First Use of Adaptive Optics Imaging to Constrain Cosmology with Gravitational Time Delays

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Outline

- Motivation
- Advantage of Adaptive Optics (AO)
- Challenge of and strategy for using AO imaging
- Blind test with mock data
- Preliminary results from Keck imaging
- Summary

H_0 provides critical independent constraints on

- nature of dark energy
- neutrino physics
- spatial curvature of the Universe

[e.g., Hu 2005, Riess et al. 2009 and 2011, Sekiguchi et al. 2010, Freedman et al. 2012, Suyu et al. 2012, Weinberg et al. 2012]

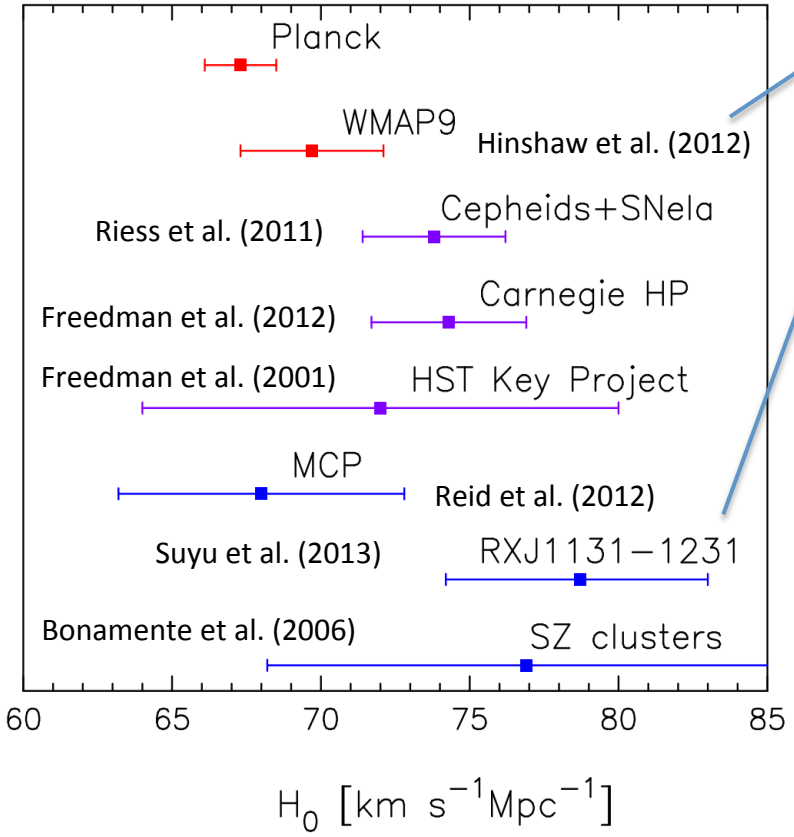


Image credit: Planck Collaboration. Ade et al. 2013 A&A

Derived H_0 based on spatially-flat ΛCDM model

Directly measure H_0 within 5.7% uncertainty with Gravitational Lensing

Thousand of lensed quasars will be found in current/future surveys. [Oguri & Marshall, 2010]

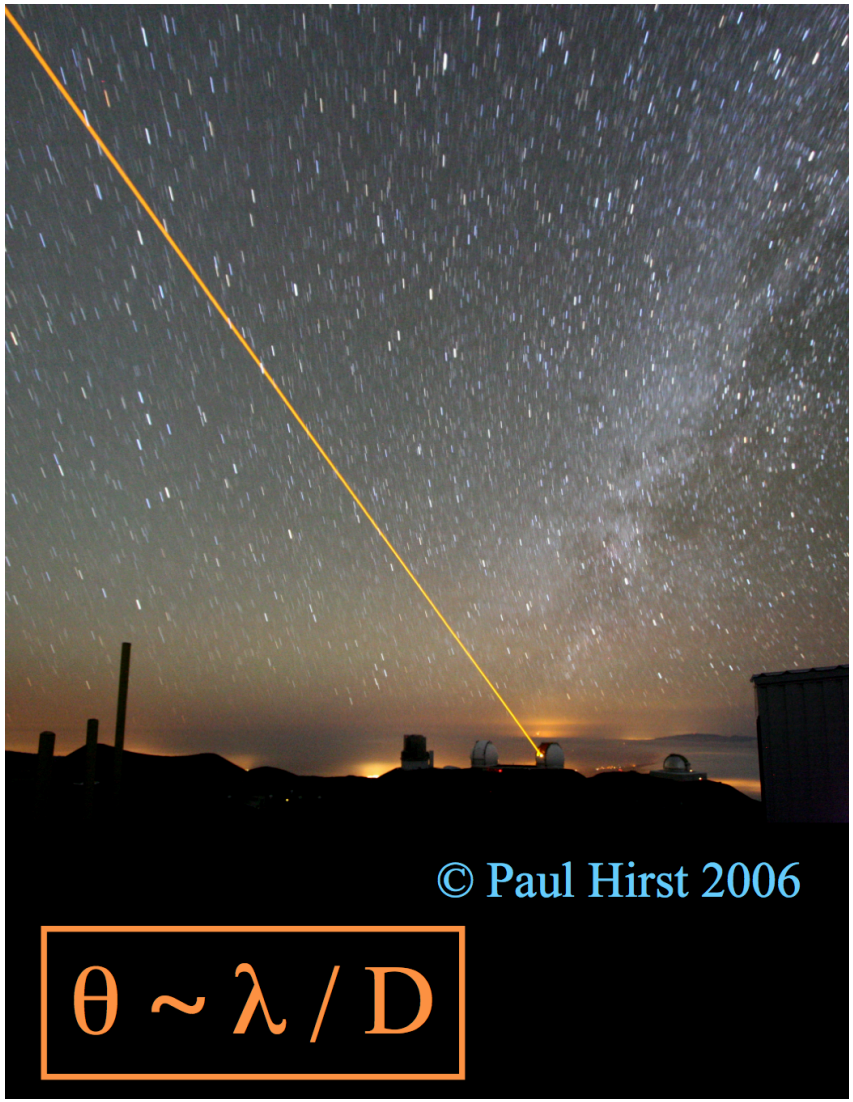
Hubble Space Telescope (HST) imaging is necessary for precise measurement of H_0.

HOWEVER

1.The HST cannot last forever.
(Last Servicing Mission is in May 2009)
2.The time of the HST is limited.
(In 2013, 18% accepted proposals are for cosmology)
3.The resolution is limited by its aperture size (2.4m)

Alternative approach

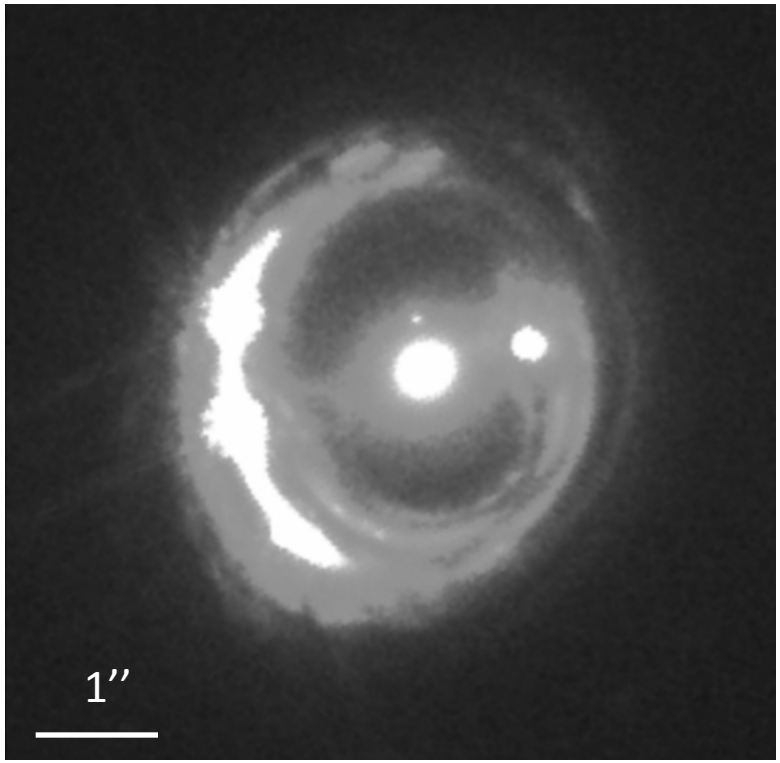
- SHARP = Strong-lensing High Angular Resolution Program
- SHARP is for studying dark matter substructure Vegetti et al. 2012 Lagattuta et al. 2012
- Use laser guide star adaptive optics with Keck II Telescope Resolution better than HST, while using a mirror that has 16x the collecting area
- Team SHARP:
  Chris Fassnacht, Simona Vegetti, John McKean, Dave Lagattuta, Leon Koopmans, Matt Auger



[Material courtesy of Chris Fassnacht]

