10th VLTI school of interferometry

HORIZON 2020

OPTICON

JMMC

GRICAD

GRENOBLE ALPES RECHERCHE
INFRASTRUCTURE DE
CALCUL INTENSIF
ET DE DONNÉES

LAGRANGE

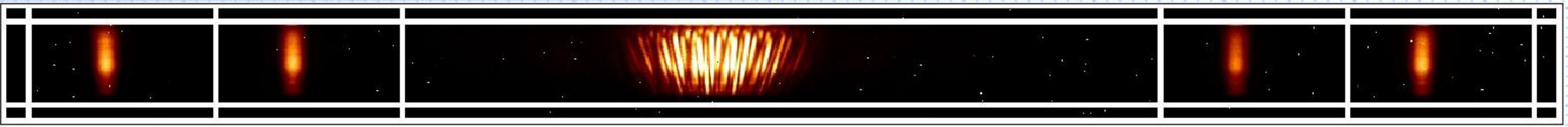
Nuclino

VLTI

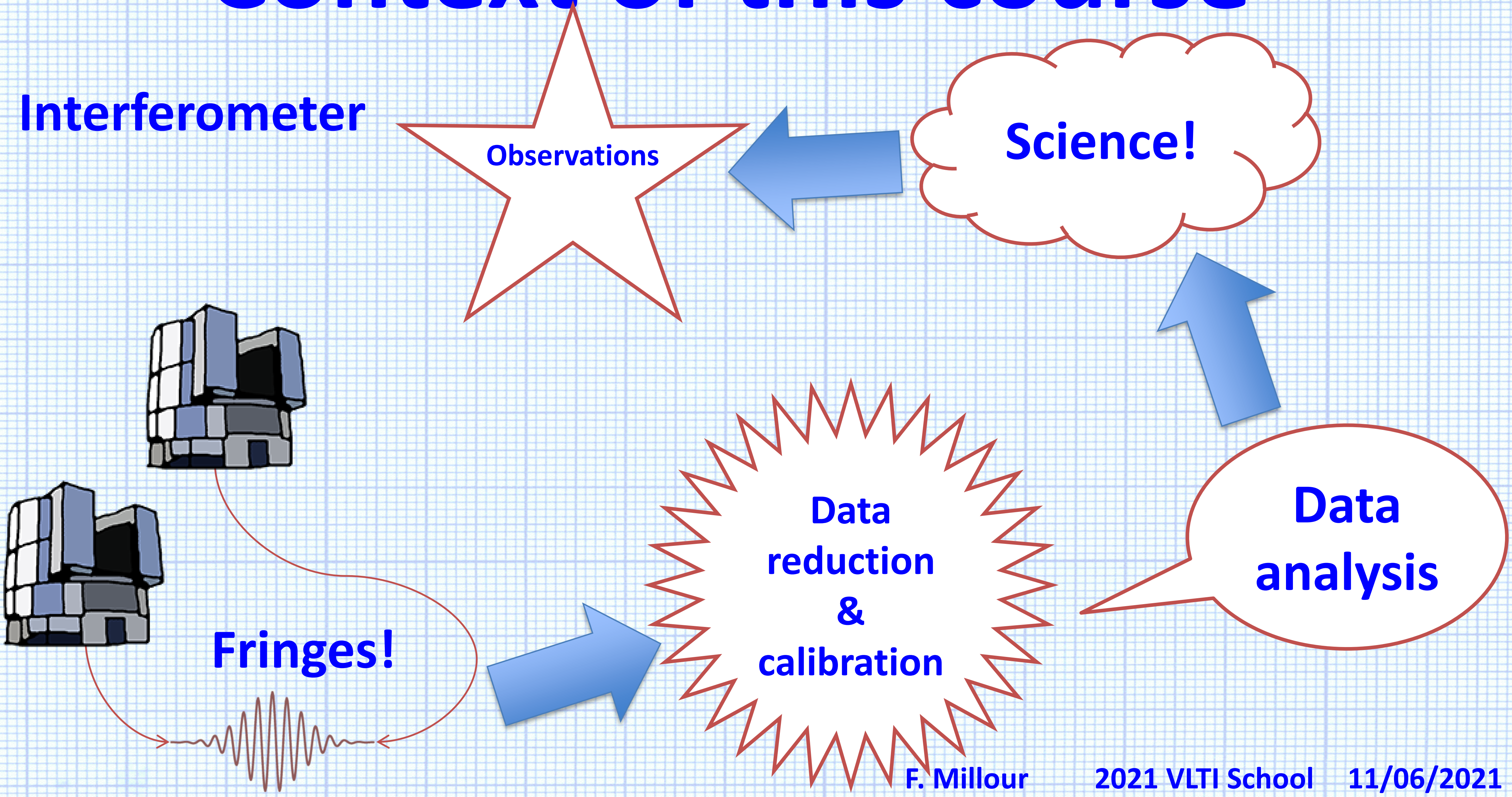
Theory of optical long-baseline interferometry data reduction

F. Millour (Lagrange lab.)
with some ideas borrowed from
O. Chesneau, C. Hummel, A. Merand,
J.B. Lebouquin, J. P. Berger, G. Perrin, etc.

MATISSE fringes



Context of this course



Outline

- Why do we care so much about data reduction?
  - What are we looking for?
  - What adversities are we fighting against?
- The interferometry observables
  - All the observables
  - Statistics
  - Calibration
- MATISSE data reduction
- Conclusions

With a practical example:

Why do we care so much about data reduction?

1^{st} of all, what are we looking for?

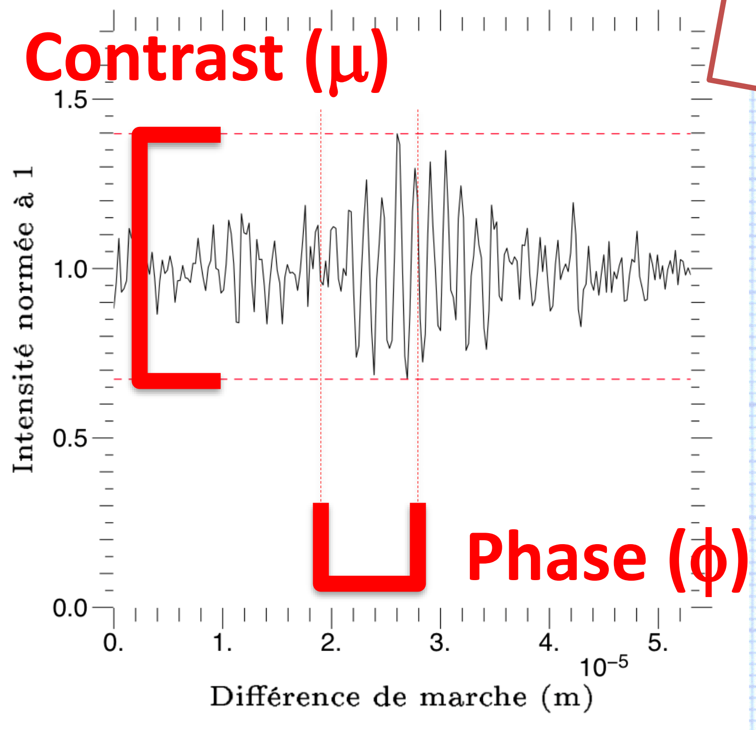
- ZVC*: complex degree of light coherence = normalized Fourier Transform of the source brightness
- Fringe = cosine modulation of light due to interferences

$$I(\delta_0) = I_0\left[1 + \mu\cos\left(\phi - 2\pi\frac{\delta_0}{\lambda}\right)\right]$$

- The fringe contrast (μ) & phase (ϕ), or fringe visibility ($V = \mu\, e^{i\phi}$)at the recombination point measures this complex degree of light coherence

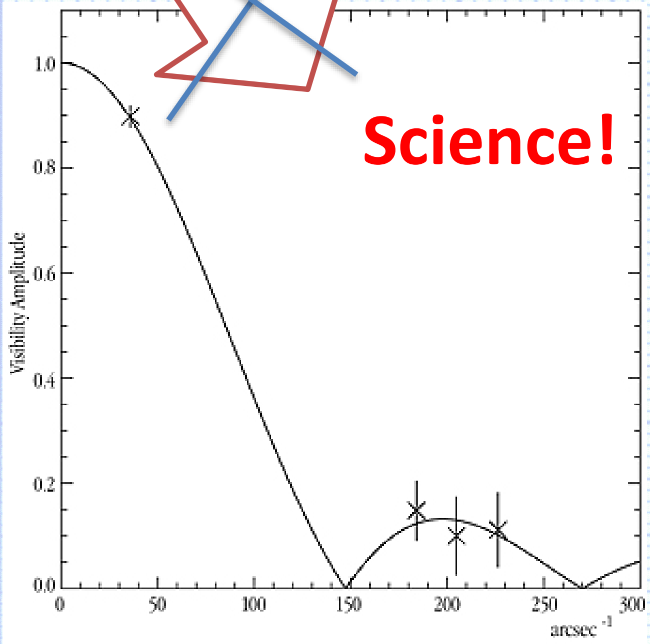
*For dummies, ZVC means: « Zernicke & van Cittert Theorem »

1st of all, what are we looking for?



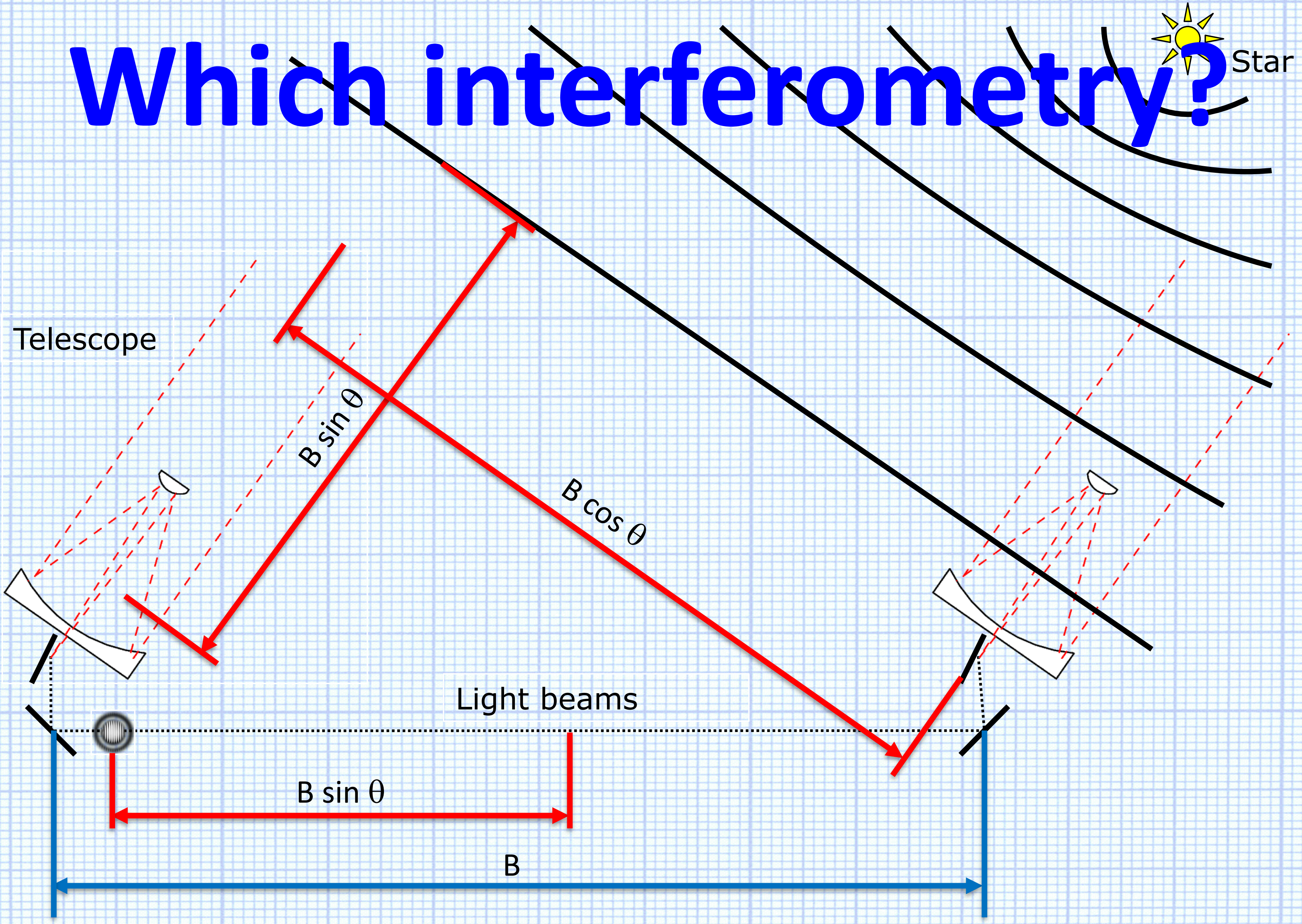
$\mu e^{i\phi}$ = TF[object](B/λ)

This course is about how do we get μ and ϕ

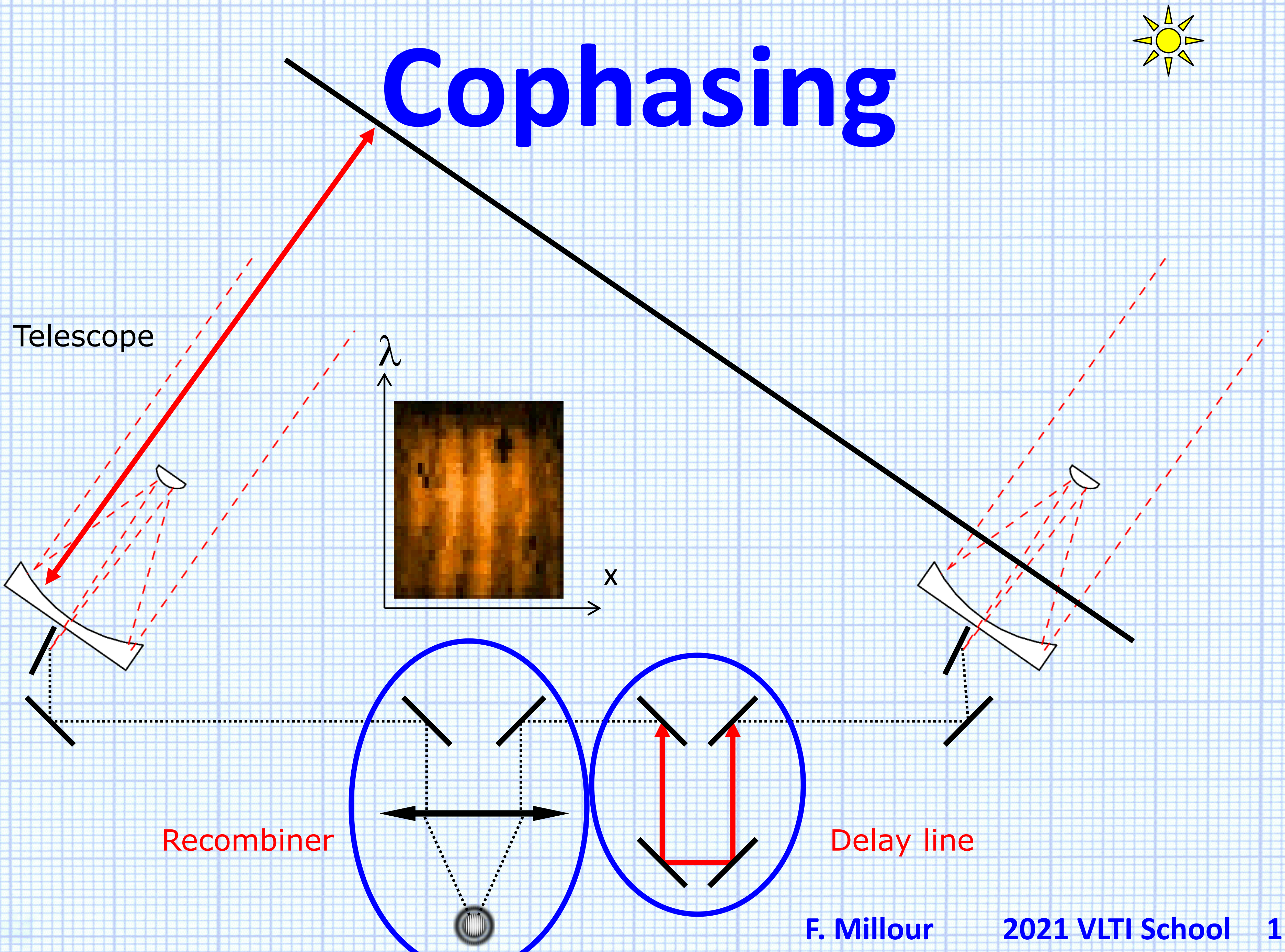


Frequency (B/λ)

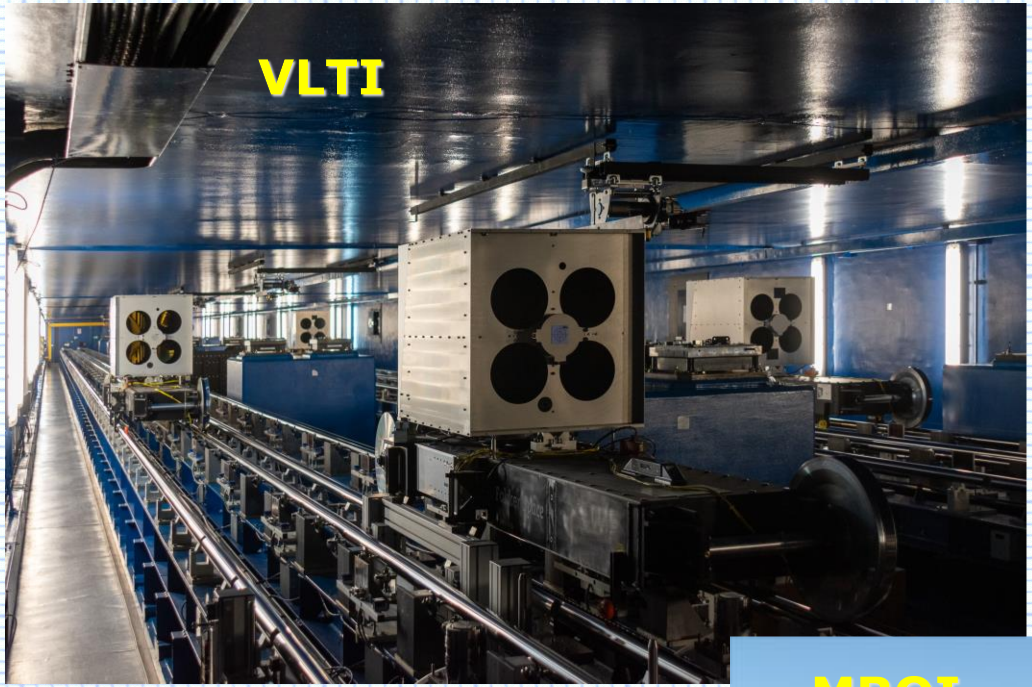
Which interferometry?



Cophasing

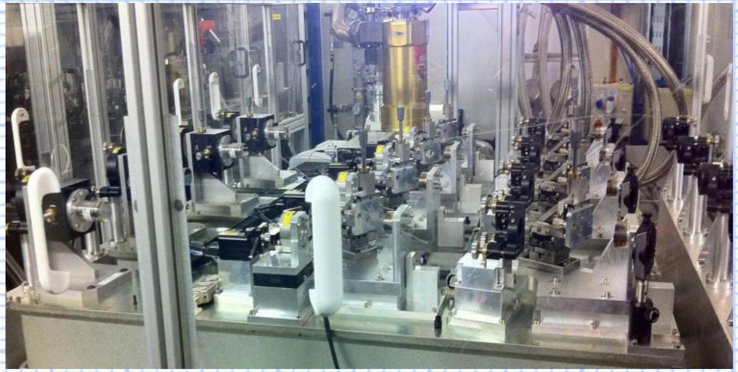


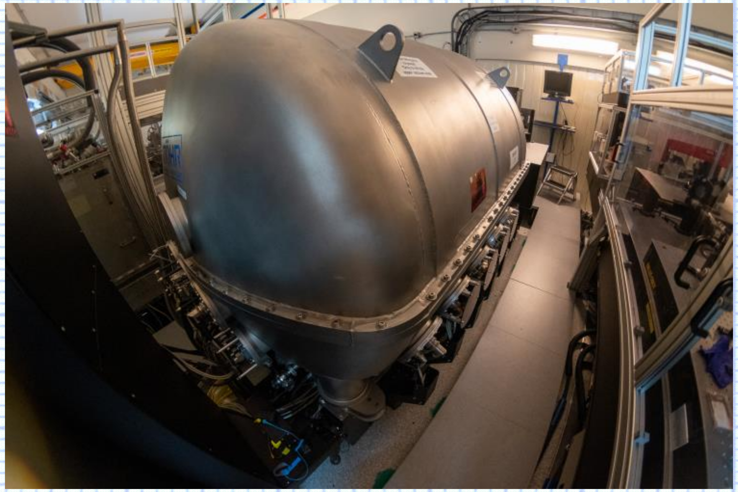
Delay lines

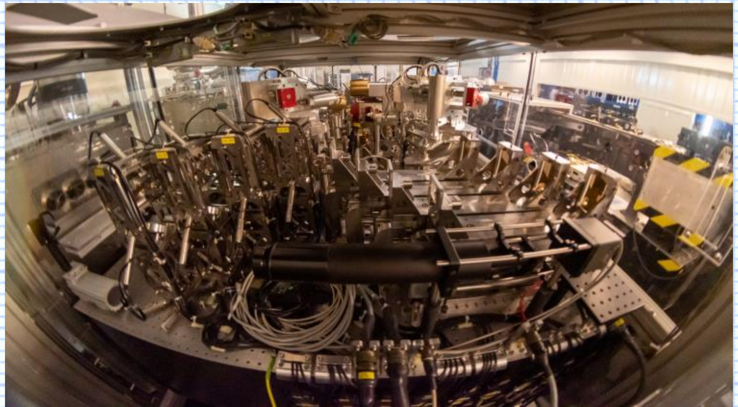


http://www.mro.nmt.edu/Projects/interferometer.htm

Recombiners







PIONIER

- 4 telescopes
- H-band
  1.65μm
- Wideband

GRAVITY

- 4 telescopes
- K-band
  2-2.5μm
- Spectral resolutions
  R=30 → 4000
- Astrometry

MATISSE

- 4 telescopes
- L. M & N-bands
  3-13μm
- Spectral resolutions
  R=30 → 3000

In a near future (2025…)

GRAVITY+

- 4 telescopes
- K-band (2-2.5μm)
- High sensitivity!

1st of all, what are we looking for?

- An interferometer produces
  - a lot of data with
  - tons of noise

Example: a MATISSE N-band file (1mn) weights 600Mb

Max. compression rate: 20%

- A DRS aims a getting the best results out of all this… noise!

Outline

- Why do we care so much about data reduction?
  - What are we looking for?
  - What adversities are we fighting against?
- The interferometry observables
  - All the observables
  - Statistics
  - Calibration
- MATISSE data reduction
- Conclusions

What are the issues?

Fringe signal has a simple expression:

$$I(\delta_0) = I_0\left[1 + \mu\cos\left(\phi - 2\pi\frac{\delta_0}{\lambda}\right)\right]$$

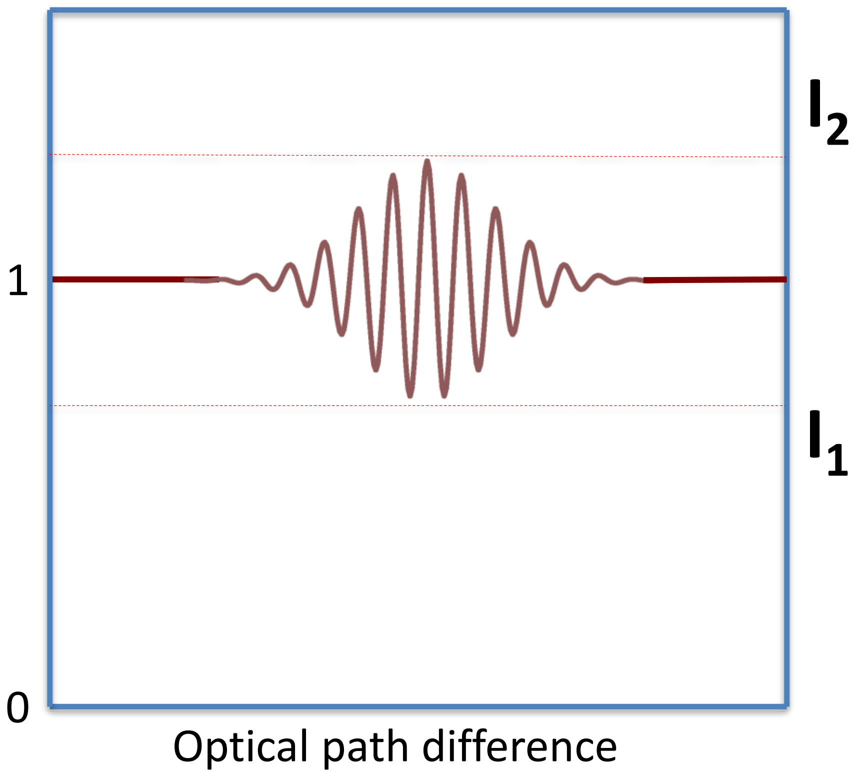
Visibility can be estimated linearly:

$$\Re(V) = I(0) - 1 \qquad \Im(V) = I(\lambda/4) - 1$$

So, there are no issues…

What are the issues?

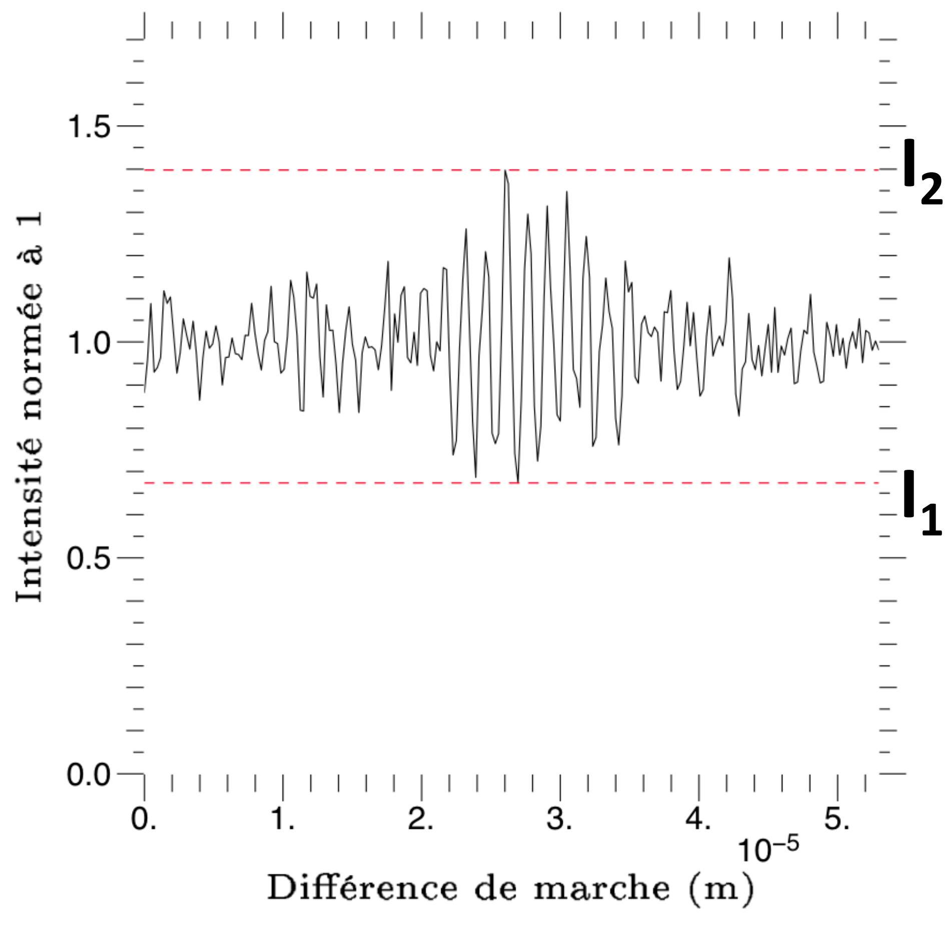
Fake data



$$\mu = \frac{I_2 - I_1}{I_2 + I_1}$$

What are the issues?

