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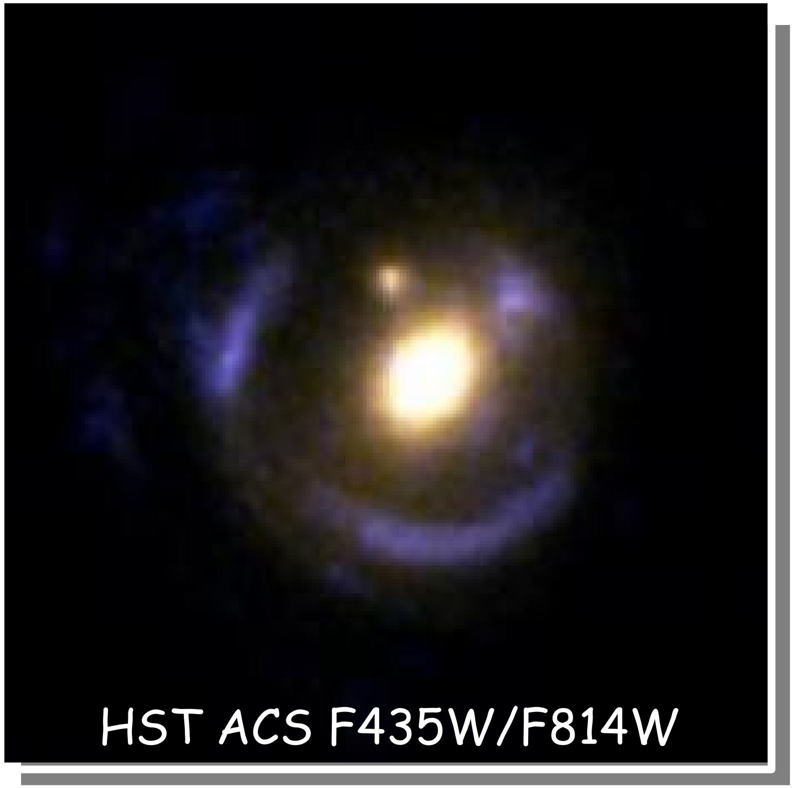
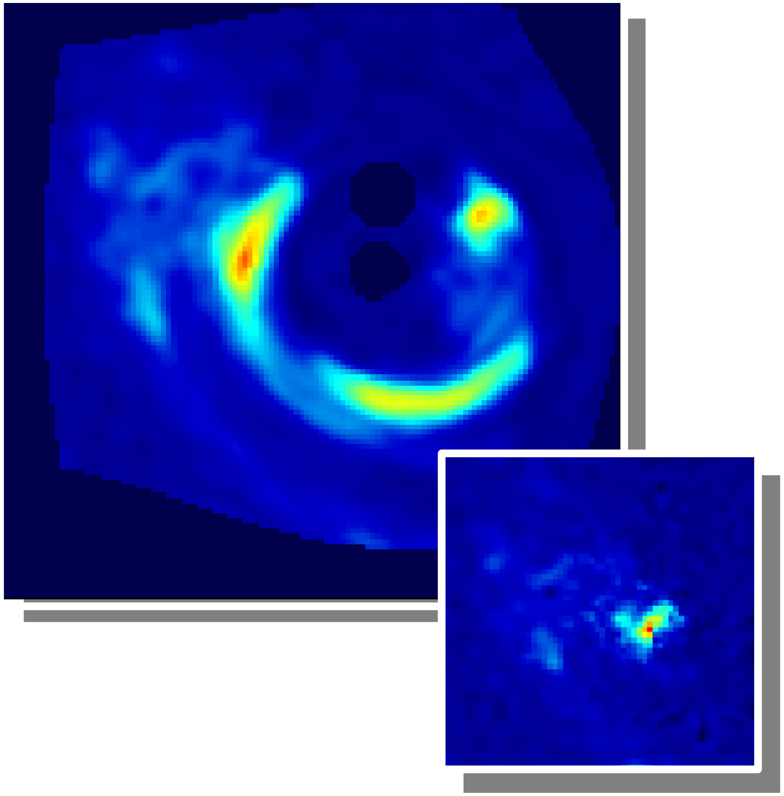
groningen

# Strong Gravitational Lensing with HST: Looking at the Future

Léon Koopmans

(Kapteyn Astronomical Institute)





# WARNING!

"Most of the science you are about to witness can not be done with anything else but the Hubble Space Telescope!"

Hence the future is the present
and with SM4 even more!

# HST's Unique Combination of Capabilities for Strong Lensing

| | |
|---|---|
| → High Angular Resolution<br>Spatially resolved imaging | ~ 0.05″ - 0.1″ |
| → High sensitivity<br>High-SNR characterization<br>of galaxy & source structure | ~26 mag in $I_{AB}$<br>(1 orbit with ACS) |
| → Relatively “Large” FoV<br>Weak gravitational lensing and<br>environmental/field studies | ~3' x ~3'<br>(WFC3/ACS) |

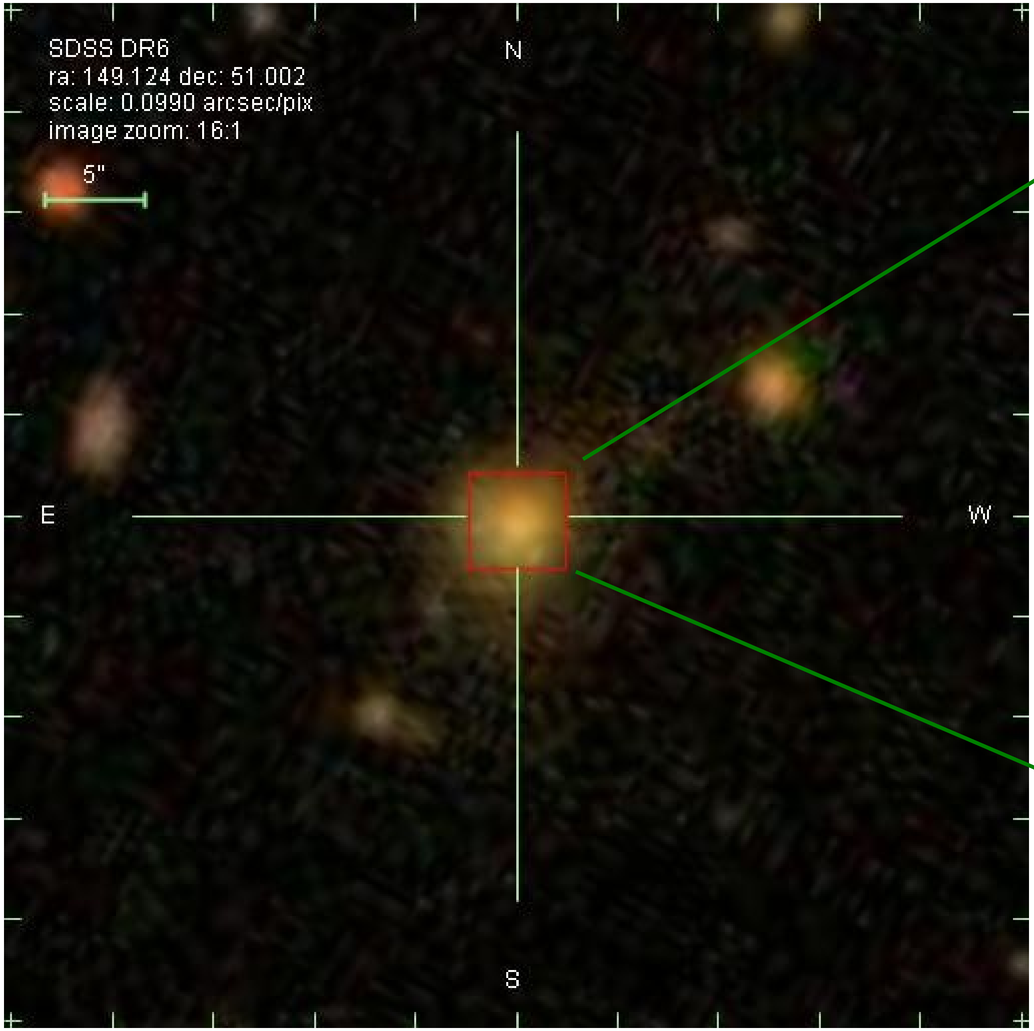
# Galaxy-Scale Strong-Lensing:

## Some results obtained with HST-ACS/WFPC2/NICMOS

## Why the use of HST is critical!

# High Spatial Resolution

From the ground (SDSS)

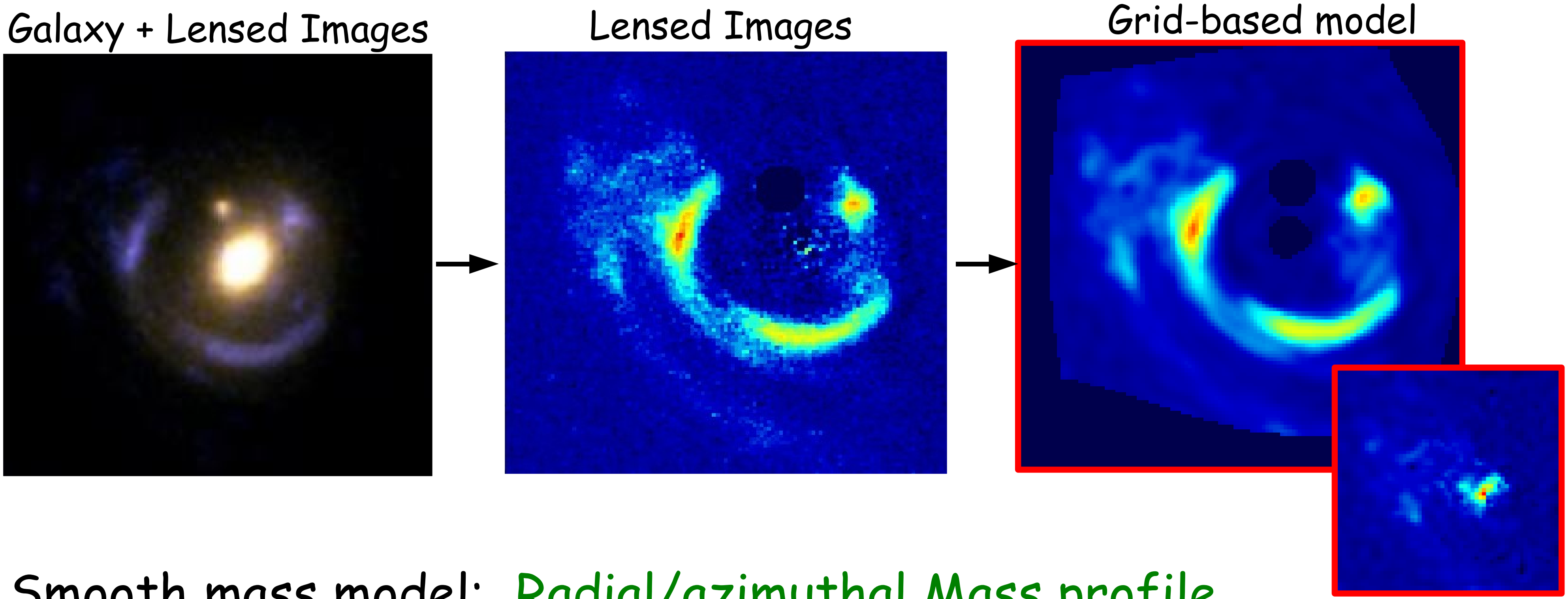


From space (HST)

(Bolton et al. 2006, Treu et al. 2006; Koopmans et al. 2006)

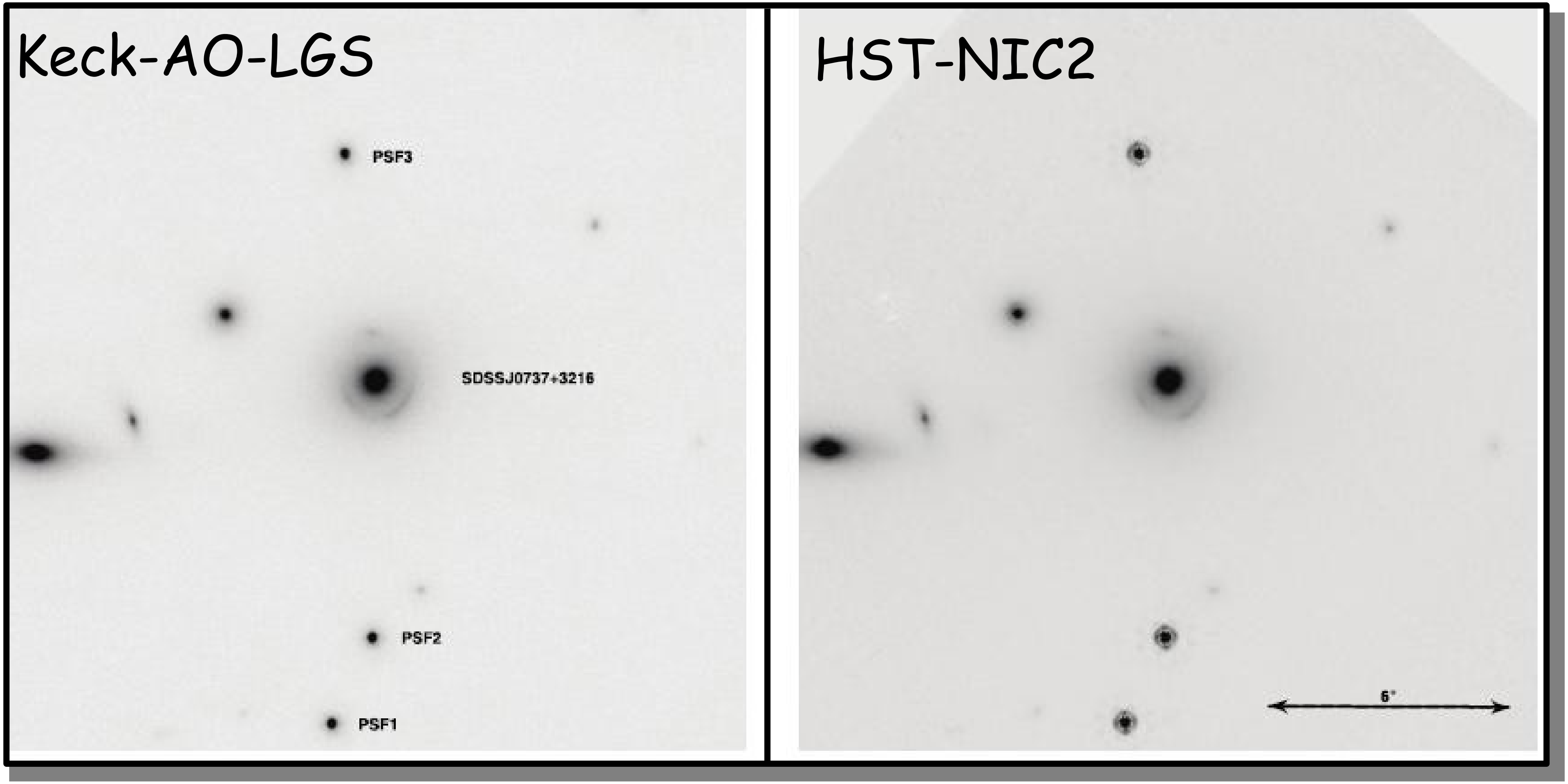
# Why is High Spatial Resolution Needed?

Surface brightness conservation + multliplicity of images:
Information about the galaxy potential can be extracted



Smooth mass model: Radial/azimuthal Mass profile
Clumpy mass model: Dark & Luminous Substructure

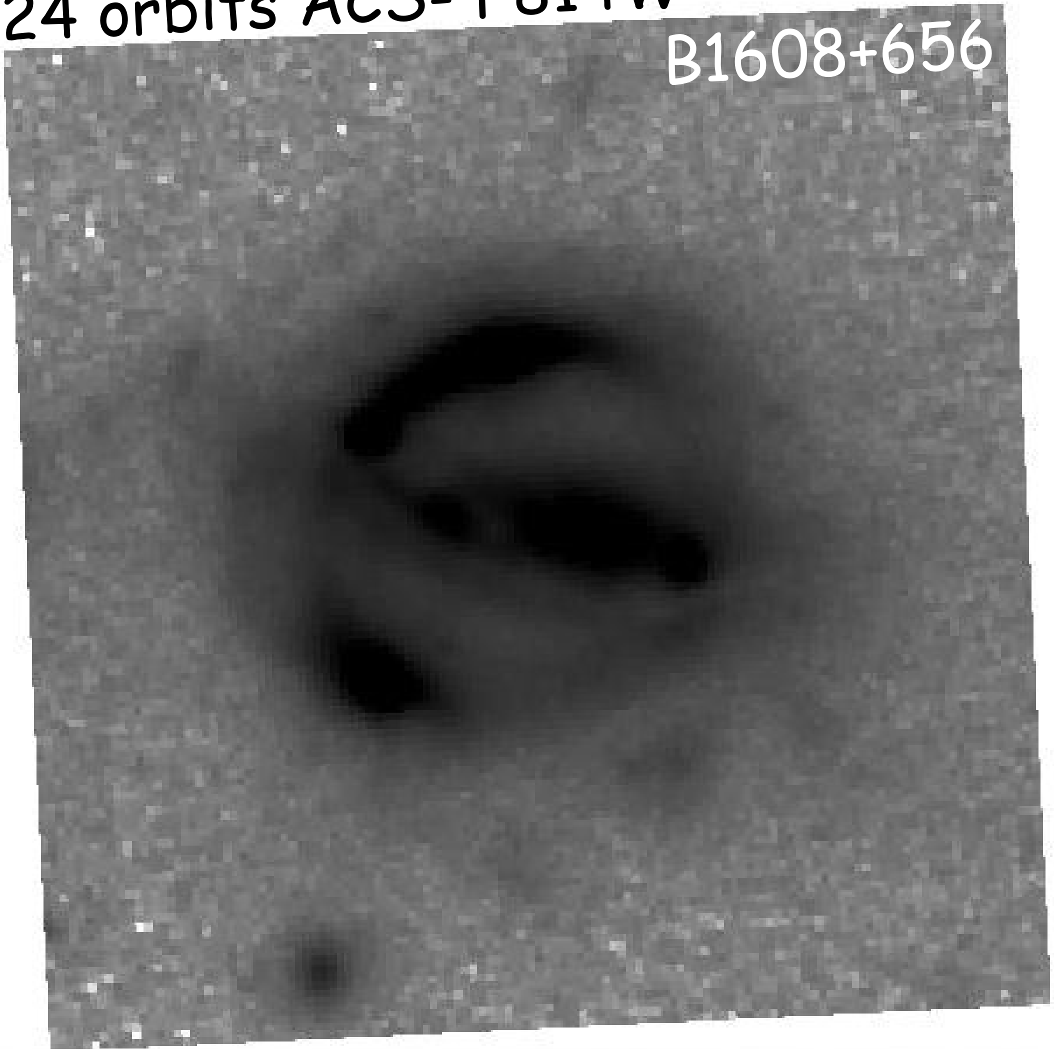
# Ground-based AO can get close to HST in the NIR, but suitable targets limited



