Theory of optical long-baseline interferometry data reduction

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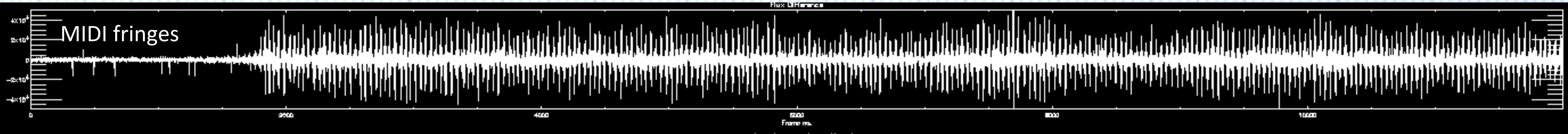
with some ideas and slides taken from
A. Merand, J.B. Lebouquin, O. Chesneau,
C. Hummel, J. P. Berger, G. Perrin, etc.

LAGRANGE

Observatoire de la CÔTE d'AZUR

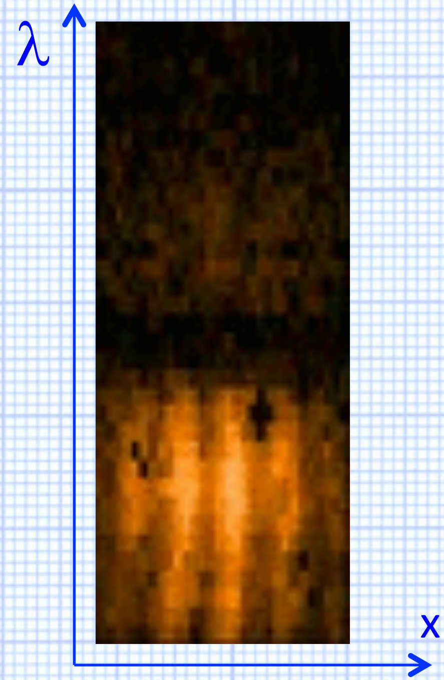


What about phase?

Remember, due to the atmosphere:

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

    ➔ Fringe phase is lost!

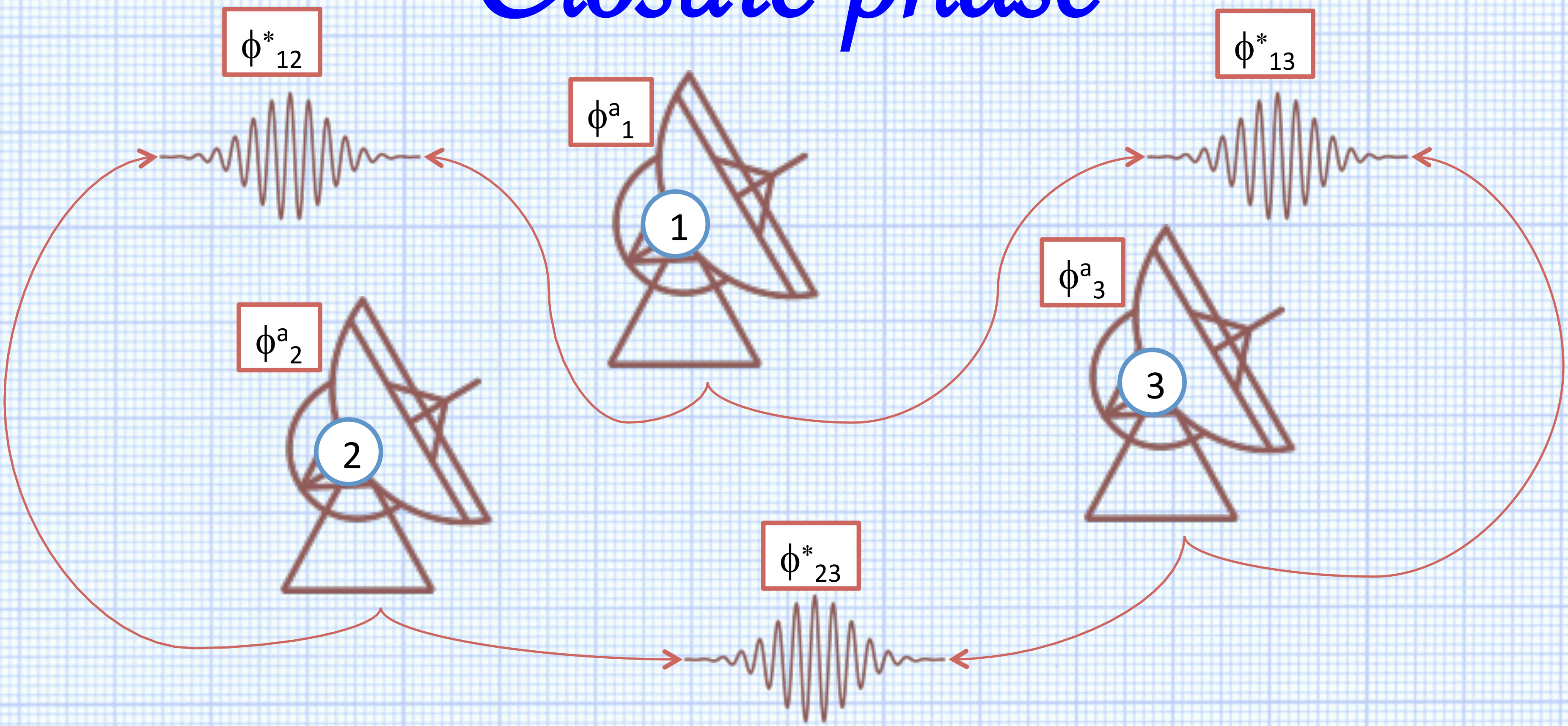


$$I\left(\delta_0, t\right) = e^{-\sigma^2_{\text{jitter}}(t)} \mu \cos\left(\phi - 2\pi \frac{\delta_0 + \delta(t)}{\lambda}\right)$$

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

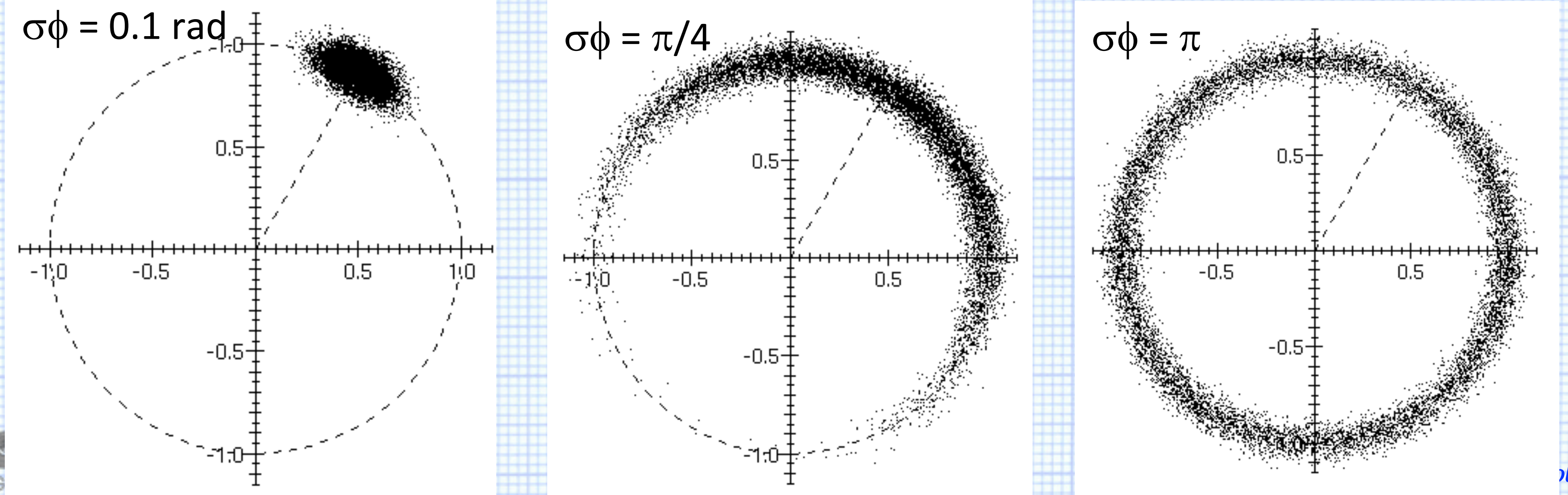
Closure phase cannot be obtained with phases sums!

why?

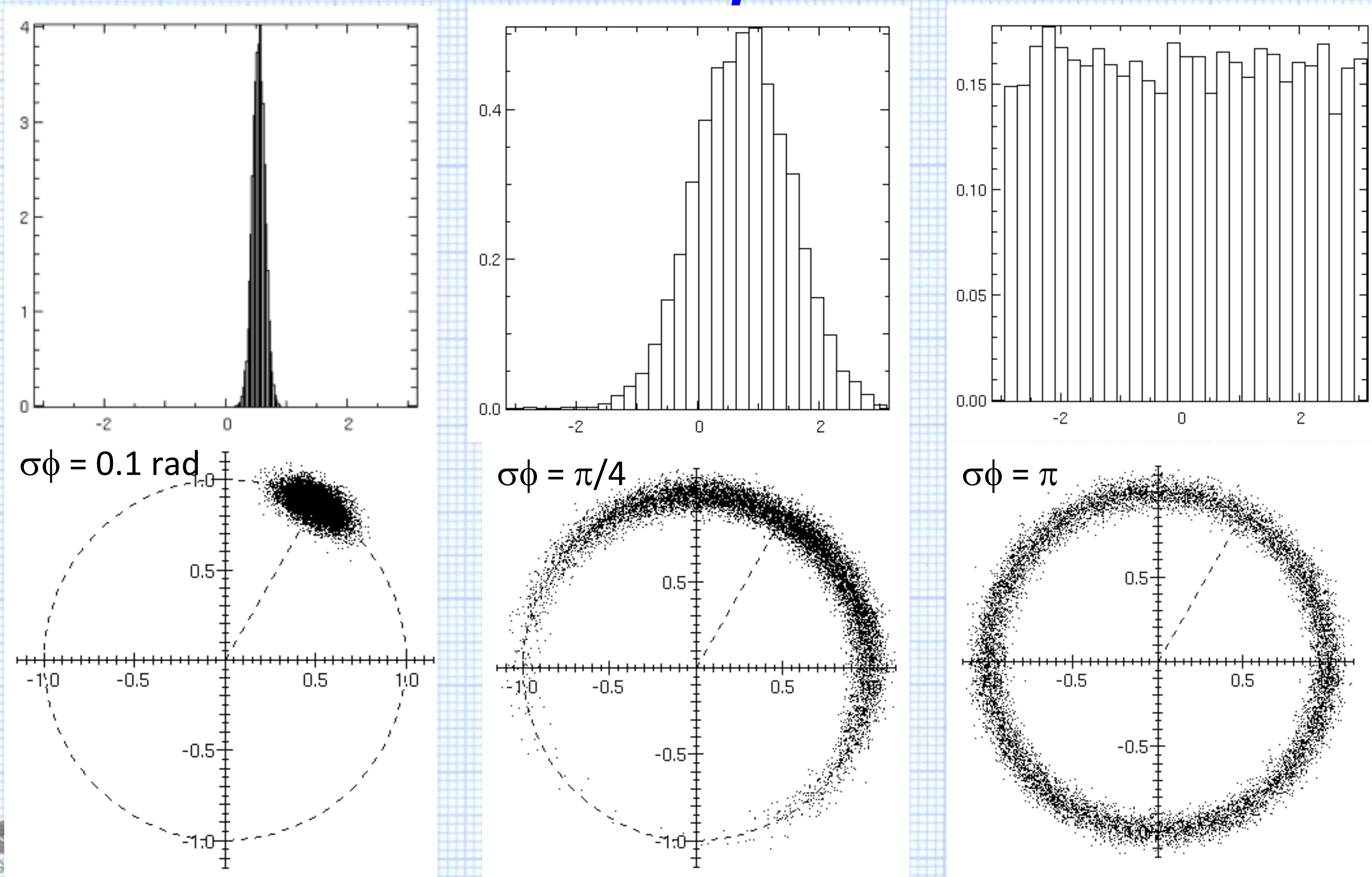
Noise!

Additive noises produce a phase wrapping

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



Closure phase

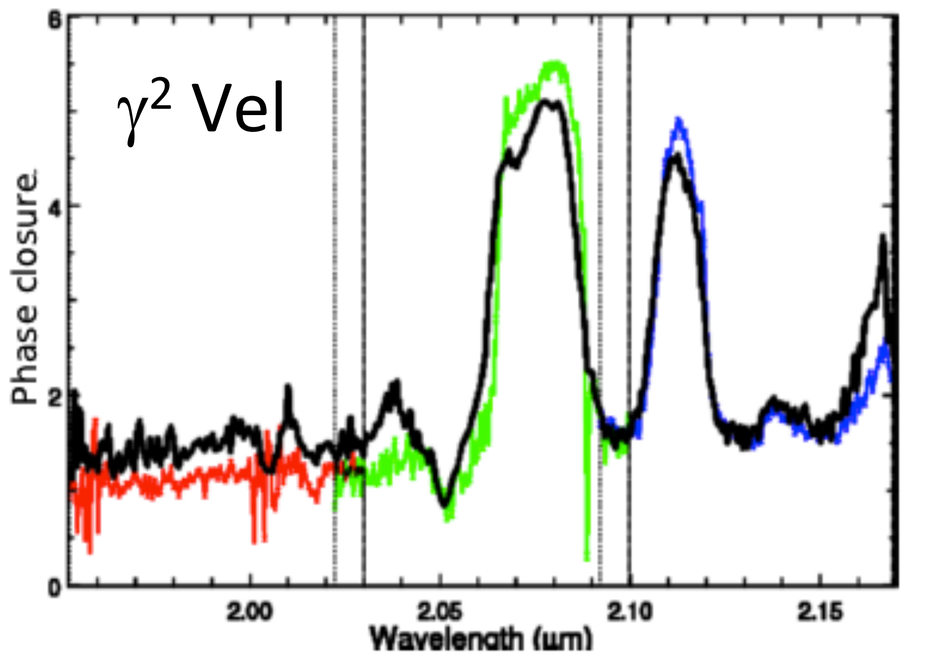


Closure phase

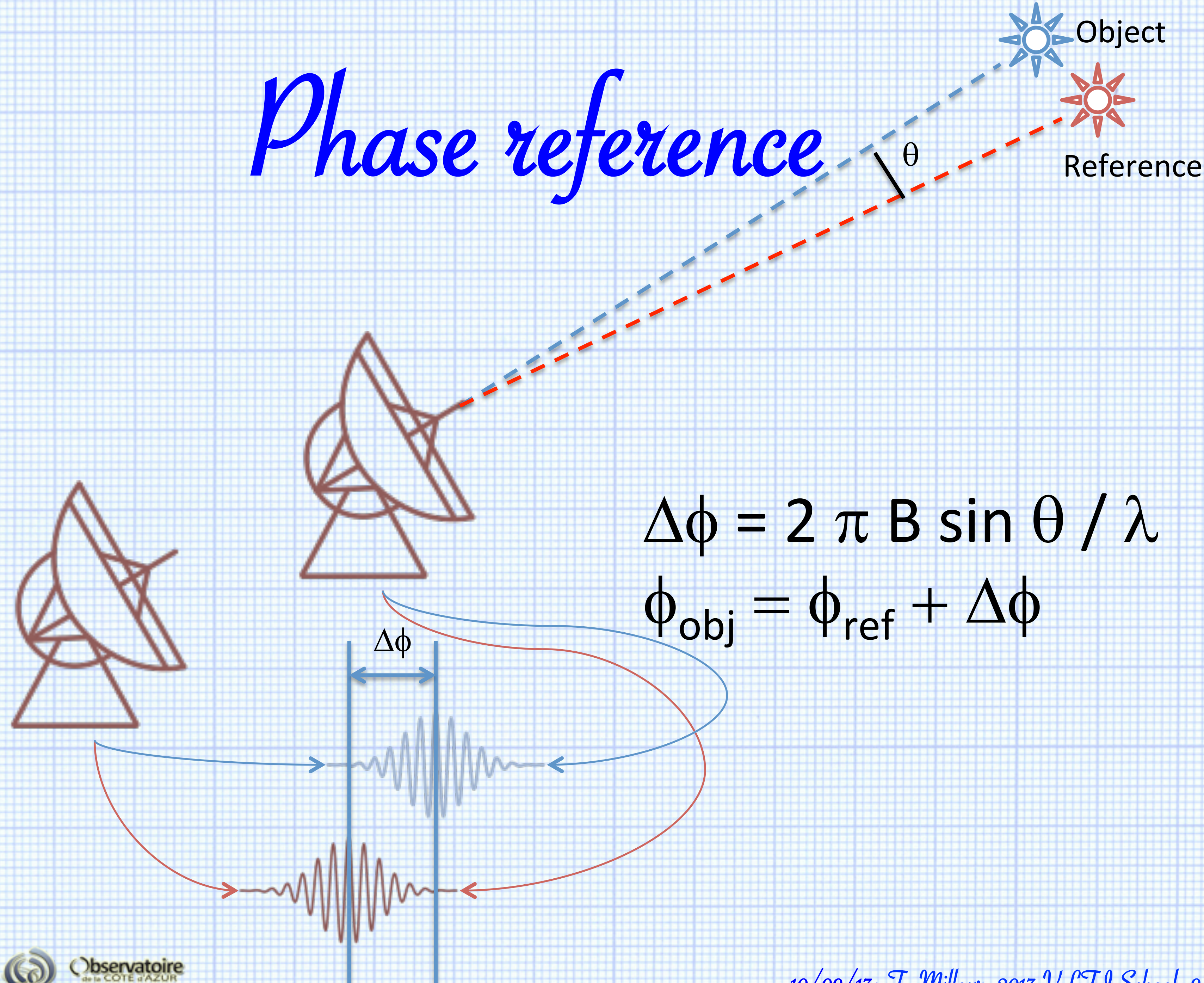
- Closure phase cannot be obtained with phases sums!
- Stay in complex plane to avoid phase wrapping:
  - Bispectrum $<C_{12}C_{23}C_{31}>$
    - Phase of the bispectrum = closure phase
    - Amplitude of the bispectrum = $V_{12}V_{23}V_{31}$

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!