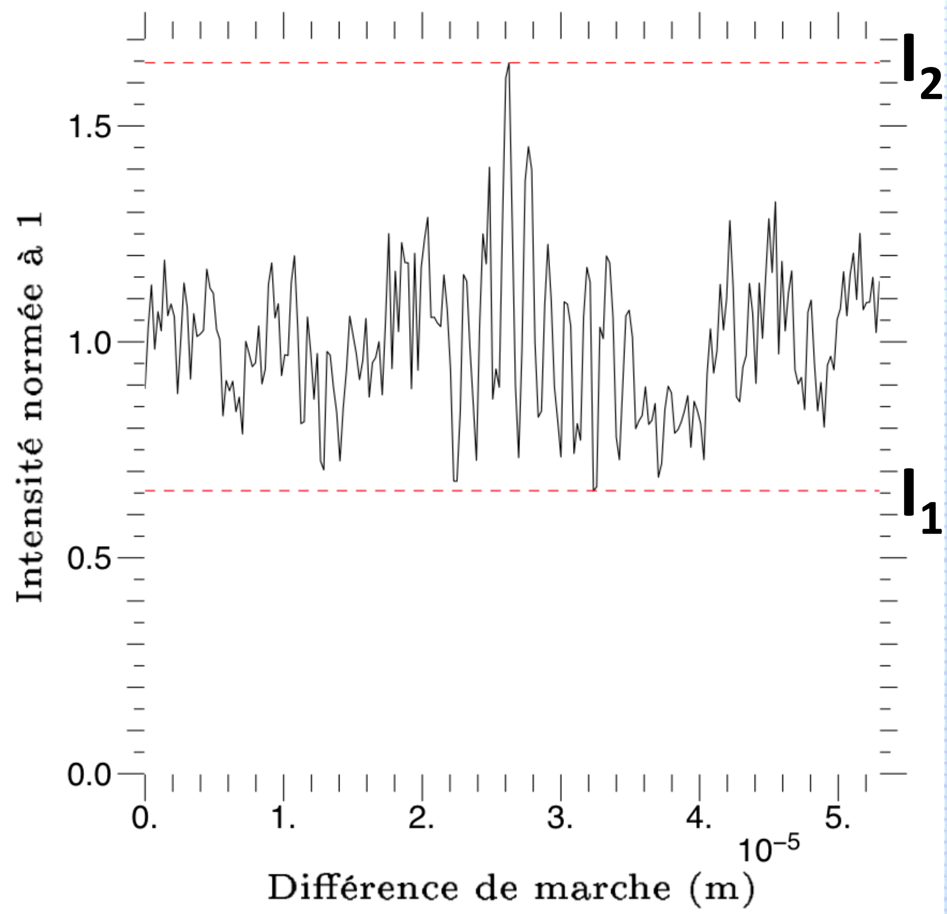
Real data (processed)



$$\mu \approx \frac{I_2 - I_1}{I_2 + I_1}$$

What are the issues?

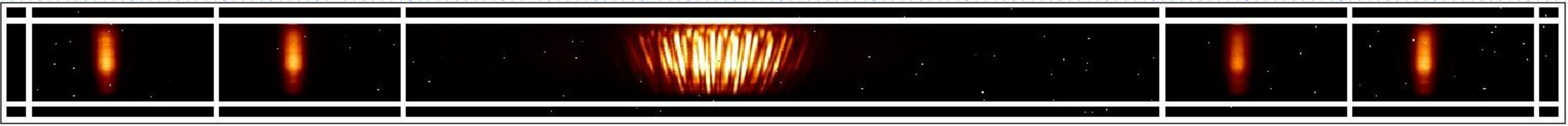
Real data (raw)



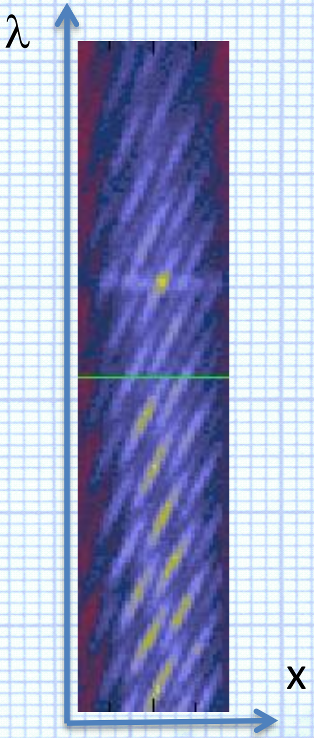
$$\mu \neq \frac{I_2 - I_1}{I_2 + I_1}$$

Real data look like this:

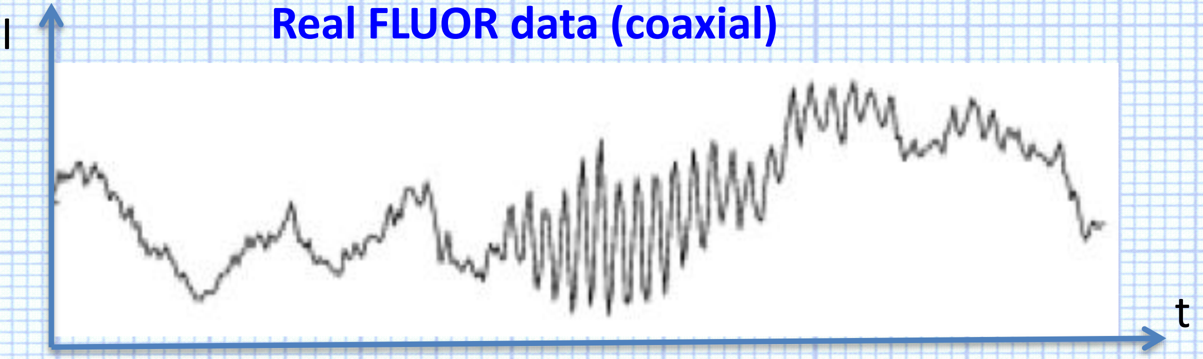
Real MATISSE data (multiaxial)



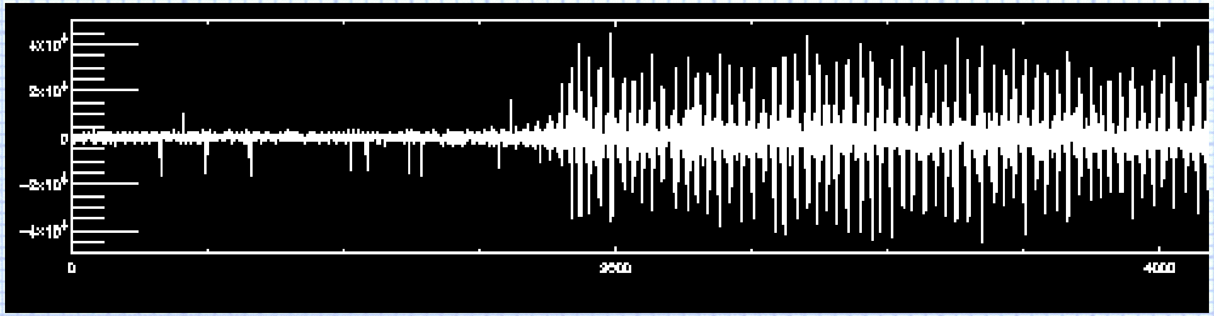
Real AMBER data (multiaxial)



Real FLUOR data (coaxial)



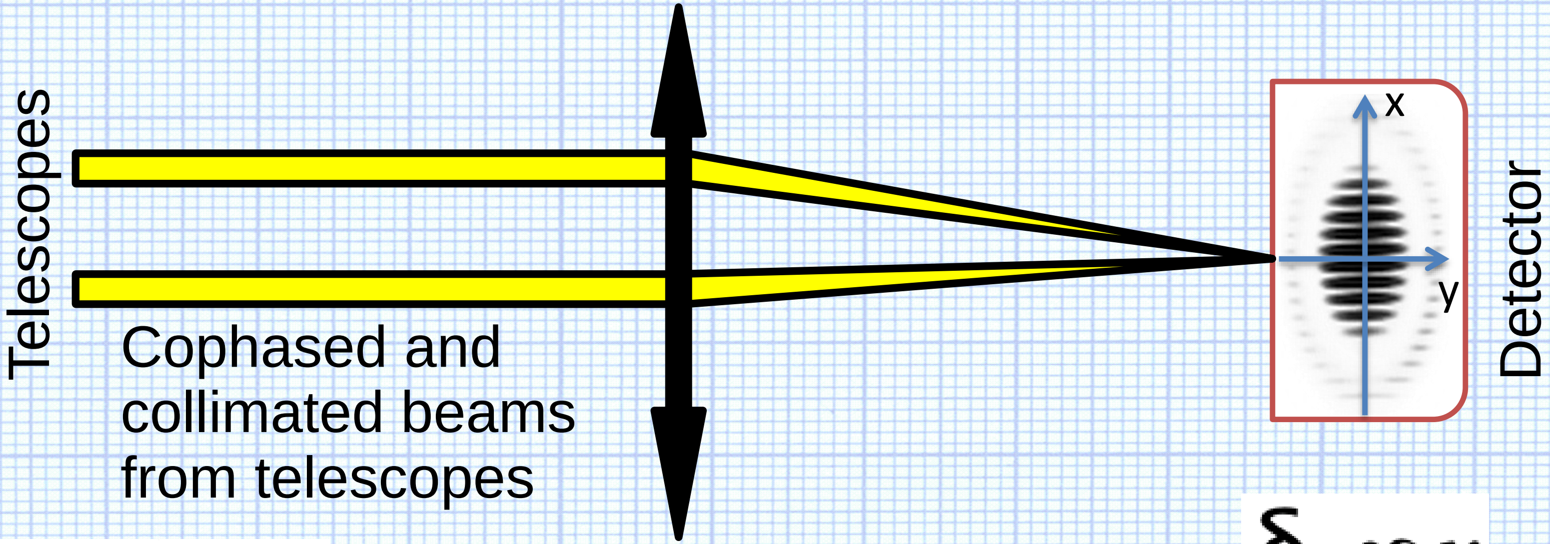
Real MIDI data (coaxial)



What means
- **Multiaxial?**
- **Coaxial?**

Multiaxial recombination

- Overlap the beams with a tilt to produce a variation of OPD (fringes of equal thickness)

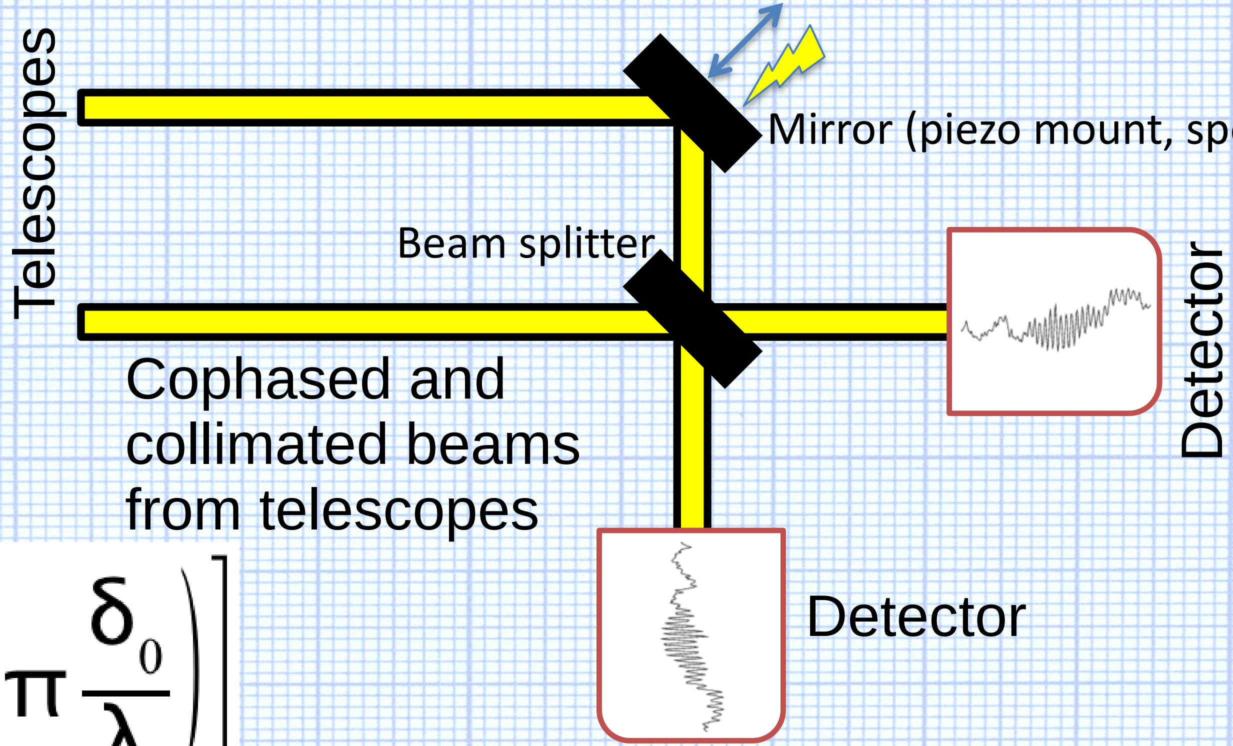


$$\delta_0 \propto x$$

$$I(\delta_0) = I_0\left[1 + \mu\cos\left(\phi - 2\pi\frac{\delta_0}{\lambda}\right)\right]$$

Coaxial recombination

- Overlap the beams on top of each other. OPD is varied with an input piston (fringes of equal path)



$$\delta_0 \propto v\,t$$

$$I(\delta_0) = I_0\left[1 + \mu\cos\left(\phi - 2\pi\frac{\delta_0}{\lambda}\right)\right]$$

What are the issues?

Real fringes have a complicated expression:

$$I(\delta_0) = I_0\left[1 + \mu \cos\left(\phi - 2\pi\frac{\delta_0}{\lambda}\right)\right]$$

What are the issues?

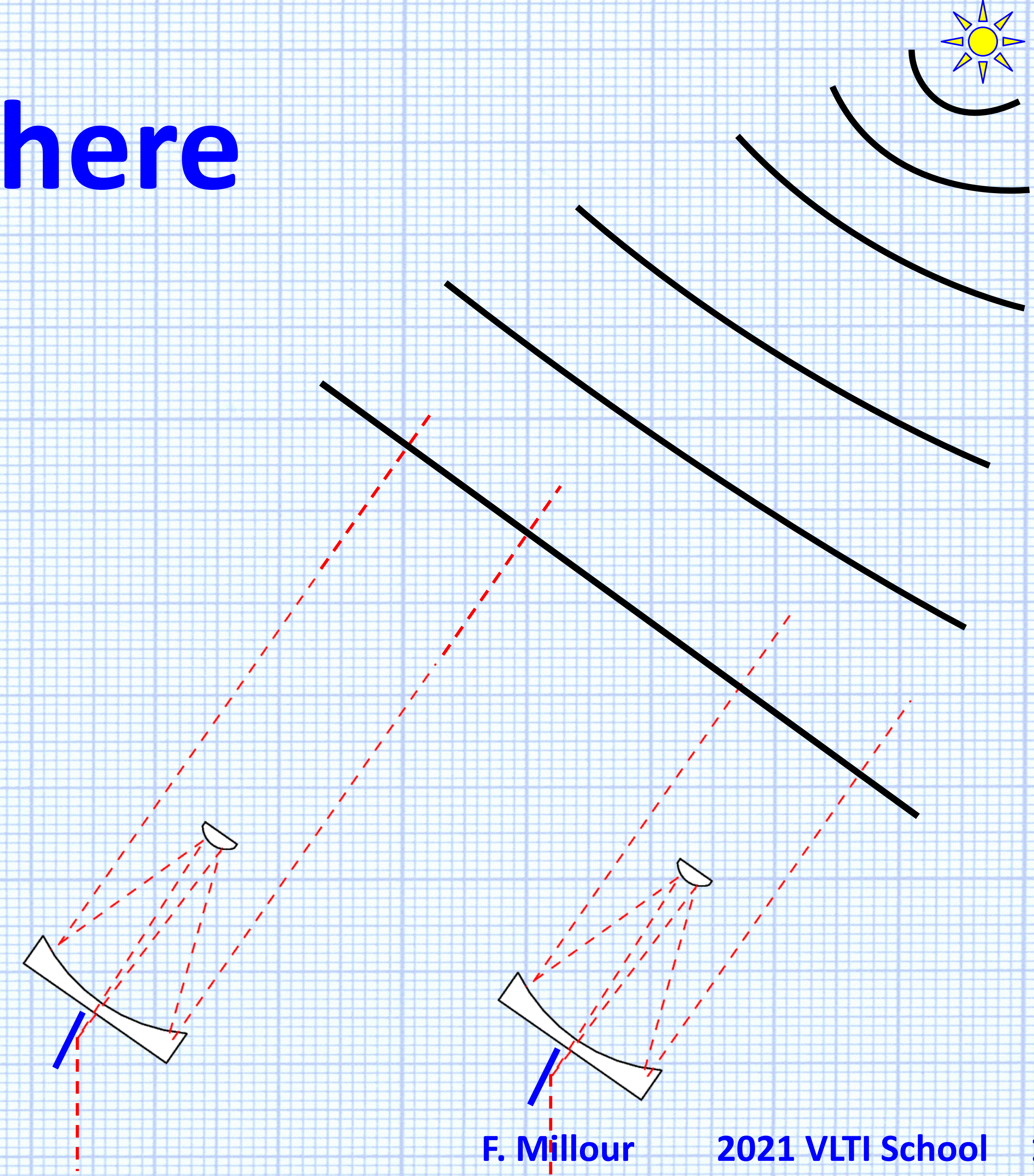
Real fringes have a complicated expression:

$$I(\delta_0,t)=\left[\frac{I_a(t)+I_b(t)}{2}+\sqrt{I_a(t)I_b(t)}\cdot e^{-\sigma^2_{turb}(t)}\cdot \mathrm{sinc}\left(2\pi\frac{\delta_0+\delta(t)}{R\lambda}\right)\cdot\mu\cos\left(\phi-2\pi\frac{\delta_0+\delta(t)}{\lambda}\right)\right]+n_b(t)+\sigma(t)$$

1. Photometry unbalance
2. Jitter
3. Fringe motion
4. Spectral decoherence
5. Additive bias
6. Additive noise

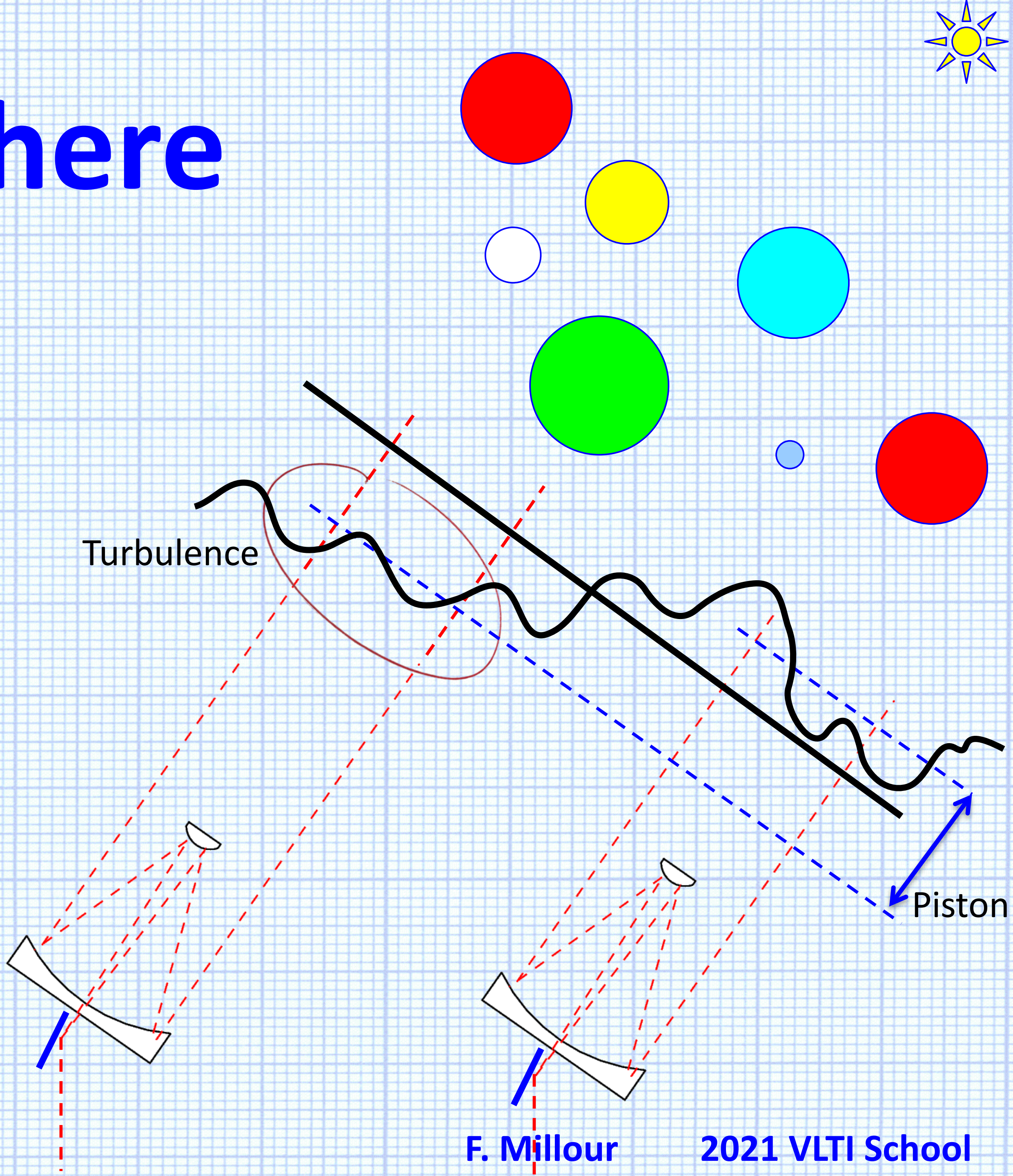
+ Bandwidth smearing
+ Baseline smearing
+ Polarization effects

The atmosphere



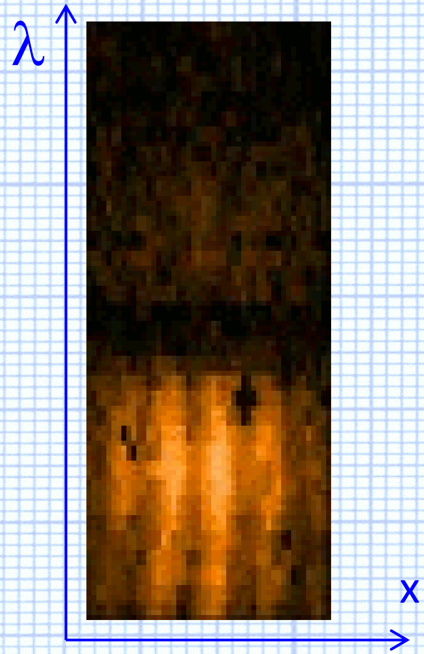
The atmosphere

- Atmospheric turbulence cells distort the incoming wavefront
- Pupil wavefront distortion
  - Turbulence
- Shift between pupils
  - Piston or OPD



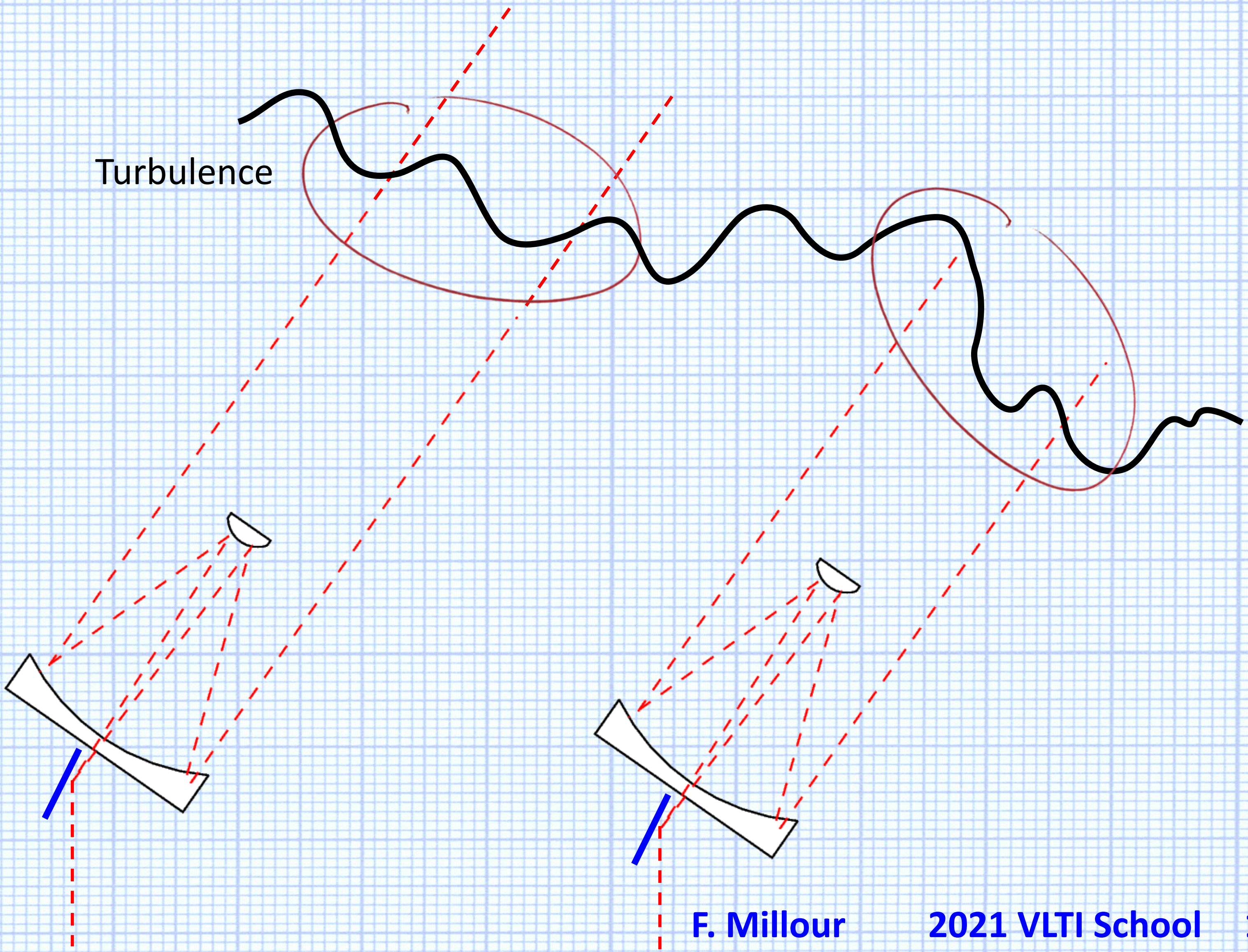
The piston creates 2 effects

- **Fringe motion**
  - Time-dependent phase shift of the fringes
    ➔ Fringe phase is lost!
- **Fringe blurring**
  - Contrast loss due to finite integration time
    ➔ Fringe amplitude is lost!

