Dissecting the Gravitational Lens B1608+656: Implications for the Hubble Constant

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Outline

- Why is H_0 important and how is strong lensing useful for H_0
- Pixellated Potential Reconstruction
  - ➢ source intensity reconstruction
  - ➢ lens potential correction
- *HST* ACS observations of B1608+656
- Potential Reconstruction of B1608+656
  - ➢ implication for H_0

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Why is H_0 important

- Age of Universe ~ $1/H_0$
- Size of Universe ~ c/H_0
- H_0 determines the critical density
- H_0 is the single most useful complement to CMB parameters for dark energy studies (Hu 2005)

Methods for Measuring H_0 [km s^{-1} Mpc^{-1}]

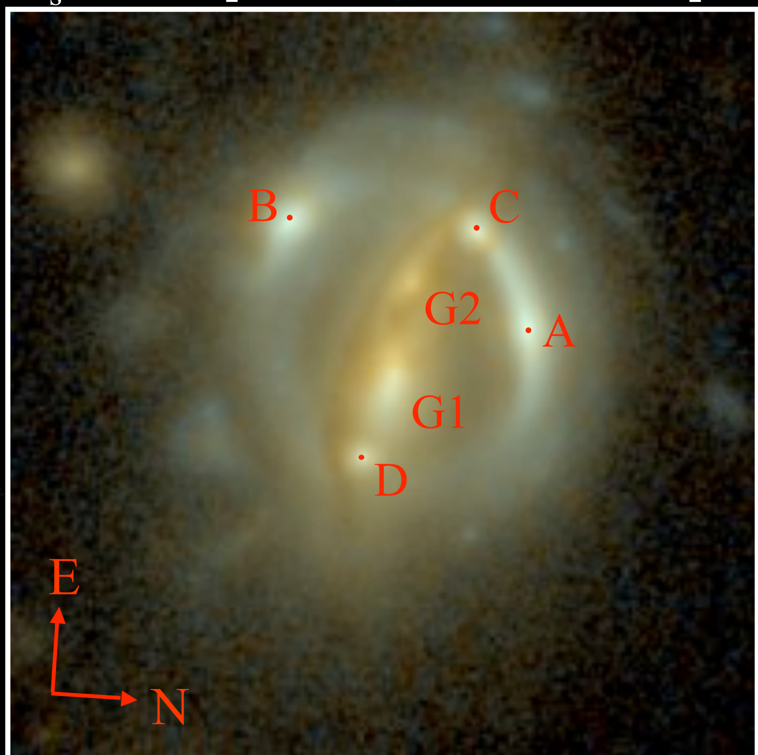
- *HST* Key Project:

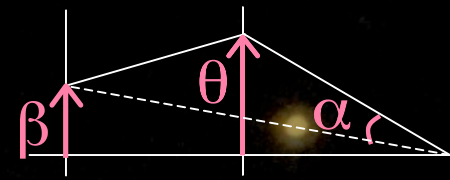
  H_0=72 ± 2(stat) ± 7(syst) [Freedman et al. 2001]
- CMB:

  H_0=73 ± 3 [Spergel et al. 2006]
- Strong Gravitational Lensing

B1608+656

$z_d = 0.63$ [Myers et al. 1995]
$z_s = 1.39$ [Fassnacht et al. 1996]





$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$$
$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}\psi(\vec{\theta})$$

Time delay function:

$$T(\vec{\theta}, \vec{\beta}) \sim \frac{1}{H_0}\underbrace{\left[\frac{1}{2}(\vec{\theta} - \vec{\beta})^2 - \psi(\vec{\theta})\right]}_{\text{Fermat pot. } \phi}$$

Goal (H_0)

B1608+656 provides opportunity to measure H_0 to high precision.
⇒ pixellated potential reconstruction

- Relative time delays [Fassnacht et al. 1999, 2002]
  - $\Delta t_{AB} = 31.5 \pm 1.5$ days
  - $\Delta t_{CB} = 36.0 \pm 1.5$ days
  - $\Delta t_{DB} = 77.0 \pm 1.5$ days
- Extended source intensity

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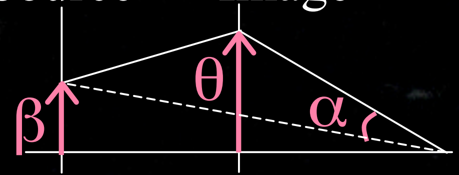
Potential Reconstruction
(Perturbative and Iterative)

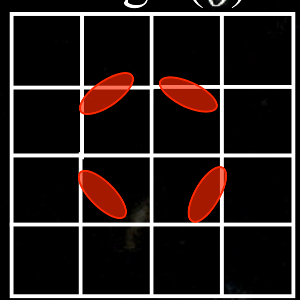


$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$$

To first order:

$$\delta I(\vec{\theta}) = \frac{\partial I(\vec{\beta})}{\partial \vec{\beta}} \cdot \frac{\partial \delta\psi(\vec{\theta})}{\partial \vec{\theta}}$$

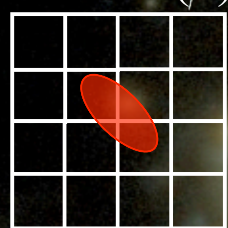
Image $(\vec{\theta})$



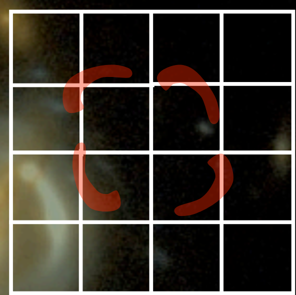
source recon.

(regularized linear inversion)

Source $(\vec{\beta})$



int. deficit $(\vec{\theta})$



potential correction

$\delta\psi$

+

Initial potential:

$$\psi(\vec{\theta}) = \psi_0(\vec{\theta}) + \delta\psi(\vec{\theta})$$

perturbed true

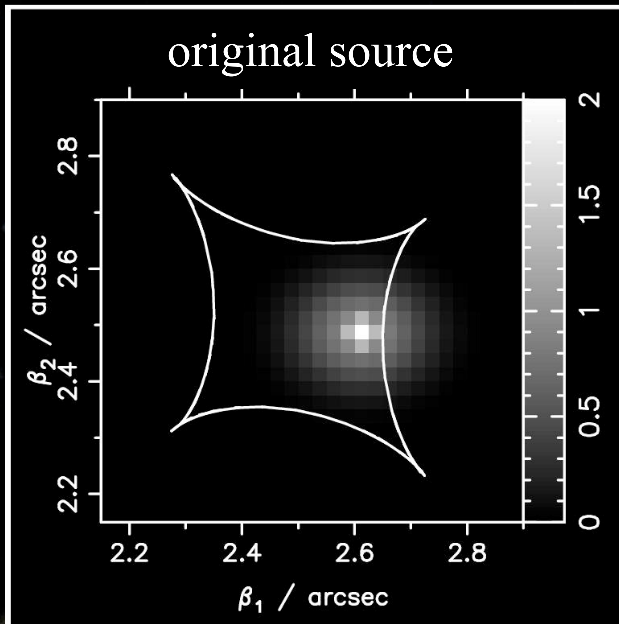
Intensity deficit:

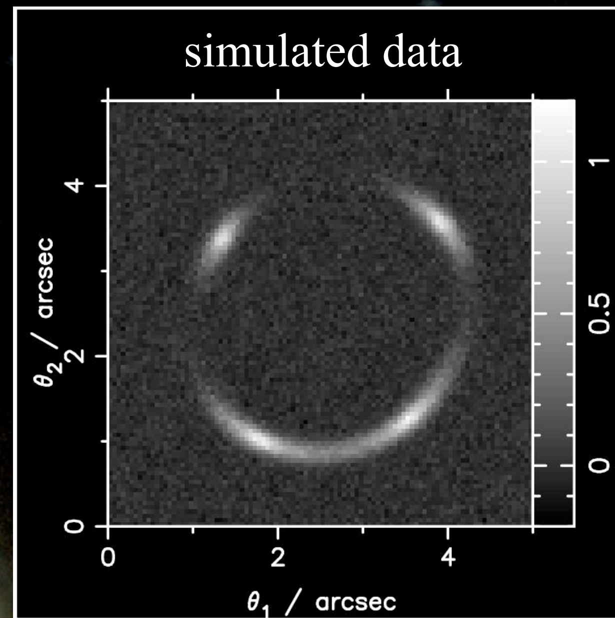
$$\delta I(\vec{\theta}) = I(\vec{\theta}) - I(\vec{\beta})$$

obs. pred.

update ψ and repeat

Demo Pot. Rec. – simulated data





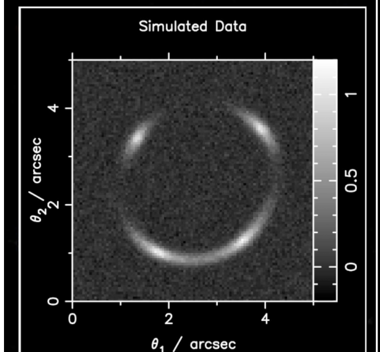
- ~Gaussian + Point Source
- $z_s = 3.0$
- $N_s = 30\times30$