Phase reference



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

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

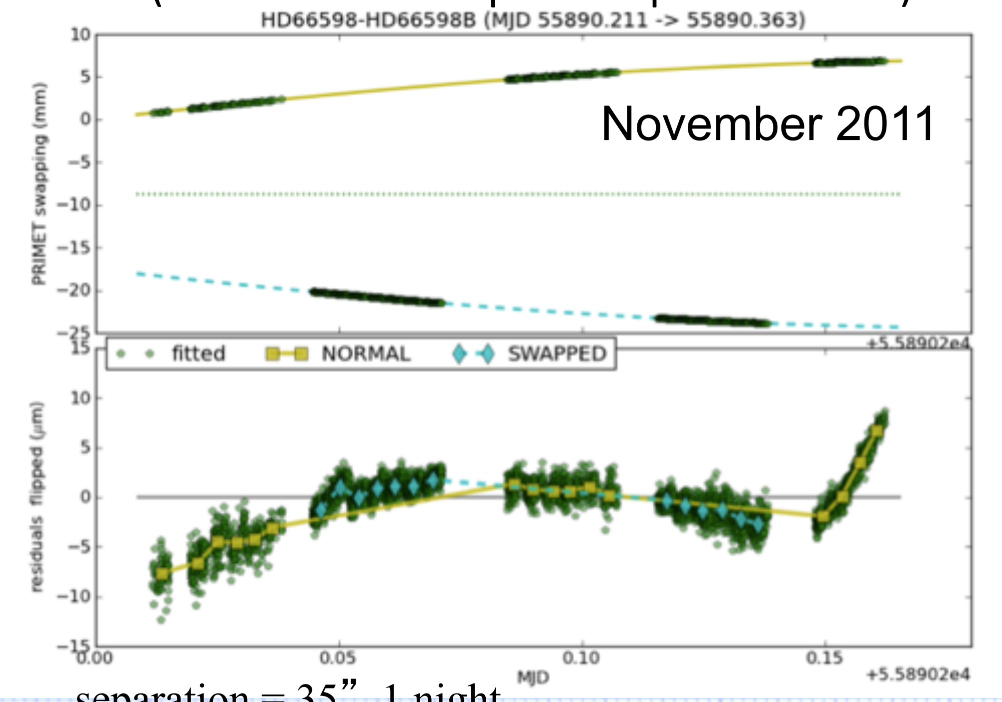
Phase reference

- 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

Phase reference

- *Many problems affect the phase reference!*
  - *Polarization effects*
  - *Telescope pointing effects*
  - *Chromatic air dispersion*
  - …

Example PRIMA data
(from 2012 F. Delplancke presentation)



separation = 35”, 1 night
Residuals 20µm PTV. Fast evolution at transit

Differential phase

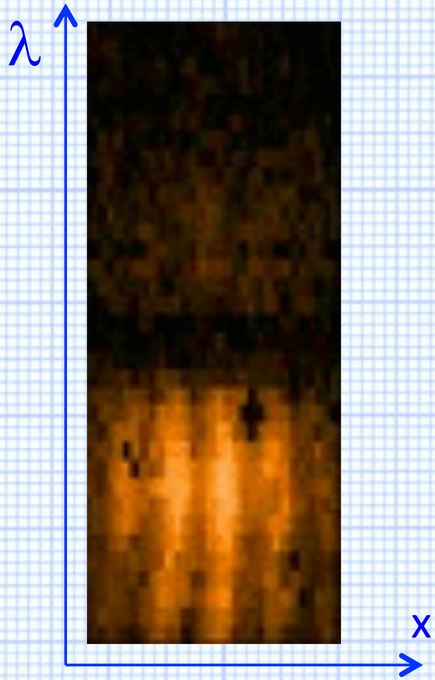
!!!!!!!!!!!

- « 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
  - …



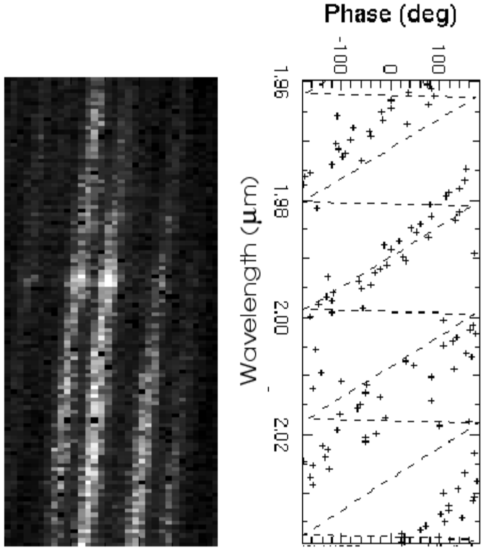
$$I(\delta_0, t) = e^{-\sigma^2_{\text{jitter}}(t)} \mu \cos\left(\phi - 2\pi \frac{\delta_0 + \delta(t)}{\lambda}\right)$$

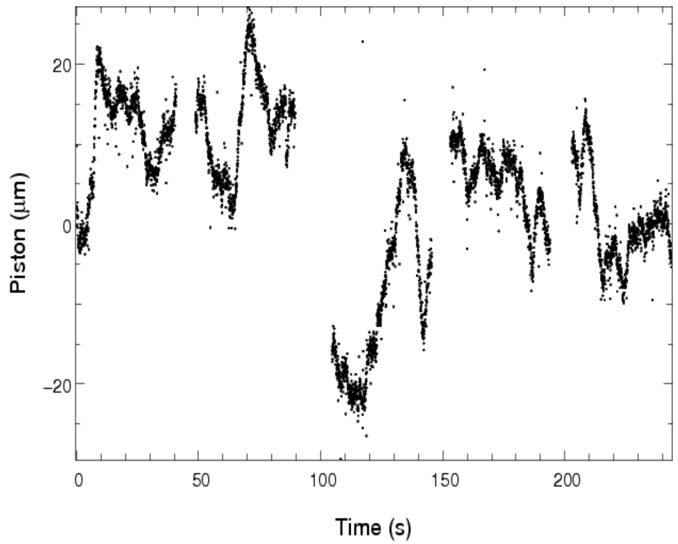
Differential phase

- 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
    ➔ $Cn = C\, e^{-2i\pi\, \delta/\lambda}$
  - $\phi_{diff} = \arg \langle Cn_{work}\, Cn^{*}_{ref} \rangle$





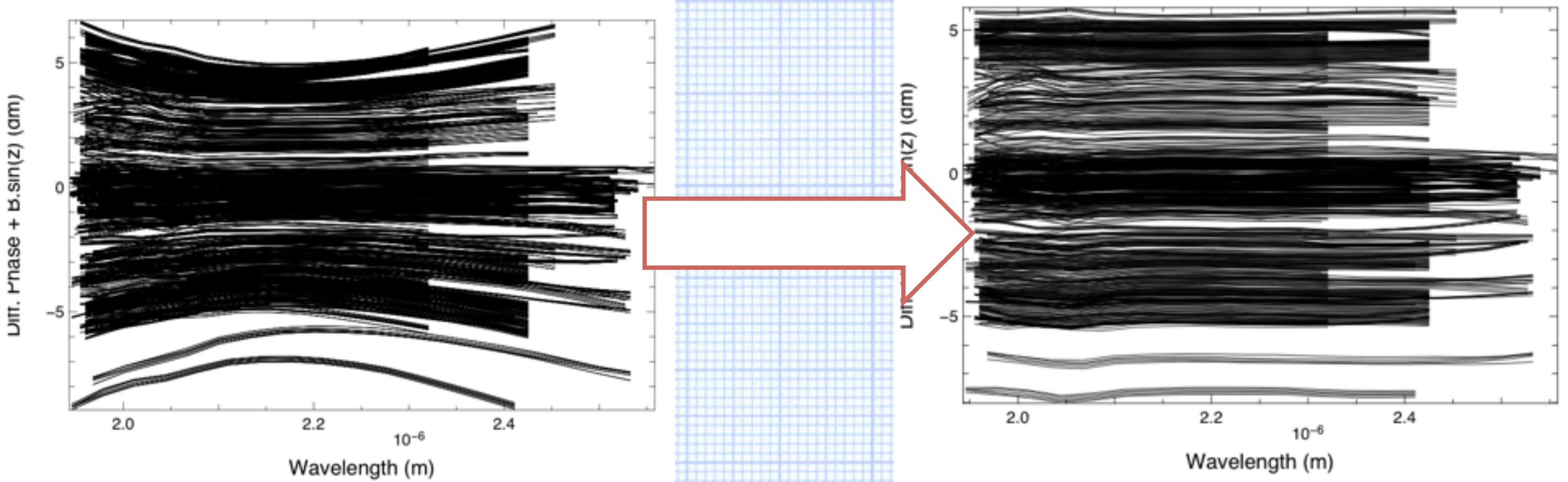
Differential phase

- *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.*

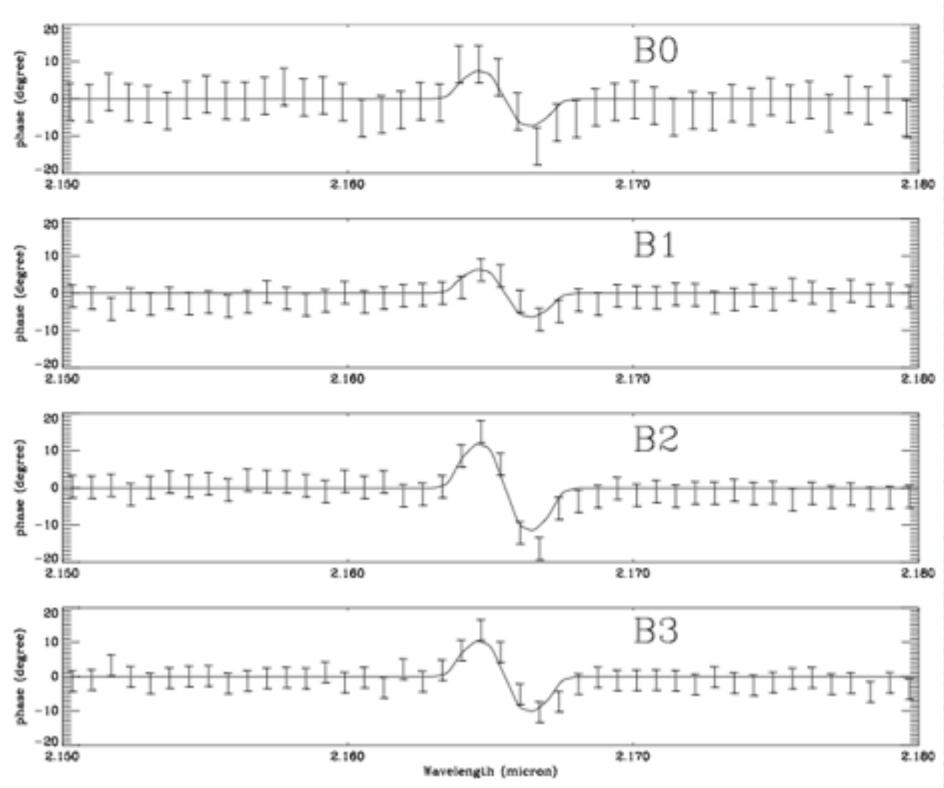
See Ciddor 1996, Vannier 2006, Mathar 2007



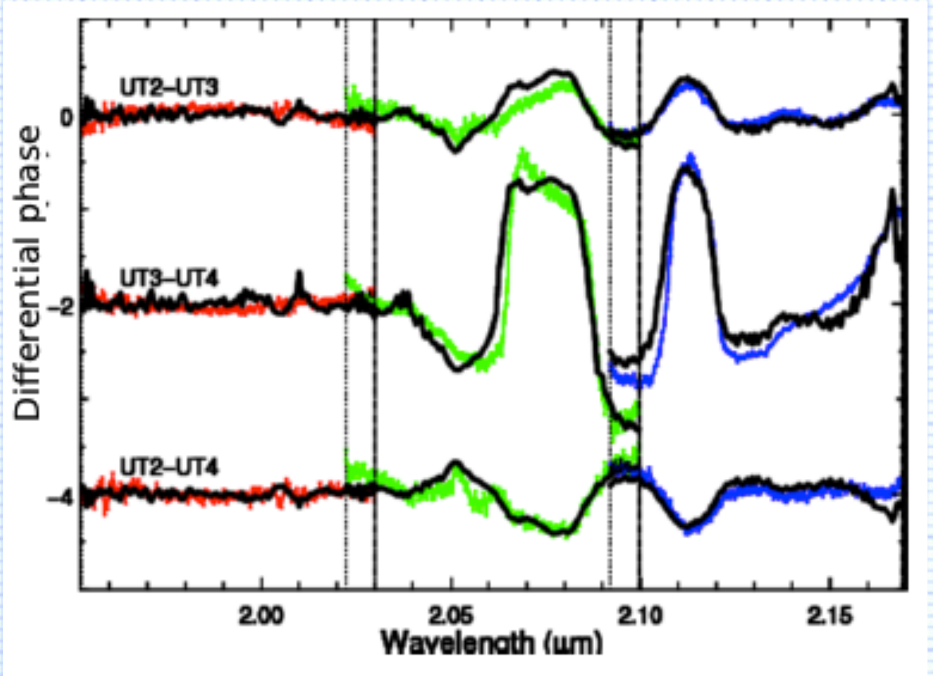
Differential phase examples

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

α Arae



γ^2 Vel



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
- A few implementations
  - AMBER data reduction
  - MIDI data reduction
- Conclusions

The interferometrist problematic

- Estimate « properly » fringe contrast & phase
  - Precise measurement
  - Accurate measurement

  WTF??
- Calibrate data
  - Calibrate,
  - Calibrate!
  - Calibrate?
  - …

Infinite loop

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

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

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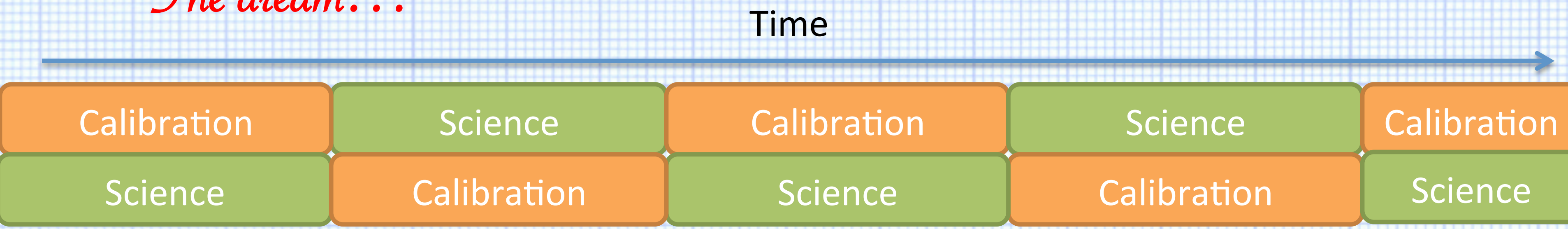
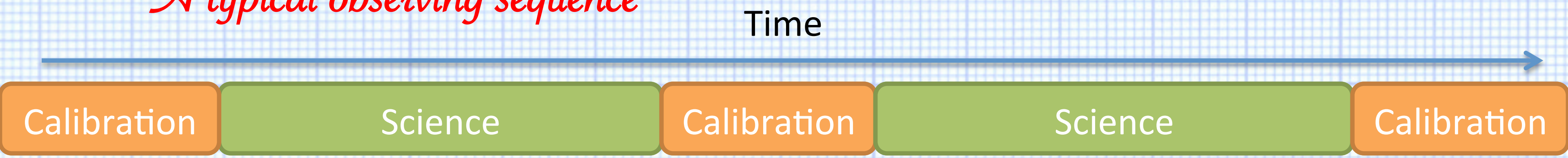
Data calibration,

- *The dream…*



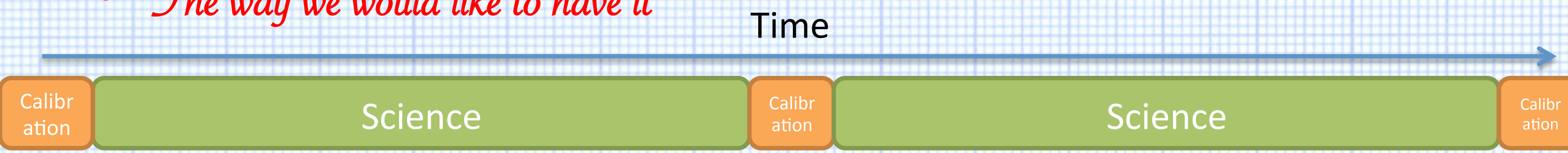
Data calibration.

- *A typical observing sequence*



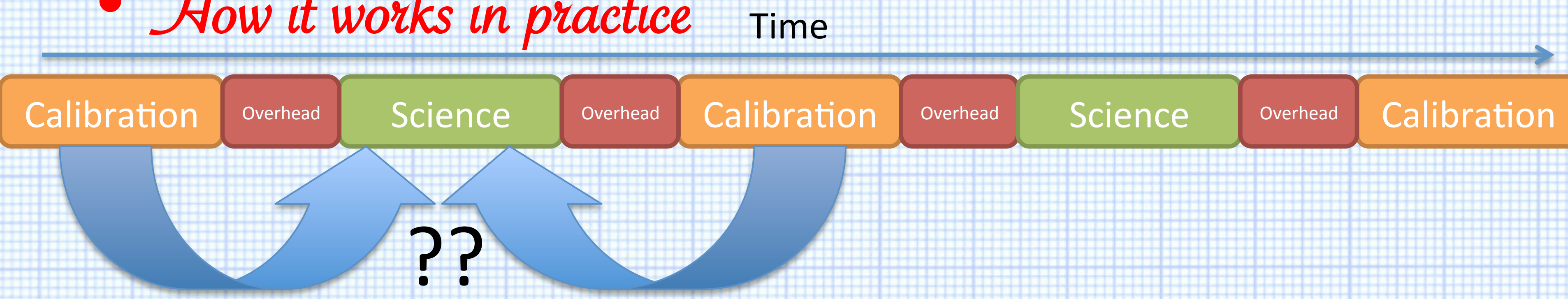
Data calibration!

- 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?

