Beta-Pictoris b as seen by ANDROMEDA

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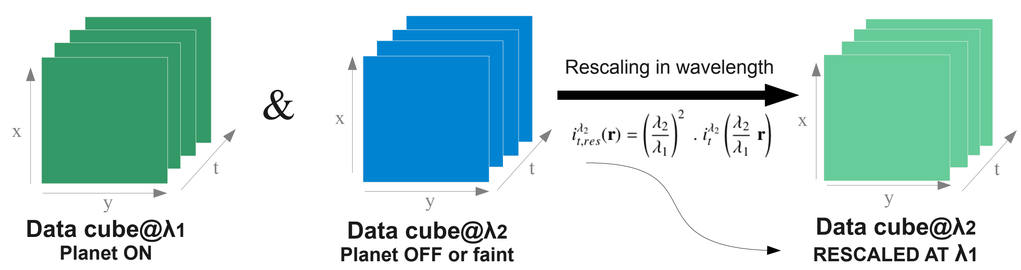
ANDROMEDA: An ADI-based method using the inverse problem approach [1], [2]

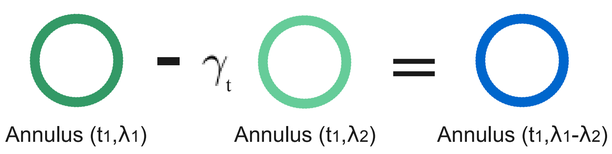
Ingredients:
- Coronagraphic or saturated images
- Pupil tracking mode (ADI-mode)
-Optionnally Dual Band Imaging mode (DBI-mode)
-1 PSF (unsaturated or off-axis exposure)

1- Optionnal Spectral Differential Imaging (SDI):

1.1: Rescaling in wavelength one of the cube along to the other

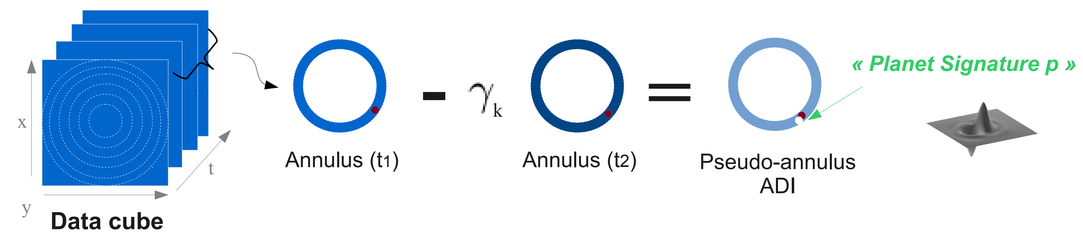


1.2: Optimized subtraction to reduce the speckle noise



For any annulus of a chosen width from every exposure

2- Angular differential Imaging (ADI):



→ **Simple but deterministic PSF subtraction providing pseudo-data**

→ **If there is a companion, we know exactly what it looks like !**

3- Model for inverse problem solving:

3.1: Model for the pseudo-data Δ(r,k)

$$\Delta(\mathbf{r},k) = a\,\mathbf{p}(\mathbf{r},k;\mathbf{r_o}) + \mathbf{n}(\mathbf{r},k)$$

Intensity ***UNKNOWN*** | *Initial position* ***UNKNOWN*** | Noise : White, Gaussian and non-stationnary **HYPOTHESIS**

3.2: Model of the planet signature *p*

Planet signature with high-pass filtering of the input images.

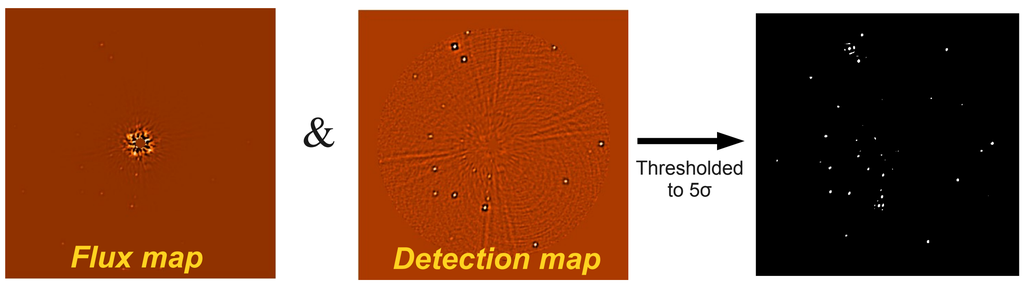
4- Maximum likelihood:

Under the hypothesis, the likelihood writes: $L(\mathbf{r_o}, a) \propto \exp\{-\frac{1}{2}\sum_k \sum_{\mathbf{r}} \frac{|\Delta(\mathbf{r},k) - a\,p(\mathbf{r},k;\mathbf{r_o})|^2}{\sigma^2(\mathbf{r},k)}\}$

By maximizing its logarithm:

→ **Flux estimation** → « Flux map »: Gives the flux of a companion ***if*** it has this pixel position

→ **Position estimation** → « Detection map »: Gives the probability of a companion to be on this pixel position = probability map / SNR map



Enables automatic detection!

Beta-Pictoris b: NaCo data (2013) using the AGPM vector vortex coronagraph [3], [4]

Beta-Pictoris b: perfect test-case for the method
-Well characterized point source,
-At short angular separation,
-AGPM provides the best inner angle for its time,
-Can investigate for closer companions.