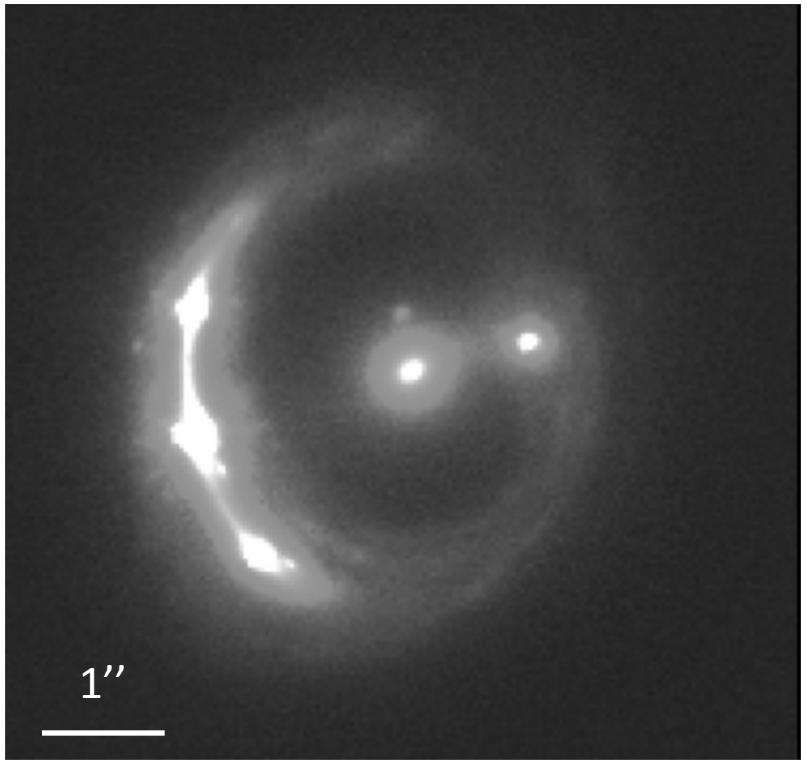
Space vs. AO : RXJ 1131-1231

HST/ACS F814W



0.05 arcsec per pixel

Keck AO Ks

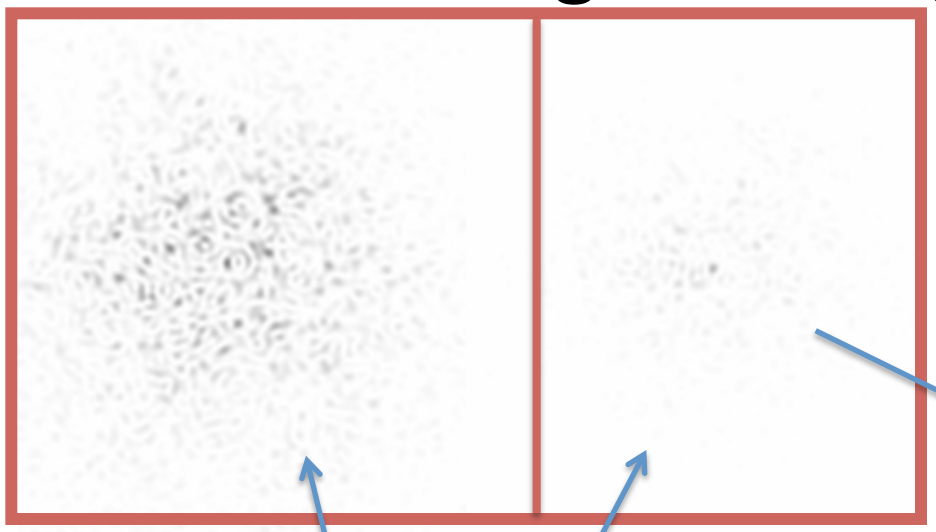


0.04 arcsec per pixel

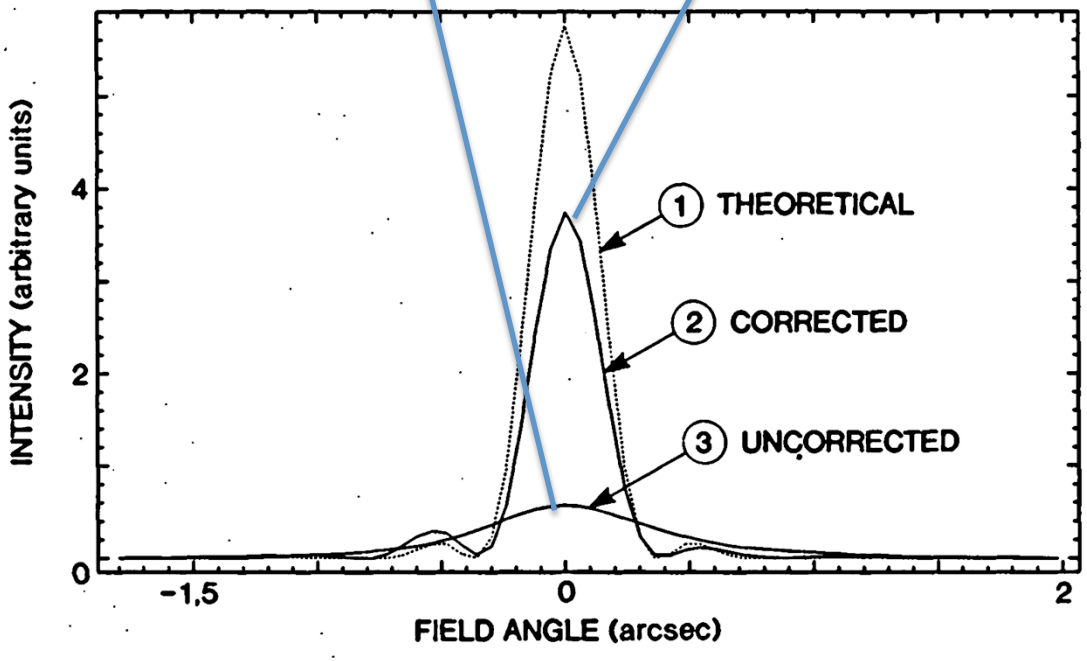
Suyu et al. 2013

We want to know whether AO data can produce similar (or better) cosmological constraints as HST data for time-delay systems (Chen et al. in prep)

The challenge of using AO imaging



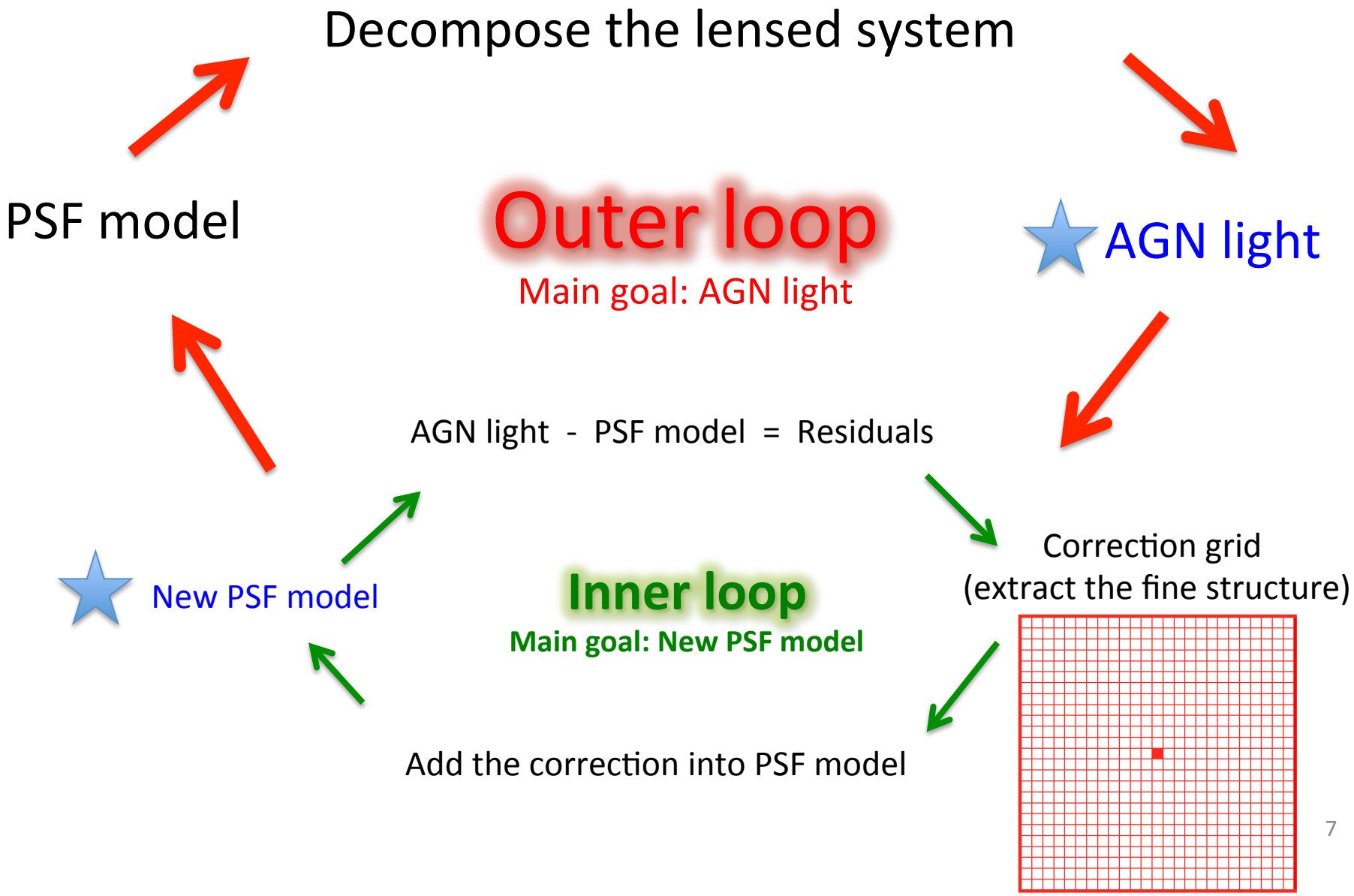
Slow motion simulation of typical adaptive optics operation at a telescope. (Wiki)



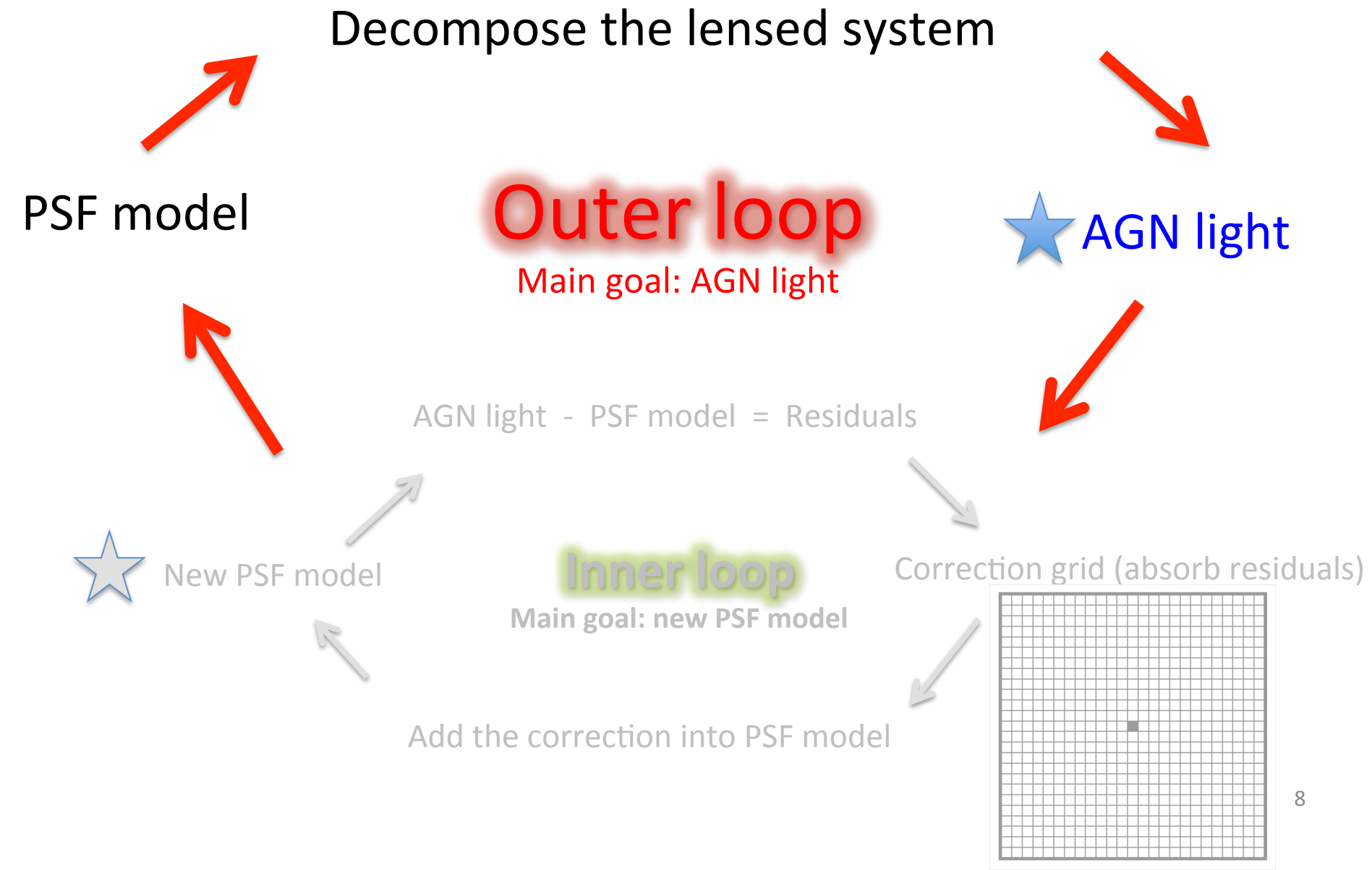
We **DO NOT** know what the Point Spread Function looks like (after AO correction)

