ACP Seminar, IPMU
February 6, 2014

Subaru Telescope Adaptive Optics Observations of the SDSS Gravitationally Lensed Quasars

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Contents

- Use of gravitationally lensed quasars & need of high-resolution imaging
- Description of the Subaru AO imaging campaign & concepts
- A new analysis techniques, morphological modeling & actual examples
- Science results on selected objects

  SDSS J1334+3315 SDSS J1330+1810 SDSS J1405+0959

- Introduction to statistical studies possible with AO data

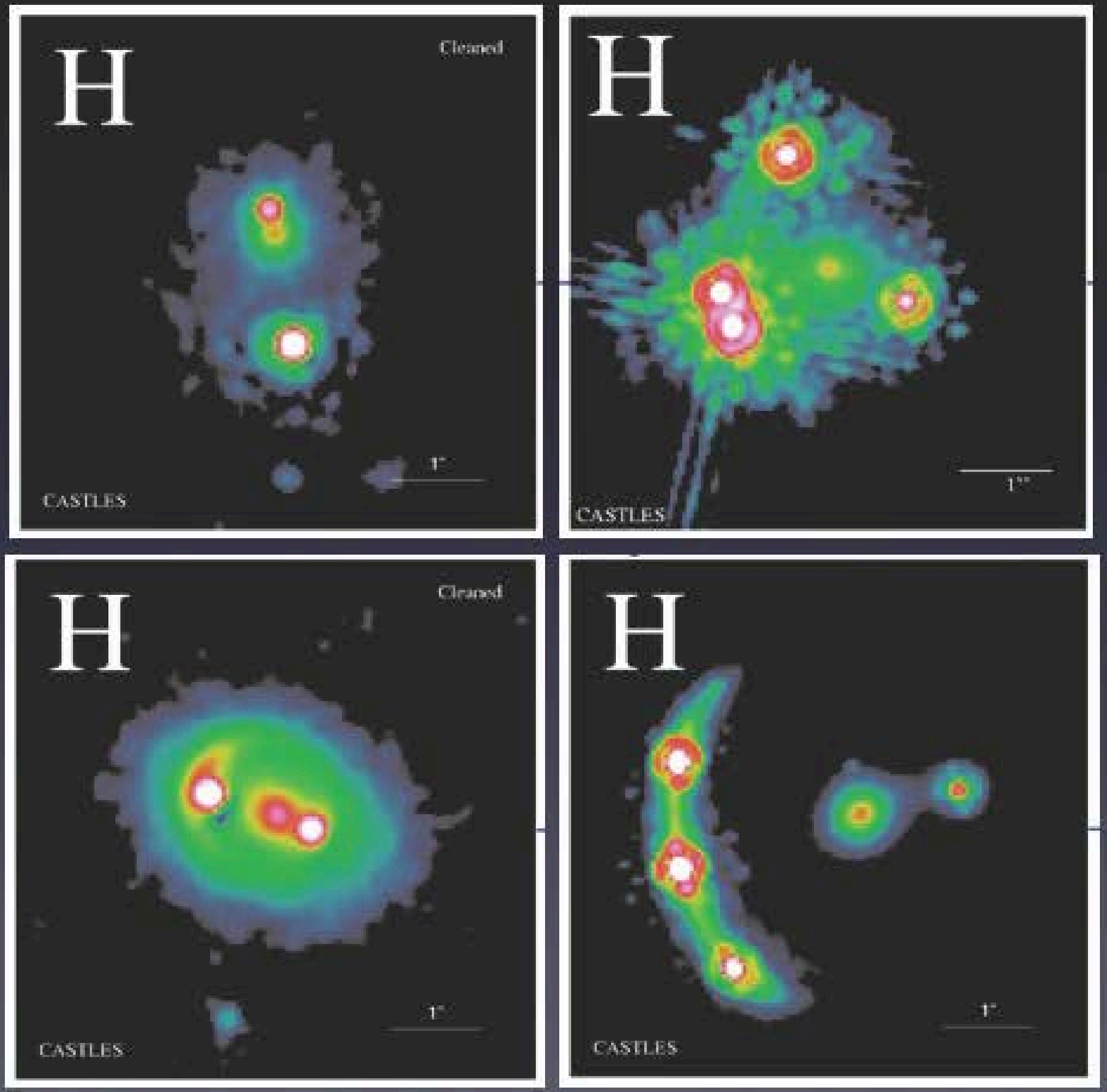
What are gravitationally lensed quasars useful for? Need of high-resolution imaging

high-res GLQs
AO concepts
SQLS
imaging campaign
analysis technique
examples
SDSS J1334+3315
SDSS J1330+1810
SDSS J1405+0959
M_{BH} - host galaxy
mean mass profile
mass and light

- First discovery Walsh et al. 1979;   ~ 120 lensed quasars known
- Typical configurations:

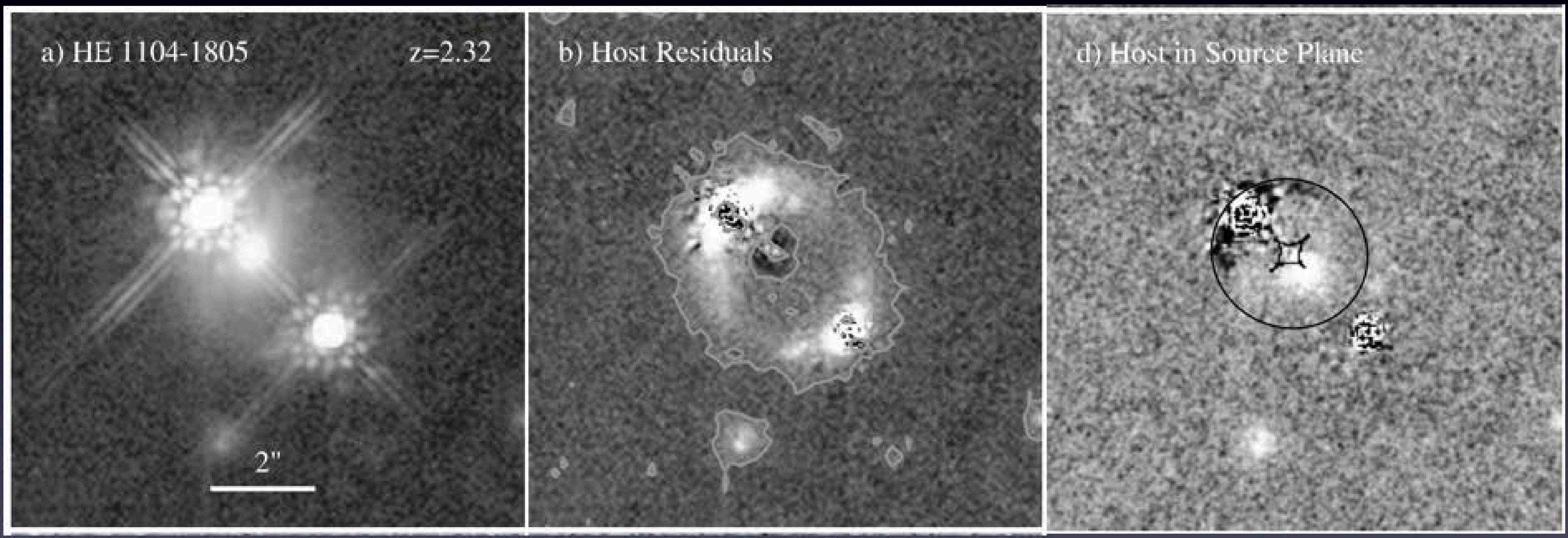
CfA-Arizona Space Telescope LEns Survey (CASTLES)

Hubble Space Telescope (HST)



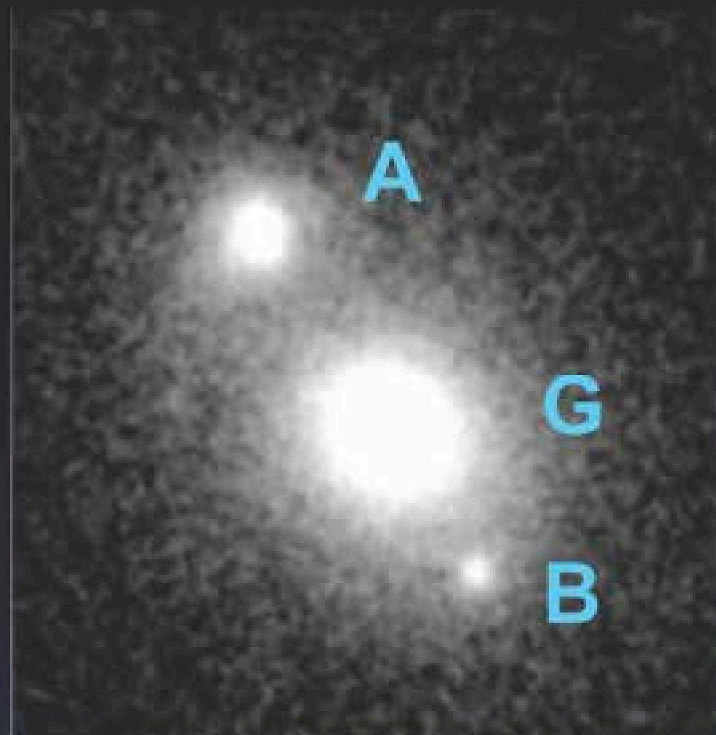
- Lensing: the most accurate mass estimate known to astronomy, inside the multiple images
- Both astrophysical and cosmological uses

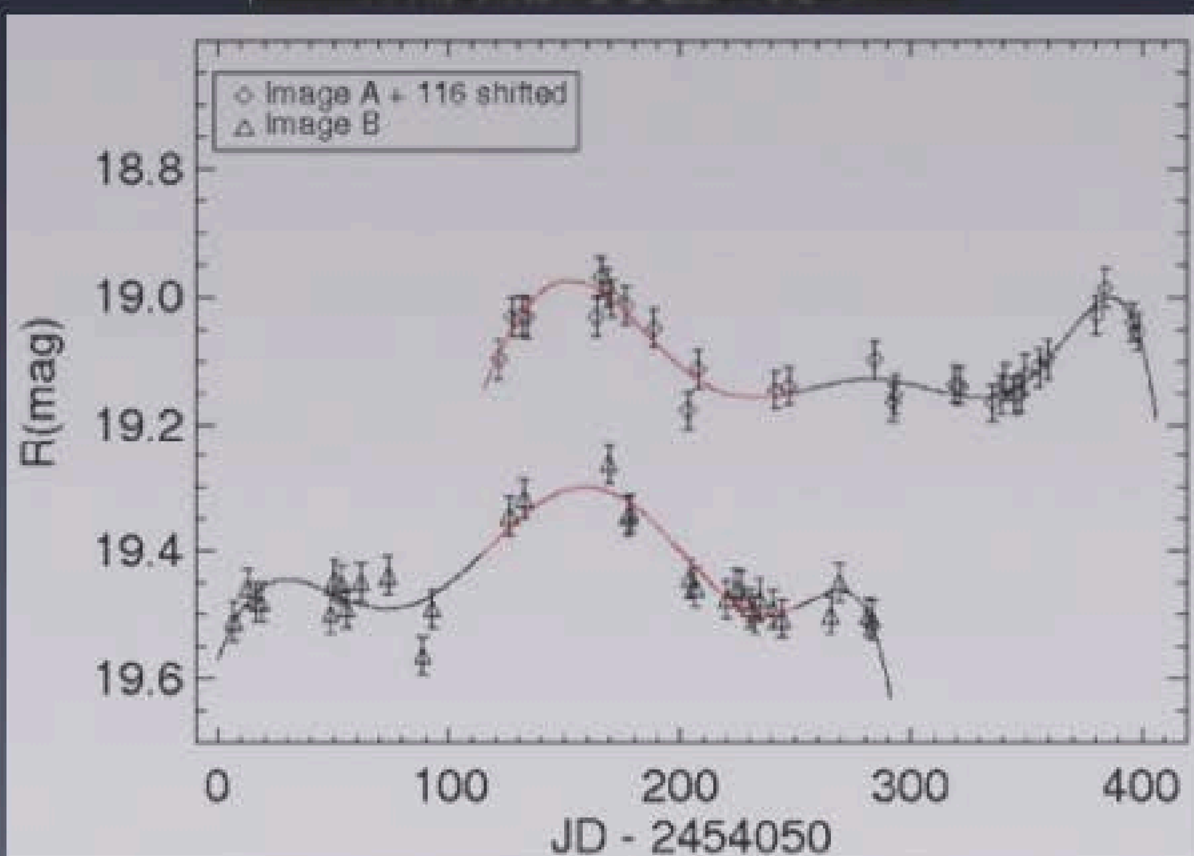
Facilitate the study of quasar hosts & M_{BH} - L_{host} correlation



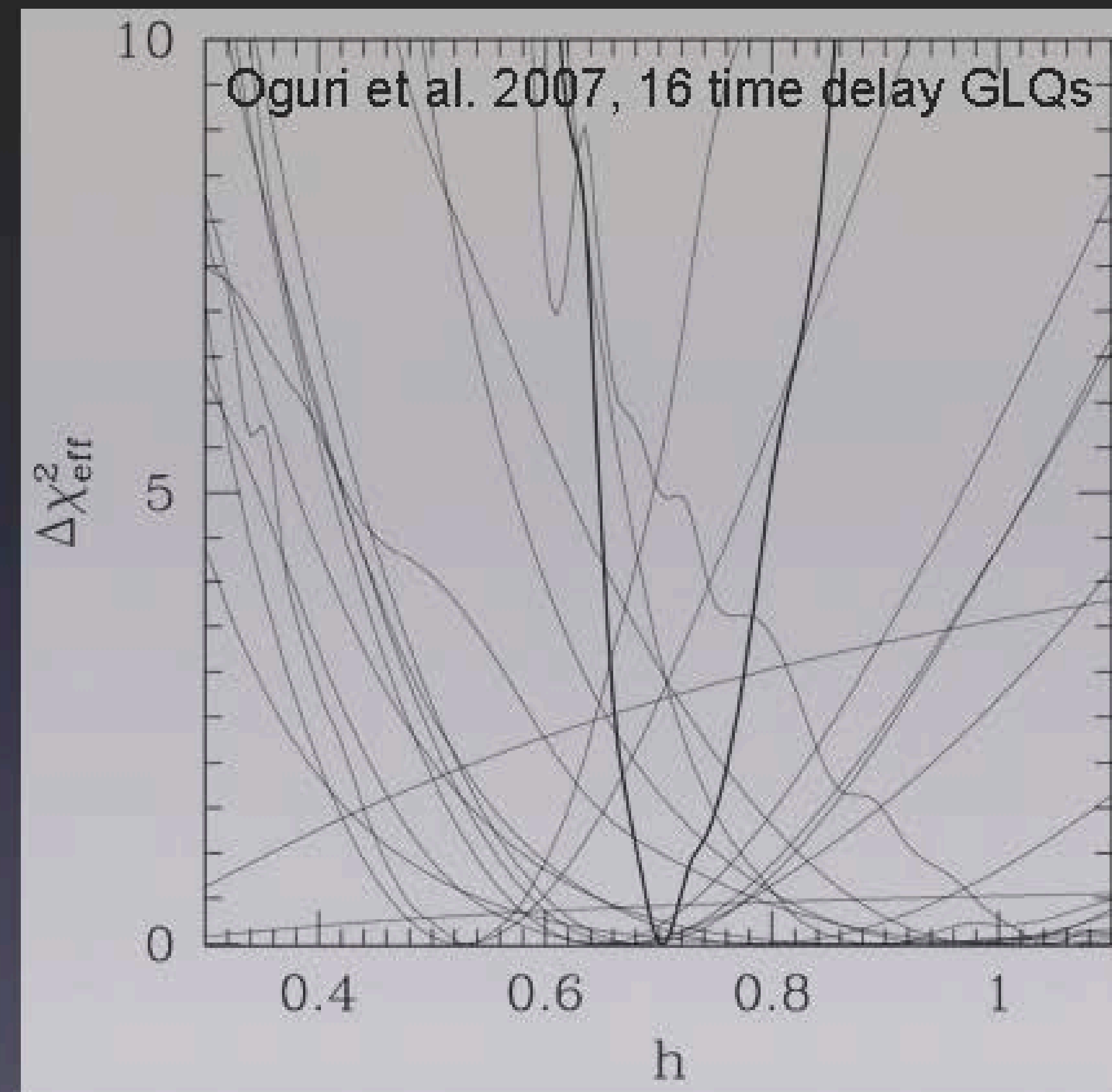
Peng et al. 2006, HST H-band

Estimate the Hubble constant from time delays



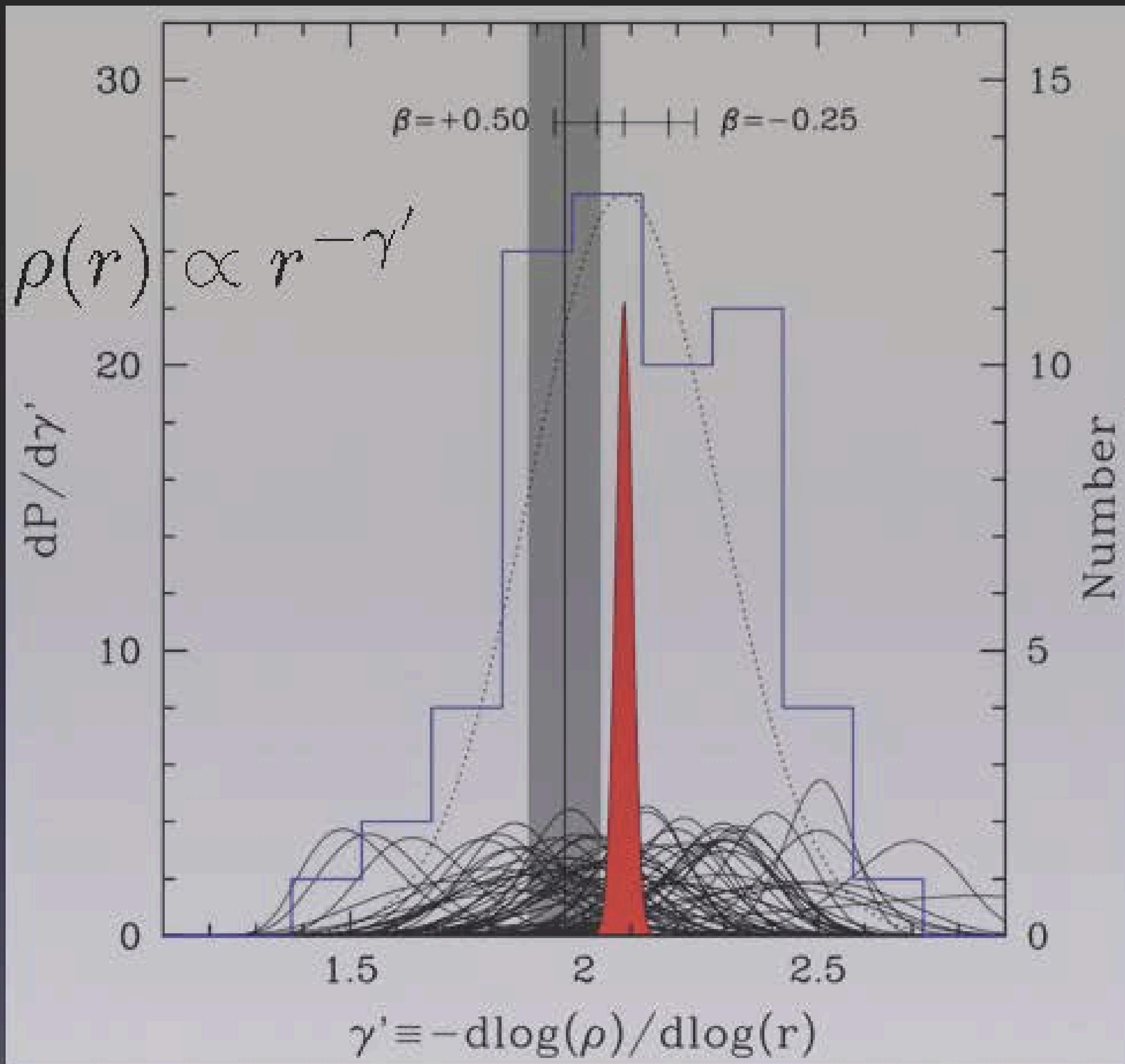


COSMOGRAIL



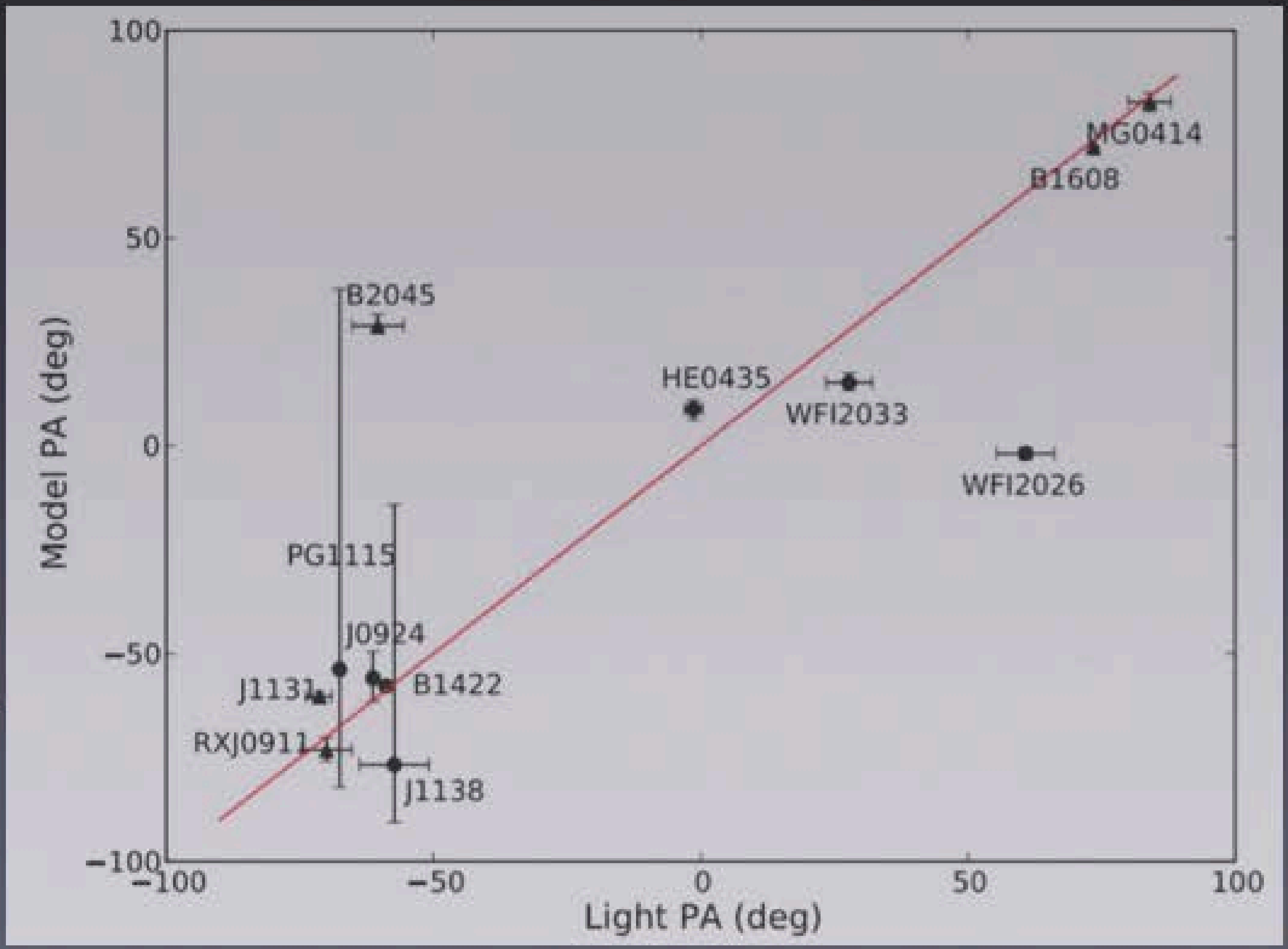
$h = 0.70^{+0.03}_{-0.02}$ at 68% confidence

