Multiple anamorphic beam combination

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Framework

Multiple-beam stellar interferometry (*n*>2).

Beams arriving from…

- **different telescopes**
  - **All telescopes have the same size**
  - **Different telescopes have different sizes (VLTI, Keck, Ohana)**
- **aperture masking**

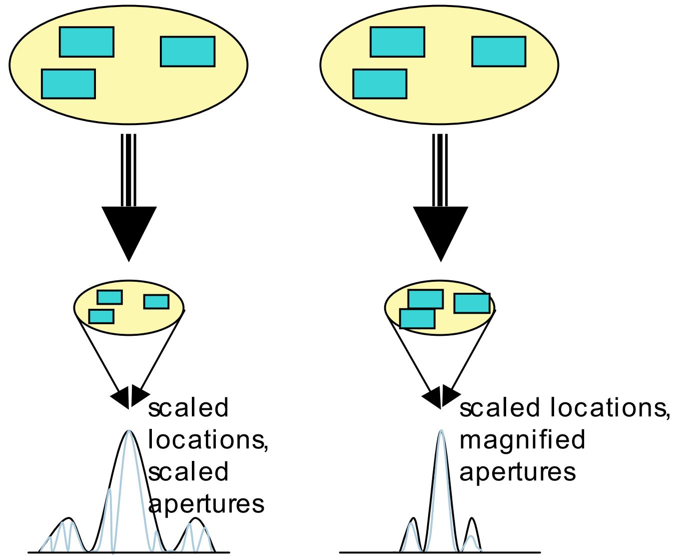
Transport and combination

- **3-d: periscope approach**
  - **re-imaged pupils**
  - **re-imaged foci**
- **2-d: Wave guides**
- **1-d: Fibres**

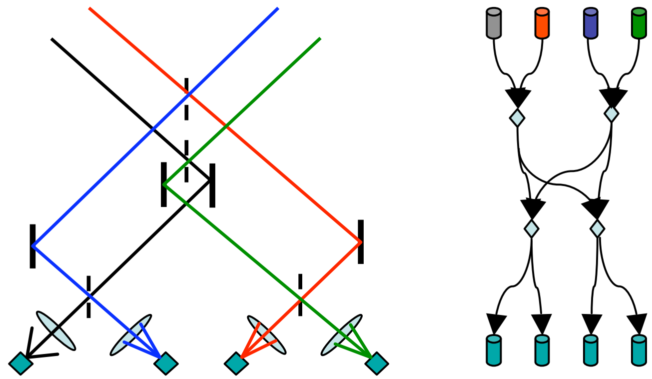
Beams

Combination modes

- **Fizeau**
  - **Direct**
  - **Densified pupil**
- **Michelson**
  - **3-d: Beam splitters**
  - **2-d: Wave guide couplers**
  - **1-d: Fibre couplers**
- **Mixed salad**
  - **Aperture masking to non-redundant combination**
  - **Redundant to non-redundant reordering**



Fizeau Densified pupil



(a) Beams (b) Fibres

Michelson approach

Measurement in the Fourier domain (n beams)

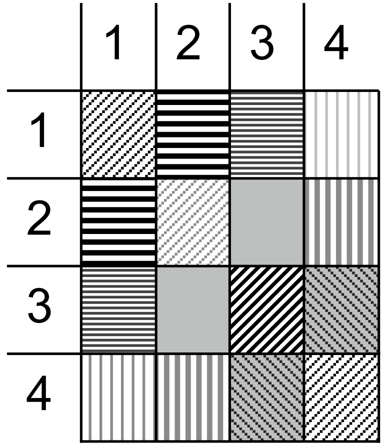
- has many fewer pixels, $p_M \sim 2n(n-1)/2+n = n^2$
  - compare to the imaging approaches, $p_F \sim [FoV/(\lambda/D)/Densification]^2 >> p_M$
  - noise dependent on total intensity and #pixels p_M
- "remembers" phase through closure
- but has complex combination optics
  - $\sim 2n$ splitters, $\sim n(n-1)/2$ combiners
  - must maintain light, polarisation, dispersion

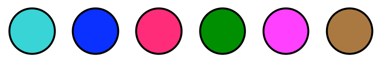
Dilemma

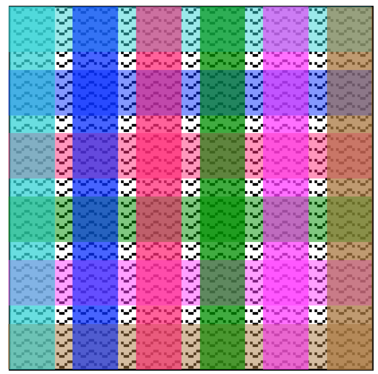
- **Question:** Under the Michelson configuration, how to simply combine all beams?
- **Answer:** By using spatial, not amplitude, division

Make a table

- Input beams: fibres or bulk optics
- Anamorphic stretching
- Create two copies
- Rotate copies
- Interfere copies