Rousset, G. et al. 1989

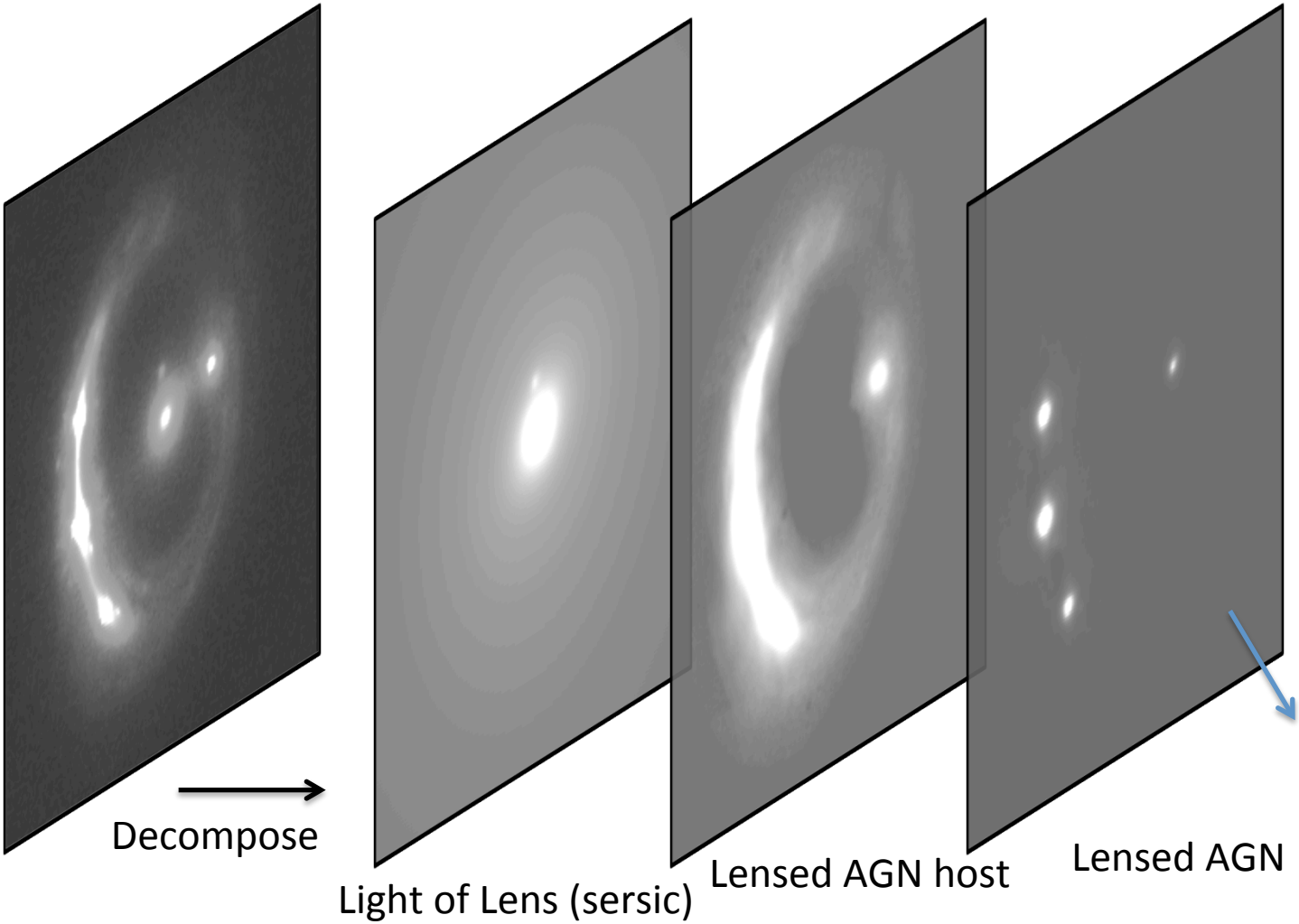
lens modeling and Iterative PSF reconstruction

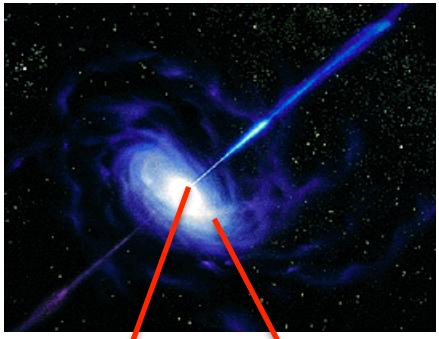


lens modeling and Iterative PSF reconstruction



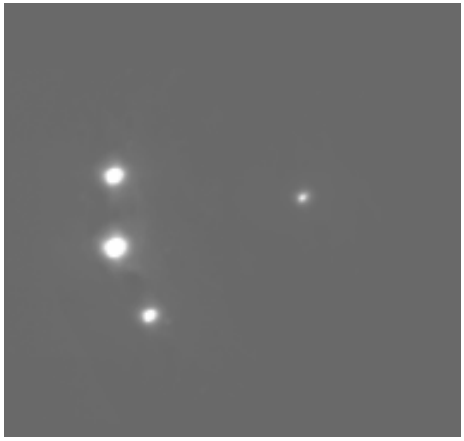
Strategy to extract the AGN light (outer loop)





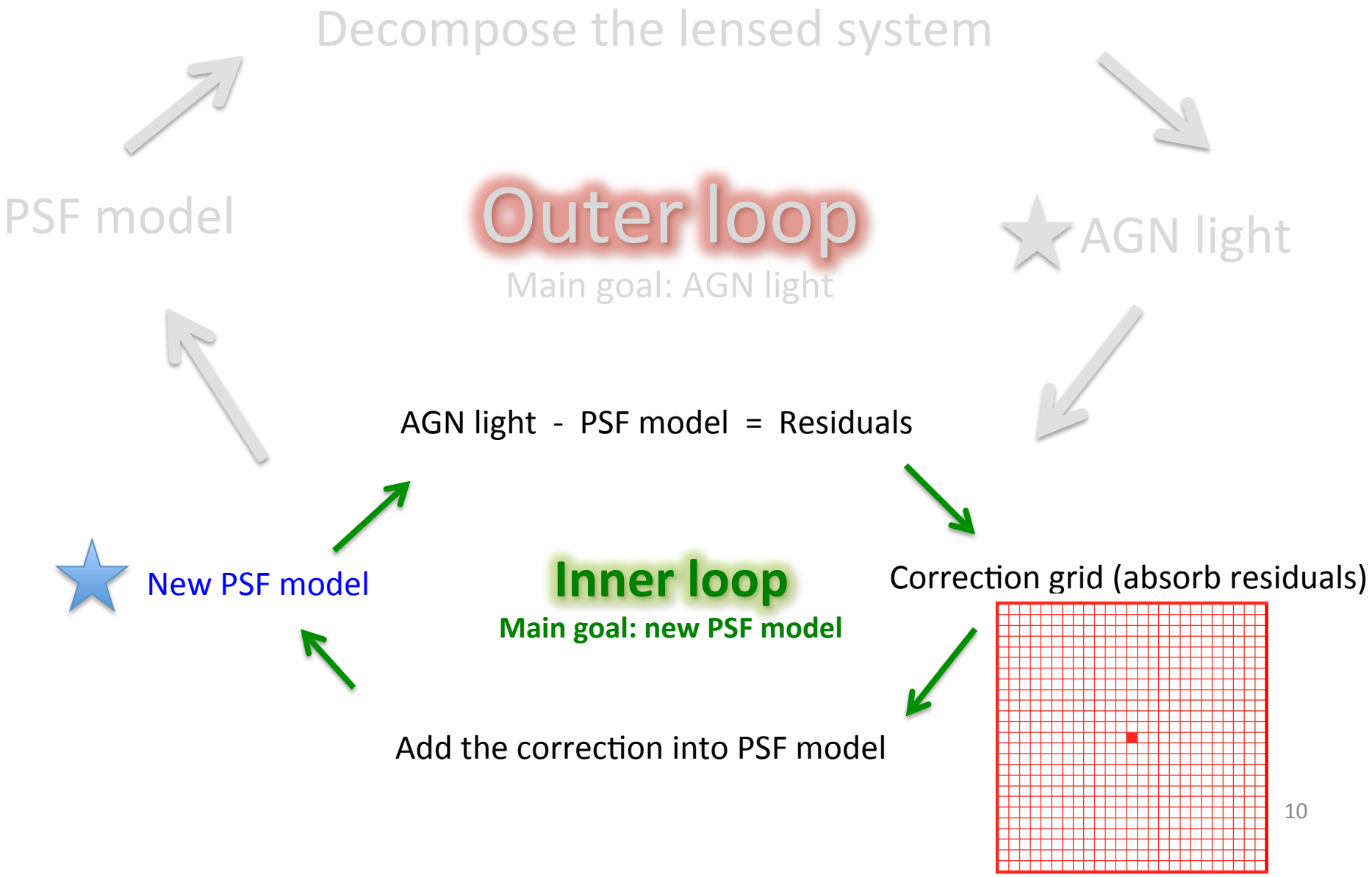
host galaxy

Active **G**alactic **N**ucleus



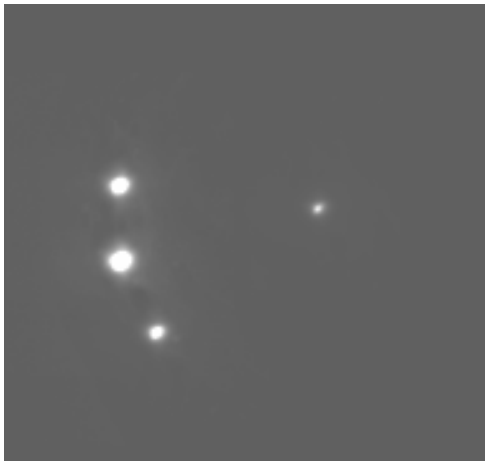
★AGN light

lens modeling and Iterative PSF reconstruction



Strategy to extract the PSF correction (inner loop)

AGN light



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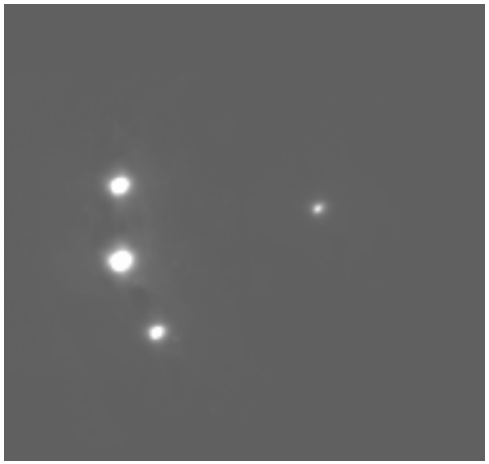
Model PSF