Radial structure and evolution of elliptical galaxy lenses



Koopmans et al. 2009, SLACS (HST)
elliptical lenses are nearly isothermal

Correlation between the mass and light profile of lenses; environment of quads



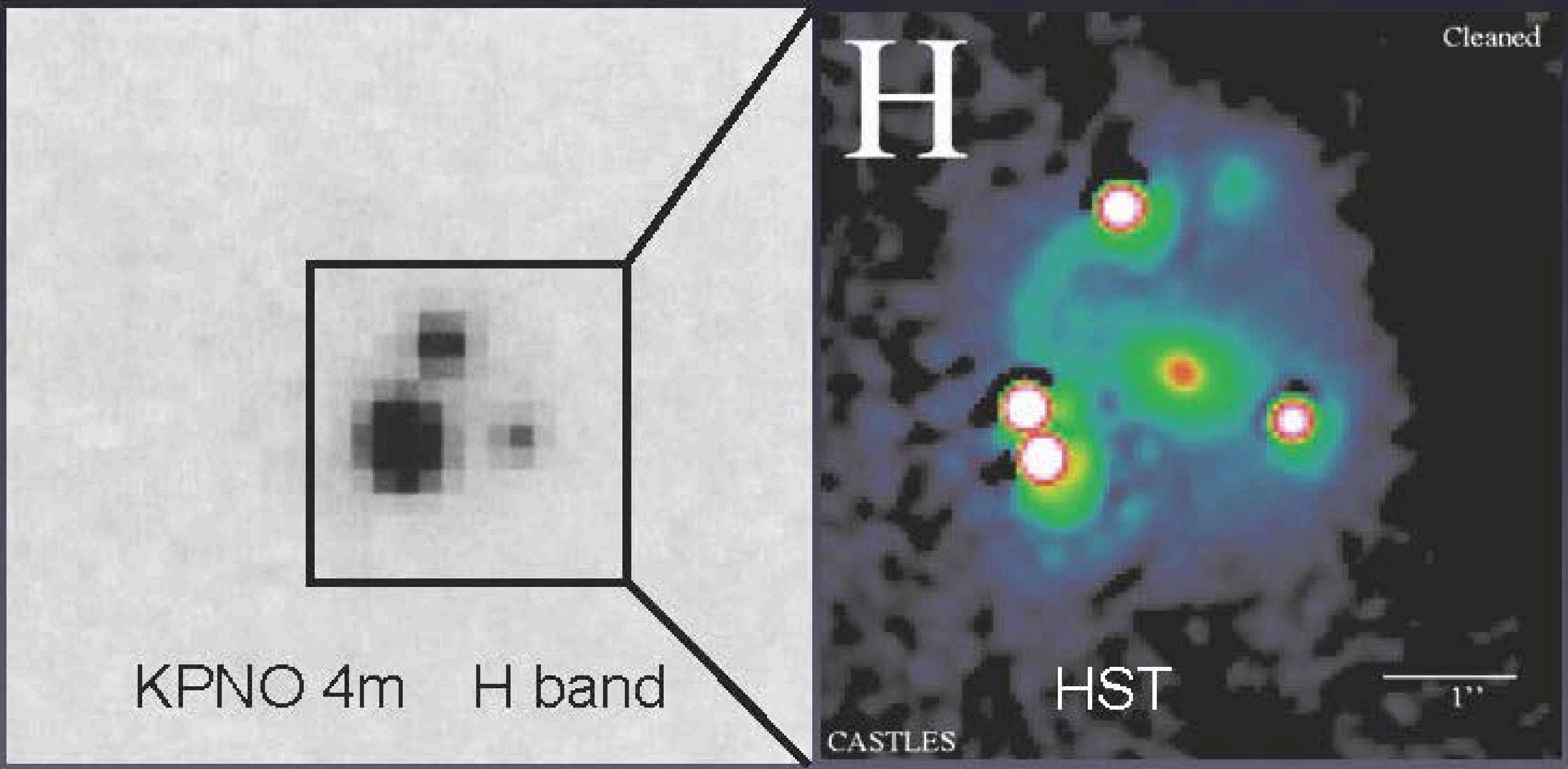
Sluse et al. 2012, COSMOGRAIL HST

High-resolution imaging with HST

Typical image separation 1”− 2” ~ atmospherical seeing size

→ all these applications require high-resolution images

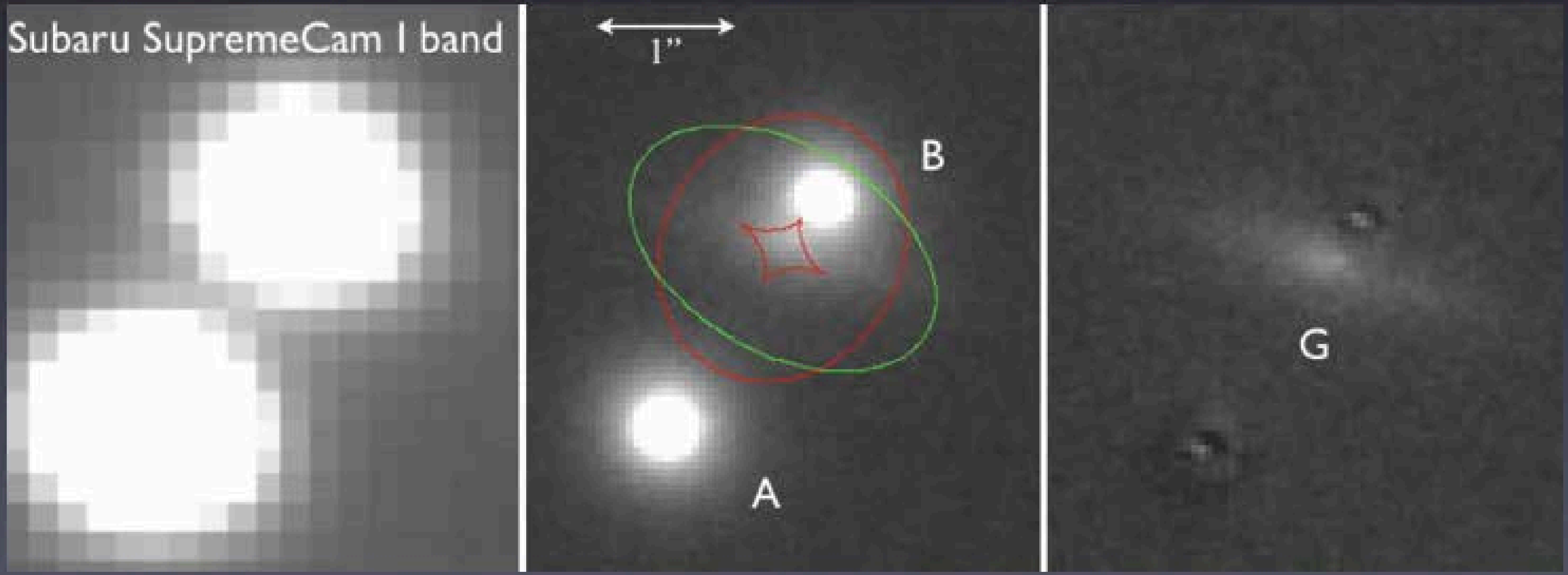
→ HST typically used for high resolution imaging



CASTLES contains 80 lenses

High-resolution imaging with AO

- The advent of AO: high resolution imaging possible from ground
- Few AO observations of lensed quasars performed so far (e.g. Sluse 2008)
- Purpose of this work: conduct the first dedicated AO campaign, as an alternative to HST/CASTLES

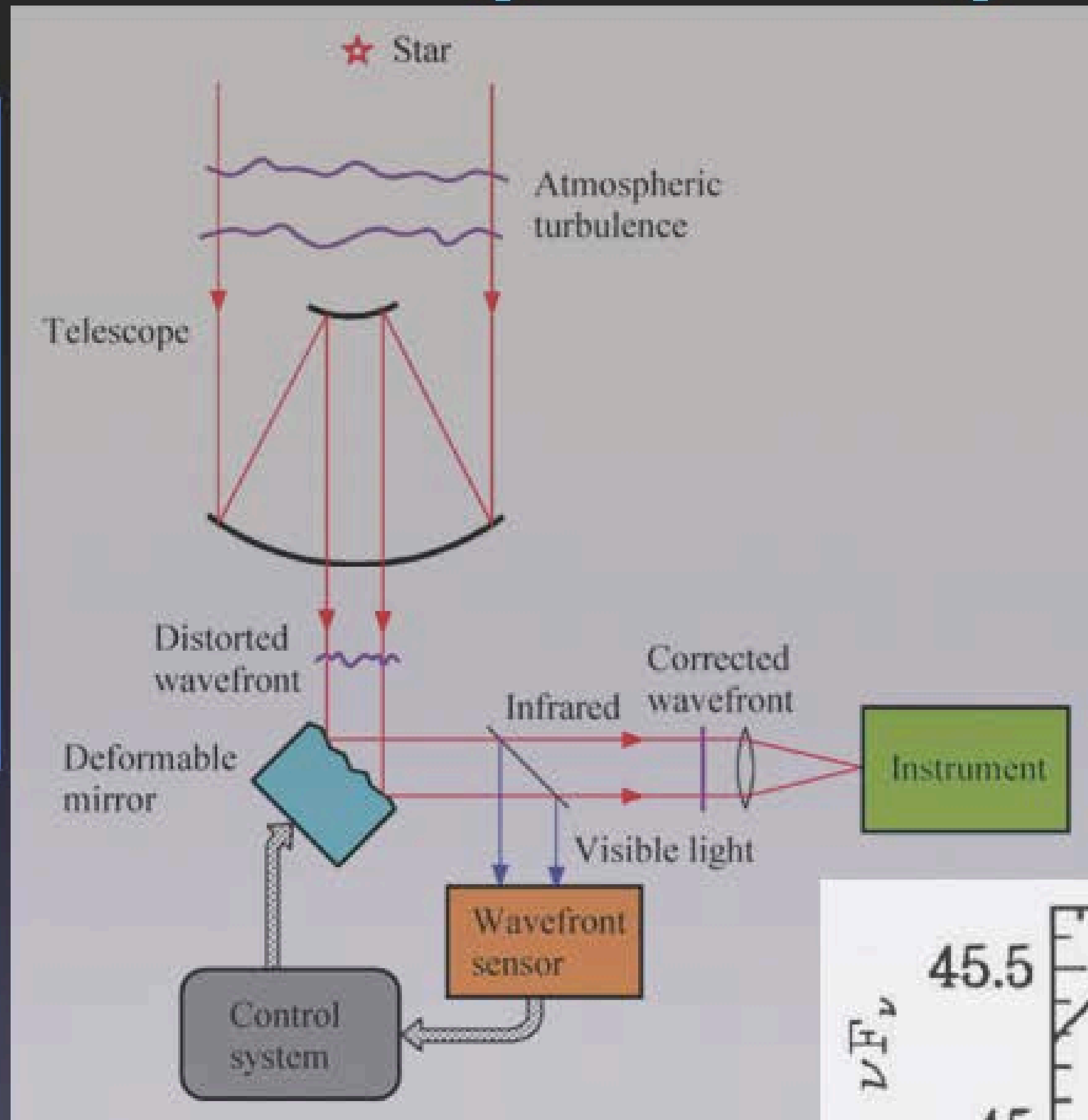


Main goals:

- obtain accurate relative astrometry/photometry/lens galaxy shape
- detect previously unseen features such as the host galaxy

Concepts of Adaptive Optics

- high-res GLQs
- AO concepts
- SQLS
- imaging campaign
- analysis technique
- examples
- SDSS J1334+3315
- SDSS J1330+1810
- SDSS J1405+0959
- M_{BH} - host galaxy
- mean mass profile
- mass and light

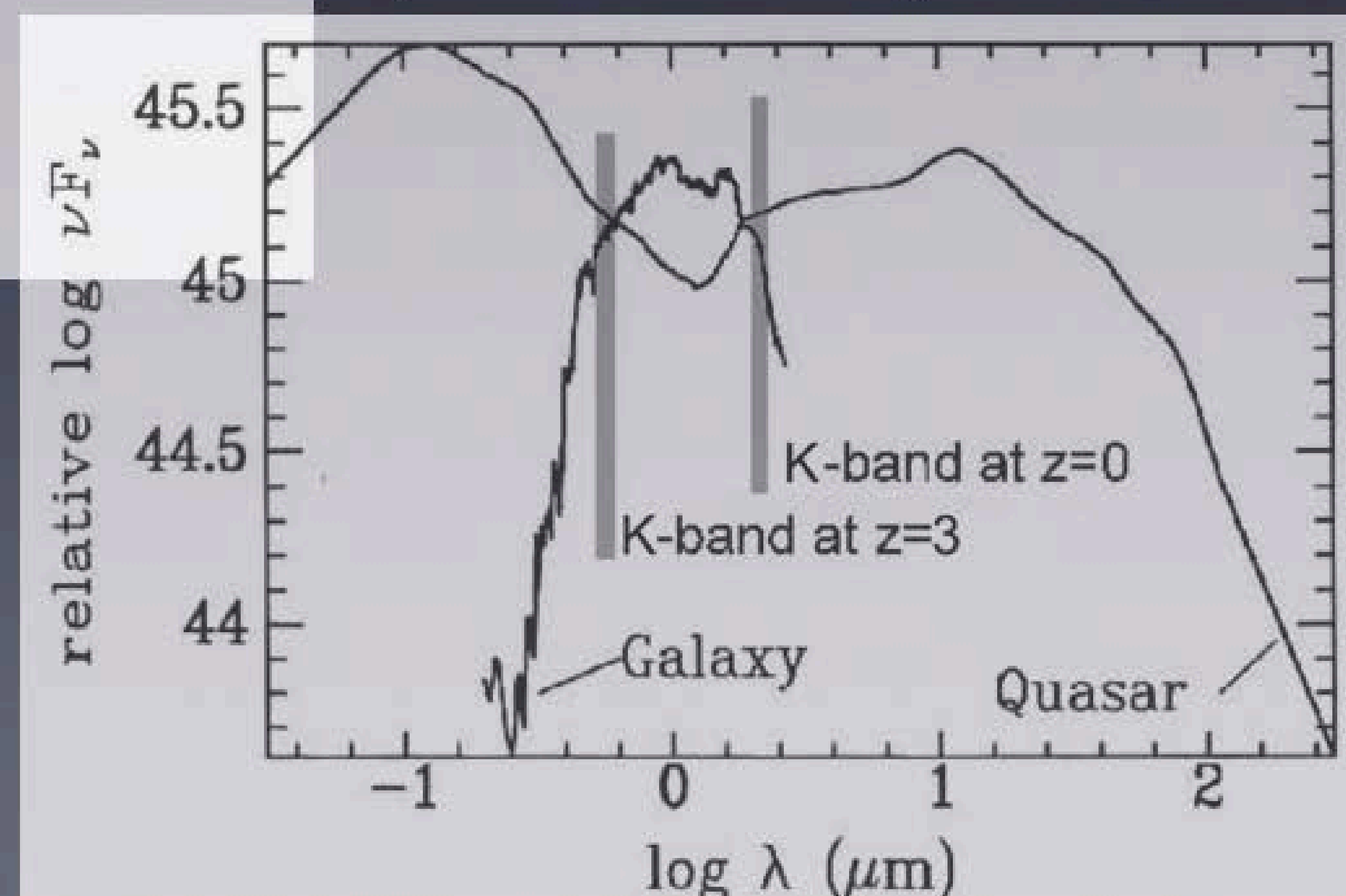


SDSS 0746+4403

- NGS R < 16.5 mag, dist. < 30"
- LGS greatly increases sky coverage: tip-tilt star R < 18 mag, dist. < 90"

K' band:

- better AO correction
- less microlensing, intrinsic variability, reddening
- host galaxy more prominent



The SDSS Quasar Lens Search (SQLS)

high-res GLQs
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- Campaign to discover new lensed quasars from SDSS (Oguri et al. 2006)
- ~ 62 lensed quasars included in the SQLS sample so far (largest); ~ 48 new discoveries
- Follow-up spectroscopy, low-res imaging with UH88 etc. to check candidates; no high-res available for most

morphological selection

color selection

Subaru AO imaging campaign (I)

high-res GLQs
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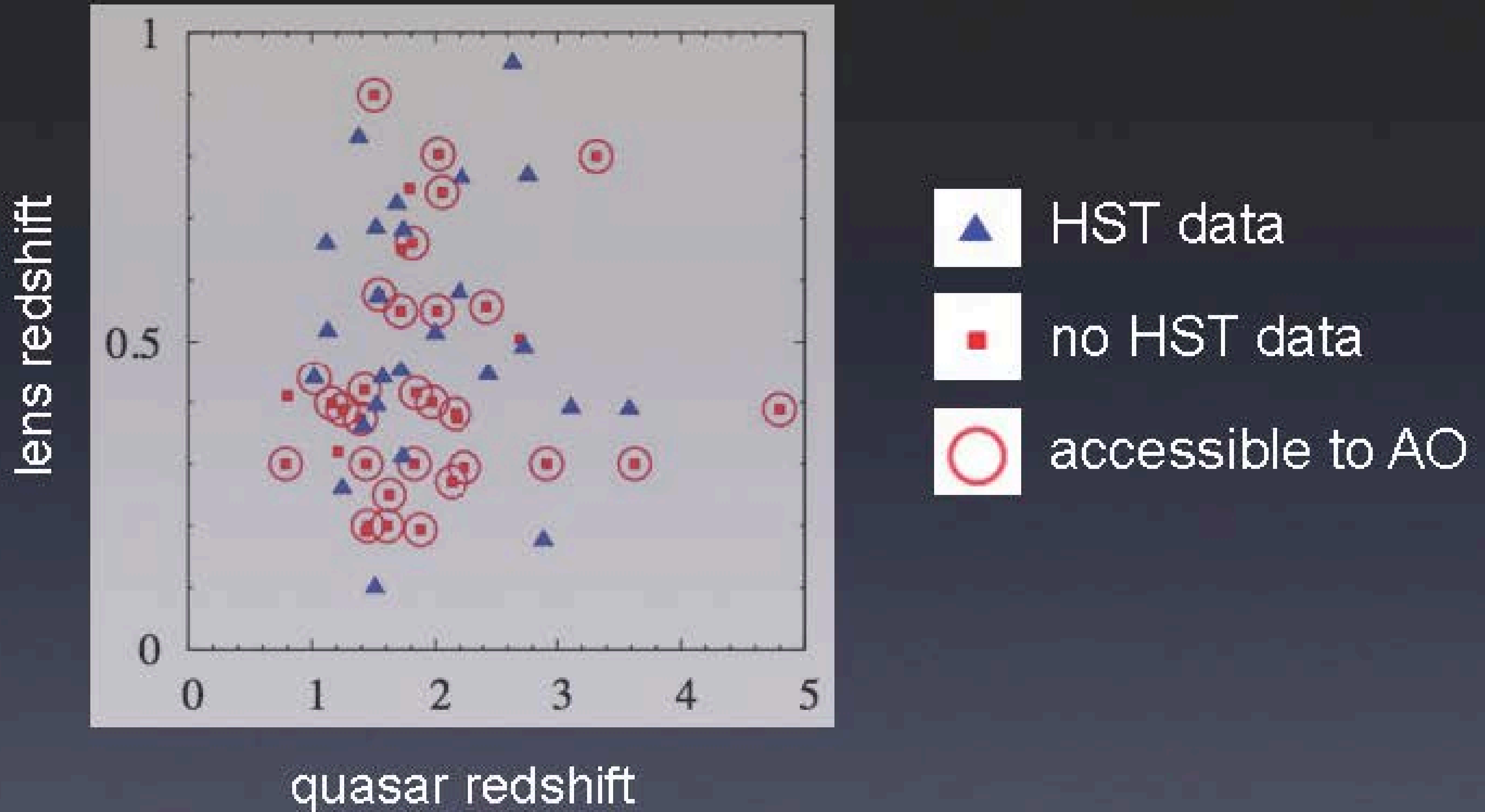
- 54/62 SQLS GLQs are accessible to Subaru LGSAO

  (~40 Keck, ~5 Gemini North)



- ~1h/target imaging (with overhead) with Subaru IRCS+(LGS)AO188
- Campaign started in Feb. 2011 (Rusu et al. 2011)

→ ~2-3 nights usable data; open use, guaranteed time, engineering

Subaru AO imaging campaign (II)

- 20 (AO) + 2 (non-AO) objects observed:

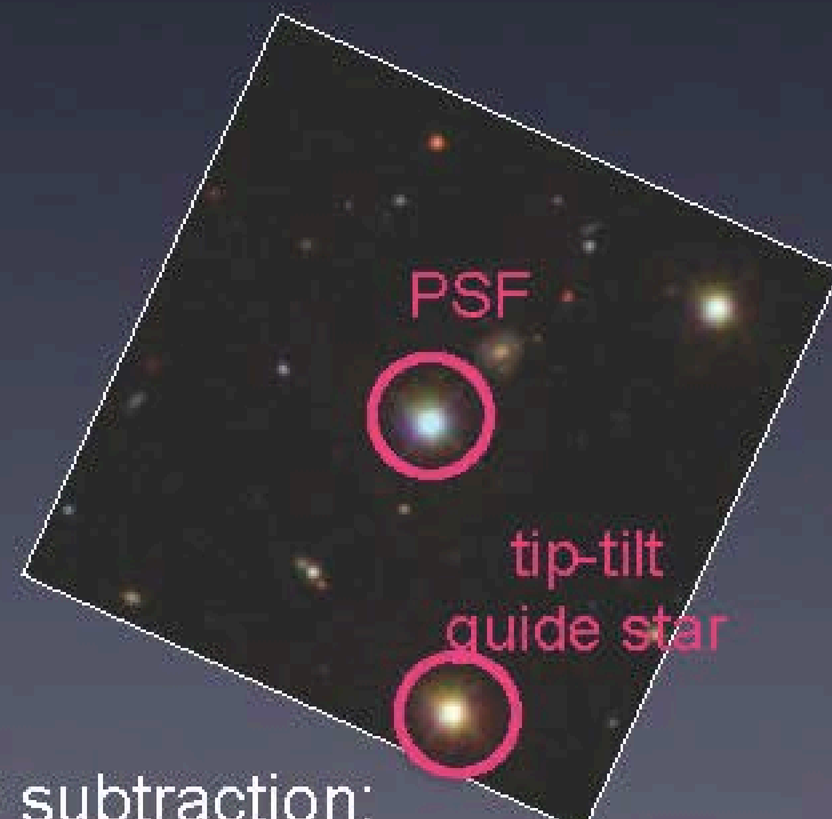
  2 lensed candidates, 20 confirmed lensed quasars

  1 quad, 1 triple (?), the rest doubles;

  4 detected host galaxies (shallow...)

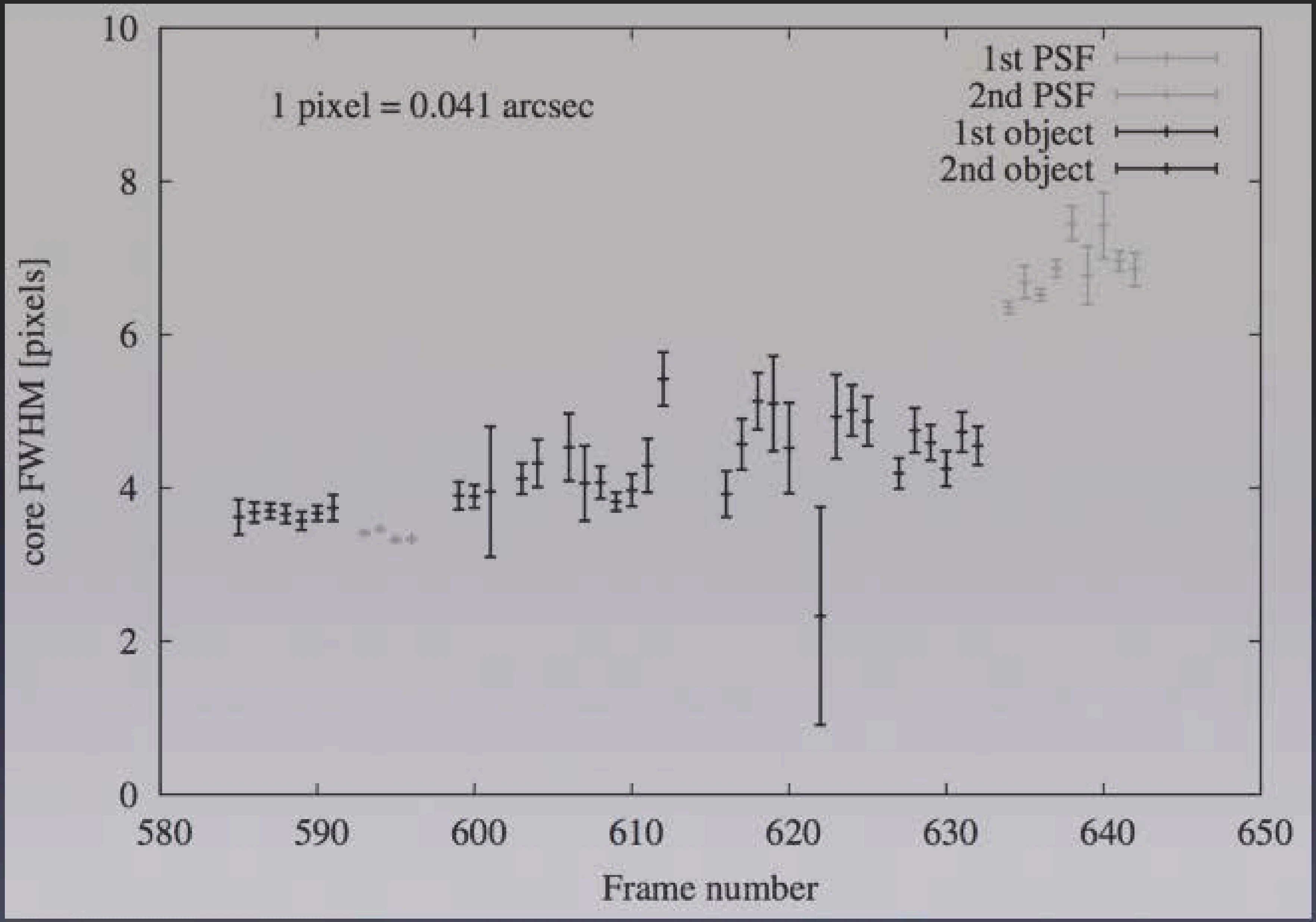
  Strehl ratio ~ 10% FWHM 0.15''-0.25''

- Observed PSF stars with same configuration (TT-star R mag, distance)



