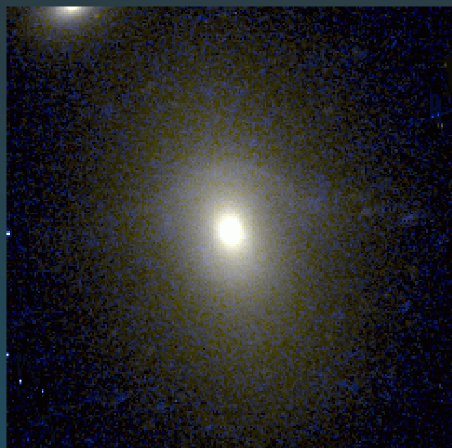
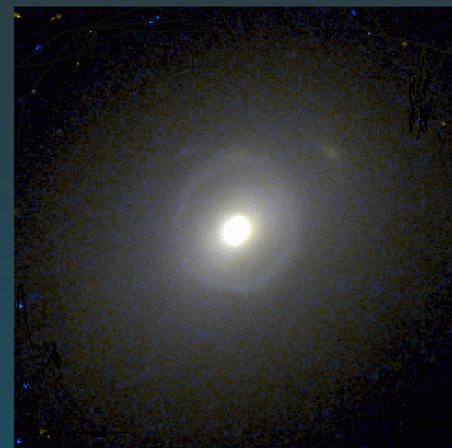
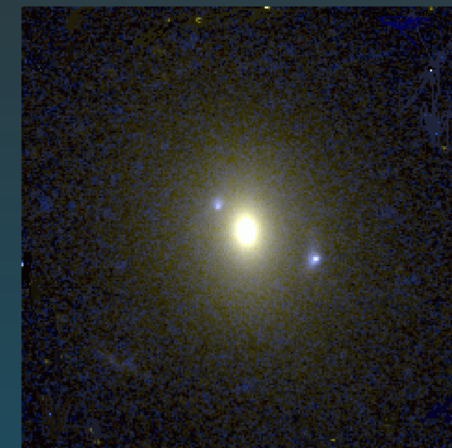
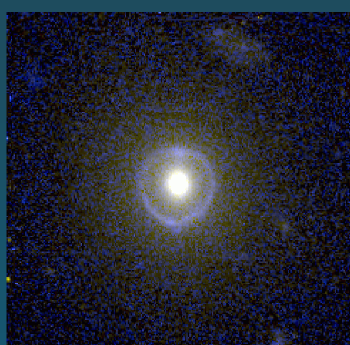
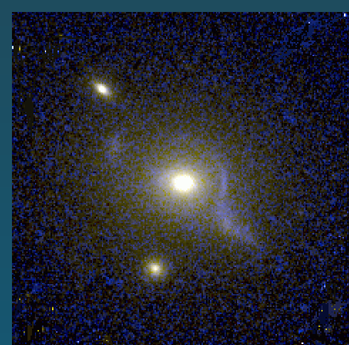
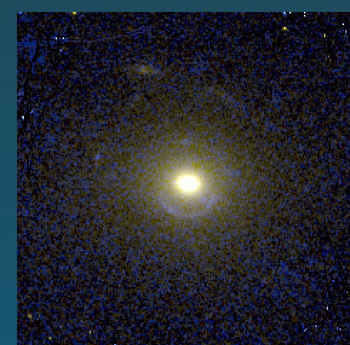
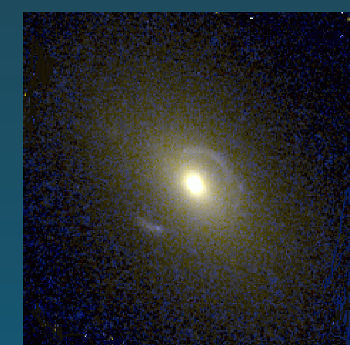
# Combining Lensing and Dynamics for SLACS Lenses

**Oliver Czoske**
**Kapteyn Institute, Groningen, NL**

**“From giant arcs to CMB lensing: 20 years of gravitational distortion”**
**Paris, 5 July 2007**

# Collaborators

In Groningen:

- Léon Koopmans (the boss)
- Matteo Barnabè (lensing + dynamics analysis: CAULDRON)
- Simona Vegetti (“non-parametric” lens modelling, substructure)

and elsewhere (the SLACS collaboration):

- Adam Bolton (IfA, Hawai‘i)
- Scott Burles (MIT)
- Raphaël Gavazzi (UCSB)
- Lexi Moustakas (JPL)
- Tommaso Treu (UCSB)

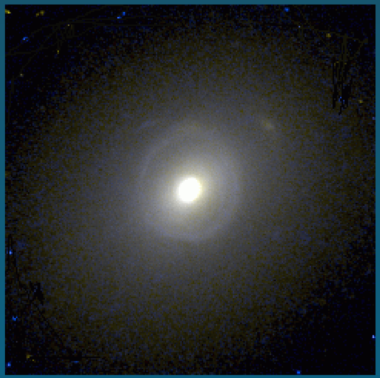
- Traditionally, samples of gravitational lenses were *source selected*:

⇒ bright sources, faint lenses
⇒ good lens models, but not a lot to compare them to
⇒ results are subject to the degeneracies inherent in the lensing method

- SLACS is *lens selected*: candidates are chosen from the SDSS luminous red galaxy sample Bolton et al. 2006

⇒ lenses are guaranteed to be bright and not outshone by the lensed background objects
⇒ our lenses are normal early-type galaxies Treu et al. 2006
⇒ SLACS is the ideal parent sample for a combined lensing/dynamical analysis

$\Longleftrightarrow$



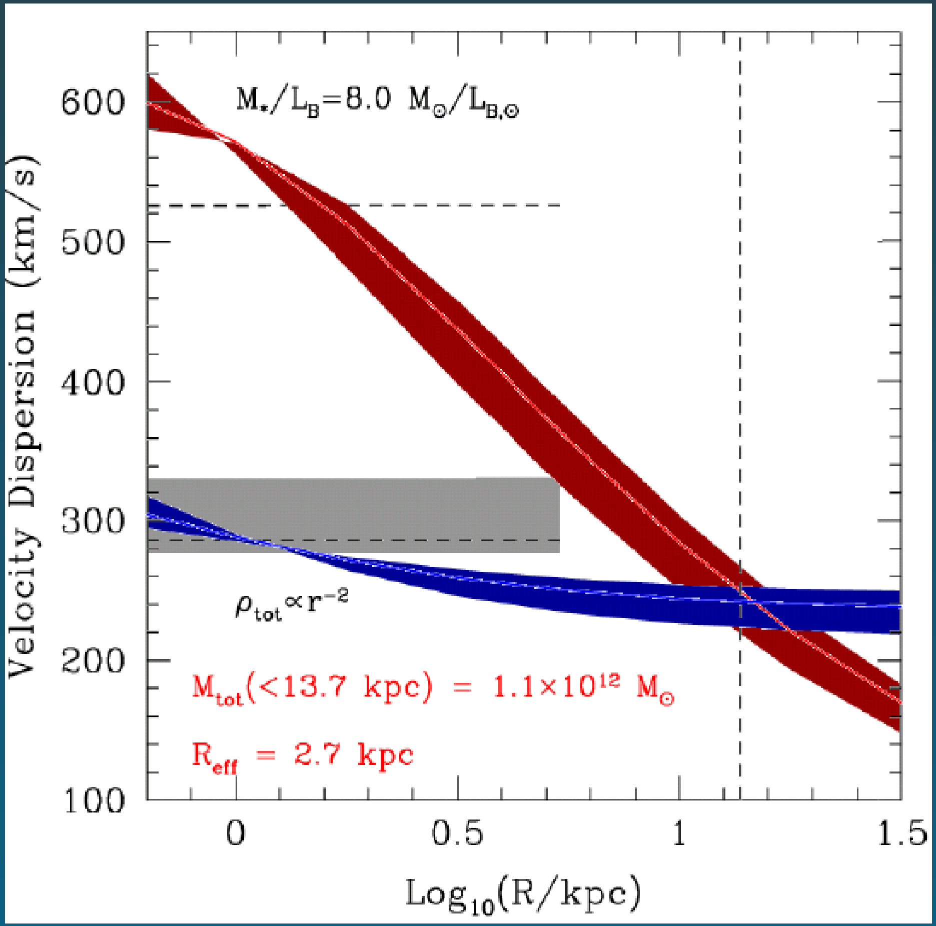
Mass-model degeneracies:

- Gravitational lensing: mass-profile degeneracy (poor constraints on mass profiles, “local” mass-sheet degeneracy)
- Stellar Dynamics: mass-anisotropy degeneracy (degeneracy between changes in mass profile and anisotropy of the stellar velocity distribution)

Degeneracies can be broken by suitable combination of these methods!

**Lenses Structures and Dynamics**
(L. Koopmans, T. Treu)

- detection of DM halos at high significance
- inner total mass profiles close to isothermal
- *etc…*



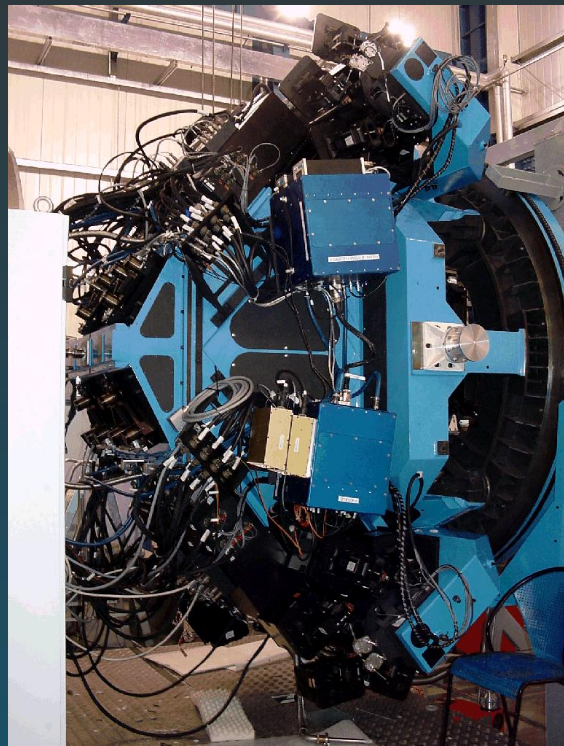

(MG2016, Léon Koopmans)