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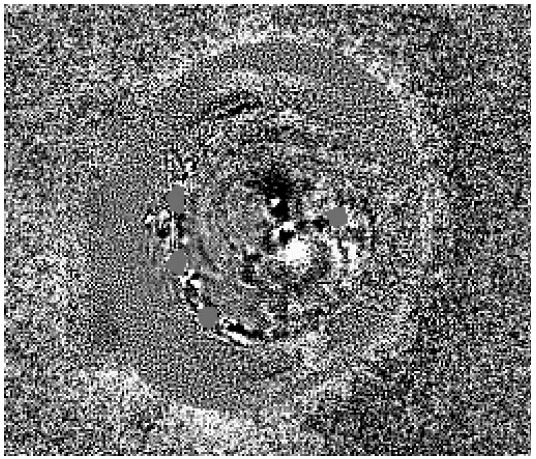
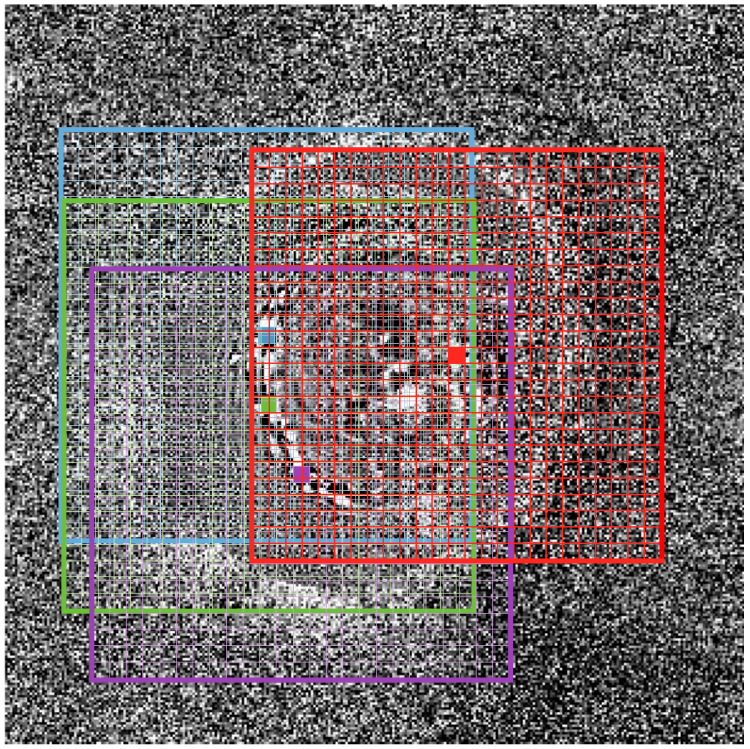
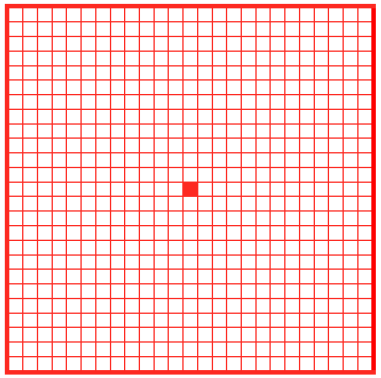
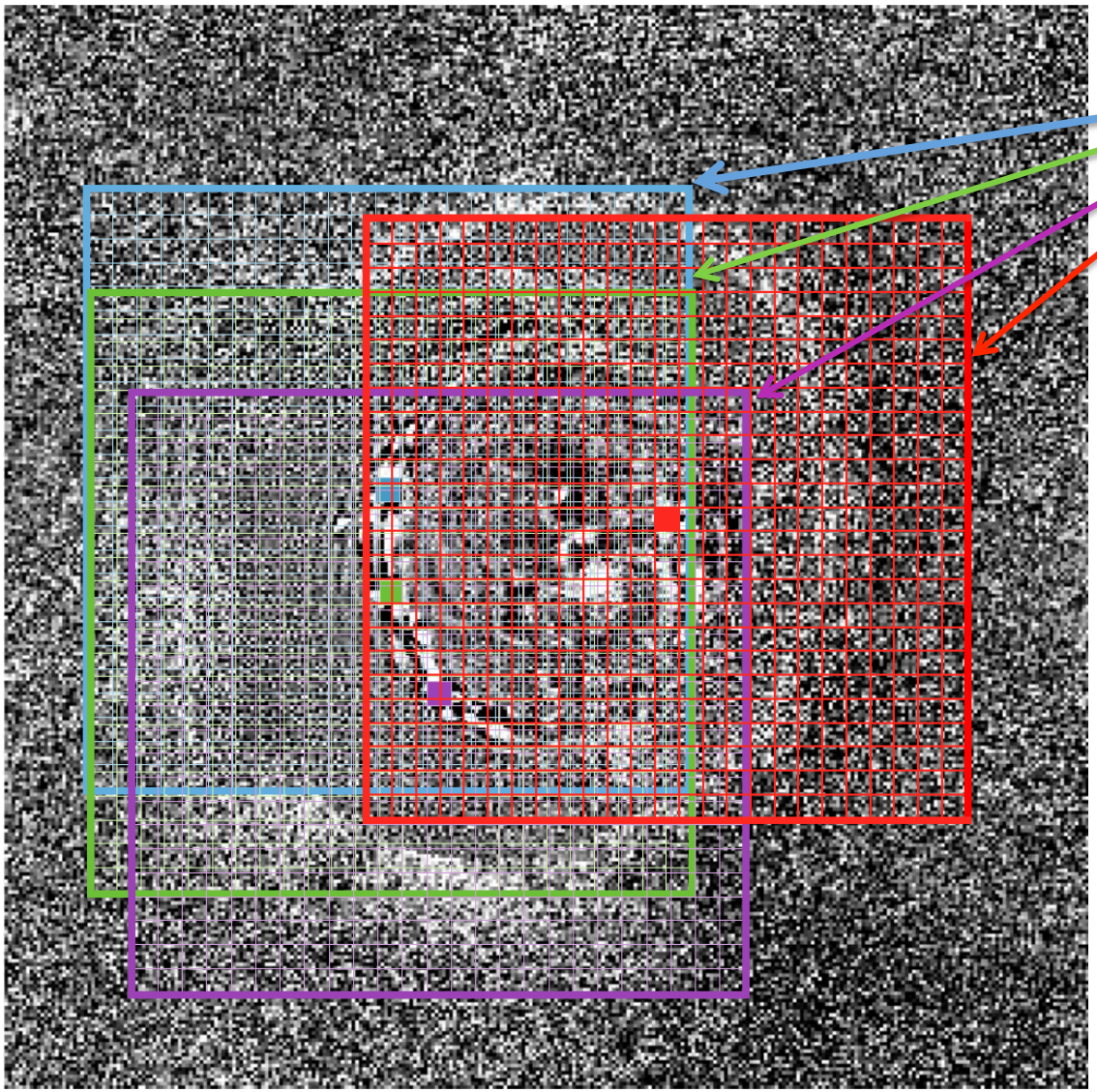
Residuals





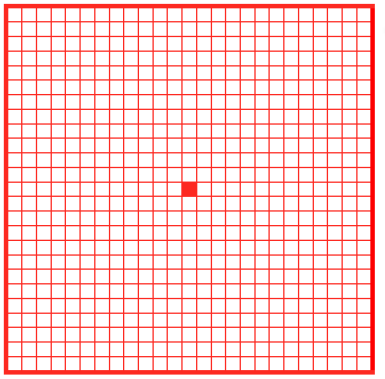
Correction grid
(fine structures of PSF)





r_i

f_{ij}



c_j

Correction grid
(fine structures of PSF)
Correction grid size=Image pixel size

f encoded with positions and
relative intensities of lensed AGN

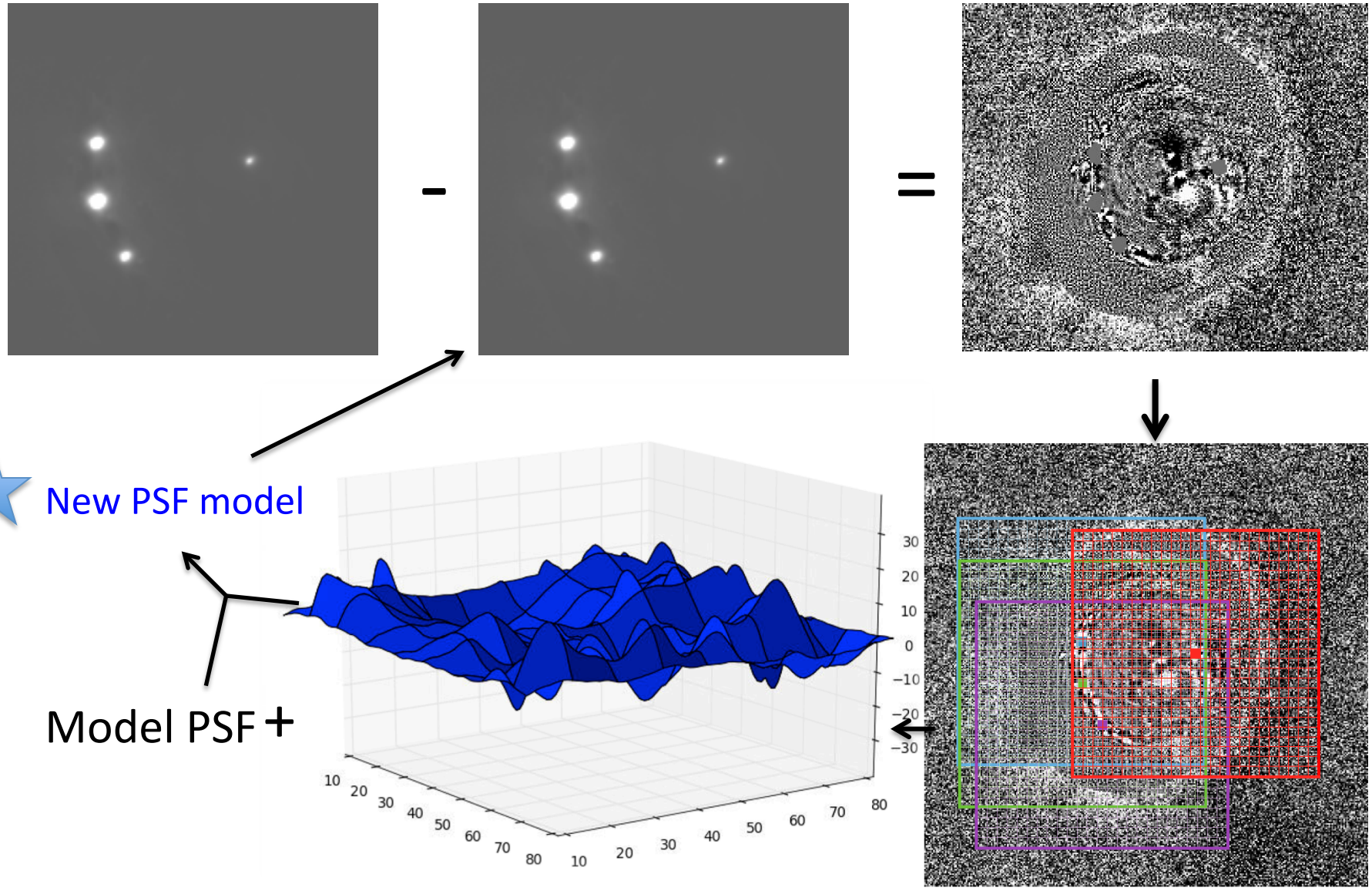
$$\chi^2 = \sum_i \frac{(r_i - f_{ij} c_j)^2}{\sigma_i^2}$$

$$M = \frac{1}{2}\chi^2 + \lambda_c \cdot E_{noise\_penalty}$$

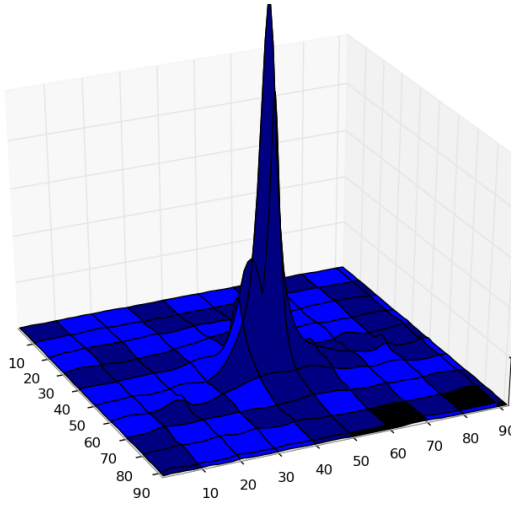
$$\nabla M = 0$$

Main assumption of the strategy:
The PSF does not change too much within a small area.

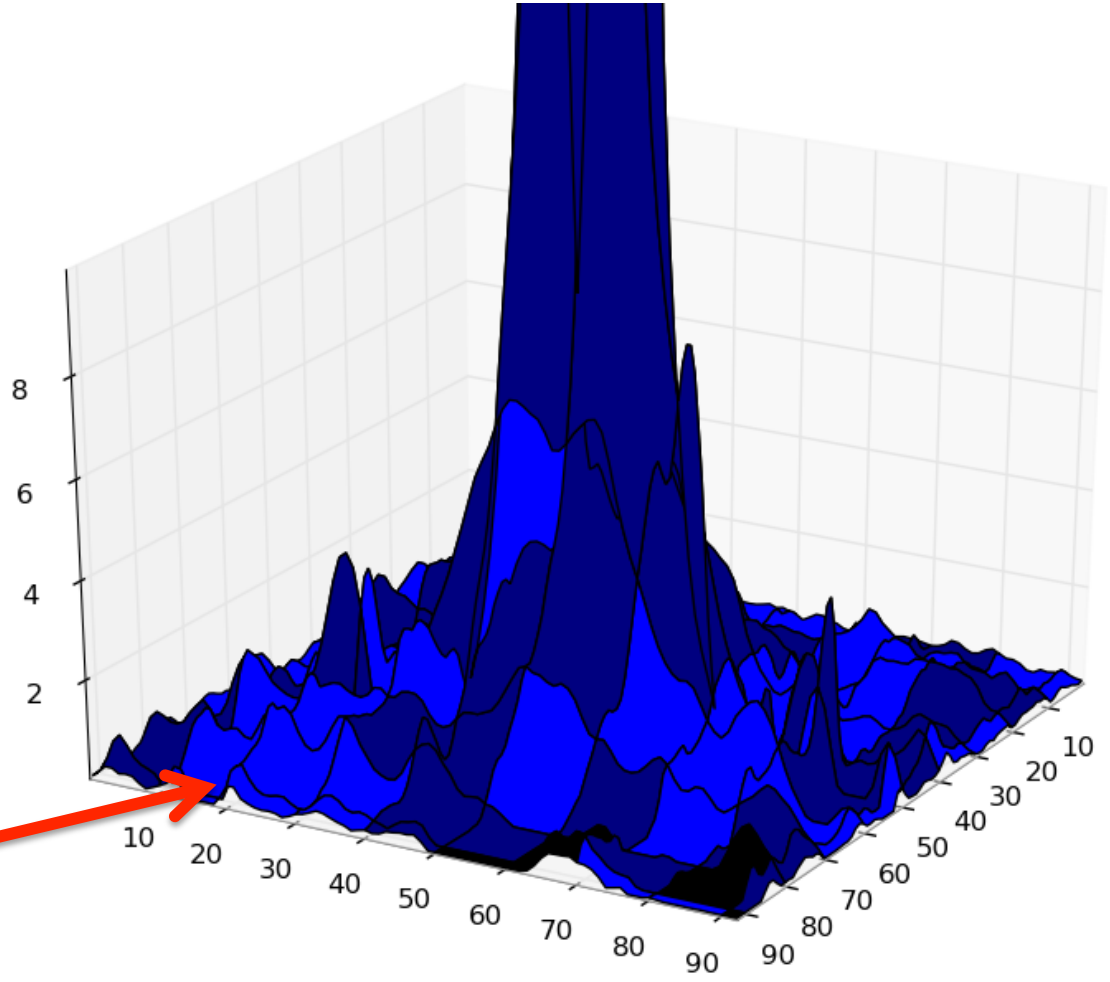
Strategy to extract the PSF (inner loop)



