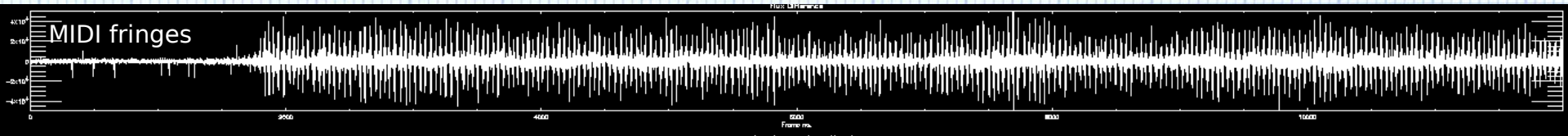

VLTI

Phases !

F. Millour (OCA, Nice)

LAGRANGE

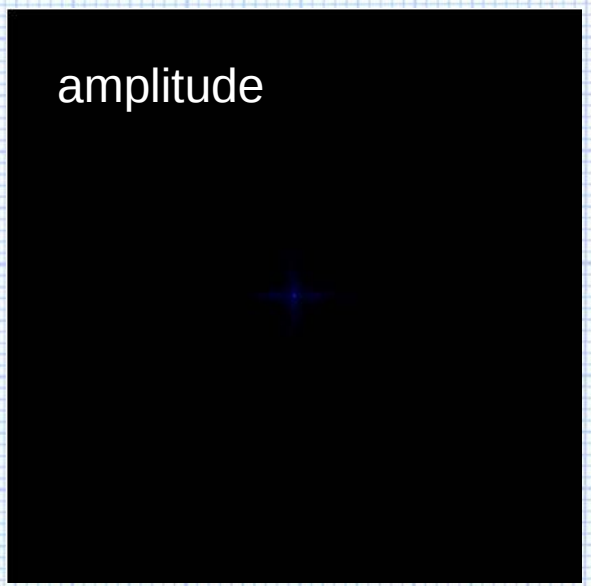
Observatoire de la CÔTE d'AZUR

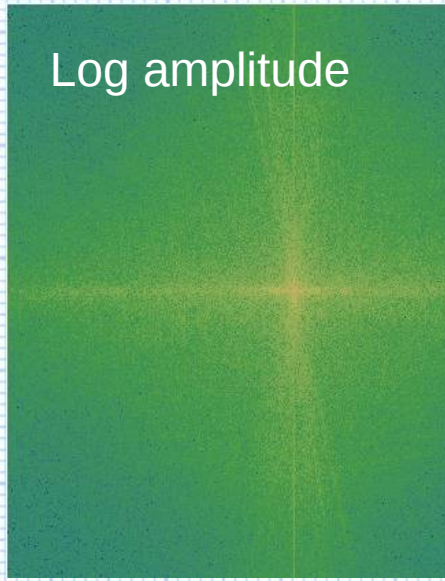

MIDI fringes

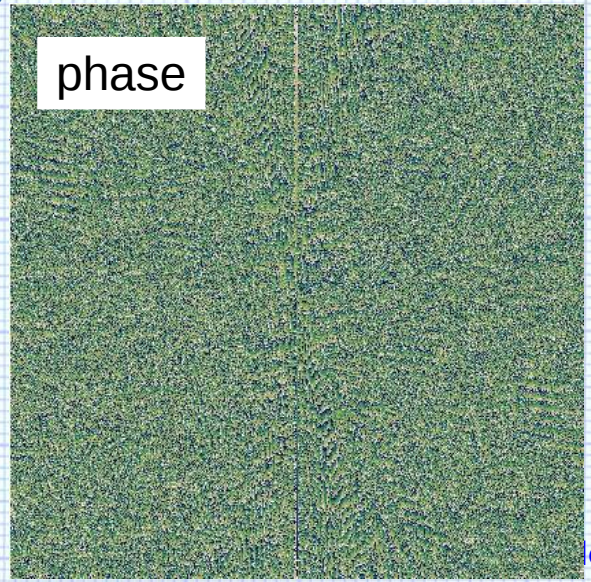
Let's play with some pictures

Let's play with some pictures

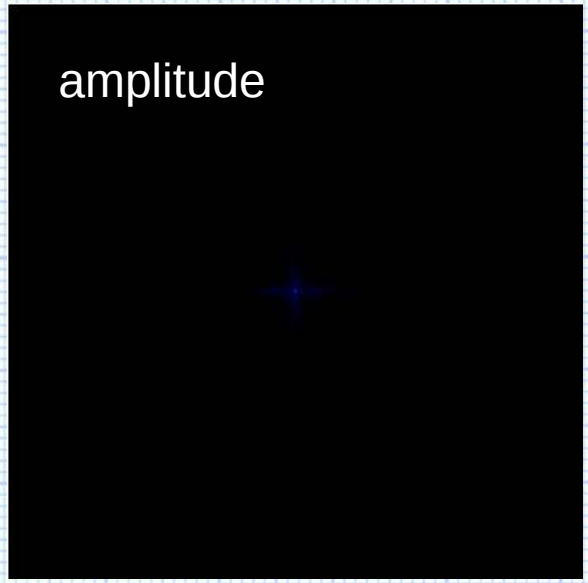
FT

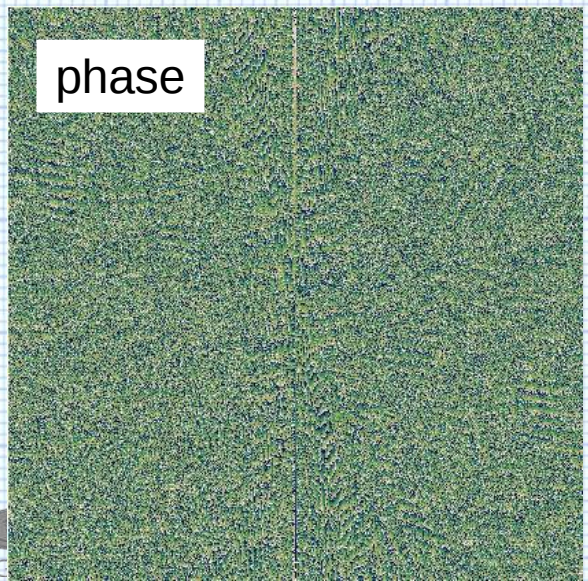






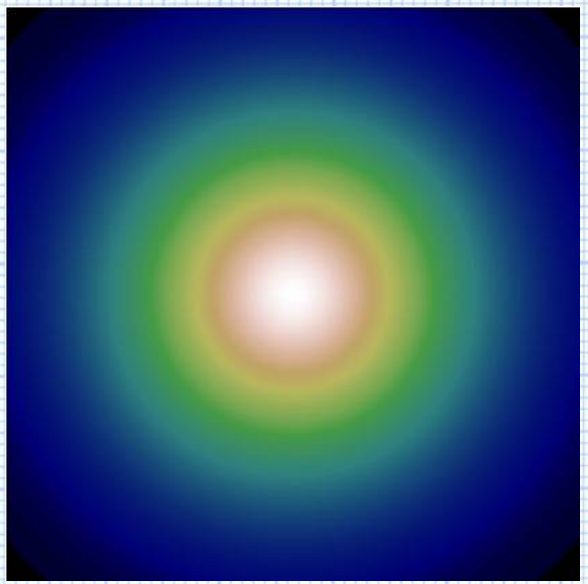
Let's play with some pictures

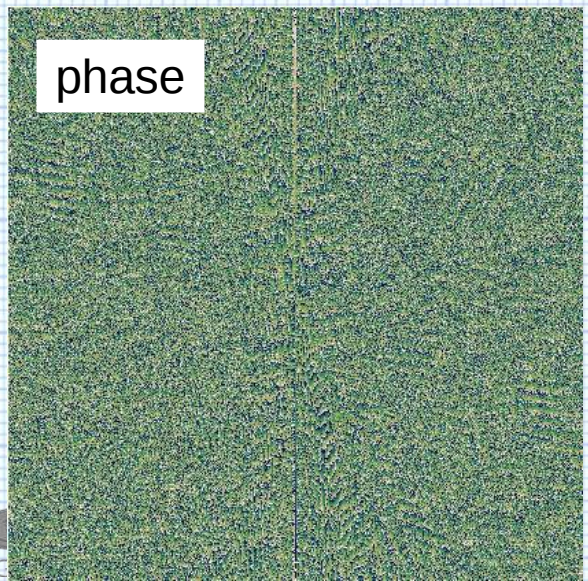




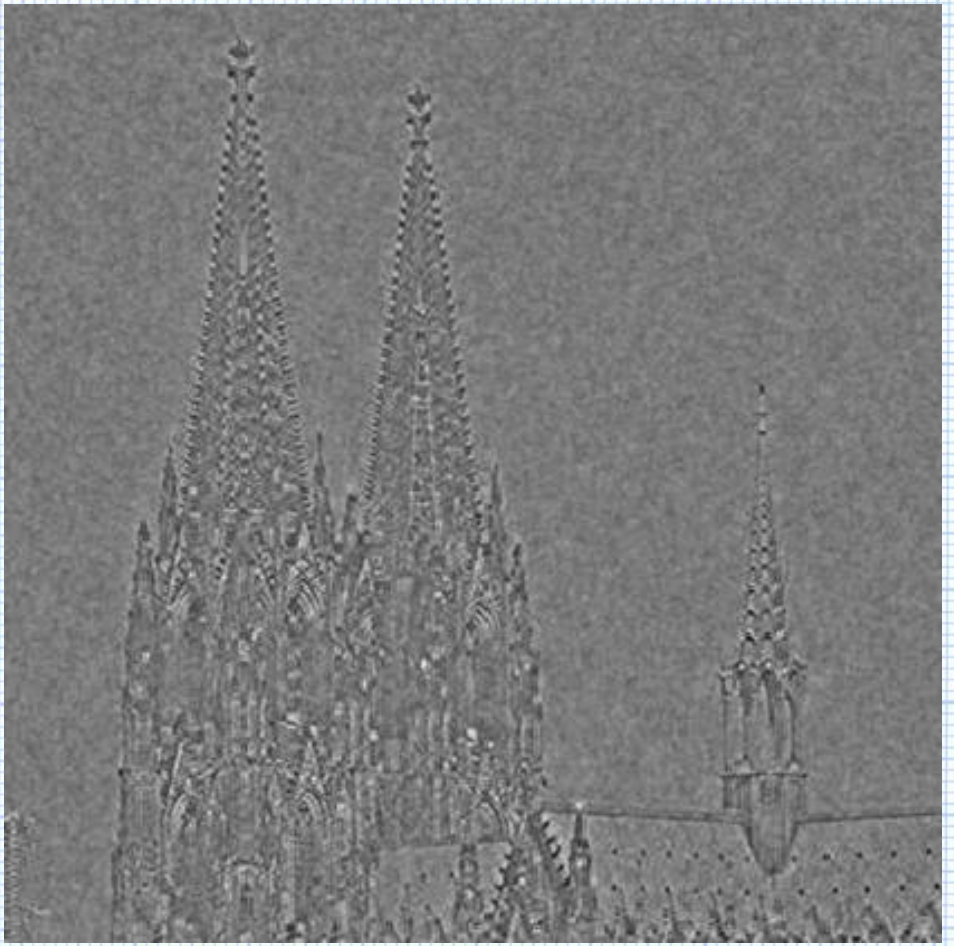
FT^{-1}

Let's play with some pictures





FT^{-1}



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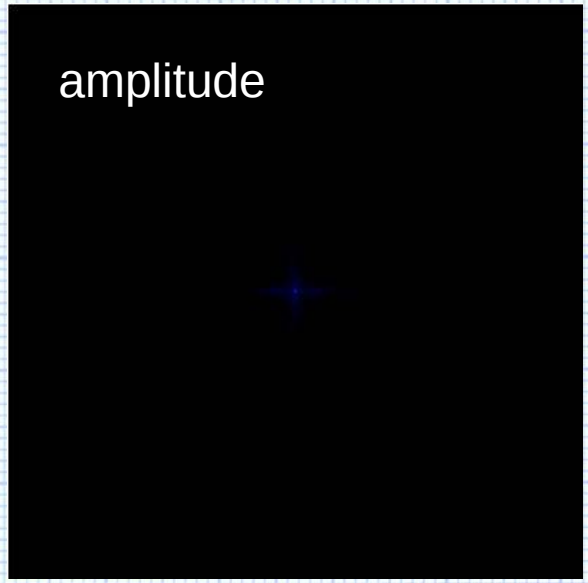
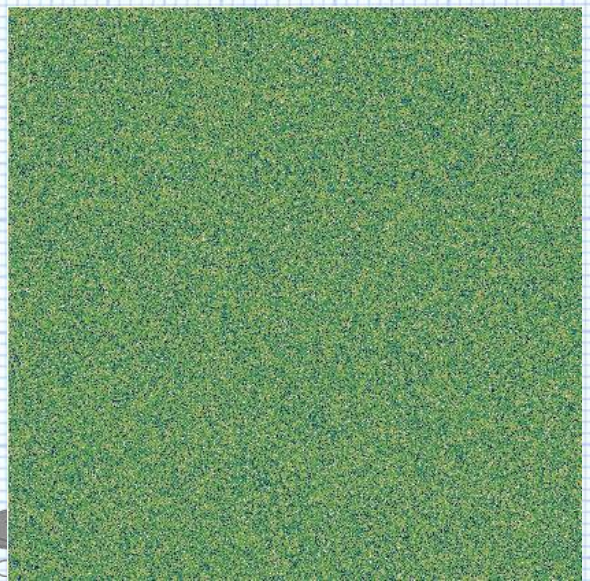
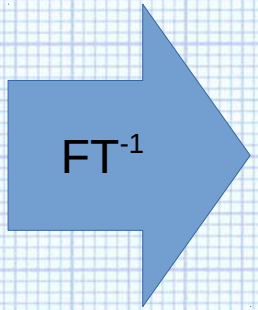
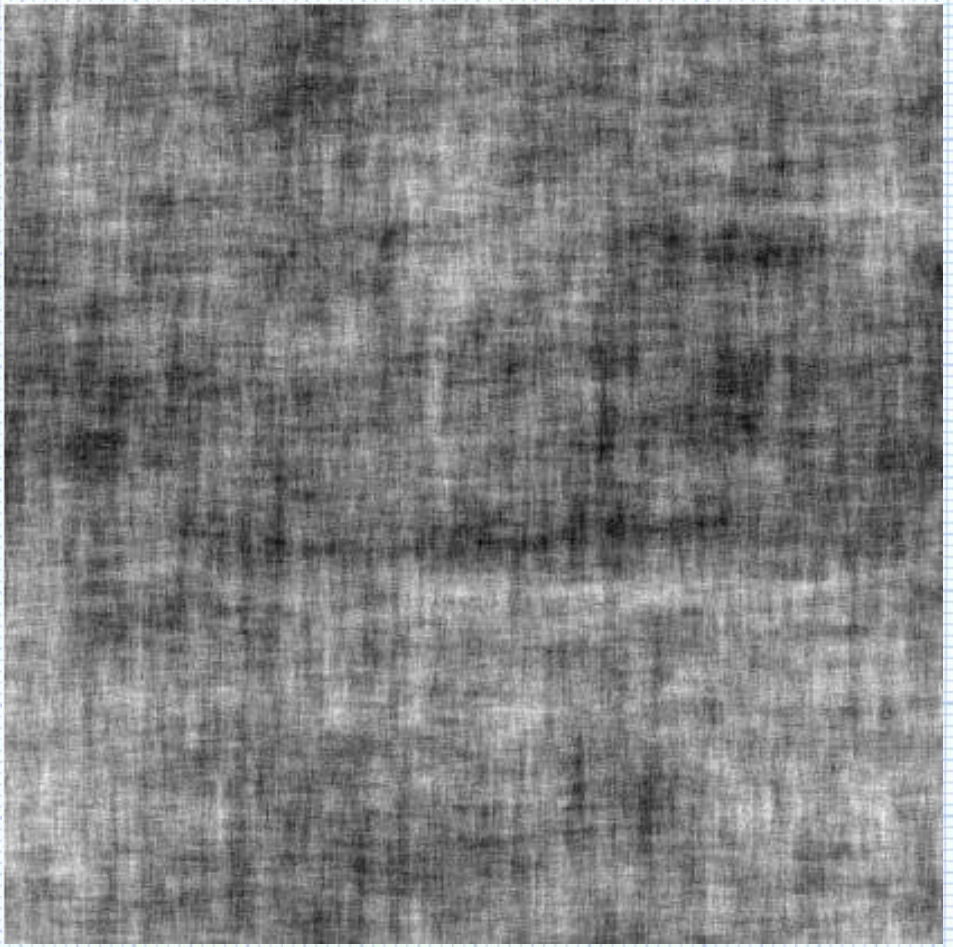


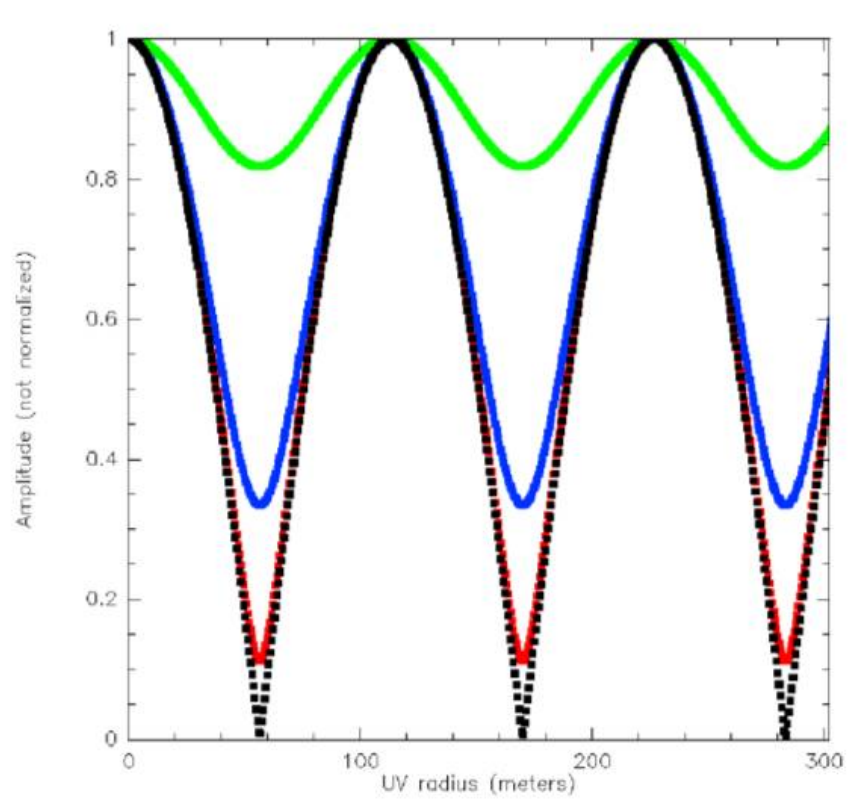






In other words...

