2010 VLTI School, April 17-28, Porquerolles Island, France

A M B E R

Overview 1999-2010

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Version 1.1, April 23, 2010

Change record

- This is version 1.1 of the AMBER presentation made at the April 17-28 2010 VLTI school in Porquerolles.
- Change record:
  - Version 1.0 April 21 Talk given at the VLTI 2010 School
  - Version 1.1 April 23 “Hiding” some “submitted for publication” material presented in version 1.0, which cannot be distributed before publication acceptance. It refers to the last results in polychromatic imaging and in very high accuracy closure phase calibration.

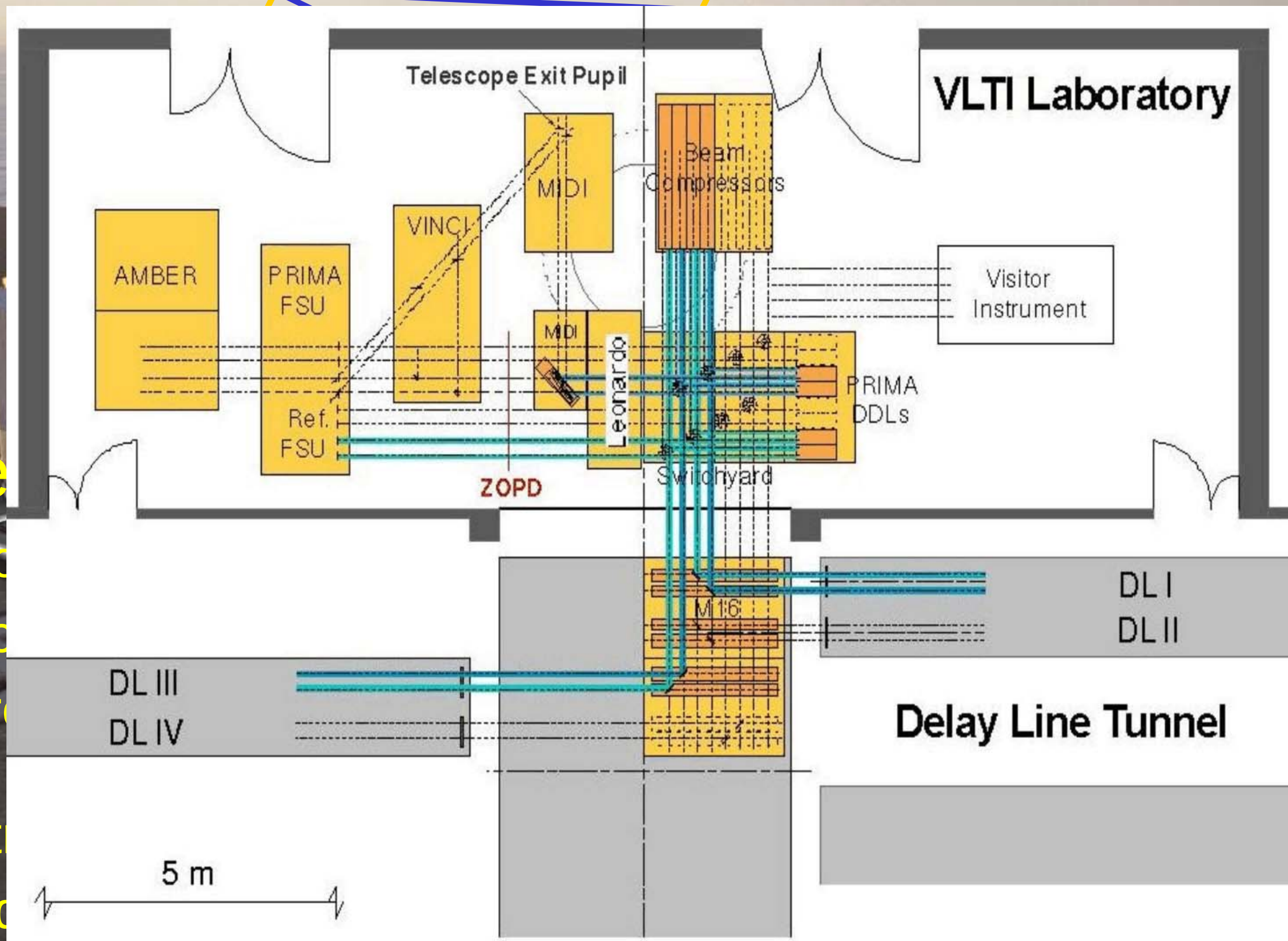
The full version will be restored on the school web site as soon as the publications have been accepted.

Introduction

- History of the project
- AMBER in the VLTI context
- AMBER predecessors
- AMBER description: principle and main features
- AMBER measures and **science result examples**
  - Spectrum
  - Absolute visibility
  - Differential visibility
  - Differential phase
  - Closure phase
- Imaging and model fitting
- Overview of science with AMBER
- Performances: past, present, future.
- AMBER and VLTI frontiers
- AMBER future
- Conclusion and “lessons”

VLTI focal instrument

B_{12}/λ



•Base

•Telesco

•Beam c

•Wavefr
(MACAO)

•Beam t

•OPD ec

ion

n

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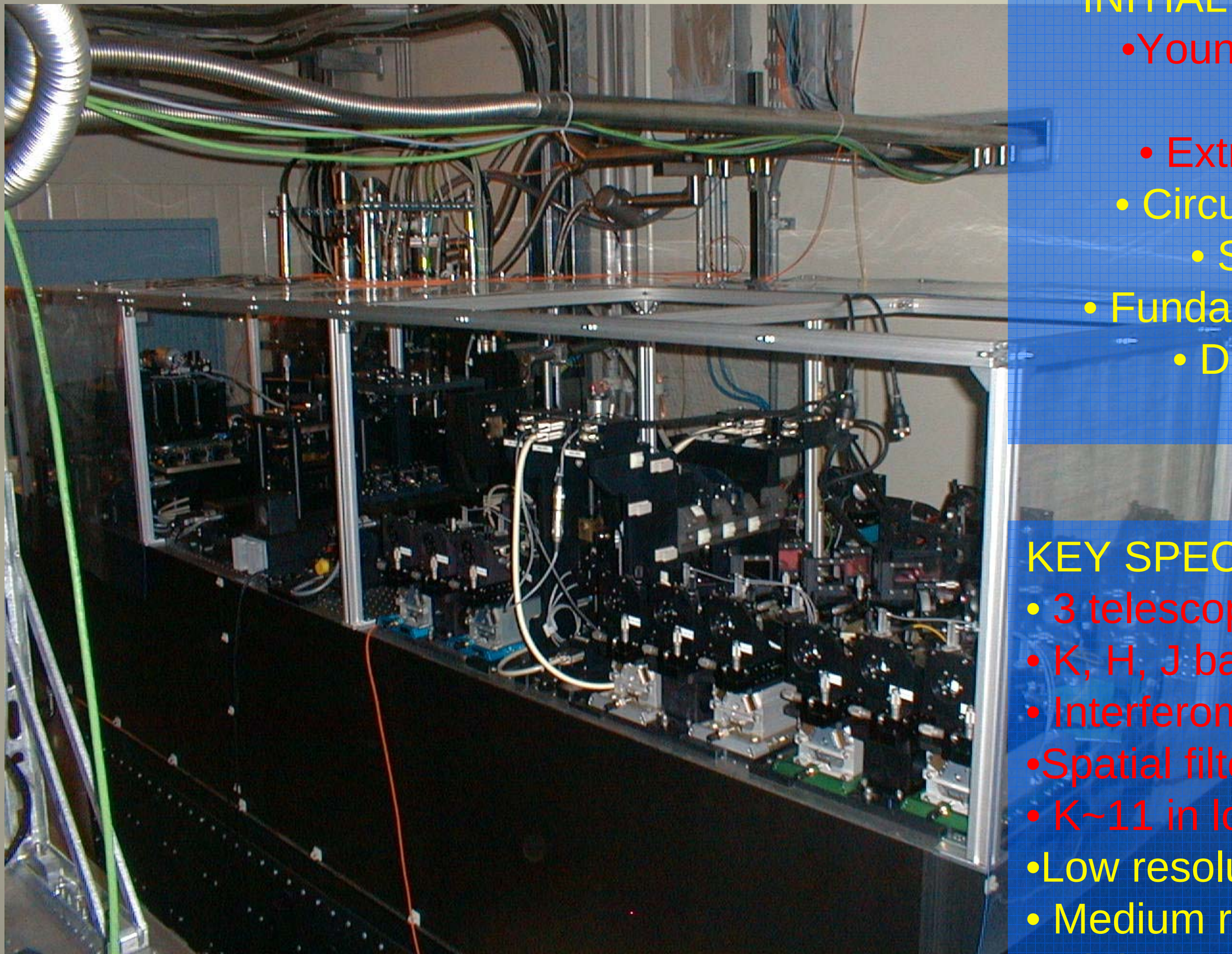
ng

•Absolute metrology

AMBER, near IR VLTI focal instrument



INITIAL SCIENCE GOALS

- Young Stellar Objects
- AGN
- Extra Solar Planets
- Circumstellar material
- Stellar activity
- Fundamental parameters
- Distance scales
- Asteroids

KEY SPECIFICATIONS

- 3 telescopes
- K, H, J bands
- Interferometry + Spectroscopy
- Spatial filtering
- K~11 in low resolution
- Low resolution: 35
- Medium resolution: 1500
- High Resolution: 12 000

Key dates

- 1996-1999: Setting up the project
  - 1996-1997: French working group on **3T IR+Visible Instrument for the VLTI**
    - 3T, AO in focal laboratory (visible with ATs, IR with UTs)
    - Spatial filtering + spectroscopy in J+H+K and R.
  - 1997: VLTI instrumentation meeting in Garching
    - Thermal IR instrument, leaded by MPIA, Heidelberg(-> MIDI)
    - Test/Demonstration instrument (-> VINCI)
    - Near IR instrument, OCA (Nice) + LAOG (Grenoble) + MPIfR (Bonn) + OAA (Firenze): international working group.
      - AO in UTs Coudé train (->MACAO)
      - Visible "later"
      - Named "AMBER" (Astronomical Multiple BEam combineR) in 1999
    - Setting up the Consortium
- 2000-2004: Building, testing and delivering AMBER
  - 1999: Concept Design Revue: **3T, JHK, R≈35, ≈1000, ≈10000.** ***(finally: 35, 1500, 12000)***
  - 2000: Preliminary Design Revue, agreements with ESO and between Institutes signed
  - 2001: Final Design Revue
  - 2003: Preliminary Acceptance Europe
  - 2004: Assembly, Integration and Tests in Paranal. **First Fringes**
  - 2005: AMBER offered in MR_K, LR_K with 3UTs in P75
- >2005 Science
  - Commissioning, repairing, improving and using AMBER and the VLTI

A part of interferometric instruments “family”

SOIR

PTI

GI2T

FM DSI

FLUOR

MIDI

VINCI

AMBER

VEGA

PIONER

MATISSE

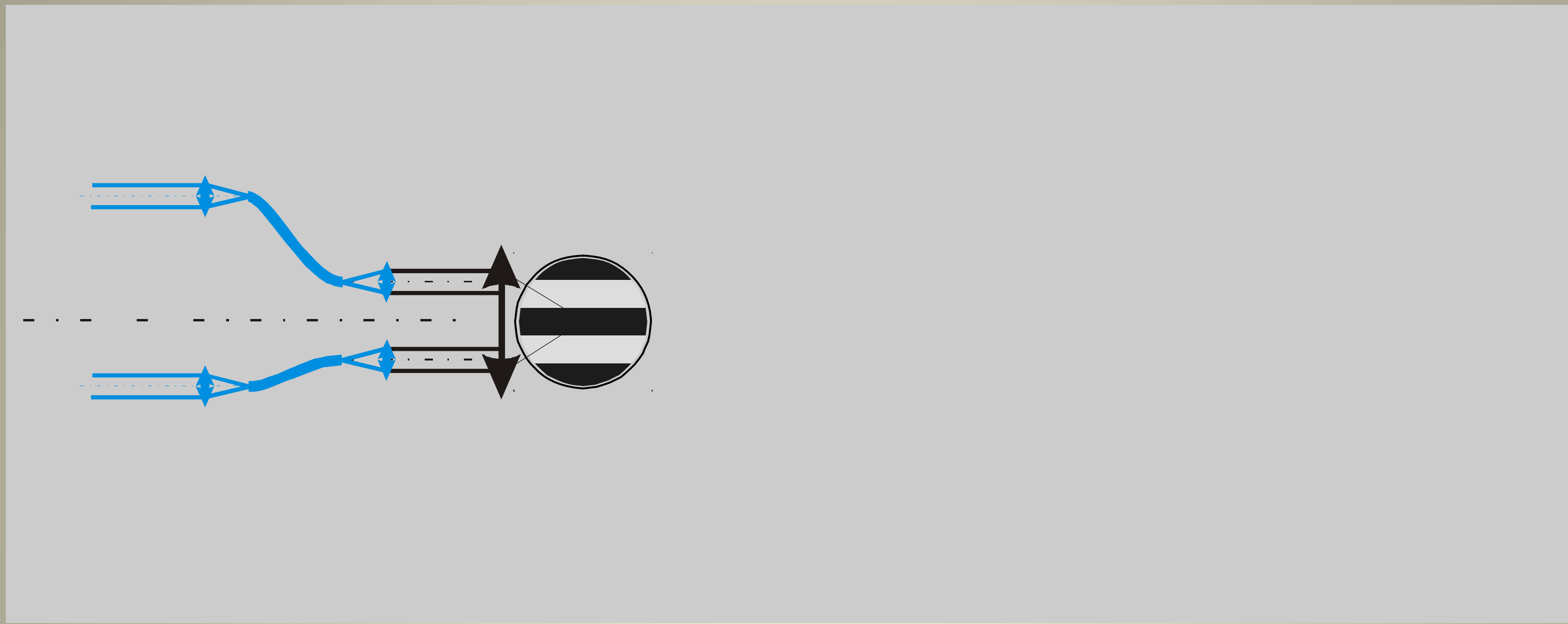
GRAVITY

VSI

Origin of AMBER key features

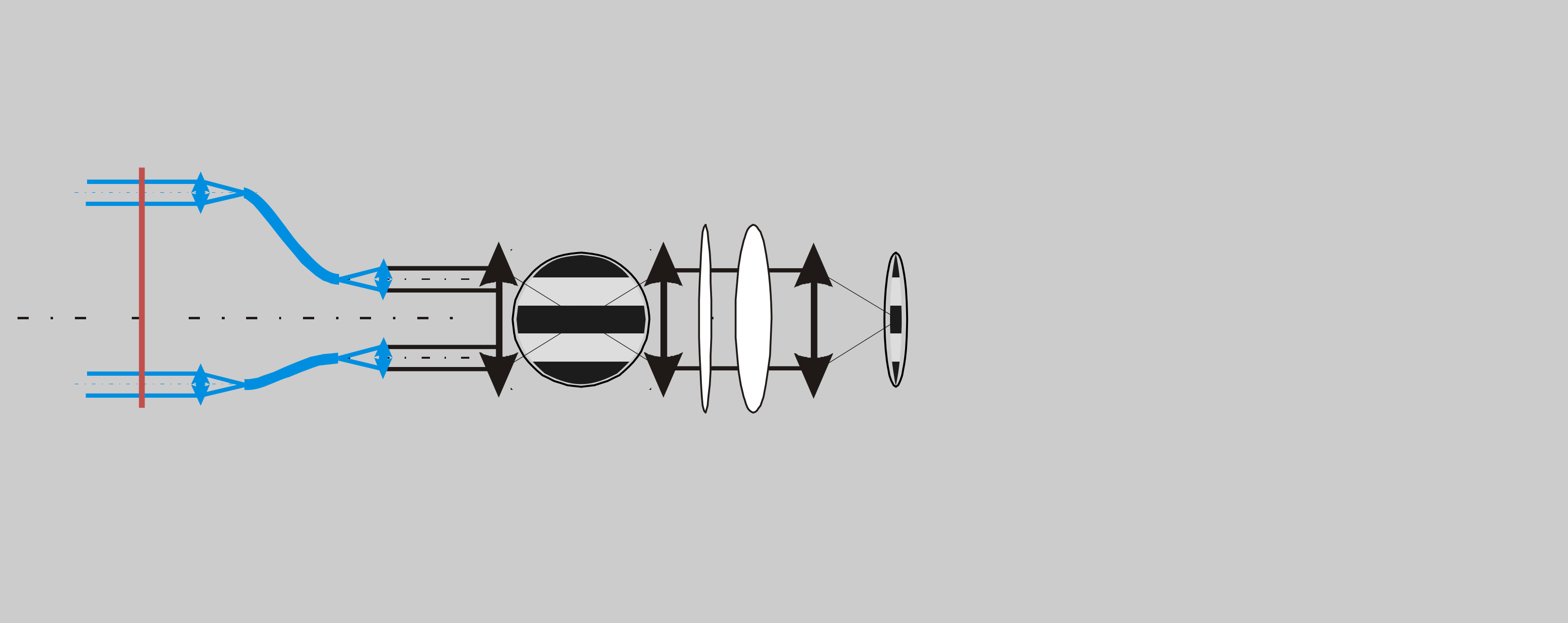
- Single mode instruments
  - FLUOR, VINCI
  - interferometric combination after filtering of each beam by single mode fibers: high accuracy absolute visibility
  - Co-axial instrument
  - Base of VINCI
- Spectro-Interferometry and Differential Interferometry
  - I2T, GI2T, Differential Speckle Interferometry...
  - Multi axial fringes on spectrograph slit
  - Piston from slope of fringes
  - Spectrally resolved HAR information
  - Polychromatic interferometry: use spectral information/spectral variation of spatial frequency in data processing, model fitting, image reconstruction
  - Super resolution
- ABCD algorithms
  - PTI used ABCD algoritms.
  - AMBER P2VM approach derives from ABCD algorithms extracting the visibility data directly from the image plane interferogram