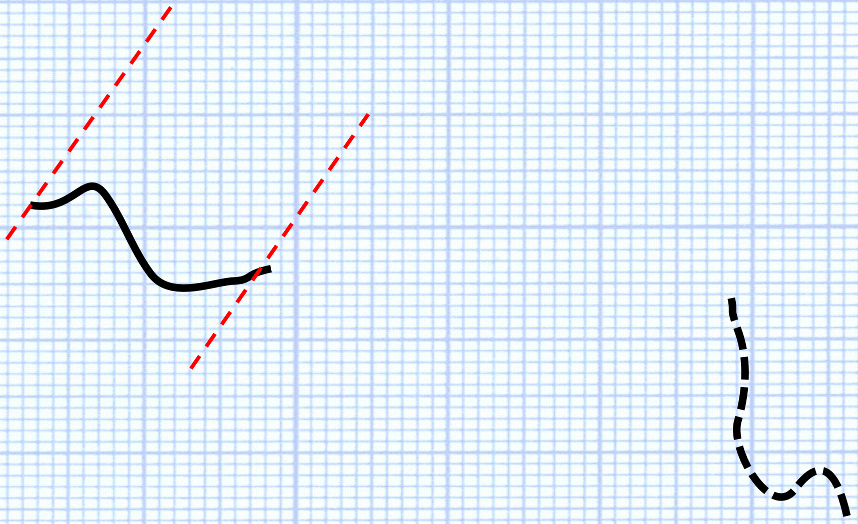


$$I\left(\delta_0, t\right) = e^{-\sigma^2_{\text{jitter}}(t)} \mu \cos\left(\phi - 2\pi \frac{\delta_0 + \delta(t)}{\lambda}\right)$$

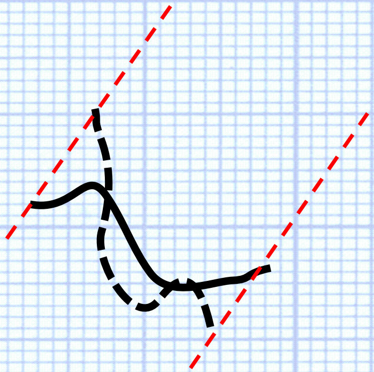
The turbulence



The turbulence



The turbulence



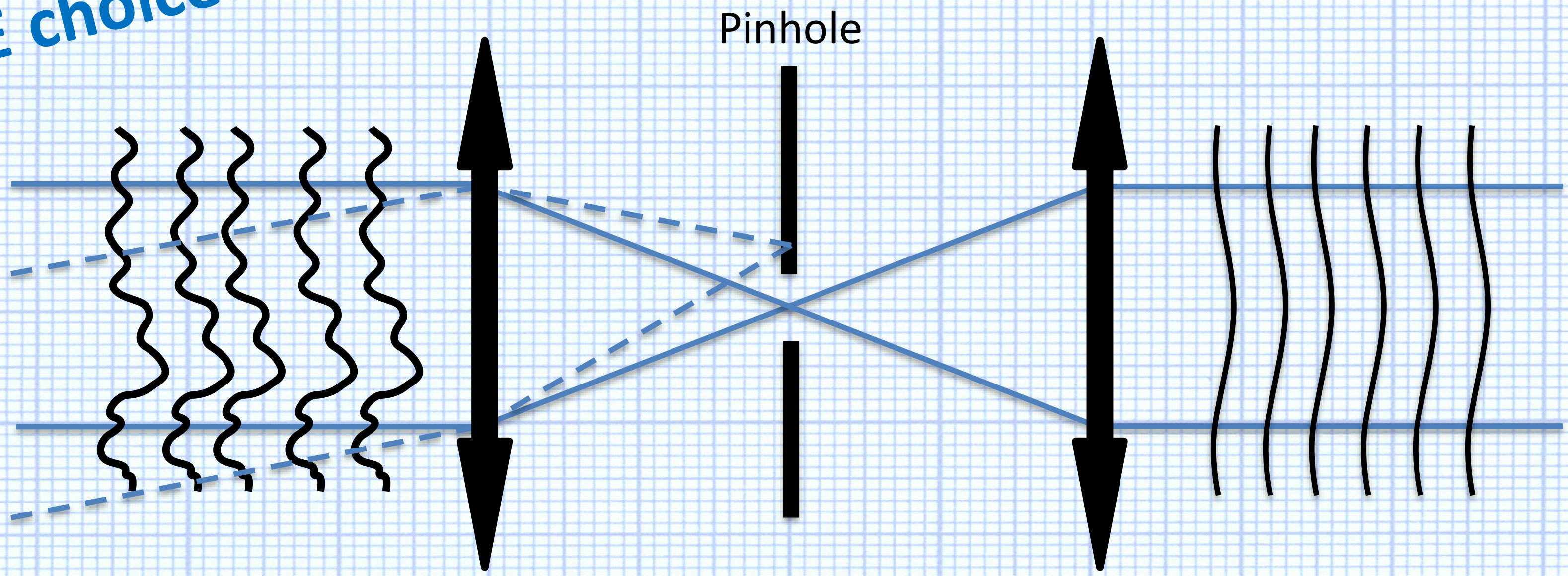
$$\rho_{turb} = e^{-\sigma^2_{turb}}$$

- **Visibility reduced by wavefront variance over pupil**
  - **If turbulence small ➔ small effect (IR interferometry)**
  - **Reduce telescopes size (SUSI, NPOI)**
  - **Use adaptive optics (better solution)**
  - **Use another technique to flatten the wavefront**

Modal filtering

- A pinhole placed in an afocal system filters out wavefront corrugations

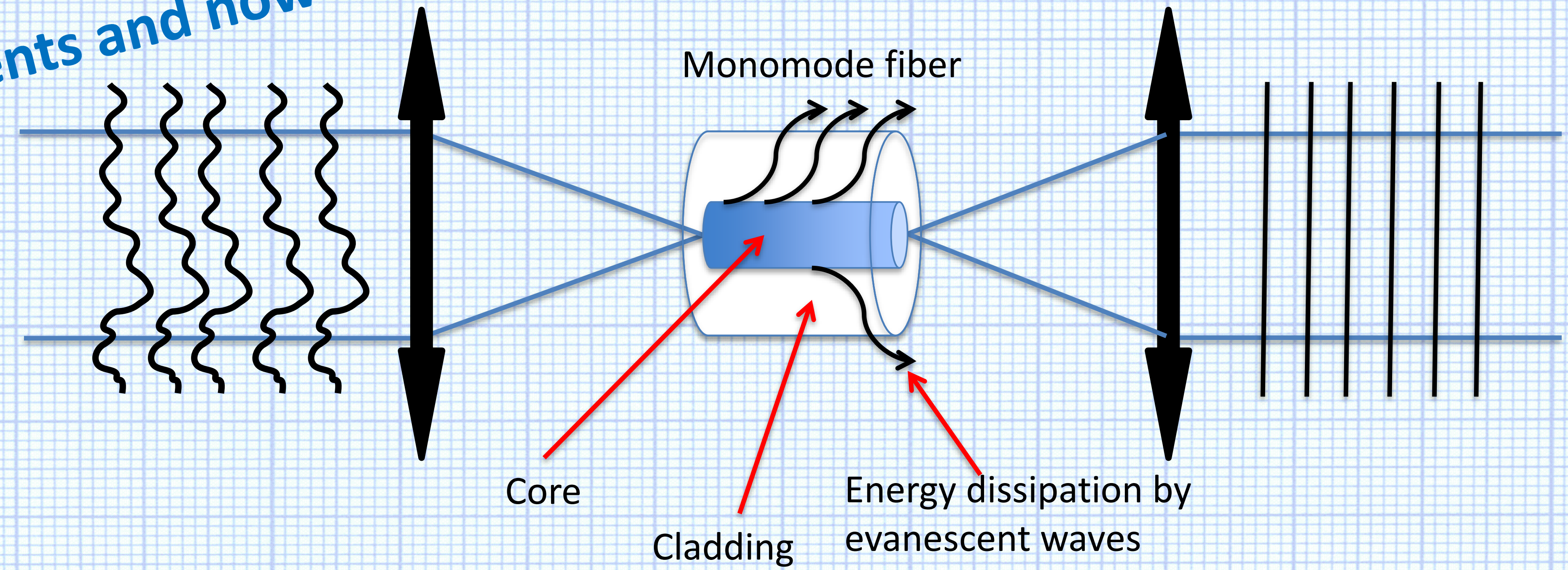
The MATISSE choice!



Modal filtering

- **A monomode optical fiber does the work even better**
  - **The corrugated part of the wavefront is rejected by the fiber**
  - **Corrugated wavefront ➔ flux variations**

Choice for NIR instruments and now VIS!



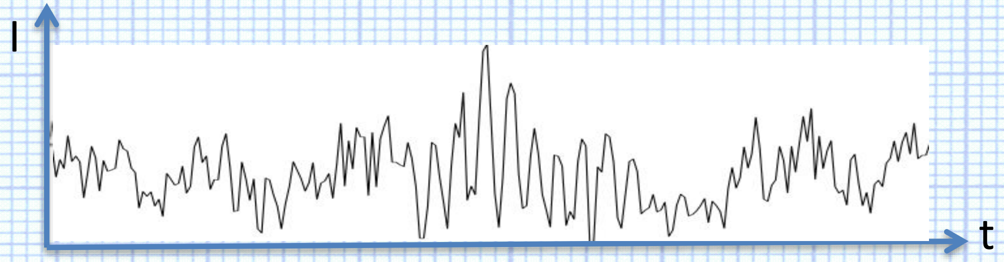
Modal filtering

$$I \sim \frac{I_a + I_b}{2} + \sqrt{I_a I_b} \cdot e^{-\sigma^2_{turb}} \cdot \mu \cos\left(\phi - 2\pi\frac{\delta_0}{\lambda}\right)$$

- **is transformed into**

$$I \sim \frac{I_a(t) + I_b(t)}{2} + \sqrt{I_a(t) I_b(t)} \cdot 1 \cdot \mu \cos\left(\phi - 2\pi\frac{\delta_0}{\lambda}\right)$$

That's why we have signals looking like that:



Remember:
OPD = vt
in coaxial

What are the issues? Photometry unbalance

$$I(\delta_0) = I_0\left[1 + \mu\cos\left(\phi - 2\pi\frac{\delta_0}{\lambda}\right)\right]$$

- In case of unbalanced beams, the interferogram becomes:

$$I(\delta_0) = \frac{I_a + I_b}{2} + \sqrt{I_a I_b}\,\mu\cos\left(\phi - 2\pi\frac{\delta_0}{\lambda}\right)$$

- Photometry is variable (scintillation, alignment, filtering):

$$I(\delta_0, t) = \frac{I_a(t) + I_b(t)}{2} + \sqrt{I_a(t)\, I_b(t)}\,\mu\cos\left(\phi - 2\pi\frac{\delta_0}{\lambda}\right)$$

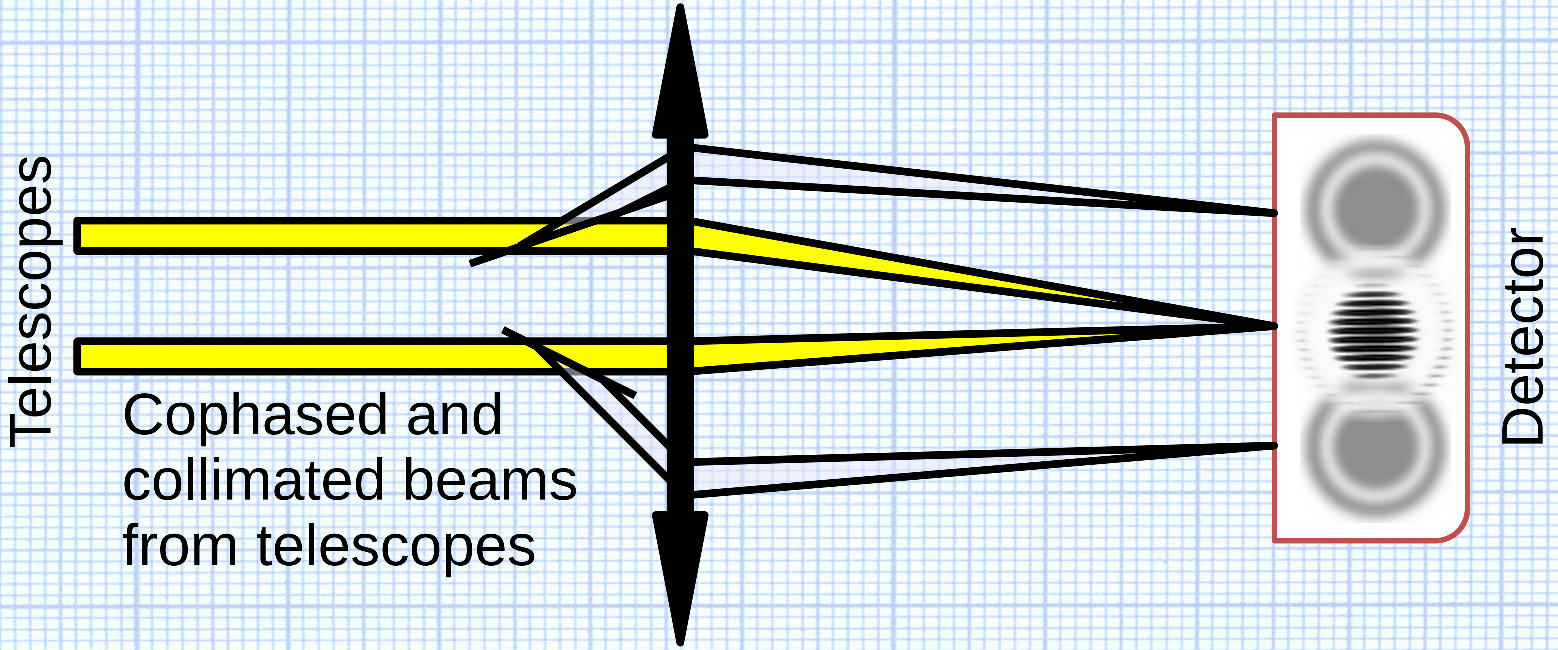
- Instantaneous contrast becomes biased by: $\frac{2\sqrt{I_a I_b}}{I_a + I_b}$

= 0.94 if $I_a = 2\,I_b$

= 0.57 if $I_a = 10\,I_b$

What are the issues? Photometry unbalance

The solution: photometric channels

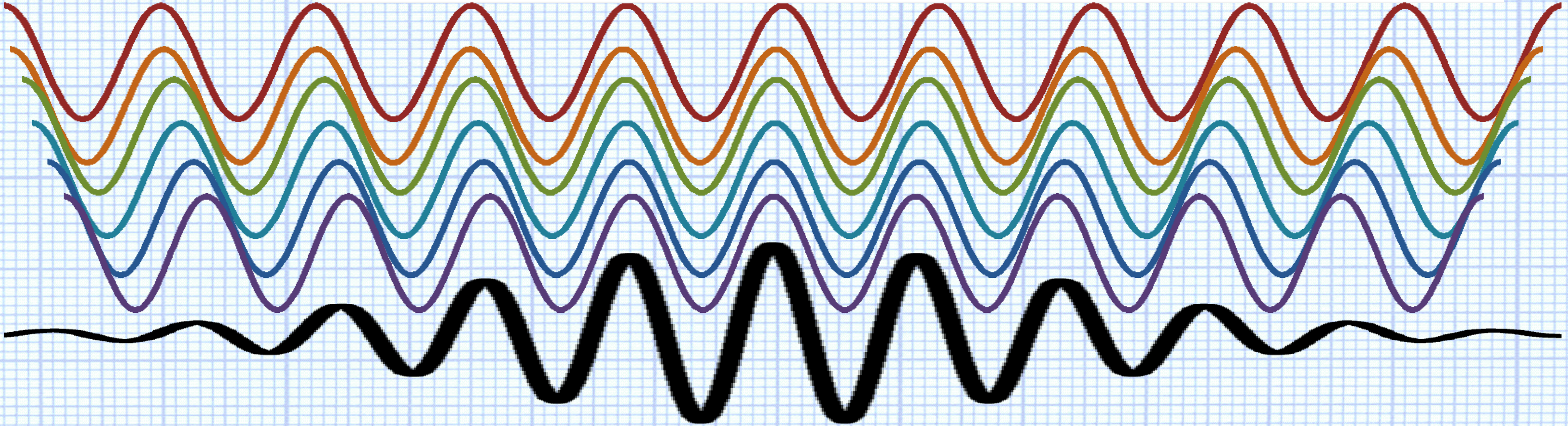


- **Measure I_a and I_b using shutters before or after taking fringes**
- **Monitor photometries simultaneously**

What are the issues? Spectral decoherence

- Fringes are not exactly cosine due to spectral bandwidth

$$I(\delta_0) = I_0 \left[1 + \int_{\lambda_1}^{\lambda_2} \mu \cos\left(\phi - 2\pi \frac{\delta_0}{\lambda} \right) d\lambda \right]$$

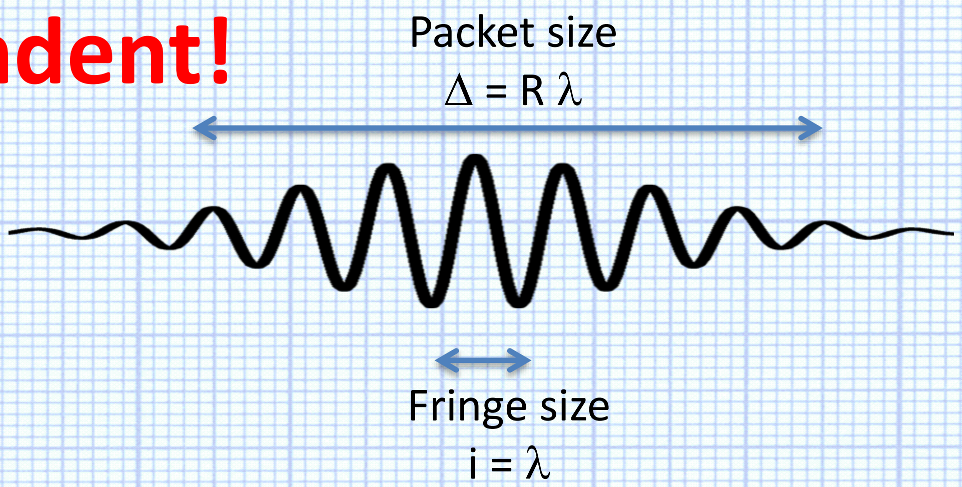


What are the issues? Spectral decoherence

- **With a square filter:**

$$I(\delta_0) = I_0\left[1 + \mathrm{sinc}\left(2\pi\frac{\delta_0}{R\lambda}\right)\cdot\mu\cos\left(\phi - 2\pi\frac{\delta_0}{\lambda}\right)\right]$$

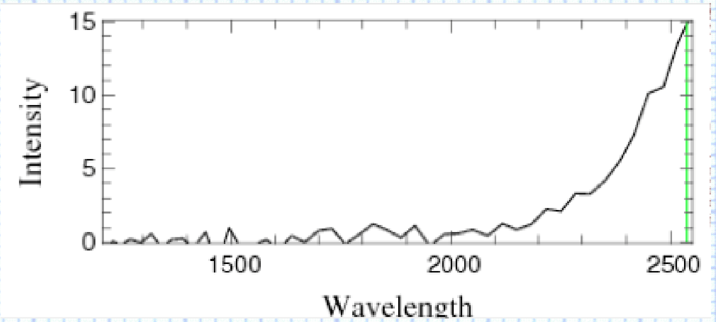
- **Fringe contrast is OPD-dependent!**
- **How to cope with that?**
  - **Be at OPD 0 !**
  - **Increase spectral resolution R**



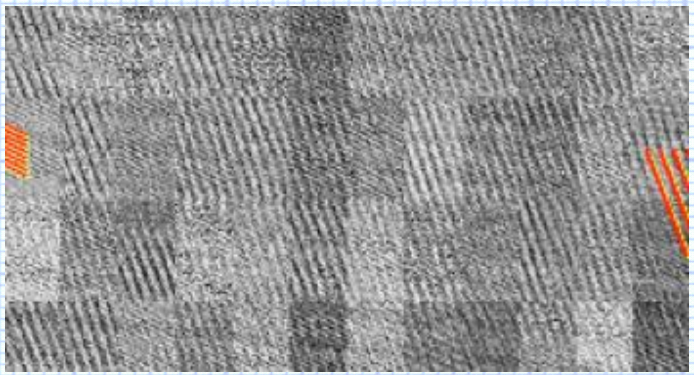
What are the issues?
Biases

- A bias is some additive value with non-zero mean
- Examples:
  - Detector bias
  - Thermal background
  - EM detector perturbations
  - Photon noise bias
- How to cope with it?
  - Estimate it and subtract it!

AMBER: Sky brightness



AMBER: Dark exposure



Spurious fringes induced by electromagnetic disturbances (Li Causi et al. 2007)

What are the issues?
Additive noises

- A noise is some additive value with a zero mean
- Examples:
  - Photon noise from the source
  - Photon noise from thermal background
  - Detector noise
- How to cope with it?
  - Statistics!
  - Error estimates!

Summary

Real fringes have a complicated expression:

$$I(\delta_0,t)=\frac{I_a(t)+I_b(t)}{2}+\sqrt{I_a(t)I_b(t)}\cdot e^{-\sigma^2_{turb}(t)}\cdot \mathrm{sinc}\left(2\pi\frac{\delta_0+\delta(t)}{R\lambda}\right)\cdot\mu\cos\left(\phi-2\pi\frac{\delta_0+\delta(t)}{\lambda}\right)+n_b(t)+\sigma(t)$$

1. Photometry unbalance
2. Jitter
3. Fringe motion
4. Spectral decoherence
5. Additive bias
6. Additive noise

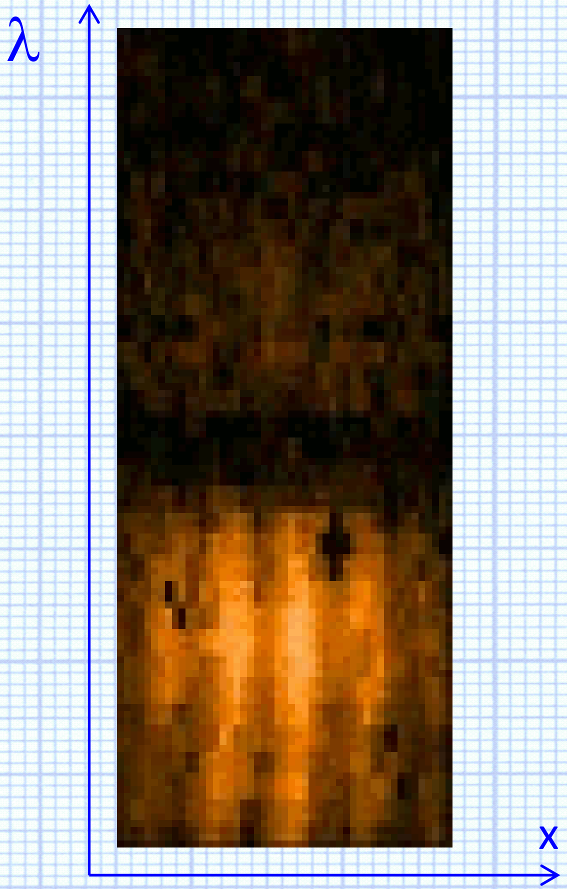
A note about « visibility »

- « Visibility » is often referred as the fringe contrast & not the complex visibility of the object
- The measured visibility is not the visibility of the object:
  - Instrument's response is not 100% of contrast (polarization, vibrations)
  - Atmosphere affects fringe contrast (jitter, turbulence)
- From now on, « visibility » means uncalibrated fringe contrast (to make it simple…)

Outline

- Why do we care so much about data reduction?
  - What are we looking for?
  - What adversities are we fighting against?
- The interferometry observables
  - All the observables
  - Statistics
  - Calibration
- MATISSE data reduction
- Conclusions

All the observables



Complex coherent flux:

$$C^{a,b} = \sqrt{I^a I^b} \cdot \mu_{\text{inst+atm}} \cdot \mu^{a,b}_{\text{object}}$$

Visibility:

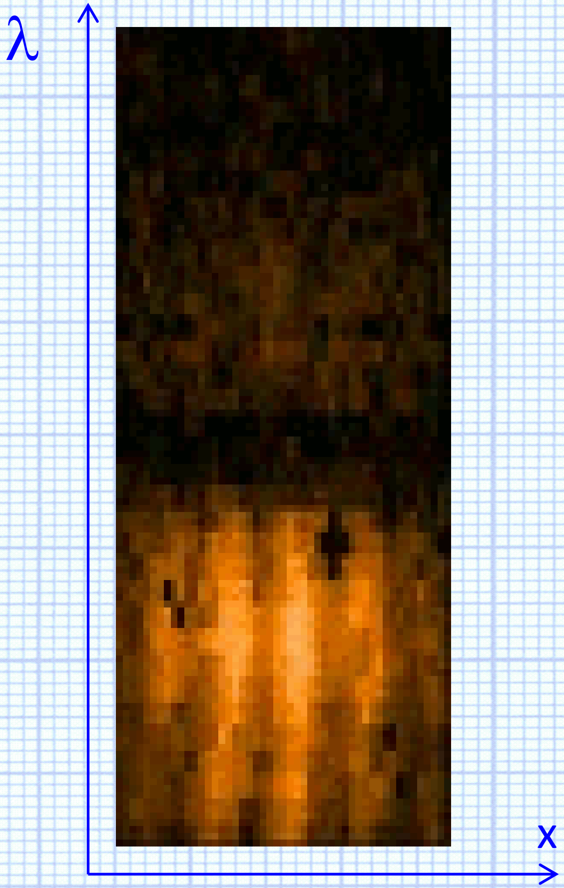
$$\mu^{a,b}_{\text{object}} = \frac{C^{a,b}}{\sqrt{I^a I^b} \cdot \mu_{\text{inst+atm}}}$$

~~**Phase:**~~

$$\phi^{a,b}_{\text{object}} = \arg\left(C^{a,b}\right)$$

All the observables

In real life:



Complex coherent flux:

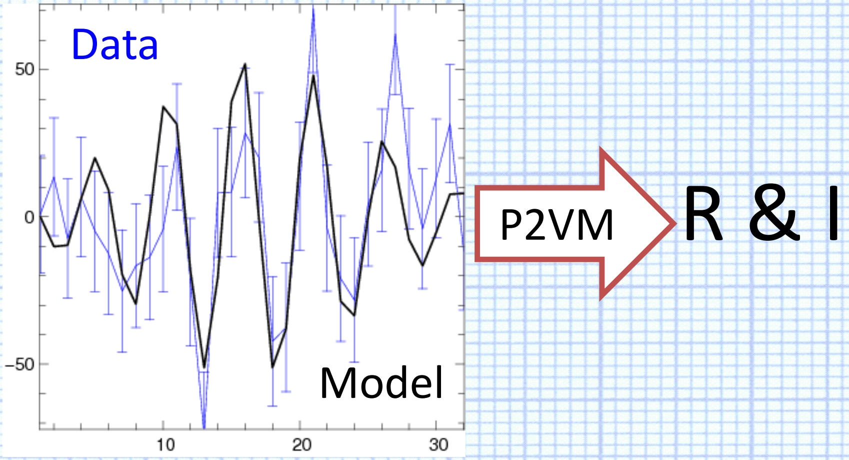
$$C^{a,b} = \sqrt{I^a I^b} \cdot \mu_{\mathrm{inst+atm}} \cdot \mu^{a,b}_{\mathrm{object}}$$

- Spectrum
- Visibility squared
- Differential phase
- Closure phase

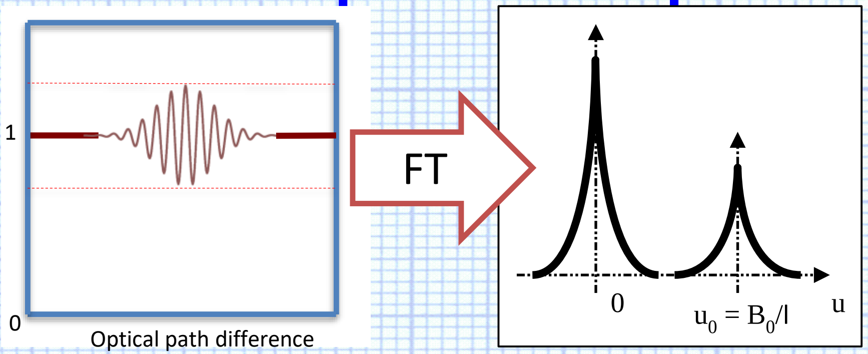
- Phase reference
- Differential visibility
- Coherent (or linear) visibility
- “differential closure phase”
- Closure amplitude

How do we get coherent flux?