The visibility of a binary star with varying flux ratio



1:1
0.8:1
0.5:1
0.1:1

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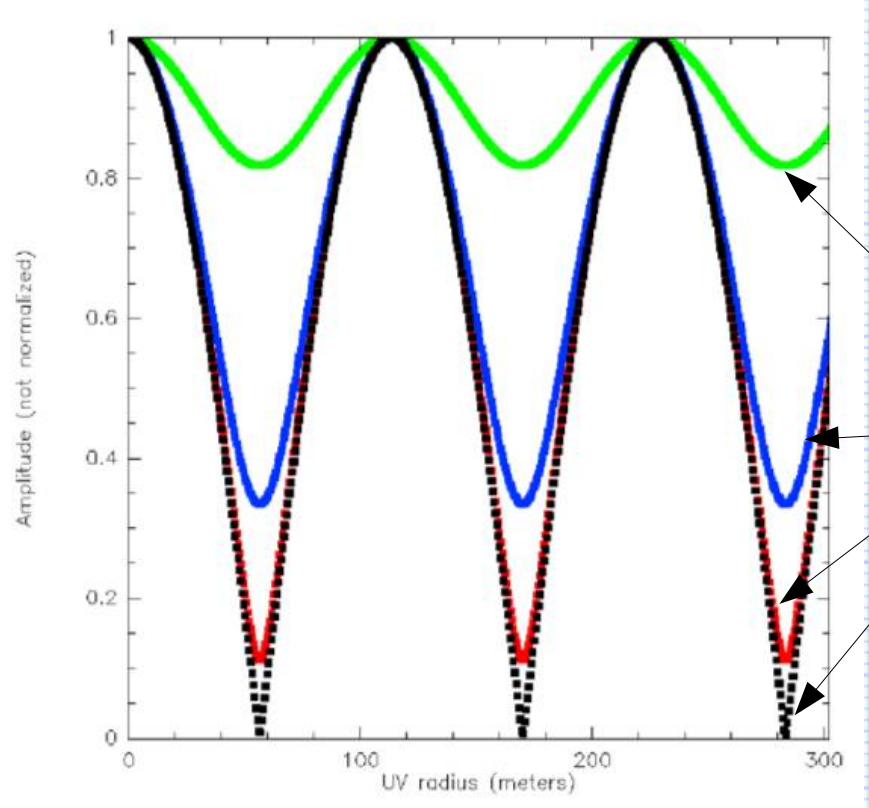
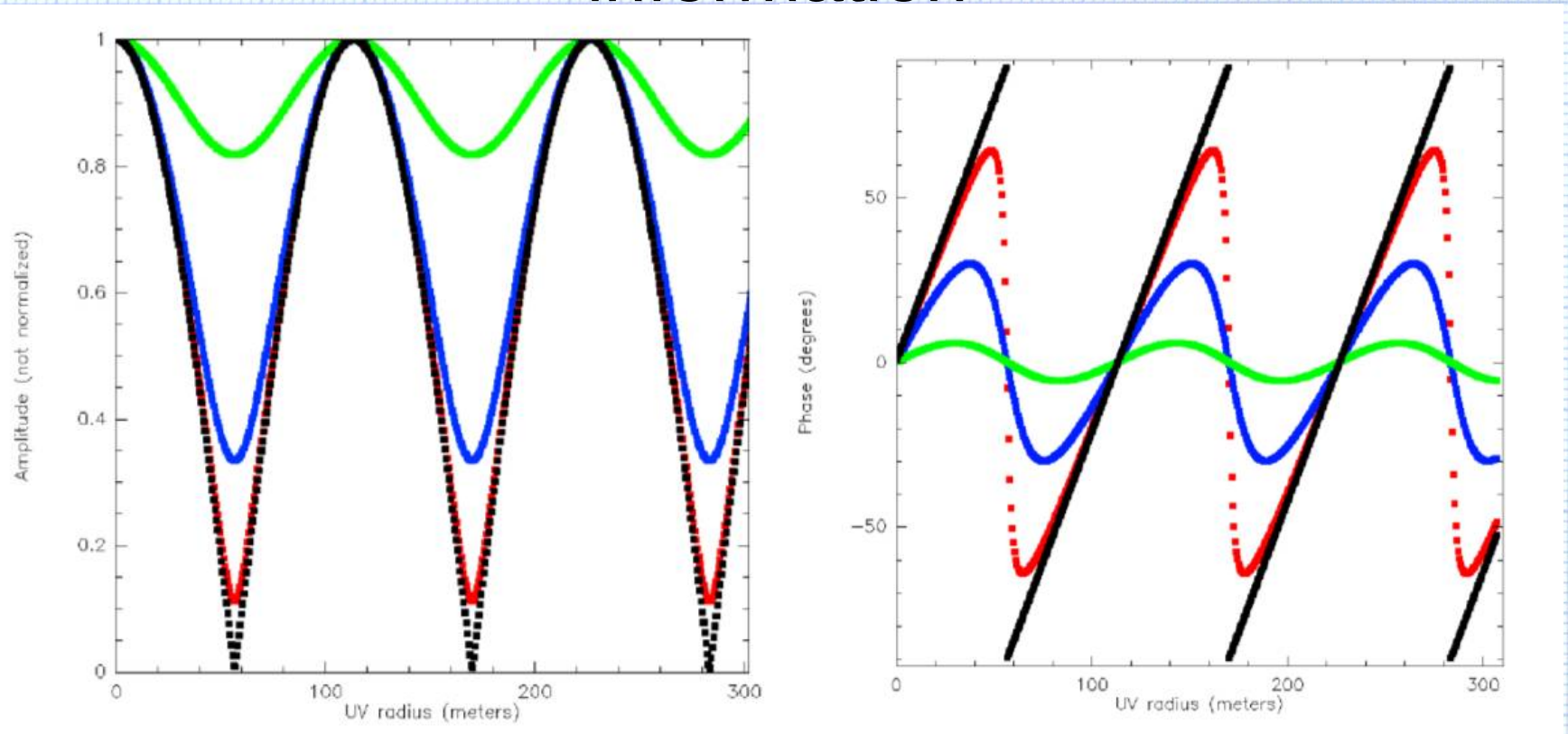


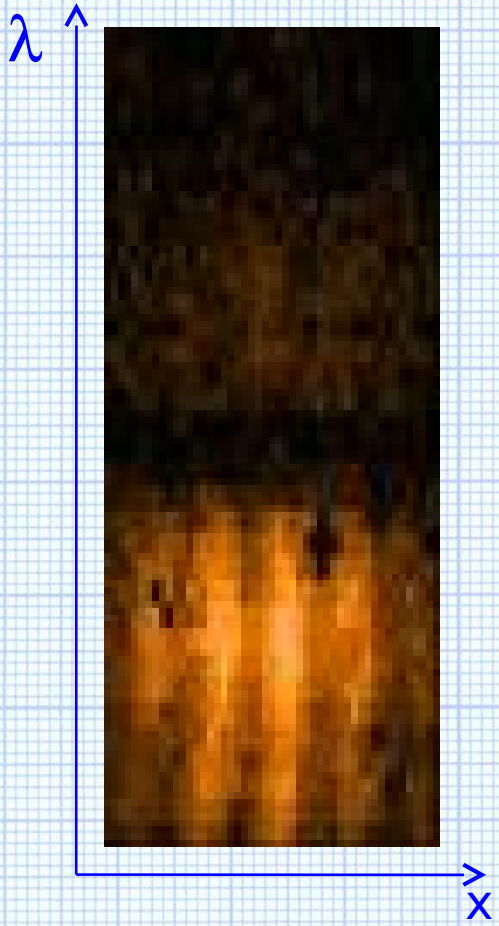
1:1
0.8:1
0.5:1
0.1:1

In other words...

Phase contains most of the astrometry information



All interferometric observables



Complex coherent flux:

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

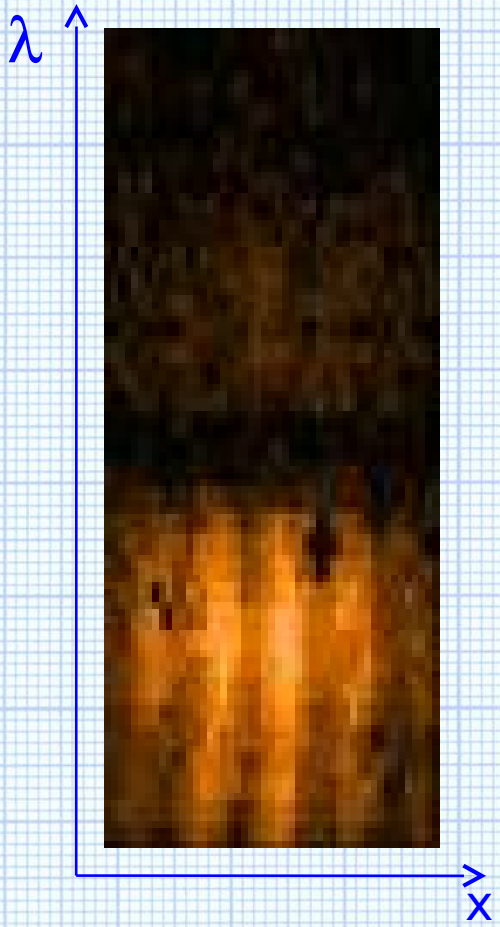
Visibility:

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

Phase:

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

All interferometric observables



Complex coherent flux:

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Visibility:

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

~~**Phase:**~~

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

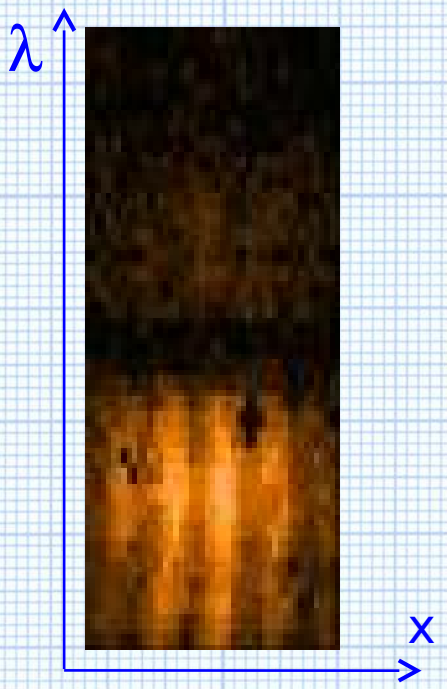
- Spectrum
- Visibility squared
- Differential phase
- Closure phase

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

What about phase?

Remember, due to the atmosphere:

- **Fringe motion**
  - **Time-dependent phase shift of the fringes**
    → Fringe phase is lost!



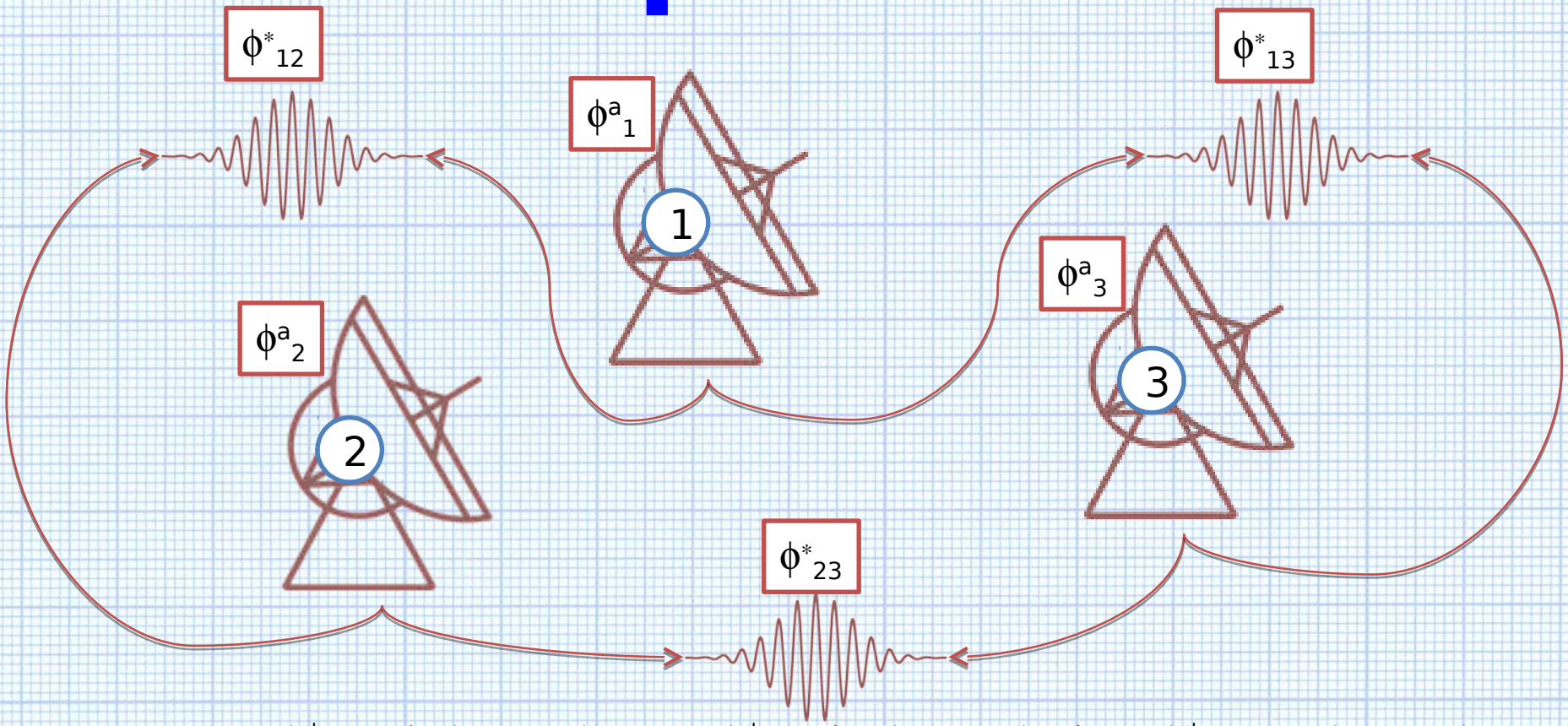
$$I(\delta_0, t) = e^{-\sigma^2_{\text{jitter}}(t)} \mu \cos\left(\phi - 2\pi \frac{\delta_0 + \delta(t)}{\lambda}\right)$$

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 reference star close-by**
    - **« Differential phase »: use a wavelength close-by**

Closure phase



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

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

Closure phase

Closure phase cannot be obtained with phases sums!

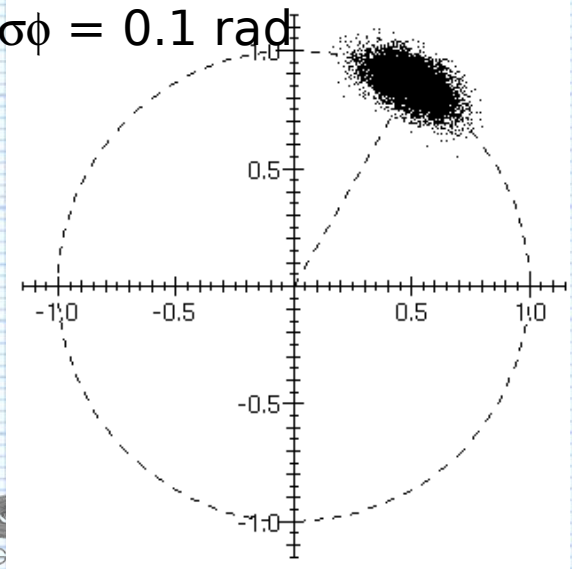
why?

Noise!

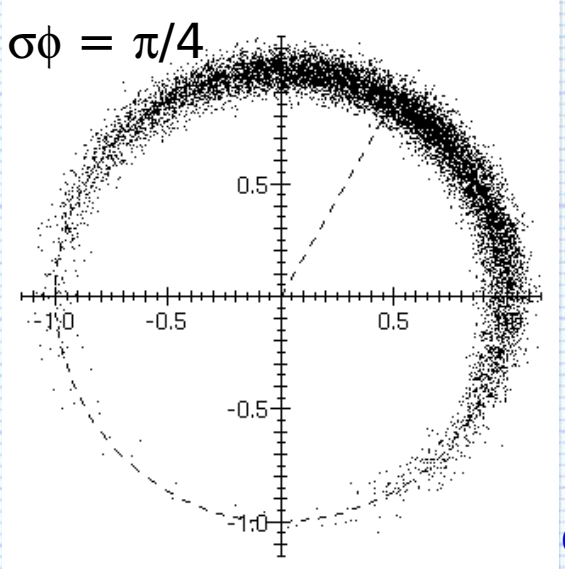
Additive noises produce a phase wrapping

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

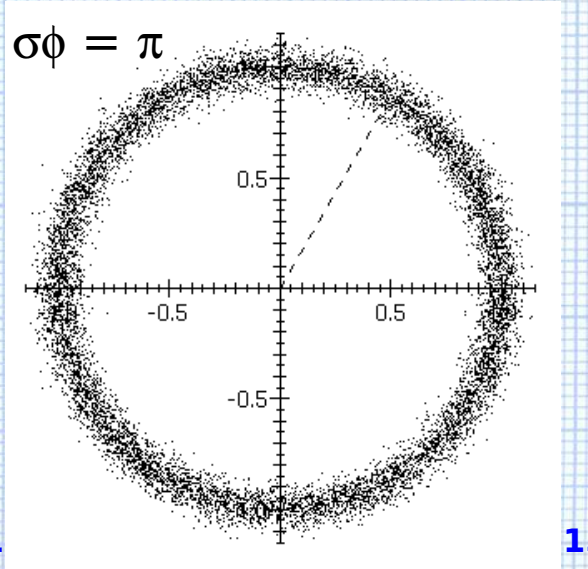
$\sigma\phi$ = 0.1 rad



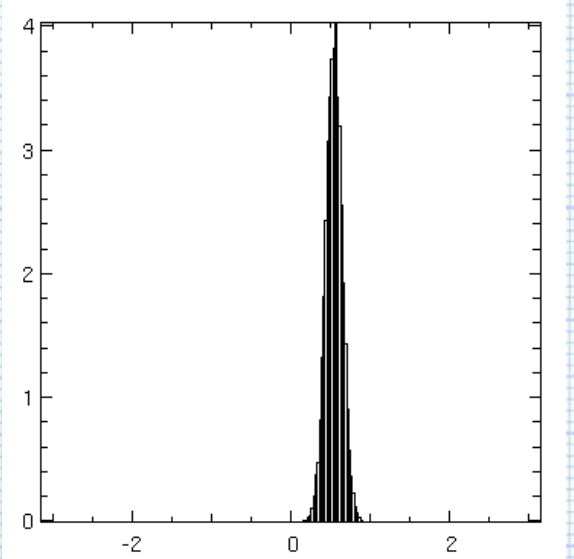
$\sigma\phi = \pi/4$

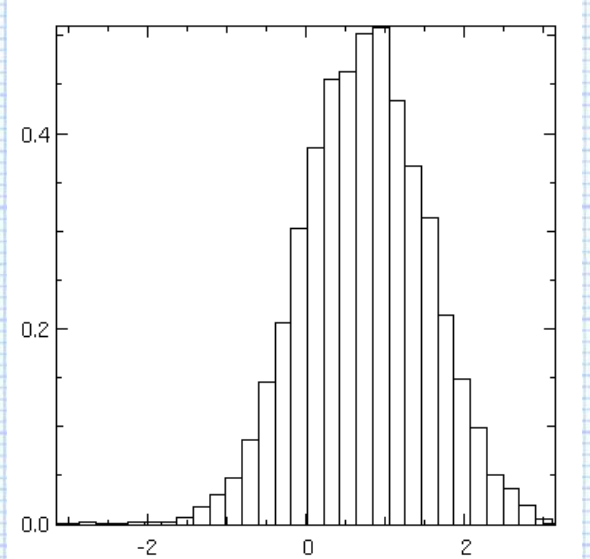


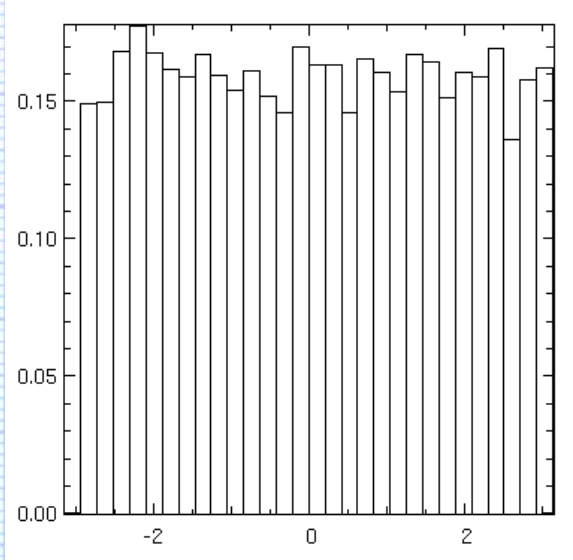
$\sigma\phi = \pi$



Closure phase







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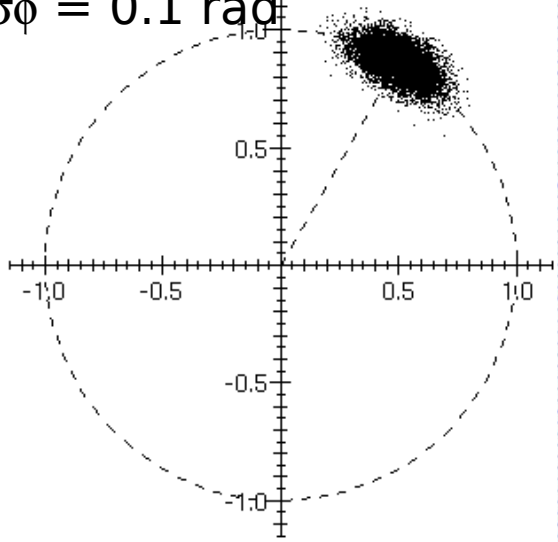