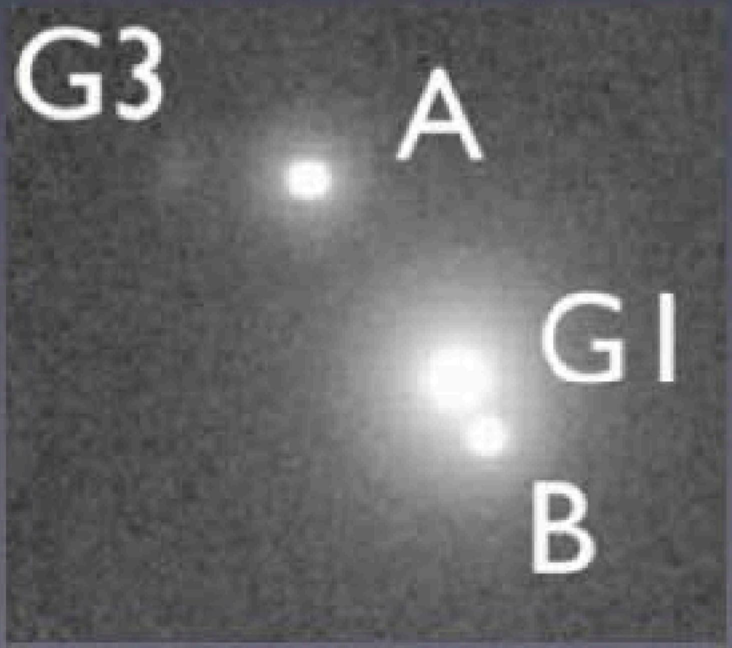
- 5/9-point dither for sky flats and sky subtraction;
- Distortion map (Y. Minowa)
- Reduction using IRCS IMGRED package (Y. Minowa)

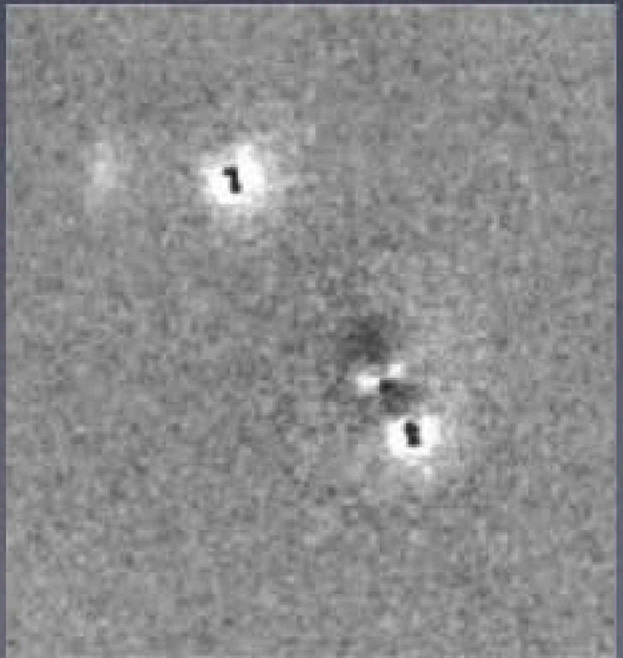
Problem: PSF variability



PSF unstable in time

→ The separately observed PSF stars cannot be used to fit the systems



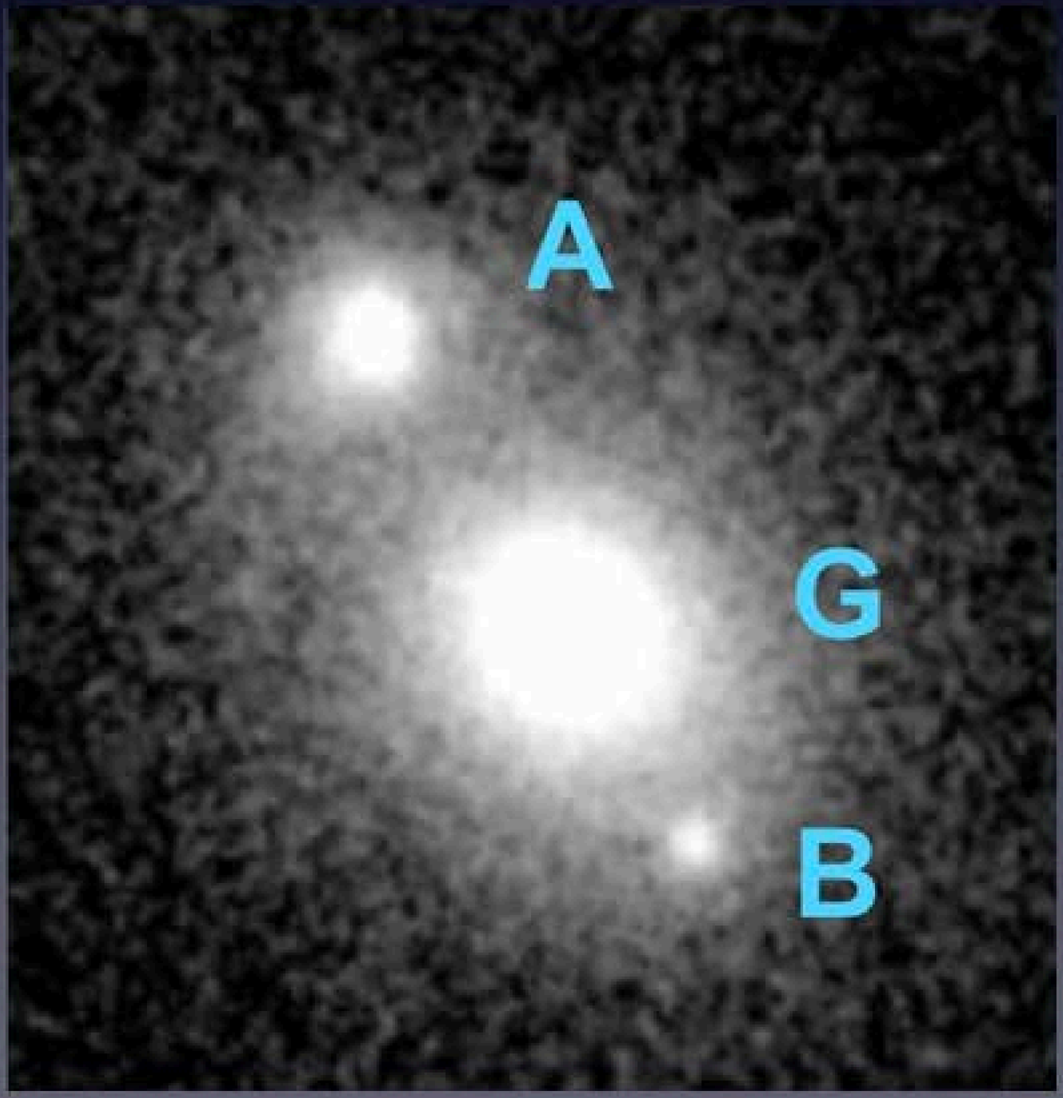


Traditional approach generally does not work with AO

→ New approach is needed

Unique feature of lensed quasars: two/four point-like sources surrounding the lens galaxy

Use the information included in each lensed system to construct the PSF on target, and fit the morphology either simultaneously, or iteratively



New morphological modeling technique (I)

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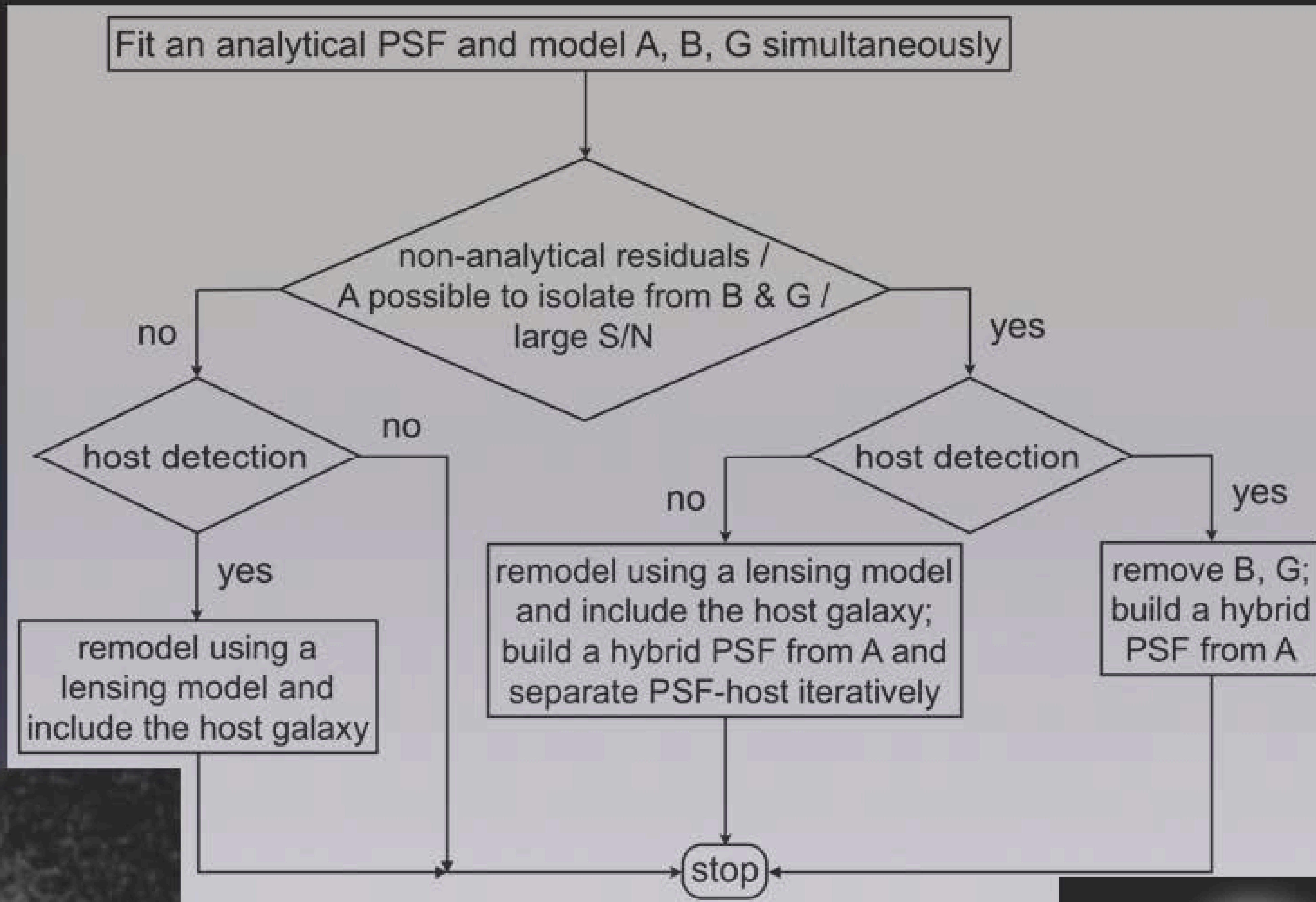
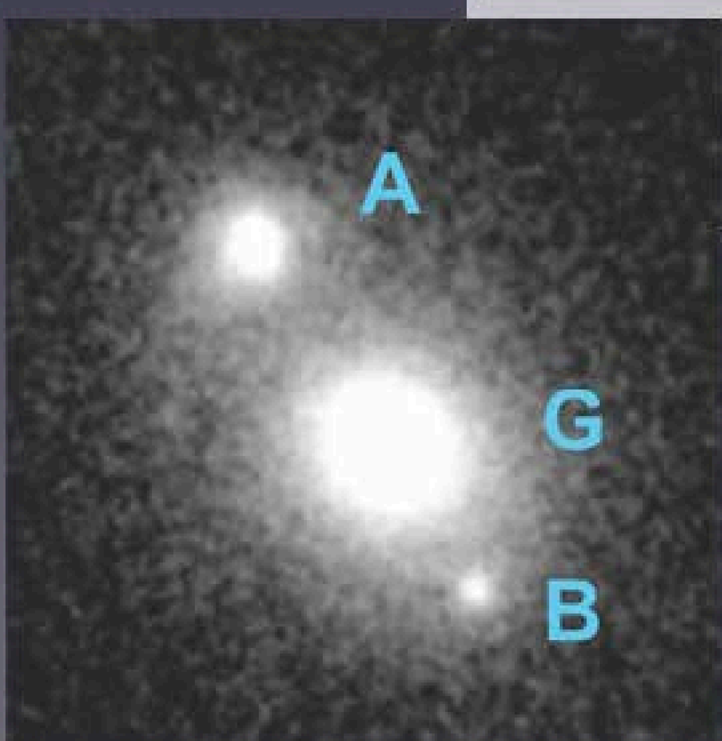
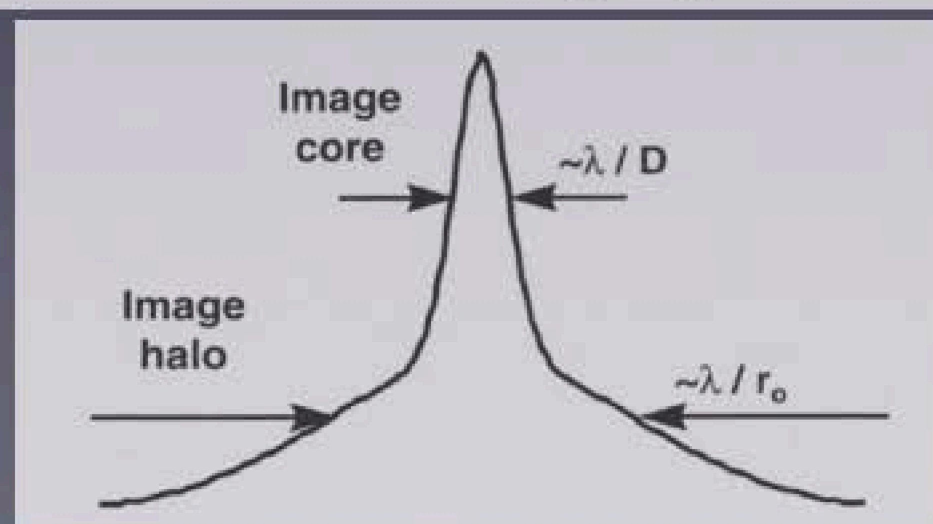
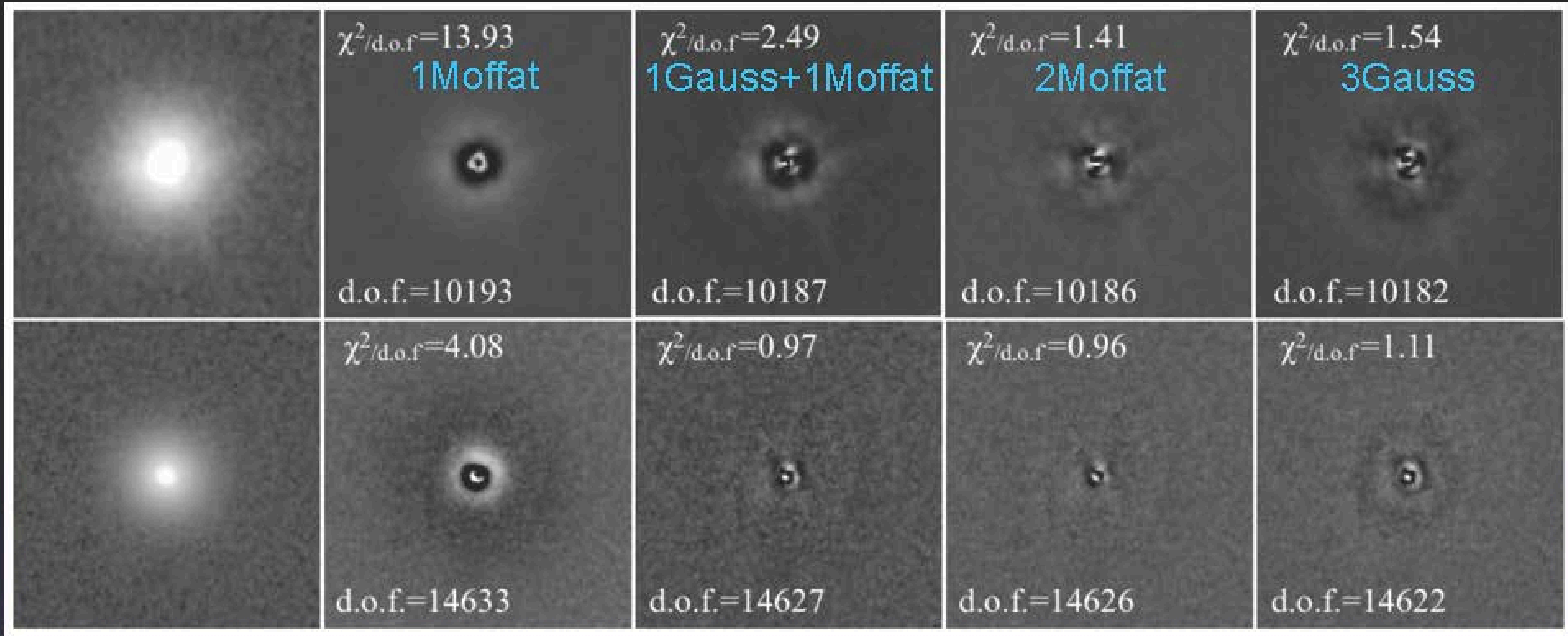
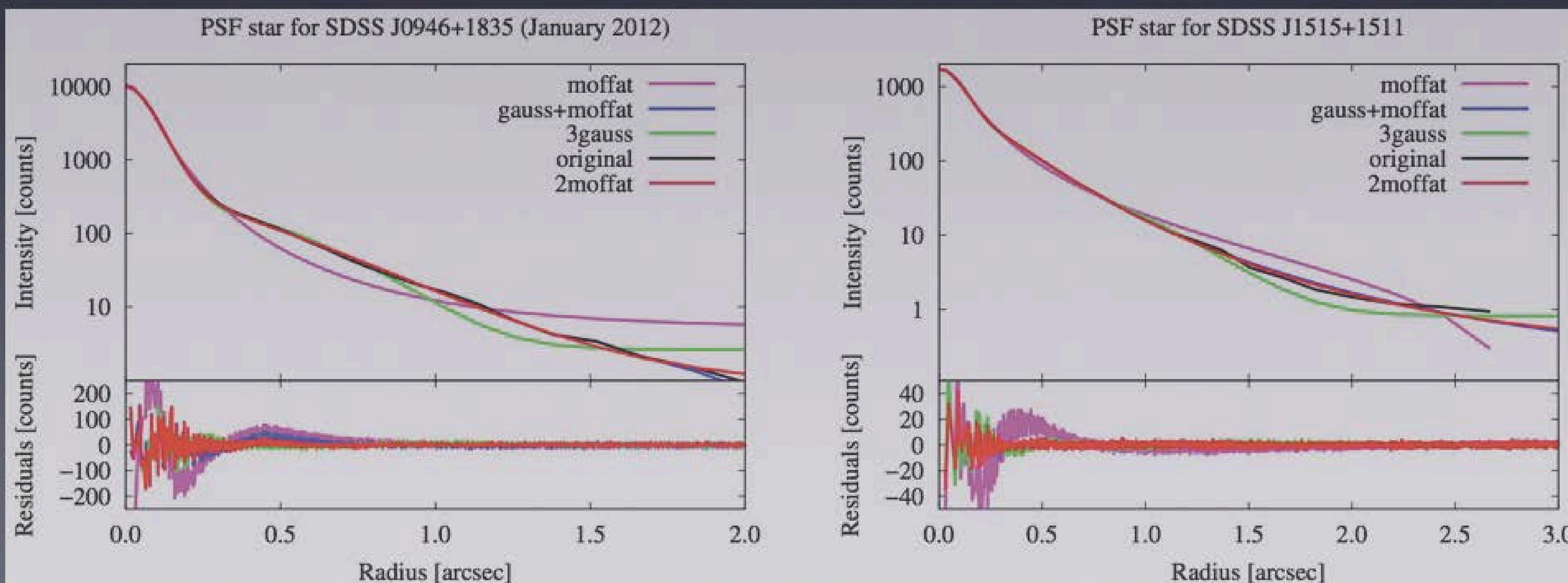







χ²/d.o.f=13.93
1Moffat
χ²/d.o.f=2.49
1Gauss+1Moffat
χ²/d.o.f=1.41
2Moffat
χ²/d.o.f=1.54
3Gauss
d.o.f.=10193
d.o.f.=10187
d.o.f.=10186
d.o.f.=10182
χ²/d.o.f=4.08
χ²/d.o.f=0.97
χ²/d.o.f=0.96
χ²/d.o.f=1.11
d.o.f.=14633
d.o.f.=14627
d.o.f.=14626
d.o.f.=14622


PSF star for SDSS J0946+1835 (January 2012)
moffat
gauss+moffat
3gauss
original
2moffat
Intensity [counts]
Residuals [counts]
Radius [arcsec]
PSF star for SDSS J1515+1511
moffat
gauss+moffat
3gauss
original
2moffat
Intensity [counts]
Residuals [counts]
Radius [arcsec]

New morphological modeling technique (II)

Use HOSTLENS (M. Oguri): fit analytical or real PSF, and model all components

PSF: concentric moffat+moffat
lens galaxy: PSF * Sersic
typical components: 2PSF (quasar images A&B) + 1Sersic (lens galaxy G) + Sky

moffat: FWHM, shape (beta), ellipticity, PA, flux1/flux2 (9)

$$I(r) = \left[1 + \left(2^{1/\beta} - 1\right)(2r/\mathrm{FWHM})^2\right]^{-\beta}$$

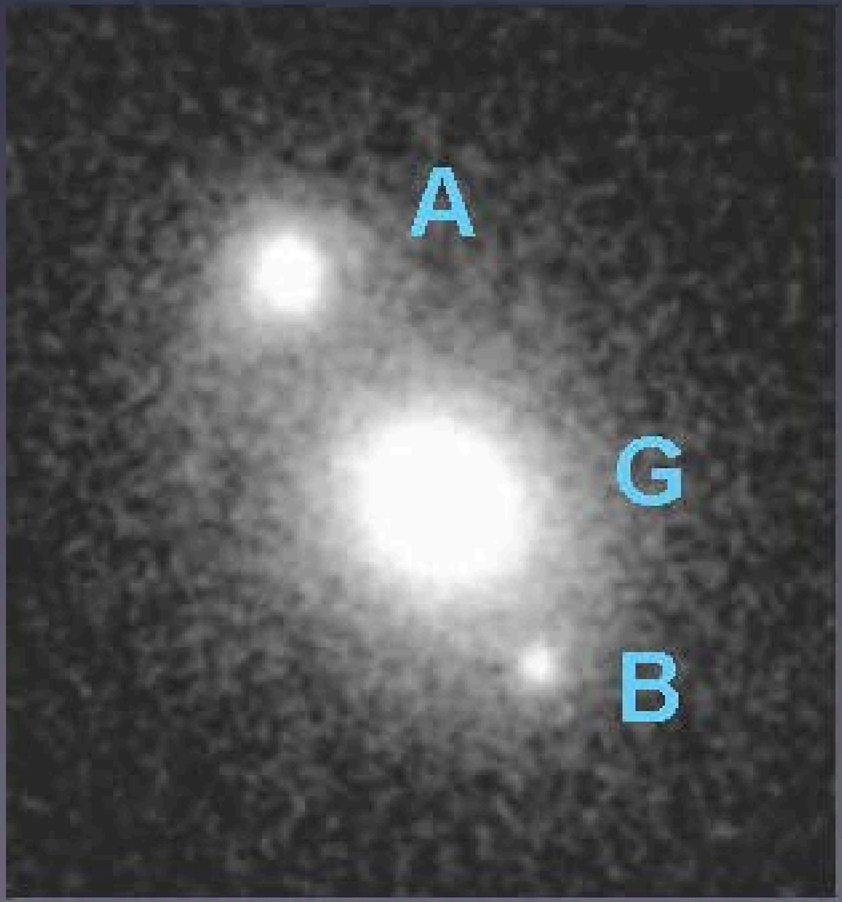


image: X, Y, mag (3)

Sersic profile:
eff. rad., ellipticity, PA, sersic index n (4)
n = 1 exponential (disk)
n = 4 De Vaucouleurs (bulge,elliptical)

$$\Sigma(r) = \Sigma_e \exp\left[-\kappa\left(\left(\frac{r}{r_e}\right)^{1/n} - 1\right)\right]$$

23 parameters w/ analytical PSF, 14 real PSF

New morphological modeling technique (III)

Fit by χ^2 minimization from 500 different positions

Refine through MCMC search

Error bars: MCMC (PSF marginalized over); 100 simulations with noise, using the PSF stars

→ 1-2 mas relative astrometry, relative photometry (A & B) ~ 0.01 mag, effective radii ~ 20%

