Hypertelescope imaging

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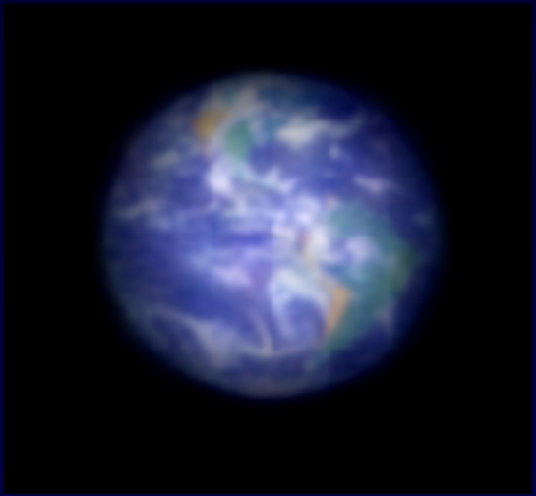
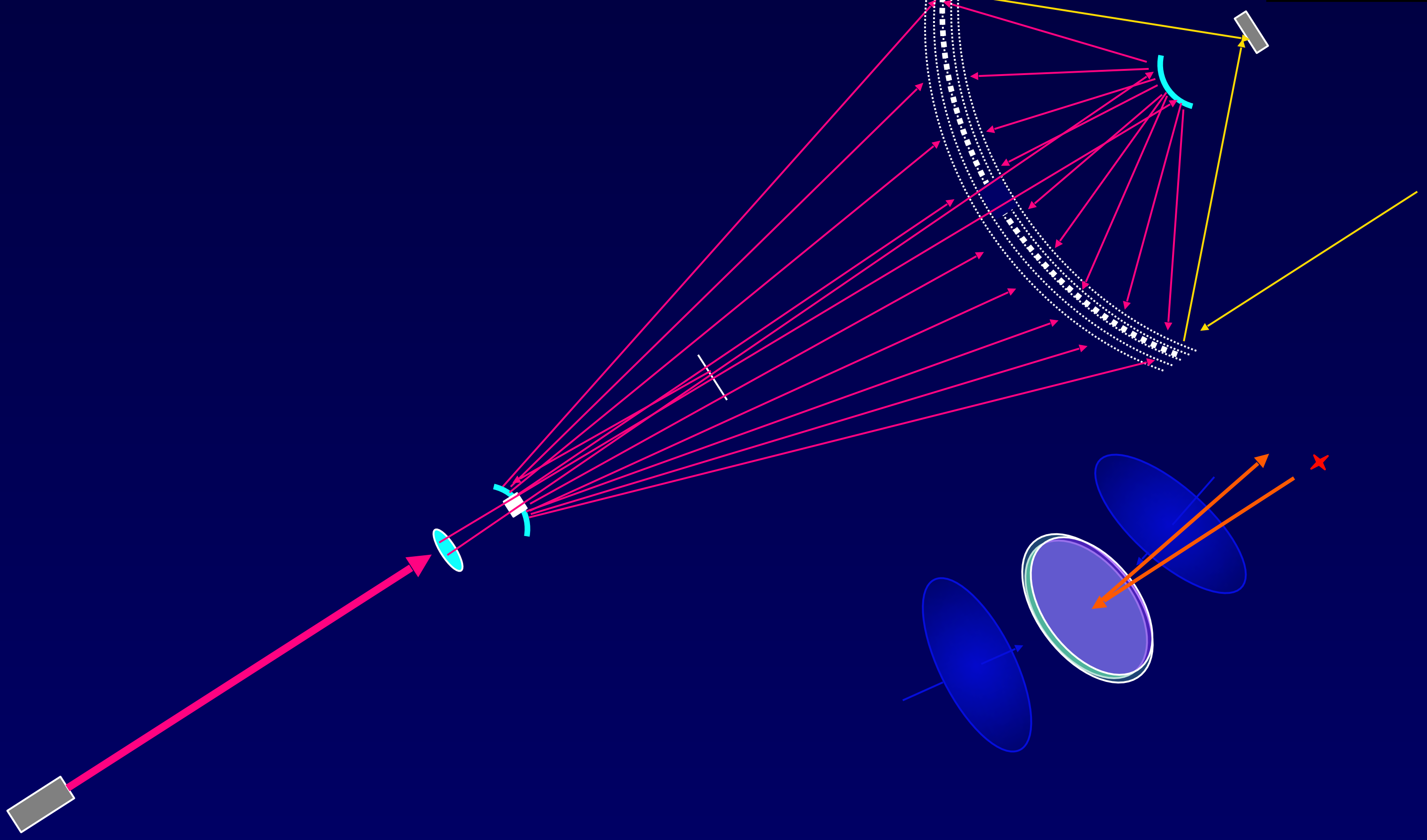
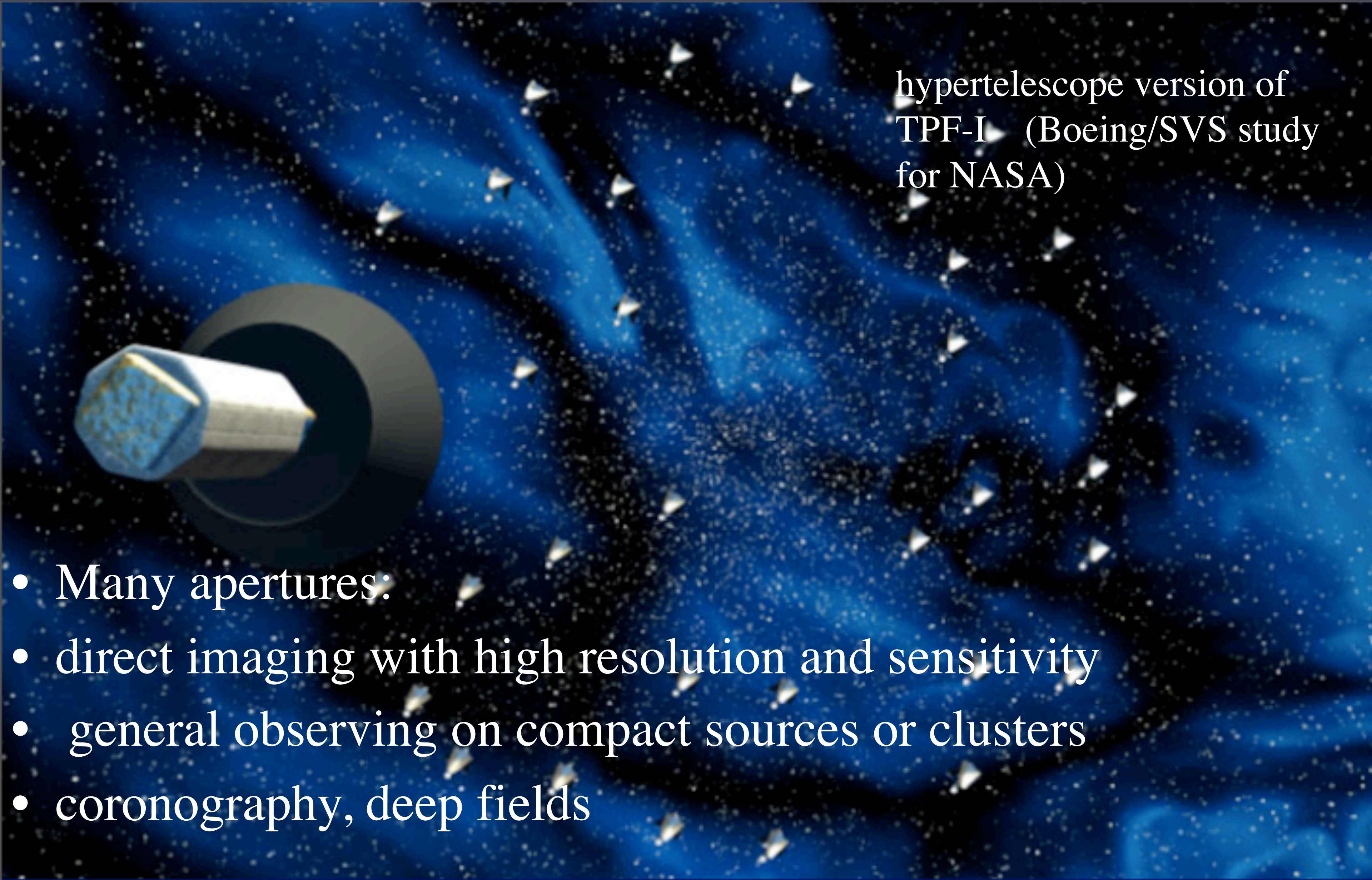
https://lise.oca.eu/





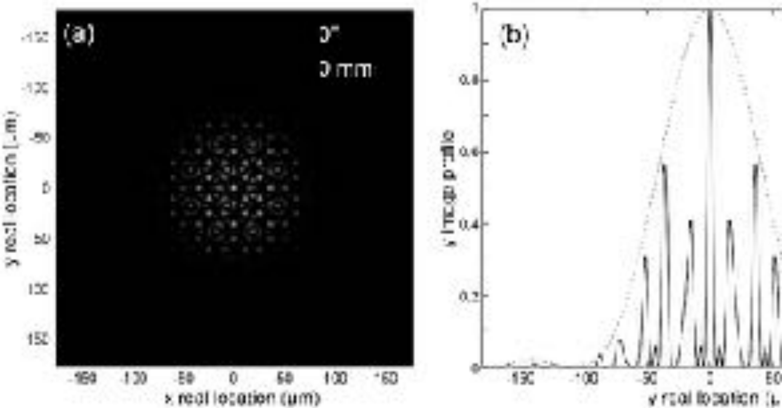
Hypertelescopes in space



hypertelescope version of TPF-I (Boeing/SVS study for NASA)

- Many apertures:
- direct imaging with high resolution and sensitivity
- general observing on compact sources or clusters
- coronography, deep fields

Artificial intelligence needed for modelling, driving and exploiting hypertelescopes



Zemax model of a 9-aperture hypertelescope
(Zongliang Xie et al. , in preparation)

Initial optical modelling : Optical model needs adapted codes for mapping wavefront errors

On Earth:

driving a complex robot:

- active co-parabolisation
- fine centering of sources in multi-field grid

adaptive cophasing needed on Earth:

- piston sensing with 3D Fast Fourier transforms
- actuators driving

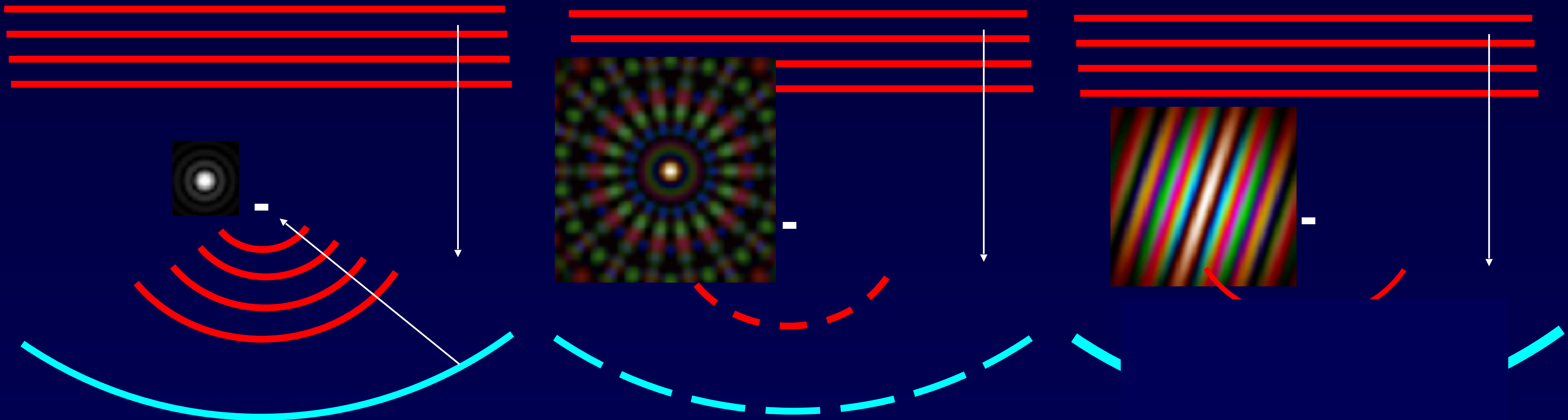
image processing :

- de-convolving the pseudo-convolved image (Mary 2015)
- science interpretation

In space:

- deployment and control of mirror flotilla
- pointing
- data compression and transmission

Interferometer:
a poor man's giant telescope



Fizeau
Interferometer

- Still works with only two elements : image is degraded, but resolution is not affected

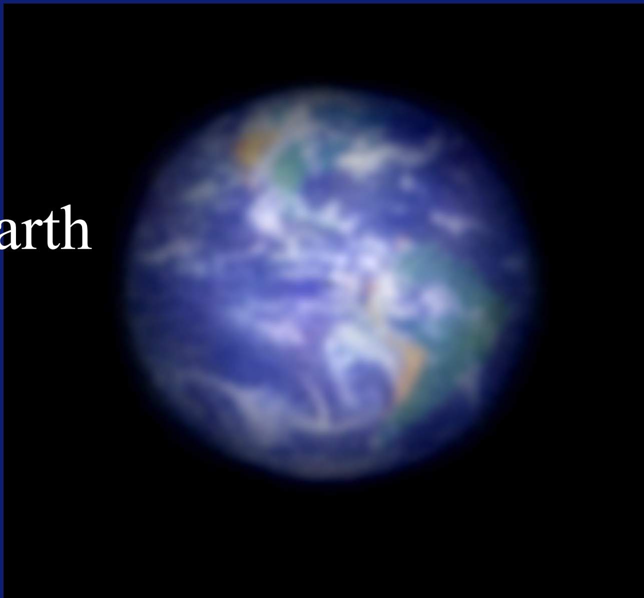
Grand interférometre à deux télescopes (GI2T)
Calern Observatory 1976-2007

γ Cass spectrum with interference fringes
(Mourard, Bosc, Labeyrie, Koechlin, Saha, Nature, 1989)

precursor of VLTI in Chile

Steps toward hypertelescopes, on Earth and in space

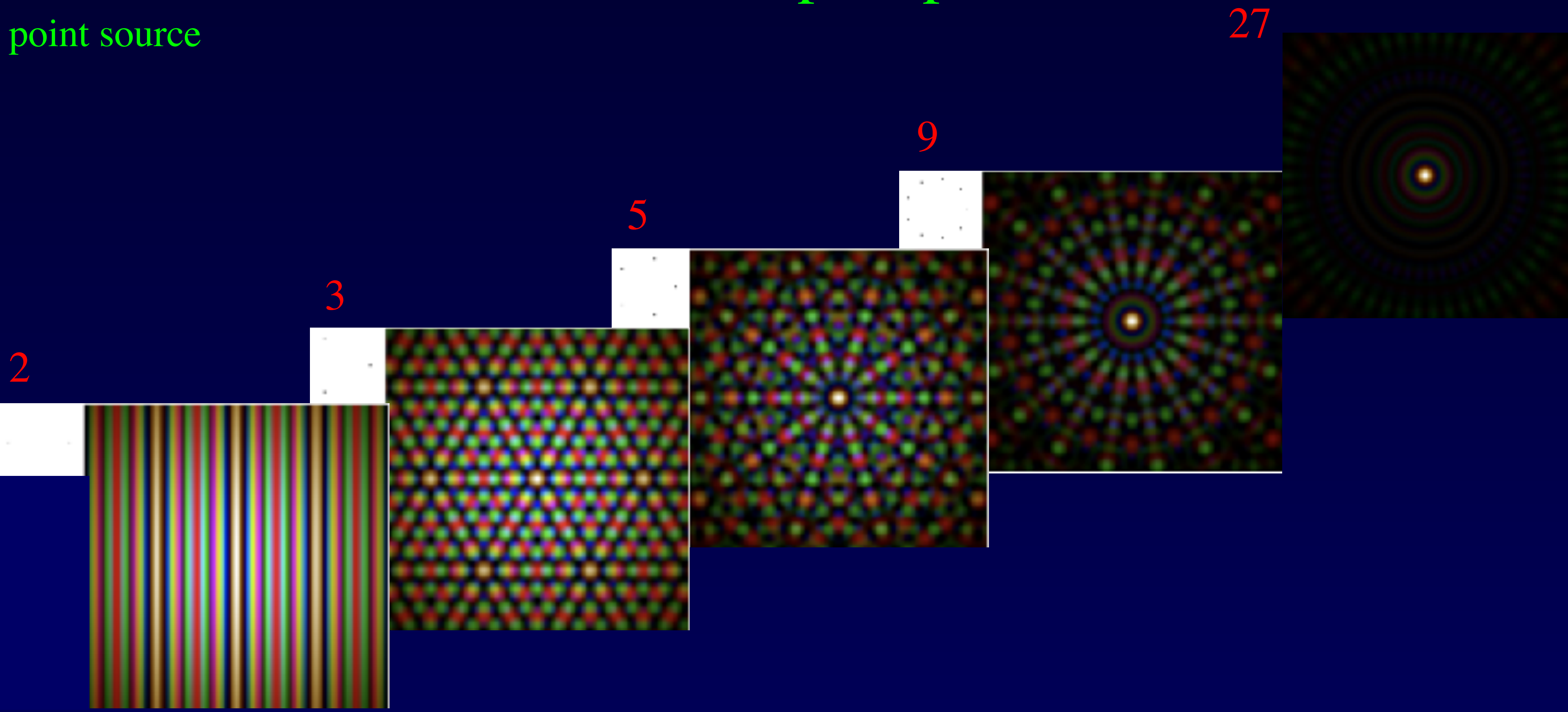
- "Ubaye Hypertelescope" prototype partially built & tested
- proposed terrestrial "Extremely Large Hypertelescope" (ELHyT) with kilometric meta-aperture
- Space versions proposed to NASA & ESA, also lunar version
- https://lise.oca.eu/IMG/file/WhitepaperProposalHypertelescope.pdf



simulated imaging of an exo-Earth
at 3pc, with a 100km
hypertelescope flotilla in space

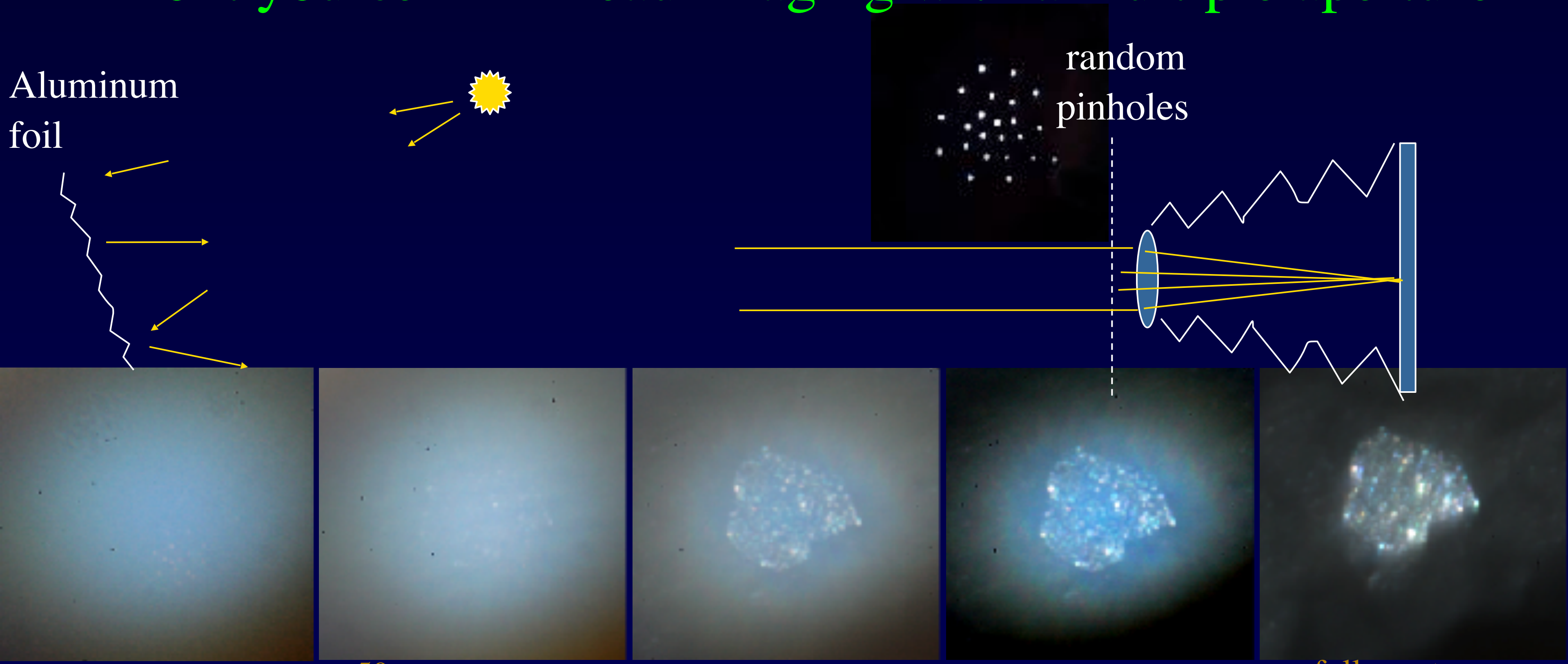
Fizeau interference with multiple apertures

point source



- The peak/halo ratio improves with more apertures
- but diffraction from each sub-aperture attenuates the interference peak
- … a problem solved with « hypertelescopic imaging »