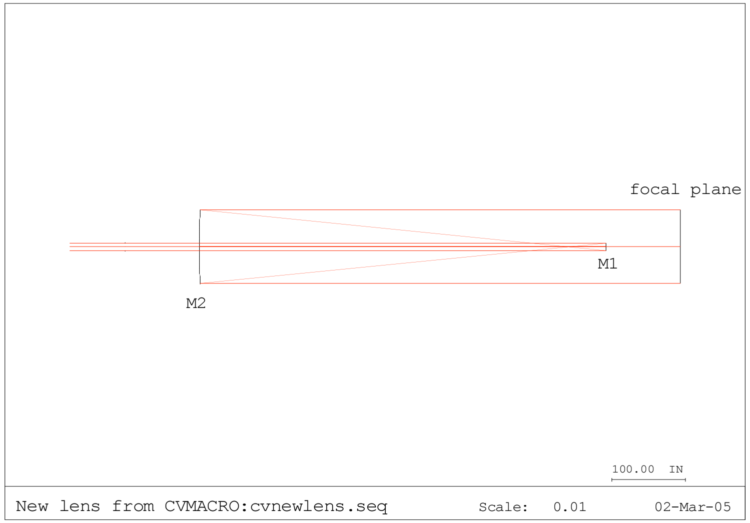




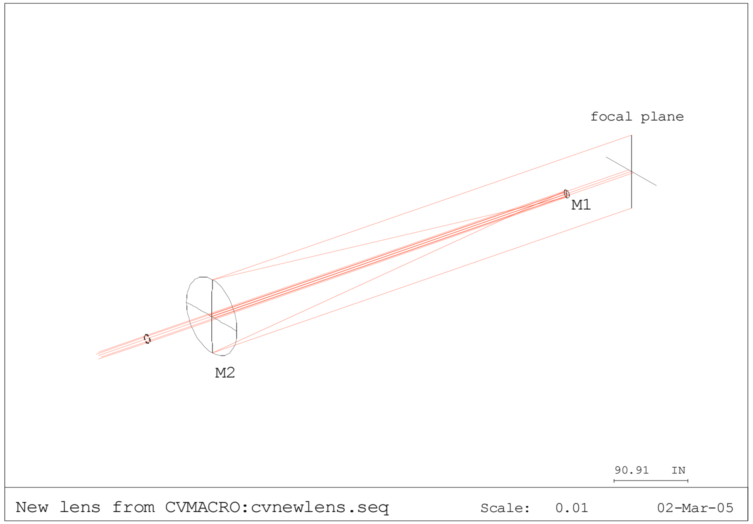


Stretching the beams

- **All collimated inputs (also from fibres), lined up**
- **Gregorian anamorphic mirrors in one axis**
- **Toroidal (conic) mirrors – 100 & 1000 mm**



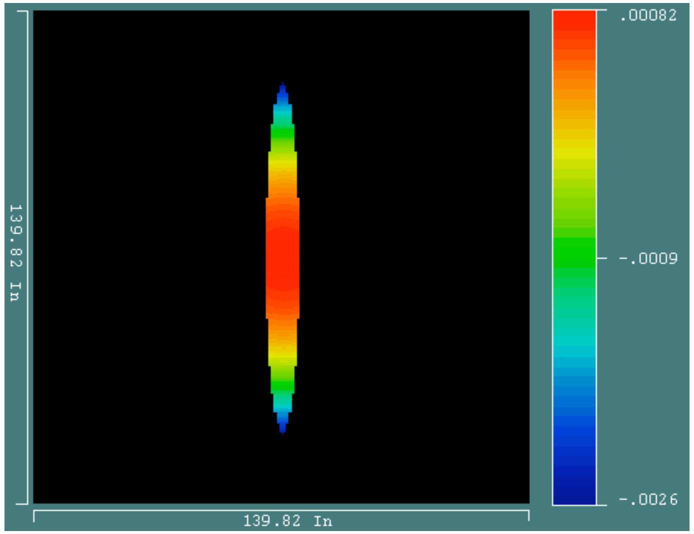
Side view



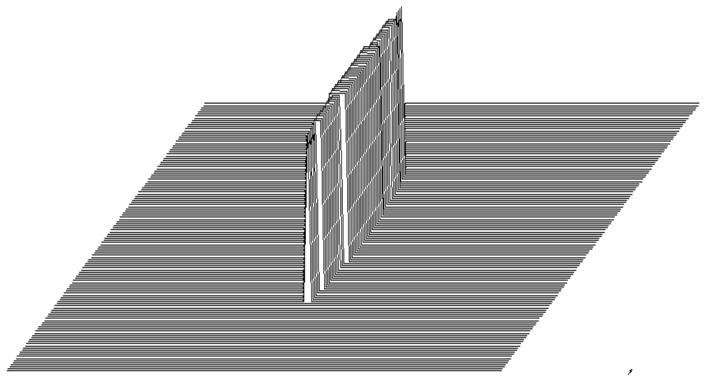
Perspective view

Optical performance

- **Phase error < 0.035 wave at 1 µm (P-V)**
- **Results shown for only one beam out of many**