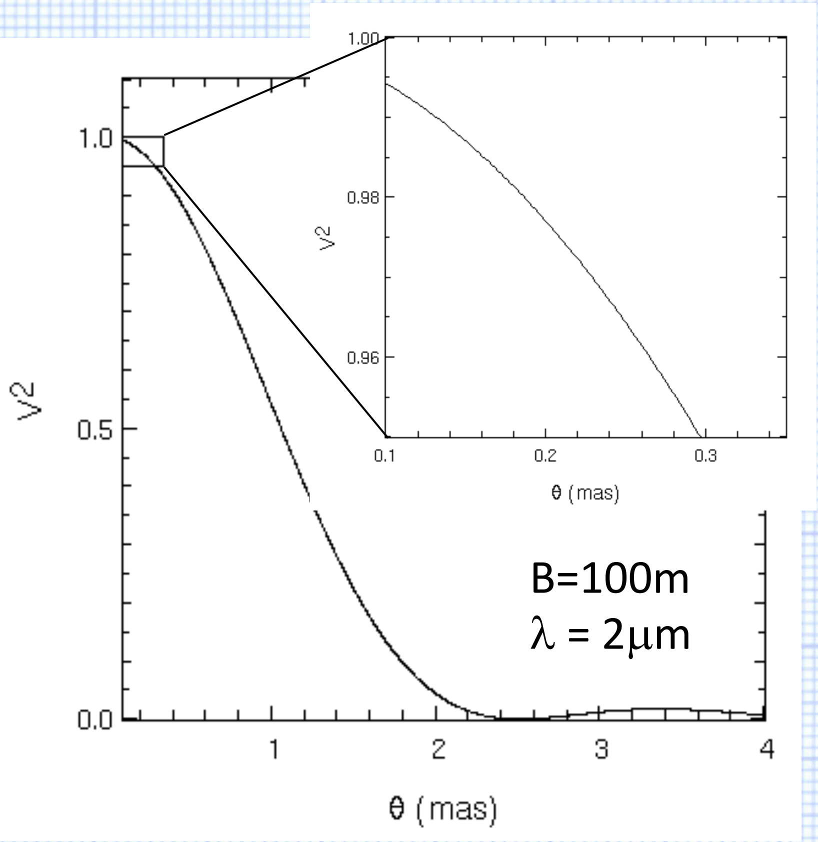
- *Calibration star = star with known* μ^2_{cal}
- *An infinitely small star at a given magnitude has an infinite surface brightness*

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

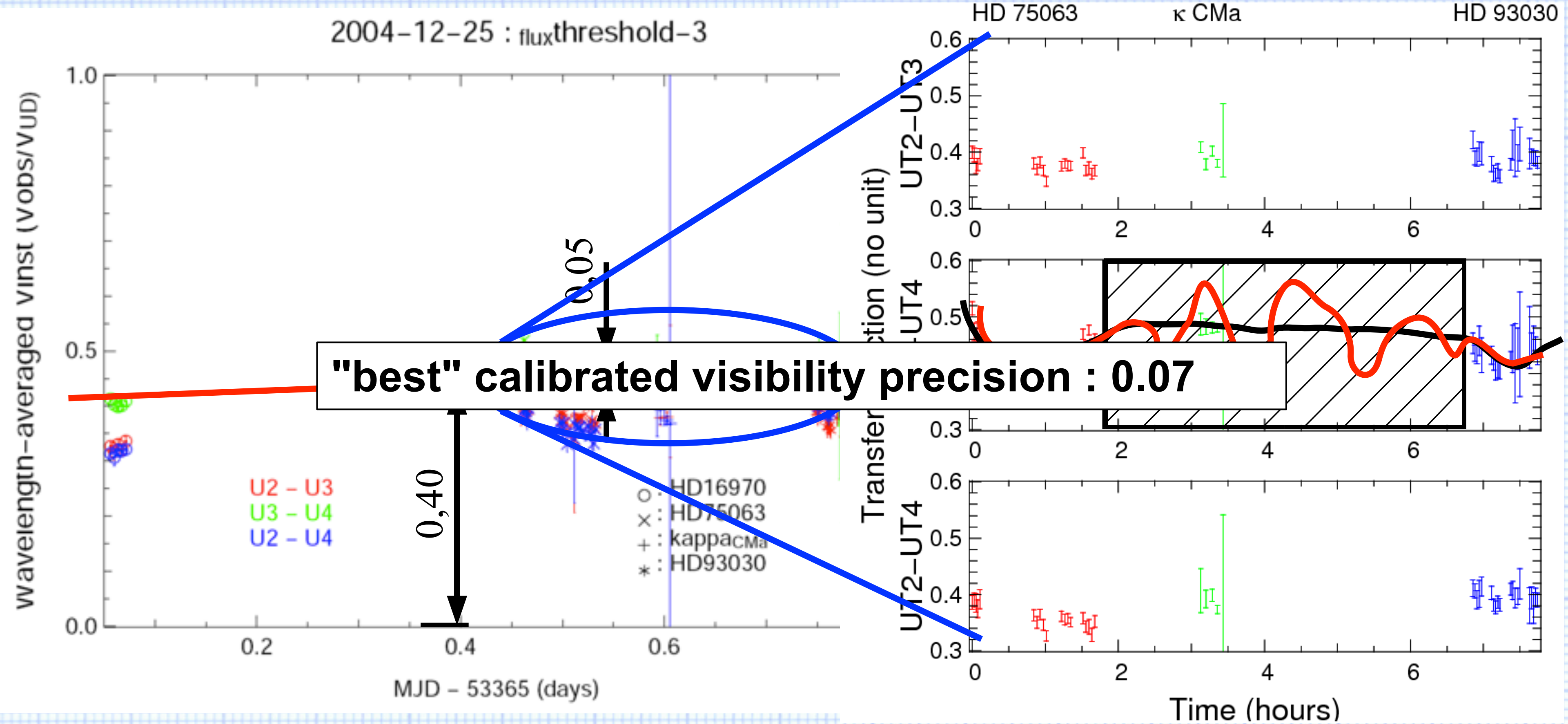
2. $\mu^2_{th} = 4\frac{J_1(2\pi\theta B/\lambda)^2}{(2\pi\theta B/\lambda)^2}$

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

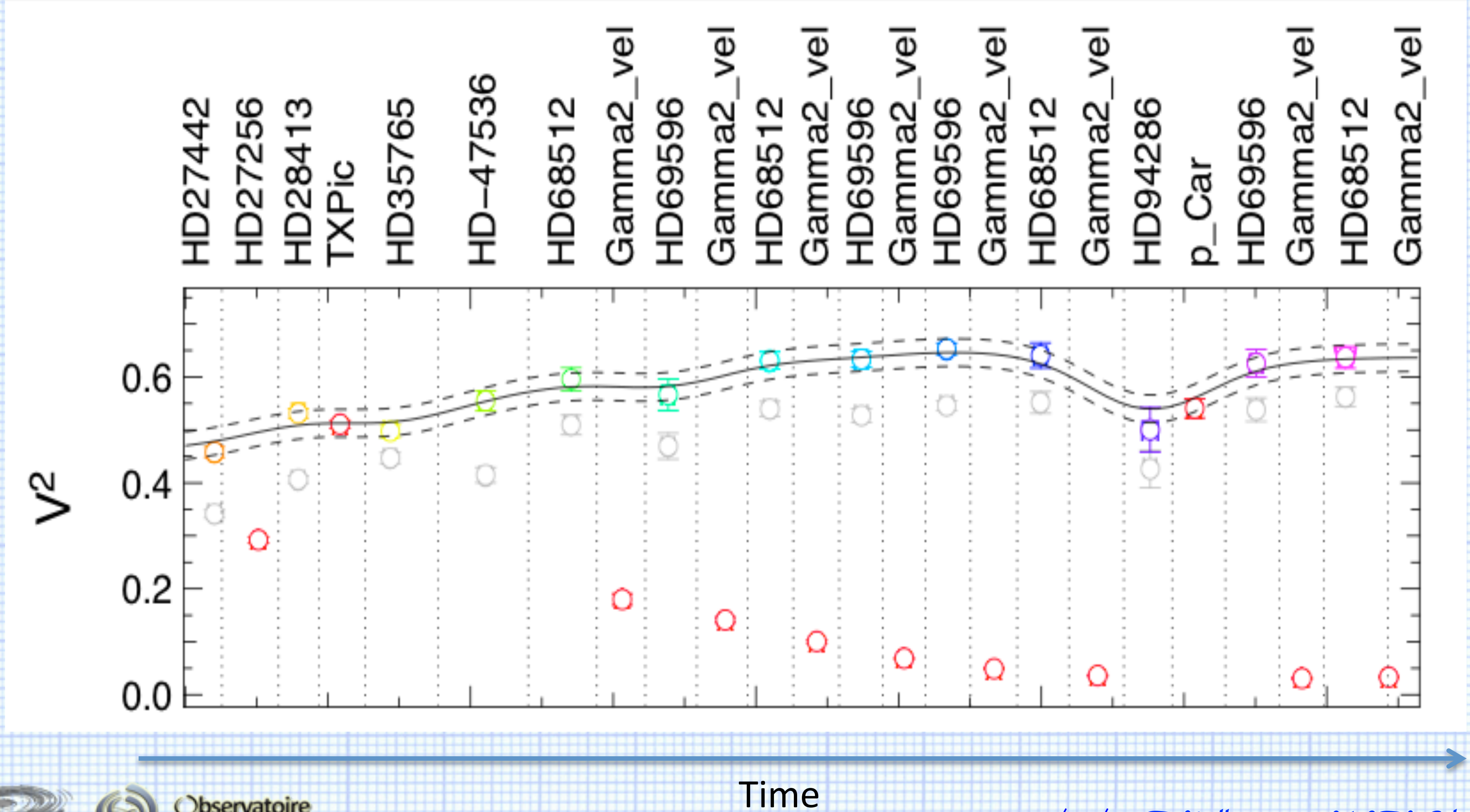
4. $T^2(t_{sci}) = f[T^2(t_{cal})]$

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

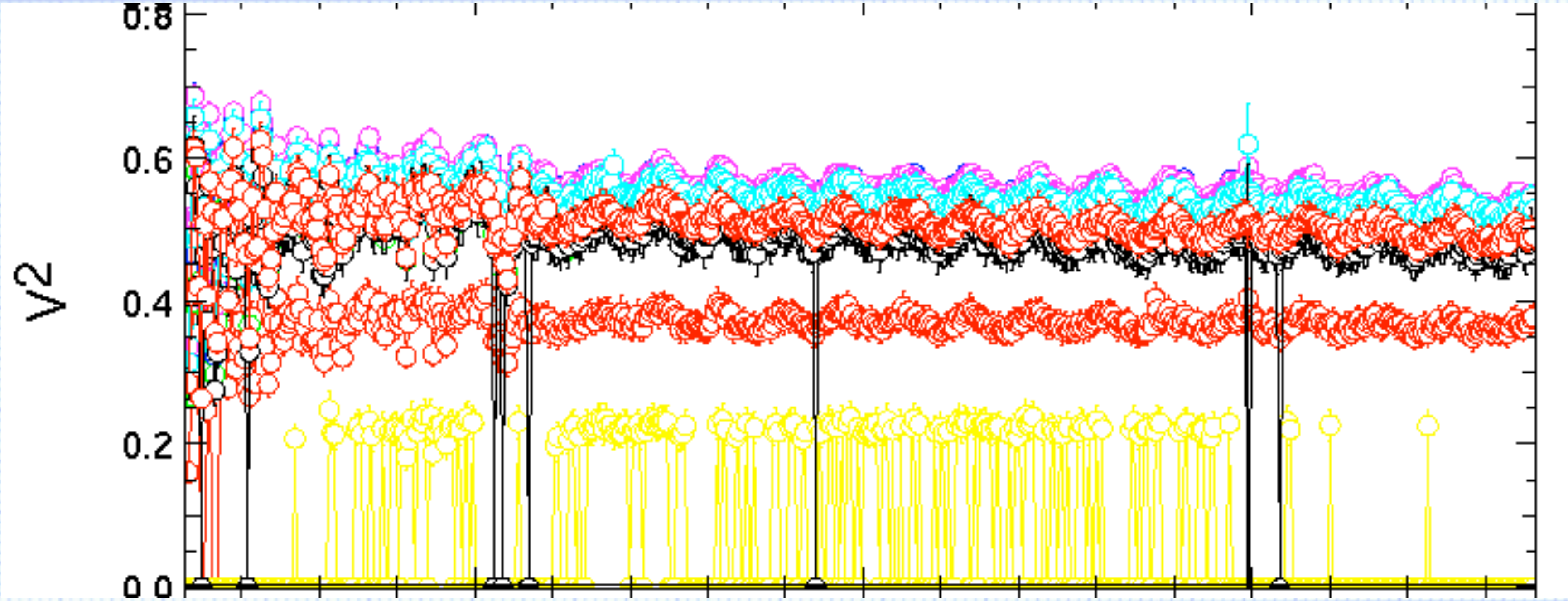
"transfer function" (AMBER in 2004)



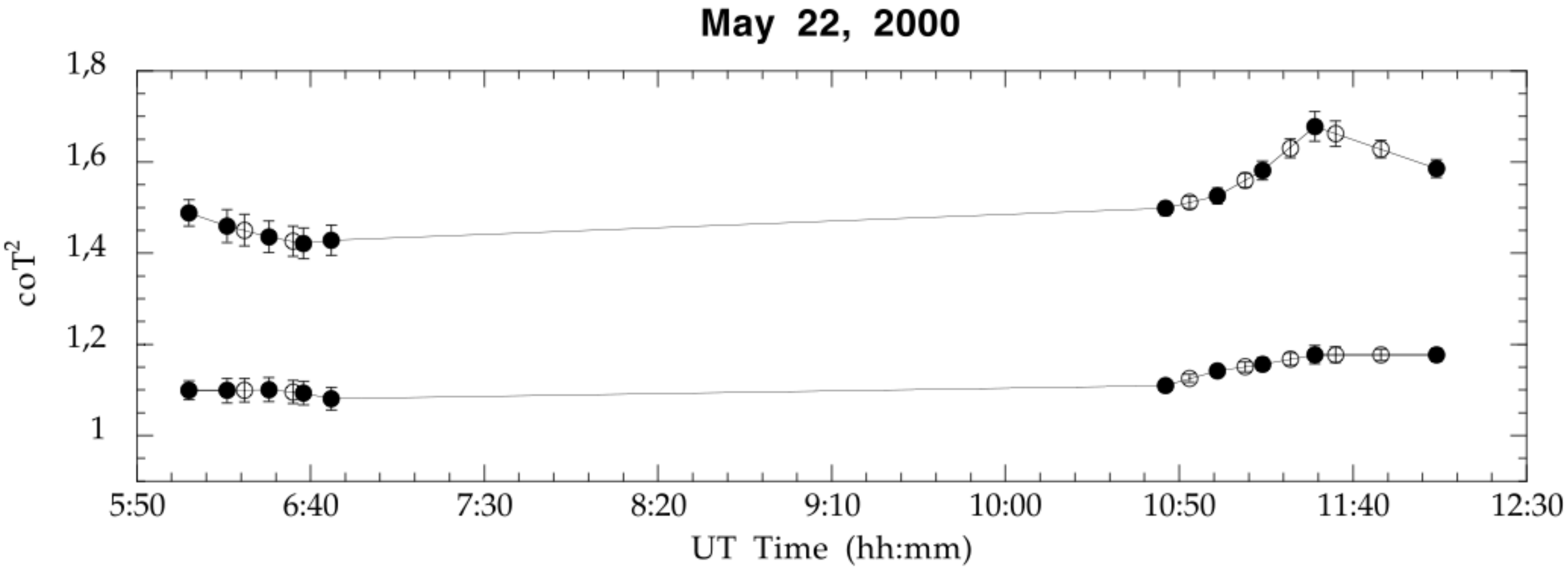
"transfer function": a better one (2008)



The same plot as a function of wavelength

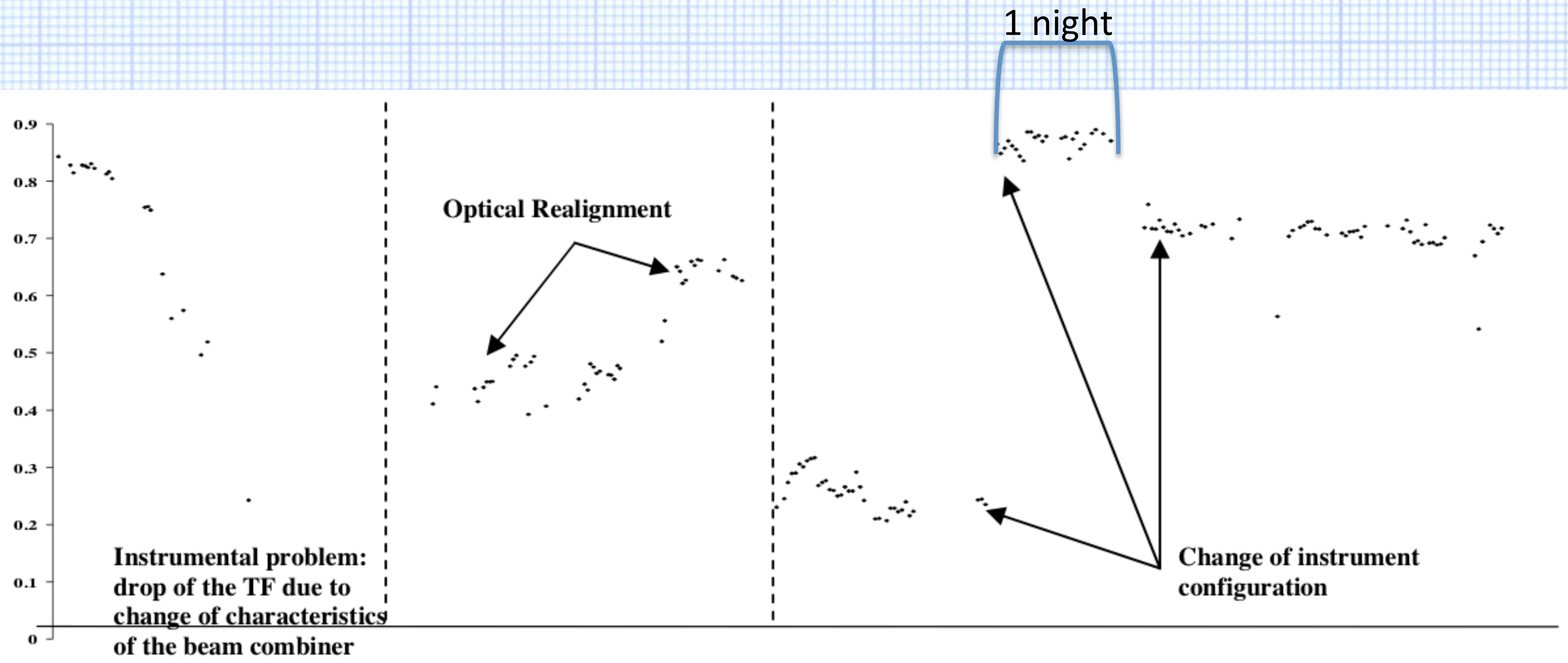


« *transfer function* »: FLUOR



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

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Black board error propagation

$$V_{sci}^2 = \frac{\mu_{sci}^2}{T_{cal}^2}$$

$$T_{cal}^2 = \frac{\mu_{cal}^2}{\mu_{th}^2}$$

$$\frac{\sigma_{T_{cal}^2}^2}{(T_{cal}^2)^2} = \frac{\sigma_{\mu_{cal}^2}^2}{(\mu_{cal}^2)^2} + \frac{\sigma_{\mu_{th}^2}^2}{(\mu_{th}^2)^2}$$