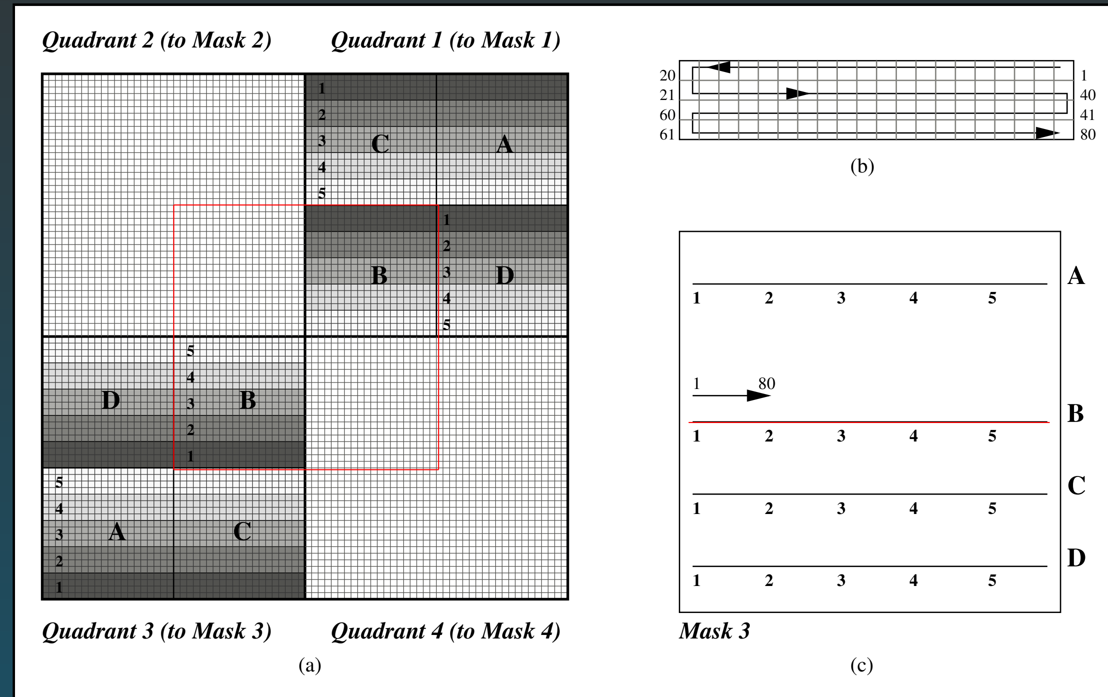
Goals of this project:

- obtain two-dimensional maps of galaxy kinematics, i.e. $v(\boldsymbol{R})$ and $\sigma_{\text{los}}(\boldsymbol{R})$ using
  1. VIMOS/IFU on VLT: 17 systems (Czoske)
  2. "mock integral field" spectra from Keck: 13 systems (Gavazzi, Treu)
- Combine lens modelling with detailed modelling of the kinematical information in a fully self-consistent way (Barnabè)

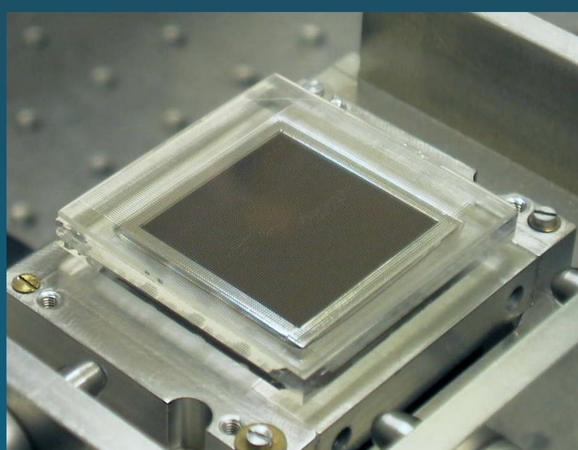
# SLACS IFS

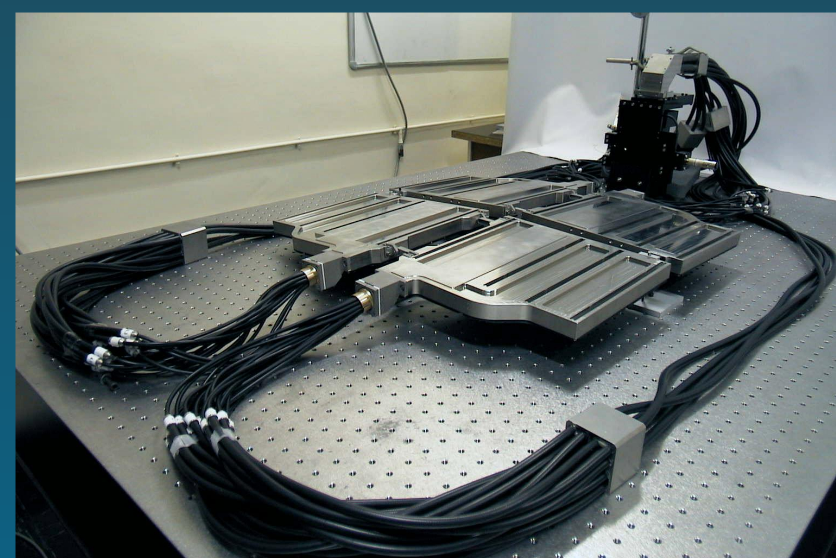
# VIMOS Integral Field Unit






Zanichelli et al. (2005)





Photos from `http://www.oamp.fr/virmos/`

# SLACS IFS — Wavelength coverage

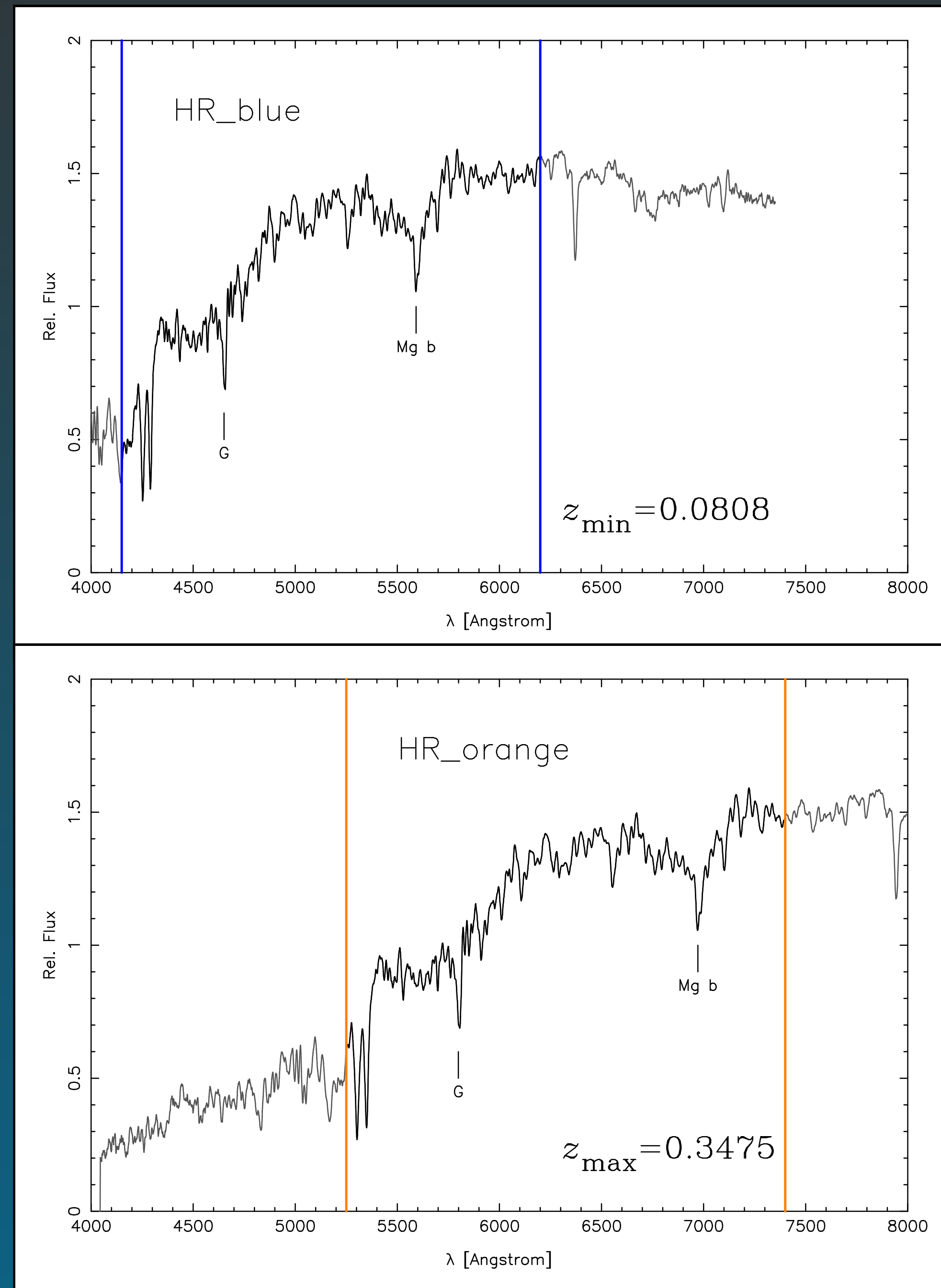
Spectral resolution:

- HR_blue grism:
  $R = 2550$, $(R = \lambda/\Delta\lambda)$
  $4200\,\text{Å} < \lambda < 6200\,\text{Å}$
- HR_orange grism:
  $R = 2650$,
  $5250\,\text{Å} < \lambda < 7400\,\text{Å}$

$\Longrightarrow \Delta v \sim 110\ldots85\,\mathrm{km\,s^{-1}}$

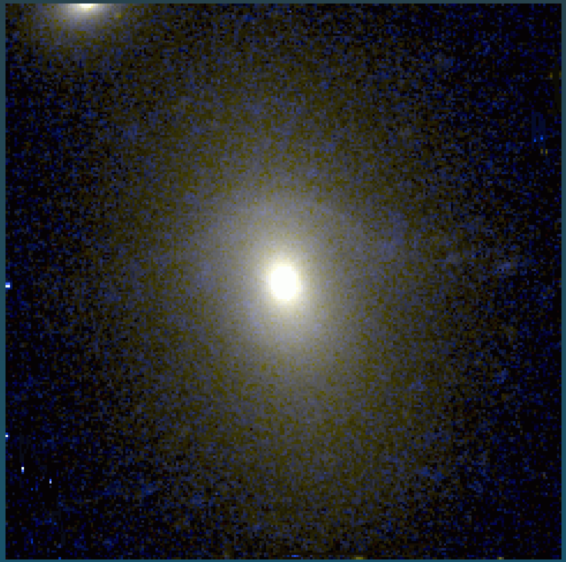
Spatial resolution:

$0\overset{''}{.}66$ per fibre ("spaxel")
$\Rightarrow$ FOV: $27'' \times 27''$
$\Rightarrow$ 10…30 fibres within $R_{\rm eff}$

