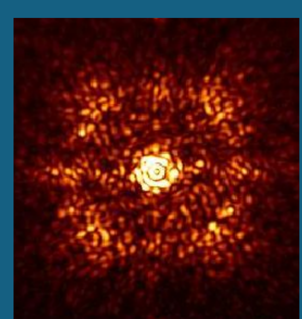
Inverse-problem VERSUS PCA-based algorithm for astronomical images

One Problem, Many Algorithms: Guiding Astronomers to the Best Choice

Problem overview

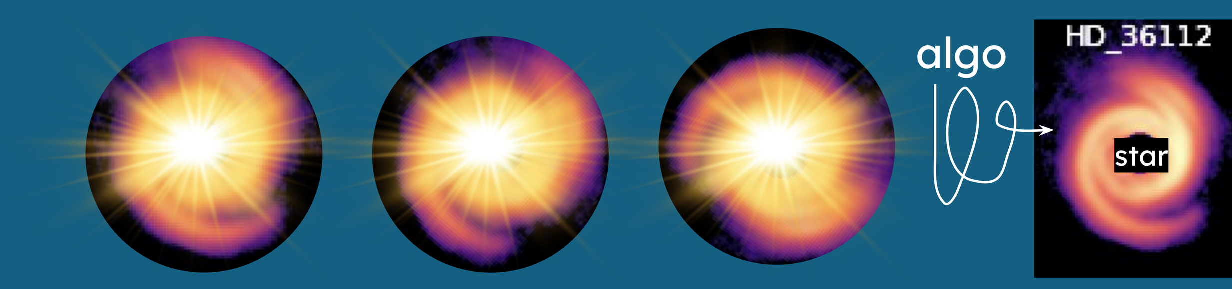
In high-contrast imaging (observing faint objects near bright stars), images are corrupted by **speckles** caused by atmospheric turbulence and instrument imperfections.

These speckles can be as bright or brighter than the observed object. Speckles from the Very Large Telescope →



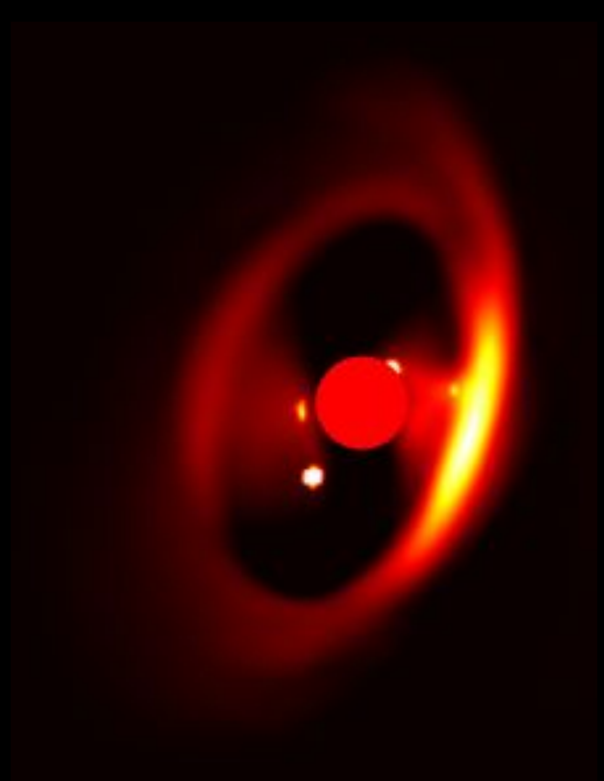
Angular diversity is a strategy that introduces a lever (diversity), which the algorithm uses to retrieve the object and cancel the speckles.

It consist to not compensate for Earth's motion, and let the sky view rotated overnight. This perceived motion affect the observed object, but not the speckles, thus creating diversity.

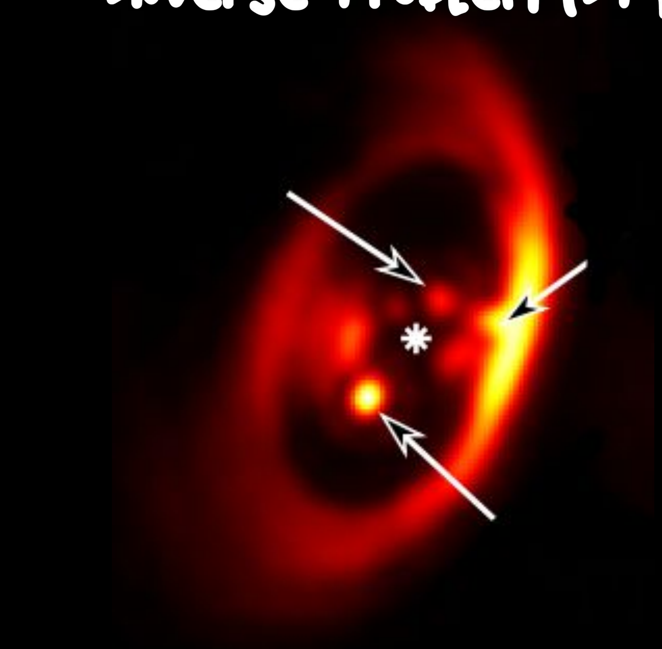


The three disk images are rotated differently, but the speckles, represented by a yellow halo, remain fixed in orientation.