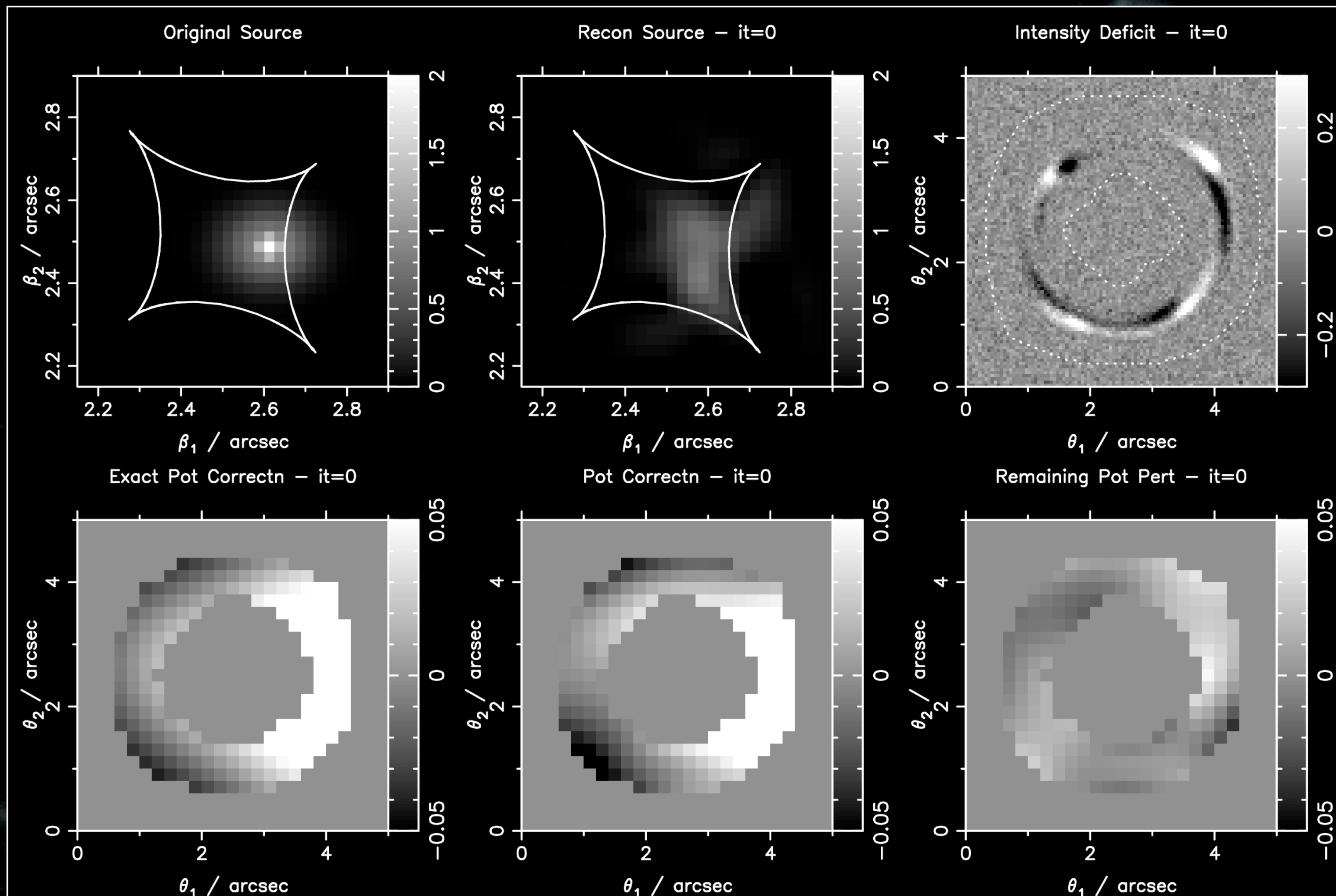
- SIEs: v=260 km/s, q=0.75, PA=45°
  v=50 km/s, q=0.60, PA=70°
- Gaussian PSF (FWHM=0.15″)
  uniform Gaussian noise (σ=0.043)
- $z_d = 0.3$ and $N_d = 100\times100$

