stellar interferometry : an overview about basics

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stellar interferometry : an overview about basics

sections

- introduction : a problem raised
- science context and motivation
- few academic reminders
- basics for interferometry and aperture synthesis
- limitations and subsequent needs
- interferometers : principle, production, typology
- difficulties in real world (and some remedies)
- managing with data and some results
- quick-look at some alternative HAR methods
- nulling interferometry and coronagraphy

difficulties in real world

and some remedies

some difficulties

prime goal : reliability of data

accuracy	no bias
precision	small error bars
sensitivity	reaching faint visibilities
reproducibility	robust measures

three key points

stability : any departure from nominal degrades measure

calibration : mandatory compensation for degradations

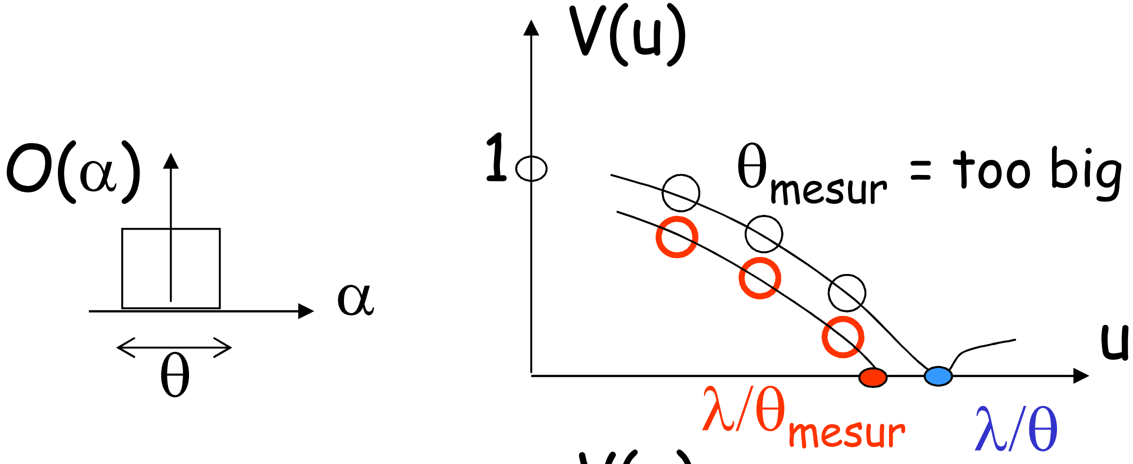
Signal to Noise Ratio : reliability of measures

several regime of difficulties

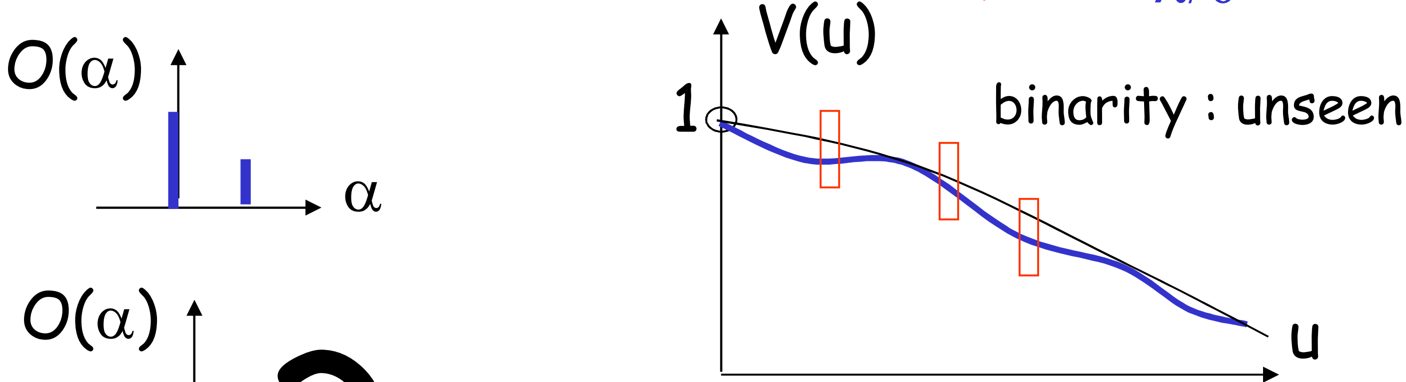
methodology, operation, data exploitation for science

illustrations

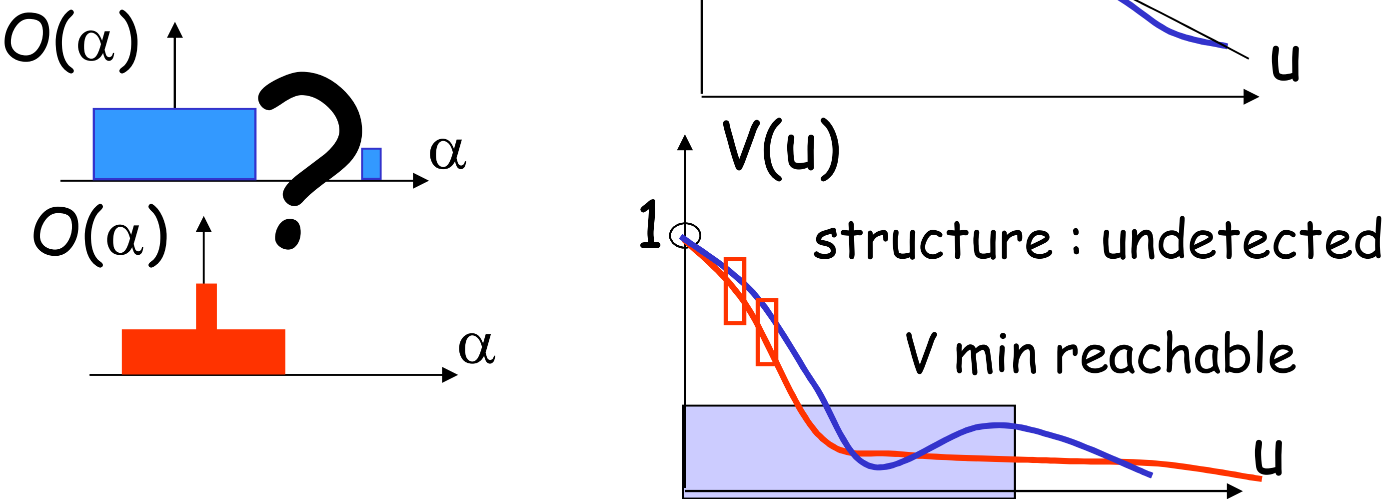
accuracy



precision



sensitivity



causes and nature of degradations in V measured

deterministic causes

non-nominal adjustment of configuration parameters

- alignements optiques, aberrations
- échantillonnage des franges (spatio-temporel)
- metrologie (maintien à zero, de la ddm)
- désequilibre photometrique ($I1 \neq I2$)

uncompensated effects of external causes

- refraction differentielle atmospherique
- conjugaison de pupilles (entrée / sortie)
- orientation des polarisations (vecteurs champs non \\)
- calage de la base

$V_{mesur} = q.V$
with $q < 1$
but q stable

random causes

any instability of instrumental parameters

But atmosphere is the main cause for ground-based

piston, tip-tilt, speckles

Here q is random,
specific processing (statistics) needed

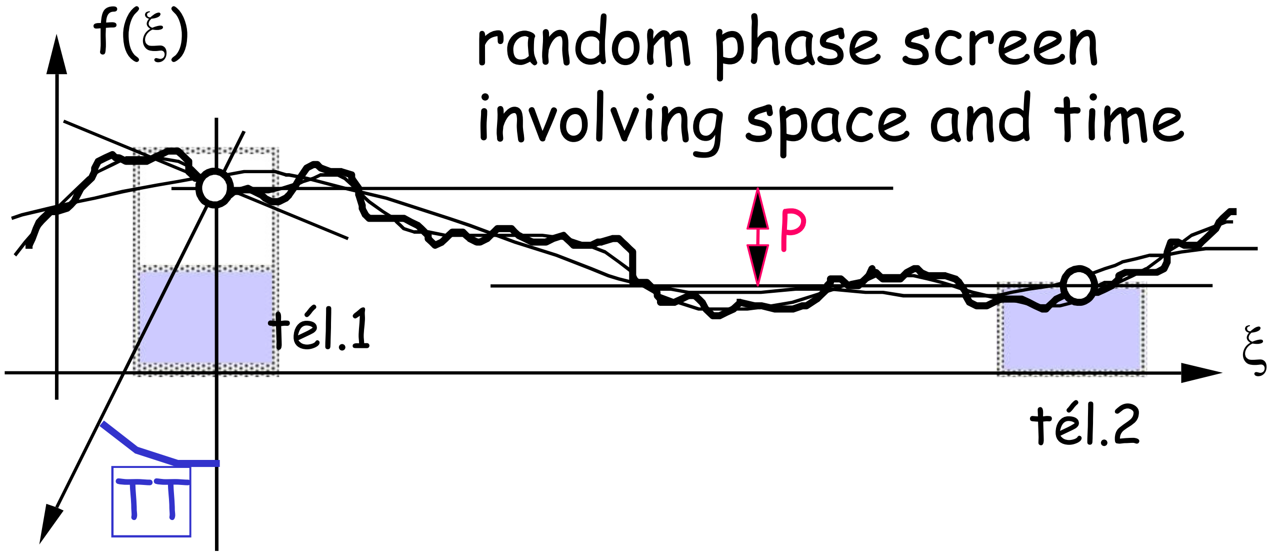
$V_{mesur} = q.V$
with $q < 1$
but q random

the major random cause : atmosphere

atmosphere !!

P : piston

phase noise
fringes
constantly and
randomly moving

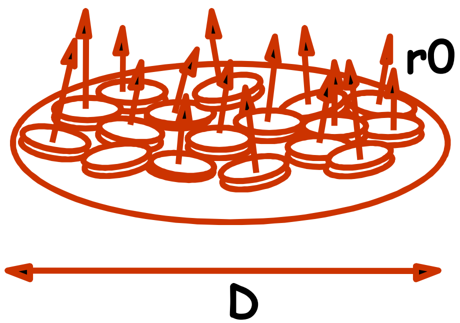


random phase screen
involving space and time

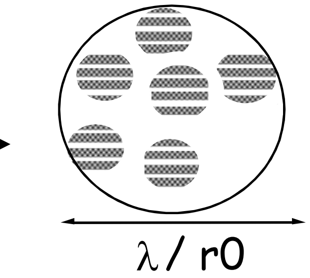
TT : tip-tilt

uncomplete superimposition of images

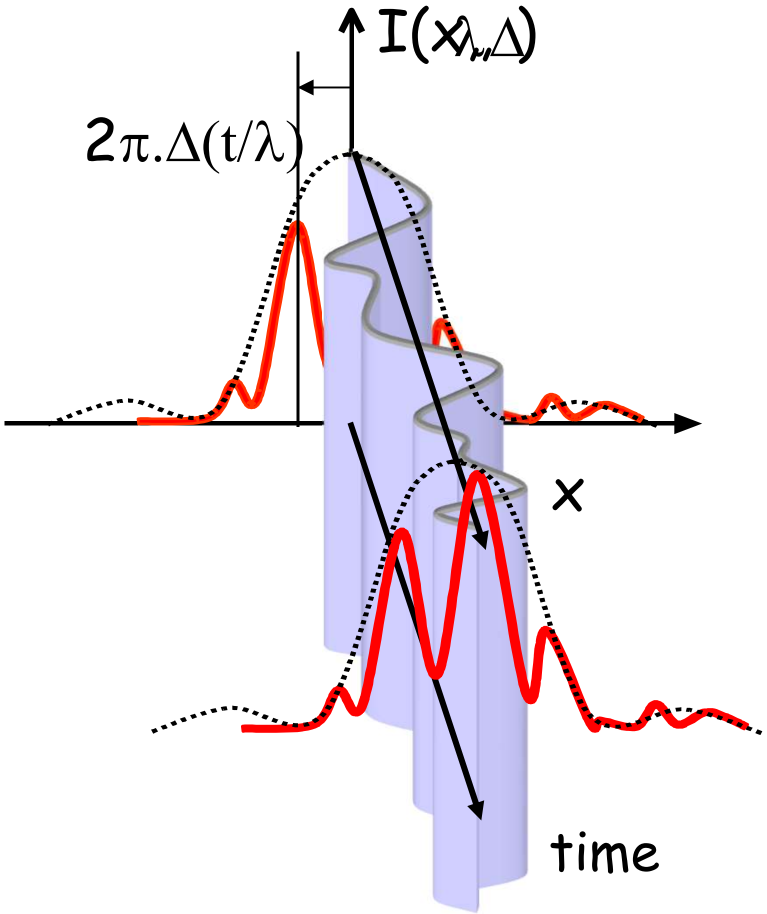
Speckles :

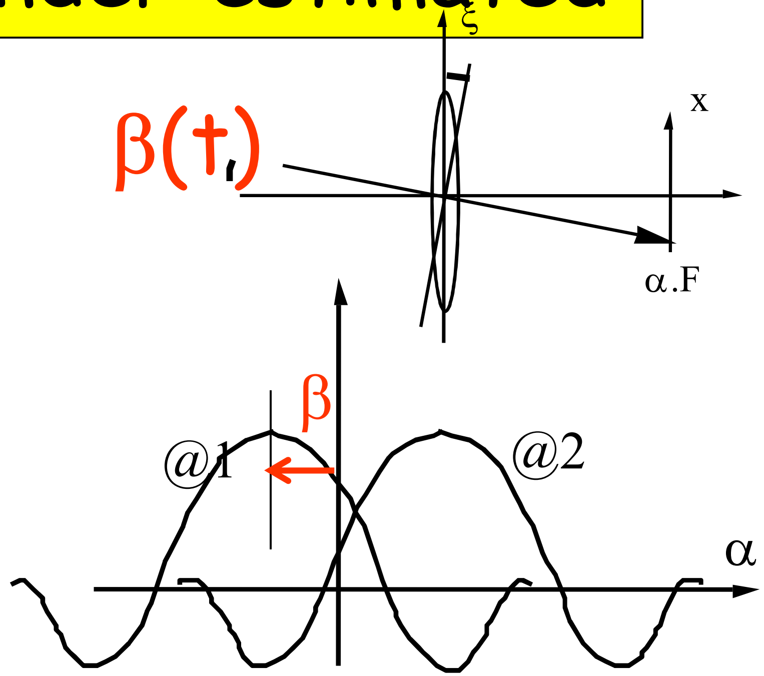


PSF rather like this
and change every ms

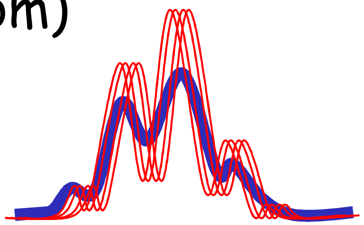


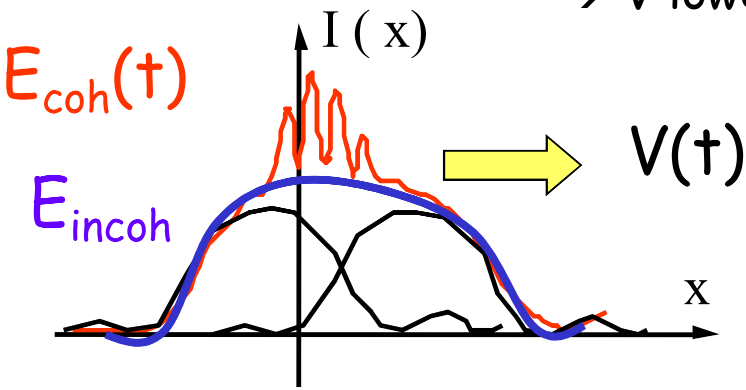
piston, tilt → V under-estimated





coherent energy reduced
incoherent energy unchanged
→ V lowered

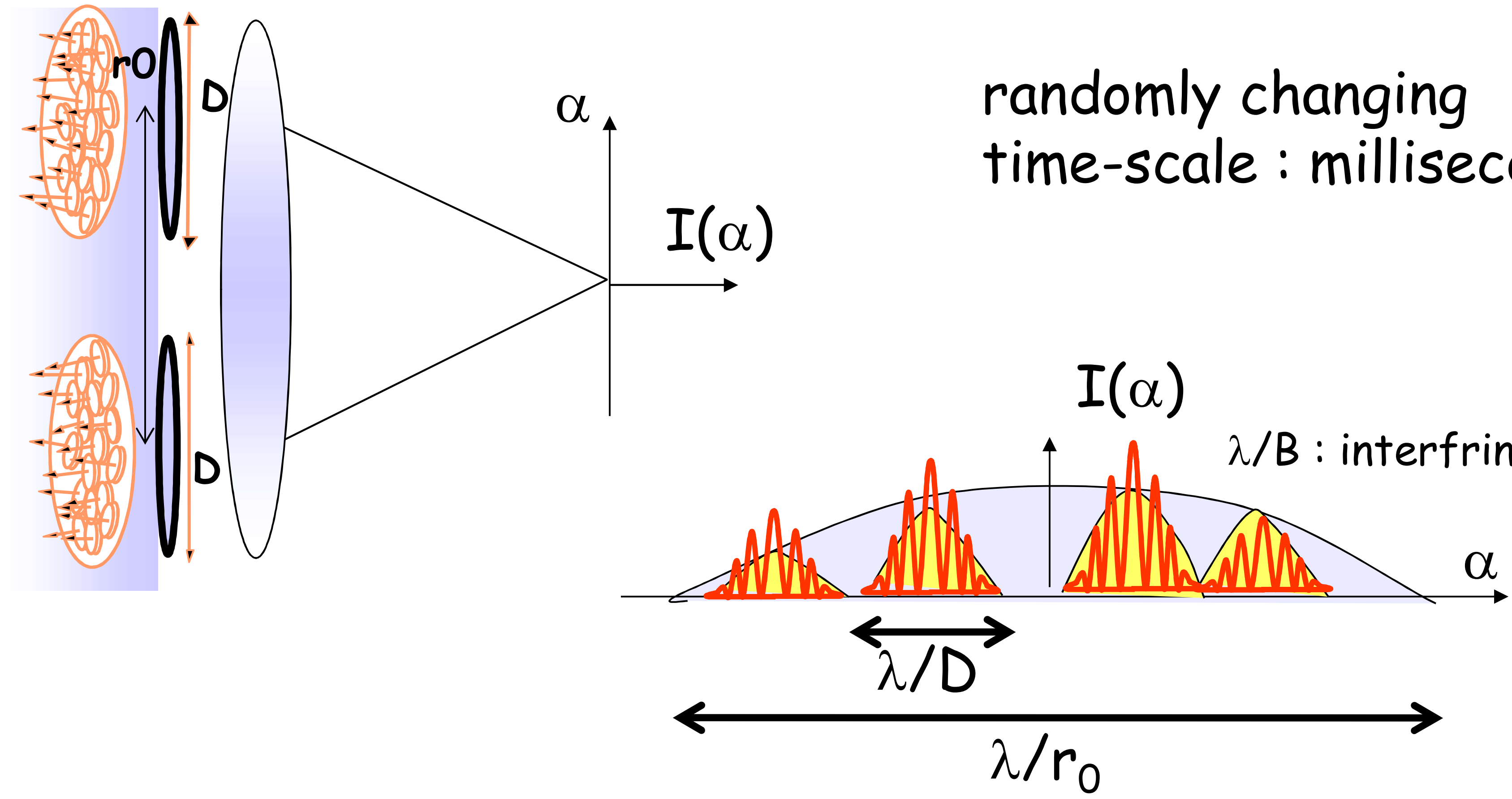




fringes motion (random)
during exposure
→blurring
→ V mader lower

illustration : intensity in presence of speckles

randomly changing
time-scale : millisecond



effects on observations

how to evaluate (characterize) the image quality (seeing) ?