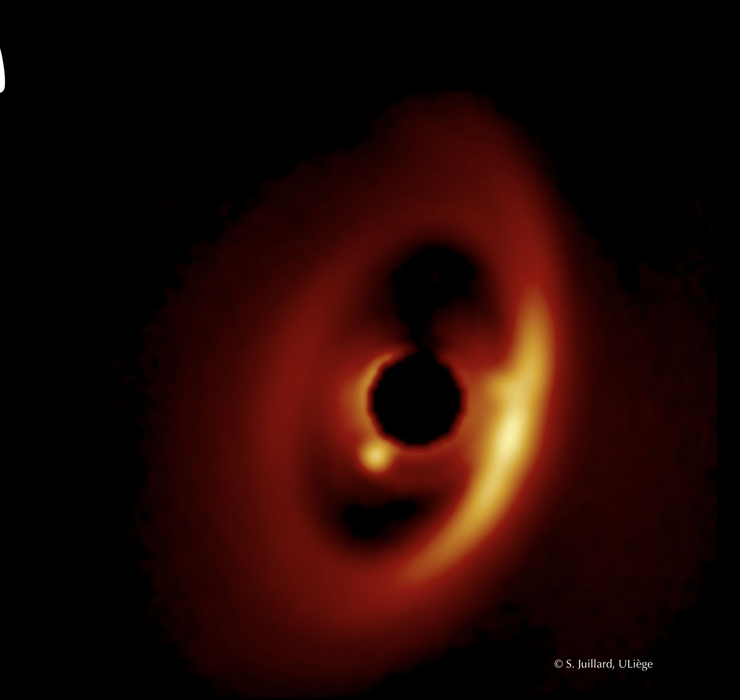
Inverse Problem (IP)



MAYONNAISE (Pairet 2021; shearlet fitting after Iterative-PCA).