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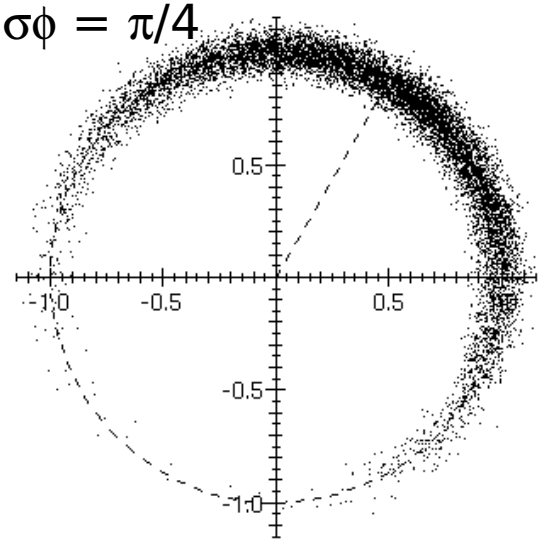
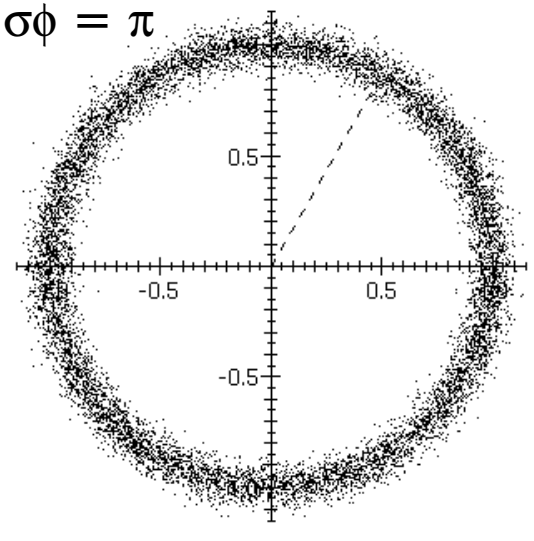


$\sigma\phi = \pi$



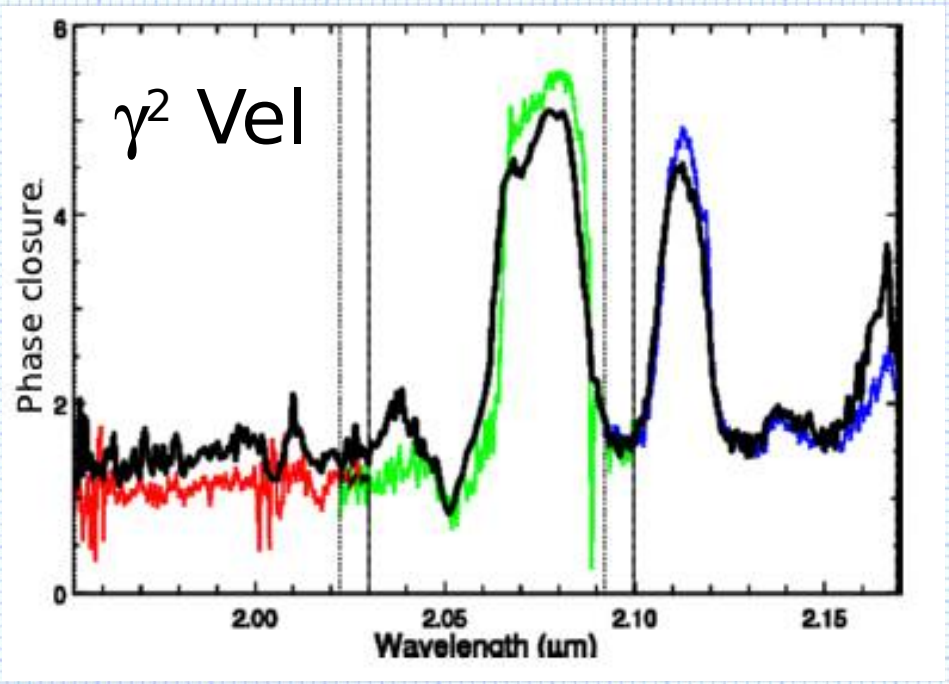
Closure phase

- **Closure phase cannot be obtained with phases sums!**
- **Stay in complex plane to avoid phase wrapping:**
  - **Bispectrum** $\langle C_{12} C_{23} C_{31} \rangle$
    - **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!**

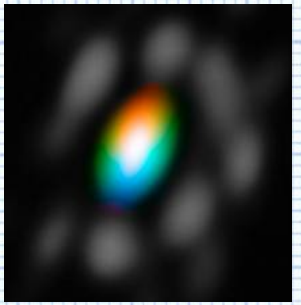
- **Closure phase is <u>not</u> straightforward to interpret!**



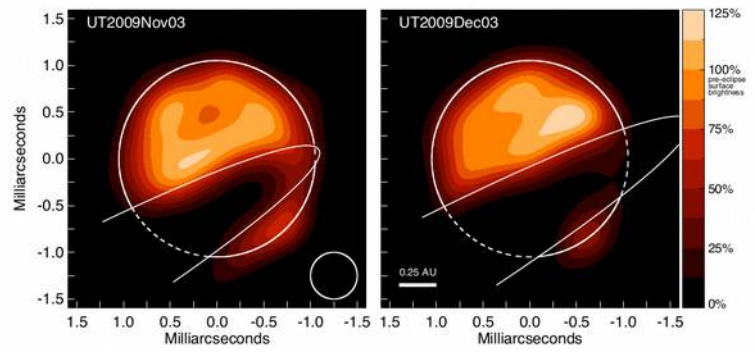
Some science made using closure phases

Tuthill et al. 1999 Discovery of a "pinwheel" nebula around WR104

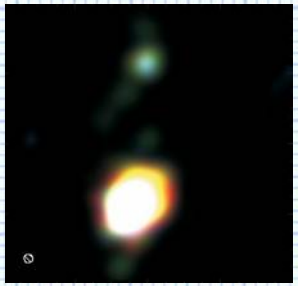
Millour et al. 2011 Imaging the asymmetric inner dust rim of a massive star disk



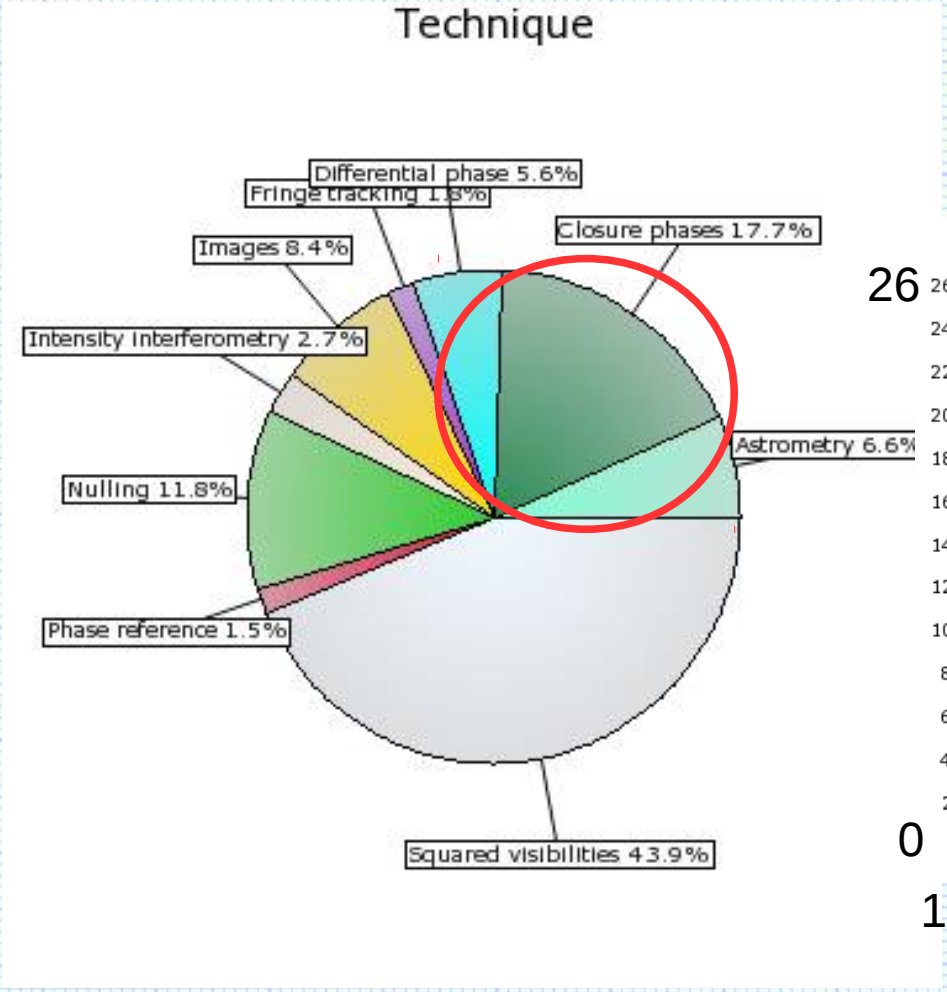
Kloppenborg et al. 2013 Imaging the transiting disk in front of Epsilon Aurigae



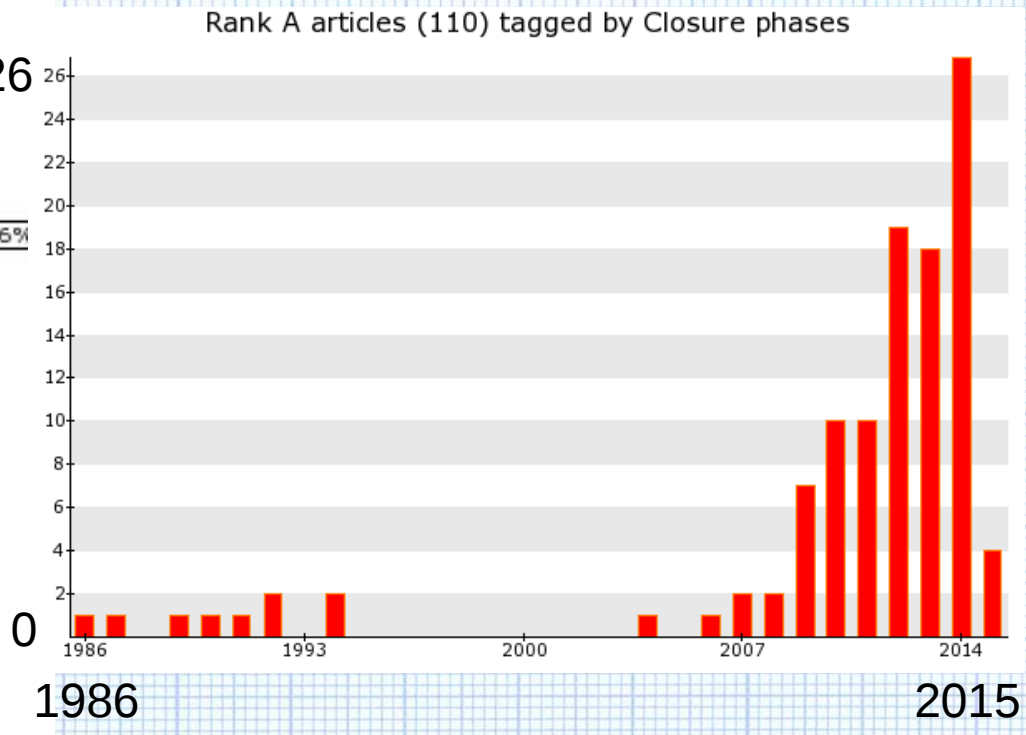
Kraus et al. 2012 Imaging the companion star & disk around a Herbig star



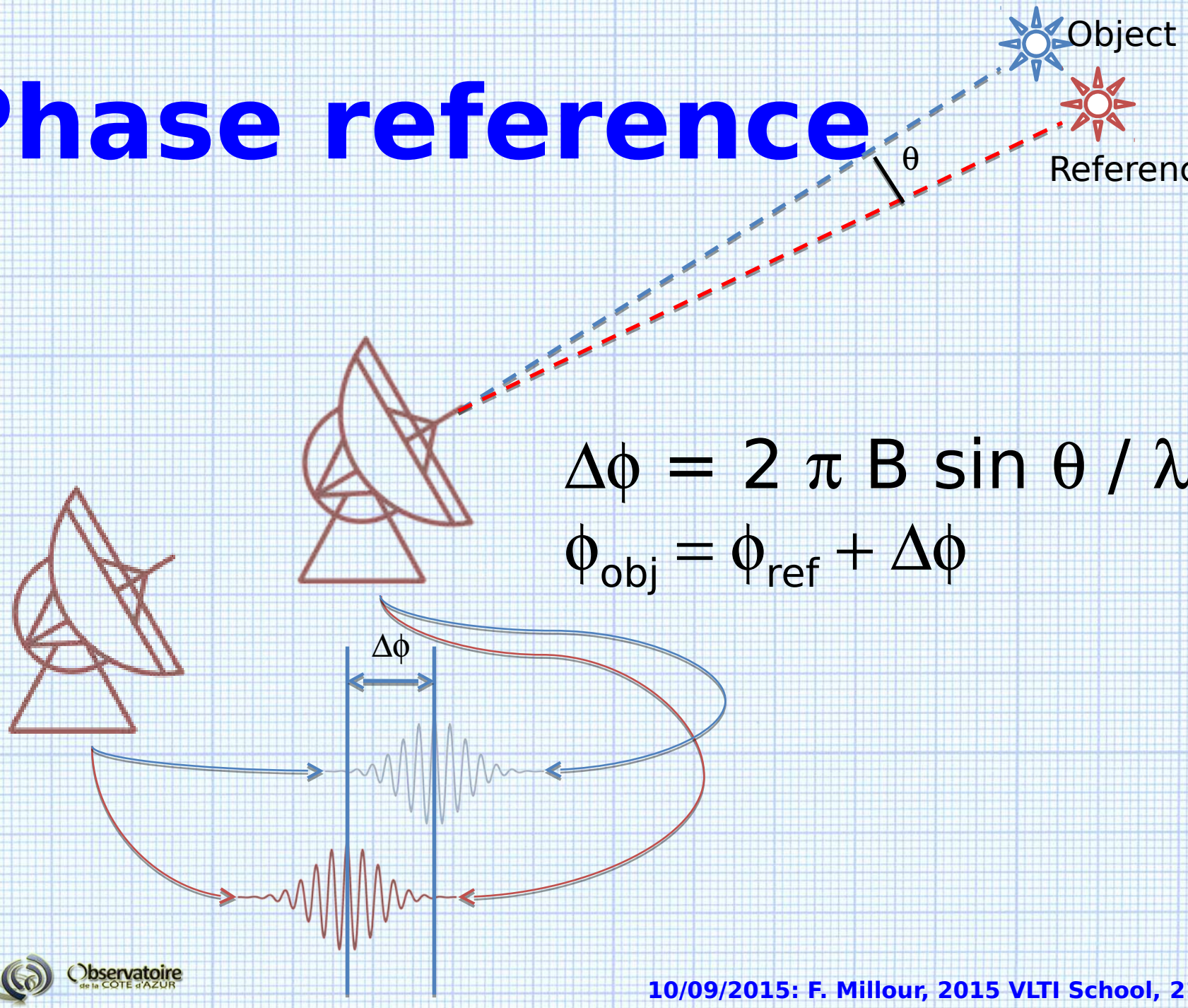
Science made using closure phases



JMMC bibliographic database
http://apps.jmmc.fr/bibdb/



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**

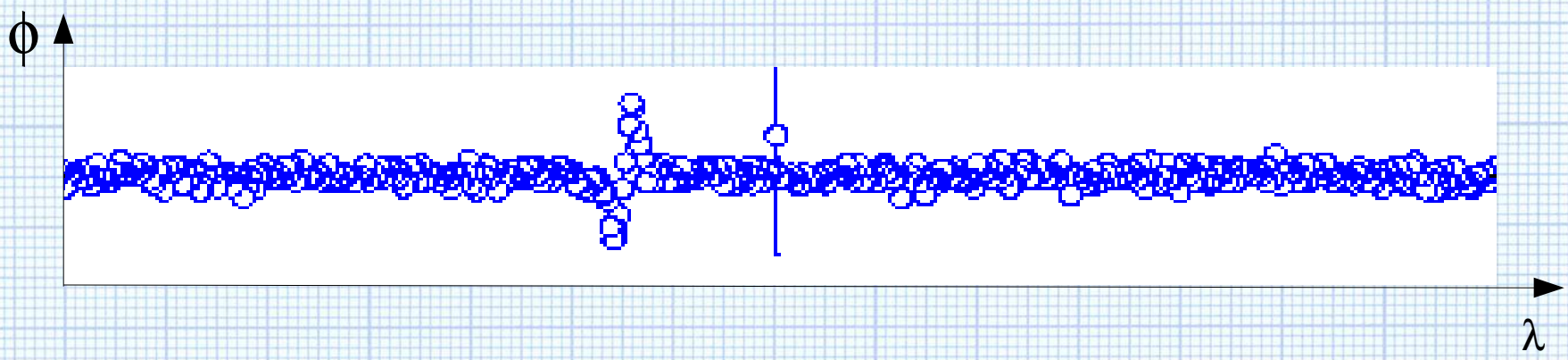
Phase reference

See A. Quirrenbach session

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



La phase différentielle

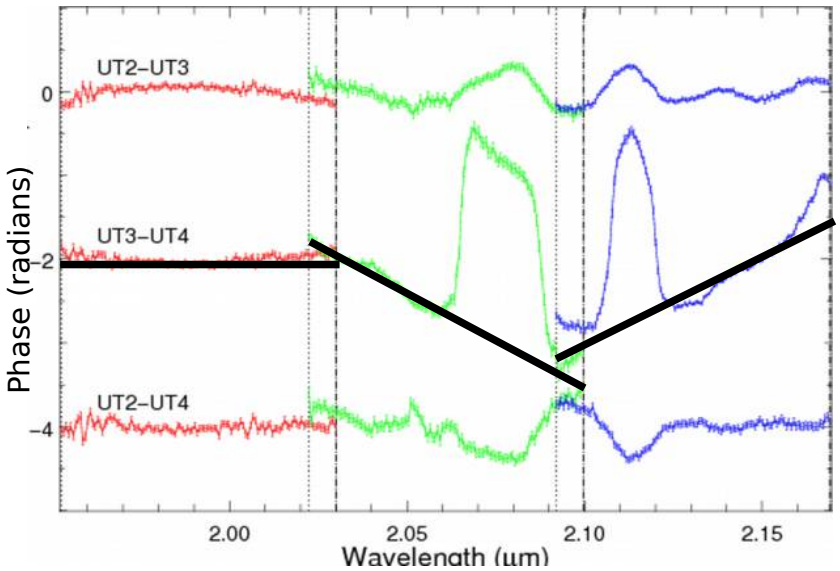
Principe

- Phase à 2 télescopes en fonction de λ
- Informations de la phase perdues :
  - Constante
  - Pente
  - Autres termes