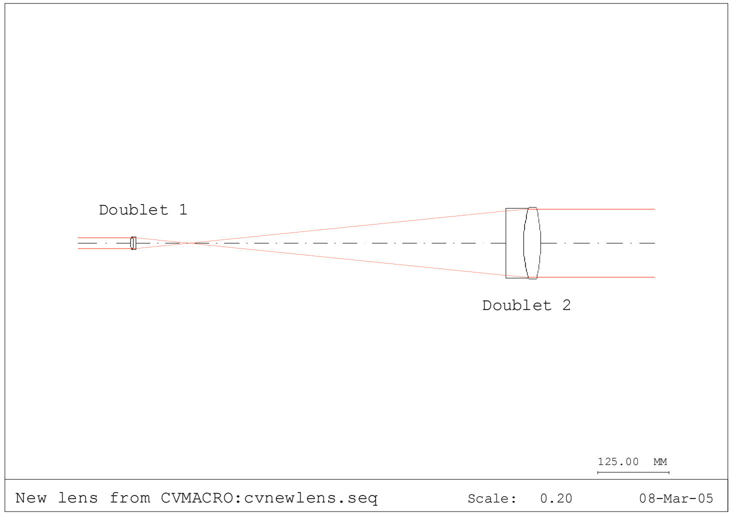
Phase error



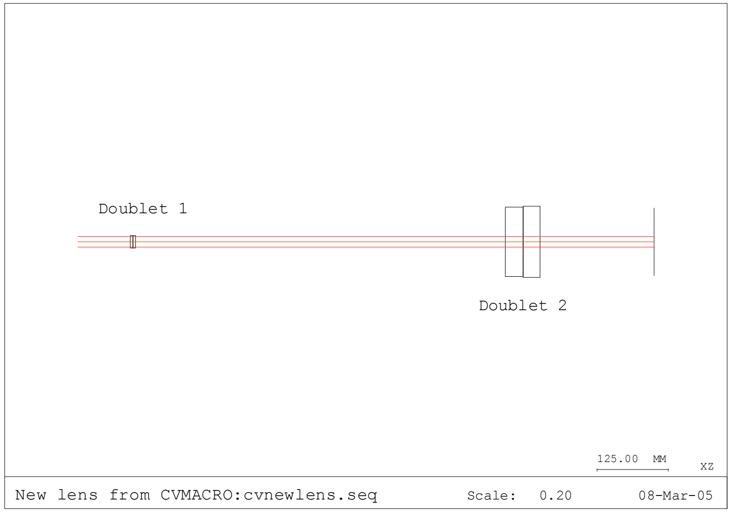
Intensity profile

Another optical design

- Anamorphic telescope: achromatic lenses
- Cylindrical doublets
- Lesser quality



