# Post-Facto image restoration after AO imaging

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- What?
  - Restoring images acquired with AO on
- Why?
  - Anisoplanaticity
  - To correct the higher orders
  - To correct low order residuals
- How?
  - Deconvolution techniques
    - Speckle imaging
    - Phase Diversity
    - Multiframe Blind Deconvolution
    - } Multi-Object Multiframe Blind Deconvolution
- So?
  - Some implementations and examples from post-facto restoration

# Image reconstruction of extended sources

The goal of the data reconstruction is to reproduce the true source distribution of the observed field.

When dealing with imaging, this includes:

- The spatial distribution of the sources
-
- The relative brightness of the individual objects
-
- The shape of the sources
-
    - → Restore the spatial frequencies down to the diffraction cut-off in the whole FOV for the whole data series

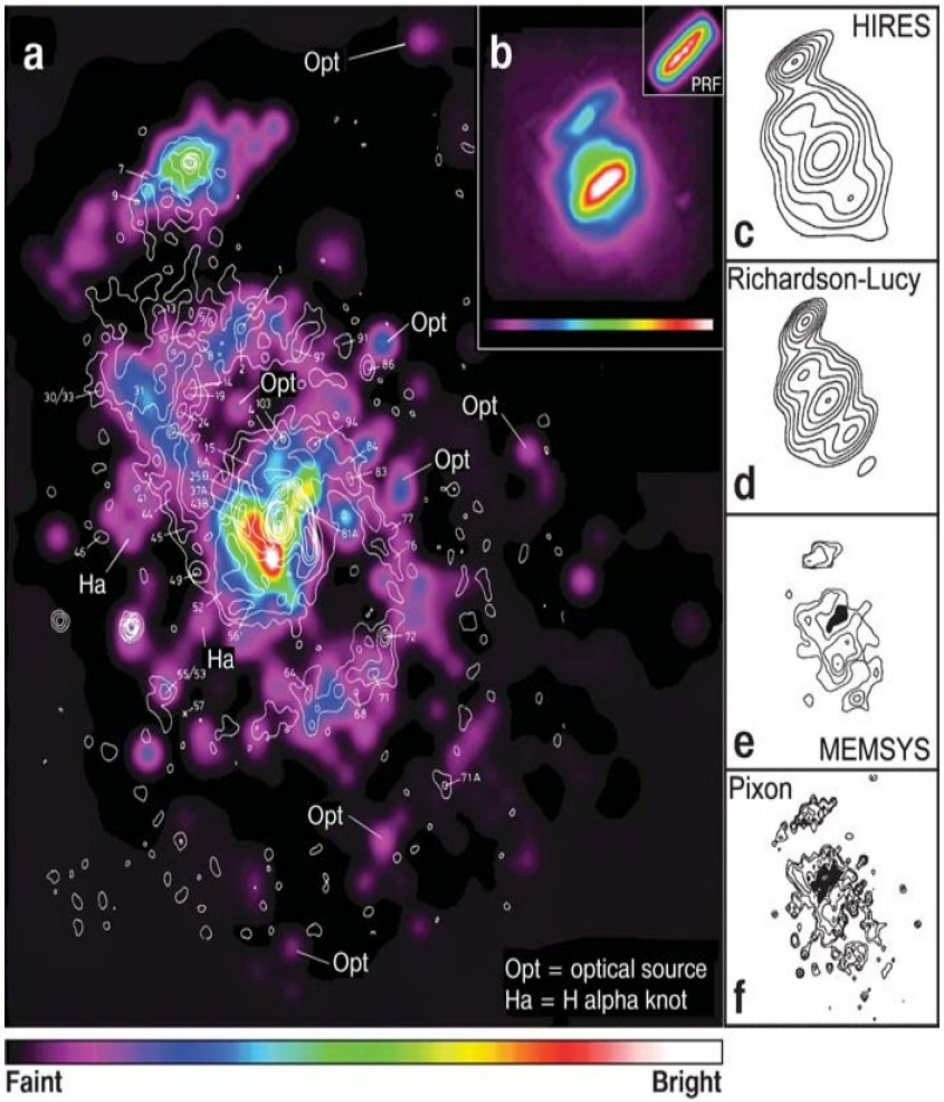
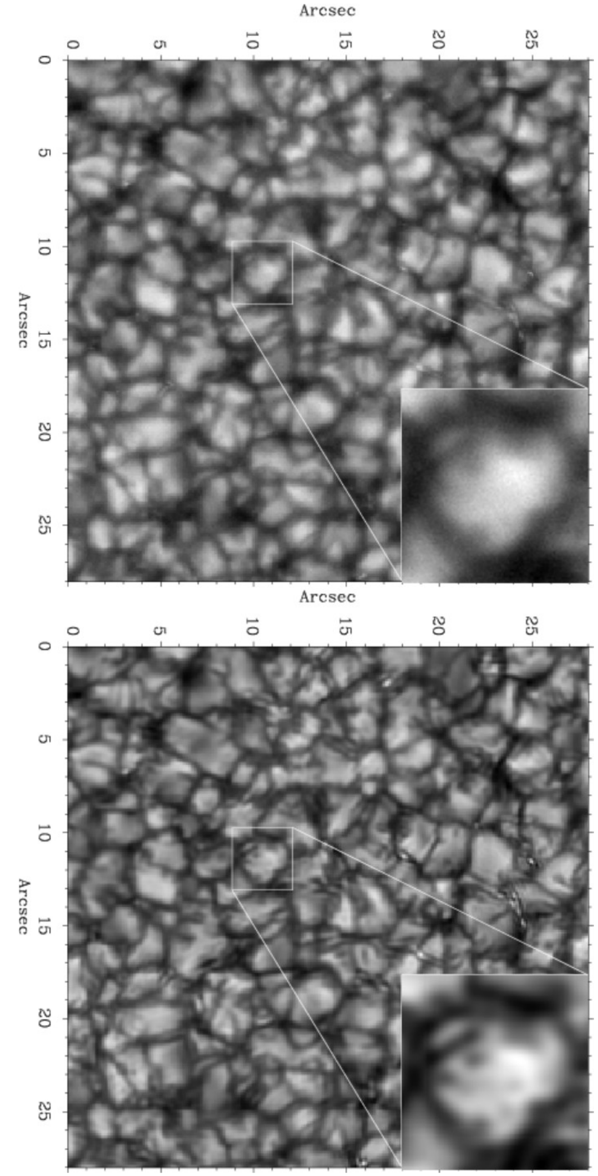


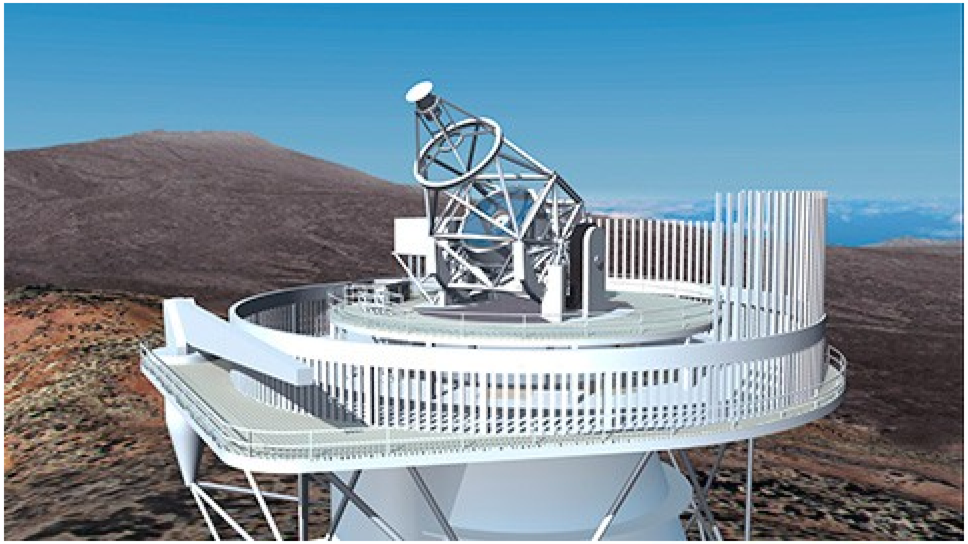

**Figure 5** Variety of image reconstructions of 60 $\mu$m scans of the galaxy pair M51/NGC5195 taken by the *Infrared Astronomical Satellite* (Bontekoe et al. 1991): (*a*) false color image of the Pixon reconstruction in (*f*) overlaid with 5 GHz radio continuum contours (van der Hulst et al. 1988), (*b*) coadded input data with the point-response function on the same scale in an insert, (*c*) NASA high-resolution reconstruction, (*d*) Richardson-Lucy reconstruction, (*e*) maximum-entropy reconstruction, and (*f*) Pixon reconstruction. Objects identified in optical images are also marked in (*a*): (Opt) stars, (Ha) $H\alpha$ emission knots. The black patches in (*e*) and (*f*) represent zero intensity. The scales of panels (*a*), (*b*) and (*c*)–(*f*) are unequal and in the ratios 1.0 : 0.18 : 0.28.