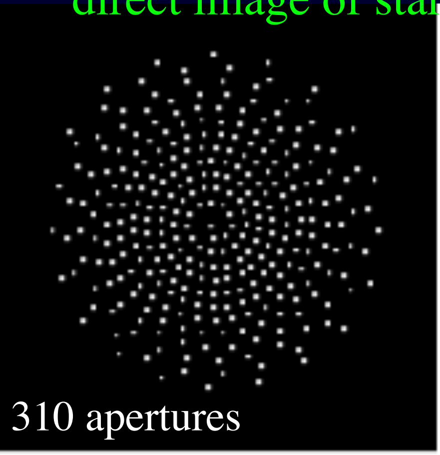
« Do it yourself » Fizeau imaging with a multiple aperture

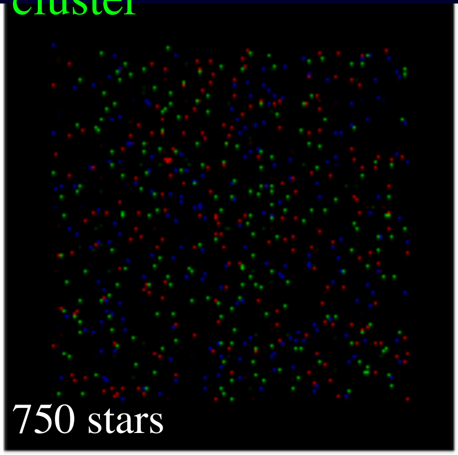


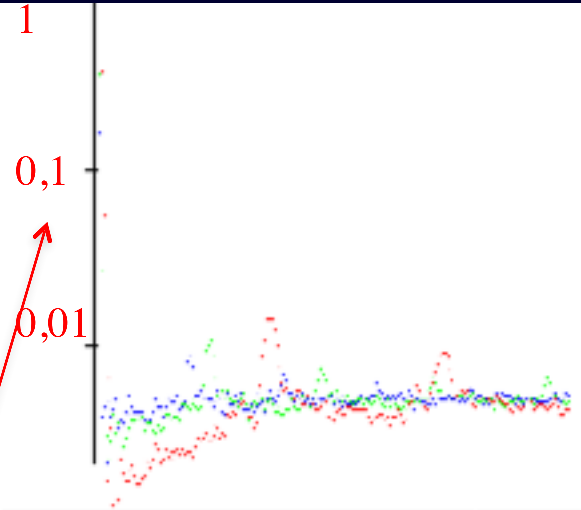
15 apertures 50 apertures 235 apertures 600 apertures full aperture

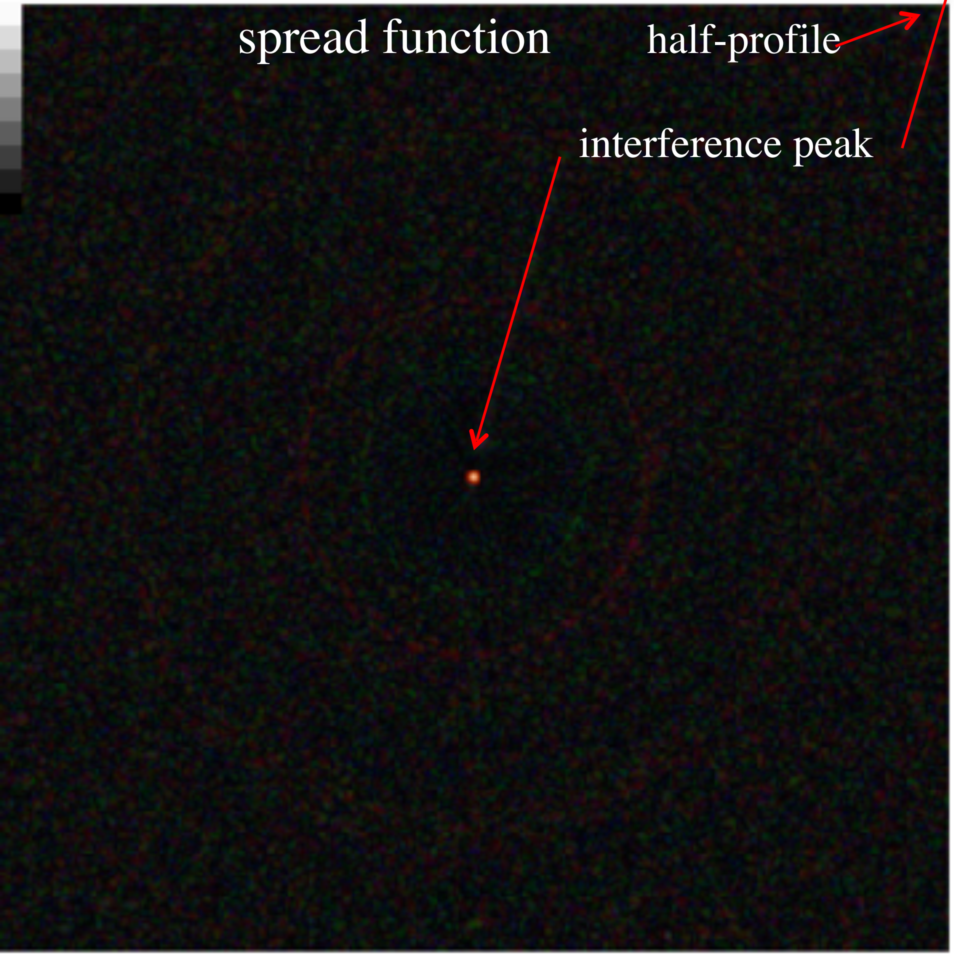
- image improves with more apertures …
- … but remains drowned in a halo …
- … caused by diffraction through the small sub-apertures, and which takes energy away from the image…
- … a loss avoided with "hypertelescope" imaging

direct image of star cluster


310 apertures


750 stars





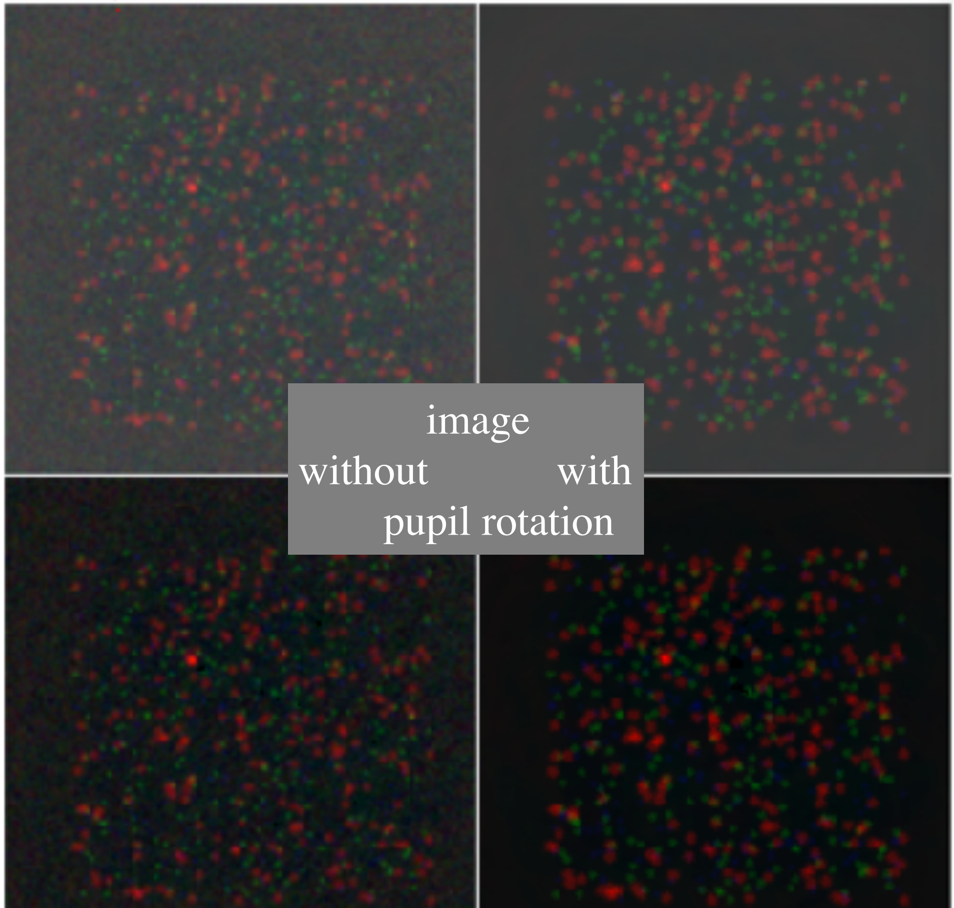
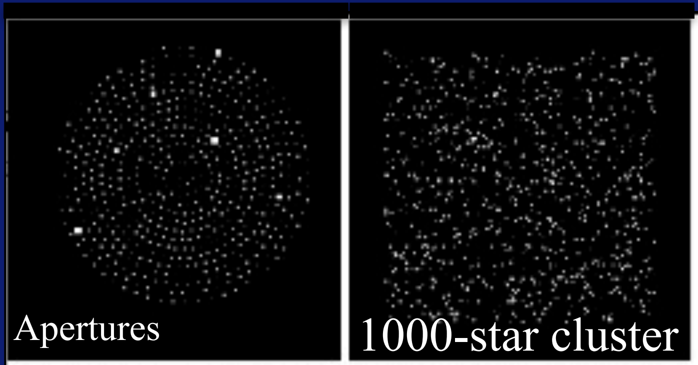
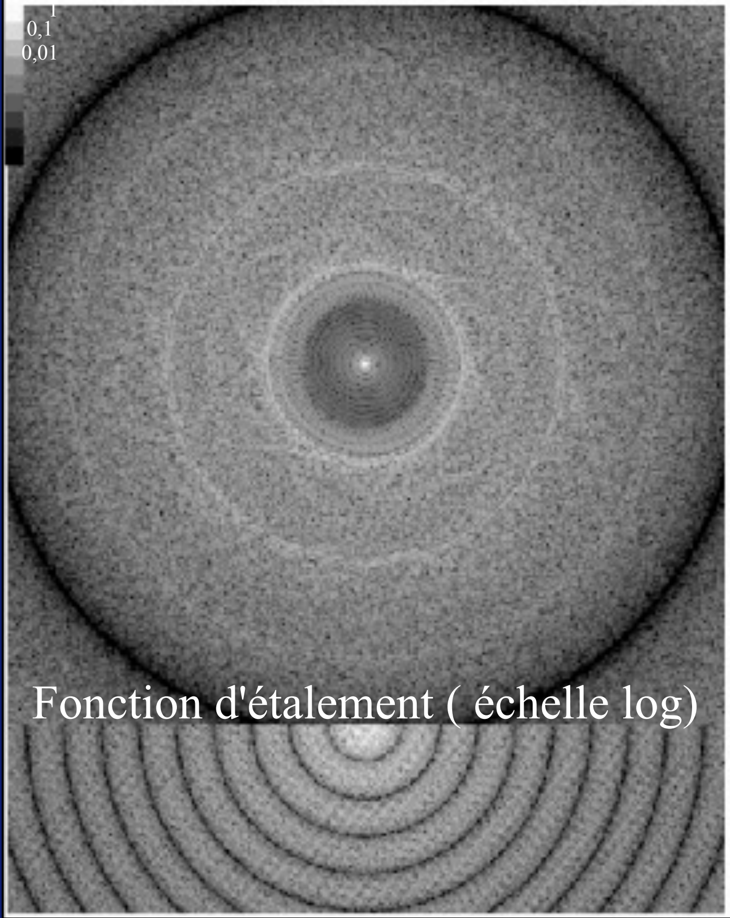


image
without with
pupil rotation

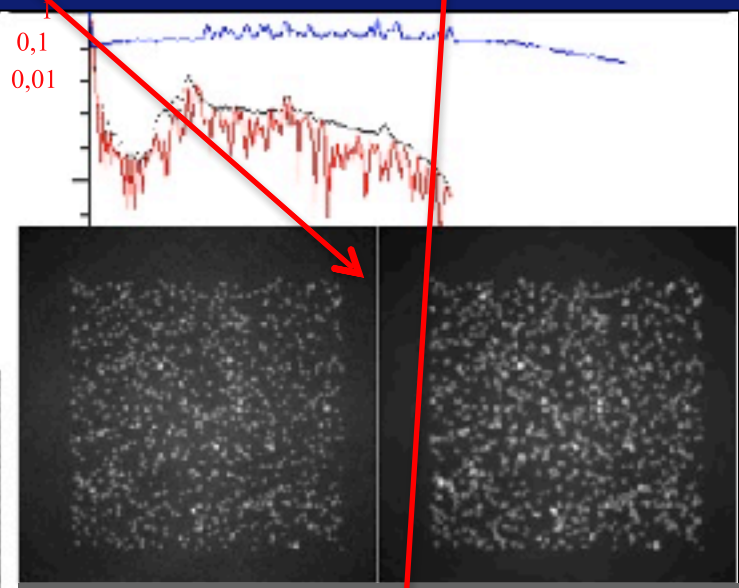
Simulated Fizeau images comparing 605 small apertures to 6 large ones, at equal collecting area & meta-aperture diameter

- crowded image with the large apertures

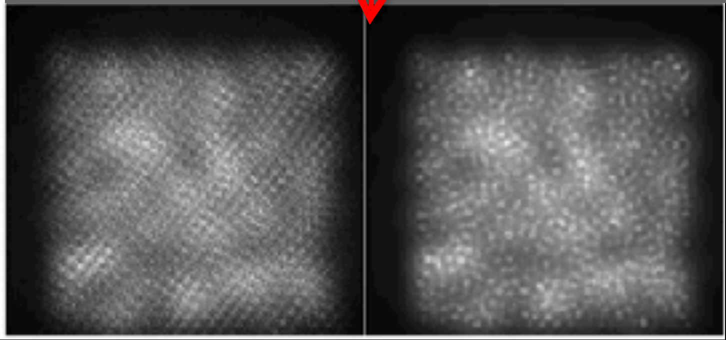




Fonction d'étalement (échelle log)

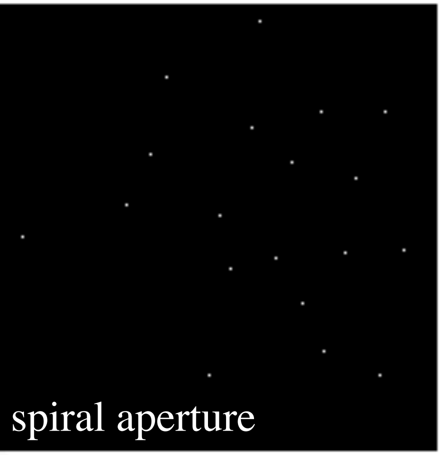


Images
without with
aperture rotation

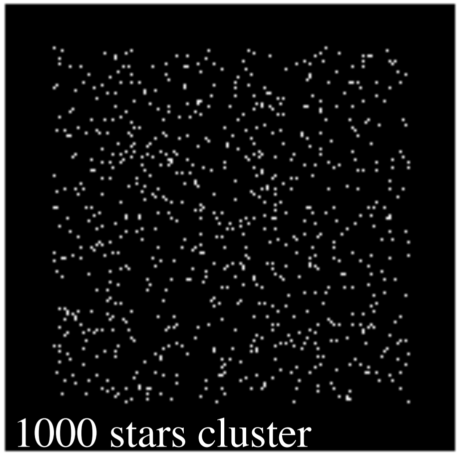


Simulated Fizeau imaging:

30 apertures and 1000 stars



spiral aperture



1000 stars cluster

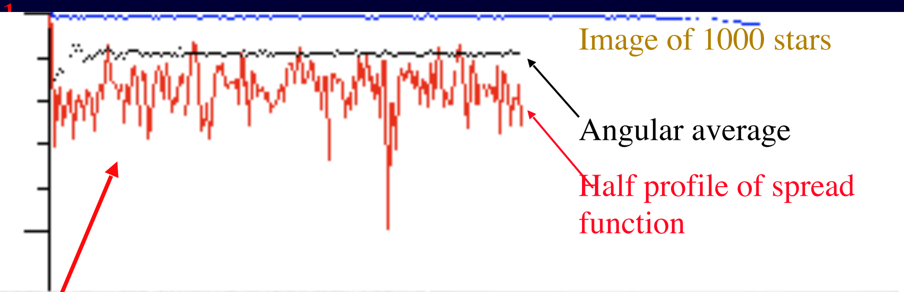
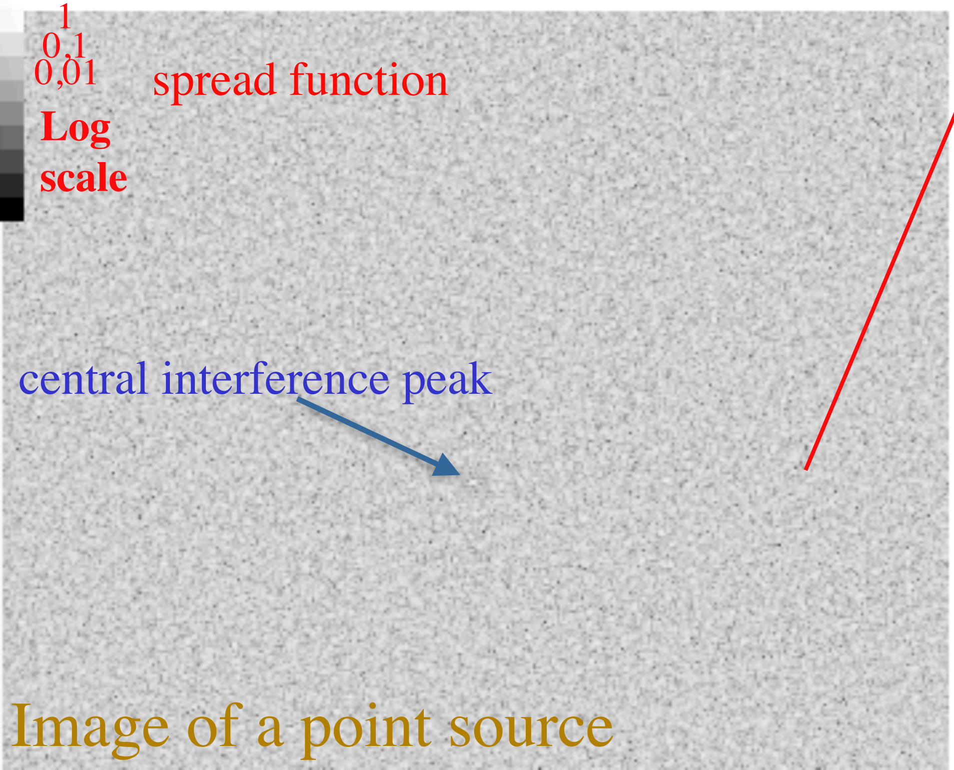