two chartacteristic parameters and their connection to space and time

r_0 : average dimension of a plane area within the wavefront
(plane is not necesseraly horizontal)

τ_0 : typical duration of a state of the wavefront

larger value → better image quality

they depend on λ (larger λ → better) **convention : r0 et τ0 concernent 0.55 μm**

typical values in the visible :

r_0 5 cm à 20 cm

τ_0 1 à 10 msec

$$r_0(\lambda) = r_0 \cdot \left[\frac{\lambda}{0.55\mu m}\right]^{\frac{6}{5}}$$

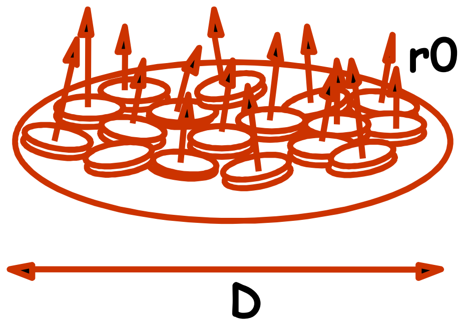
$$\tau_0(\lambda) = \tau_0 \cdot \left[\frac{\lambda}{0.55\ \mu m}\right]^{\frac{6}{5}}$$

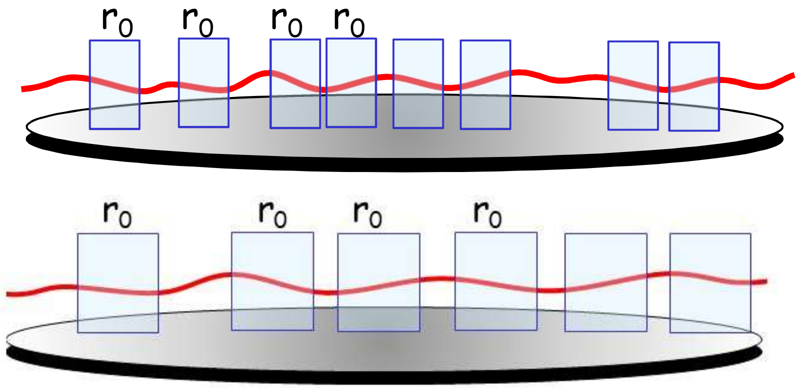
deendancy on z (zenithal angle) : far from zenith → less good

$$r_0(z) = r_0 \cdot [\cos z]^{3/5} \qquad \tau_0(z) = \tau_0 \cdot [\cos z]^{3/5}$$

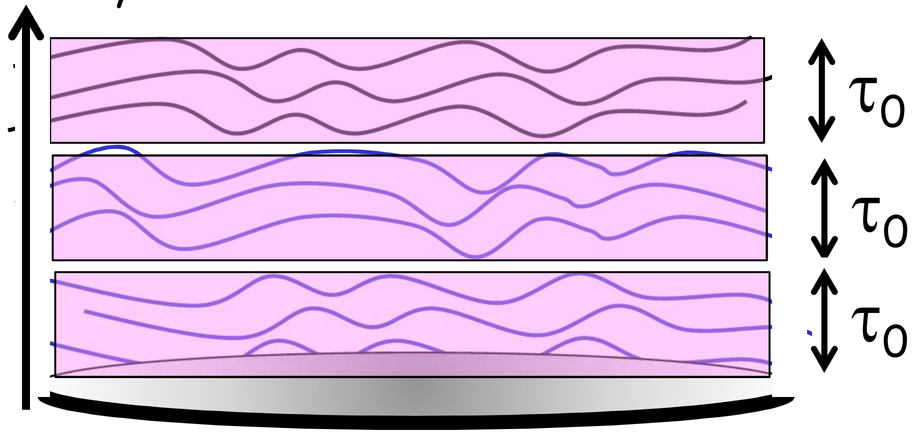
tentative graphic illustration
parameters ssociated to the « seeing » (state of turbulence)

spatial characterization
(also said « coherence length of the wavefront »)





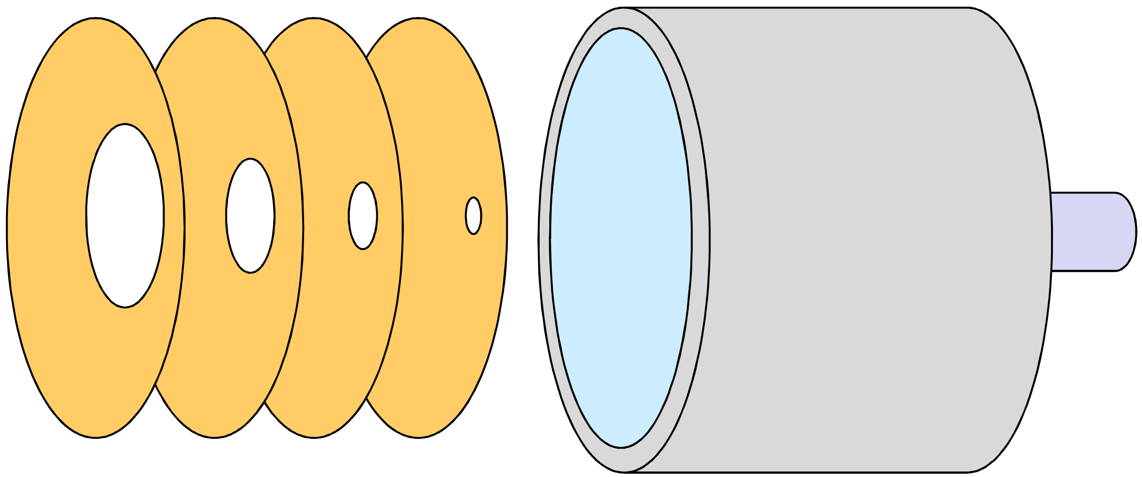
temporal characterization
(also said « coherence time of the wavefront »)
the « memory » of the wavefront



coarse estimation of r_0

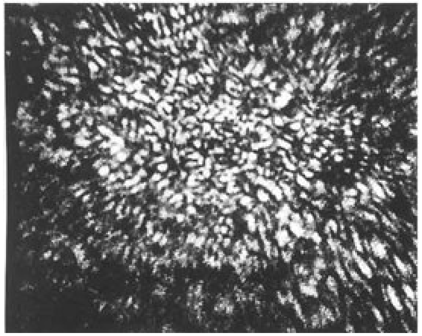
several approaches and dedicated software
but also a « rustic' method the one of using a set of holes placed on top of telescope :

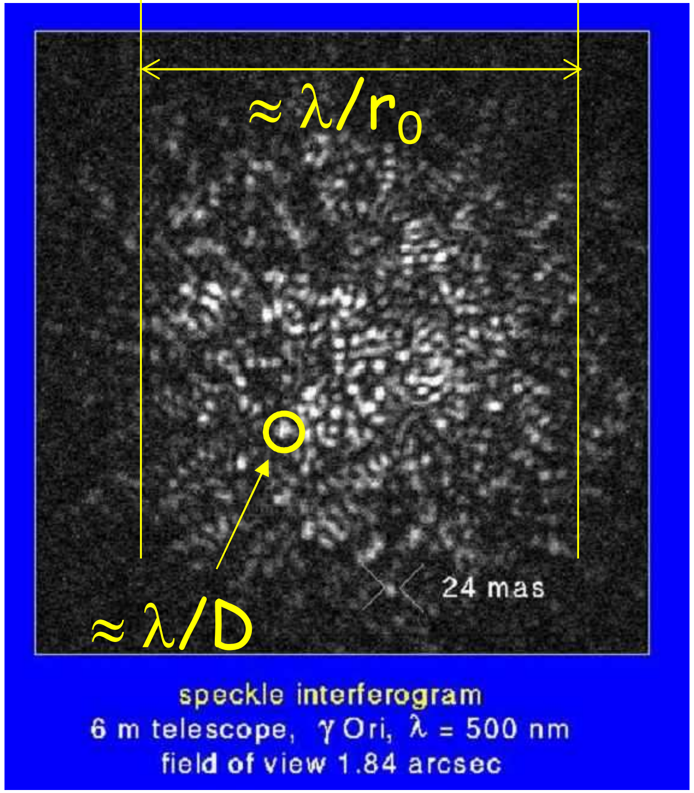
successive observations with increasing diameter

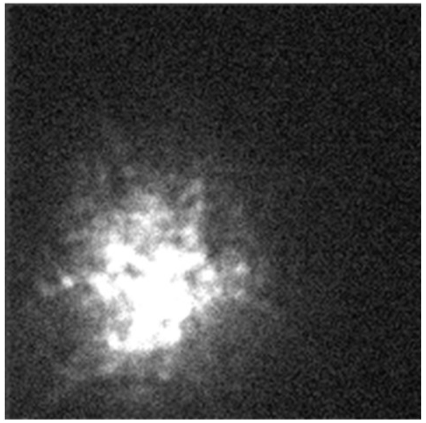


when increasing diameter the focal image
the expected Airy pattern is progressively degraded
The last diameter allowing an Airy structure gives an estimate of r_0

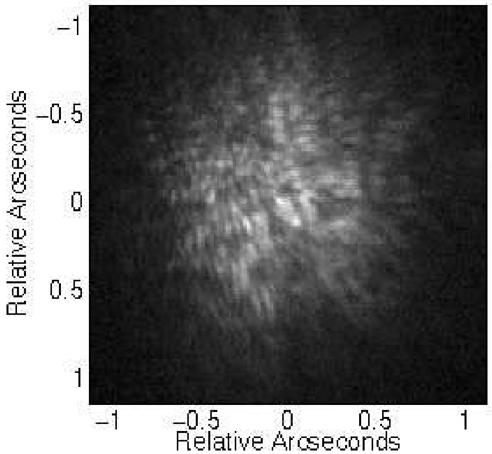
illustration speckles (clic on image up,right

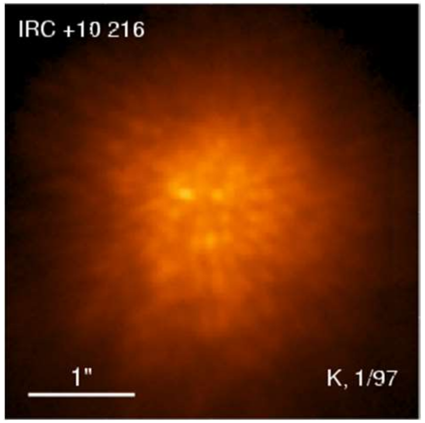






Typical speckle image of a 0.2" binary star





degradations "live"

faint urbulence

typical turbulence

Airy structure yet present

image is moving as a whole

Airy structure destroyed
and speckle pattern is formed

fighting against adverse effects of turbulence

- sero-loop to correct for tilt and piston
- adaptive optics (reduction/elimination of speckles)
- monomode optic fibers (total cleaning of wavefront)
- rely on space-based instruments
  (but from proposal to launch
  it is about 20 years and gigaeuros)

- .....??

degradation of measured visibility

the measured visibility is n ot the true (astrophysic) visibility
bad estimation of spatial spectrum

each cause "k" of degradation is traced by a degradation factor "q_k"
varying between 0 and 1 (never 1,actually)

a relation must be considerer :

$$V_{measure} = (q_1.q_2.....q_K).\ V_{true}$$

$$V_{measure} = \text{(response to visibility)}.V_{true}$$

challenge to face :
V_{true} must be recovered and the q_k
must be made as close as possible to 1

Note :
the "response to visibility" varies with time (observing conditions unstabilities)
and not only because of atmosphere

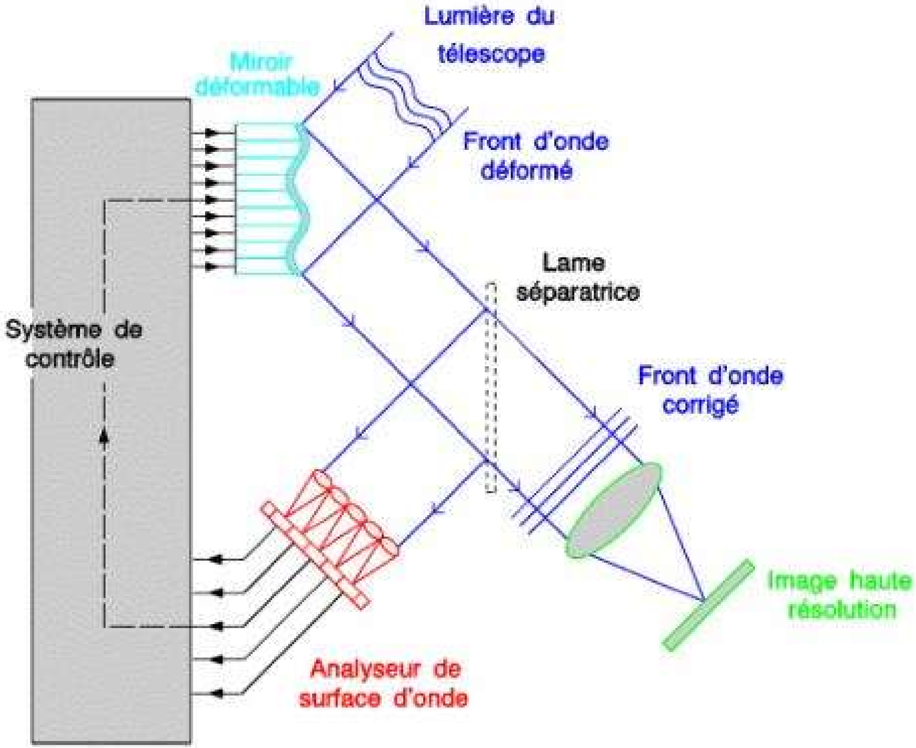
some remedies

calibration of data

adaptive optics

fiber linked telescopes

optique adaptative



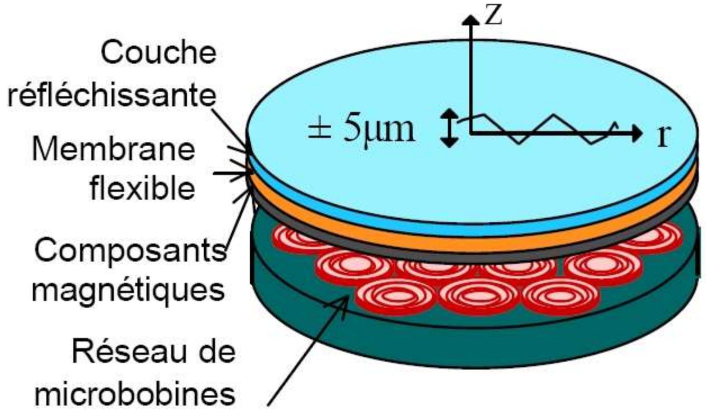
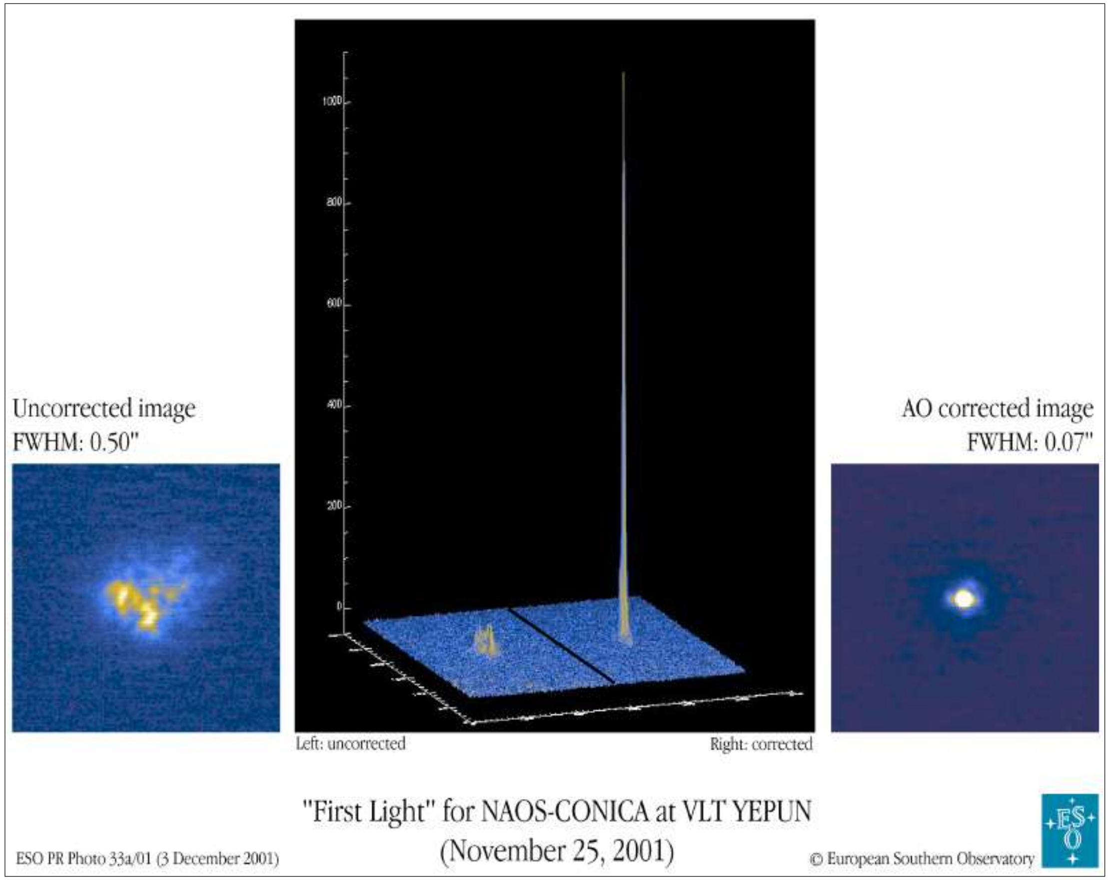