# Image reconstruction of extended SOLAR sources

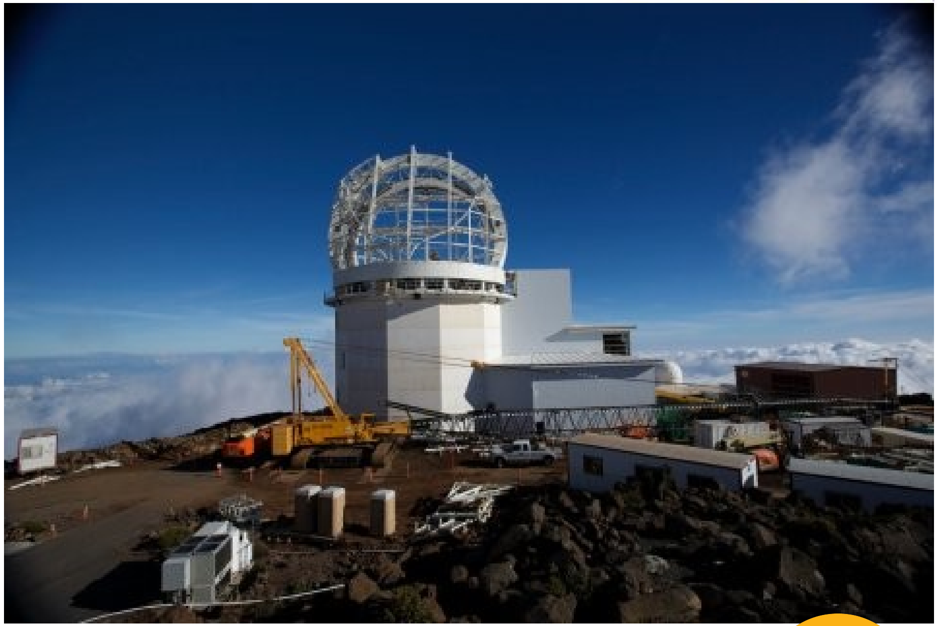
- Staring at **the Sun**:
  - Extended sources
  - Low contrast
  - Evolving
  - Strong seeing evolution
  - Strong anisoplanatism
- **AO struggles**:
  - Lock point loss
  - Image quality variation during obs and along FOV
  - BUT **tons of photons**!



# Image reconstruction of extended SOLAR sources

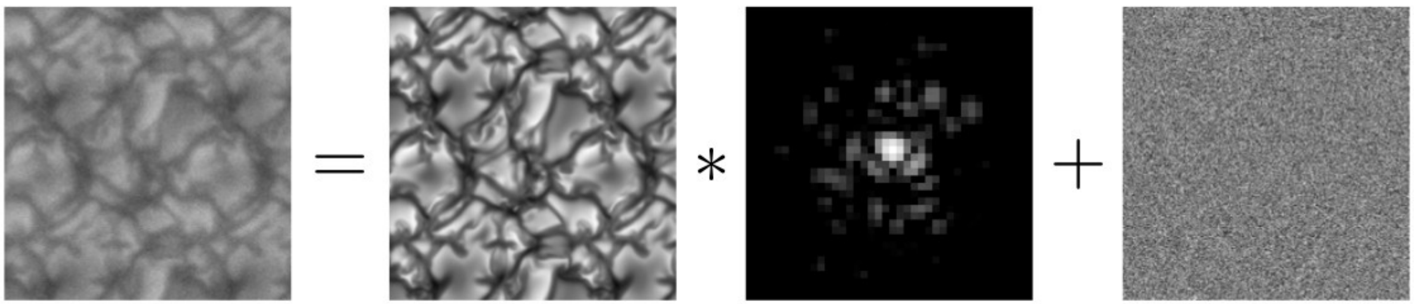


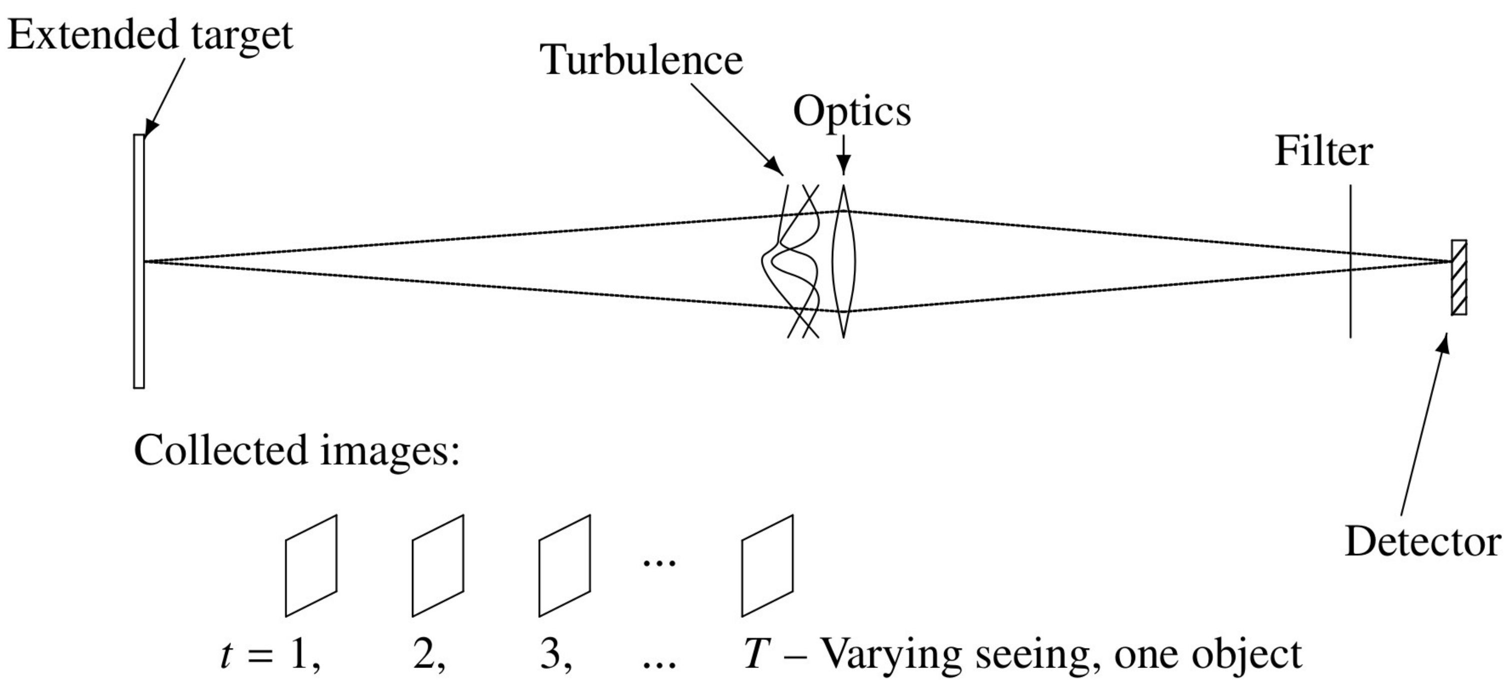
- Staring at the Sun:
-
  - **Tons of photons!**
  - **Even more** with the **upcoming 4m class** telescopes
  -
  -
- But **even stronger** anisoplanatism →
  - Image quality variation during obs and along FOV



# Image formation model:

$$i_t = f * psf_t + n_t$$



# Image formation model:

$$i_t = f * psf_t + n_t$$

$$psf_t = |\mathcal{F}^{-1}\{ P_t \}|^2$$

$$P_t = A\, exp(\, \mathrm{i} \Phi_t \,)$$

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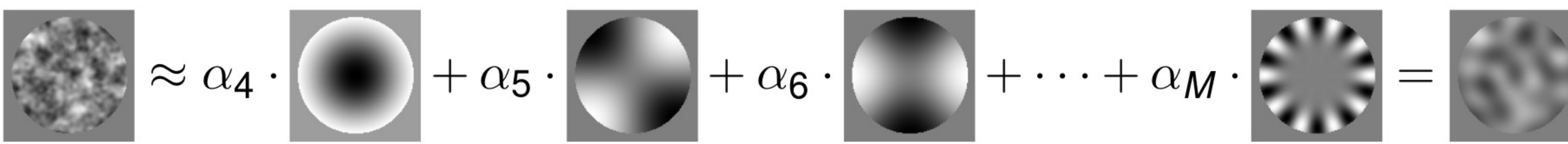
$$psf_t = |\mathcal{F}^{-1}\{ P_t\}|^2$$

$$P_t = A\, exp(\, \mathrm{i}\Phi_t )$$

$$\Phi_t \approx \Sigma_m \,(\alpha_{mt}\, \varphi_m) = \Phi^{ext}_t$$



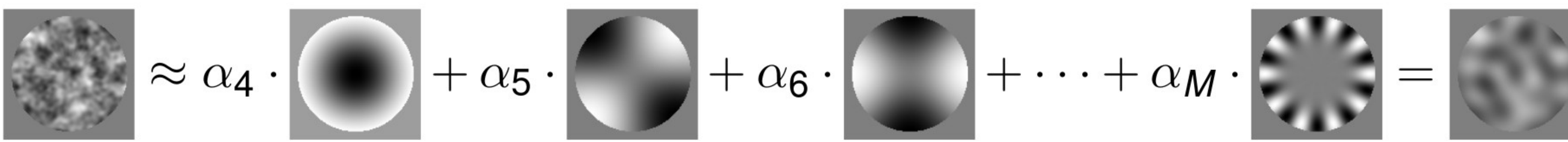
# Image formation model:

$i_t = f * psf_t + n_t$ image

$psf_t = |\mathcal{F}^{-1}\{ P_t \}|^2$ psf

$P_t = A \exp( \mathrm{i}\Phi_t )$ *Pupil Function*

$\Phi_t \approx \Sigma_m (\alpha_{mt}\ \varphi_m) = \Phi^{ext}_t$ *Pupil Phase*

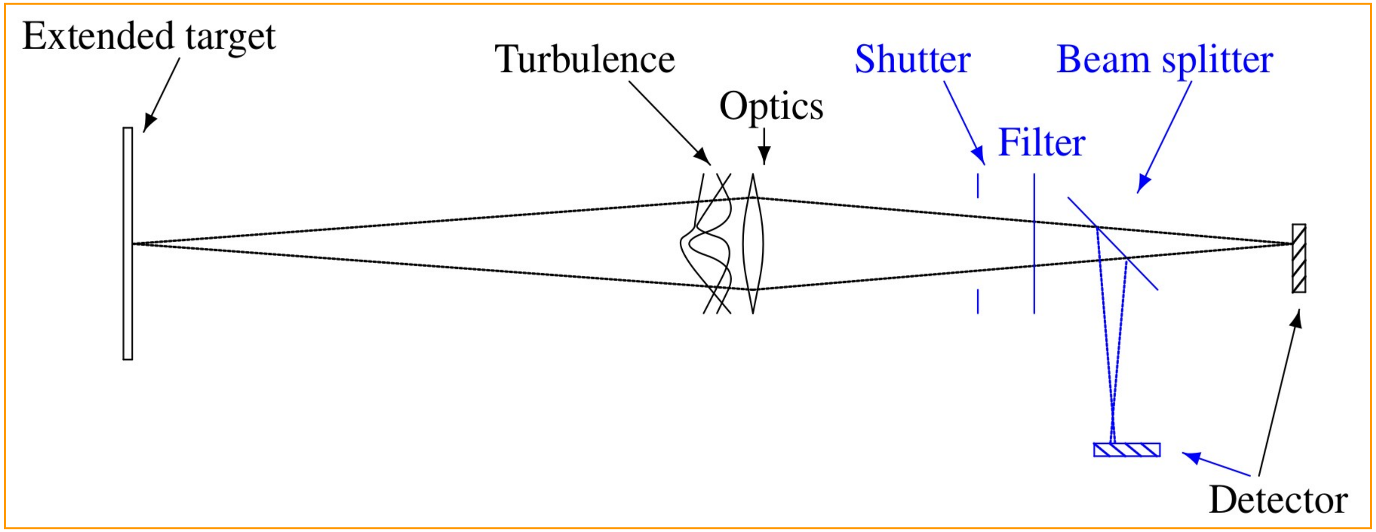



Find the minimum difference between the data and the model data:

$$min_\alpha ( \Sigma_t \Sigma_{pixel} |i_t - f^{ext} * psf_t^{ext}|^2 )$$

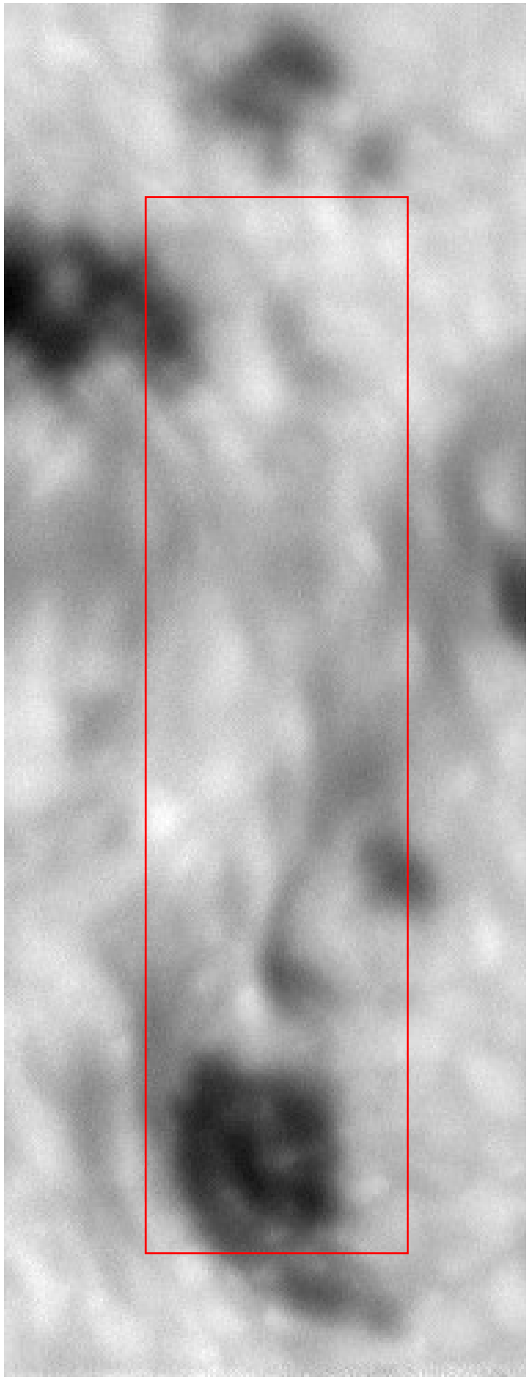
Search for the $\{\alpha_m\}$ set.

# Phase Diversity

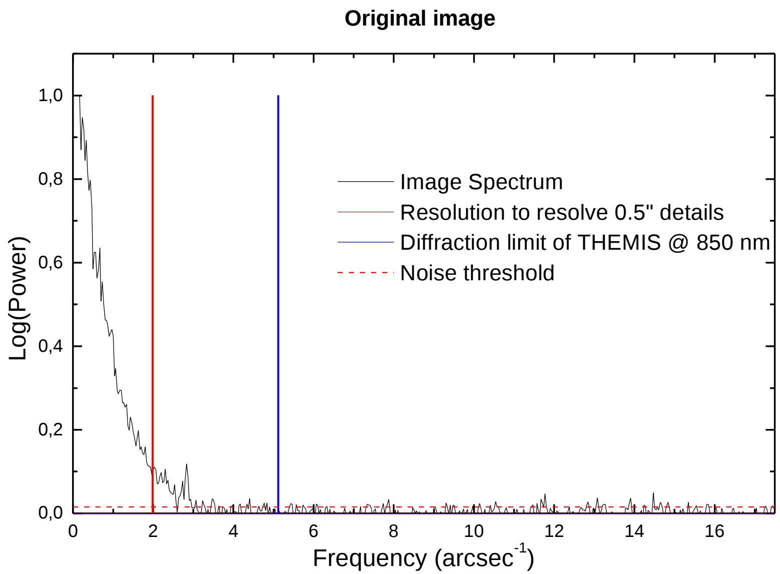


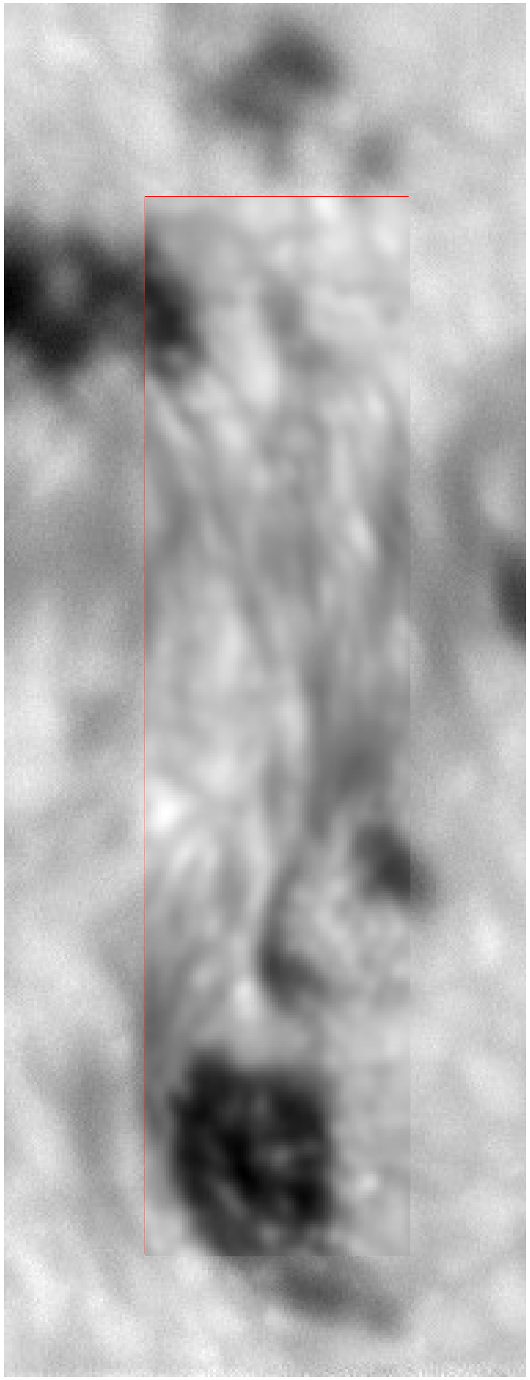

**Two** images!

1) $i_f$ **focused +** $i_d$ **defocused;**
2) **same and simultaneous exposure;**
3) **same pixel scale;**
4) **same light path;**
5) **aligned;**
6) **exposure time < atmospheric coherence time**