Marshall et al. 2007

# Deep integration in ACS-F814W

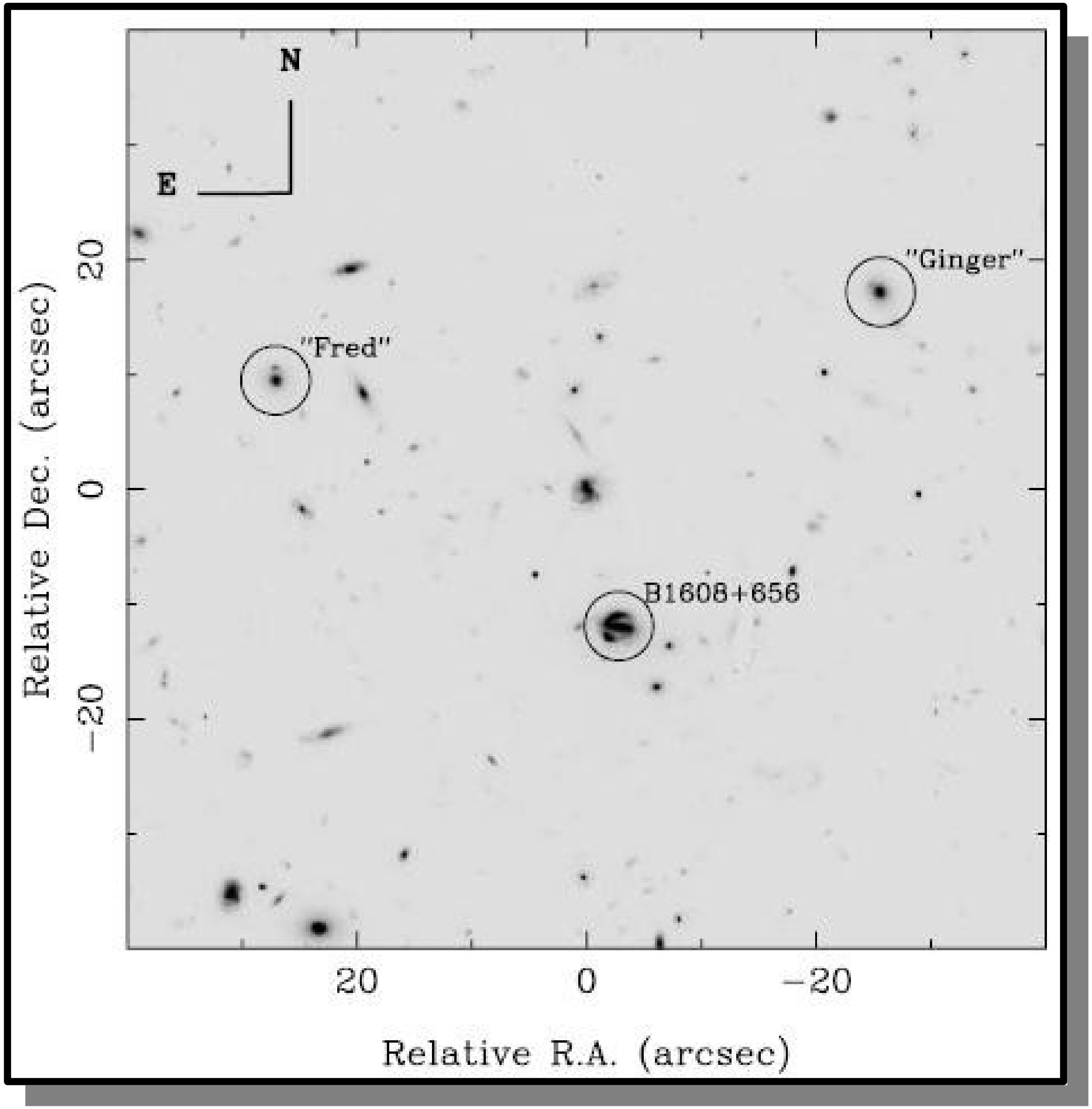
24 orbits ACS- F814W



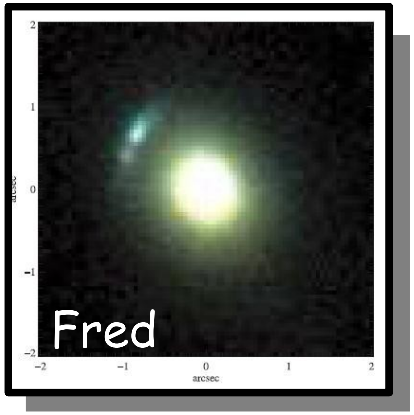
Suyu et al. 2008, in prep.

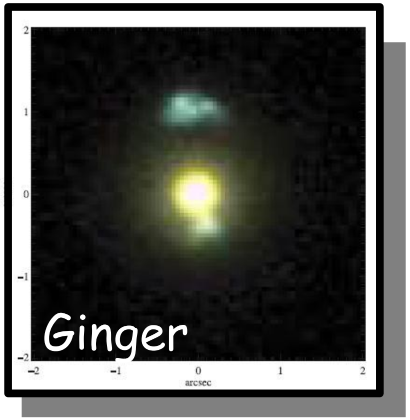
- Depth allows mapping of the full Einstein ring
- Dust correction trough multi-color imaging can be done.
- Grid-based modeling is underway to map lens potential
- Time-delay (few % accuracy) gives $H_0$ (upto mass-sheet)
- Stellar vel. disperion of G1 and spectroscopy of field yield mass-sheet limits

# Deep integration in ACS-F814W



Fassnacht et al. (2006)



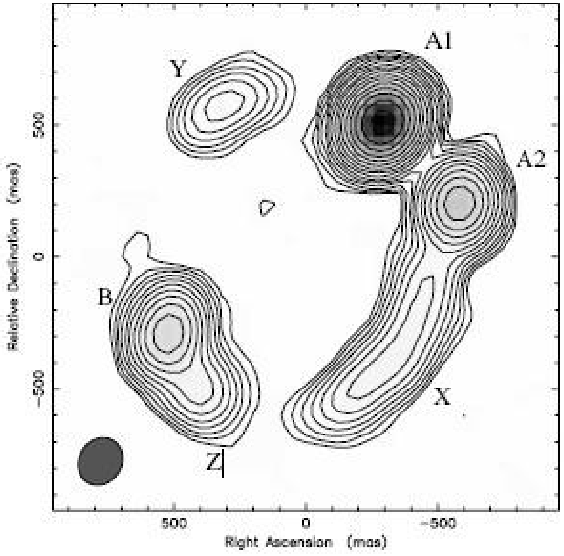


Additional bonus:

- Three grav. lenses in one ACS field within ACS field-of-view.
- Statistically expected: ~2 extra lenses.

# High-resolution multi-waveband data

1.7GHz MERLIN

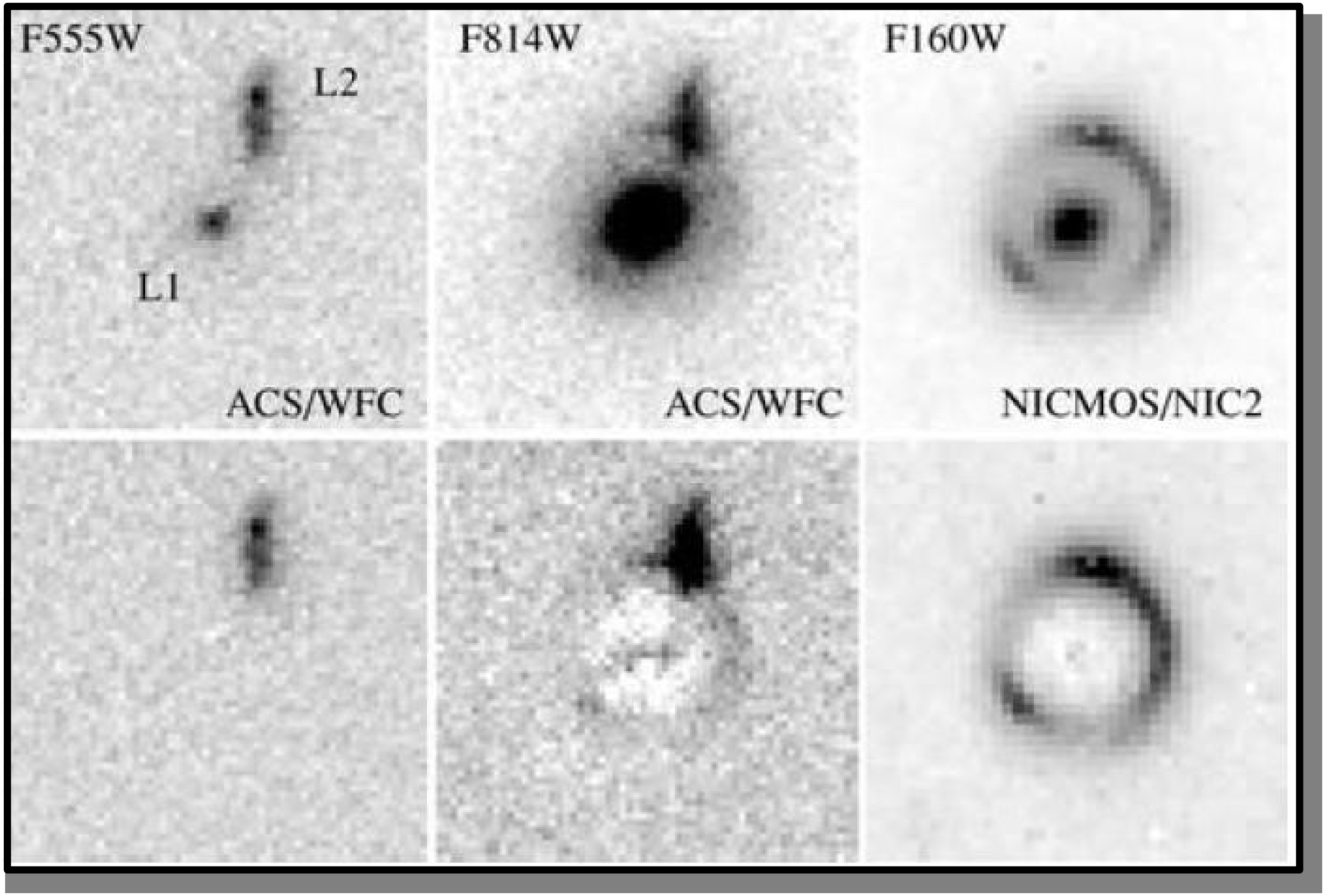


York et al. (2005)

Src Invisible

HST-ACS

Src Visible



# So now that we have seen the power of HST, what can we learn from Strong Lensing by Galaxies?

Collaborators:

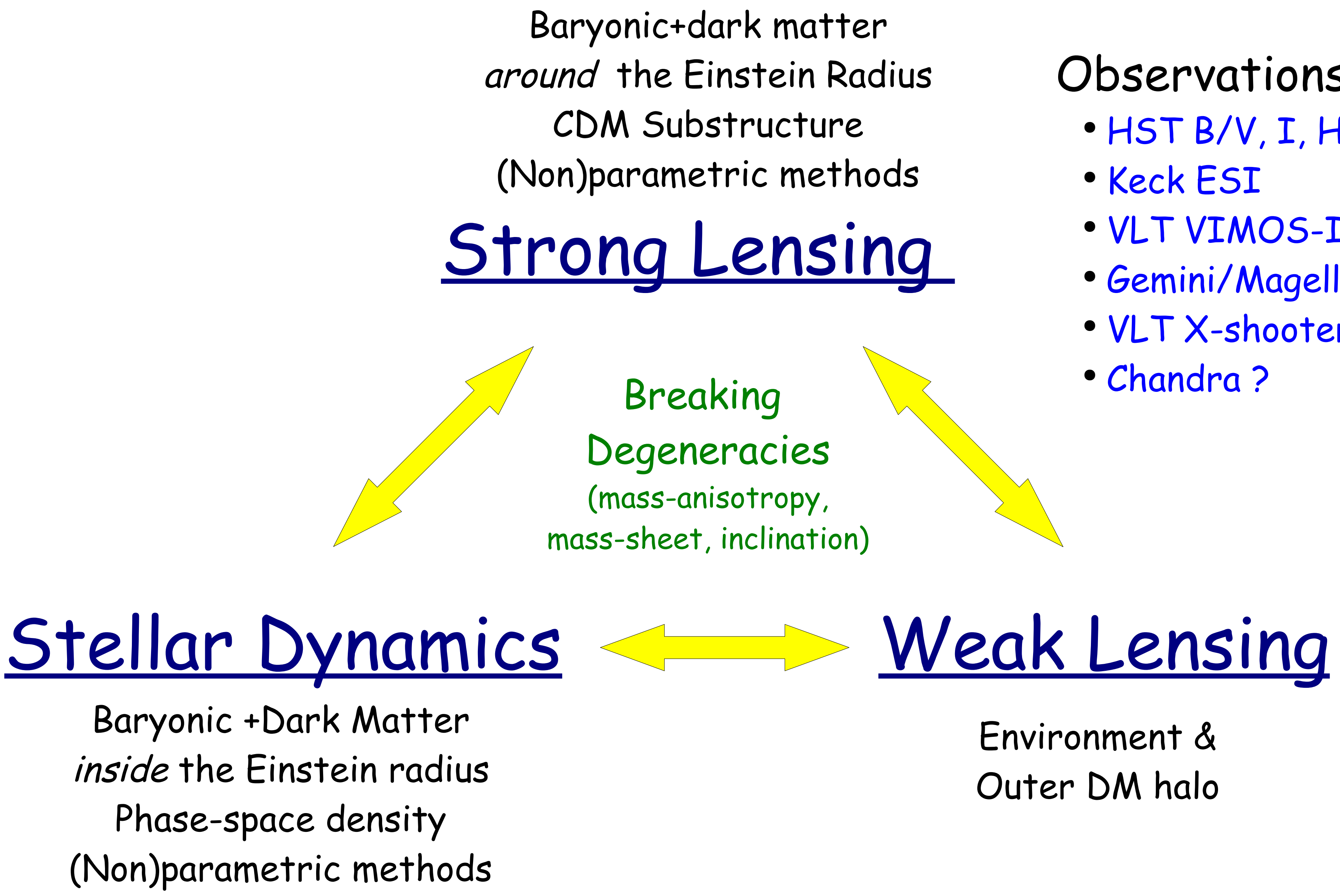
| | |
|---|---|
| Tommaso Treu | (UCSB) |
| Adam Bolton | (IfA) |
| Scott Burles | (MIT) |
| Lexi Moustakas | (JPL) |
| Matteo Barnabè | (Kapteyn) |
| Simona Vegetti | (Kapteyn) |
| Oliver Czoske | (Kapteyn) |
| Raphael Gavazzi | (Paris) |

# What can the Hubble Space Telescope and Strong Lensing do for You?

- Galaxy Mass Structure & Evolution
- Fundamental Plane/Scaling Relations

- Super-resolved sources structure
- Lens-Galaxy/Src Stellar Populations
- Dust properties through src absorption
- Hubble + Cosmological Parameters (see Courbin's talk)
- Structure of AGN through μ-lensing
- ...

# A Coherent Methodology



Baryonic+dark matter
*around* the Einstein Radius
CDM Substructure
(Non)parametric methods

## Strong Lensing

Observations

- HST B/V, I, H
- Keck ESI
- VLT VIMOS-IFU
- Gemini/Magellan
- VLT X-shooter ?
- Chandra ?

Breaking Degeneracies
(mass-anisotropy,
mass-sheet, inclination)

## Stellar Dynamics

Baryonic +Dark Matter
*inside* the Einstein radius
Phase-space density
(Non)parametric methods

## Weak Lensing

Environment &
Outer DM halo

# Integrated Approach to Gravitational Lensing

## "The Sloan-Lens ACS Survey"

### HST Program

- Lensed Images
- Galaxy Surface Brightness
- Optical/IR Colors
- Weak Lensing

### VLT-IFU Program + Keck Spectroscopy

- 2D Stellar Kinematics
- Stellar population
- Source kinematics?

### Models + Theory

- Grid-based Lens Modeling
- Combined Lensing & Stellar Dyn.

Bolton et al. 2005, 2006, 2007; Treu et al. 2006; Koopmans et al. 2006; Gavazzi et al. 2007, 2008; Bolton et al. 2008a&b; Barnabè & Koopmans 2007; Czoske et al. 2008; more to come soon...