Side view

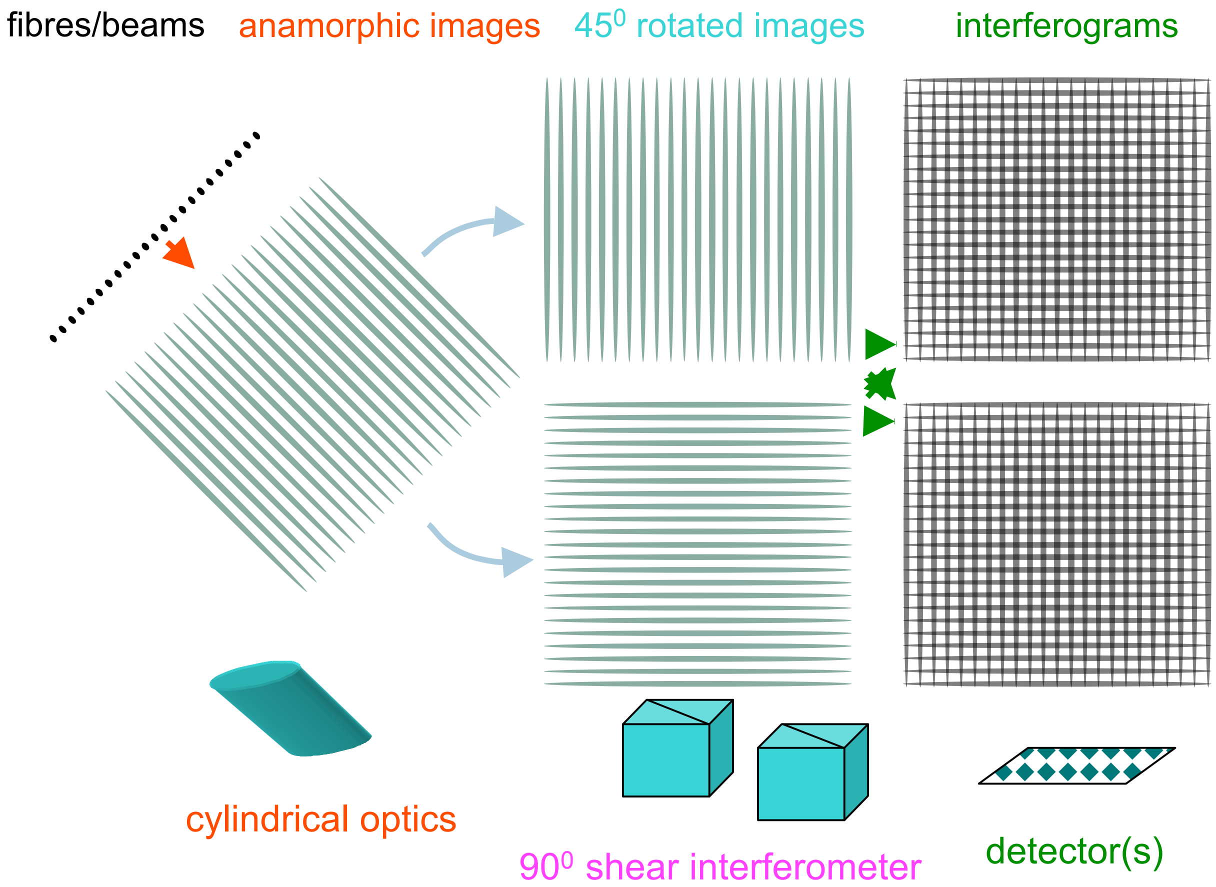


Top view

Handling the stripes

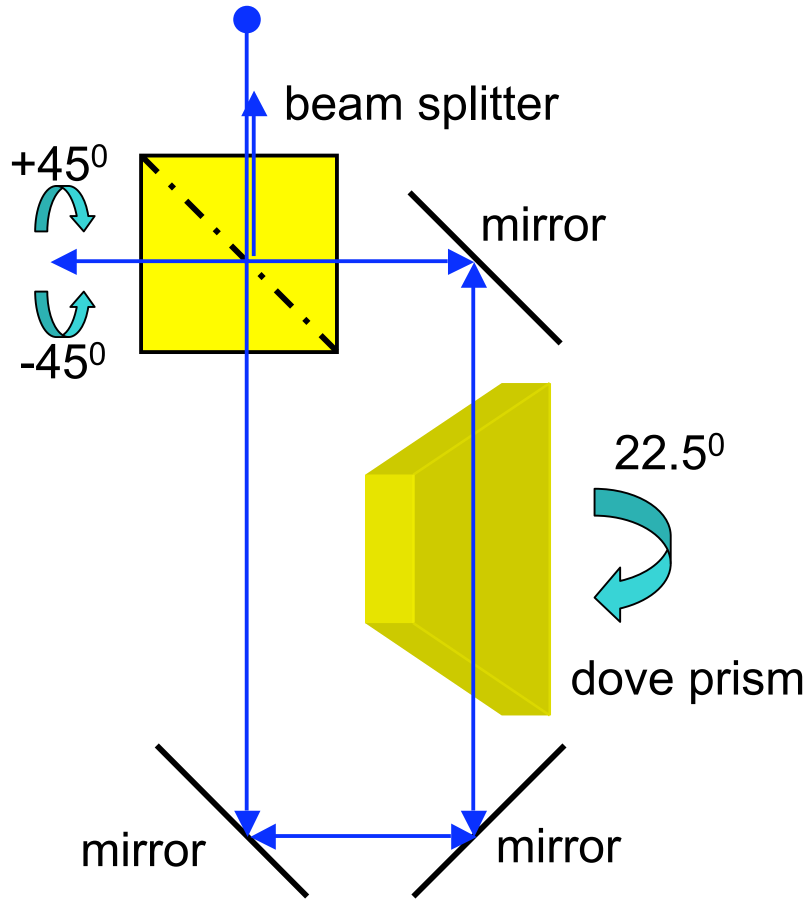
The whole pattern of stretched beams is now passed in a 90° rotational shear interferometer:

0. **The beams are stretched**
- **The pattern is split into two by a beam splitter**
- **Each copy is rotated by 45° in opposite directions**
- **The two copies are interfered by a beam splitter**
- **Two interference patterns result**