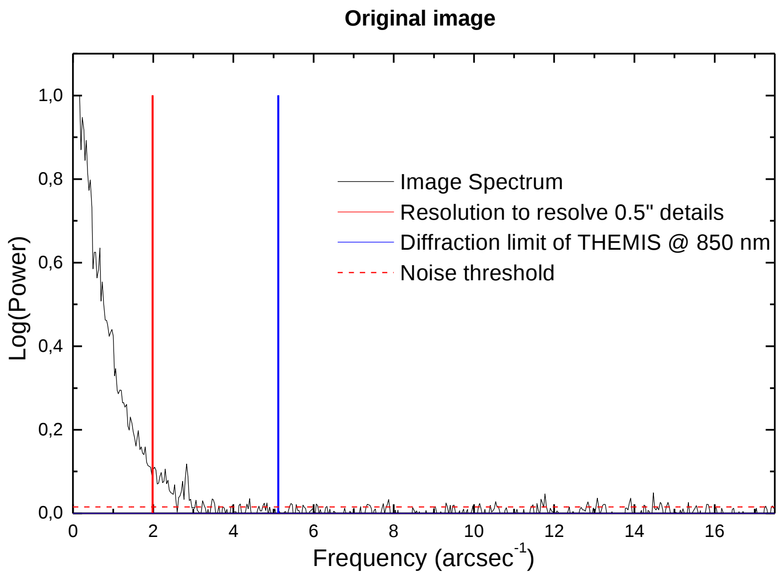


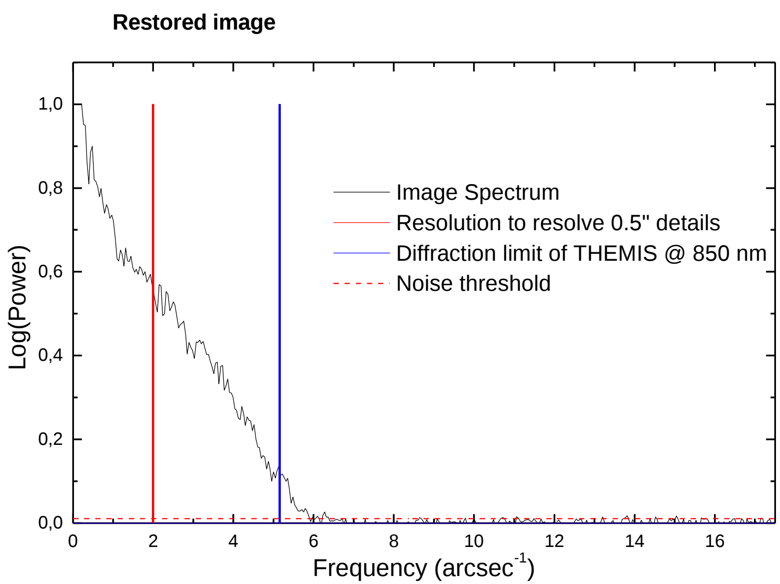
Original image acquired at THEMIS (90cm)