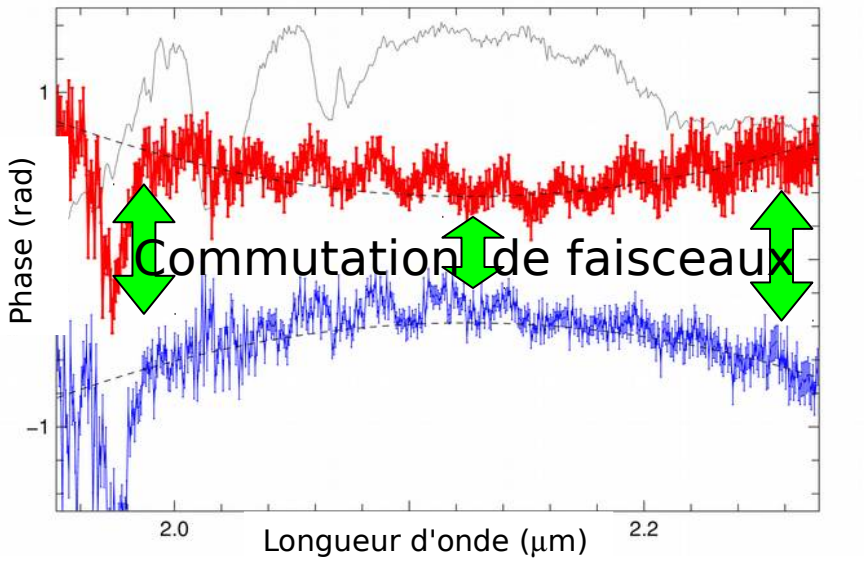
Précision 10^{-2} radians (6μas)
effets dominants

- Dispersion chromatique de l'air
- Problèmes instrumentaux (stabilité, dichroiques, polariseurs)

γ^2 Velorum (Millour et al. 2007)

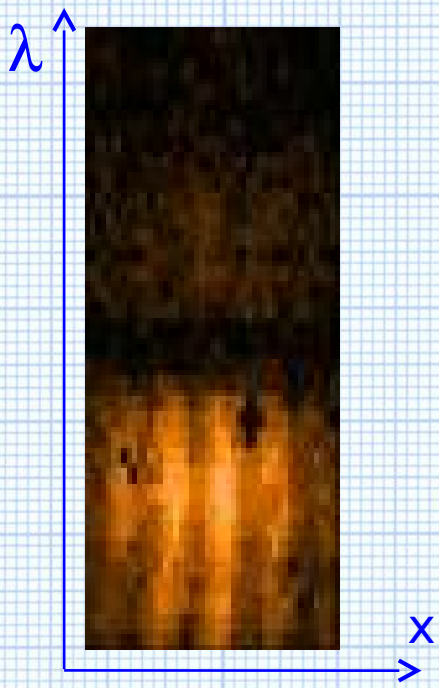


Rapport sur les phases d'AMBER (2007)



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

- Is the result of subtracting an **atmospheric + instrumental model** to the measured phase

$$\phi_{ij}^{m}(t,\sigma) = \phi_{ij}^{*}(\sigma) + 2\pi\delta_{ij}(t)\sigma + 2\pi s_{ij}(t)\sigma^{2} + \ldots + o(\sigma^{n})$$

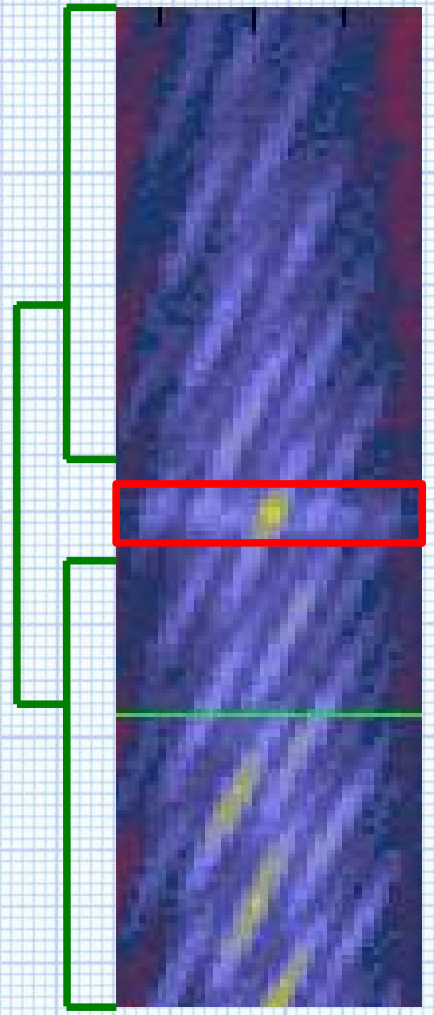
- Can be understood as the residual of a Taylor expansion of the measured instantaneous phase

$$\phi_{ij}^{*}(\sigma) = a_0^{*} + a_1^{*}\sigma + a_1^{*}\sigma^{2} + \ldots + \delta\varphi_{ij}^{*}(\sigma)$$

- Number of terms of the Taylor expansion depends on the spectral coverage

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)**

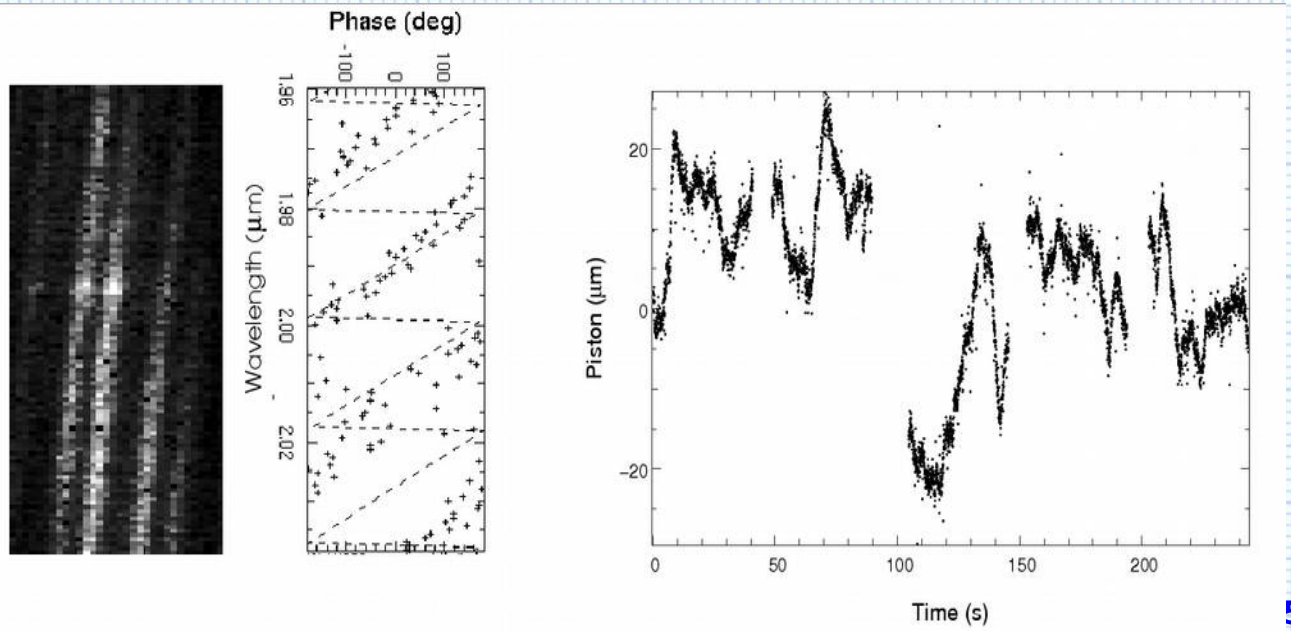


Differential phase

- **Problem: phase slope changes with time**
  - **Evaluate and correct OPD prior to calculating the cross product**

→ $Cn = C\, e^{-2i\pi\, \delta/\lambda}$

$\phi_{diff} = \arg \langle Cn_{work}\, Cn^{*}_{ref} \rangle$



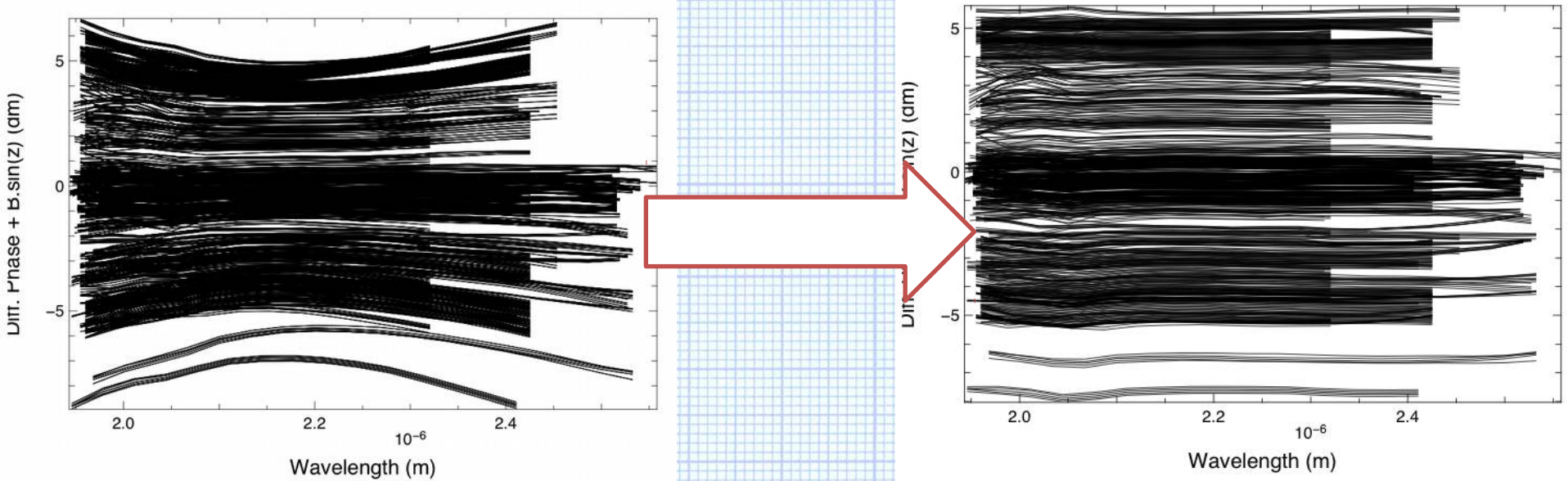
Differential phase

- **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.**

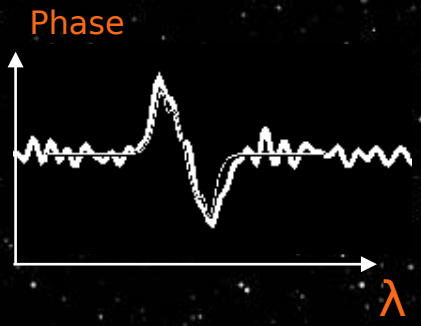
See Ciddor 1996, Vannier 2006, Mathar 2007



The organizers decline responsibility for anything laid after this slide

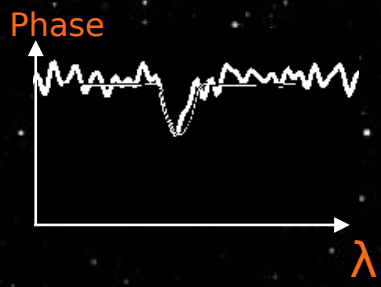
« Differential phase zoology »

Rotation



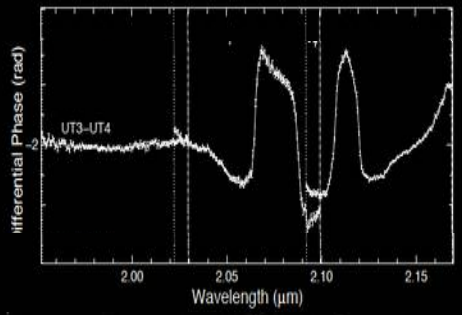
‘Snake’ phase

Asymmetries



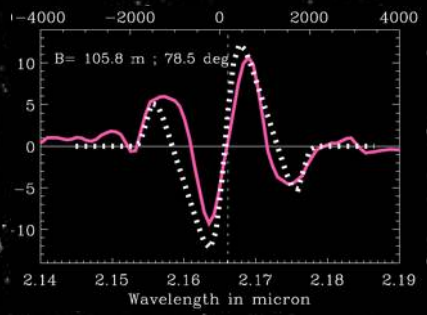
‘Dromedary’ phase

… Complex!



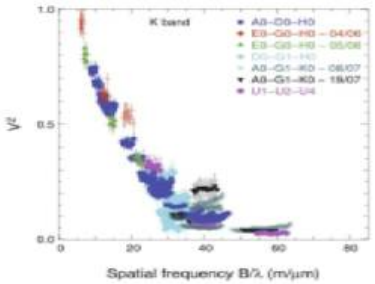
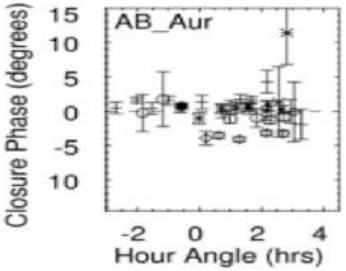
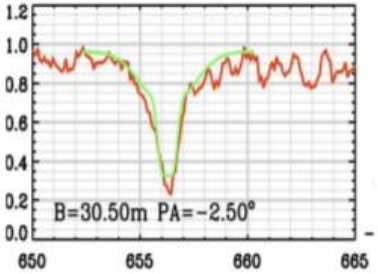
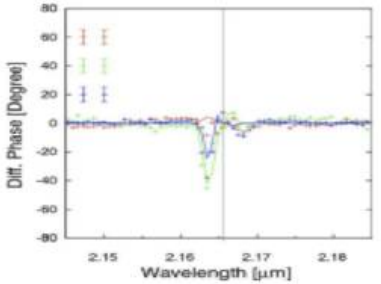
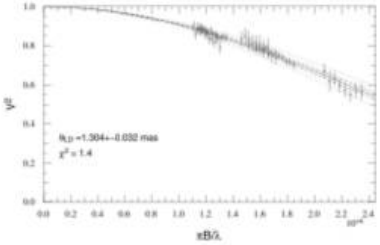
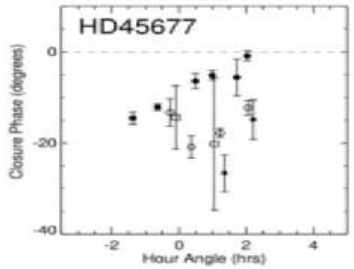
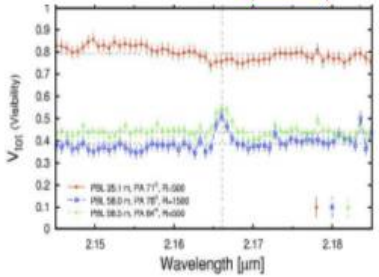
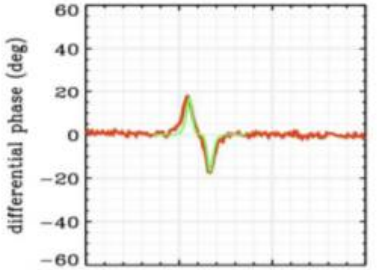
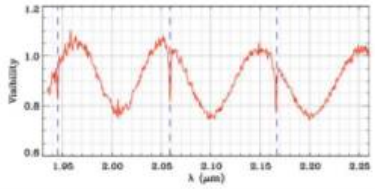
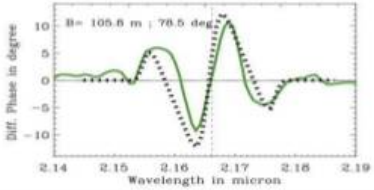
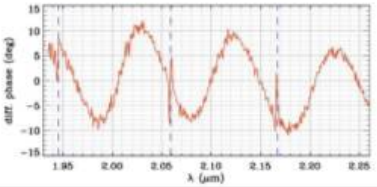
‘Platypus’ phase

Bipolar expansion



‘Camel’ phase

Table 3. The optical long-baseline interferometric "observables zoo", showing all the different cases one can face with current spectro-interferometric instruments, illustrated with actual published interferometric data. The letters link to the Table 2. Reproduced with permission.

Visibility	Closure phase	Diff. Vis.	Diff. Phase
(a) Resolved source Benisty *et al.* (2010)	(b) Zero Monnier *et al.* (2006)	(c) ↘ in emission line Stee *et al.* (2012)	(d) "V" shape Weigelt *et al.* (2007)
			
(e) Unresolved source Demory *et al.* (2009)	(f) Non-zero Monnier *et al.* (2006)	(g) ↗ in emission line Kraus *et al.* (2008)	(h) "S" shape Meilland *et al.* (2012)
			
(i) Cosine shape Meilland *et al.* (2011)	(j) "W" shape Chesneau *et al.* (2011)		(k) Sine shape Meilland *et al.* (2011)
			

«observables zoo »

Table 2. Qualitative information which can be retrieved from interferometric observables.

Observable	Value or features	Qualitative information	Model-fitting guidelines	Illustration Table 3
Visibility	Close to 0	Object $\varnothing \gg 1.22\lambda/B$ rad	Add a resolved component	(a)
	Close to 1	Object $\varnothing \ll \lambda/B$ rad	Uniform disk size	(e)
	Cosine shape	Binary star!	Use a binary model	(i)
Diff. vis.	$\searrow$ in an emission line	Bigger emission	Add an emitting envelope	(c)
	$\nearrow$ in an emission line	Smaller emission	Add an inner region/disk	(g)
	$\searrow$ in an absorption line	Central object in absorption	Absorbing central object	
	$\nearrow$ in an absorption line	Shell in absorption	Absorbing shell	
Clos. phase	$\neq 0°$ and $180°$	Asymmetric object	Add a point source	(f)
	$= 0°$ or $180°$	Object possibly symmetric	-	(b)
Diff. phase	Sine shape	Binary star!	Use a binary model	(k)
	"S" shape in a line	Object is rotating!	Use a kinematic model	(h)
	"V" shape in a line	Asymmetric object in line	See Weigelt *et al.* (2007)	(d)
	"W" shape in a line	A bipolar outflow?	See Chesneau *et al.* (2011)	(j)

See Millour 2015, in "What the highest angular resolution can bring to stellar astrophyics?" EAS publication series

Spectrally dispersed interferometry ??