Figure 18 : Schéma de principe du miroir déformable magnétique à membrane souple.

adaptative optics NACO VLT



VLT at Paranal

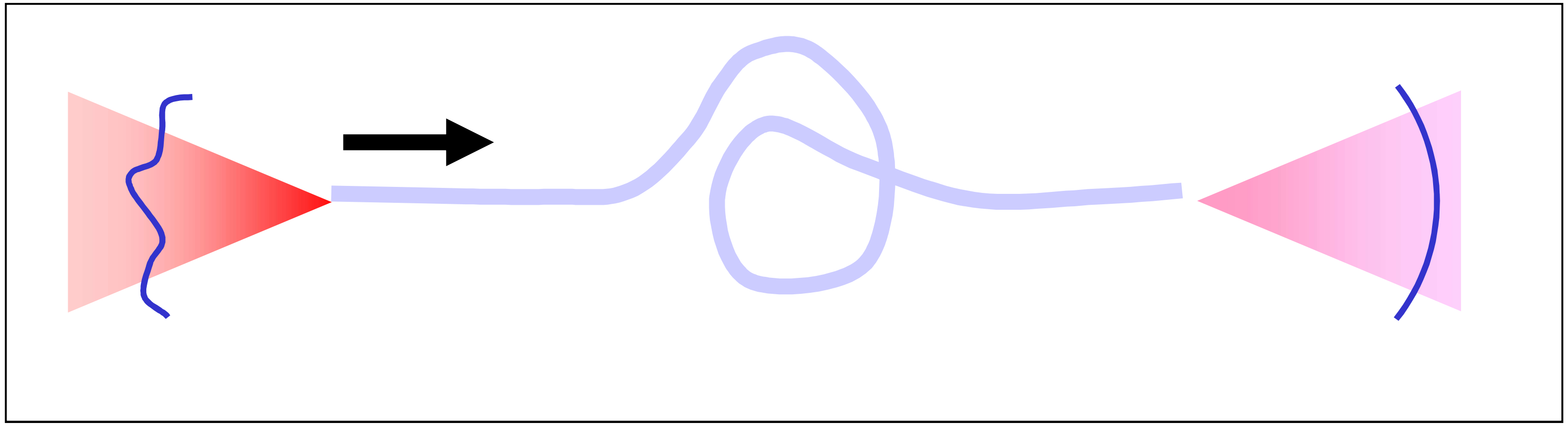
ESO PR Photo 43a/99 (8 December 1999) © European Southern Obse

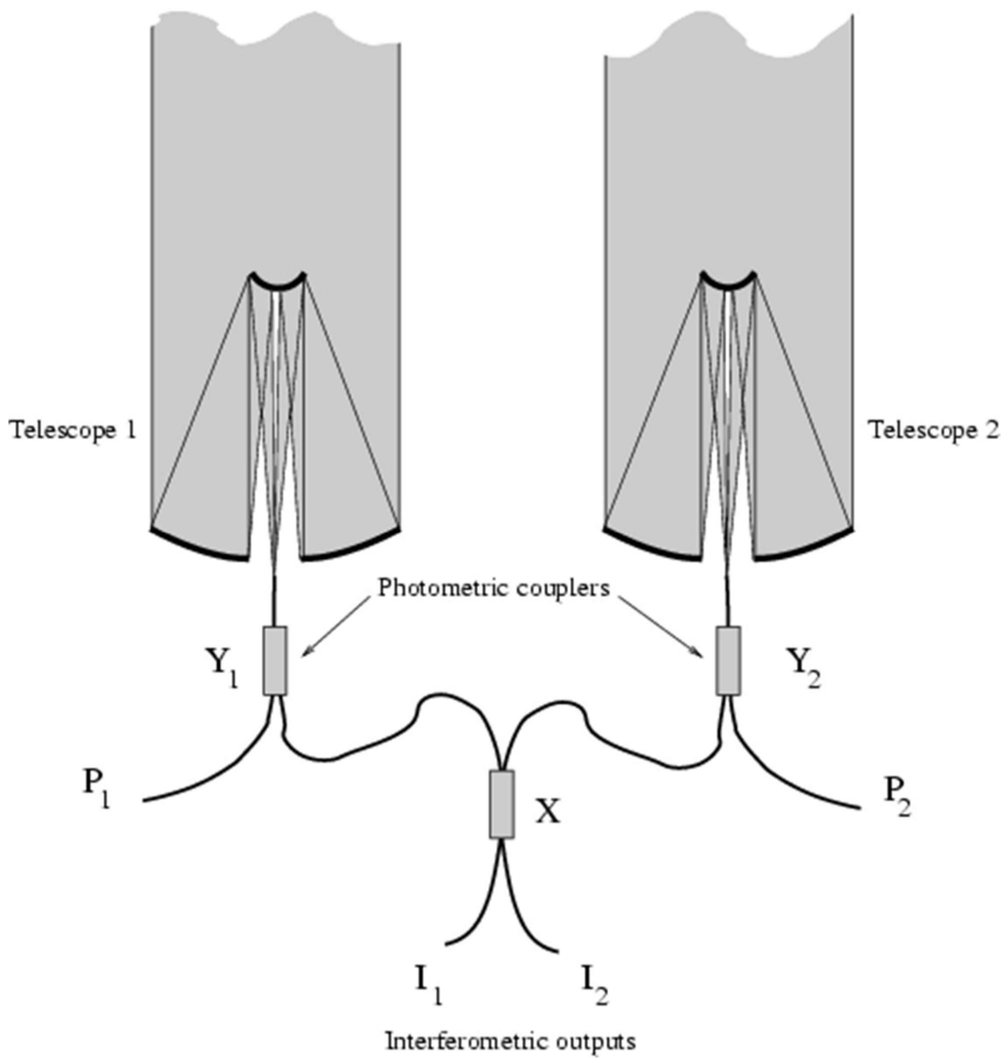
monomode optics fibers

even with adaptive optics wavefronts have residual distorsions

it is possible to make the wavefront quasi perfect in shape
by sending the beams through monomode optics fibers
that performs spatial filtering

the price is "less photons" but the ones you keep are
the "efficiently interfering" photons




Telescope 1
Telescope 2
Photometric couplers
Y1
Y2
P1
P2
X
I1
I2
Interferometric outputs

imaging..... ?

interferometric imaging requires to come back from a sampled u-v plane to a brightness distribution in other words : from Fourier space to normal space

the currently used approach still is model-fitting
(exceptions for binaries)
individual phases would be of great help
phase closure also is indirectly helping

the straight way (inverse Fourier from sampled spectrum) is difficult and unsafe in optical interferometry (sparse sampling, uncertainties on visibility, uncomplete phase information, "non-regular data (?)", ...)

this approach is somewhat claimed to be an "ill-posed inverse problem"

radio interferometrists have done much work in image recovery (theory and results) and have achieved great success with VLA

supersynthesis u-v coverage

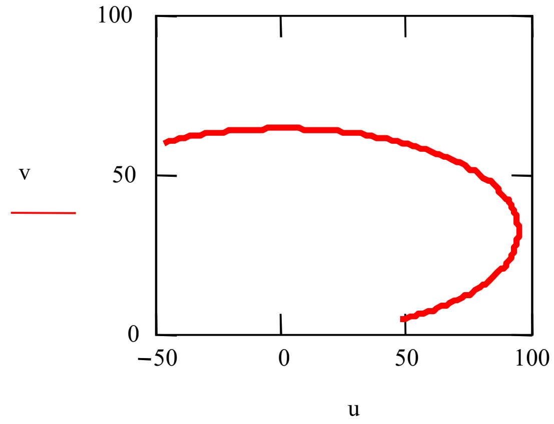
during observation the baseline, as seen by the star, is changing

and so do the explored spatial frequencies (u,v)
since they are determined by
baseline projected over the sky coordinates

this effect, extending the range of explored spatial frequencies,
is named "super synthesis"

To know how the u-v plane is sampled it is necessary to know
the variation of the measured spatial frequencies

maps of this sampling along time
can be calculated
(currently nowadays
by using software packages)



declin = 20

lat = 70

B = 100

X = −46.985
Y = 81.38

Z = 34.202

$-6 < H < +6$

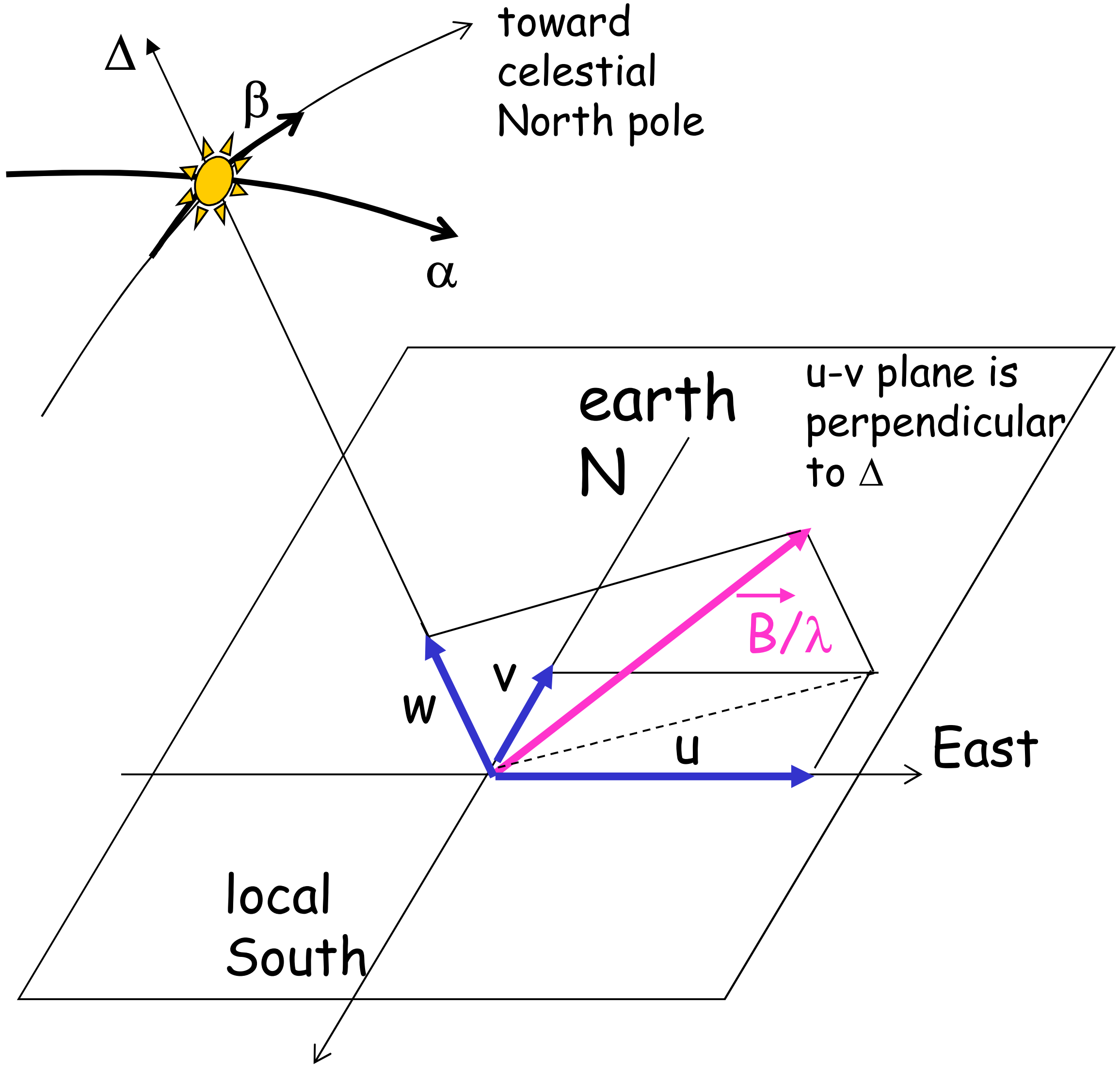
d = 90° - lat = 20°
η = - 120°

u-v coverage overview_1

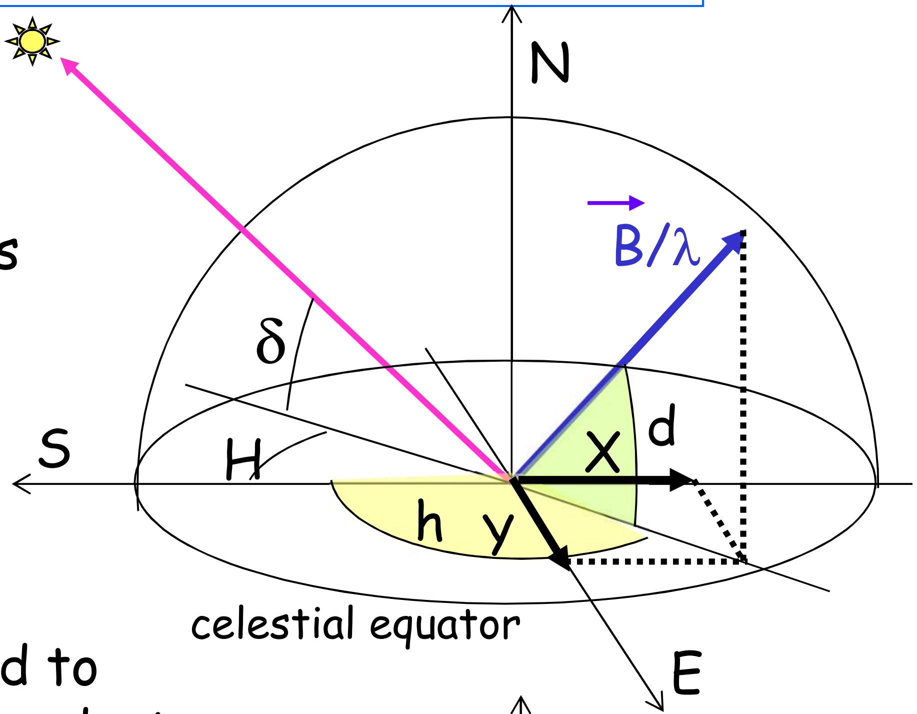
the geometry
of the baseline-star
system

u and v
are components of
the projected baseline
onto the u-v plane

w is only concerned
by optical path in excess
which is compensated
within the instrument



u-v coverage overview_2

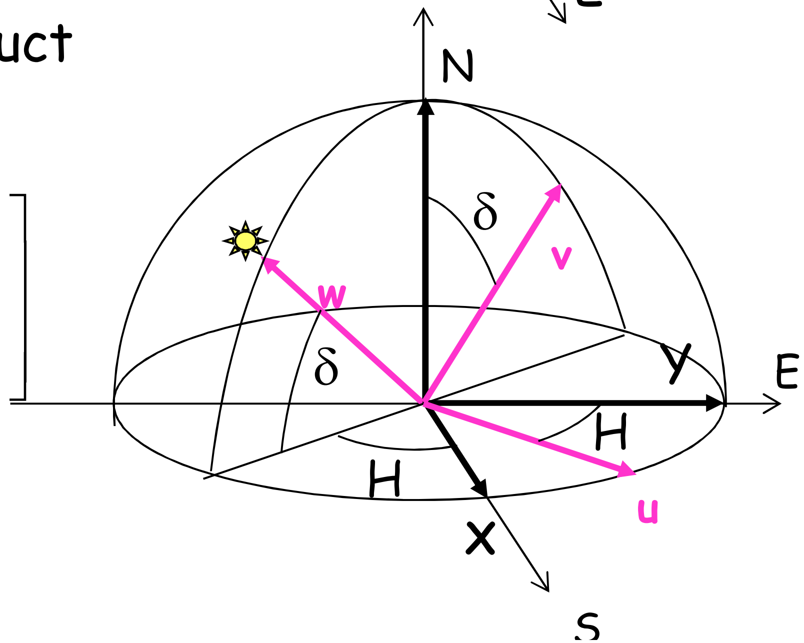


components (X,Y,Z) of the baseline
are refered to equatorial coordinates

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{B}{\lambda} \cdot \begin{bmatrix} \cos d . \cos h \\ -\cos d . \sin h \\ \sin d \end{bmatrix}$$

components (u,v,w)
of the projected baseline are refered to equatorial coordinates, via a matrix product involving (X,Y,Z) and star coordinates