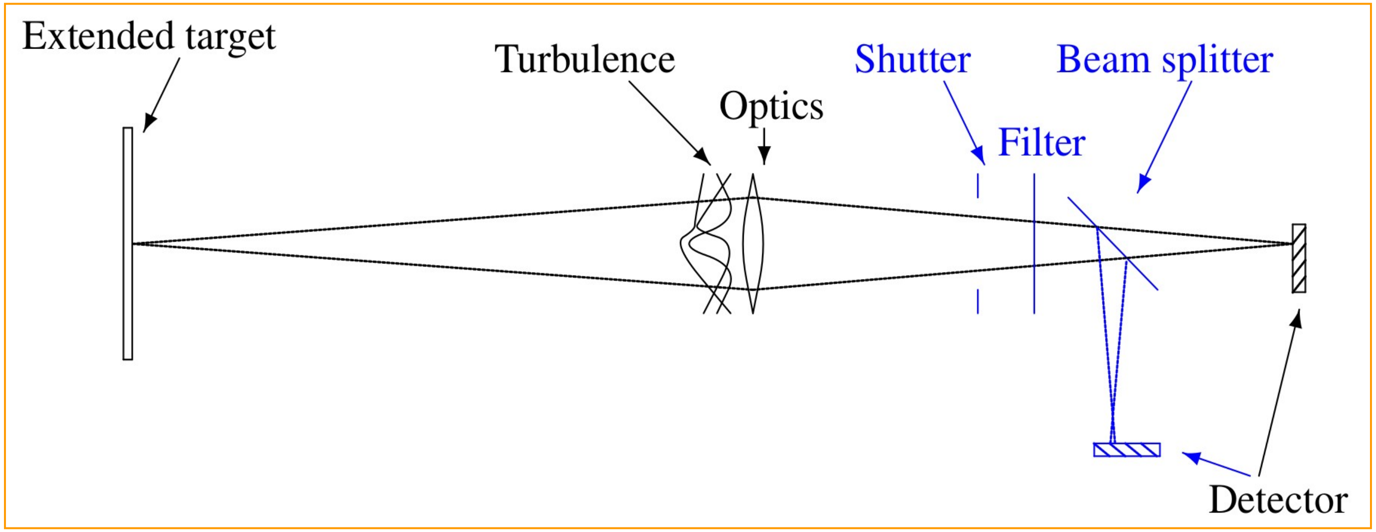


# Restored image



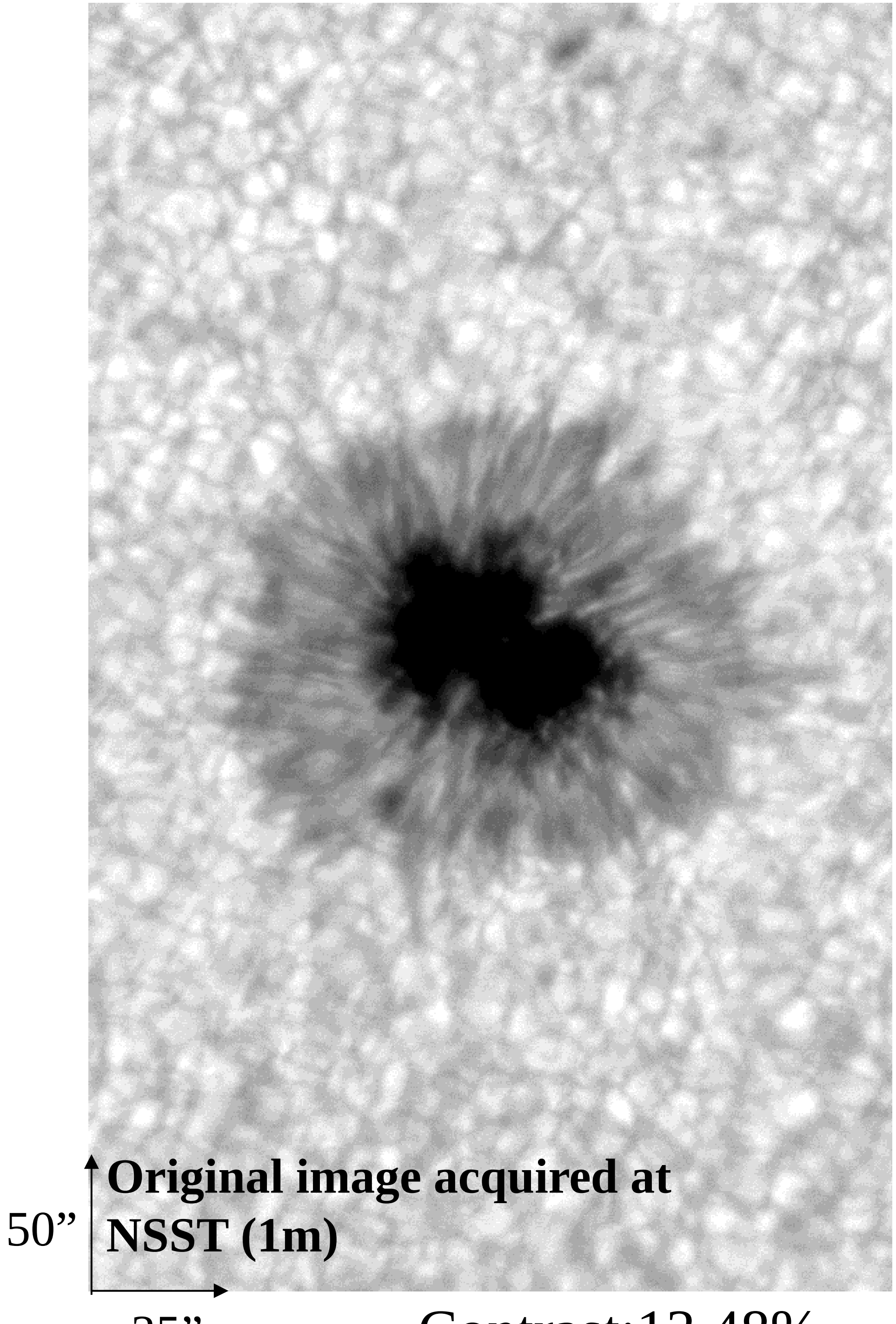



# Multiframe Phase Diversity

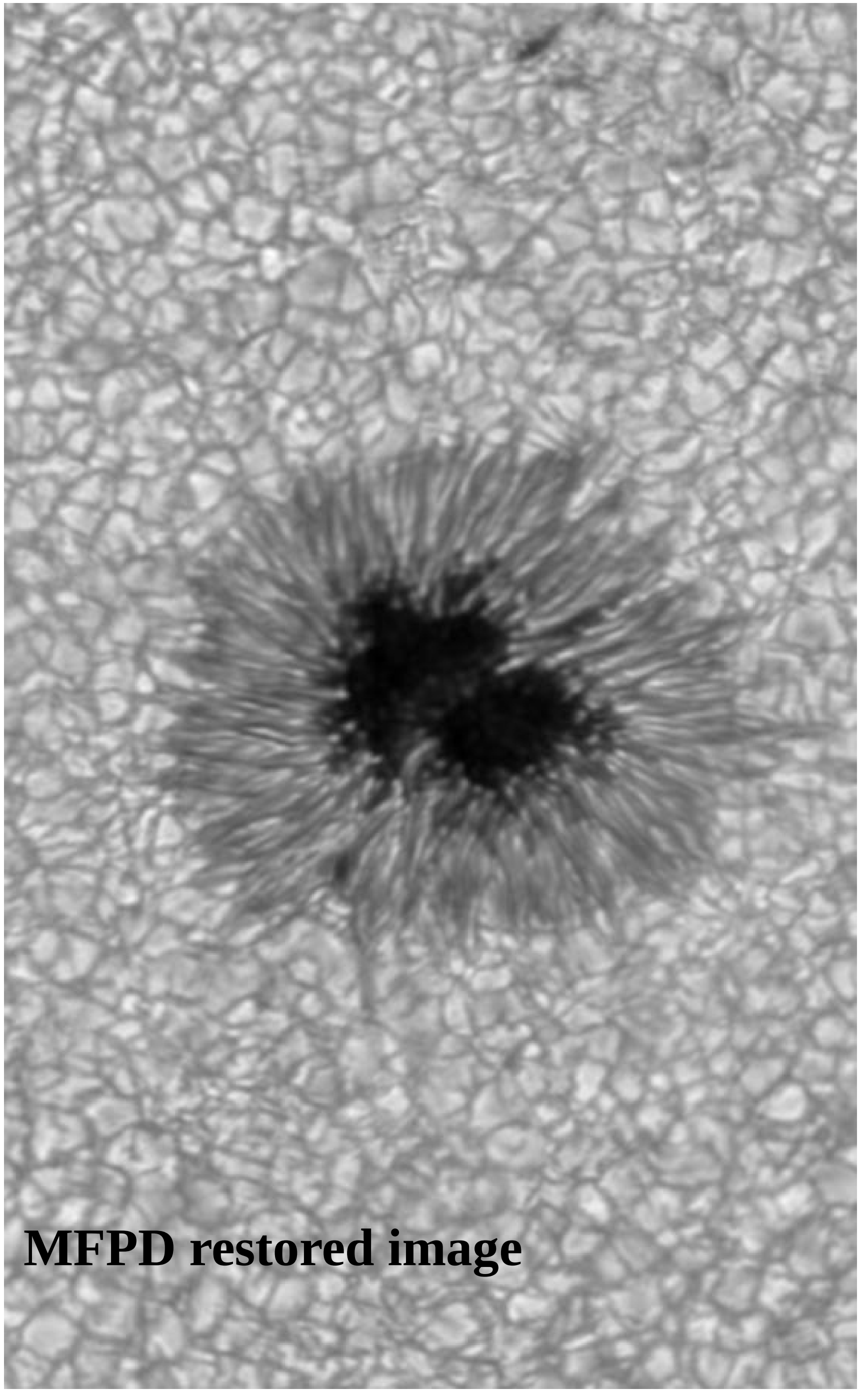



OR two **sets** of images!

1) $i_{f,t}$ focused + $i_{d,t}$ defocused;
2) same and simultaneous exposure;
3) same pixel scale;
4) same light path;
5) aligned;
6) exposure times < atmospheric coherence time