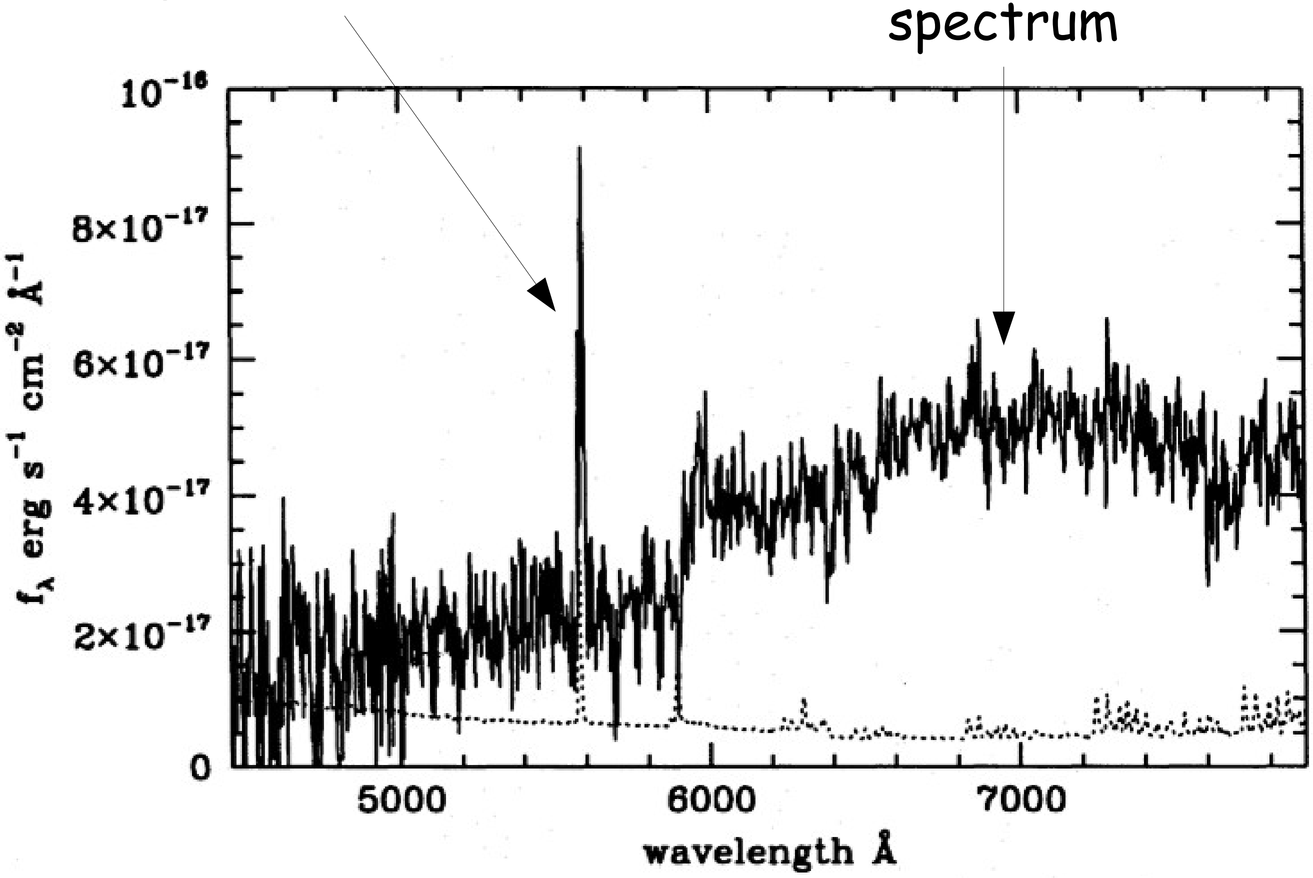
# The Sloan Lens ACS (SLACS) Survey

- Initial selection from SDSS spectra
  - ✓ Absorption dominated stellar continuum of early-type galaxy
  - ✓ Nebular emission lines (Balmer series, [OII] 3727, or [OIII] 5007) at another higher redshift
  - ➔ Candidate src/lens redshifts + lens stellar vel. disp.
- HST ACS/WFPC2/NICMOS follow-up
  - ✓ High (SIS) lens cross-section
  - ✓ High SNR emission lines
  - ✓ Reasonable range of redshift and stellar vel. dispersion
  - ➔ Lens & Src brightness distribution + colors
- Spectroscopic follow-up: Long-slit & IFU
  - ➔ Extended stellar kinematics
  - ➔ Src emission line structure
  - ➔ Stellar populations

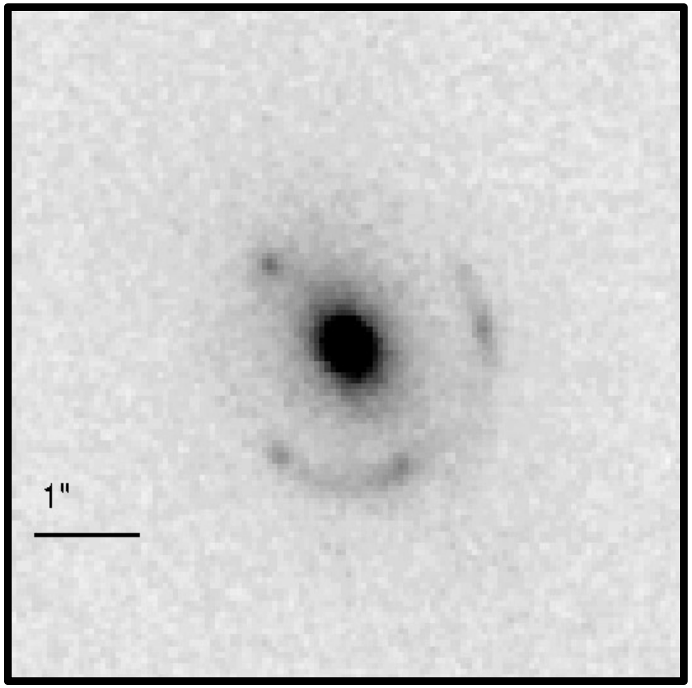
# Selection from SDSS Spectra

Higher-z emission line

Early-type galaxy spectrum



HST F814W



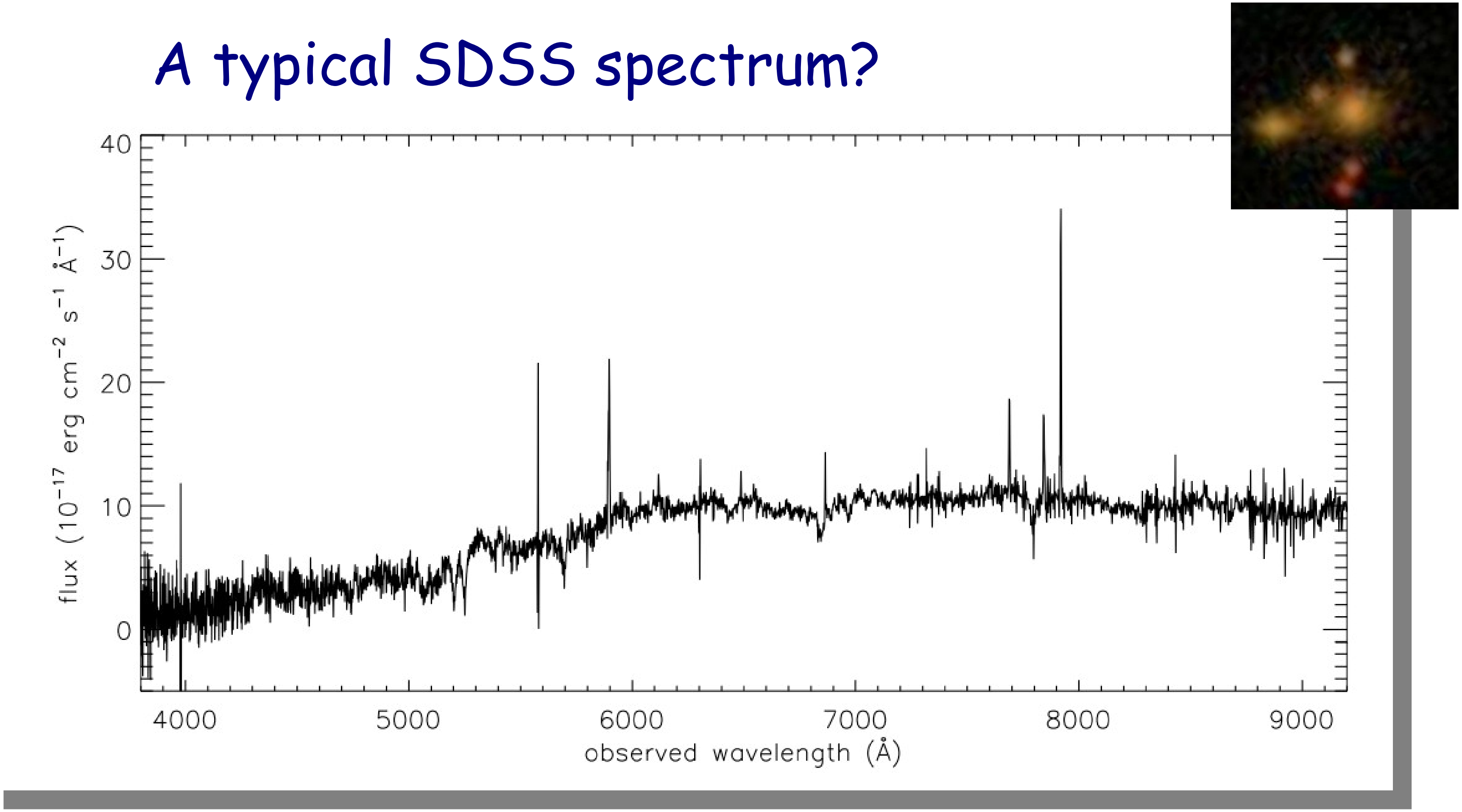
Q0047-2808

(Warren et al. 1996, 1998, 1999)

Courtesy: Adam Bollton

# Selection from SDSS Spectra

## A typical SDSS spectrum?



Courtesy: Adam Bollton

# Selection from SDSS Spectra

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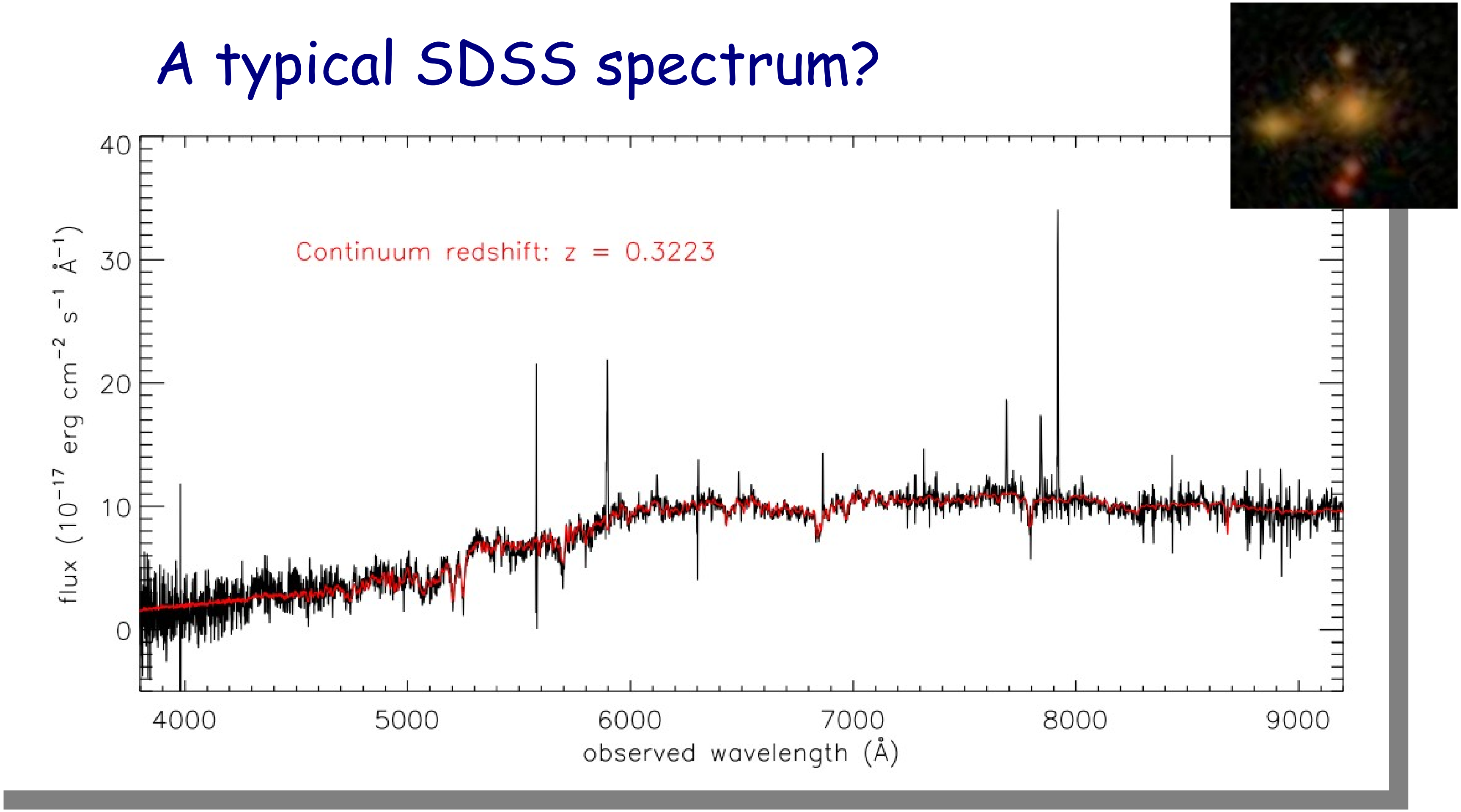

Courtesy: Adam Bollton

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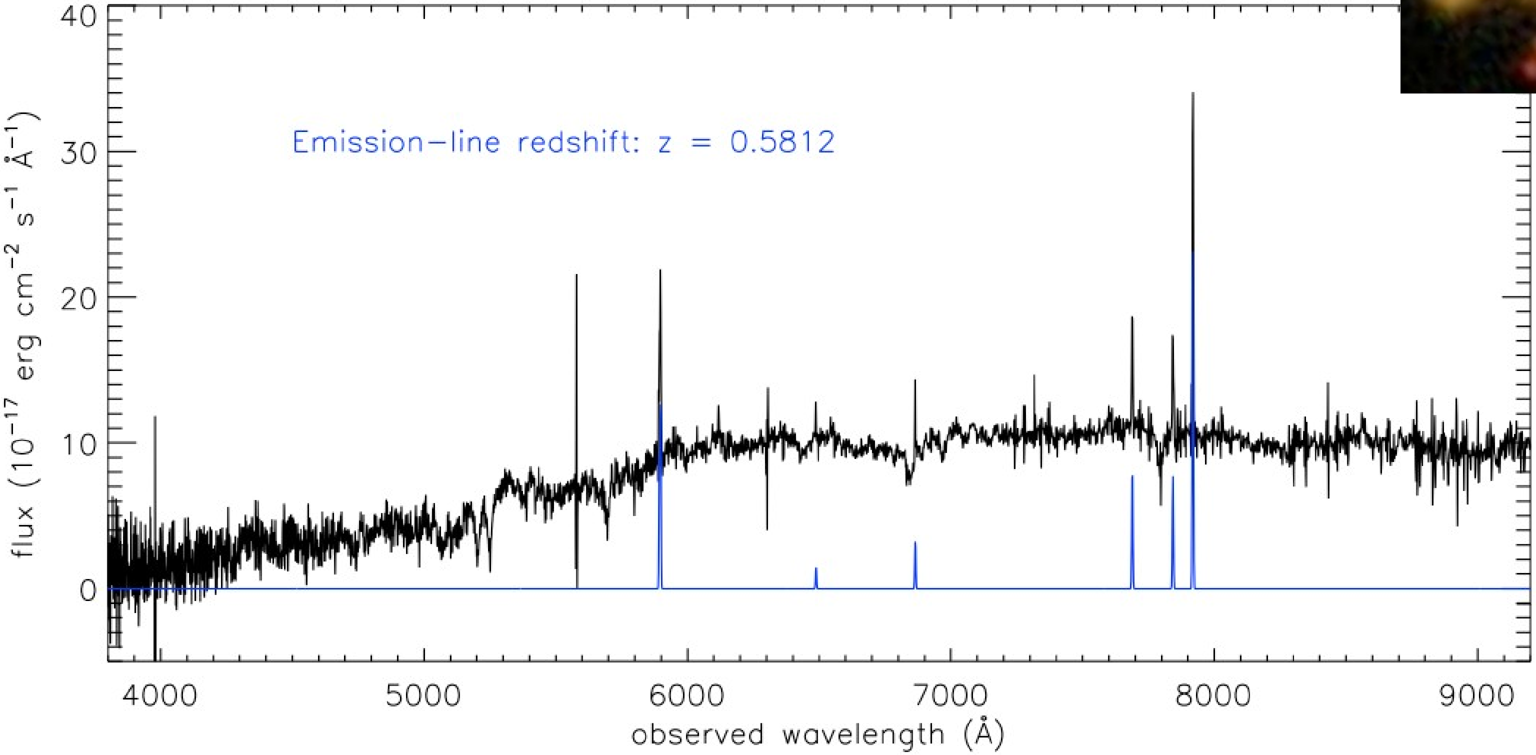

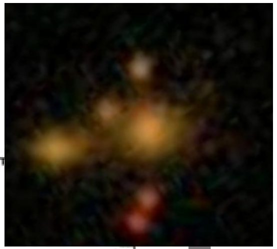

Courtesy: Adam Bollton

# Advantages of SLACS lens selection

1- They have observationally accessible lens galaxies:

- o known foreground AND background redshifts
- o known stellar velocity dispersions
- o known lens colors and magnitudes

(This is *not* true of most lenses, at least not without a lot of extra work)

2- They are selected homogeneously from within a well-characterized survey (the SDSS)

(This is also *not* true of most lenses)

3- They are strong *galaxy-galaxy* lenses (if lensed), affording more constraints on the lens mass than with quasar lenses.

4 - They would constitute a qualitatively new astrophysical sample.

5 – There are LOTS of them (100-200 in SDSS with good SNR)

# Advantages of SLACS lens selection

BUT ARE THEY LENSES?