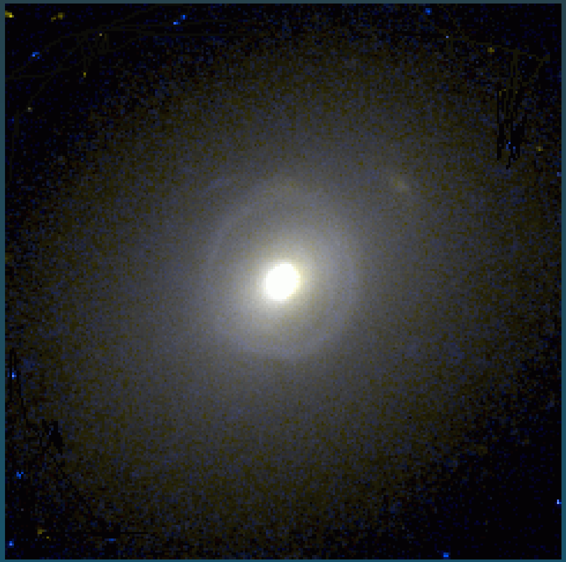


# Observations

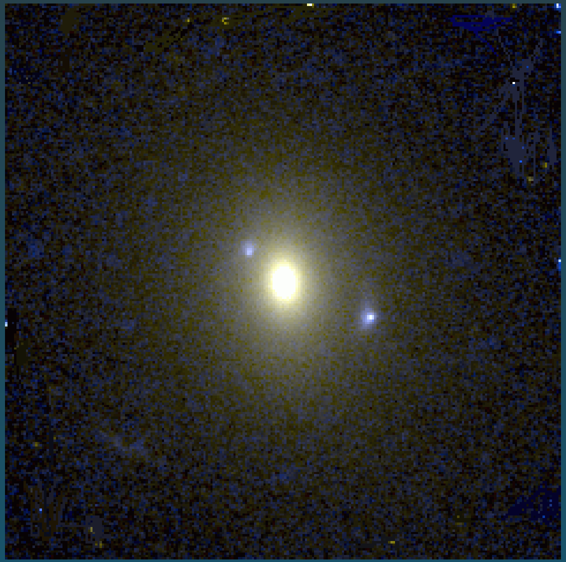
- Pilot programme 075.A-0226: 3 lenses, observations complete, data reduced (or so)



J091205.30+002901.1
$z_{\rm lens} = 0.1642$
$z_{\rm source} = 0.3239$
$\sigma_{\rm v} = (313 \pm 12)\,{\rm km\,s^{-1}}$

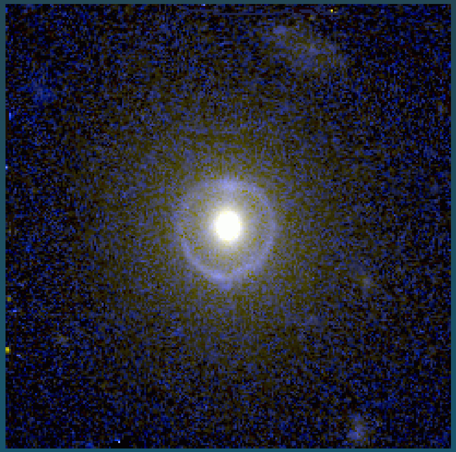


J232120.93−093910.2
$z_{\rm lens} = 0.0819$
$z_{\rm source} = 0.5324$
$\sigma_{\rm v} = (236 \pm 7)\,{\rm km\,s^{-1}}$

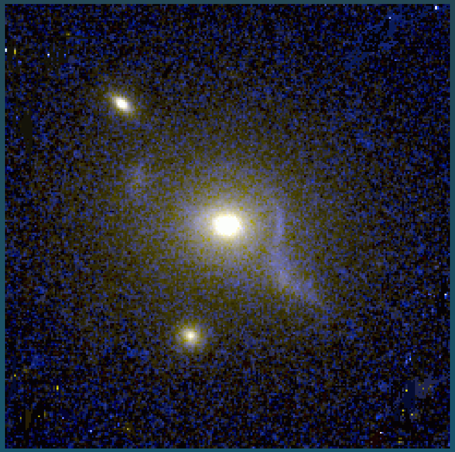


J003753.21−094220.1
$z_{\rm lens} = 0.1954$
$z_{\rm source} = 0.6322$
$\sigma_{\rm v} = (265 \pm 10)\,{\rm km\,s^{-1}}$

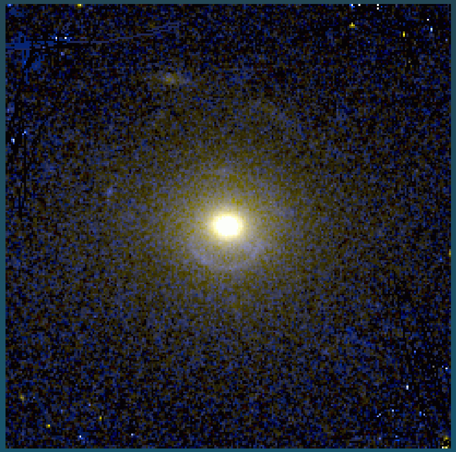
- Large programme 177.A-0682: 14 lenses, observations spread over two semesters, complete and data on my desk
- uses HR-Orange instead of HR-Blue, one exposure per OB, no dithering



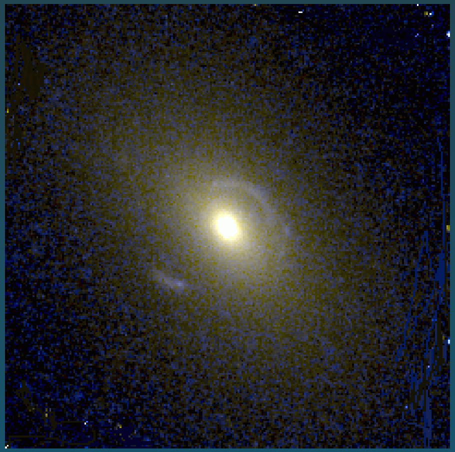
J162746.44−005357.5
$z_{\rm lens} = 0.2076$
$z_{\rm source} = 0.5241$
$\sigma_{\rm v} = 275 \pm 12$



J021652.54−081345.3
$z_{\rm lens} = 0.3317$
$z_{\rm source} = 0.5235$
$\sigma_{\rm v} = 332 \pm 23$



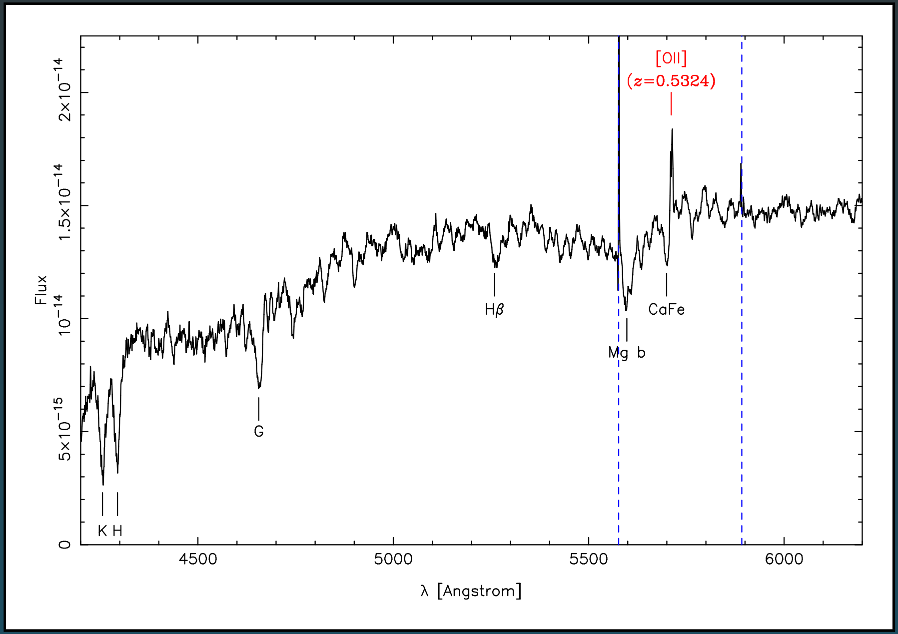
J230053.14+002237.9
$z_{\rm lens} = 0.2285$
$z_{\rm source} = 0.4635$
$\sigma_{\rm v} = 283 \pm 18$

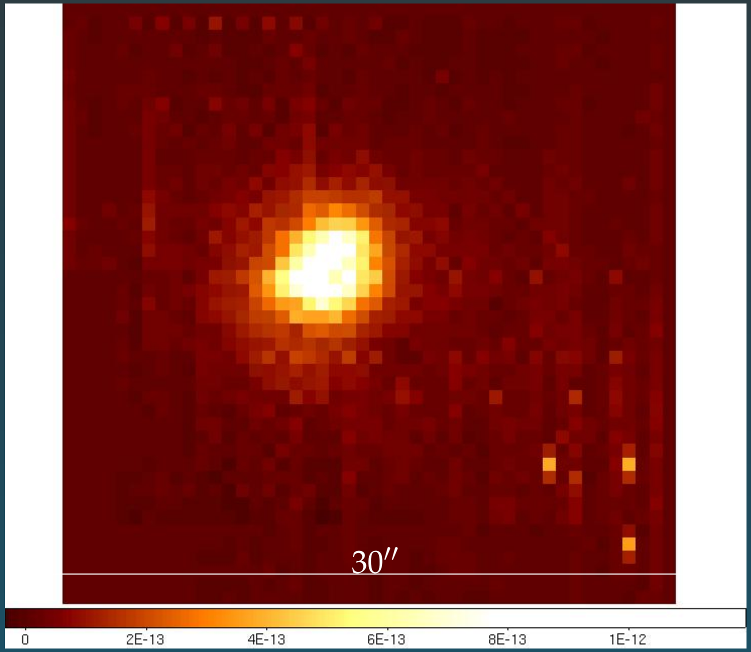


J230321.72+142217.9
$z_{\rm lens} = 0.1553$
$z_{\rm source} = 0.5170$
$\sigma_{\rm v} = 260 \pm 15$

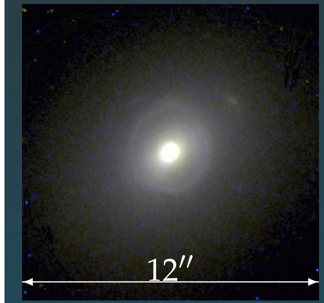
| Target | $m_R$ | $z_{\rm lens}$ | $R_{\rm eff}$ | OBs done |
|---|---|---|---|---|
| SDSS-0472 | 16.1 | 0.1642 | $3\farcs4$ | 4 |
| SDSS-0645 | 15.1 | 0.0819 | $2\farcs2$ | 5 |
| SDSS-0655 | 16.7 | 0.1954 | $1\farcs2$ | 9 |
| SDSS J0216 | 17.6 | 0.3317 | $3\farcs0$ | 14 |
| SDSS J0935 | 17.6 | 0.3475 | $3\farcs6$ | 12 |
| SDSS J0959 | 17.6 | 0.1260 | $1\farcs2$ | 4 |
| SDSS J1204 | 17.4 | 0.1644 | $1\farcs5$ | 5 |
| SDSS J1250+05 | 17.3 | 0.2318 | $1\farcs8$ | 6 |
| SDSS J1250−01 | 15.7 | 0.0870 | $3\farcs1$ | 6 |
| SDSS J1251 | 17.6 | 0.2243 | $3\farcs6$ | 12 |
| SDSS J1330 | 17.6 | 0.0808 | $0\farcs8$ | 3 |
| SDSS J1443 | 17.6 | 0.1338 | $1\farcs2$ | 4 |
| SDSS J1451 | 16.8 | 0.1254 | $2\farcs5$ | 7 |
| SDSS J1627 | 17.6 | 0.2076 | $2\farcs1$ | 11 |
| SDSS J2238 | 16.9 | 0.1371 | $2\farcs2$ | 6 |
| SDSS J2300 | 17.8 | 0.2282 | $1\farcs8$ | 10 |
| SDSS J2303 | 16.9 | 0.1553 | $3\farcs0$ | 11 |