Image of 1000 stars

Angular average

Half profile of spread function

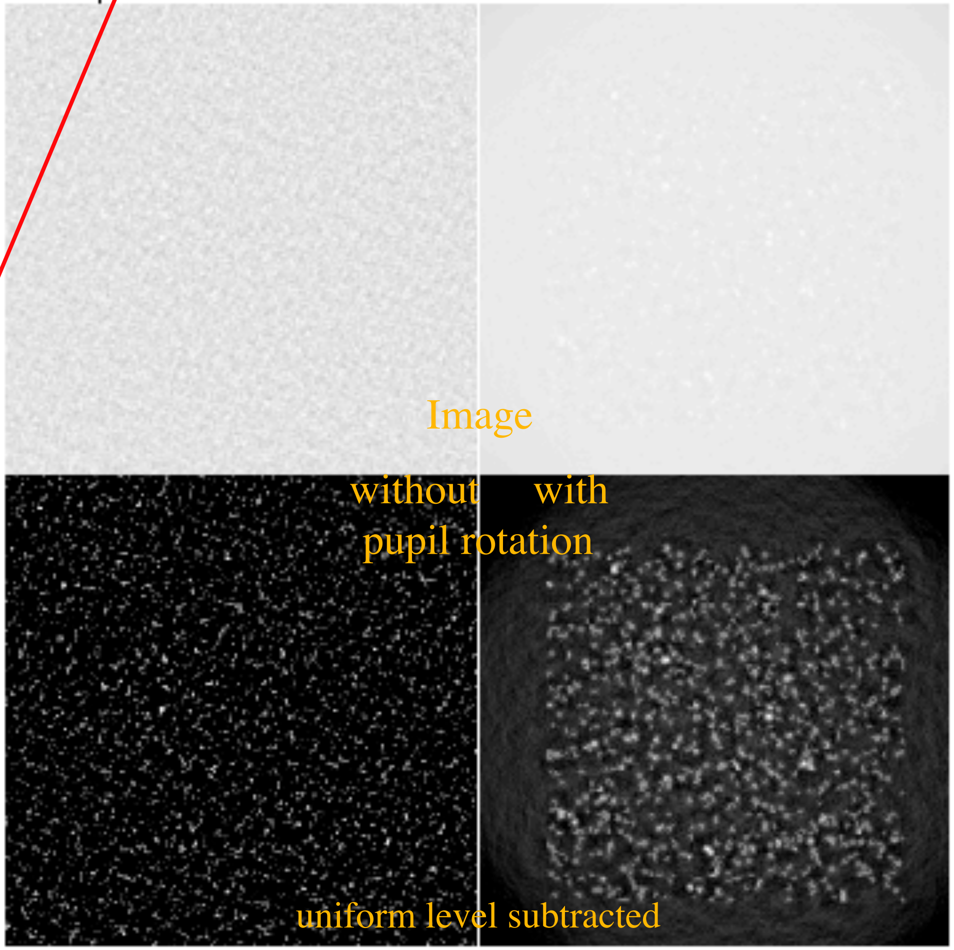


spread function

Log scale

central interference peak

Image of a point source



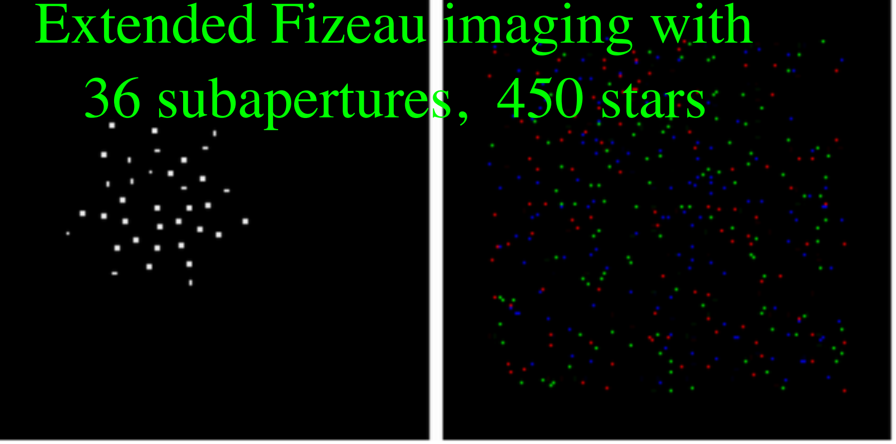
Image

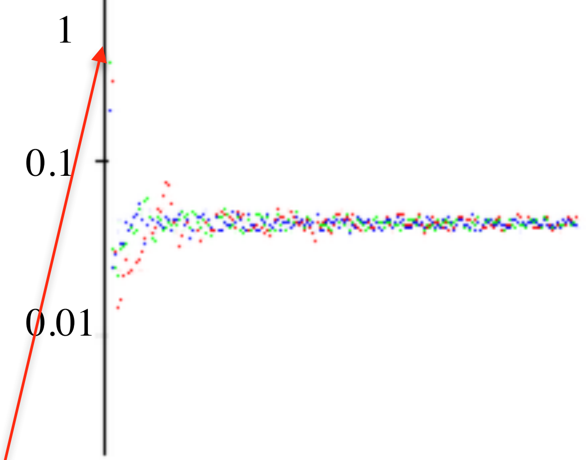
without with

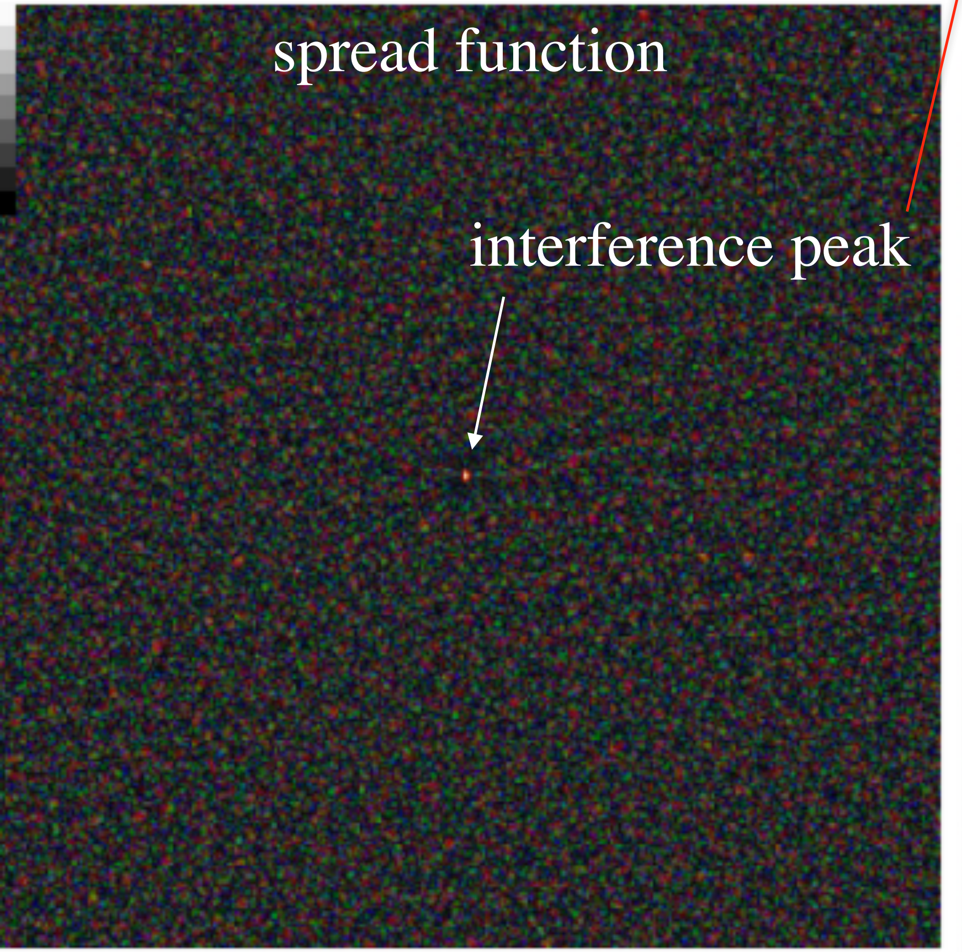
pupil rotation

uniform level subtracted

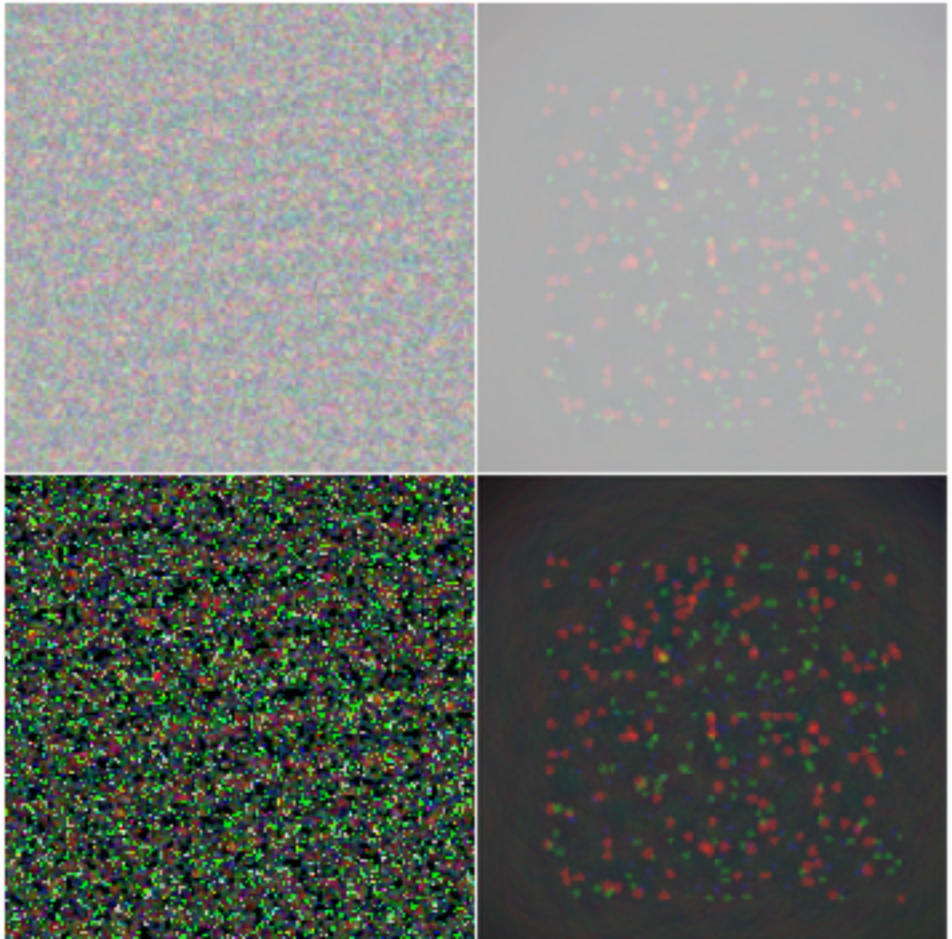
Extended Fizeau imaging with 36 subapertures, 450 stars






spread function

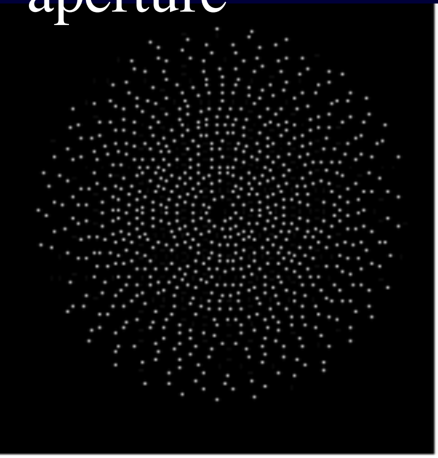
interference peak



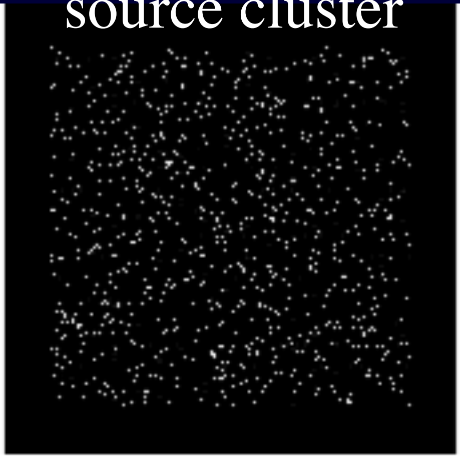
Fizeau imaging simulation:

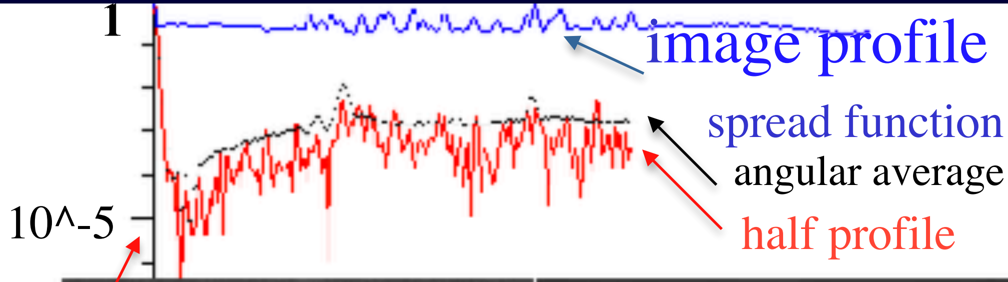
1000-element apodizing spiral aperture & 1000 stars

aperture

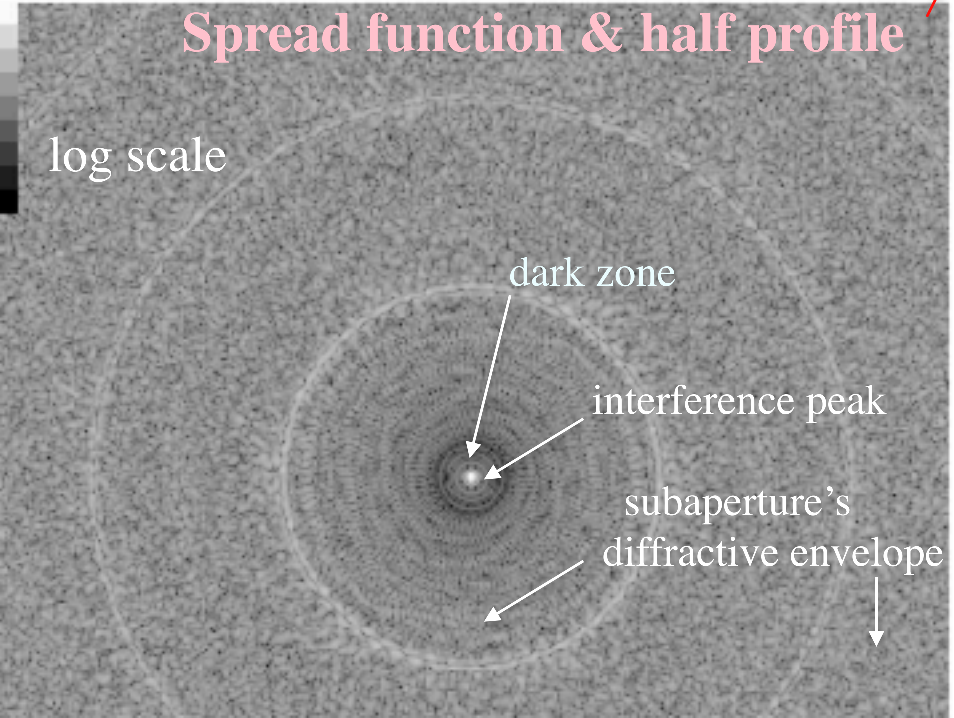


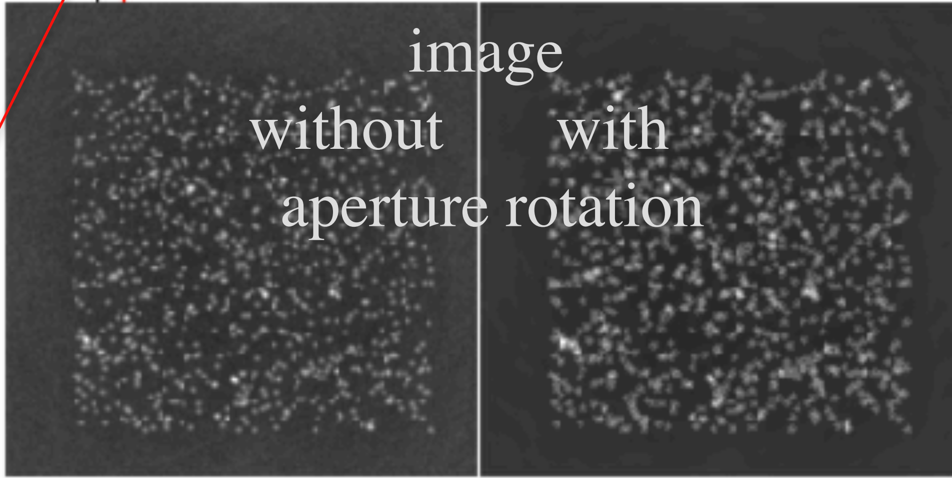
source cluster



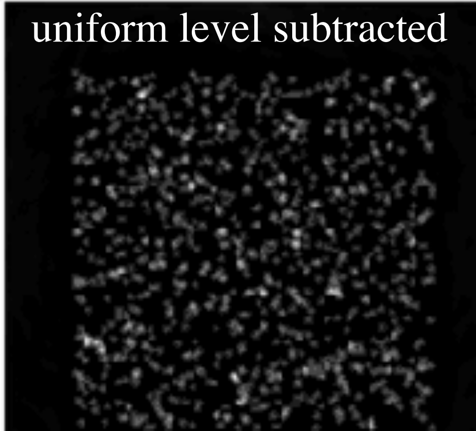


Spread function & half profile



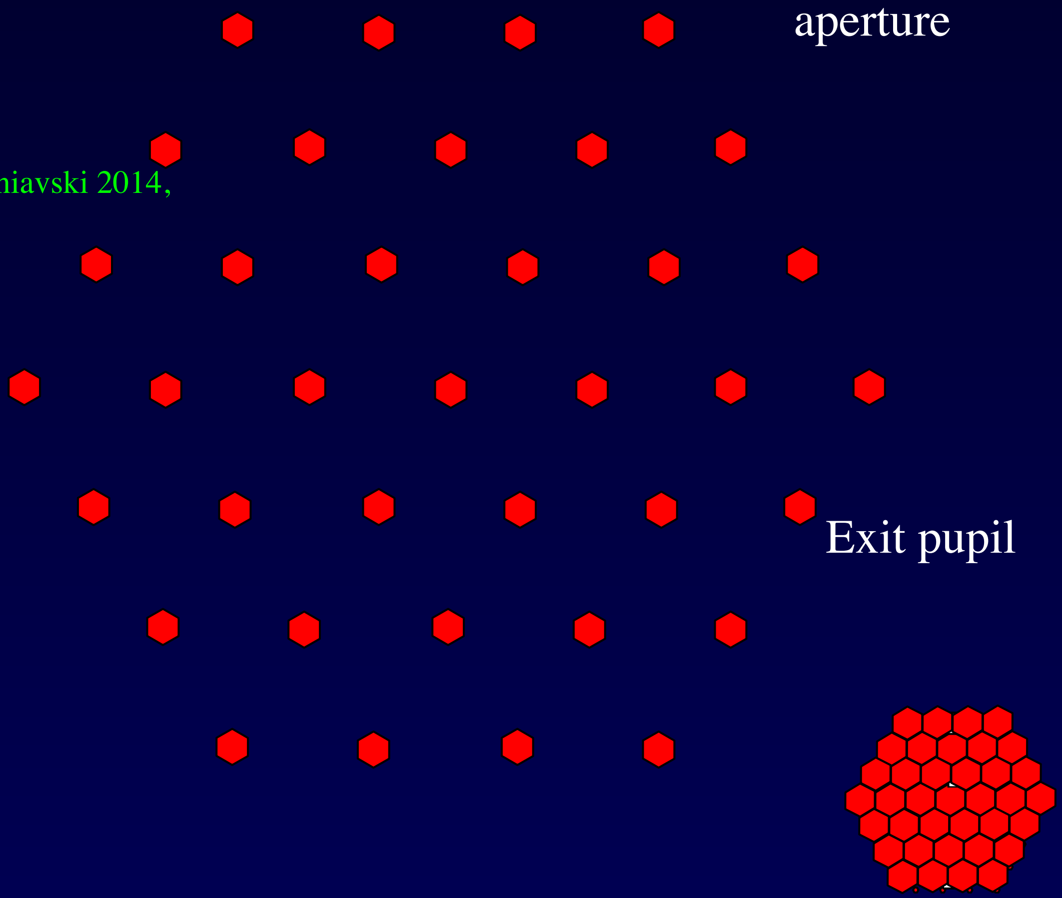


uniform level subtracted



Hypertelescope

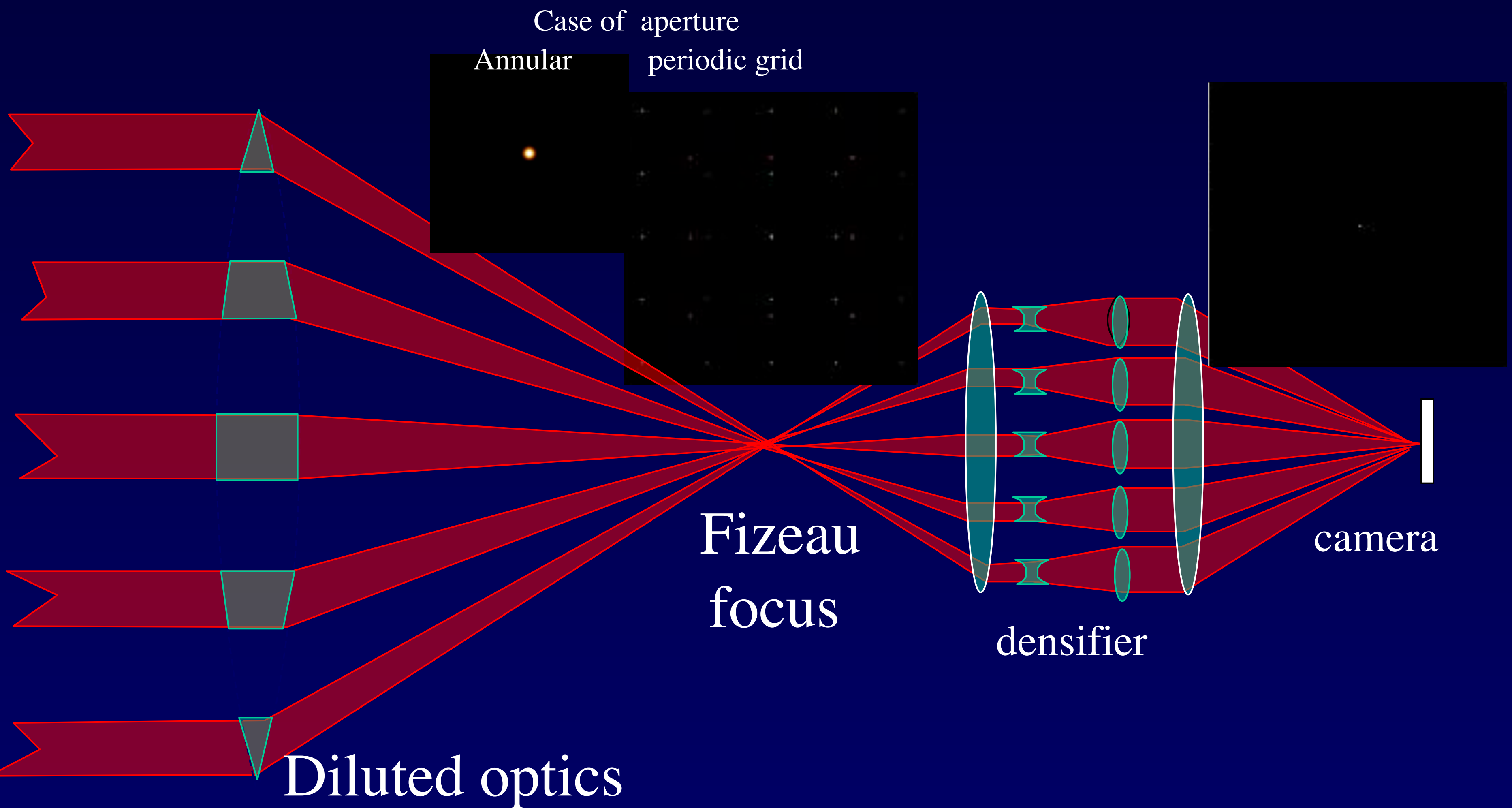
(Labeyrie, 1996; Lardière et al., 2006,
Patru et al. 2006, Mourard et al, Martinache 2004. Tcherniavski 2014,
Nakai et al. 2016)