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} \sin H & \cos H & 0 \\ -\sin\delta . \cos H & \sin\delta . \sin H & \cos\delta \\ \cos\delta . \cos H & -\cos\delta . \sin H & \sin\delta \end{bmatrix} . \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$



latitude of observatory is involved
and is related to "d"

quick-look at some technical approaches for angular resolution

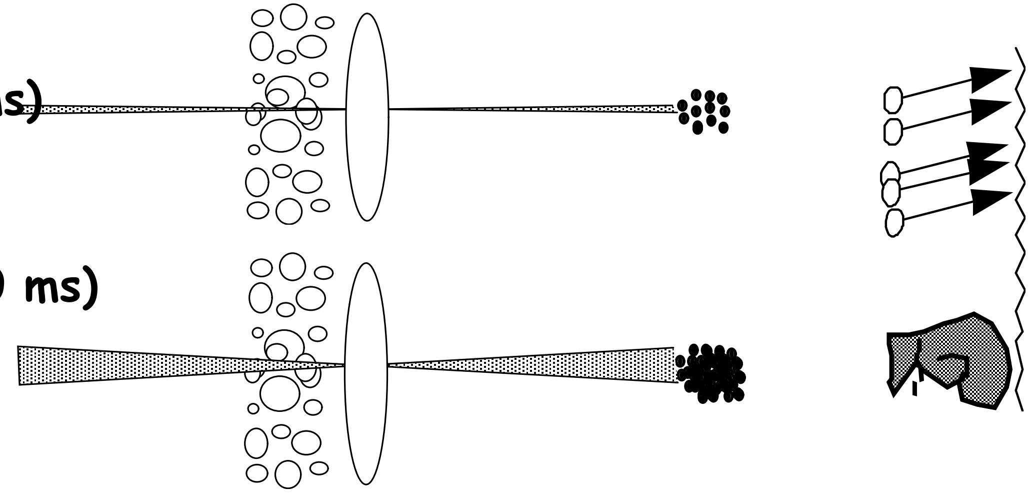
speckle interferometry - 1

the problem : theoretical resolving power destroyed

short exposure (1 ms)

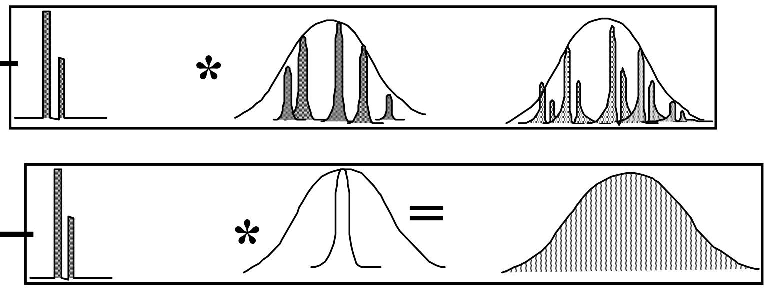
long exposure (> 100 ms)

classic imaging



here we can hopefully retrieve some theoretical resolution

here we cannot

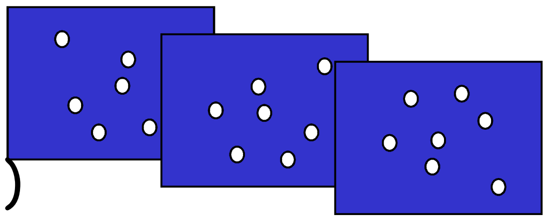


how can we fight ?

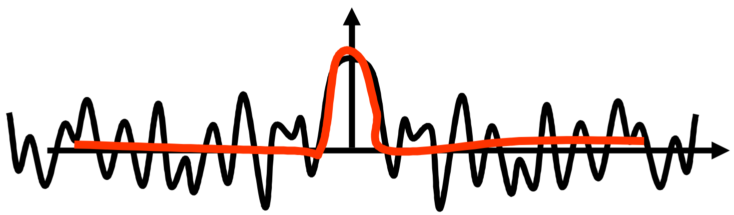
how can we restore the theoretical resolution ?

the optimistic view (thus too much candid with interferometry) :
perform a FT on the instantaneous image

too bad ! frames look like this →



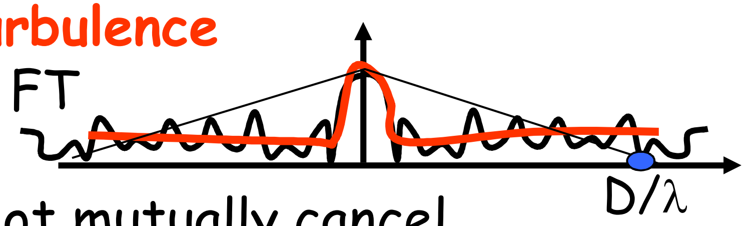
adding images ? (again exceedingly candid)
everything is moving
We have a randomly unstable
Transfert function beyond
a (low) frequency set by the
atmospheric turbulence
high frequencies lost



so what ?

adding what remains stable in spite of turbulence

autocorrelation or squared modulus of the FT

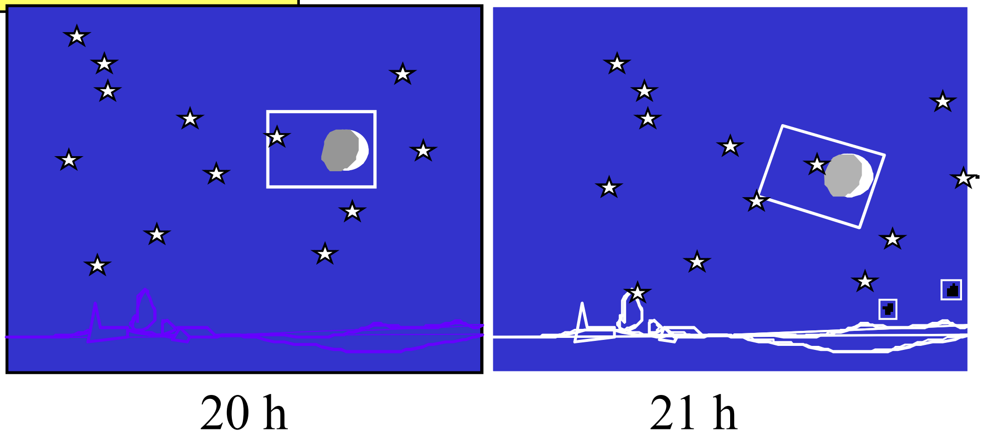


then , when summing, random features do not mutually cancel
and some high frequency information is saved

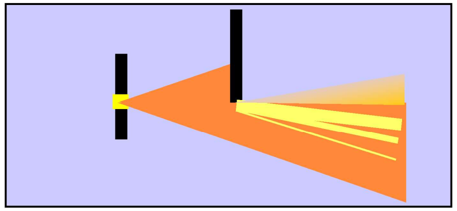
occultations of stars by the moon- 1

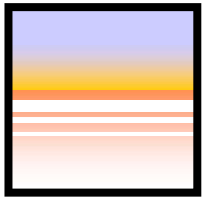
the phenomenum:

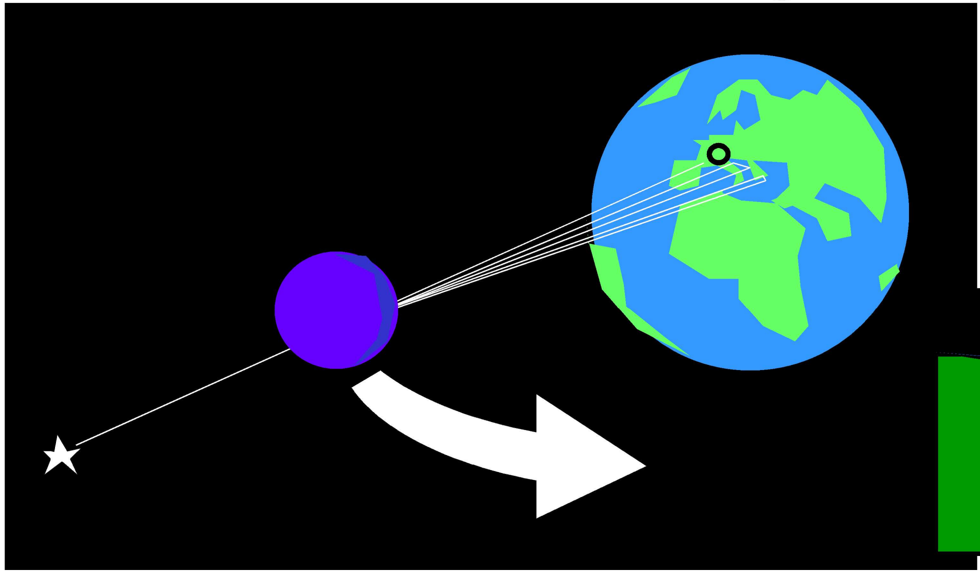
the moon drifts
with respect to the big carousel,
and she comes to hide stars

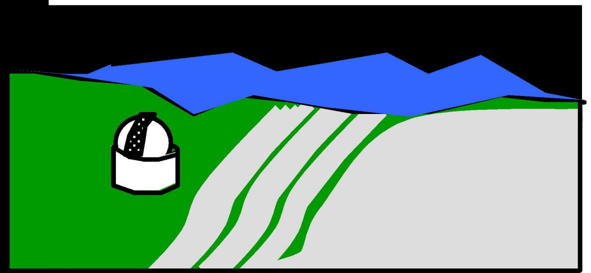


because of Fresnel diffraction
the light of the star projects on Earth
fringes from a screen rectilinear edge

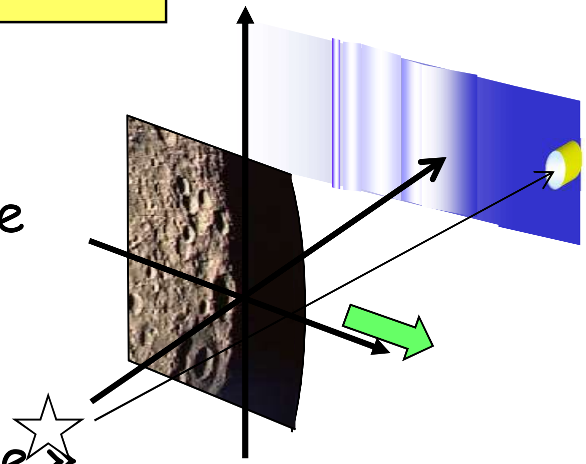








occultations of stars by the moon- - 2



observing the phenomenum

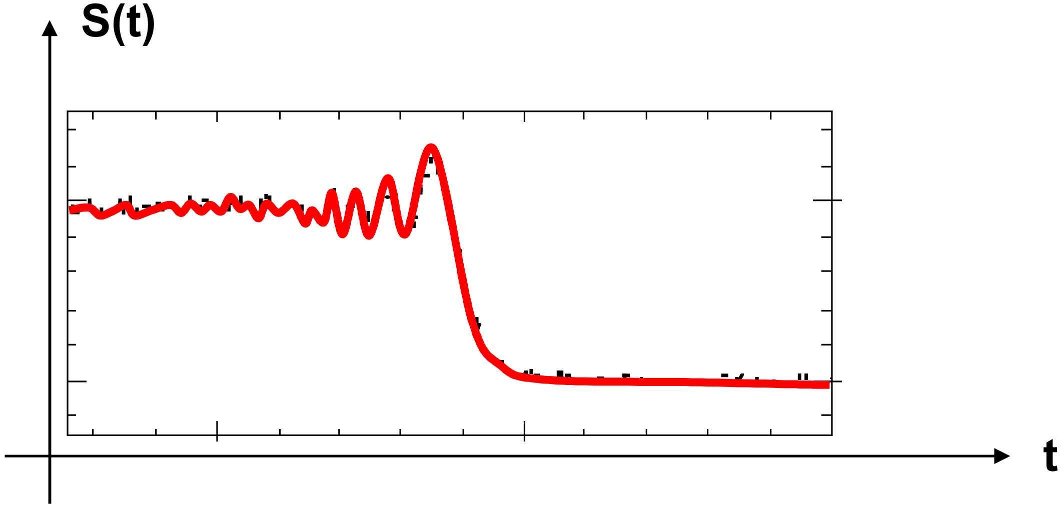
fringes are sliding in front of the telescope

speed : roughly 700 m/s

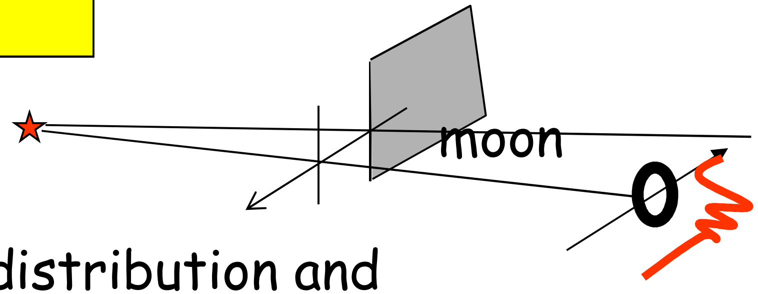
the observable is a (noisy) « light curve »

which is a photometric signal yielding the power collected during the passing of the fringes

(typical duration of the pass 0.1 sec in visible domain)

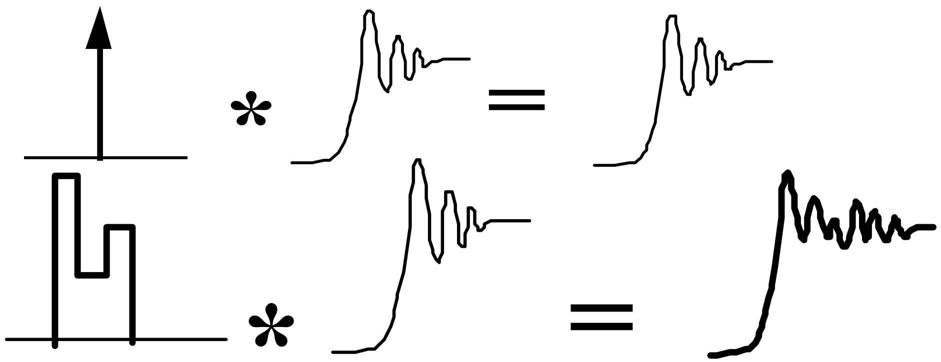


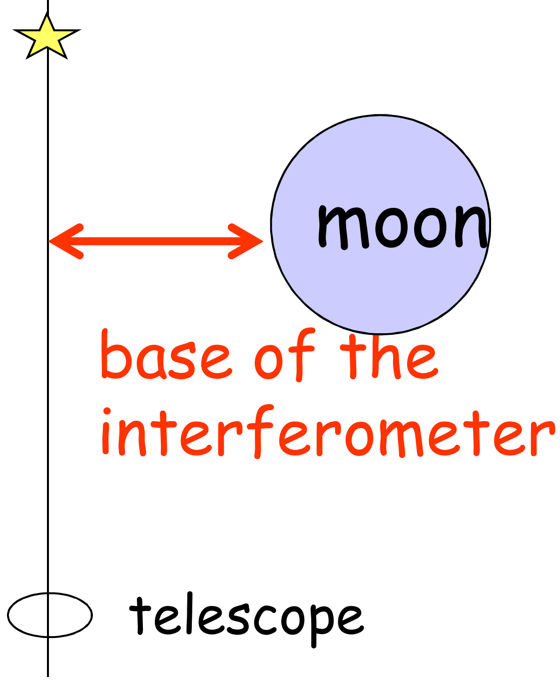
occultations of stars by the moon- _3
a « big like this !! » interferometer



exploitation of the phenomenum

the profile of the fringes is given
by the convolution of the source's angular distribution and
the instrument impulse response $I_{fringes}(\alpha) = O(\alpha) * R(\alpha)$



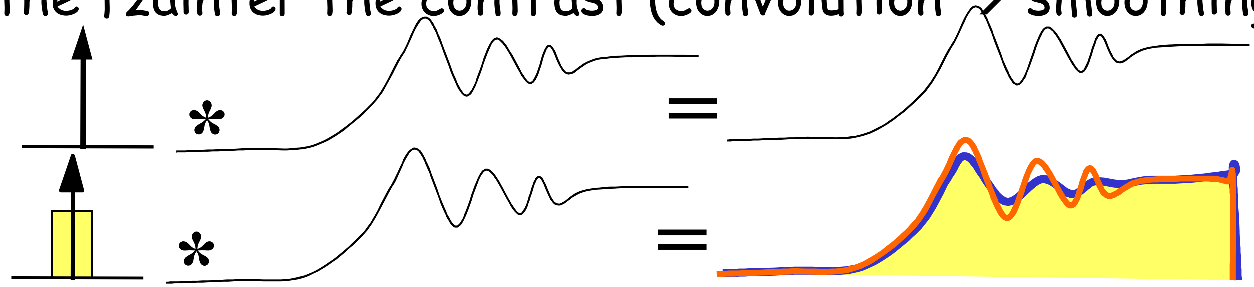


the information on HRA is in the shape
of thercurve (contrast and enveloppe of fringes)

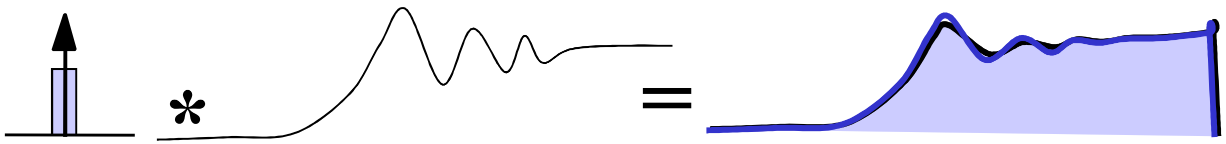
we may say that we have an interferometer
the « Augustin Fresnel's interferometer »

occultations of stars by the moon _4
a « big like this !! » interferometer? and a « that small » instrument

lthe profile of the fringes is given by $I_{franges}(\alpha) = O(\alpha) * R(\alpha)$
the bigger the star, the fzainter the contrast (convolution → smoothing)



the recorded profile contains the smoothing by the telescope
$I_{telescope}(\alpha) = I_{fringes}(\alpha) * T(\alpha)$
so : the smaller the telescope, the more detailed the recdord ?



possible, but also the higher the noise level
and the less reliable the exploitation of fringes,
so the less good the interferometer

il faut tout de même
évoquer le spatial

[redacted]

nulling interferometry and coronagraphy

definitions and broad lines of the topic

what ?

nulling techniques belong to the more general domains

High Angular Resolution
Very High Contrast Imaging

a tentative definition for VHCI

set of instrumental methods and devices dedicated to
the study (morphology)
of faint emitting sources
in the close environment of a point-like source