Perturbed potential: rotation of primary SIE by 5° & absent secondary SIE

Demo Pot. Rec. – Iteration 0 results

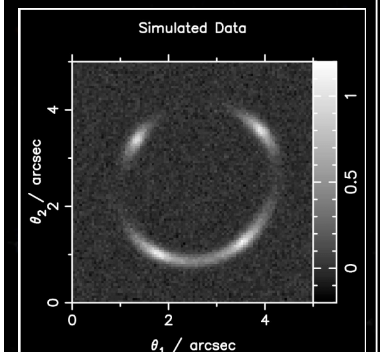
simulated data

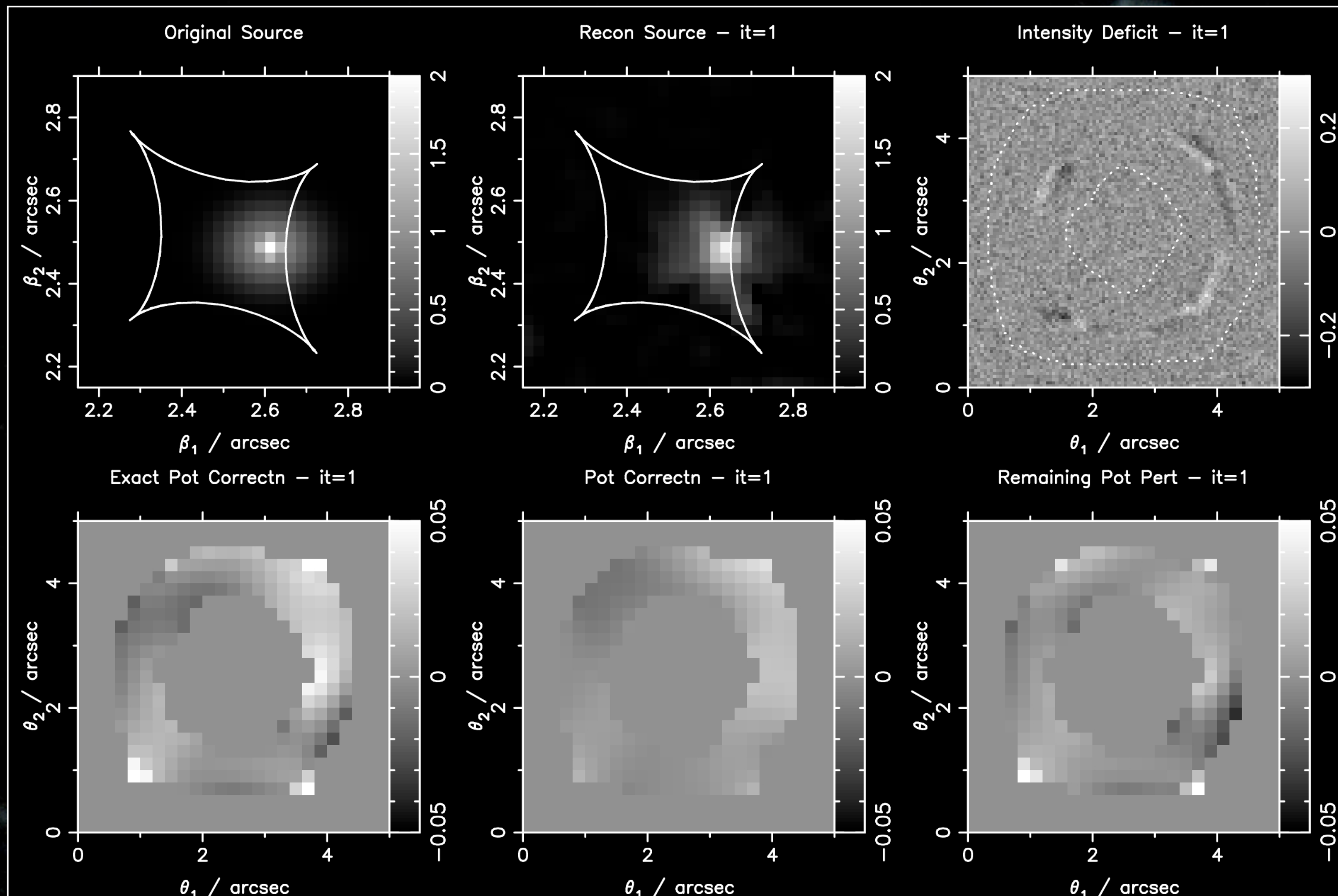




Demo Pot. Rec. – Iteration 1 results

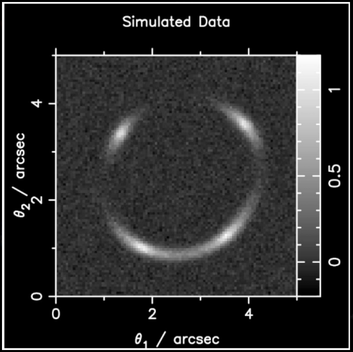
simulated data

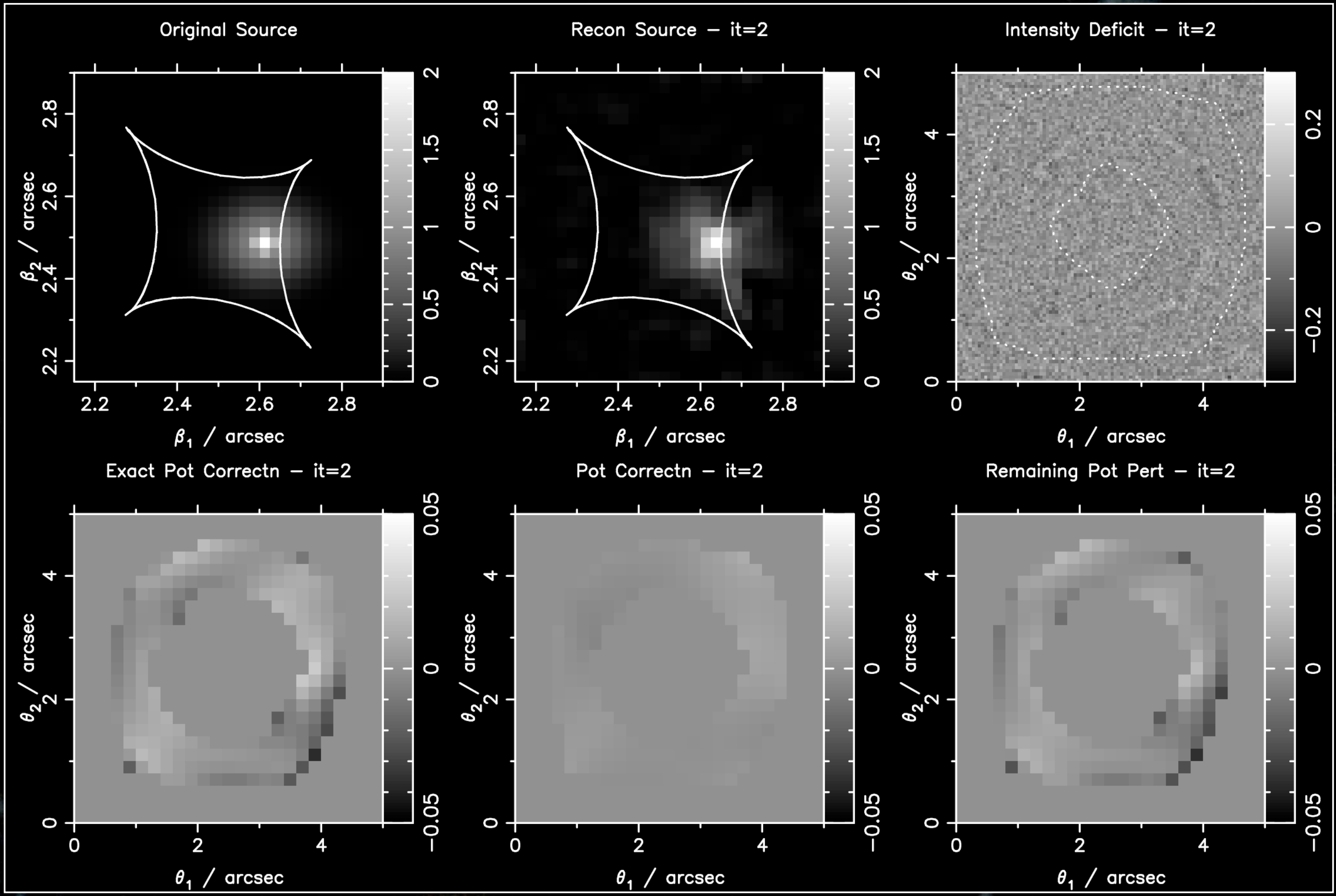




Demo Pot. Rec. – Iteration 2 results

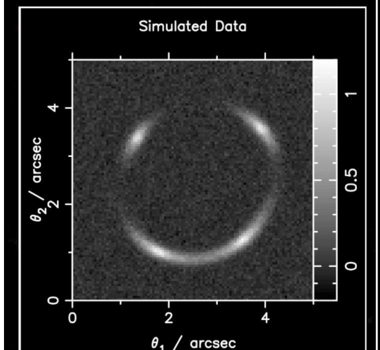
simulated data

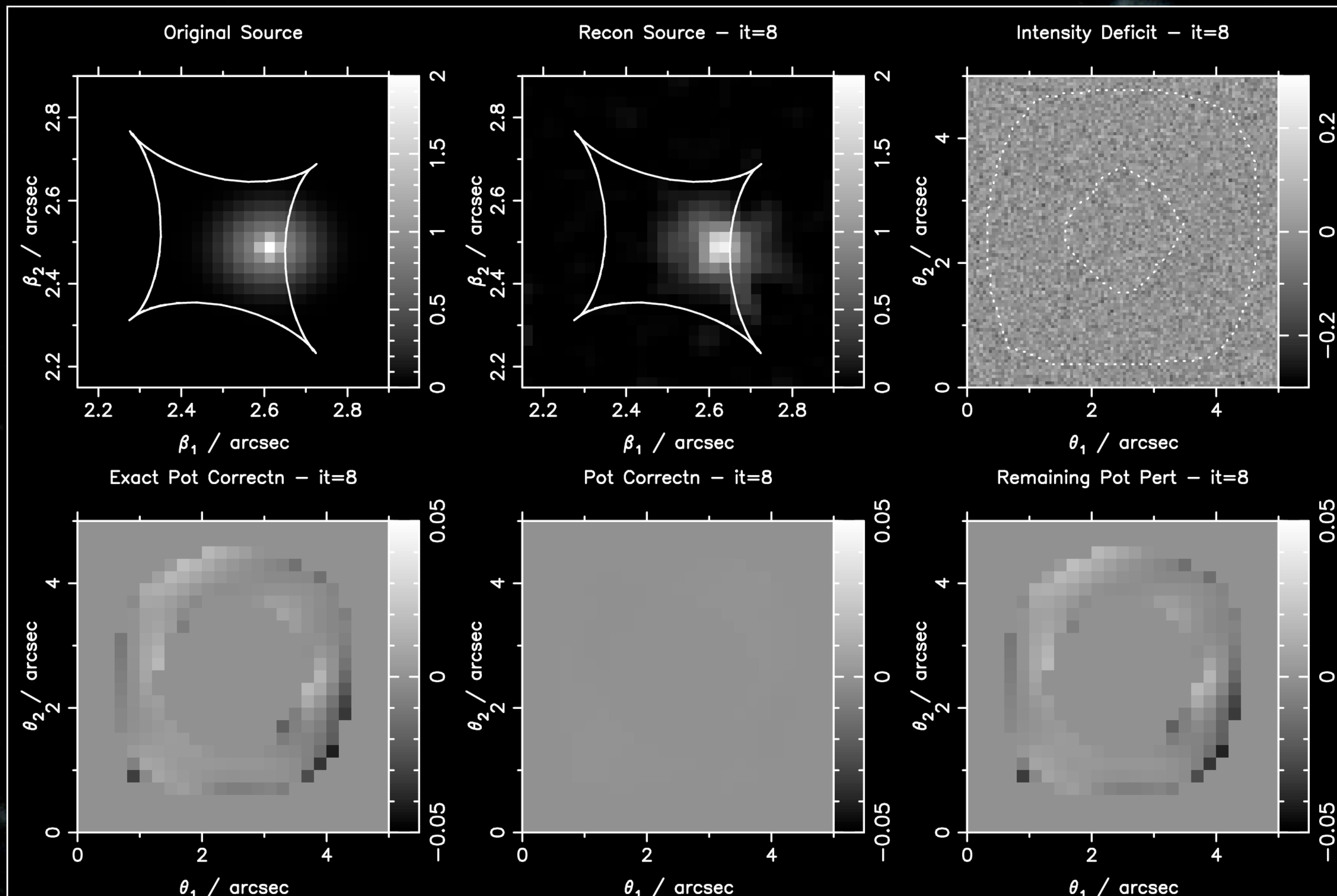




Demo Pot. Rec. – Iteration 8 results

simulated data





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- Bayesian Pixellated Potential Reconstruction
  - source intensity reconstruction
  - lens potential correction
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HST ACS Observations

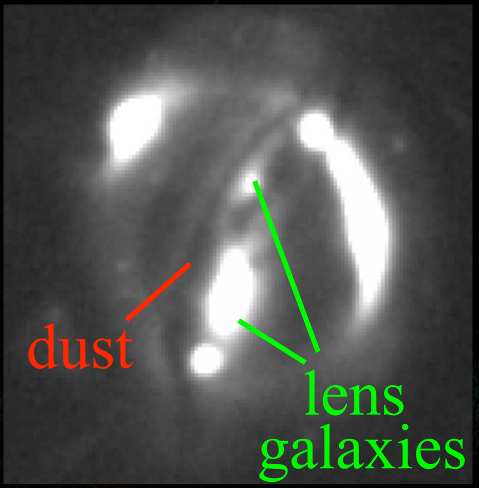
Utopia

obs. pred. noise

$$d = \mathbf{B}\mathbf{L}s + n$$

blurring (PSF) — Lensing (ψ) — extended source

Reality



obs. — extended source — lens galaxies — noise

$$d = \mathbf{B}\mathbf{K}\mathbf{L}s + \mathbf{B}\mathbf{K}g + n$$

$\mathbf{B}$ = blurring (PSF)

$\mathbf{K}$ = dust extinction

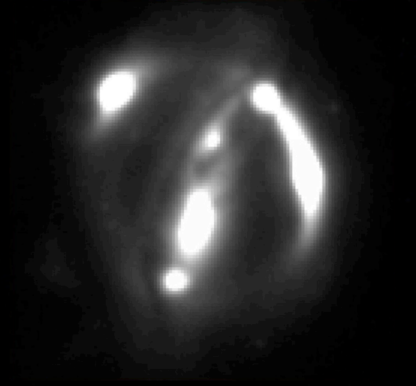
$\mathbf{L}$ = lensing (ψ)

g = lens' light

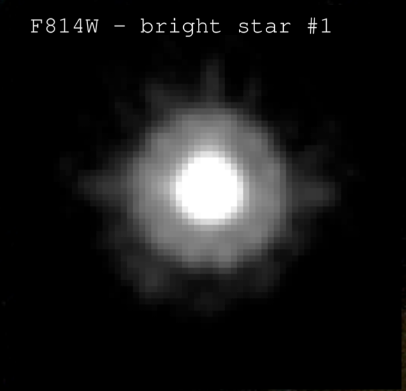
$\Rightarrow$ Use Bayesian evidence to rank models $\mathbf{B}$, $\mathbf{K}$, $\mathbf{L}$, g