- Directly-imaging interferometer, multi-aperture, with a pupil densifier
- Forms direct images….
- …. in a smaller field than a Fizeau interferometer, but intensified

Principle of the hypertelescope

or « multi-aperture imaging interferometer with pupil densifier »



Case of aperture

Annular

periodic grid

Fizeau focus

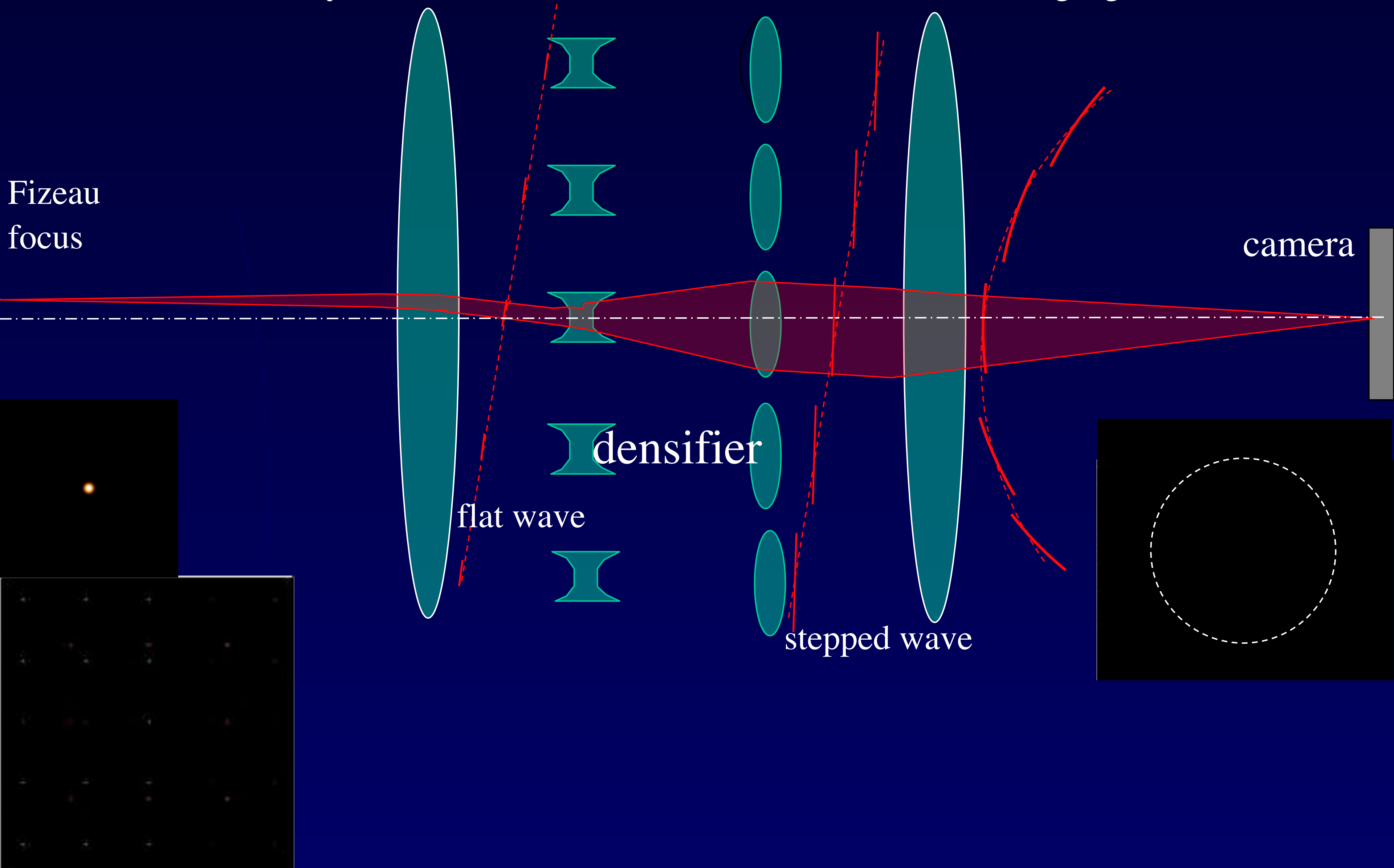
densifier

camera

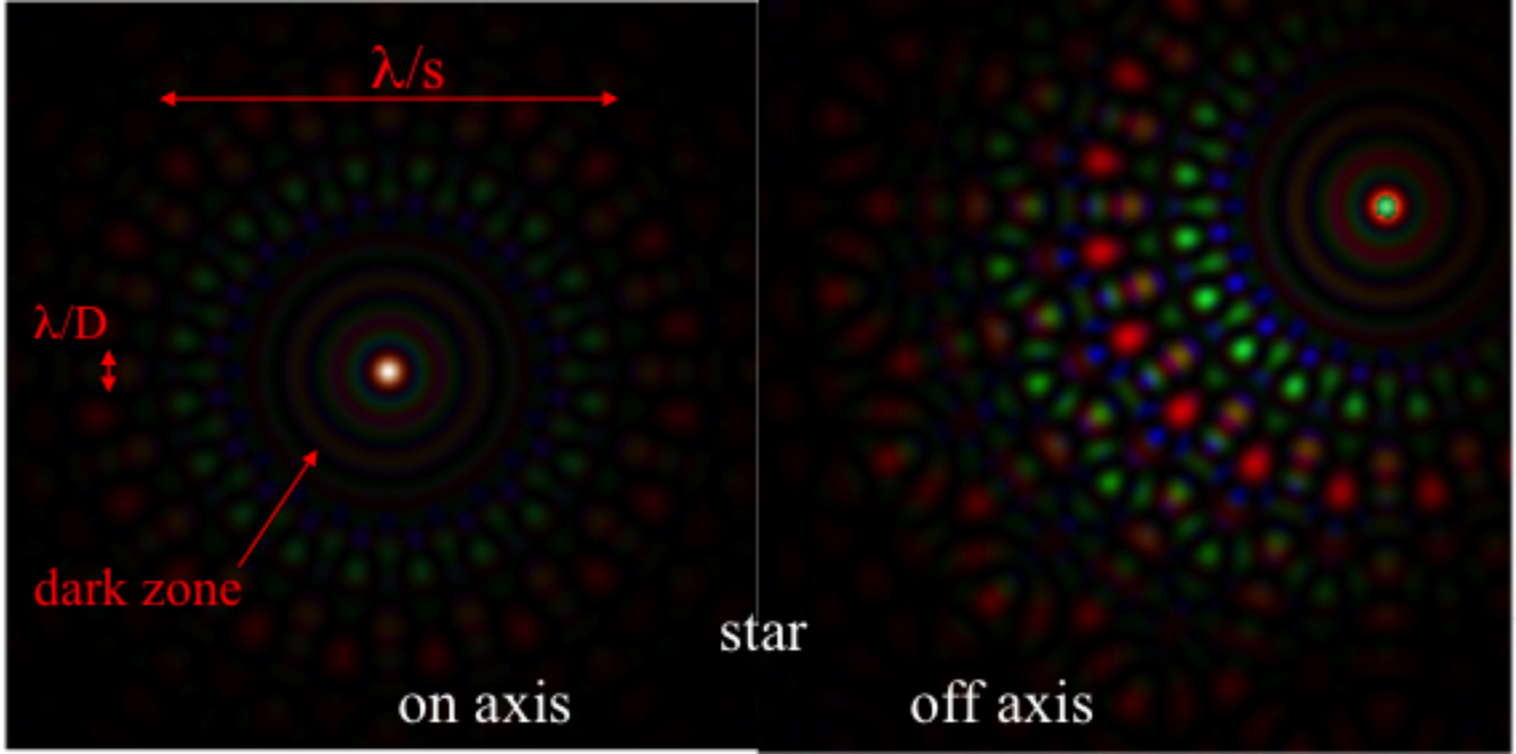
Diluted optics

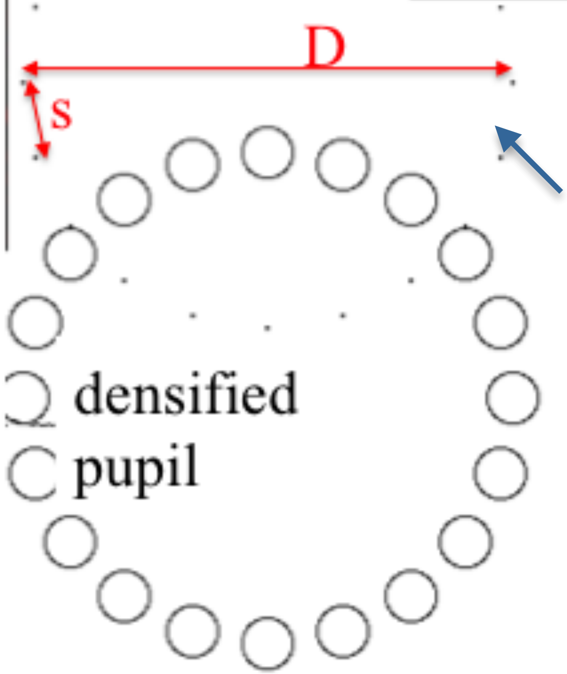
Off-axis star

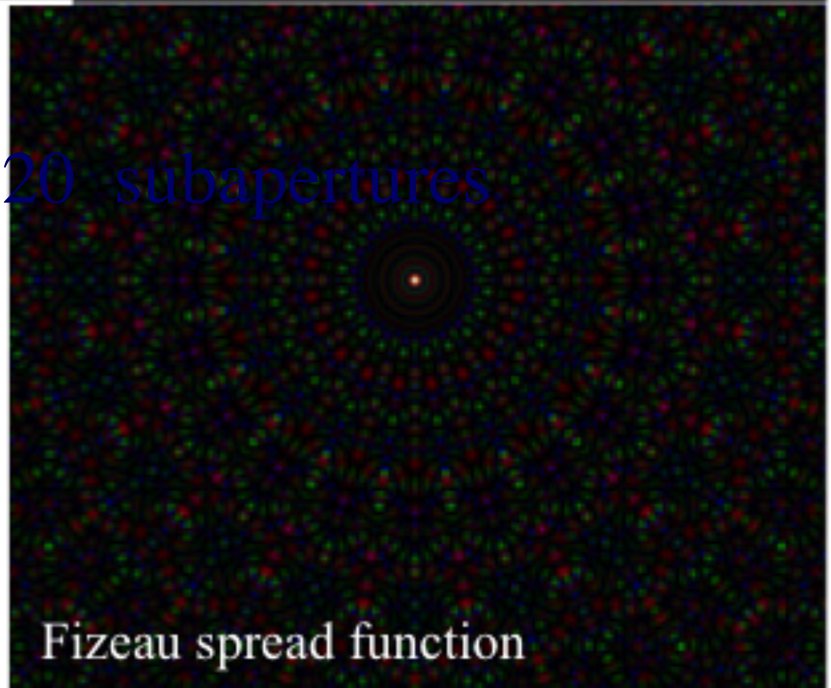
- Its image is shifted more than the envelope…
- … and eventually moves out of it => limitation of "direct imaging field"



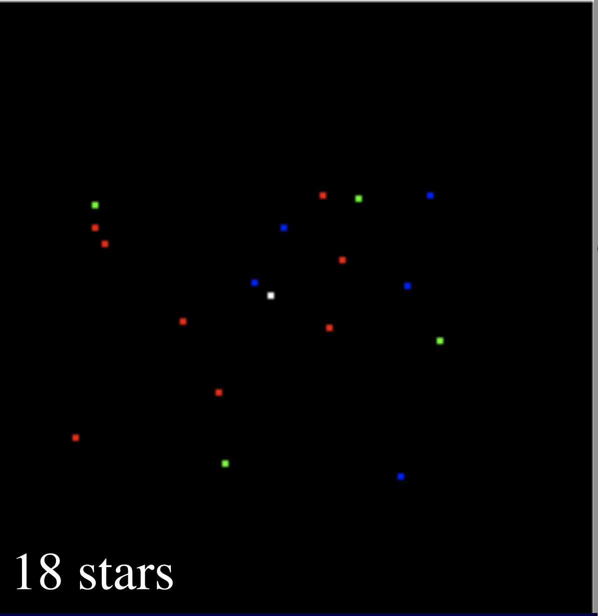
Hypertelescope's Direct Imaging Field

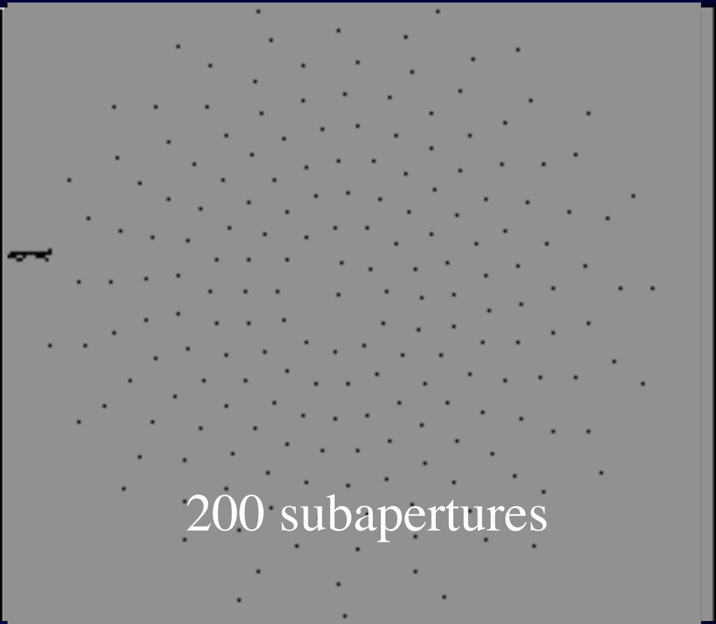


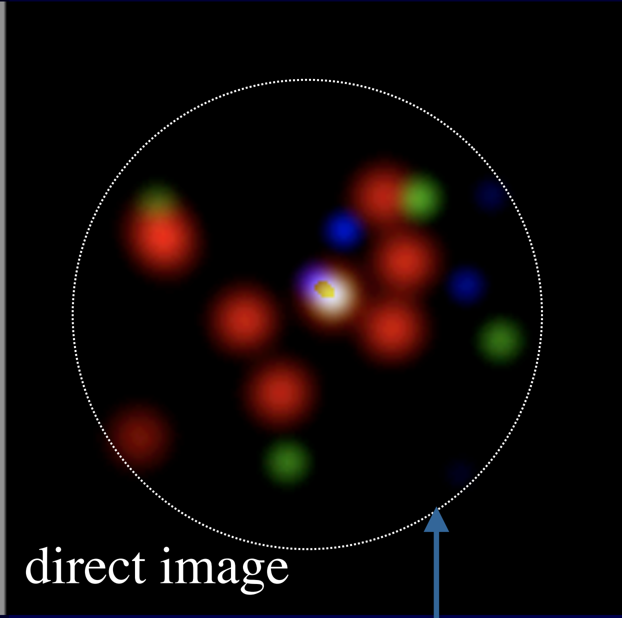




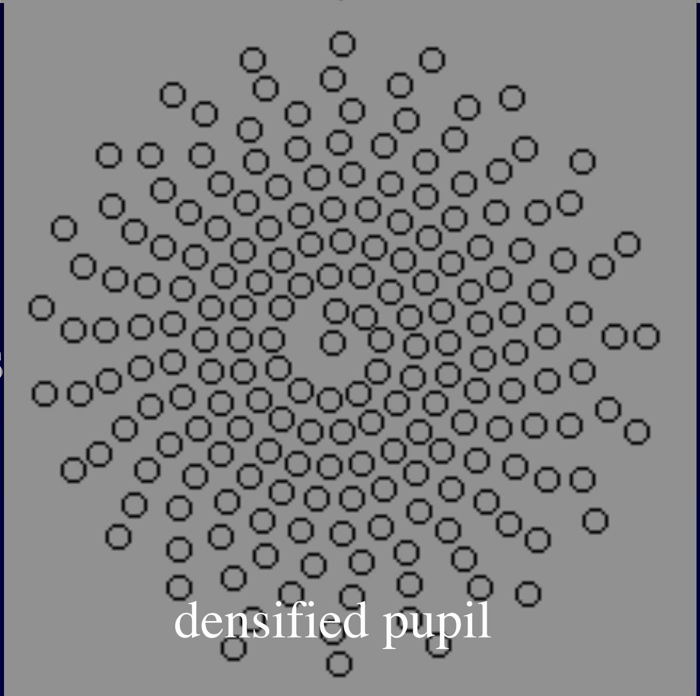
Simulated hypertelescopic imaging







- pupil densifier shrinks the image’s diffractive envelope
- thus concentrating its light …
- …and shrinking the field of view



limit of « Direct Imaging Field »

Interferometer flotilla:

Why many apertures ?