"Nulling Techniques" are those methods based on the coherence of light and destructive interferences

alternative approaches to the same goal exist
and will only be evoked

Very High Contrast Imaging _ 1

the morphology paradygm to tackle

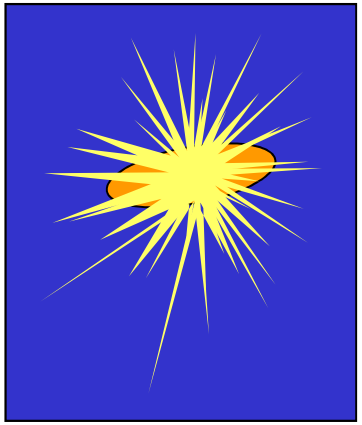
an unresolved source with closely surrounding matter
which morphology is looked for
and which emitted flux is largely fainter than the source flux

galaxies — AGNs,...

stars {
- circumstellar features (mass loss)
- binaries with faint companions
- exoplanets

planeto {
- exoplanets
- protoplanetary or post planetary disks
- multiple asteroïds

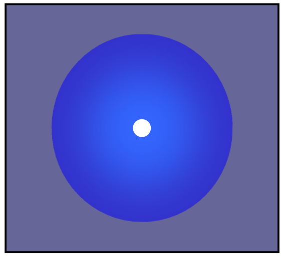
unfortunately

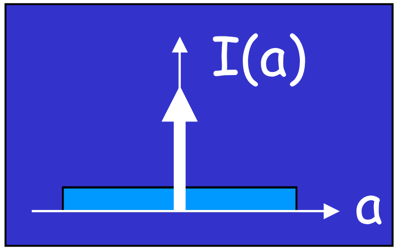


central source is blinding and prevents detection of surrounding sources

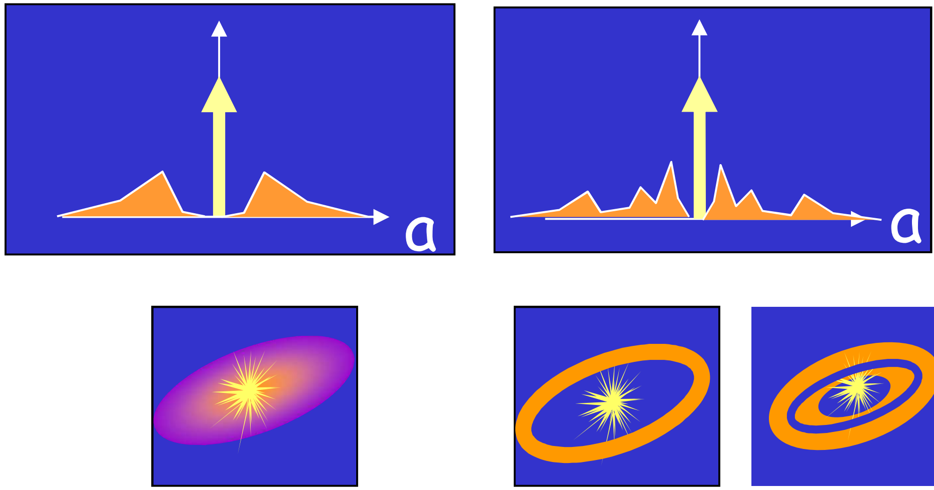
Very High Contrast Imaging _ 2 the problem : "see around"

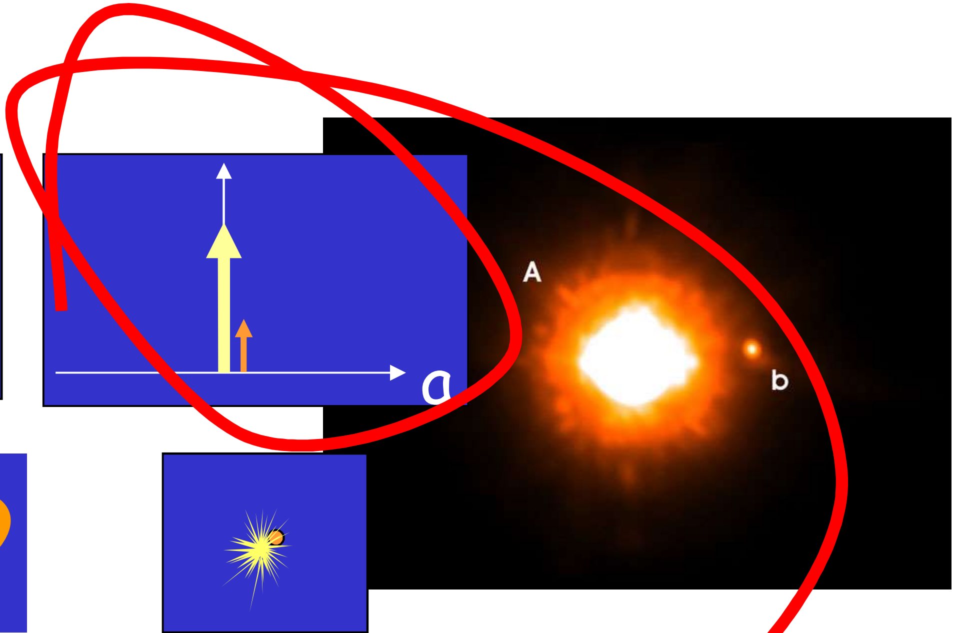
typical target : central point-like source on-axis, and features around





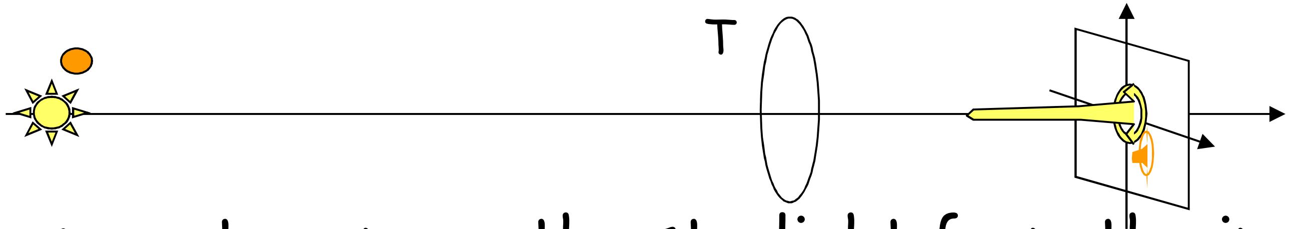
examples of surrounding features



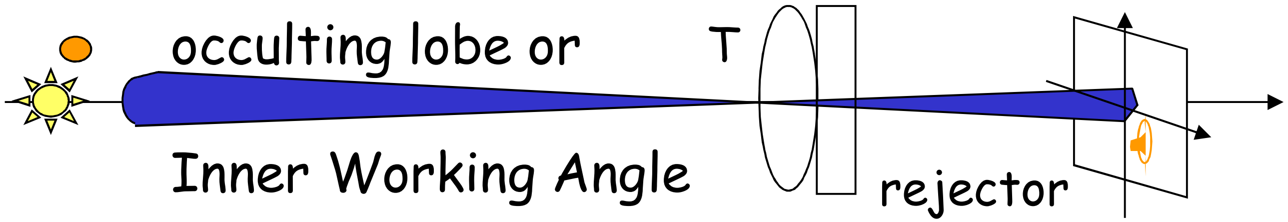


here we will focus on : star + faint companion
and even more specifically : star + planet

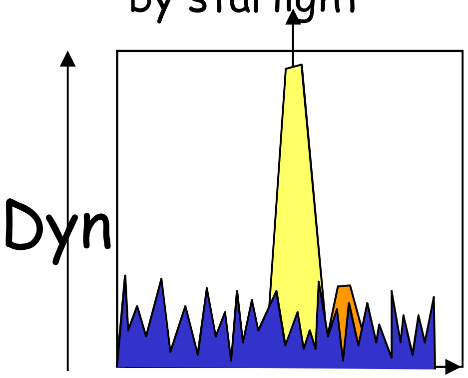
VHCI _ 3 a first need : rejection on-axis



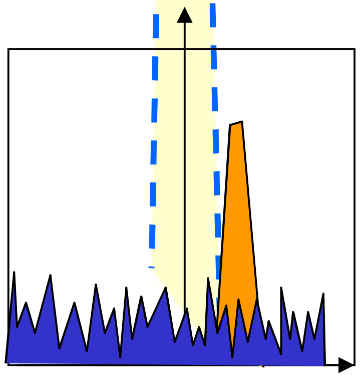
must manage to remove the starlight from the image,



camera photometric dynamics
saturated
by starlight



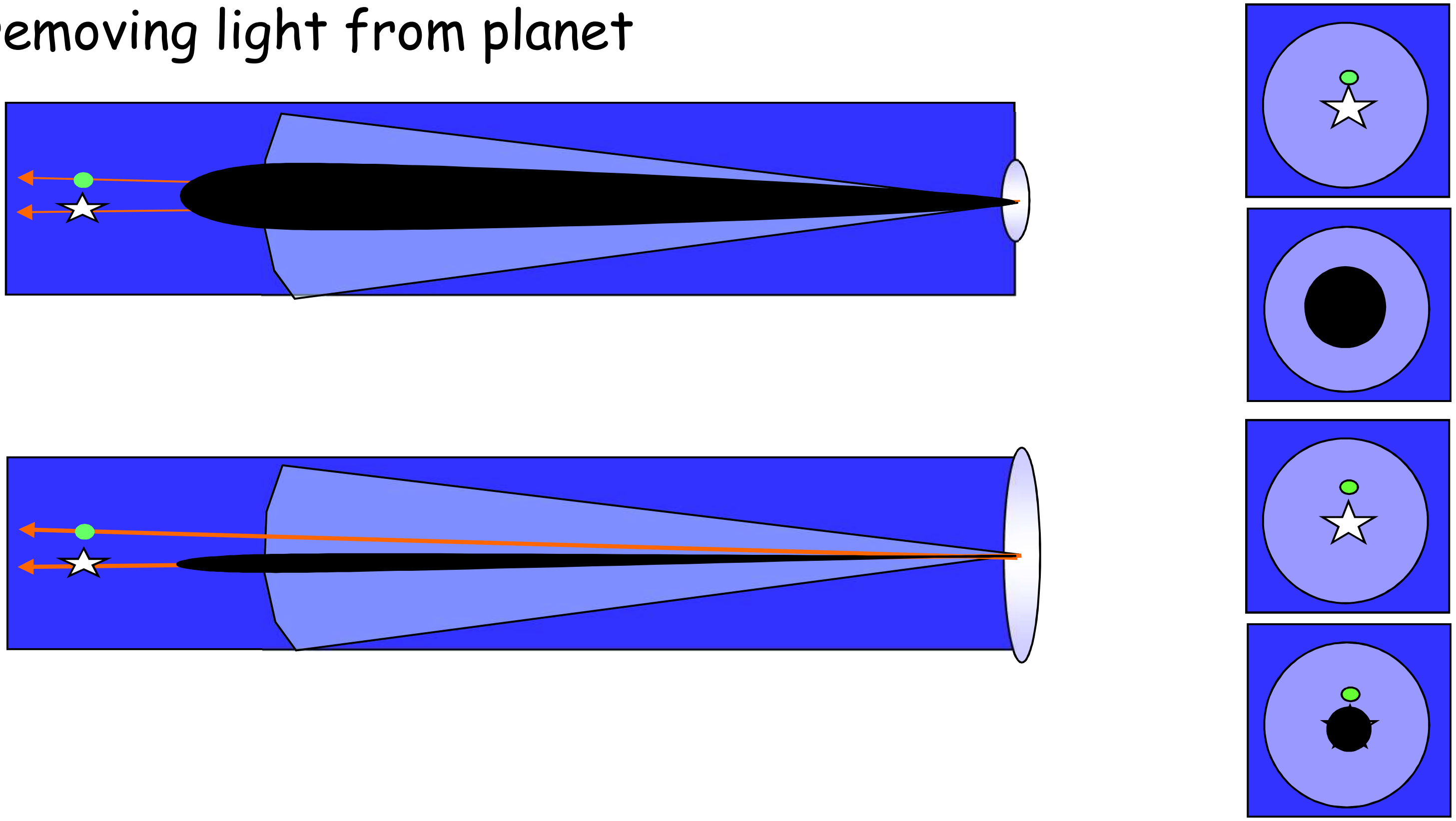
rejection of starlight =>
recovering photometric dynamics
for faint features
to overshoot noisy background



VHCI_4 a second need : angular resolution

such interesting features as planets
or ejected matter (mass loss tracing)
are very close to the central source :

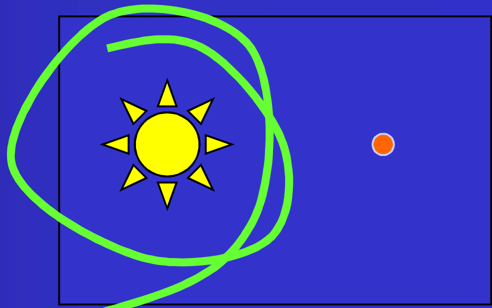
occulting lobe must be narrow enough to
avoid removing light from planet



non-direct / direct : what does that mean ??

non-direct detection

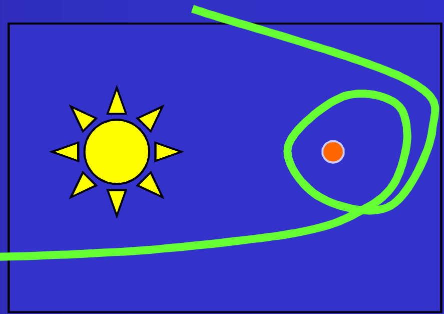
the planet is revealed
by its effects on the light coming
from the parent-star



and this light
is the one to analyse

direct detection

what we want now is
the light from the planet itself !!



and especially
NOT AT ALL the one from the star

non-direct methods : a quick-look

assessing the presence of a non-visible companion

we observe the parent star

- **analysis of motion :**

variable position : perturbated proper motion, **astrometry**
variable radial velocity : spectral lines motion, **velocimetry**
pulsar : perturbation of pulse periodicity, **timing**

- **monitoring of brightness**

occultations / transits
micro-effect of gravitational lensing

photometry

all that, rather out of the scope of the talk

direct methods

no other light wanted than the one from the planet

here is the **BIG** problem

requiring to conceive, develop and operate
specifically dedicated methods and instruments

among them
coronography and nulling interferometry

strange terminology, we come back later to that

observations : what to expect ? short overview

assume we have planetary photons !
why did we want them ?
why can we do with them ?

flux and spectrum (depending wavelength domain)
provide pieces of information pertaining
to (among others) such questions as

- temperature
- presence of an atmosphere
- **search for life**
- chemistry, physics and climate diagnostics
- albedo
- seasonal changes
- ....

immediate constraints to get planetary photons

photometric dynamics (very high contrast)

need to tackle very large flux ratio (star/planet)

angular resolution

need to separate star and planet, very close objects

photometric sensitivity

planet = very faint object, few photons

very large ?, very close ?, very faint ?
what does it mean ?

need numbers !!!

photometric dynamics (contrast)

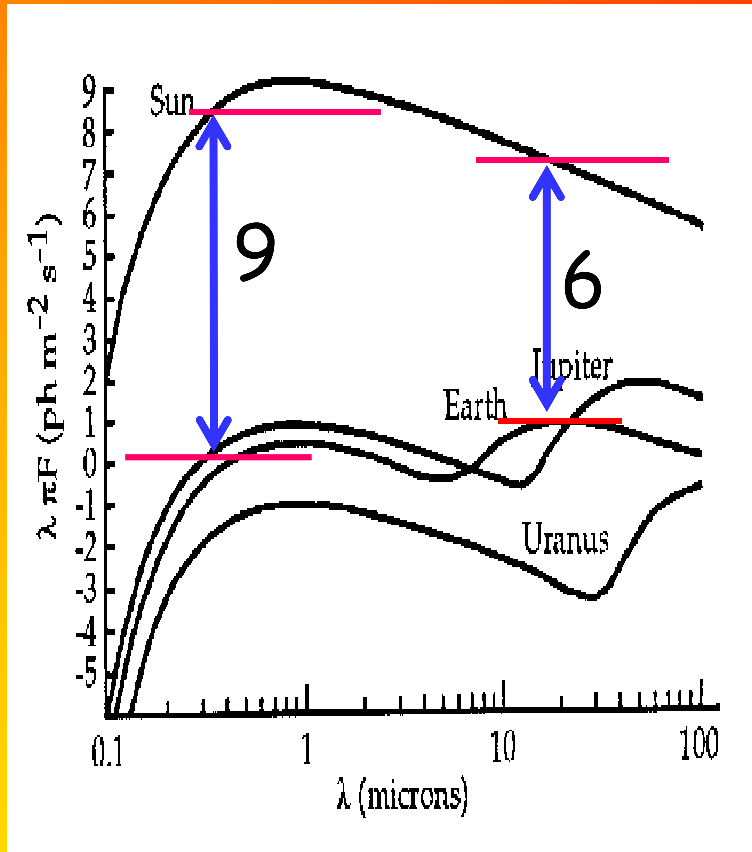
key parameter :
ratio R_{flux} = flux star/flux planet