1- The data set:

1.1: VLT/NaCo-AGPM data

+

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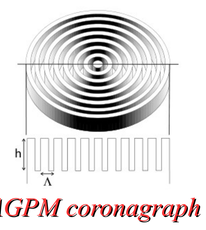
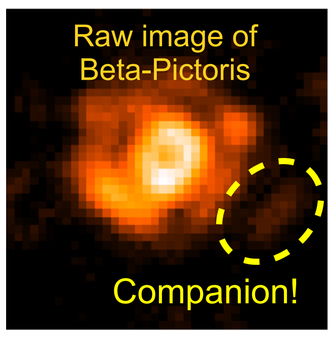


AGPM coronagraph [3]

Observation date	Duration	Filter	Pixel scale
31/01/2013	3h30	L' (3,8 µm)	27,15 mas/px

1.2: Beta-Pictoris observation

Image size	Number of images	Parallactic angle span	Imaging conditions
70 x 70 pixels	29054 (total) 24726 (sorted out)	83,7° (-15,6° → 68,1°)	Seeing ~ 1'' τ_0 ~ 2ms



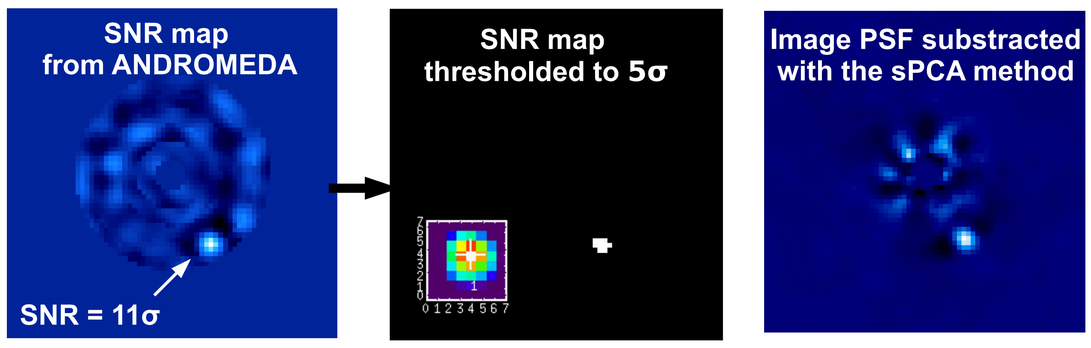
Error source	value
Profil AGPM hors-axe	$0.024mag$
Variation de la PSF	$0.05mag$
PCA : Figure de mérite	$0.15mag$
ANDROMEDA : Erreur robustesse	$0.05mag$

← Astrometry errors

Error source	value
Erreur sur position source	$8.5mas$
Erreur sur centering PSF	$0.1mas$
Erreur sur la calibration (platescale)	$0.04mas$
PCA : Erreur statistique (figure de mérite)	$4.5mas$
ANDROMEDA : Erreur robustesse de l'algo	$2mas$

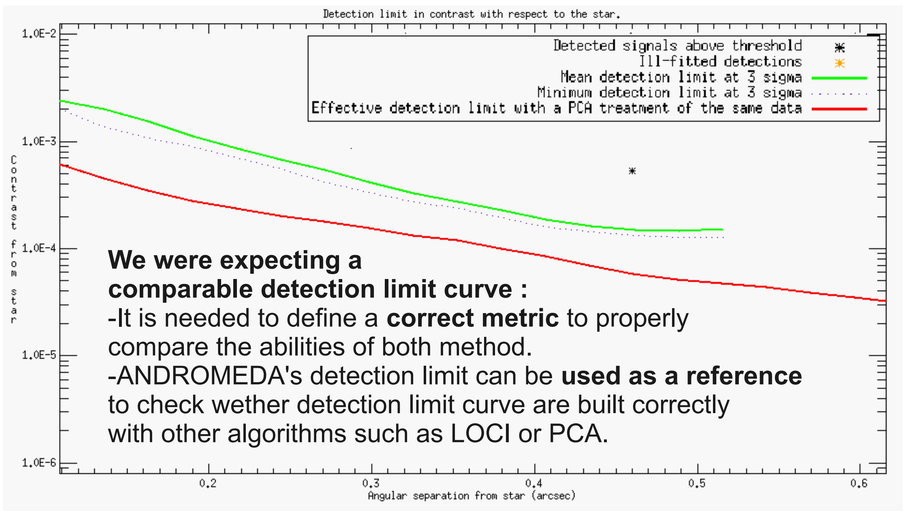
← Photometry errors

2- ANDROMEDA vs sPCA:



Parameter	Sorted out images	sPCA results
Number of images	24726	29054
Separation (mas)	459.94 ± 9	452 ± 10
PA (deg)	207.8 ± 0.5	211.2 ± 1.3
ΔL' (mag)	8.18 ± 0.07	8.01 ± 0.16
Total processing time :	*~20min*	*~20min*

*the image cube is cleaned of its bad SR images



References

- [1] Mugnier et al., *Optimal method for exoplanet detection by angular differential imaging.* J. Opt. Soc. Am. A, 26(6):1326–1334, June 2009.
- [2] Cantalloube et al. (in prep)
- [3] Mawet et al., *Annular Groove Phase Mask Coronagraph*, ApJ, 633, 1191, 2005.
- [4] Absil et al., *Searching for companions down to 2 AU from β Pictoris using the L'-band AGPM coronagraph on VLT/NACO.* A&A, 559, L12, Novembre 2013.

Conclusion

-ANDROMEDA's principle (using **inverse problem**) is very different to the other widely used algorithms such as LOCI or PCA; It is thus **complementary** to these methods;
-Thresholding the probability map by a constant gives the **confidence level** of the detection;
-It also enables to perform an **automatic detection** along with an efficient **artefacts rejection**;
-**Direct flux retrieval** from the flux map which is a brand new feature in exoplanet imaging;
-Speed & accuracy of the results due to the realistic model of noise taken into account.