In case of QSO host detections:

detection: visible arcs that are well fitted with lensing models

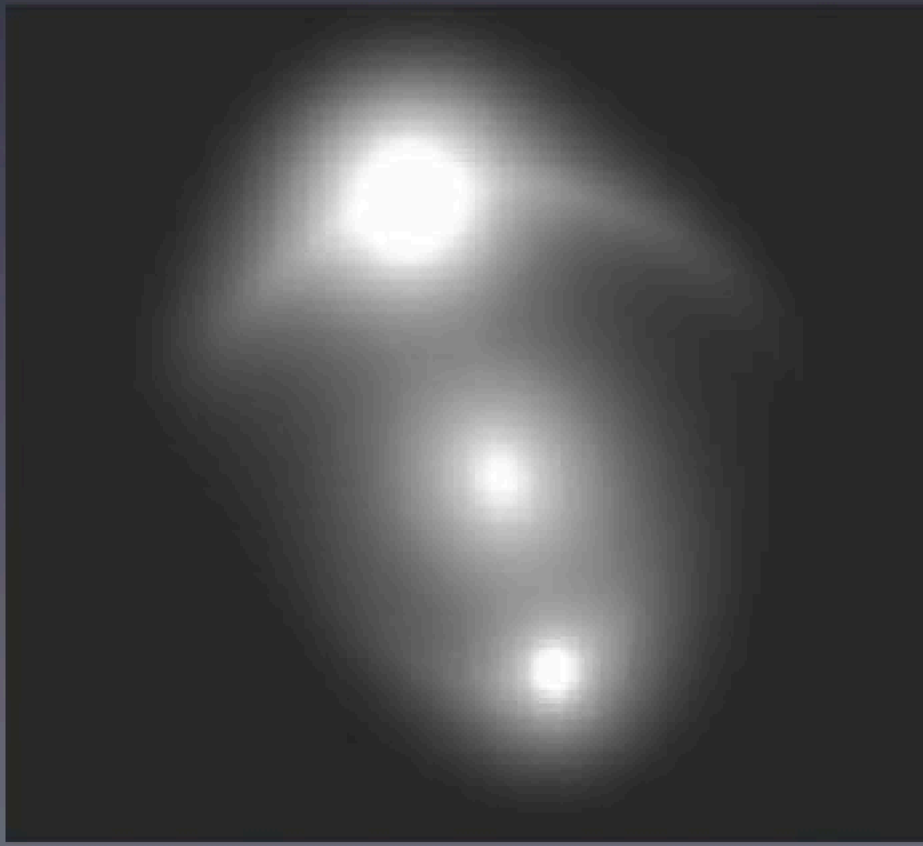
Components: 1) lens galaxy (7)

2) host: de Vaucouleurs profile with central point source (8)

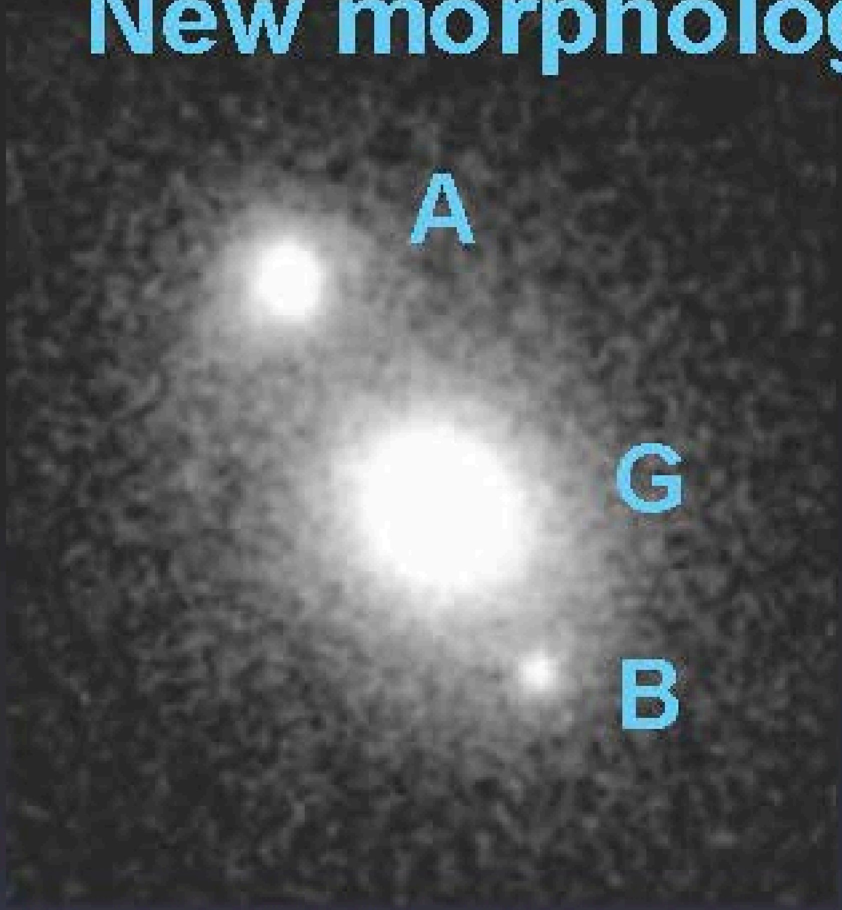
3) lensing model: SIS+γ (3) SLACS: lenses are ~ isothermal

28 parameters including analytical PSF

→ use the fitting procedure above

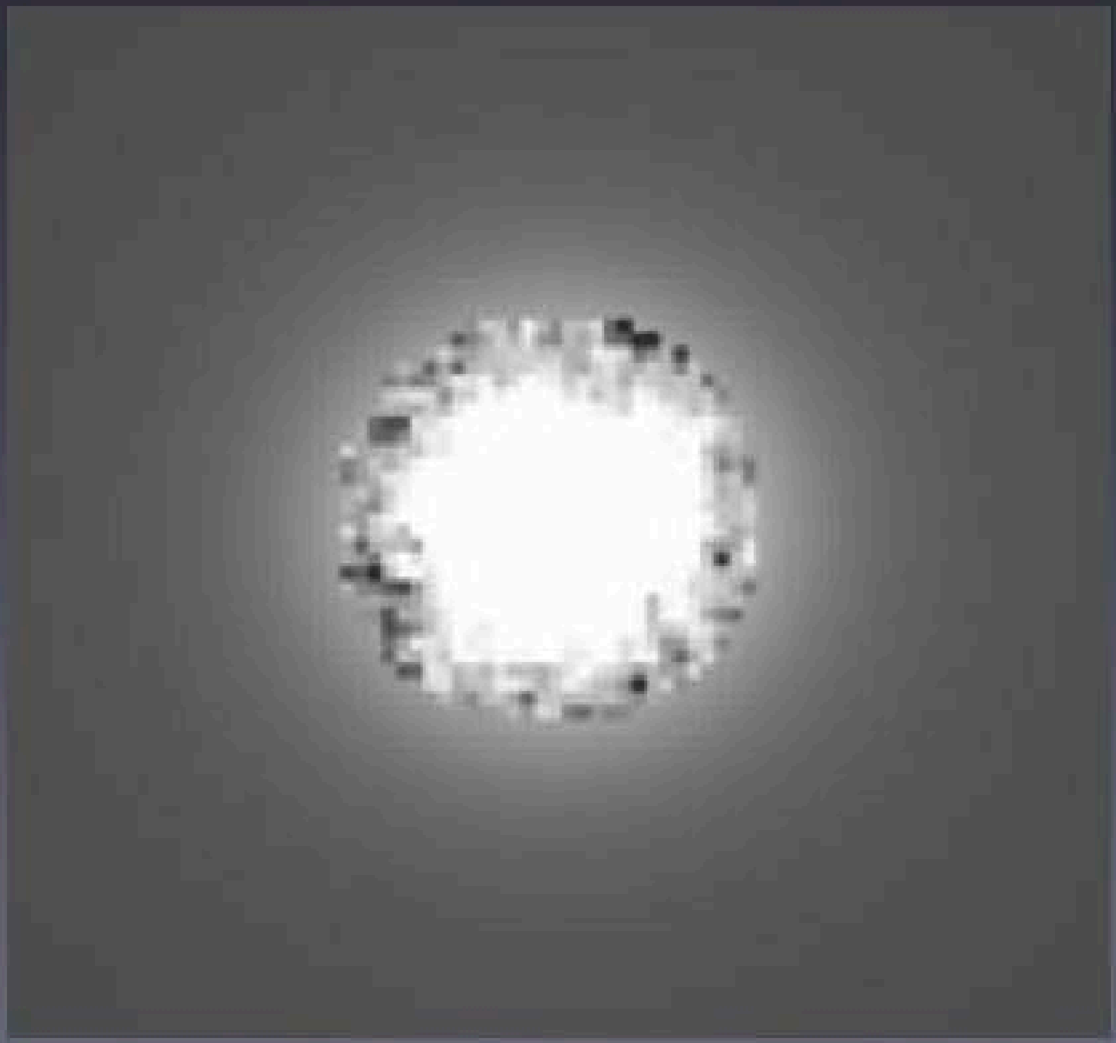


New morphological modeling technique (IV)



Case of non-analytical residuals at A (large S/N)

→ Use image A as a hybrid PSF



- core: use observed flux distribution
- wings: replace profile analytically
- use different cut radii to avoid systematics

Examples

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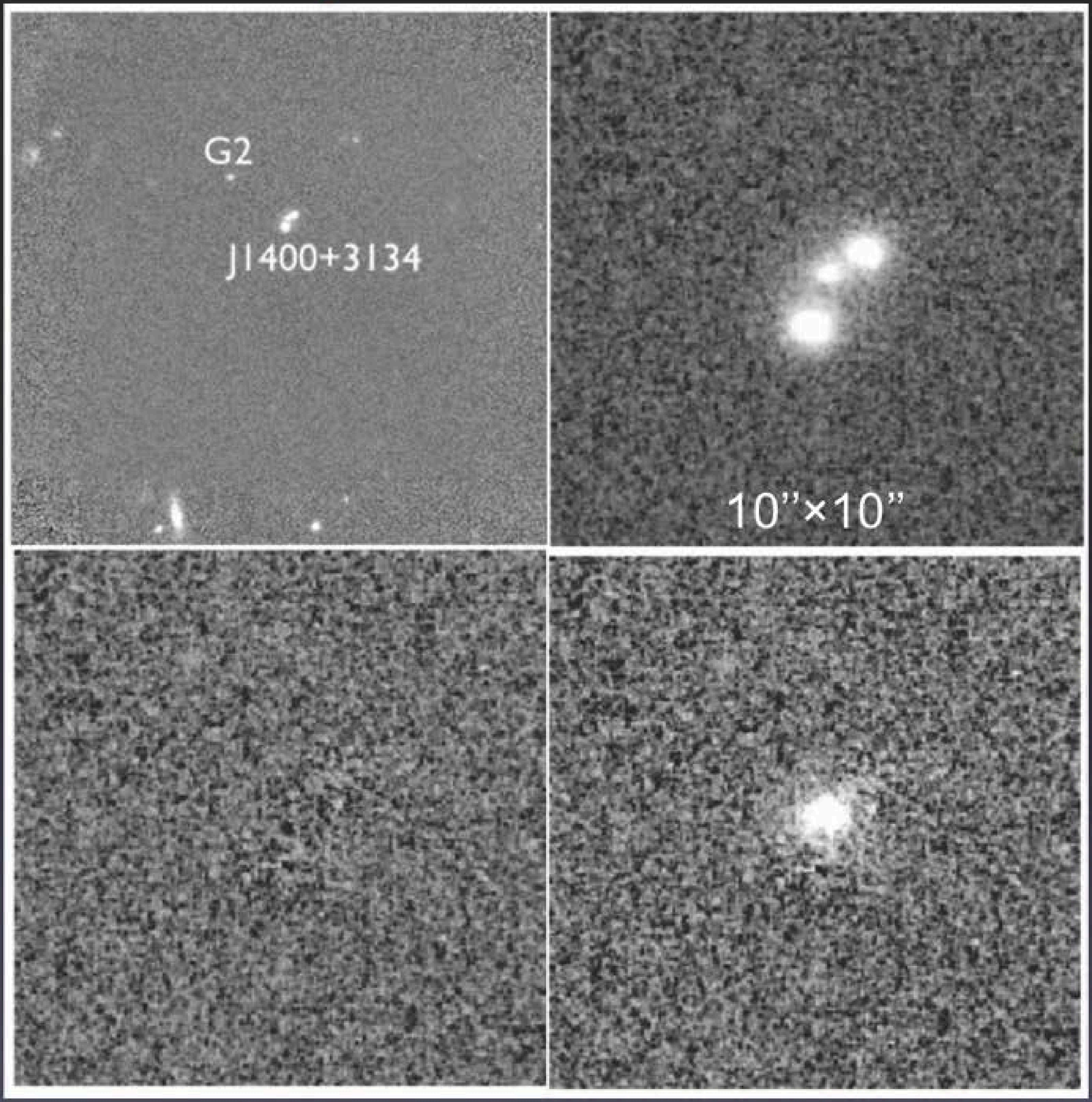
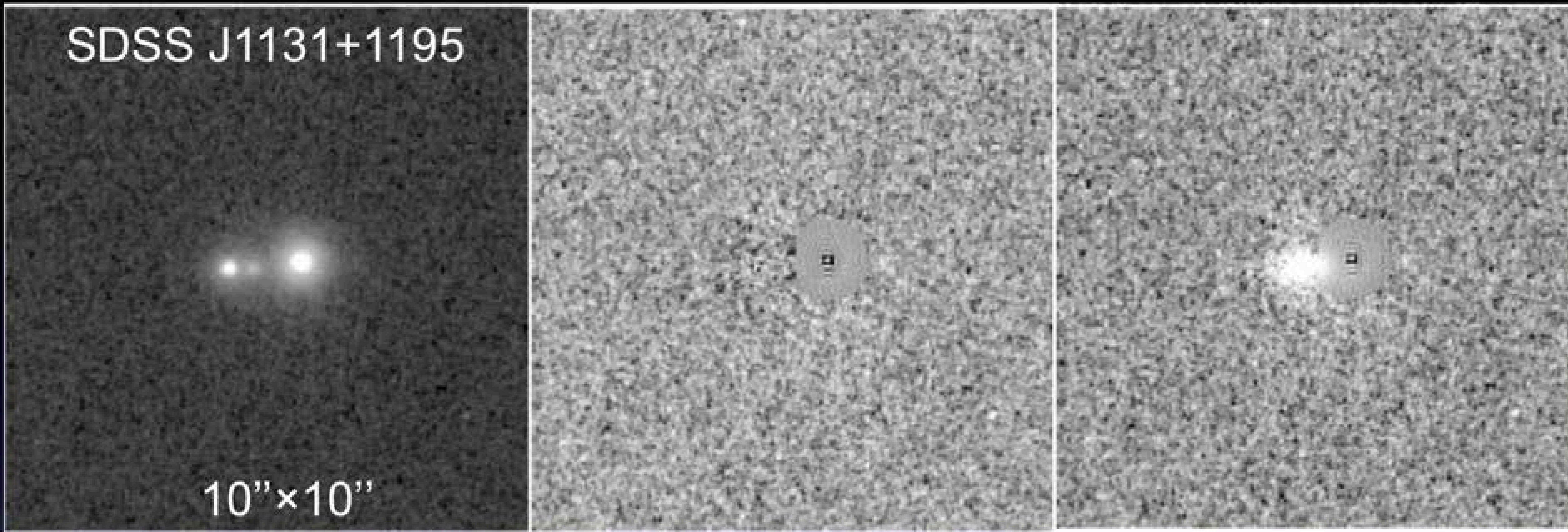
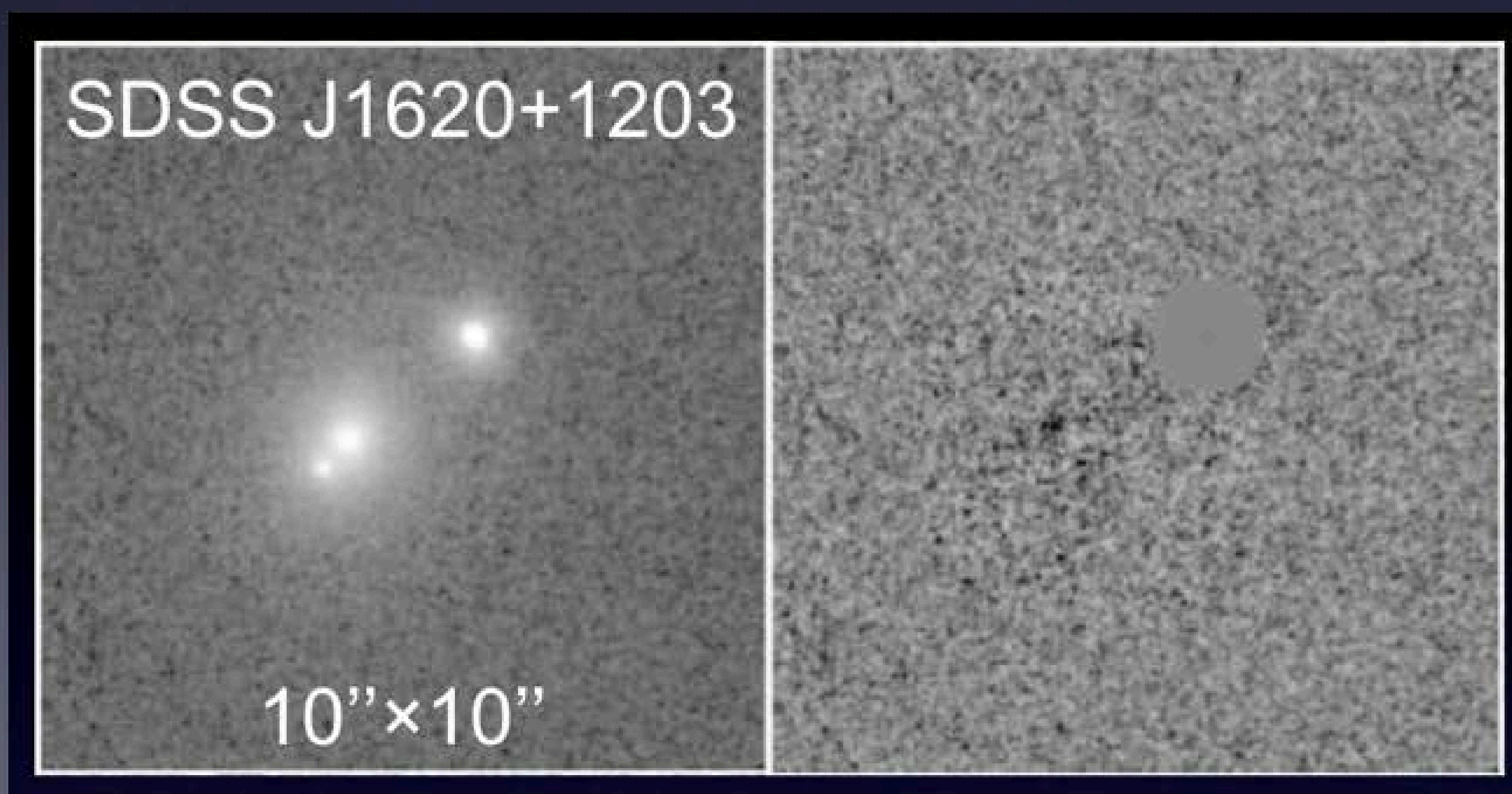
Analytical PSF results in very clean residuals

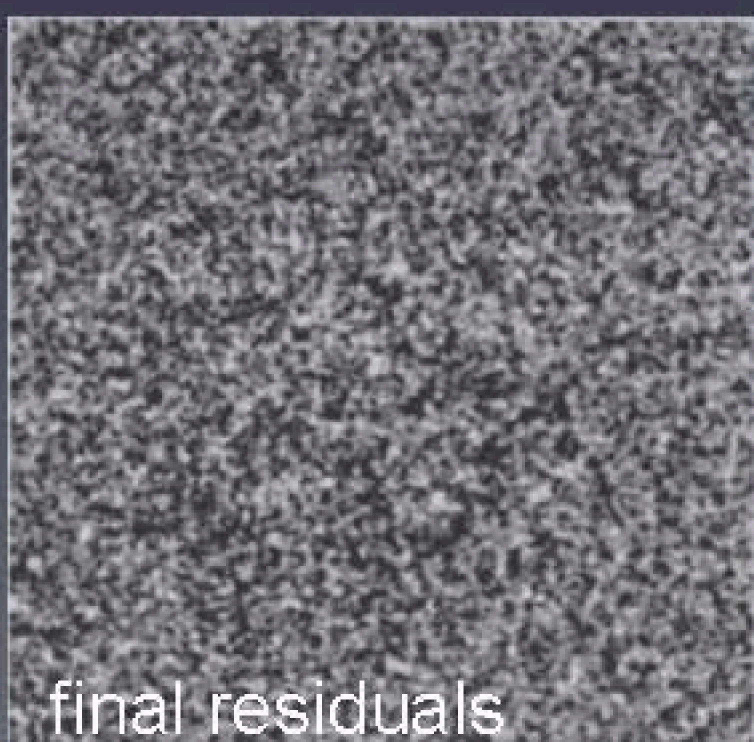




Two systems fitted with a hybrid PSF

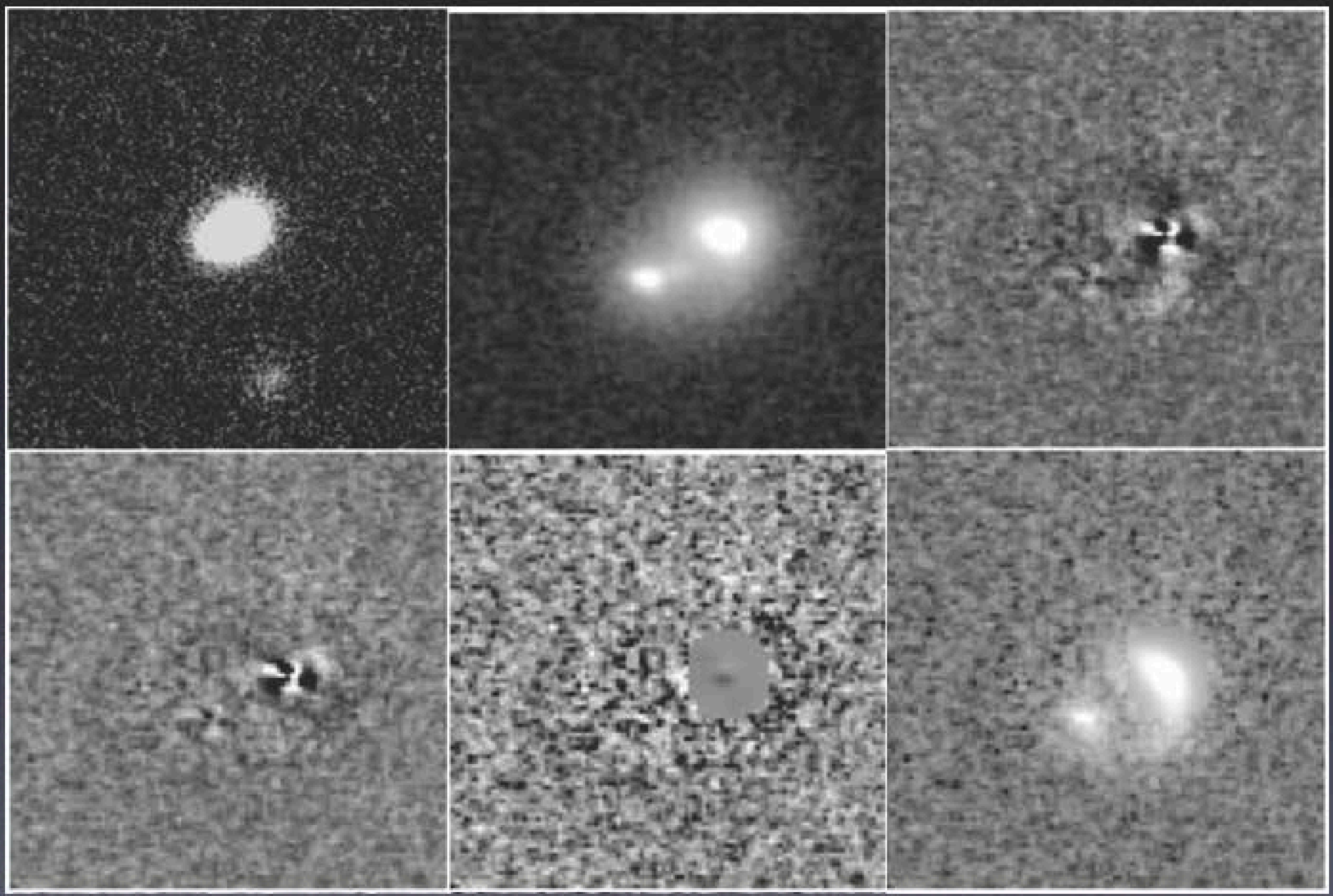


SDSS J0819+5356: a host characterization using analytical PSF $z_{quasar} = 2.24$