Spectroscopy

Analysis of light dispersion

Information on :

- **Chemistry**
- **Radial Velocity**
- **Temperatures**
- **Magnetic field**

Interferometry

Analysis of light coherence

Information on :

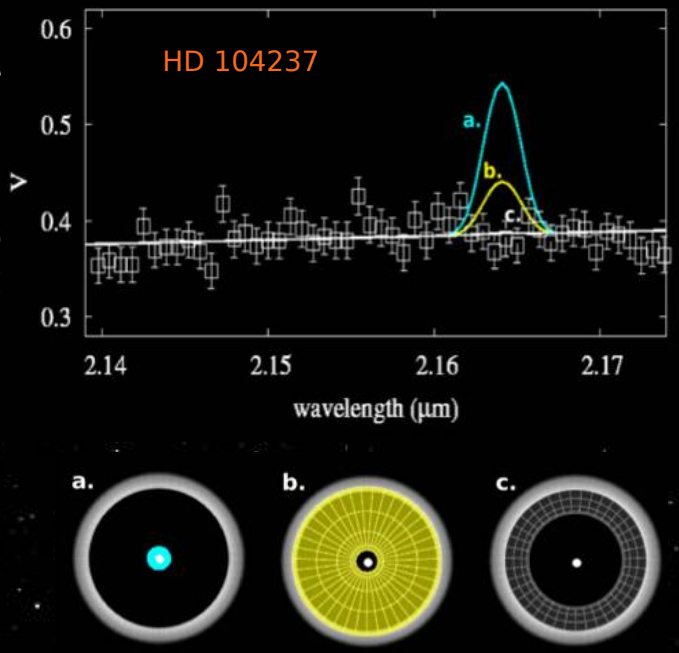
- **Position (astrometry)**
- **Size**
- **Shape**

Spectro-interferometry

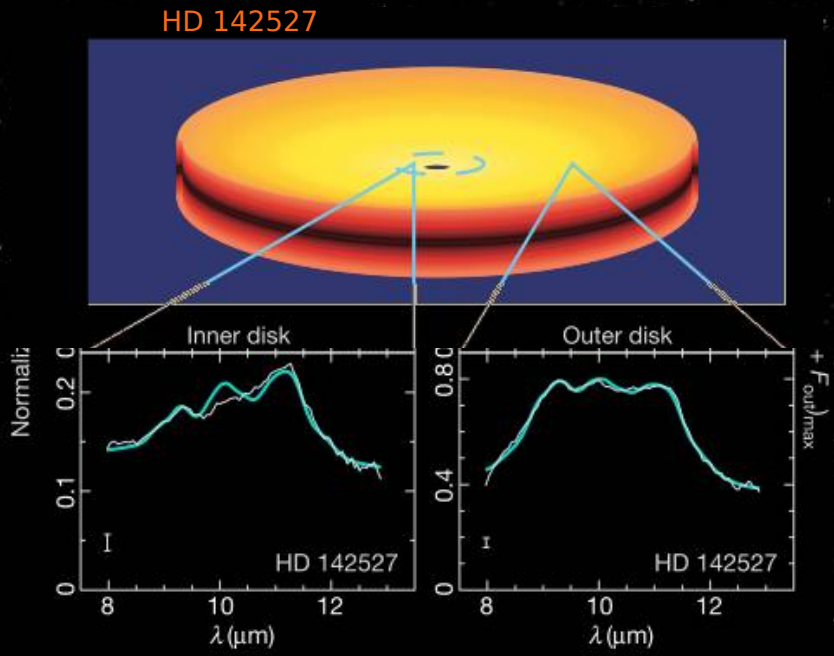
Best of both worlds !

Chemistry + Size
= material-forming zones

- **Characteristic features in the spectrum**
  - **@2µm: Hydrogen / metallic lines + CO lines**
  - **@10µm: Silicates dust features**



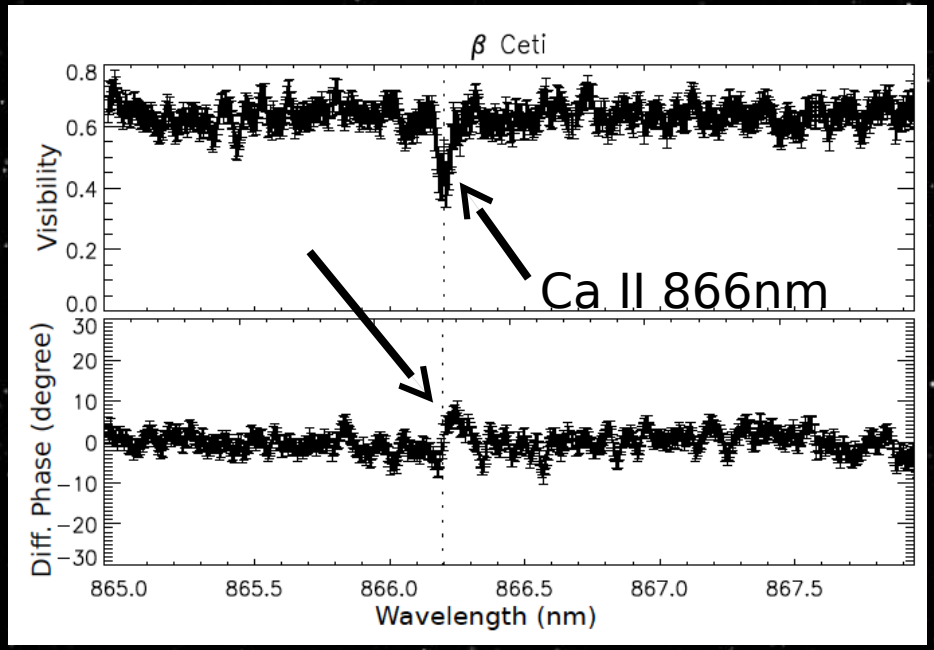
Tatulli et al. 2007



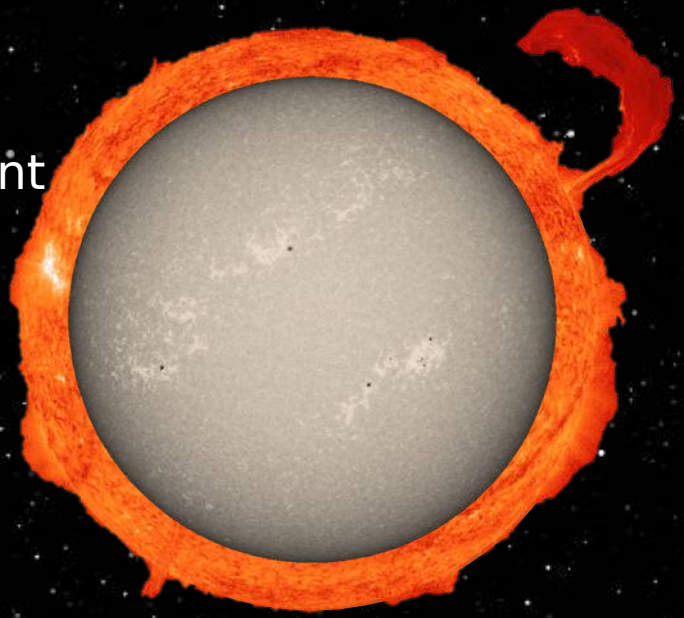
Van Boekel et al. 2004

Chemistry + Size = material-forming zones

- **Example: Berio et al. 2011**
- **Direct measurement of chromosphere extent in 4 K-giants!**



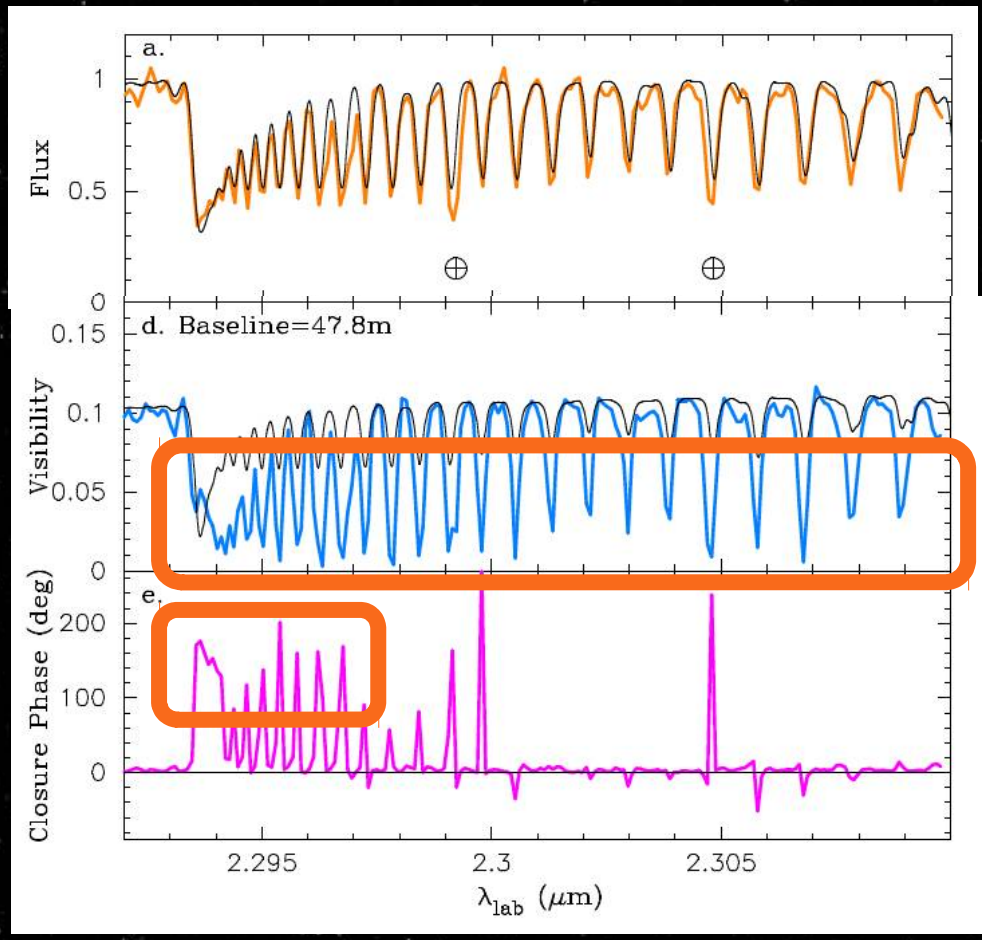
This is a K giant



- **Surprise: K giant chromospheres are ~16 to 47% larger than photosphere**

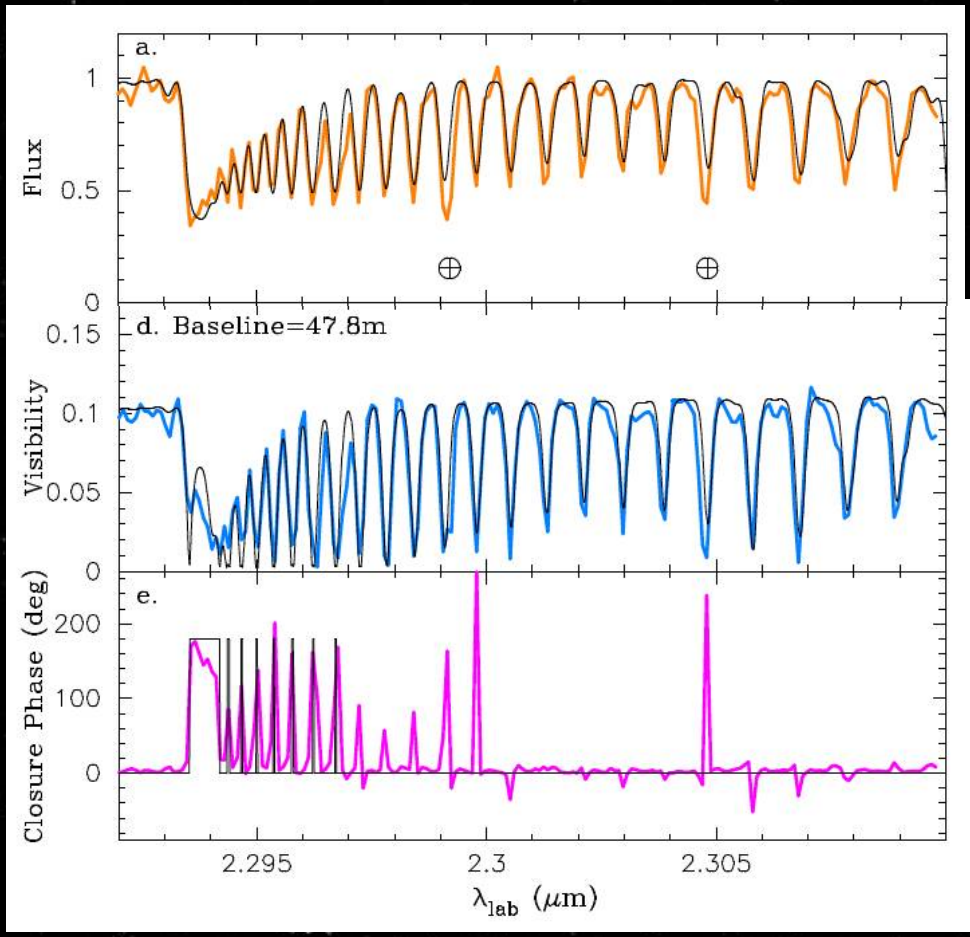
Chemistry + Size = material-forming zones

- Example: Ohnaka et al. 2012
- M giant star BK Vir
- CO lines match MARCS models
  - in the spectrum
  - but not in visibilities & phases



Chemistry + Size = material-forming zones

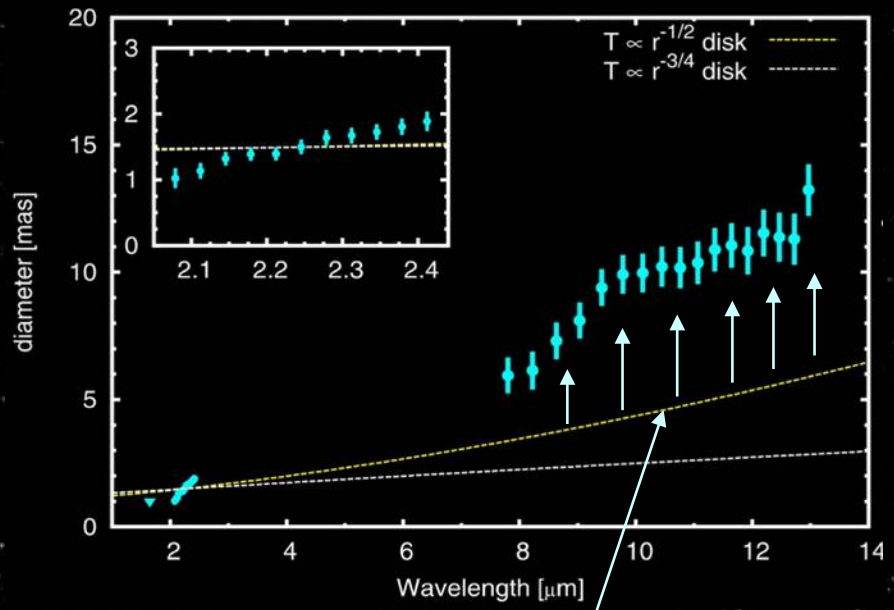
- Example: Ohnaka et al. 2012
- M giant star BK Vir
- CO lines match MARCS models
  - in the spectrum
  - but not in visibilities & phases
- Need to add outer CO shells, hotter and denser than expected