- **Image-plane method(s)**
  - Image space fringe-fitting
    - ABCD, P2VM
      - We get directly R & I of the coherent flux



- **Fourier-plane method(s)**
  - Fringes look like a cosine
    - signature is a single peak in the Fourier plane
      - Amplitude of the peak = coherent flux
      - Phase of the peak = phase



ABCD vs Fourier

- **Image-plane method(s)**
  - Strong a priori (model of the fringes)
  - Extra data needed to build fringe model
  - Optimized: the fringe packet is modelized using the instrument itself

- **Fourier-plane method(s)**
  - No a priori except « fringes look like a cosine »
  - Extra data needed to integrate fringe peak
  - Not optimized: a fringe packet is not really a sine wave

Visibility estimator

- **Coherent flux:**

$$C^{a,b} = \sqrt{I^a I^b} \cdot \mu_{\mathrm{inst+atm}} \cdot \mu^{a,b}_{\mathrm{object}}$$

- **Visibility:**

$$\mu^{a,b}_{\mathrm{object}} = \frac{\left|C^{a,b}\right|}{\sqrt{I^a I^b} \cdot \mu_{\mathrm{inst+atm}}}$$

Outline

- Why do we care so much about data reduction?
  - What are we looking for?
  - What adversities are we fighting against?
- The interferometry observables
  - All the observables
  - Statistics
  - Calibration
- MATISSE data reduction
- Conclusions

Visibility estimator

$$\mu_{\text{object}}^{a,b} = \frac{\left|C^{a,b}\right|}{\sqrt{I^a I^b} \cdot \mu_{\text{inst+atm}}}$$

- Modulus
- Division
- Product
- Square root

Amplitude of a complex number

$$V = \mu e^{i\phi}, \langle n \rangle = 0$$

$$\begin{aligned} V' &= V + n \\ |V'| &= |V + n| \\ \langle |V'| \rangle &= \langle |V + n| \rangle ?? \end{aligned}$$

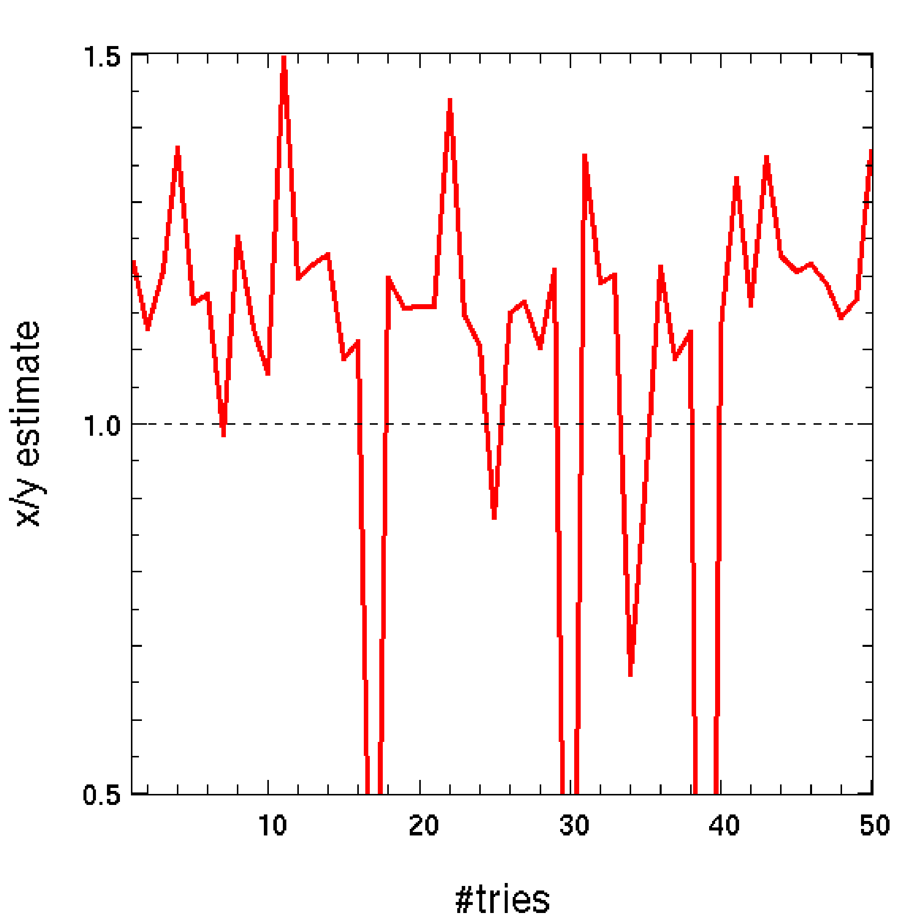
$$\begin{aligned} \langle |V'|^2 \rangle &= \langle |V + n|^2 \rangle \\ &= \langle |V|^2 \rangle + \langle 2\Re[V n] \rangle + \langle |n|^2 \rangle \\ &= |V|^2 + 2\Re[V \langle n \rangle] + \langle |n|^2 \rangle \\ &= |V|^2 + \langle |n|^2 \rangle \end{aligned}$$

- Transforms a zero-mean noise into a bias
  - Correction = estimating the bias. Here, bias= variance of the noise

Division of 2 numbers

Let $x = \alpha+n_1$ **and** $y=\beta+n_2$, $\langle x\rangle=\langle y\rangle=3$, $\sigma n_1=\sigma n_2=1$

- **How to average** $z = x/y$?
- **Let's try with** $z_1 = \langle x/y\rangle$ **(1000 samples)**



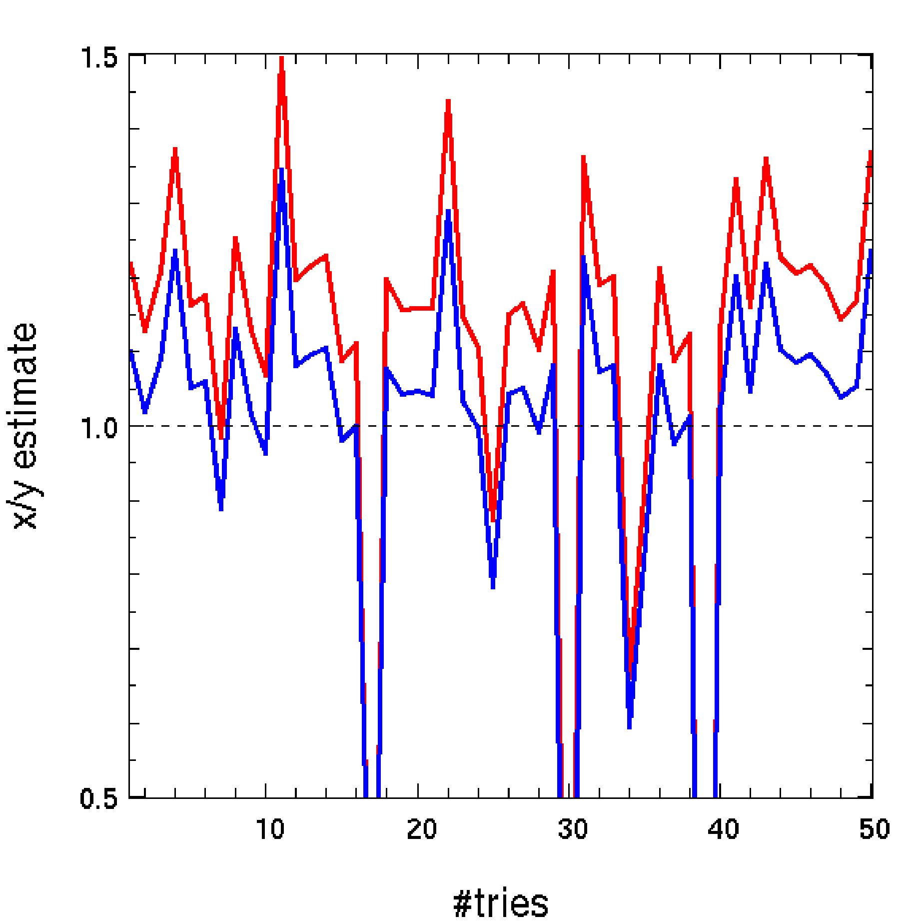
Such estimate is highly biased!

Bias depends on the noise!

Division of 2 numbers

- **Solution 1**
  - **De-bias the estimator**

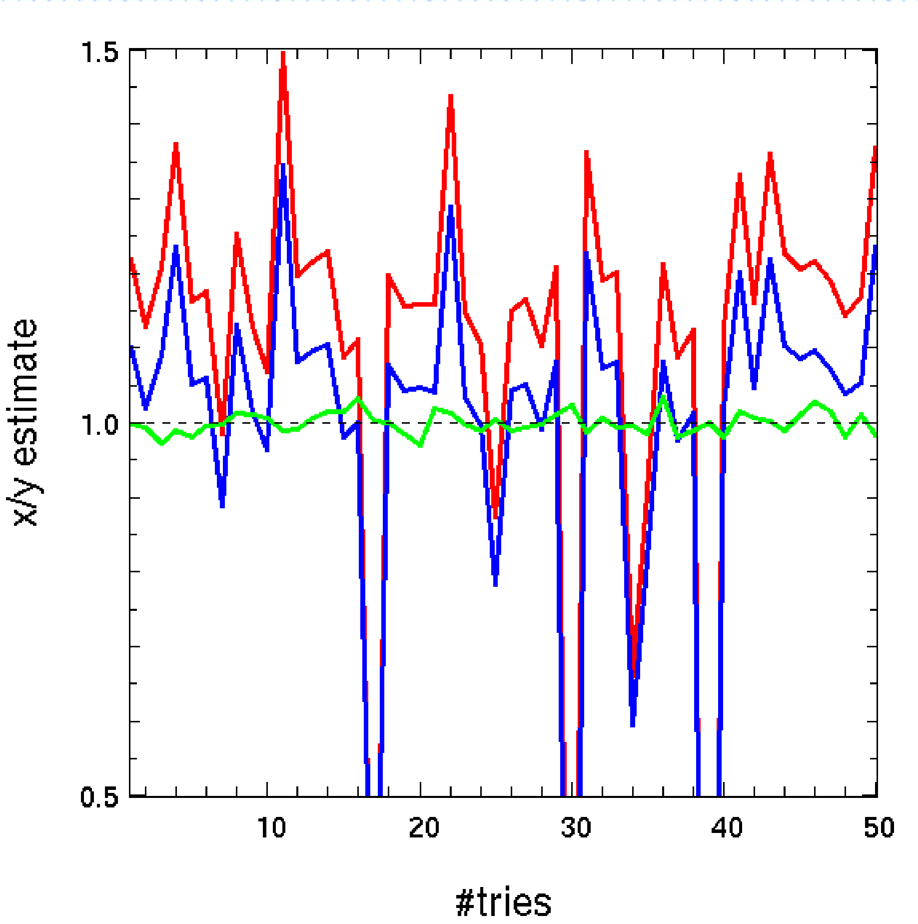
$$z_2 = \langle x/y \rangle / (1 + \sigma y / \langle y \rangle^2)$$



Division of 2 numbers

- **Solution 2**
  - Use an unbiased estimator

$z_3 = \langle x\rangle / \langle y\rangle$



You used to fear dividing by zero?

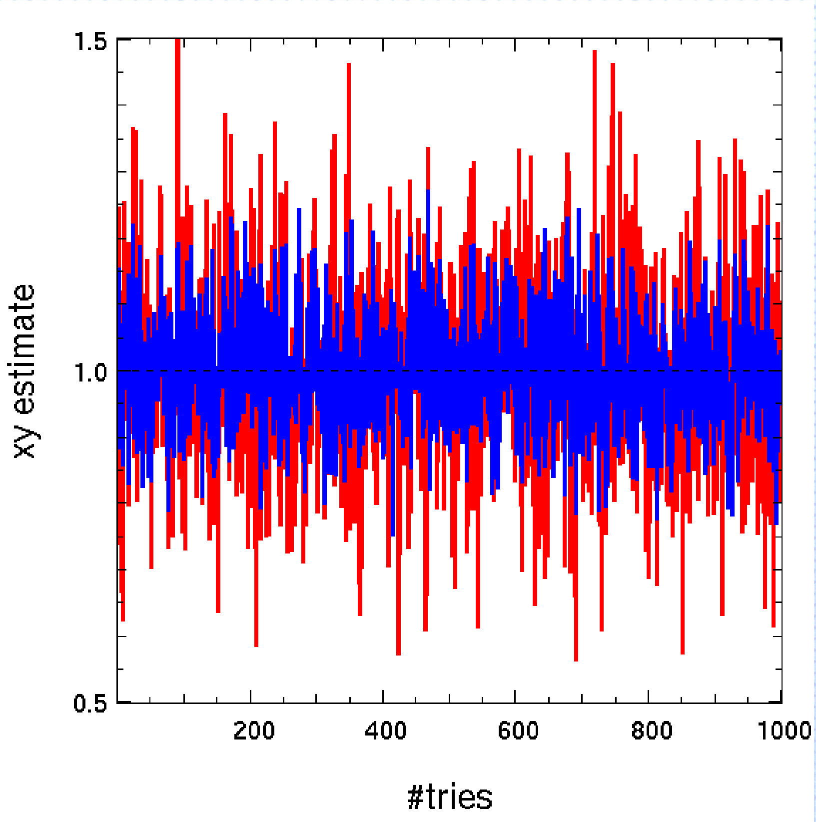
Now fear dividing by a noisy variable!

Multiplication of 2 numbers

- **Be careful when multiplying 2 random variables!**

$x = \alpha + n_1$ and $y = \beta + n_2$

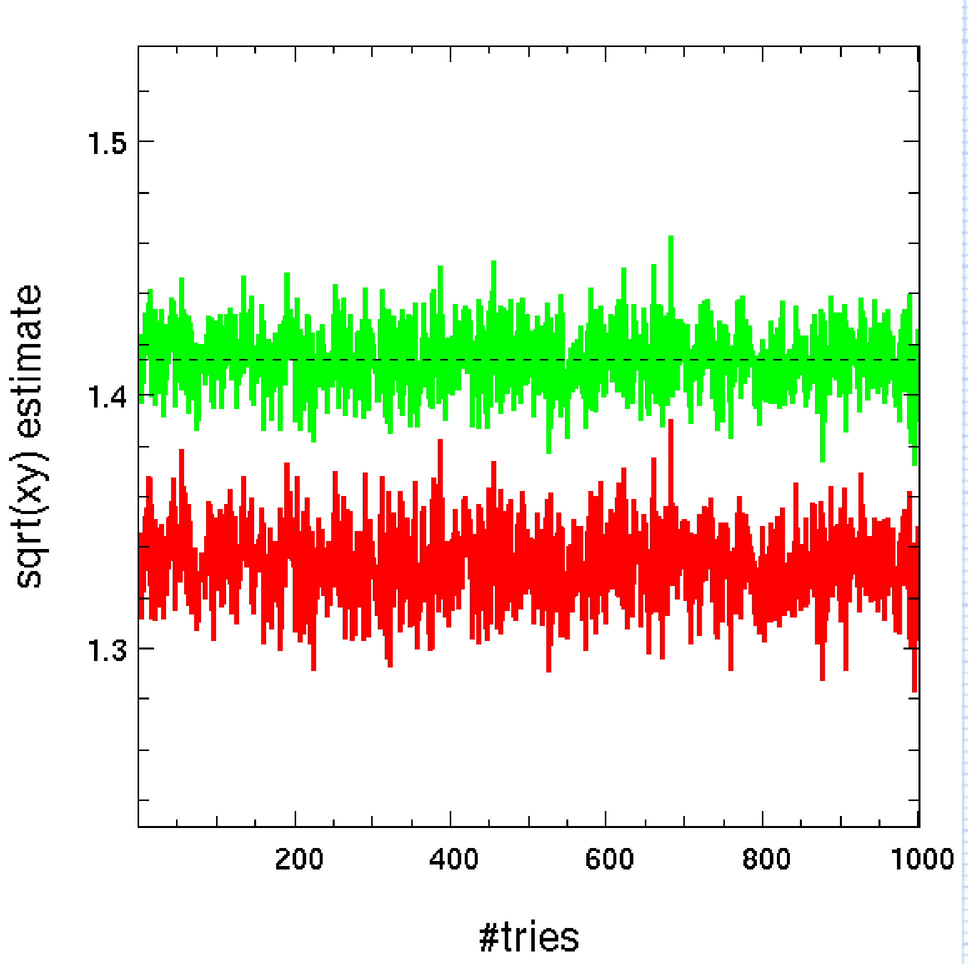
$z_1 = \langle xy \rangle$



$z_2 = \langle x \rangle \langle y \rangle$

Square root of 2 numbers

$x = \alpha + n_1$ and $y = \beta + n_2$



$z_1 = <\mathrm{sqrt}(x)> * <\mathrm{sqrt}(y)>$

$z_2 = \mathrm{sqrt}(<x><y>)$

Visibility estimator recipe

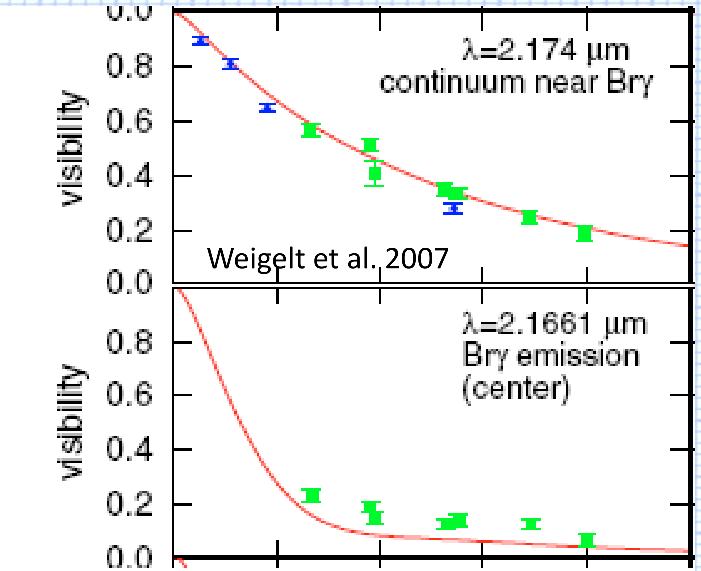
- **Go for squared visibility! Avoid pitfalls!**
  - **Extract** $|C^{a,b}|$ **(coherent flux) for each frame**
  - **Estimate** I^a **and** I^b **for each frame**
  - **Estimate noise variance** $<|n|^2>$
  - **Calculate** $\mu^2 = <|V|^2>$ **by**
    $(<|C^{a,b}|^2> - <|n|^2>) / <I^a> <I^b>$

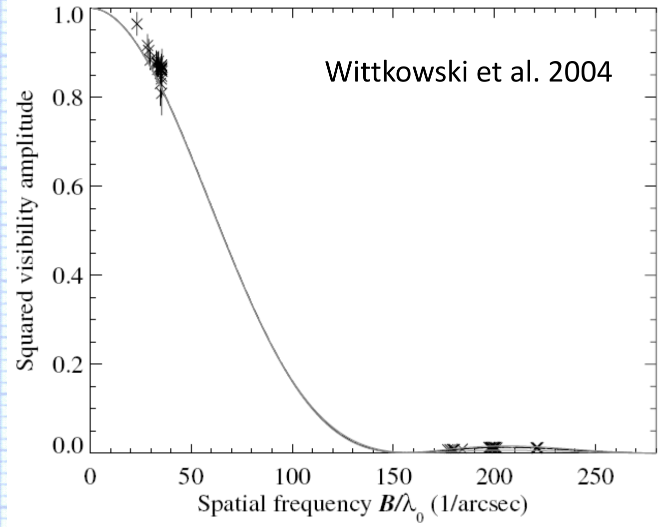
raw squared visibility

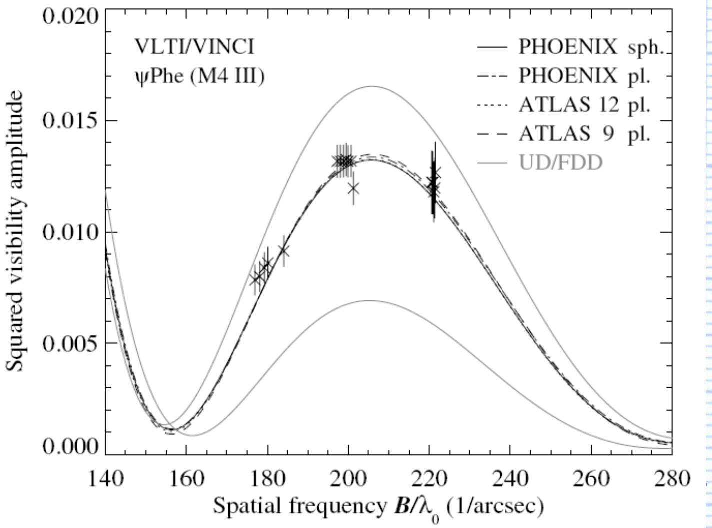
- **And then?**
  - **Calibrate!**

A few examples: circular objects

- **Visibility measures typical size of the object**
  - The bigger the object, the lower the visibility
  - A bounce in visibility is a sign of a sharp edge in the image
  - A modulation of visibility is a sign of binarity
- **η Car observed with AMBER**
- **ψ Phe observed with VINCI**

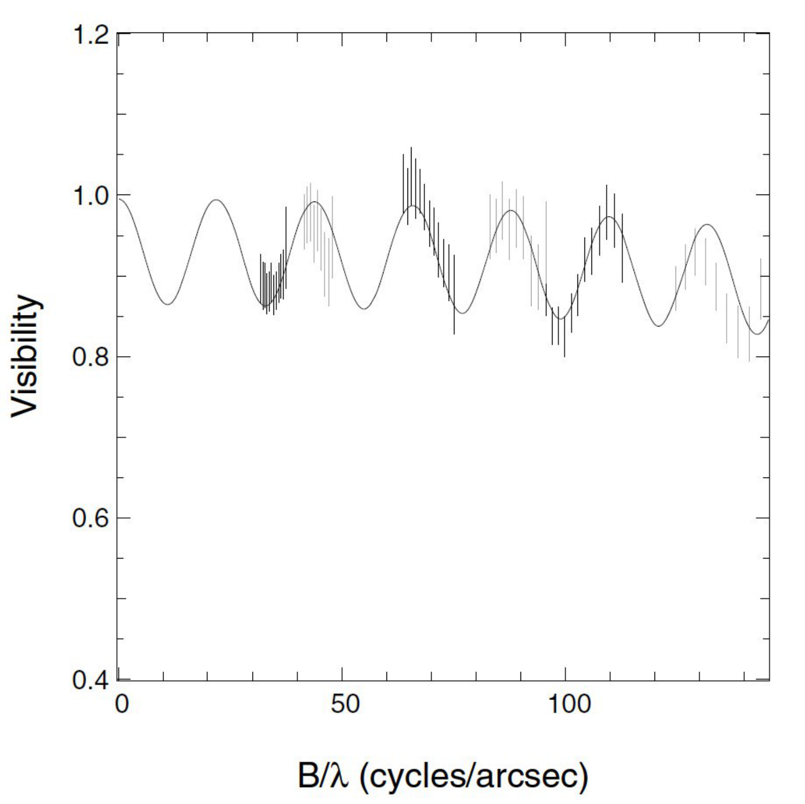




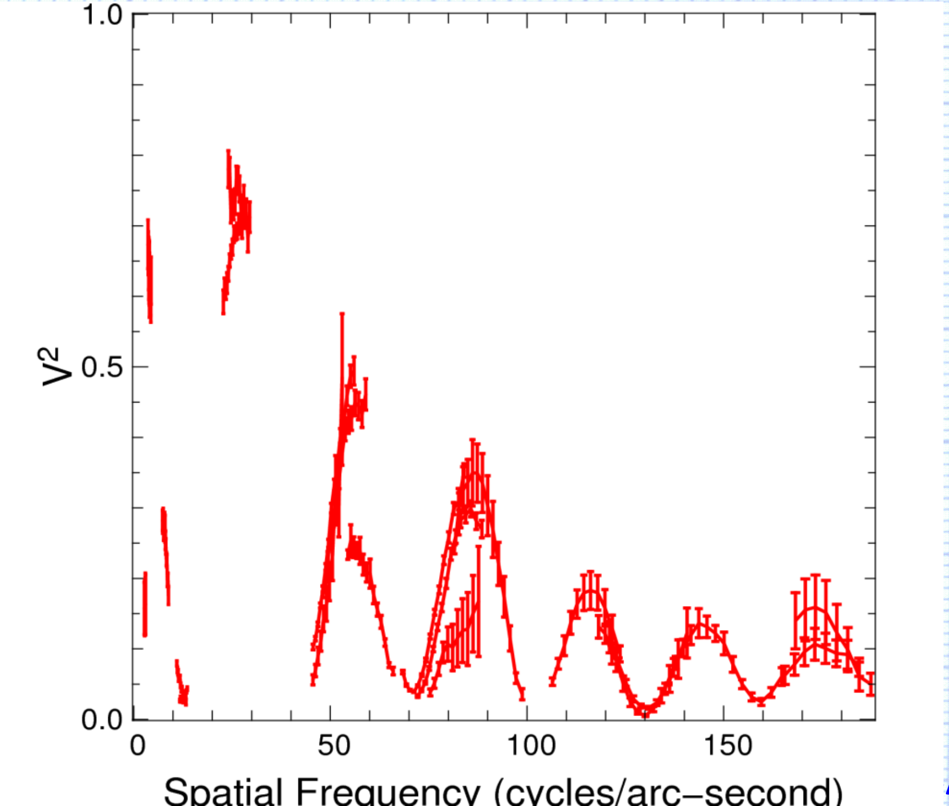


A few examples: binaries

δ Cen

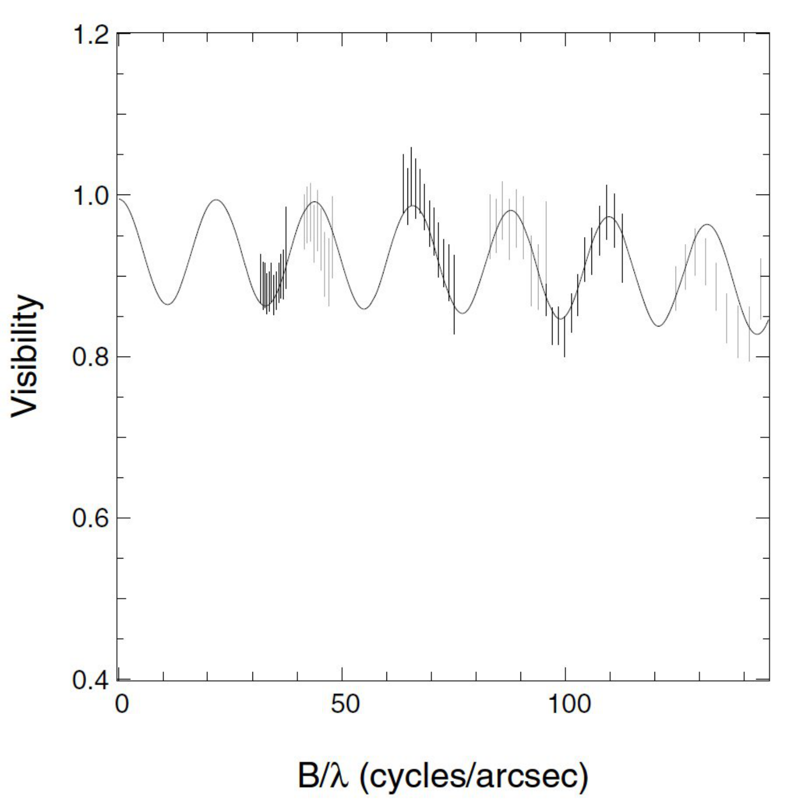


HD87643

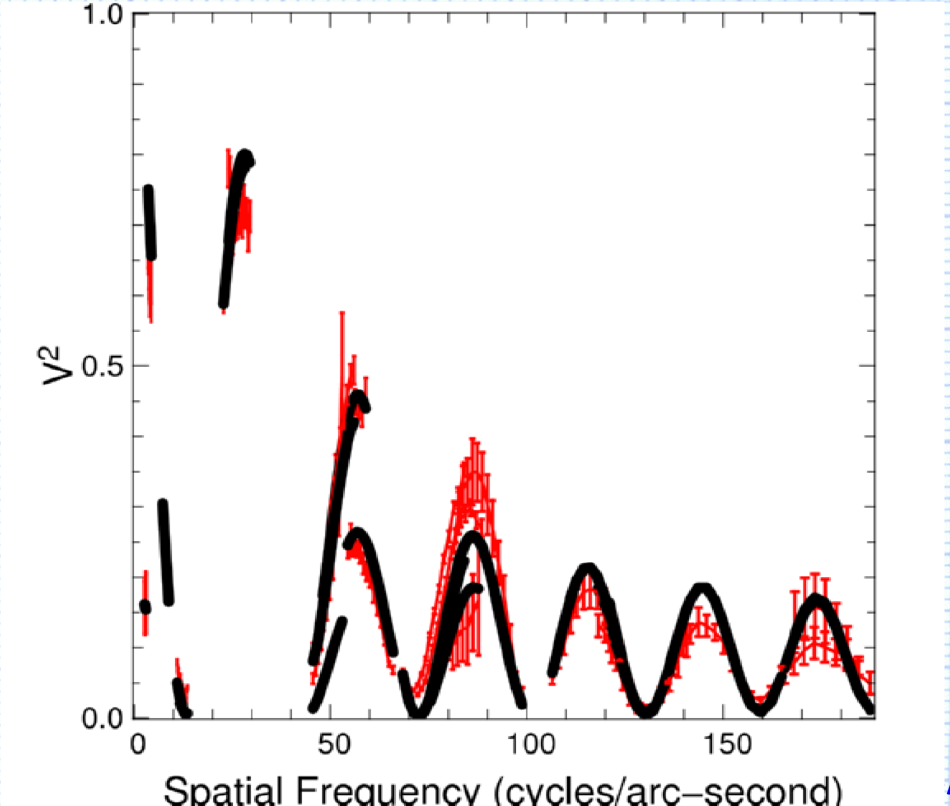


A few examples: binaries

δ Cen



HD87643

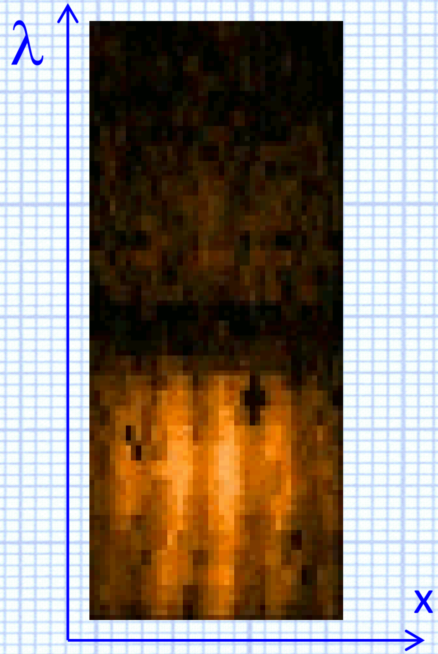


What about phase?