# SLACS IFS — Reduction Results: SDSS-0645



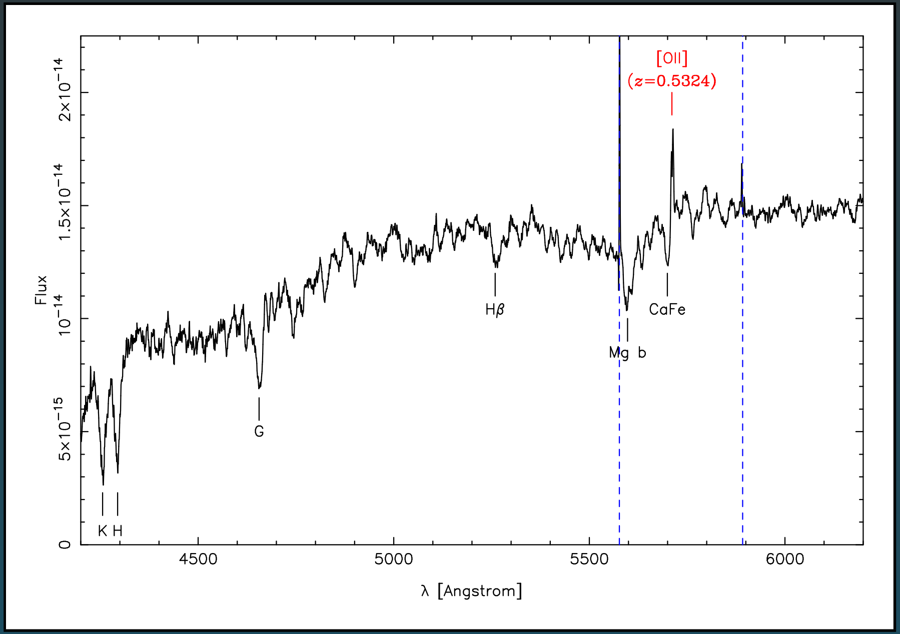



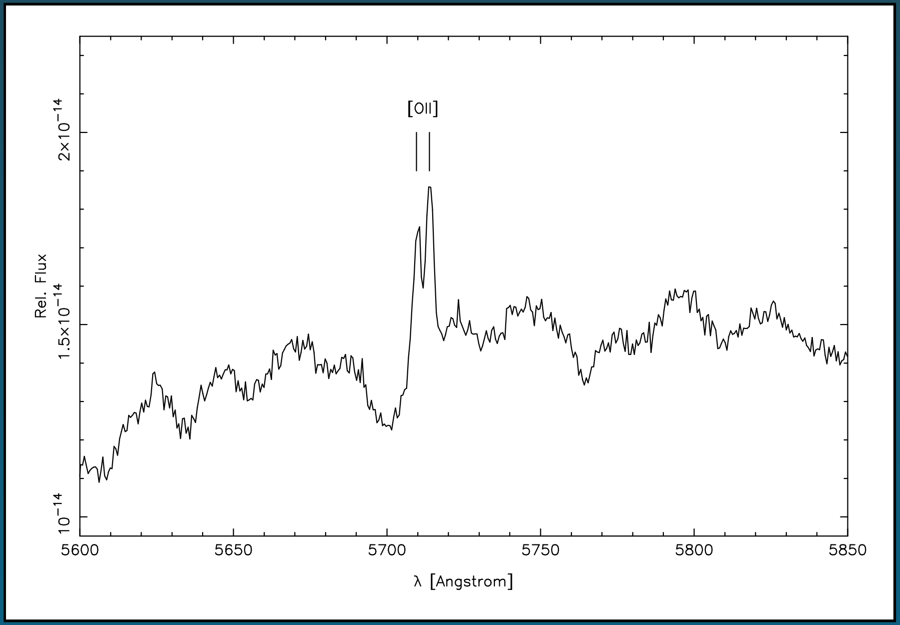

SDSS J232120.93−093910.2

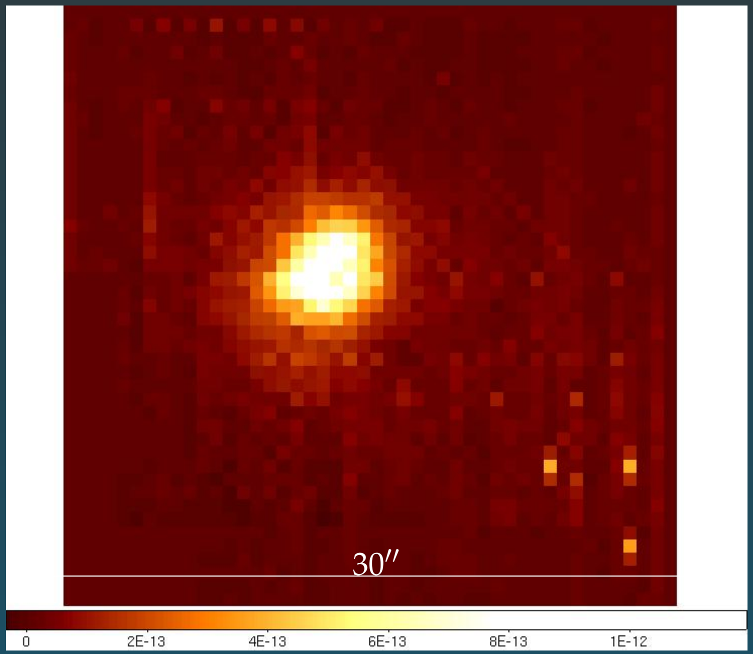



HST / ACS

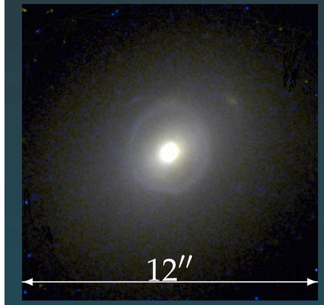
# SLACS IFS Reduction Results: SDSS-0645