Extracted PSF



The intensity in full scale



Corrected PSF

Zoomed-in intensity

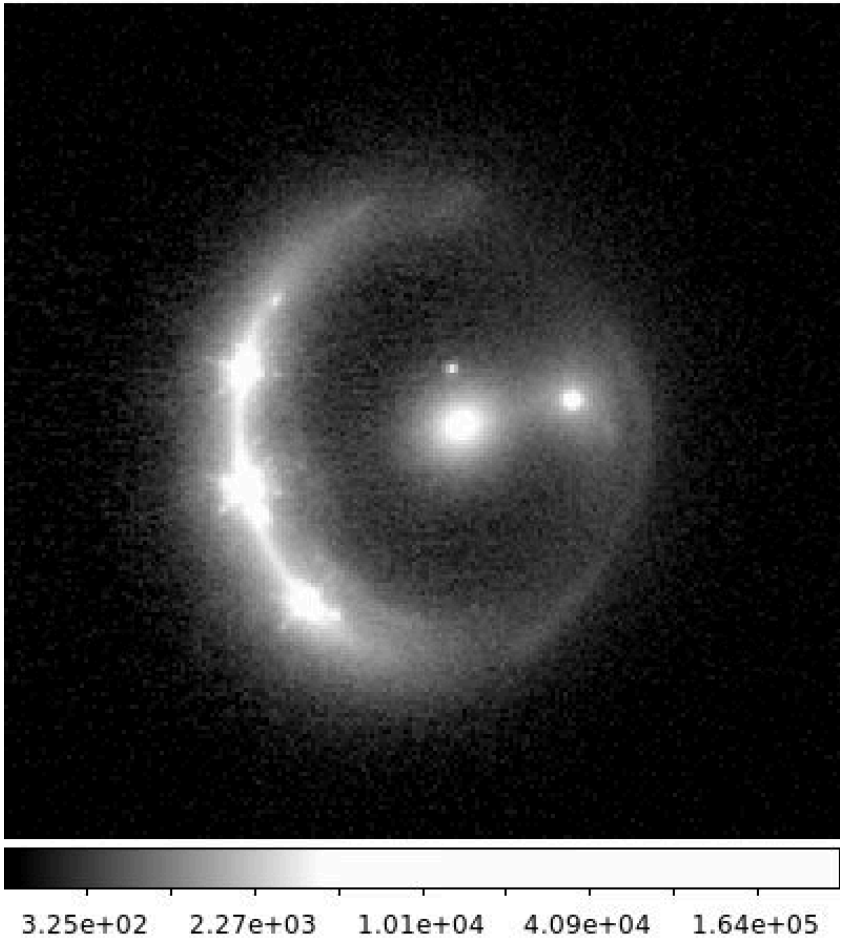
Blind test with mock data

- Purpose: to test whether we can recover the input time-delay distance by the strategy.
- Method:

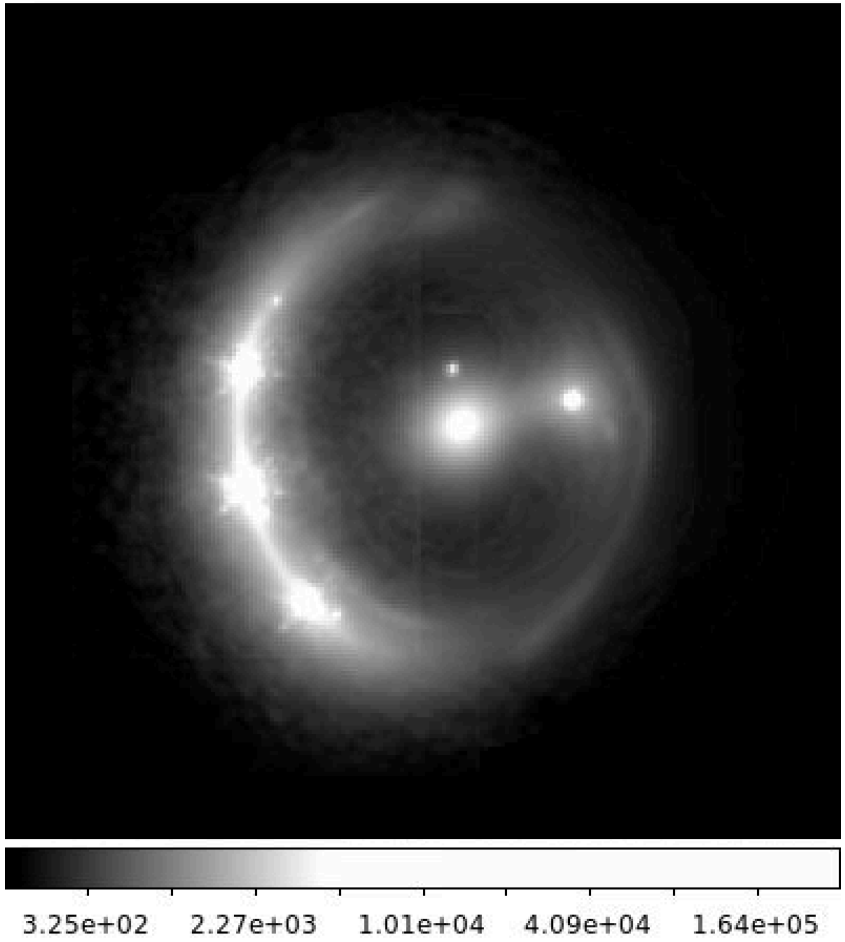
  - Sherry created a mock lensed system which is similar to RXJ1131

  - Chih-Fan modeled the lensed system with time-delay information but without a PSF model a priori