Remember, due to the atmosphere:

- **Fringe motion**
  - **Time-dependent phase shift of the fringes**

    ➔ **Fringe phase is lost!**

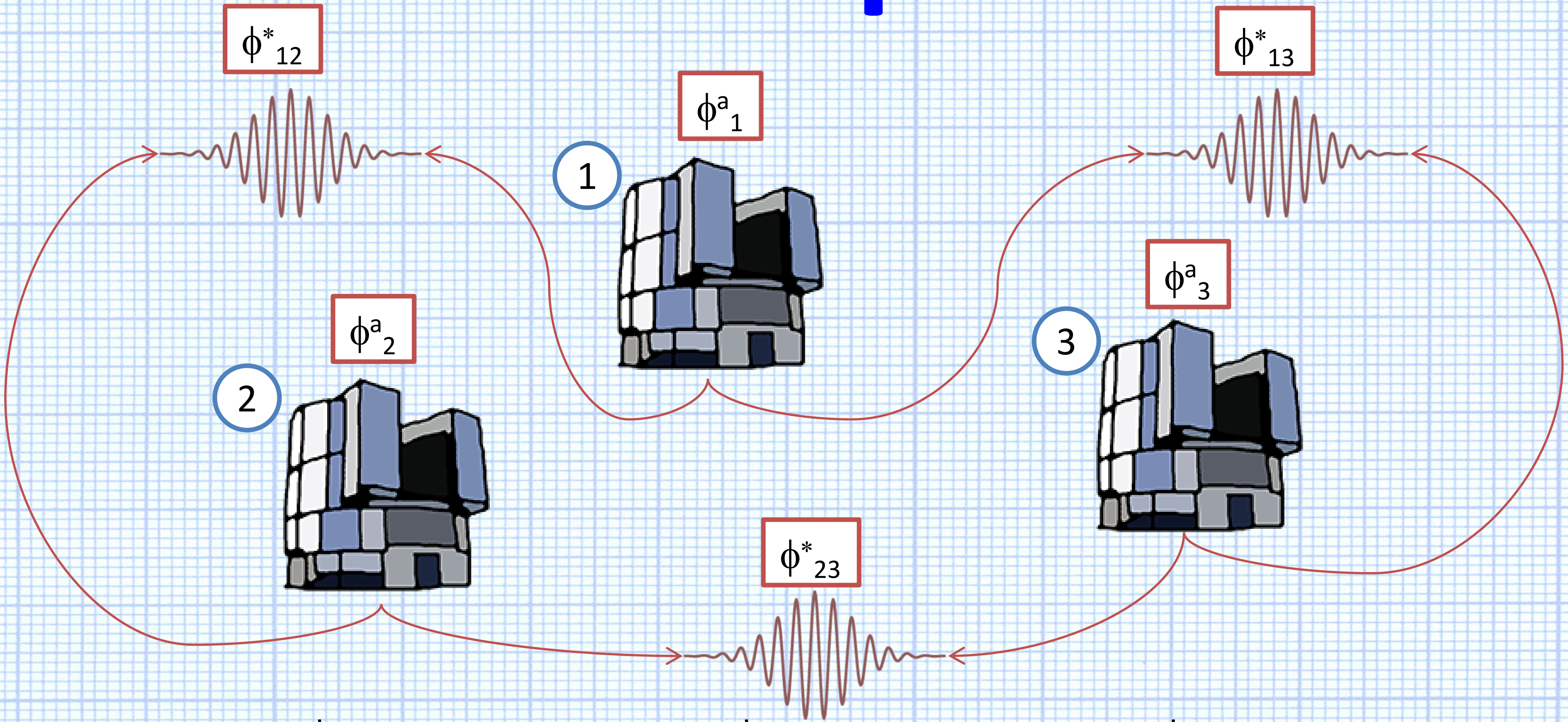


$$I(\delta_0, t) = e^{-\sigma^2_{\mathrm{jitter}}(t)} \mu \cos\left(\phi - 2\pi \frac{\delta_0 + \delta(t)}{\lambda}\right)$$

What about phase?

- Phases are lost in long-baseline interferometry
- How to work that around?
  - Get a phase which do not need a reference
    - Closure phase
  - Find a way to reference the phase (set the « zero phase »)
    - « Phase reference »: use a reference star close-by
    - « Differential phase »: use a wavelength close-by

Closure phase



$$\Phi_{123} = \phi^*_{12} + \cancel{\phi^a_2} - \cancel{\phi^a_1} + \phi^*_{23} + \cancel{\phi^a_3} - \cancel{\phi^a_2} + \phi^*_{31} + \cancel{\phi^a_1} - \cancel{\phi^a_3}$$

$$\boxed{\Phi_{123} = \phi^*_{12} + \phi^*_{23} + \phi^*_{31}}$$

Closure phase

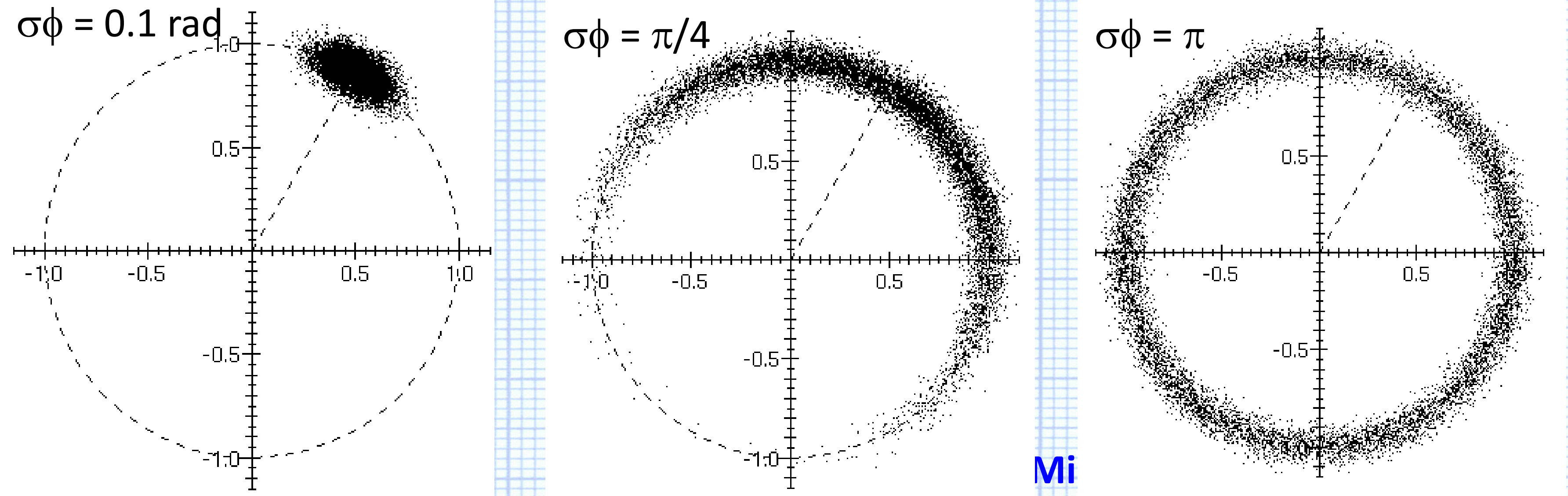
Closure phase cannot be obtained with phases sums!

why?

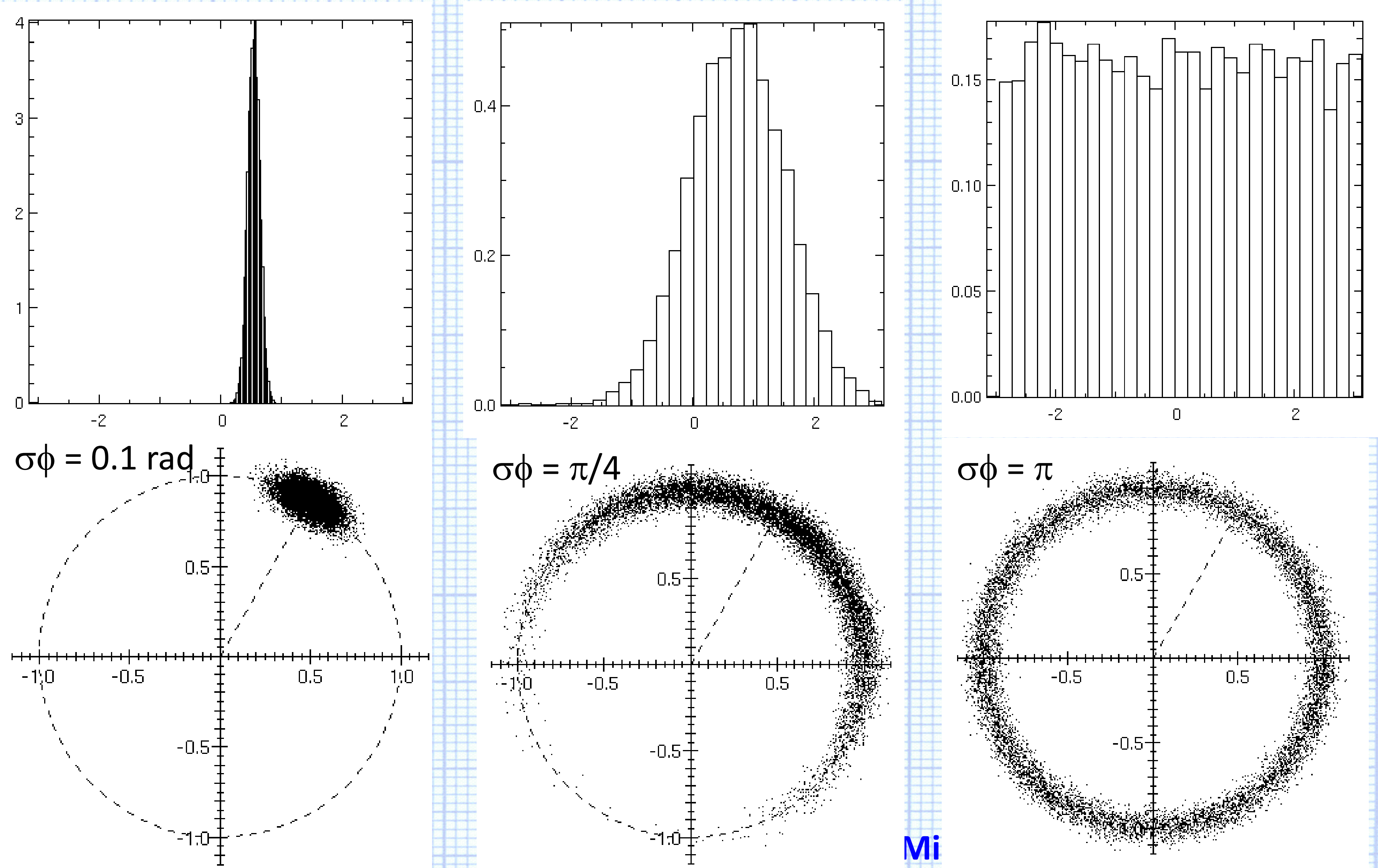
Noise!

Additive noises produce a phase wrapping

wrapped noisy phases have a top-hat distribution, when noise variance is high



Closure phase

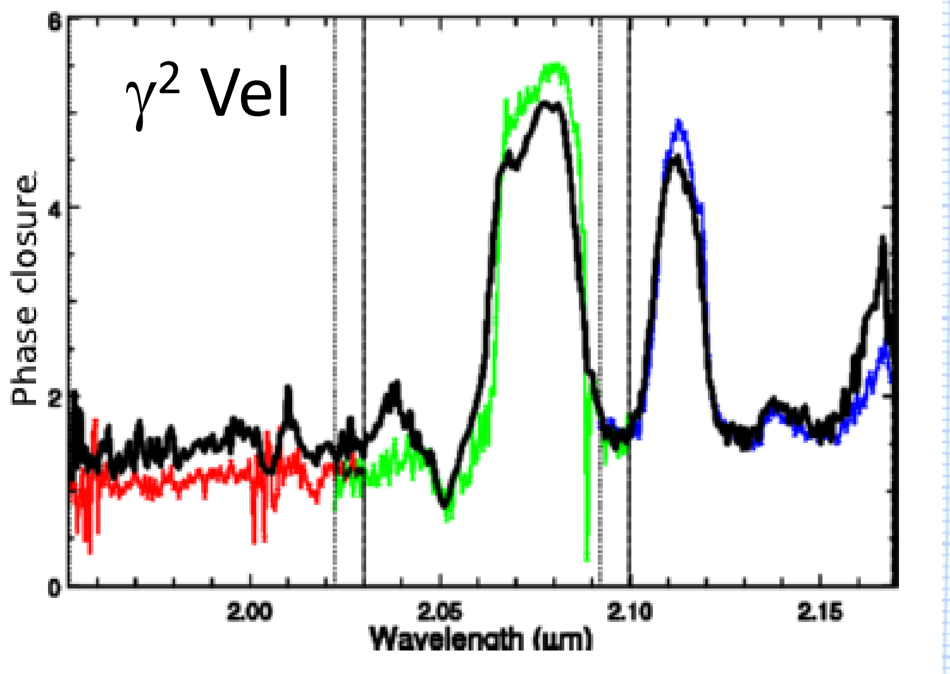


Closure phase

- **Closure phase cannot be obtained with phases sums!**
- **Stay in complex plane to avoid phase wrapping:**
  - **Bispectrum** $<C_{12}C_{23}C_{31}>$
    - **Phase of the bispectrum** = closure phase
    - **Amplitude of the bispectrum** = $V_{12}V_{23}V_{31}$

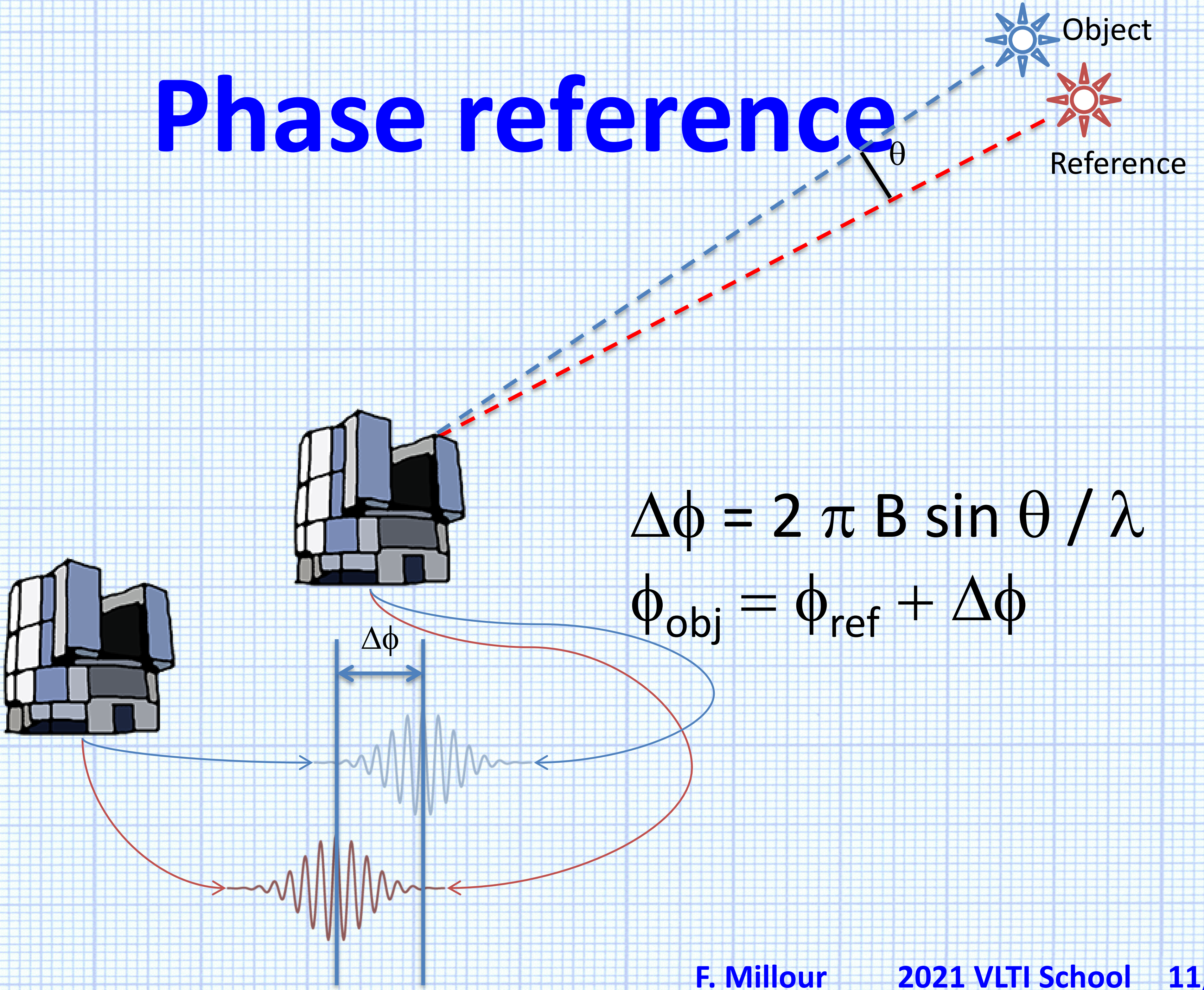
Closure phase example

- Closure phase measures asymmetries
  - A non-zero closure phase means asymmetries in the object
  - A zero closure phase means… nothing!
- Closure phase is not straightforward to interpret!



F. M

Phase reference



$$\Delta\phi = 2\,\pi\,B \sin\theta\,/\,\lambda$$

$$\phi_{obj} = \phi_{ref} + \Delta\phi$$

Phase reference

- Measuring a phase difference is equivalent to measuring an angle between 2 sources
  - → Can be used for astrometry
  - → The longer the baseline, the more precise the angle
- The reference star provide an absolute phase reference
  - →No more indetermination of phase → imaging

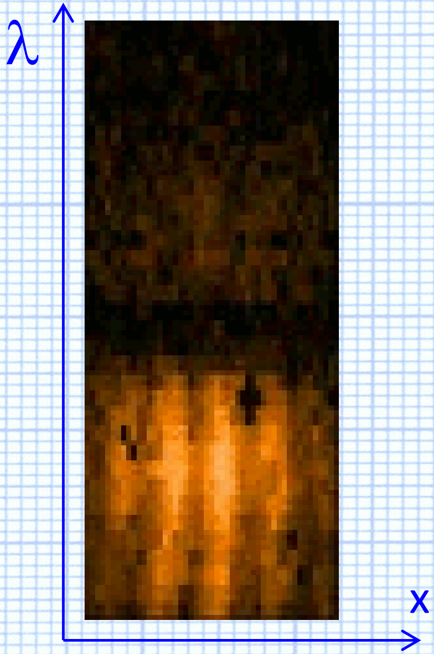
Differential phase

- « Differential phase » can mean many things
  - Phase difference between 2 telescopes
    - ➔ a.k.a. « phase »
  - Phase difference between 2 polarizations
  - Phase difference between 2 wavelengths

The latter will be used next

Differential phase

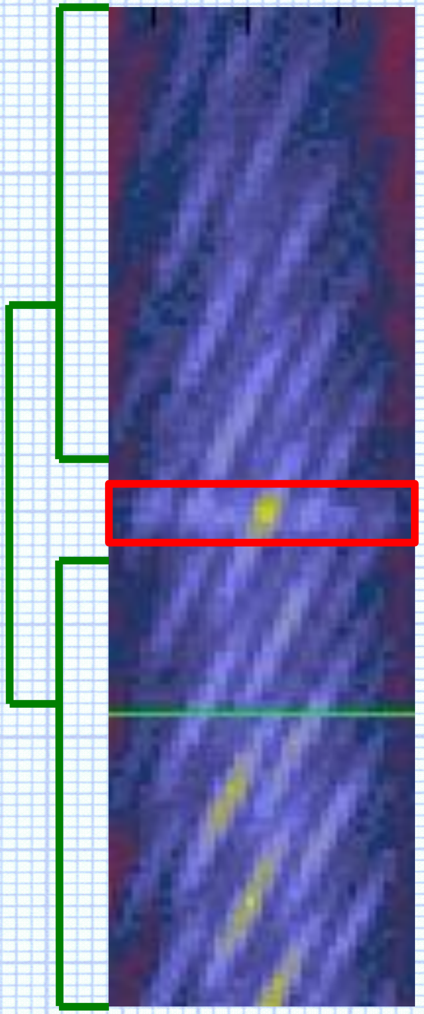
- **Idea: take profit of λ-dependence of atmospheric phase**
  - 1st order = ensemble-displacement of fringes
  - 2nd order = fringes slope
  - …



$$I(\delta_0, t) = e^{-\sigma^2_{\text{jitter}}(t)} \mu \cos\left(\phi - 2\pi \frac{\delta_0 + \delta(t)}{\lambda}\right)$$

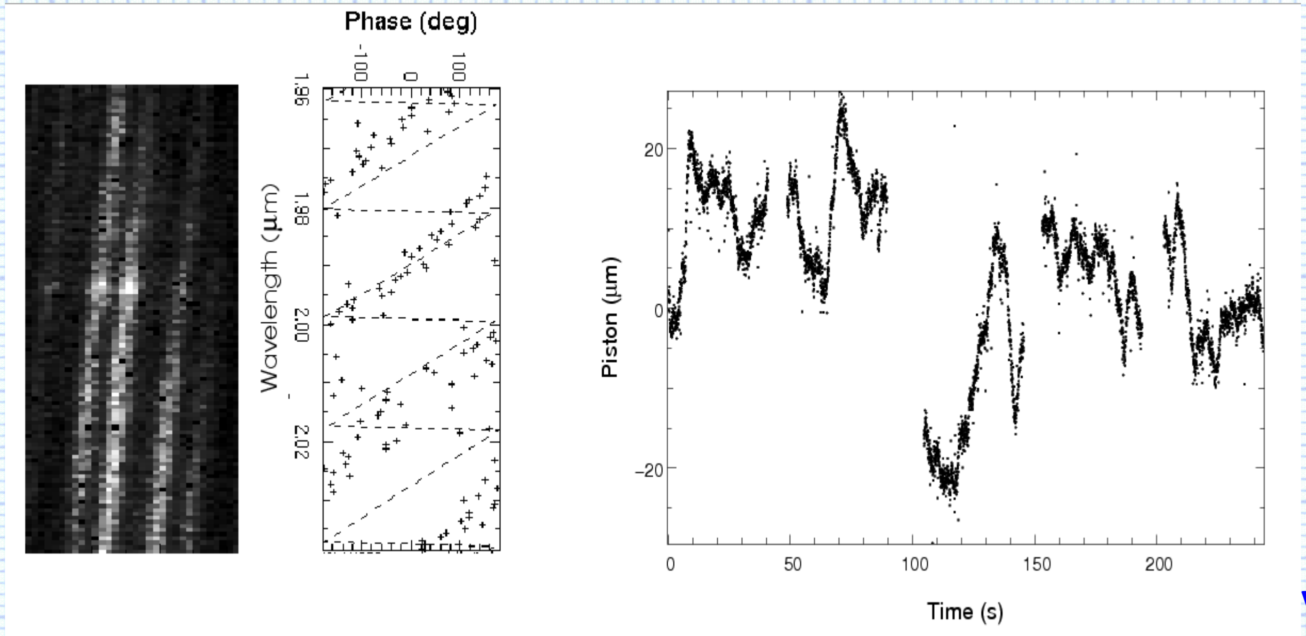
Differential phase

- **Define a work wavelength channel** ϕ_{work}
- **Define a reference wavelength channel** ϕ_{ref}
- **Compute phase difference between work channel and reference channel**
  - $\phi_{diff} = \phi_{work} - \phi_{ref}$
- **!!! One cannot compute directly phases difference !!!**
  - **Calculate cross product in the complex plane instead:**
    $\phi_{diff} = \arg \langle C_{work}\, C^{*}_{ref} \rangle$
- **Reference channel must not contain the work channel (square bias)**



Differential phase

- **Problem: phase slope changes with time**
  - **Evaluate and correct OPD prior to calculating the cross product**
    ➔ $Cn = C\, e^{-2i\pi\, \delta/\lambda}$
  - $\phi_{diff} = \arg \langle Cn_{work}\, Cn^{*}_{ref} \rangle$



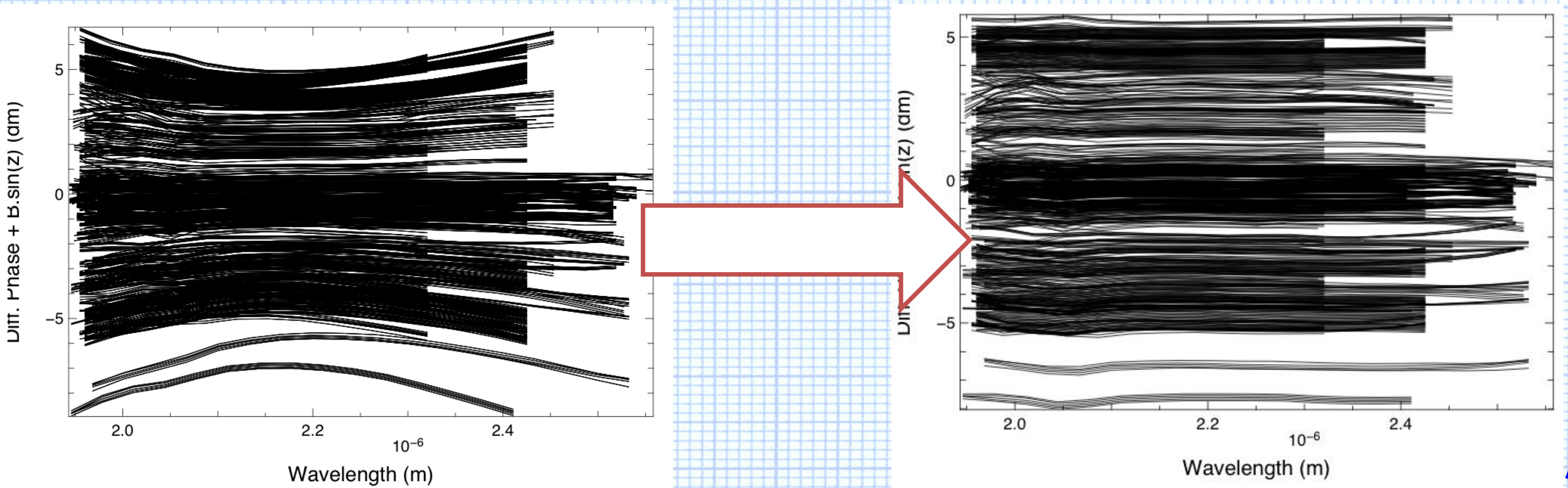
Differential phase

- **Problem: Chromatic dispersion affects DP**
  - **Evaluate and correct chromatic OPD:**

    $\delta_{OPD}(\lambda) = OPD\ (a + b / \lambda + c / \lambda^2 + \ldots)$

    a, b, c **depend on partial water vapour pressure, CO_2 content, etc.**

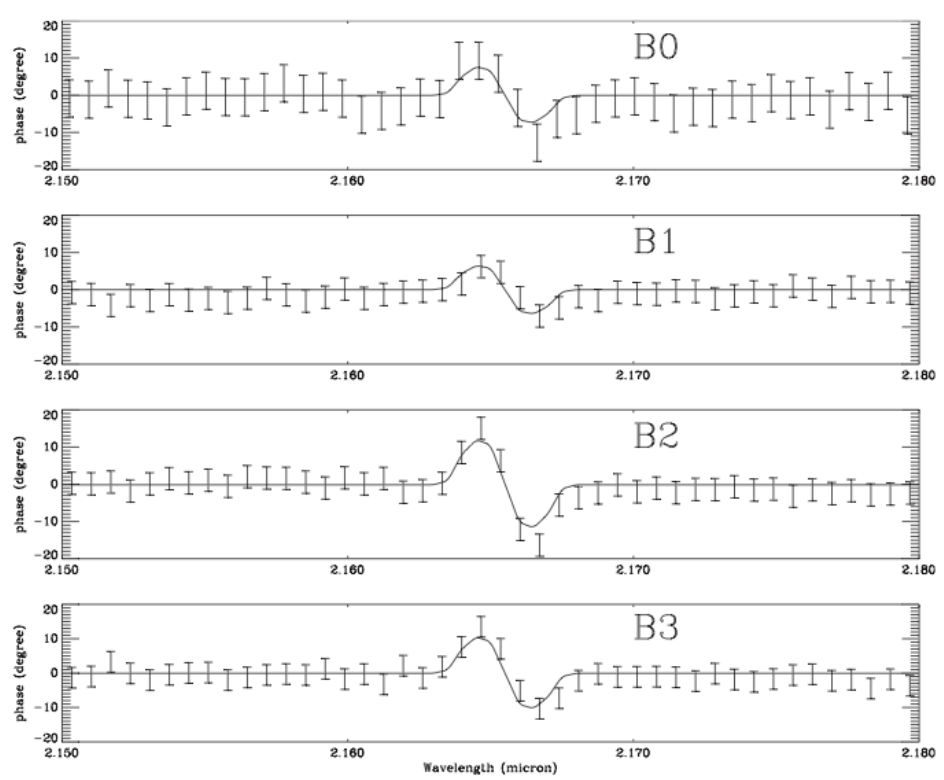
See Ciddor 1996, Vannier 2006, Mathar 2007