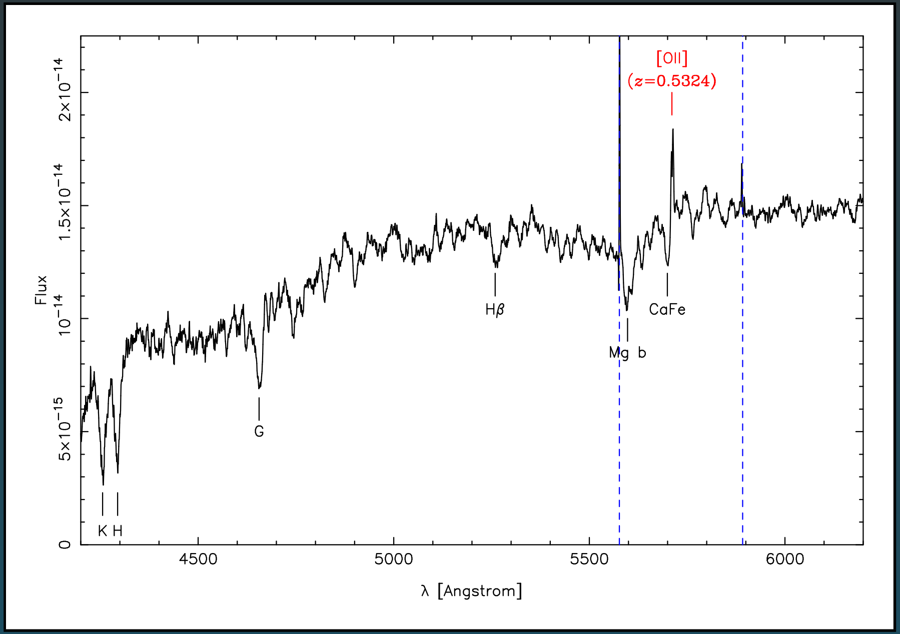



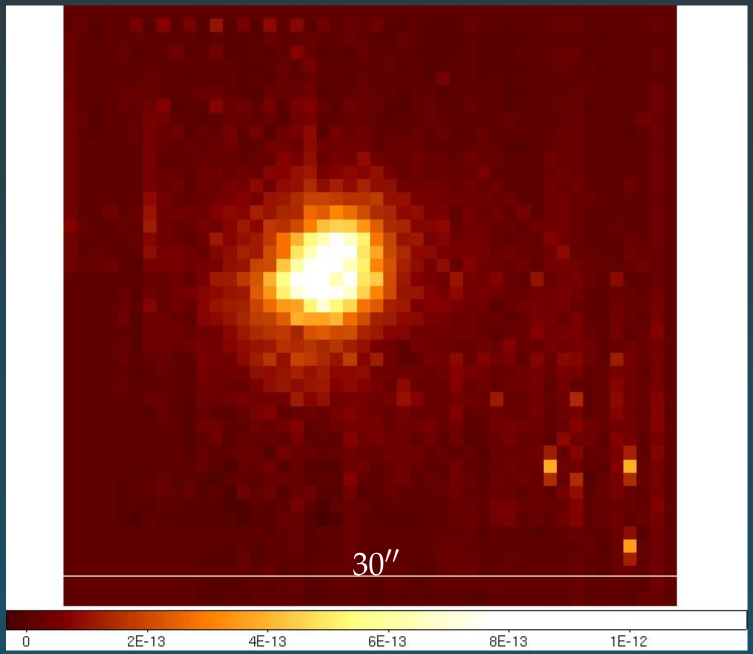

SDSS J232120.93−093910.2

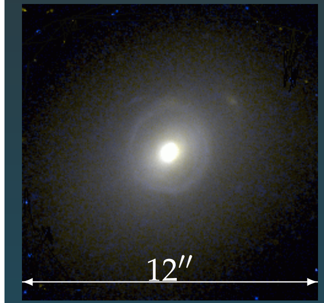



HST / ACS

# Reduction Results: SDSS-0645

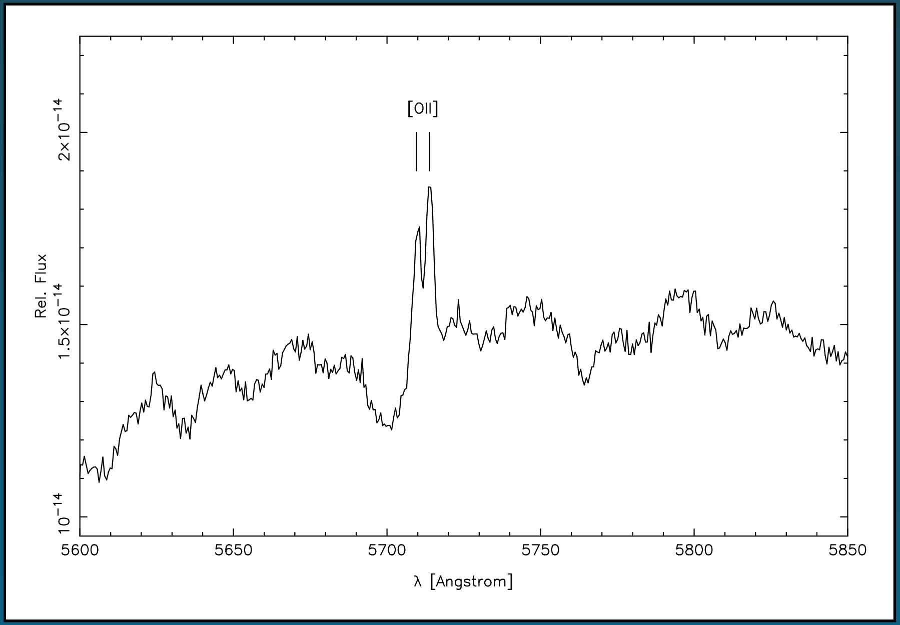



HST/ACS

SDSS J232120.93−093910.2

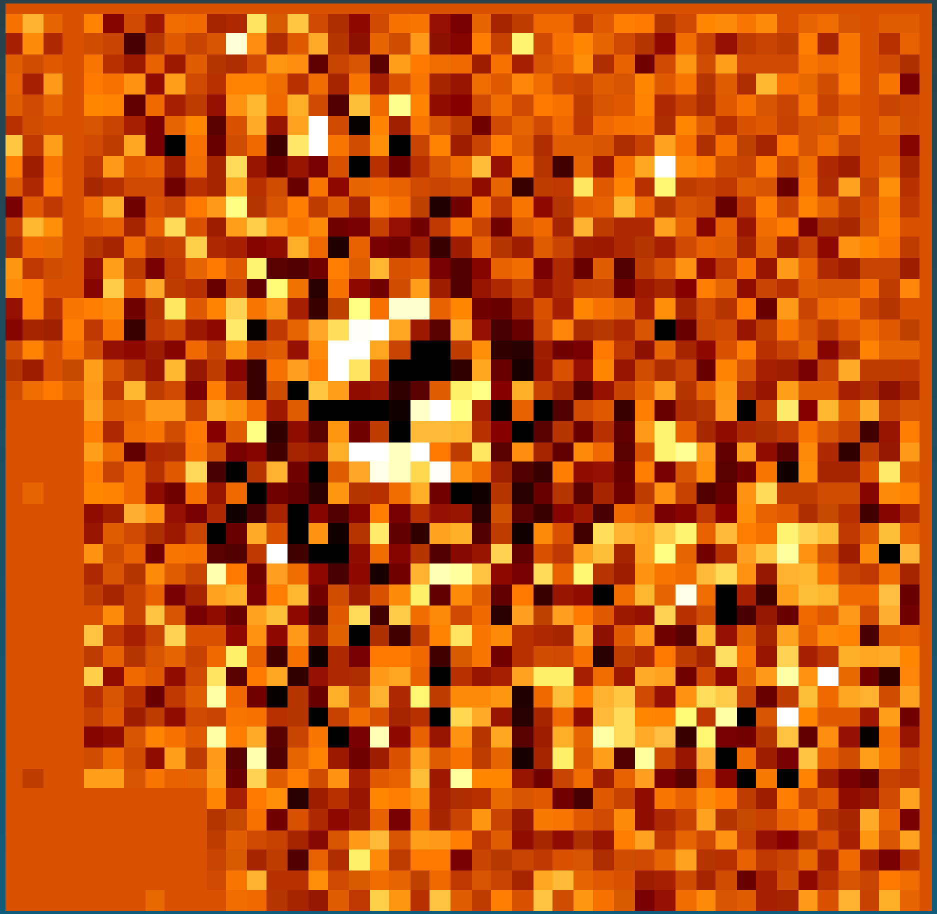



Results from fitting the global spectrum:

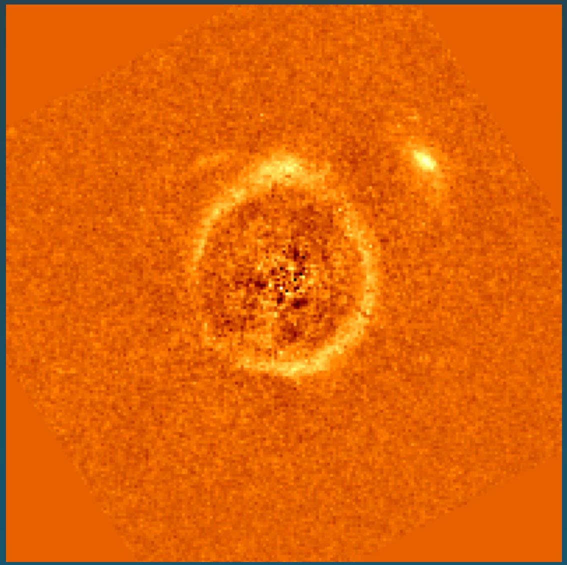
- $S/N = 32$ (per pixel)
- $\overline{v} = 14.5^{+9.8}_{-9.4}\,\mathrm{km\,s^{-1}}$
- $\sigma_{\mathrm{glob}} = 237.5^{+12.5}_{-7.8}\,\mathrm{km\,s^{-1}}$ (SDSS: 236)

## [OII] narrow band image

We can recover the structure of the lensed source with a narrow-band image centred on [O II]:



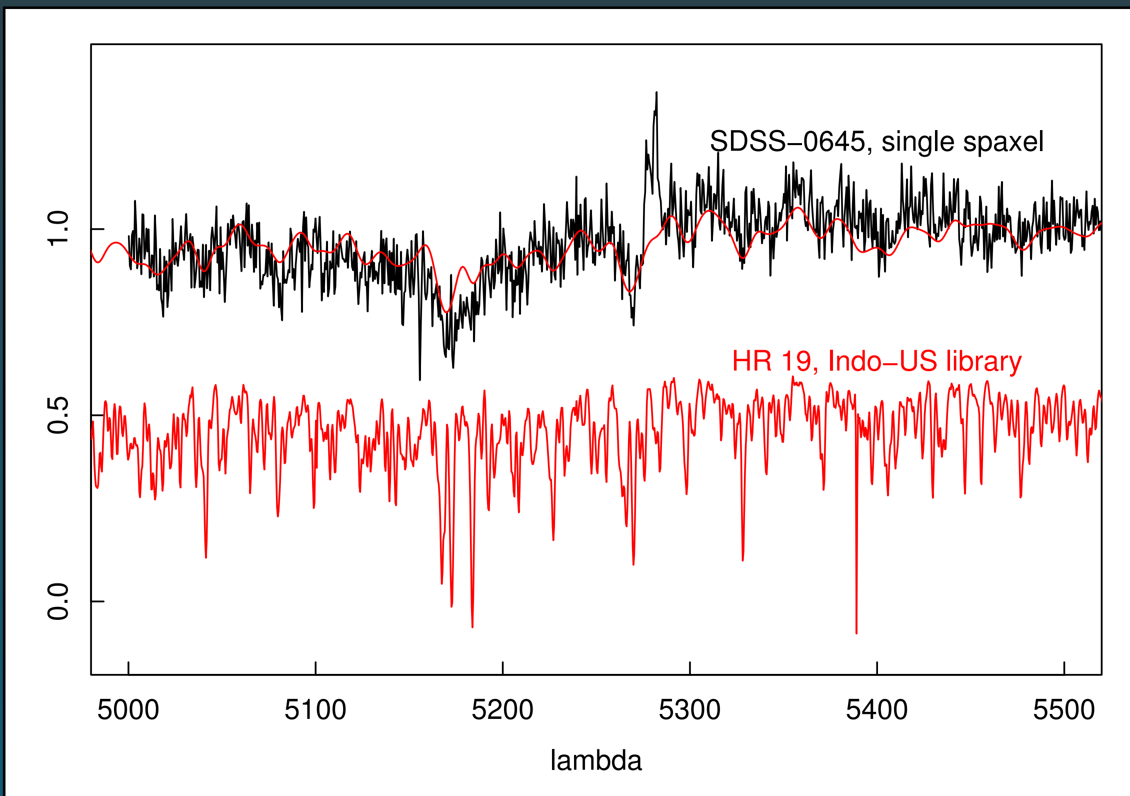
VIMOS/IFU, narrow-band [O II] − continuum

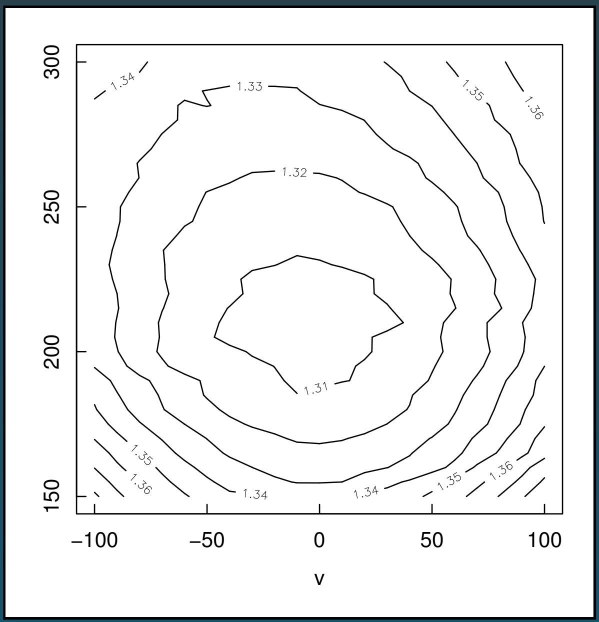


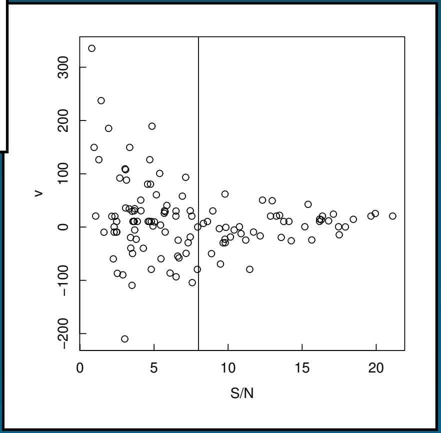
HST/ACS, lens subtracted

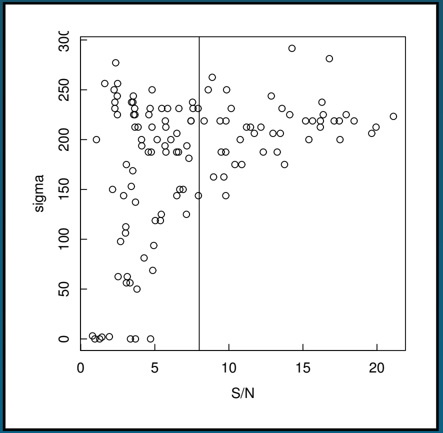
# SLACS IFS — Kinematics

We measure the kinematic parameters $v(R)$ and $\sigma_{\mathrm{los}}(R)$ with a direct pixel fitting method, implemented in R.