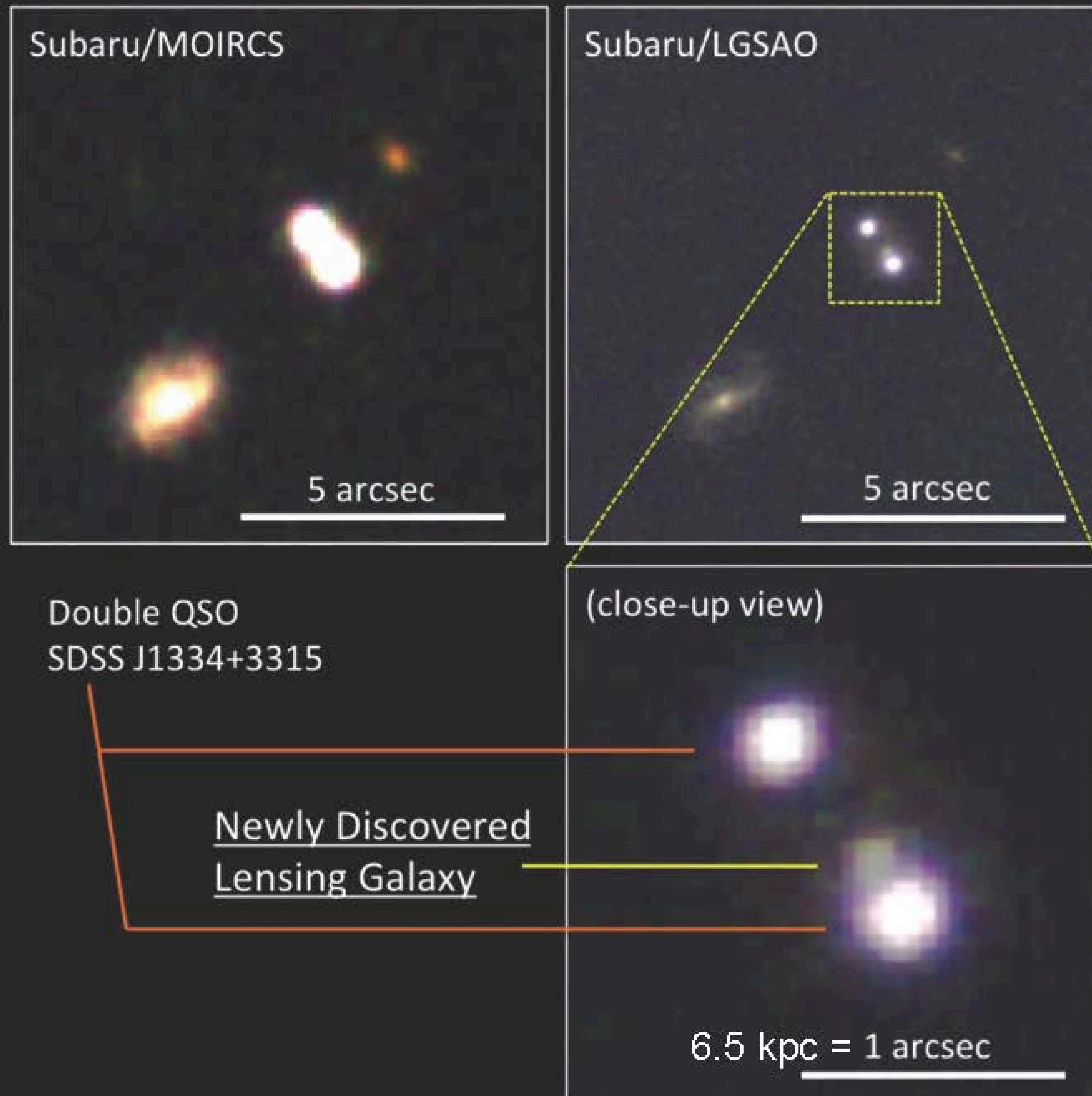
arcs around image A are well fitted if
a lensed host galaxy is considered

SDSS J0904+1512: a source characterization using hybrid PSF $z_{quasar} = 1.83$



- analytical PSF residuals show arcs
- arcs removed by fitting a host galaxy
- using analytical PSF fit, remove only the host
- build hybrid PSF on A
- refit the host using the hybrid PSF
- iterate until minimum χ^2 is reached

SDSS J1334+3315

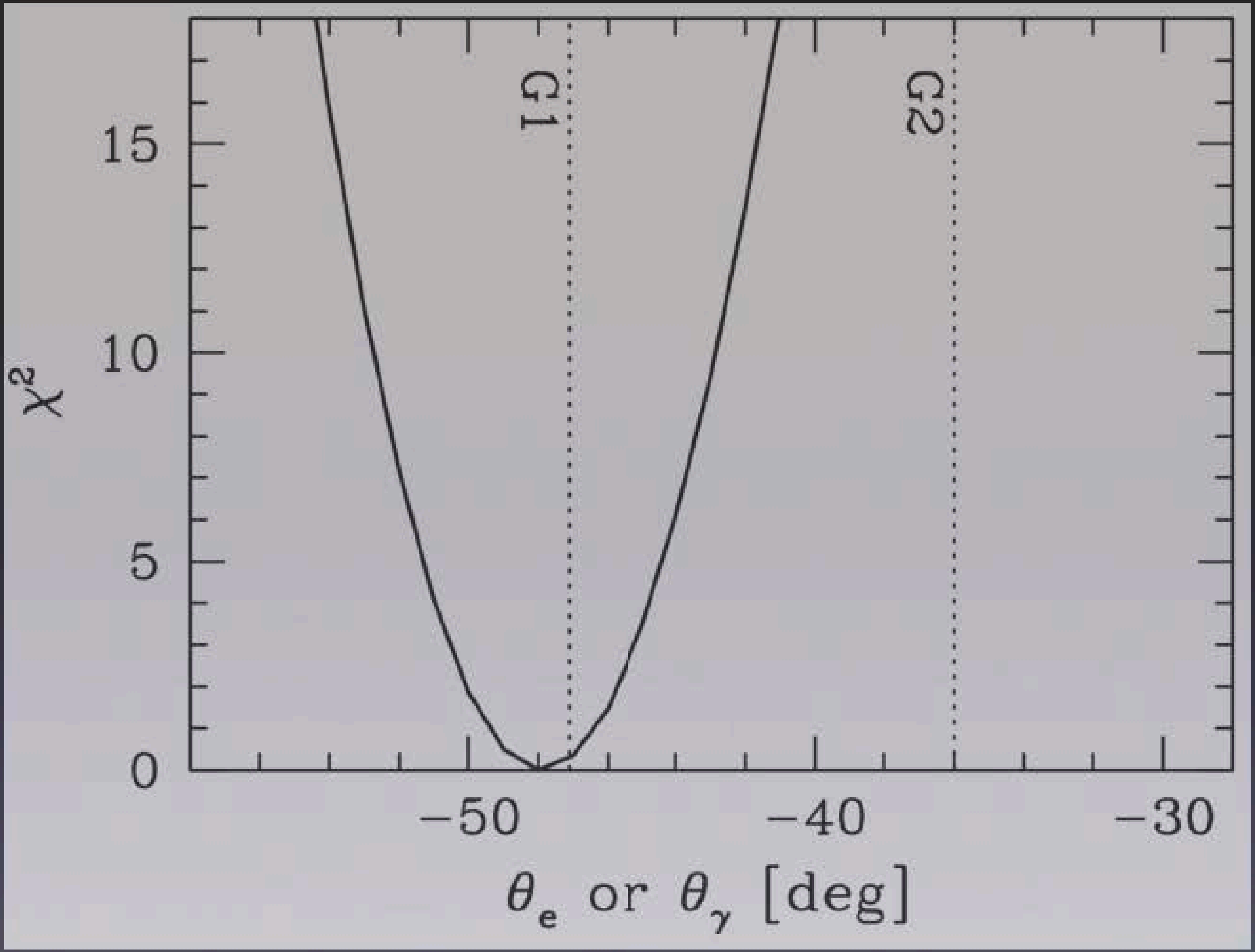


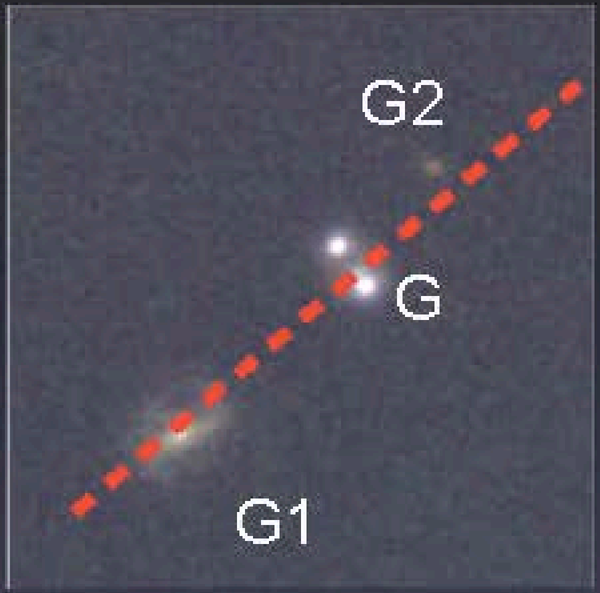
Press release July 6, 2011

$\Delta\theta$ = 0.83'' smallest in SQLS

J,H,K'

Contribution of G1, G2 to the lensing model





$\gamma \sim R_{\rm Ein}/2d \sim 0.1$ using Faber-Jackson relation

$\gamma \sim 0.11$ for the SIS+γ model

photo-z for G & G1 z ~ 0.56, but much higher for G2

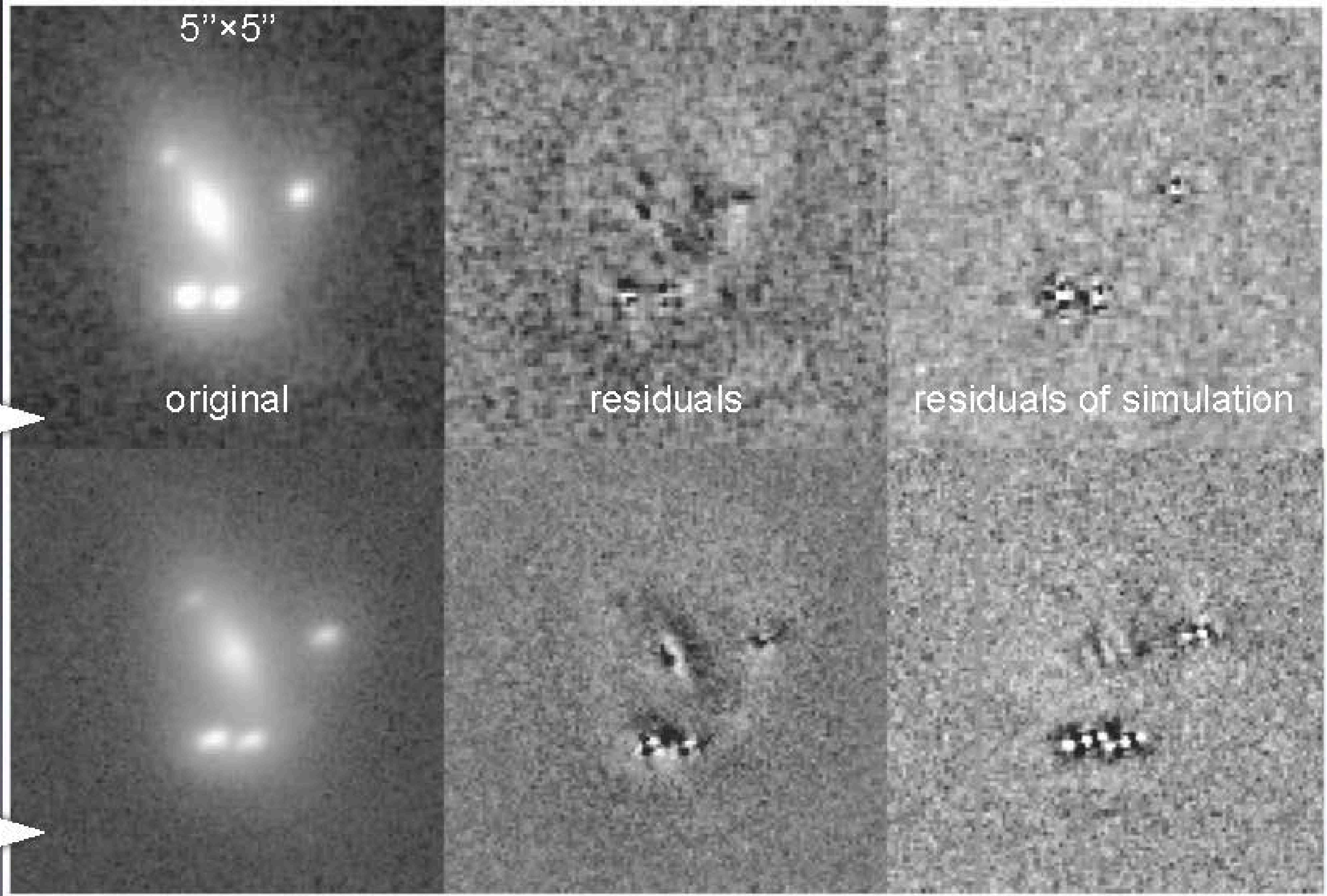
→ consistent with the lensing model

SDSS J1330+1810

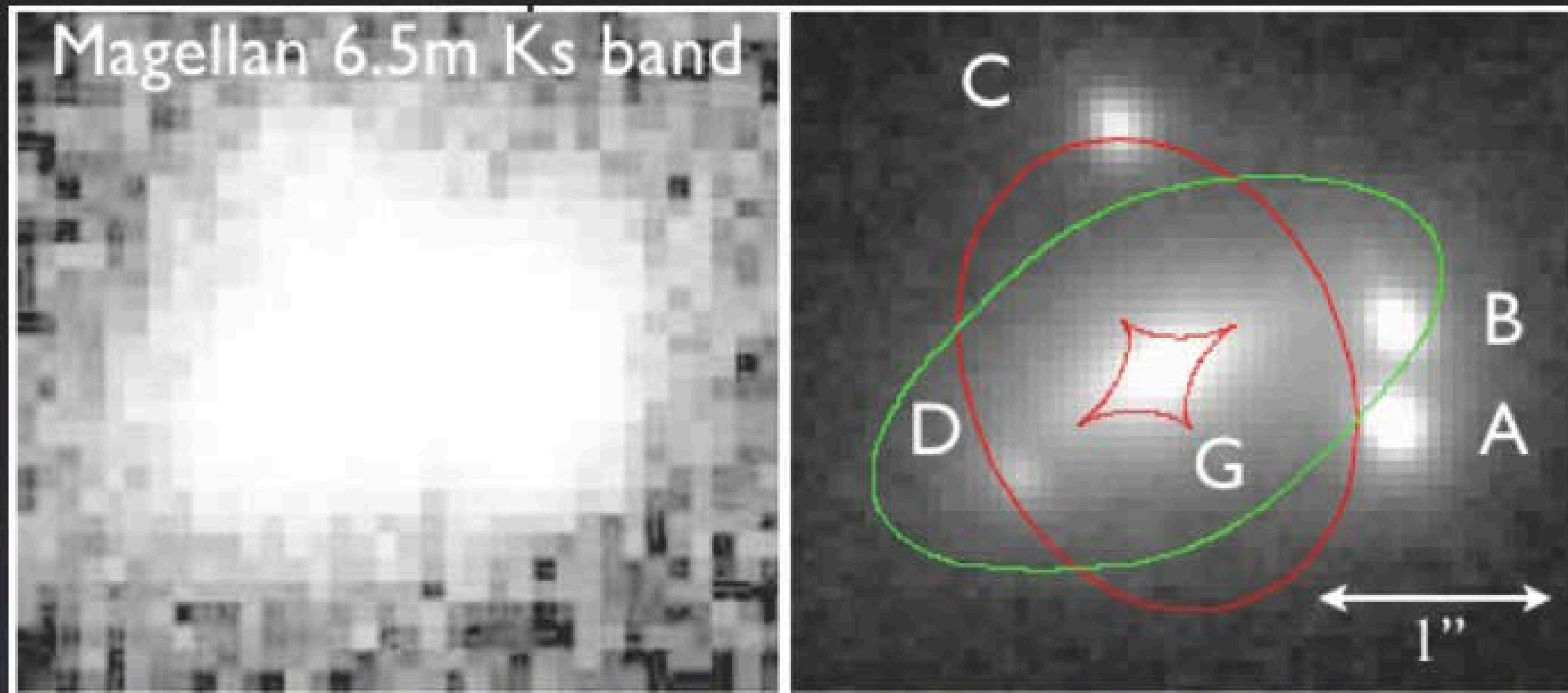
The only quad in the AO sample

Fit with analytical psf;   no host detection

12 min
52mas



52 min
40mas

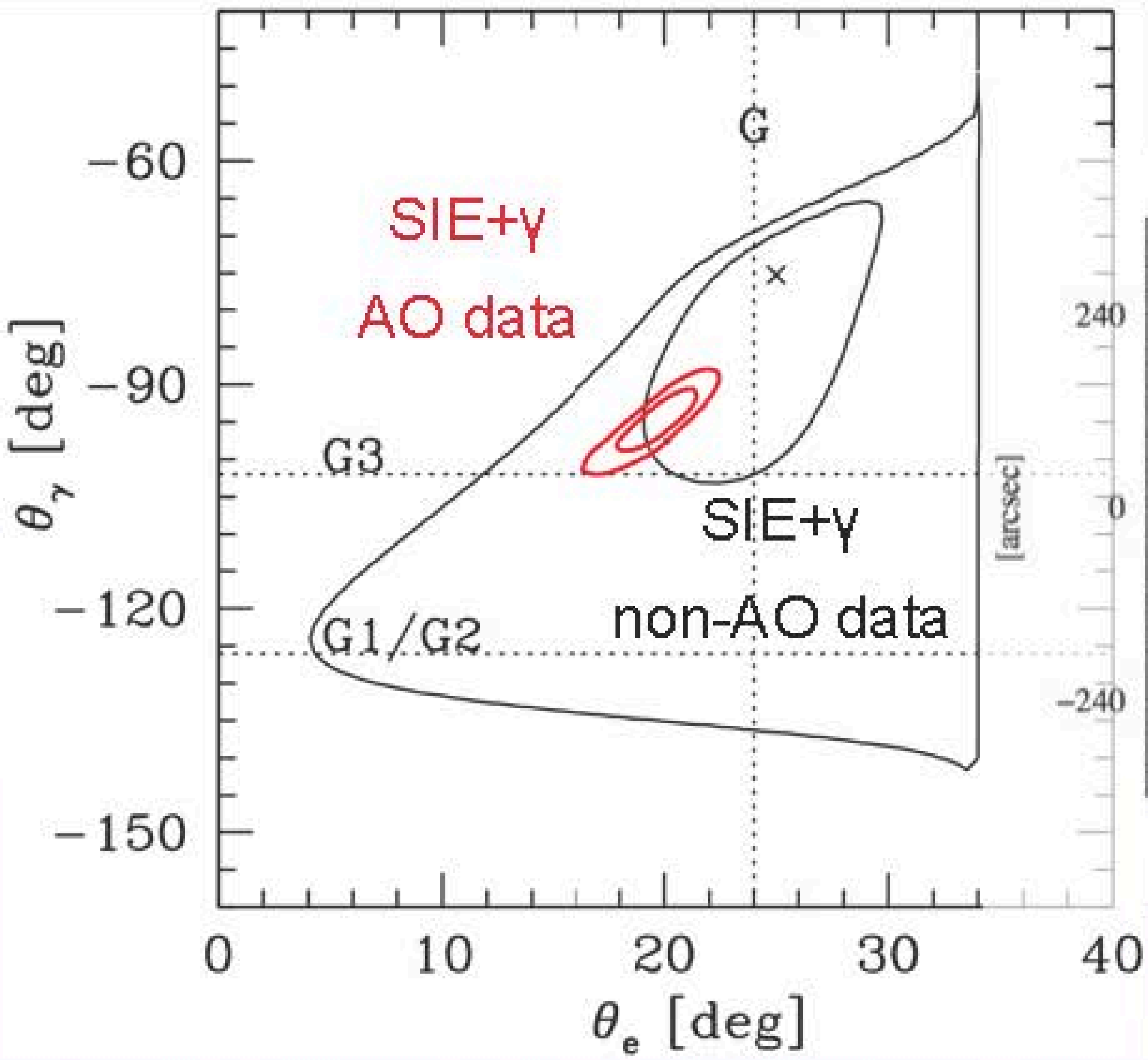


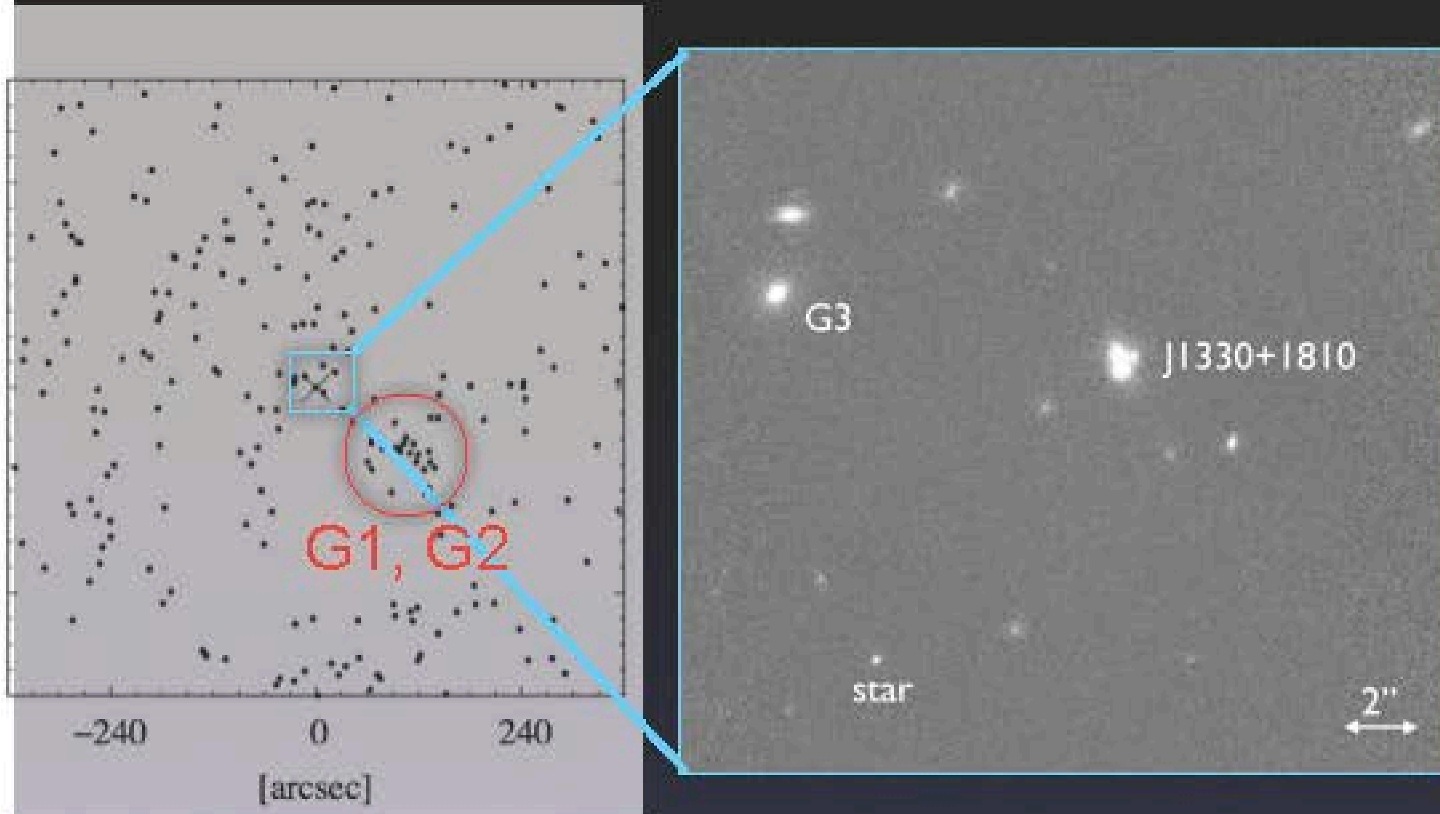
Name	x [arcsec]	y [arcsec]
A	$\equiv 0$	$\equiv 0$
B	0.42 ± 0.03	-0.01 ± 0.03
C	1.30 ± 0.03	1.19 ± 0.03
D	-0.24 ± 0.04	1.58 ± 0.04
G	0.24 ± 0.03	0.97 ± 0.03

scatter 5 bands
(Magellan 6.5m, UH88)