Differential phase examples

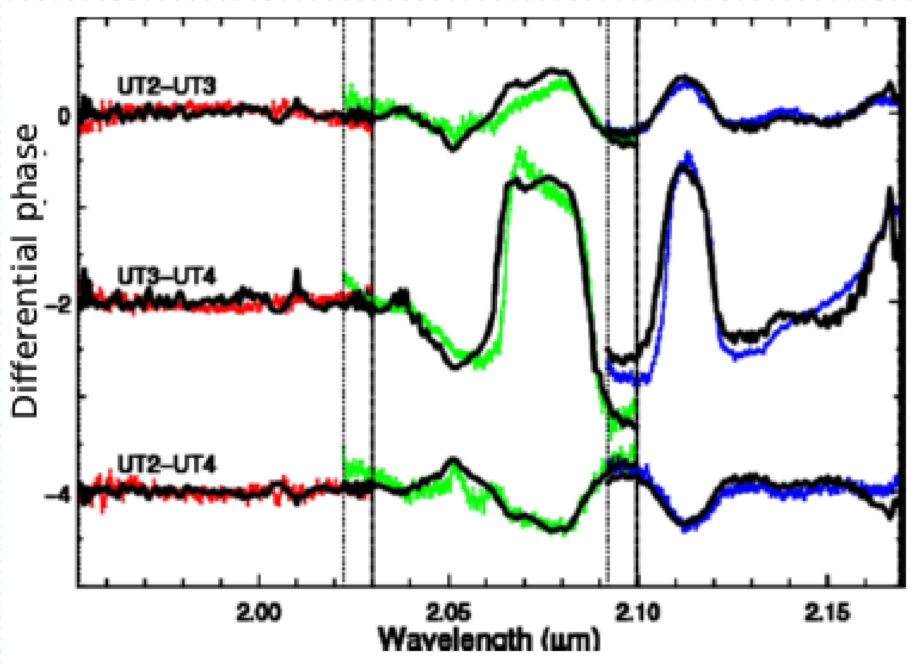
- **Rotating disk**

α Arae



- **Complex system (binary with changing flux ratio)**

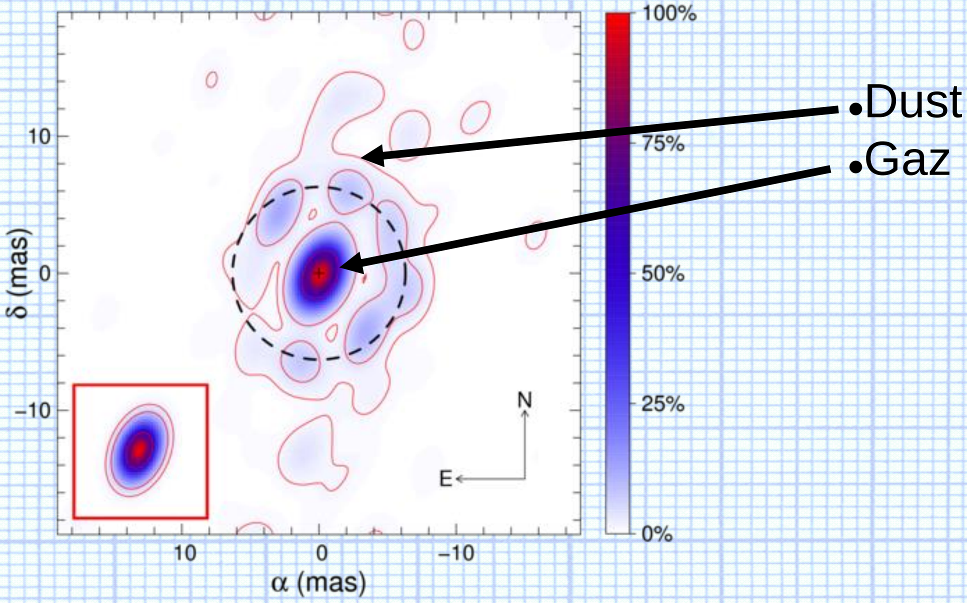
γ^2 Vel



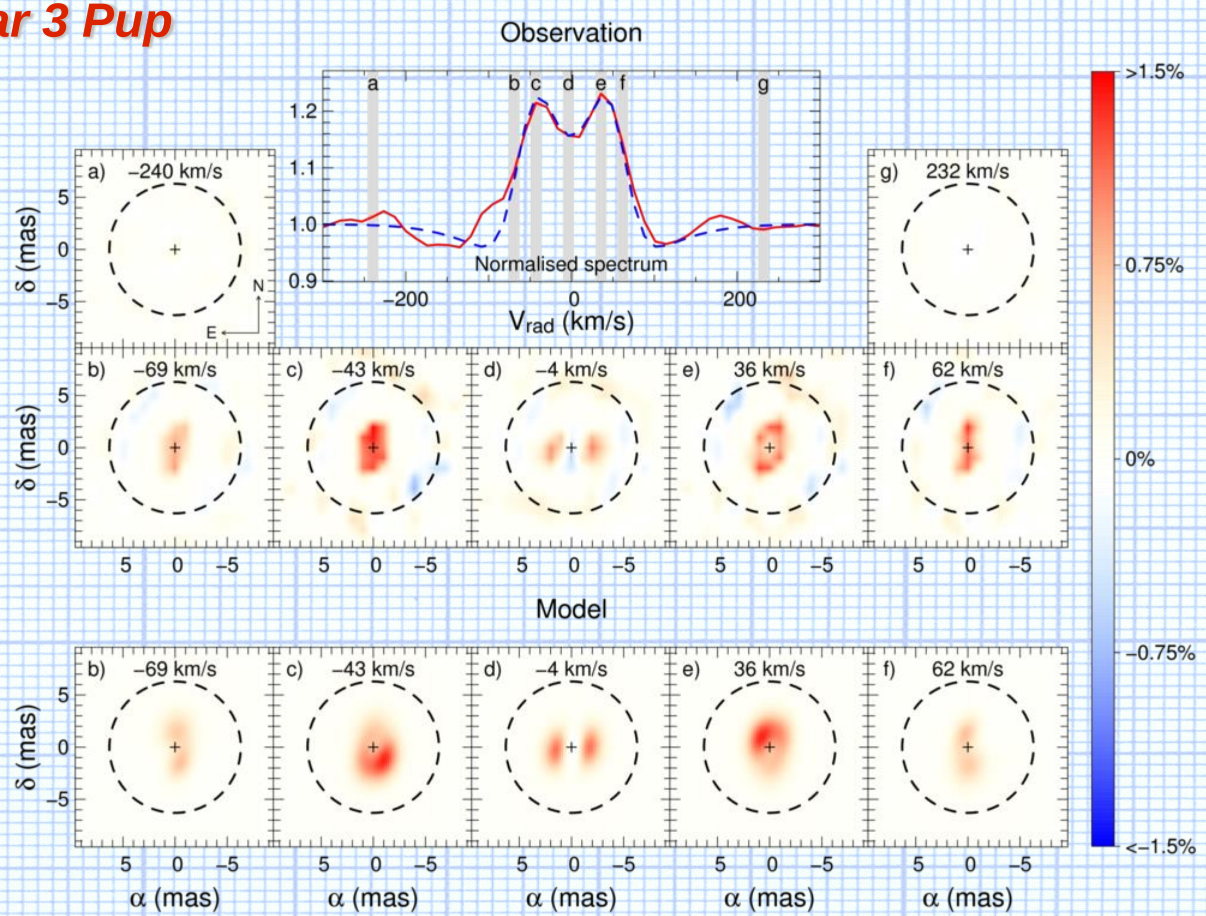
Differential phase can be used in imaging!

Self-cal (inspired from radio-astronomy)

A[e] supergiant star 3 Pup



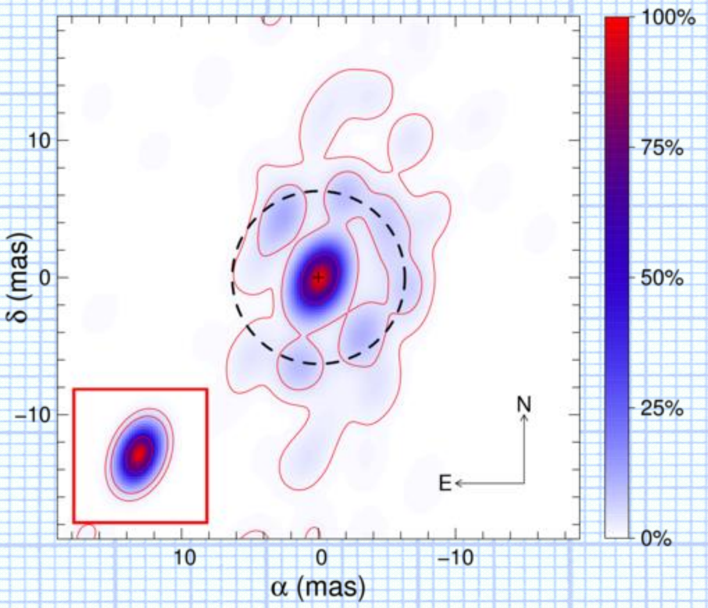
Détection des disques de poussières et de gaz

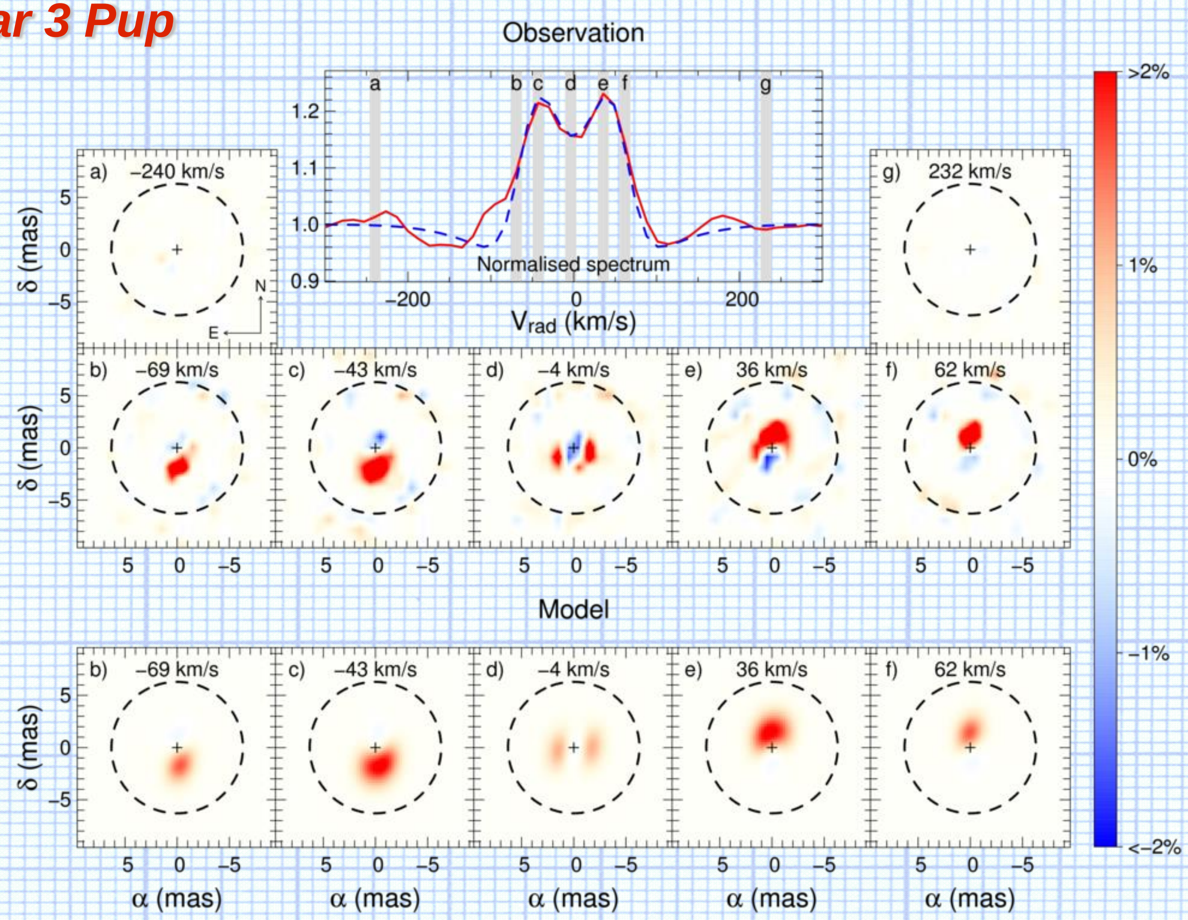


Differential phase can be used in imaging!

Self-cal (inspired from radio-astronomy)

A[e] supergiant star 3 Pup





Cinématique des disques
de poussières et de gaz

Outline

- Why do we care so much about data reduction?
  - What are we looking for?
  - What adversities are we fighting against?
- The interferometry observables
  - All the observables
  - Statistics
  - Calibration
- MATISSE data reduction
- Conclusions

The interferometrist problematic

- Estimate « properly » fringe contrast & phase
  - Precise measurement
  - Accurate measurement
- Calibrate data
  - Calibrate,
  - Calibrate!
  - Calibrate?
  - …

Data calibration

- Why calibrate?
  - Time-variable multiplicative visibility loss due to
    - atmosphere (jitter, turbulence, etc.)
    - instrument (polarization effects, bandwidth smearing, etc.)
  - Phase reference is not well known / instrument dependent
- How to calibrate? Measure « transfer function » on calibration sources:
  - Same conditions as science
    - Same atmospheric conditions (close in time)
    - Similar flux (same magnitude)
  - Same instrument as science
    - Same detector: same integration time, frame rate, etc.
    - Same filter, spectrograph setup, number of telescopes, etc.

Data calibration,

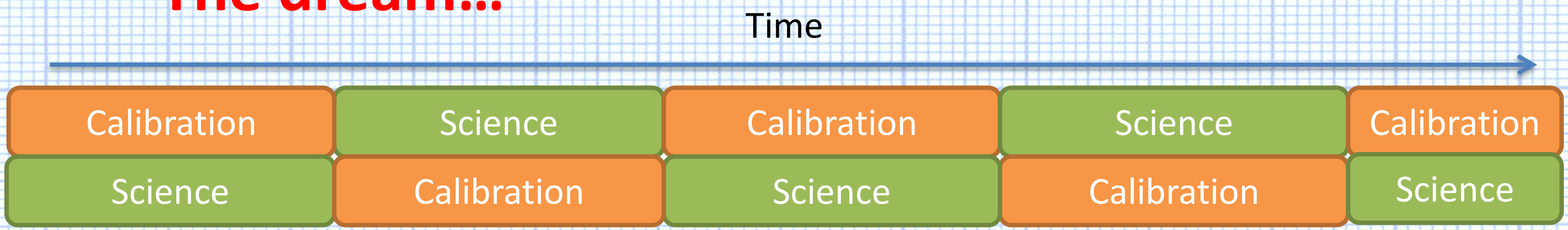
What are calibration sources?

- **Stars!**
- **Most stars look like disks (same as the Sun)**
- **Visibility easy to predict**
  - **Baseline B, wavelength λ, star's apparent diameter θ**

$$V^2_{cal} = 4\frac{J_1\left(2\pi\theta\frac{B}{\lambda}\right)^2}{\left(2\pi\theta\frac{B}{\lambda}\right)^2}$$

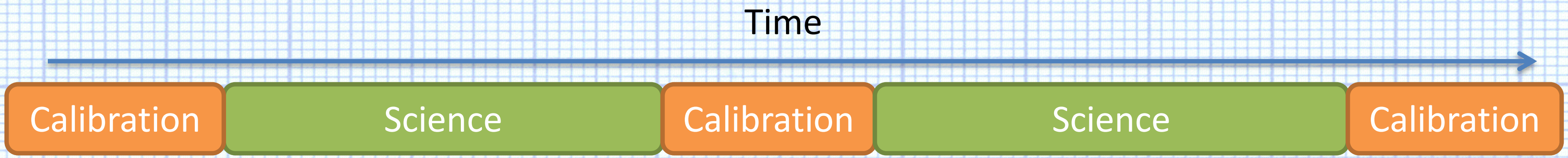
Data calibration,

- **The dream…**



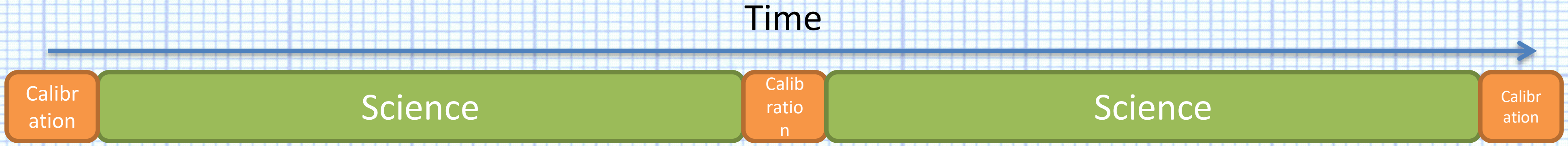
Data calibration.

- **A typical observing sequence**



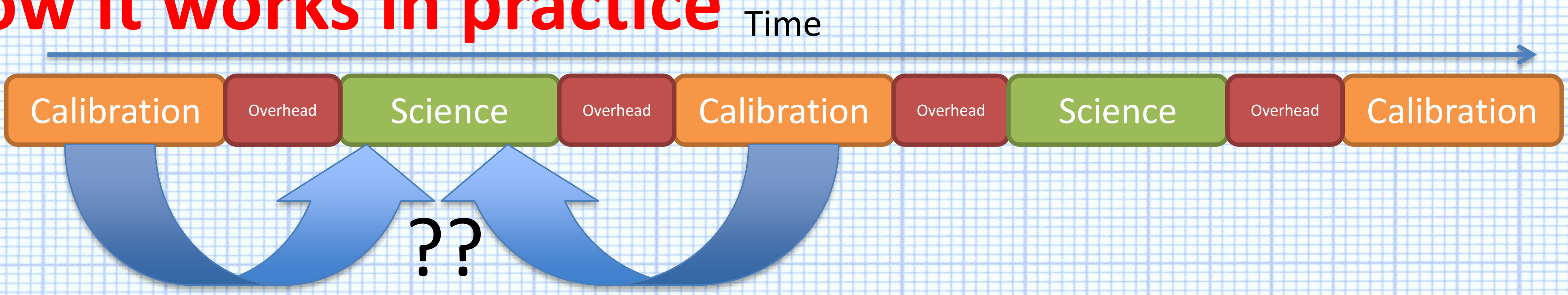
Data calibration!

- **The way we would like to have it**



Data calibration?

- **How it works in practice**



- **about half the observing time is spent on calibration**
- $\mu^2_{final} = \mu^2_{star} / \mu^2_{cal}$
- **Same problem as for V^2 measurement:**
  an error on μ^2_{cal} translates into a bias (systematics)

Calibrators?

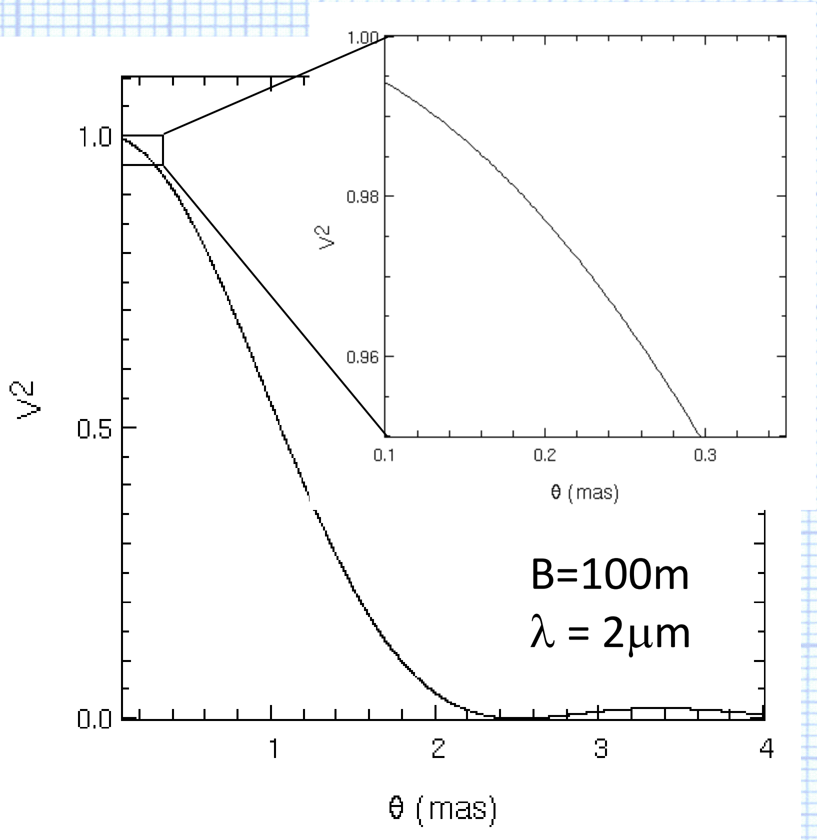
- Calibration star = star with known μ^2_{cal}
- An infinitely small star at a given magnitude has an infinite surface brightness

problem1: we want V^2 independent of θ

→ θ~0.1 for B=100m and λ=2μm

problem2: 0.1 mas T=10000K (A0) has mag>7

→ impossible to avoid resolved stars



Data calibration…

1. Measure visibility on science and (at least) a calibrator
2. Derive expected visibility on calibrator
3. Compute transfer function
4. Interpolate transfer function to the time of science
5. Calibrate contrast

1. $\mu^2_{sci}(t_{sci}) \qquad \mu^2_{cal}(t_{cal})$

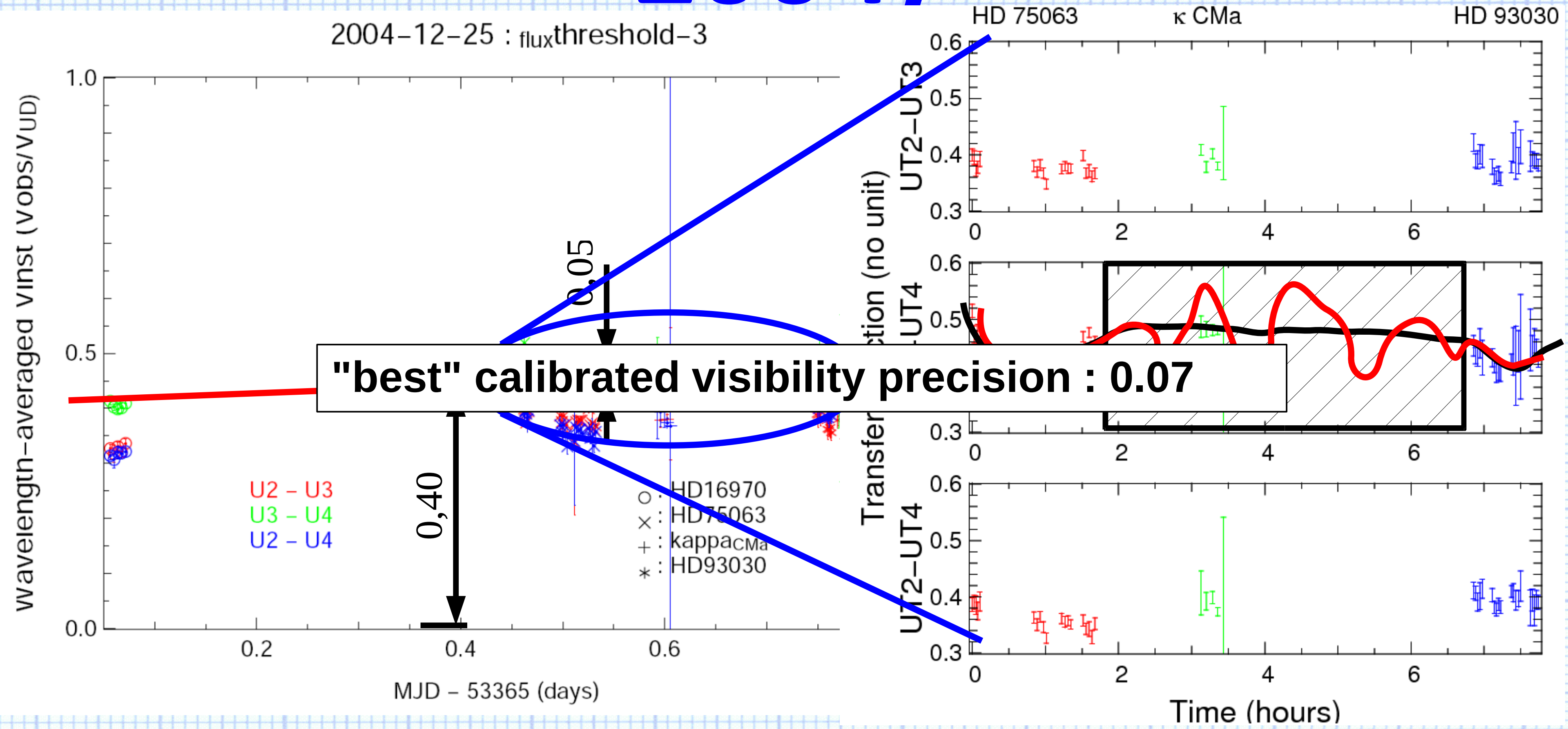
2. $$\mu^2_{th} = 4\frac{J_1(2\pi\theta B/\lambda)^2}{(2\pi\theta B/\lambda)^2}$$

3. $$T^2(t_{cal}) = \frac{\mu^2_{cal}(t_{cal})}{\mu^2_{th}(t_{cal})}$$

4. $$T^2(t_{sci}) = \mathrm{f}[T^2(t_{cal})]$$

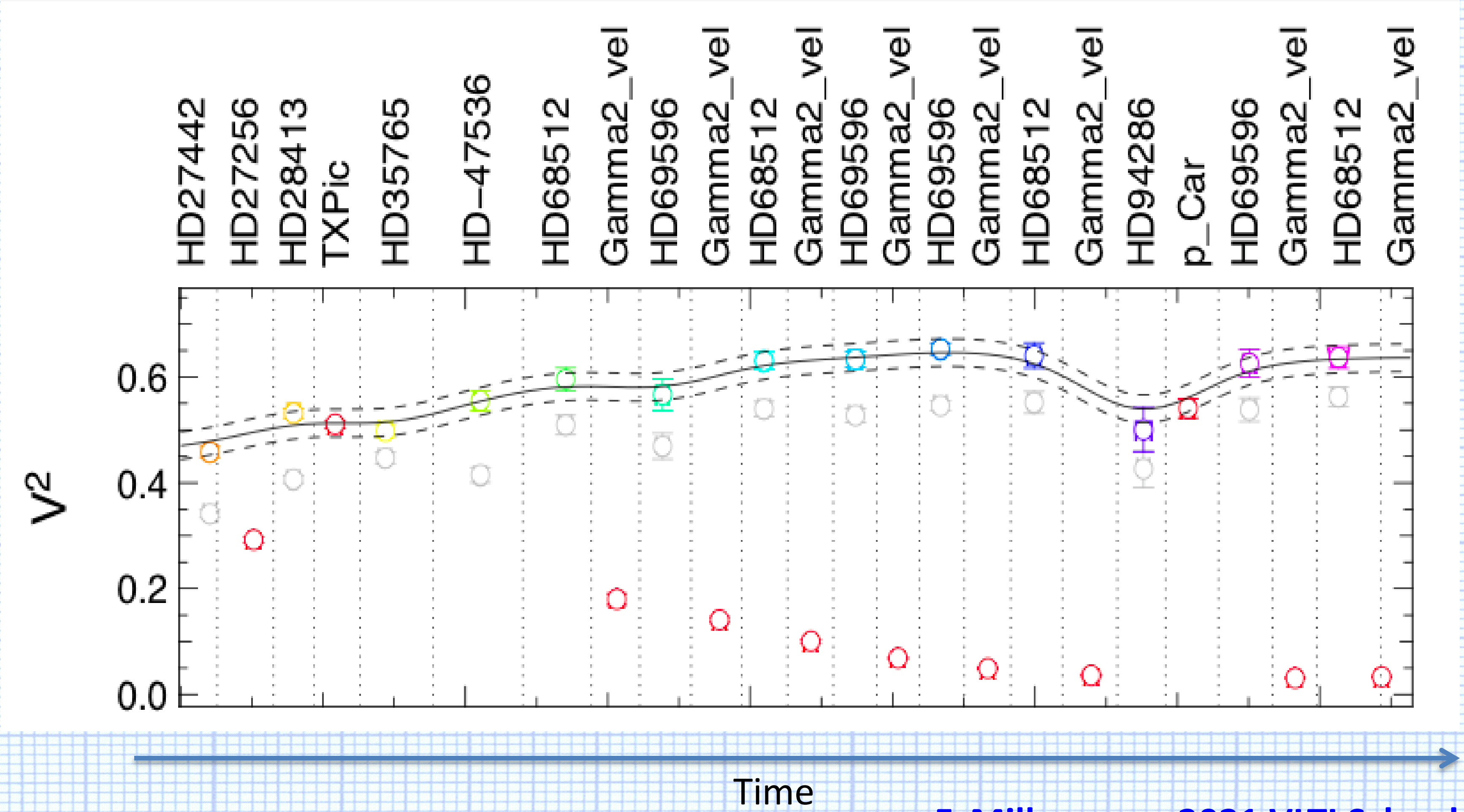
5. $$V^2_{sci} = \frac{\mu^2_{sci}(t_{sci})}{T^2(t_{sci})}$$