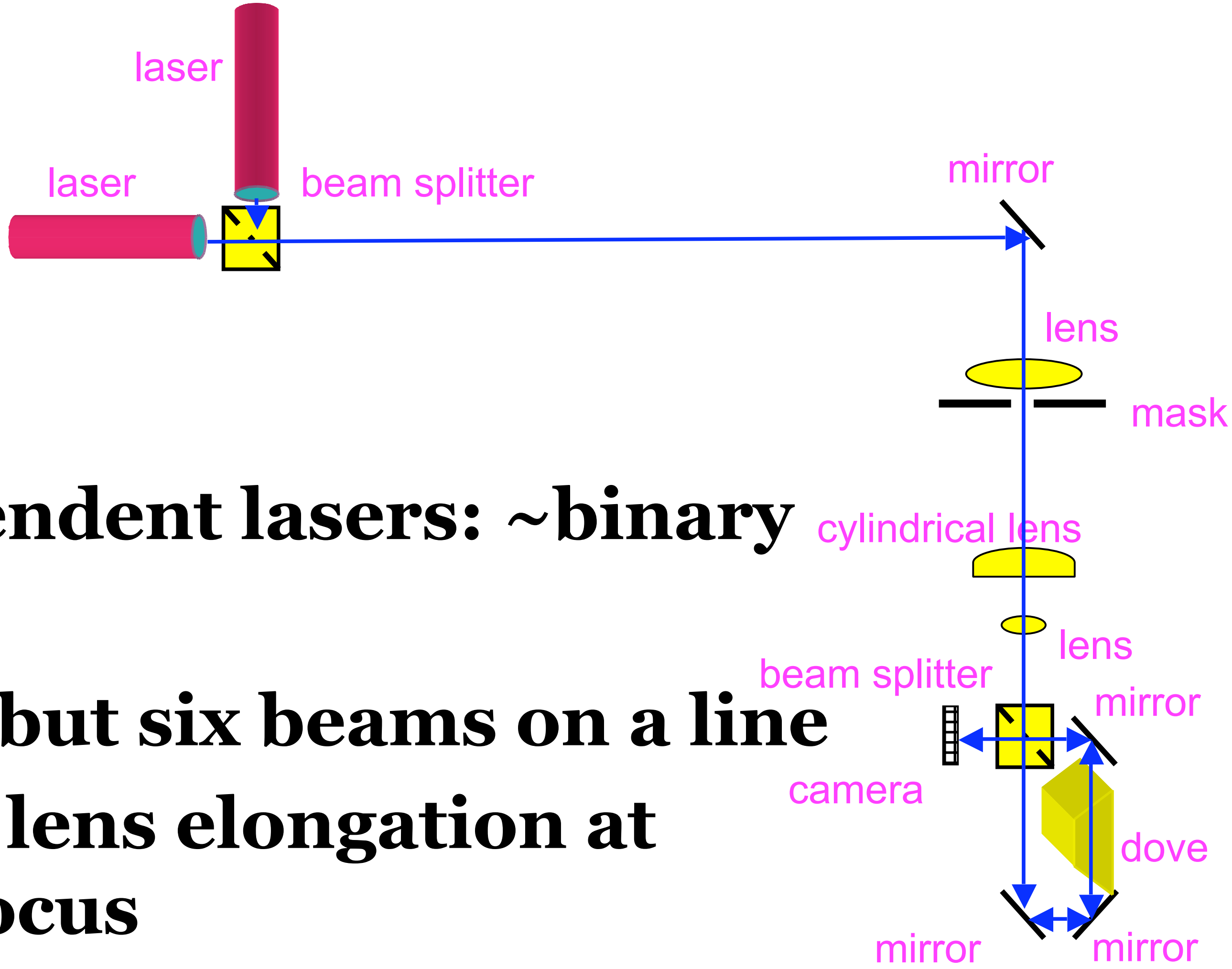


Rotational shear interferometer

- Demonstration: square Sagnac interferometer
- Opposite pattern rotation was achieved by a dove prism
- Sagnac: easy to set up, difficult to extract one output



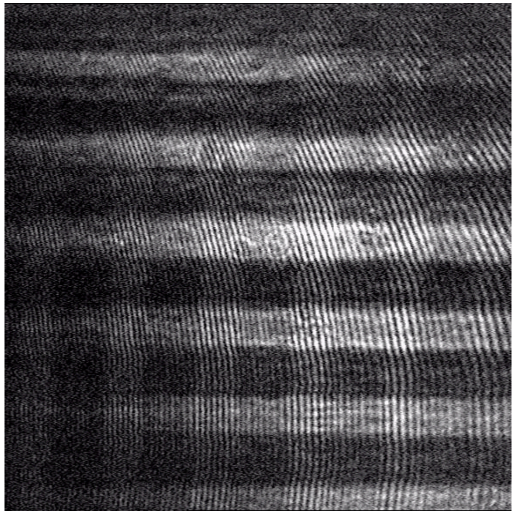
Set up



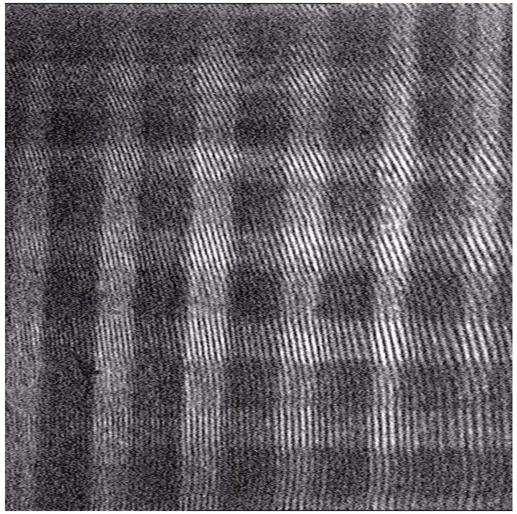
- Two independent lasers: ~binary
- Telescope
- Masked all but six beams on a line
- Cylindrical lens elongation at telescope focus
- Rotational shear interferometer
- CCD camera

