Interferometric Image Reconstruction Work-package of Opticon FP7

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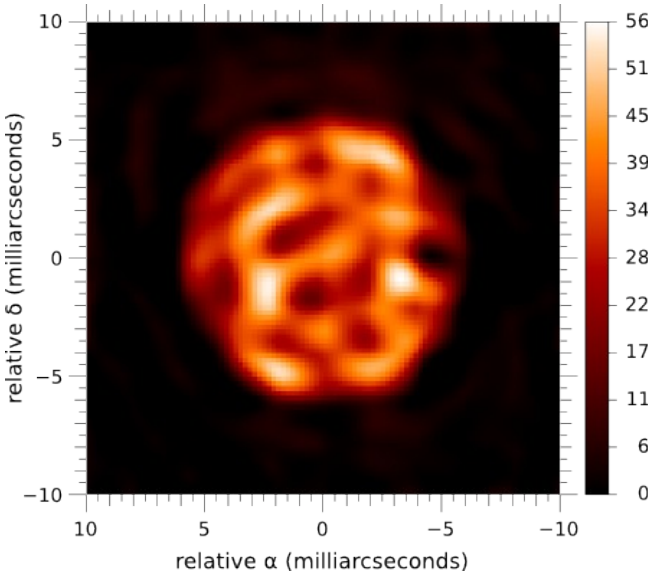
Image reconstruction project for OPTICON FP7

Rationale and context

- with 4 to 6 telescopes recombiners, 2nd generation VLTI instruments and recent optical interferometers (e.g., CHARA) are targeted at multi-spectral imaging (**$R \sim 10^4$, $\Delta\theta \sim 10^{-3}$ ”**)
- for the scientific returns of these instruments, tools for image reconstruction usable by non-expert astronomers are required
- image reconstruction algorithms for interferometry (BSMEM, WISARD, MiRA, *etc.*) are mature but:
    - require substantial expertise
    - mostly provide monochromatic image reconstruction
    - lack of documentation
    - not necessarily freely available



Giant star surface from simulated NPOI data (Berger *et al.*, 2012, A&A Rev. **20**, 53)

Summary of the project

- make the R&D and tutorial/software development to provide image reconstruction algorithms from optical interferometry data to general users

What kind of science with R ~ 10^4 and $\Delta\theta \sim 10^{-3}$" ?

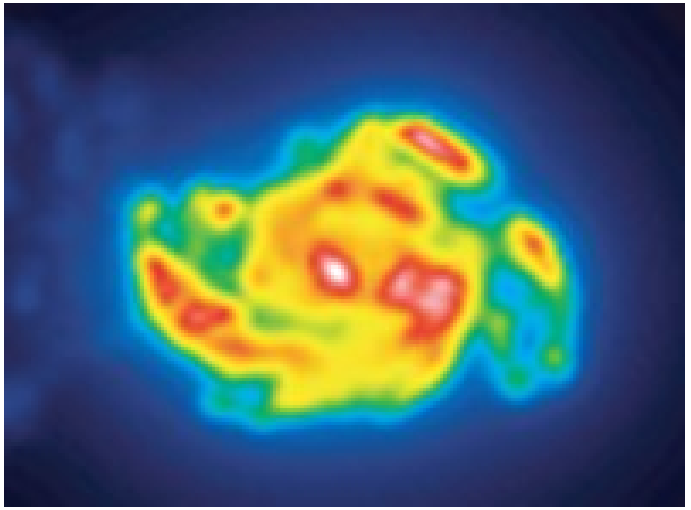
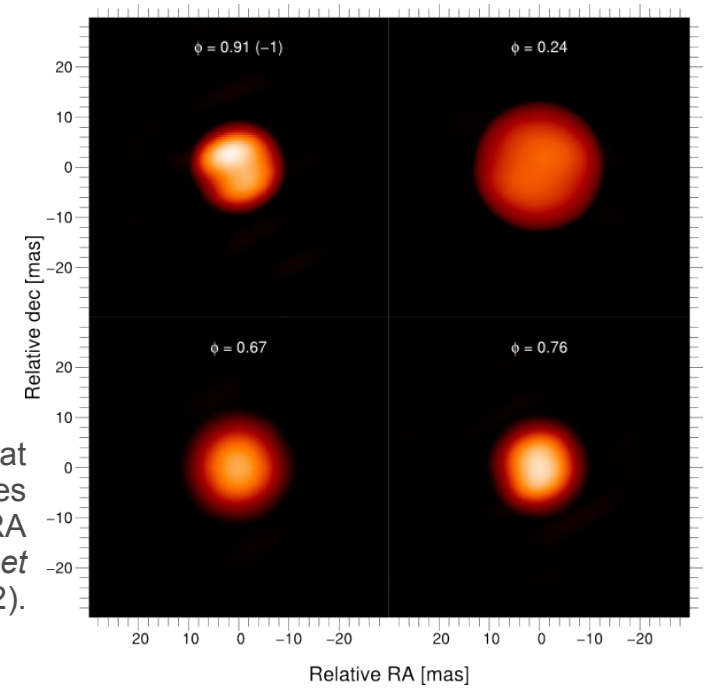


Image of the galaxy NGC 3504 at the resolution of a 23m telescope. The image was reconstructed by the *Building Block* algorithm from simulated interferometric LBT/LINC images (Hofmann *et al.* 2005, A&A **444**, 983).