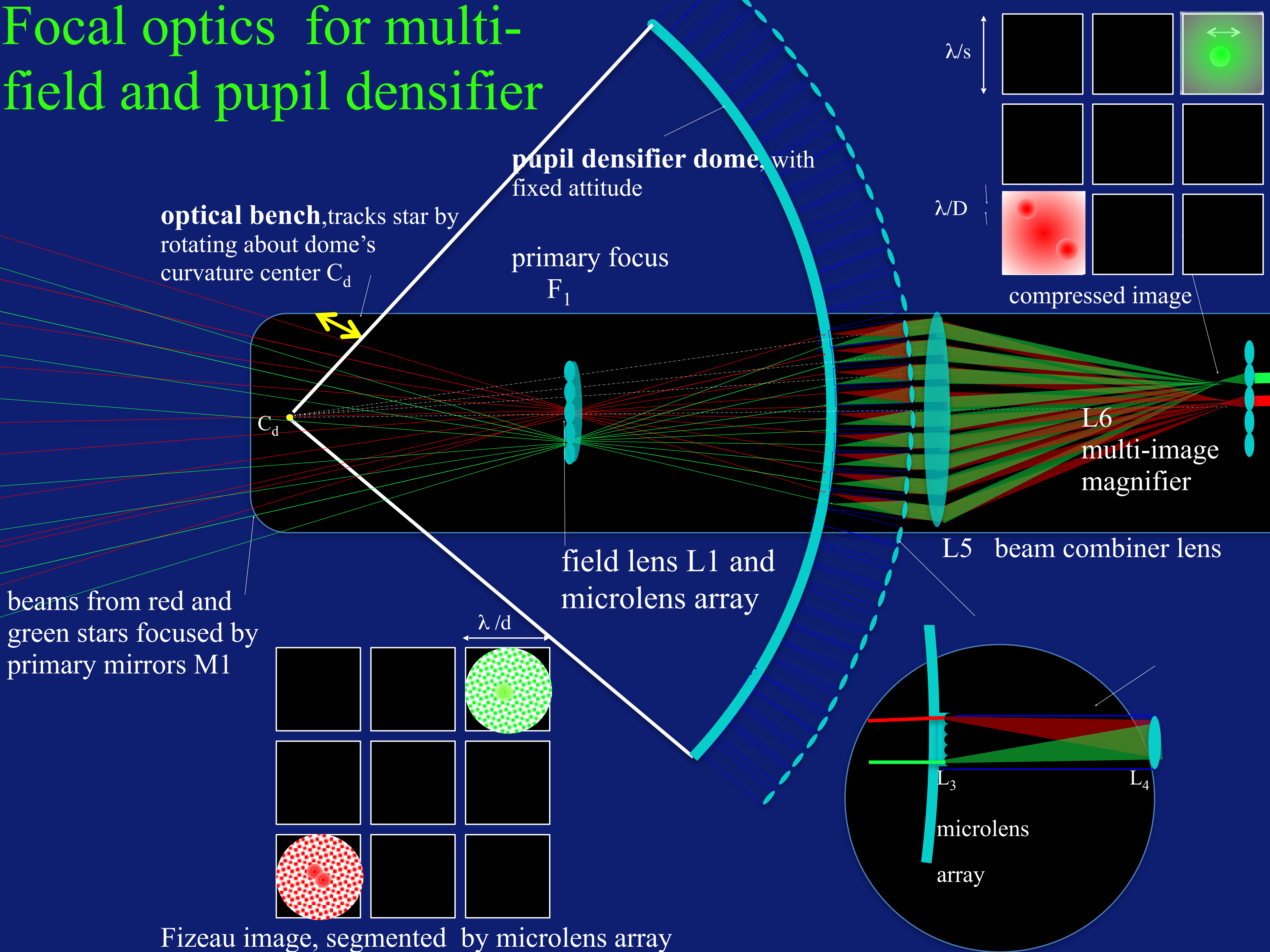
(Labeyrie et al., Experimental Astronomy, 2008)

- Image becomes crowded if number of point sources in Direct Imaging Field exceeds N^2
- Science vs. mirror size d , at given cost $C_{pa} = N d^{\gamma}$, where $\gamma = 2$ to 3

$$Sc = C_{pa}^{2} \, d^{-2\gamma} \, \{(7/4) \log_2 C_{pa} + (1-7\gamma/4) \log_2 d\}$$

- Strong science gain with decreasing d
- Many small mirrors better than few large ones, at given collecting area and meta-aperture diameter
  - same resolution and limiting magnitude
  - improved dynamic range, crowding limit, Direct Imaging Field
  - cost saving
- But how small ? d= 30mm diffracts a 1.5m lobe at 100km
- 40,000 mirrors of 30mm needed for the same collecting area as JWST : feasible with « Laser-trapped flotilla « ?

Focal optics for multi-field and pupil densifier



pupil densifier dome, with fixed attitude

optical bench, tracks star by rotating about dome's curvature center C_d

primary focus F_1

compressed image

L6 multi-image magnifier

L5 beam combiner lens

field lens L1 and microlens array

beams from red and green stars focused by primary mirrors M1

microlens array

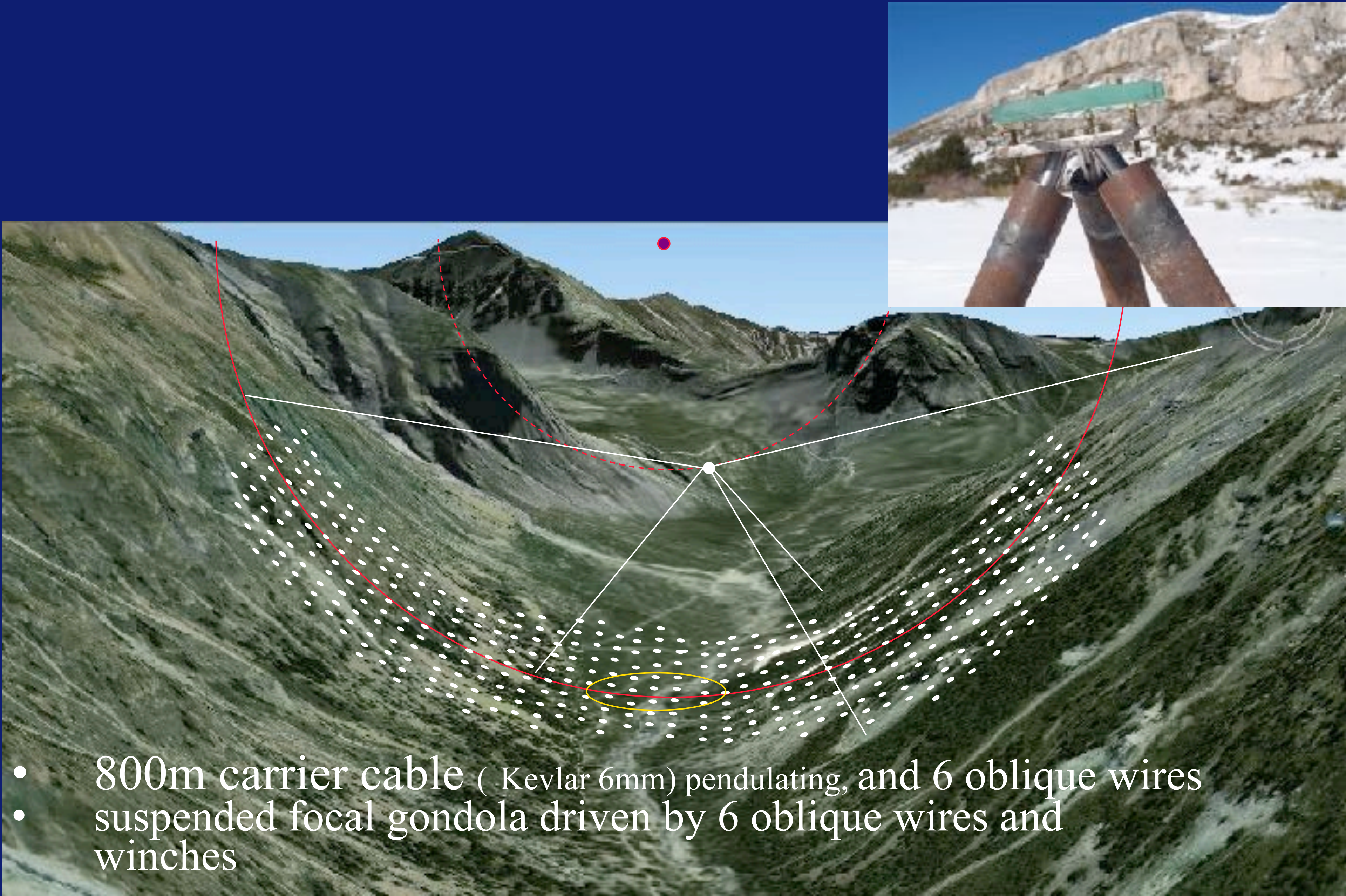
Fizeau image, segmented by microlens array

Testing of « Ubaye hypertelescope »

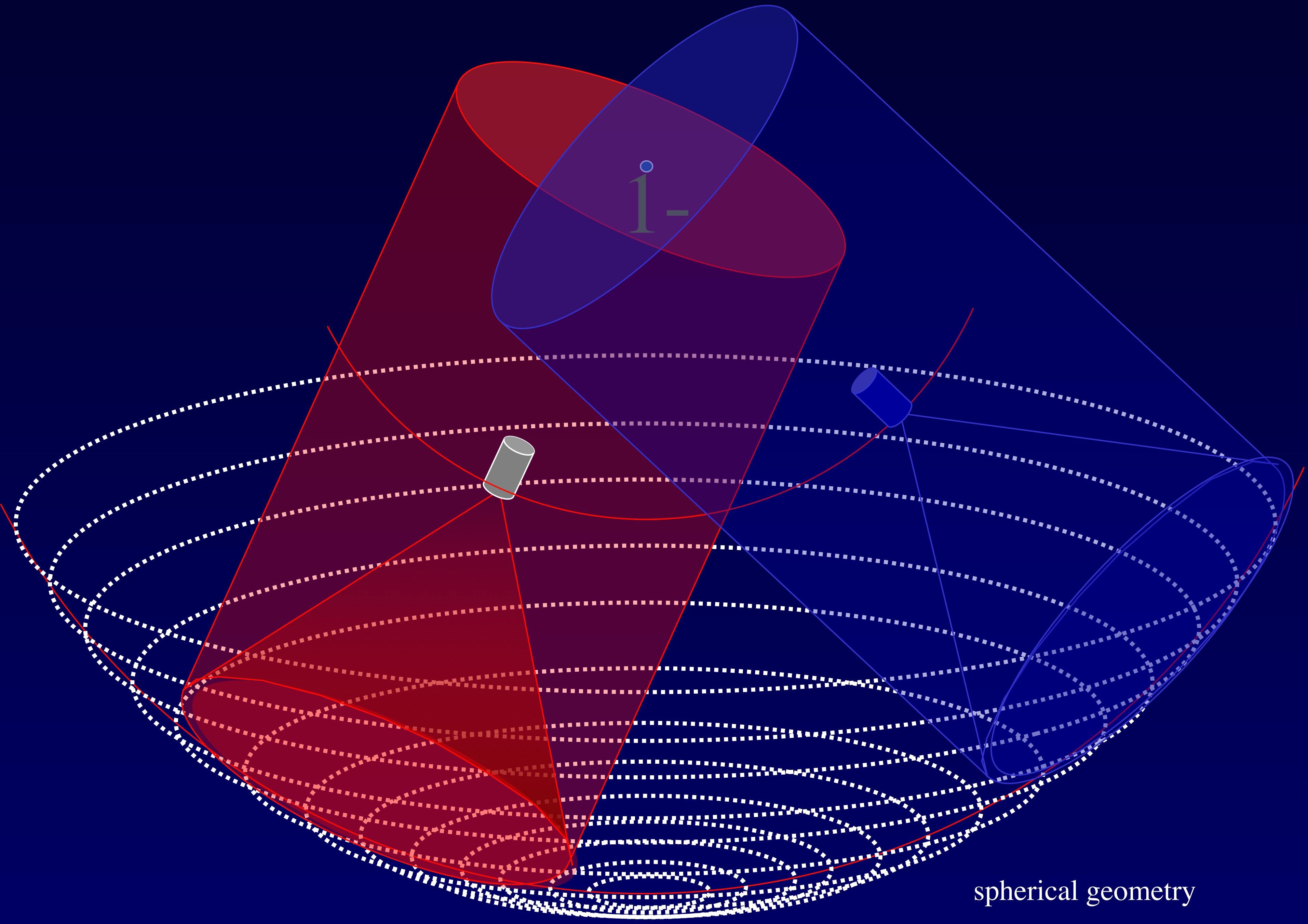
- following a smaller prototype at Haute-Provence (Le Coroller et al. 2014)
- under test with two 15cm mirrors, expandable to hundreds
- for a meta-aperture diameter up to 200m

photo Wassila Dali-Ali

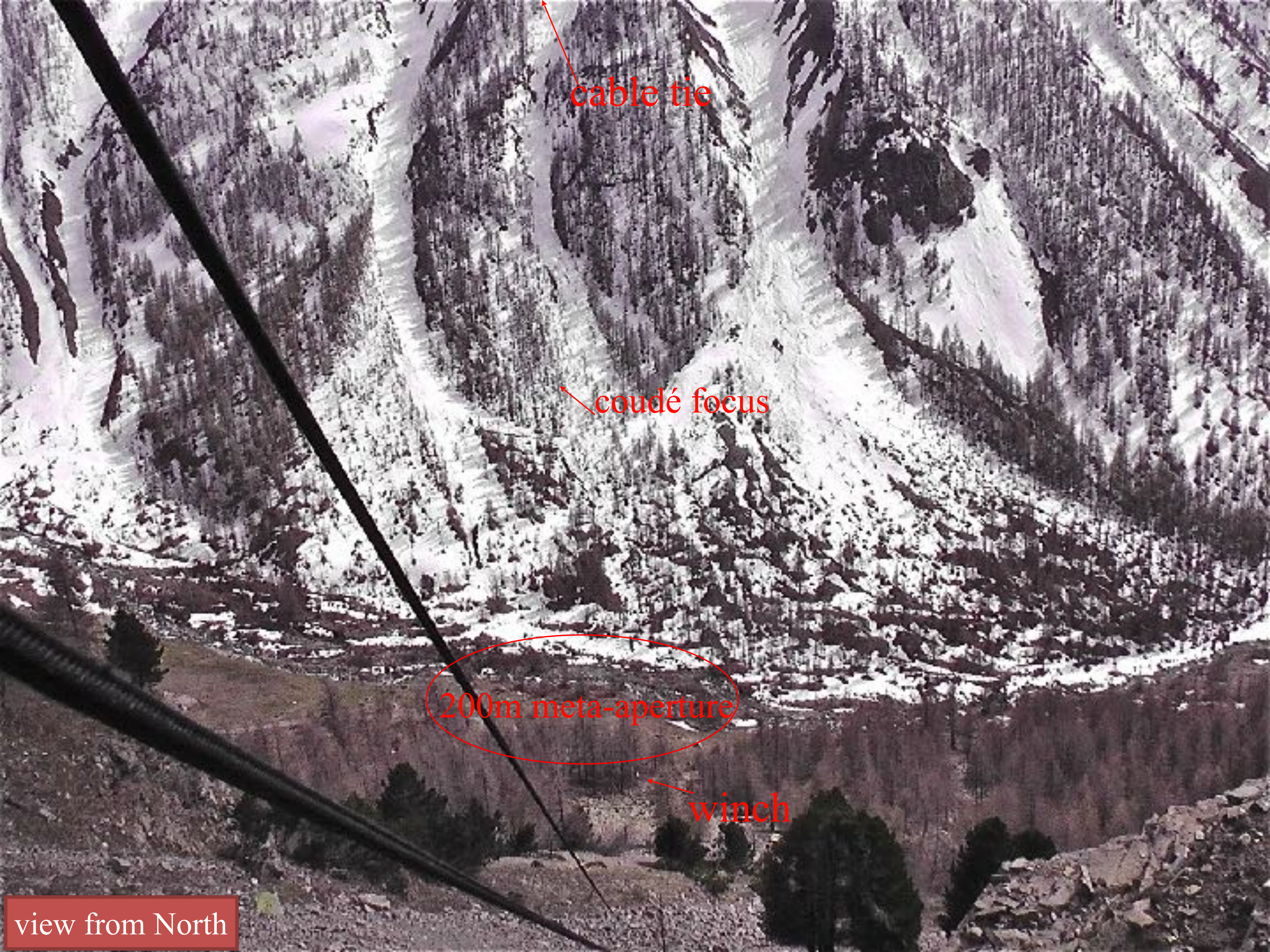
« Ubaye Hypertelescope » concept



- 800m carrier cable (Kevlar 6mm) pendulating, and 6 oblique wires
- suspended focal gondola driven by 6 oblique wires and winches



spherical geometry

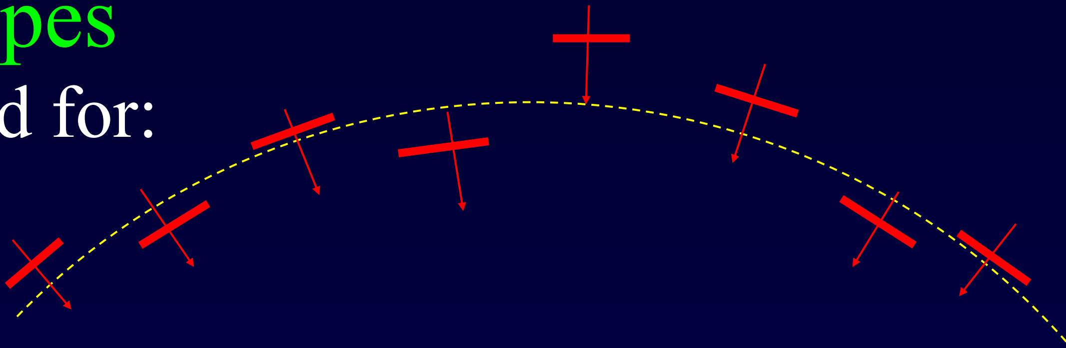

cable tie
coudé focus
200m meta-aperture
winch
view from North

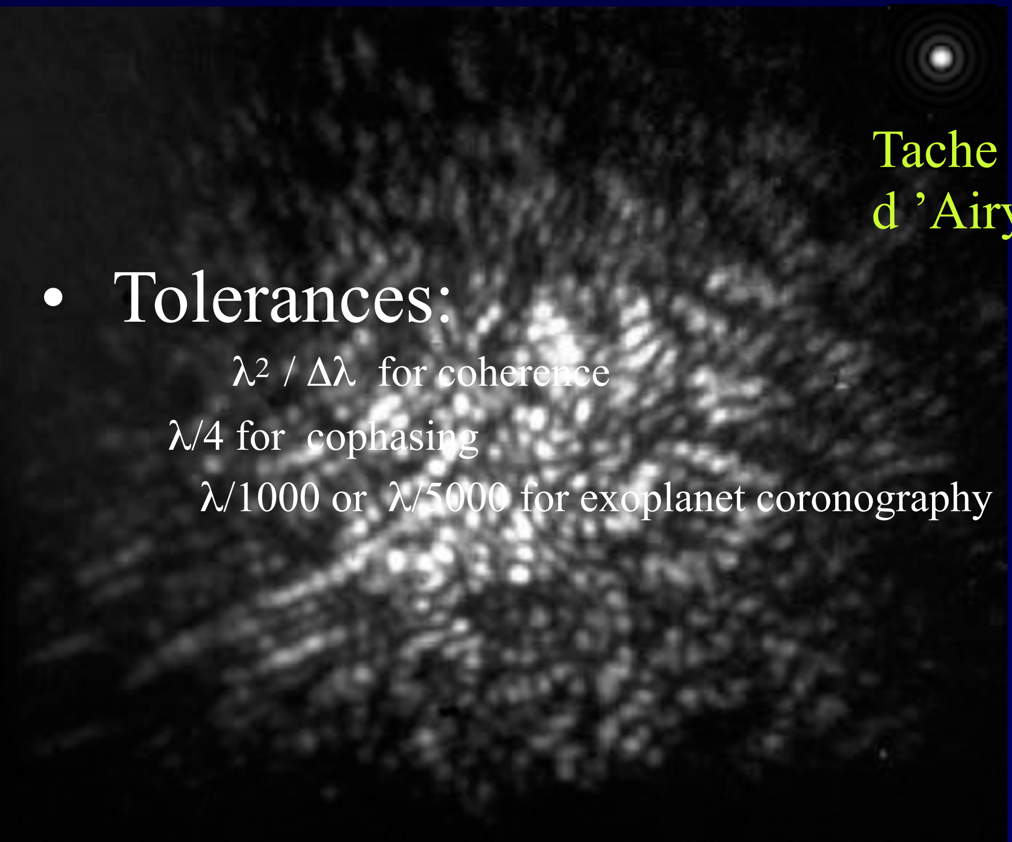
Suspended focal camera

mirror element

Cophasing hypertelescopes

- Wavefront control needed for:
  - coherencing,
  - interference
  - cophasing : Airy peak
  - easier in space !