- 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

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Precision ≠ Accuracy

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

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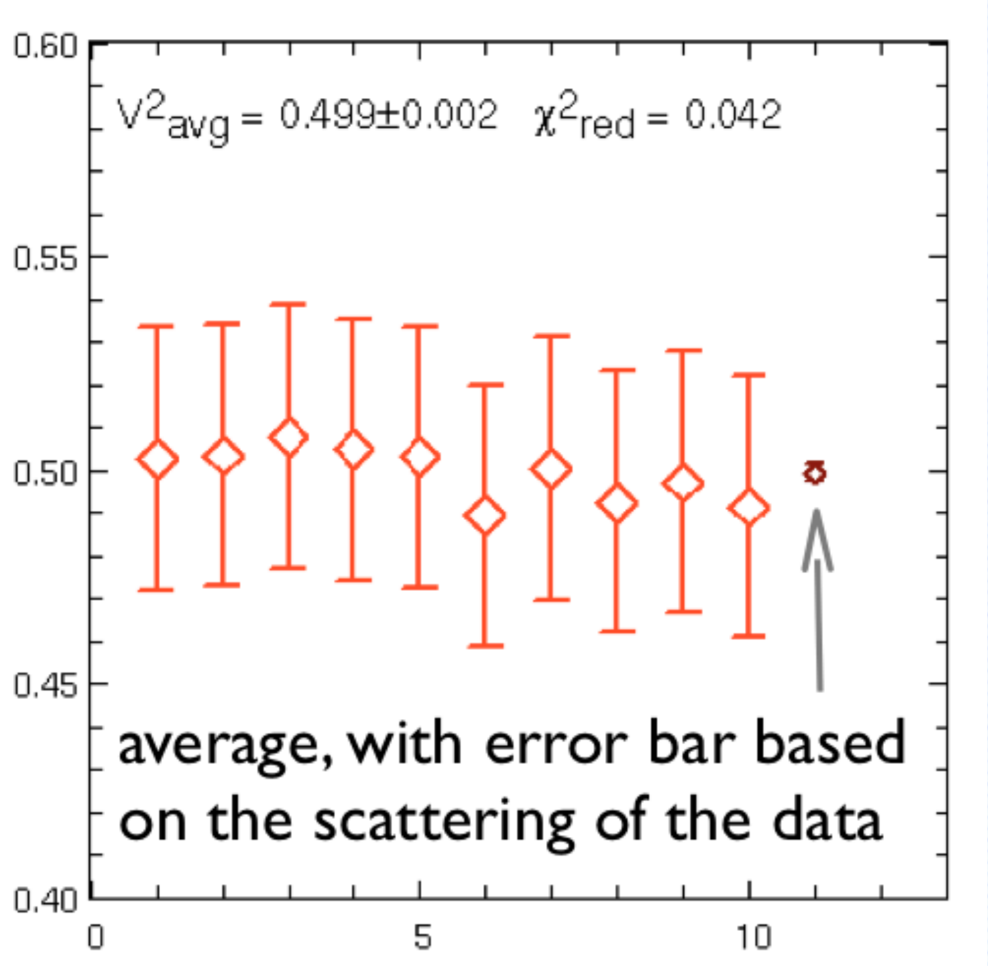
A simple case

- Fitting a constant provide a precise result

  but

- unrealistically small χ^2
- Are uncertainties overestimated?

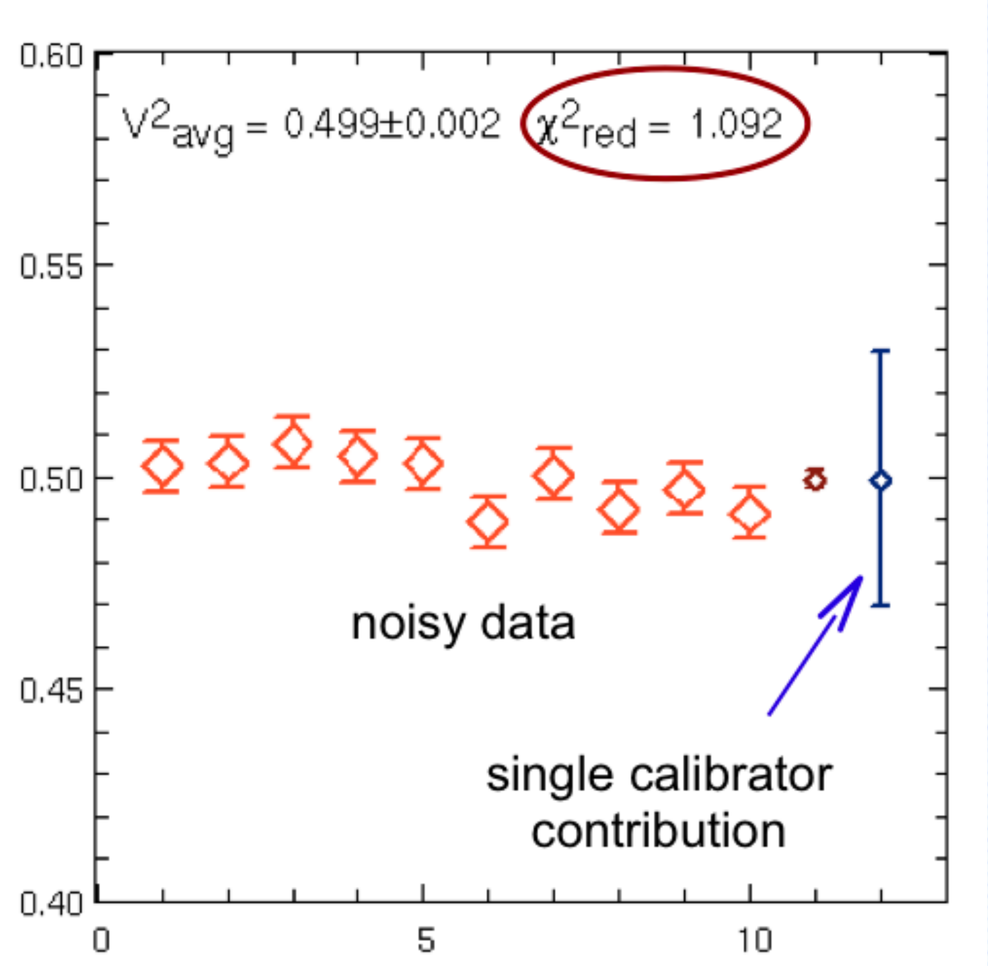


From Merand 2010 Porquerolles

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

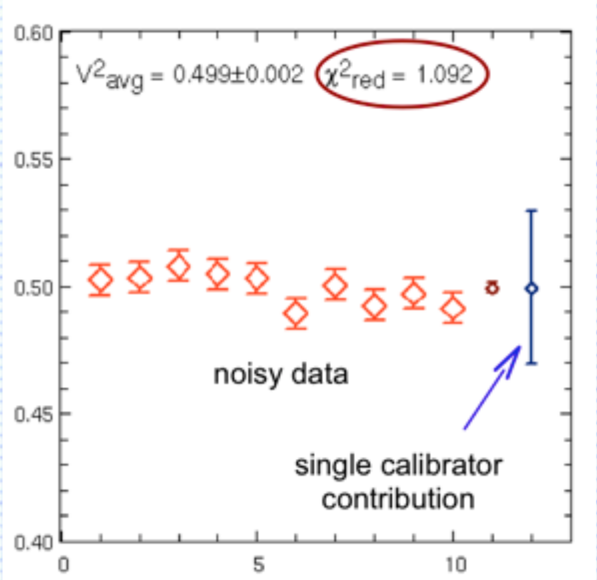
$$V^2_{\rm avg} = 0.499 \pm 0.002_{\rm stat} \pm 0.030_{\rm cal}$$



From Merand 2010 Porquerolles

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!

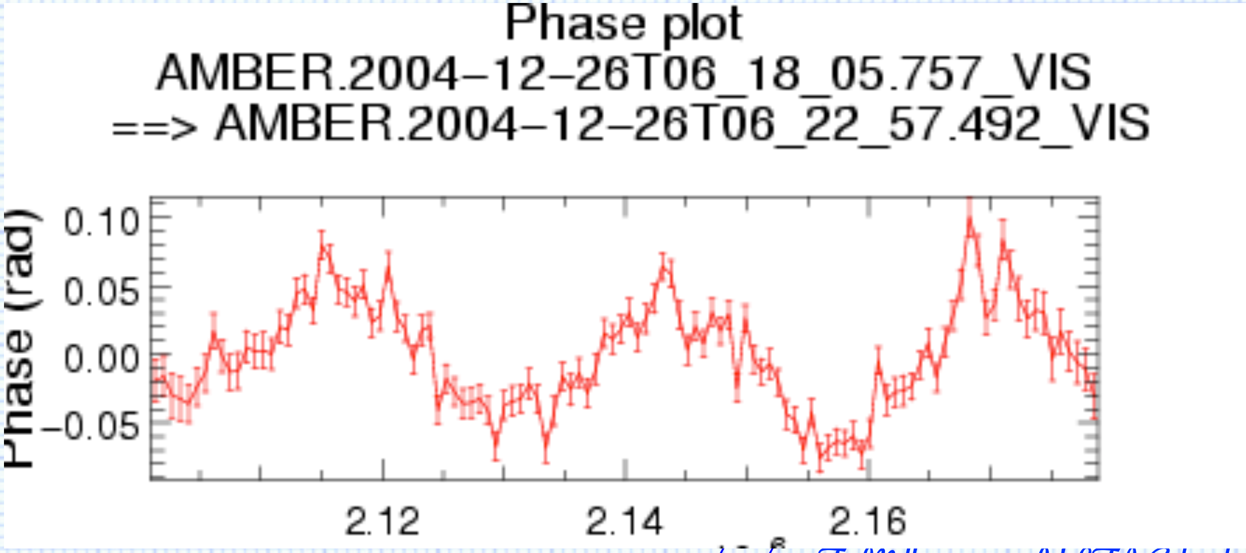
From Merand 2010 Porquerolles

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
  - Problem: need to quatify systematics
  - Example: AMBER data selection can introduce an unknown systematic

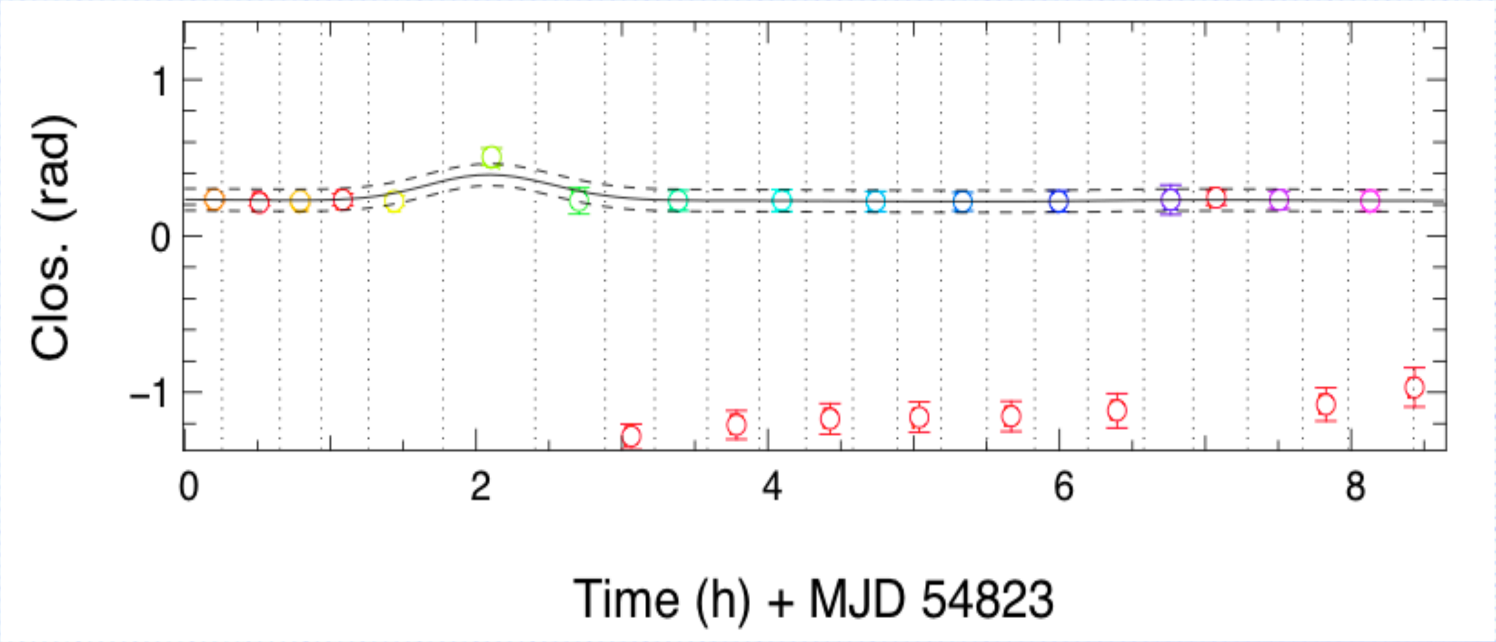
Do phases need calibration?

- 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



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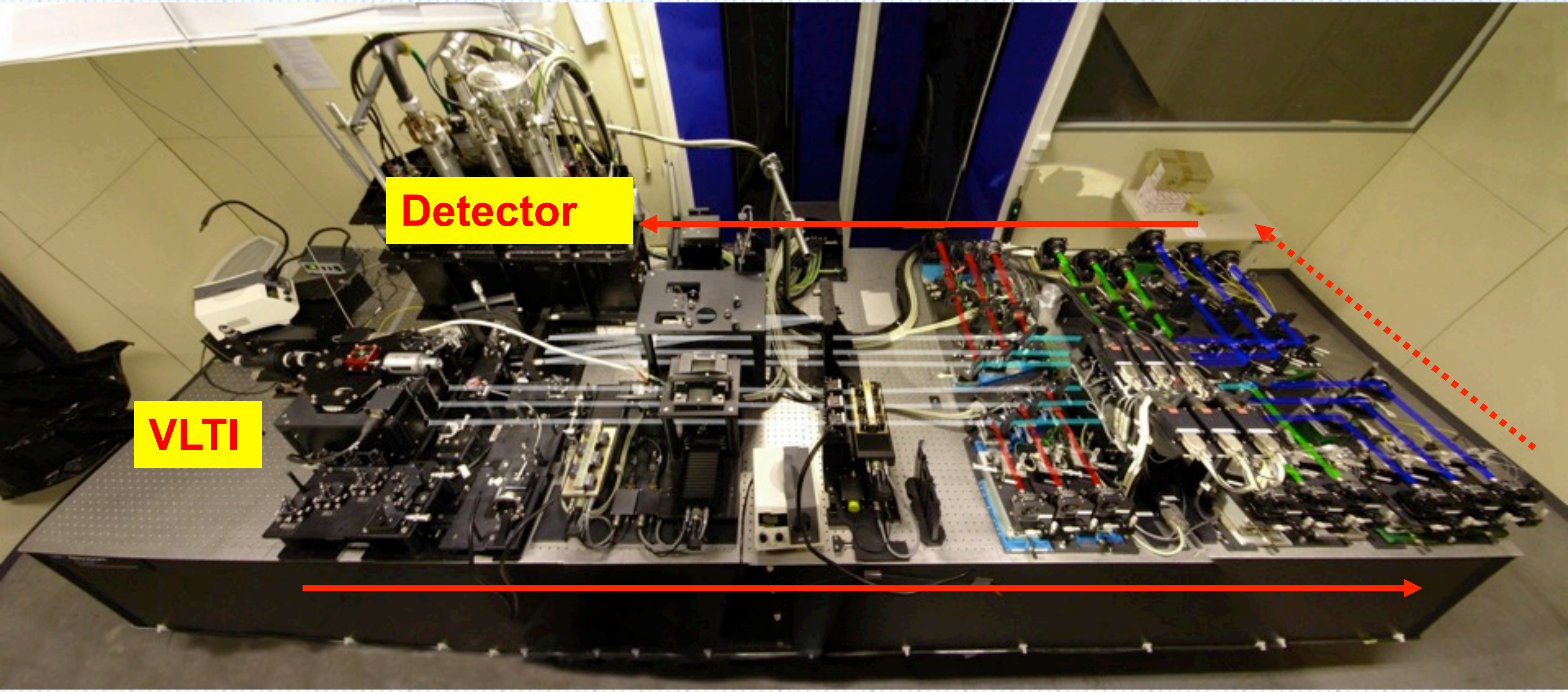
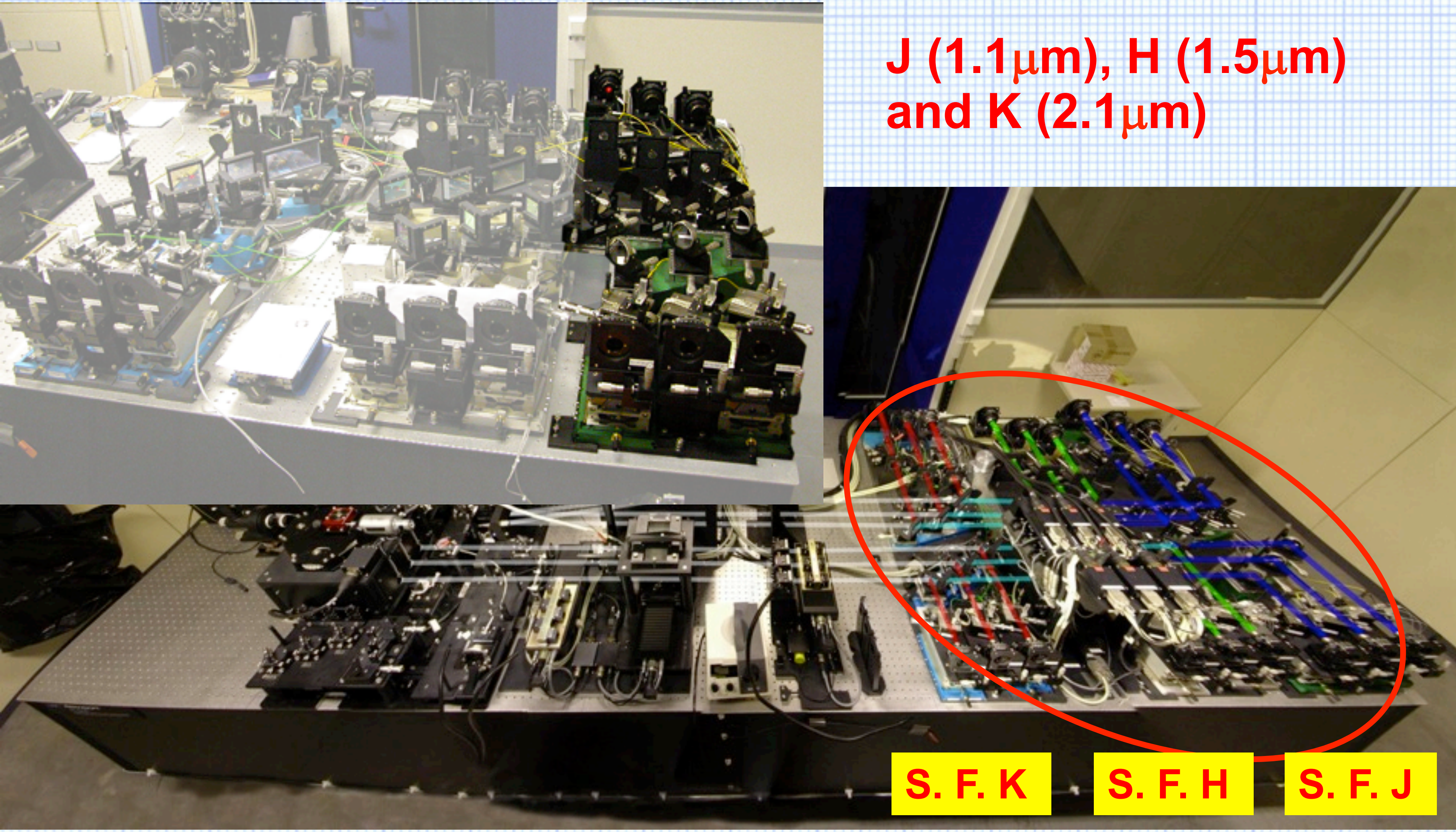
AMBER