Initial results

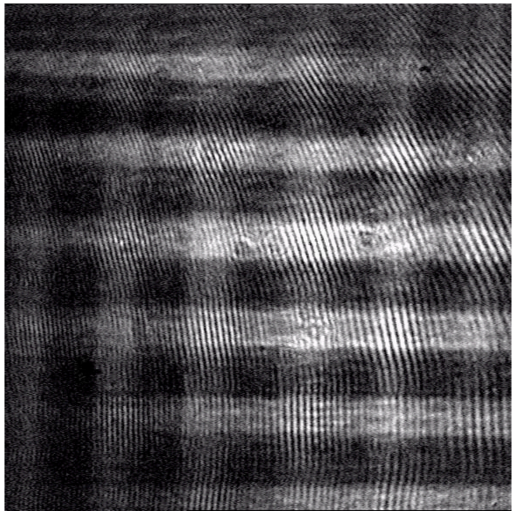
Laser 1



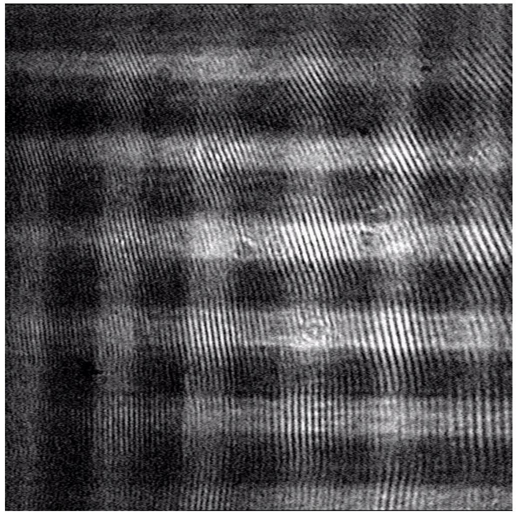
Laser 2



Both 1

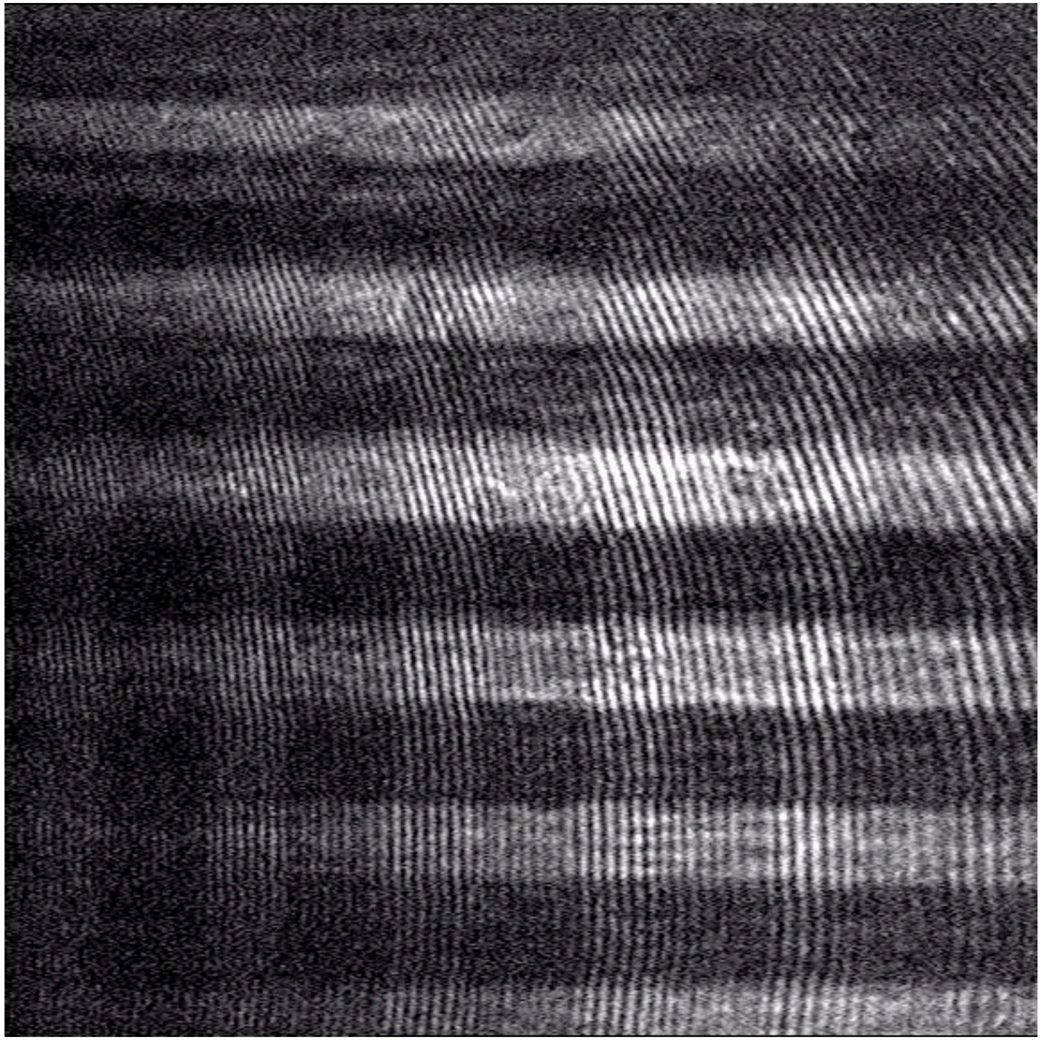


Both 2



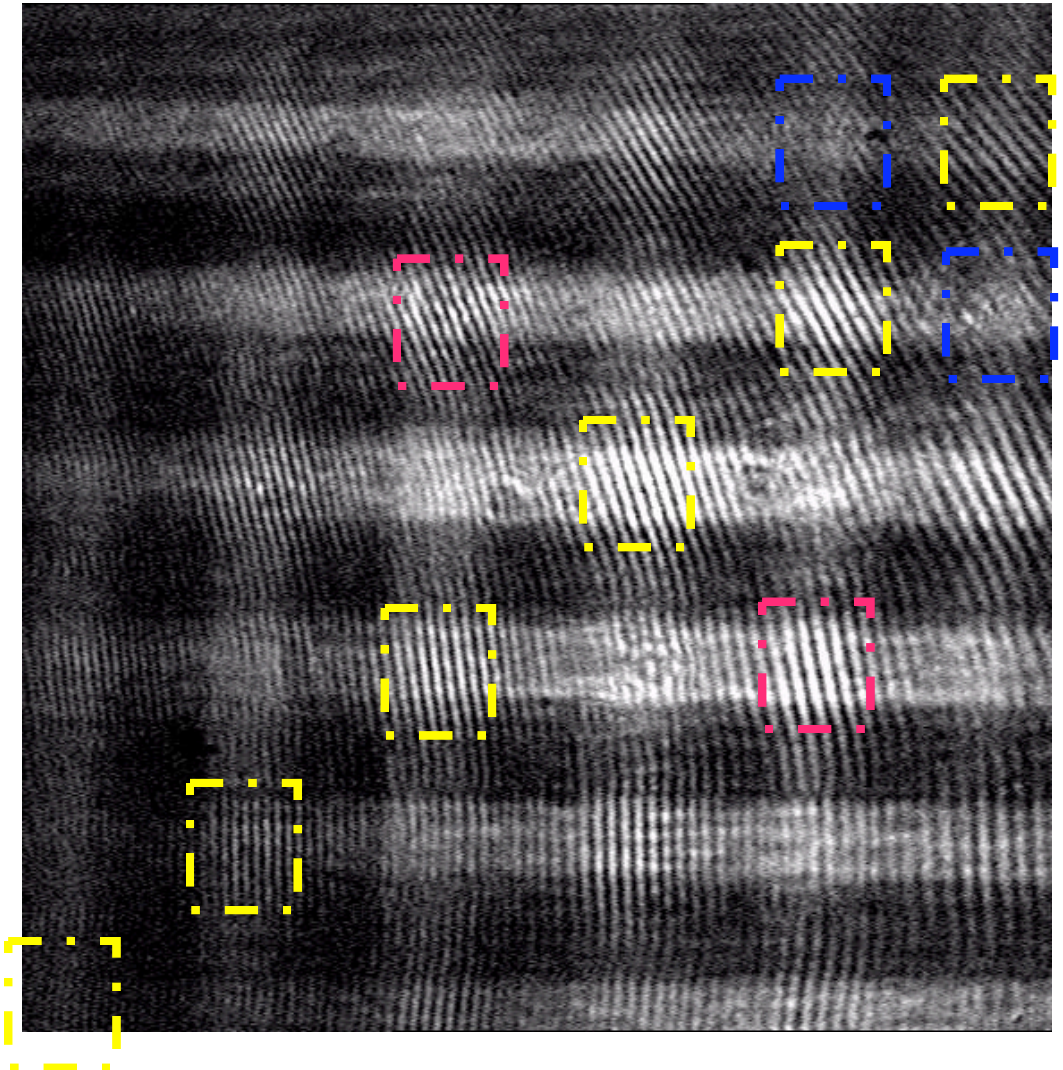
Single laser

- High contrast on all junctions
- Distance between stripes (lost light) can be narrower
- Misalignment between telescope and Sagnac sets fringe spacings for better visibility