Tache d 'Airy

- Tolerances:

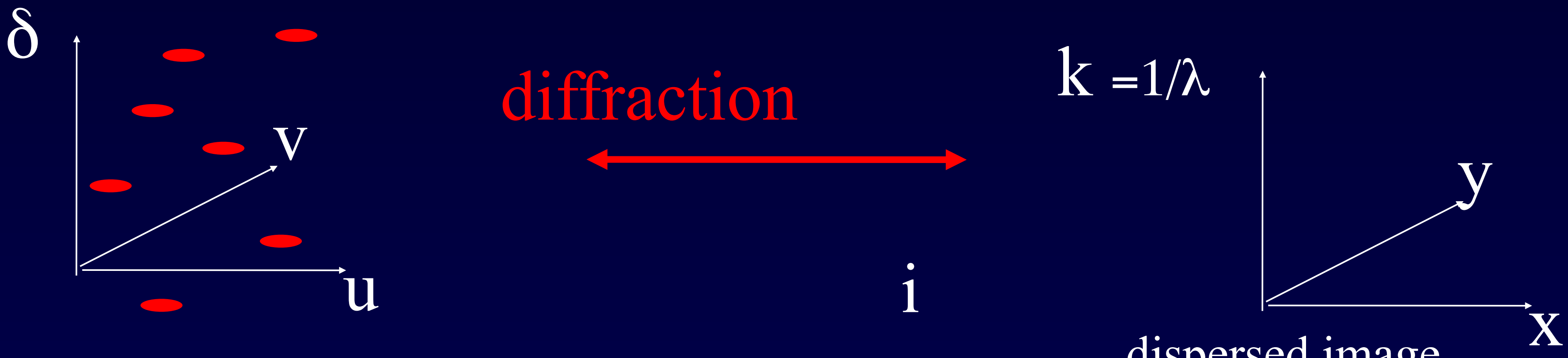
  $\lambda^2 / \Delta\lambda$ for coherence

  $\lambda/4$ for cophasing

  $\lambda/1000$ or $\lambda/5000$ for exoplanet coronography

Formalism of « dispersed speckle wave sensing »

(Martinache 2004, Borkowski et al. 2005)



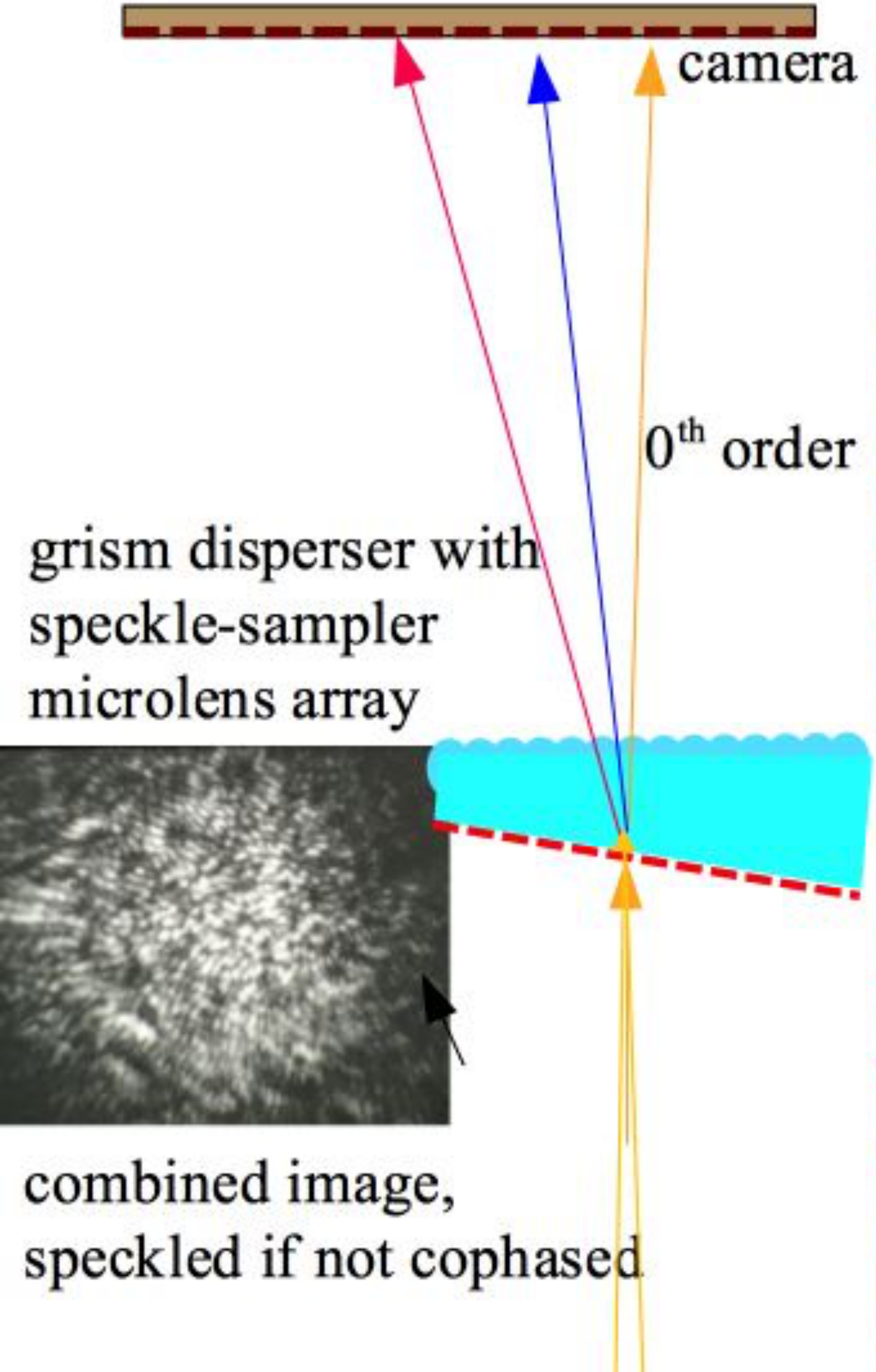
dispersed image

dilute aperture τ(u,v,δ)

0 or 1

$$I(x,y,k) = |TF|^2\left[\tau(u,v,\delta)\right]$$

- The Fourier Transform of the dispersed image is the autocorrelation of τ(u,v,δ) , tridimensional
- Inversible for calculating δ (u,v) if aperture is non redundant
- if redundant: use Fienup's algorithm (Martinache, 2004)

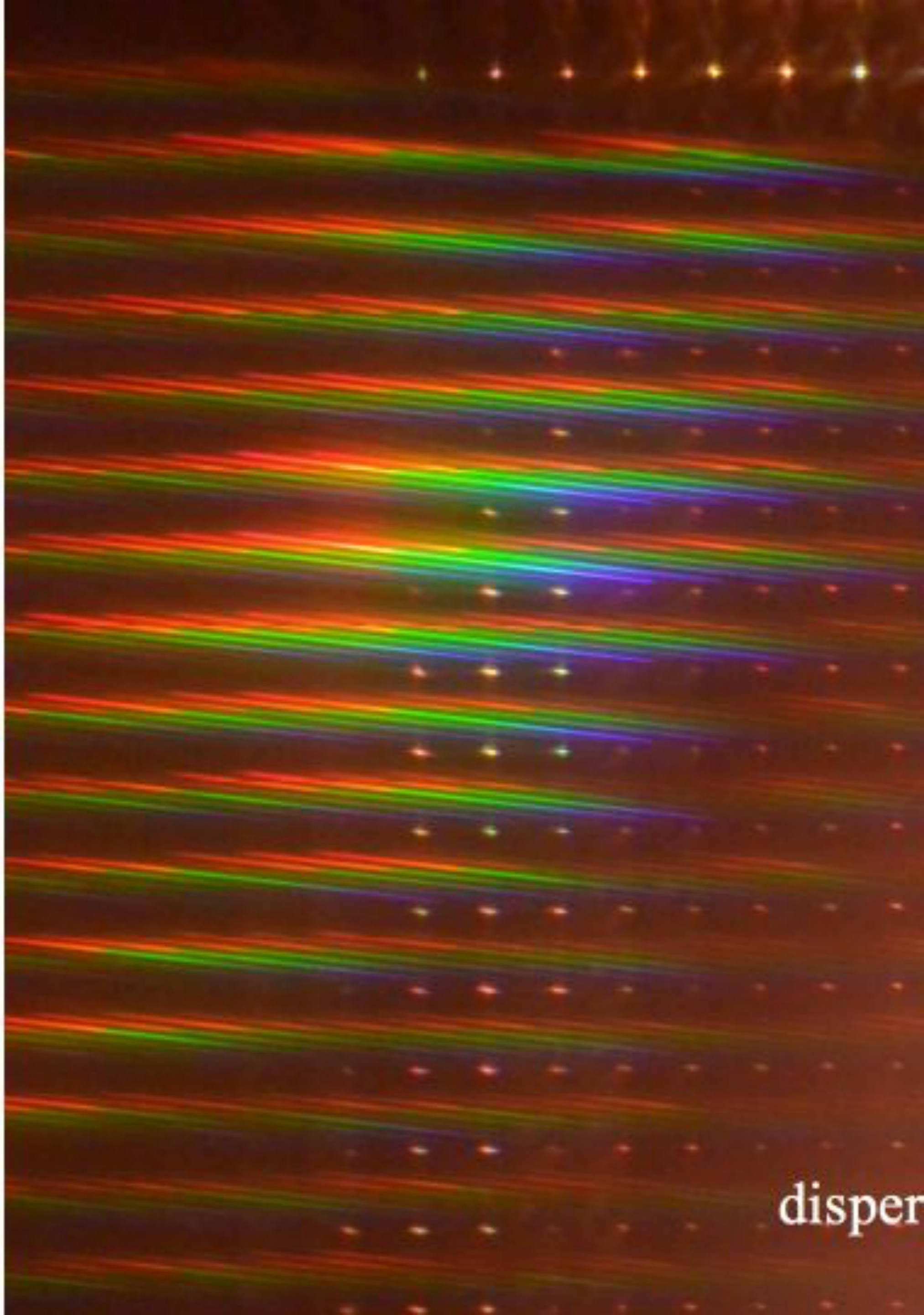


camera

0^{th} order

grism disperser with
speckle-sampler
microlens array

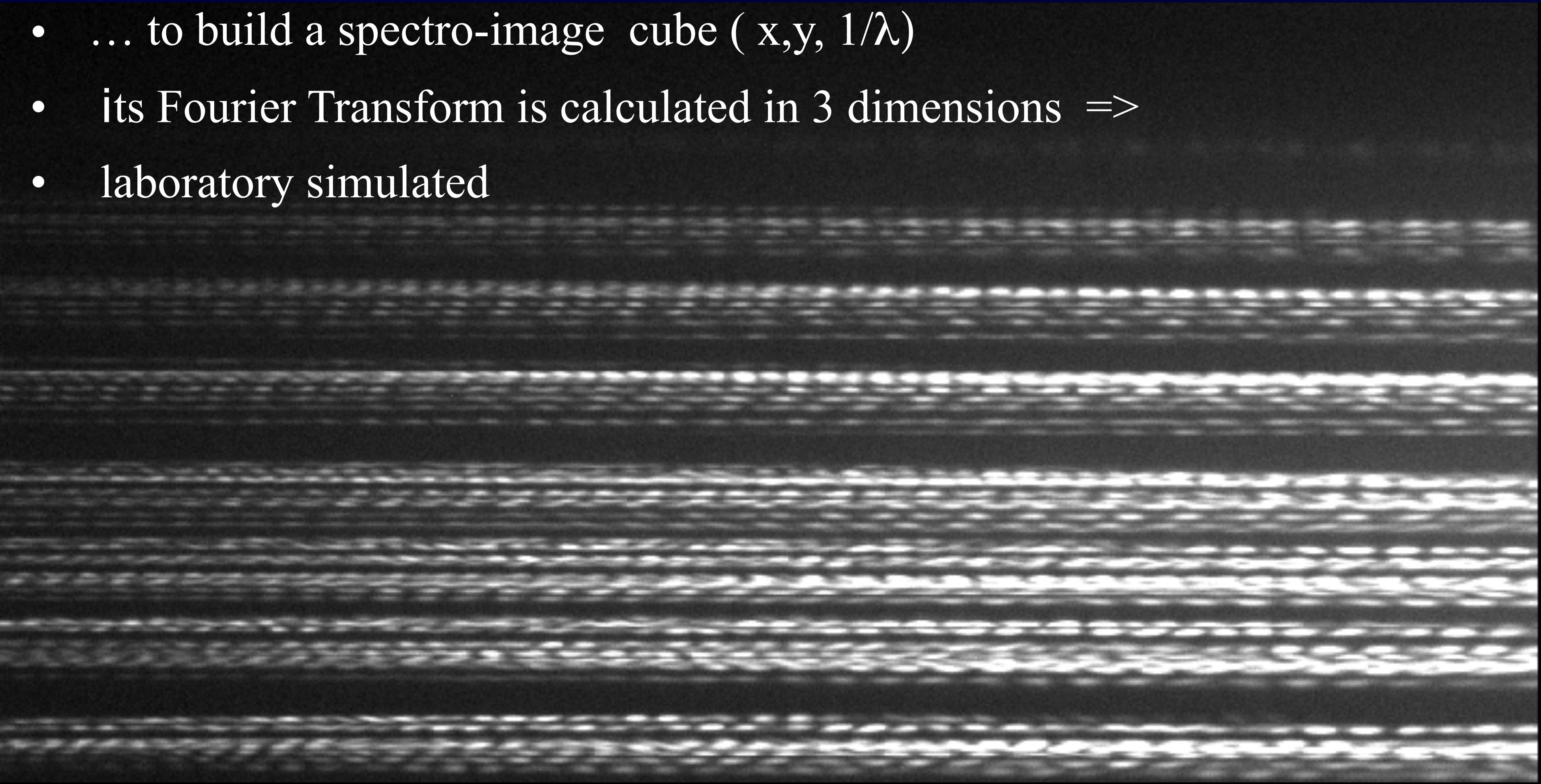
combined image,
speckled if not cophased



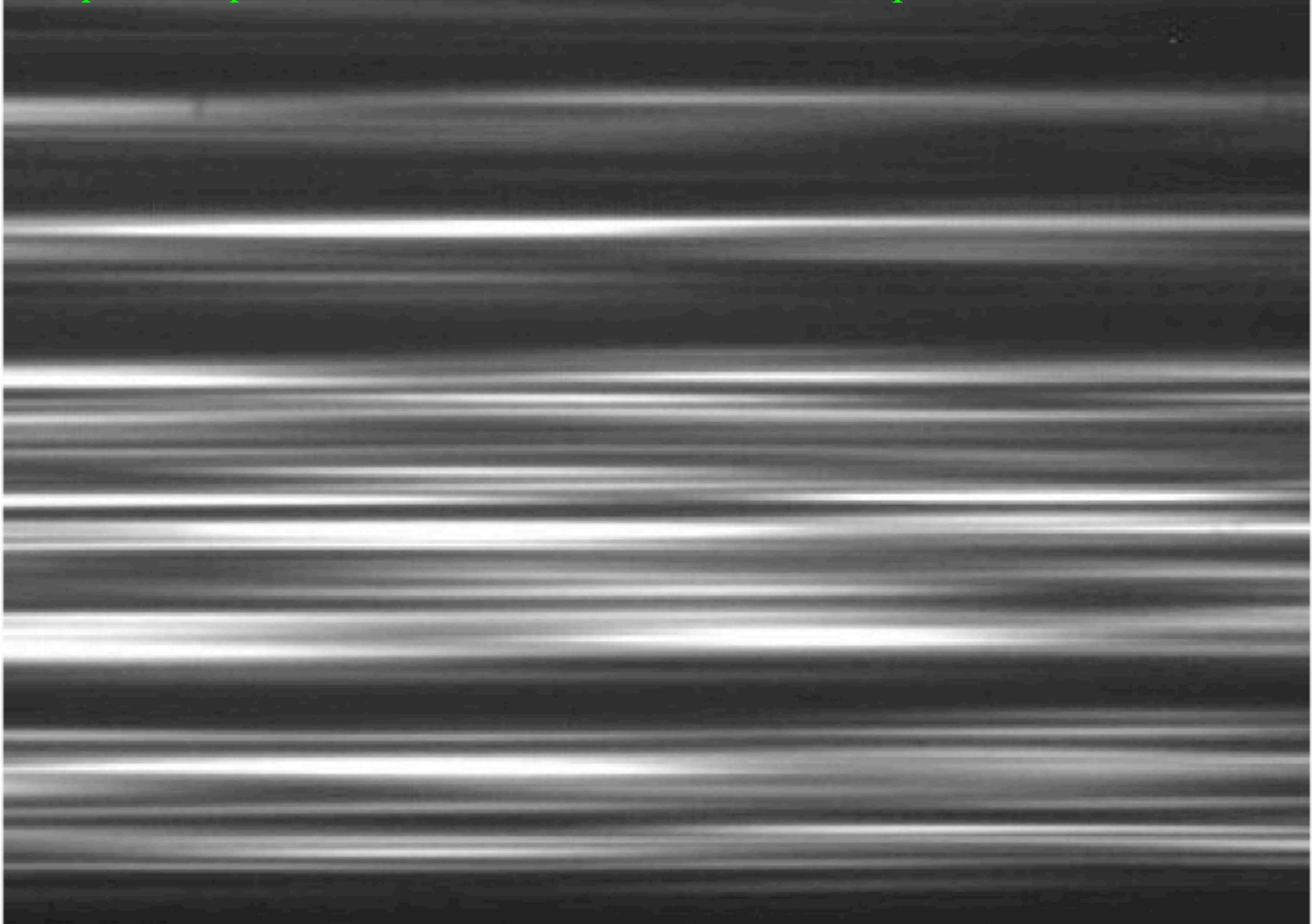
Dispersed-speckle piston sensor

(Borkowski, et al. , 2005)

- series of spectra from vertically adjacent speckles (red at right)
- … to build a spectro-image cube (x,y, 1/λ)
- its Fourier Transform is calculated in 3 dimensions =>
- laboratory simulated

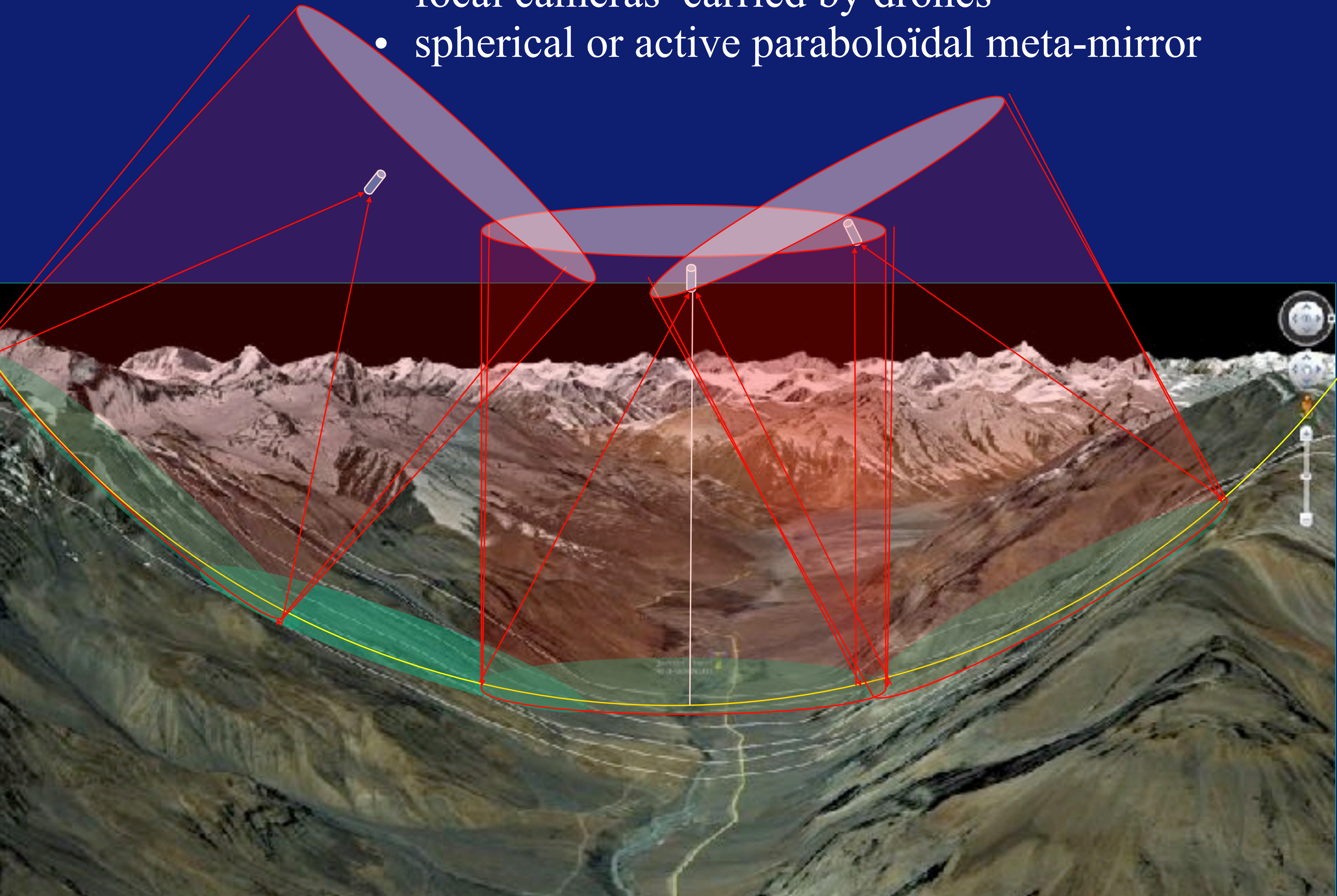


Dispersed speckle: lab simulation with smaller piston errors



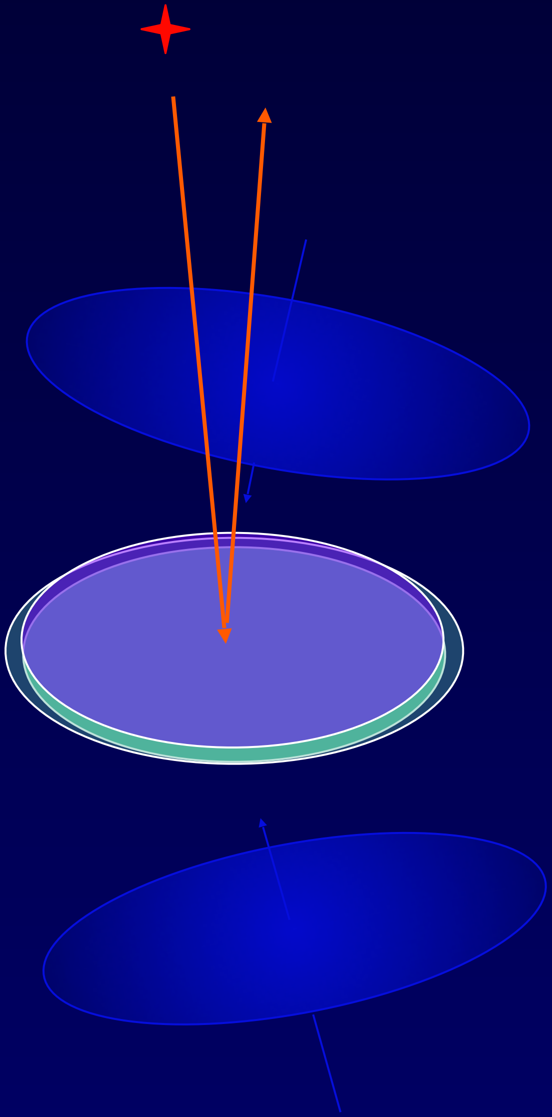
Extremely Large Hypertelescope (ELHyT) in Himalayan valley