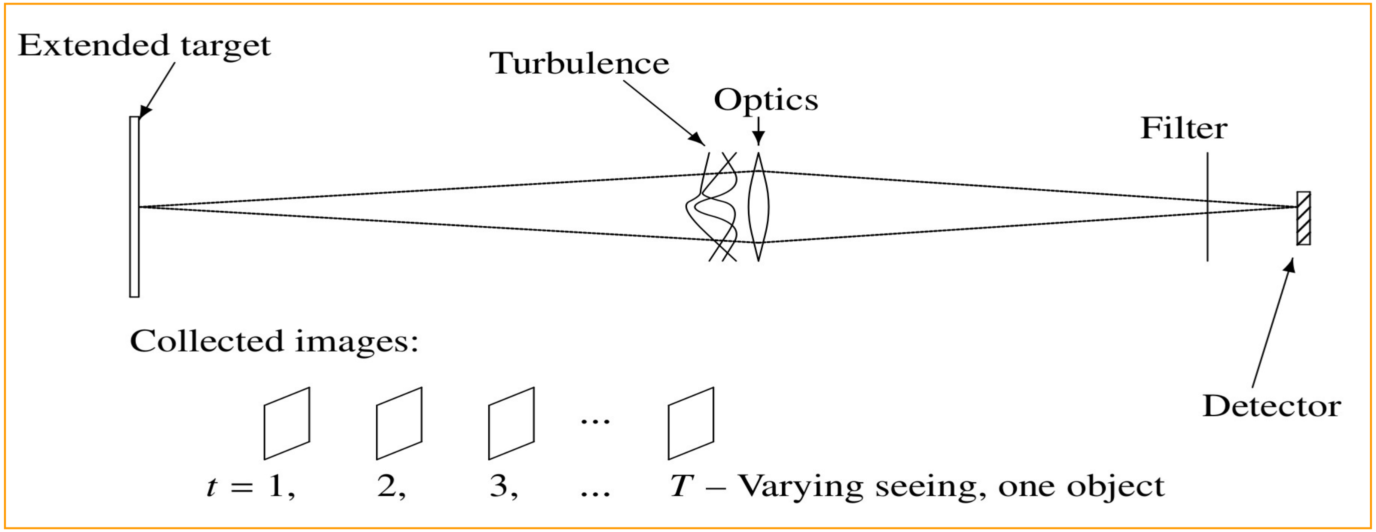



Contrast:13.48%




Contrast: 17.84%

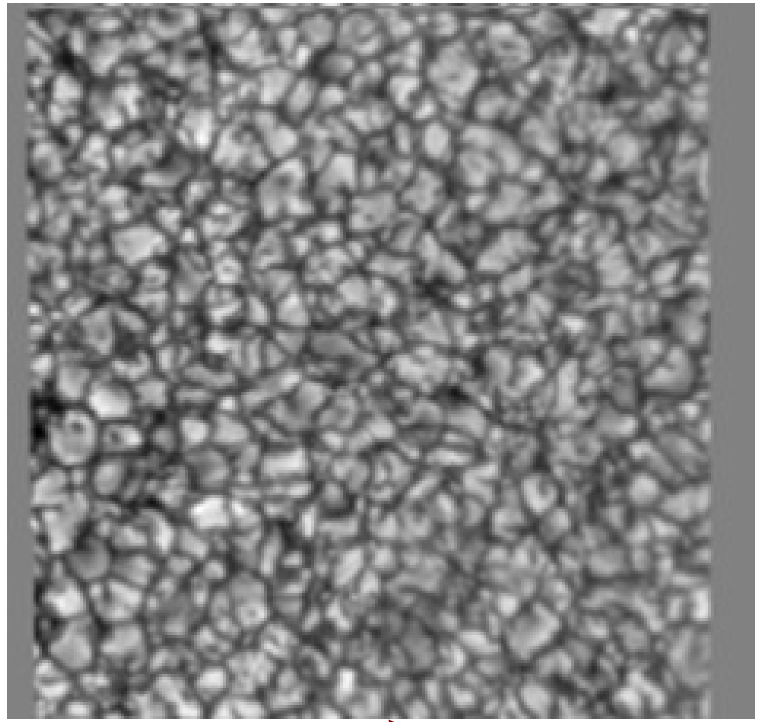
# Multiframe blind deconvolution

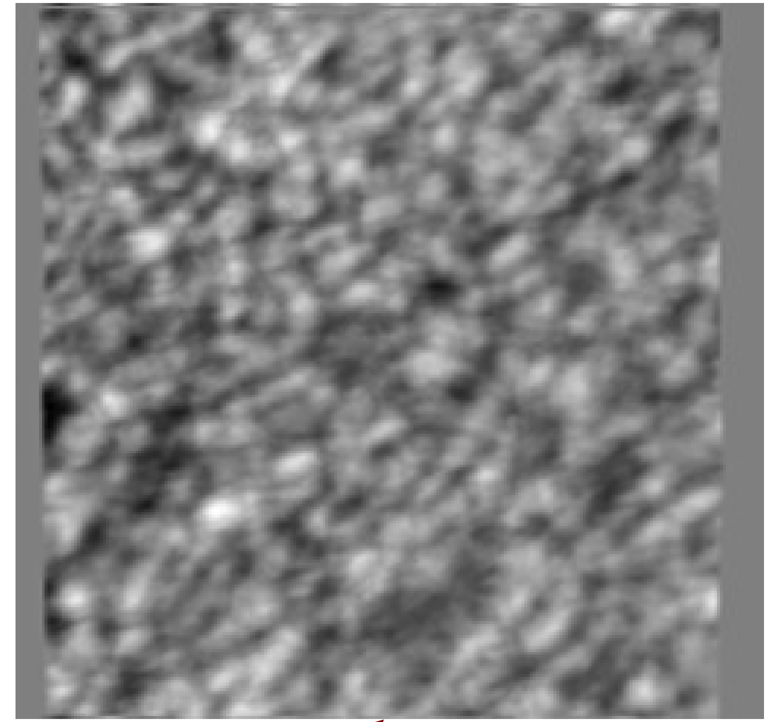


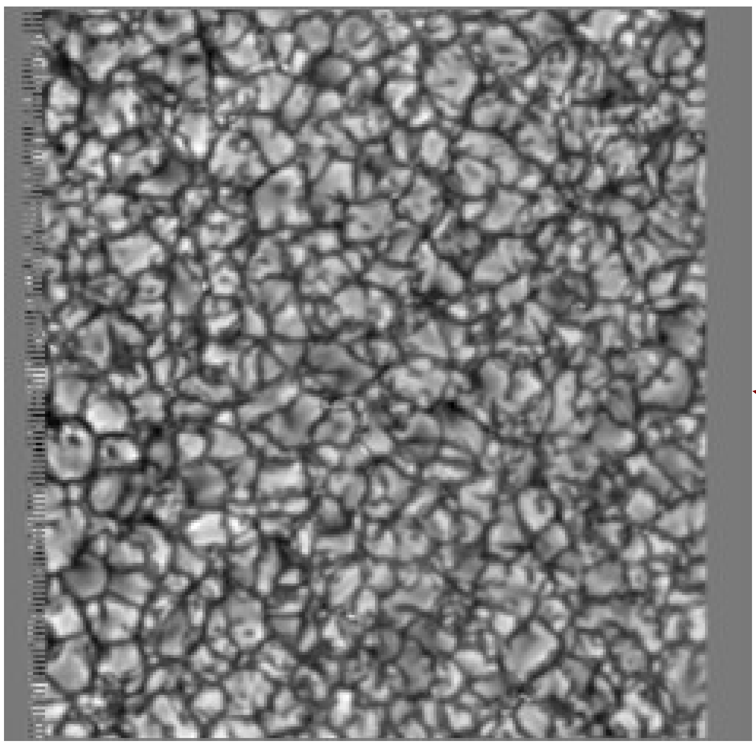

OR **one set** of images!

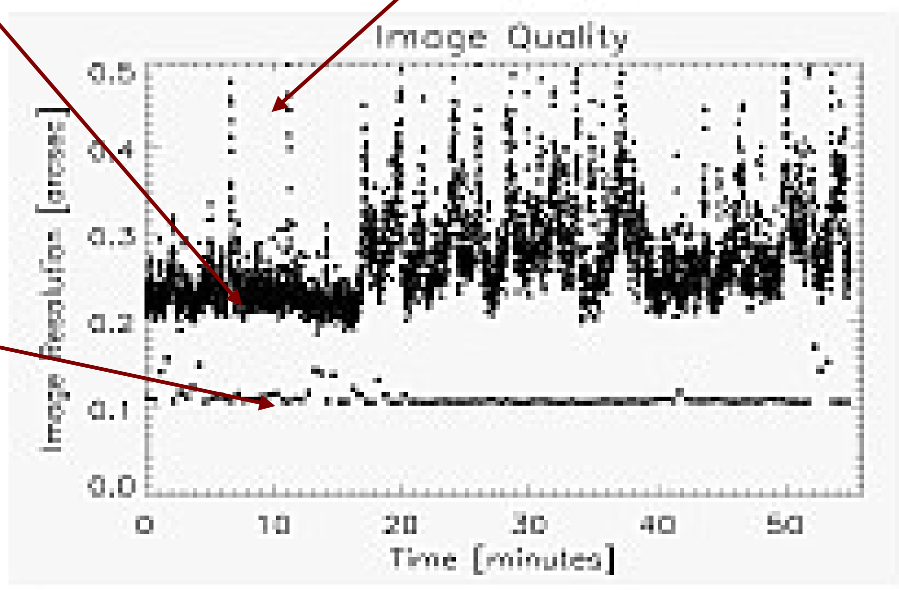
1) **$i_{f,t}$ focused ;**
2) **~~same and simultaneous exposure~~;**
3) **~~same pixel scale~~;**
4) **~~same light path~~;**
5) **~~aligned~~;**
6) **exposure times < atmospheric coherence time**