Size + Temperature = nature of material

- **Importance of multi-λ information**

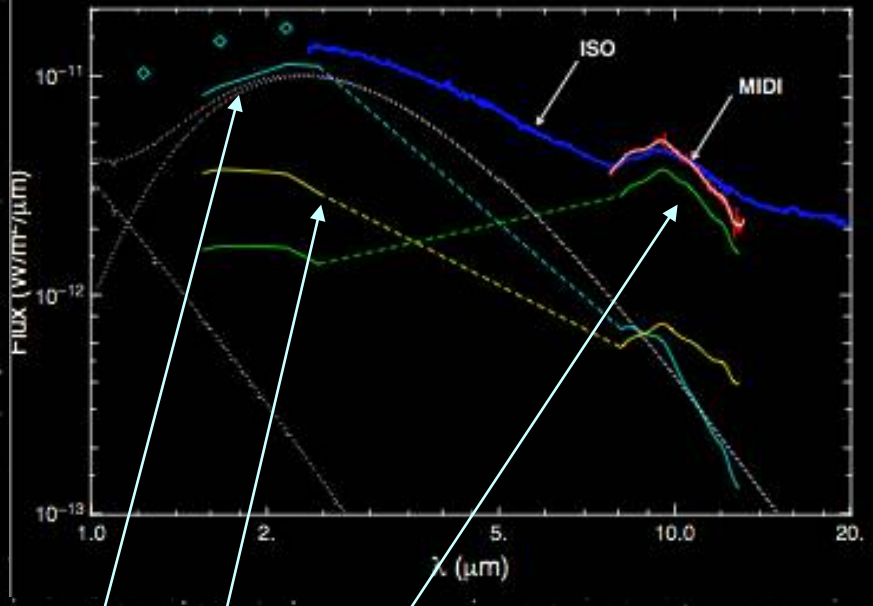
YSO: MWC 147



Kraus et al. 2008

An inner gaz disk is needed to explain the observed size deficit

Supergiant: HD 87643



Millour et al. 2009

Main star disk dust-sublimation rim

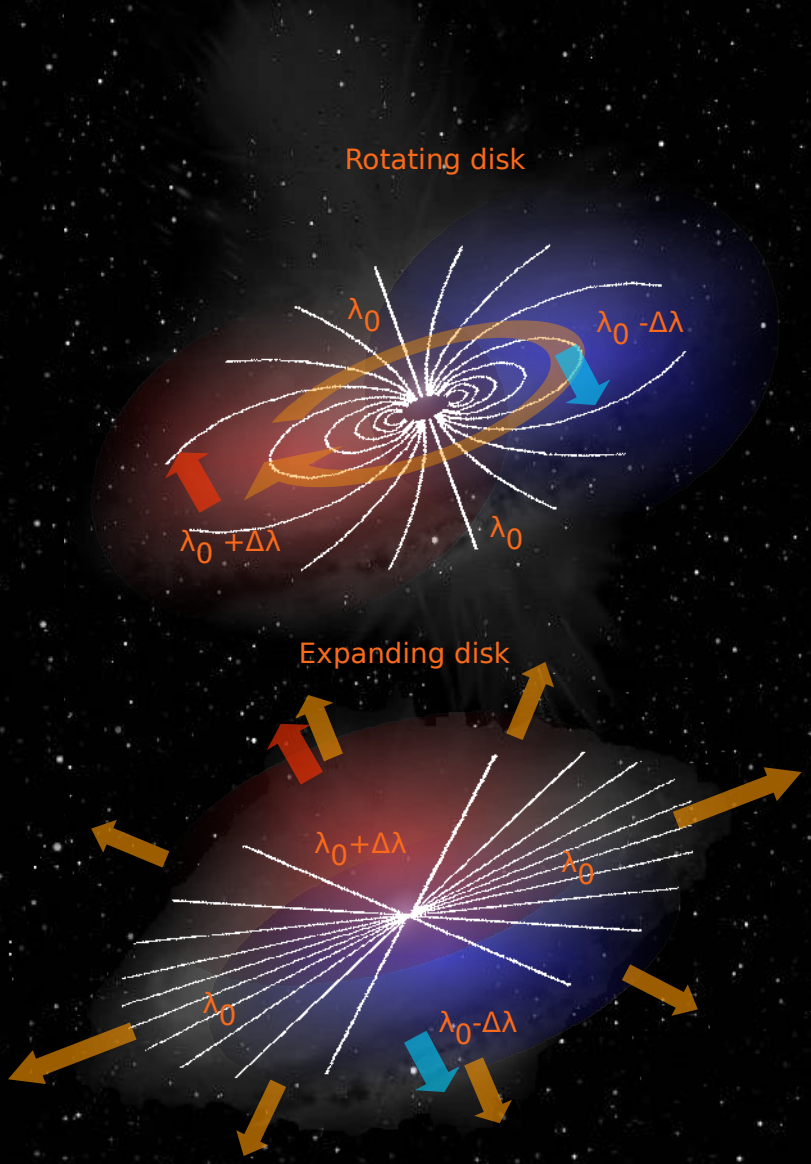
Companion star envelope

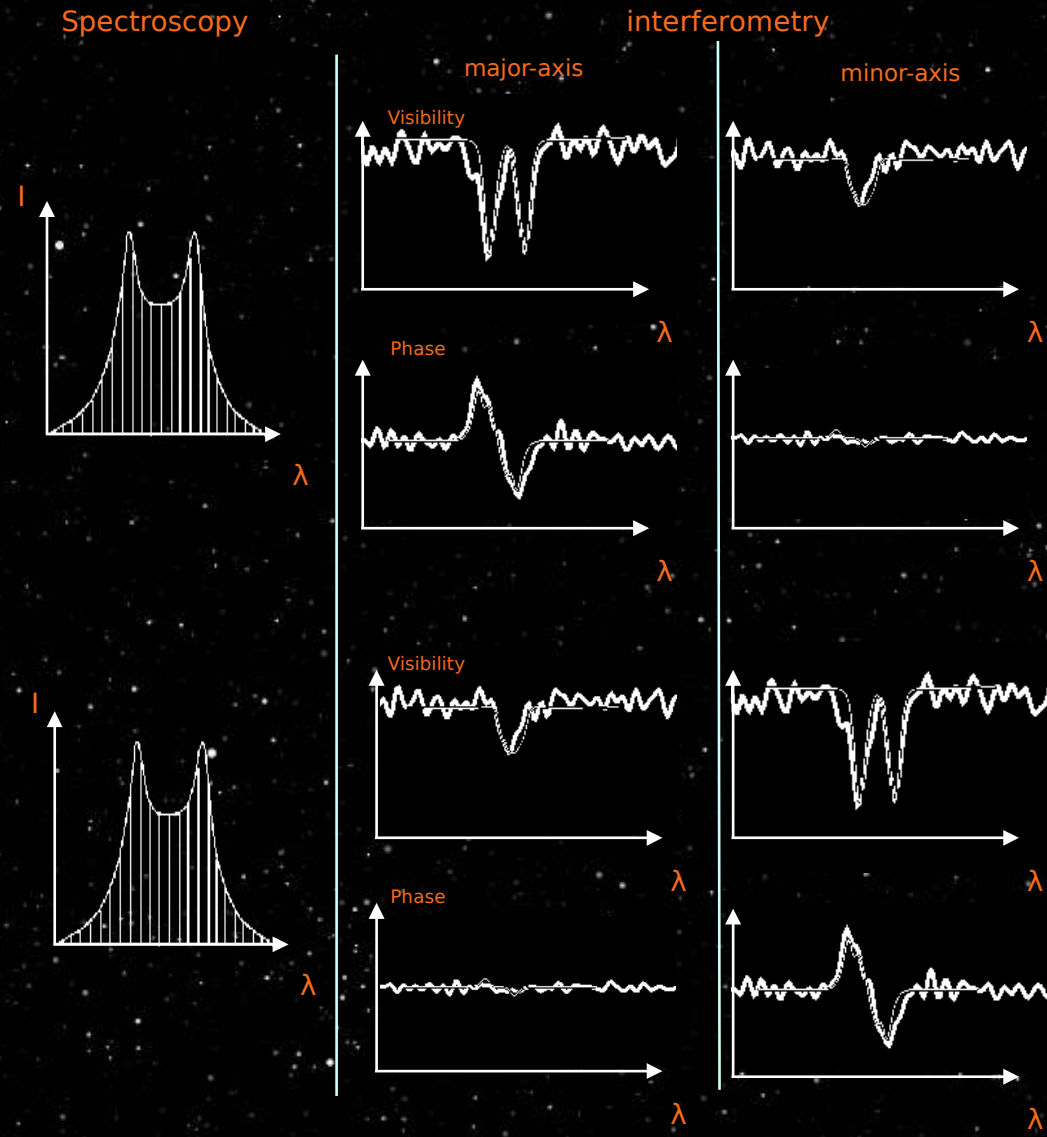
Circumbinary disk

Radial velocities + Position = kinematics

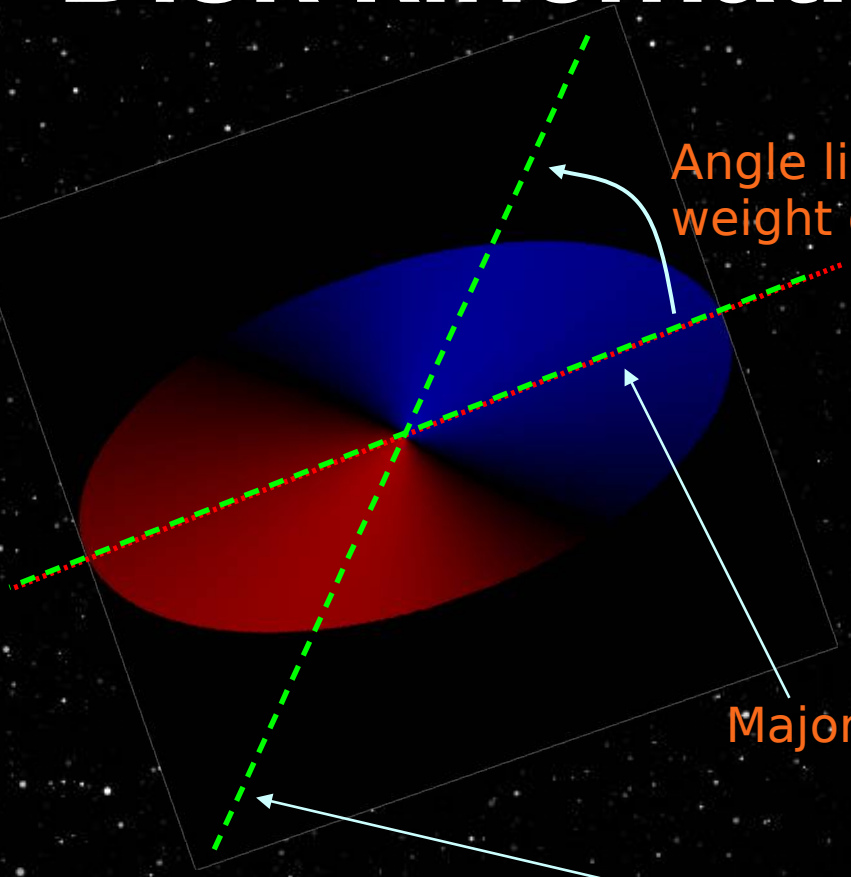
- Disks
  - Rotation
    - Keplerian
    - Solid
    - Angular momentum conservation
  - Accretion/Decretion
  - Disk-wind (YSOs)
- Winds
  - Prolate winds
  - Fireballs / Bipolar outflows
  - Inhomogeneous winds

Disk kinematics





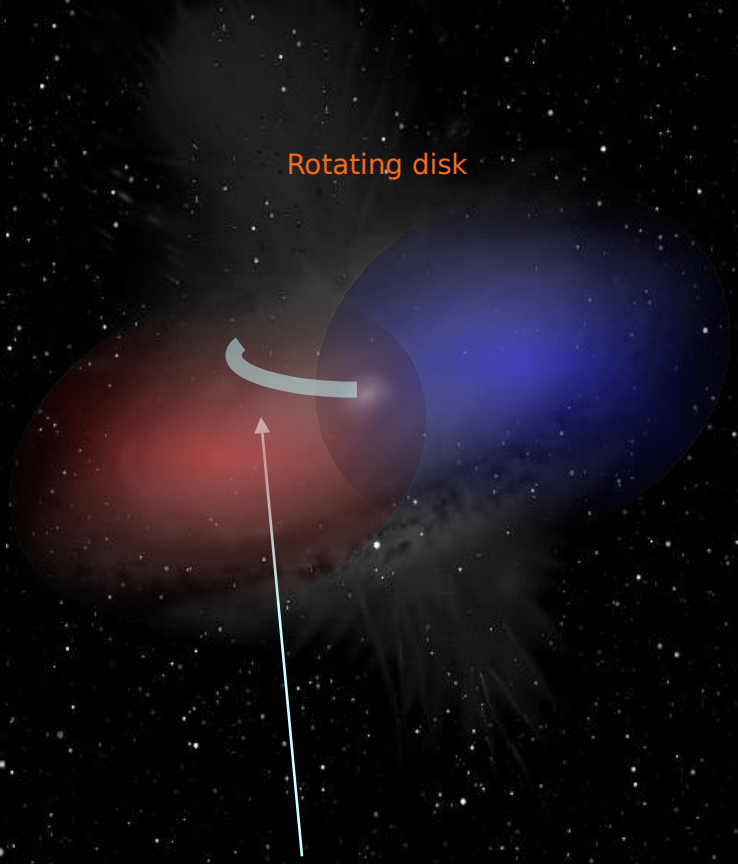
Disk kinematics

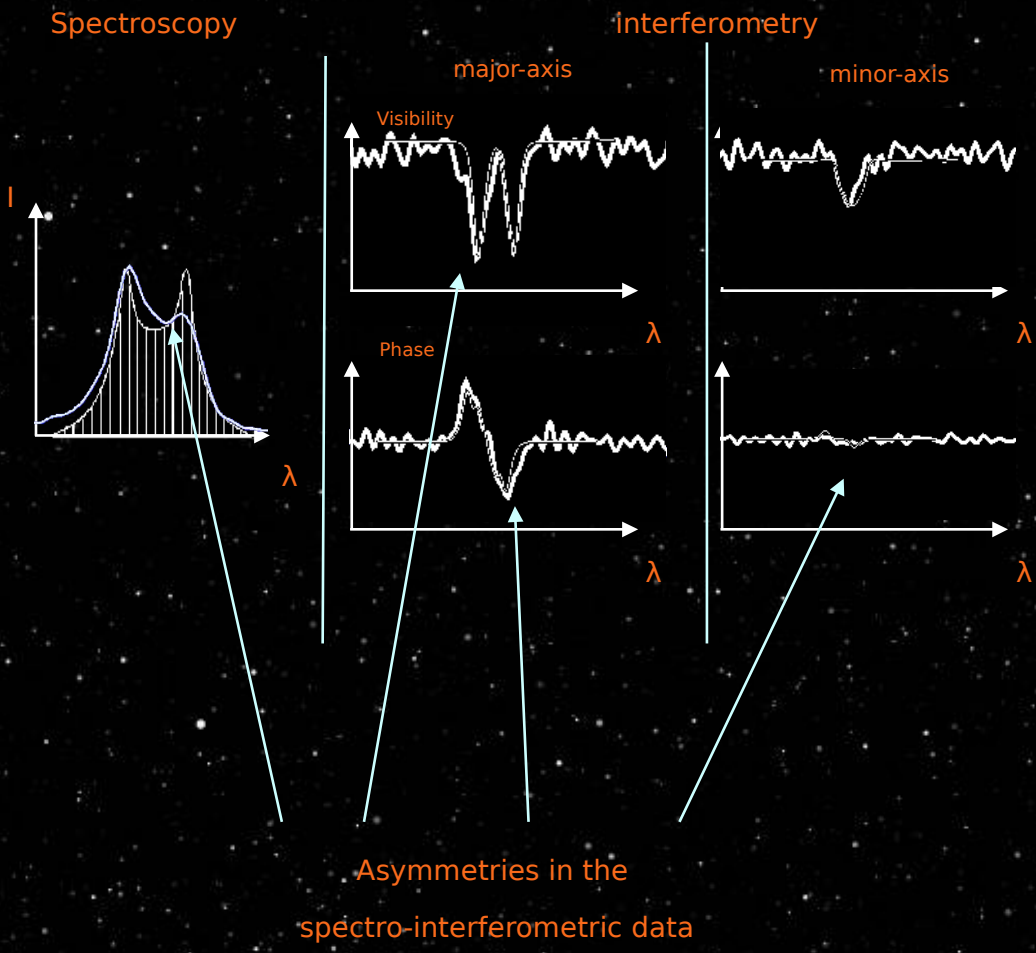


Adding expansion to
a rotating disc:

Rotation of the photocente
shift axis !

Disk inhomogeneities

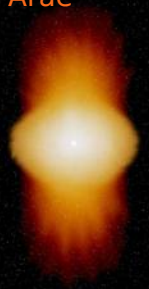




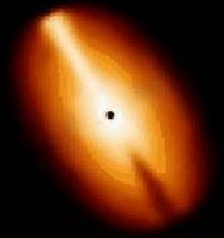
Disk kinematics: applications

- **Be stars**

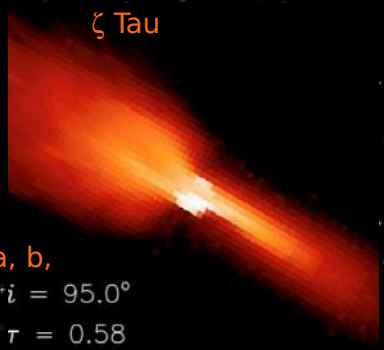
α Arae



κ CMa



ζ Tau



Meilland et al. 2007a, b, 2011, 2012a, b,

Delaa et a. 2011,

Carciofi et al. 2009,

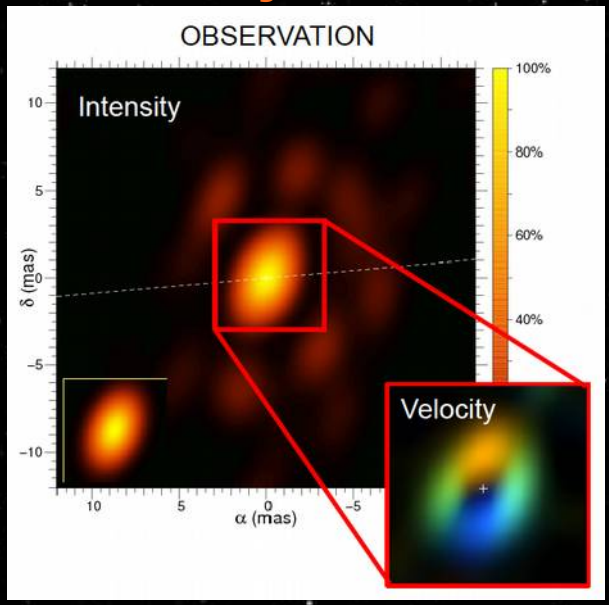
Kraus et al. 2012,

Pott et al. 2010,

All in Keplerian rotation

- **Supergiant stars**

HD 62623: image!



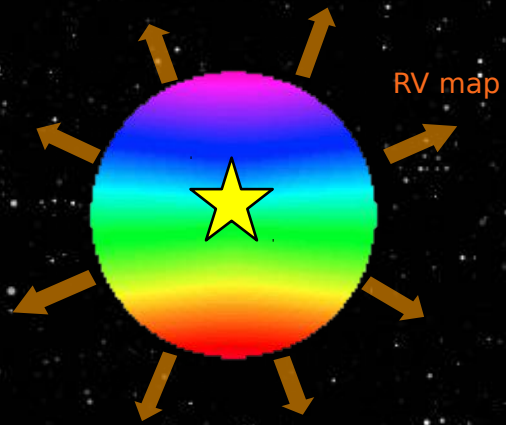
Keplerian rotation

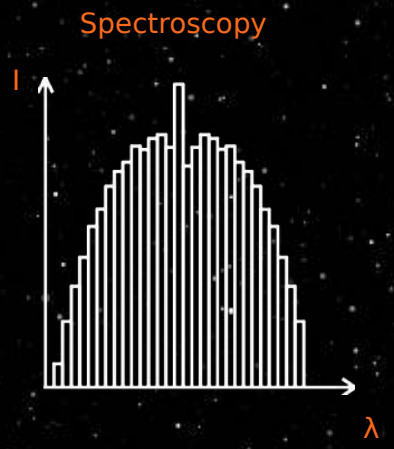
Millour et al. 2011 A&A

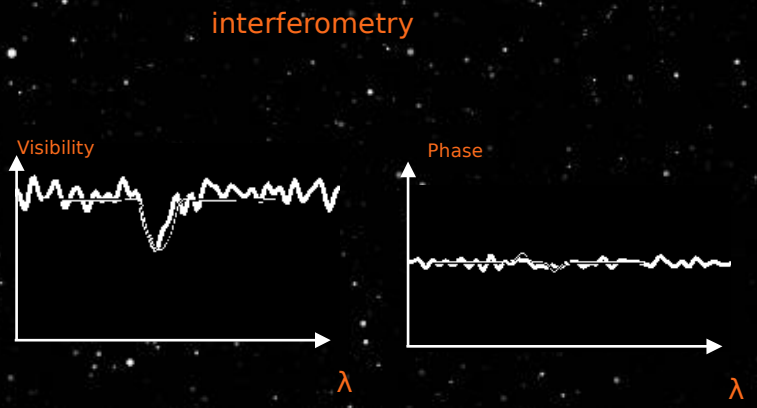
… Are all observed disks in Keplerian rotation?