- focal cameras carried by drones
- spherical or active paraboloïdal meta-mirror



For space: « Laser-Trapped Hypertelescope Flotilla »:

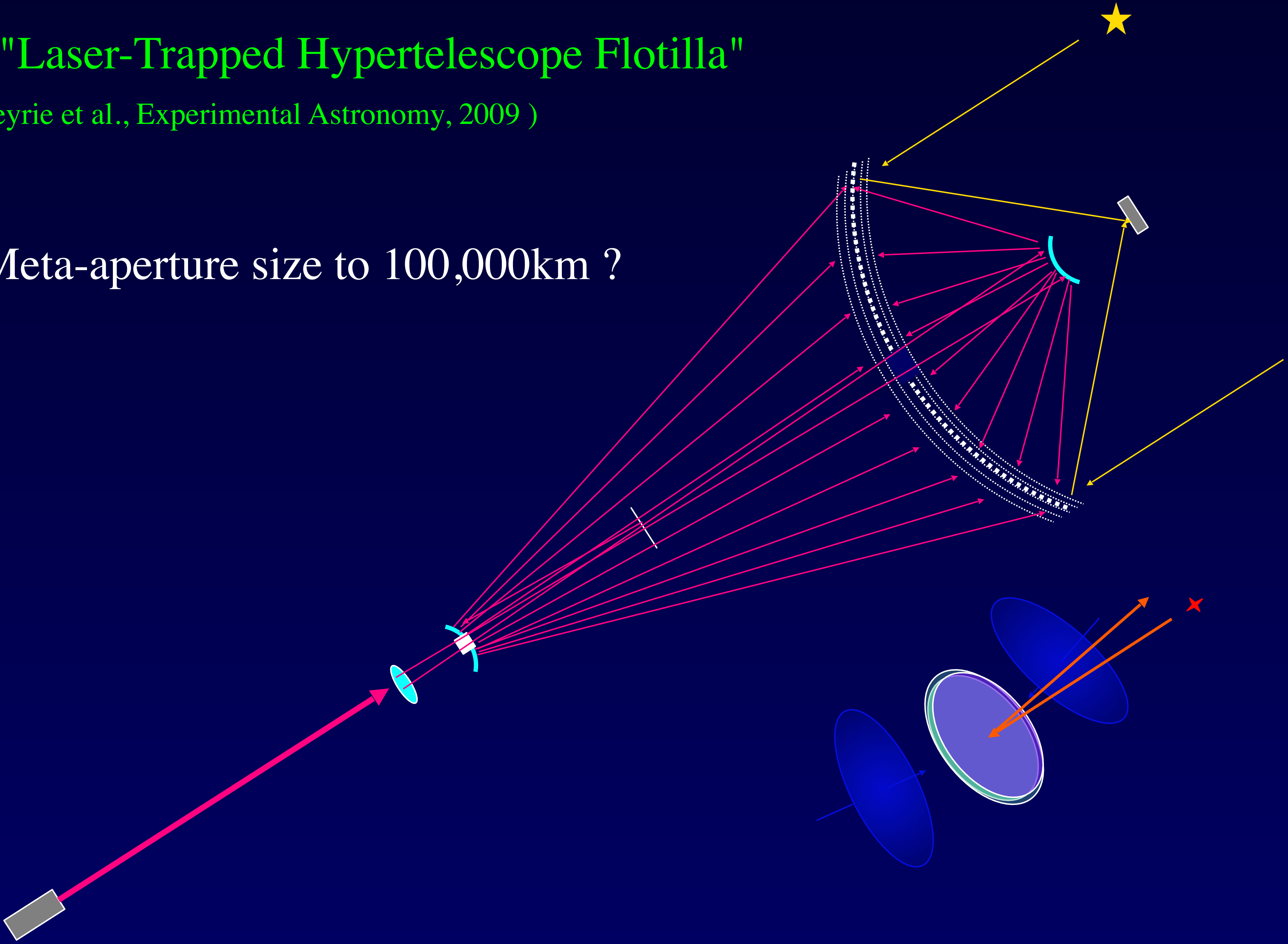
Pellicle Beam Splitter
produced by National
Photocolor Corp.



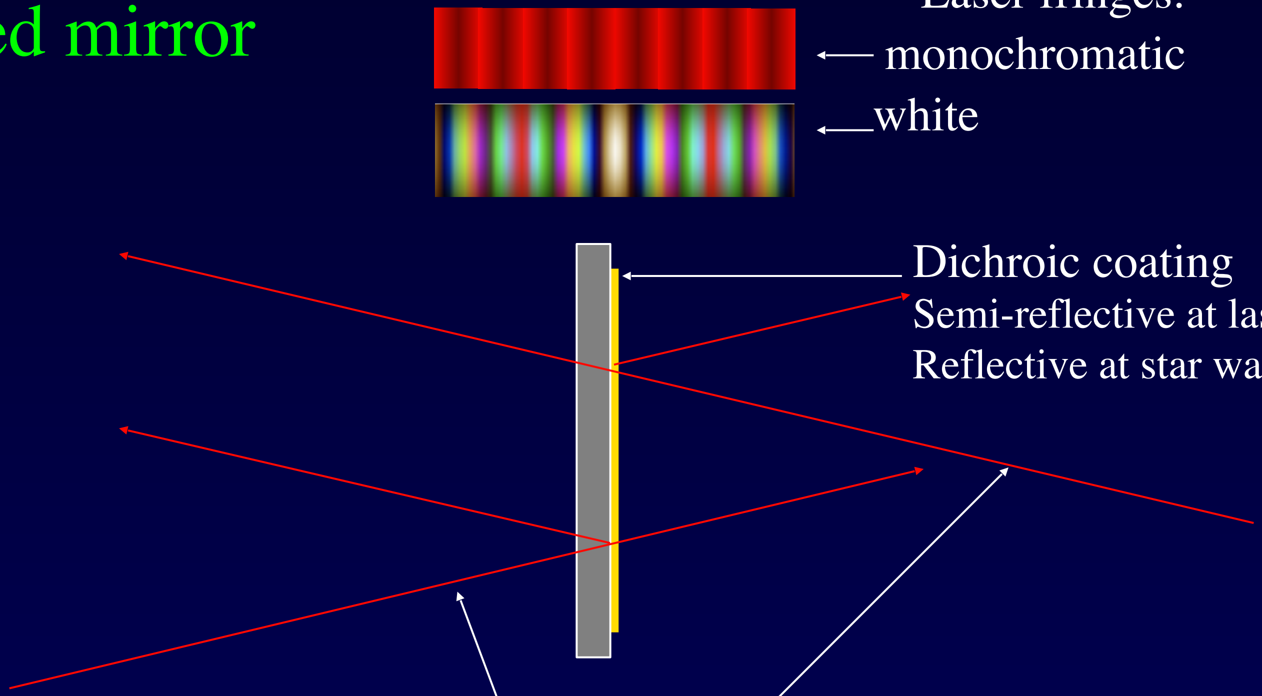
"Laser-Trapped Hypertelescope Flotilla"

(Labeyrie et al., Experimental Astronomy, 2009)

- Meta-aperture size to 100,000km ?



Laser-trapped mirror



Laser fringes:

monochromatic

white

Dichroic coating

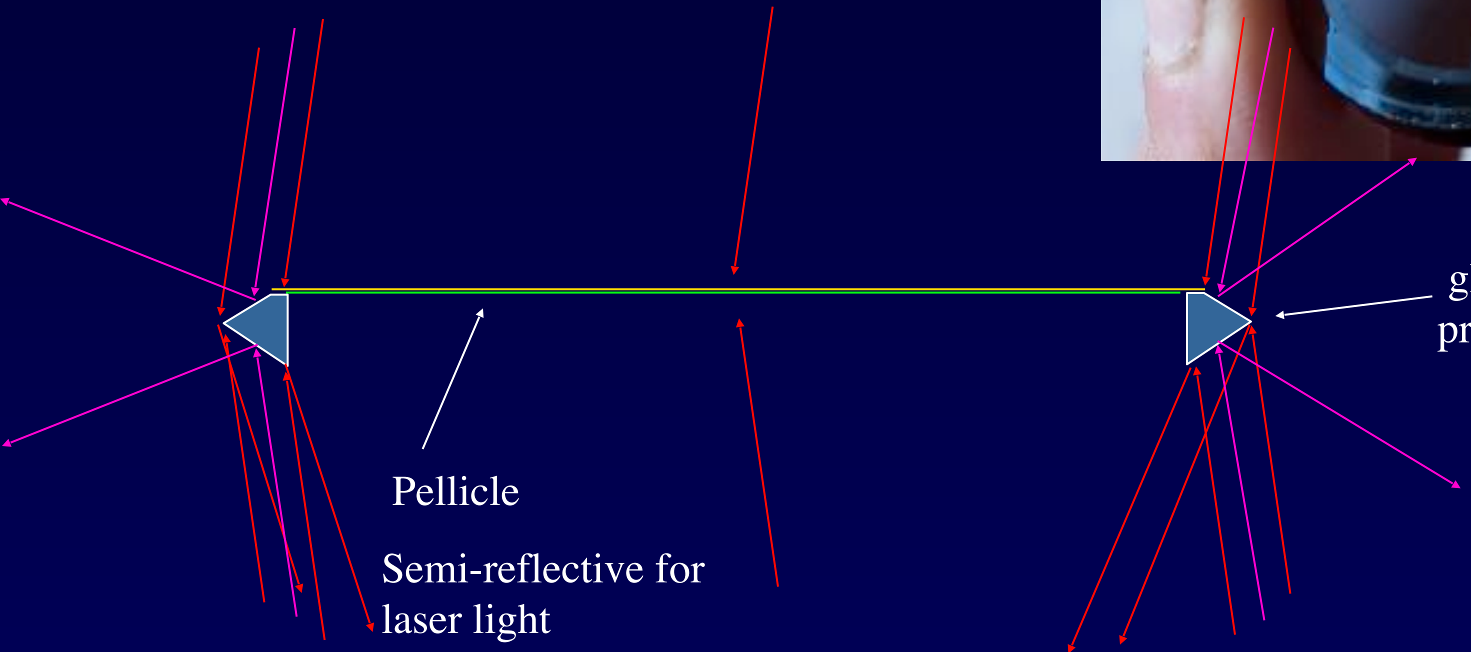
Semi-reflective at laser wavelengths

Reflective at star wavelengths

pair of incident laser beams, coherent and repeatedly blue-ward color-shifted

- interference of laser beams modulates the output intensities
- radiation pressure P/c reverses vs. position…
- … at $\lambda/4$ intervals
- cyclic blueward color shift for "pumping" toward central fringe

Pellicle beam-splitters for "Laser Trapped Hypertelescope"

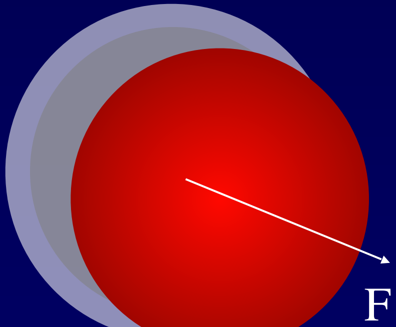


glass frame, prism profiled

Pellicle

Semi-reflective for laser light

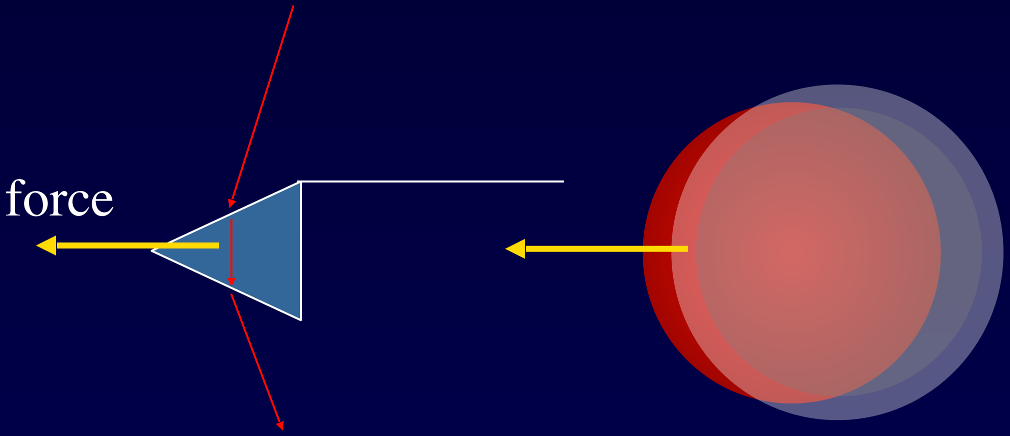
Reflective for star light



Self-centering in laser beam

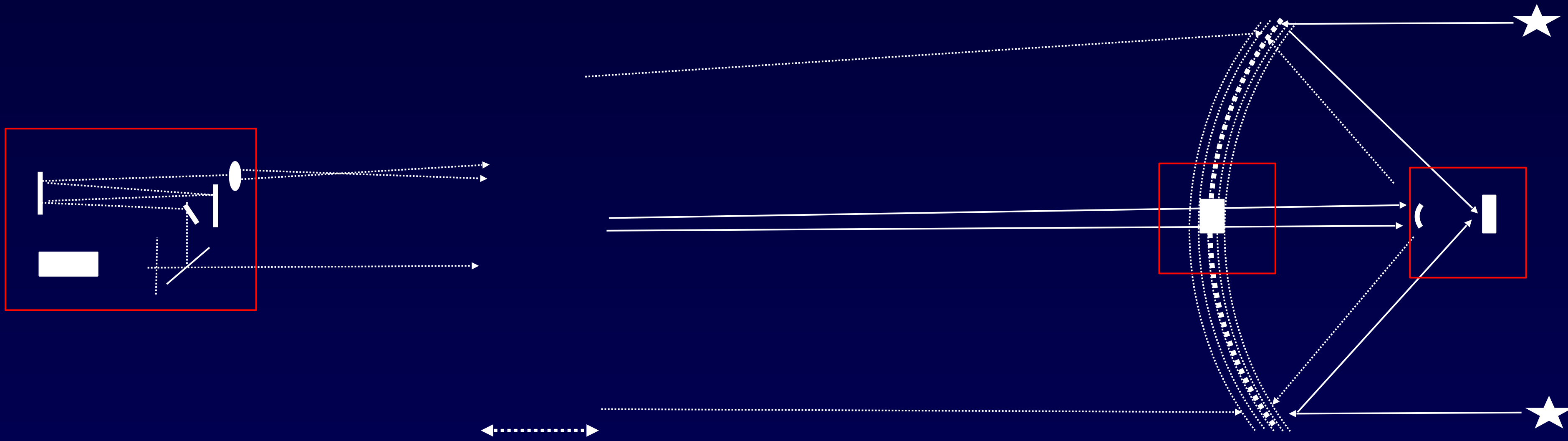
Self-centering in laser beam

through "laser tweezer" effect



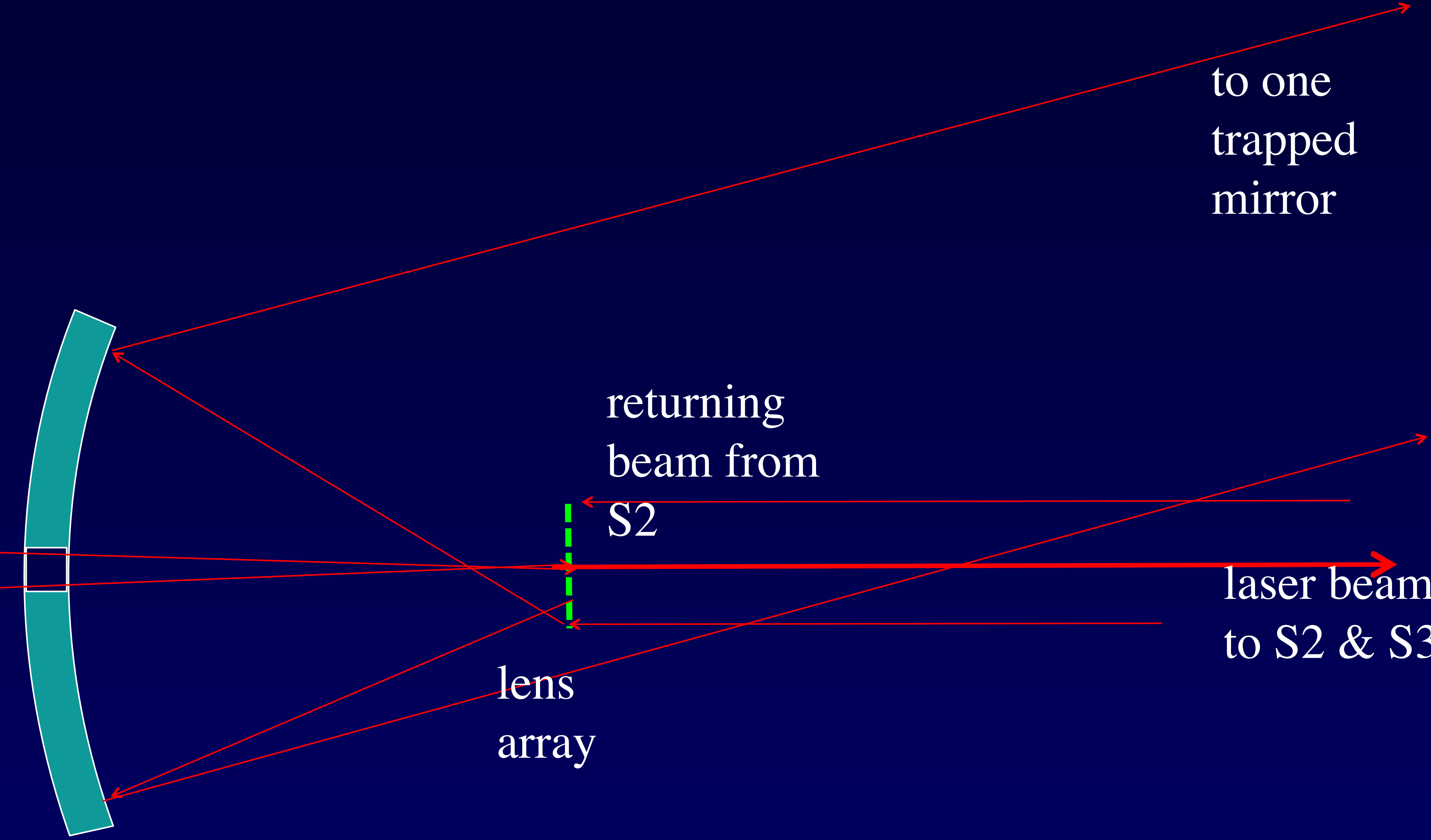
attitude also self-adjusting

Solution with only 2 or 3 herder spaceships



- Requires a delay line, or virtual delay line, attached to the laser
- deployable from same satellite as camera