**Multi-Frame-Blind-Deconvolution Continuum @709 nm**

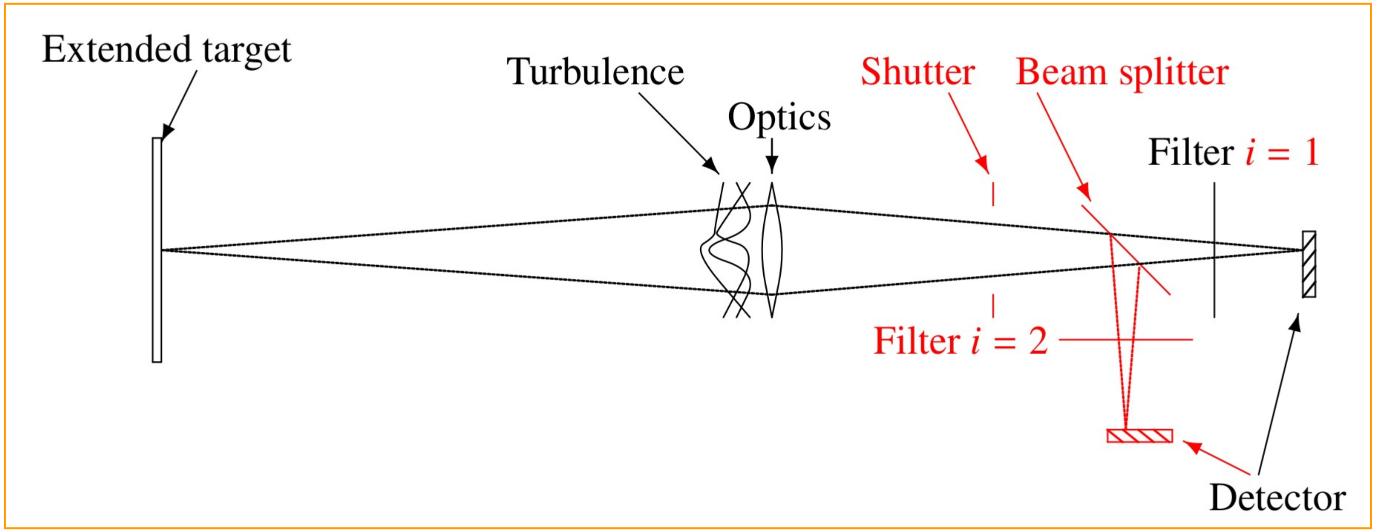






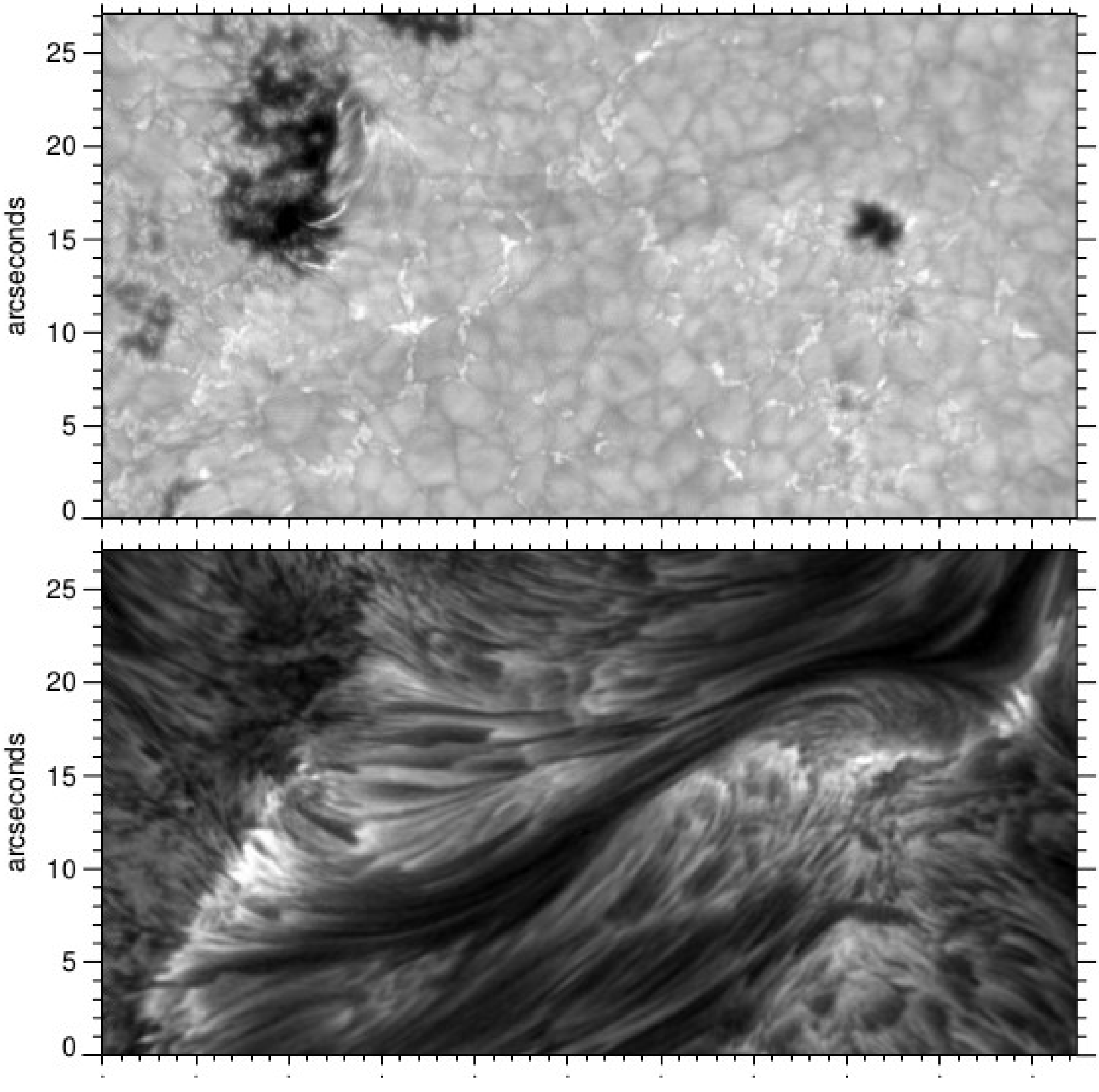


# Multi-object multiframe blind deconvolution




OR **two sets** of images of **different objects**!

1) **$i_{1,t}$ red filter + $i_{2,t}$ blue filter;**
2) **same and simultaneous exposure;**
3) **same pixel scale;**
4) **same light path;**
5) **aligned;**
6) **exposure times < atmospheric coherence time**


arcseconds
0
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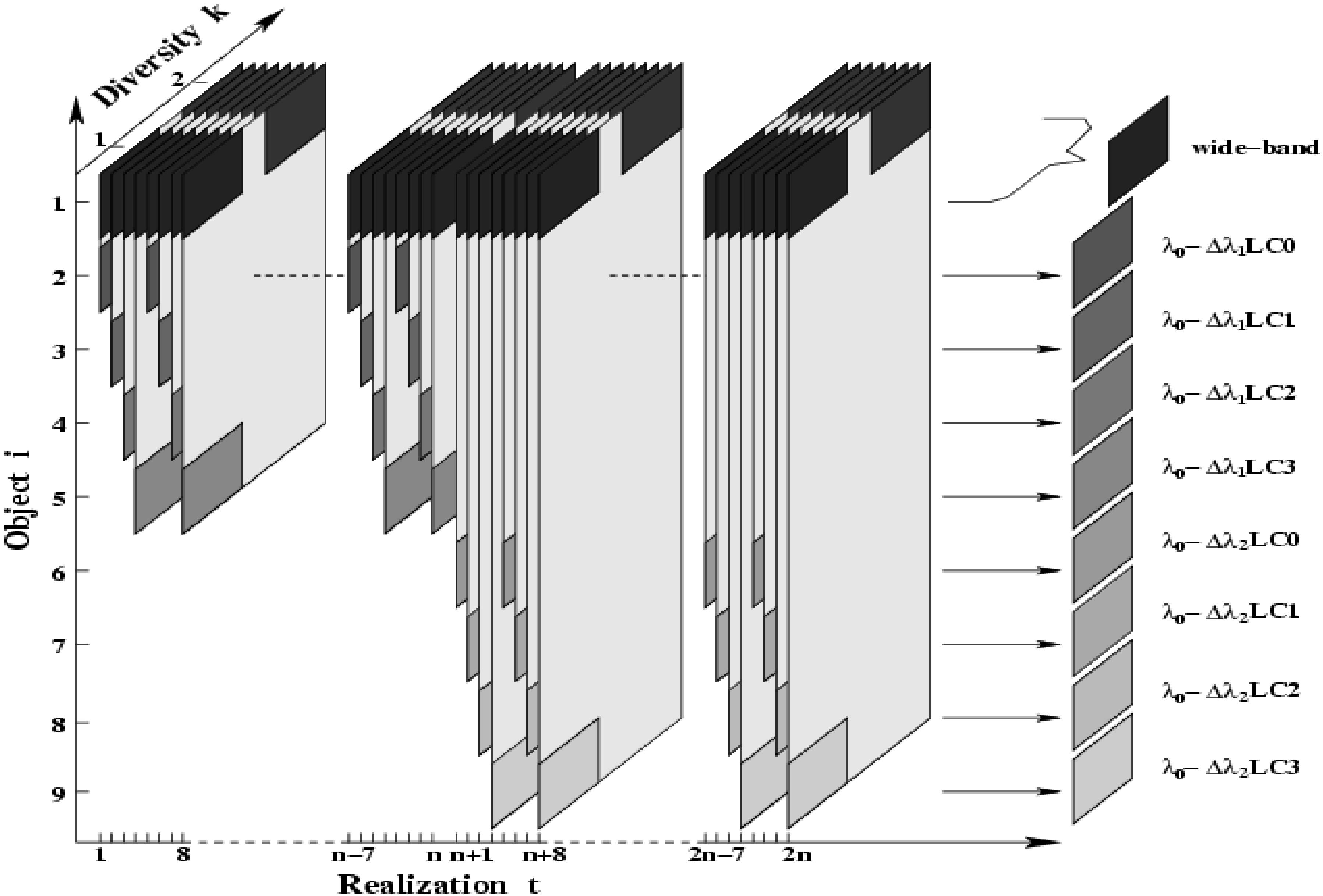
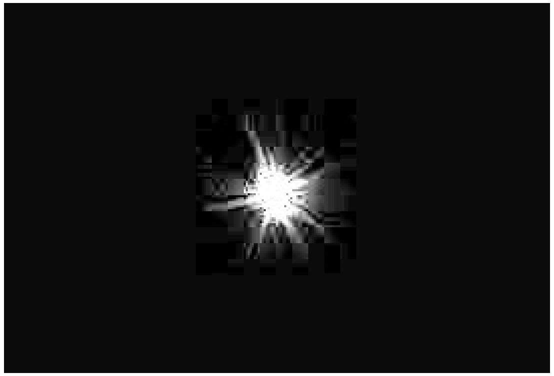
15
20
25
arcseconds
0
5
10
15
20
25


Diversity k
1
2
Object i
1
2
3
4
5
6
7
8
9
Realization t
1
8
n−7
n n+1
n+8
2n−7
2n
wide−band
λ0− Δλ1LC0
λ0− Δλ1LC1
λ0− Δλ1LC2
λ0− Δλ1LC3
λ0− Δλ2LC0
λ0− Δλ2LC1
λ0− Δλ2LC2
λ0− Δλ2LC3

Limits:

Limited number of modes in the pupil → limits to the psf shapes → loose contrast

Model mismatch → no convergence
→ Care for the pupil shape
→ The non-common paths
→ The mis-alignments