Wind kinematics

- A spherical wind does NOT produce phase signal
  - Need for
    - inhomogeneities
    - Aspherical wind



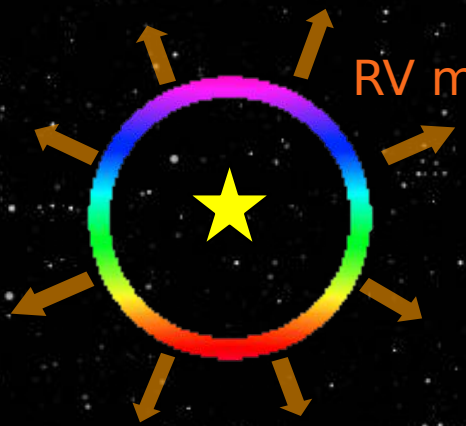


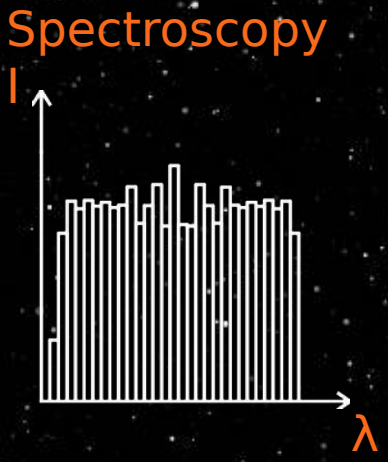


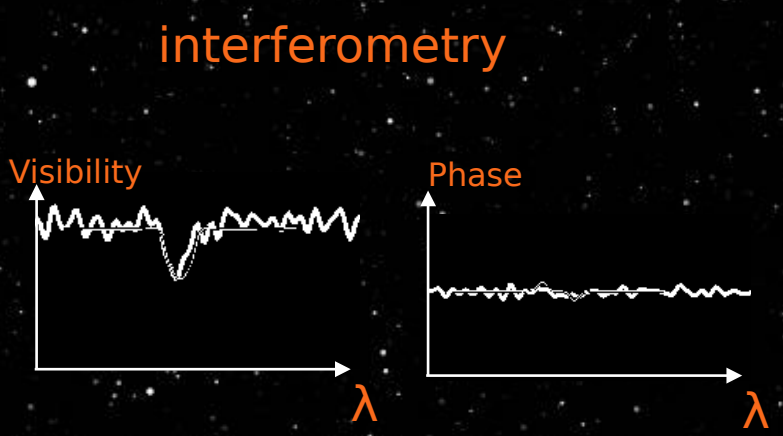
Wind kinematics

Observer

- **A spherical wind does NOT produce phase signal**
  - **Need for**
    - **inhomogeneities**
    - **Aspherical wind**



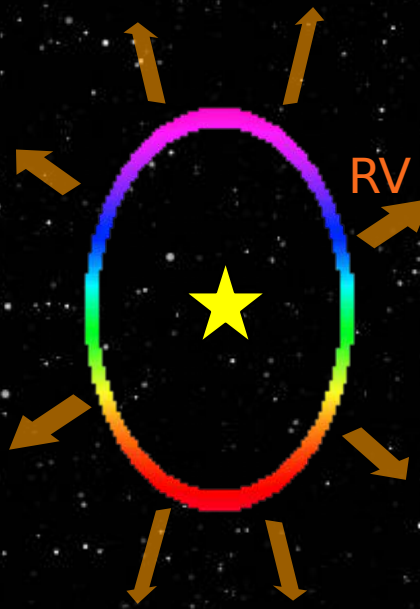




Wind kinematics

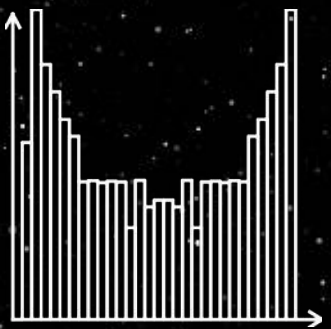
Observer

- **A spherical wind does NOT produce phase signal**
  - **Need for**
    - **inhomogeneities**
    - **Aspherical wind**

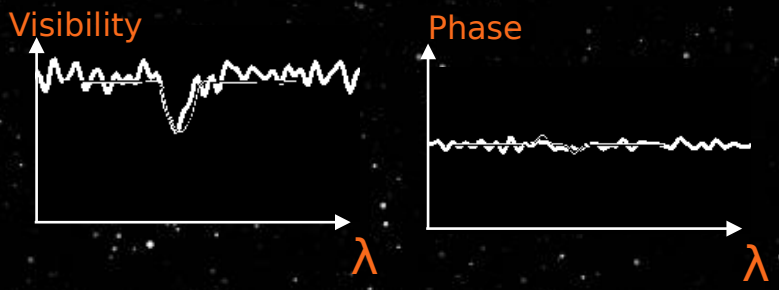


Spectroscopy

I

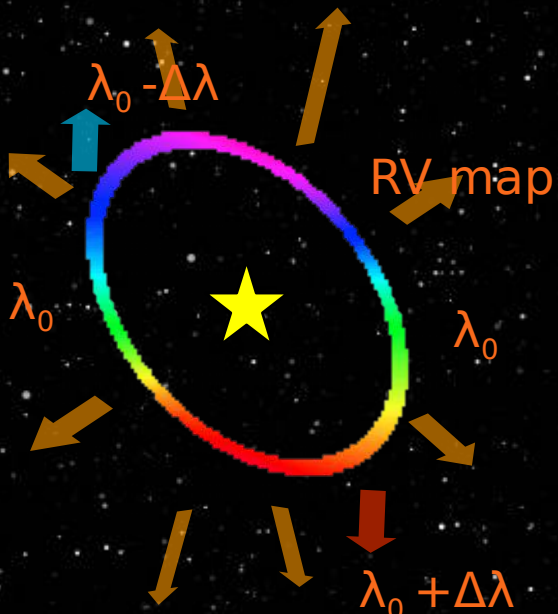


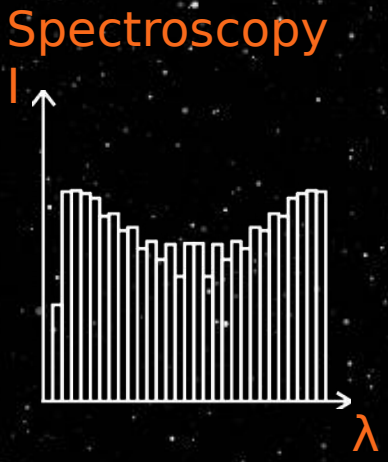
interferometry

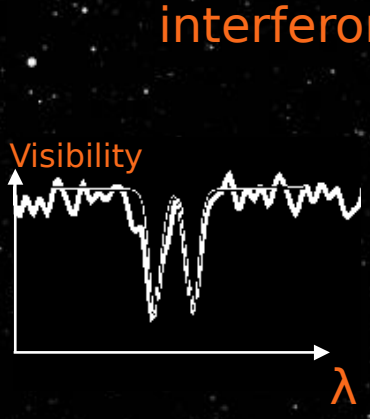


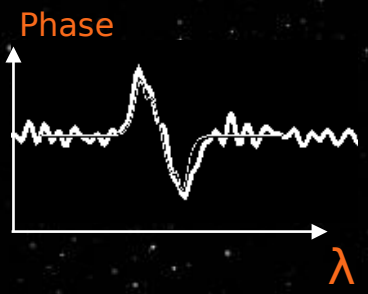
Wind kinematics

- **A spherical wind does NOT produce phase signal**
  - **Need for**
    - **inhomogeneities**
    - **Aspherical wind**





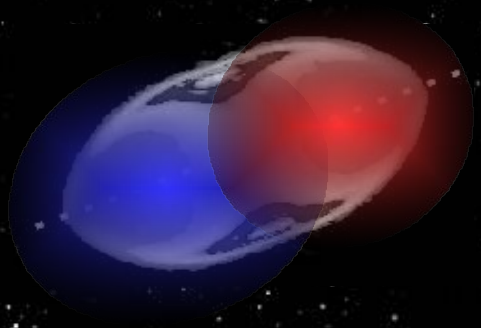




Wind / outflow kinematics:

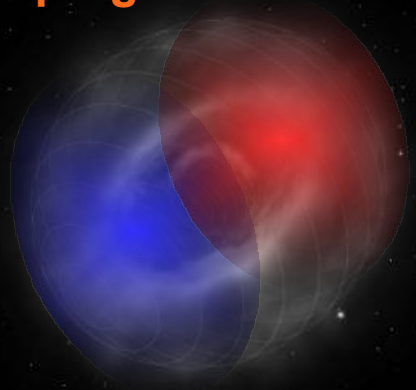
applications

- **Novae**



- RS Oph
  - Chesneau et al. 2007
- T Pyx
  - Chesneau et al. 2011

- **Supergiant**



- η Car
  - Weigelt et al. 2007
  - Groh et al. 2010
- IRC 10+420
  - Driebe et al. 2008
- CPD-57+2874
  - Domiciano de Souza et al. 2007

… Are bipolar winds ubiquitous? Is there an observing bias?

The end

More stuff

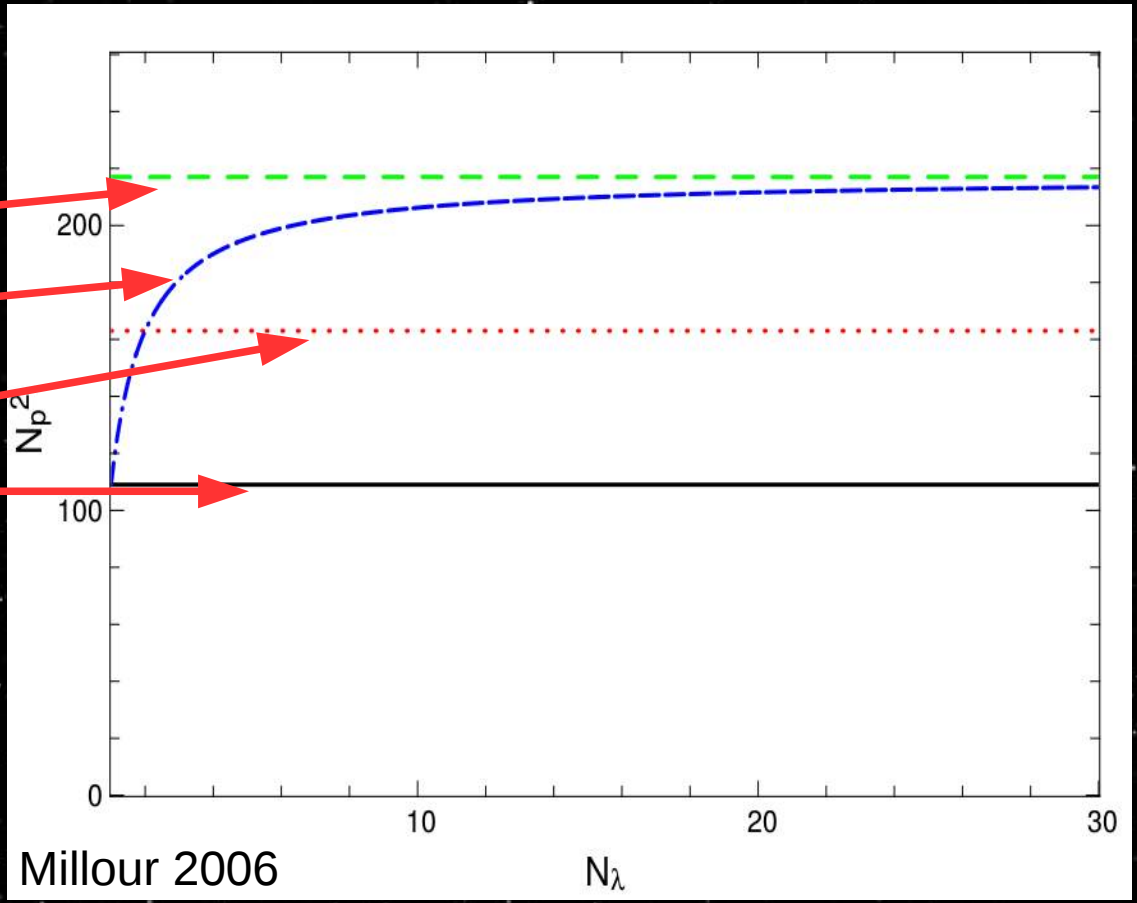
More stuff

Do we use all the available information in image reconstruction ?

- **Spectrum**
- **Visibility squared**
- **Closure phase**
- **Differential phase**

More stuff

Image reconstruction with:
- Visibility & phase
- Visibility, closure phase & differential phase
- Visibility & closure phase
- Visibility alone



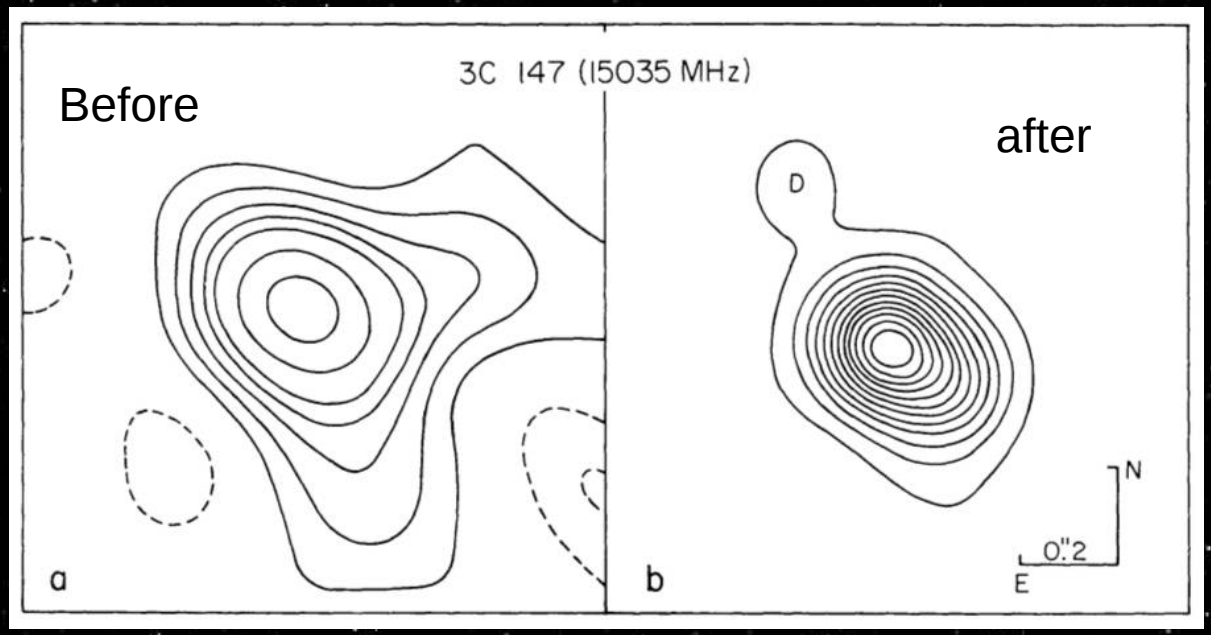
More stuff

- **How to include differential phase in image reconstruction ?**
- **A difficult task !**
- **Diff. Phases have lost the absolute astrometric information**
- **Need to calibrate it with external information**
- **Visibility + Closure phase !**

More stuff

How does it work in radioastronomy ?

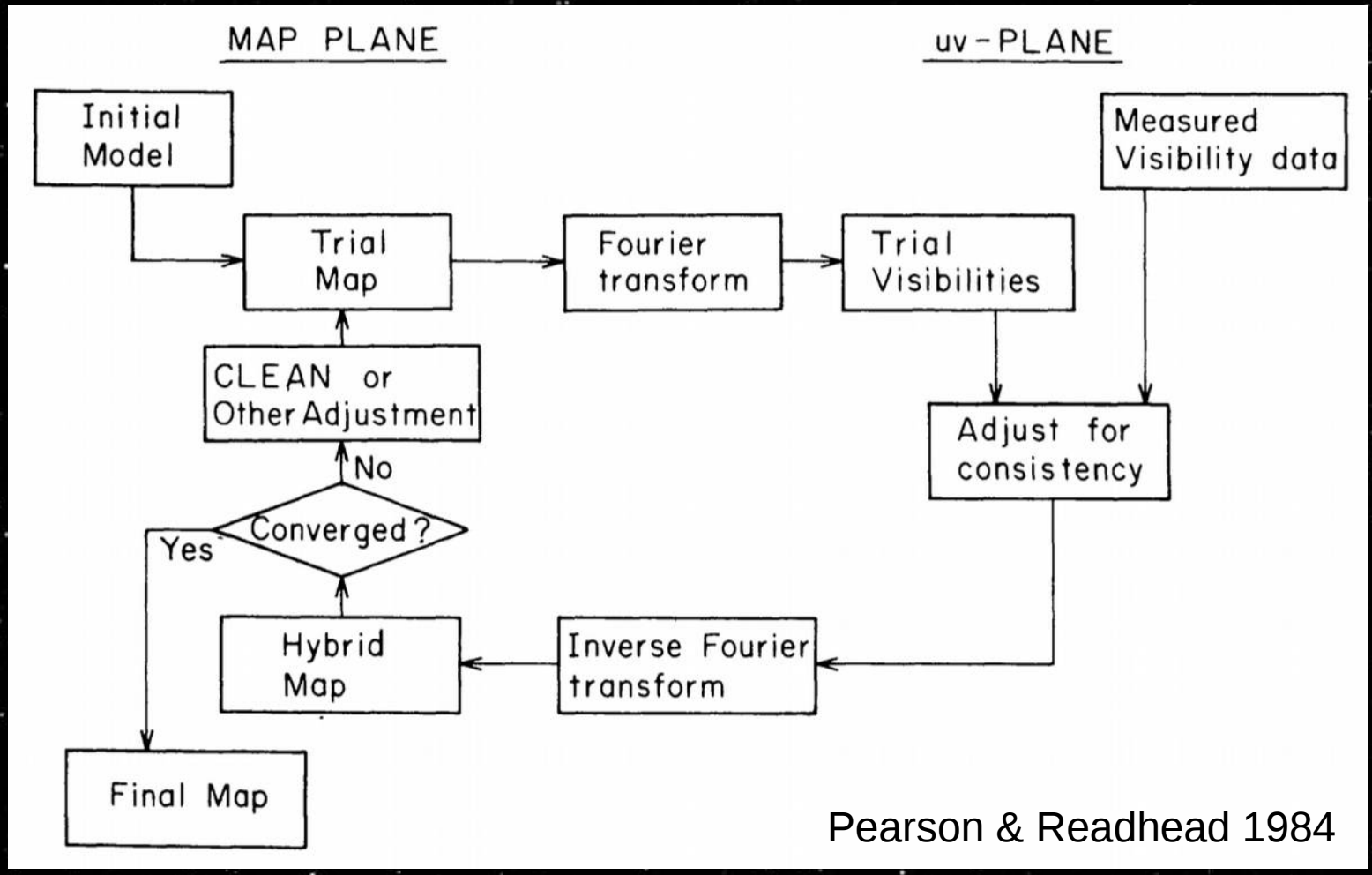
Self-calibration !



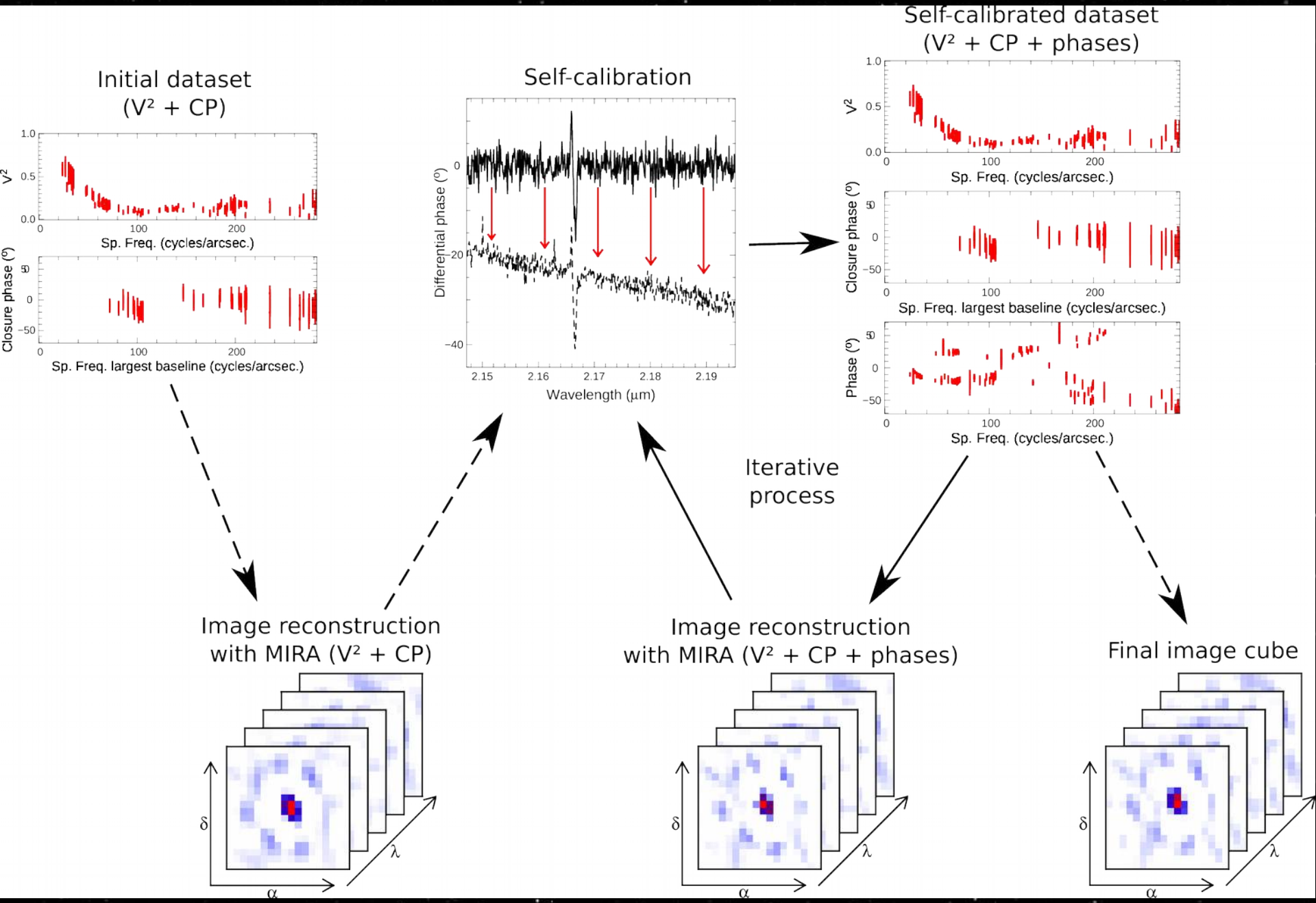
Pearson & Readhead 1984

More stuff

Self-calibration !