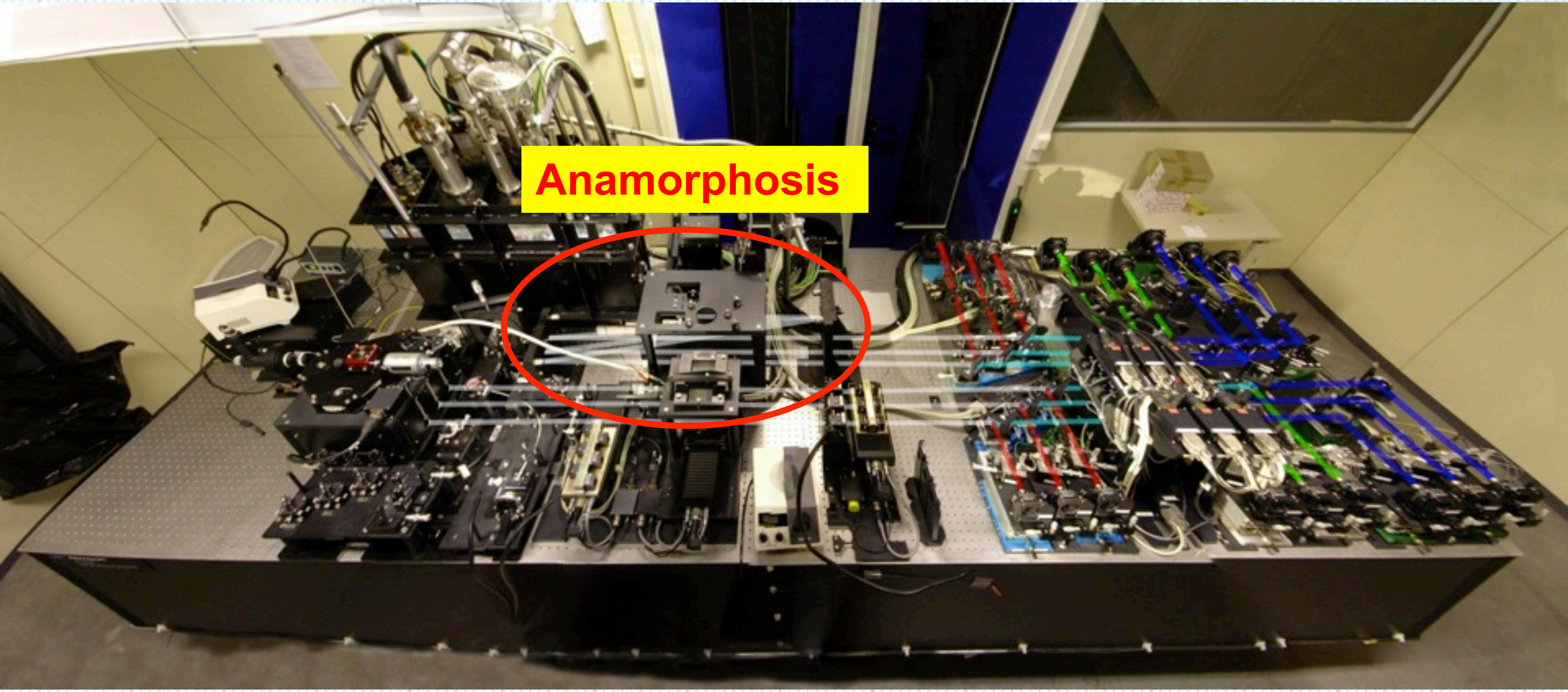


AMBER

J (1.1μm), H (1.5μm)
and K (2.1μm)

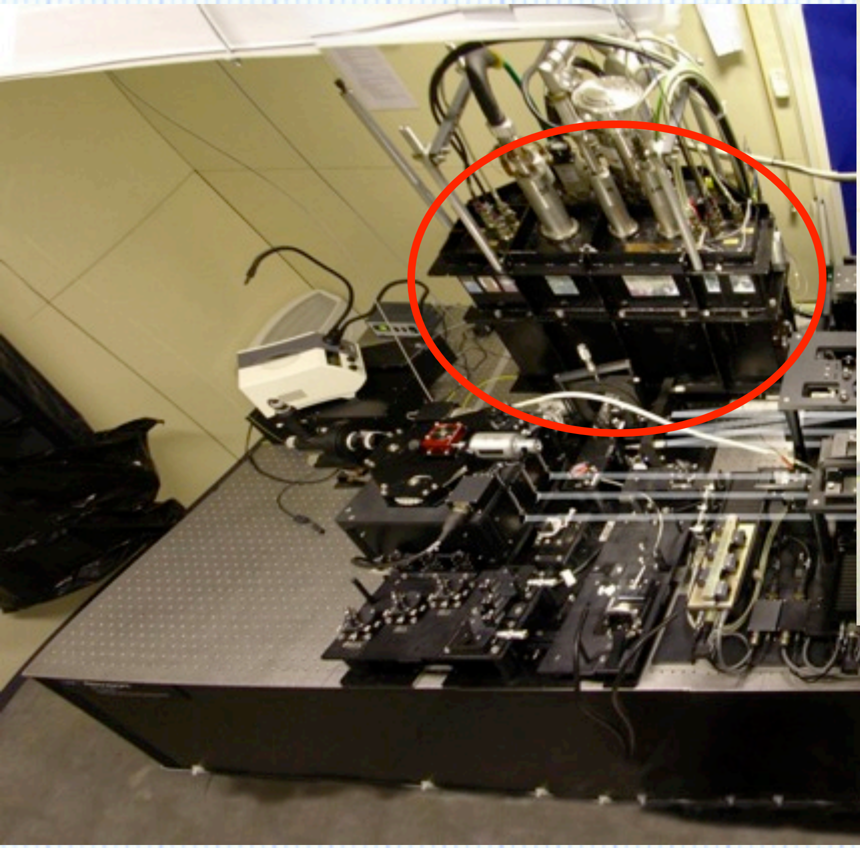


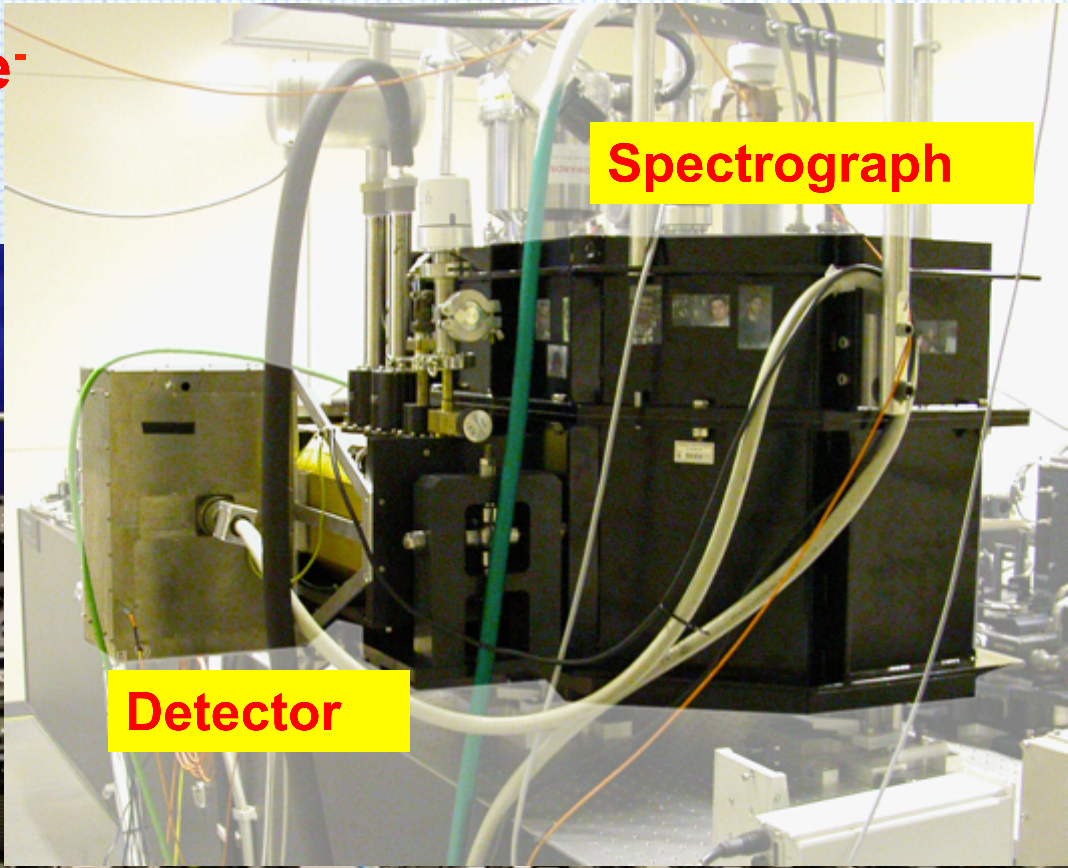
AMBER



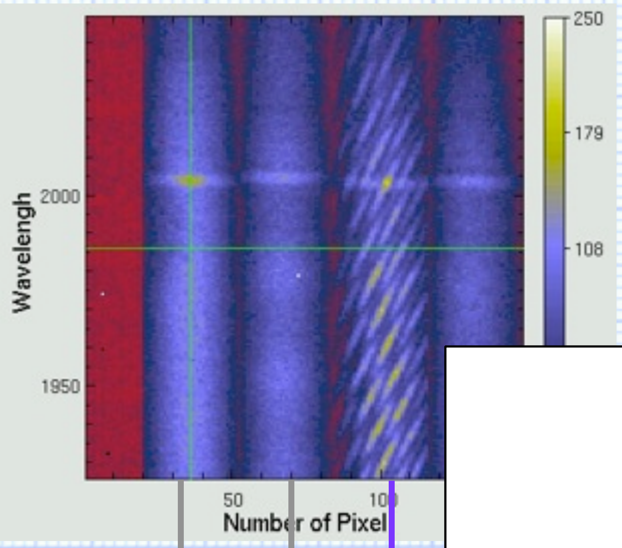
AMBER

Rockwell Hawaii, s_{det} = 12e$^-$
R = 35, 1500 ou 12000





The P2VM algorithm



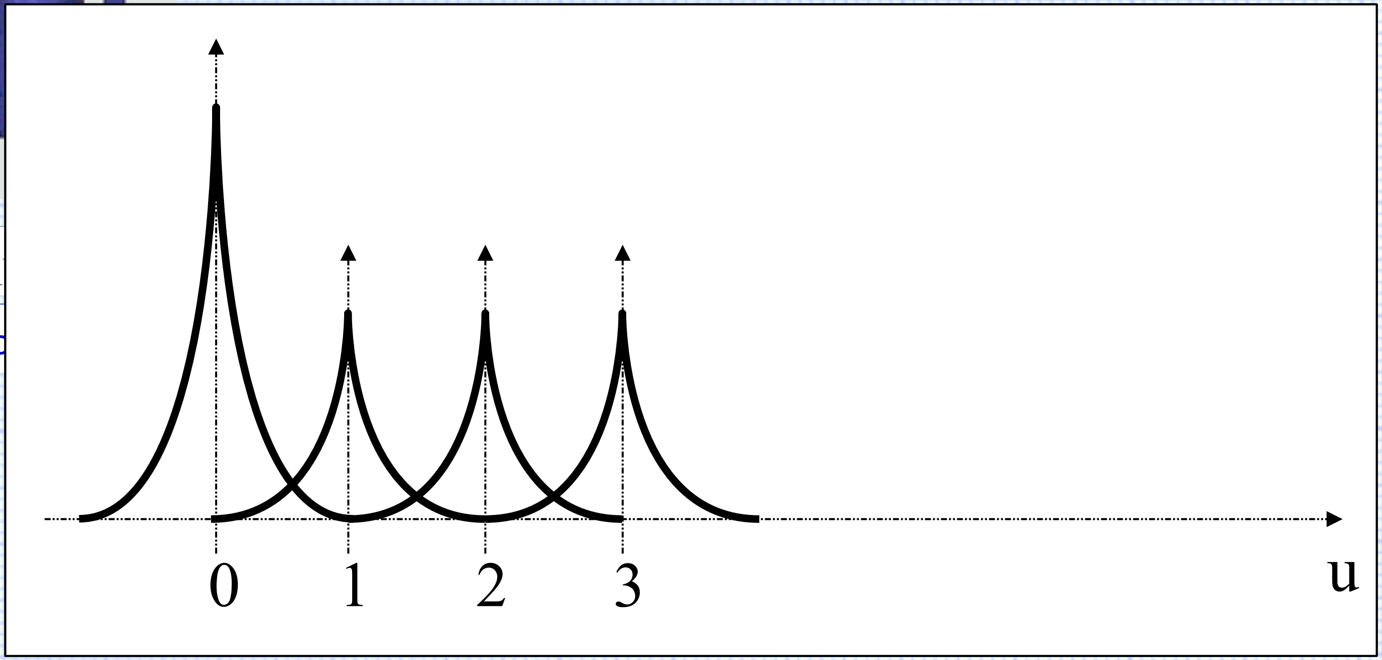
Voies photométriq

Voie interféro

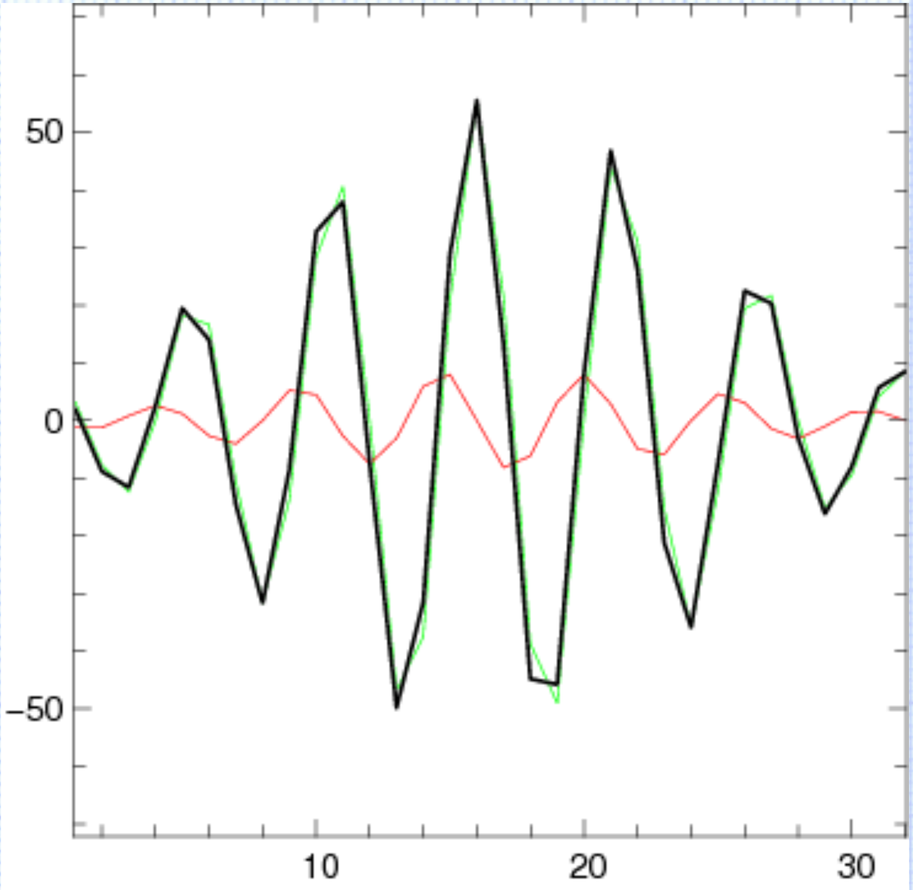
Better RSB ?