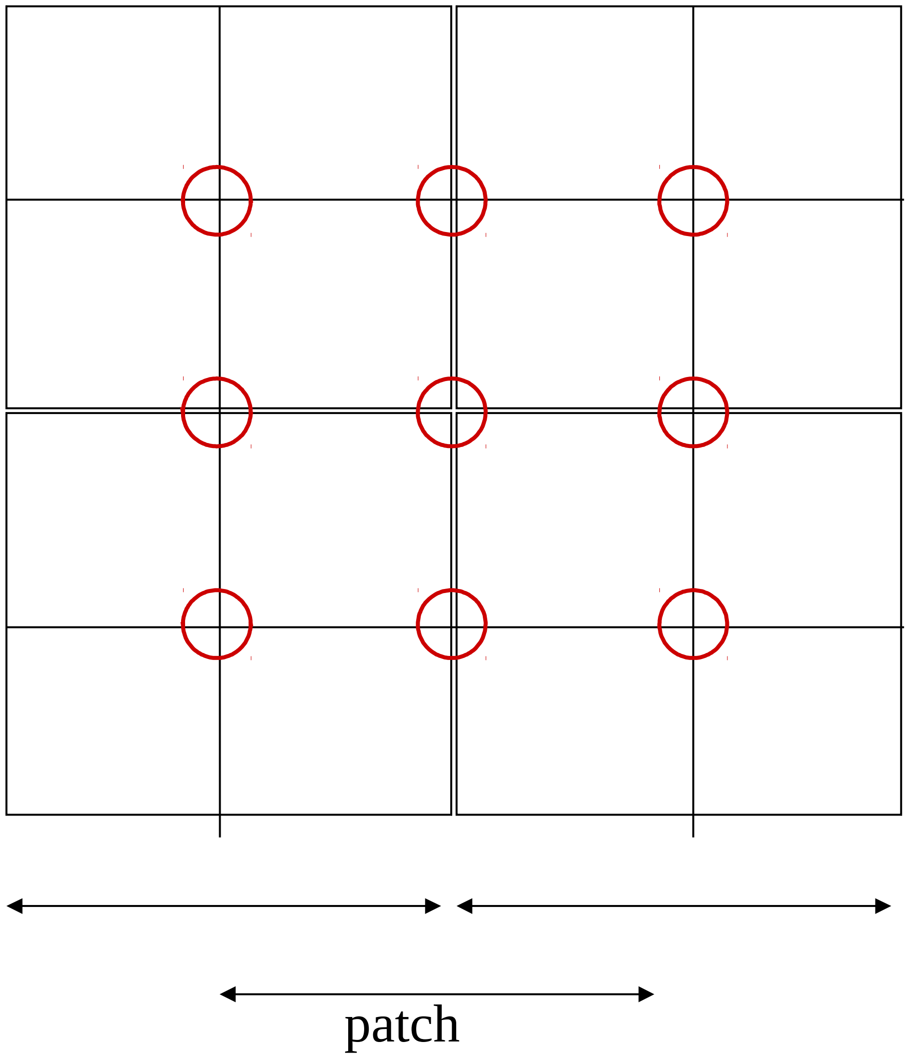


Quite **LARGE** computing needs

Day-time driver: high spatial resolution and low stray light are required for accurate magnetic field strength measurements of photospheric and chromospheric structures

Night-time driver: high spatial resolution and low stray light are required for:
Exo-planet direct imaging
Any Extended source
…
…

Thank you for the attention!




The image is divided in patches, restored and reassembled
The circles represent the centres of singles patches, which are superimposed for 50% on their neighbours.

# Image formation model:

$$i_t = f * psf_t + n_t$$

$$psf_t = |\mathcal{F}^{-1}\{ P_t\}|^2$$

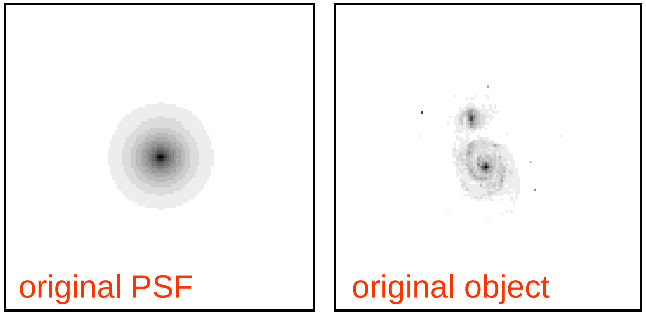
$$P_t = A\, exp(\, \mathrm{i}\Phi_t)$$

$$\Phi_t \approx \Sigma_m (\alpha_{mt}\, \varphi_m) = \Phi^{ext}_t$$

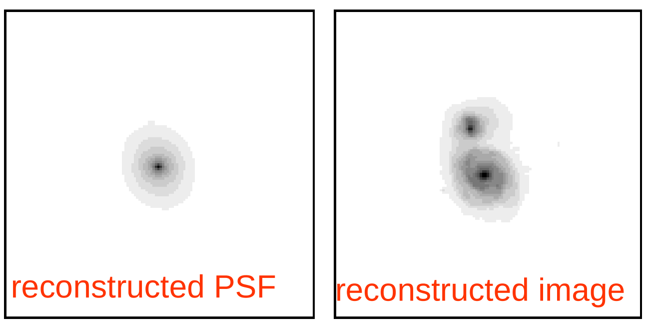
Pupil wavefront phase constraint:
***P(u)*** is the pupil, i.e. a mask of unity within the pupil support and zero outside, and ***Φ(u)*** represents the phase aberrations in the pupil plane. This replaces the PSF image and band-limit constraints by expressing the PSF as the Power Spectrum of the wavefront in the pupil, thus permitting the recovery of the phase aberrations in the pupil. It also reduces the number of possible PSFs using the band-limit constraint.

# Blind Deconvolution

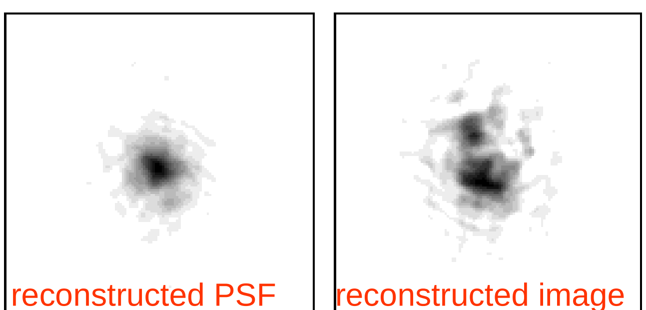
Blind deconvolution of a partially corrected noise-free image.





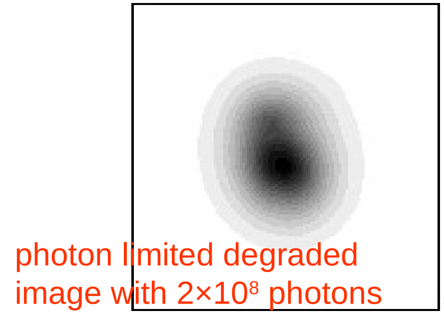


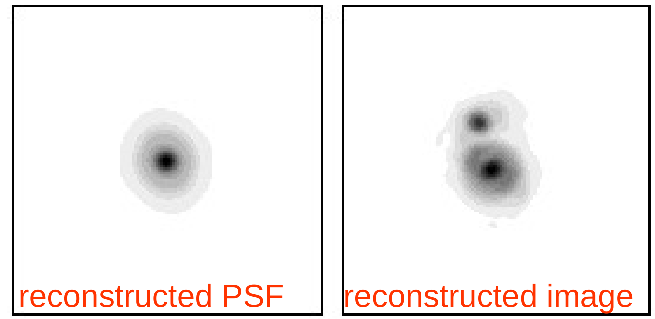

using strict positivity constraints;



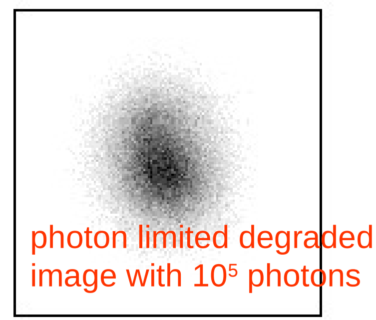

using loose positivity constraints.

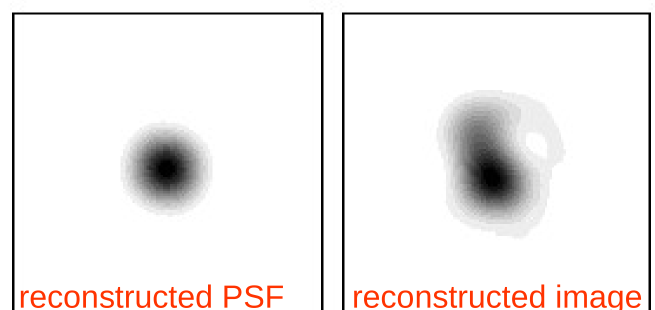
Blind deconvolution of a partially corrected image with photon noise.




using strict positivity and loose band-limited constraints ($u_c$ was set to 1/3 of telescope cut-off frequency);




using the same constraints (with $u_c$ set to 1/6 of telescope cut-off frequency).

# Post-Facto image restoration after AO imaging

**Del Moro, D.; Stangalini, M.; Berrilli, F.; Ermolli, I.; Zuccarello, F.**

The correction achieved by AO is strongly field dependent, with the correct FOV decreasing as the anisoplanatic effects grow stronger.

Even within the corrected FOV, where AO systems are designed to provide diffraction limited imaging, the physical limitations of AO systems imply that very high orders modes are not corrected. Also, the AO performance is often sub-optimal, so that the residual wave front error shows also lower order modes.

These are just a few reasons to combine image restoration techniques and AO supported observations: the image restoration can strongly enhance the performance of AO systems.

However, it must be taken into account that the AO itself modifies the statistics of the aberrations, therefore algorithms that are based on a statistical expectation of the various atmosphere realization should be modified accordingly.

Here, we present some results of the restoration post-facto of solar dataset acquired with AO correction.