AMBER principle



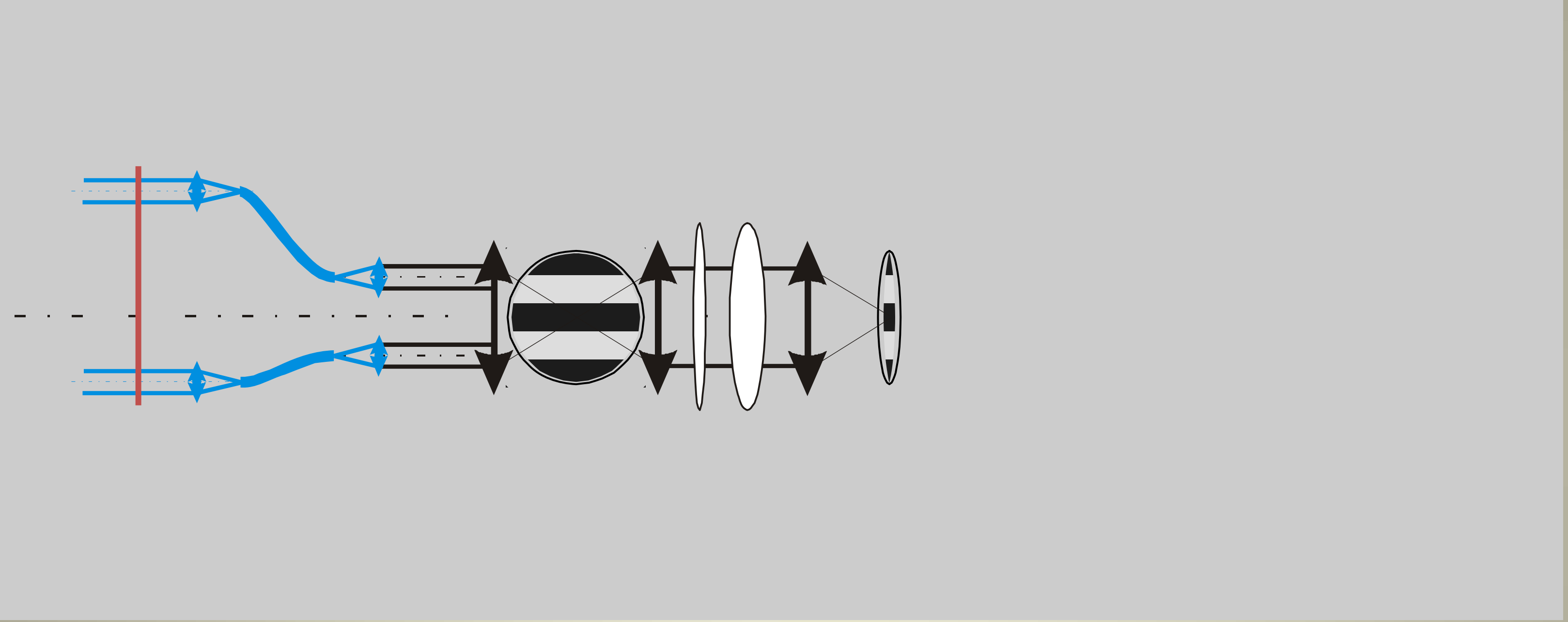
- Spatial filtering
- 2 Telescope multi axial beam combiner

AMBER principle

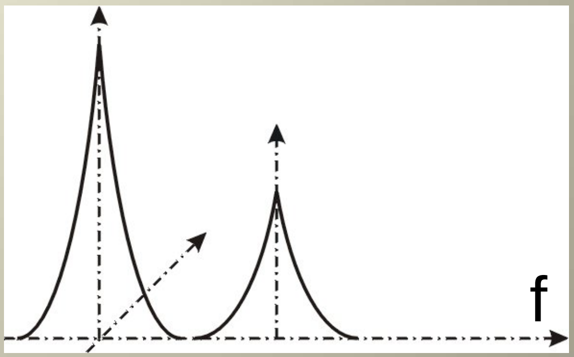


- Spatial filtering
- 2 Telescope multi axial beam combiner with cylindrical optics anamorphosis

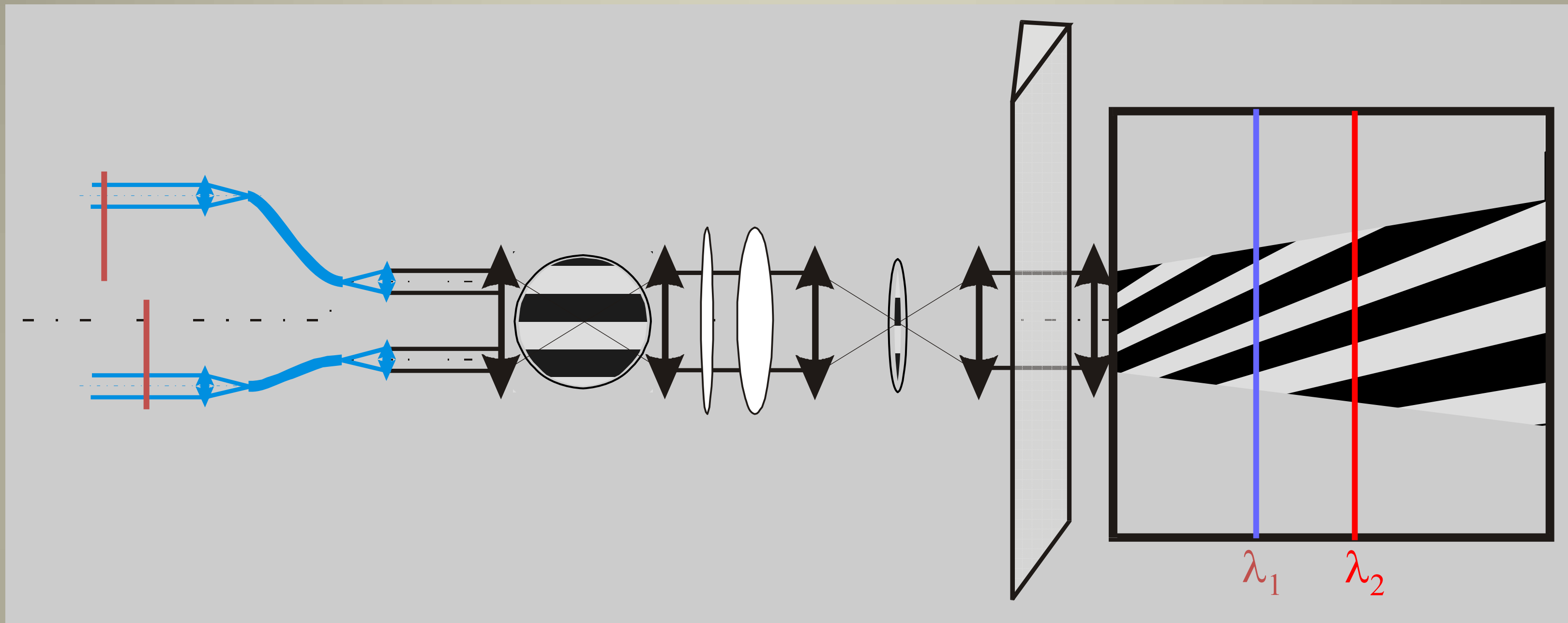
AMBER principle



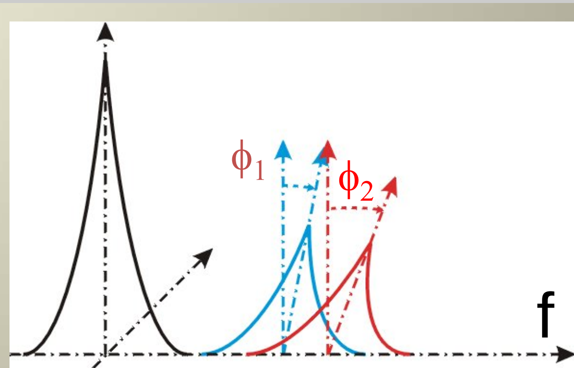
- Spatial filtering
- 2 Telescope multi axial beam combiner with cylindrical optics anamorphosis
- Fringe peak in Fourier interferogram
    - o with with zero piston



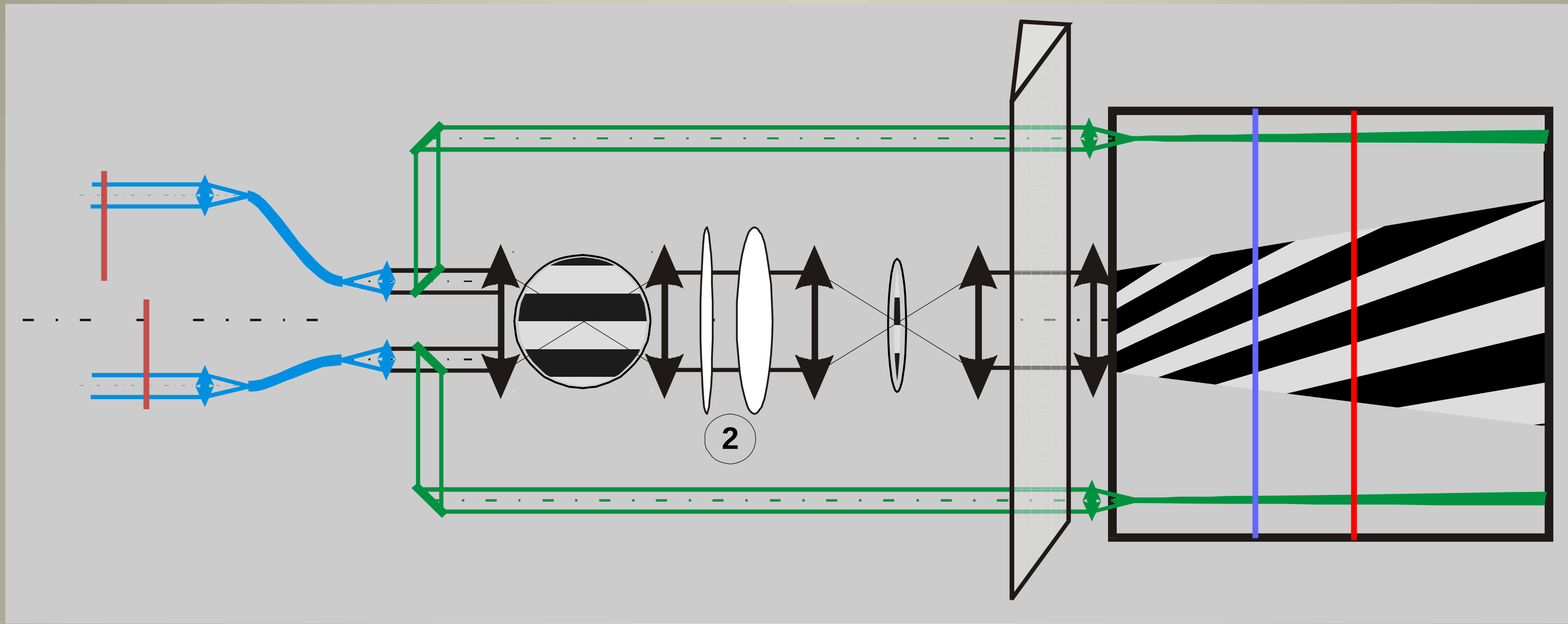
AMBER principle



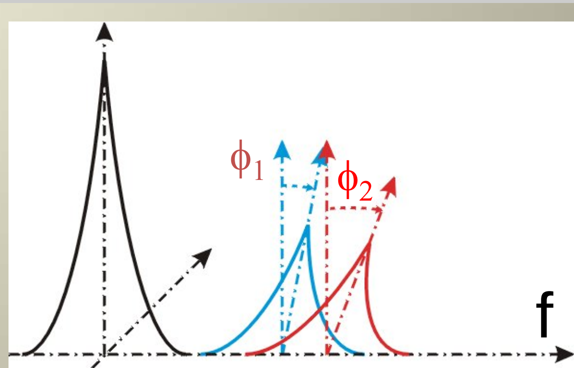
- Spatial filtering
- 2 Telescope multi axial beam combiner with cylindrical optics anamorphosis
- Spectrograph and dispersed fringes
- Differential phase (fringe slope) allows to measure piston.



AMBER principle



- Spatial filtering
- 2 Telescope multi axial beam combiner with cylindrical optics anamorphosis
- Spectrograph and dispersed fringes
- Differential phase (fringe slope) allows to measure piston.
- Photometric monitoring



AMBER principle

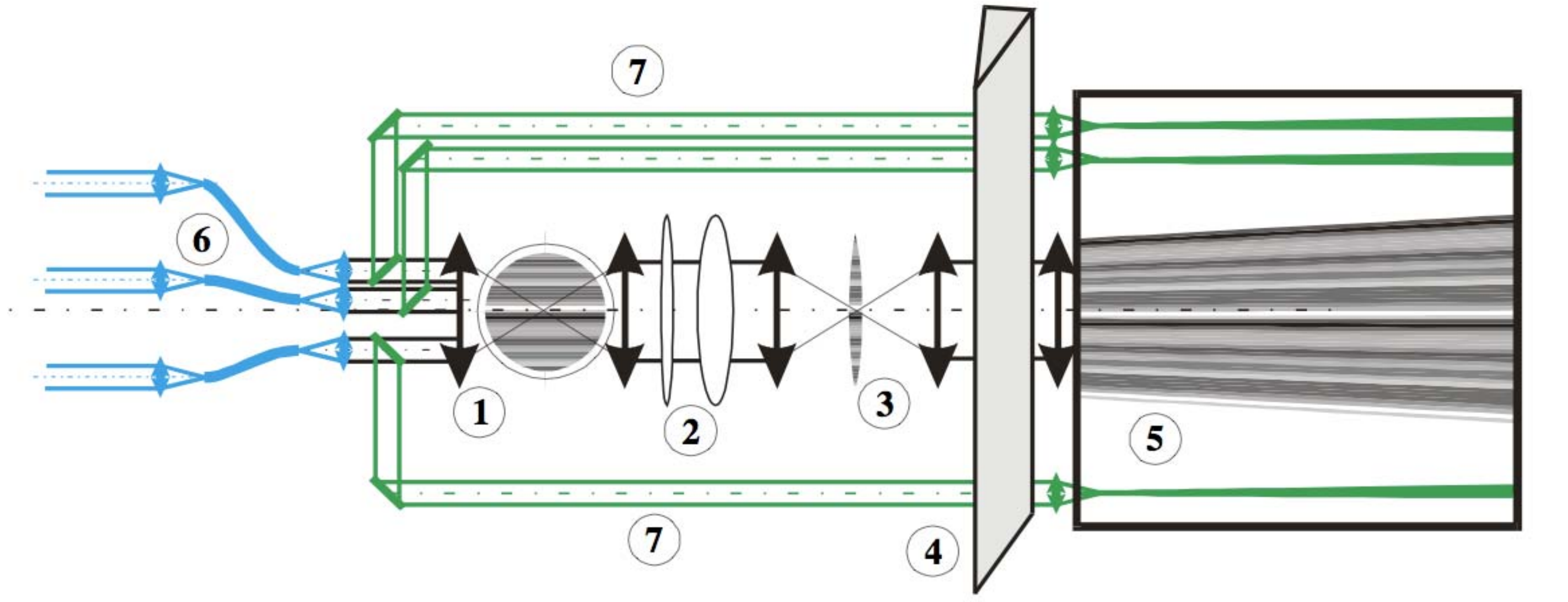
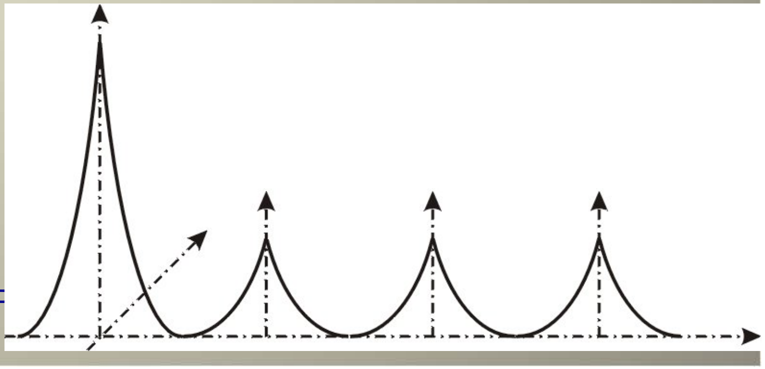


Figure 1: Basic concept of AMBER: (1) multi axial beam combiner. (2) cylindrical optics. (3) anamorphosed focal image with fringes. (4) "long slit spectrograph". (5) dispersed fringes on 2D detector. (6) spatial filter with single mode optical fibers. (7) photometric beams.