Two lasers

- High contrast only on diagonal junctions
- Diagonal junctions serve as intensity calibrators
- Opposite junctions have equal contrast



Benefits

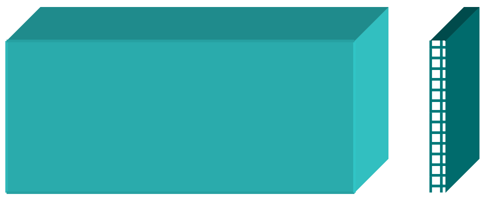
- Each output pattern uses single camera of same QE and noise
- Relatively few pixels: relatively low SNR
- Every 2 beams have 4 fringe patterns for
  - amplitude measurement
  - phase determination and closure (*ABCD*)
  - phase or envelope tracking
- Diagonal allows intensity calibration of each beam
- Only mirrors in final design, except for beam splitter/combiner
  - no dispersion
  - all wave lengths are possible
  - little loss on splitters, couplers, reflections on mirrors
  - little polarisation losses
  - losses, if at all, equal for all beams
- Common path means no noncommon-path-errors
- Relatively compact volume: 5×7×15 cm + camera
- No moving parts inside combiner

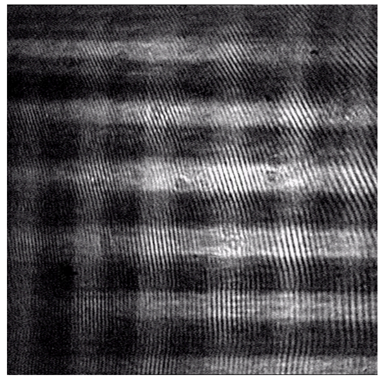
Disadvantages

- Anamorphic stretch limited to n~20 beams
- Few percent of light lost between stripes
  - use n planar optics 1→n devices (narrow band)
  - use n lenses to concentrate light back into junctions
- Different magnifier or different combiner for n = 2…8 beams
- For envelope tracking, need more fringes and pixels
  - for k fringes at junctions, #pixels: $p = 4k^2n^2$
- Require fast camera for fringe/envelope tracking
- Reference star requires separate combiner
- Limited spectral capability
  - split to bands after combiner (beams)
  - split to bands after telescopes (fibres)
  - disperse fringes and lose some light
  - use $n \times n$ lenslet array and fibres into spectrometer

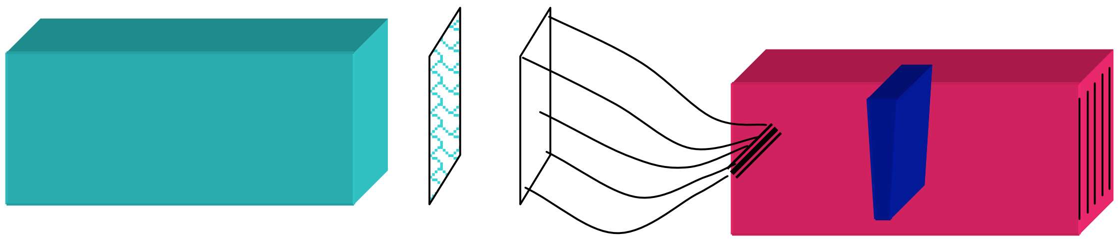
Faint objects or spectrum?

- ***n*×*n* wide band camera**





- ***n*² lined-up spectra**



$\lambda/\Delta\lambda$=100…100,000

Work until now

- Optical design performed in Turin
- Initial results obtained in Haifa
- New 90^{o} shear interferometer designed
  - very stable and compact
  - both outputs available
  - employs only mirrors and beam splitters

To do

- Finalise optical design
- Calculate best swath widths for combining small and large telescopes
- Light budget study and comparison
- Test new 90° shear interferometer
- Polarising beam-splitter option
  - Berry's phase might require λ/4 plates
- Build full prototype

Science case

- **Repeat some previous presentations**
  - **general purpose component with some extended capabilities**

Technology gaps

- **None encountered, none foreseen**

Labour and cost

- Use existing beam transport, detectors
- Modify only beam combiner
- One person-year or two student-years, student available now
- Cost for full prototype <€100,000, negotiable
- Group with combiner seeking group with too few beams for cohabitation

References

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Beam combination in a multi-telescope, monolithic interferometer.
Proc. ESO **29, 1105-15, Munich (1988).**
used Lloyd's mirror interferometer

E N Ribak, G Perrin, S Lacour:
Multiple beam combination for faint objects.
SPIE **5491, 1624-9, Glasgow (2004).**
for aperture masking