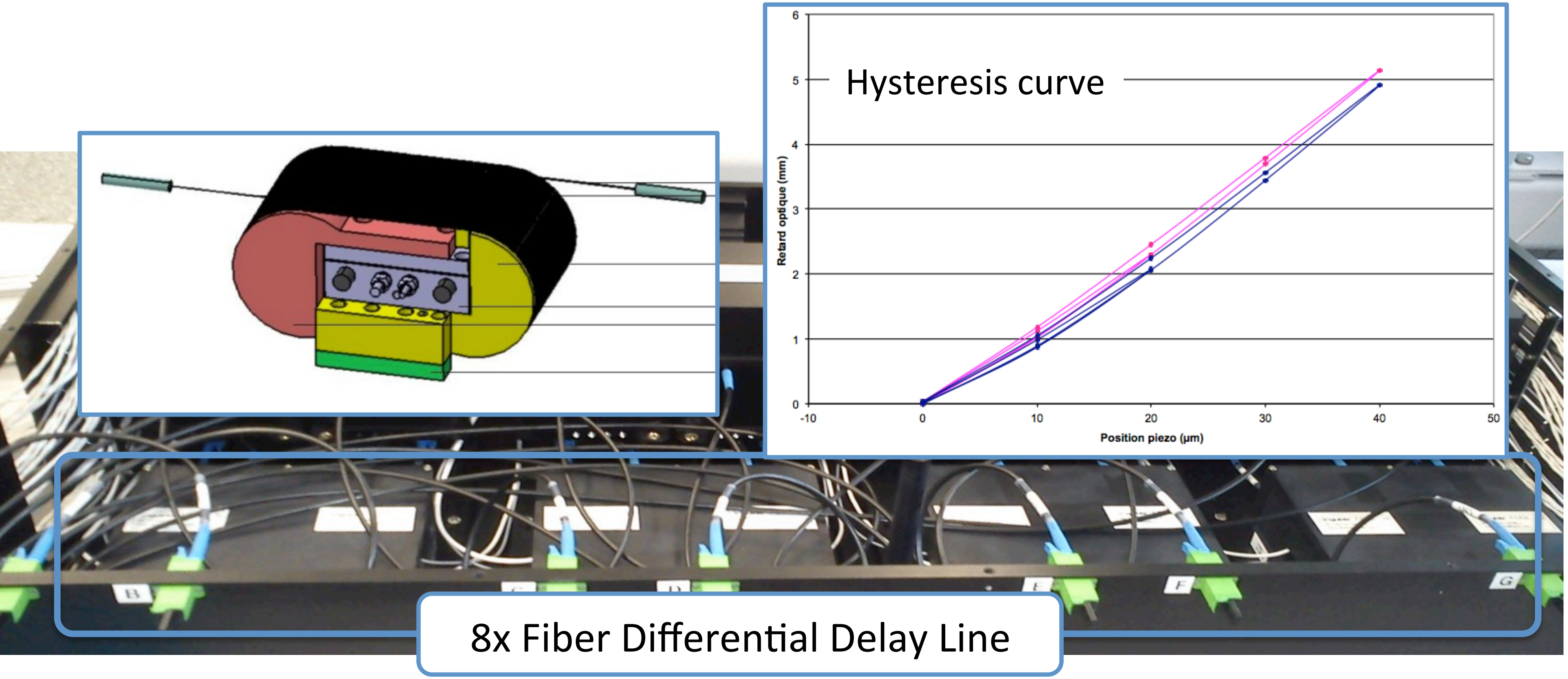
The fiber control unit of GRAVITY: The FDDLs



δODP = B . (α - β)

- Compensate for differential delay between beams
- Maximum delay: 2mm for UTs; 6mm for ATs
- Precision = 60 nm

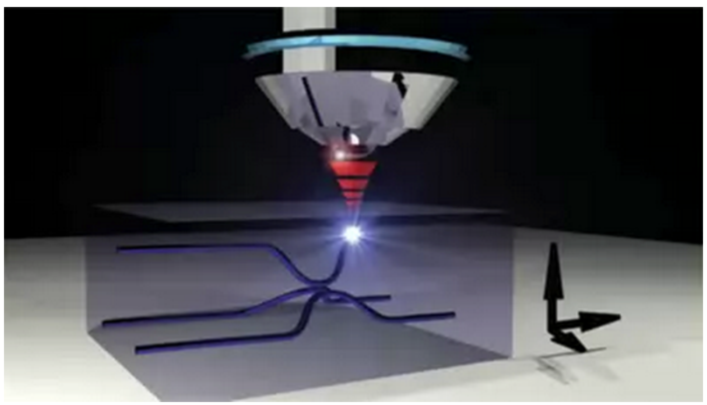
The fiber control unit of GRAVITY
The FDDLs