- 3 Telescopes implementation with non redundant fringe coding



AMBER principle

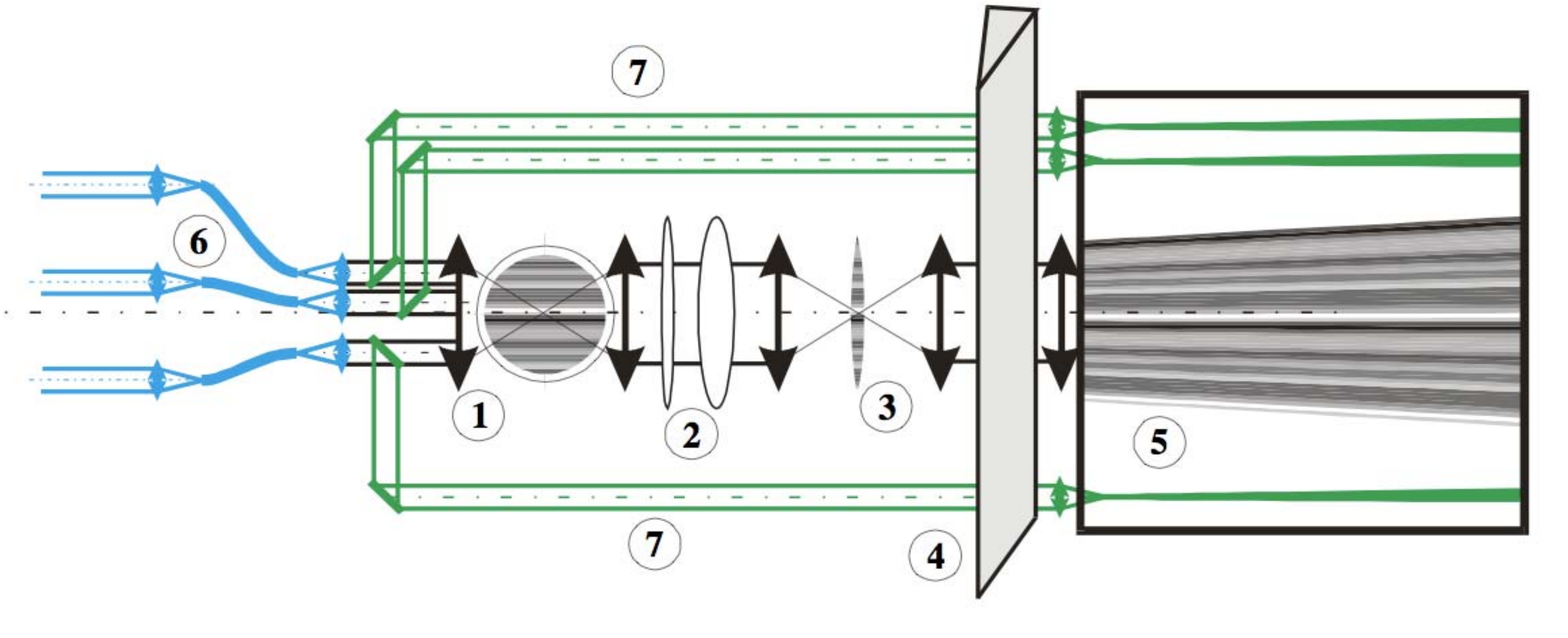
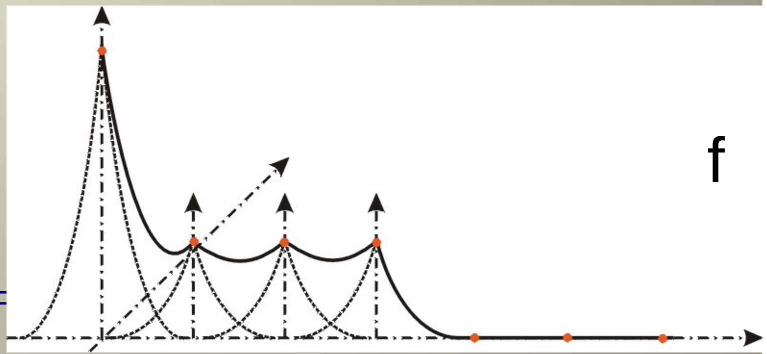
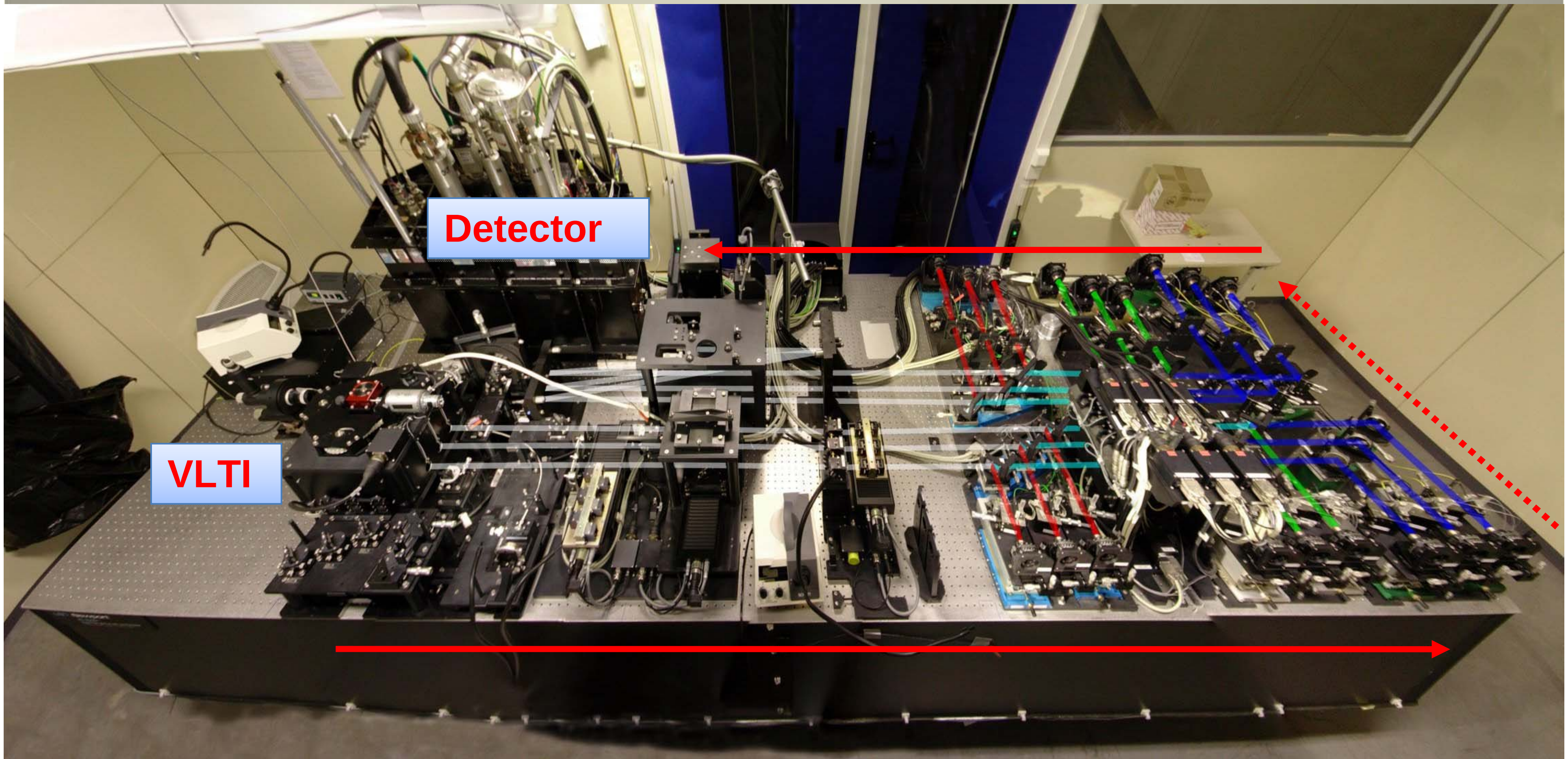


Figure 1: Basic concept of AMBER: (1) multi axial beam combiner. (2) cylindrical optics. (3) anamorphosed focal image with fringes. (4) "long slit spectrograph". (5) dispersed fringes on 2D detector. (6) spatial filter with single mode optical fibers. (7) photometric beams.

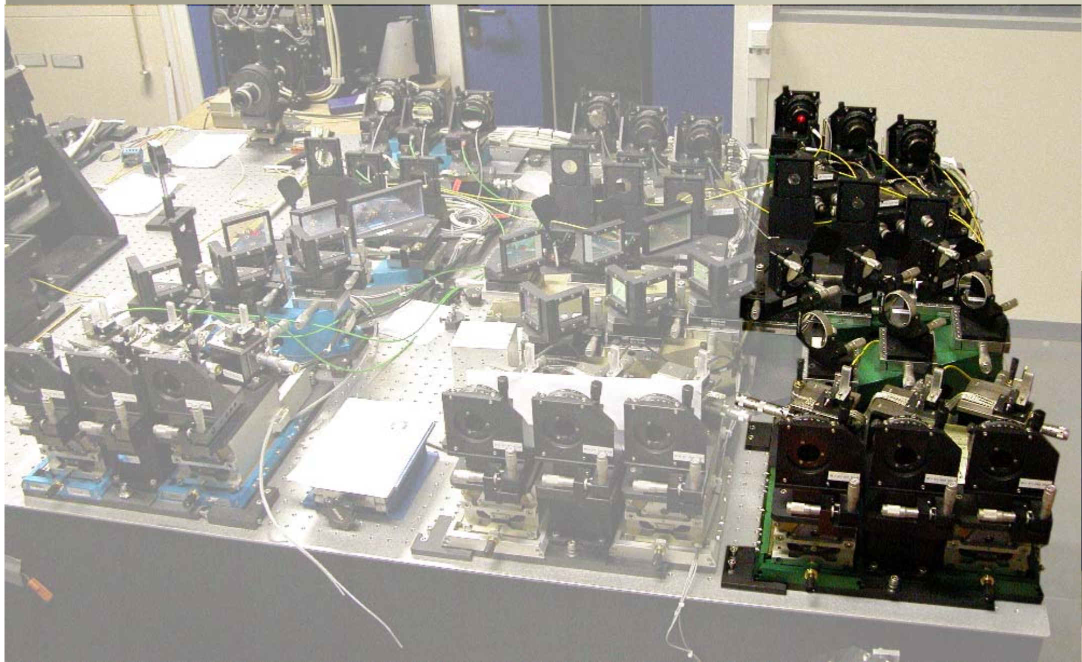
- 3 Telescopes implementation with **compact** non redundant fringe coding