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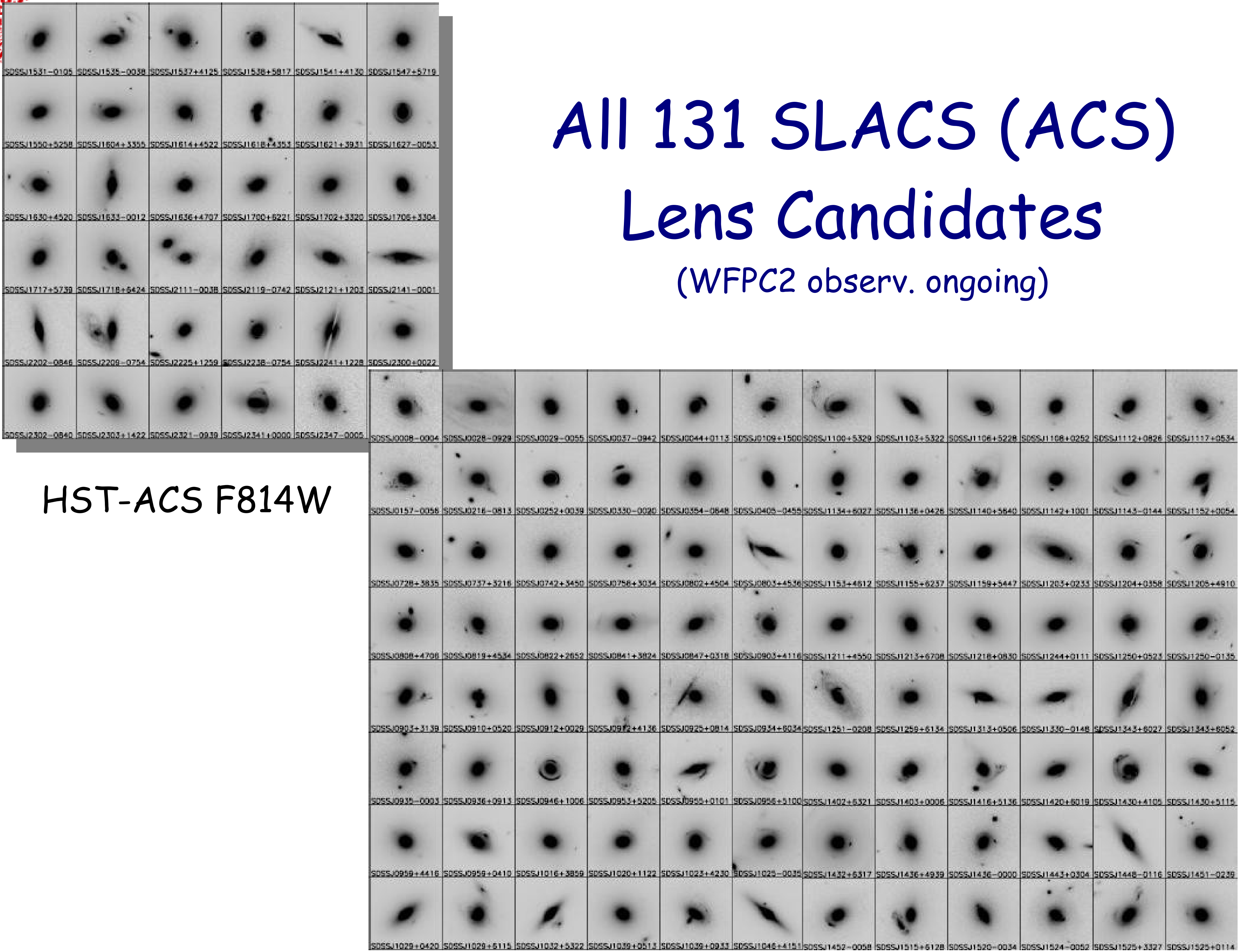
# HST ACS/WFPC2/NICMOS follow-up

- Cycle – 13:
  - SNAP-10174 (PI: Koopmans) : Snapshot imaging F435W/F814W – **39/49 Orbits**, ACS
- Cycle – 14:
  - GO-10494 (PI: Koopmans): Single-orbit multi color follow-up – **45 orbits**, ACS+NIC
  - SNAP-10587 (PI: Bolton): Snapshot imaging F814W – **55/118 Orbits**, ACS
- Cycle – 15:
  - GO-10798 (PI: Koopmans): Single-orbit multi color follow-up – **60 orbits**, ACS/WFPC2+NIC
  - GO-10886 (PI: Bolton): Single-orbit multi color follow-up – **60 orbits**, ACS/WFPC2
- Cycle – 16:
  - GO-11202 (PI: Koopmans): Single-orbit multi color follow-up – **159 orbits**, WFPC2+NIC

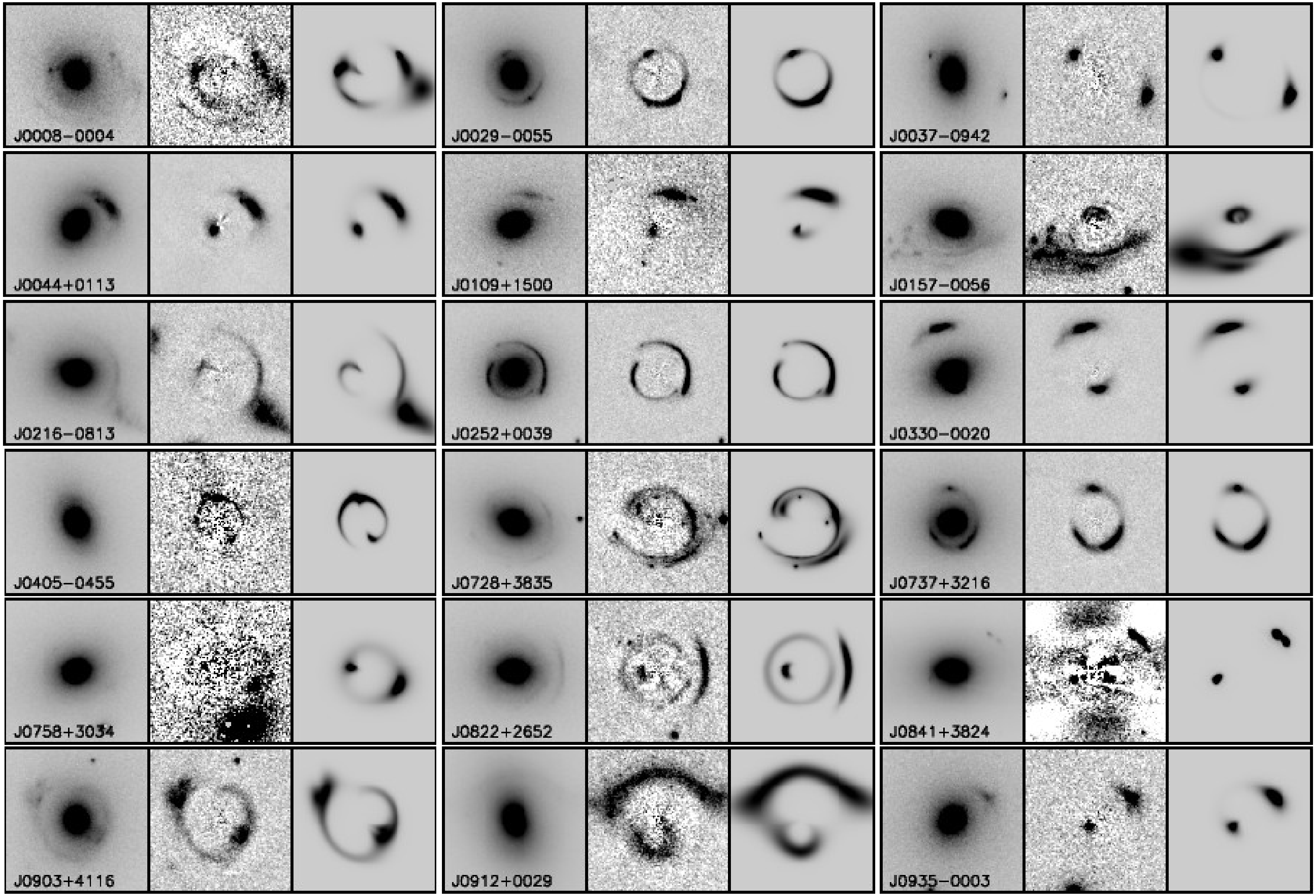
# All 131 SLACS (ACS) Lens Candidates

(WFPC2 observ. ongoing)

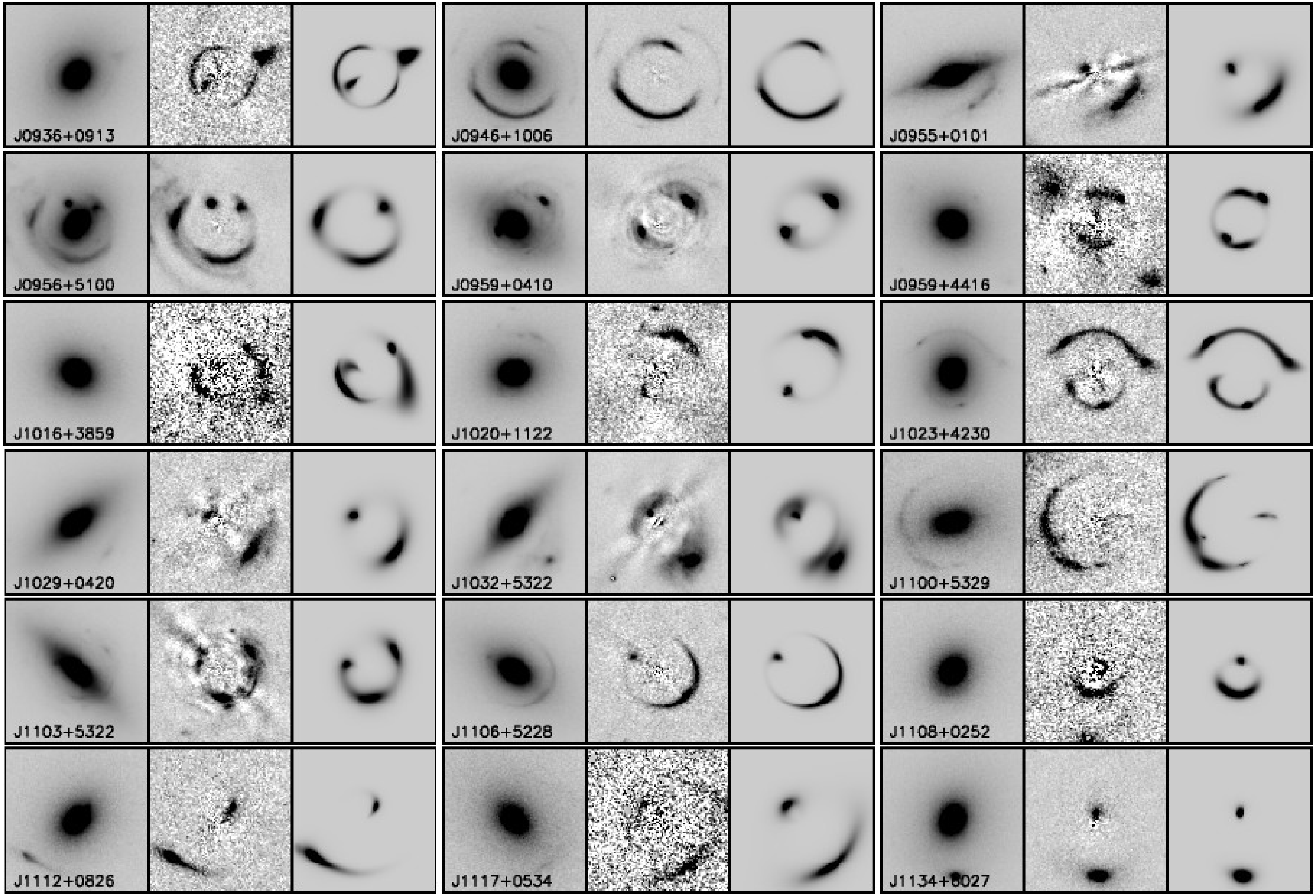


HST-ACS F814W

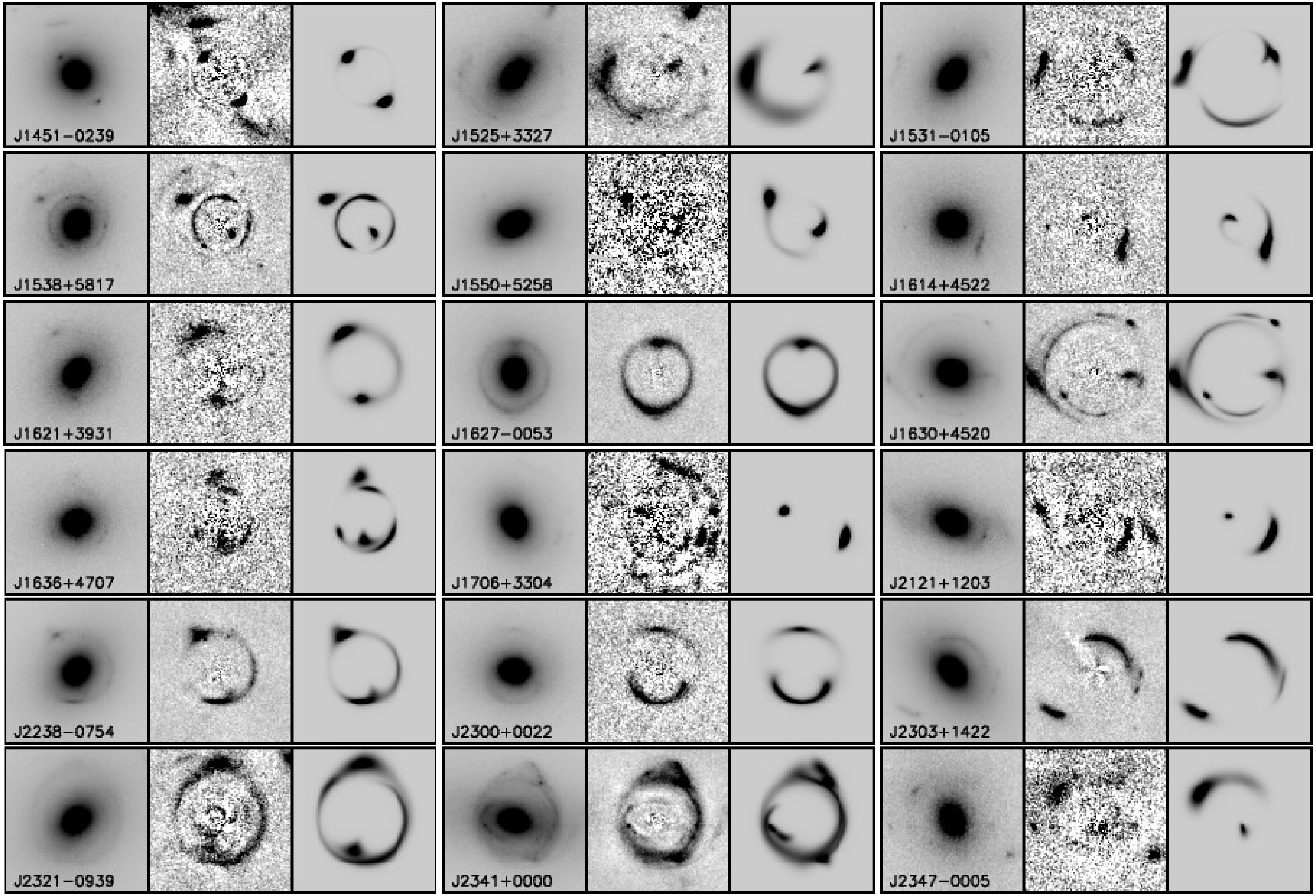
# Confirmed (ACS) Lenses with simple model -1-



# Confirmed (ACS) Lenses with simple model -2-



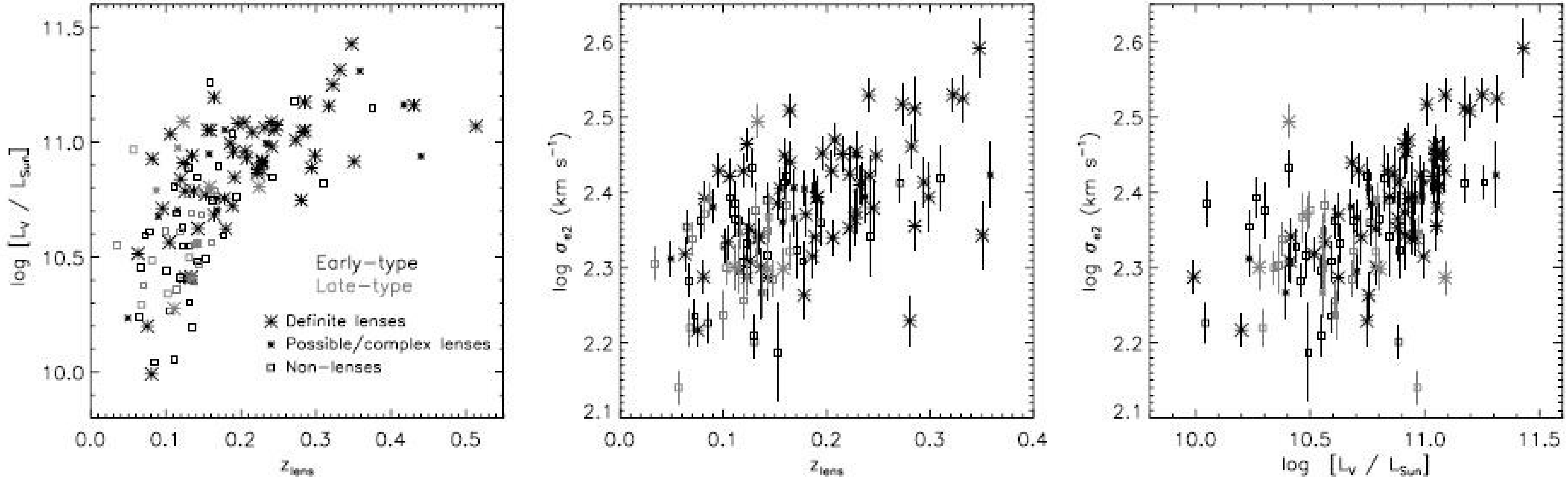
# Confirmed (ACS) Lenses with simple model -3-



# Overview of the SLACS Sample

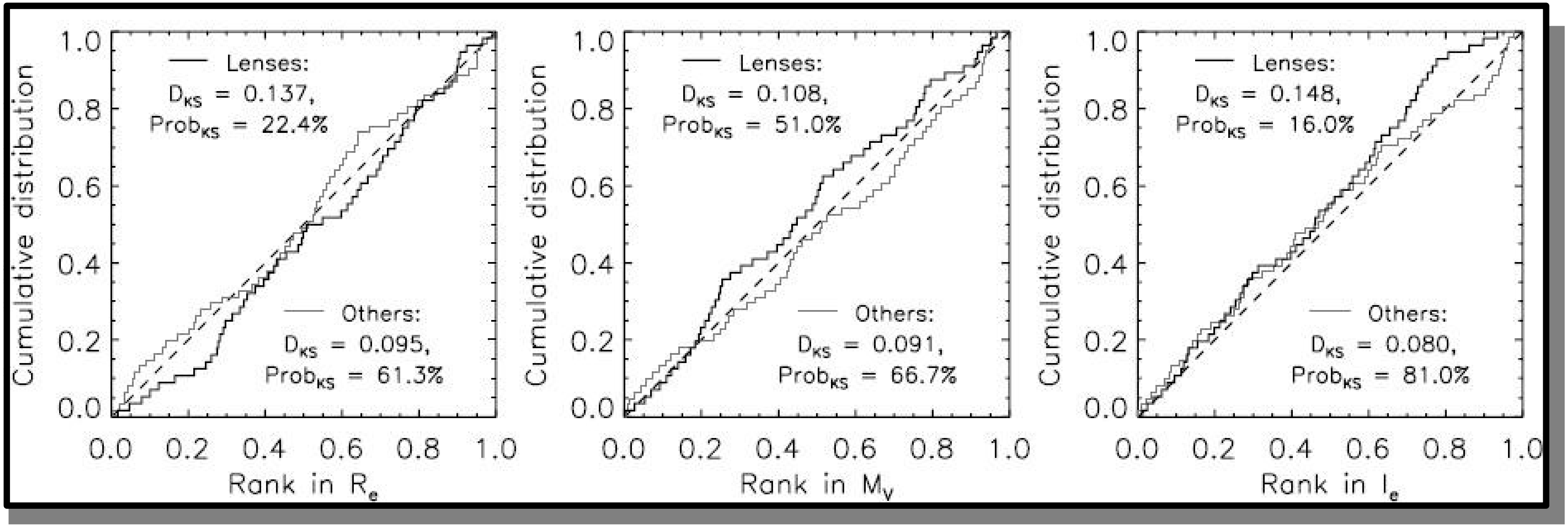
**General Lens Properties:**

| | |
|---|---|
| Redshifts: | 0.05 – 0.50 |
| Vel. Dispersions: | 160 - 400 km/s |
| Log($L_v$/$L_{sun}$): | 10.0 - 11.5 |



# Is the SLACS galaxy sample biased?

A KS-test of galaxies with similar properties in the SDSS parent sample shows no significant difference between lens galaxies and non-lens galaxies



Hence, conclusions hold for both!