The Mira-type star Chi Cygni at several epochs. Images reconstructed with the MiRA algorithm from IOTA data (Lacour *et al.*, 2007, A&A **707**, 632).

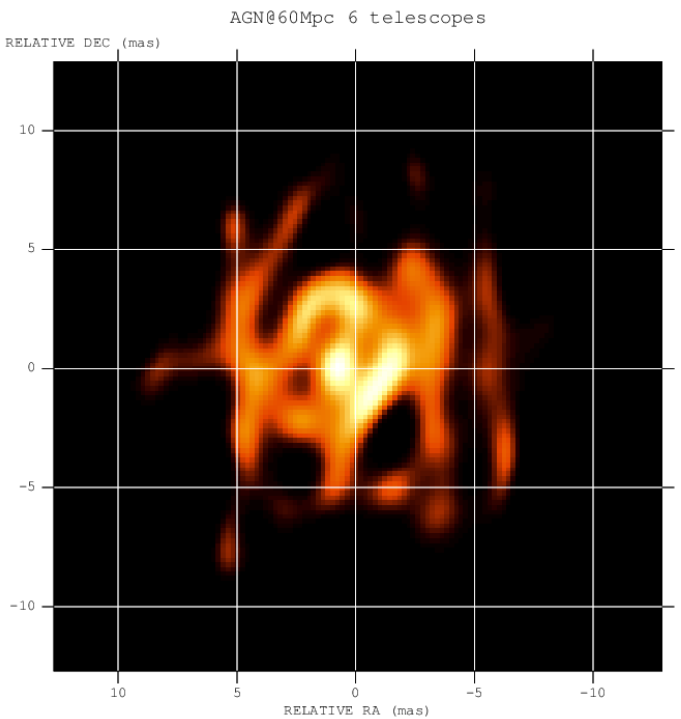
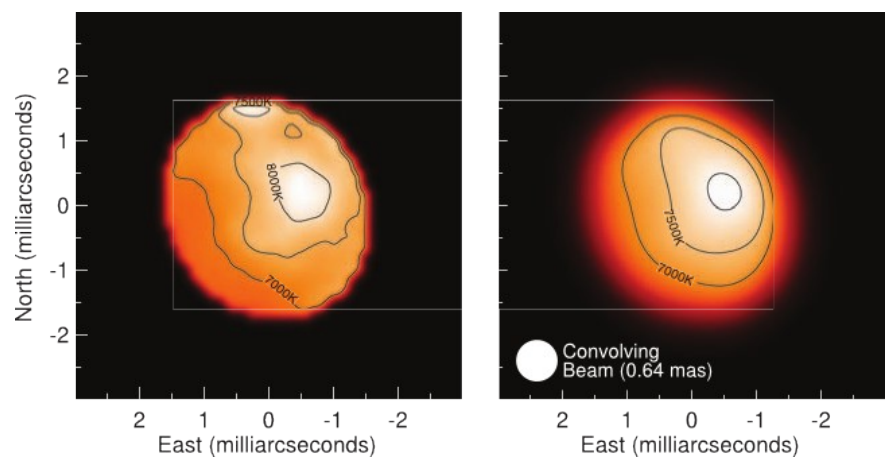


Image of a clumpy AGN torus (model by Schartmann *et al.*, 2008, A&A **482**, 67) reconstructed by BSMEM algorithm from synthetic 6-telescope MROI data (Young *et al.*, 2011, conf. "*Resolving the future of astronomy with long-baseline interferometry*", Socorro).



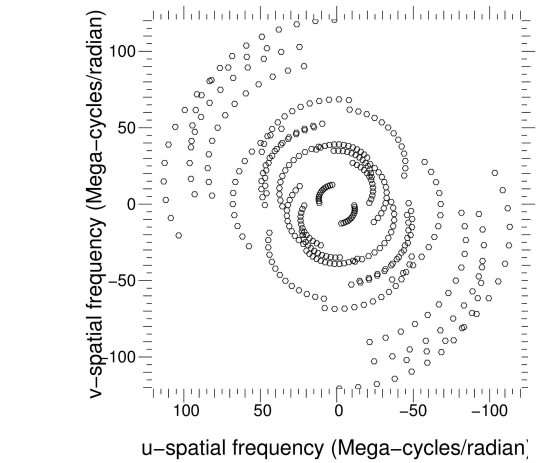
Intensity image of the surface of Altair (λ = 1.65 μm) from CHARA data, reconstructed by MACIM (Monnier *et al.*, 2007, Science **317**, 342).