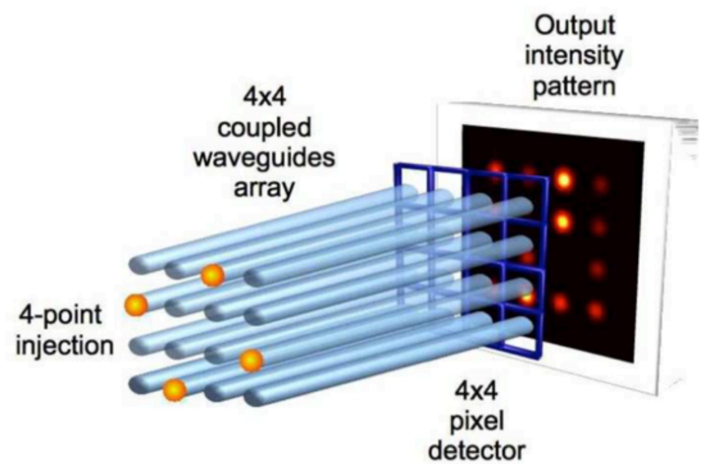


- FDDL: Compensate for the differential OPD between FT and SC, up to 4mm stretch
- Fluoride fiber wrapped ~20x around a cylinder mounted on a piezo
- Dispersion varies with stretch
- Important hysteresis, few 10 microns → need for the metrology for closed loop control of the piezo

What's next?

- Developments towards longer wavelengths (L, M bands)
    - Chalcogenide fibers and IO
    - $LiNbO_3$ IOBC
- Laser written 3D waveguides





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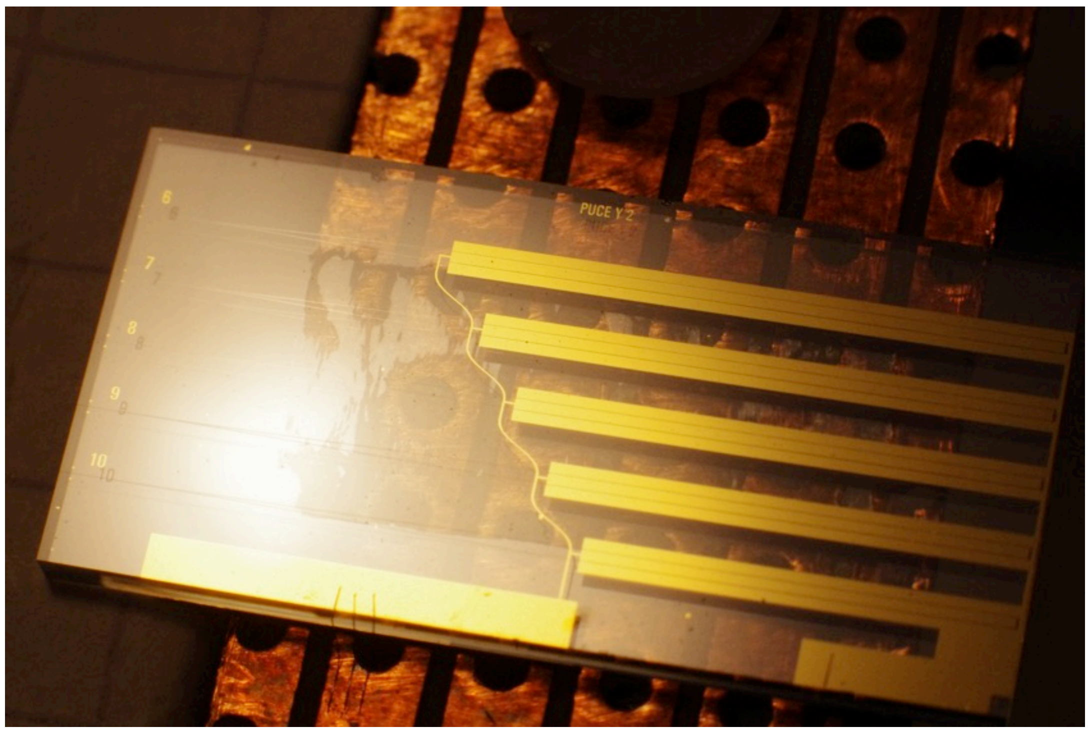

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  - $LiNbO_3$ IOBC
  - Laser written 3D waveguides
- Active functions in $LiNbO_3$
- AO on small telescopes are coming
  - Implementation on-going at CHARA
  - Study of AO for ATs at VLTI…