"hot" jupiters
exoplanets of Pegasides type
R_{flux} 10^4, 10^5

exo-earths

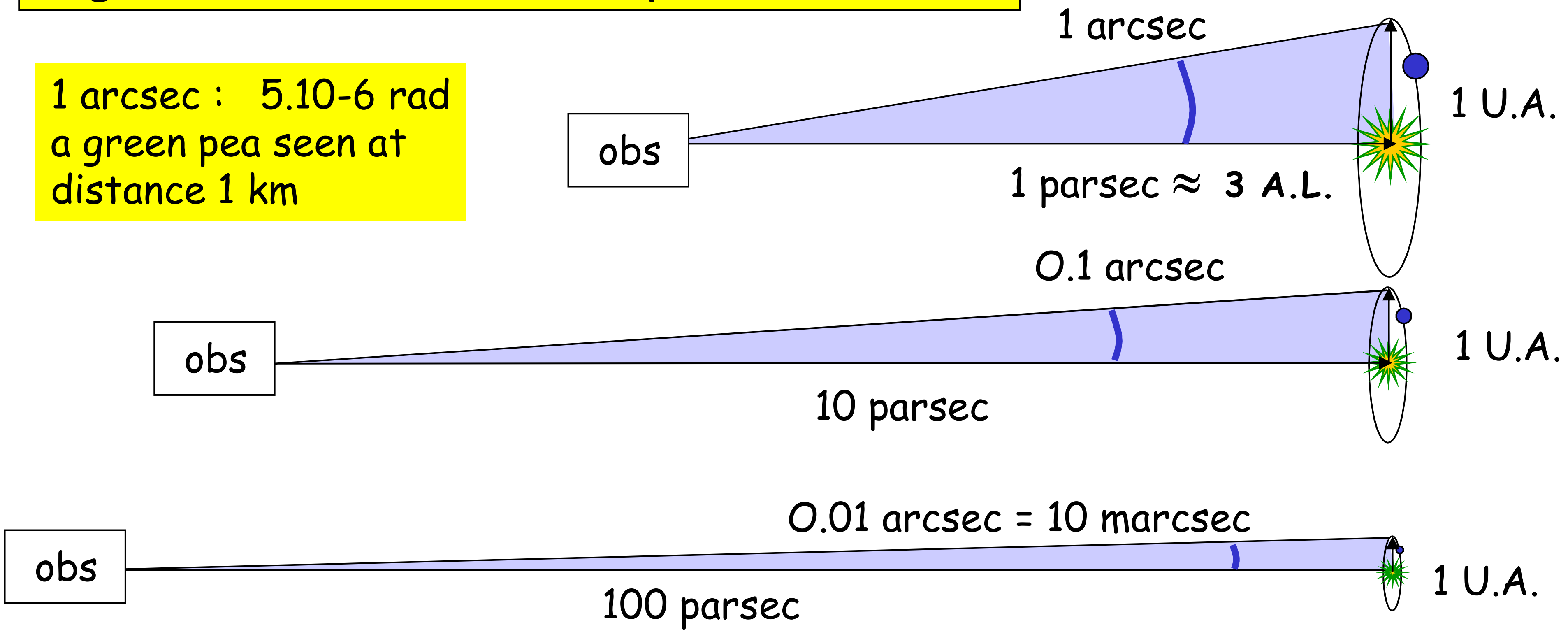
mid IR, : millions 10^6, 10^7

visible : billions 10^9, 10^{10}



angular resolution : example earth-sun

1 arcsec : 5.10-6 rad
a green pea seen at
distance 1 km



Rayleigh criterium : separation must exceed ≈ λ /DiamTel

λ µm	0.6	2.2	11
requested diameter for 100 parcsec	≈ 10	≈ 40	≈ 200

photometric sensitivity

example : Sun-earth at d = 10 psc (about 30 AL)

collected power from planet (λ) = 10^{-n} $.S_{tel}.\Delta\lambda$.transm. $Flux_{star}(\lambda)$

visible n = 9, thermal IR n = 6

V band λvis = 0.55 μm **N band** λir = 10.2 μm

telescope		Number photons/sec			
D (m)	S (m²)	Sun 10 psc		Earth	
		V	N	V	N
10	100	10^{10}	1.5 10^{9}	10	1500
3.6	10	10^{9}	1.5 10^{8}	1	150

warning atmosph radiation

short-cut :
10^{6} flux ratio → magnitude gap 15
10^{9} flux ratio → magnitude gap 22 to 23

technical answers to science requirements for exo-earths _1

very high contrast :
dedicated instruments : coronagraphs, nulling interfeometry
to be seen later on

key parameter :
rejection = ratio residual on-axis energy / collected energy

better performance :
go to space (no atmosphere : no background in mid IR, no turbulence) !
(though ground-based projects remain under study) :

photometric sensitivity : large collectors, high quality detectors, ...

spectral coverage : again go to space
and achromatic rejection (large working bandwidth)

technical answers to science requirements for exo-earths _2

angular resolution :

need : narrowest extinction lobe , smallest λ / D

spectral domain dependancy

visible : largest single aperture, 10 m class OK

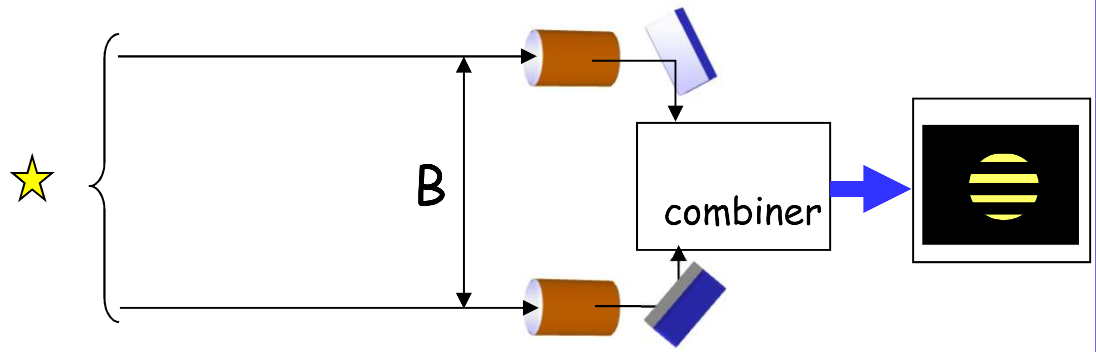
mid infrared : interferometers required

interferometer: 2 or N telescopes which outcoming beams are combined (superimposed on a same detector)

resolution is now λ / B (instead of λ / D)

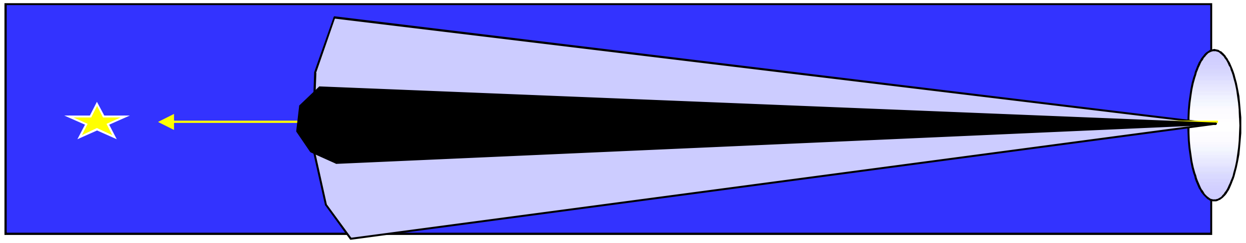
significant gain, even with small telescopes (2m, 4m class)

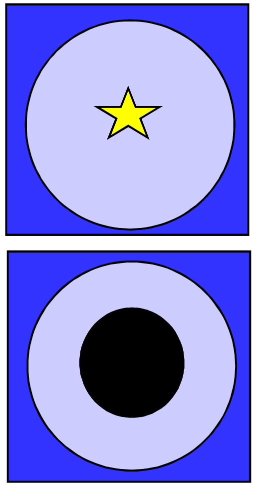
note : accomodation of several small telescopes in space launcher is currently feasible



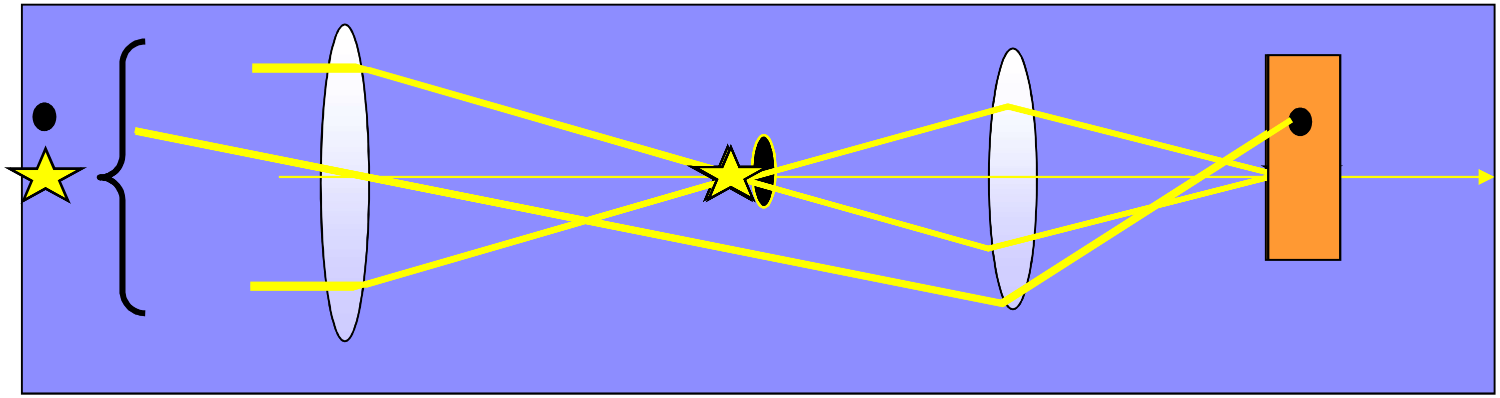
material focal mask : stellar Lyot coronagraph _1

telescope transmission is corrupted by a focal mask
so as to make an occulting lobe





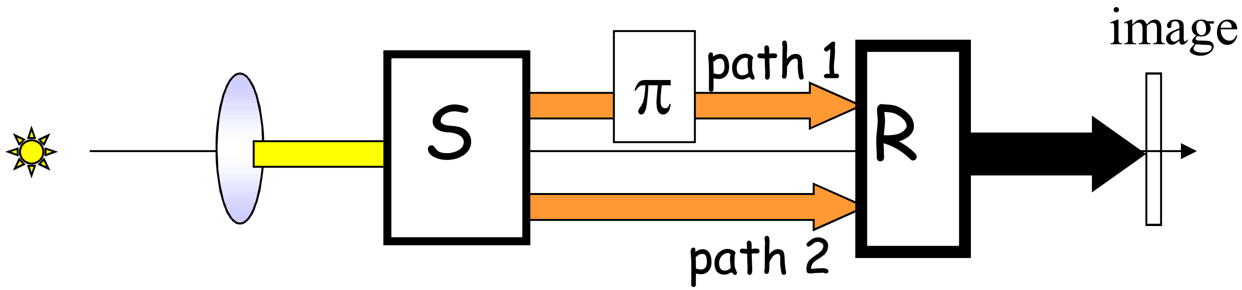
example : Lyot-type coronagraph (originally for Sun, 1936)



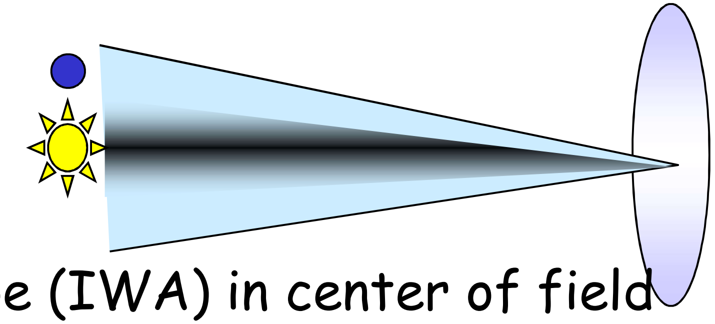
nulling coronagraphy

incident wave is divided in two "sub-waves" (beamsplitter : BS)
extinction of star (on-axis) is obtained
by destructive interference between recombined sub-waves (BS again)
destructive interference obtained by inserting π -phase shift

what about the planet ?
it escapes this "nulling process" because the incoming wavefront is tilted and induce an extra phase shift (see later on)

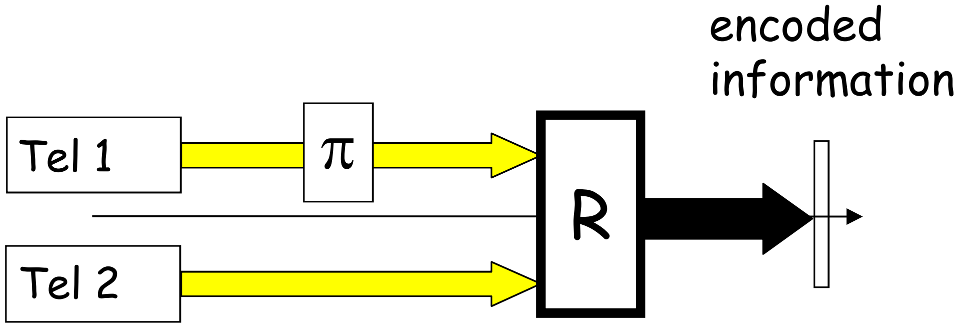


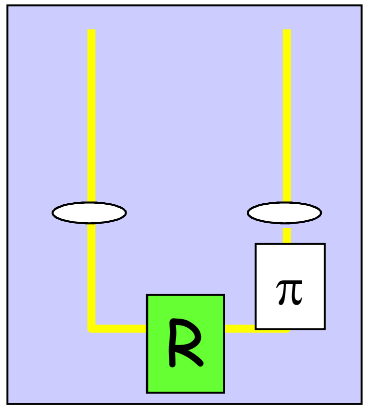
S : separation by amplitude "splitting"
R : recombination for interference



the "transmission map" set an occulting lobe (IWA) in center of field
we have a non-material mask, or a "coherence" mask

nulling interferometer (2 telescopes, Bracewell concept)

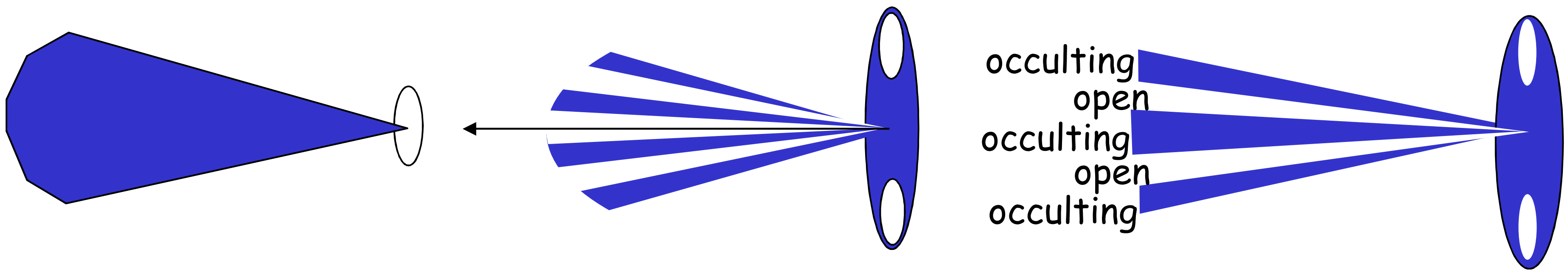




differences with interfero coronagraphs,

- the interferometer explores the sky with a grid
  (non connex occulting lobe, fringed lobe)

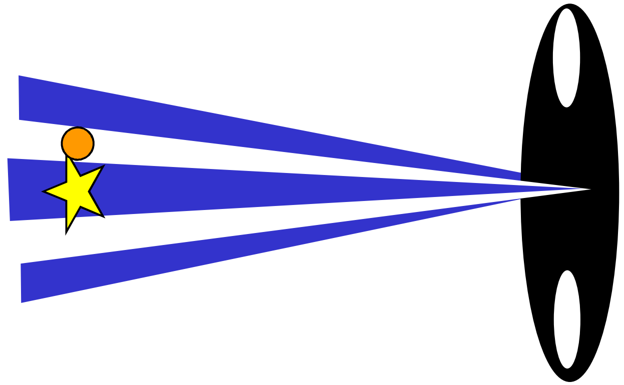
- resolution (spacing of the grid) now is λ / B instead of λ / D



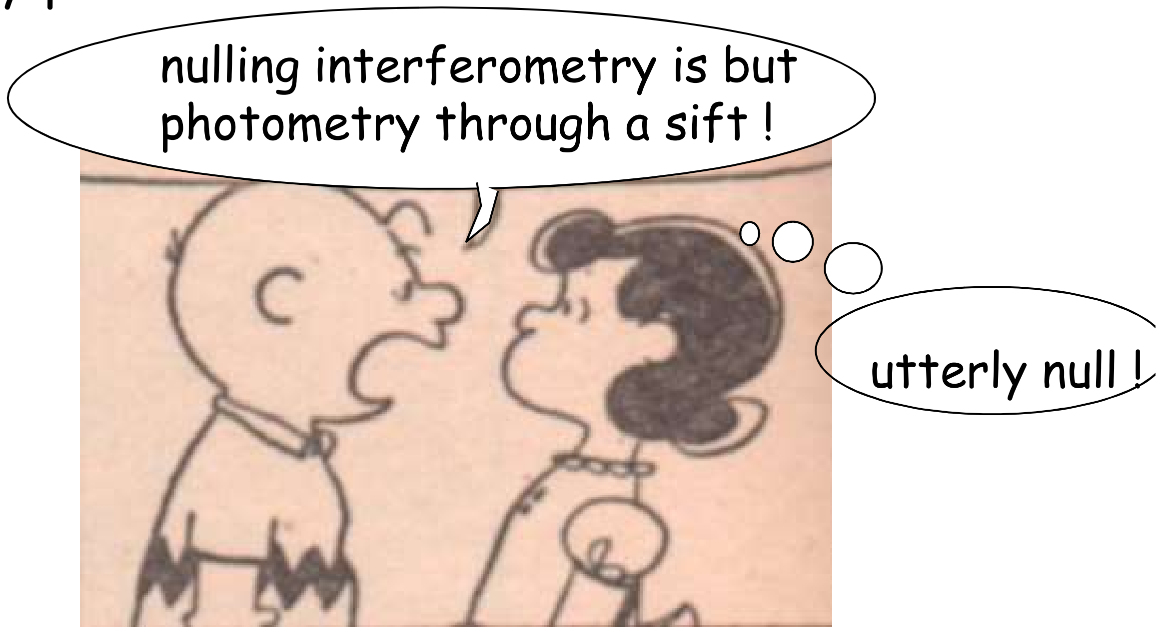
coronagraph conventional interferometry nulling interferometry

nulling interfero ? a provocative short-cut

basically
the interferometer simply built
by destructive interferences
an appropriate transmission map



this map is used like a sift,
through which only planetary photons
are (ideally) allowed to pass
while
stellar photons (ideally)
are blocked



additional constraints

exo-zodiacal matter :

planet immersed in comparatively bright exo-zodiacal cloud
appropriate modulation needed (discriminate contributions)

free flying telescopes :

formation flight to be controled
relative positions : needed accuracy few millimiters (laser auxiliaries)