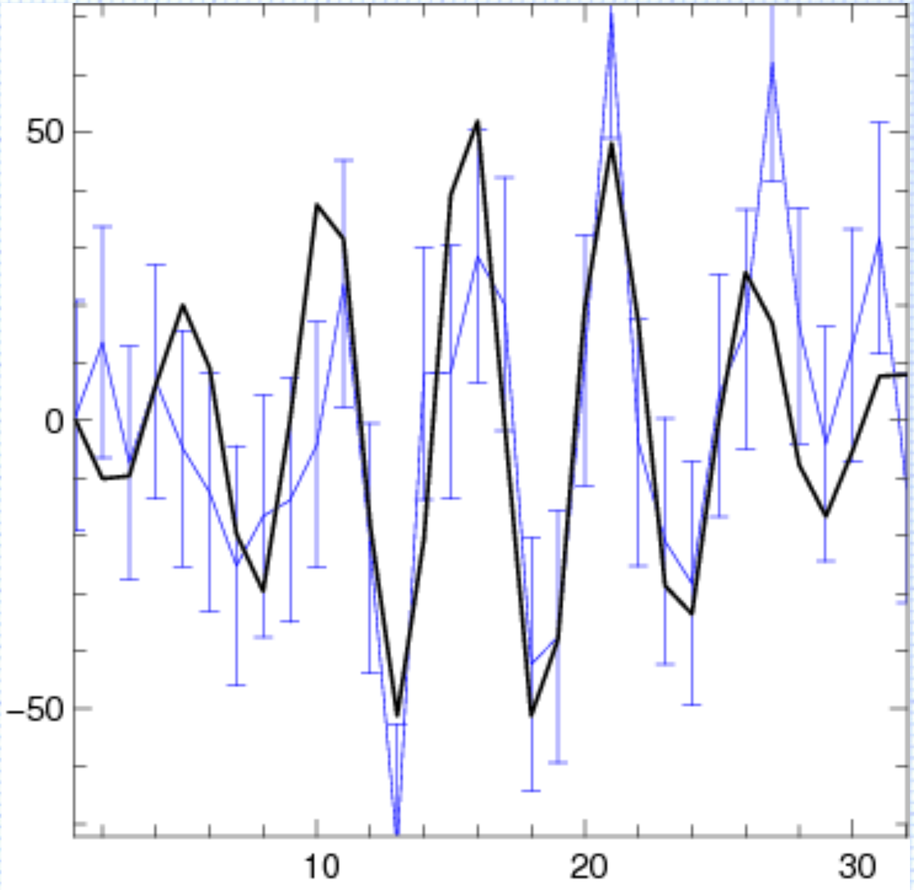
→ **Reduce pixels number**

→ **Pb with Fourier processing**



The P2VM algorithm





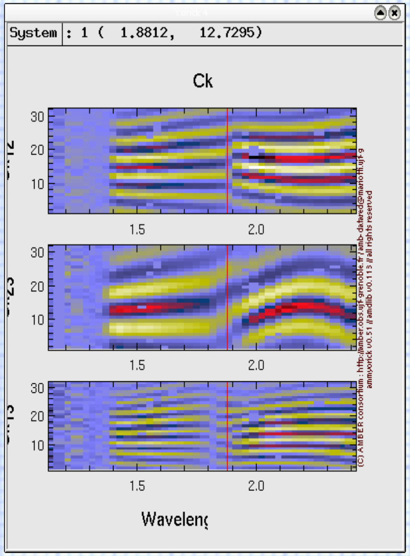
The P2VM algorithm

C=R+iI determined by minimizing:

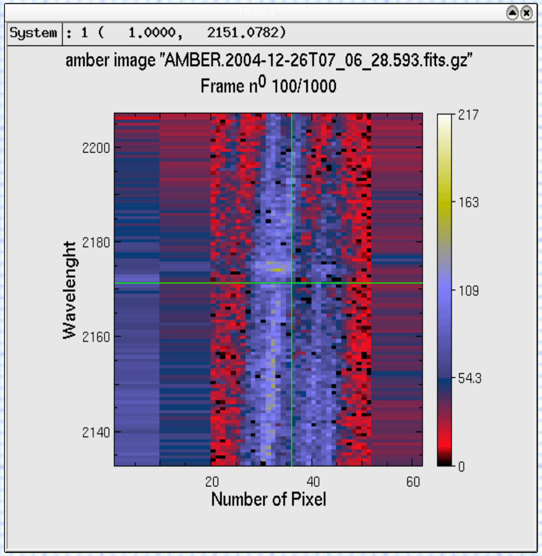
$$\chi^2 = \sum_{k=1}^{n} \left(\frac{m_k - c_k R + d_k I}{\sigma_k} \right)^2$$

which provides:

$$\begin{bmatrix} R \\ I \end{bmatrix} = [P2VM] \times [m_k]$$



X



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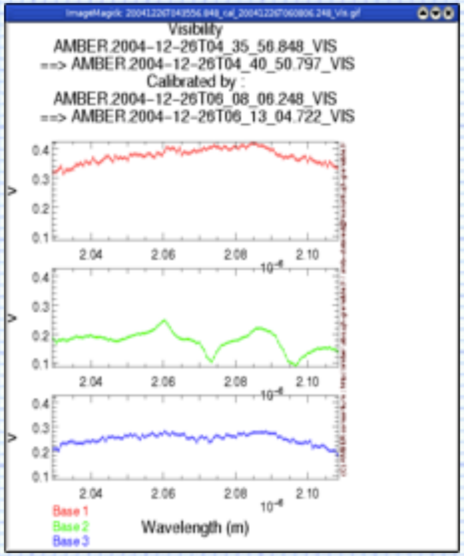


P2VM

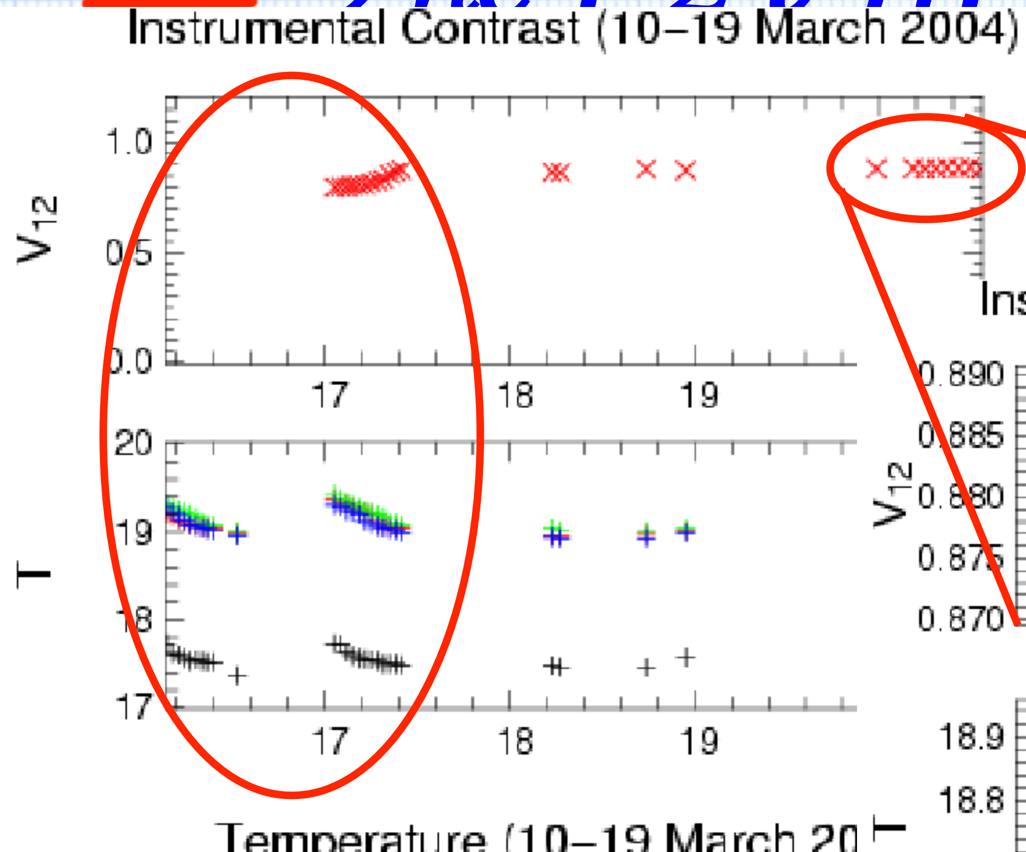
« carrying waves » or
« instrument's fringes »

Matrix multiply

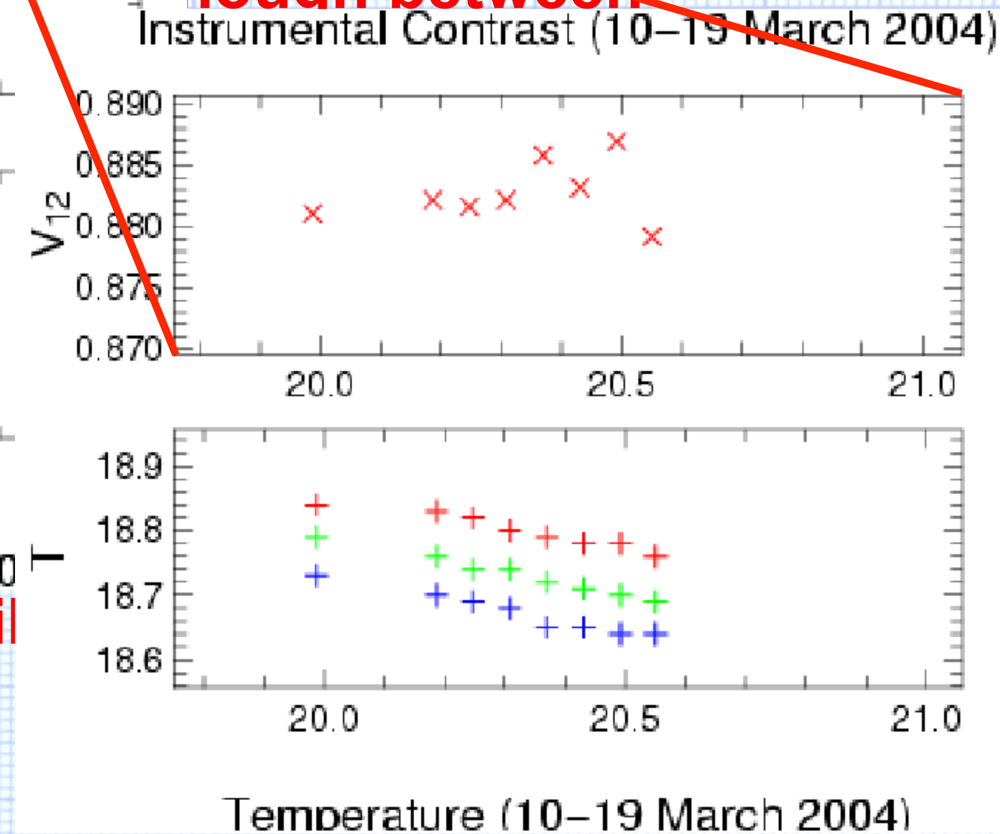
Raw data

Observable
(complex coherent flux)

The P_2VM algorithm



nough between

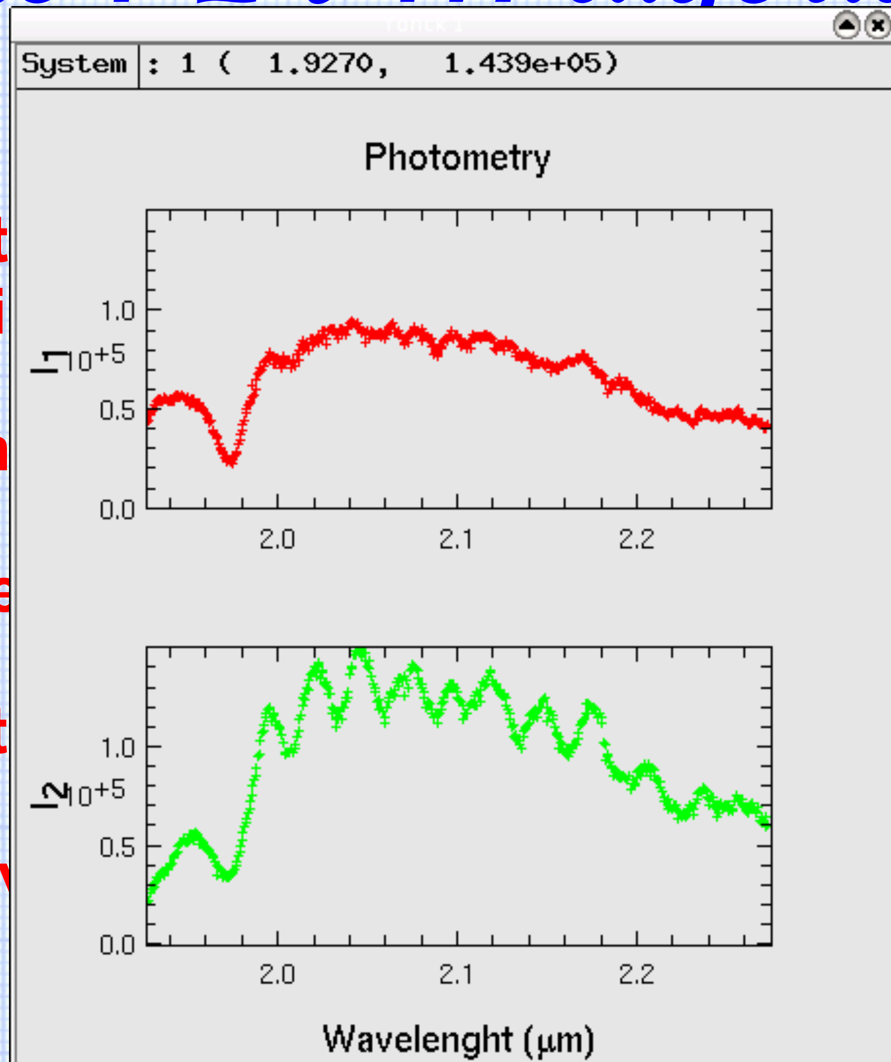


- The wavelength calil

The P2VM algorithm

Is valid IF

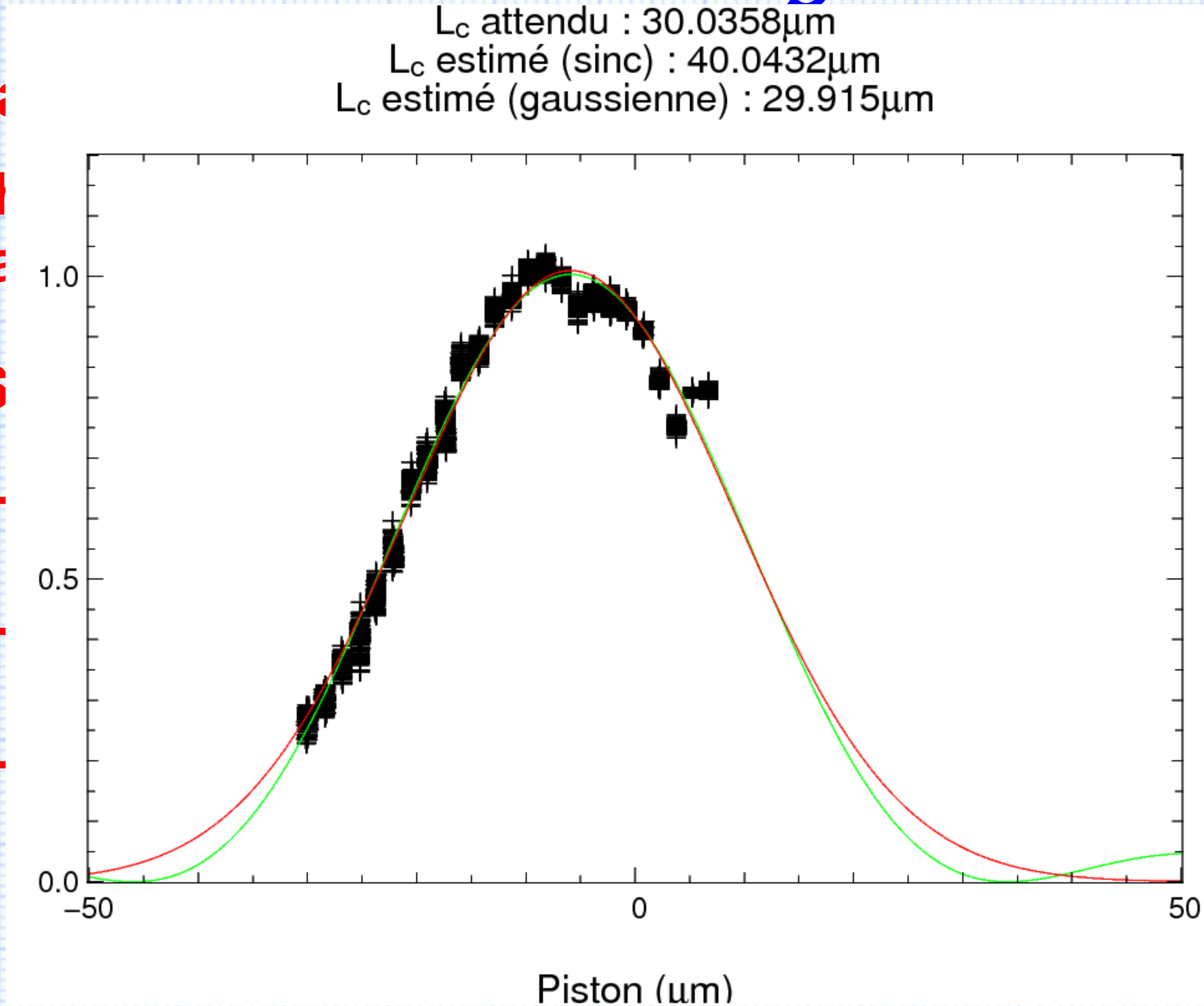
- the inst... ...ween calibrati...
- SNR on...
- The spe... ...gh
- The det... ...gh known
- The wa...