Bolton et al. (2007)

As a result of its selection procedure, the SLACS E/S0 galaxy sample is the largest unbiased sample (60-80) of gravitational lens systems to date

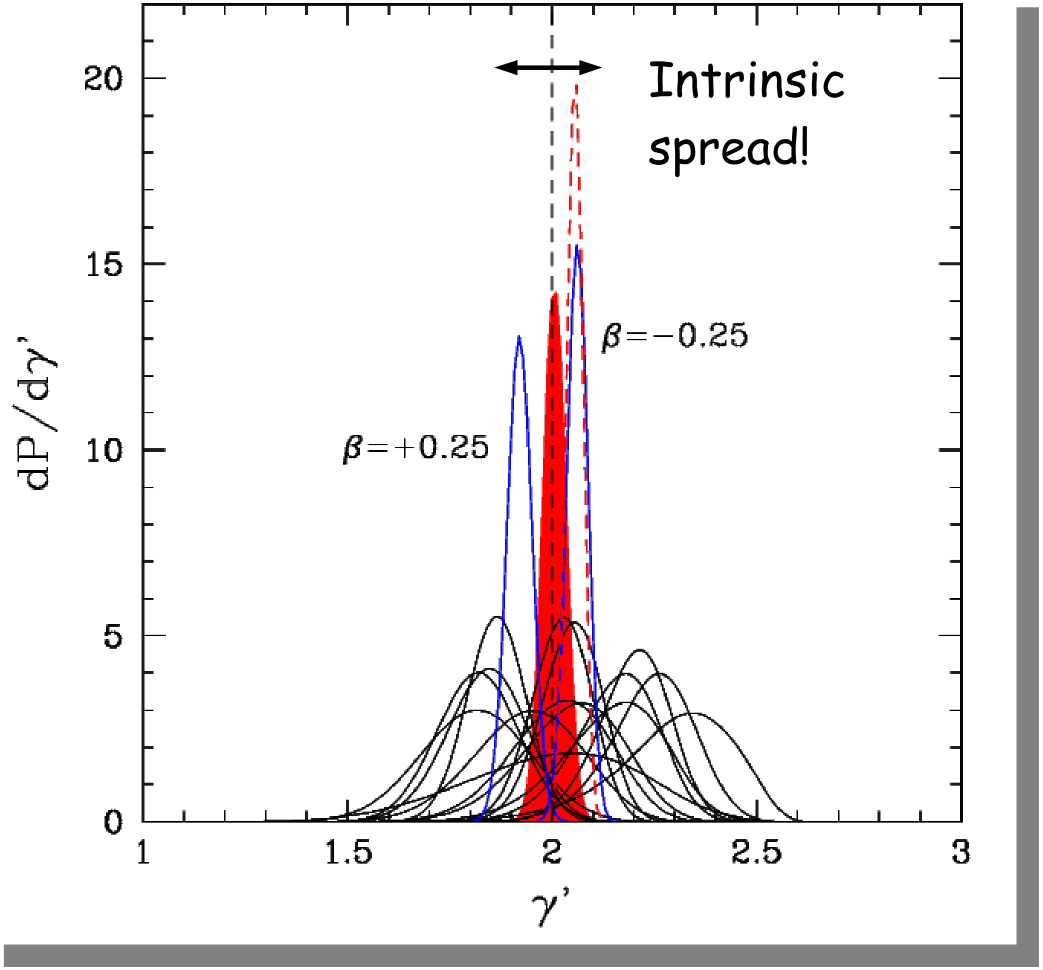
As a results, conclusions can be extended to ALL parent sample galaxies (i.e. LRG and MAIN galaxy samples of the SDSS)

# Now … Some recent results from SLACS

- Lensing & Dynamics - Density Profiles
- Scaling Relations - Fundamental Plane
- Weak Lensing - DM haloes

# The density slope of E/S0 galaxies

Combining lensing and stellar dynamics, assuming spherical power-law mass distribution, Jeans eqns and a Hernquist or Jaffe luminosity density



Total density slope inside ~4 kpc

<slope> = 2.01 ± 0.03

ML analysis:
Intrinsic spread is only 6%
(similar to Gerhard et al. 2001)

(Koopmans et al. 2006)

# Going from 1D to 3D lensing & dynamics modeling

Theoretical methodology is given in Barnabè & Koopmans (2007)
[Bayesian, axisymmetric, two-integral $f(E,L_z)$, grid-based modeling]

# VLT VIMOS-IFU Large Program

- 128 hrs (pilot + LARGE) of time was awarded on the VLT for spatially resolved spectroscopy (PI: Koopmans) for 17 SLACS targets.

- 13 targets (5 nights) were scheduled with Keck (long-slit/pseudo-IFU) (PI: Treu)

GOAL: Spatially resolved kinematics to be combined
with gravitational-lensing data.

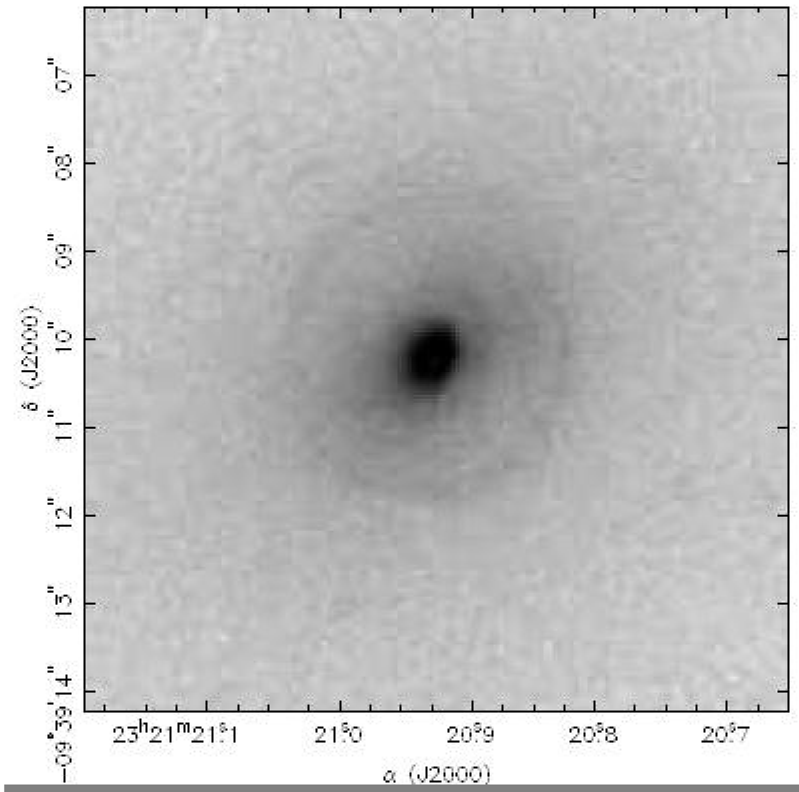
Full Bayesian ultra-fast (few seconds) non-parametric axisym. 2I dynamical code was developed to model these data iteratively, self-consistently with lensing data (grid-based).

See Barnabè & Koopmans (2007) for details
and Czoske et al. (2008) for first results.

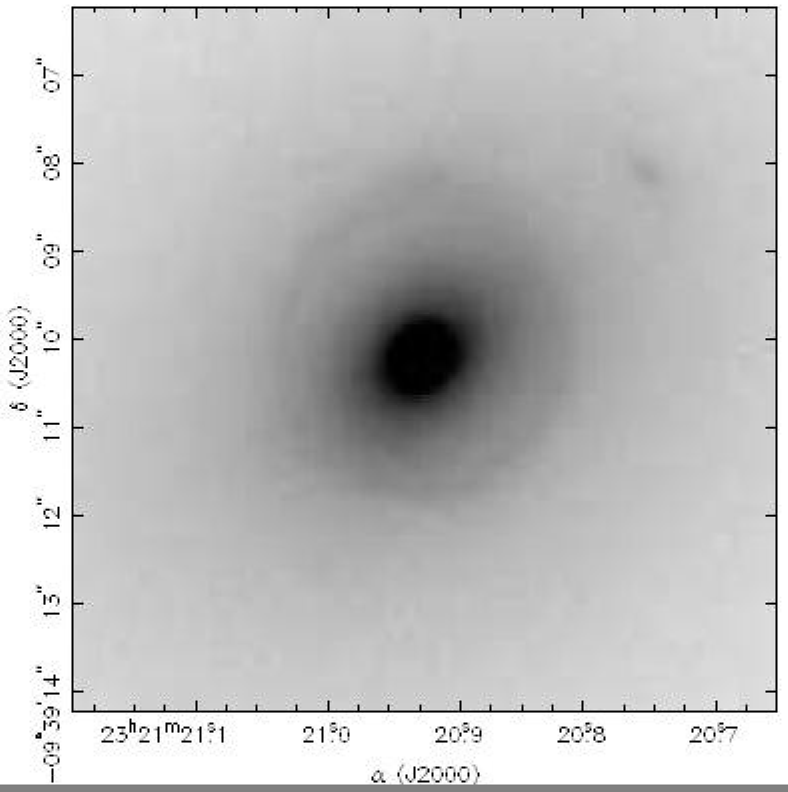
# HST & VLT-IFS of J2321-097

Combining HST imaging & VLT IFU Spectroscopy

HST F435W



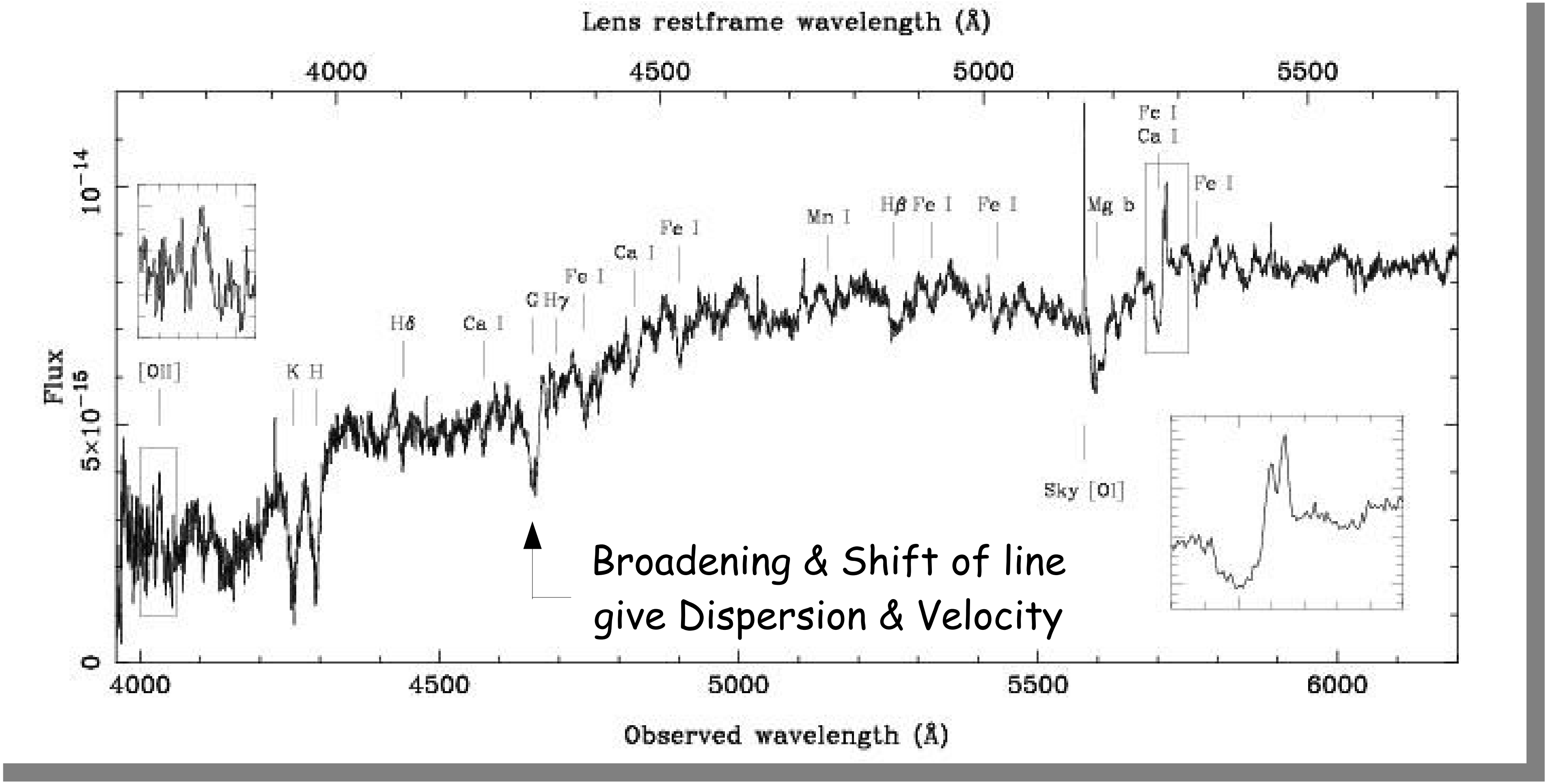
HST F814W



Czoske, Barnabè et al. 2007, in press

# HST & VLT-IFS of J2321-097

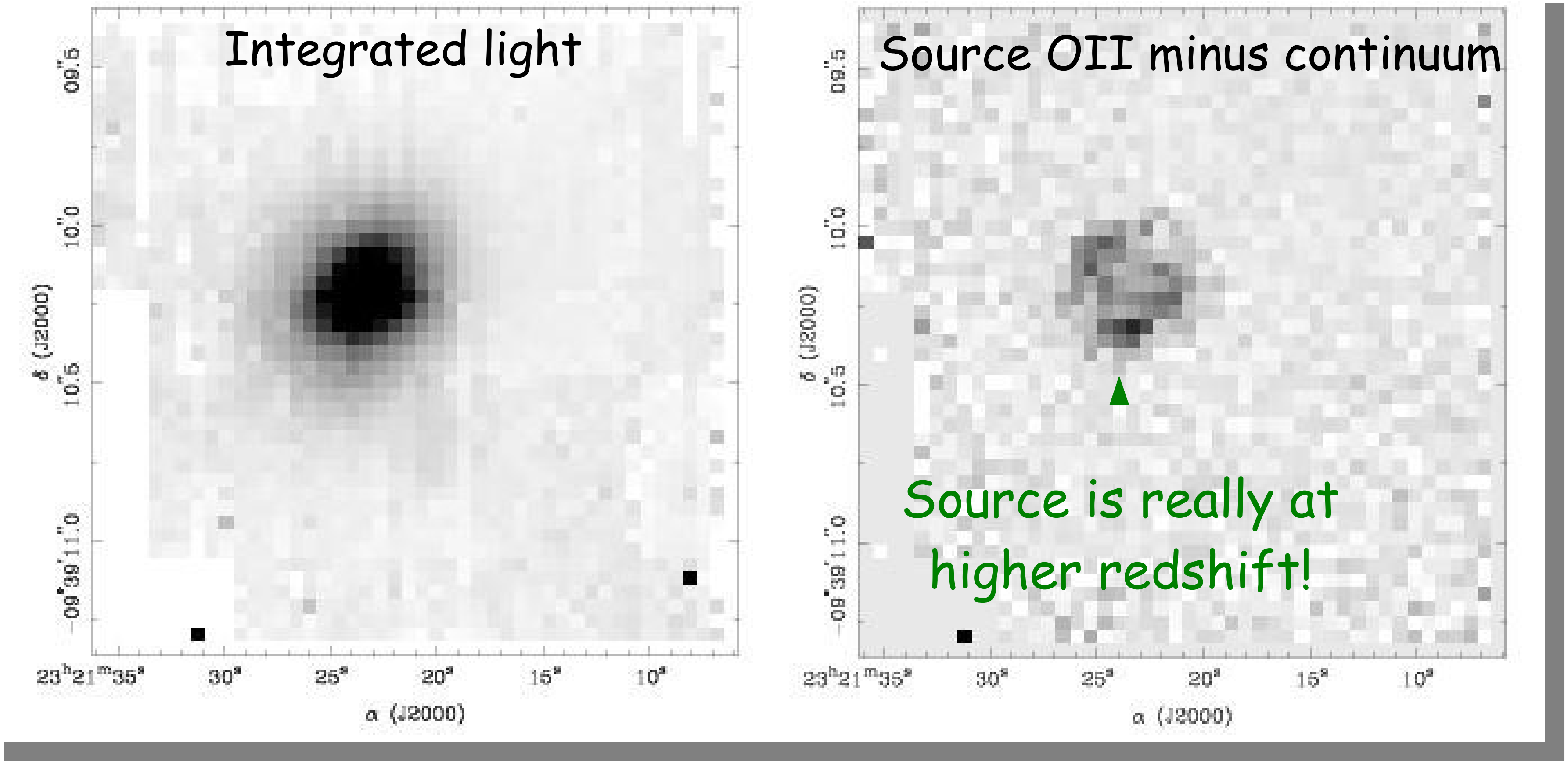
## VLT VIMOS-IFU luminosity-weighted spectrum