A	0.000 ± 0.001	0.000 ± 0.000
B	0.414 ± 0.0015	-0.013 ± 0.001
C	1.253 ± 0.003	1.163 ± 0.0015
D	-0.237 ± 0.0055	1.580 ± 0.002
G	0.225 ± 0.009	0.965 ± 0.001

scatter 2 observations
Subaru LGSAO

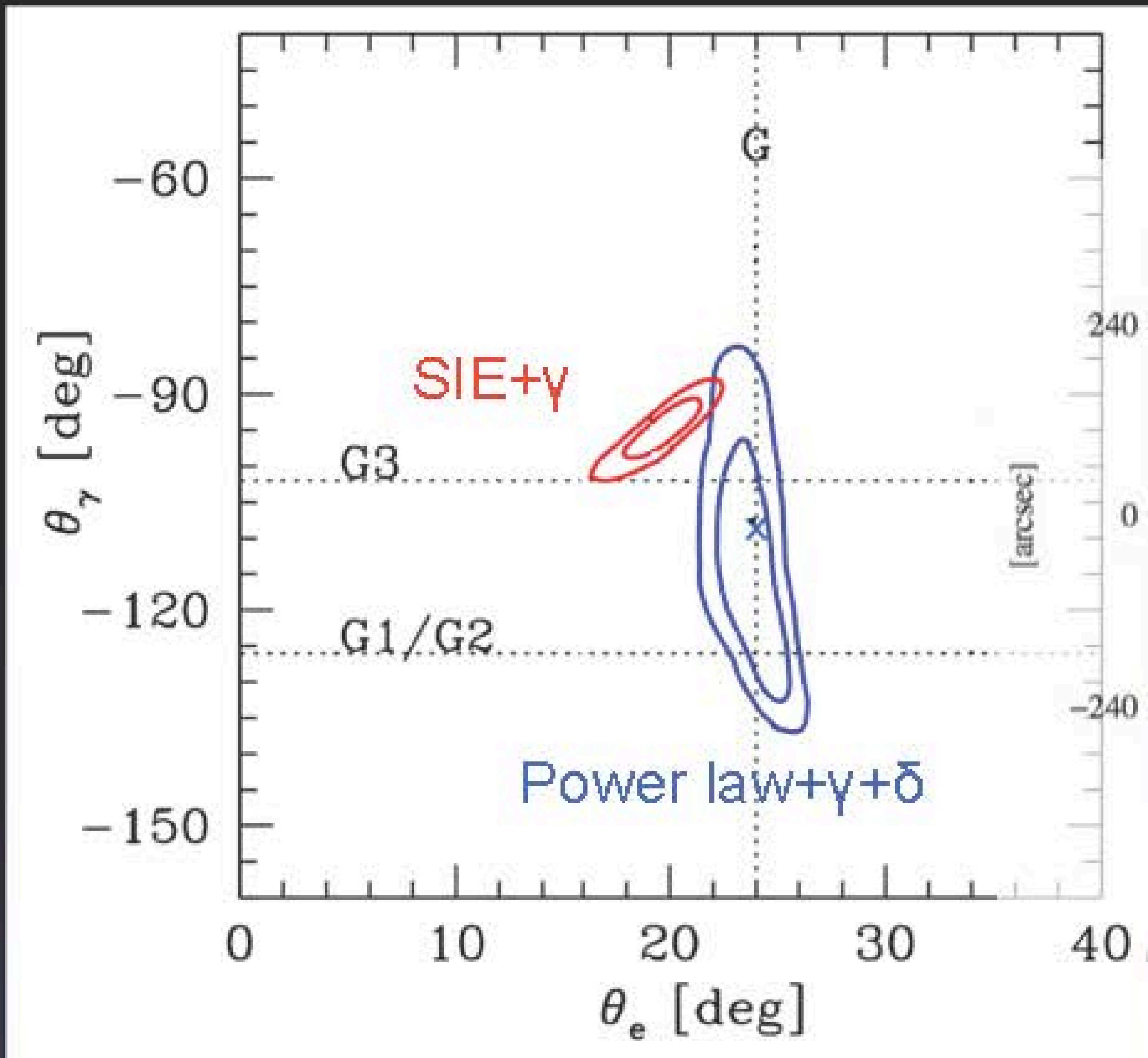


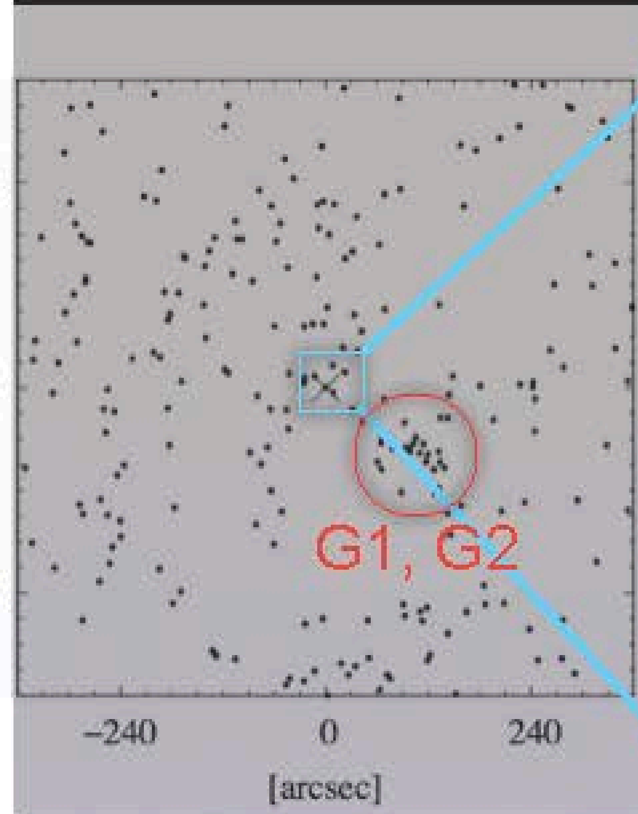


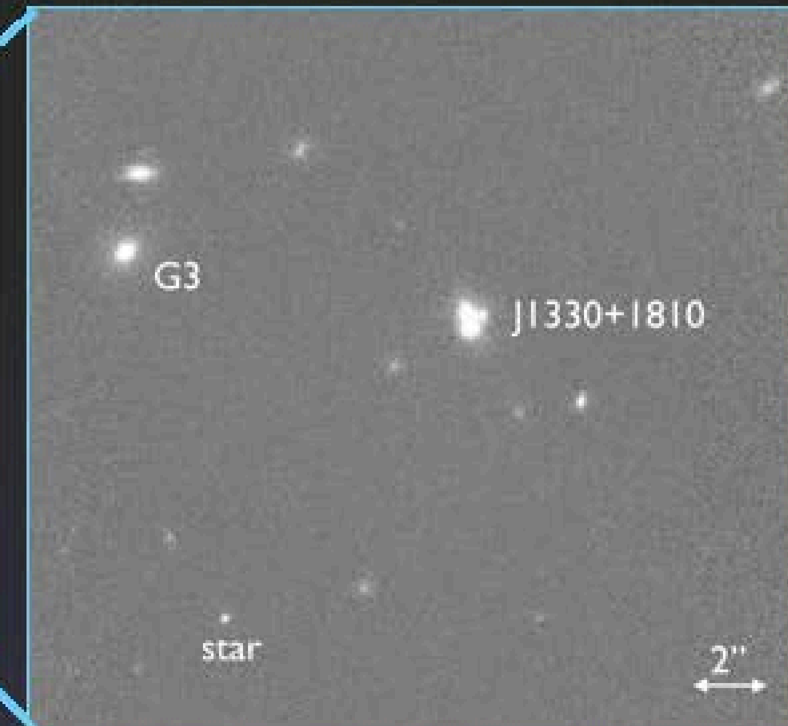
1.1/4 χ^2/dof SIE+γ original

Model	w/ flux [χ^2/ν]	w/o flux [χ^2/ν]	field w/ flux [χ^2/ν]	field w/o flux [χ^2/ν]
Sersic+$\gamma+\delta$	20/4	15/4	20/4	15/4
Sersic+γ	43/6	29/3		29/3
NFW+Sersic+γ	11/2		11/2	
Sersic+γ+substruct.	43/3	0/0		
SIE+γ+substruct.	0.9/1	0/-1	1/1	0/-1
SIE+γ	46/4	17/1	20/4	14/1
SIE+γ (gal pos. free)	2/2	0/-1	0.6/2	
SIE+$\gamma+\delta$.	15/2	0/0	29/2	
Power law ellipsoid +γ	11/3	0/0	7/3	0/0
Power law ellipsoid +$\gamma+\delta$	1/1		0.4/1	

A more flexible model that accounts for the crowded environment is a good fit

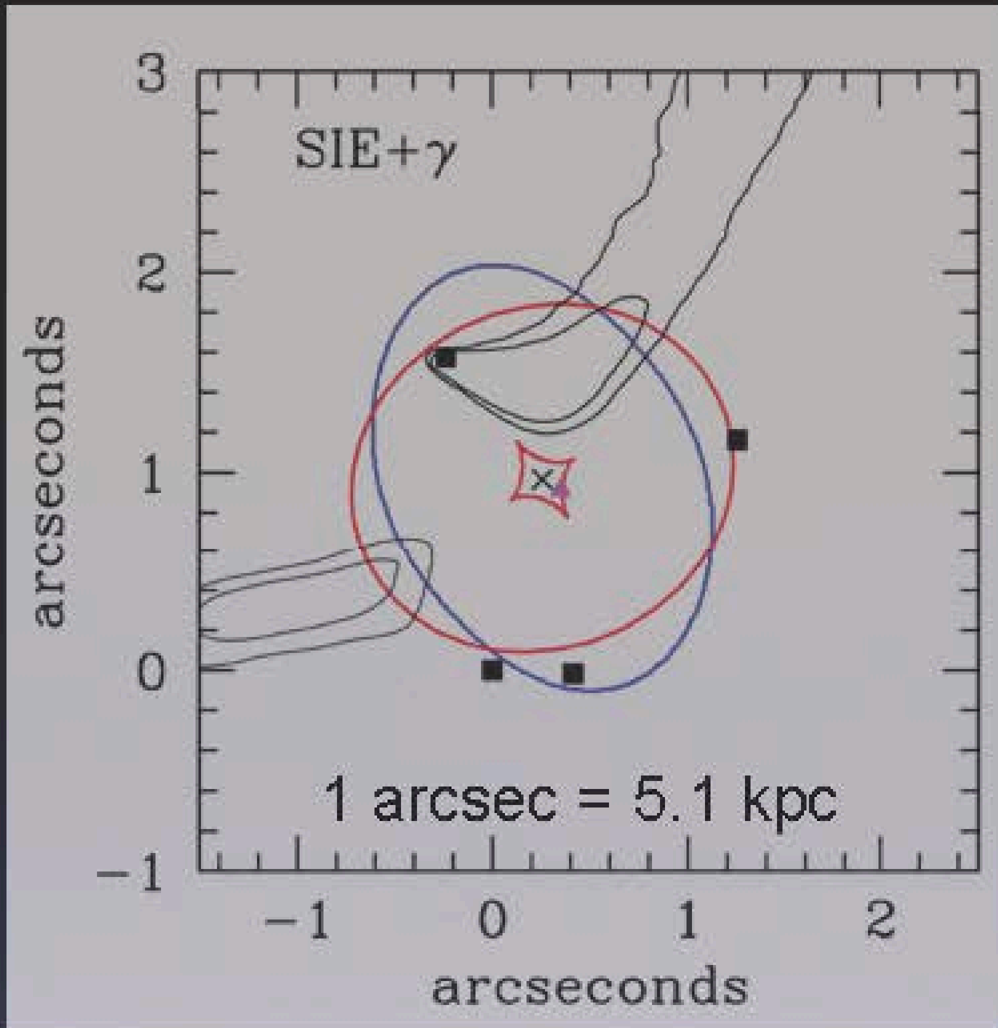


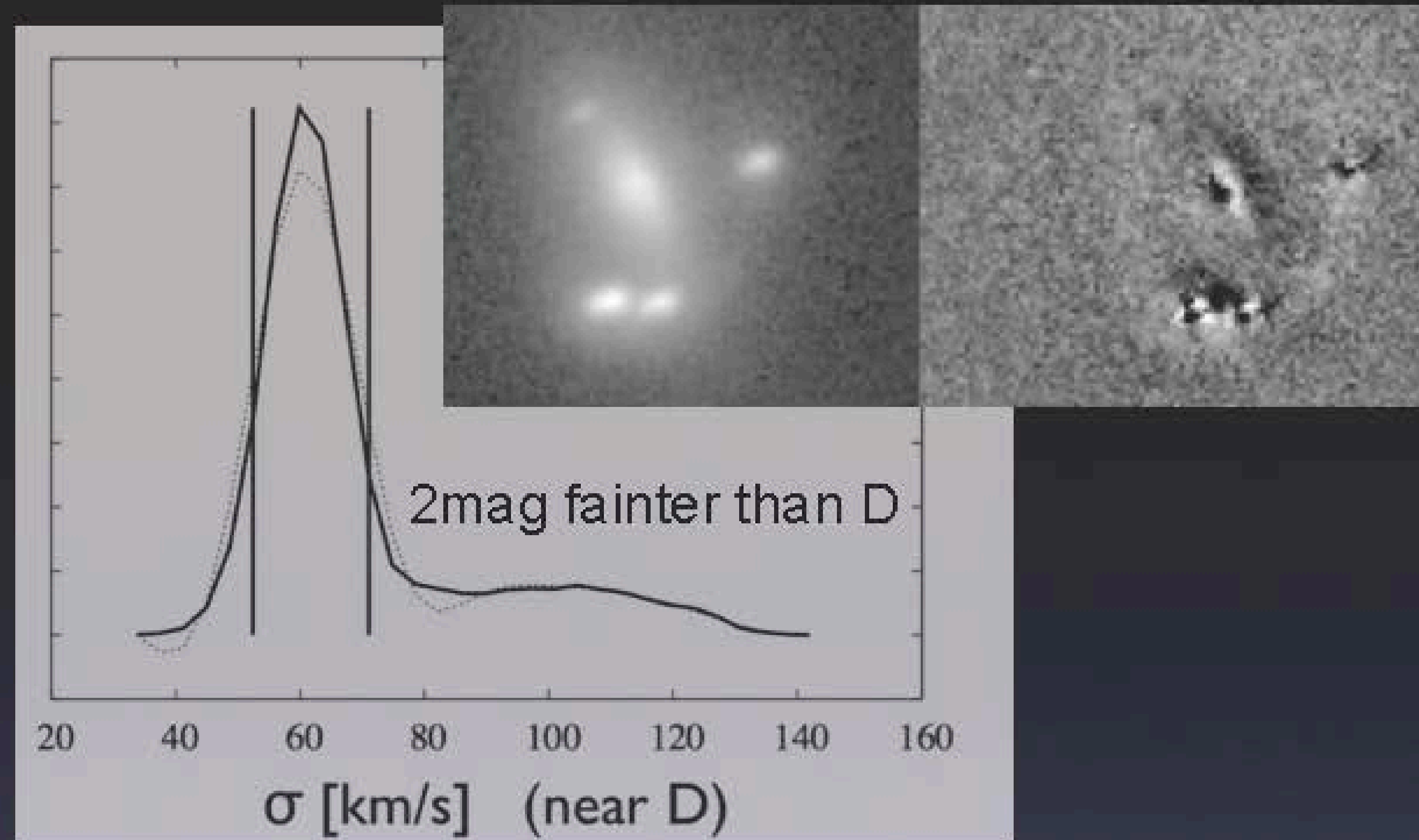




Model	w/ flux $[\chi^2/\nu]$	w/o flux $[\chi^2/\nu]$	field w/ flux $[\chi^2/\nu]$	field w/o flux $[\chi^2/\nu]$
Sersic$+\gamma+\delta$	20/4	15/4	20/4	15/4
Sersic$+\gamma$	43/6	29/3		29/3
NFW+Sersic$+\gamma$	11/2		11/2	
Sersic$+\gamma+$substruct.	43/3	0/0		
SIE$+\gamma+$substruct.	0.9/1	0/-1	1/1	0/-1
SIE$+\gamma$	46/4	17/1	20/4	14/1
SIE$+\gamma$ (gal pos. free)	2/2	0/-1	0.6/2	
SIE$+\gamma+\delta$.	15/2	0/0	29/2	
Power law ellipsoid $+\gamma$	11/3	0/0	7/3	0/0
Power law ellipsoid $+\gamma+\delta$	1/1		0.4/1	

However... anomalous astrometry may be due to substructure

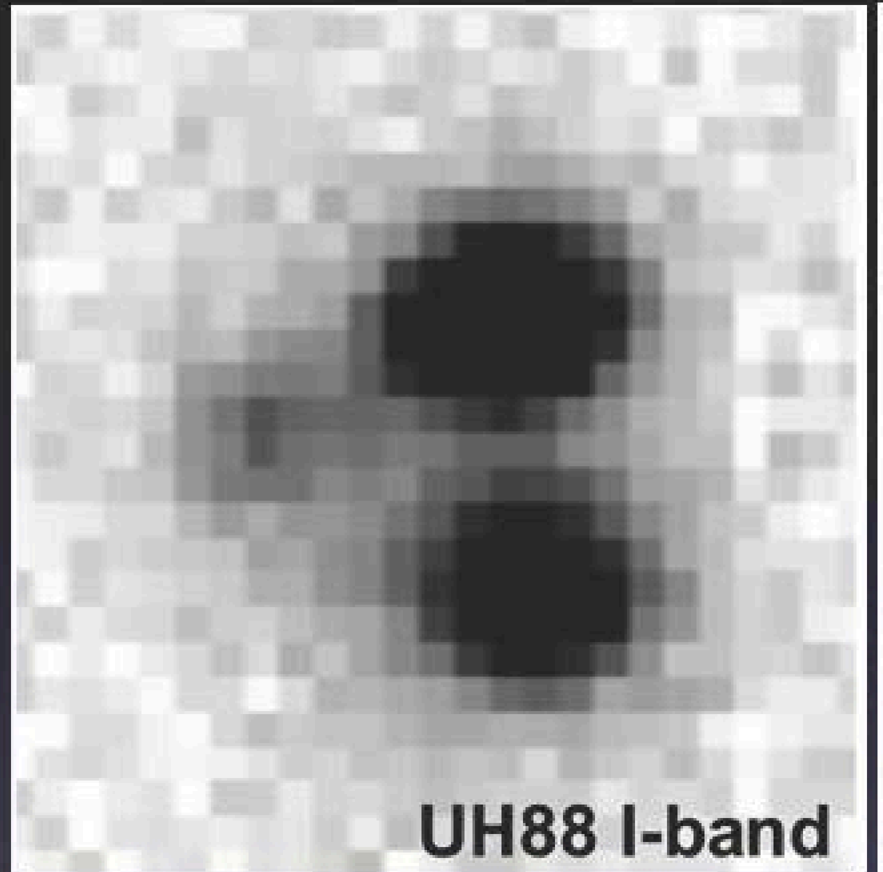


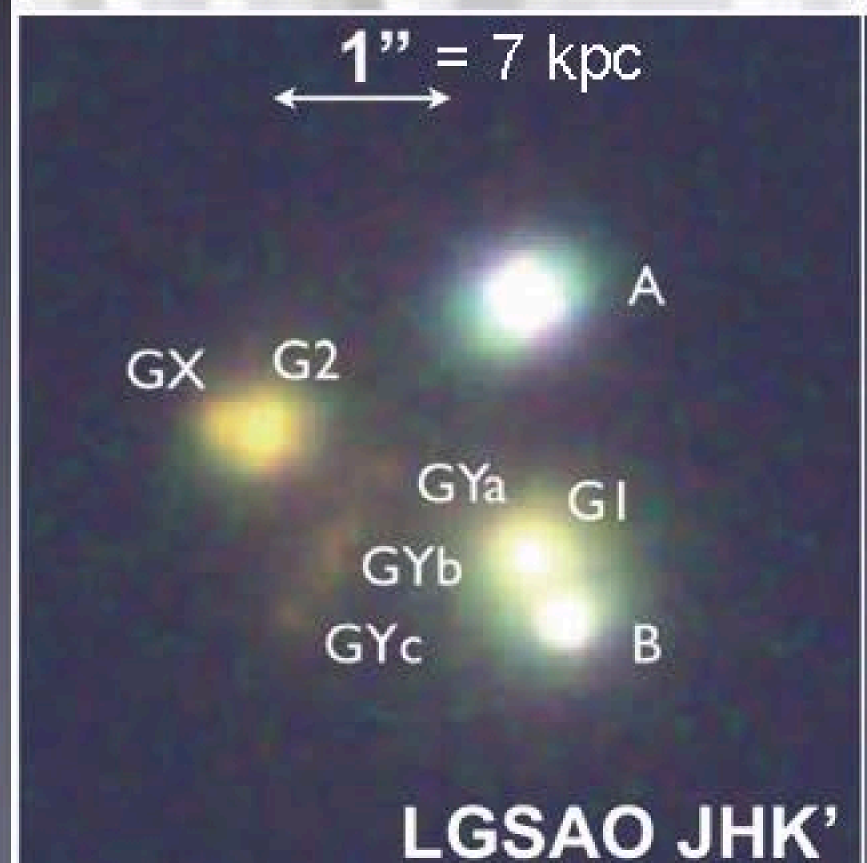


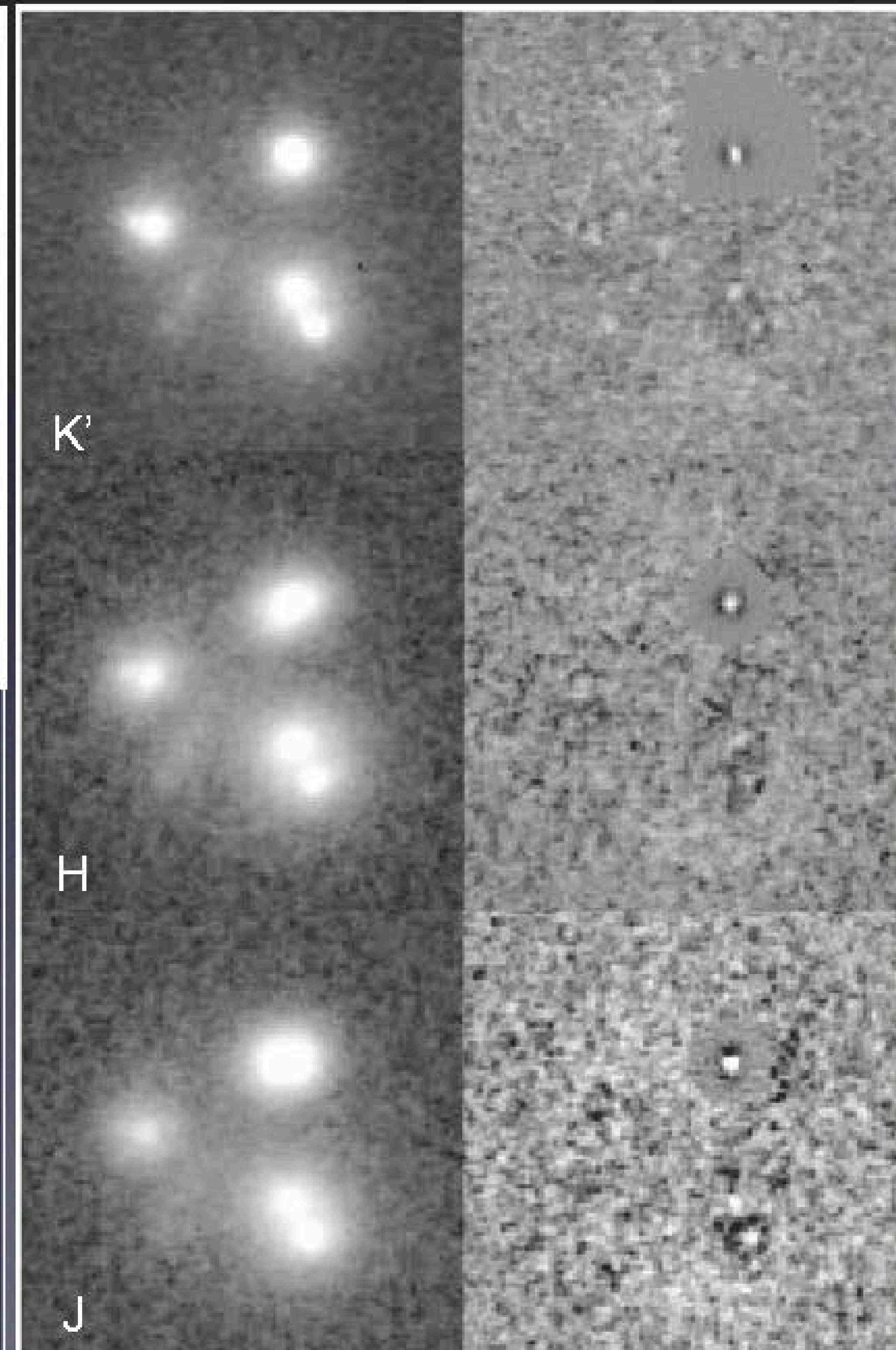
characterization of the host galaxy would discriminate between environment / substructure

Model	w/ flux $[\chi^2/\nu]$	w/o flux $[\chi^2/\nu]$	field w/ flux $[\chi^2/\nu]$	field w/o flux $[\chi^2/\nu]$
Sersic+$\gamma+\delta$	20/4	15/4	20/4	15/4
Sersic+γ	43/6	29/3		29/3
NFW+Sersic+γ	11/2		11/2	
Sersic+γ+substruct.	43/3	0/0		
SIE+γ+substruct.	0.9/1	0/-1	1/1	0/-1
SIE+γ	46/4	17/1	20/4	14/1
SIE+γ (gal pos. free)	2/2	0/-1	0.6/2	
SIE+$\gamma+\delta$.	15/2	0/0	29/2	
Power law ellipsoid $+\gamma$	11/3	0/0	7/3	0/0
Power law ellipsoid $+\gamma+\delta$	1/1		0.4/1	

SDSS J1405+0959







- z_{lens}=0.66 z_{QSO}=1.98
- new components: GX, GY
- GX: morphology unclear
- J,H, K' imaging for photo-z