HST Image Analysis Prelim. Results

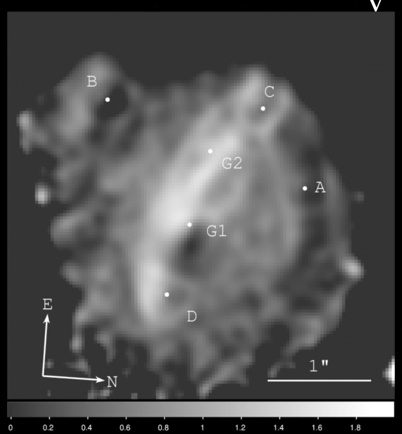
Drizzled F814W



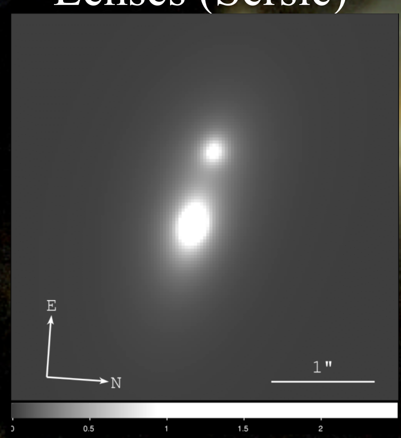
PSF - B1



Dust Extinction A_V



Lenses (Sersic)



+ Koopmans et al. (2003) SPLE1+D model

obs. — extended source — lens galaxies — noise

$$d = \mathbf{B}\mathbf{K}\mathbf{L}s + \mathbf{B}\mathbf{K}g + n$$

$\mathbf{B}$ = blurring $\mathbf{K}$ = dust extinction

$\mathbf{L}$ = lensing g = lens' light

Given the models $\mathbf{B}$, $\mathbf{K}$, g and initial $\mathbf{L}$

- can apply pixellated potential reconstruction method to correct $\mathbf{L}(\psi)$ and get s
  - ACS data
  - time delays with input H_0=76 km s^{-1} Mpc^{-1}

HST Image Analysis Prelim. Results

Model	PSF	dust map	(n_{G1},n_{G2})
2	drz	drz/3-band	(3,3)
3	C	C/3-band	(3,4)
4	C	C/2-band	(3,3)
5	B1	B1/3-band	(3,4)
6	B1	B1/2-band	(2,2)
7	B2	B2/3-band	(2,2)
8	B2	B2/2-band	(2,2)
9	C	B1/3-band	(3,4)
10	B1	C/2-band	(3,3)

+ Koopmans et al. (2003) SPLE1+D model

obs. — extended source — lens galaxies — noise

$$d = \mathsf{BKL}s + \mathsf{BK}g + n$$

B = blurring K = dust extinction
L = lensing g = lens' light

Given the models B, K, g and initial L

- can apply pixellated potential reconstruction method to correct $\mathsf{L}(\psi)$ and get s
  - ACS data
  - time delays with input H_0=76 km s^{-1} Mpc^{-1}

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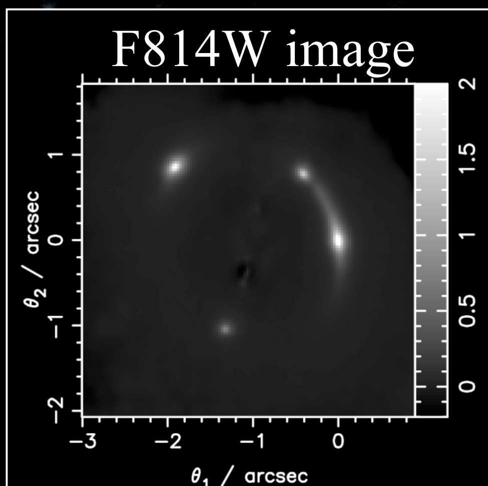
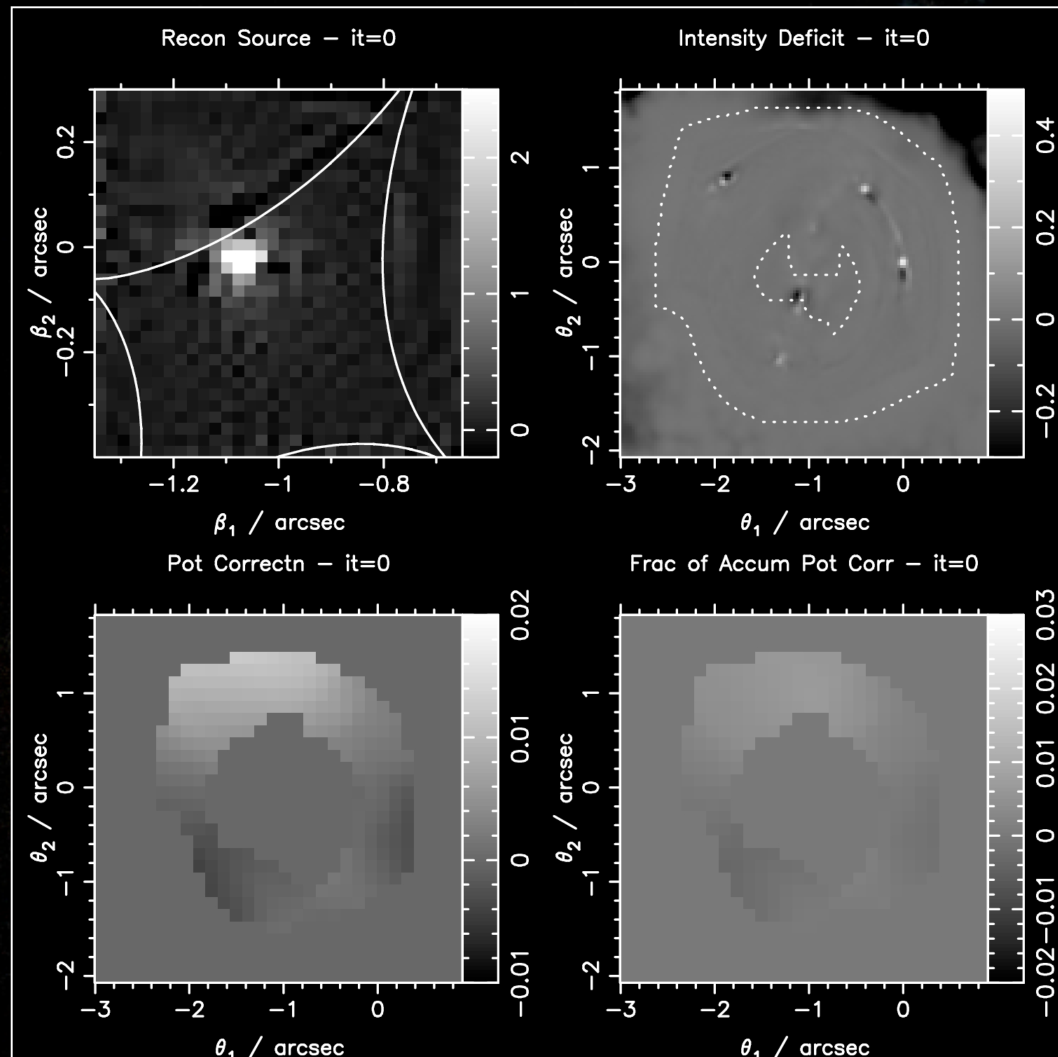
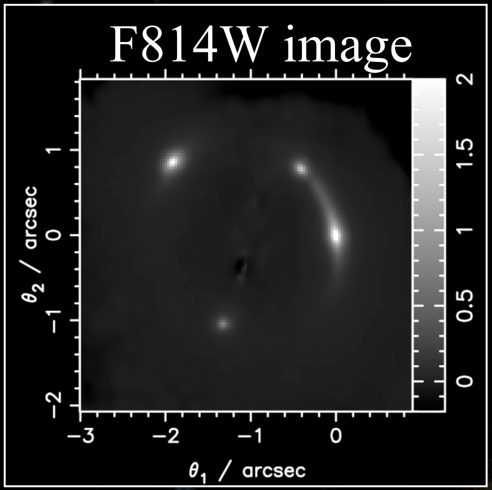
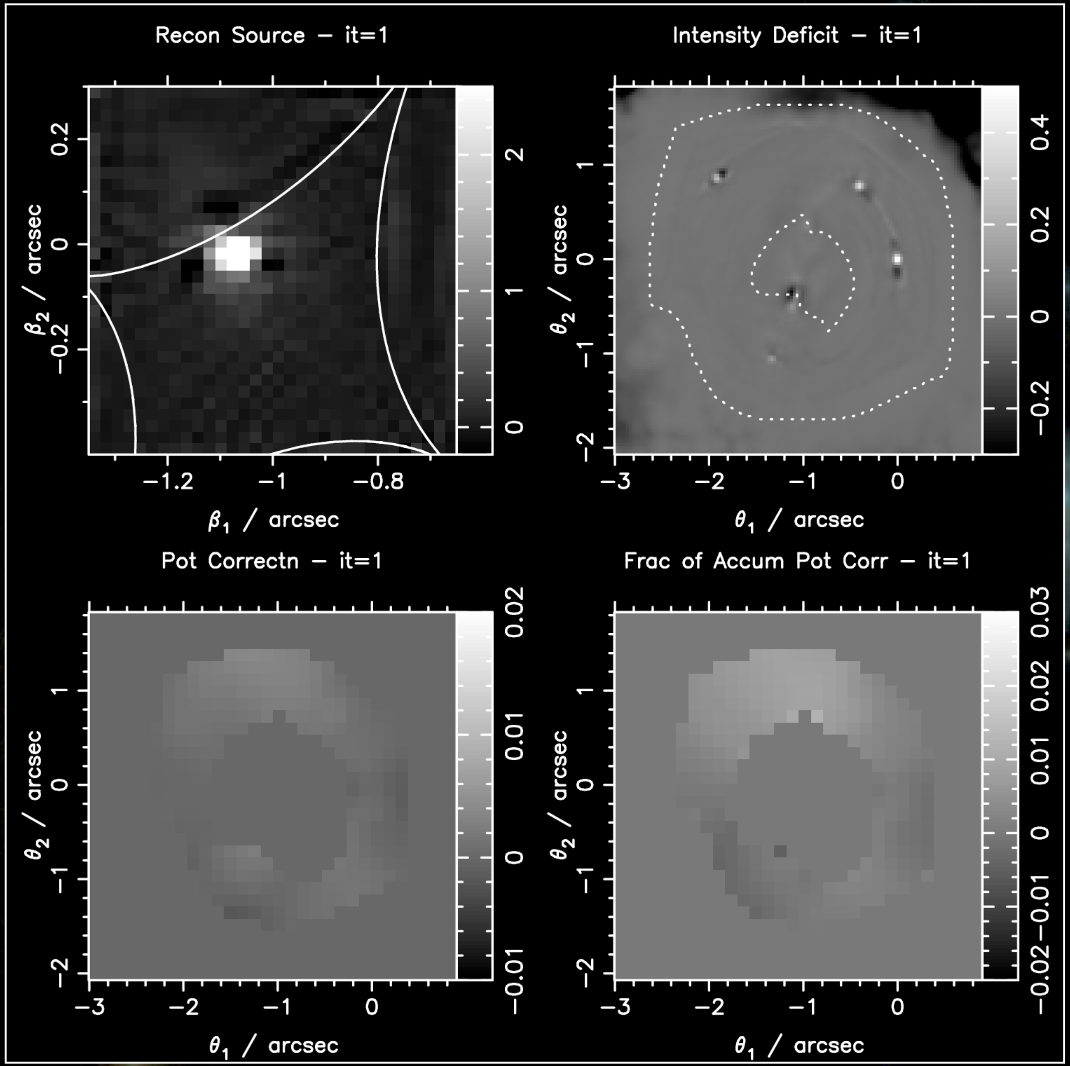
Pot. Rec. of B1608+656 – Iteration 0