Broadening & Shift of line
give Dispersion & Velocity

# HST & VLT-IFS of J2321-097

## Combining HST imaging & VLT IFU Spectroscopy



Integrated light

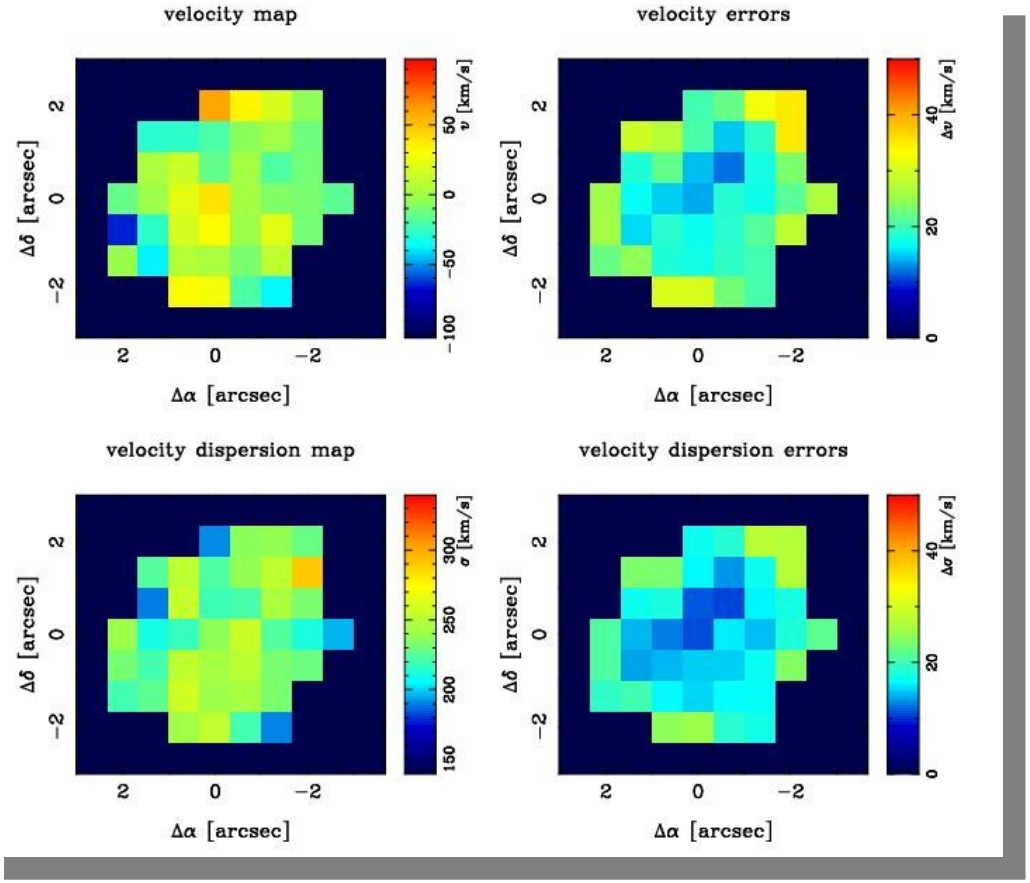
Source OII minus continuum

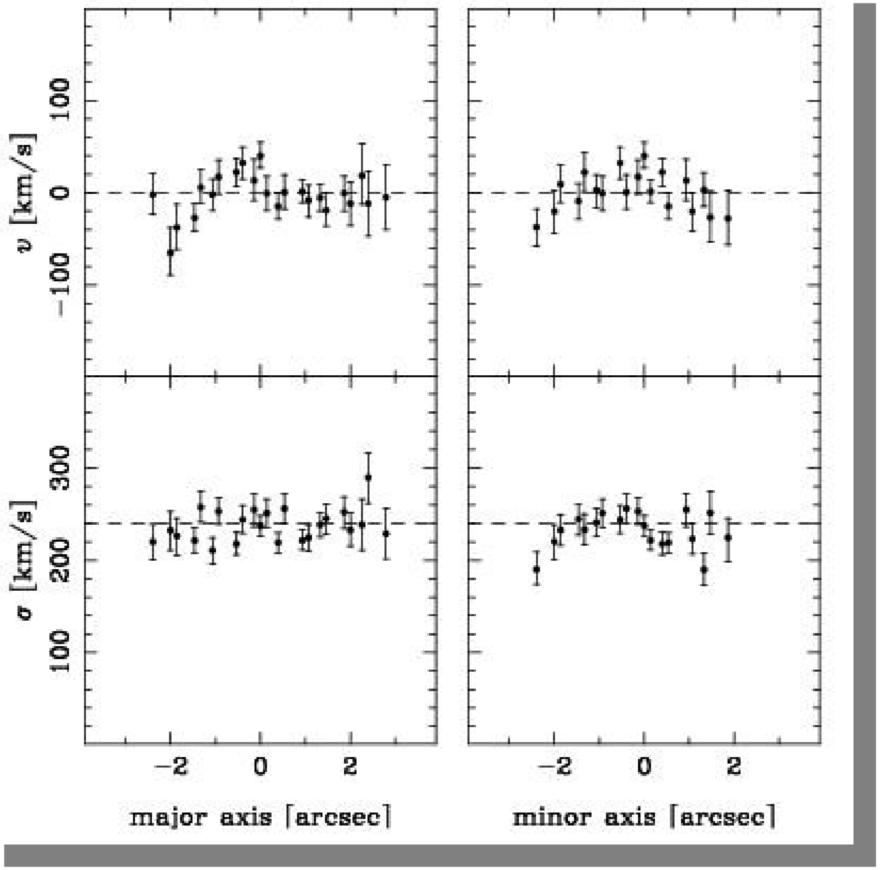
Source is really at higher redshift!

Czoske, Barnabè,  et al. 2007, in press

# HST & VLT-IFS of J2321-097

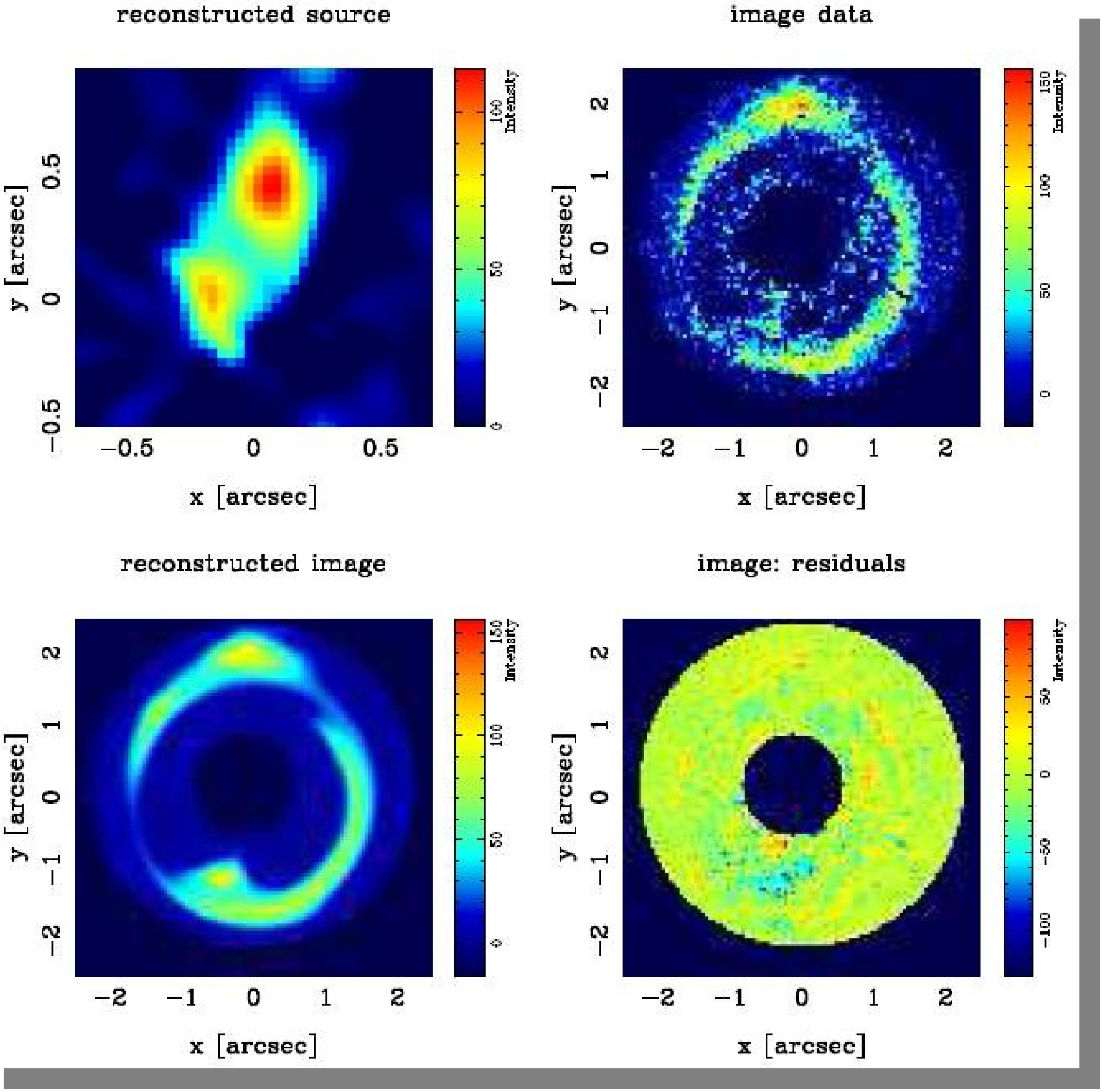
## VLT VIMOS-IFU : Kinematic Fields





Czoske, Barnabè, et al. 2007, in press

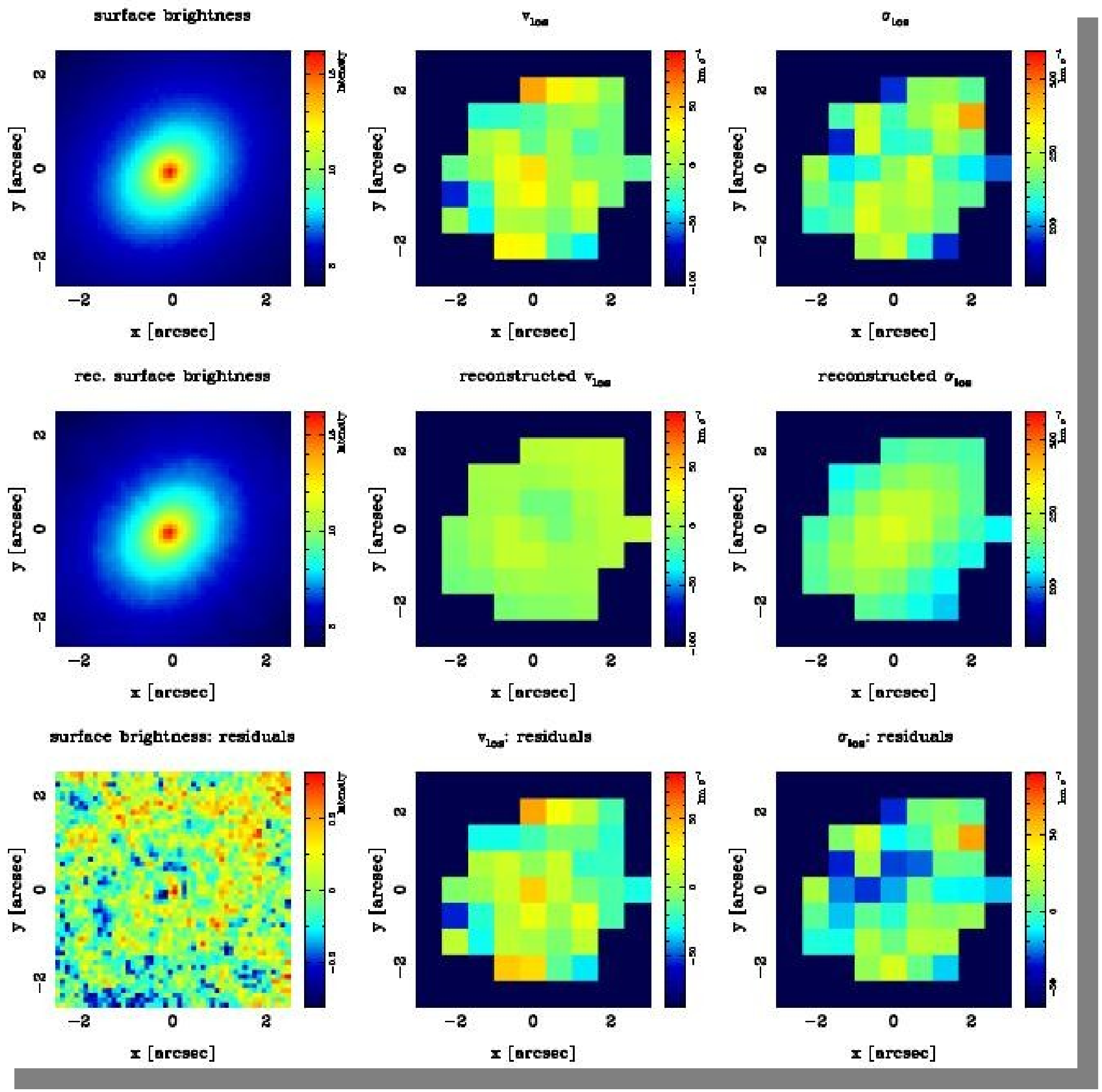
# HST & VLT-IFS of J2321-097



Grid-based reconstruction of the lensed source: Grav. lensing provides tight constraints on projected mass distribution.

Czoske et al. 2007, in press

# HST & VLT-IFS of J2321-097

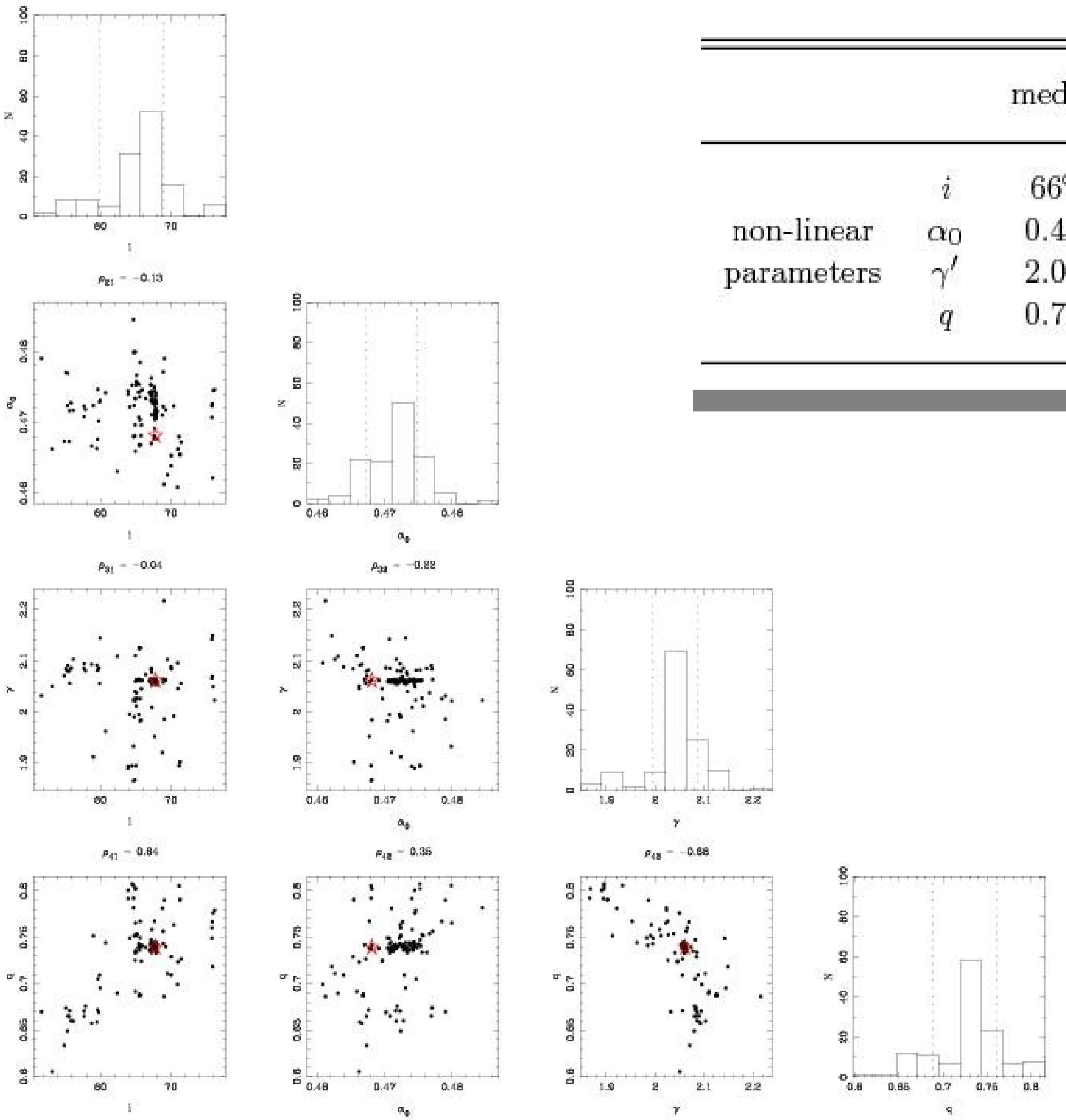


Grid-based reconstruction of the DF(E,$L_z$):

Kinematics provides extra constraints on 3D mass distribution.