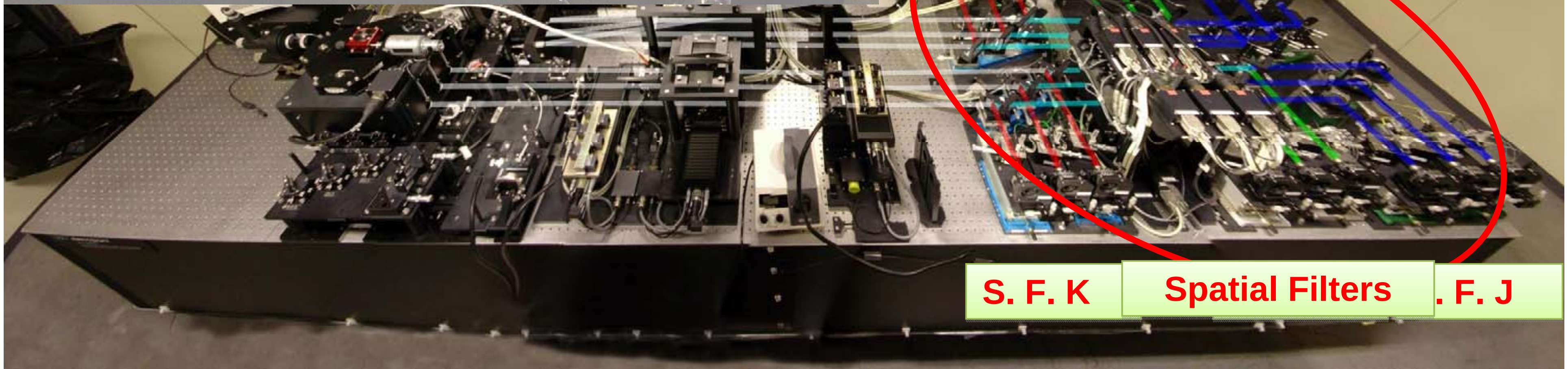
AMBER set up



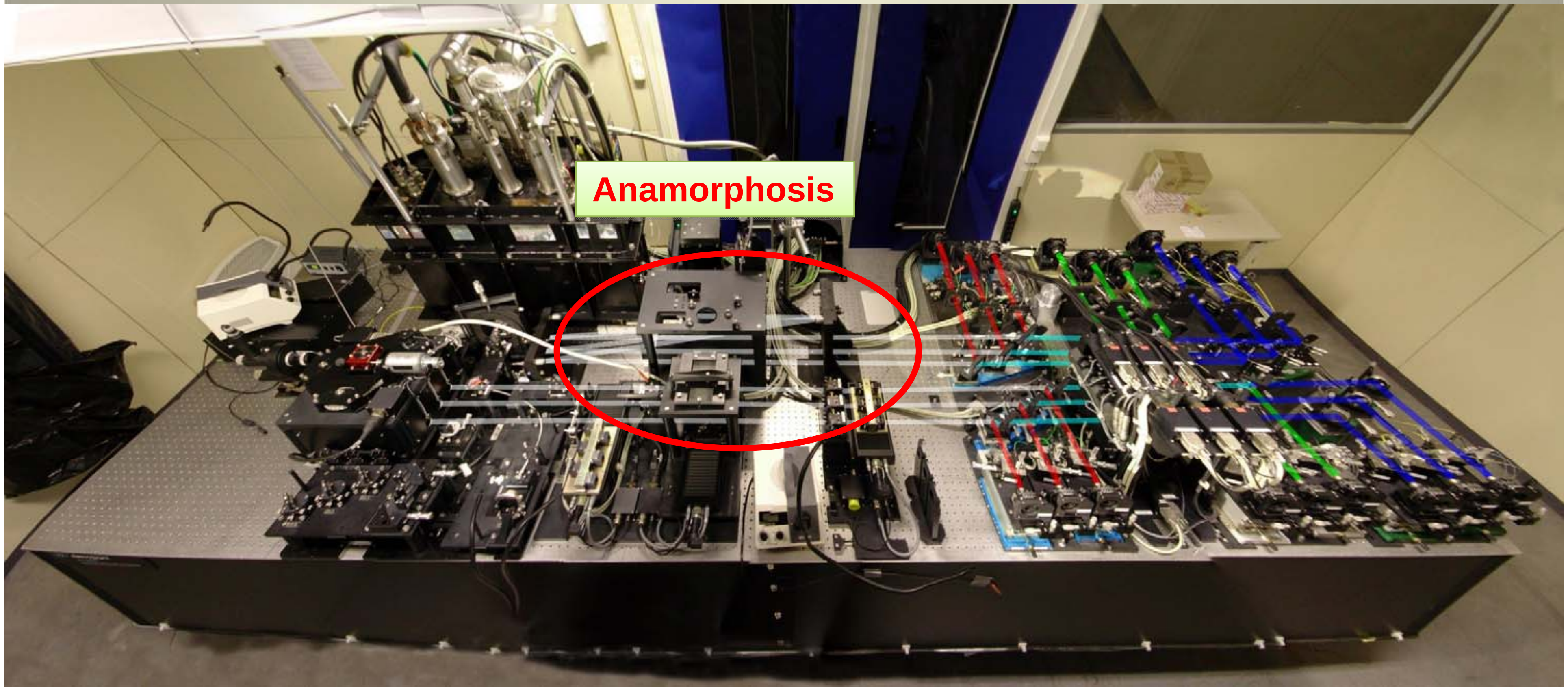
AMBER set up



J (1.1μm), H (1.5mm)
and K (2.1mm) simultaneously

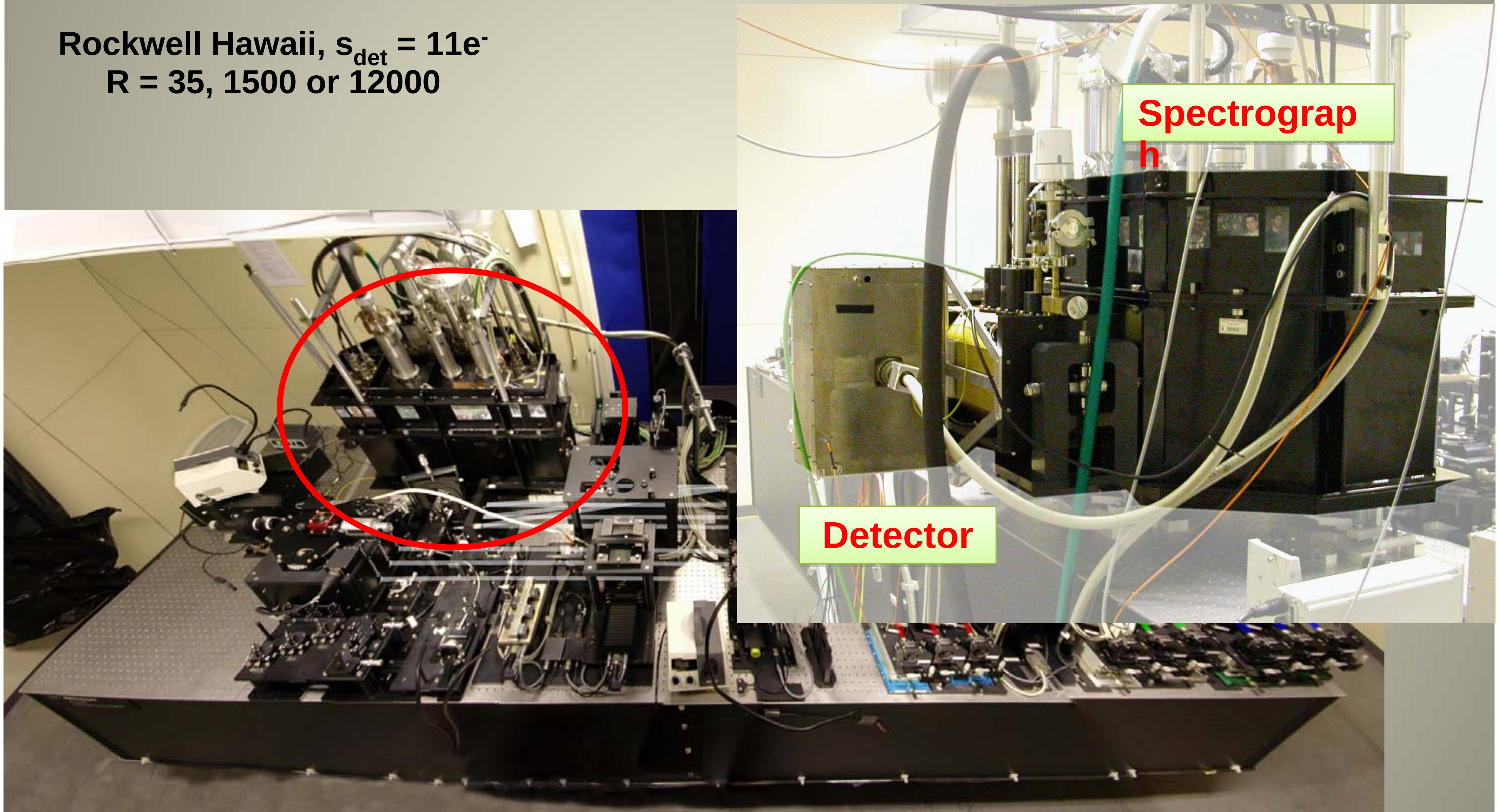


AMBER set up



AMBER set up

Rockwell Hawaii, s_{det} = 11e^{-}
R = 35, 1500 or 12000



AMBER principle

Petrov et al., A&A 2007

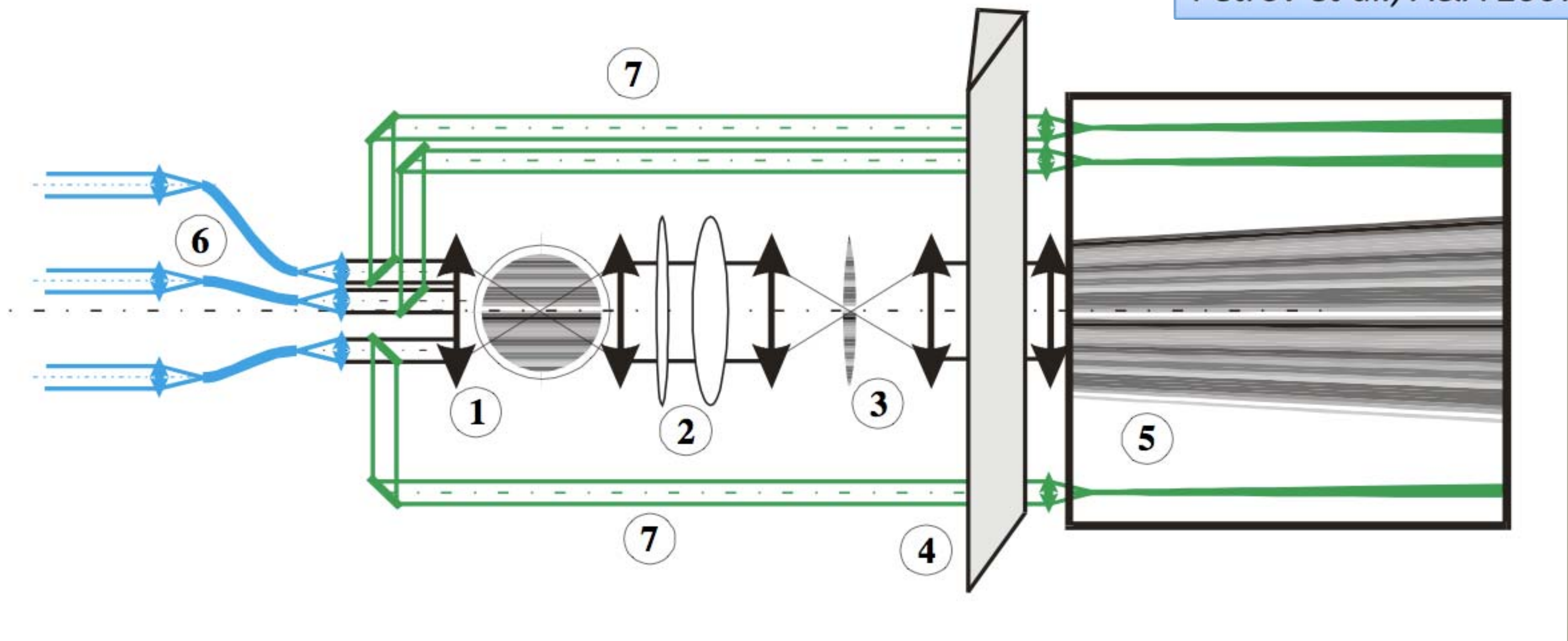
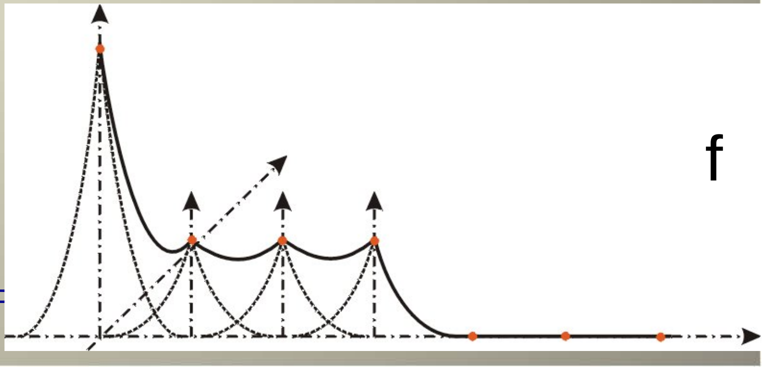
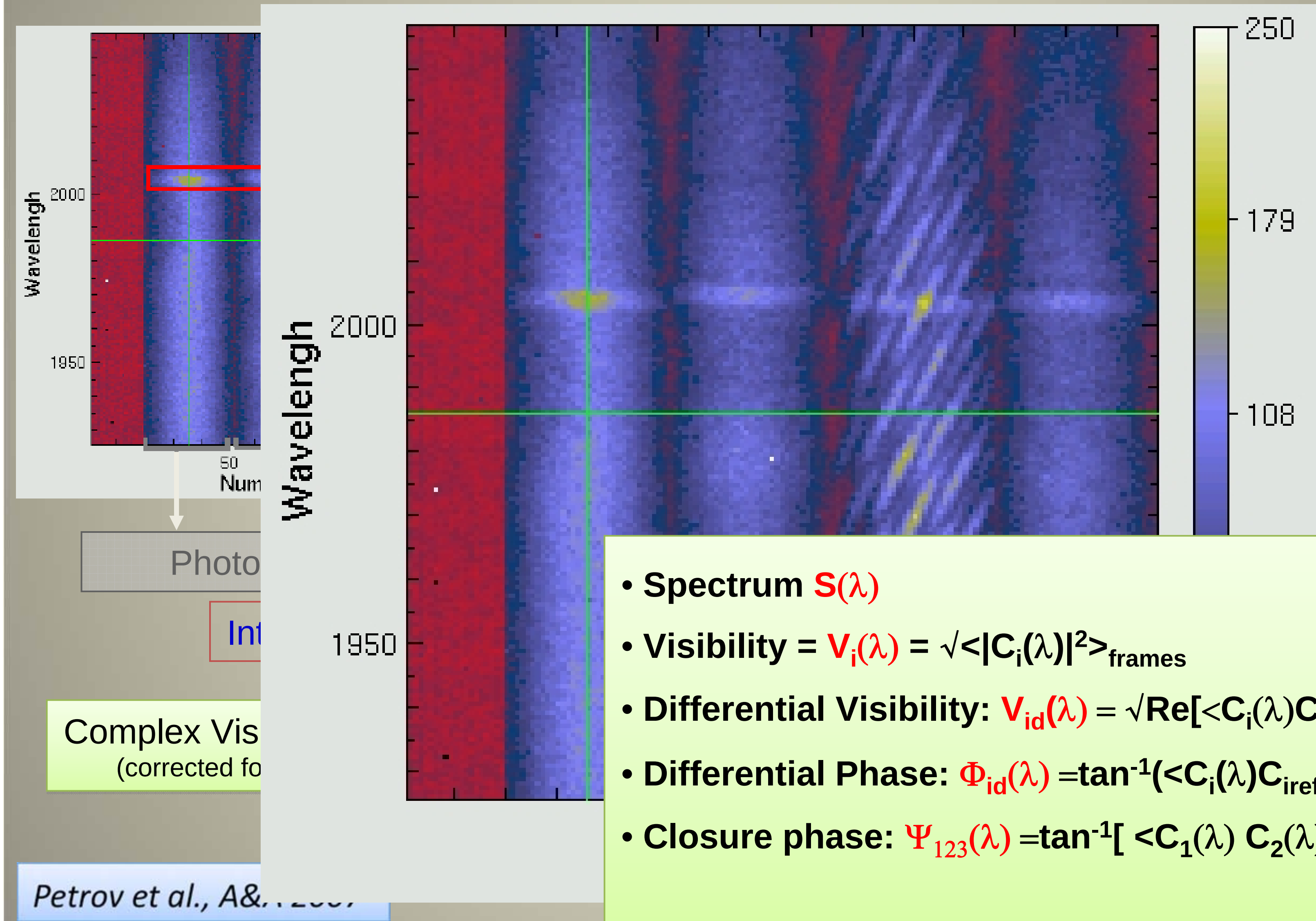


Figure 1: Basic concept of AMBER: (1) multi axial beam combiner. (2) cylindrical optics. (3) anamorphosed focal image with fringes. (4) "long slit spectrograph". (5) dispersed fringes on 2D detector. (6) spatial filter with single mode optical fibers. (7) photometric beams.

- 3 Telescopes implementation with **compact** non redundant fringe coding
- Image plane fringe fit: P2VM (Pixel to Visibility Matrix) algorithm.



AMBER data and measures



- **Spectrum** $S(\lambda)$
- **Visibility** = $V_i(\lambda) = \sqrt{<|C_i(\lambda)|^2>_{frames}}$
- **Differential Visibility:** $V_{id}(\lambda) = \sqrt{\mathrm{Re}[<C_i(\lambda)C_{iref}^*>_{frames}]}$
- **Differential Phase:** $\Phi_{id}(\lambda) = \tan^{-1}(<C_i(\lambda)C_{iref}^*>_{frames})$
- **Closure phase:** $\Psi_{123}(\lambda) = \tan^{-1}[\, <C_1(\lambda)\, C_2(\lambda)\, C_3^*(\lambda)>_{frames}\,]$

AMBER “typical” performances as “guaranteed” by ESO

2.5 AMBER typical performances

These are typical performances in good conditions (seeing of 0.8” with the UTs, 0.6” with the ATs, coherence time of 4ms or better), for targets at least 1 magnitude brighter than the limiting magnitudes and with a standard number of frames taken. Better performances can be obtained in better conditions or by stacking more frames (should be specifically asked), see foot notes [1,2,3,4] for exceptions. “NG” means not guaranteed.

mode	FINITO	calibrated V	diff. ϕ	CP
low HK	not used	10%	NG	5^{o1}
	coherencing	5%	NG	3^{o1}
	cophasing	7%	NG	3^{o1}
medium K	coherencing	5%	2^{o}	4^{o}
	cophasing	5%	1^{o}	2^{o}
medium H	any mode[3]	5%	2^{o2}	4^{o2}
high K	cophasing	5%	1^{o}	2^{o}

[1] The closure phase error in low resolution is dominated by systematics, namelly a strong dependency of the closure phase with the piston (fringes’ phase shift, or OPD shift). We believe is is not possible to reach a better precision, even by stacking frames.

[2] The medium H band phase products suffer from systematics not understood at the moment.

[3] Usually, the use of the fringe tracker biases the calibrated visibility. The main source of bias when using the fringe tracker is when a jump of one fringe does not correspond to a jump of one fringe in the science channel. FINITO operates in the H band, hence AMBER H band data collected using FINITO in cophasing are much less biased than medium K data.

ESO, AMBER user manual v86

Spectrum

- Under looked in AMBER and AMBER/DRS users documents ?
  - Each science user makes its own calibration
- Use spectral calibrators in accurate wavelength calibration is needed
- Seek complementary spectroscopic data
- Sub pixel accuracy but complaints
  - LR: half pixel, i.e. about 1%, not enough for spatial frequency measure
  - MR: 50-100 Km/s on telluric lines
  - HR: 8-12 Km/s when many telluric lines available
- Calibrating λ is also calibrating spatial frequency B/λ

One absolute visibility measure

Visibility Error in 0.03 to 0.05 range, can reach 0.1

4 M. Benisty et al.: The complex structure of the disk around HD 100546

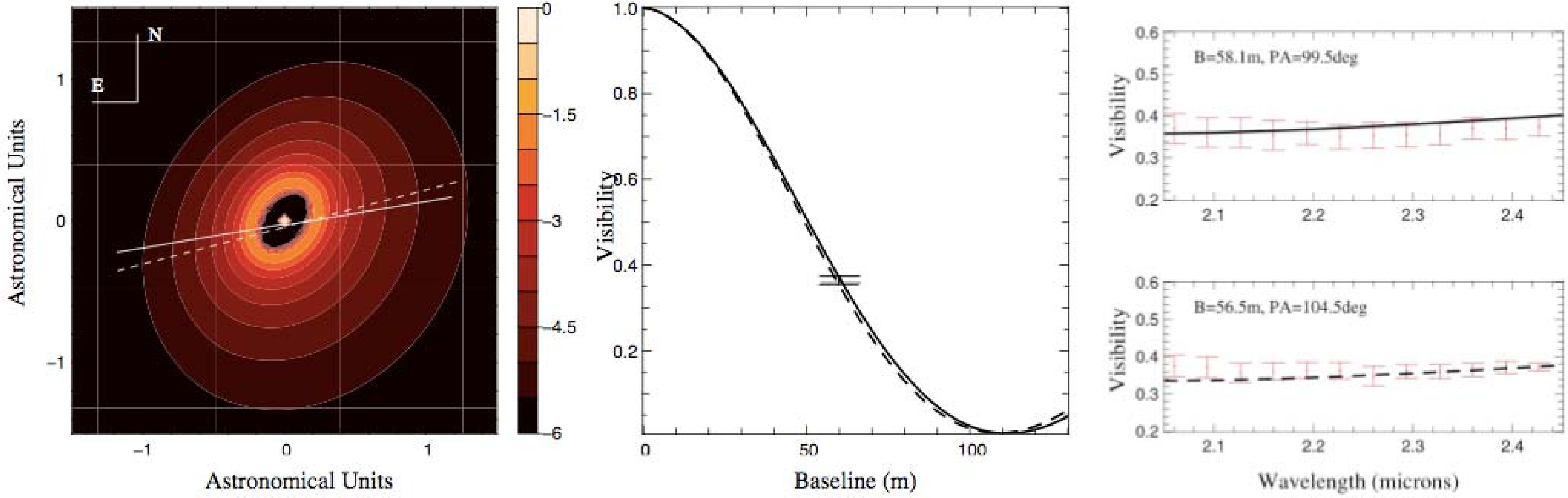


Fig. 2. Left: K-band model image of HD100546. The full and dashed lines indicate the position angles of the observations (PA = 99.5° and PA = 104.5°, respectively). Middle: model visibilities, as a function of baseline length. The broad band K-band AMBER visibilities are overplotted. Right: spectrally dispersed AMBER visibilities versus wavelength, for both measurements (upper and lower pannels respectively). The spectral profiles of the model visibilities, as derived from our best model, are added.

Benisty et al., A&A 2010

Accurate absolute visibilities

- Select data sets “insensitive” to data selection (with ATs, vibrations might affect only one station, and not all the time; with UTs the situation is time variable)
- Observe in good seeing conditions

It is possible to have σ_V<0.01.

Ohnaka et al., A&A 2009

K. Ohnaka et al.: Spatially resolving the inhomogeneous atmosphere of Betelgeuse 189

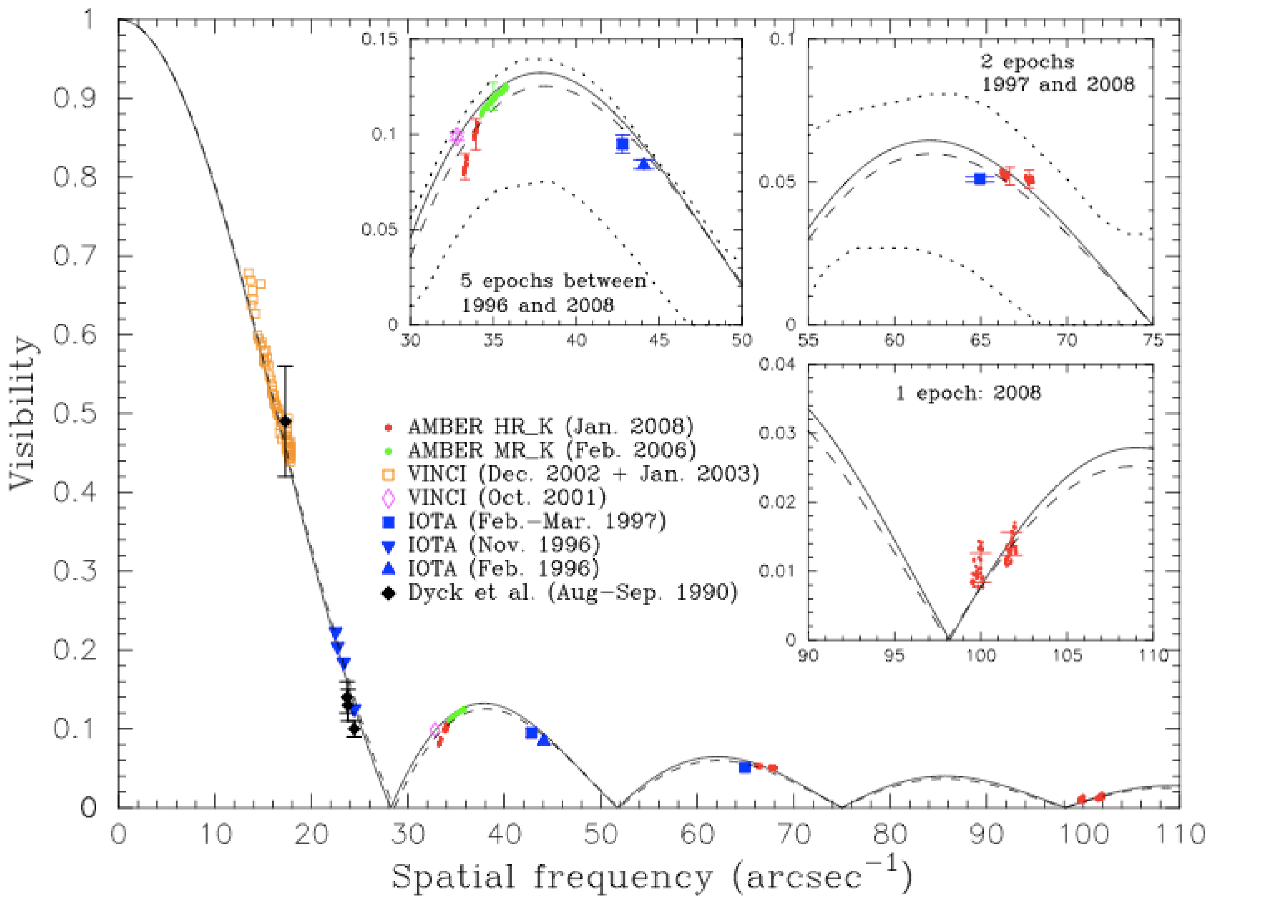
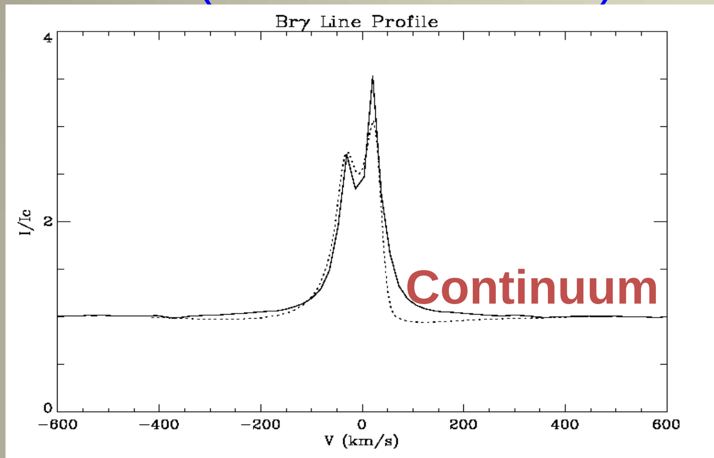
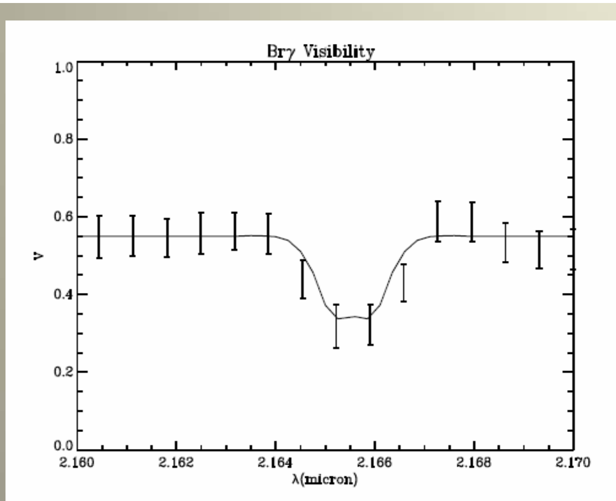