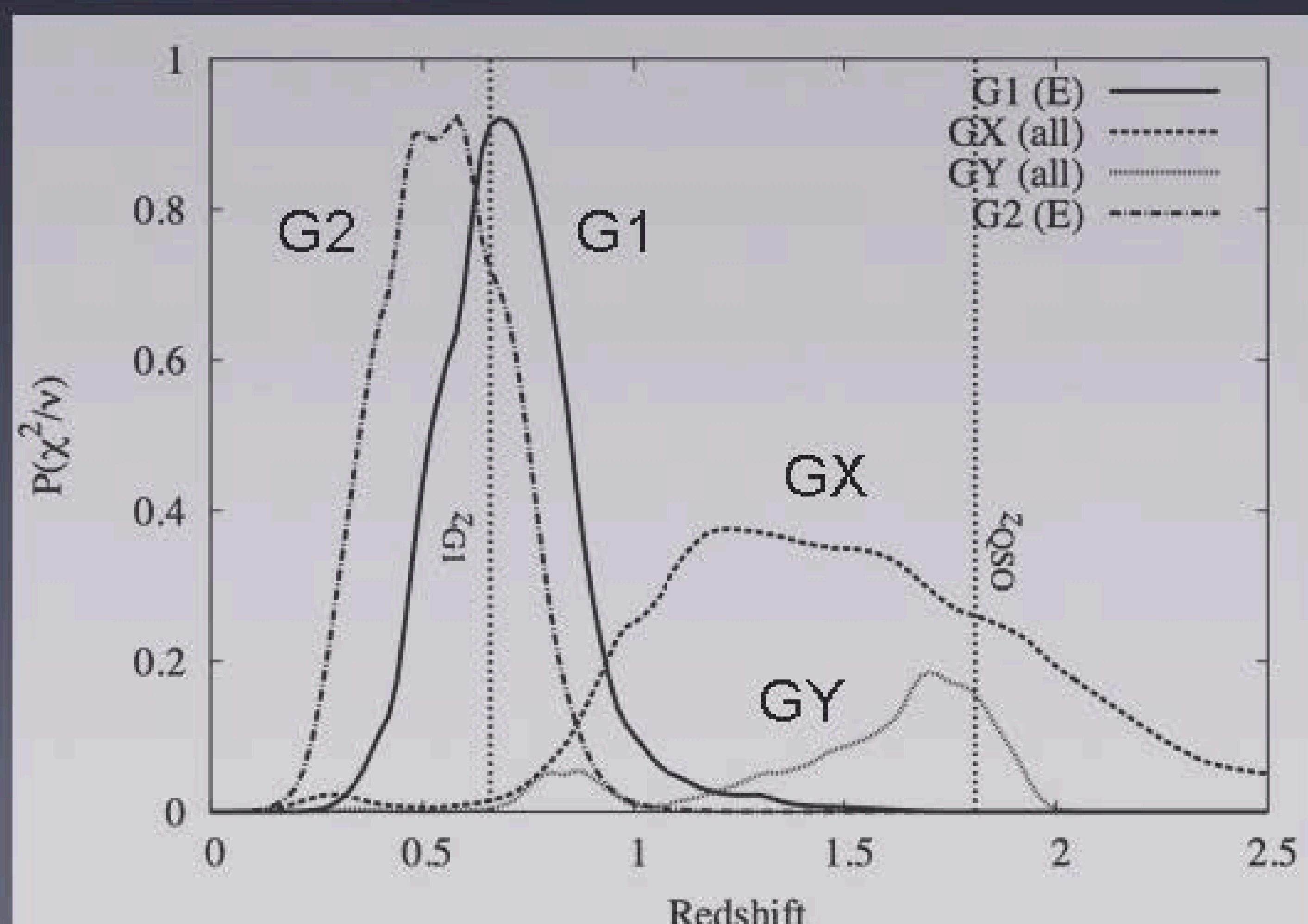
Photo-z estimates

G1, G2 ellipticals consistent with same redshift

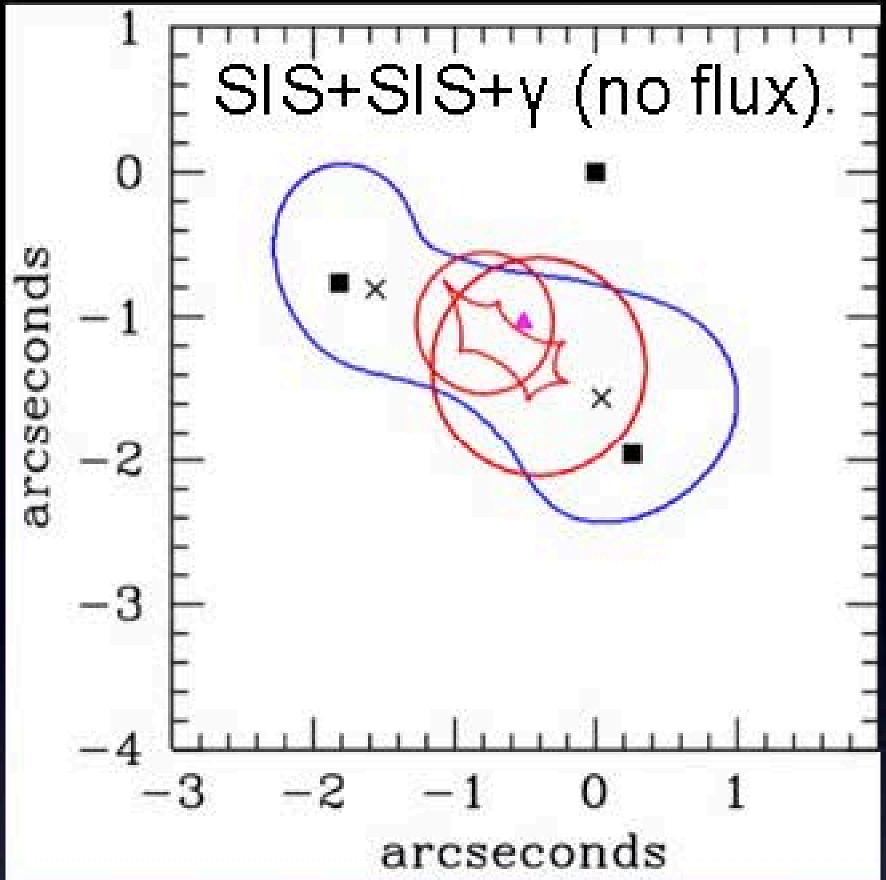
GX (assuming galaxy): larger, broad redshift

GY (aperture photometry) consistent with quasar redshift

can it be the host?



Nature of GX



1) galaxy at high-z: unlikely, multiply imaged by G2

2) star: NO, different colors from any stars in near-IR

3) 3rd quasar image: lensing models with GX as the 3rd quasar image produce a good fit

Assuming color difference due to extinction, can GX be the 3rd quasar image?

$$m_{C,i} - m_{A,i} = -2.5 \log C/A + A_{\lambda,i}$$

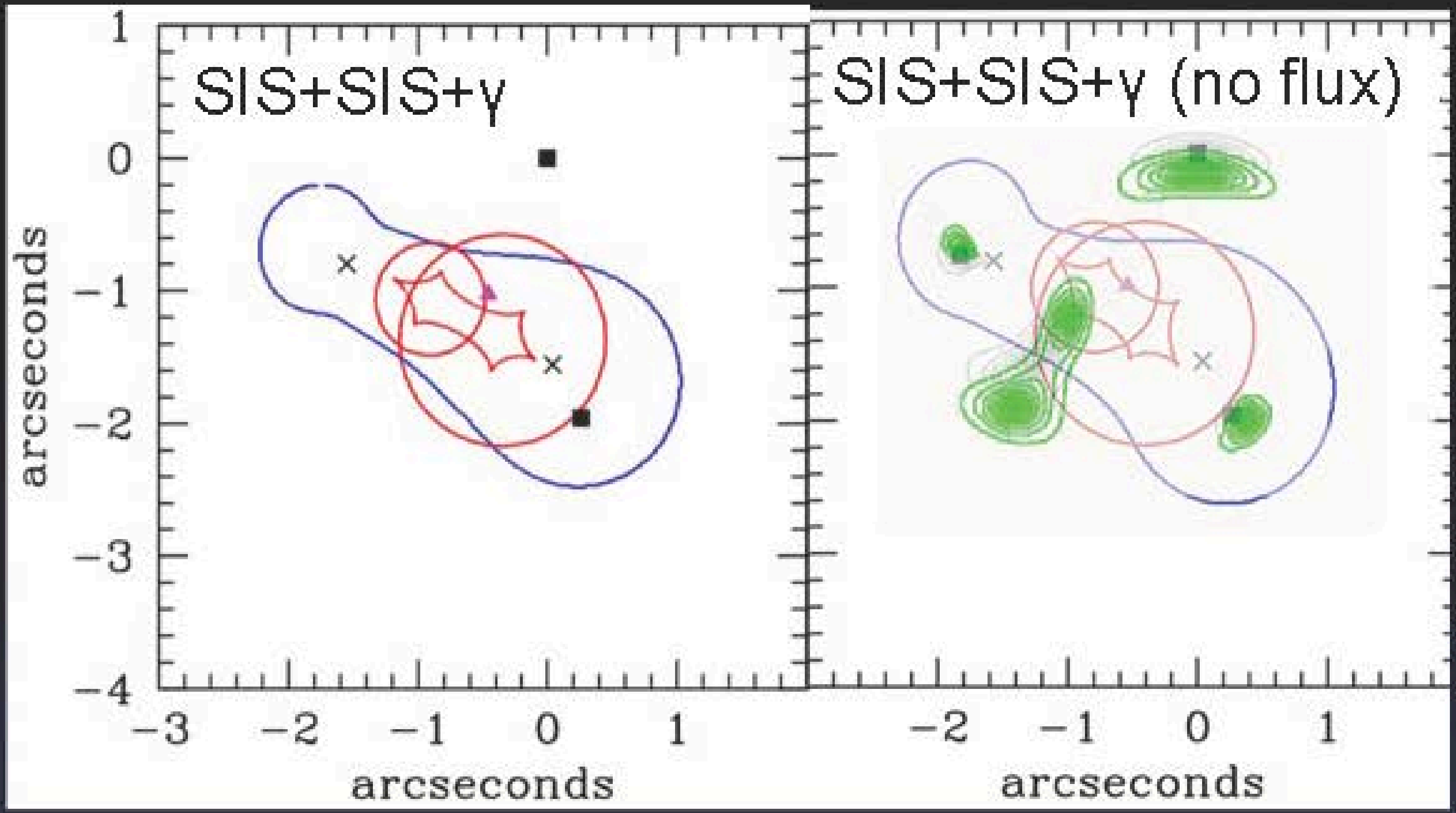
$$R_V = 3.1$$

$$A_V = 2.5(J), A_V = 2.3(H), A_V = 2.4(K') \rightarrow E(B-V) = A_V/R_V \sim 0.8$$

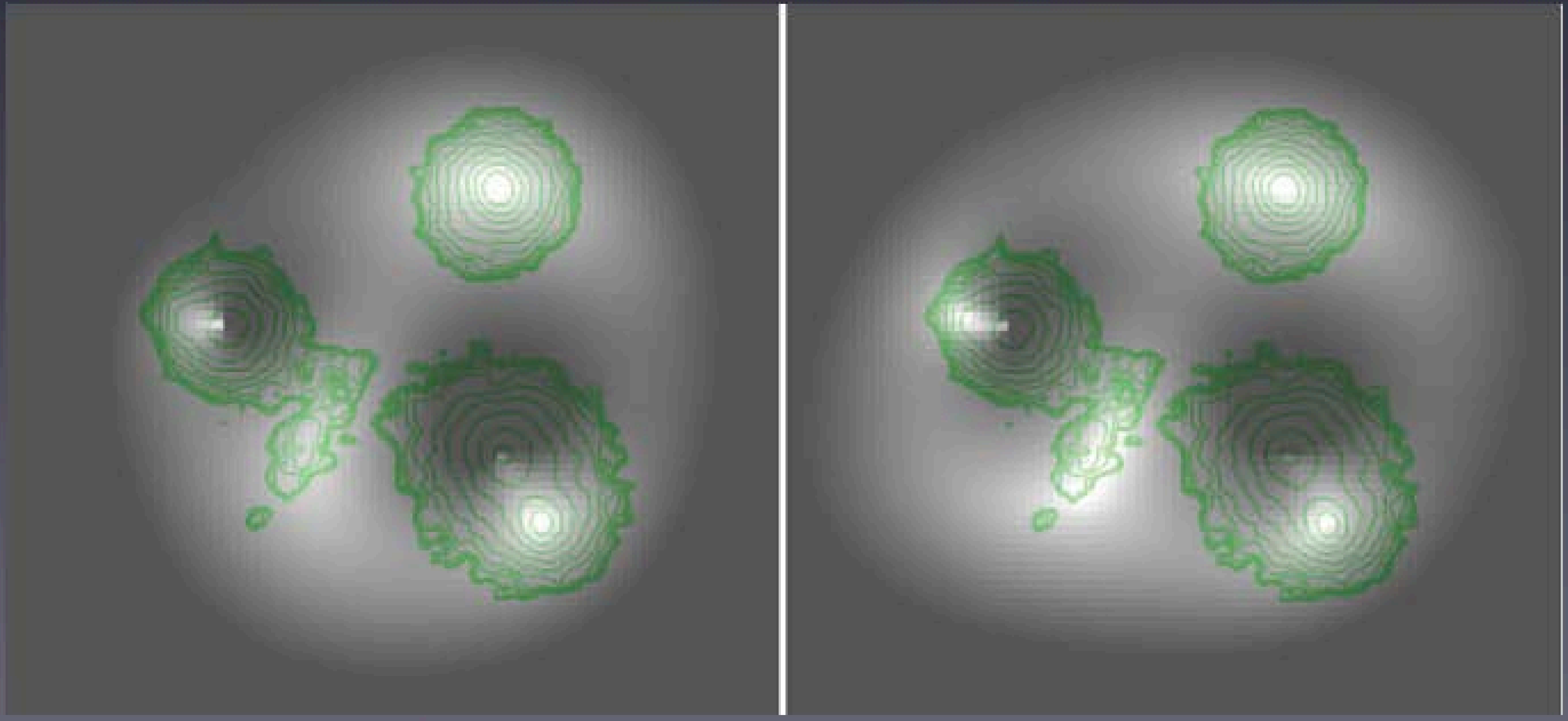
Such extinction has been found in other lensed quasars

Nature of GY

GX not an image



GX image



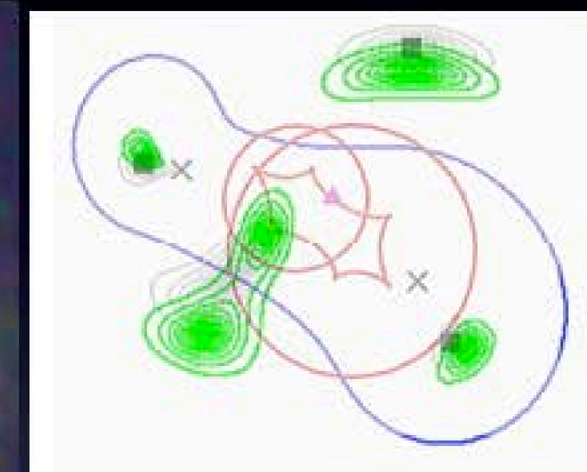
Position, elongation and orientation of GY consistent with expected host

Alternative explanations for GY:

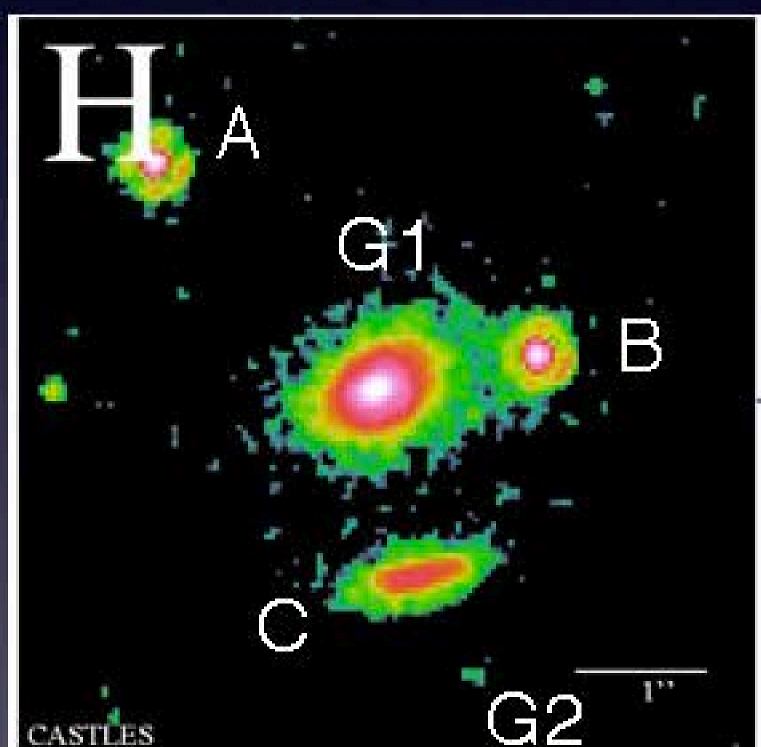
1) GY at higher redshift galaxy but not host? NO - multiply imaged

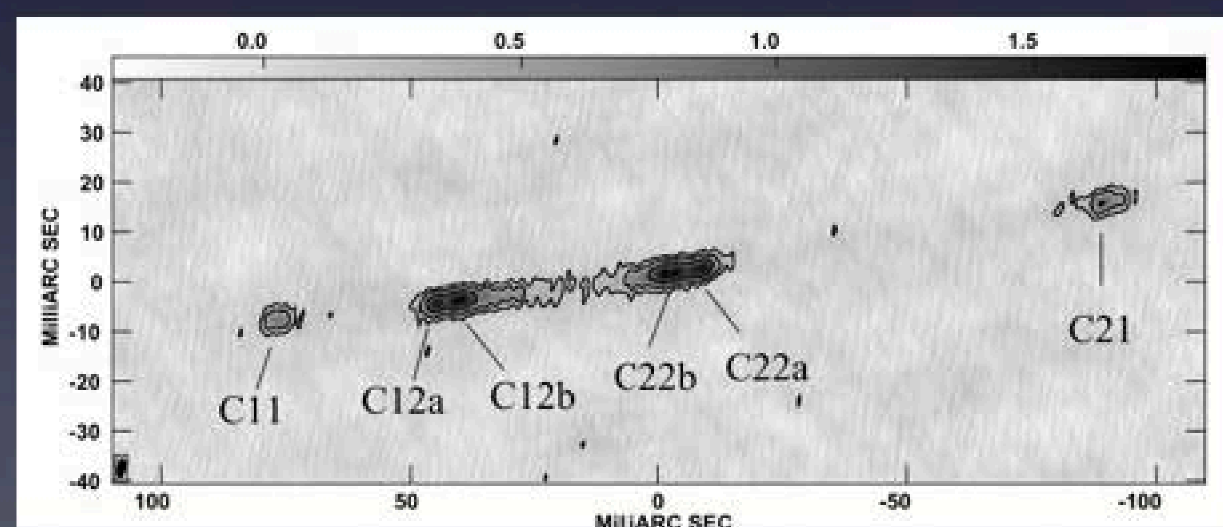
2) Two of GYa, GYb, GYc are quasar images (the case of 5 images)? NO - bad fit

→ SDSS J1405+0959 is only the second known lensed quasar having an observed host galaxy arc without an attached central quasar image



MG 2016+112





Conclusions:

- AO was crucial in interpreting the system
- Spectroscopy needed to confirm GX as image

Statistical studies where AO can complement HST
M_{BH} - L_{host} correlation

- Peng et al. 2006 extended the BH mass - host galaxy luminosity correlation study to large redshifts using HST lensed quasars

- Check if the discovered hosts follow the same correlations

    - demagnified host & quasar luminosity and redshift known → K correction to rest-frame R-band

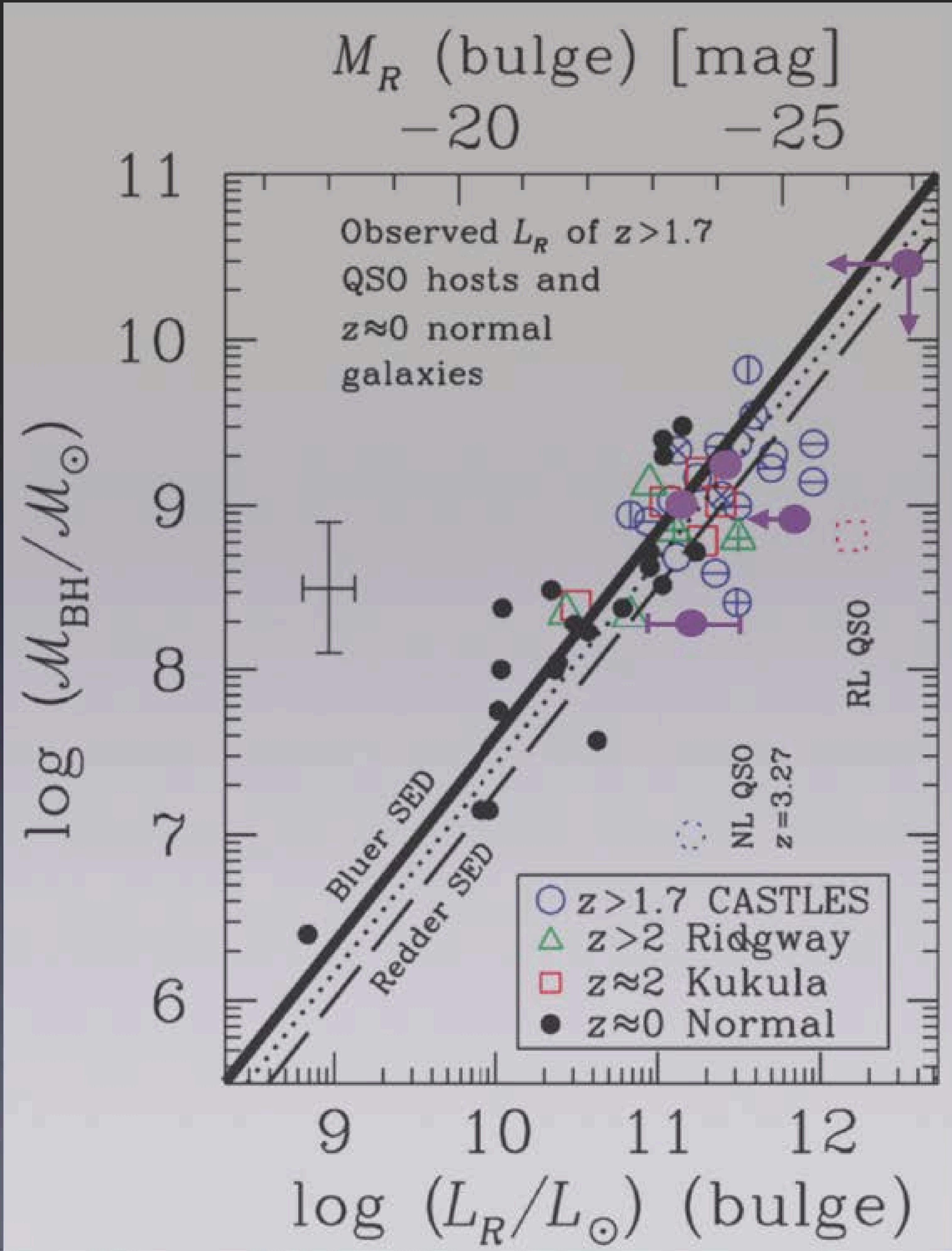
    - measure BH mass:

CIV, MgII broad emission lines

virial relation $$M_{BH} = f\frac{R_{\rm BLR}(\Delta V)^2}{G}$$

reverberation mapping using continuum luminosity

Vestergaard & Peterson 2006



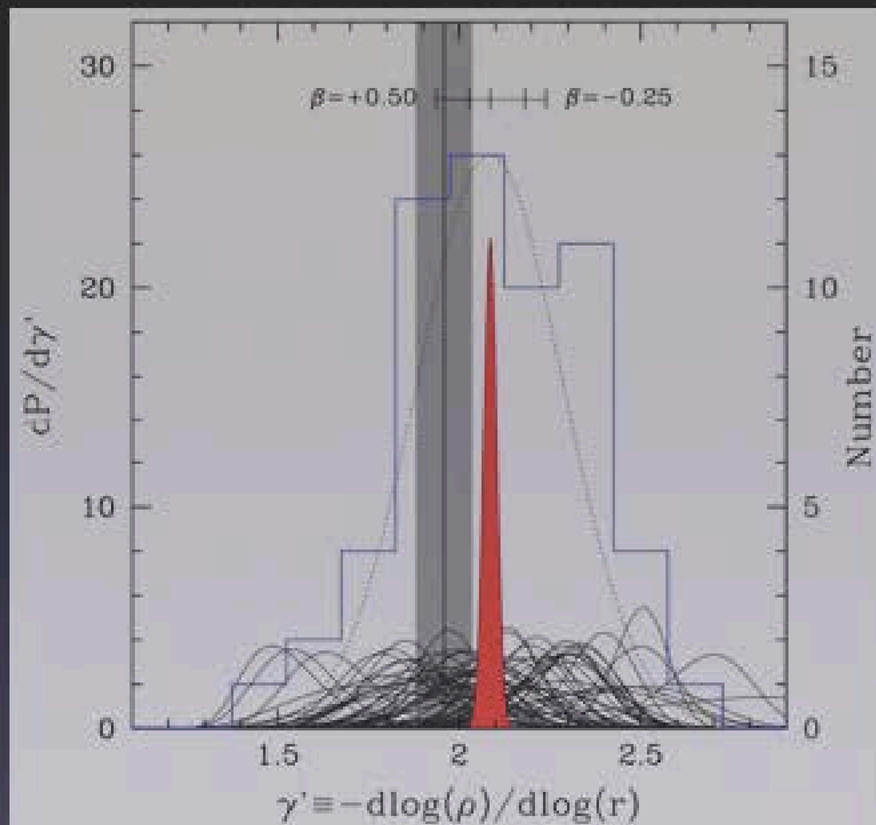
The three modeled hosts follow M_{BH} - L_{host} correlation from Peng et al. 2006