Mock data test

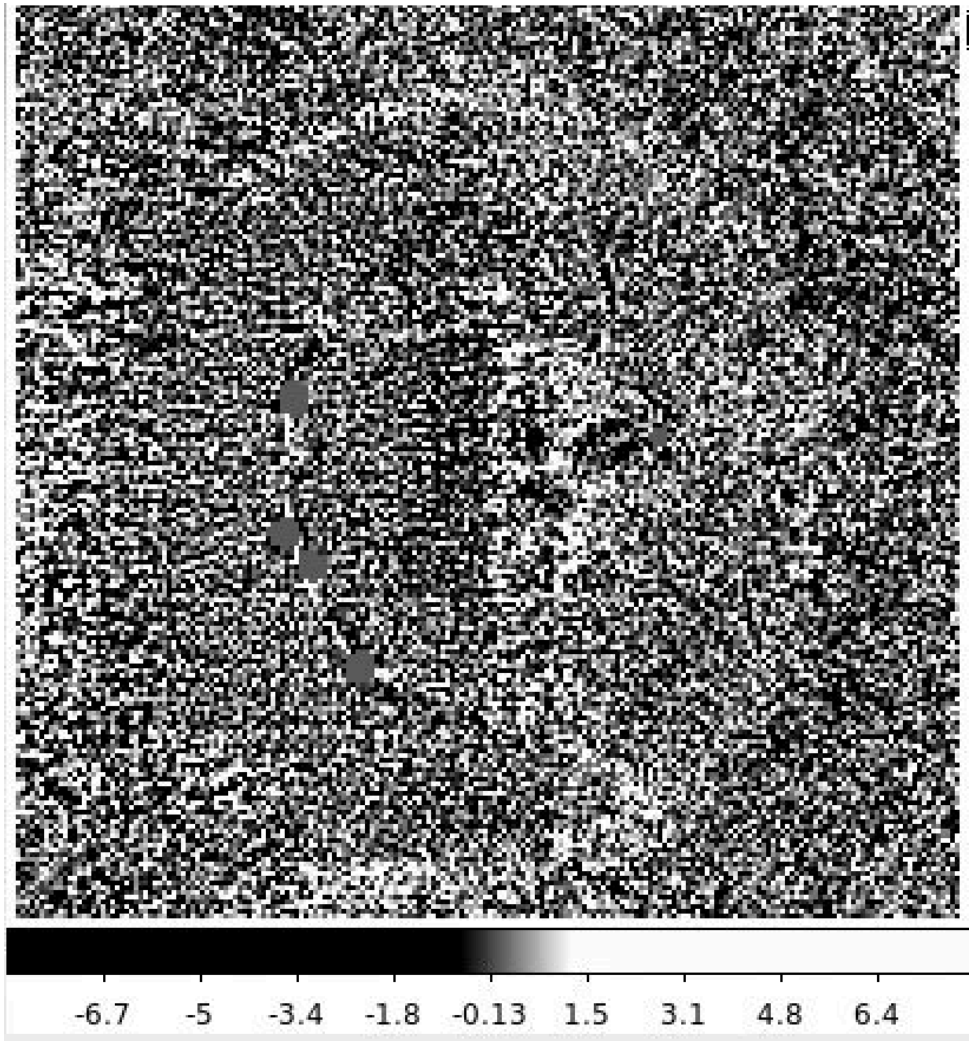


Mock image



Model image

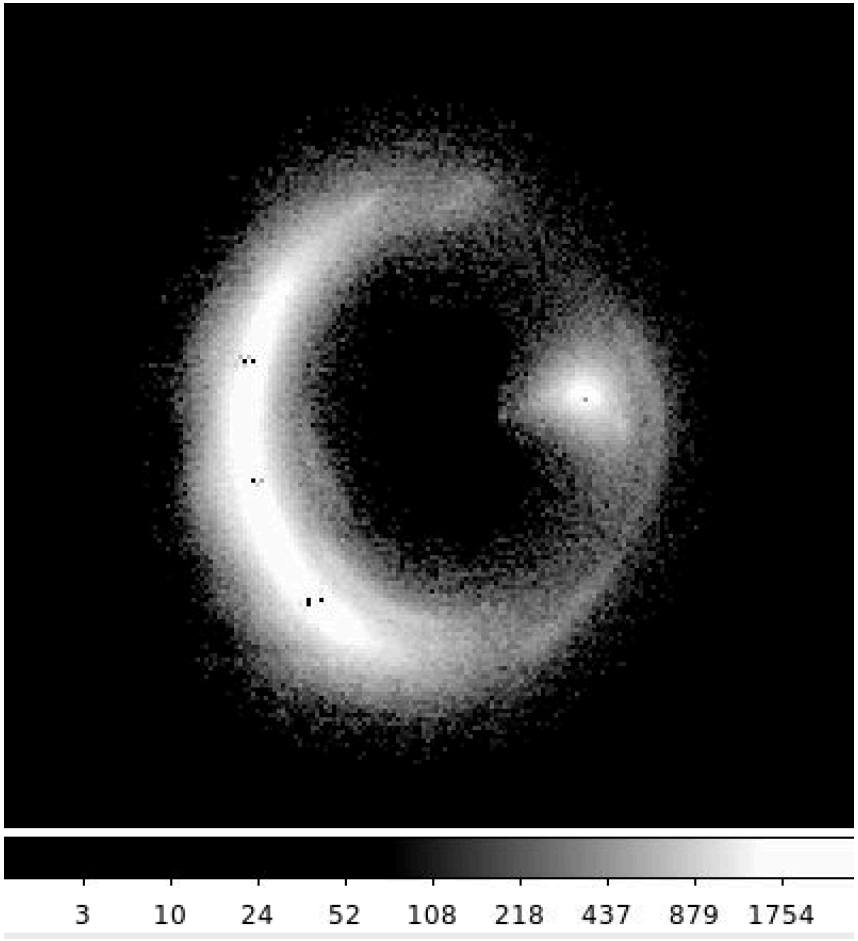
Mock data test



Normalized residuals

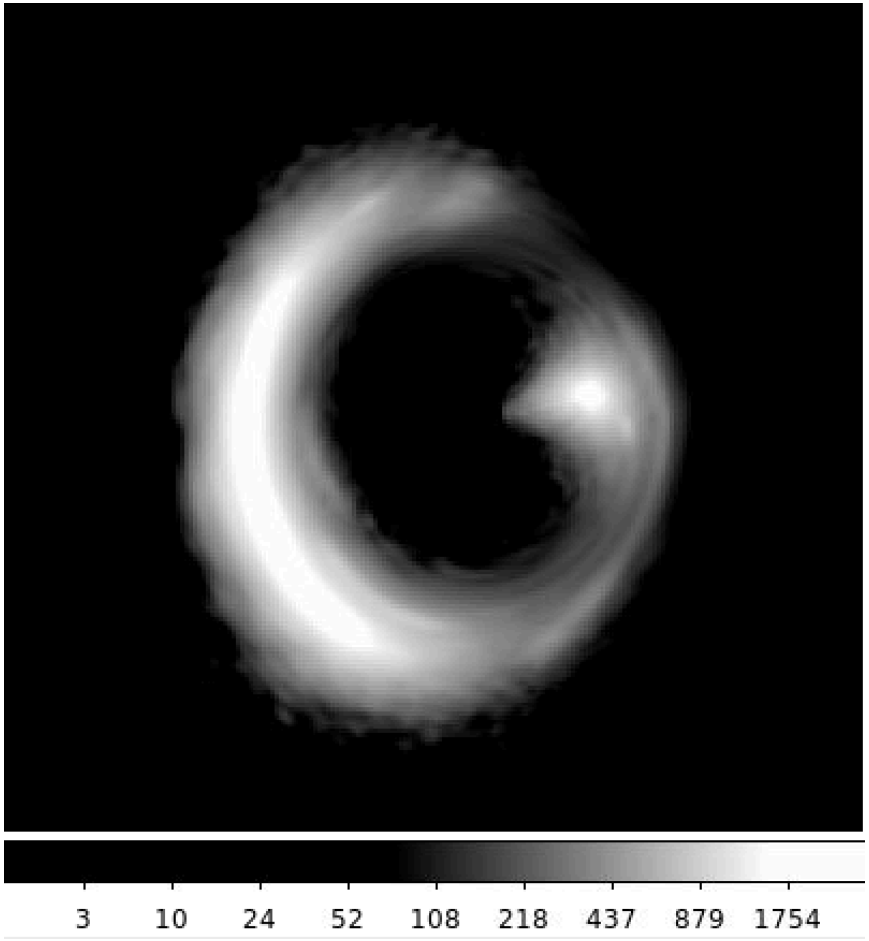
1. Reduced $\chi^2 \approx 1$
2. 12 to 16 iterations

Mock data test



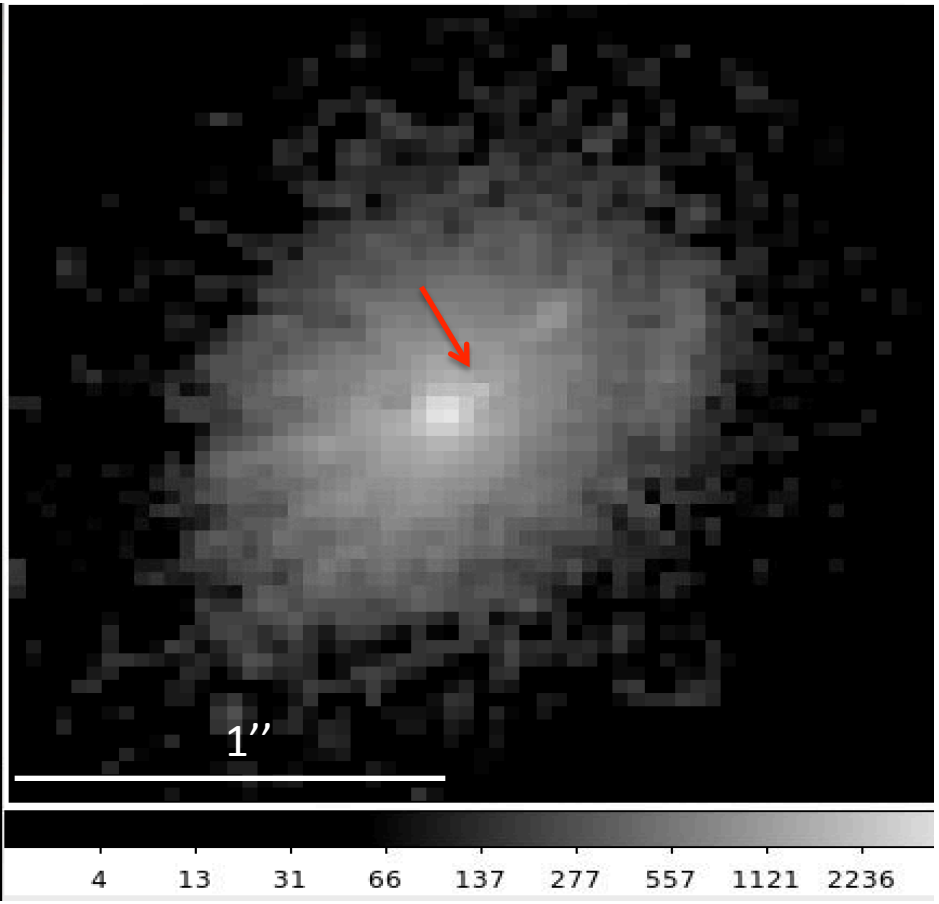
Arc light

(Image – lens light – AGN light)