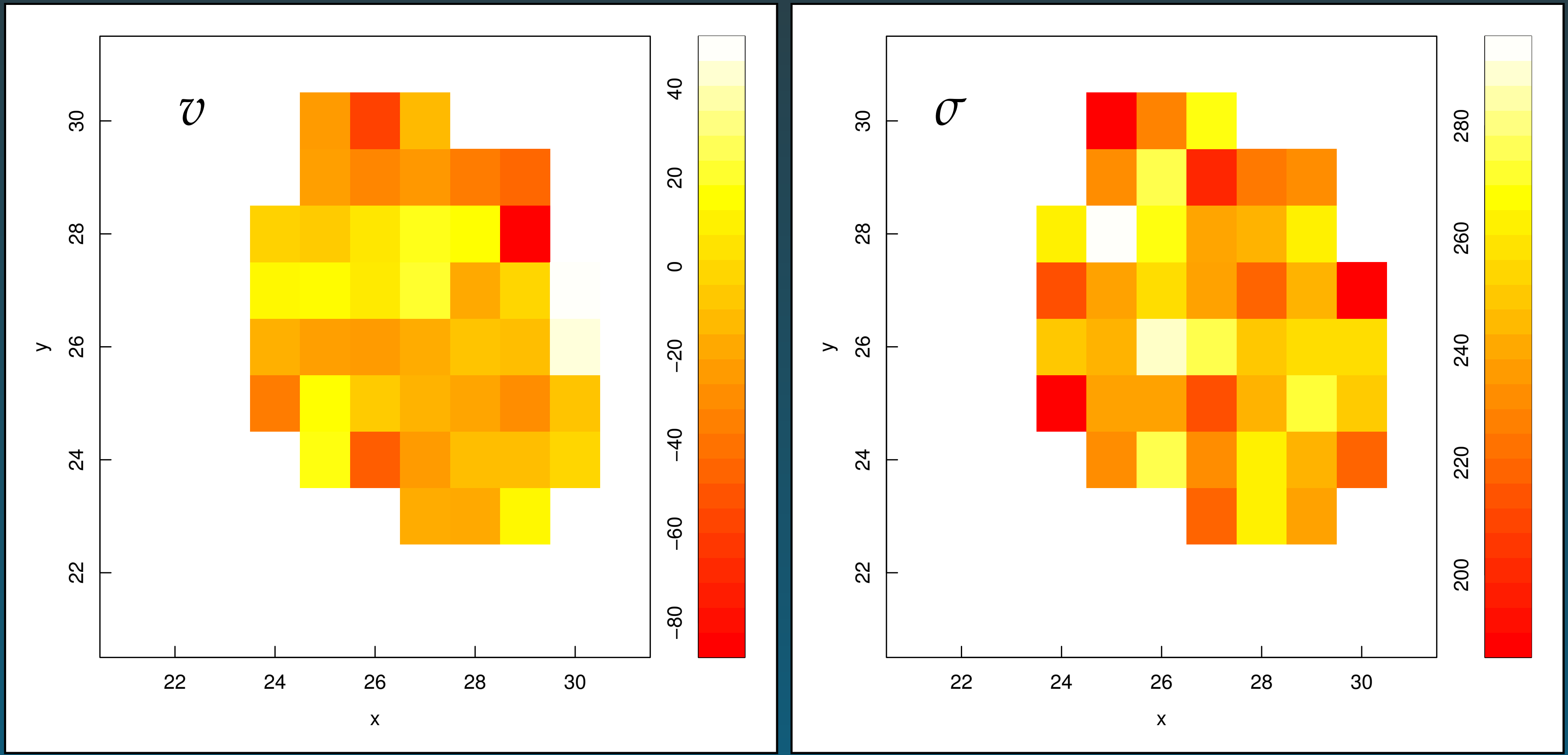



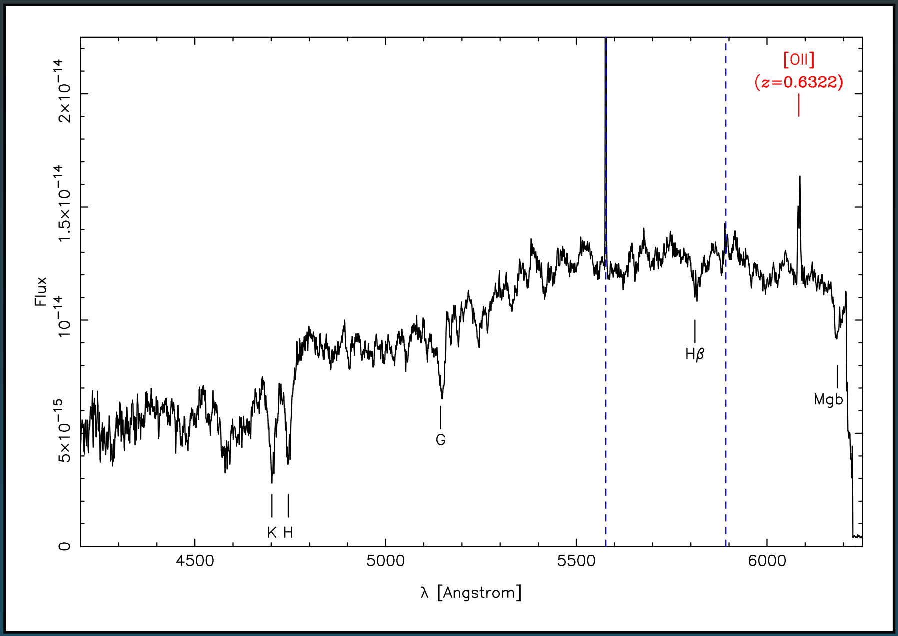
# Kinematics SDSS-0645

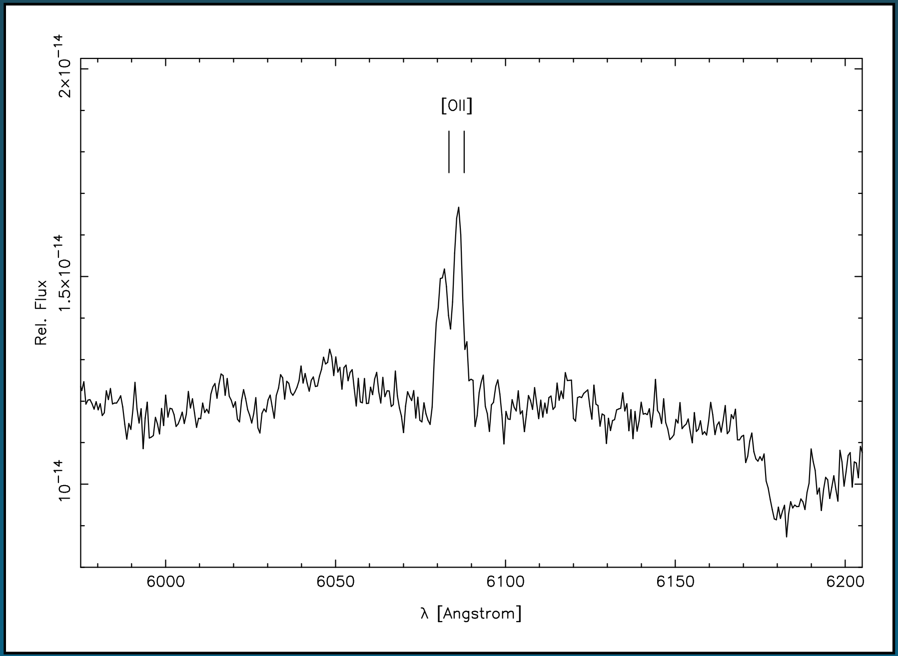
$z_{\text{lens}} = 0.0819$

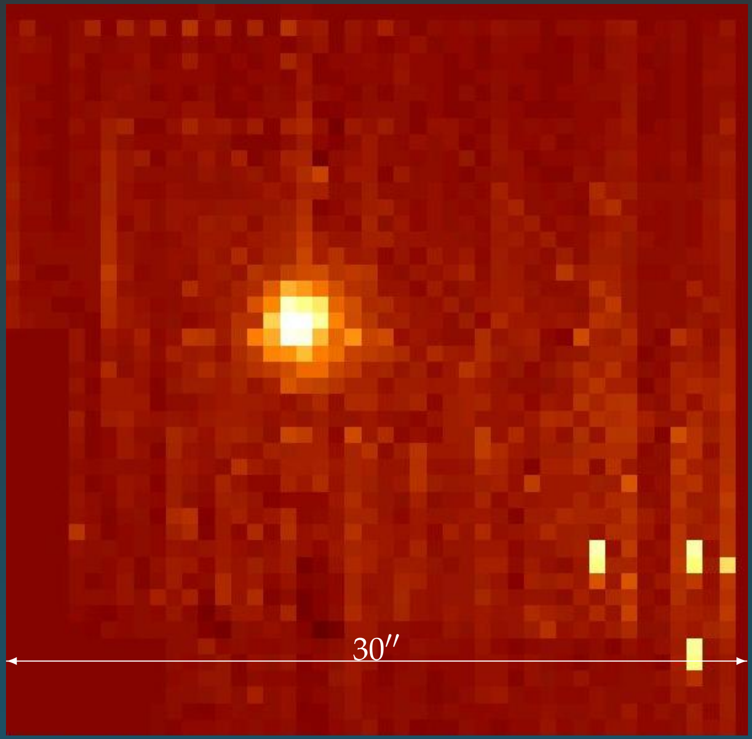



$S/N > 8$

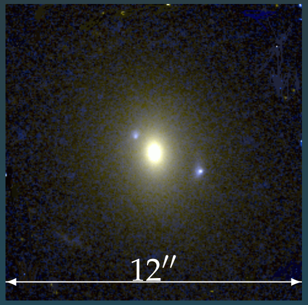
## SLACS IFS — Reduction Results: SDSS-0655