Beam fanning optics



to one
trapped
mirror

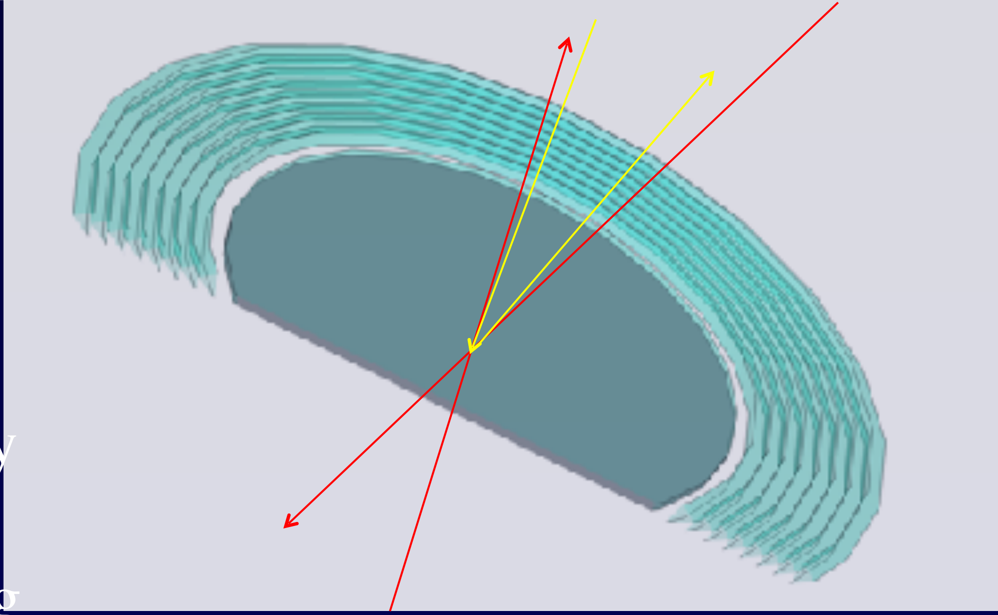
returning
beam from
S2

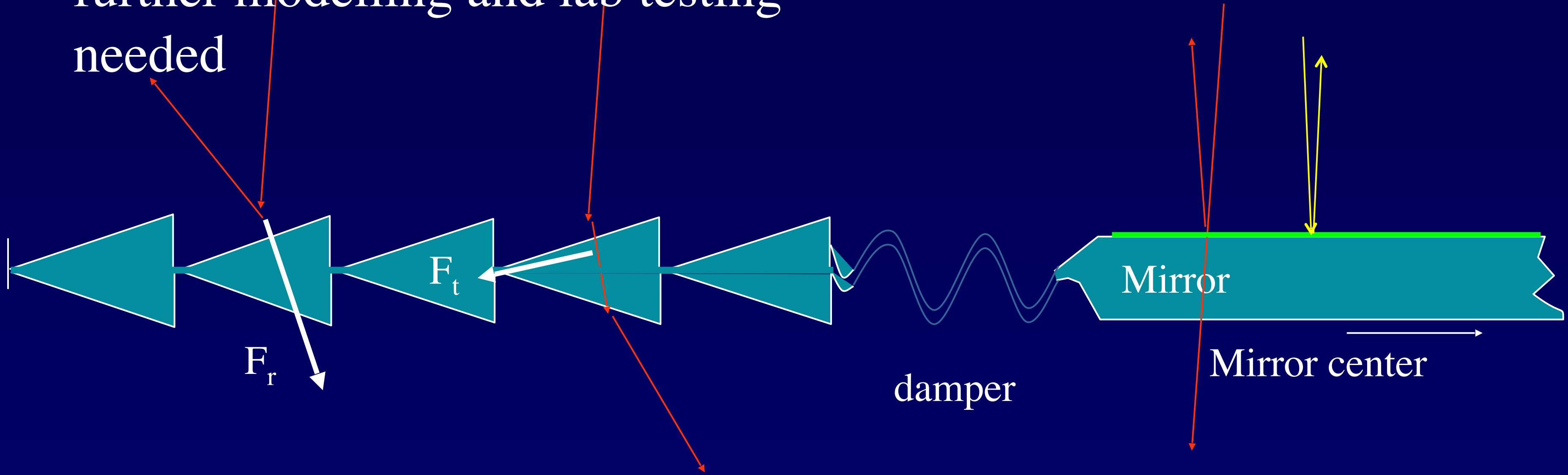
laser beam
to S2 & S3

lens
array

Laser-trapped mirror element

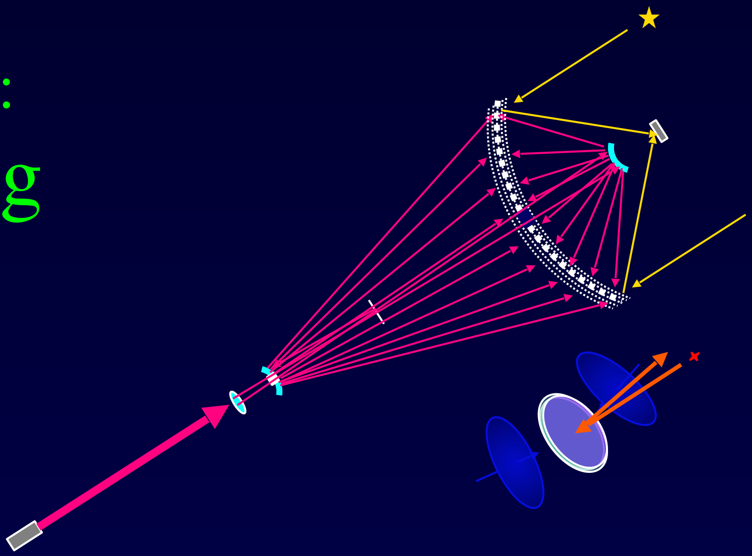
- coarse alignment by laser radiation pressure on peripheral Fresnel lens
    - laser deviation translates
    - laser reflection by prismatic facets controls the coarse attitude
- fine alignment and cophasing by standing waves
- further modelling and lab testing needed





Laser-Trapped Hypertelescope Flotilla:

Typical sizing



- Flotilla span : 1 kilometer
- Size of mirror elements: 30mm, mass 0.5 gram
- Laser power : 3mW per mirror
- max. acceleration: 0.02 micron.s-2
- Escape velocity of mirrors (axial) : 30nm/s
- Collecting area of 6.5m JWST matched with 40,000 mirrors

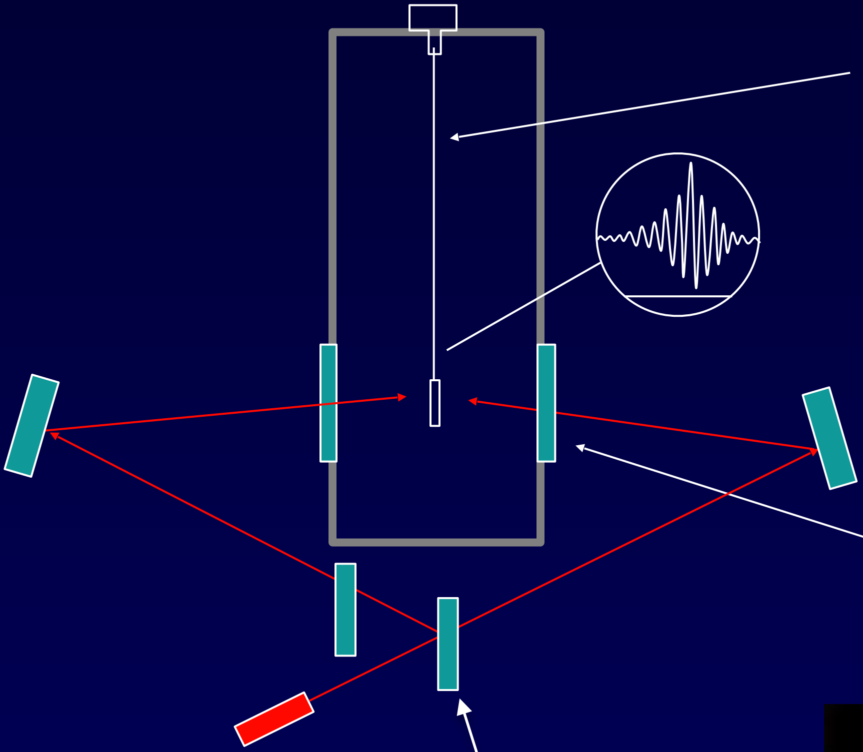
  … requiring a 120 Watt laser.
- Delivery package for mirrors: volume < 0.2 m3
- Deployment: with pair of directed laser beams

Operation at L2 in Earth penumbra

- Laser located in full sunlight, at edge of penumbra
- Full sky coverage in 6 months with continuous scan, transverse to Sun direction

Lab testing initiated in high vacuum , with torsion wire suspension

(Bortolozzo & Residori)



Torsion wire

Optical windows

beam splitter

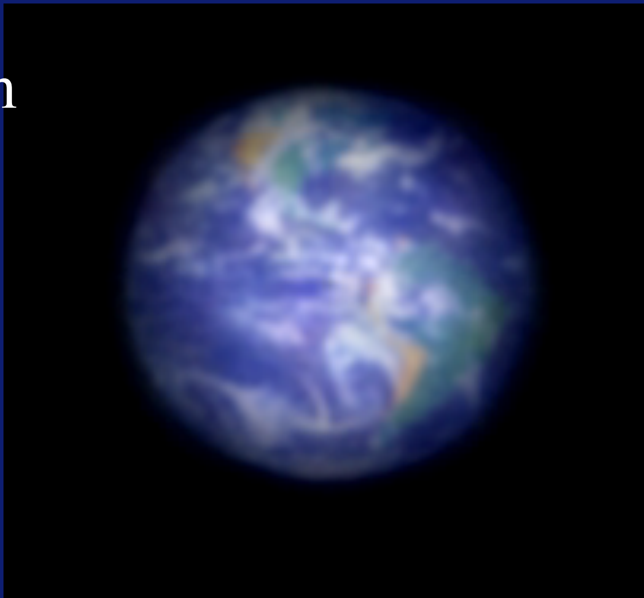
- magnetic levitation also proposed by P.Riaud

Hypertelescopes in space:

Searching for life on exoplanets

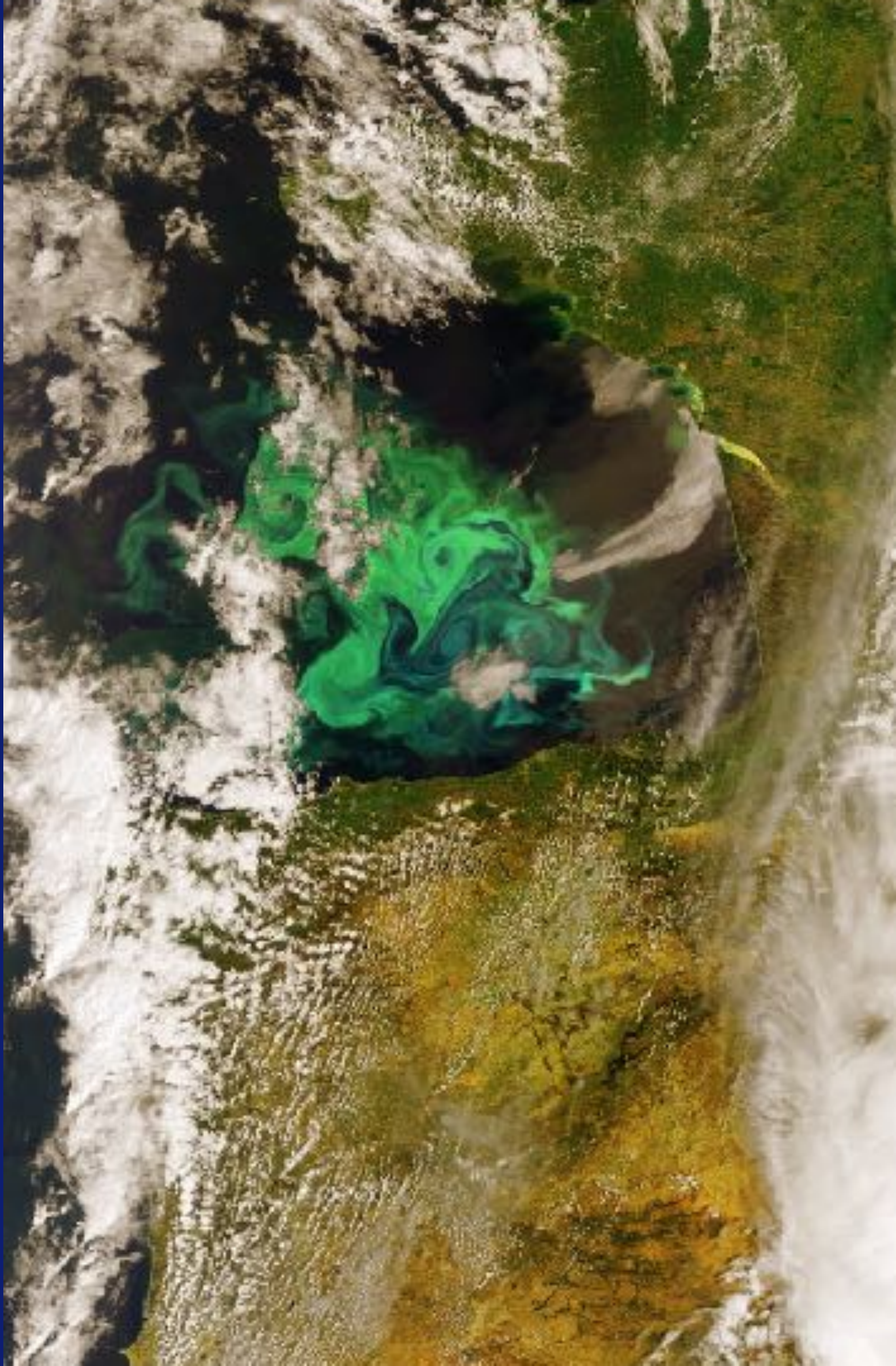
- global atmospheric spectroscopy is not conclusive
- multi-pixel spectro-imaging may detect seasonal changes analogous to the « indian summer »

simulated image of an exo-Earth at 3 pc
100km hypertelescope , with 150 apertures of 3m
enhanced contrast by subtracting a uniform level

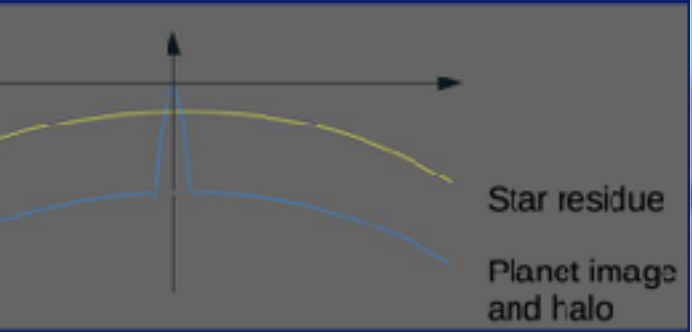


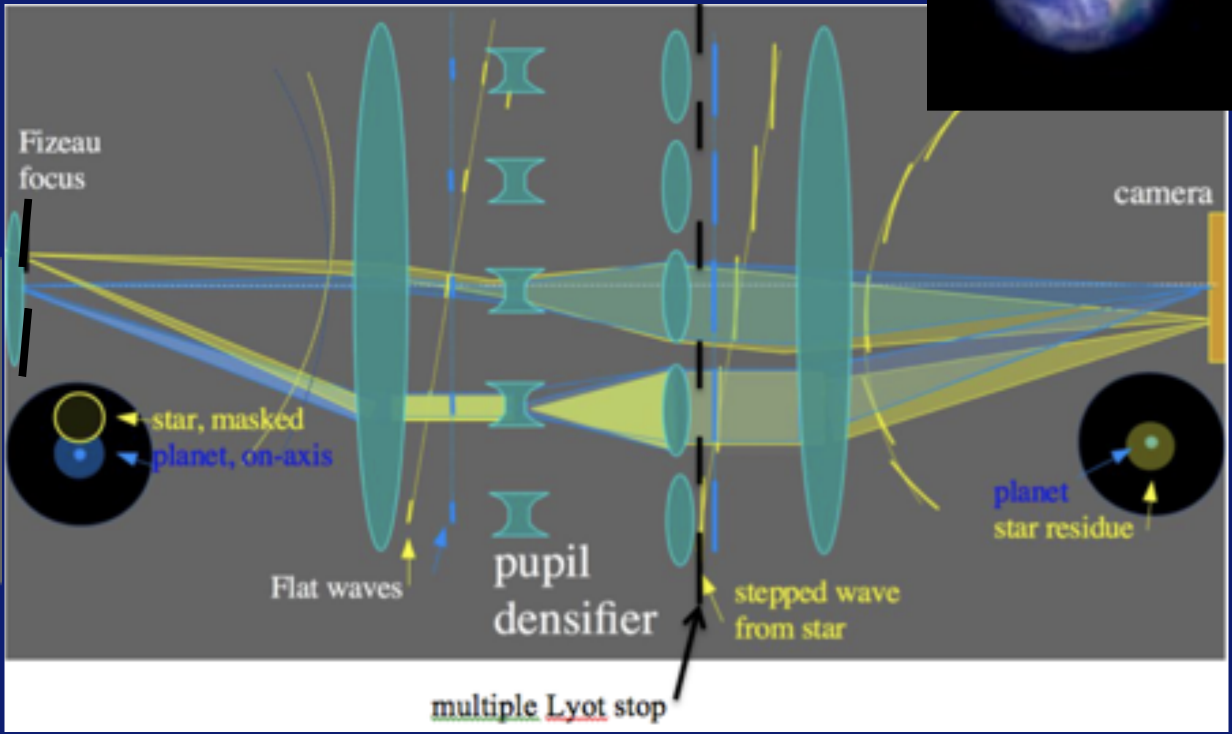
Signatures of exo-life

- Examples:
  - marine algal bloom
  - indian summer
- fast varying



Searching for life: exoplanet coronagraphy with the Exo-Earth Imager hypertelescope





Condition for multipixel imaging of exoplanet :

$$N > F_{star/planet} \; R_{planet} \; C$$

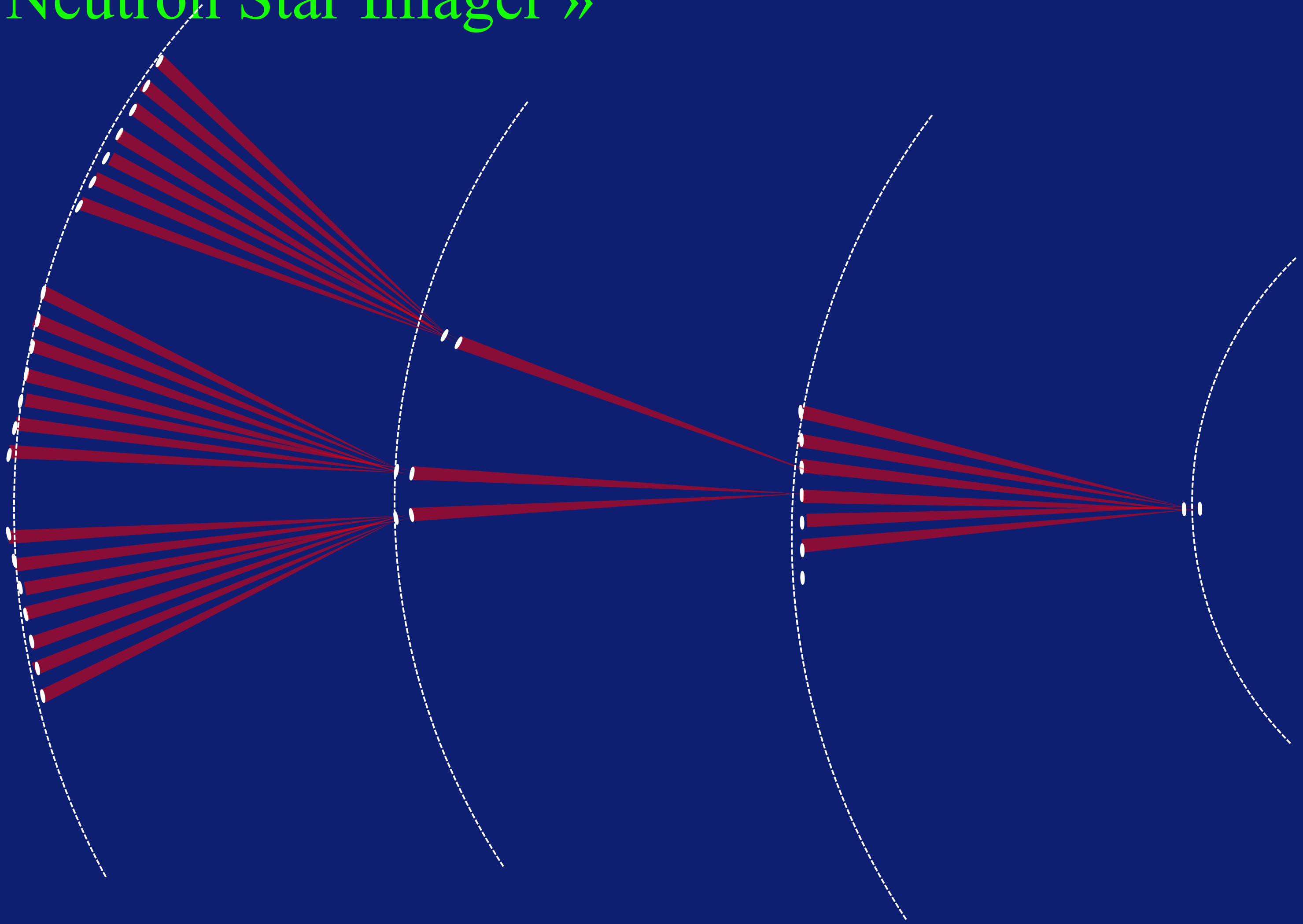
number of subapertures

resels in area

coronographic gain

Example: 1000 mirrors for 30x30 resels on exo-Earth 10^{-10} at 3pc, if coro gain = 10^{10}

100,000km flotilla with hierachical beam combiner for « Neutron Star Imager »



- reduces mirror sizes needed for primary array and beam combiners

Conclusions and future work

- space concepts for large hypertelescopes must be further validated…

  … through numerical simulation, together with dynamic behaviour of flotilla

  … and in the laboratory
- also testable in low Earth orbit (ISS ?)

- laser-trapping concept may provide a low-cost route toward large interferometer flotillas
- science: a large gain is expected with the numerous mirrors and large meta-aperture flotillas in space
- … even on very faint sources
- … coronagraphy also needed for multi-pixel imaging of exoplanets