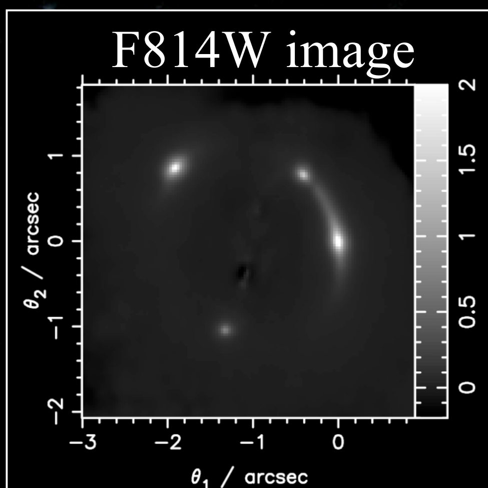


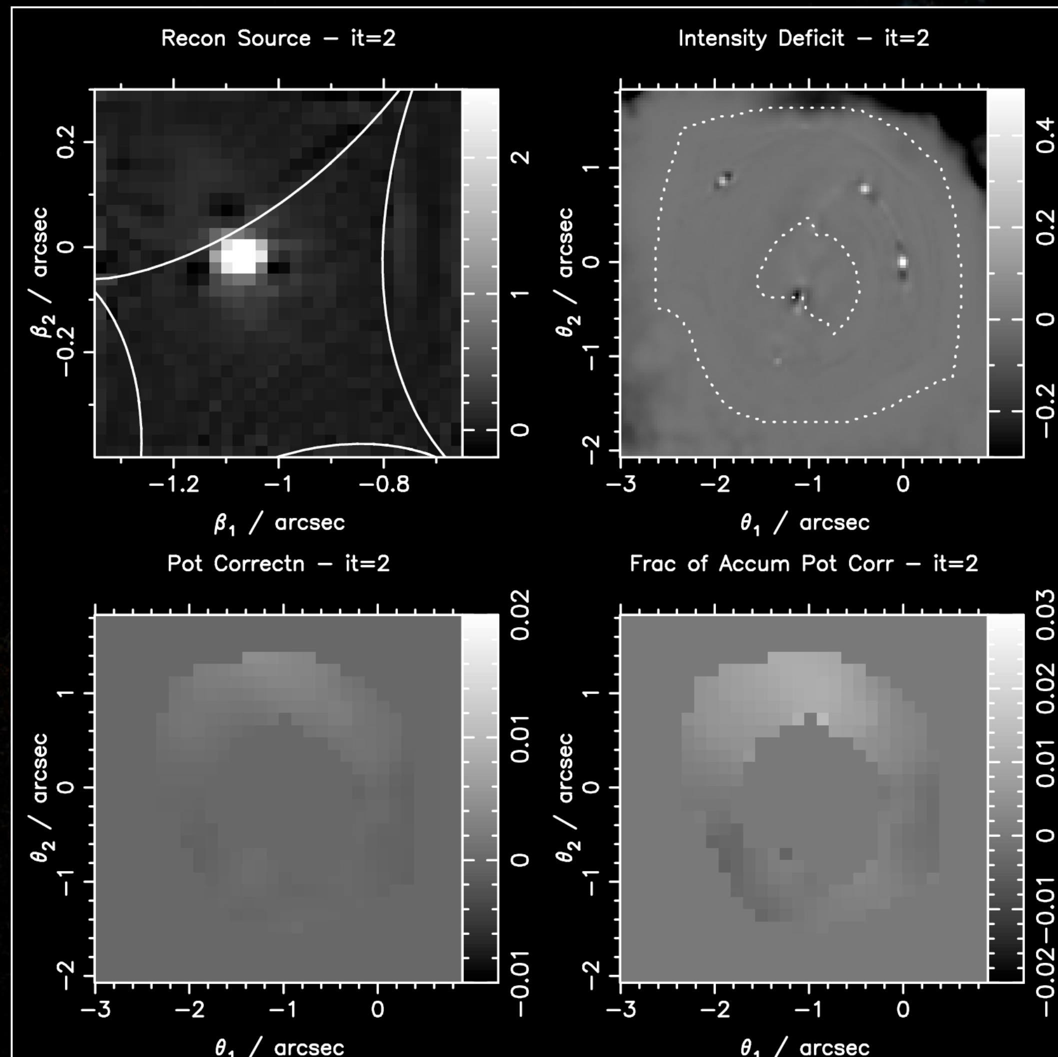
Pot. Rec. of B1608+656 – Iteration 1



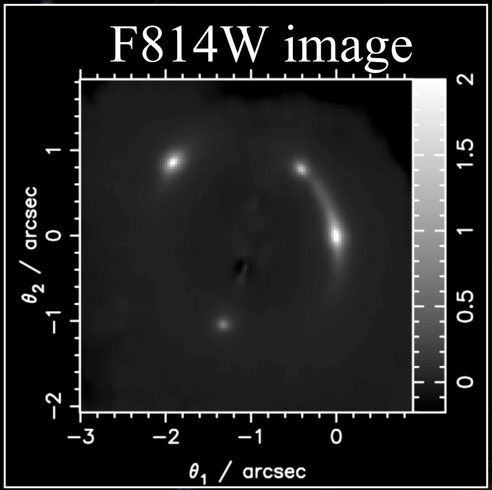


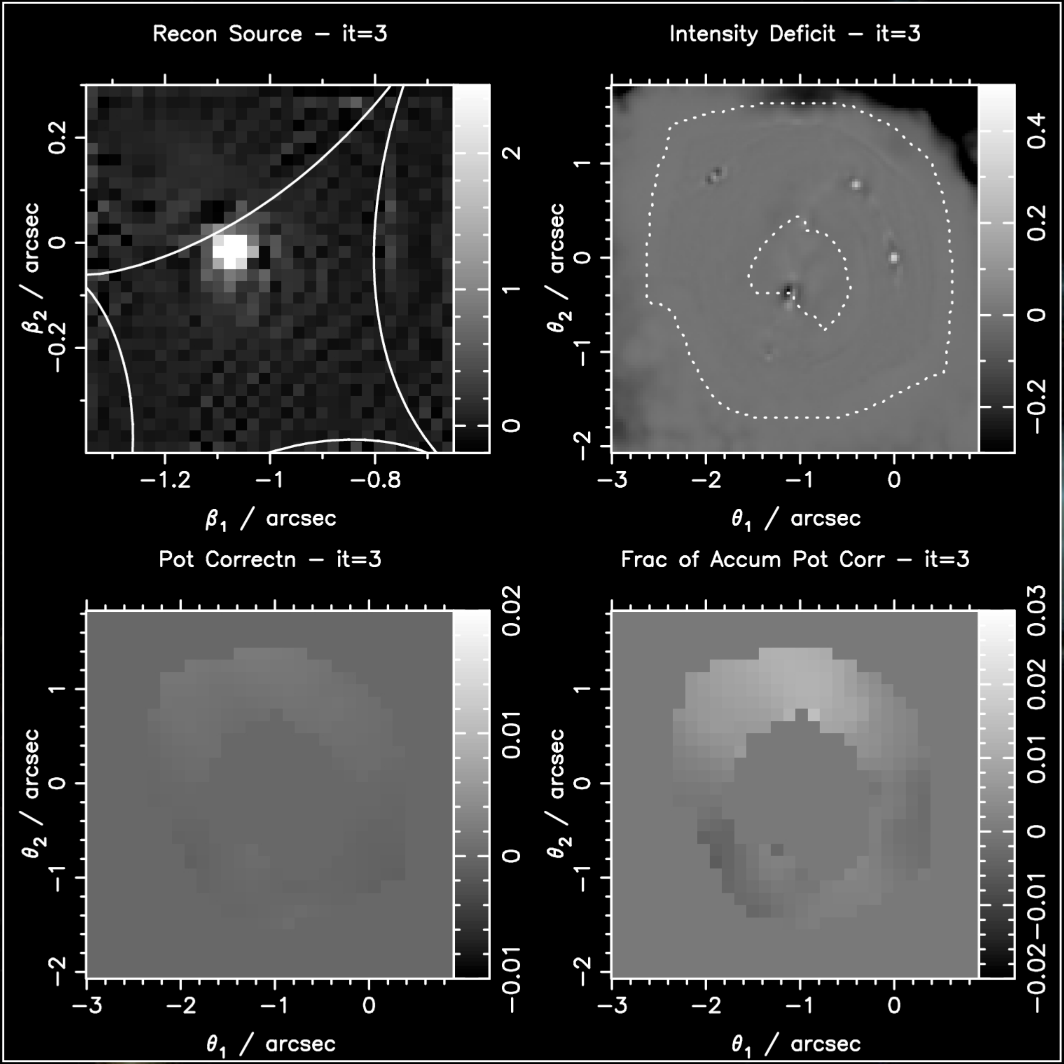
Pot. Rec. of B1608+656 – Iteration 2



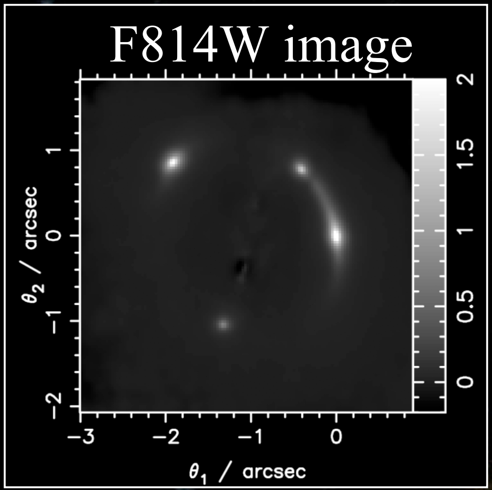


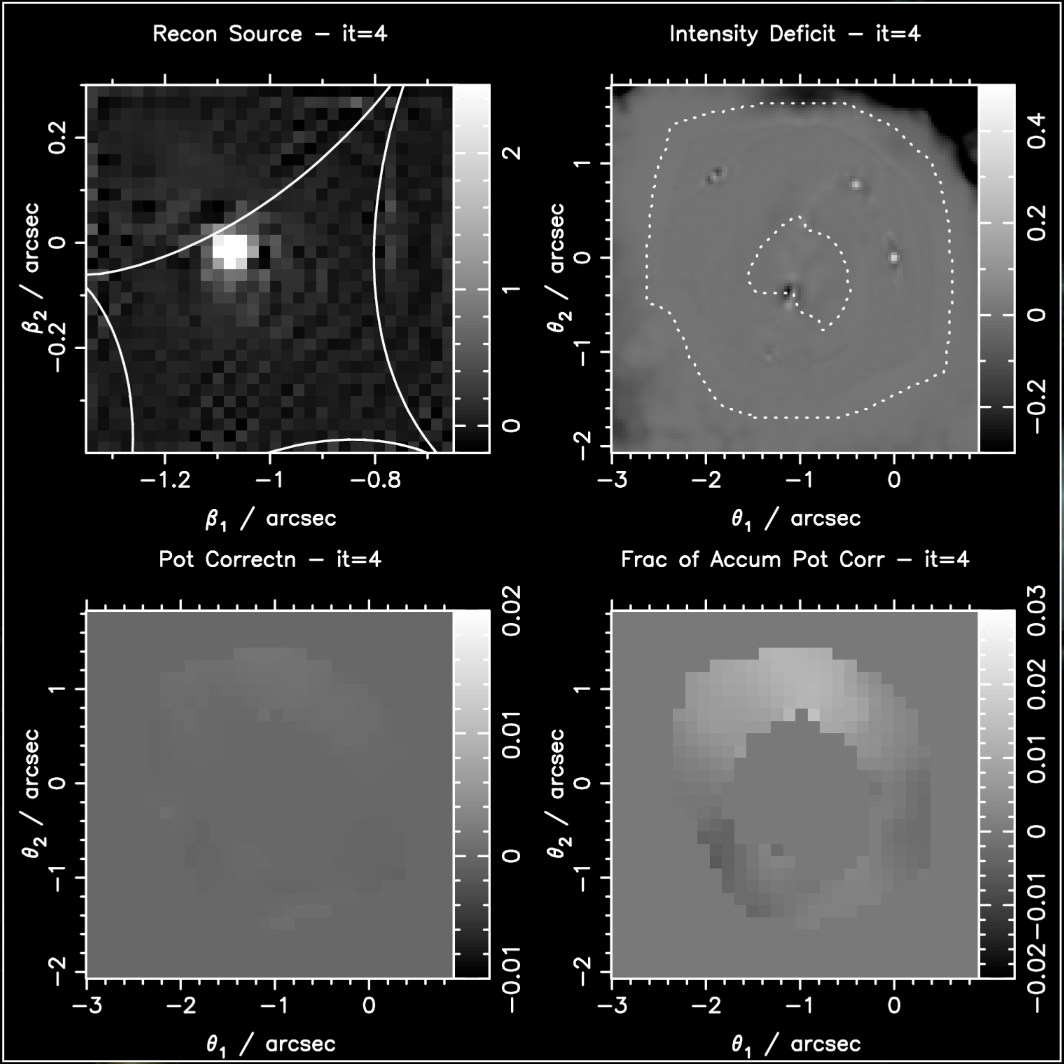
Pot. Rec. of B1608+656 – Iteration 3



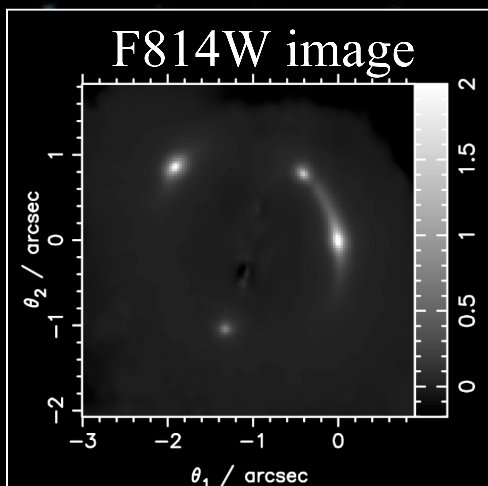


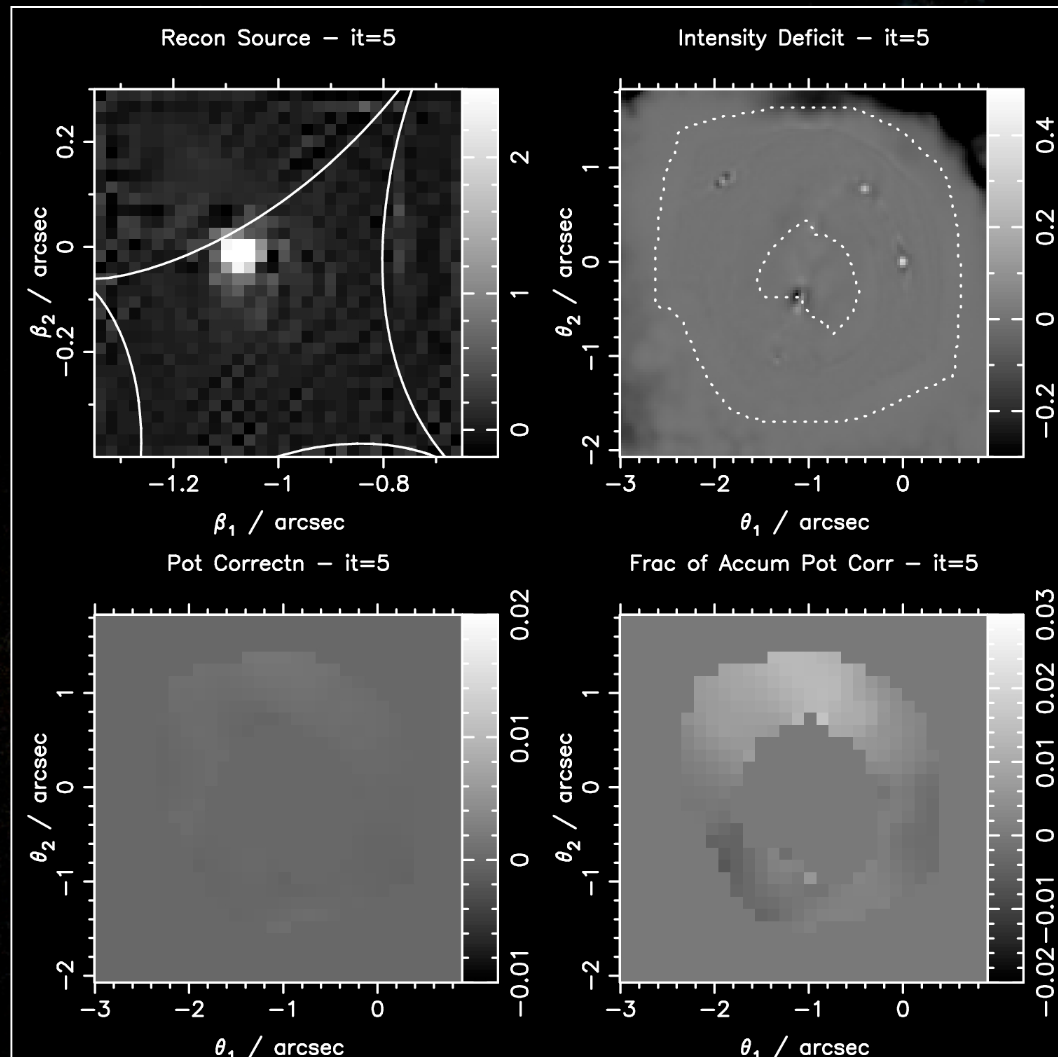
Pot. Rec. of B1608+656 – Iteration 4



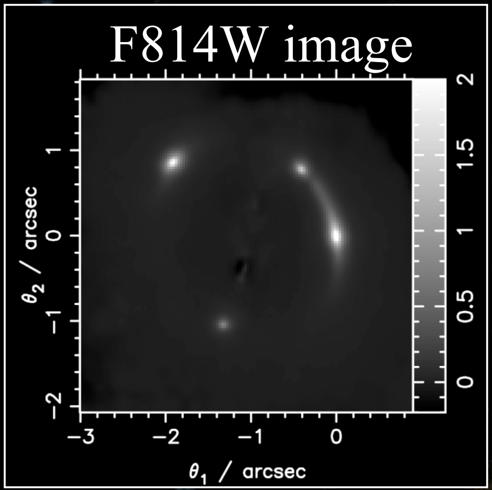


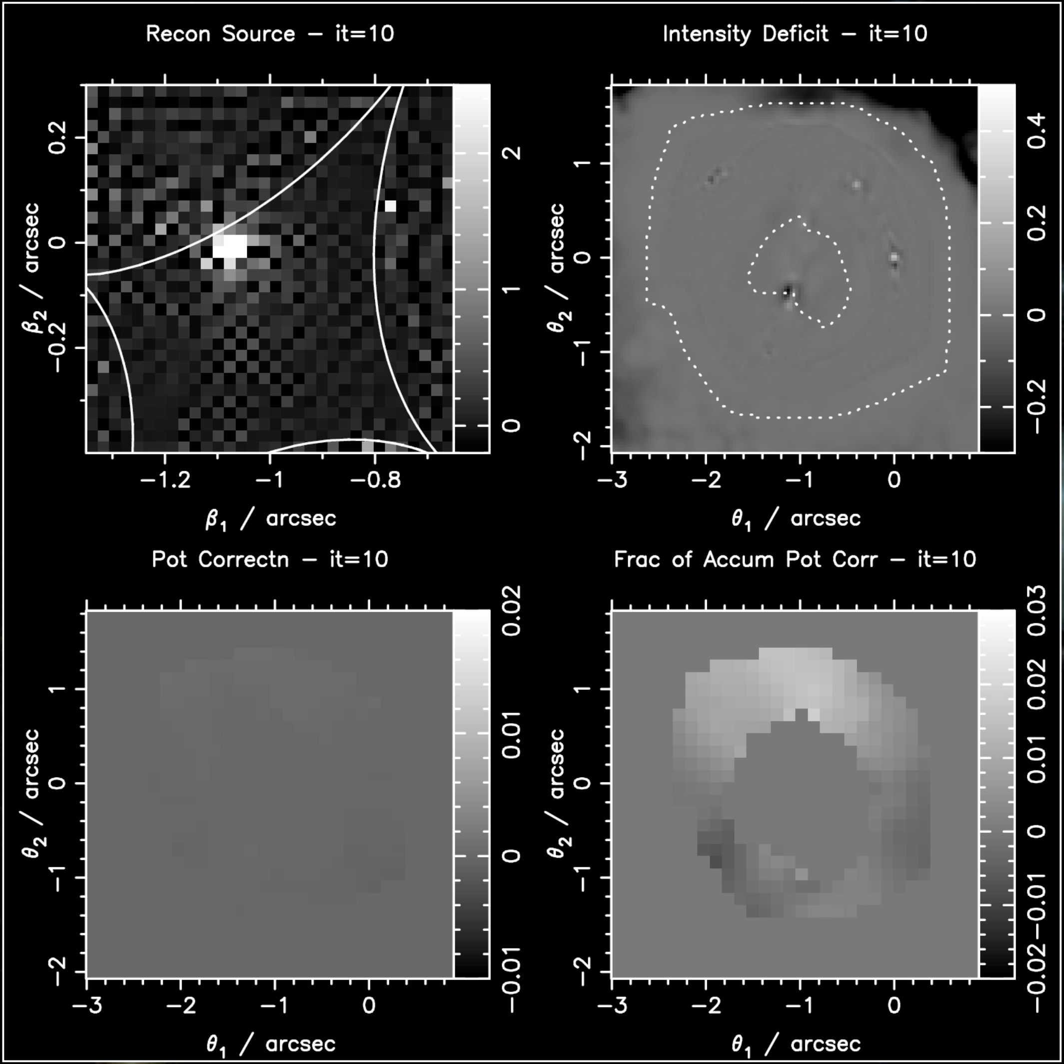
Pot. Rec. of B1608+656 – Iteration 5



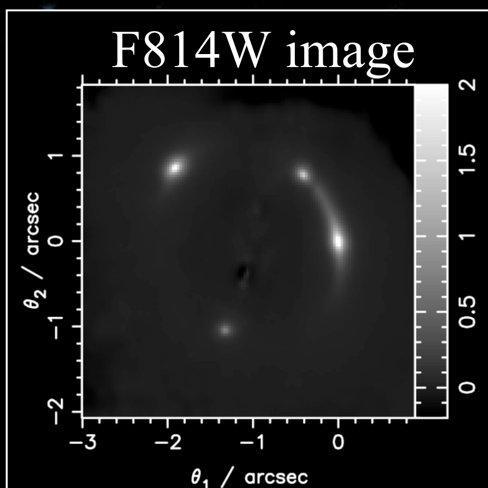


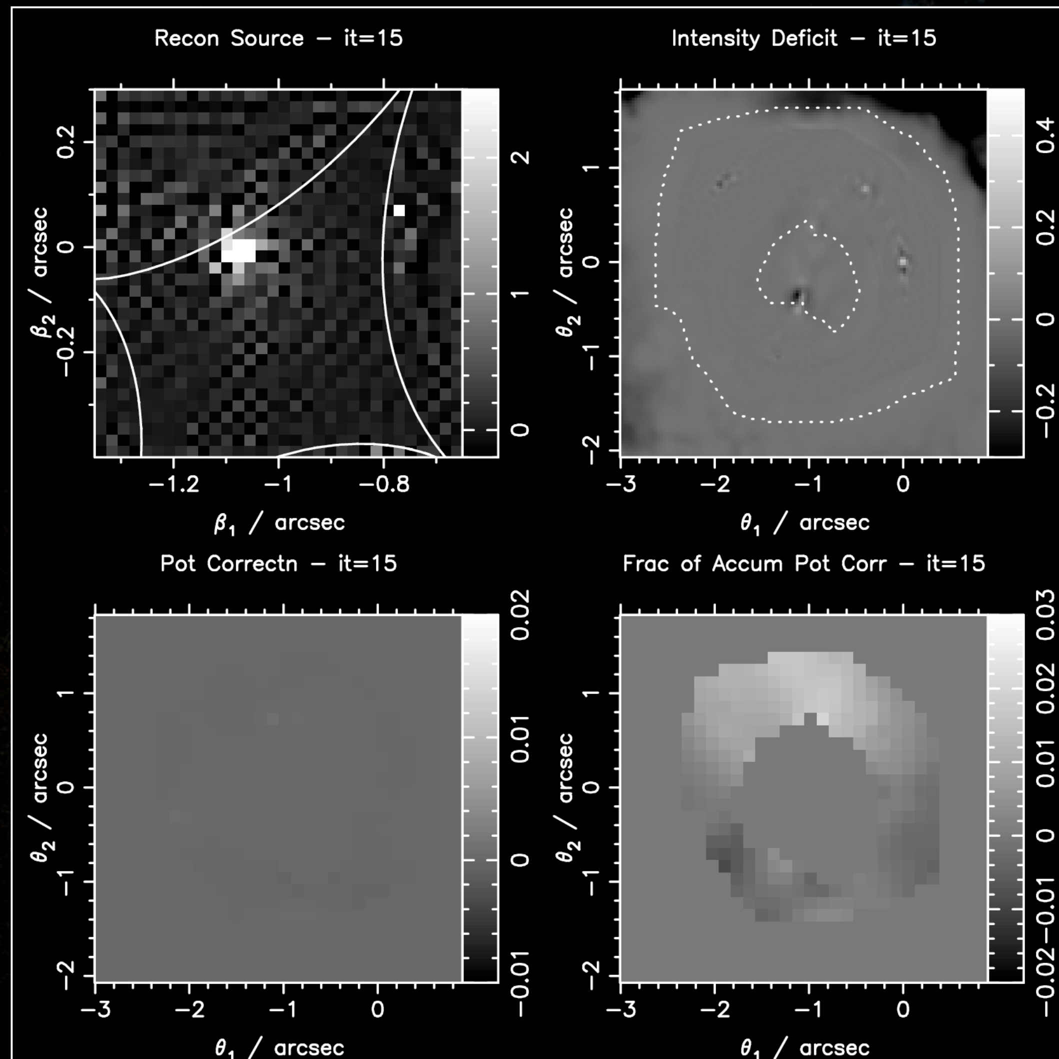
Pot. Rec. of B1608+656 – Iteration 10





Pot. Rec. of B1608+656 – Iteration 15





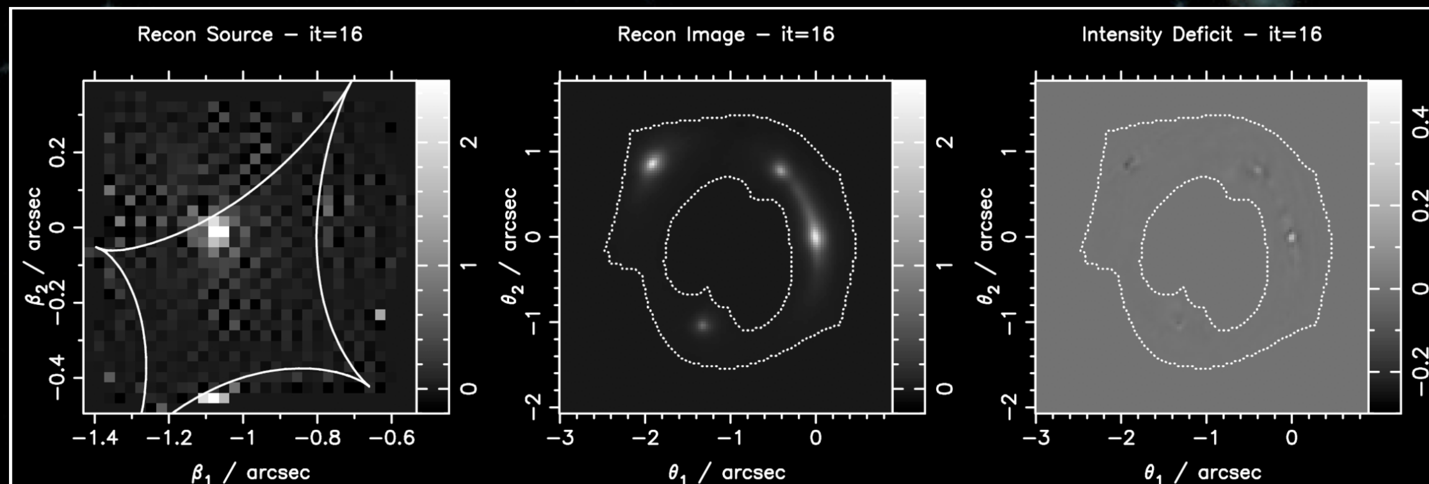
H_0: error from modeling (preliminary)