BUT at recombination, nanometer accuracy needed (not the job of flyers)

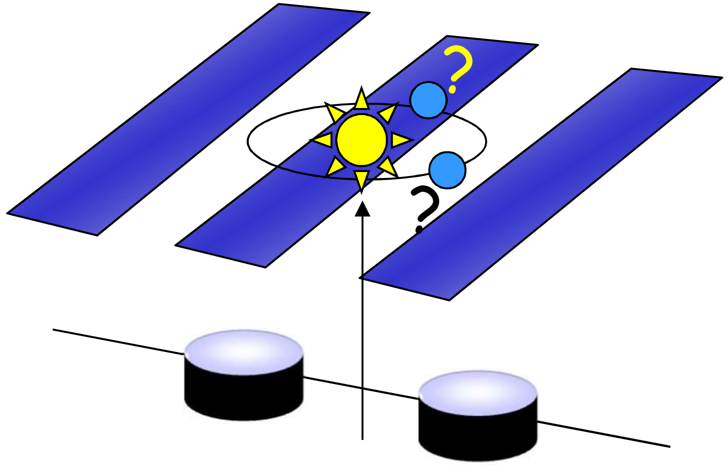
achromaticity of π phase shift :

highly accurate phase shift (< 10^{-3} rad) needed for 10^{-6} rejection
and this over the whole $\Delta\lambda$
to allow large working bandwidth (more photons from planet)

achromatic phase shifters are the heart of the instrument
several technical constraints to be added (see later)

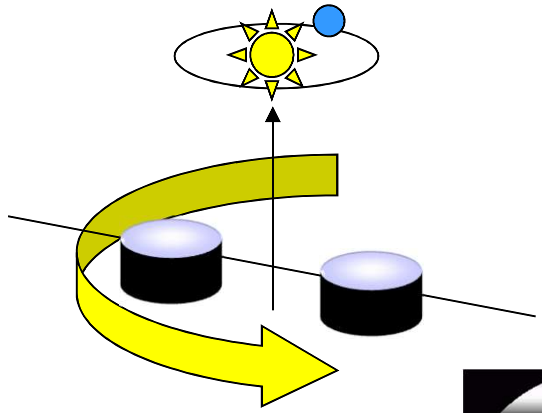
Bracewell : sensing along one_direction only

where is the planet ?



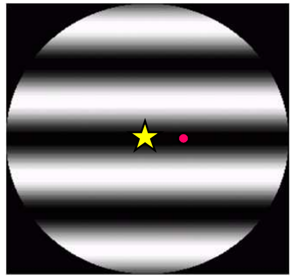
for exo-earths we may have
an idea of the angular separation star-planet
from the "habitable zone" constraint
but orientation of the couple is unknown

need to explore all orientations
for example by making the interferometer
rotate as a whole around pointing axis
(Bracewell concept)



extra interest : modulation of planet signal
(synchronous detection)

not really appropriate
time and energy consuming, technically not easy
and problem with exo-zodiacal matter remains



courtesy
Olivier Absil

dedicated instrumentation : an example ESA-Darwin

possible instrumental options in response to science needs

target : direct detection and spectroscopy of exo-earths

signatures of bio-activity (carbon chemistry)

very small angular separation (star-planet) , range < 0.01 arcsec

flux ratio : flux star/flux planet tremendously high (> 10^6)

interferometry

"nulling" techniques

thermal InfraRed
large bandwidth (6-18 μm)

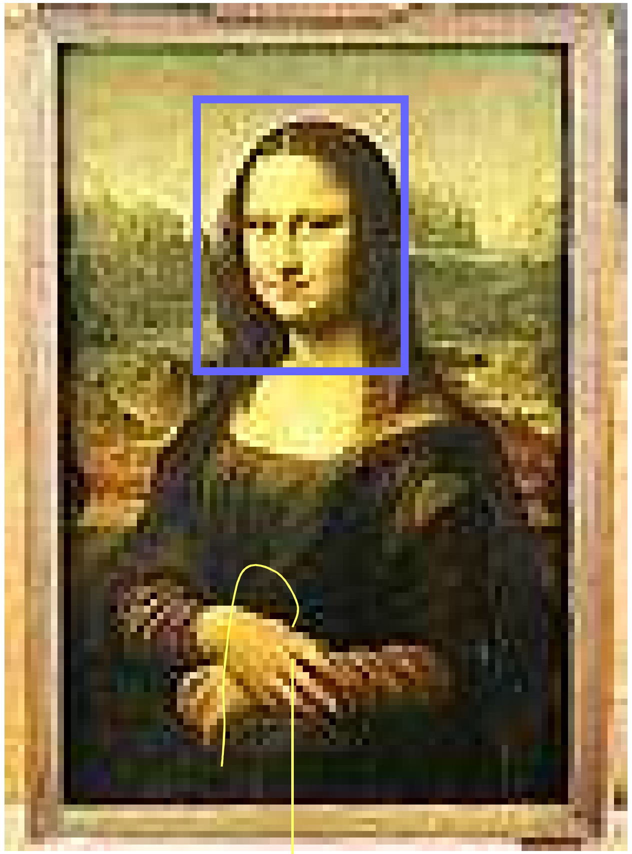
ESA choice : nulling interferometry in thermal InfraRed

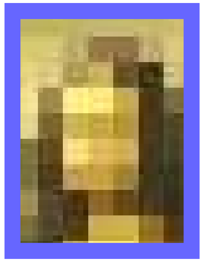
to keep in mind :

what we measure in interferometry
generally is pertaining to a MODEL

be careful not to be too confident
to models

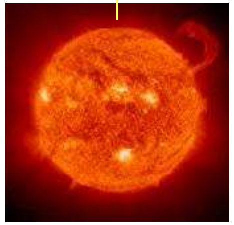
the Joconde's syndrom - 1



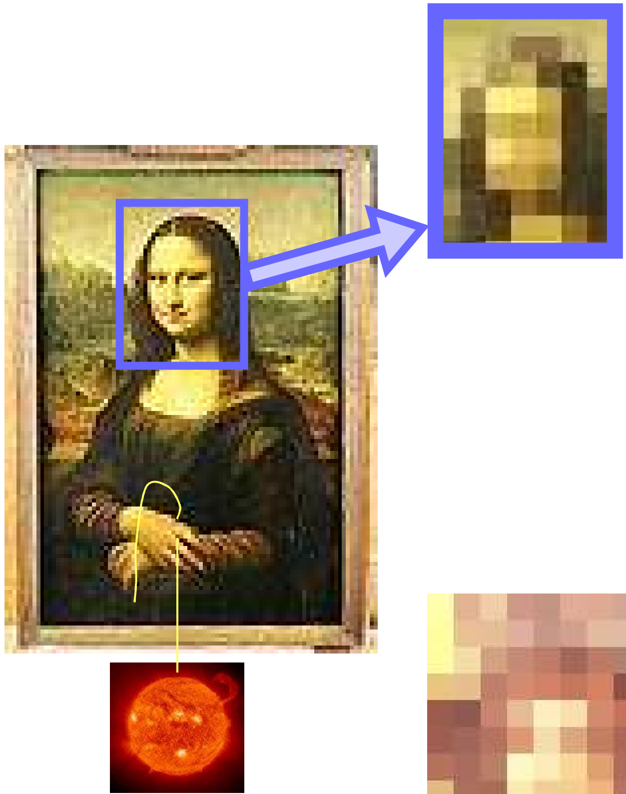


with La Joconde , it is a bit
like for the sun,
we know the face with many details

If we would observe
with a degraded angular resolution
we would find
for example this



the Joconde's syndrom - 2

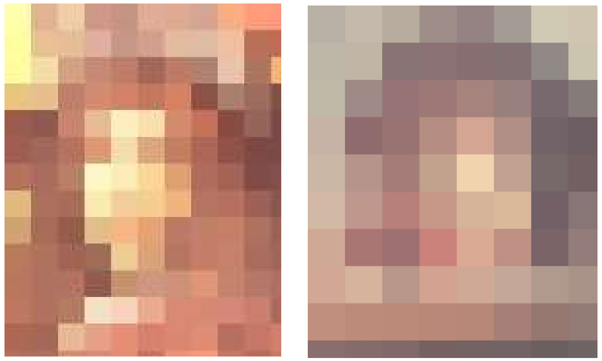


if we ave an « a priori model »
(here la Joconde)
and that we observe

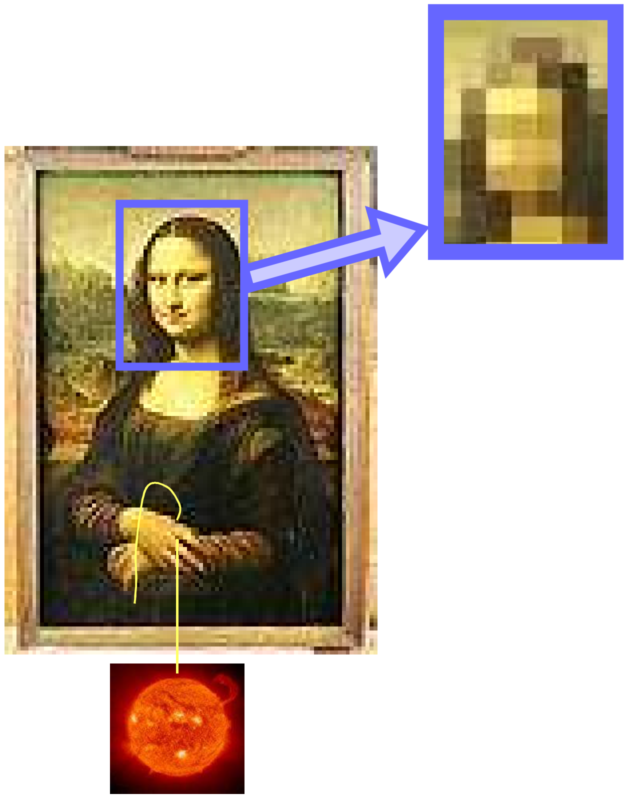
things like this

then we might think that the objects are

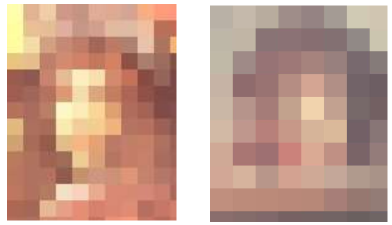
like this



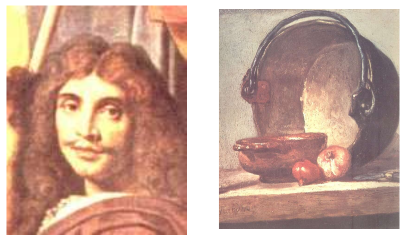
the Joconde's syndrom - 3



actually I have made
the two representations
shown here beside



by degrading the resolution of the images
shown beside



the « a priori model » has sent us
far from reality
in particular for
the second example

ok, finished now

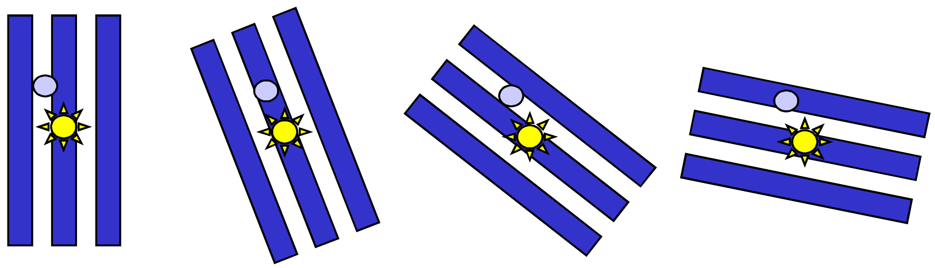
you can wake up

thank you
for listening

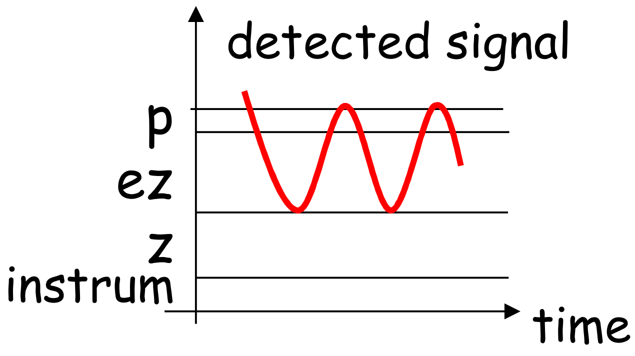
supplementary slides for fanatics

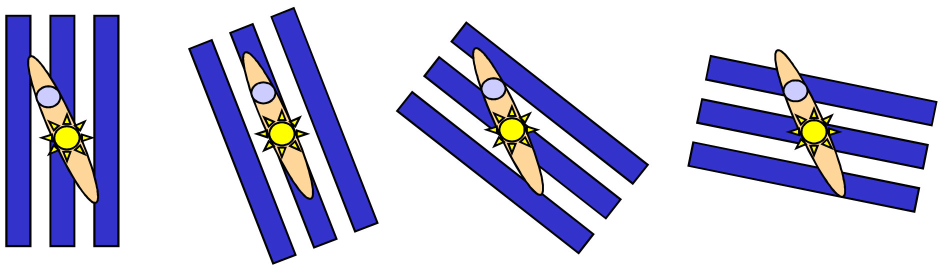
Bracewell concept : contamination of exo-earth signal

modulation of planetary signal by global rotation



problem : exo-zodi also modulated
heavy contamination





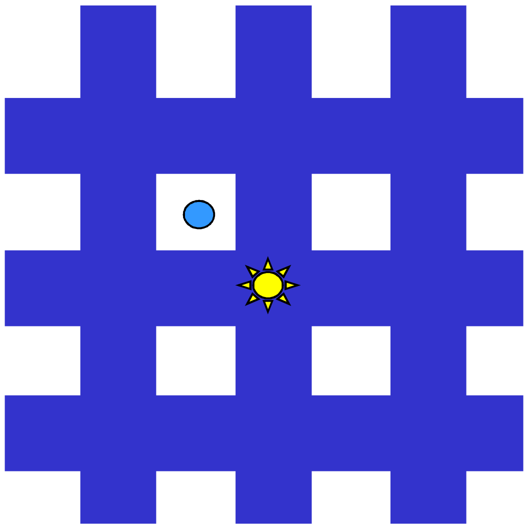
possible solutions

- more than 2 telescopes
  (non symmetrical configuration)
- internal modulation

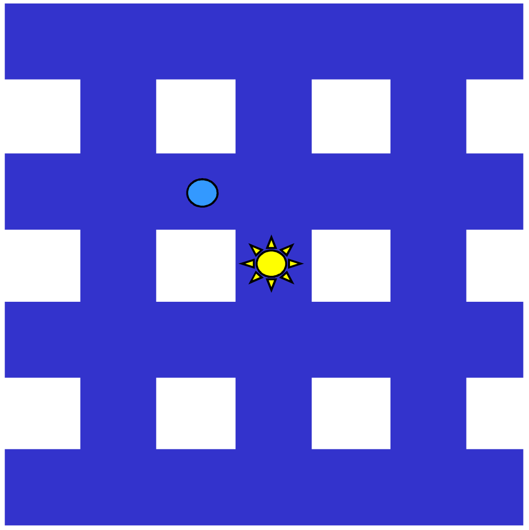
a schematic example of internal modulation (no rotation)

just "hand waving" approach

two Bracewell Nullers with perpendicular baselines
and so
two fringed maps working together



periodic π phase shift added in one nuller
one grid remains untouched, the other is reversed
so as to
keep star in dark zone
planet periodically seen and unseen



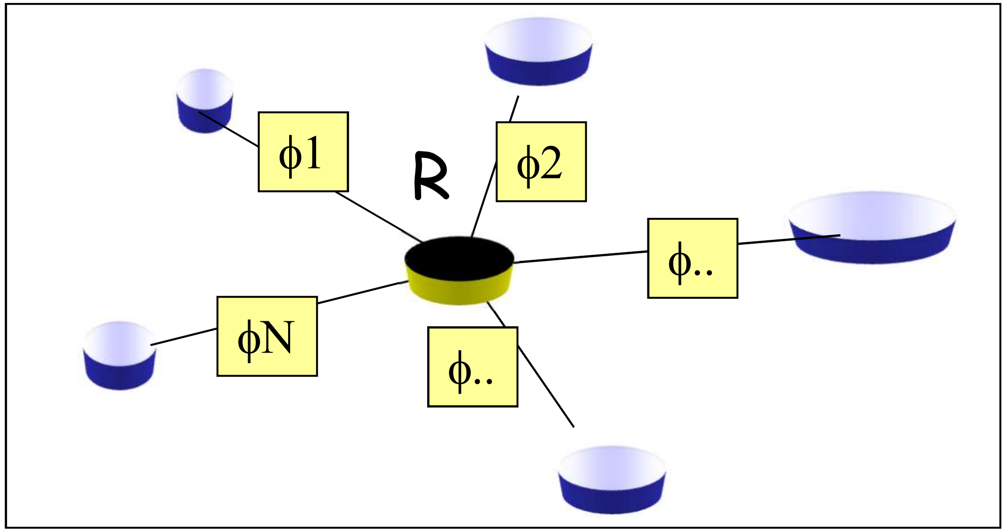
more than 2 telescopes

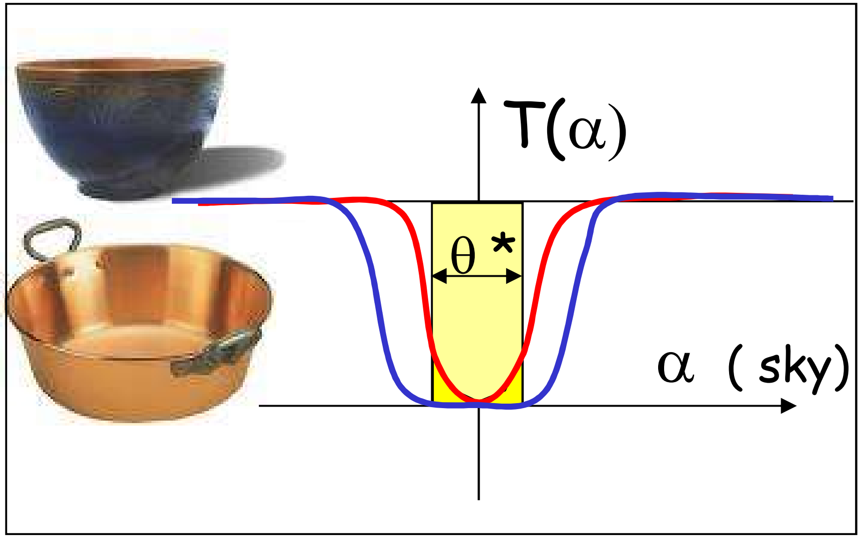
interest and difficulties

- stiff edges of transmission profile (star leakage)
- internal modulation (no rotation needed)
- non_symmetrical configuration (exo-zodi)