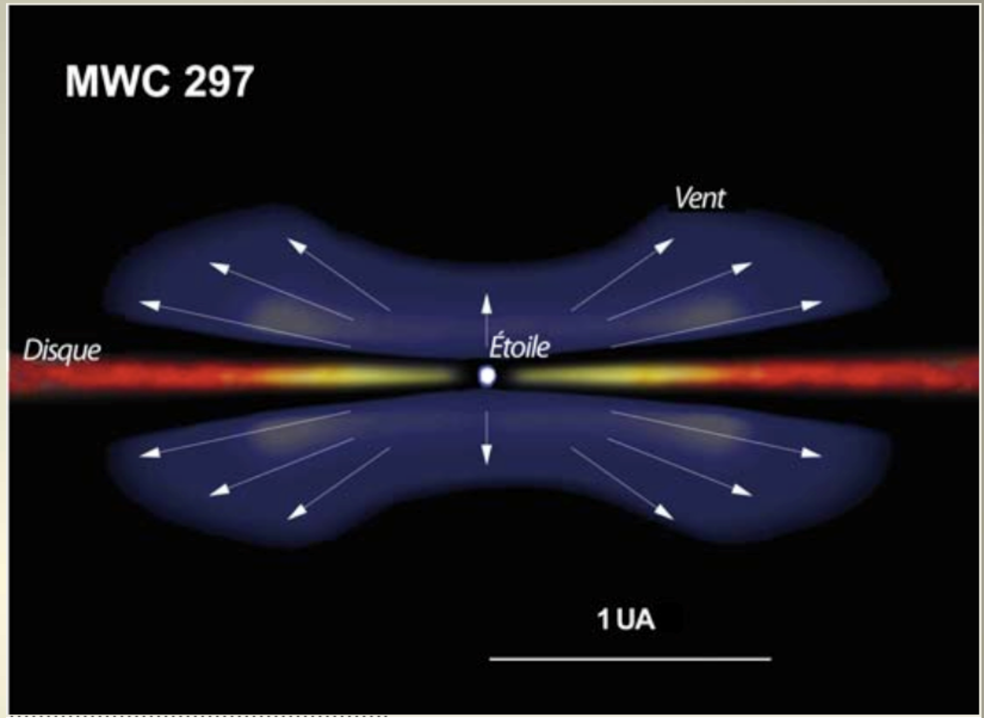
Fig. 2. *K*-band continuum/broadband visibilities of Betelgeuse plotted as a function of spatial frequency. The insets show enlarged views of the second, third, and fifth lobes. The error bars of the single AMBER data points are exemplarily shown in the insets. The errors of the VINCI and IOTA data are also shown in the insets. The solid and dashed lines represent the visibilities for a uniform disk with a diameter of 43.19 mas and for a limb-darkened disk with a diameter of 43.56 mas and a limb-darkening parameter of 0.12 (power-law-type limb-darkened disk of Hestroffer 1997), respectively. The dotted lines represent the full amplitude of the variations in the 2.22 μm visibility due to time-dependent inhomogeneous structures predicted by the 3-D convection simulation of Chiavassa et al. (2007).

One Differential Visibility in line: MWC 297

(first science result)







Photospheric density	$1 \pm 0.5 \times 10^{12}$ cm^{-3}
Equatorial rotational velocity	400 ± 50 km s^{-1}
Polar terminal velocity	600 ± 50 km s^{-1}
Terminal velocity above disk	70 ± 20 km s^{-1}
Polar mass flux	$3.2 \pm 0.2 \times 10^{-9}\ M_\odot$ yr^{-1}
C_1	0.25 ± 0.05
m_1	30 ± 10
m_2	10 ± 2
Inclination angle (i)	$25 \pm 5°$

Malbet et al., A&A 2007

Differential visibility in continu

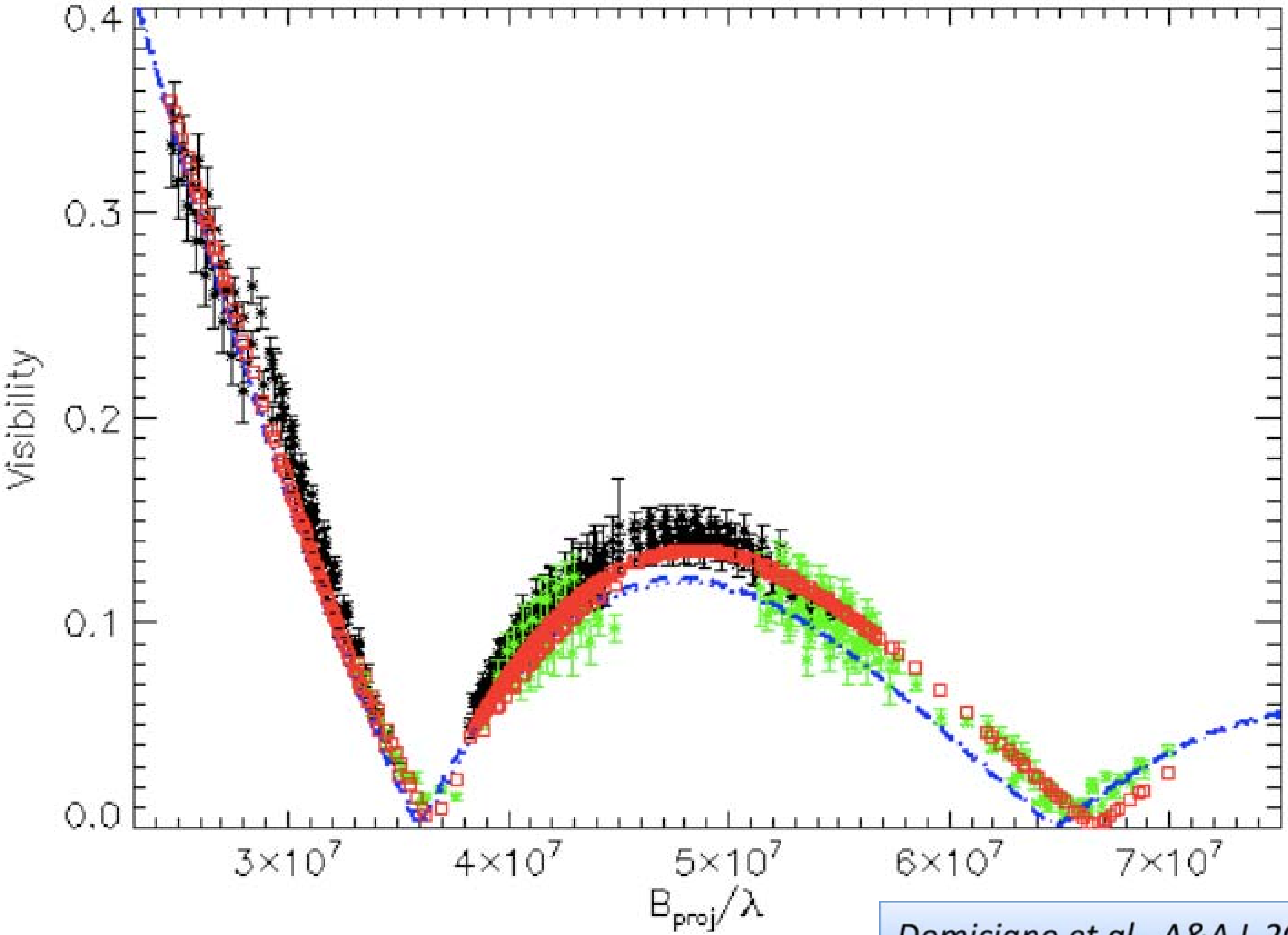
• Variation o with λ

• Increased

• Very accur measureme

Φ=6.9

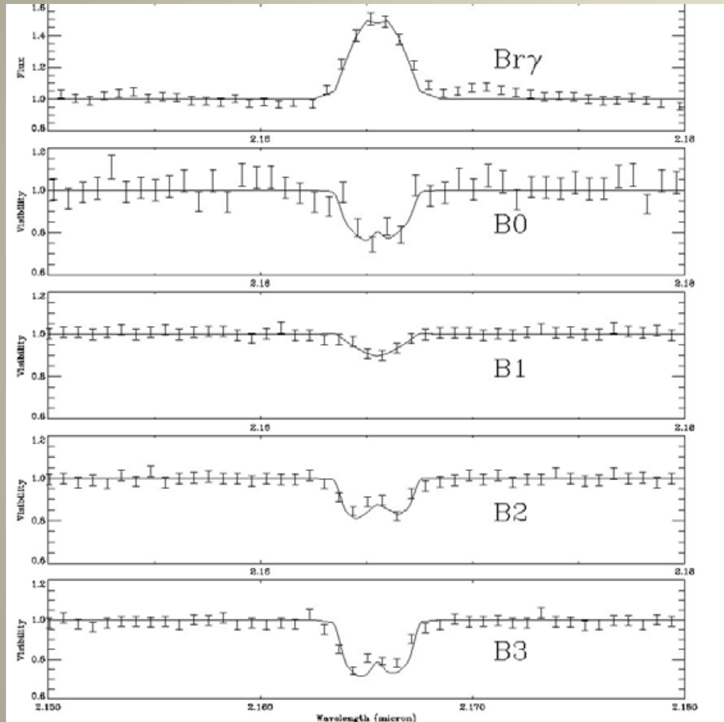
•Detection c



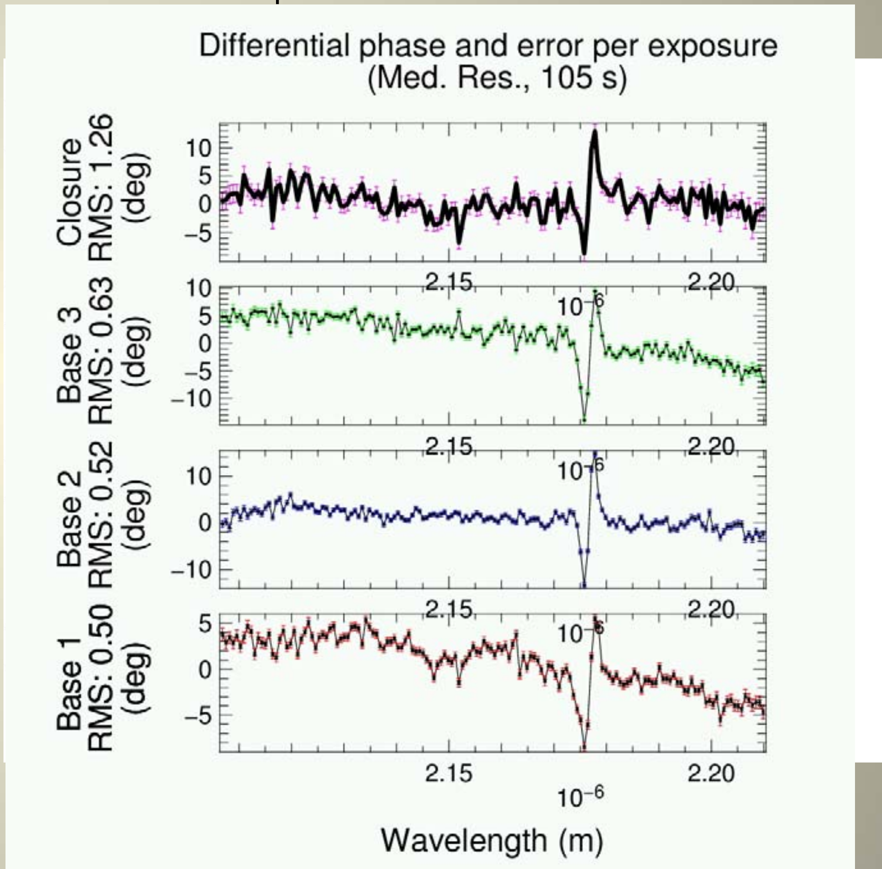
Domiciano et al., A&A L 2008

Differential visibility and phase in line
The classical Be star α Arae

The classical Be star: B3Ve, T_{eff}=18000K, M_*= 9.6$M_\odot$, R_*= 4.8$R_\odot$, L_*= 5.8 10^3 $L_\odot$, i=45°, v_e sin*i*=300 km/s, $v_{e\infty}$=179 km/s, $v_{p\infty}$=2000 km/s



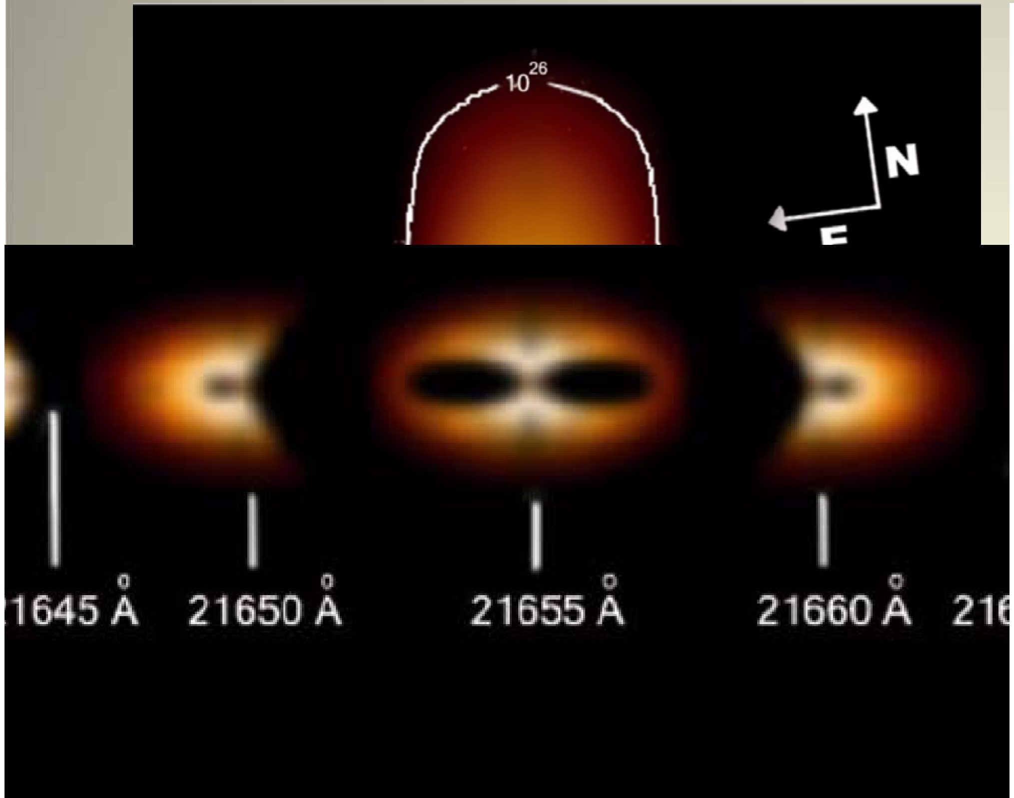
Line profile and
Differential visibility



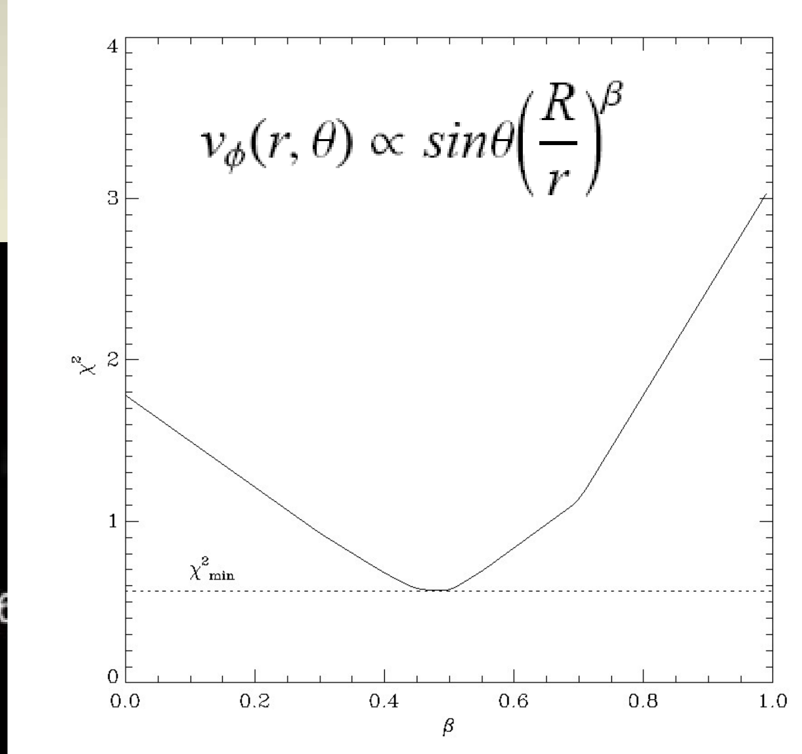
Differential phase

Stee et al., A&A 2007

Differential visibility and phase in line
Keplerian rotation in α Arae disk
(a question since 1866…)



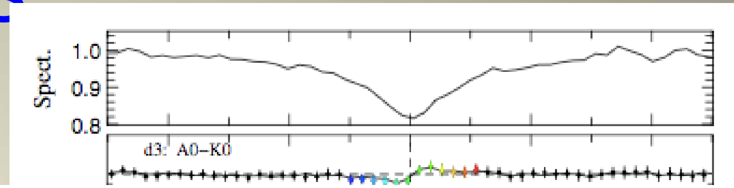
Brightness map computed by the SIMECA code (cont @ 2μm)



0 = constant rotation
0.5 = Keplerian rotation
1 = constant angular momentum

Stee et al., A&A 2007

Differential phase on unresolved sources



L44 J.-B. Le Bouquin et al.: The spin-orbit alignment of Fomalhaut probed by OLBIN

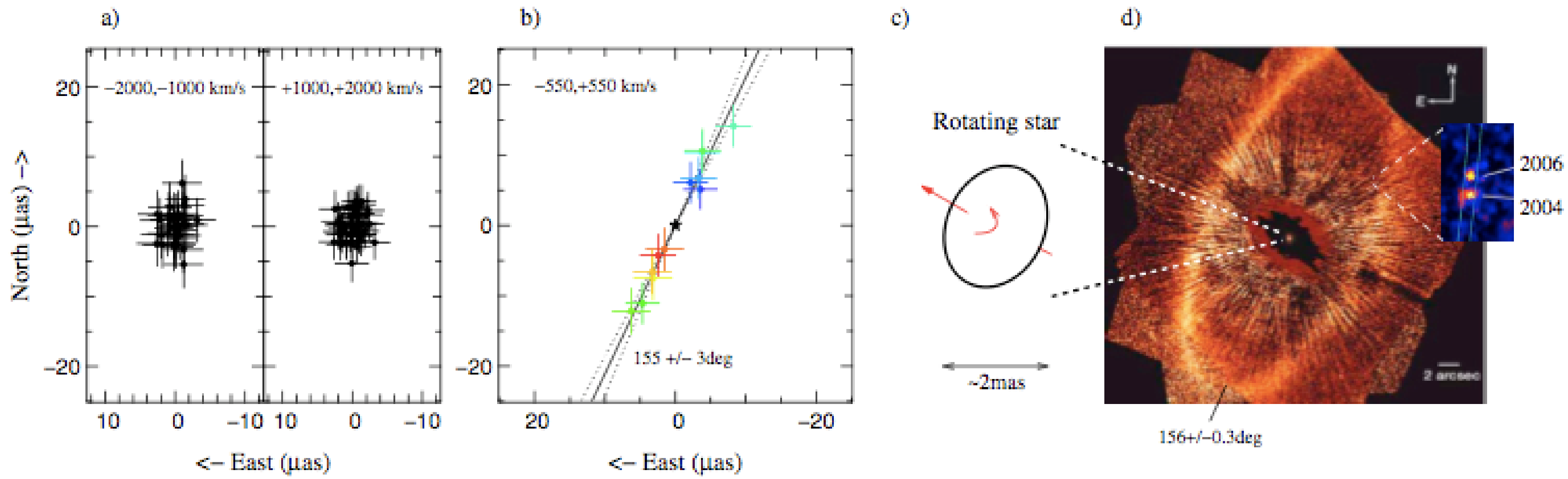
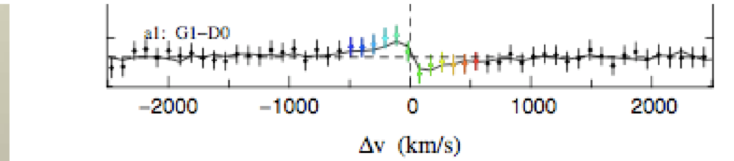


Fig. 3. AMBER spectro-astrometric positions $p(\lambda)$ in the continuum **a)** and across the Br-γ absorption line **b)**. Colors refer to the wavelength bin, as shown in Fig. 2. The signature of the rotating photosphere **c)** is clearly detected and is compared to the debris disk and the planetary companion **d)** imaged in the visible by Kalas et al. (2008). For the sake of clarity, the astrometric error ellipses are represented by their projection in the North and East directions.