“transfer function” (AMBER in 2004)

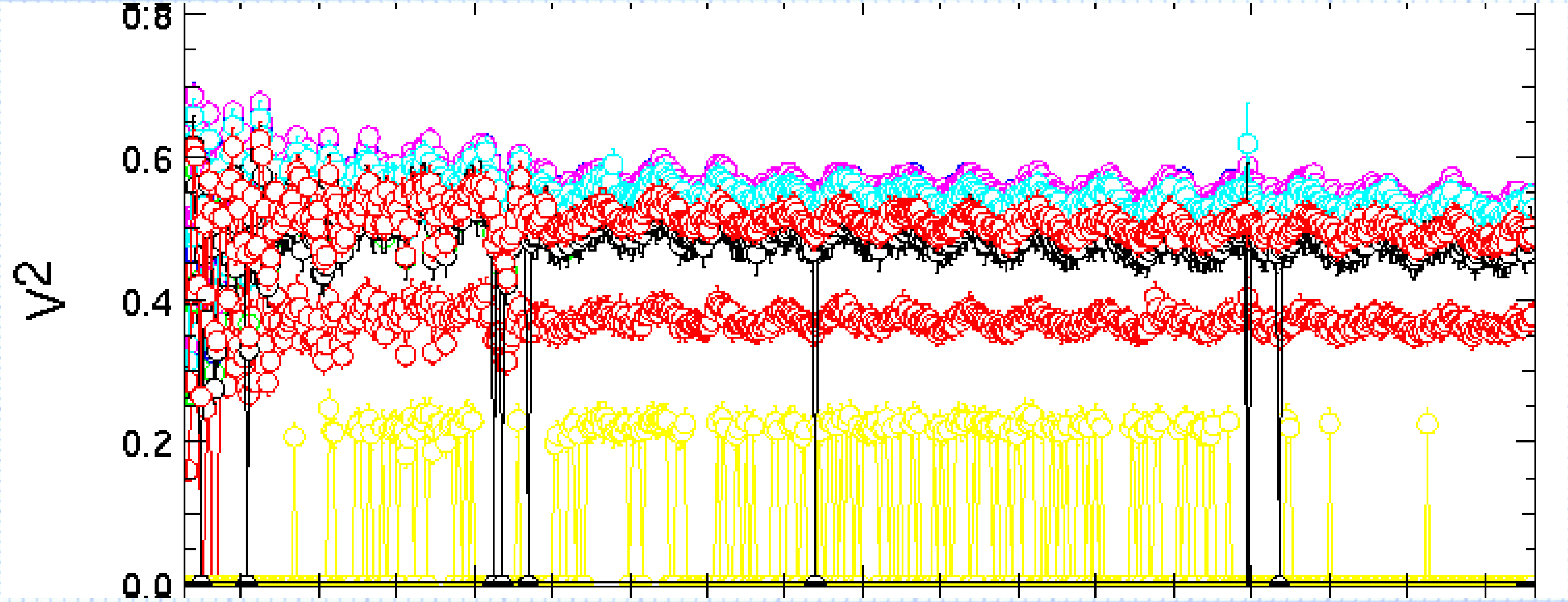


"best" calibrated visibility precision : 0.07

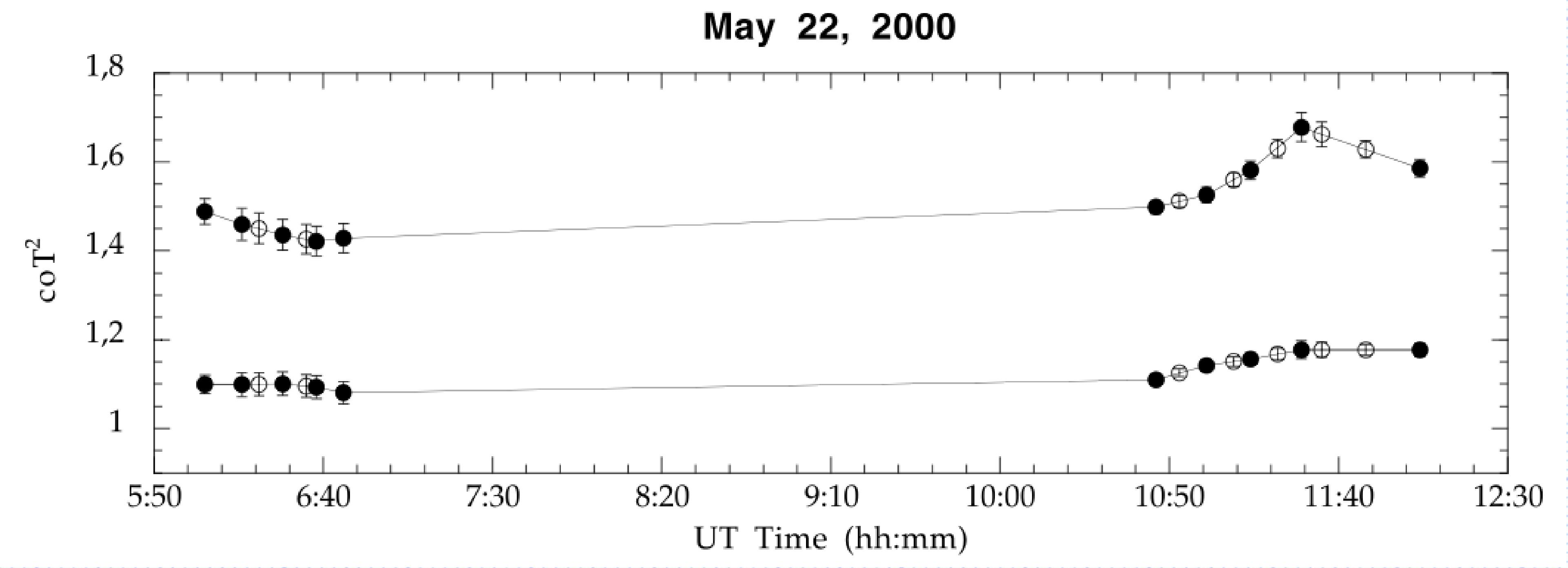
“transfer function”: a better one (2008)



The same plot as a function of wavelength

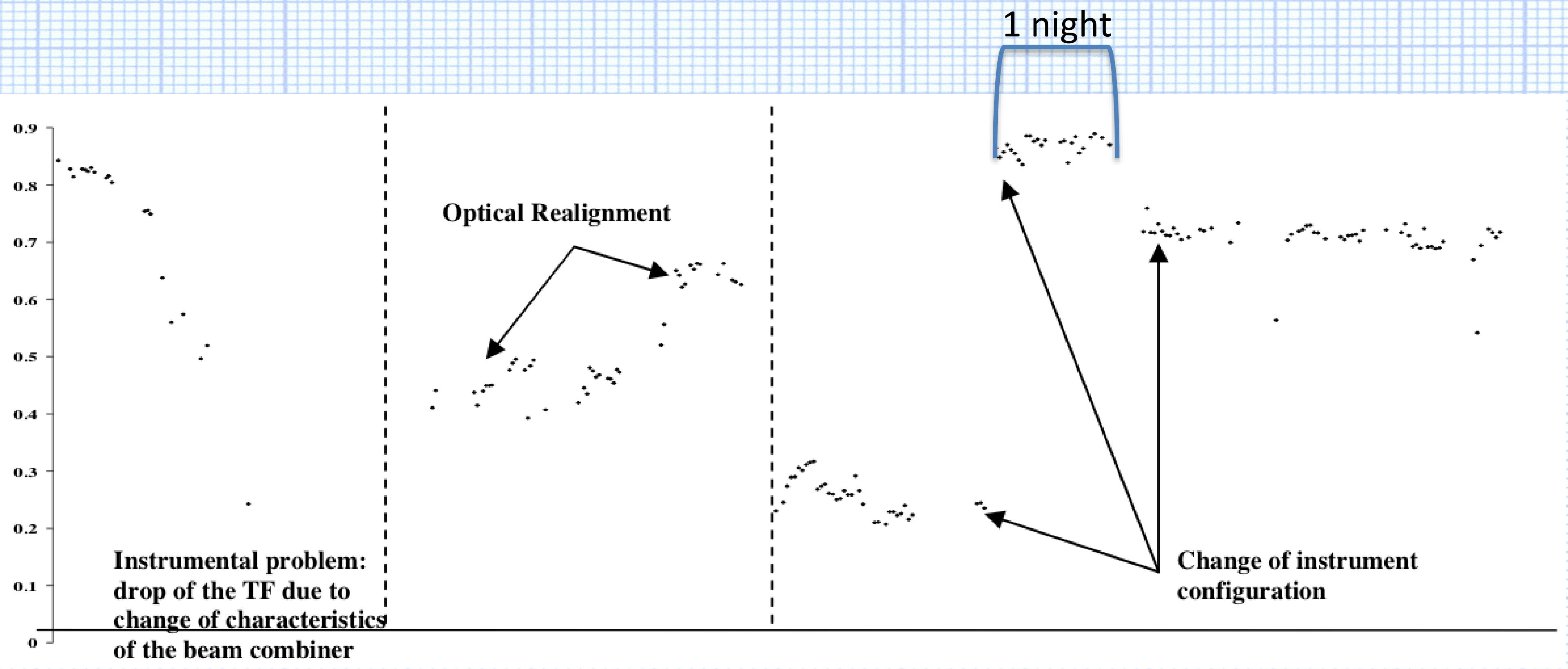


« transfer function »: FLUOR



Perrin 2003

« transfer function »: VINCI



Percheron et al. 2004

How to propagate errors?

- **Error sources:**
  - Raw visibilities
  - Calibrator diameter
  - Calibrator model
  - Is the interpolation function right?
- **Error propagation is not trivial**
  - Statistics vs systematics
- **Classical formulae work:**
  - for small errors
  - Gaussian statistics

- **Formal methods**
  - Derive errors in a simple way
  - Estimate covariances and pray they are right

- **Empirical methods**
  - Estimate systematics and add the variances
  - Treat statistics independently from systematics

Black board error propagation

$$V^2_{sci} = \frac{\mu^2_{sci}}{T^2_{cal}}$$

$$T^2_{cal} = \frac{\mu^2_{cal}}{\mu^2_{th}}$$

$$\frac{\sigma^2_{T^2_{cal}}}{\left(T^2_{cal}\right)^2} = \frac{\sigma^2_{\mu^2_{cal}}}{\left(\mu^2_{cal}\right)^2} + \frac{\sigma^2_{\mu^2_{th}}}{\left(\mu^2_{th}\right)^2}$$

- **Calibration error are as important as other errors**
  - **uncertainty on the estimated visibility** μ_{th}
  - **uncertainty on the measured visibility** μ_{cal}

Estimating calibrators diameters

- Idea = use apparent luminosity & surface brightness
  - From models (stellar templates)
  - From colors (e. g. V-K)
- See review Cruzalèbes et al. (2010)
  - « Angular diameter estimation of interferometric calibrators – example of lambda Gruis, calibrator for VLTI/AMBER »
- See Bonneau et al. (2006)
  - « Searchcal: a virtual observatory tool for searching calibrators in optical long-baseline interferometry »
- For boring stars: works well down to ~1% accuracy

Precision ≠ Accuracy

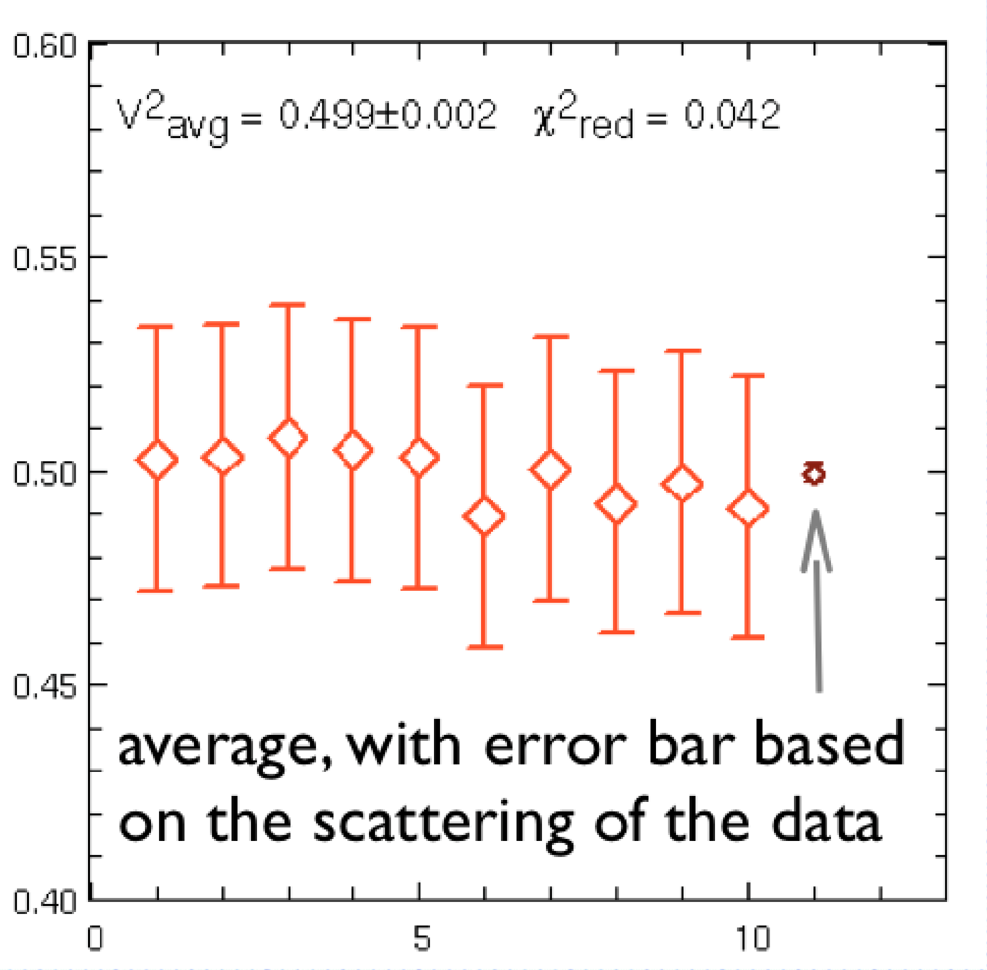
- **By averaging all my** V^2_{sci} **I get a super-precise visibility**
- **I derive** $\theta_{sci} = 1.523 \pm 0.001$ mas
- **… compared to calibrator which has a diameter** $\theta_{cal} = 1.50 \pm 0.02$ mas
- **If cal has** 1.52 mas, $\theta_{sci} = 1.543 \pm 0.001$ mas **(20 sigma!)**

A simple case

- **Fitting a constant provide a precise result**

  but

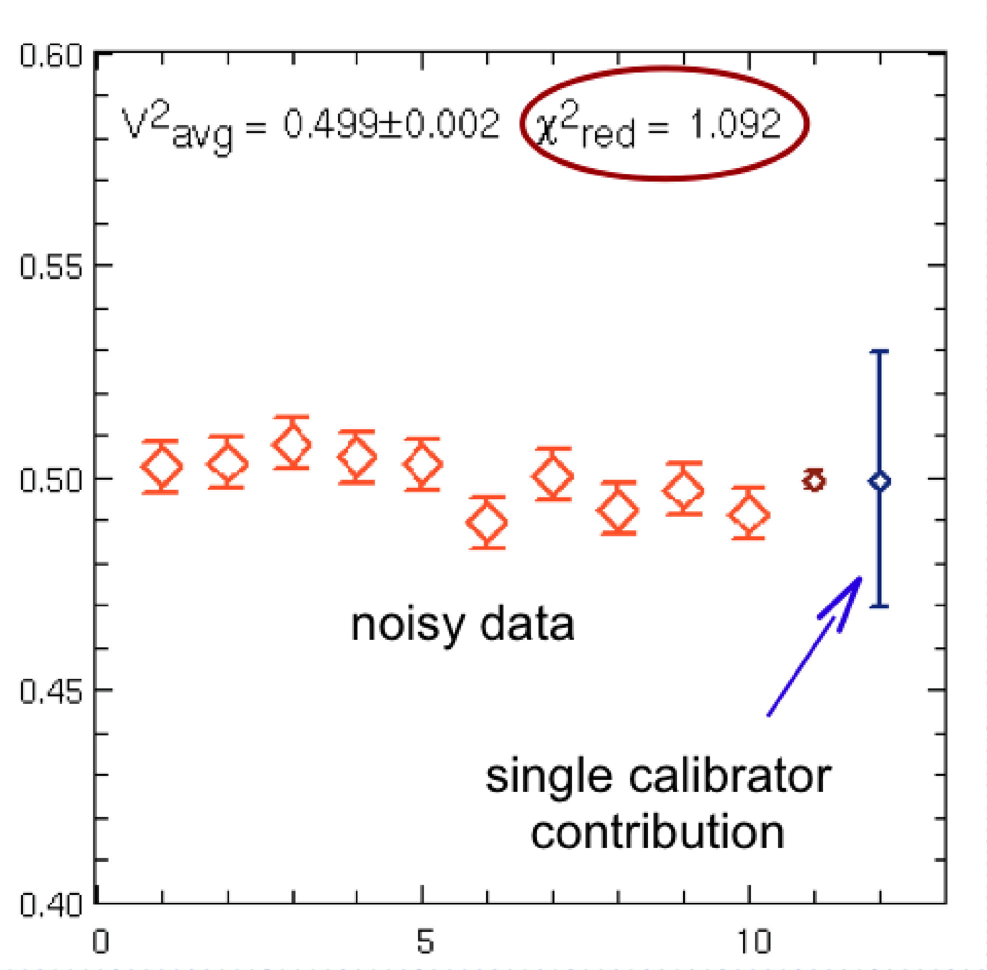
- **unrealistically small χ^2**
- **Are uncertainties overestimated?**



A simple case

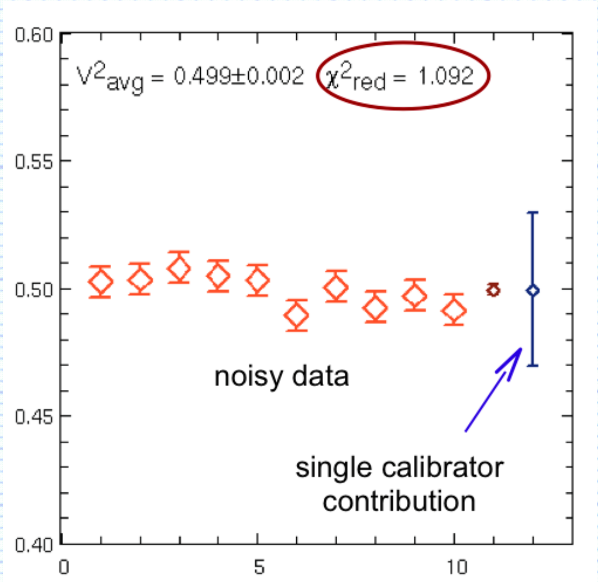
- Calibrators contribution is not an uncertainty, it is common to all measurements
- It is a systematic
- Separating the systematic, everything gets back to normal

$$V^2_{\mathrm{avg}} = 0.499 \pm 0.002_{\mathrm{stat}} \pm 0.030_{\mathrm{cal}}$$



What NOT to do

- I consider my errors obviously overestimated
- I think I made a mistake in error propagation
- I take the scatter and set it as the error because « data never lies »
- I fit my model and find a χ^2 close to 1
- I publish inaccurate result (i.e. wrong) with ridiculously small error bars
- I get in fight with colleagues because my results are off by 20 sigmas



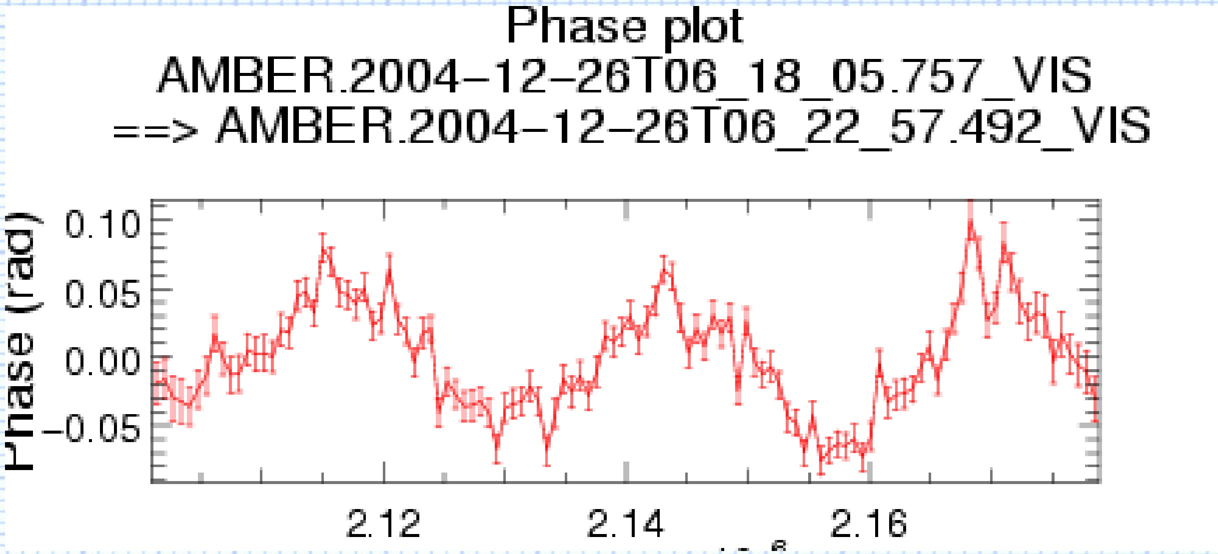
Do not think this never happened!

How to overcome systematics?

- **Simple case:**
  - Each observation uses a different calibrator
  - Calibrators contribution independent from one point to another
  - Then, there are no systematics
- **More general case:**
  - Take covariances into account: Perrin 2003 (A&A)
  - Problem: need to quantify systematics
  - Example: data selection can introduce an unknown systematic

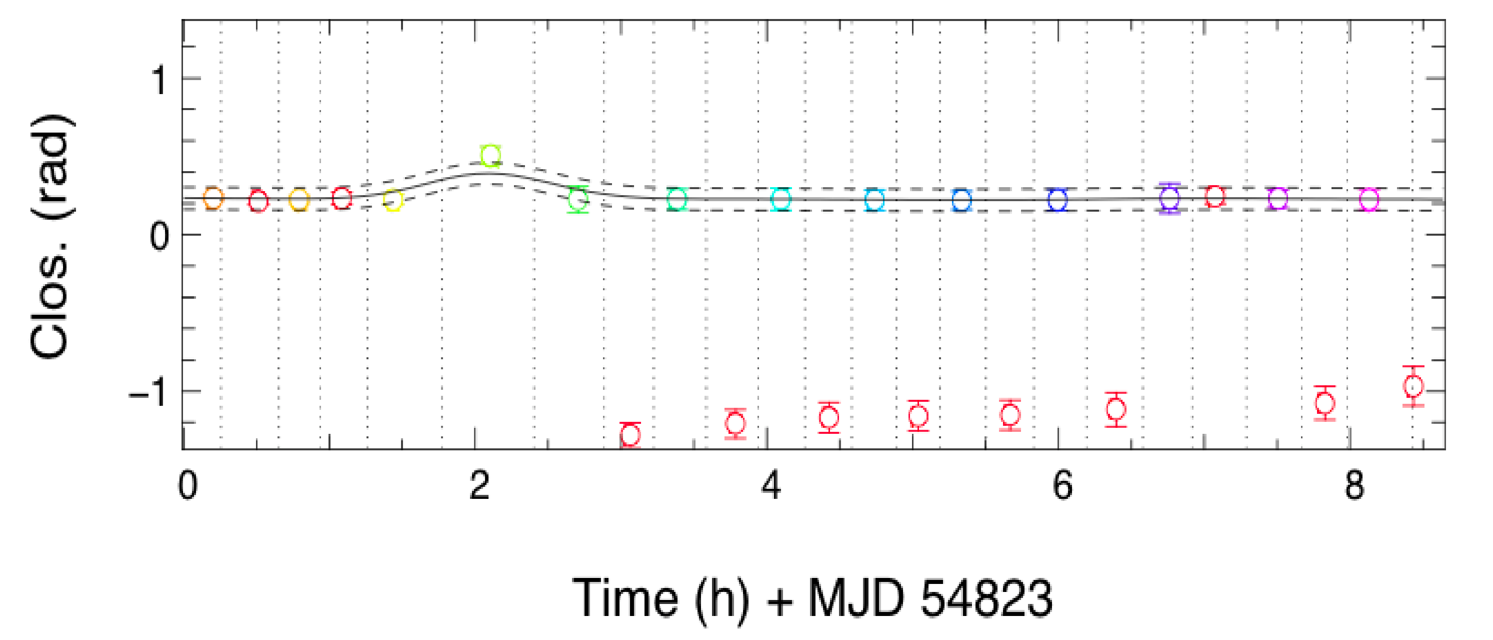
Do phases need calibration?

- Example: we saw closure phase eliminates all telescope-based perturbations
- BUT: affected by polarization, beam overlap, detector cosmetics, etc.