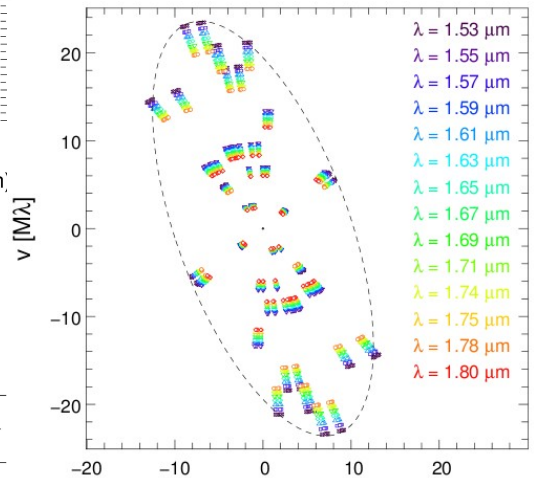
Why do we need image reconstruction algorithms?

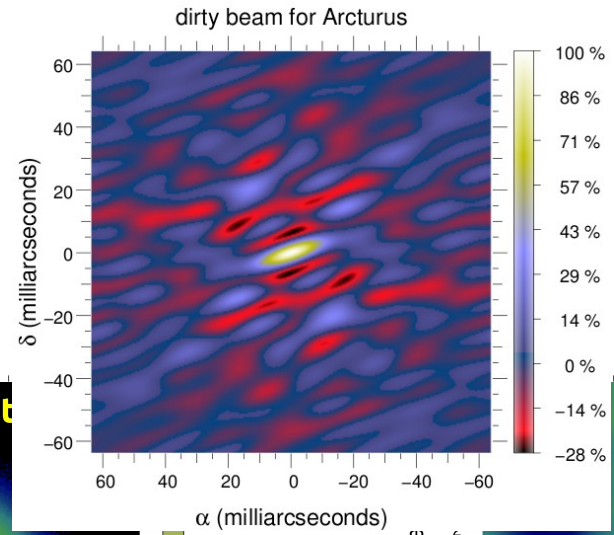
observing with an interferometer → PSF ~ dirty beam

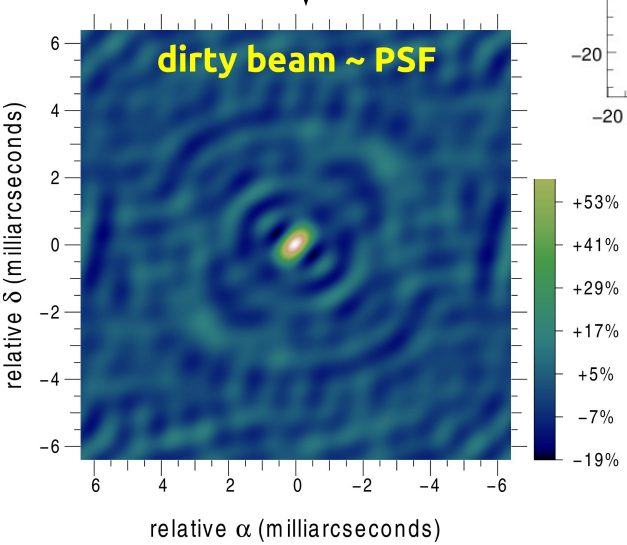
at optical wavelengths is even worse:

- due to turbulence, part of Fourier phase information is lost
- (u,v) coverage is really an issue → 4 – 6 telescope instruments









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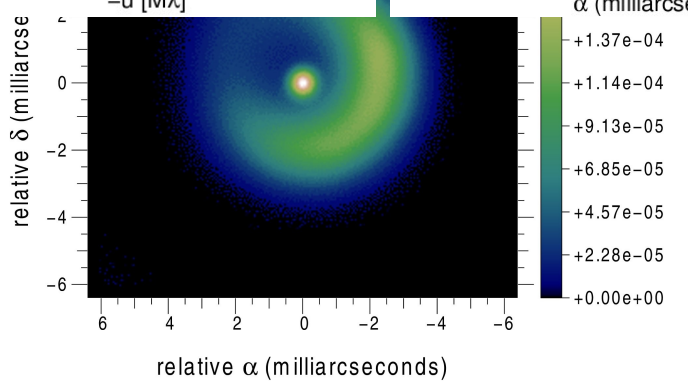