Le Bouquin et al., A&A L 2009

Using the closure phase“alone”:phase closure nulling

G. Duvert, A. Chelli, F. Malbet and P. Kern: Phase closure nulling of HD 59717 3

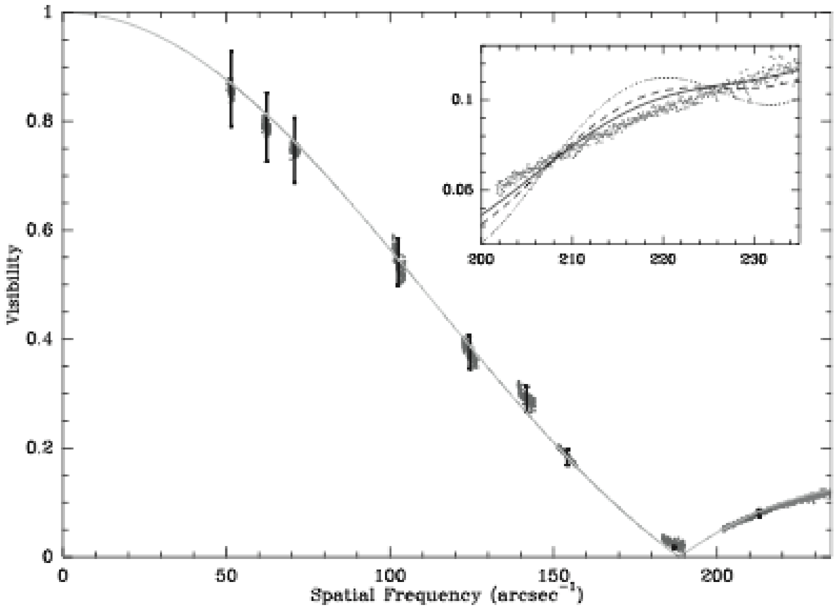


Fig. 2. Visibility of HD 59717 as a function of the spatial frequency. Errorbars illustrate the calibration errors resulting from the visibility dispersion shown in Fig. 1. The measurements obtained with the fringe tracker are plotted in grey in the second lobe. The full curve corresponds to a single uniform disk model of diameter 6.436 mas. The insert shows the second lobe measurements and three binary models with separation 30 mas and flux ratio: 5×10^{-3} (continuous line), 1×10^{-2} (dashed line) , 2×10^{-2} (dotted line).

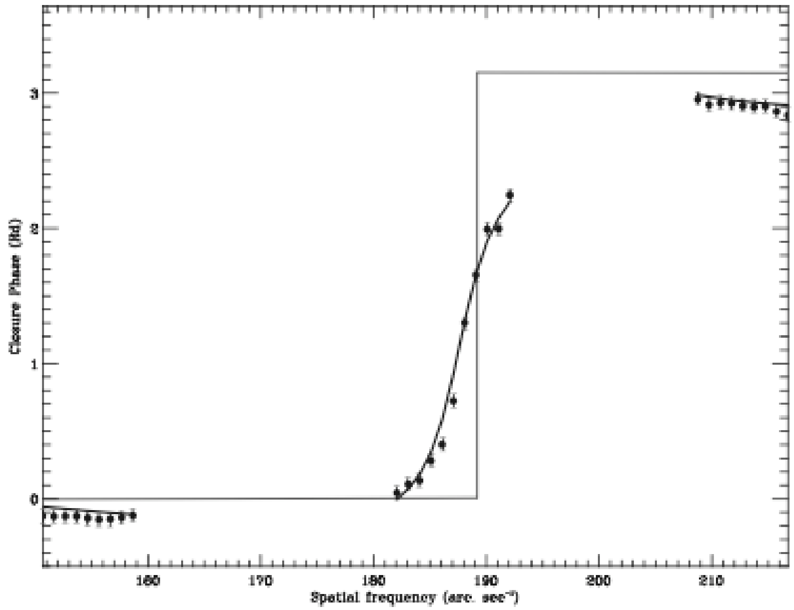


Fig. 3. Phase closure of HD 59717 as a function of the largest spatial frequency of the closure triangle. The thin curve corresponds to the best fit for a single uniform disk model with diameter 6.451 mas. The full curve corresponds to the best fit with a double system and parameters: primary stellar diameter 6.55 mas, secondary projected distance −11.2 mas and flux ratio 0.017.

Duvert et al., A&A 2010

HR Differential measures

192 K. Ohnaka et al.: Spatially resolving the inhomogeneous atmosphere of Betelgeuse

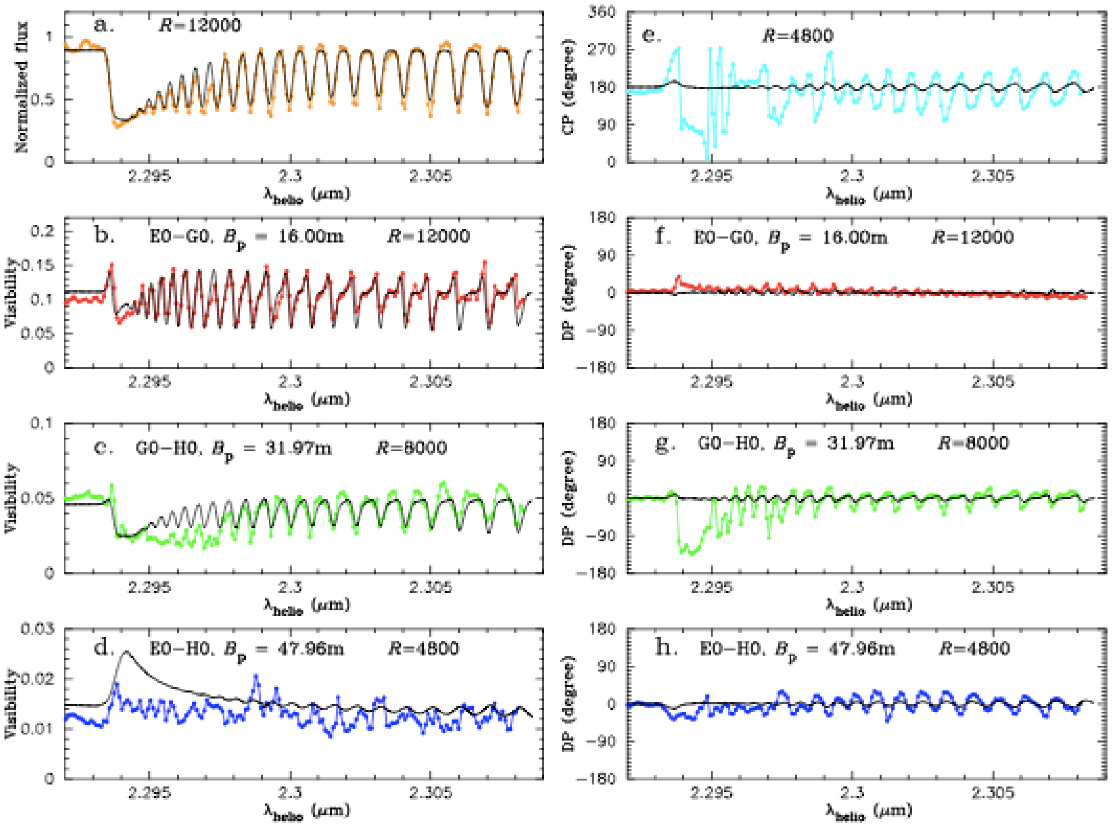
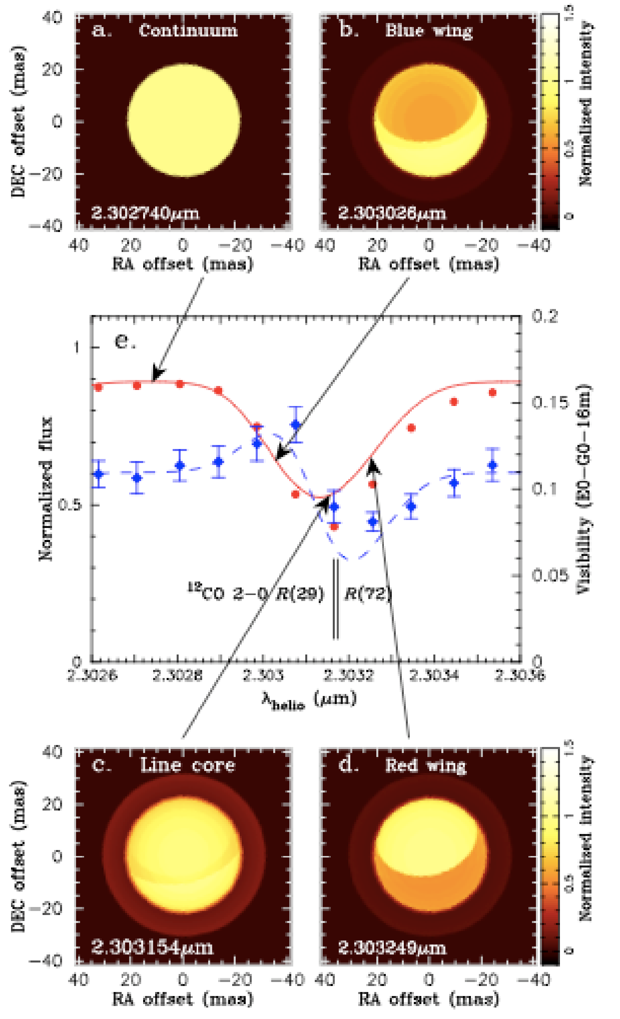


Fig. 5. Comparison between our patchy model ($T_{\rm in}$ = 2250 K, $N_{\rm out}$ = 1 × 10^{20} cm^{-2}, $v_{\rm flow}$ = 10 km s^{-1}, Θ = 60°, θ = 40°, and ϕ = 10°) and the AMBER data for Betelgeuse. In all panels, the solid lines represent the model, while the dots represent the observational data (data set #1). **a)**: Normalized flux. **b)–d)** Visibilities on the E0-G0-16 m, G0-H0-32 m, and E0-H0-48 m baselines. The observed and model visibilities on the last two baselines are binned with three and five pixels, respectively. **e)**: Closures phase. The observed data and the model are binned with five pixels. **f)–h)**: Differential phases on the E0-G0-16 m, G0-H0-32 m, and E0-H0-48 m baselines. The observed and model DPs on the last two baselines are binned with three and five pixels, respectively.



Ohnaka et al., A&A 2009

Monochromatic imaging (in H and K)
B[e] star HD 87643

- Very strong variations of visibility and closure phase, typical of a binary, but more complex

- Image reconstruction reveals binarity and southern component with resolved but compact dust disk in K band.

- Extensive reliability tests show that all other features are probable artifacts

- Reconstruction without the phase yields very similar result: the phases are poorly used

Millour et al., A&A 2009

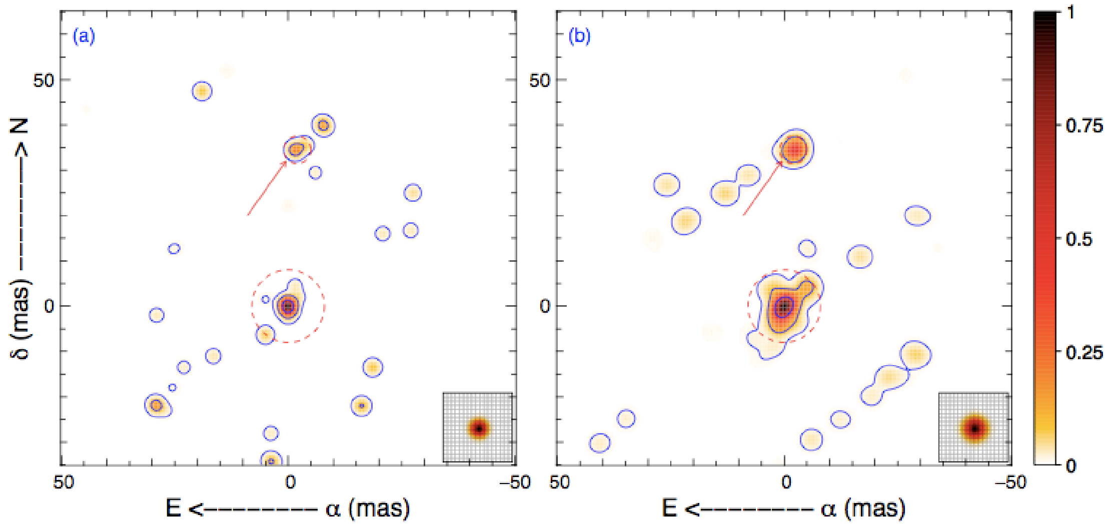


Fig. 2. Aperture-synthesis images of HD87643 reconstructed from the H-band AMBER data (panel 2a) and the K-band data (panel 2b), assuming the source is achromatic in each band. Contours with 50, 10, and 1% of the maximum flux are shown, and the beam size is shown in the lower-right box. The arrow shows the companion star, whereas the dashed circles show the trusted structures in the images.

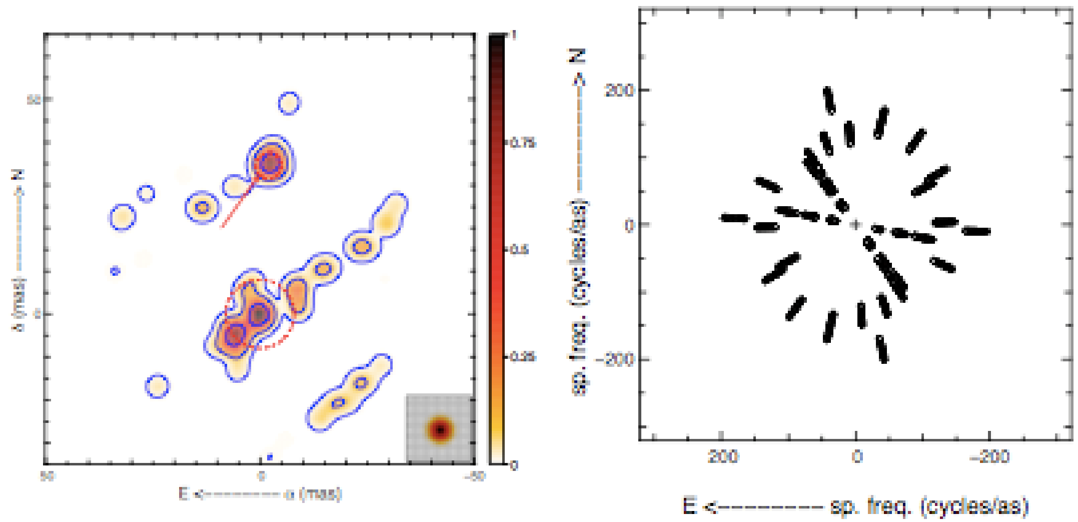


Fig. A.2. Removing high spatial frequencies to have a more symmetric UV coverage.

Multi monochromatic imaging VX Sgr

Cool late type star, type discussed.