Model	PSF	dust map	H_0^{AB}	H_0^{CB}	H_0^{DB}	σ_{H_0}	log evidence
5	B1	B1/3-band	77.8	77.2	75.2	1.3	1.64×10^4
3	C	C/3-band	76.4	76.6	75.1	0.7	1.46×10^4
9	C	B1/3-band	72.8	73.0	73.5	2.9	3.89×10^3
2	drz	drz/3-band	79.4	79.3	74.5	2.8	-1.35×10^3
10	B1	C/2-band	76.7	74.9	74.2	1.3	-1.79×10^3
7	B2	B2/3-band	71.9	72.2	74.8	3.3	-4.26×10^3
6	B1	B1/2-band	65.8	66.6	71.7	8.4	-5.86×10^3
4	C	C/2-band	66.0	67.4	71.4	8.1	-9.69×10^3
8	B2	B2/2-band	61.5	62.8	72.0	11.6	-1.67×10^4

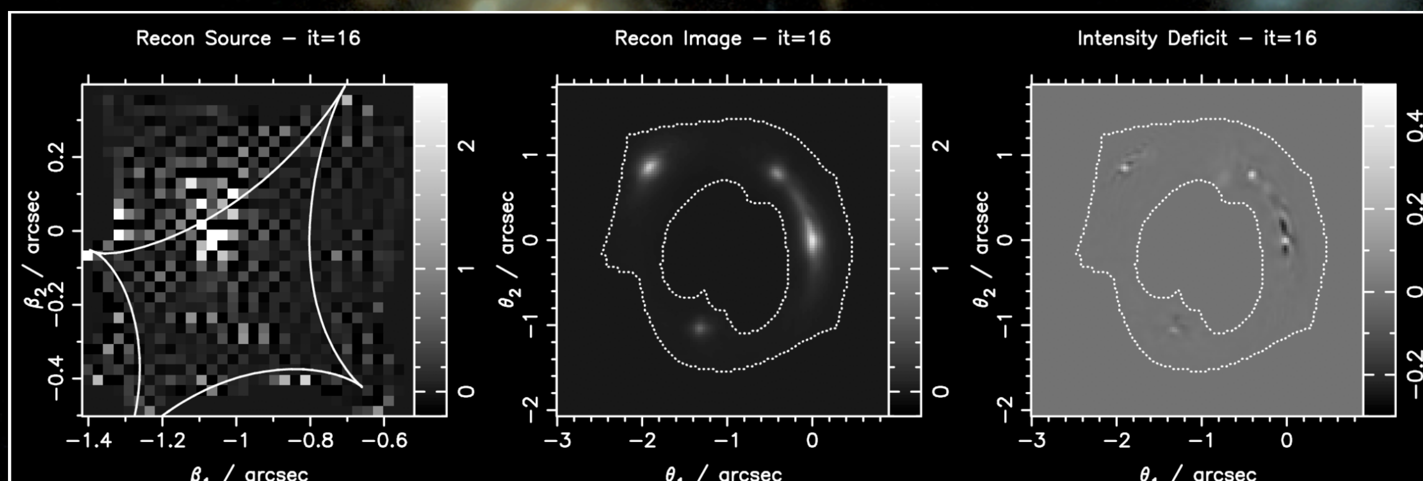
- generally, good/bad model with high/low evidence leads to good/bad H_0 recovery
- in good models, error in H_0 ~ smallest time delay uncertainty ($t^{DB} = 77.0 \pm 1.5$ days)
  $\Rightarrow$ conservatively adopt modeling (statistical) error of ± 2 km s^{-1} Mpc^{-1}

H_0: error from modeling (preliminary)

Model 5:
Log evidence
= 1.64×10^4



Model 8:
Log evidence
= -1.67×10^4