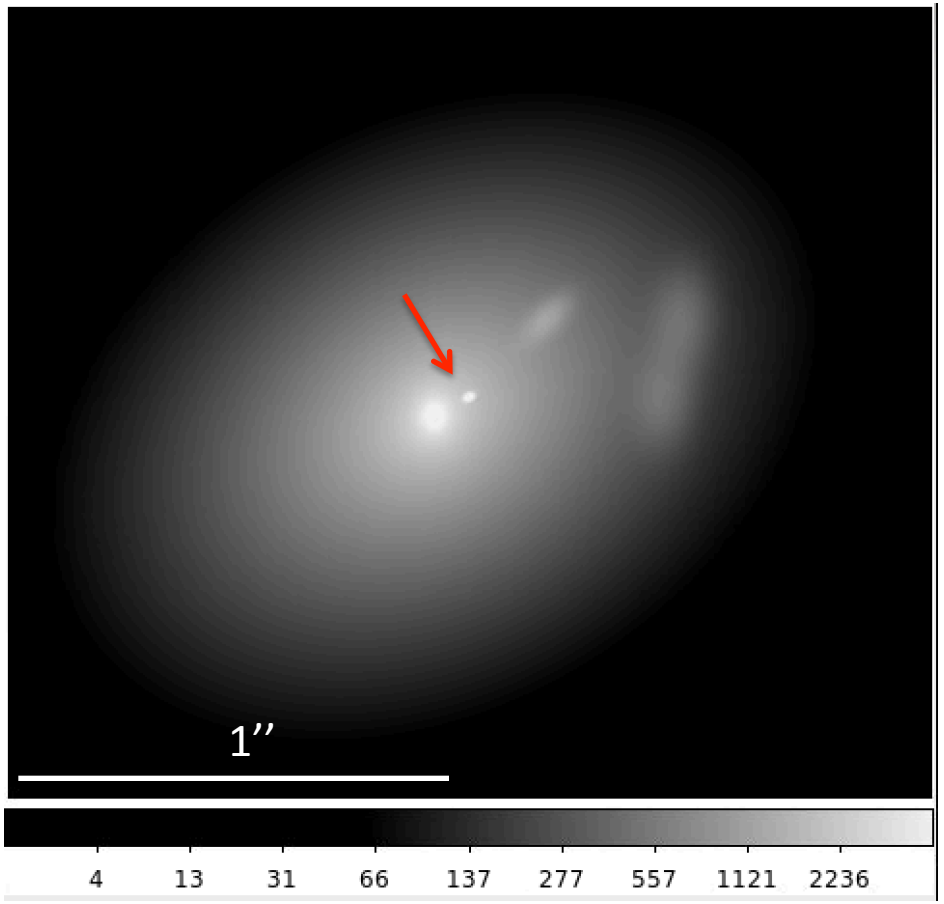


Model arc

Mock data test

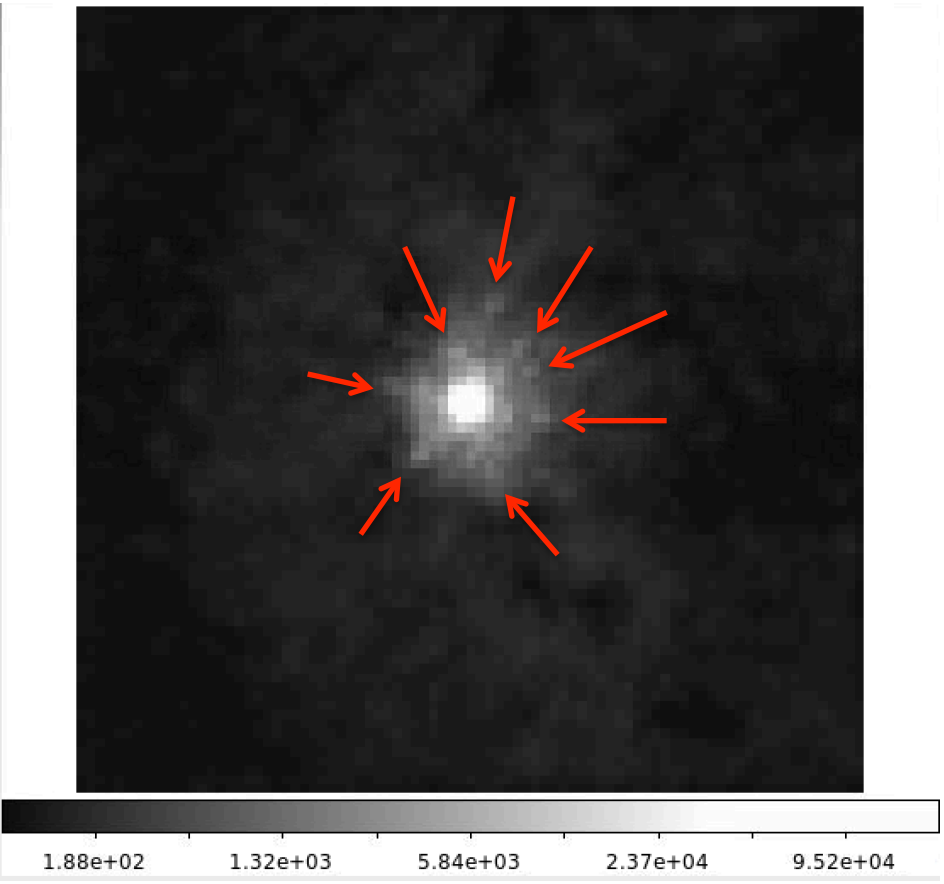


Reconstructed source



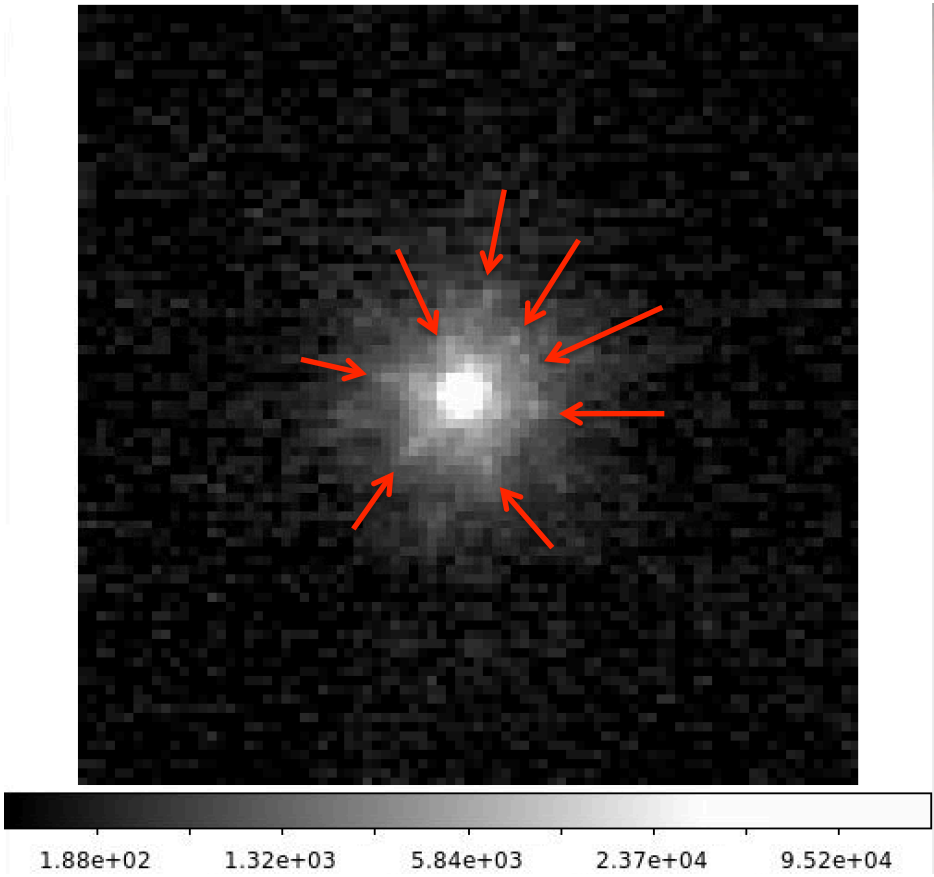
Input source

Mock data test



Reconstructed PSF

0.04 arcsec per pixel



Input PSF

0.04 arcsec per pixel

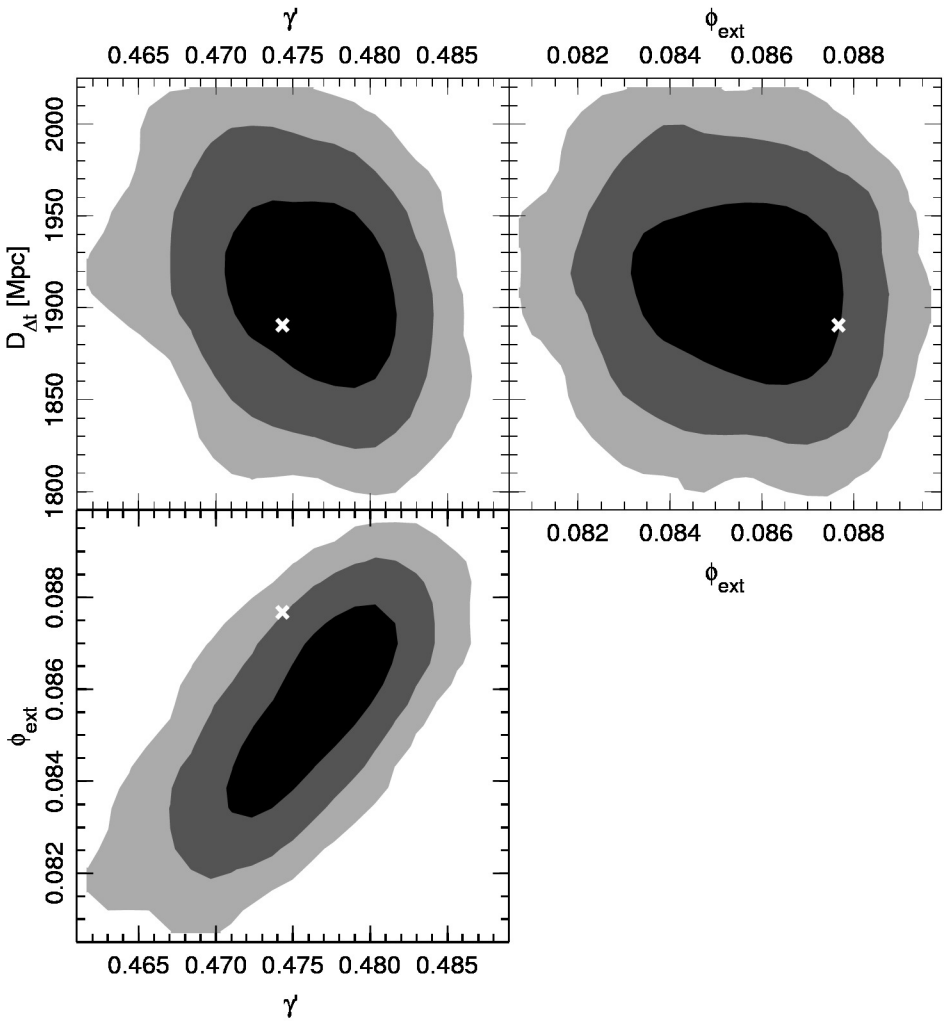
Important parameters for inferring H_0

slope

External shear

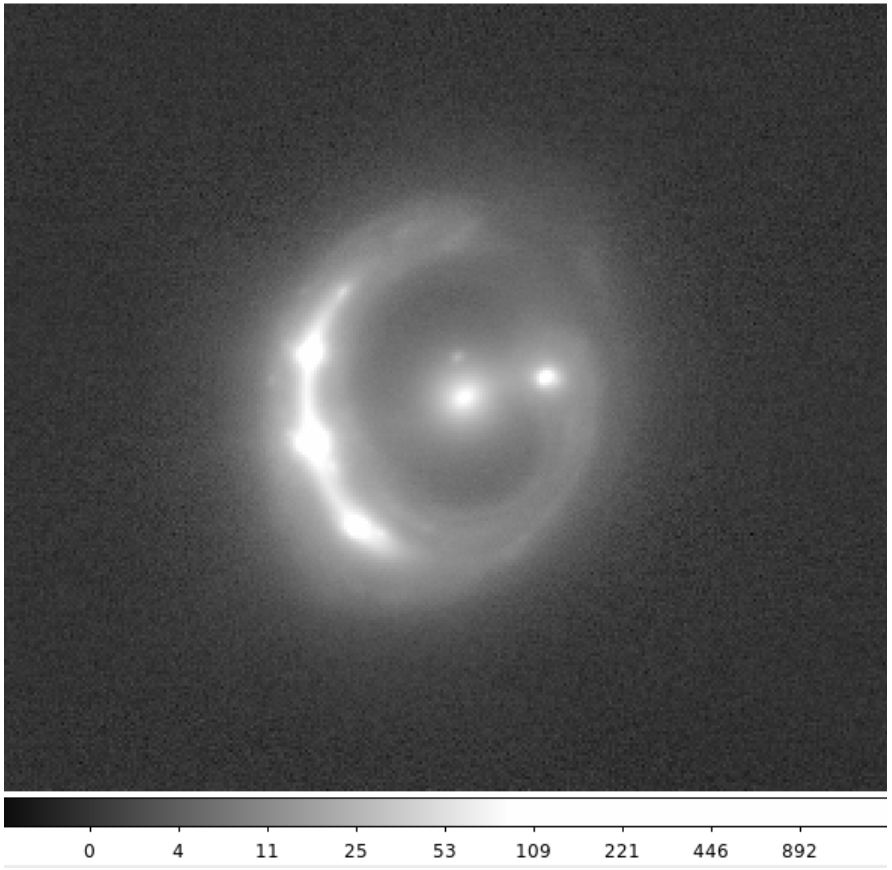
Time-delay distance

External shear

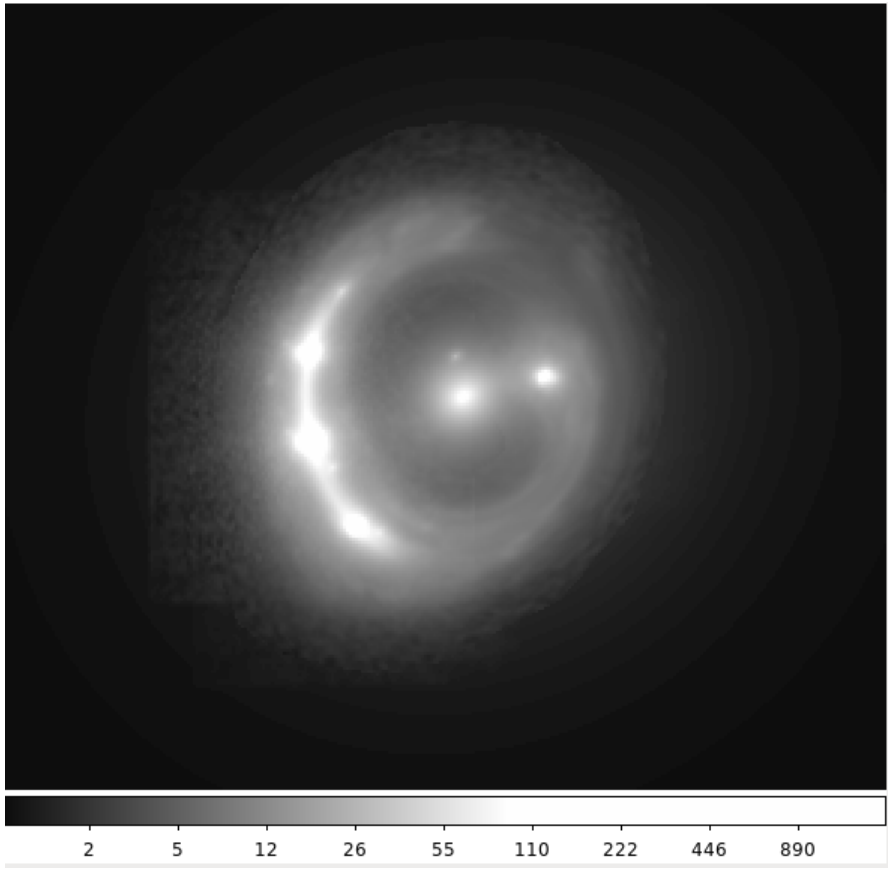


Preliminary results of real data

The SHARP team (PI: Chris Fassnacht) provides the AO RXJ1131-1231 image with Keck AO Ks