SDSS J003753.21−094220.1

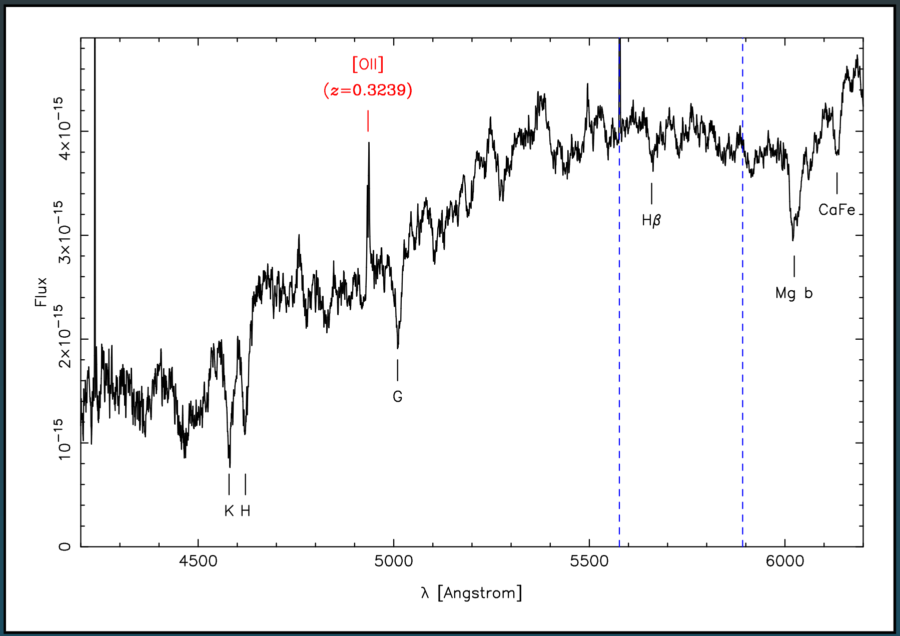


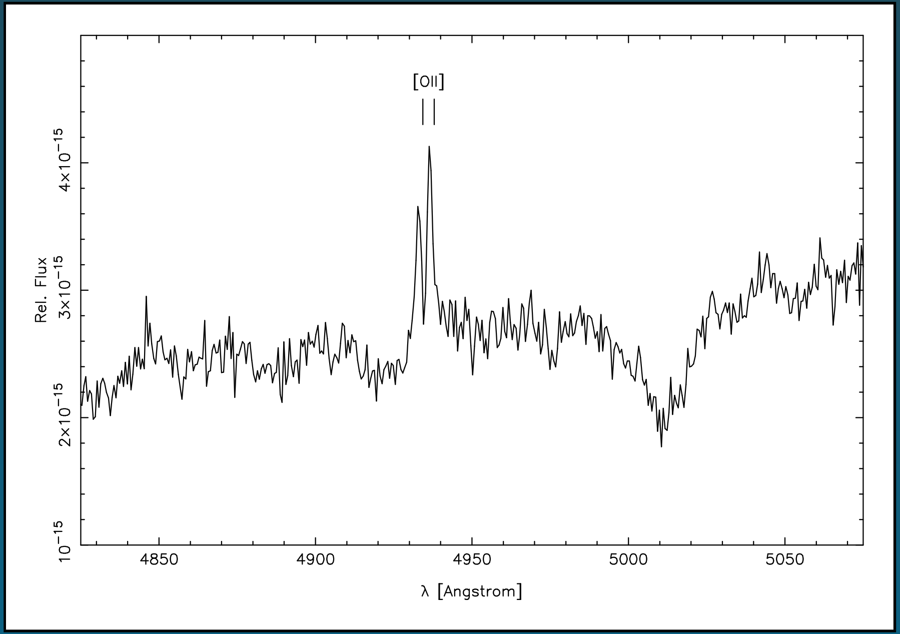

HST/ACS

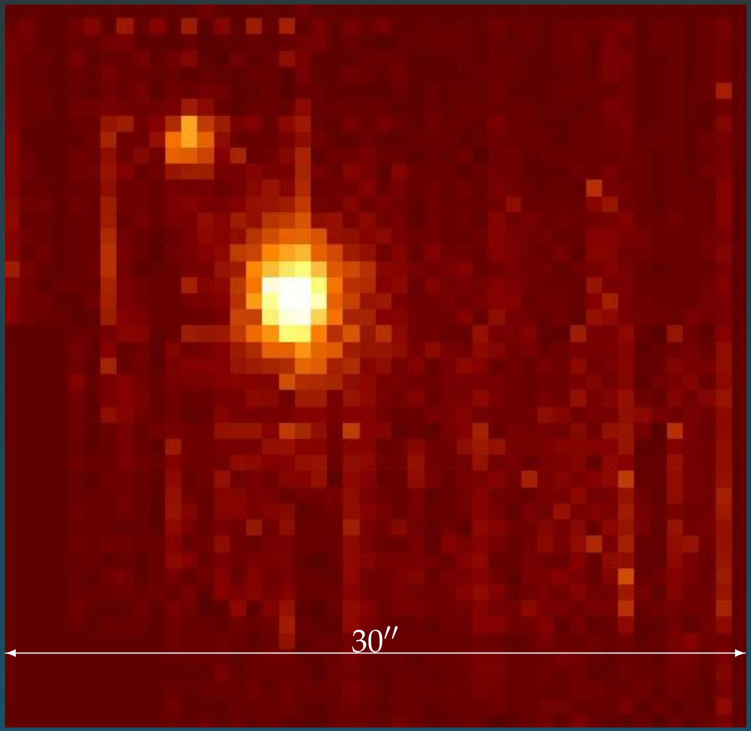
Results from fitting the global spectrum:

- $S/N = 26$ (per pixel)
- $\overline{v} = 25.9^{+20.6}_{-20.1}\,\mathrm{km\,s^{-1}}$
- $\sigma_{\mathrm{glob}} = 281.3^{+18.8}_{-15.4}\,\mathrm{km\,s^{-1}}$ (SDSS: 265)

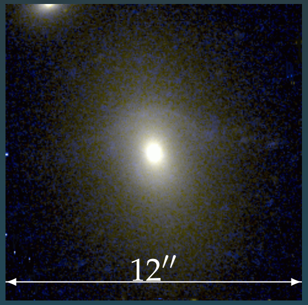
# Reduction Results: SDSS-0472




SDSS J091205.30+002901.1




HST/ACS

Results from fitting the global spectrum:

- $S/N = 32$ (per pixel)
- $\overline{v} = 42.4^{+21.4}_{-21.6}\,\mathrm{km\,s^{-1}}$
- $\sigma_{\mathrm{glob}} = 323.7^{+18.8}_{-21.6}\,\mathrm{km\,s^{-1}}$ (SDSS: 313)

# CAULDRON

Combined Algorithm for Unified Lensing and Dynamics ReconstructiON

Axisymmetric density distribution: $\rho(R, z)$

Gravitational potential: $\Phi(R, z, \eta_k)$

linear optimization

**Lensed image reconstruction**

$\mathsf{L}\boldsymbol{s} + \boldsymbol{n}_{\mathrm{L}} = \boldsymbol{d}$

linear optimization

**Dynamical model**

$\mathsf{Q}\boldsymbol{\gamma} + \boldsymbol{n}_{\mathrm{D}} = \boldsymbol{p}$

Maximize the Bayesian evidence

allows model comparison

automatically embodies Occam's razor

non-linear optimization: vary $\eta_k$

at convergence

Best values for the non-linear parameters $\eta_k$

source reconstruction & DF reconstruction

Barnabè & Koopmans (2007)

- source plane reconstruction can be formulated as a linear inverse problem:

$$\mathsf{L}[\Phi(\boldsymbol{\eta})] \cdot \boldsymbol{s} + \boldsymbol{n}_{\mathrm{L}} = \boldsymbol{d} \quad \text{(image plane SB after subtraction of lens galaxy)}$$

- Construct L using
  - ⋆ lens equation: $\boldsymbol{\beta} = \boldsymbol{\theta} + \boldsymbol{\alpha}[\theta, \Phi(\boldsymbol{x}, \boldsymbol{\eta})]$
  - ⋆ conservation of surface brightness: $\Sigma[\beta(\theta)] = \Sigma(\theta)$
  - ⋆ convolution with point spread function
- Curvature regularization — Suyu et al. (2006)
- Under assumption of Gaussian errors minimize

$$\mathcal{P}[\boldsymbol{s}, \Phi(\boldsymbol{\eta})] = \frac{1}{2}(\mathsf{L}\boldsymbol{s} - \boldsymbol{d})^{\mathrm{T}}\,\mathsf{C}_{\mathrm{L}}^{-1}\,(\mathsf{L}\boldsymbol{s} - \boldsymbol{d}) + \frac{\lambda_{\mathrm{L}}}{2}||\mathsf{H}\boldsymbol{s}||^2$$

to find most probable source plane SB $\boldsymbol{s}_{\mathrm{mp}}$ in model $\eta$

- Compute evidence

$$P(\boldsymbol{d}|\lambda_{\mathrm{L}}, \eta) = \text{analytic though lengthy}$$

- Reconstruction of the stellar distribution function can also be formulated as a linear equation:

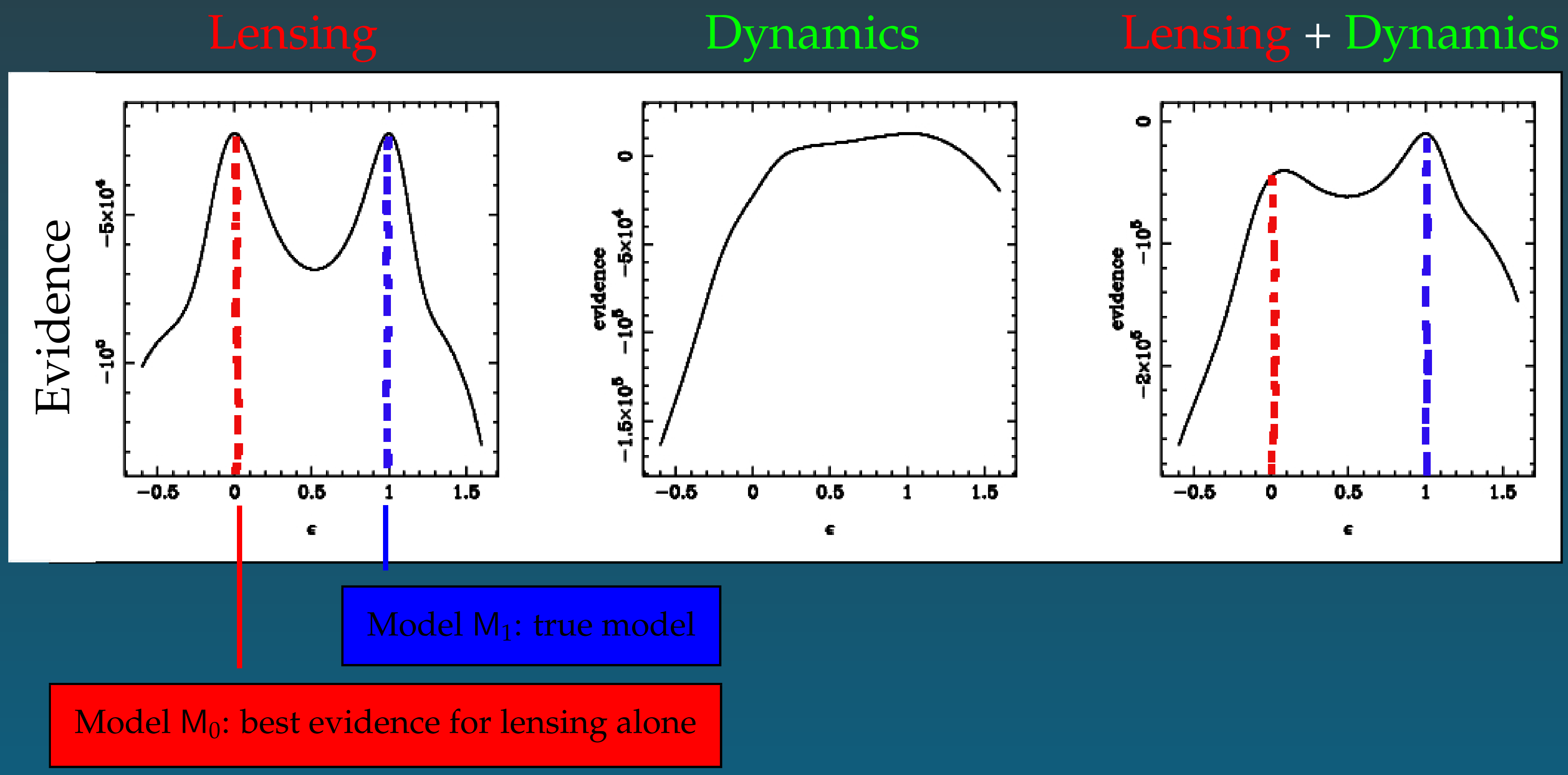
$$Q[\Phi(\boldsymbol{\eta})] \cdot \gamma + \boldsymbol{n}_\mathrm{D} = \boldsymbol{p} = \begin{cases} \Sigma_i & \text{surface brightness} \\ \Sigma_i \, \overline{v}_{\mathrm{los},i} & \text{ordered motion} \\ \Sigma_i \, \sigma_{\mathrm{los},i} & \text{random motion} \end{cases}$$