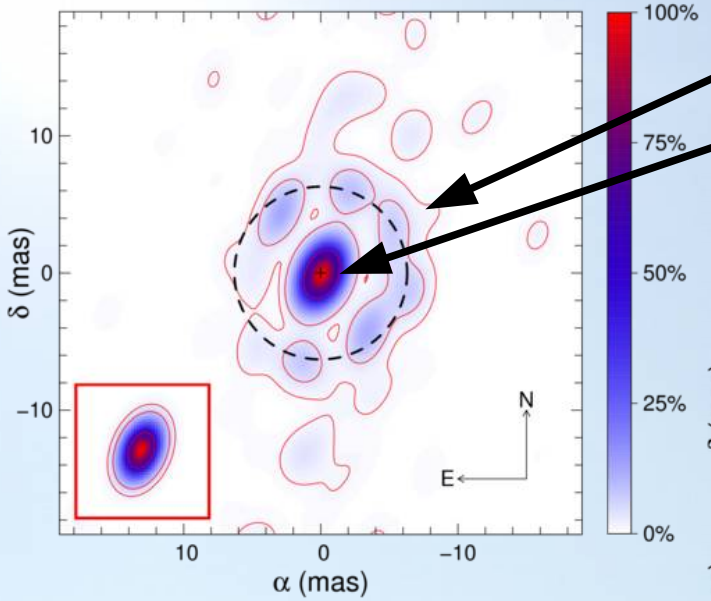


Pearson & Readhead 1984


Initial dataset
(V² + CP)
V²
Sp. Freq. (cycles/arcsec.)
Closure phase (°)
Sp. Freq. largest baseline (cycles/arcsec.)
Self-calibration
Differential phase (°)
Wavelength (μm)
Self-calibrated dataset
(V² + CP + phases)
V²
Sp. Freq. (cycles/arcsec.)
Closure phase (°)
Sp. Freq. largest baseline (cycles/arcsec.)
Phase (°)
Sp. Freq. (cycles/arcsec.)
Iterative
process
Image reconstruction
with MIRA (V² + CP)
Image reconstruction
with MIRA (V² + CP + phases)
Final image cube
δ
α
λ

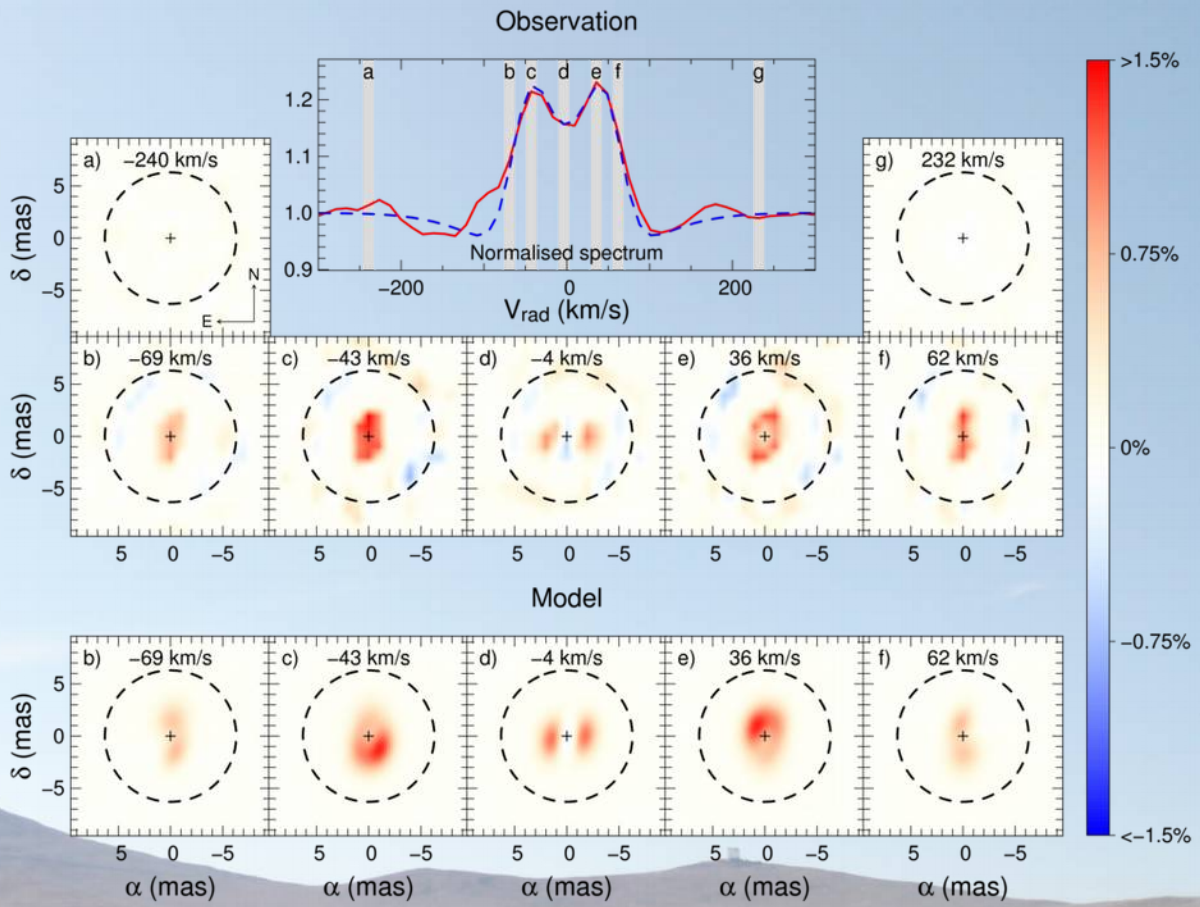
Test-case 1 (HD62623)

3 Pup : étoile supergéante A[e]



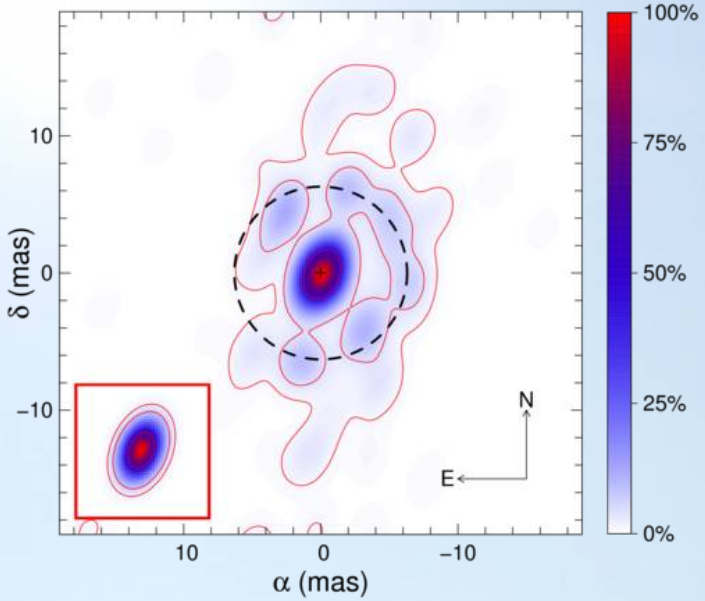
- Poussière (anneau interne de sublimation)
- Gaz (disque proche de l'étoile)

Détection des disques de poussières et de gaz



Test-case 1 (HD62623)

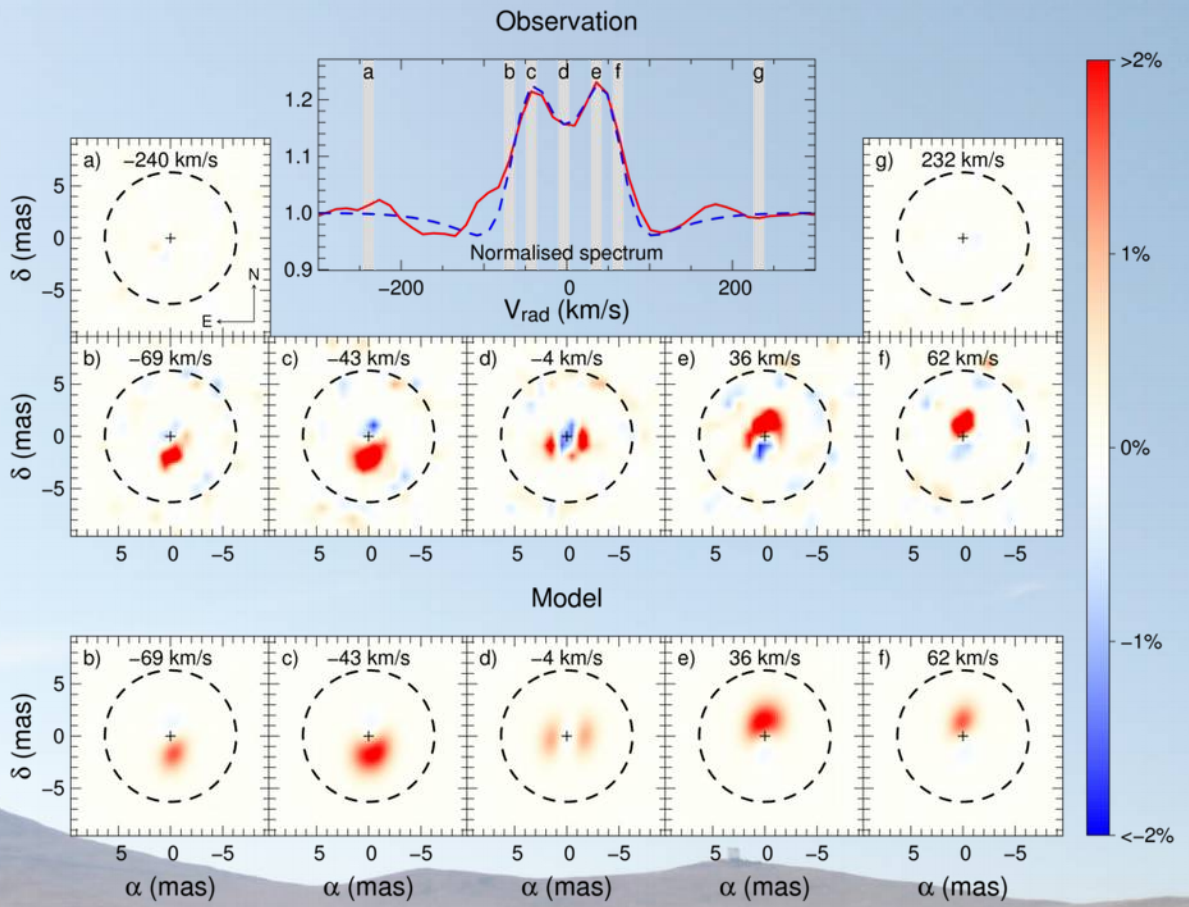
3 Pup : étoile supergéante A[e]



Cinématique des disques
de poussières et de gaz

Millour et al. 2011

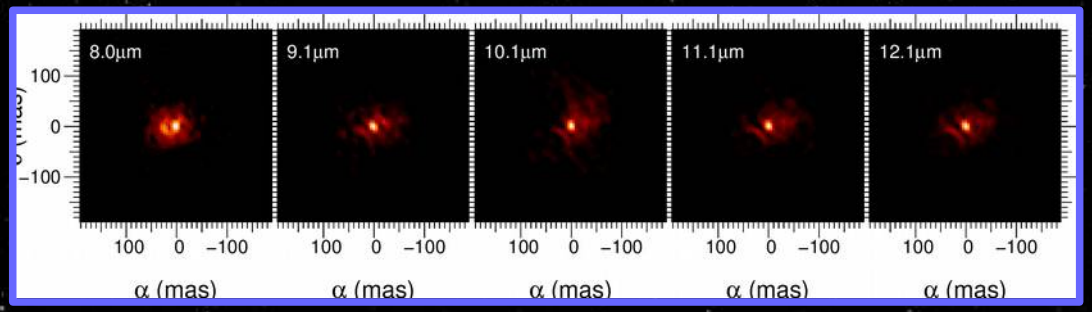
"self-calibration" : phases différentielles dans la reconstruction d'images



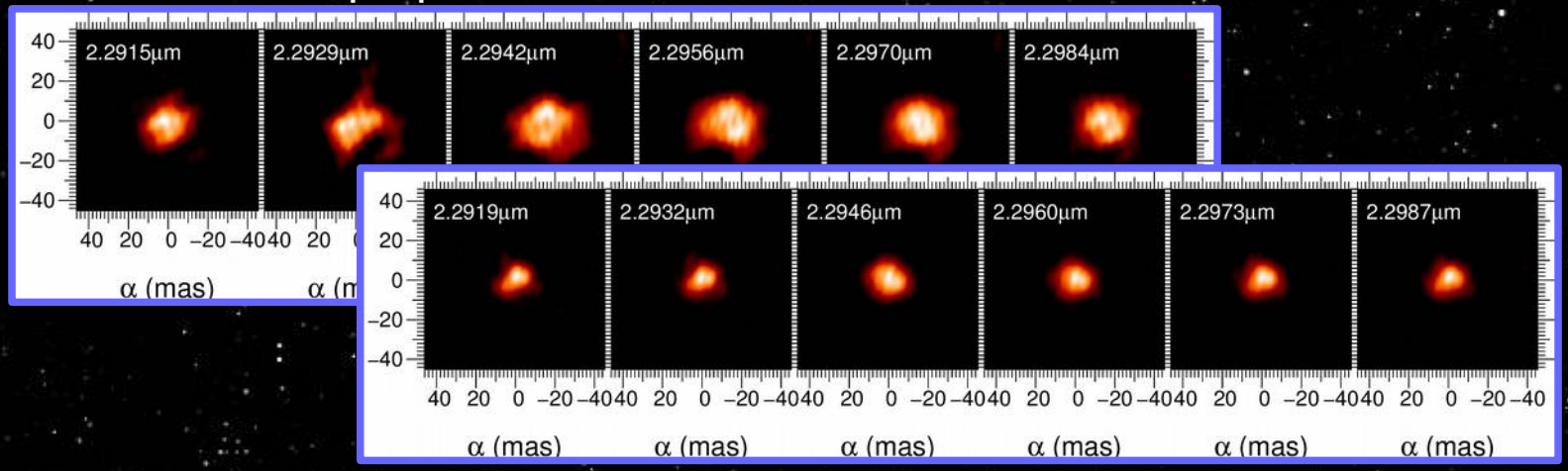
More stuff

Self-cal
More objects

Test on Circinus data



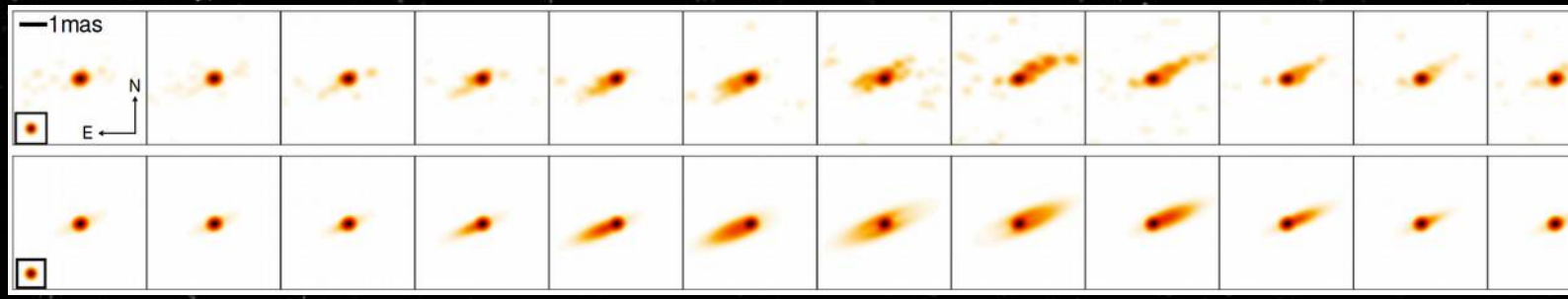
Fabas et al. In prep. Molecular shells around AGB stars



Mourard et al. 2015 the disk around the Be star Phi Per

Reconstructed image

Model



Back-home message

Phases are important for interferometry

Closure phase → part of the phase information

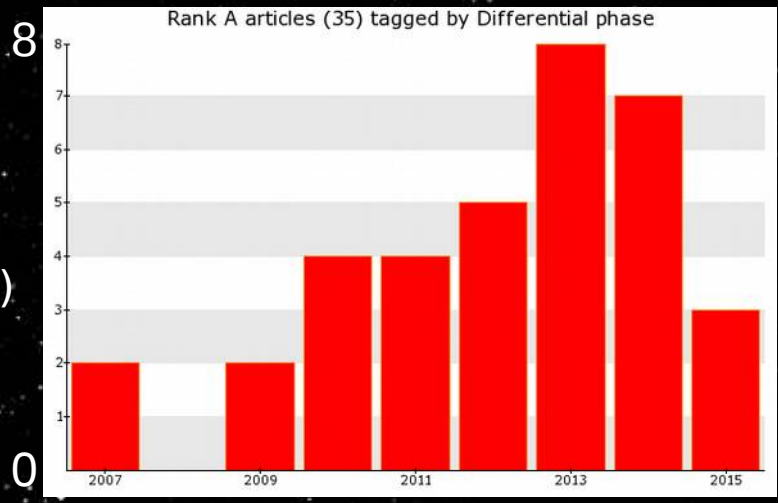
Differential phase → more phase information

There are ways to take differential phases into account

- In model-fitting
  - → fitomatic – Millour et al. 2009
  - → Your model-fitting software :-)
- In image reconstruction
  - → Self-cal – Millour et al. 2011
  - → PAINTER – Schutz et al. 2015
  - → Your image-reconstruction software :-)

You have the future in your hands
(brand new field of studies)

Papers with diff. Phases (bibdb)



2007 2015

http://apps.jmmc.fr/bibdb/

Thank you