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7	B2	B2/3-band	71.9	72.2	74.8	3.3	-4.26×10^3
6	B1	B1/2-band	65.8	66.6	71.7	8.4	-5.86×10^3
4	C	C/2-band	66.0	67.4	71.4	8.1	-9.69×10^3
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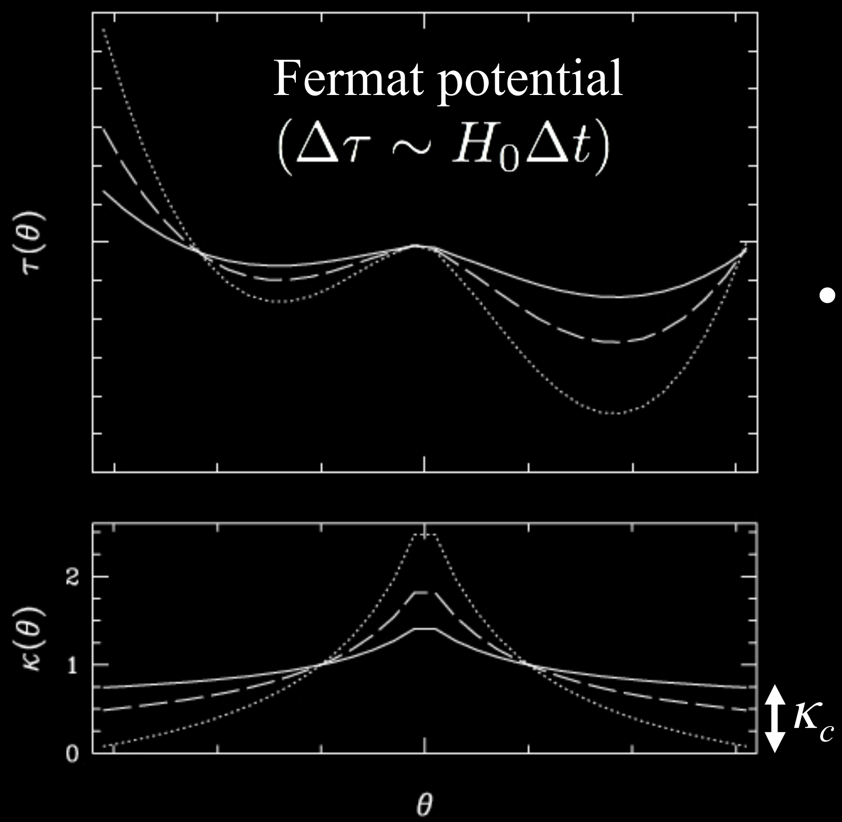
H_0: error from mass sheet degeneracy

[Courbin et. al. 2002]



<u>To break the MSD:</u>

- stellar dynamics
  - σ_{G1} = 247 ± 35 km/s [Koopmans et. al. 2003]
  - error on σ_{G1} constrains amount of κ_c
  - Stellar dynamics constrains error due to MSD to be ±7 km s^{-1} Mpc^{-1}
- lens environment of B1608+656
  - Spectroscopic survey discovered 4 galaxy groups along line of sight to B1608+656 with one group at z_d [Fassnacht et. al. 2006]
  - each group contains ~10 members and provides $\kappa_c \sim 0.005–0.06$
  - B1608+656 appears to lie along an over dense line-of-sight. Preliminarily, estimate $\kappa_c = 0.05 \pm 0.05$ [Fassnacht et. al., in prep]

→ $H_0 = 72 \pm 2$(stat.) ± 4(syst.) km s^{-1} Mpc^{-1}

Summary

- Bayesian Source and Potential Reconstruction:
  - iterative and perturbative potential correction scheme works for potential perturbations of ~5%
- *HST* observations of B1608+656:
  - obtained a representative suite of PSF, dust, and lens galaxies' light models using ACS and NICMOS images
- Potential reconstruction of B1608+656:
  - corrected initial potential SPLE1+D(isotropic) on a grid of pixels for each set of PSF, dust, lens galaxies' light models.
  - Bayesian techniques can be used to compare objectively different PSF, dust, lens galaxy light, and lens potential model and used to quantify modeling (statistical) error.
  - Mass sheet degeneracy is the strongest systematic error
  - H_0=72 ± 2(stat.) ± 4(syst.) km s^{-1} Mpc^{-1}