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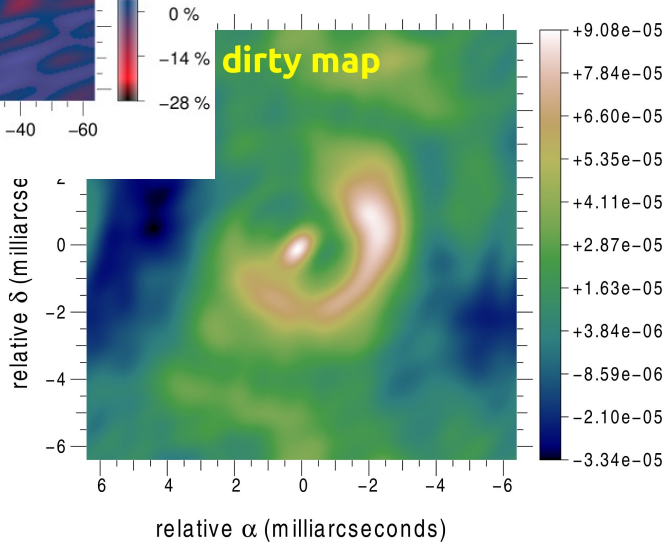
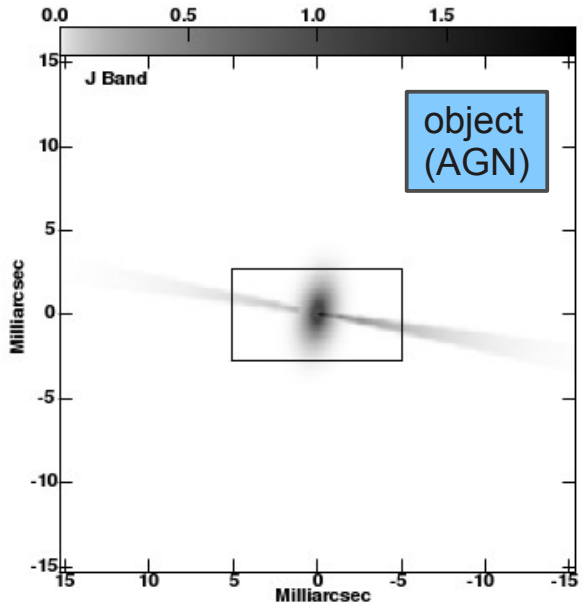
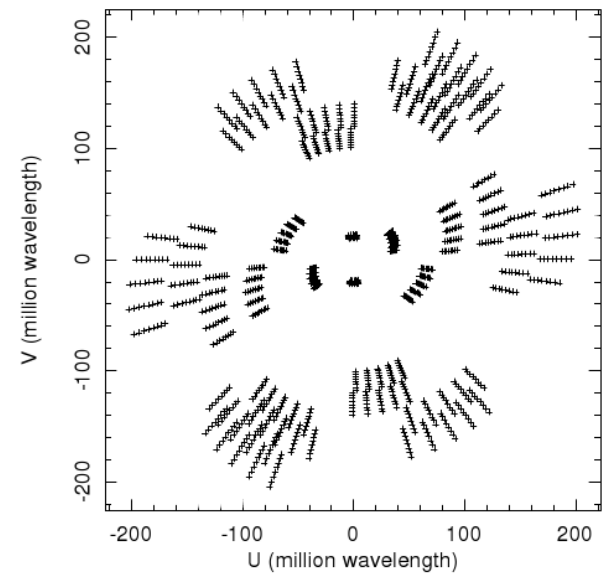
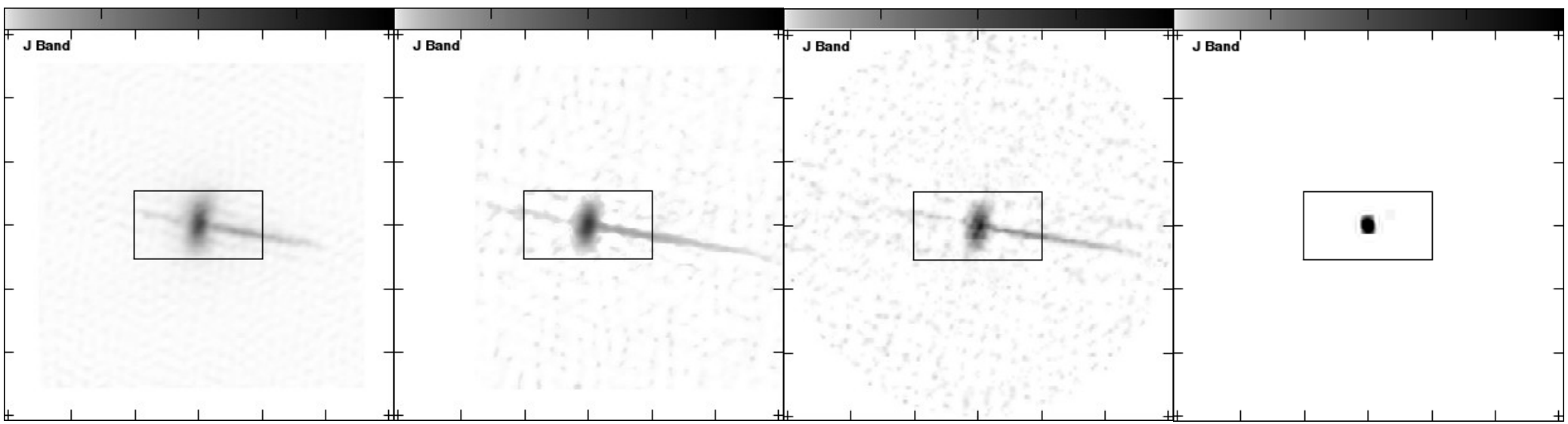