The P2VM algorithm

Is va

- **th ca**
- **S**
- **T**
- **T … n**
- **T**

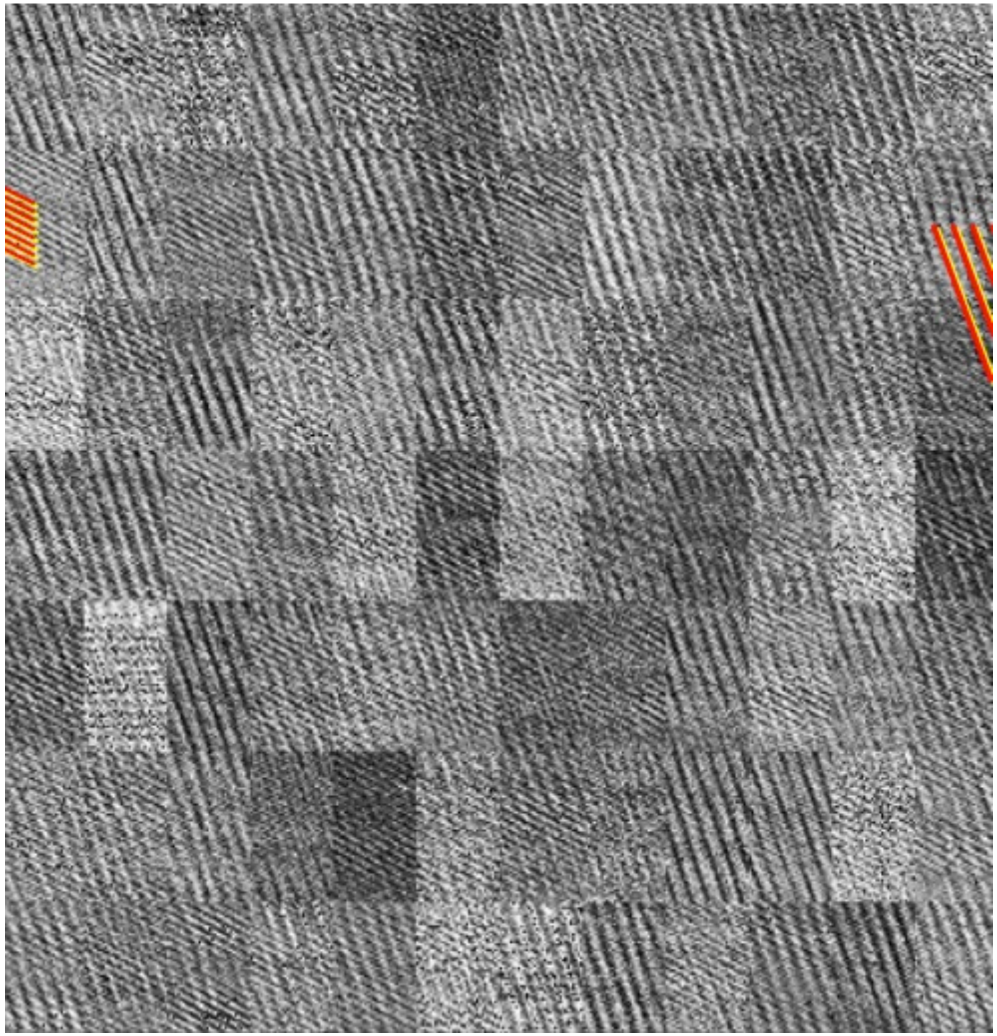


LAGRANGE Observatoire de la CÔTE d'AZUR

The P_2VM algorithm

Is valid I

- **the in ... n calibra**
- **SNR c**
- **The s**
- **The d ... nown**
- **The w**

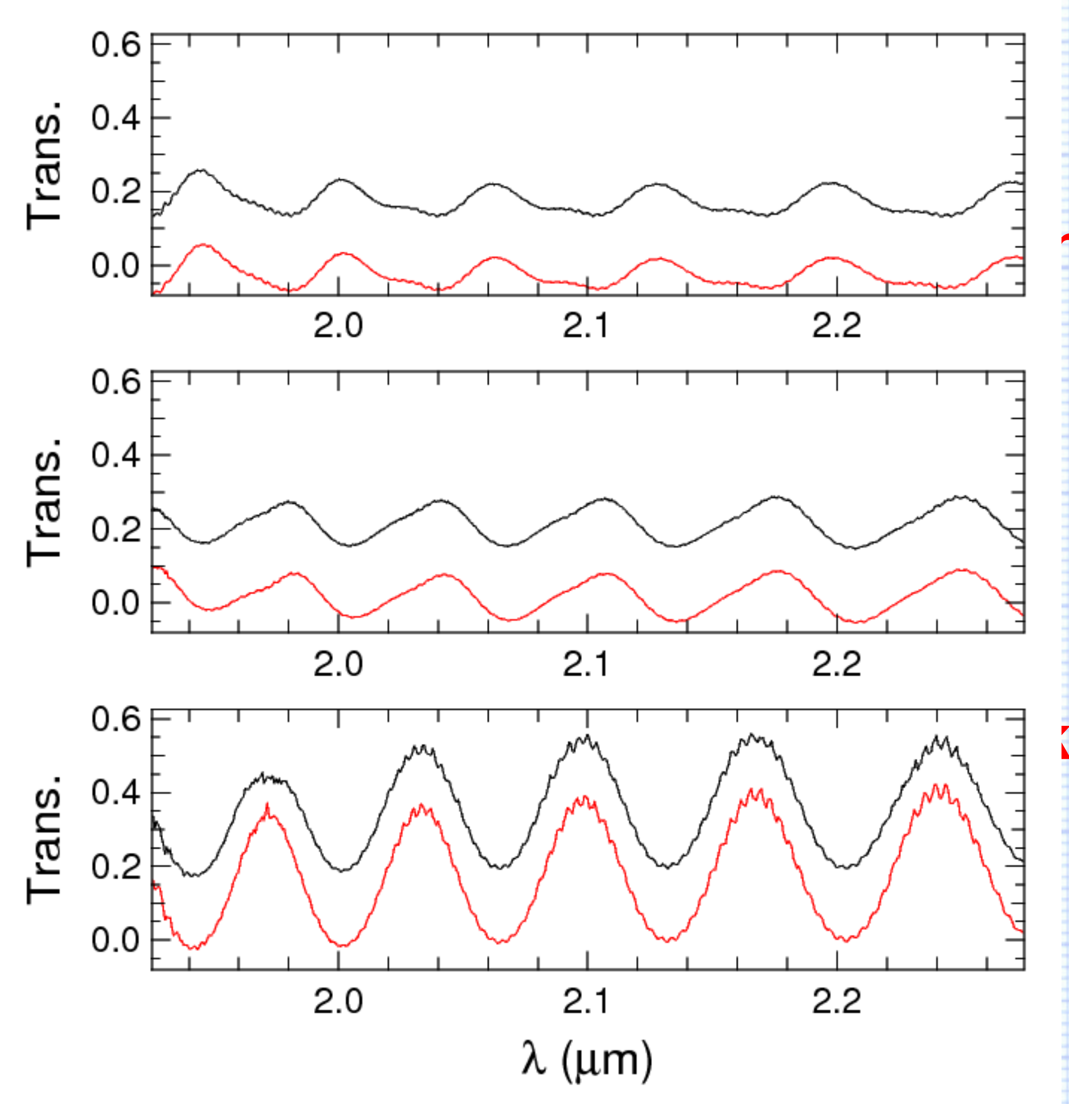


G. Li Causi 2007

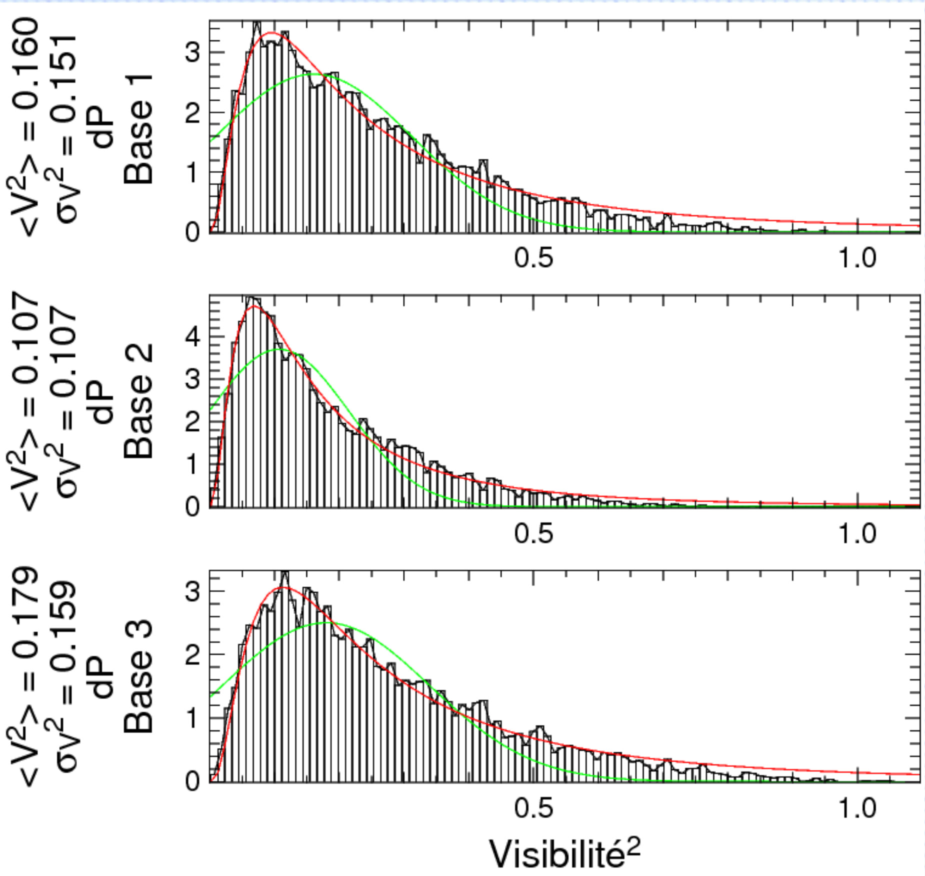
The P2VM algorithm

Is valid

- **the ir ... n calibr**
- **SNR**
- **The s**
- **The c ... known**
- **The w**



The big AMBER problem (a.k.a. the « banana » problem)



- Lab visibility : 0.85
- On sky exp. visibility (FSU) : 0.85
- On sky exp. visibility (no FSU) : 0.60

NO FINITO ! :

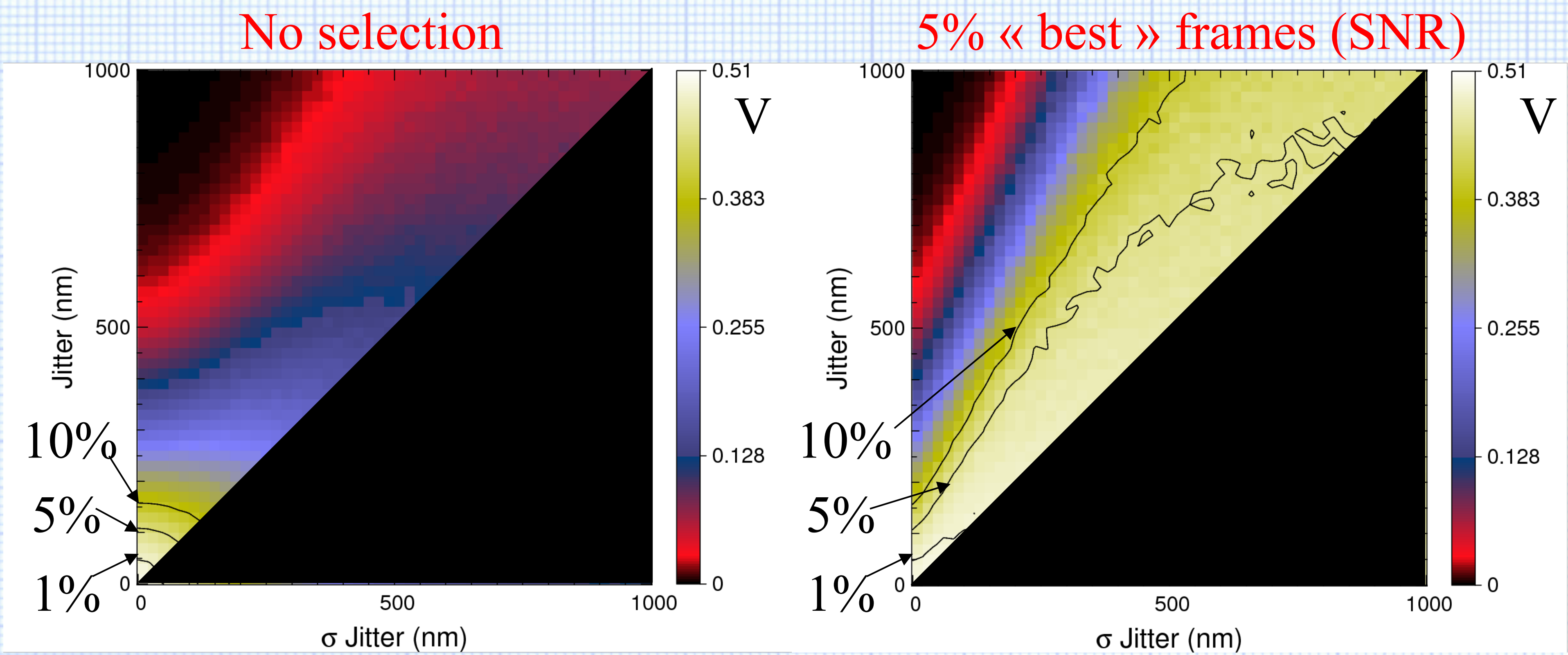
- Average on-sky UT visibility : 0.20
- Average on-sky AT visibility : 0.60

"VLTI / UT vibrations"
OPD modulation between 0.2 & 1μm
Frequency >20Hz

We have a problem

What do we do?

- We do what we can!
  - Frame selection
  - Use of fringe tracker
  - Improve VLTI infrastructure

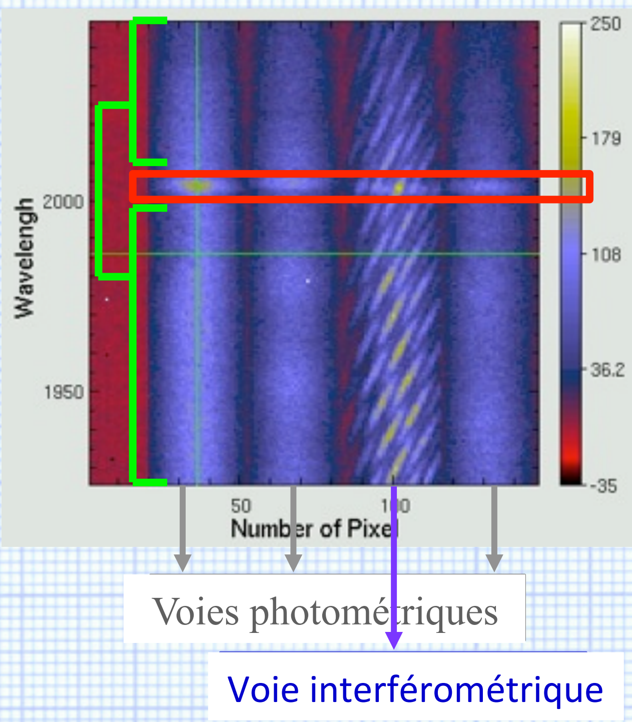


All the AMBER observables

Complex coherent Flux :

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

measured on M frames



Spectrum: $S(\lambda) = N(\lambda)$

Visibility: $V^{i,j}(\lambda) = |C^{i,j}(\lambda)| / N(\lambda)$

Closure phase: $\Psi^{123}(\lambda) = \text{atan}\langle C^{1,2} C^{2,3} C^{*1,3} \rangle$

Differential phase: $\Phi^{i,j}_{\text{diff}}(\lambda)$

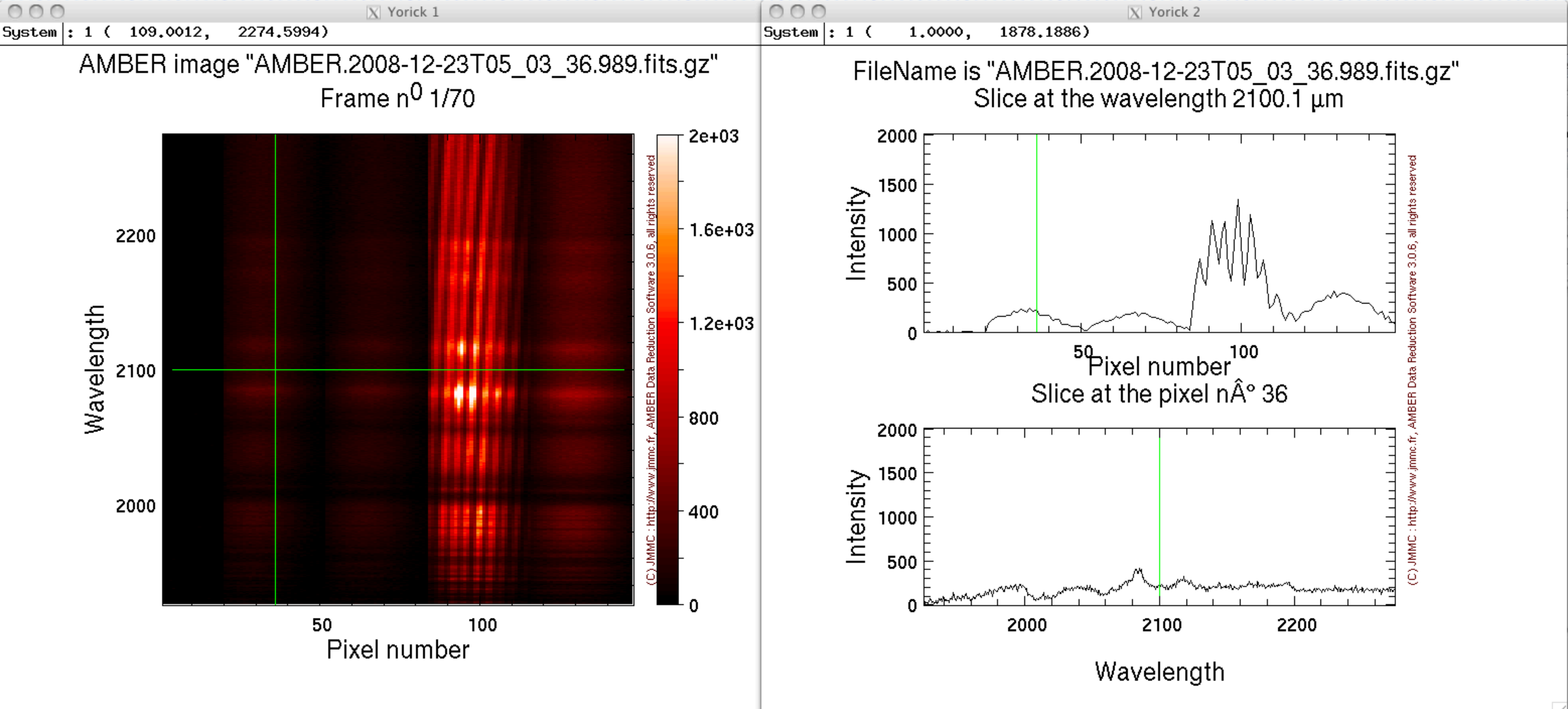
Différential visibility: $V^{i,j}_{\text{diff}}(\lambda)$