Czoske et al. 2007, in press

# HST & VLT-IFS of J2321-097



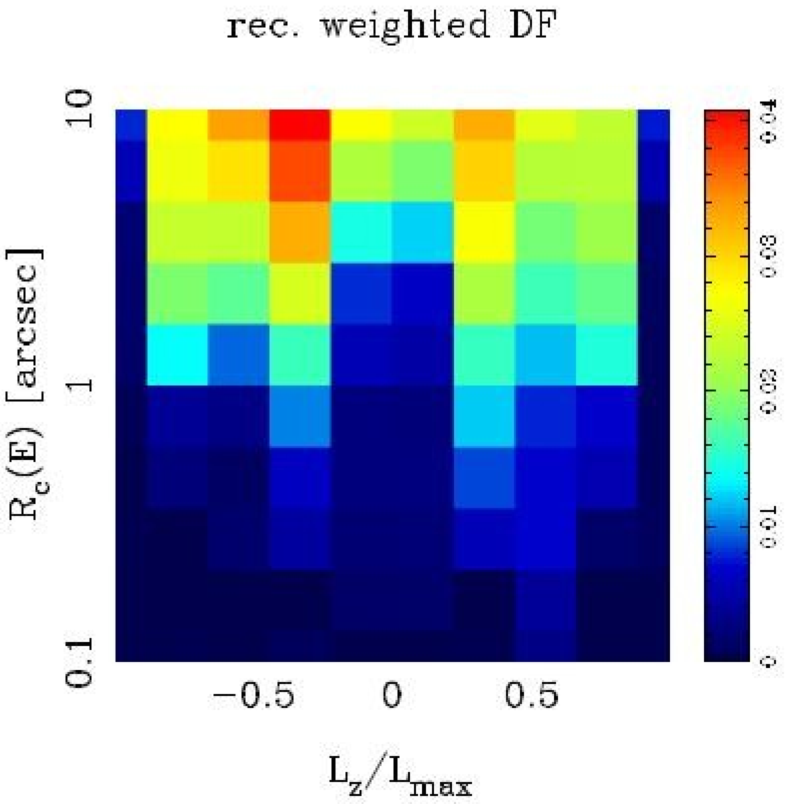
| | | median | mean | 68% C.I. | 95% C.I. | $\mathcal{M}_{\rm best}$ |
|---|---|---|---|---|---|---|
| non-linear parameters | $i$ | 66.°1 | 65.°2 | [60.°0, 68.°9] | [55.°1, 75.°8] | 67.°8 |
| | $\alpha_0$ | 0.472 | 0.472 | [0.467, 0.475] | [0.463, 0.479] | 0.468 |
| | $\gamma'$ | 2.061 | 2.046 | [1.996, 2.085] | [1.894, 2.142] | 2.061 |
| | $q$ | 0.739 | 0.730 | [0.688, 0.760] | [0.657, 0.802] | 0.739 |

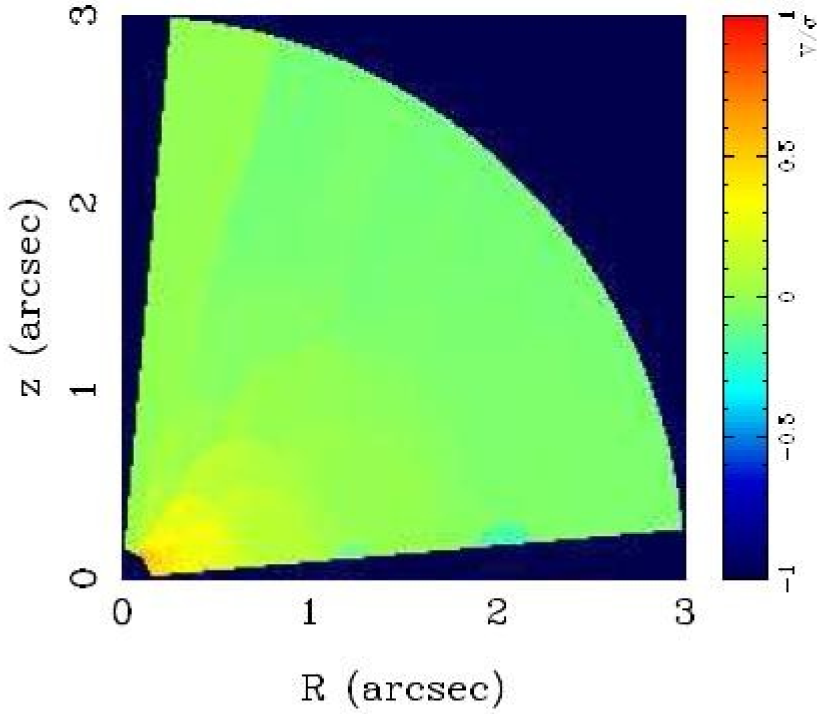
Error analysis through noise-resampling & MC

Parameters are well-constrained, also the inclination!

# HST & VLT-IFS of J2321-097

The internal kinematic structure:
The system is a slow rotator





Czoske, Barnabè, et al. 2007, in press

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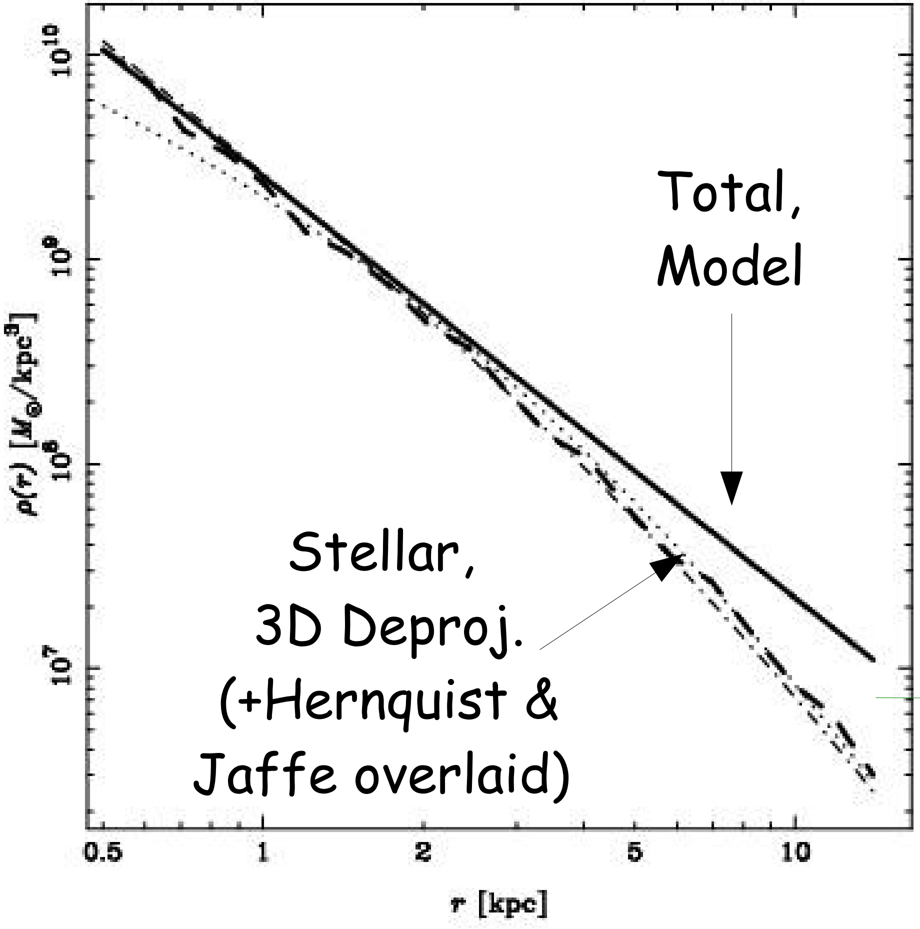


Total,
Model

Stellar,
3D Deproj.
(+Hernquist &
Jaffe overlaid)

Best fit P.L. density profile derived from lensing, dynamics and the stellar phase-space density

Dark Matter?

Not yet convincing in this system, but this system has the smallest $R_{Einst}/R_{eff}$

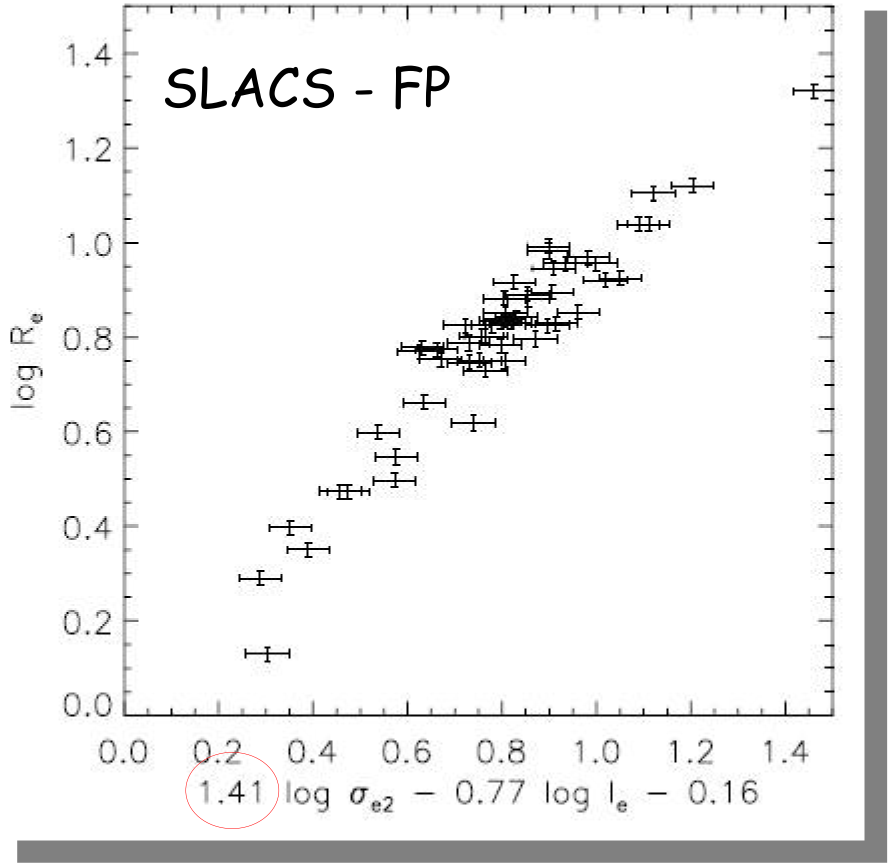
# Question:

Since we have deep high-resolution HST images and stellar kinematics of all lens galaxies, what can we learn about E/S0 scaling relations?

# The Fundamental Plane

Massive elliptical occupy a Fundamental Plane in the space of effective radius, effective surface brightness and central velocity dispersion

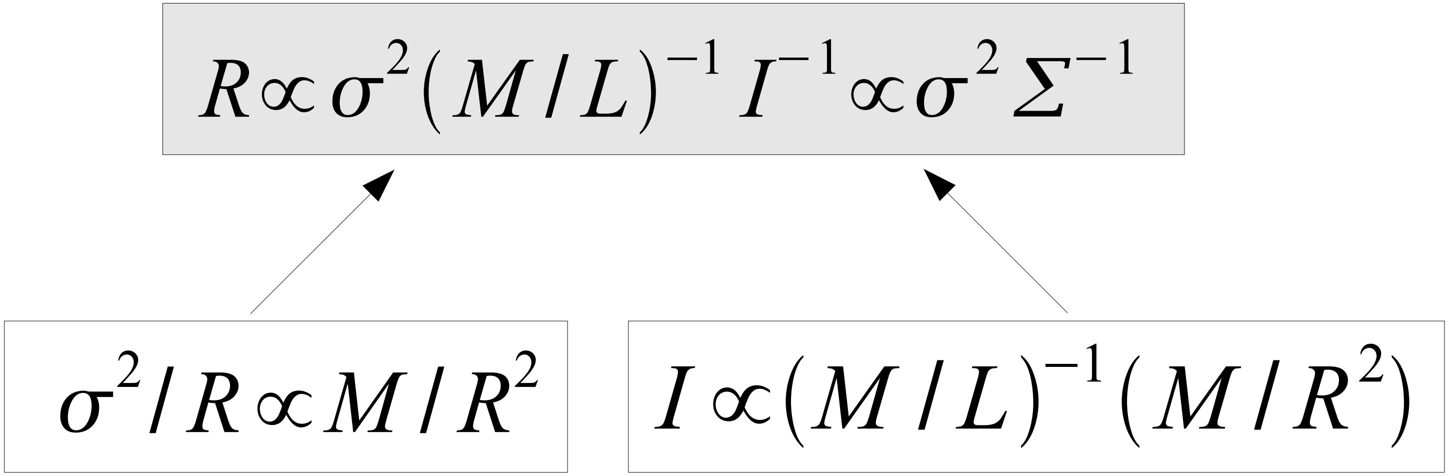
(e.g. Dressler et al. 1987; Djorgovski & Davis 1987).



Also SLACS E/S0's occupy the same FP as their parent population from the LRG and MAIN SDSS samples.

# A More Fundamental Plane?

On the other hand, the virial theorem tells us:



$$R \propto \sigma^2 (M/L)^{-1} I^{-1} \propto \sigma^2 \Sigma^{-1}$$

$$\sigma^2 / R \propto M / R^2$$

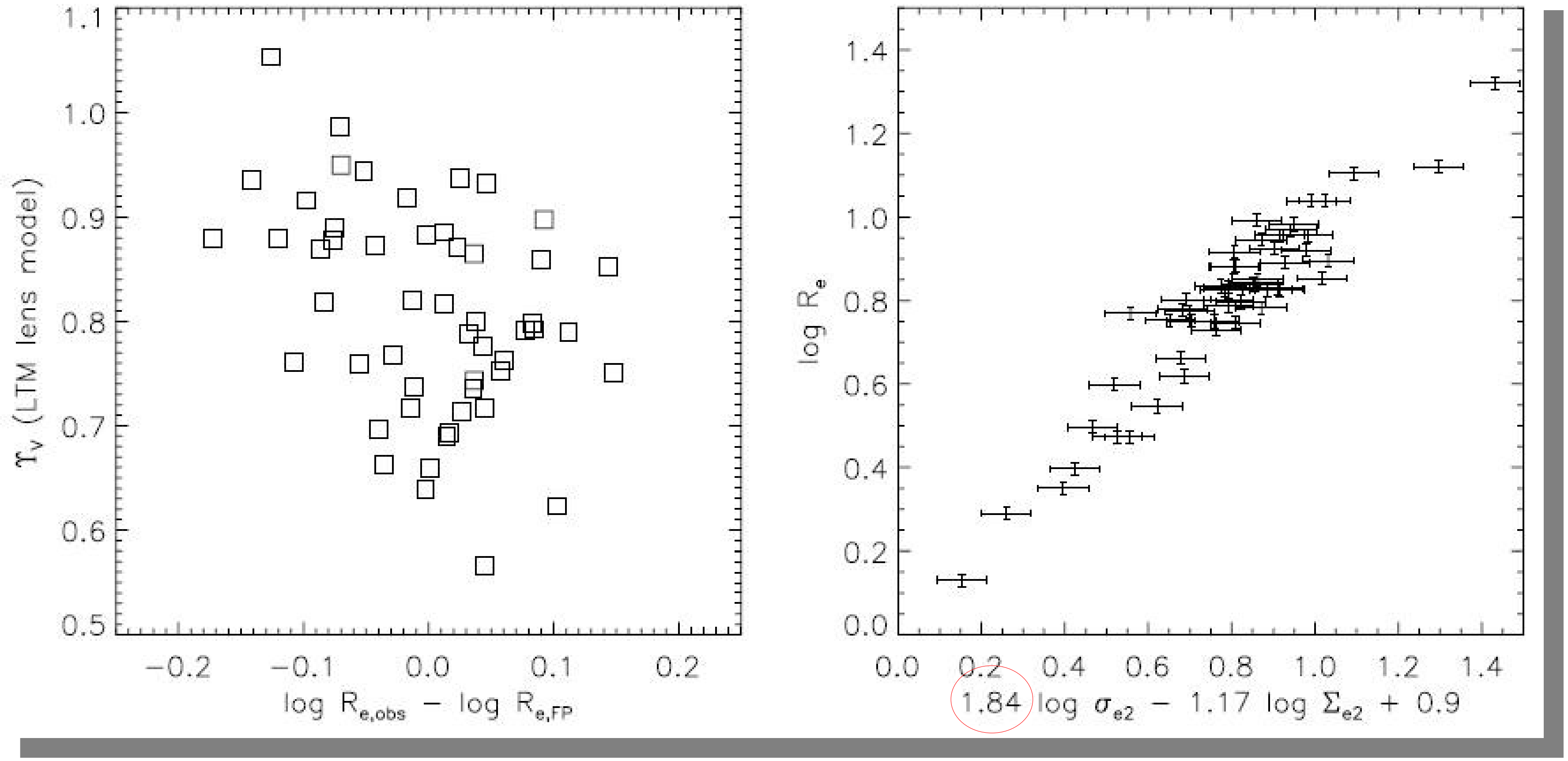
$$I \propto (M/L)^{-1} (M/R^2)$$

Why do the slopes differ from the FP?

(M/L) varies with galaxy mass, i.e velocity dispersion,
or structural non-homology?