Compare and select *state of the art* algorithms





(Cotton *et al.*, 2008)



BSMEM
(Baron et al. 2008)

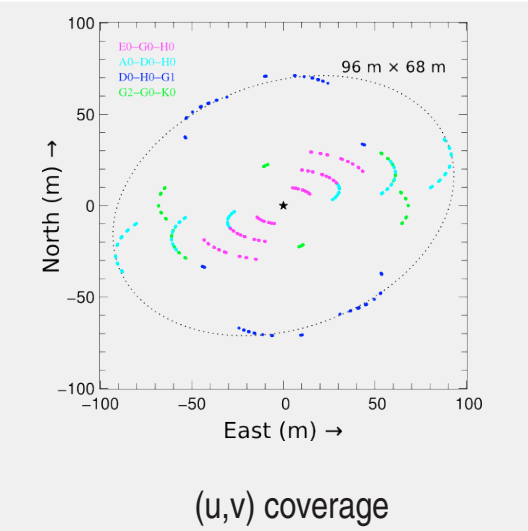
MiRA
(Thiébaut 2008)

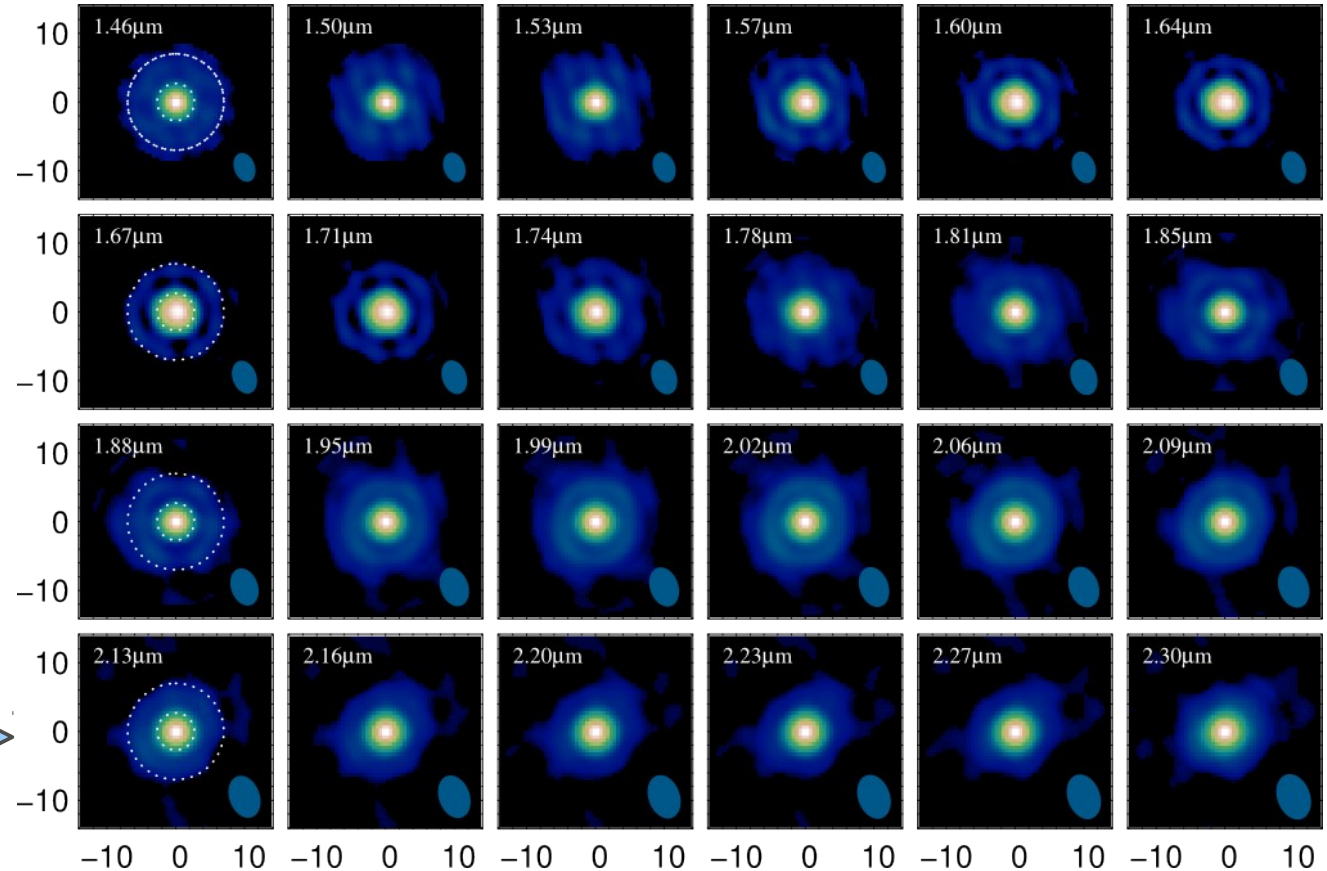
building-blocks method
(Hofmann & Weigelt, 1983)