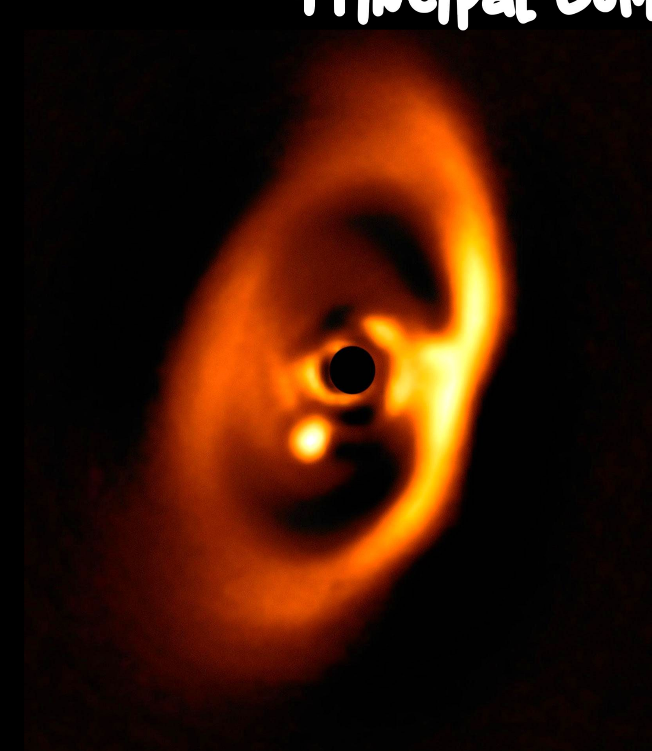


REXPACO (Flasseur 2021; patch-based noise statistics),

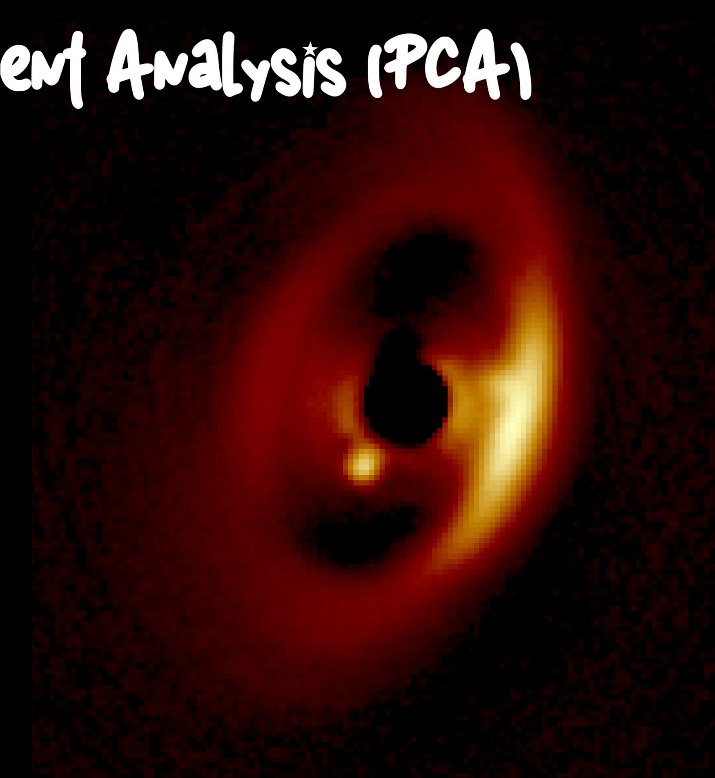


MUSTARD (Juillard 2022; rotation invariant speckle regularization),

Principal Component Analysis (PCA)



PCA (One of the most commonly used technics for this task)



Iterative-PCA (Pairet et al. 2021; iteratively do PCA while removing unique disk features at each step,

All of these images have been created from the same dataset of the PDS-70 disk, using different algorithms.
This raises the question: Which one is closest to the truth?

Model
Can I trust it ?

- **Angular diversity have a core ambiguity**
rotation-invariant components are indistinguishable from rotation, so the strategy alone can't differentiate between disks and speckles. Consequently deformation of extended signal will appears.
- **Speckle field is hard to describe**, consisting of bright, slowly moving structured light dots. PCA, often called **'black boxes,'** offers an abstract but practical way to model speckle fields and its variability.

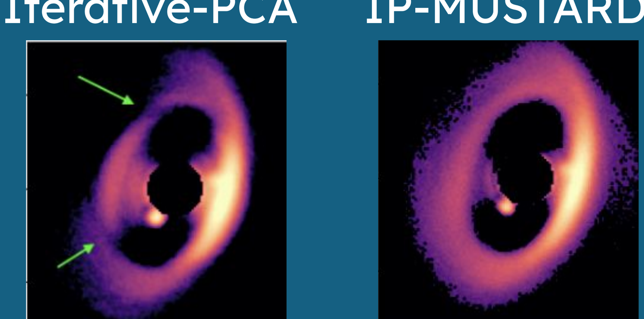
Practibility
Is it easy to use ?

- **Tuning parameters can be daunting**, especially when they have a significant impact (e.g., IP-MUSTARD requires defining the speckle profile, and IP-MAYO requires setting the number of planets and number of shearlets components). PCA-based methods also need parameters (e.g., rank), but are typically easier to define.

Performance
Does it work well ?

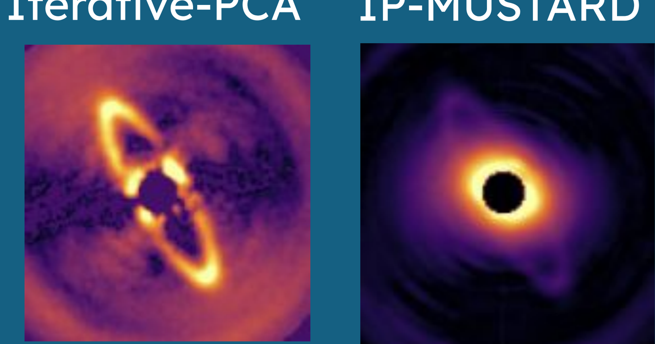
- We tested the algorithms in various scenarios to assess their robustness, using 60 test datasets with different speckle fields (stable, unstable, poor stellar light extinction, and atmospheric noise) and disk types (shape, size, and brightness levels, from bright to faint)

Iterative-PCA IP-MUSTARD



- MUSTARD's IP approach regularizes flux invariant to rotation, correcting deformation of bright disks in steady datasets.

Iterative-PCA IP-MUSTARD



… but PCA has a broader scope of validity, whereas other methods fail if priors, noise statistics, or models are inaccurate.

Images from (Juillard et. al. 2023).
Scan QR code to know more.

CONCLUSION : **In challenging environment a abstract model like PCA is better than a approximative model.** The lack of strong guarantees is inevitable in such environments, and abstract models are perfectly valid in this context.

Establishing an appropriate strategy is the best way to ensure reliability and result quality. In our case, ambiguity arises with circular components, data-driven solutions, such as using reference stars, are preferred.

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