« Phases transfer function »

- We indeed see some variability!
- Can be calibrated out with a careful monitoring

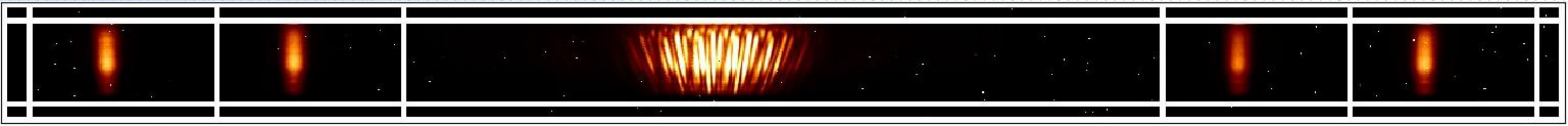


Outline

- Why do we care so much about data reduction?
  - What are we looking for?
  - What adversities are we fighting against?
- The interferometry observables
  - All the observables
  - Statistics
  - Calibration
- MATISSE data reduction
- Conclusions

MATISSE data reduction

- Based on Fourier transforms
- Careful calibration of detector & atmosphere contributions
- Modulation/demodulation

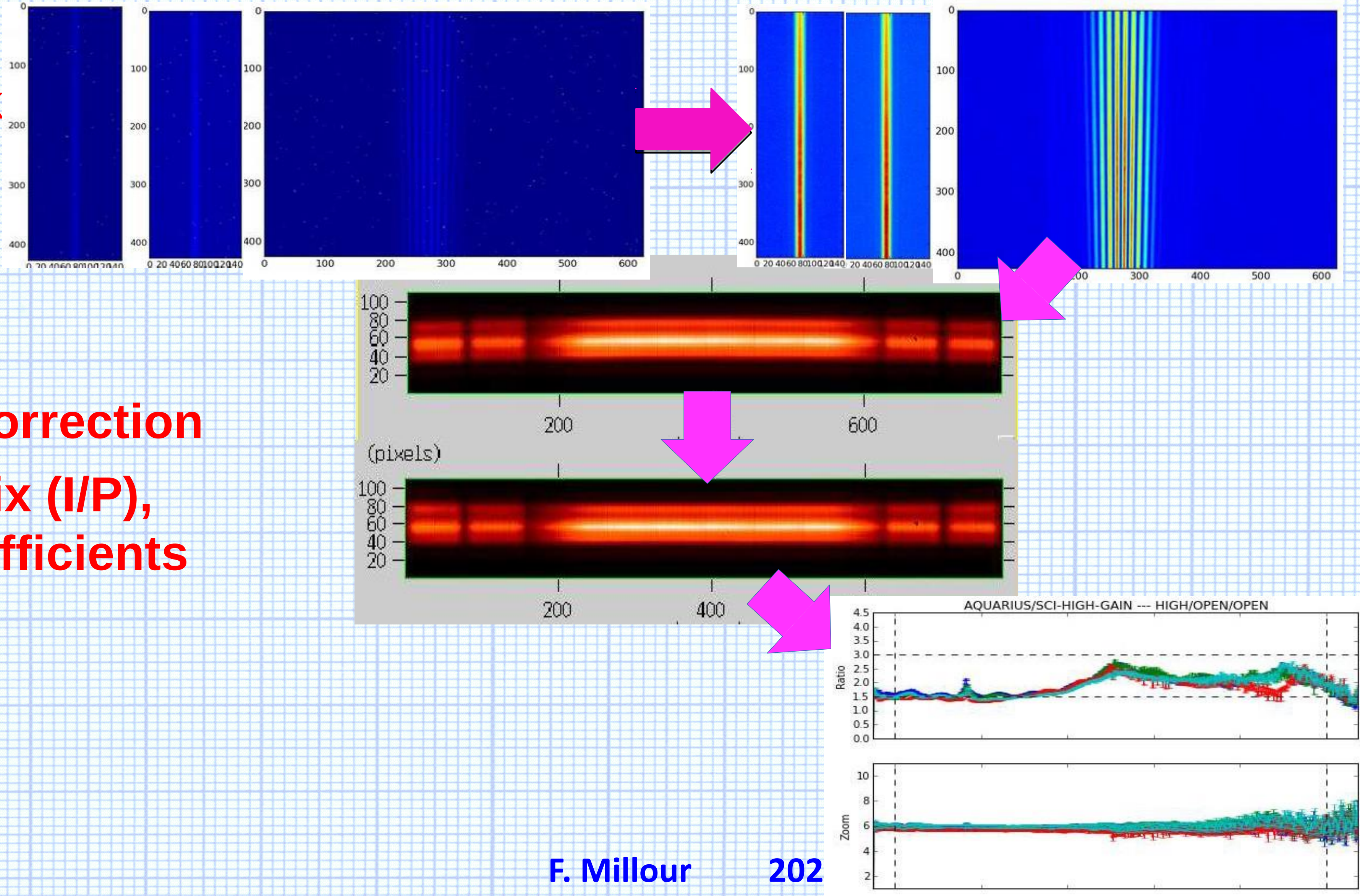


Cosmetics corrections

- Subtract cold dark
- Divide by flat field
- Interpolate bad

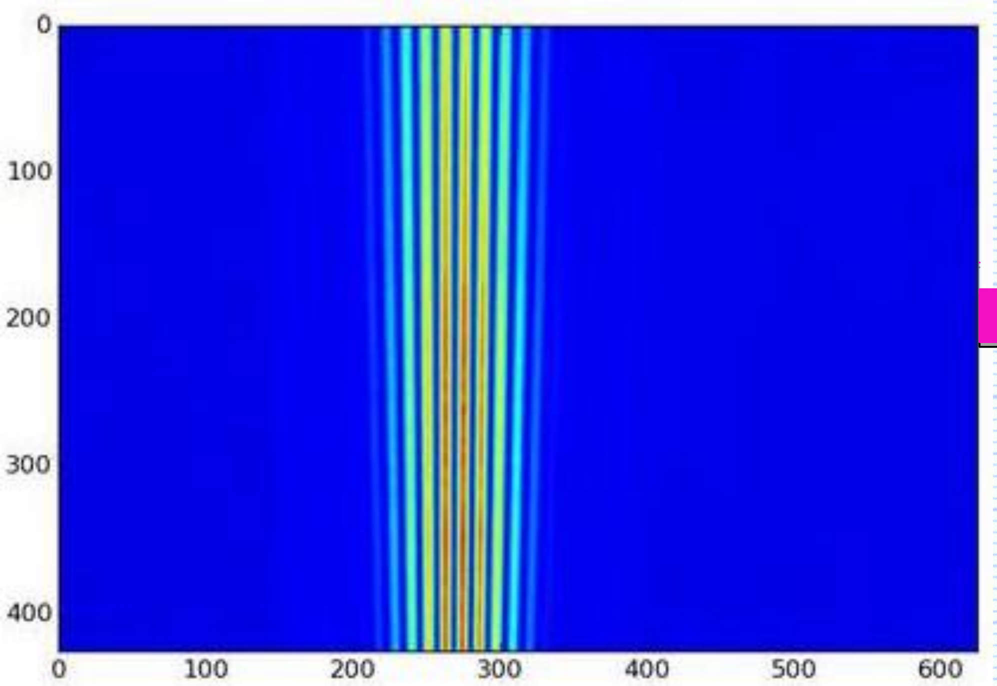
pixels

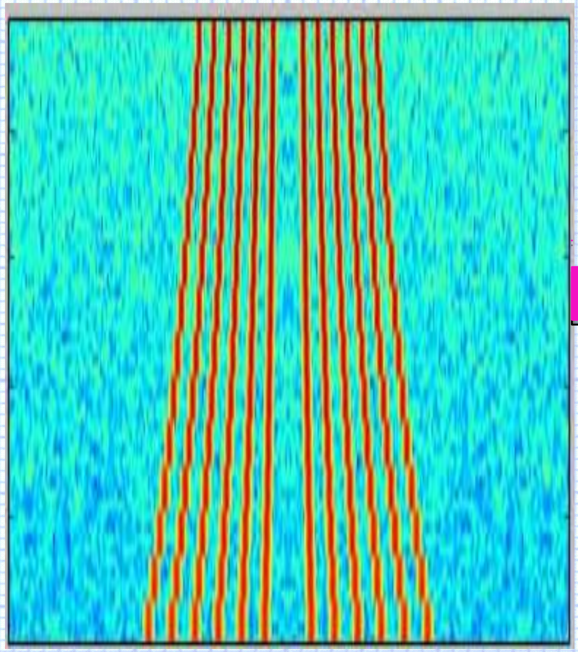
- Apply distortion correction
- Apply Kappa Matrix (I/P),
  Shift & Zoom coefficients

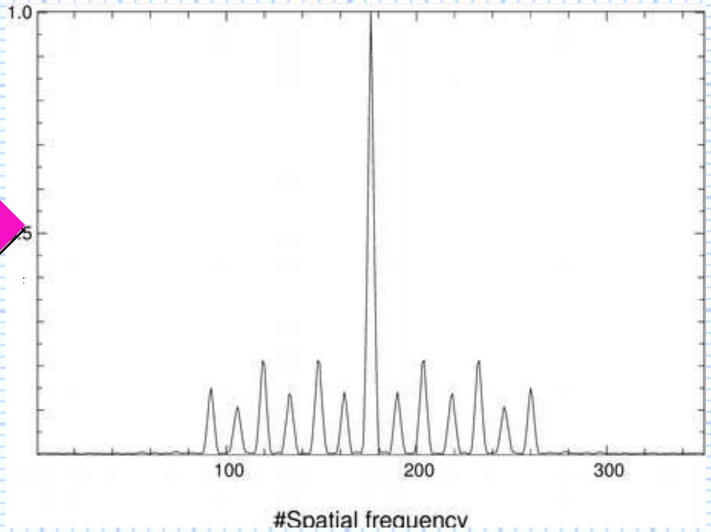


Compute Fourier transform

That's in fact 1st step (out of 3) of demodulation

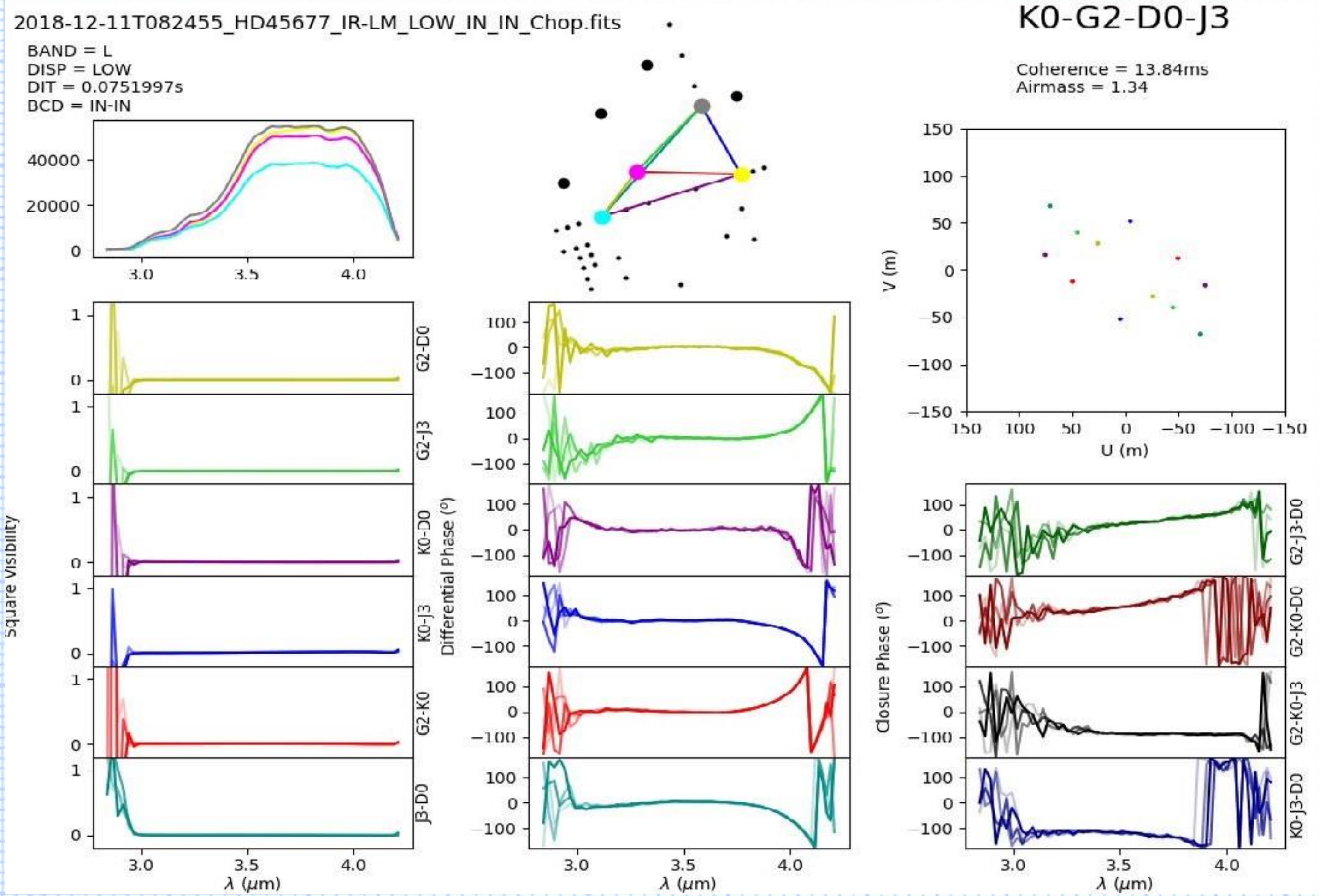




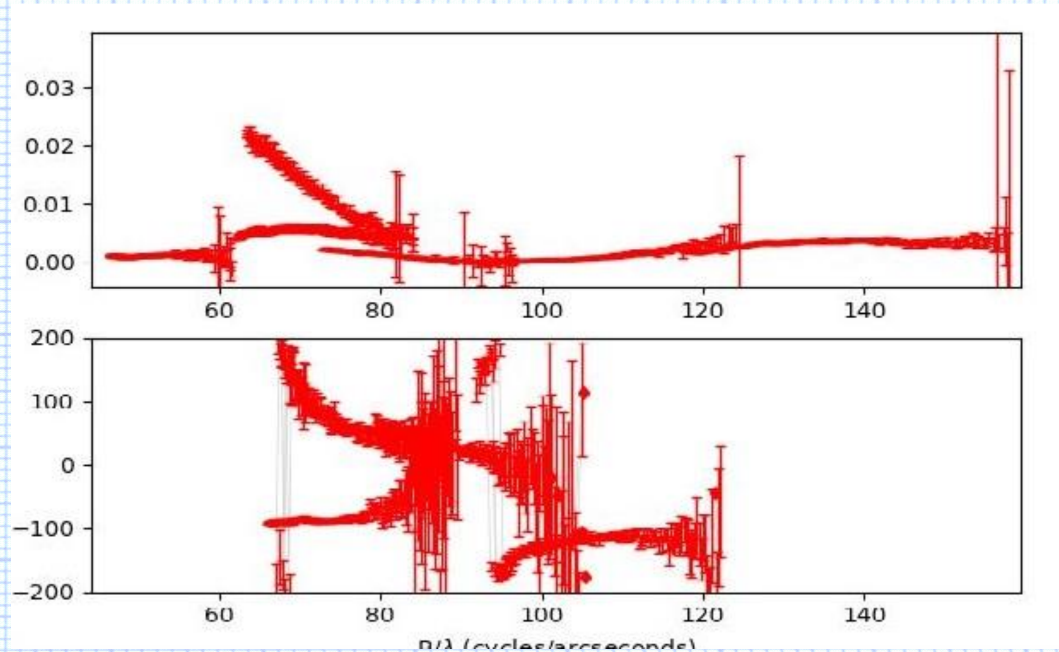


Compute observables

mat_showOiFits.py

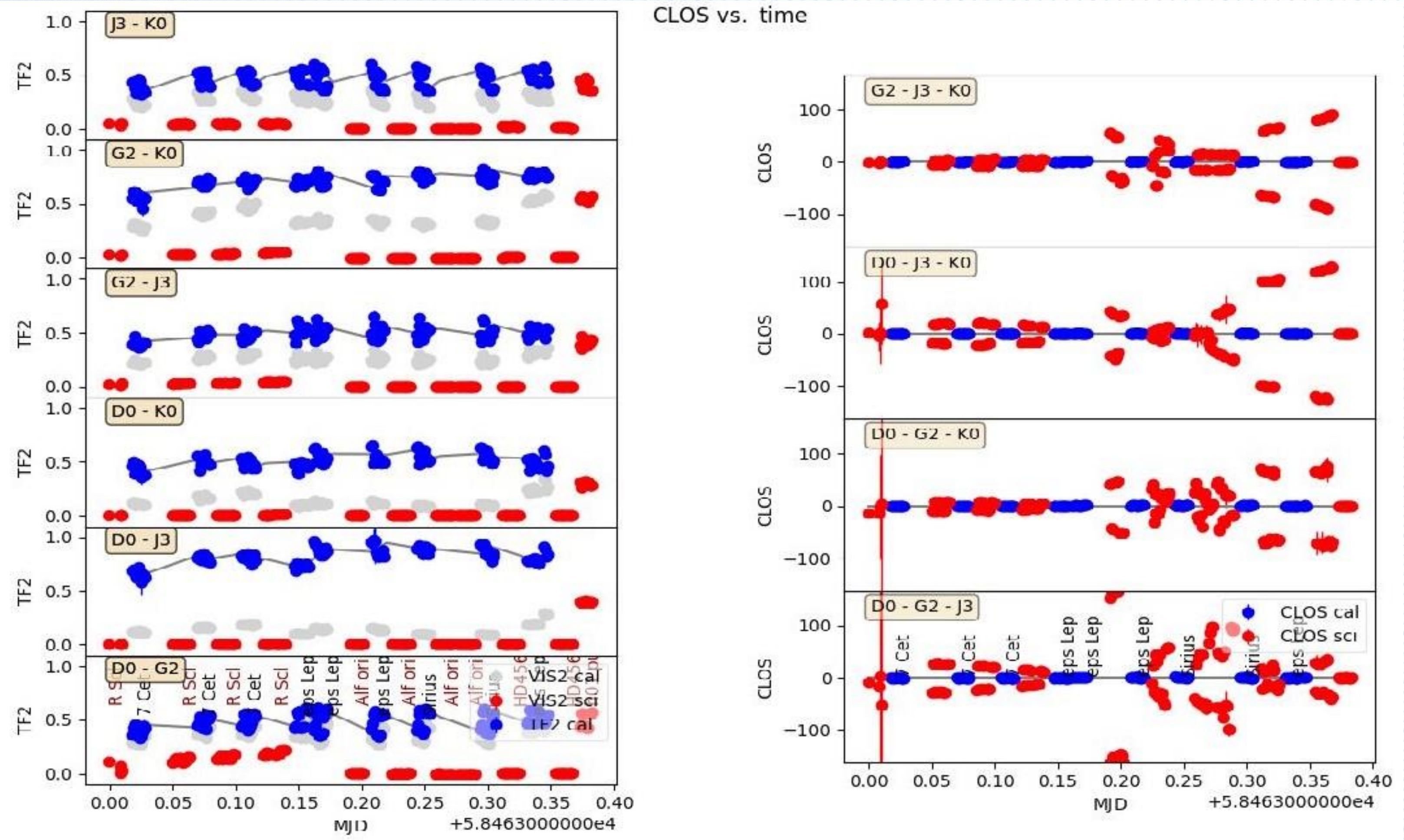


mat_showOiFreq.py

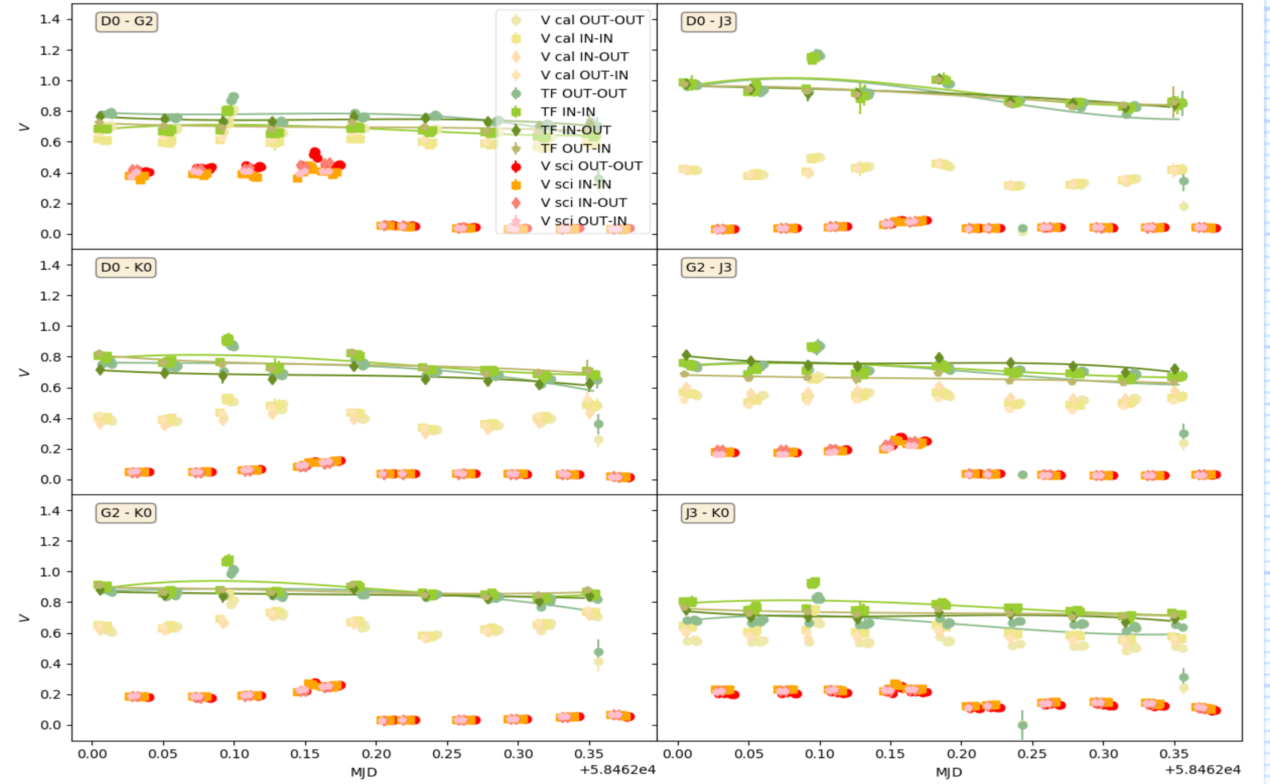


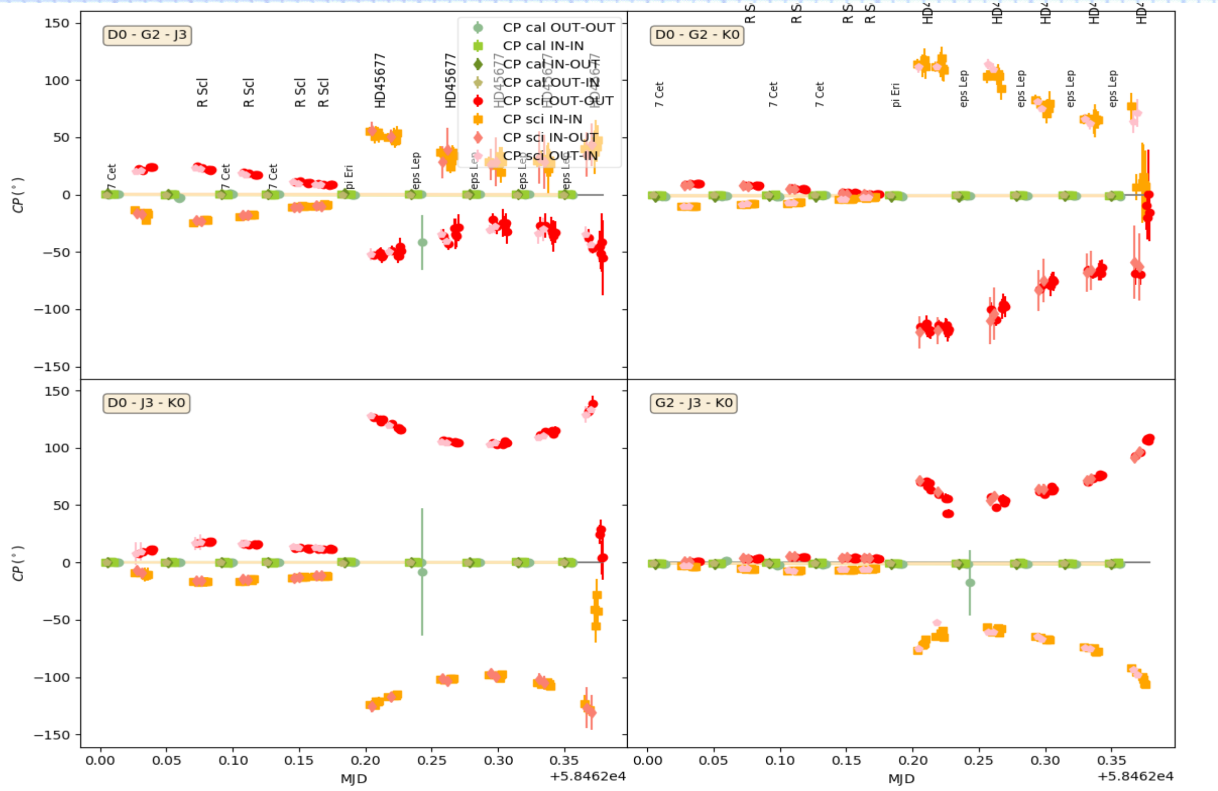
Transfer function

Mat_showTransFunc.py



Transfer function

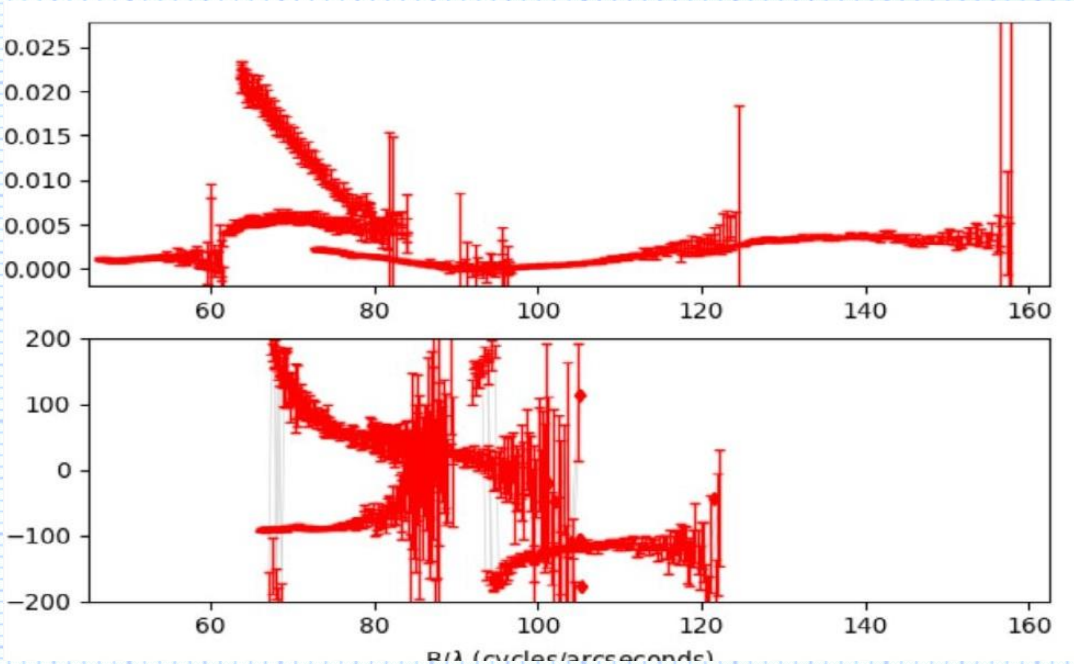




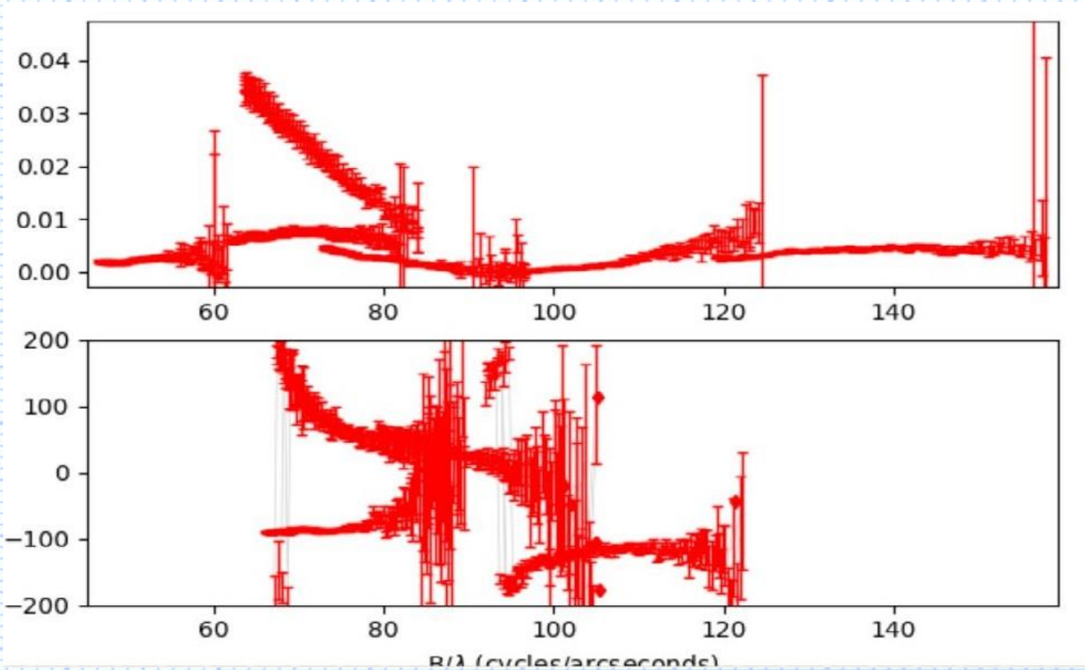
Calibration

- **mat_autoCalib.py… you will see that tomorrow!**

raw



calibrated



Outline

- Why do we care so much about data reduction?
  - What are we looking for?
  - What adversities are we fighting against?
- The interferometry observables
  - All the observables
  - Statistics
  - Calibration
- MATISSE data reduction
- Conclusions

Conclusions

- Interferometric data reduction is somehow tricky
  - Visibility disturbed by noise and systematics
  - Phase is lost but: closure phase and differential phase

be critical…

- Never use a DRS as a « black box »!
  - Understand limitations
  - Think about strategy (including for observations)
  - Be critical on everything!

Be Critical.

- Calibrate:
  - Calibrate: do not forget to be critical after battling to obtain visibilities,
  - Calibrate, check the self consistency of your datasets
  - Calibrate… Never forget everything is biased!

BE CRITICAL!