MACIM
(Ireland et al., 2008)

now: *separable* multi-spectral image reconstruction

- interferometers provide multi-spectral data (R ~ 30 – 12000 for AMBER)
- 2 alternatives for reconstruction
  - separable processing (one image per spectral channel)
  - global processing (accounts for spectral continuity)



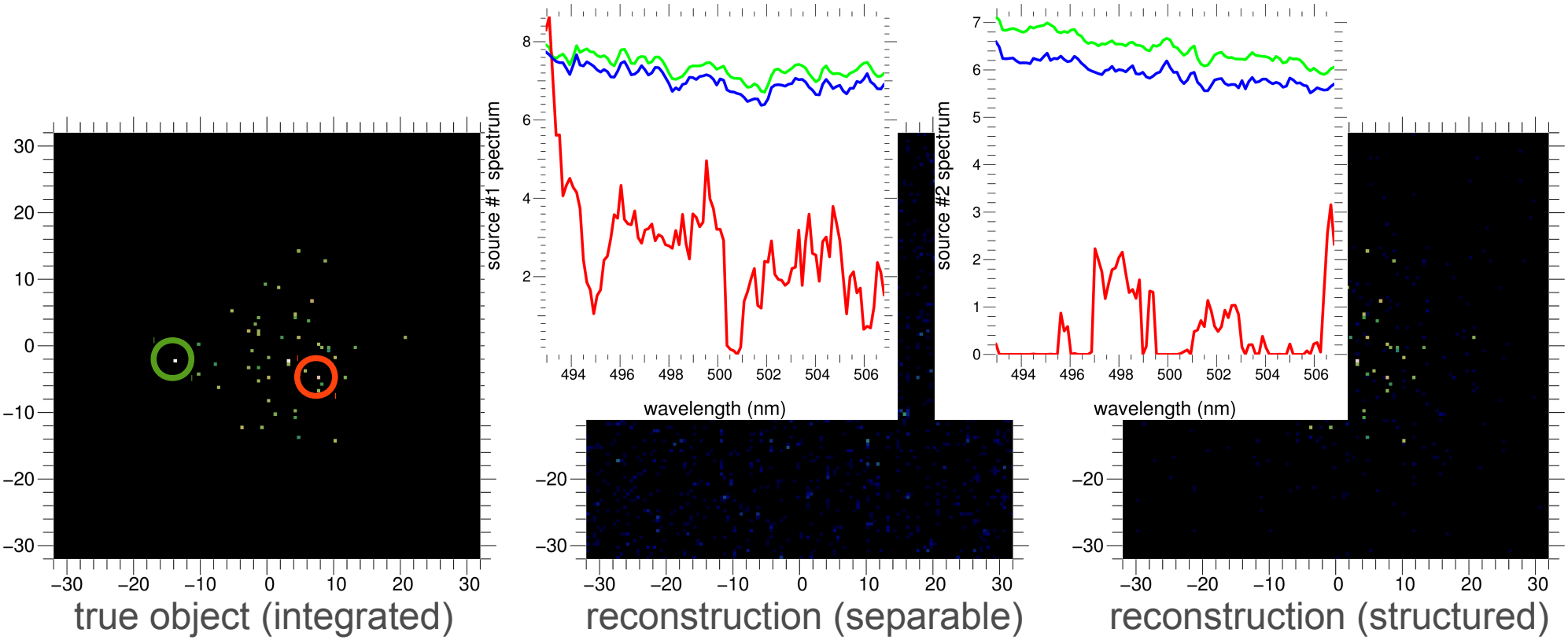


TLep. Source: Le Bouquin *et al.*, (A&A **496**, L1, 2009); data: AMBER (H & K bands); algorithm: MiRA.