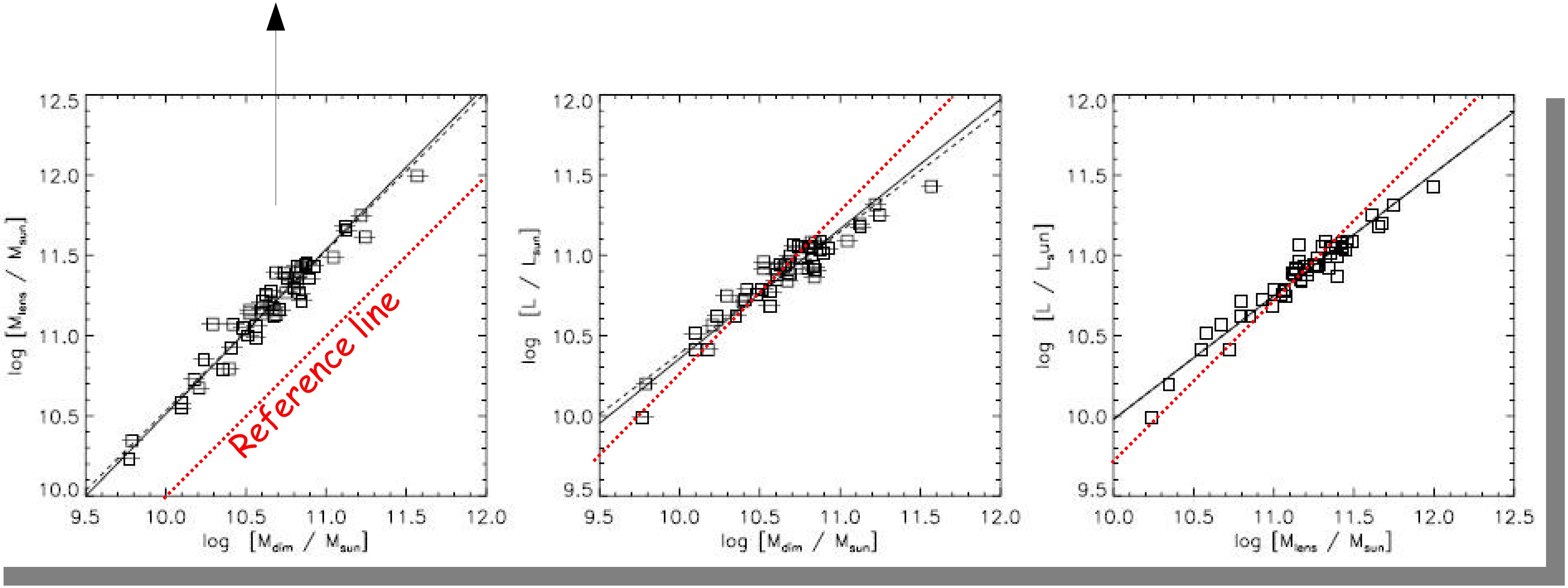
# A More Fundamental Plane?

Idea: Replace surface brightness by surface density



# Scaling Relations:
# The Fundamental Plane

$$\log_{10}[M_{\rm lens}/10^{11}M_\odot] = (1.02\pm0.03)\log_{10}[M_{\rm dim}/10^{11}M_\odot] + (0.54\pm0.02)$$



Lens and dynamical masses ($\propto\sigma^2 R_{\rm eff}$) scale linearly

Masses do NOT scale linearly with V luminosity

# Scaling Relations:
# The Fundamental Plane

Hence, (M/L) scales with mass or stellar velocity dispersion:

-1- More massive galaxies have a larger M/L inside their effective radius.

-2- No strong correlation of M/L with $D_n(4000)$ exists, so most likely the DM fraction inside increases with galaxy mass.
(a more detailed stellar pop. analysis must be done using spectra/colors)

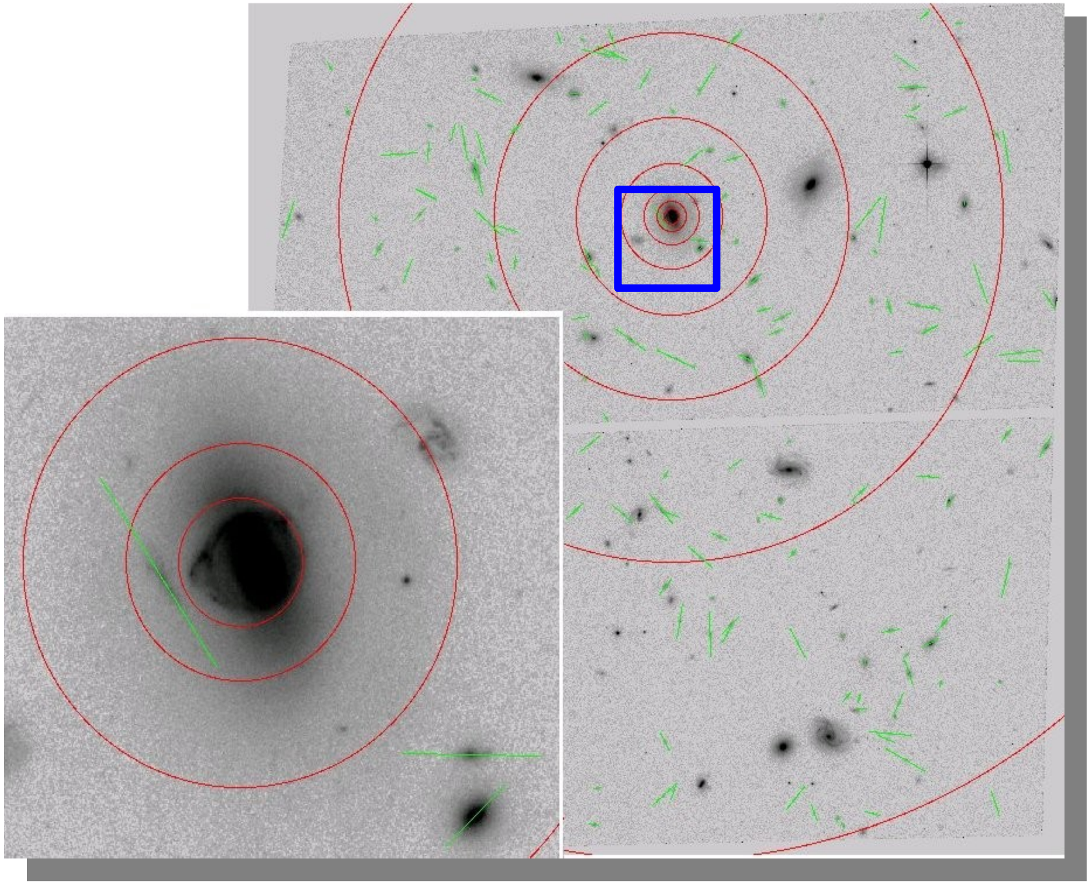
This quantatatively confirms w/o any doubt that
the tilt in the Fundamental Plane is dominated by an increase
in M/L with galaxy mass and not structural non-homology
(Bolton et al. 2008; see also Capellari et al. 2006)

# Finally, what happens far beyond the effective radius?

# Weak Lensing of Strong Lenses

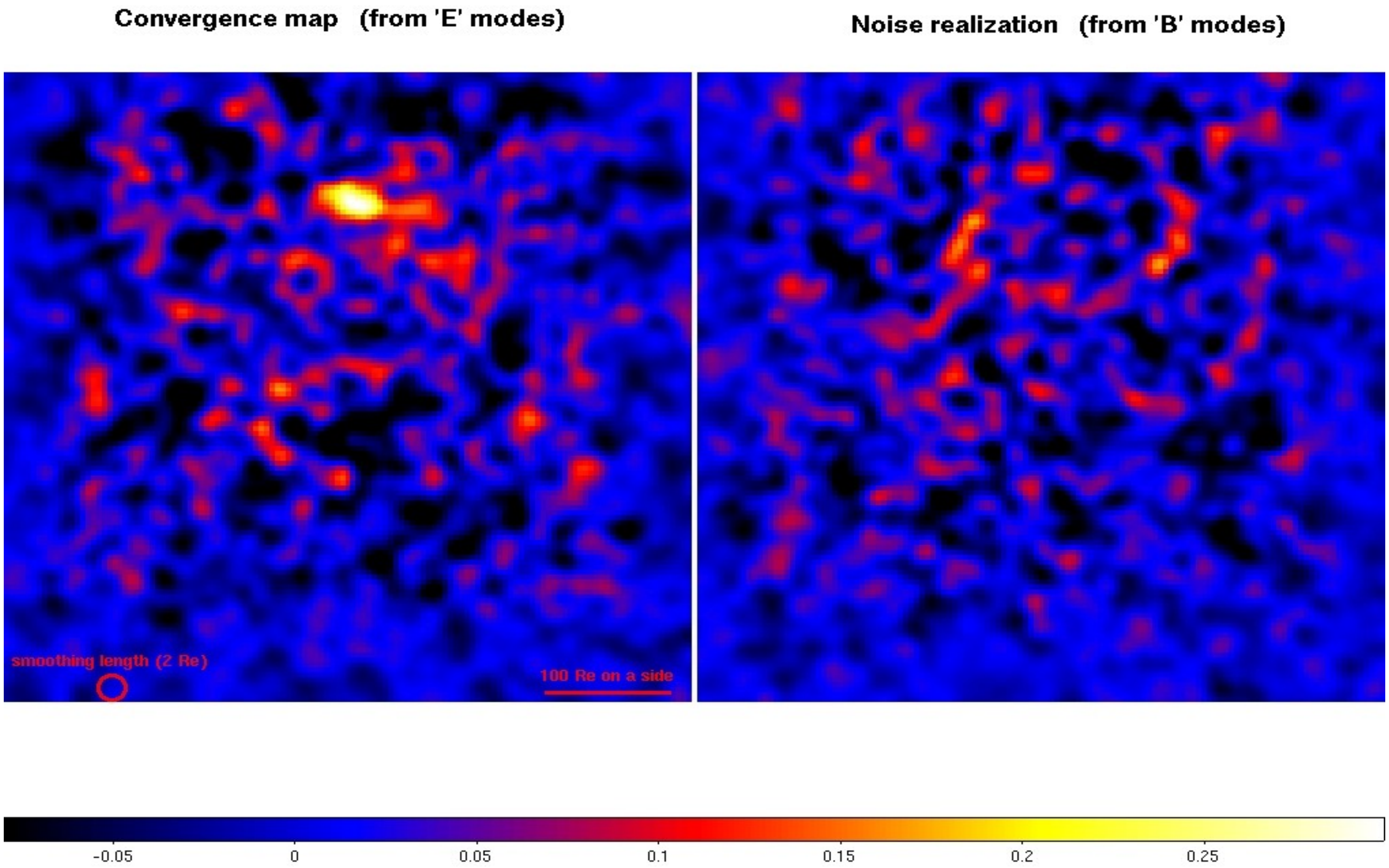
- 22 lenses ($z\sim0.1$-$0.3$) with velocity dispersion ~200-330 km/s
- F814W/ACS images (1 orbit) with FOV 200''x200''
- Large surface density of sources $I_{AB} < 26.2$ $n_{bg} \sim 80$ arcmin$^{-2}$.

(Gavazzi et al. 2007)



# Weak Lensing of Strong Lenses

2D mass mapping => ellipticity of haloes?

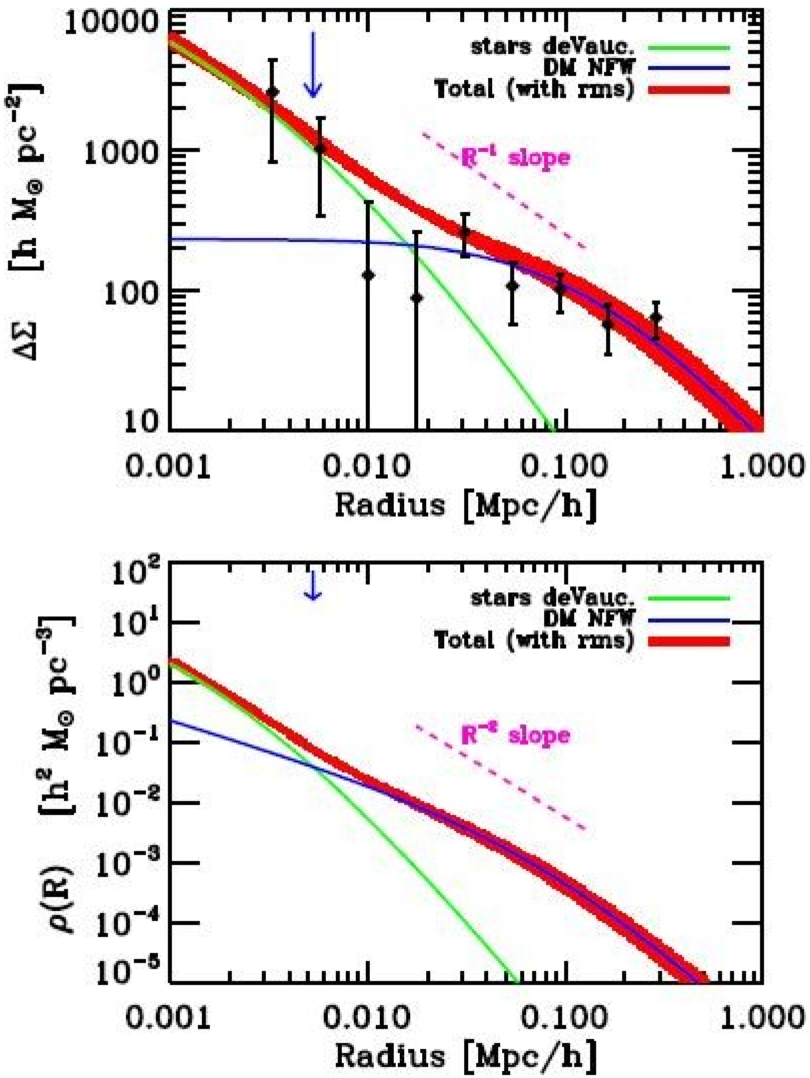


Convergence map (from 'E' modes)

Noise realization (from 'B' modes)

(Gavazzi et al. 2007)

# Weak Lensing of Strong Lenses



Shear measure over 3-300 kpc

DeVauc+NFW Fit+concentration index from numerical sims:

$M_*/L_V = 4.4 \pm 0.5\ M_{sun}/L_{sun}$

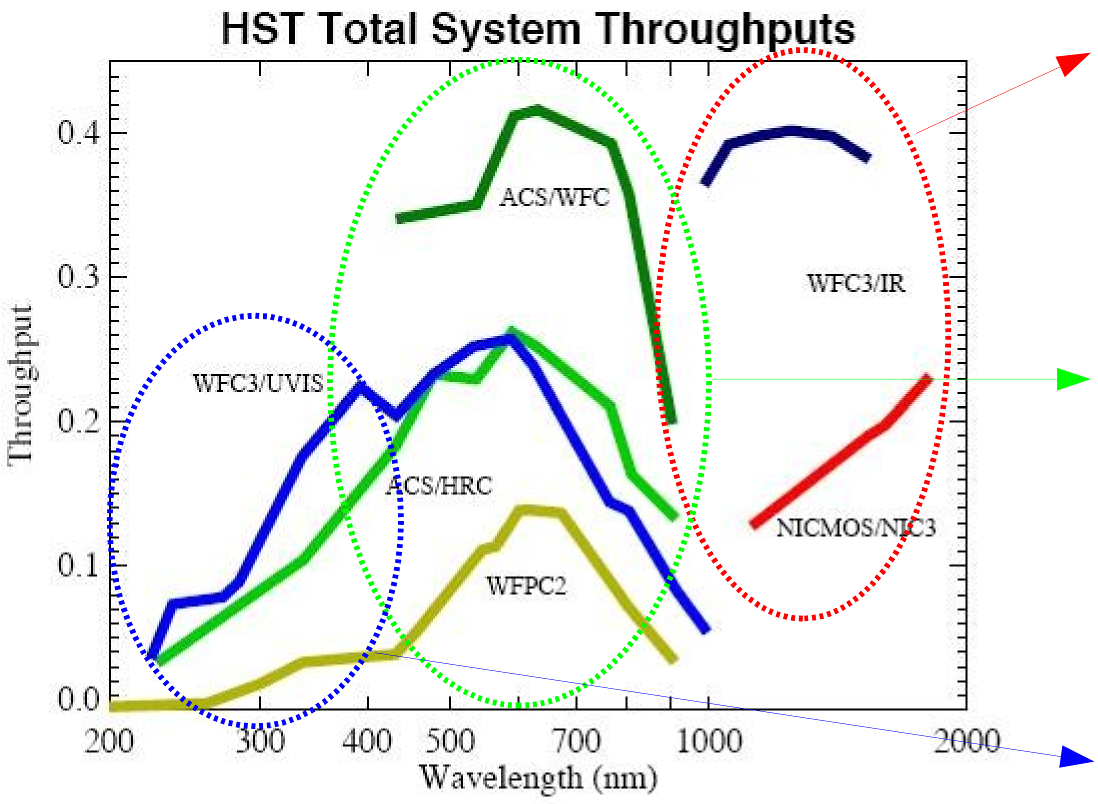
$M_{vir}/L_V = 350 \pm 150\ M_{sun}/L_{sun}$

27±4% DM inside a sphere of 1 effective radius

(Gavazzi et al. 2007)

# What do ACS, WFC3 and COS provide for Strong Lensing Studies?

# What can be (re)done after SM4?



1) Much improved IR imaging: studies of field, higher-z lenses, old stellar pops in lenses/src, etc.

2) Continued deep high-res imaging of strong lenses for mass-structure, stellar-pop, weak-lensing, substructure studies, etc.

3) Detail src. (emission lines) studies in the blue.

# What can be done better after SM4?

- NIR/Blue imaging of large FoVs around lens systems (multi-color characterization of field/environement, improve analysis of old-stellar pops in lens galaxies)
- NIR imaging or higher-z (red) lenses becomes feasible
- Imaging of the blue (emission lines) sources with WFC3 (and COS?)
- Grism Spectroscopy with WFC3 to get bright field-galaxy redshifts and of lenses with unkown redshifts

# Conclusions

- The Hubble Space Telescope provides a unique combination of capabilities to study strong gravitational lenses (before and after SM4!):
  - High resolution (~0.05-0.1")
  - Depth/Signal-to-Noise (I ~ 26 in 1 orbit)
  - Reasonable FoV (~3'x3')

- These capabilities allow combined lensing, stellar dynamical and weak-lensing studies of galaxies beyond the realm (redshift, mass, etc) of traditional techiques, breaking their degeneracies (e.g. mass-anisotropy, mass-sheet, inclination, etc.)

# Conclusions

- Illustrated by the SLACS survey, we have shown many unique and new results that w/o HST would **NOT** have have been possible:
  - Stellar dynamics and lensing can be combined: Density profiles of E/S0 are isothermal:
  - FP tilt is due to increase of DM, i.e. M/L, in $R_{eff}$
  - Weak lensing of strong lenses probes density profile to ~100 $R_{eff}$
  - Much more not shown here ....

- After SM4 this great science can continue and be further extended, especially in the IR/blue with WFC3