"Closure" of the differential phases:

$\Psi^{123}_{\text{diff}}(\lambda) = \Phi^{1,2}_{\text{diff}}(\lambda) + \Phi^{2,3}_{\text{diff}}(\lambda) + \Phi^{3,1}_{\text{diff}}(\lambda)$

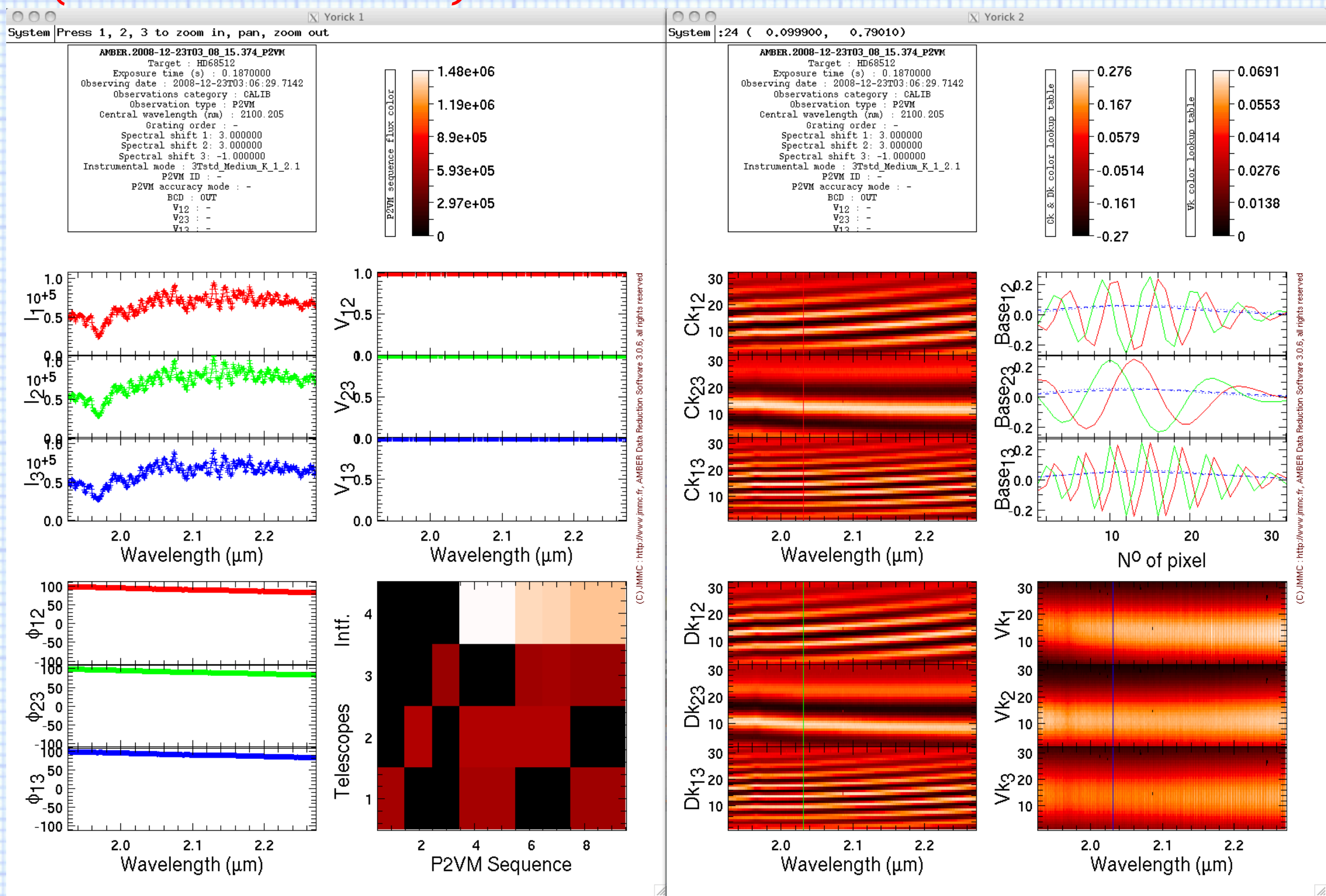
AMBER DRS tour

- *Visualization of raw data (amdlibShowRawData)*



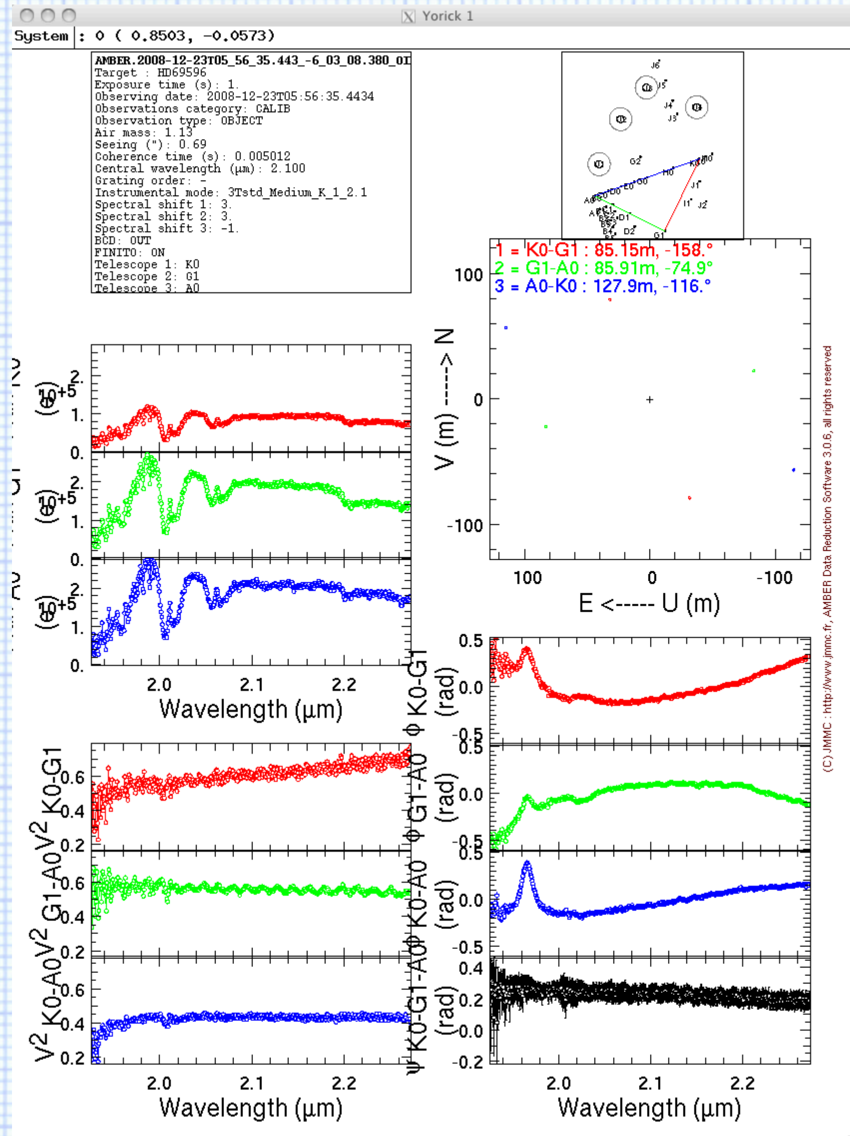
AMBER DRS tour

- Compute P2VM (amdlibComputeP2vm)
- Visualize P2VM (amdlibShowP2vm)



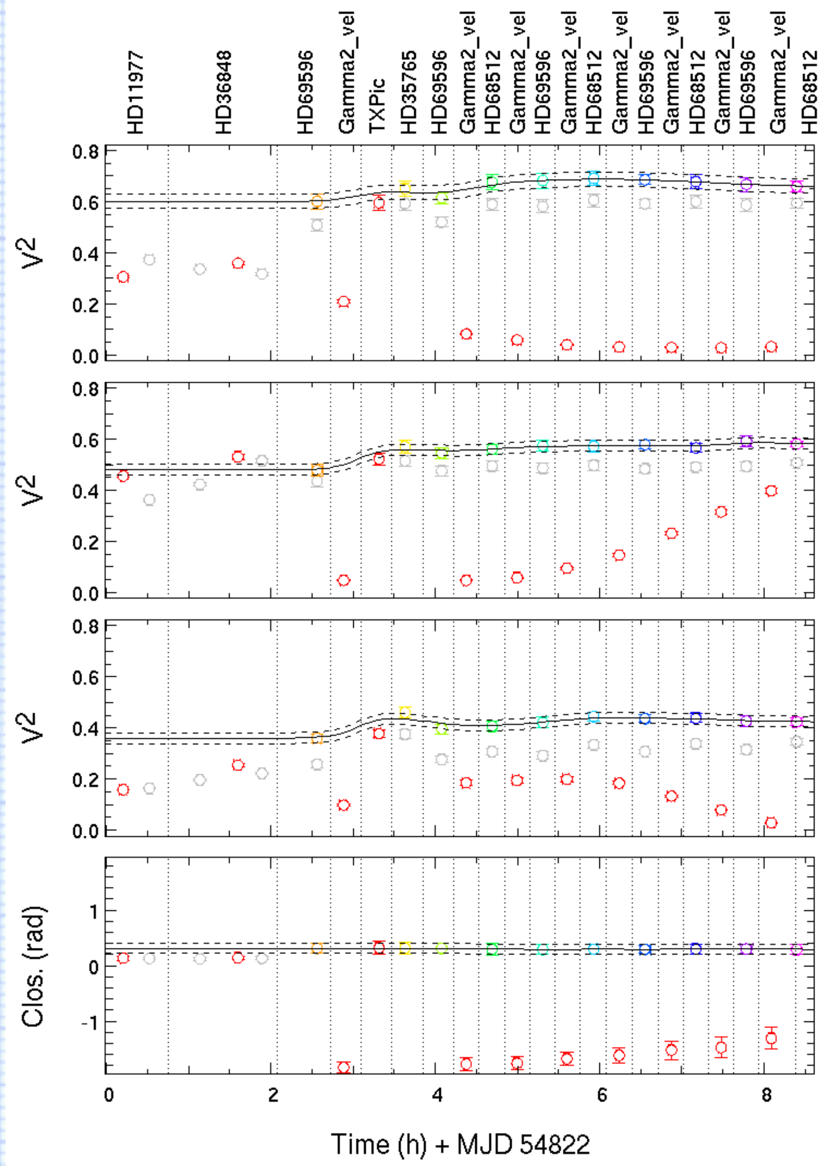
AMBER DRS tour

- Compute OI fits (amdlibComputeOiData)
- Visualize OI fits (amdlibShowOiData)



AMBER DRS tour

- Estimate stellar diameters (amdlibSearchAllStarDiameters)
- Compute transfer function (amdlibComputeTransferFunction)
- Visualize transfer function (amdlibShowTransferFunctionVsTime, amdlibShowTransferFunctionVsWavelength)



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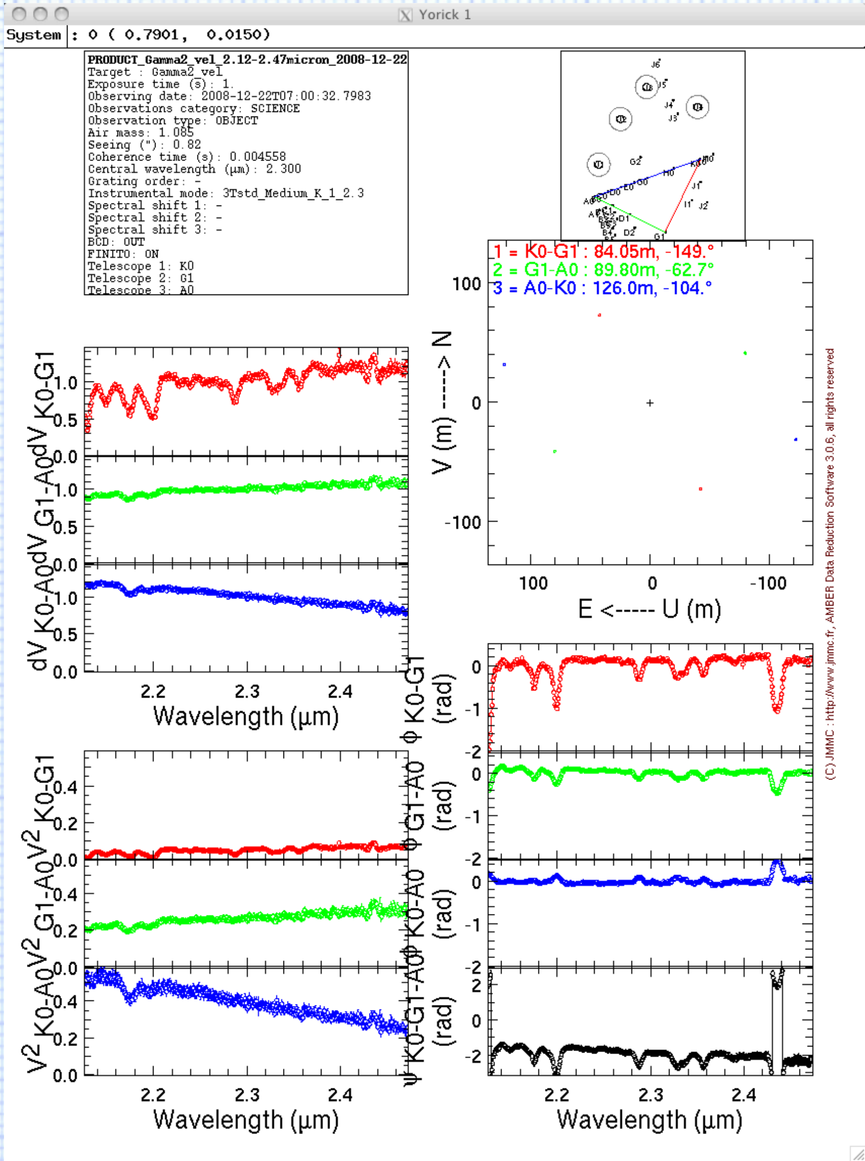
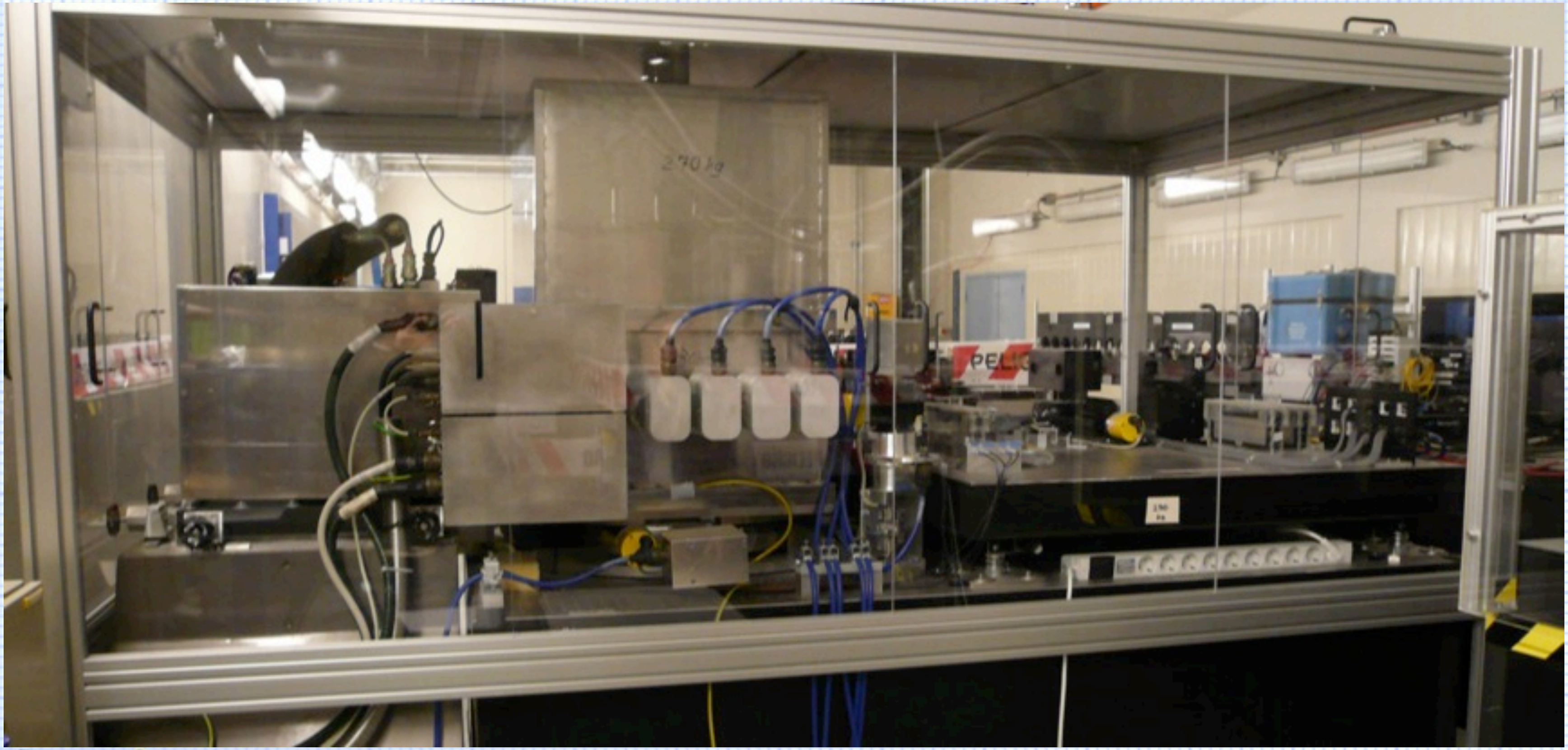
AMBER DRS tour

- Calibrate your data!
  (2 flavours:
  amdlibCalibrateOiData or
  amdlibCalibrateAllOiData)



MIDI *data reduction*

See W. Jaffe practice session



Conclusions

- Interferometric data reduction is somehow tricky
  - Visibility disturbed by noise and systematics
  - Phase is lost but: closure phase and differential phase
- Never use a DRS as a « black box »!
  - Understand limitations
  - Think about strategy (including for observations)
  - Be critical on everything!
- 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!