to be done: multi-spectral *global* image reconstruction

global processing accounts for spectral continuity

- 2D + λ = 3D multivariate reconstruction (more difficult)
- yields results of much superior quality (cf. results of Bongard, Soulez et al. for IFUs in MNRAS)



Thiébaut et al. (2012, arXiv:1209.2362)

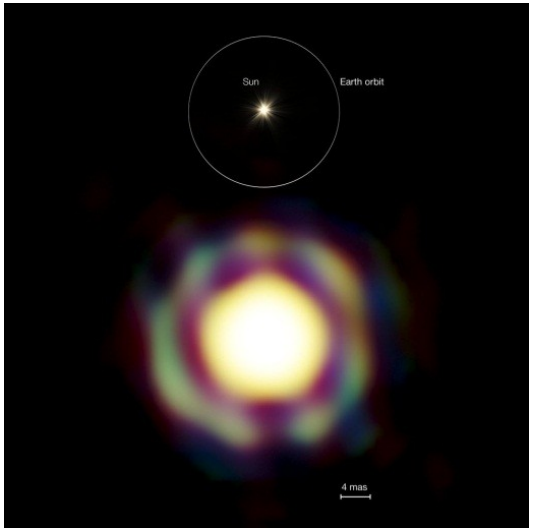
Toward interferometric image reconstruction for astronomers

- image reconstruction is an off line data processing task
- image reconstruction is a compromise between objective information (the data) and priors (e.g. the object is compact or smooth)
- there exist successful algorithms (MSMEM, MiRA, Wisard), some of them free, but none really easy to use
- make algorithms easier to use
  - adapted to the different instruments (VLTI, VEGA, etc.)
  - unified to share inputs/outputs, knowledge, improvements
  - sample data files, guidelines and cookbook to help users
  - GUI interface
- further developments
  - multi-spectral data (less loss but more difficult to handle)
  - unsupervised methods to tune the hyper-parameters

Tasks and deliverables

Tasks

- selection of *state of the art* methods (MSMEM, MiRA, Wisard, …)
- typical data samples
- R&D on image reconstruction algorithms:
  - solve issues for non-experts (*e.g.* **unsupervised algorithms**)
  - **multi-wavelength data**
- validation on experimental data from existing instruments



Multi-color image of the Mira-type star T Leporis showing the molecular layer around the star. Image reconstructed with the MiRA algorithm from VLTI/AMBER data (le Bouquin *et al.*, 2009, A&A **496**, L1).

Deliverables

- improved standardization (e.g. updating of OI-FITS)
- algorithm prototypes (in high level languages)
- algorithm specifications (scientific publications and technical reports)
- tutorials and cookbooks based on real and typical cases
- implementation of algorithms with a simple user interface (command line) for in-line and batch processing
- graphical user interface

Work-packages

- WP1 – Project management (CRAL)
- WP2 – Data samples and astrophysical model images
  - model images of astrophysical objects (FEUP)
  - synthetic data for LINC-Nirvana, Gravity and Matisse (MPIA, LESIA, OCA)
  - real data from Amber, LINC-Nirvana, Vega/Chara and Pionier (IPAG, MPIA, OCA)
- WP3 – Image reconstruction algorithms
  - unified image reconstruction description (UC)
  - algorithms derived from BSMEM, MiRA and Wisard (UC, CRAL, OCA)
- WP4 – User interface and user guides
  - algorithm interface specification (CRAL)
  - graphical user interface (JMMC)
  - tests and benchmarks (JMMC)
  - documentation and cookbooks (FEUP)

Deliverables

	Del. No.	Deliverable Name	WP No.	Del. Date (month)
	4.1	Model images of astrophysical objects	4.2	6
4.1	4.2	Unified image reconstruction description	4.3	12
	4.3	Synthetic data for Gravity	4.2	18
	4.4	Synthetic data for Matisse	4.2	18
	4.5	Real data from Pionier	4.2	18
	4.6	Data from Vega/Chara	4.2	18
	4.7	Algorithm interface specifications	4.4	18
	4.8	Synthetic and real data for LINC-Nirvana	4.2	30
	4.9	Prototype of algorithm derived from BSMEN	4.3	30
	4.10	Data reduction tools for Fizeau interferometry	4.3	30
	4.11	Prototype of algorithm derived from Wisard	4.3	30
	4.12	Prototype of algorithm derived from MiRA	4.3	30
4.3	4.13	Graphical user interface (GUI)	4.4	36
	4.14	Test and benchmark results	4.4	48
4.2	4.15	Documentation and cookbooks	4.4	48