Strong size variation with wavelength

Hot spots, max contrast in H

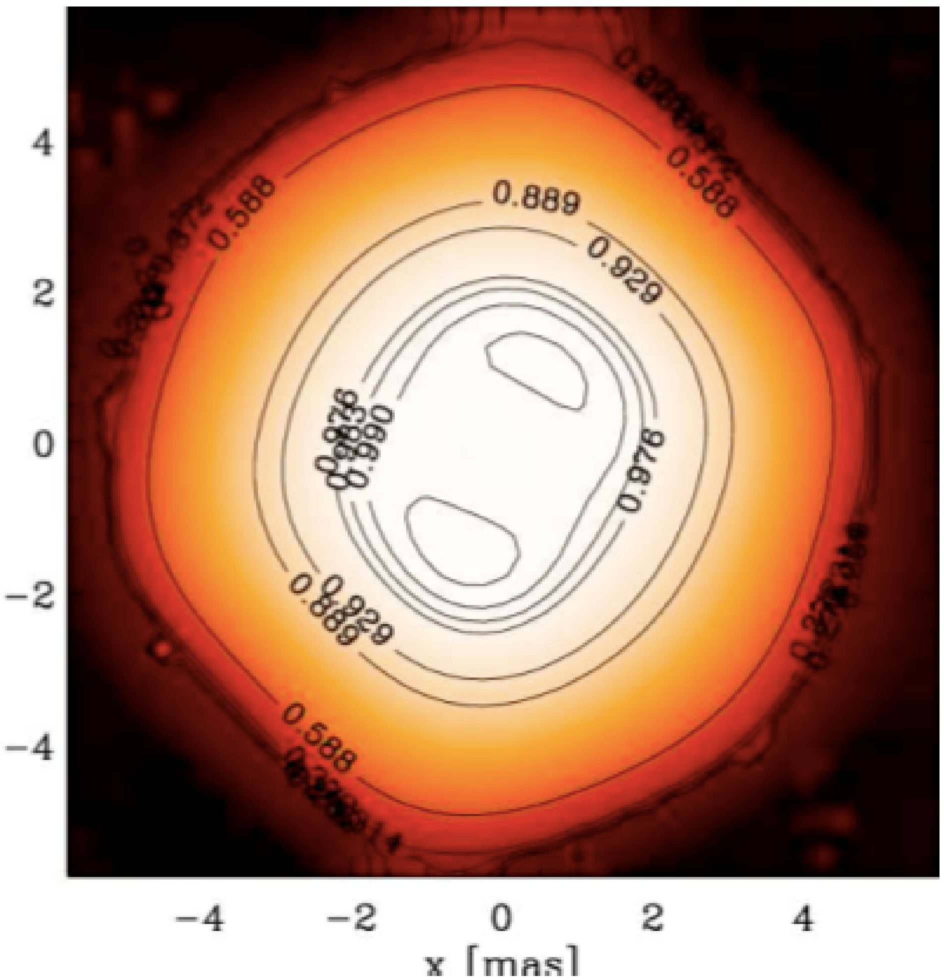
Extended molecular layers (water dominant) at 2 and 2.35-2.5 microns

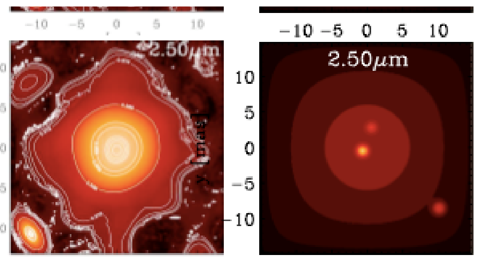
Conclusion: closer too MIRA type

Confirmation of image features by model fitting:

Image="objective" detection of features

Model="extracting parameters" from features





Chiavasa et al., A&A 2009

Polychromatic Imaging using the differential phase.

- Polychromatic image reconstruction of the A[e] star HD62623
  - Very nice illustration of an image reconstruction clearly resolving the ring shaped dust envelope and the rapidly rotating gas envelope.
  - The image reconstruction uses the differential phases and the closure phases to iteratively rebuild all the phases in all channels
  - The embedded “monochromatic” image reconstruction program is MIRA
  - This reconstruction is the first example of fully polychromatic image reconstruction treating the full u-v-λ data cube.
  - The images will be restored in this presentation as soon as the paper will be accepted

Millour, Meilland et al., Submitted April 2010.

Principle of self calibrated polychromatic imaging

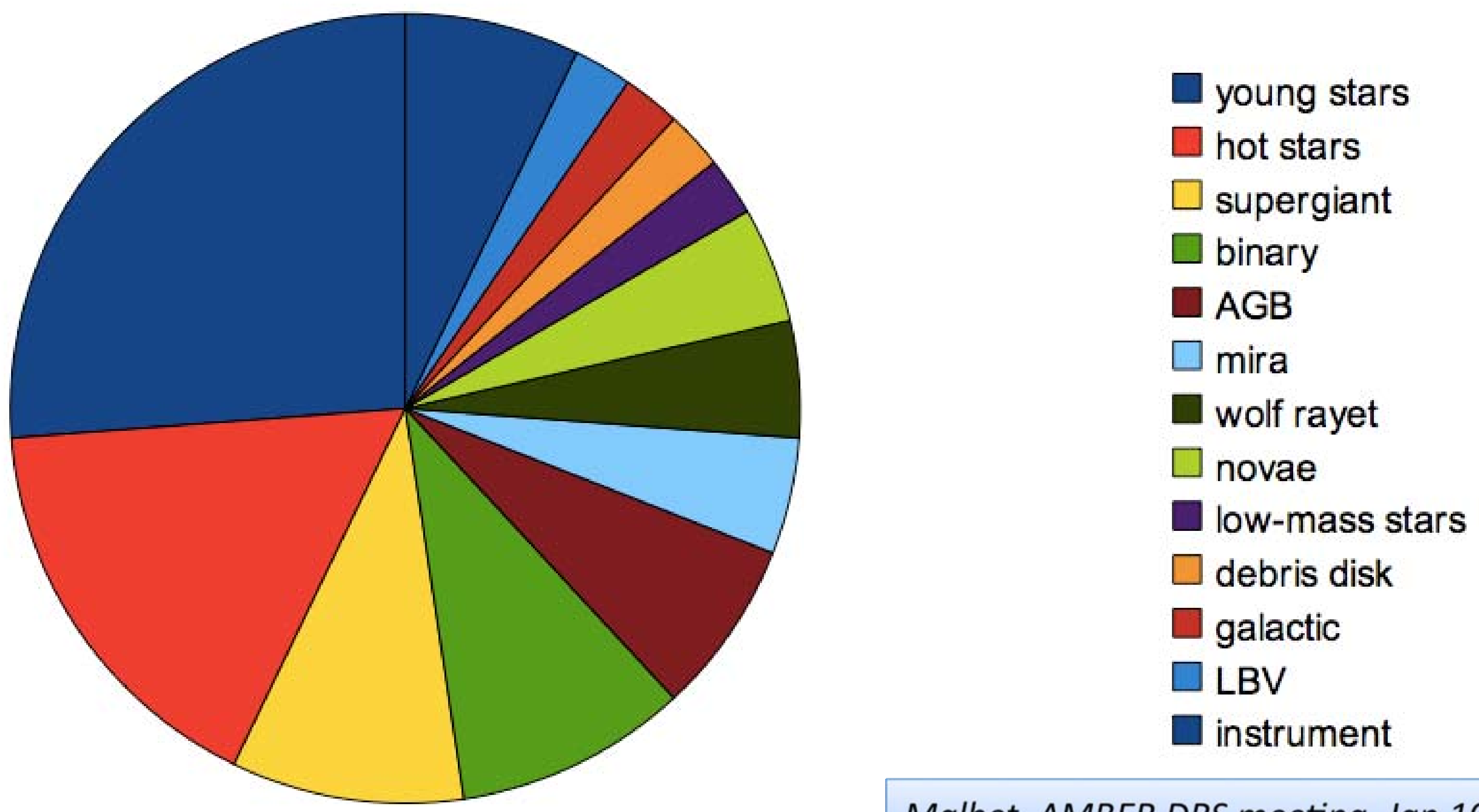
- Principle of polychromatic image reconstruction
  - The image reconstruction uses the differential phases and the closure phases to iteratively rebuild all the phases in all channels
  - The embedded “monochromatic” image reconstruction program is MIRA
  - This reconstruction is the first example of fully polychromatic image reconstruction treating the full u-v-λ data cube.
  - The images will be restored in this presentation as soon as the paper will be accepted

Millour, Meilland et al., Submitted April 2010.

AMBER Science status

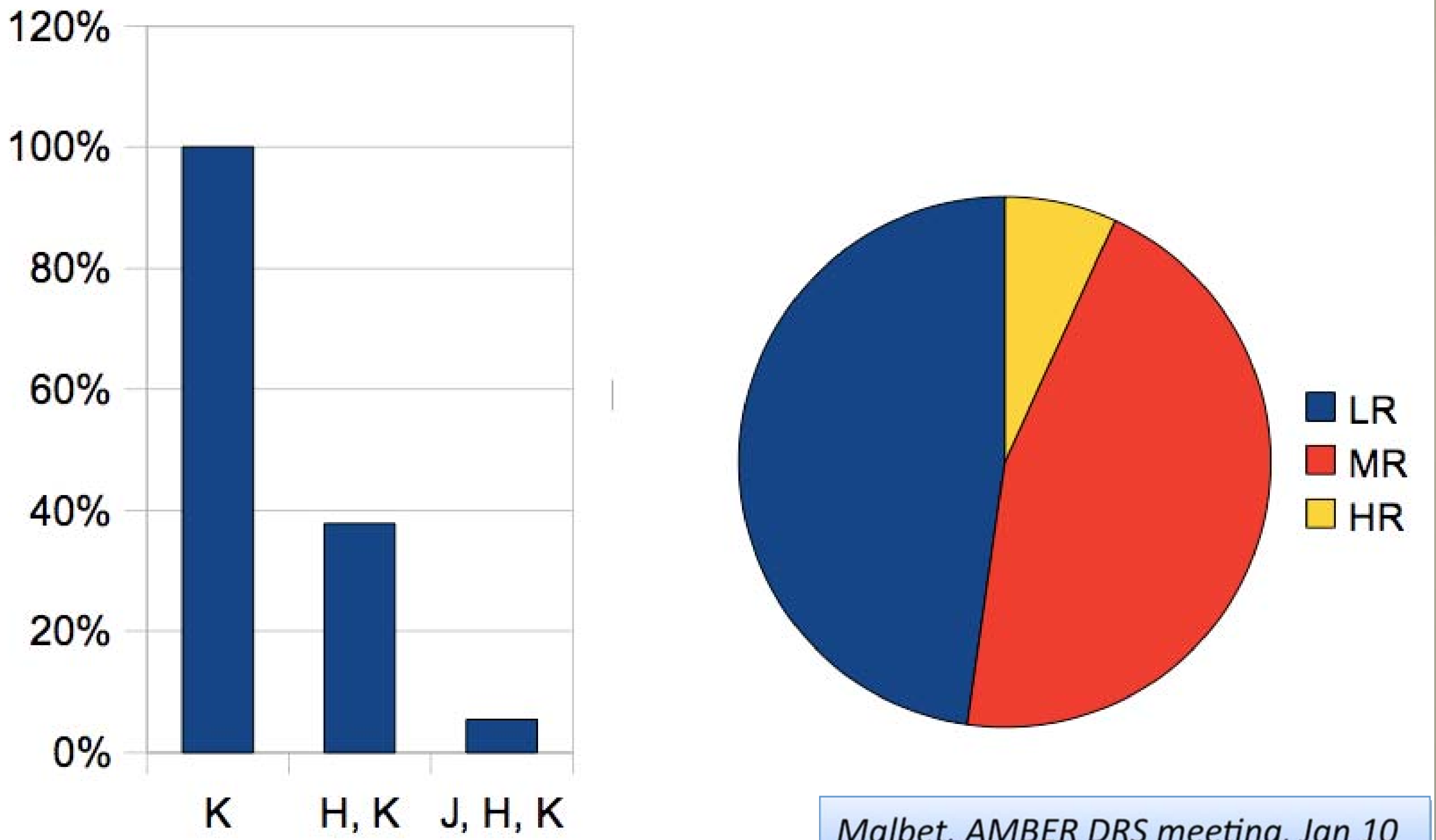
- April 2010: 50 refereed papers accepted
  - 38 Science papers
    - 2007: 9
    - 2008: 12
    - 2009: 11
    - 2010: 6
  - 12 Instrumental or data processing papers
  - Several submitted papers
  - Actively processed data
- P74: Oct 2004-Apr 2005: advanced GTO and SDT
- P76: Oct 2005-Apr 2006: Open Time with 3 UTs
- P78: Oct 2006-Apr 2007: advanced GTO with 3 ATs
- P79: Apr 2007-Oct 2008: Open Time with 3 ATs
- P80: Oct 2007-Apr 2008: FINITO with 3 ATs

Science topics in accepted publications



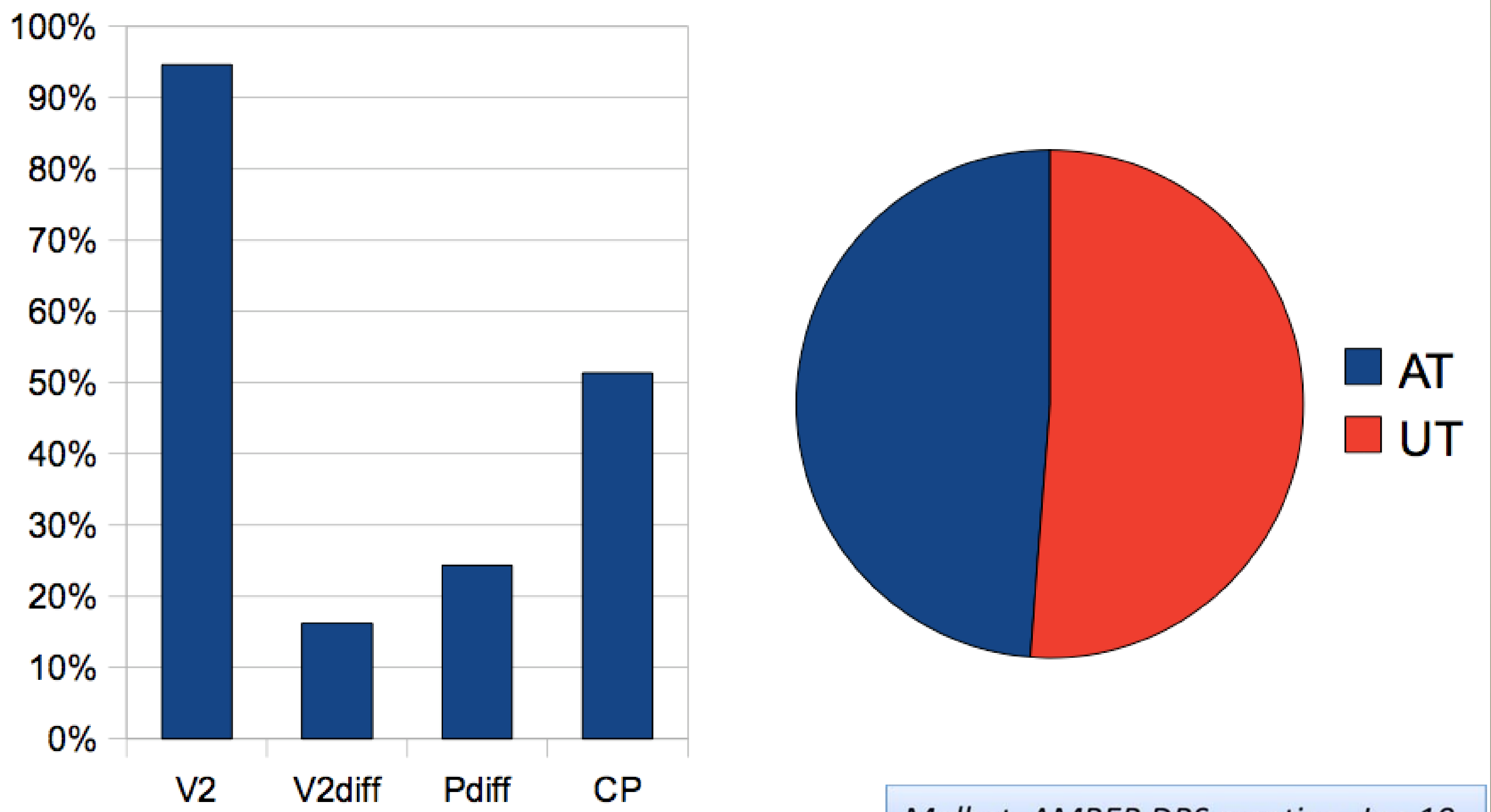
Malbet, AMBER DRS meeting, Jan 10

Observing modes used in accepted publications



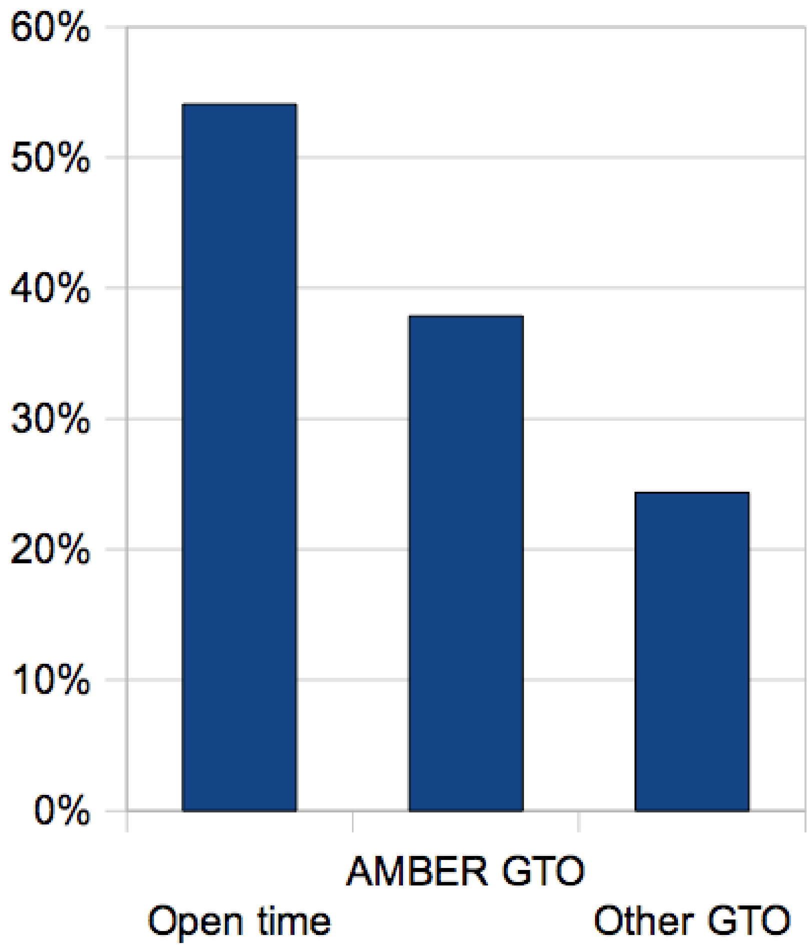
Malbet, AMBER DRS meeting, Jan 10

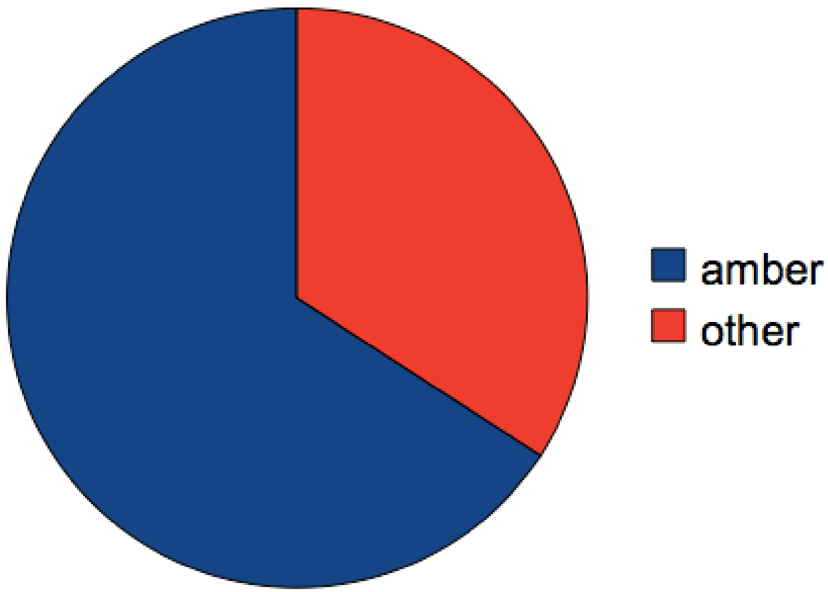
AMBER mesurables used in accepted publications



Malbet, AMBER DRS meeting, Jan 10

Shares of open time and GTO time contributions





other GTO: MPG, CNRS, INAF, Belgian, Swiss

Malbet, AMBER DRS meeting, Jan 10

AMBER "typical" performances as "guaranteed" by ESO

2.5 AMBER typical performances

These are typical performances in good conditions (seeing of 0.8" with the UTs, 0.6" with the ATs, coherence time of 4ms or better), for targets at least 1 magnitude brighter than the limiting magnitudes and with a standard number of frames taken. Better performances can be obtained in better conditions or by stacking more frames (should be specifically asked), see foot notes [1,2,3,4] for exceptions. "NG" means not guaranteed.

mode	FINITO	calibrated V	diff. ϕ	CP
low HK	not used	10%	NG	5^{o}[1]
	coherencing	5%	NG	3^{o}[1]
	cophasing	7%	NG	3^{o}[1]
medium K	coherencing	5%	2^{o}	4^{o}
	cophasing	5%	1^{o}	2^{o}
medium H	any mode[3]	5%	2^{o}[2]	4^{o}[2]
high K	cophasing	5%	1^{o}	2^{o}

[1] The closure phase error in low resolution is dominated by systematics, namelly a strong dependency of the closure phase with the piston (fringes' phase shift, or OPD shift). We believe is is not possible to reach a better precision, even by stacking frames.