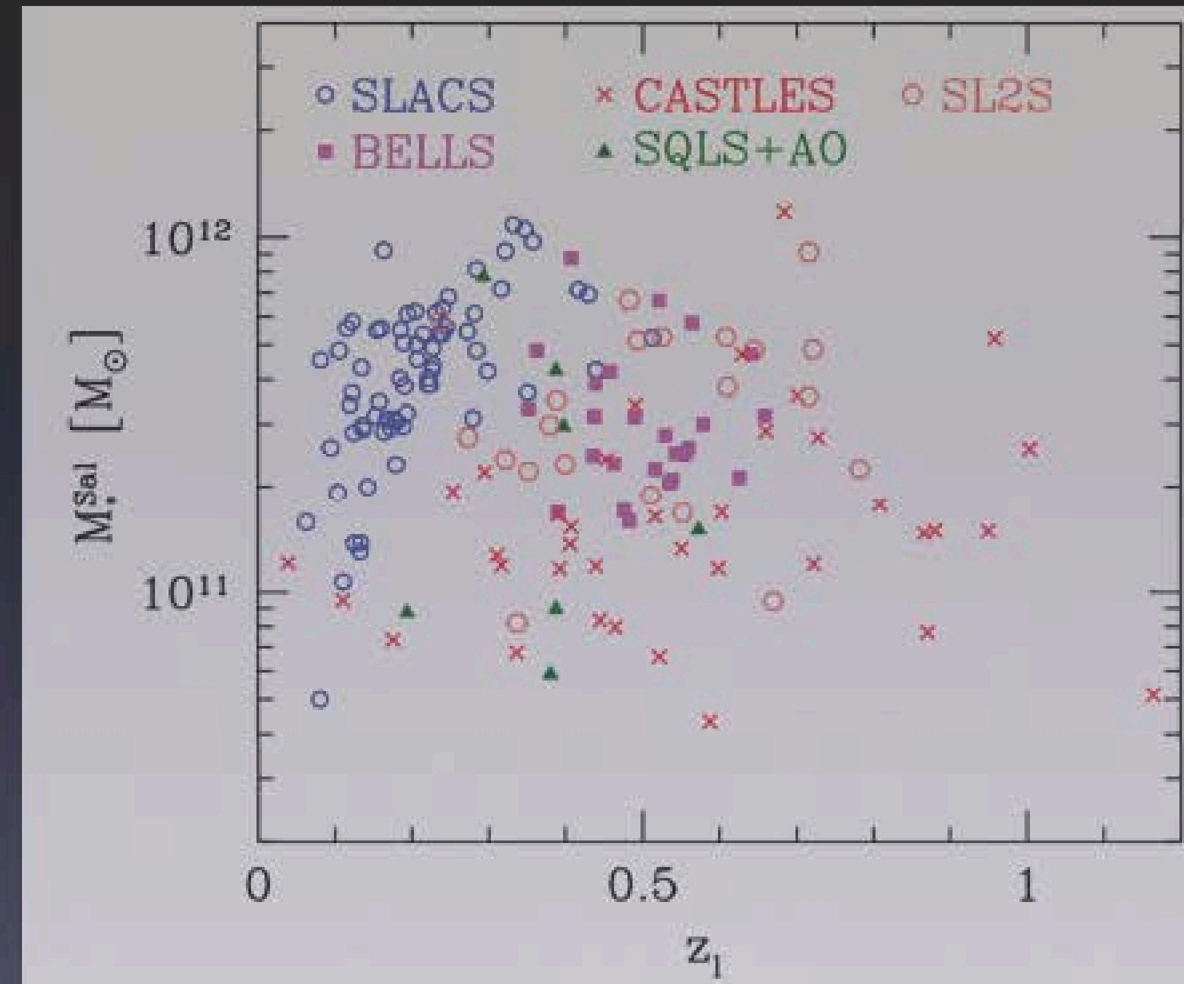
First time using lensed quasars observed with AO

Mean radial mass profile of elliptical galaxies

- high-res GLQs
- AO concepts
- SQLS
- imaging campaign
- analysis technique
- examples
- SDSS J1334+3315
- SDSS J1330+1810
- SDSS J1405+0959
- M_{BH} - host galaxy
- mean mass profile
- mass and light

- SLACS: 58 lensed galaxies; stellar kinematics + lensing → mass profile
- Alternative approach: determine mean profile from lensing alone



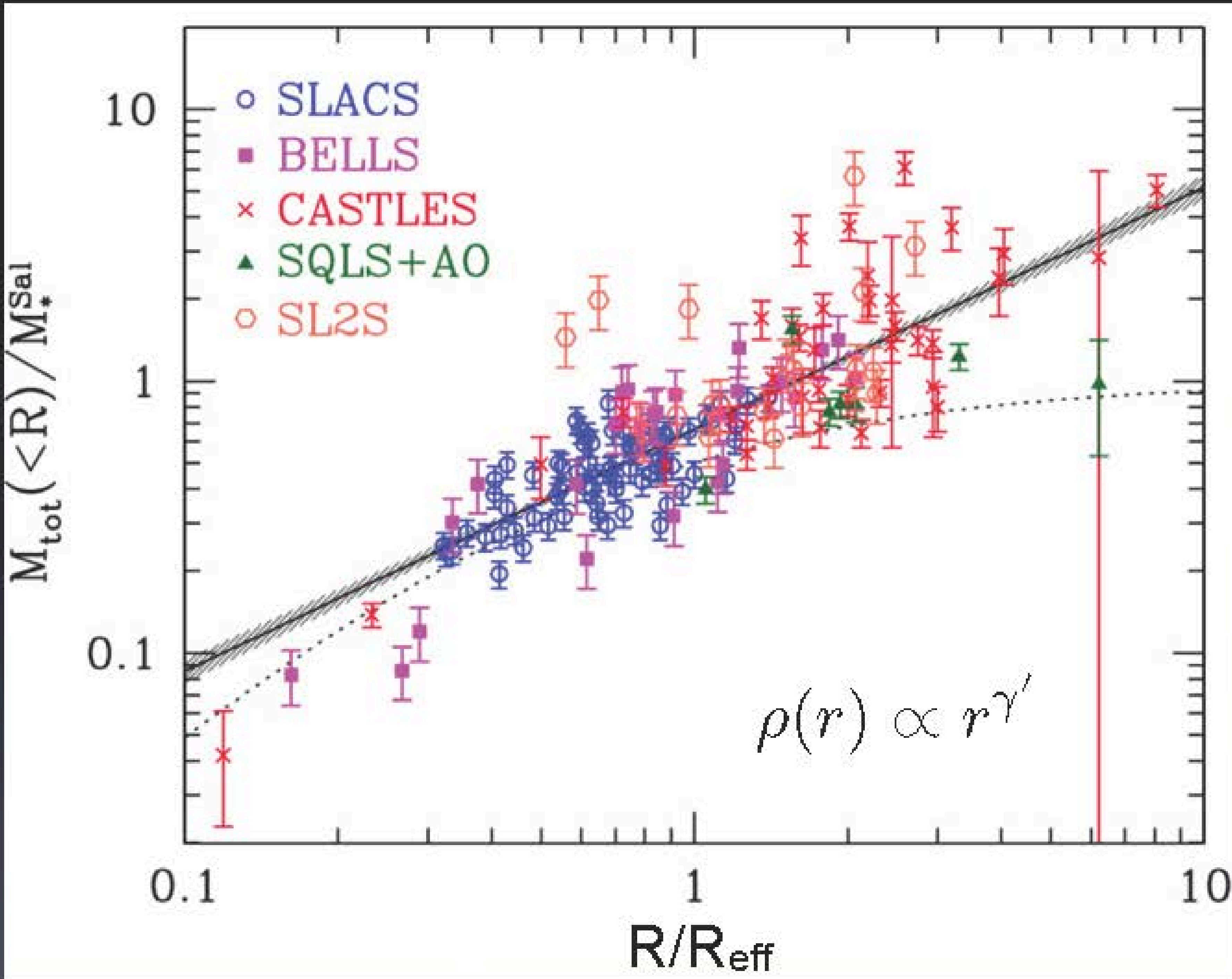


161 lensed quasars/galaxies

Assume scaling relation between observables to combine different systems:

R_{ein}, $M_{tot}(<R_{ein})$, effective radius (need high res.), stellar mass

Relation: total mass profile scales with stellar mass and effective radius



$$\frac{M_{\rm tot}(<R)}{M_*^{\rm Sal}} = A\left(\frac{R}{R_{\rm eff}}\right)^{3+\gamma'}$$

$$\gamma' = -2.11 \pm 0.05$$

AO sample follows the relation

Other scaling choice: profile scales with L_{eff} and R_{eff} (Koopmans 2009)

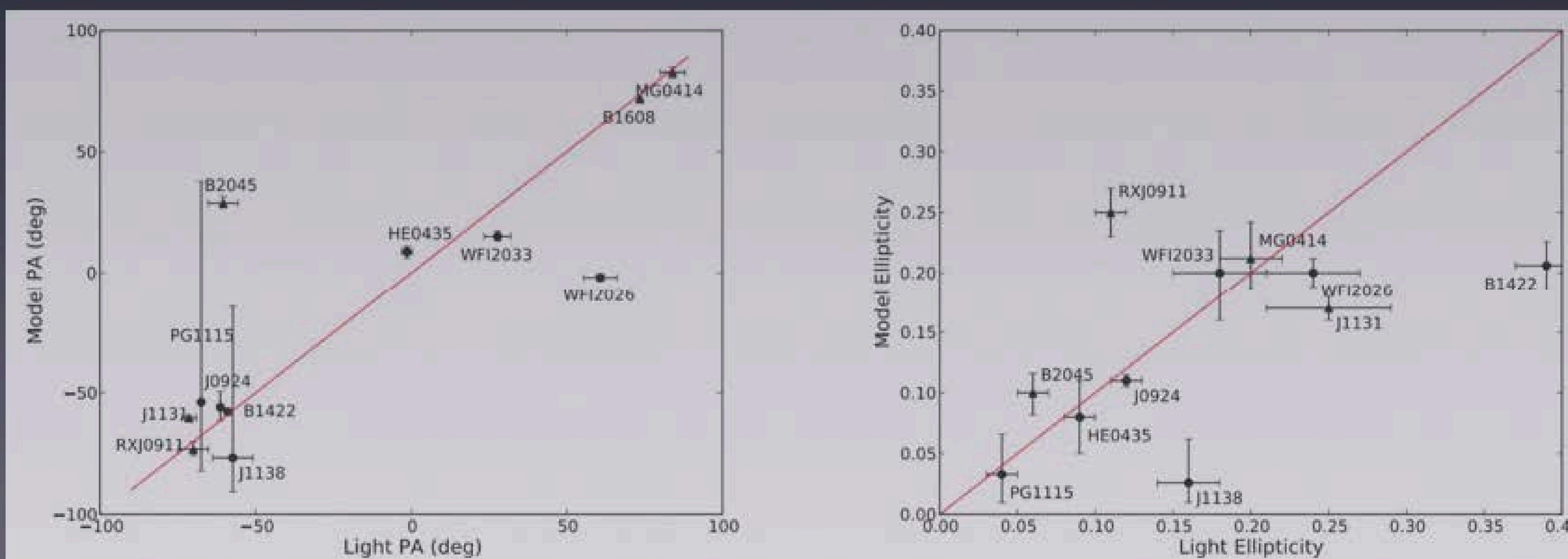
Consult Oguri, Rusu & Falco 2014 for details

Mass and light ellipticity and alignment

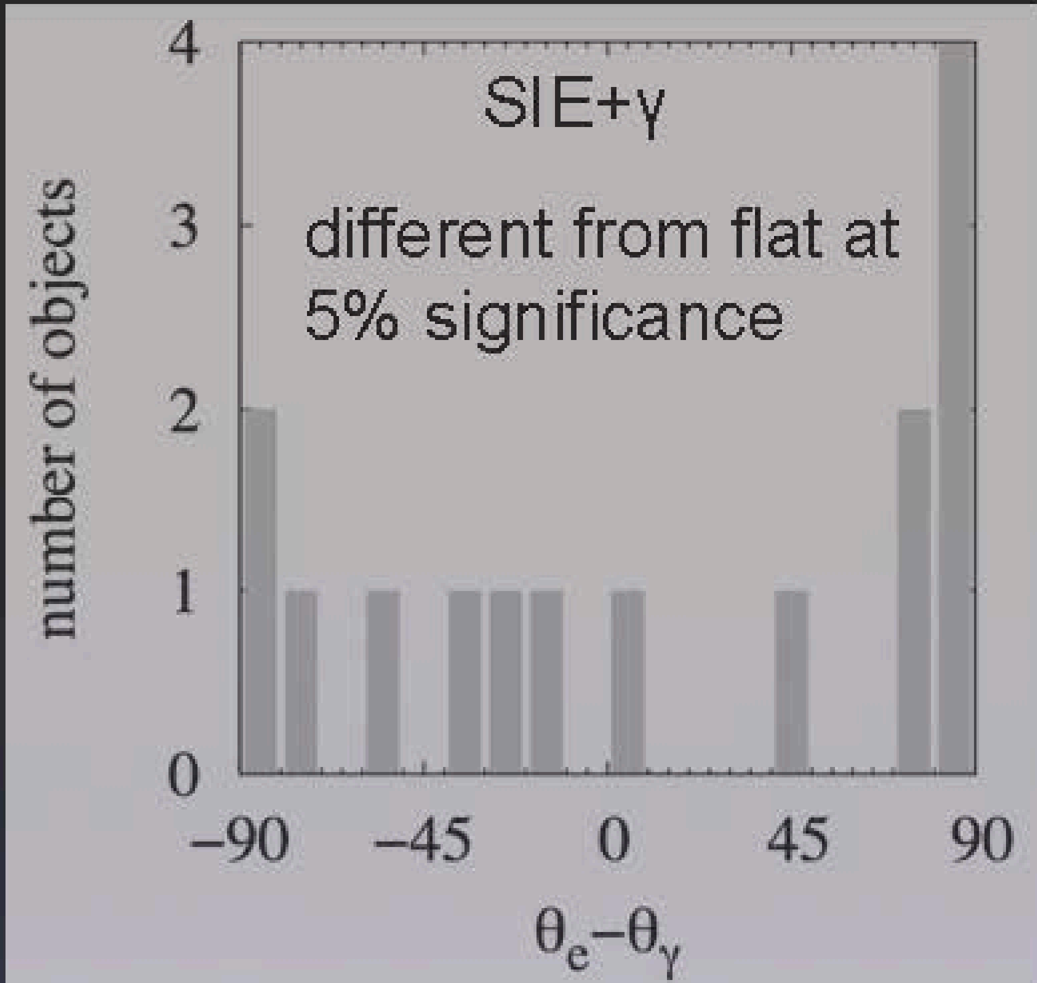
- mass-light orientation correlates for lensed quasars/galaxies
- studies: mass-light ellipticity do not correlate (lensed quasars)
- SLACS (HST): mass-light ellipticity correlates for $R_{einst}/R_{eff} < 1$
- Sluse et al. 2012: mass-light ellipticity correlates from high-res HST

quads for lensed quasars with small light ellipticity; larger ellipticity?

Sluse et al. 2012



doubles: SIE+γ with prior: mass-light ellipticity and orientation match



SIE+γ: half the sample has perpendicular shear

but distribution expected to be nearly flat

→ mass ellipticity < light ellipticity

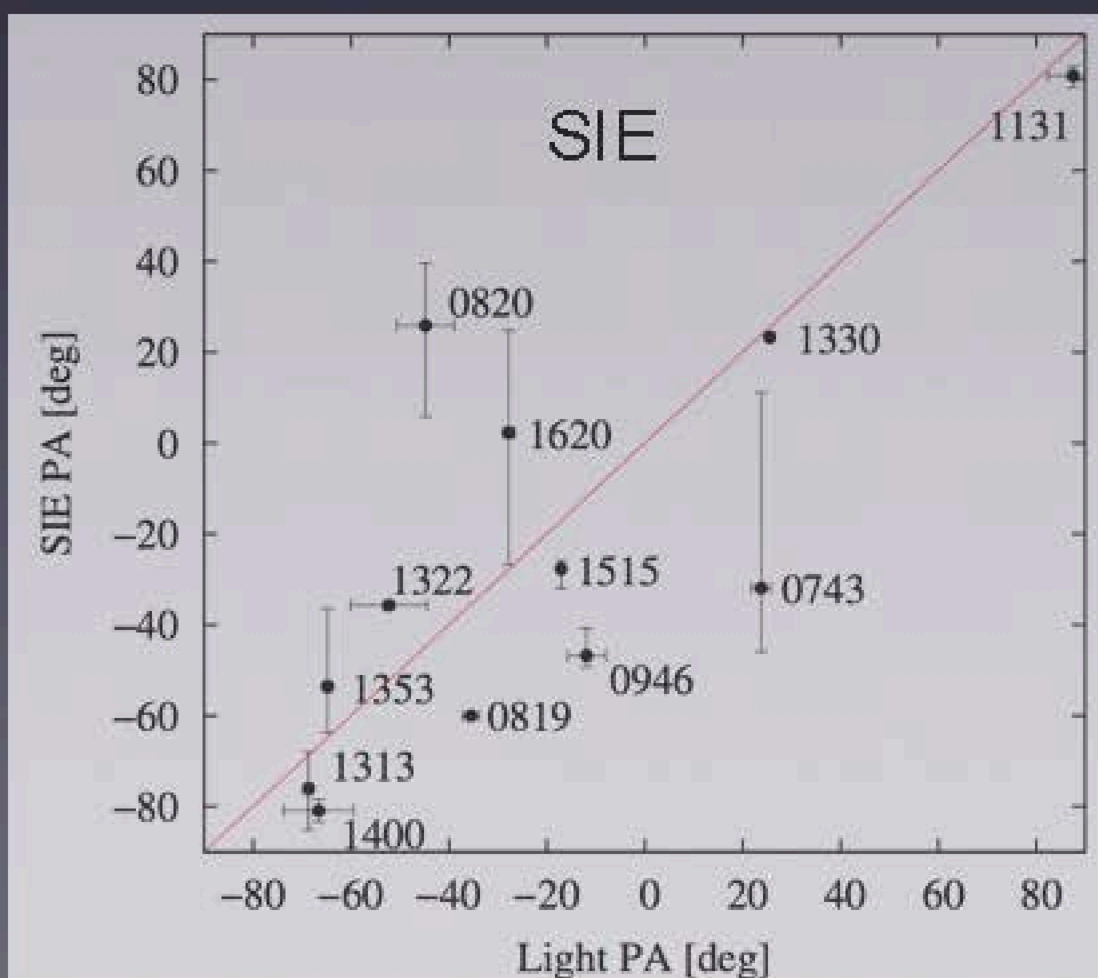
SIE: fairly good PA alignment, smaller mass

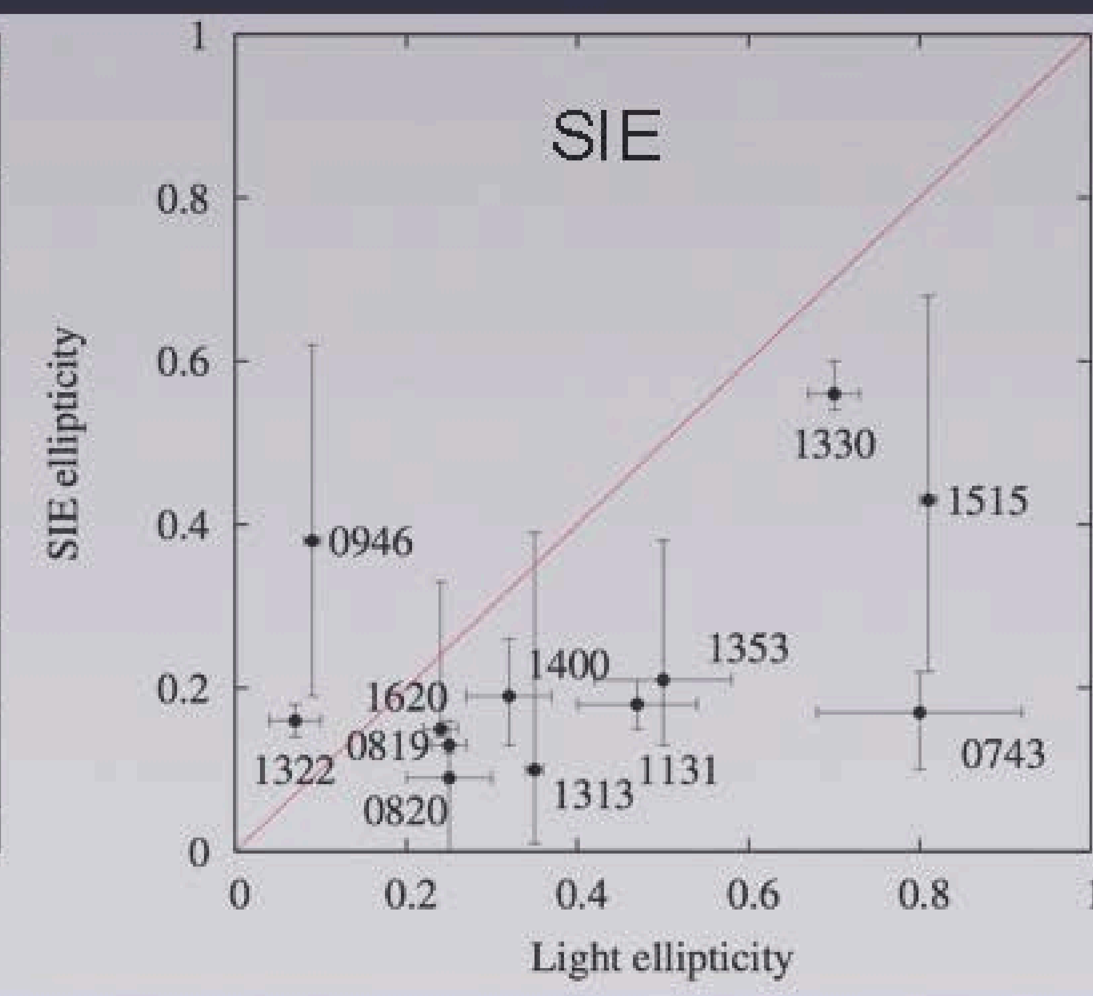
ellipticity (ignore objects with large environment contribution)

lensed quasars: R_{einst} = a few R_{eff}

agreement with weak lensing (e.g. Hoekstra 2004)

at R_{einst} ~ 10s of R_{eff}





Conclusions and future prospects

- Conducted the first imaging campaign of a large number of lensed quasars with AO

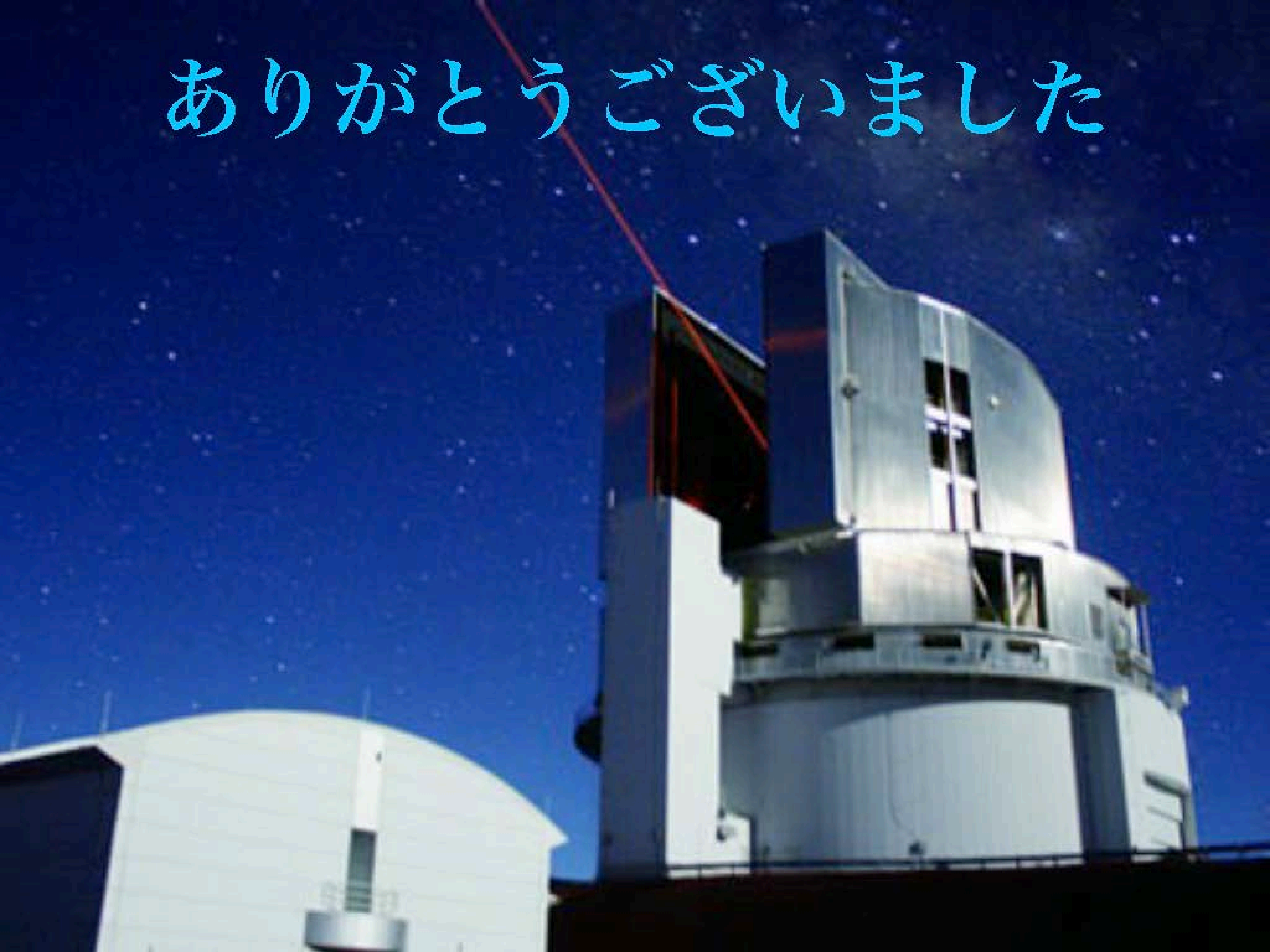
- Developed a new modeling technique that uses the unique structure of lensed quasars to fit the systems without a-priori known PSFs; tested via simulations

- For the first time, modeled quasar hosts without a-priori PSF

- Obtained astrometry and mass models competitive with HST results → vast improvement over results from low-resolution data

- Similar to HST, obtained unique insights into individual objects & showed that HST and AO data can be used jointly for statistical studies

- Overall conclusion: AO can be used as HST alternative to model some of the 1000s of lenses expected in the upcoming wide-field surveys: HSC, LSST etc.


ありがとうございました