Partnership

- Lyon: CRAL (Éric Thiébaut)
  - image reconstruction (MiRA)
- Univ. Porto (Paulo Garcia)
  - sciences cases, cookbooks, tests
- Univ. Cambridge (John Young)
  - image reconstruction algorithm (BSMEM)
- MPIA Heidelberg (Jörg-Uwe Pott)
  - LINC-Nirvana (LBT) case
- IPAG/JMMC (Gilles Duvert, Jean-Baptiste le Bouquin)
  - data from PIONIER and AMBER
  - graphical user interface
- OCA (Martin Vannier)
  - data from VEGA, simulations (MATISSE)
  - algorithm
- LESIA (Sylvestre Lacour)
  - simulation and test cases (GRAVITY)

Work-packages

	Work-packages	Leader	MPIA	UC	FEUP	CRAL	OCA	CNRS JMMC	LESIA	IPAG	total	MPIA	UC	FEUP	CRAL	OCA	CNRS JMMC	LESIA	IPAG
		Level of involvement									Amount of Work (person-months)								
1.	*project management*	CRAL				100%					**2**	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0
2.	*data samples and astrophysical model images*										**23**								
2.1.	*model images of astrophysical objects*	FEUP	5%	5%	75%		5%		5%	5%	5	0.3	0.3	3.8	0.0	0.3	0.0	0.3	0.3
2.2.																		0.0	3.0
2.3.																		0.0	0.0
2.4.																		0.0	0.0
2.5.																		0.0	0.0
2.6.																		0.0	3.0

	Work-packages	Leader	MPIA	UC	FEUP	CRAL	OCA	CNRS JMMC	LESIA	IPAG
		Level of involvement								
1.	p									
2.	d									
2.1.	n									
2.2.	s									
2.3.	s									
2.4.	s									
2.5.	r									
2.6.	d									
3.	in									
3.1.	u									
3.2.	p									
3.3.	d									
3.4.	p									
3.5.	p									
4.	u									
4.1.	a									
4.2.	g									
4.3.	te									
4.4.	d									

	Work-packages	Leader	total	MPIA	UC	FEUP	CRAL	OCA	CNRS JMMC	LESIA	IPAG
			Amount of Work (person-months)								
1.	*project management*	CRAL	**2**	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0
2.	*data samples and astrophysical model images*		**23**								
2.1.	*model images of astrophysical objects*	FEUP	5	0.3	0.3	3.8	0.0	0.3	0.0	0.3	0.3
2.2.	*synthetic data for Gravity*	LESIA	4	0.0	0.0	1.0	0.0	0.0	0.0	3.0	0.0
2.3.	*synthetic and real data for LINC-Nirvana*	MPIA	4	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.4.	*synthetic data for Matisse*	OCA	4	1.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0
2.5.	*real data from Pionier*	IPAG	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0
2.6.	*data from Vega/Chara*	OCA	3	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0
3.	*image reconstruction algorithms*		**40**								
3.1.	*unified image reconstruction description*	UC	4	0.2	2.4	0.0	1.2	0.2	0.0	0.0	0.0
3.2.	*prototype of algorithm derived from BSMEN*	UC	9	0.0	9.0	0.0	0.0	0.0	0.0	0.0	0.0
3.3.	*data reduction tools for Fizeau interferometry*	MPIA	9	7.7	0.0	0.0	1.4	0.0	0.0	0.0	0.0
3.4.	*prototype of algorithm derived from Wisard*	OCA	9	0.0	0.0	0.0	0.0	9.0	0.0	0.0	0.0
3.5.	*prototype of algorithm derived from MiRA*	CRAL	9	0.0	0.0	0.0	9.0	0.0	0.0	0.0	0.0
4.	*user interface and user guides*		**22**								
4.1.	*algorithm interface specifications*	CRAL	2	0.0	0.2	0.0	1.4	0.2	0.2	0.0	0.0
4.2.	*graphical user interface*	JMMC	12	0.0	0.0	0.0	1.2	0.0	10.8	0.0	0.0
4.3.	*test and benchmark results*	JMMC	4	0.2	0.2	0.8	0.2	0.2	2.4	0.0	0.0
4.4.	*documentation and cookbooks*	FEUP	4	0.4	0.4	1.6	0.2	0.2	1.2	0.0	0.0
				13.7	***12.5***	***7.2***	***16.6***	***16.1***	***14.6***	***3.3***	***3.3***
			87		***33.3***				***53.7***		
							77	75	68	15	15
		EU funding:		103	93	54			250		
		Total:		500							