[2] The medium H band phase products suffer from systematics not understood at the moment.

[3] Usually, the use of the fringe tracker biases the calibrated visibility. The main source of bias when using the fringe tracker is when a jump of one fringe does not correspond to a jump of one fringe in the science channel. FINITO operates in the H band, hence AMBER H band data collected using FINITO in cophasing are much less biased than medium K data.

Error on absolute visibility measurements

- **P74 to P85: 5%<σ_V<10% in LR, about 5% in MR and HR**
- Coupling between visibility and SNR
  - All images selections introduce biases
  - Use Cal-Sci-Cal sequence with calibrators and “best n%” selection (same n% on all targets)
    - Close in time
    - Close in air mass
    - Close in coherent flux
- Sensitive to ghost images, contamination and cross talk between beams
  - Software solutions
  - Definitive solution with AMDLIB 3.0 ?
- Very sensitive to non zero OPD
  - Relationship biased in early data processing
  - Easy to correct now, to be checked by science user
- **Very sensitive to piston jitter**
  - Because of the finite DIT of multi axial images (minimum for 3T, LR_K: 20 ms). FLUOR and VINCI are coaxial.
  - Jitter is variable in time
  - Software correction possible if piston jitter is dominated by seeing
  - Has failed so far: piston jitter is not dominated by seeing, even with ATs
- **Situation improved by FINITO ?**
  - Yes, if FINITO operates perfectly: piston jitter decreased
  - No, if many frames have unknown FINITO status
- **Solution (?) with ATs: select data sets insensitive to data selection**
- **Possible progress:**
  - Assess situation with new polarizers, new IRIS dichroïcs, AMDLIB 3.0
  - Go on with vibration reduction
  - Try again to implement jitter correction.
- **Approach the 1% limit ?**

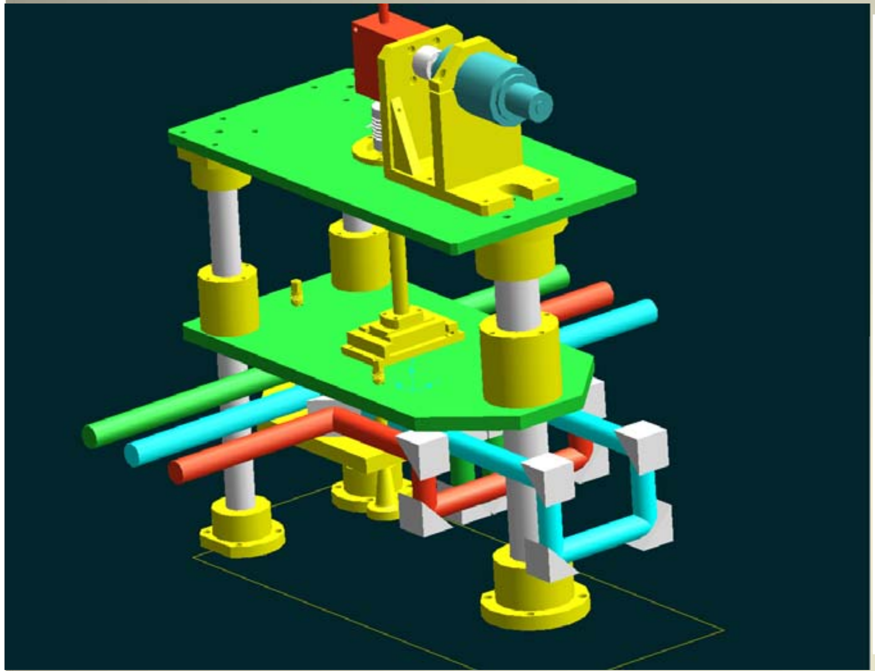
Errors on the LR differential phase and closure phase

- Differential phase is dominated by chromatic OPD effect coming from the difference in air path in the tunnels.
  - Currently no limit is set (NG)
  - Chromatic OPD effect can reach 0.5 radians (25°)
  - AMBER instrumental effect varies of about 0.015 radians (3°)/hour
  - Change between well chosen calibrators is of the order of 0.5°, after simple compensation of length of travel in air
  - Standard calibration limited to **3° DP accuracy**
  - With instrumental calibration with the BCD and good choice of calibrators (same airmass, close in time, Cal-Sci-Cal...) we should reach at least the

    0.5° DP accuracy
- Closure phase is contaminated by achromatic piston and chromatic OPD
  - The current limit is about **3° CP error**
  - The piston effect can be calibrated for small pistons (FINITO in coherencing mode)
  - Without BCD, the correction of piston effect on Sci and Cal yields about **1° CP error**
  - With BCD, the correction of piston effect on Sci and Cal yields about **0.2° CP error**

Stay tuned !

Calibration of Differential Phase with Beam Commutation



Beam Commuting Device (BCD).
It commutes two of the beams without image inversion. It is activated by inserting the central plate in the beams. It allows to reduce the calibration period down to 60 s or less. To avoid introducing extra effects the specifications are:

- tip-tilt accuracy: 2 arc seconds
- beam jitter accuracy: 10μm
- pupil motion: <30 cm
- opd accuracy: 1 μm

Without Beam Commutation:

$$\Delta\Phi_m(\lambda,t_1) = \Delta\Phi_*(\lambda,t_1) + \Delta\Phi_a(\lambda,t_1) + \Delta\Phi_i(\lambda,t_1) + \delta_\Phi(\lambda,t_1)$$

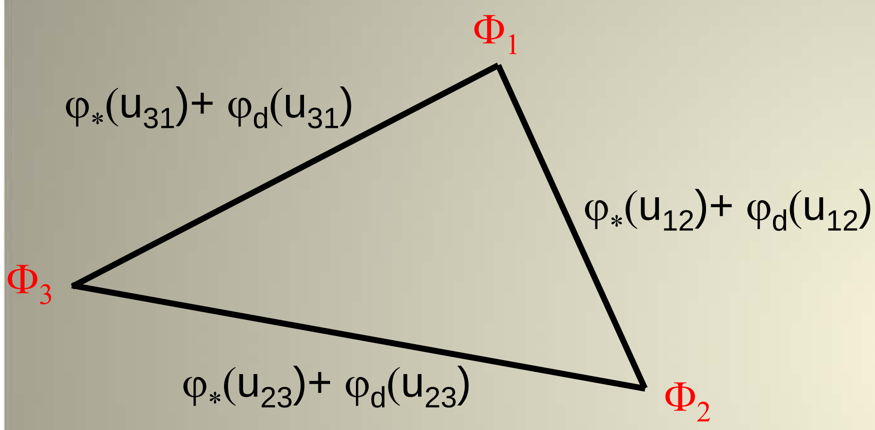
With Beam Commutation:

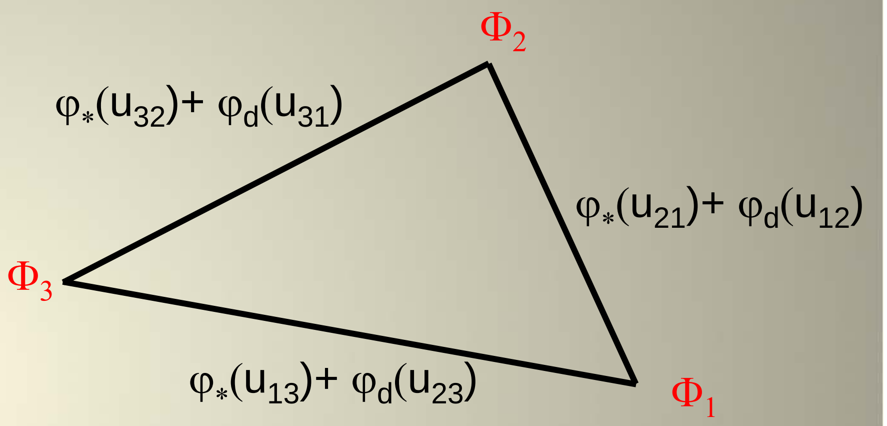
$$\Delta\Phi_{\underline{m}}(\lambda,t_2) = -\Delta\Phi_*(\lambda,t_2) - \Delta\Phi_a(\lambda,t_2) + \Delta\Phi_i(\lambda,t_2) + \delta_\Phi(\lambda,t_2) + \Delta\Phi_{BCD}(\lambda,t_2)$$

Difference:

$$\Delta\Phi_m(\lambda,t_1) - \Delta\Phi_{\underline{m}}(\lambda,t_2) = 2\Delta\Phi_*(\lambda) + 2\Delta\Phi_a(\lambda) + \delta_\Phi(\lambda,t_1) - \delta_\Phi(\lambda,t_2) + \Delta\Phi_{BCD}(\lambda,t_2)$$

Calibration of Closure Phase with Beam Commutation





Without BCD:

$\Psi_{123\_o}=$

$\Phi_1-\Phi_2+\varphi_*(u_{12})+\ \varphi_d(u_{12})$

$\Phi_2-\Phi_3+\varphi_*(u_{23})+\ \varphi_d(u_{23})$

$\Phi_3-\Phi_1+\varphi_*(u_{31})+\ \varphi_d(u_{31})$

–

With BCD:

$\Psi_{123\_I}=$

$\Phi_2-\Phi_1-\varphi_*(u_{12})+\ \varphi_d(u_{12})$

$\Phi_1-\Phi_3-\varphi_*(u_{31})+\ \varphi_d(u_{23})$

$\Phi_3-\Phi_2-\varphi_*(u_{23})+\ \varphi_d(u_{31})$

$$\Psi_{123}=2\ [\varphi_*(u_{12})+\ \varphi_*(u_{23})+\ \varphi_*(u_{31})]$$

Exoplanets and very high accuracy closure phases

- The first figure illustrates the visibility, differential phase and closure phase which is expected from the best models of the hot super giant start orbiting at about 0.05 AU of the star τ Boo.
- The flux ratio ranges from 0.1 to 2 milliradians between 1.6 and 2.5 μm.
- The maximum planet signatures are 0.002 in V and 2 milliradians in differential and closure phase.

Petrov, Vannier, Millour, Accepted ESO Obs. Prop. 085.C-0880, 2009

- The second figure illustrates our best calibration of the closure phase, with an accuracy better than 2 milliradians, on a single orbital phase.
- With more points on the orbit, we would be able to say if we really have detected the τ Boo planet, and to measure its spectra.
- A key point underlined in the report sent to ESO is the possibility to achieve closure phase accuracy of about 2 milliradians (0.1°)
  – The images will be restored in this presentation as soon as the report to ESO and a paper will be accepted

Petrov, Vannier, Millour, VLT-TRE-AMB-15830-7021, 2010

AMBER limiting magnitudes

- AMBER consortium records:
    - •Coherent flux=9.3 in LR
    - •Calibrator K=9
    - •NGC3783 (K=8.6, V=0.8)
    - •MR; K>6 avec ATs

	AMBER	FINITO	Kcorr	Hcorr	H	VisK	VisH	AM	Vmag	Dist
UT	LR-HK	**no**	<7*	<7*	-	>10%	>10%	<2.0	1...17	<55"
	LR-HK	group tracking	<7.5*	<7.5*	> 1			<1.5	1...15	<13"
	LR-HK MR-K	fringe tracking	<7	<7						
	MR-H	fringe tracking	-	<5		-				
	HR-K	fringe tracking	<6	<6		>10%				
AT	LR-HK	**no**	<5.5 (4.1, 3.1)**	<5.5 (4.1, 3.1)**	-	>5%	>5%	<2.0	-1.7...13.5	<60"
	LR-HK	group tracking	<5.5 (4.5, 3.5)**	<5.5 (4.5, 3.5)**	> -2		>15%	<1.5	-1.7...11	<15"
	MR-H	fringe tracking	-	<4 (3, 2)		-				
	LR-HK MR-K HR-K	fringe tracking	<5 (4, 3)	<5 (4, 3)		>5%				

AMBER/VLTI frontier

- Operate at the sensitivity frontier: K≈9 possible
  - Find mode to observe difficult targets in good conditions
  - Consider blind mode for MR and HR
  - Dare to acquire data with SNR/frame ≈ 1.
  - Develop (?) software for SNR/frame < 1.
- Improve AMBER sensitivity: potential for gain of two magnitudes (but expensive)
  - Improve coherent flux (vibration issue)
  - Improve AMBER transmission
  - Change Interferometry/photometry ratio
  - Find a way to use both polarizations without contrast loss
  - Improve FT limiting magnitude
- Absolute visibility accuracy: approach 1% specification ?
  - Re assess with new polarizers, software, IRIS dichroïc
  - Vibration issue
  - Implement jitter estimate/correction (when vibration reduced enough) using FINITO
- Phase accuracy in HR and MR: consolidate possibility to have 0.2°
  - Use BCD to go below typically 2°: potential is at least 0.2° when photon noise permit
- Closure phase accuracy in LR: at least 0.3° achievable
  - Piston fit to get down to 1°-2°
  - BCD to get down to 0.3°
- Differential phase in LR: push chromatic OPD fits below 0.25° accuracy ?
  - Correction of chromatic OPD with BCD: down to 0.25° and further progress possible

Conclusion and "lessons"

"Experience is the name everyone gives to their mistakes", Oscar Wilde...

- Things learned on projects, consortia and ESO... Second generation instruments (and ESO) will invent new errors.
- The VLTI and its instruments are a "system".
  - Avoid too strong separation between infrastructure and instrument, ESO and Consortia. Have frequent common system meetings, with Garching AND Paranal people.
- Peak of Consortium activity must be after assembly in Paranal, not before.
- AMBER was intended to be a high accuracy, spectro-interferometric and imaging instrument.
  - Accuracy has been disappointing so far and might remain poor in absolute visibility
  - The time of loose accuracy in differential and closure phase is coming to an end. Model fitters: "there will not be comfortable error bars any more!"
  - The potential of spectro interferometry has been more than confirmed
  - Imaging is possible in spite of slow u-v coverage (and so far poor, but this is improving), with "almost general user" tools.
  - Polychromatic imaging and polychromatic model fitting are solutions, not additional problems.
  - Large spectral coverage (H+K) and the associated boost in u-v plane coverage has been a real plus.
  - The fight toward faint sources is tough, but not desperate...

Think Spectro-Interferometry...

Key dates (2)

- 2004-2009: Commissioning, using, correcting, upgrading AMBER (and the VLTI)
  - P75: open time with 3UTs, MR_K; LR_JHK: 90 minutes per calibrated point (including 500 s of open shutter time). AMBER tuned daily.
    - Very slow acquisition procedure (spiral search by moving the telescopes)
    - Slow fringe search in LR (bad DL models)
- 2005: Commissioning 2: the VLTI vibrates badly
  - 2005: installing the ADC (refraction corrector) and the BCD (Beam Commutation Device)
  - 2005: first commissioning of IRIS
- 2006: first science results from "1 observation" point in December 2004 "advanced GTO run" and spring 2005 "science demonstration time"
  - After March 2006: improving DL models (real access to LR mode)
  - Summer 2006: commissioning with 2 ATs
  - Fall 2006: optical fibers replaced (parabolas-fiber coupling not optimum anymore)
- 2007 January: special A&A issue with 11 AMBER papers (3 instrumental and 8 science results)
  - 2007 October: first "non consortium" AMBER paper
  - P79 (April 2007): AMBER offered with 3 ATs
  - Strong reduction of overheads. <60 minutes per calibrated point
  - 2007: first phase commissioning report: strong beatings in wavelength, partially corrected by BCD
  - 2007: spectrograph run_away
  - 2007: is AMBER maintainable (tuning frequency) ? Are the thermal dissipation and noise levels acceptable ?
  - 2007 October: KAT meeting, AMBER "surge", "PAC punch list", ATF (AMBER Task Force), software corrections
- 2008: AMBER SURGE: spectrograph repair, full optical tuning, stability improvement, **ATF run**
- 2009 January: replacement of polarizers: **last time we were allowed to touch AMBER.**
  - 2009 August: all actions required for PAC closed by consortium