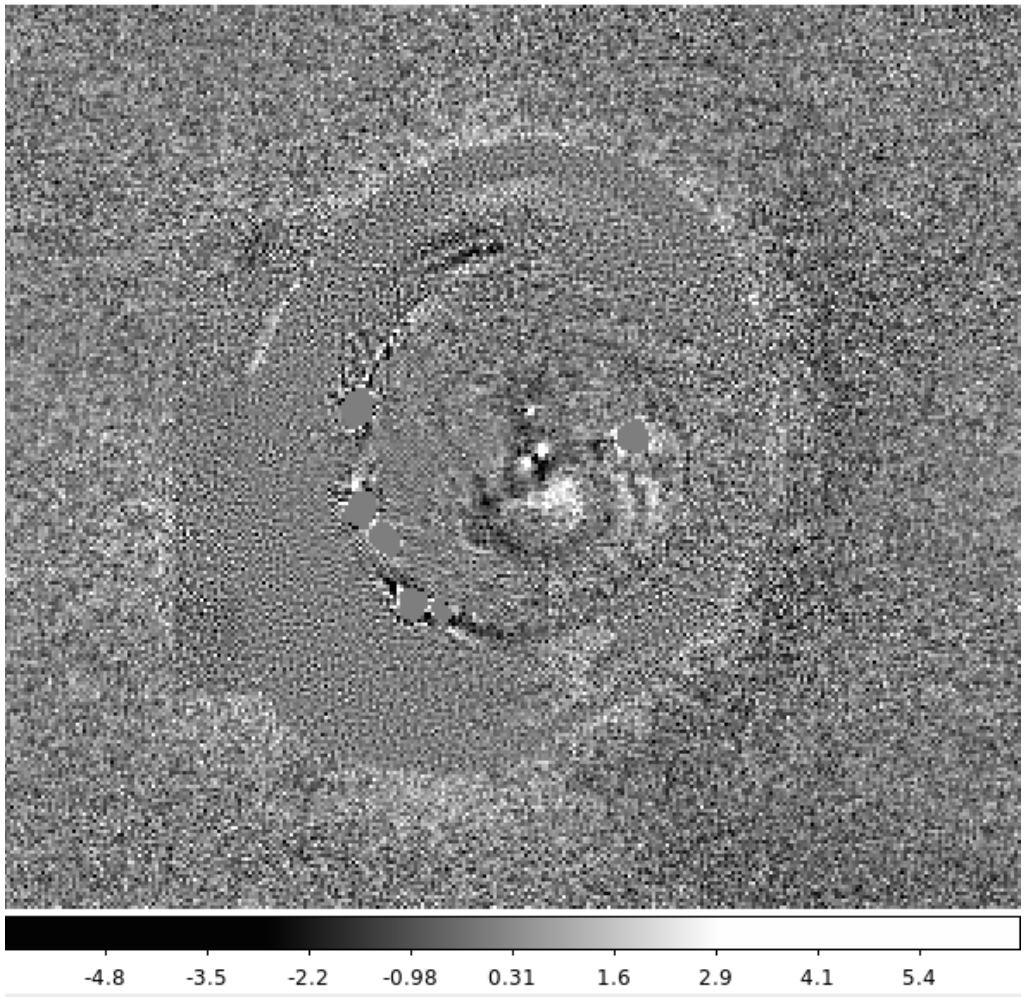


Observed image



Predicted image

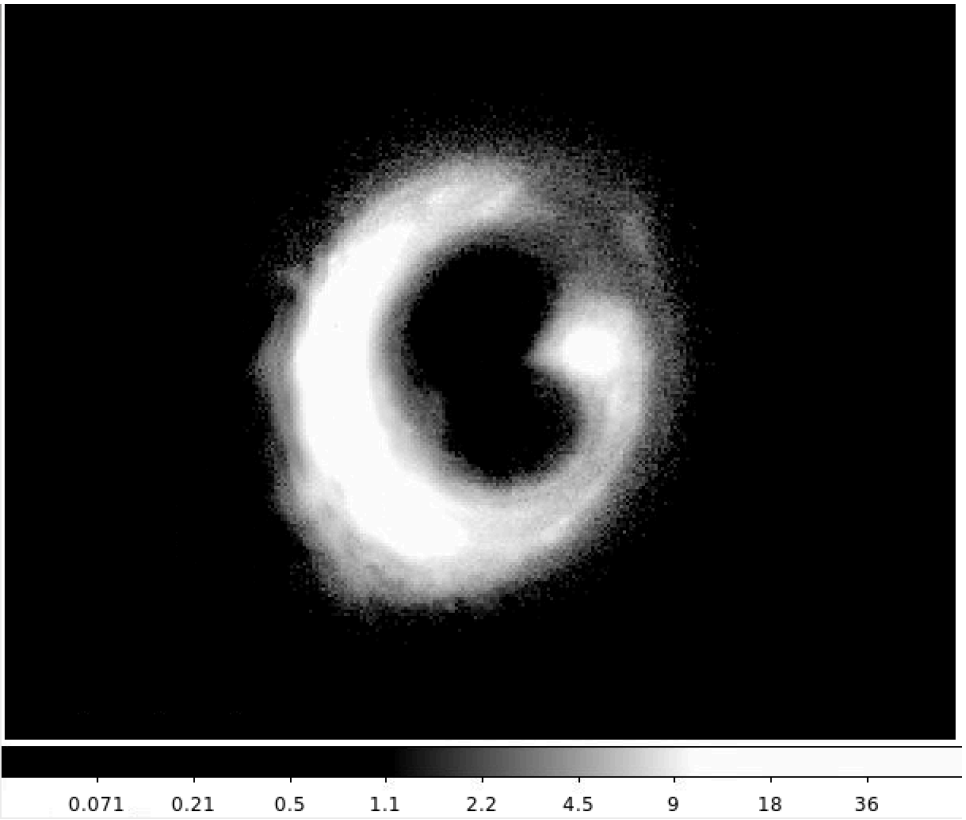
Preliminary results of real data
(RXJ 1131-1231)

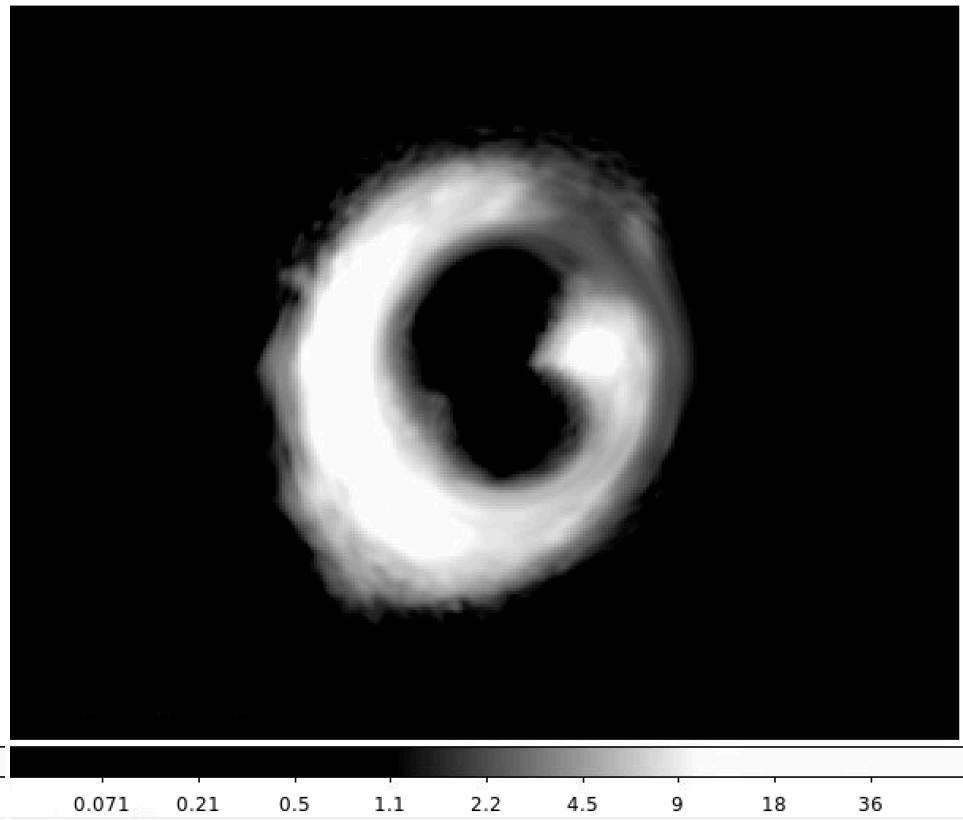


Normalized residuals

Reduced $\chi^2 \approx 1.04$

Preliminary results of real data
(RXJ 1131-1231)

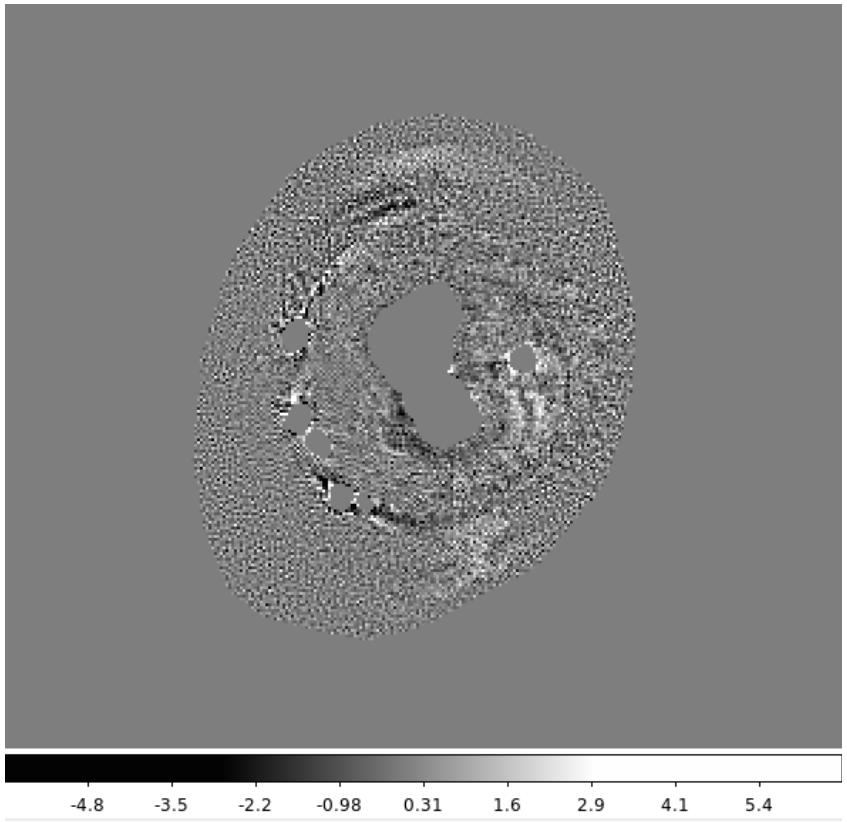




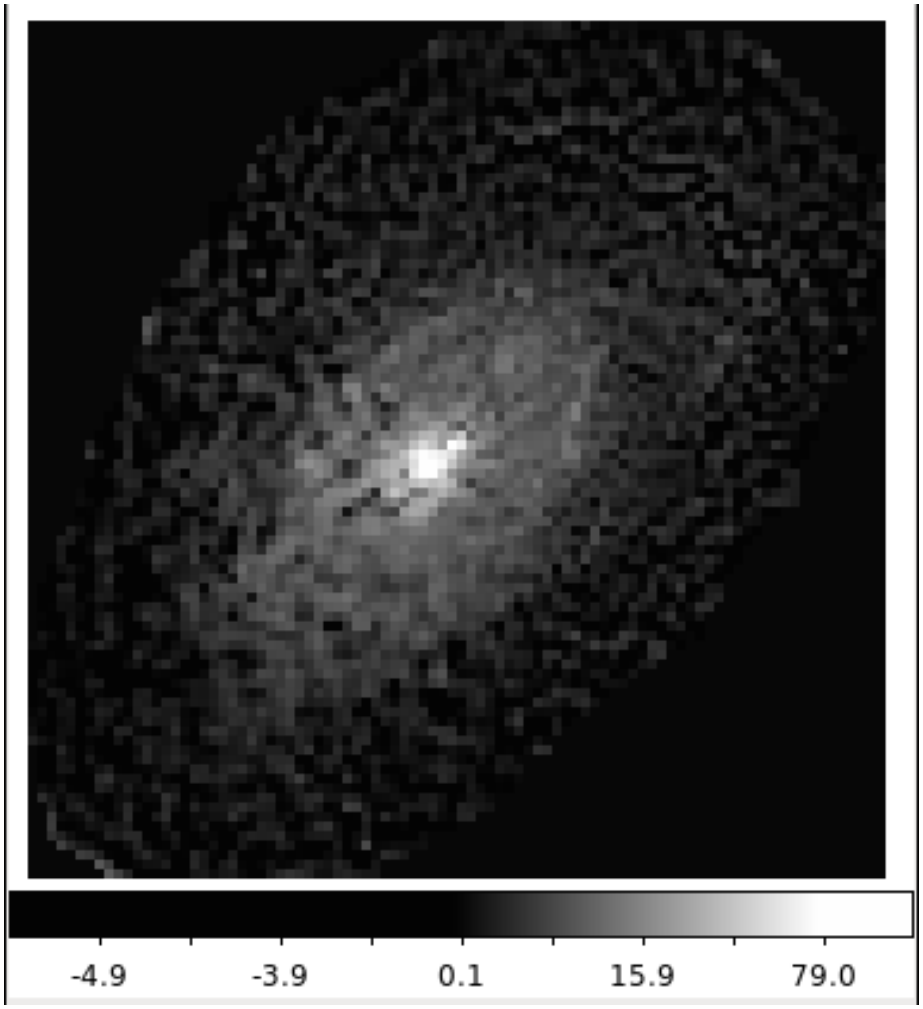
Arc light
(Image – lens light – AGN light)

Reconstructed arc

Preliminary results of real data
(RXJ 1131-1231)



Normalized residuals of arc



Reconstructed source

Summary

- High accuracy in H_0 is needed for understanding dark energy and possibly revealing new physics
- New method to model lens using AO data
- Blind test on mock AO data shows that we can recover the input time delay distance with our strategy
- Work is underway to model the Keck AO image
- AO can be a future way to follow up time-delay lenses

Many thanks to

Sherry Suyu (ASIAA)
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Chris Fassnacht (UC Davis)
SHARP team
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Anja von der Linden (Standford)
James Chan (NTU)
Thomas Lai (ASIAA)
胡亦行 (NTU)