BUT

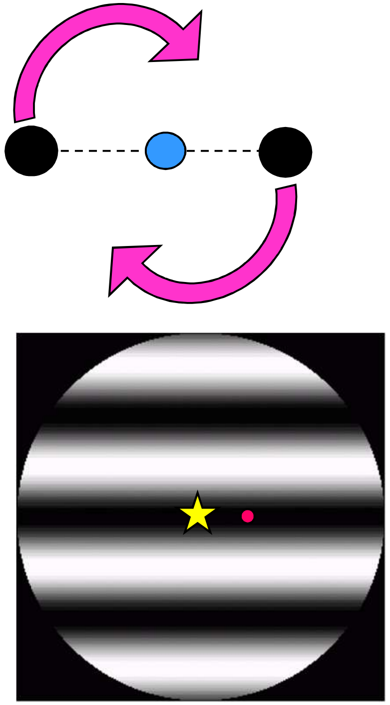
- several phase shifts on interferometer respective arms, not simply π, but fractions of 2π (technical challenge)
- flight formation control (mm accuracy, baselines hundreds of meters)

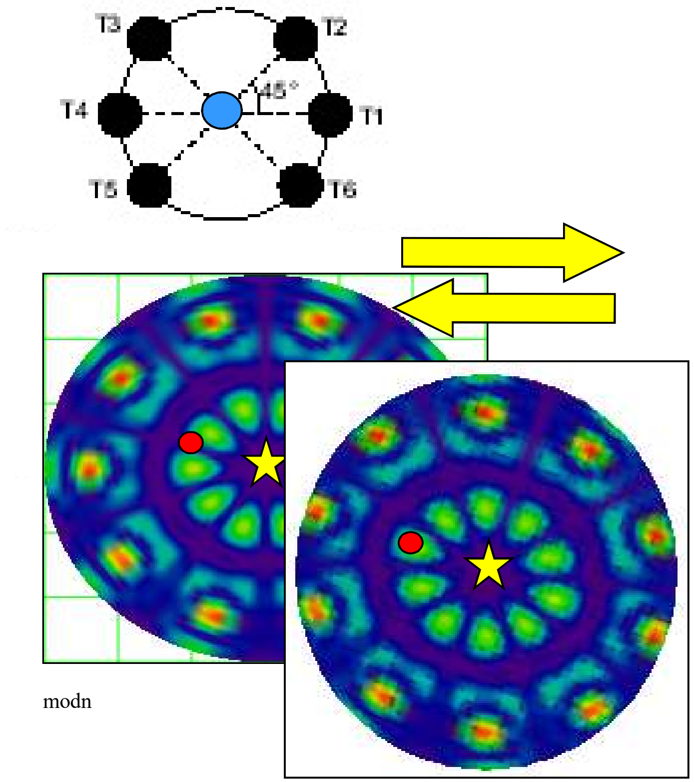


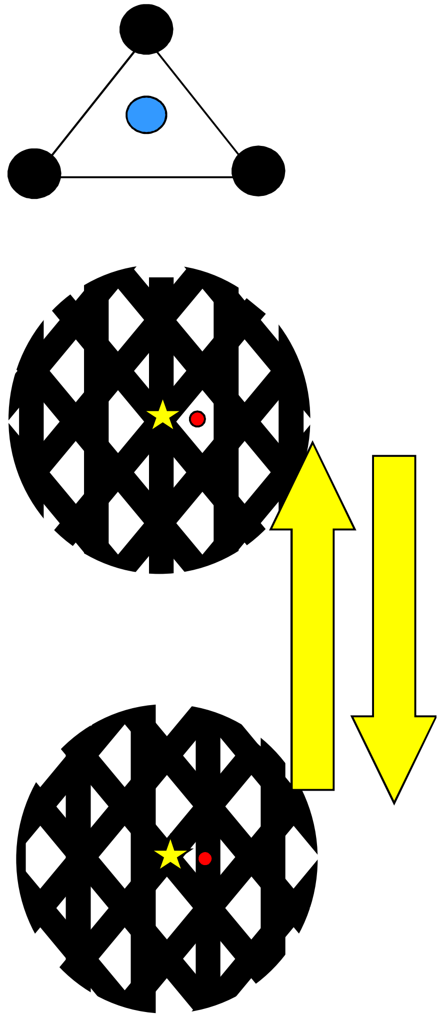


configurations, transmission maps, modulation

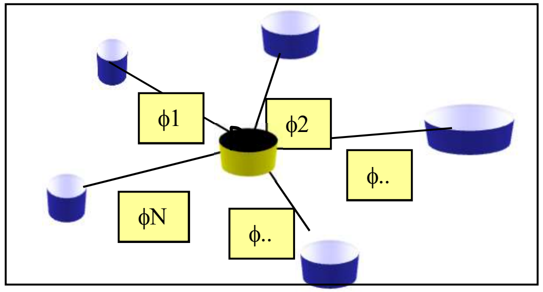
both map and modulation processes depend on the number of telescopes and on
their relative positio





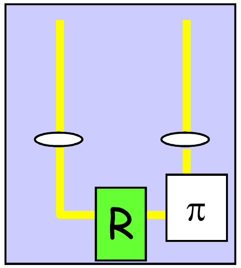


key system : the APS's Achromatic Phase Shifters



function : inserting the appropriate phase shift in each interferometer arm

example for a 2-telescope interferometer
need : π nominal phase shift



science requirements

targeted null depth 10^{-5} , stability level 10^{-6} over....days

subsequent specifications :

- phase shift accuracy at 0.001 radian over large bandwidth
- intensity relative mismatch at 0.001
- optical paths balance at less than few nanometers
- Wavefront quality at recombination at few nanometers level
  only achievable bu using spatial filtering (optical fibers)

key system : the APS's Achromatic Phase Shifters

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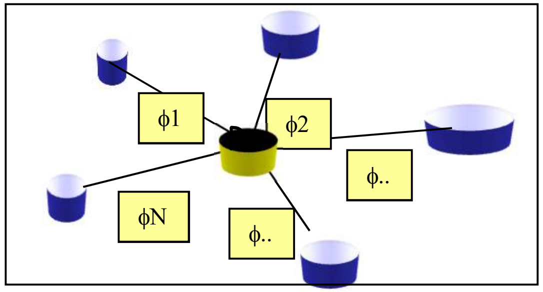

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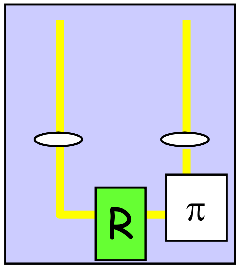

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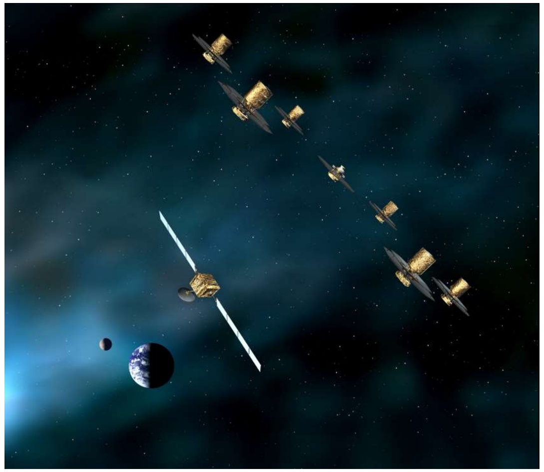
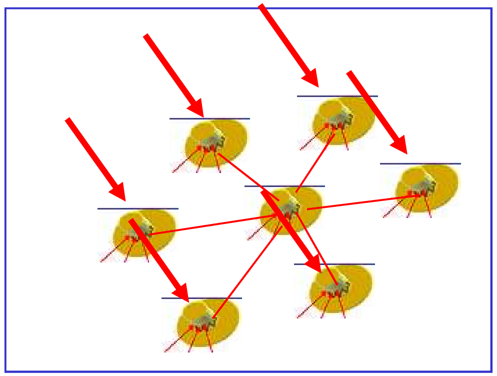
- intensity relative mismatch at 0.001
- optical paths balance at less than few nanometers
- Wavefront quality at recombination at few nanometers level
  only achievable bu using spatial filtering (optical fibers)

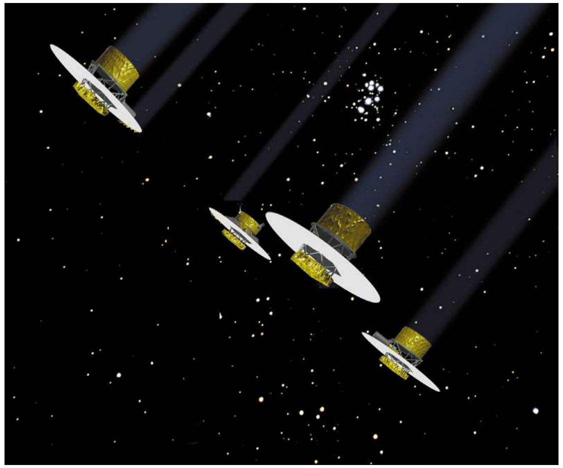
ESA-Darwin : a sequence of configurations
key-word MONEY ! !

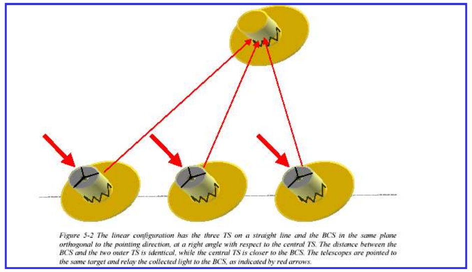
proposal July 2000

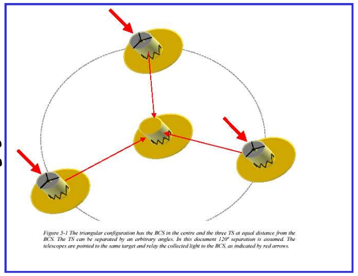




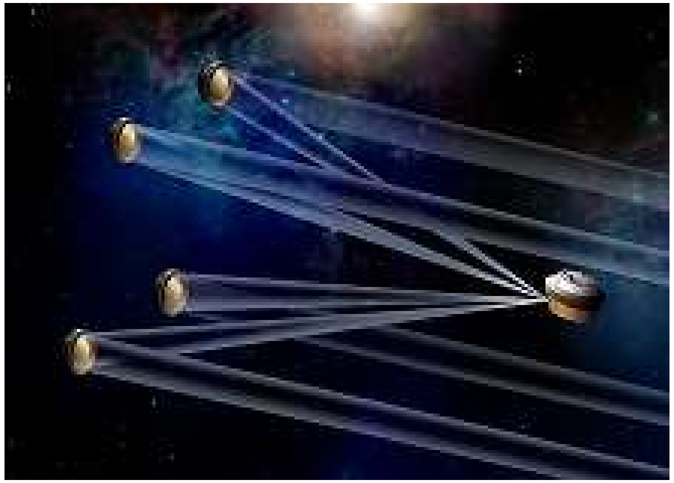
proposal Oct 2004





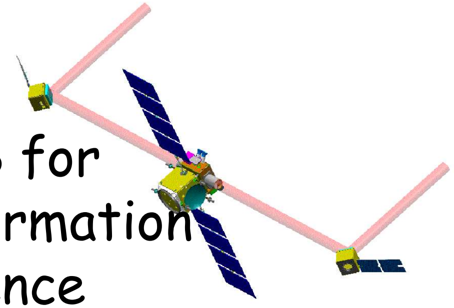


the most recent (2007) X_Emma (Lady Darwin) proposal to ESA Cosmic Vision

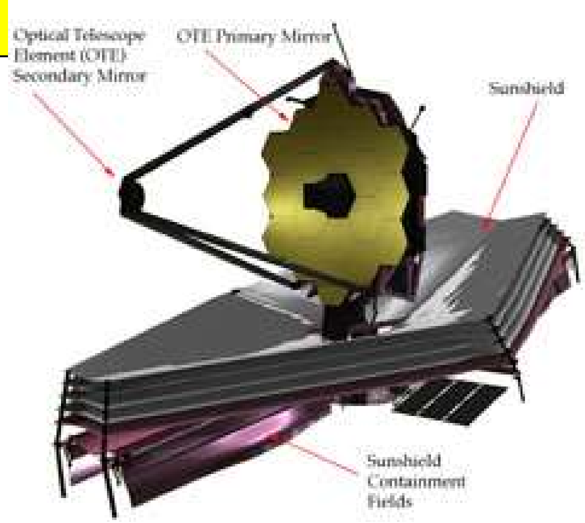


Darwin estimated cost (2007): over 650 Meuros

a discarded precursor : Pegase proposal to CNES for flight formation and Science

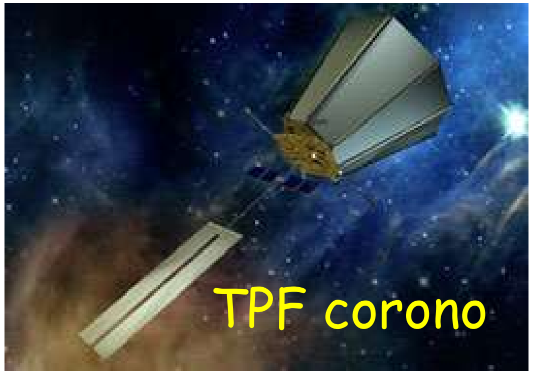


other projects for coronagraphy and nulling interferometry in space



NASA

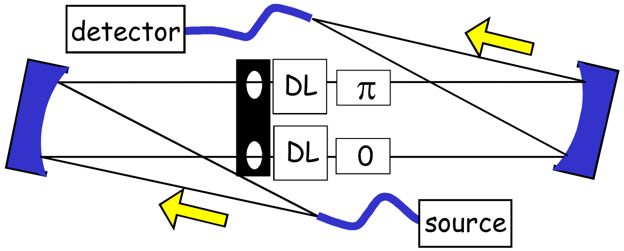
- James Webb Space Telescope
- Terrestrial Planet Finder- Coronagraph
- Terrestrial Planet Finder- Interferometer

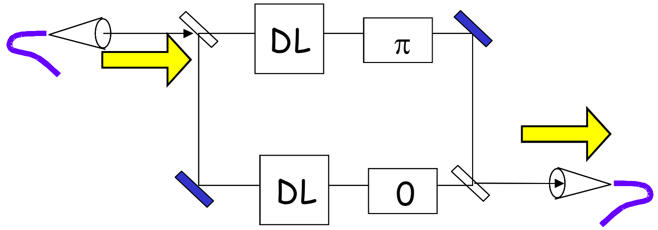


Europ

R&D : achromatic phase shifters

generic schemes : Young'sType or Mach-Zehnder test-benches



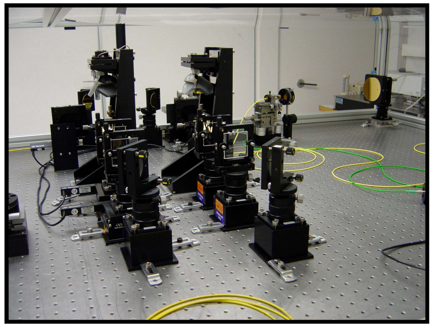


DL = delay lines

monomode optic fibers mandatory (when existing at working λ)
for spatial coherence of the source and clean outcoming wavefronts

Thales : 10^{-5}, 5% at 1.55 μm,

stability > 1 hour at $\sigma = 10^{-7}$ (2006)



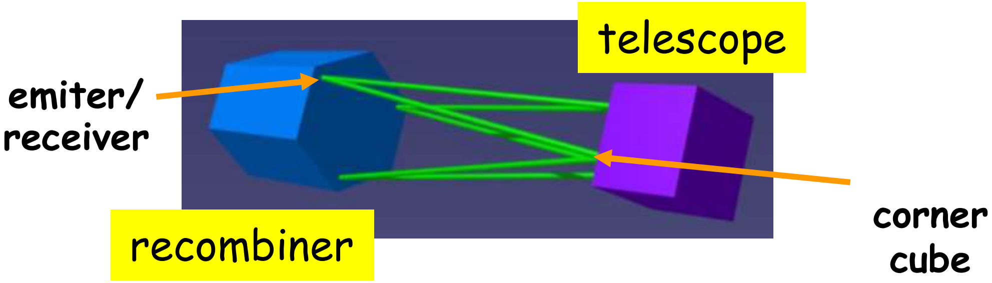
JPL : 10^{-5}, 32% at 10 μm,

stability 2 hours (2008)

R&D : flight formation control

modulated laser link (OCA)

under way



specifications

longitudinal resolution ~ 1 µm (absolute) per link

~ **1 nm (relative between interferometric arms)**

global: ~ 1 µm lateral shift , angular error box ~ 10 mas

air-sustended vehicles (JPL)

operational since 2007