- Model stellar DF as a weighted superposition of "two integral components" (TICs): Schwarzschild (1979), Verolme & de Zeeuw (2002)

$$f(E_j, L_{z,i}) = \frac{C_j}{2} \delta(E - E_j) \, \delta(L_z - L_{z,j})$$

- Use efficient Monte Carlo implementation to derive observables for each TIC: $\boldsymbol{\Sigma}_j$, $\boldsymbol{\Sigma}_j \langle \boldsymbol{v}_{z'} \rangle_j$, $\boldsymbol{\Sigma}_j \langle v^2_{z'} \rangle_j$
- Convolve with PSF
- $\gamma$ are weights of the TICs $\Rightarrow$ stellar DF
- Compute most probable $\gamma_\mathrm{MP}$ from regularized penalty function, compute evidence $P(\boldsymbol{p} | \lambda_E, \lambda_L, \boldsymbol{\eta})$

- Dynamics is crucial in breaking the degeneracies from lensing alone
  ⇒ reliably recover the best values for the non-linear parameters



- Parameters of the problem are:
  - ⋆ $\boldsymbol{s}, \gamma \longrightarrow$ linear parameters
  - ⋆ $\lambda_{\text{len}}, \lambda_{\text{dyn},E}, \lambda_{\text{dyn},L_z} \longrightarrow$ regularization parameters
  - ⋆ $\boldsymbol{\eta} \longrightarrow$ non-linear model parameters

- Parameters are determined from a repeated application of Bayes' theorem:

$$P(\boldsymbol{s}|\boldsymbol{d},\lambda,\boldsymbol{\eta}) = \frac{P(\boldsymbol{d}|\boldsymbol{s},\lambda,\boldsymbol{\eta})\,P(\boldsymbol{s}|\lambda,\boldsymbol{\eta})}{P(\boldsymbol{d}|\lambda,\boldsymbol{\eta})}$$ linear optimization

$$P(\lambda|\boldsymbol{d},\boldsymbol{\eta}) = \frac{P(\boldsymbol{d}|\lambda,\boldsymbol{\eta})\,P(\lambda|\boldsymbol{\eta})}{P(\boldsymbol{d}|\boldsymbol{\eta})}$$ regularization parameters

$$P(\boldsymbol{\eta}|\boldsymbol{d}) = \frac{P(\boldsymbol{d}|\boldsymbol{\eta})\,P(\boldsymbol{\eta})}{P(\boldsymbol{d}|\text{model})}$$ non-linear optimization

- evidence $P(\boldsymbol{d}|\text{model})$ allows objective model comparison

# J2321−097: preliminary analysis

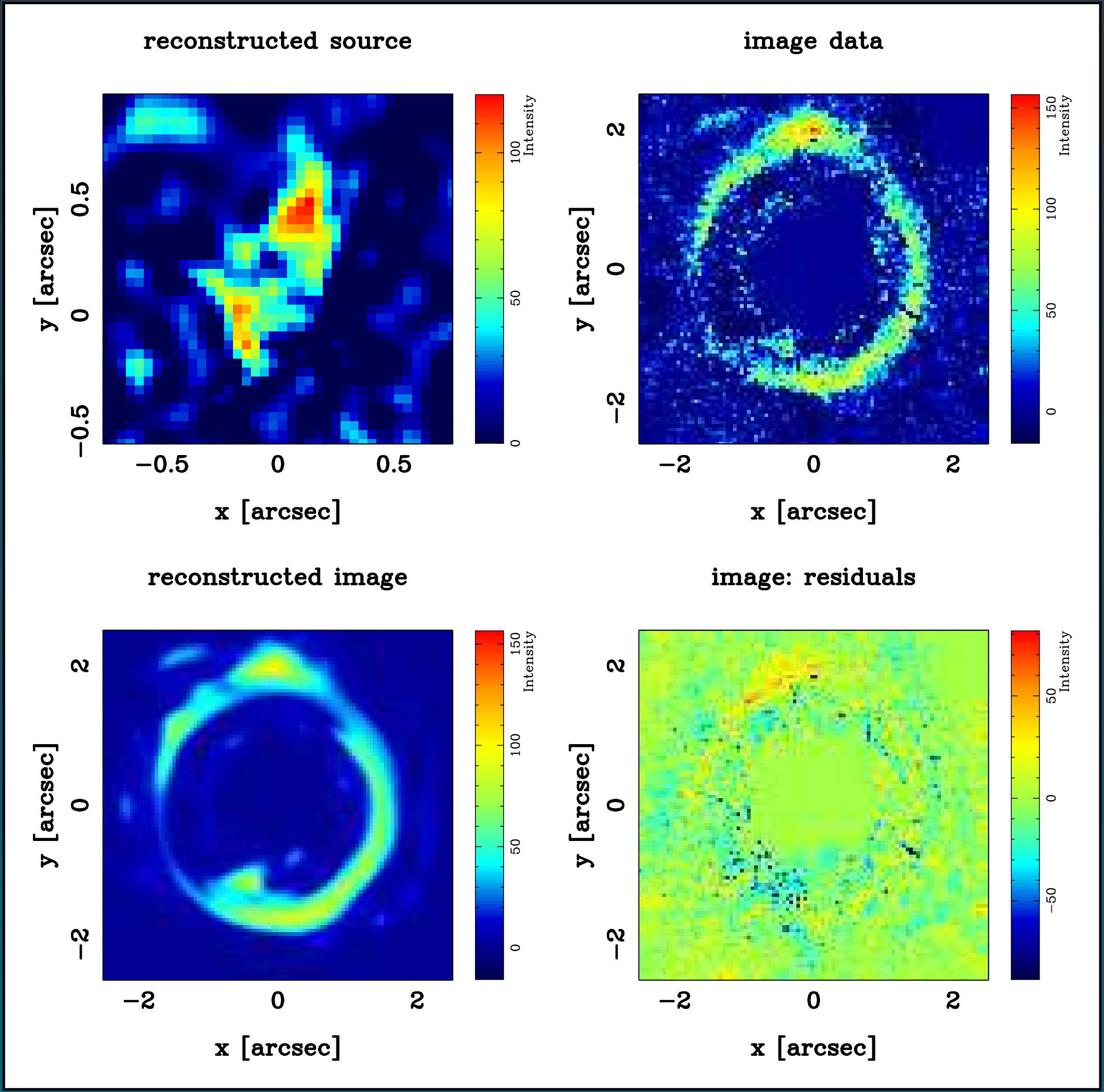


adopted model:
Power Law
$\rho(R,z) \propto (R_c^2 + R^2 + z^2/q^2)^{-\gamma}$

image grid $= 100 \times 100$

source grid $= 40 \times 40$

There are some problems with systematics...

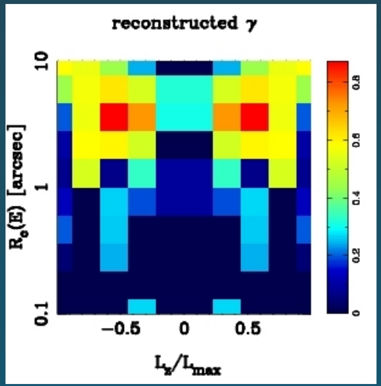


# J2321−097: preliminary analysis

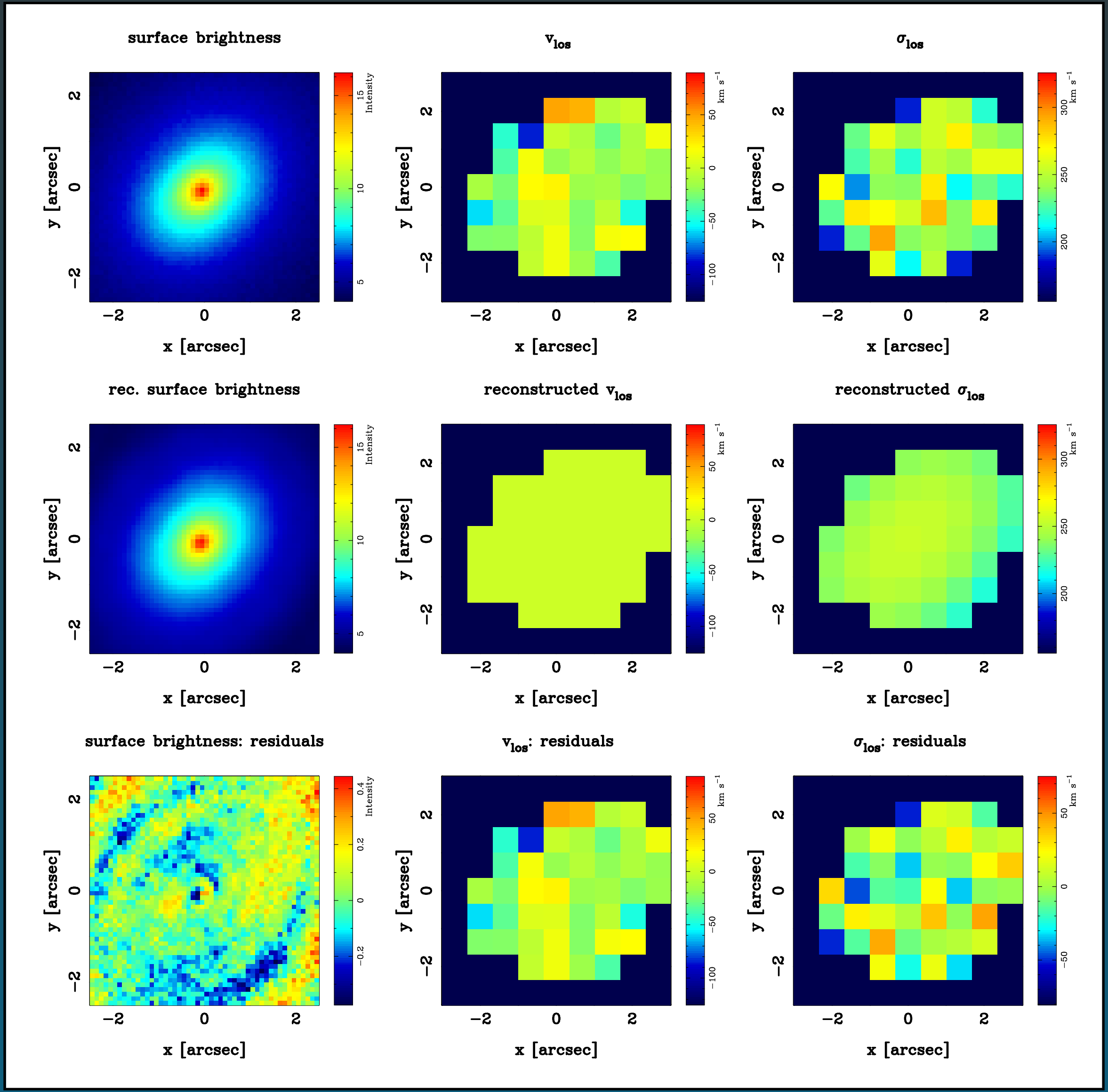
surface brightness grid $= 50 \times 50$

velocity moments grid $= 9 \times 9$
(only "spaxels" with $S/N > 8$ are used)

$N_{\mathrm{TIC}} = 100$

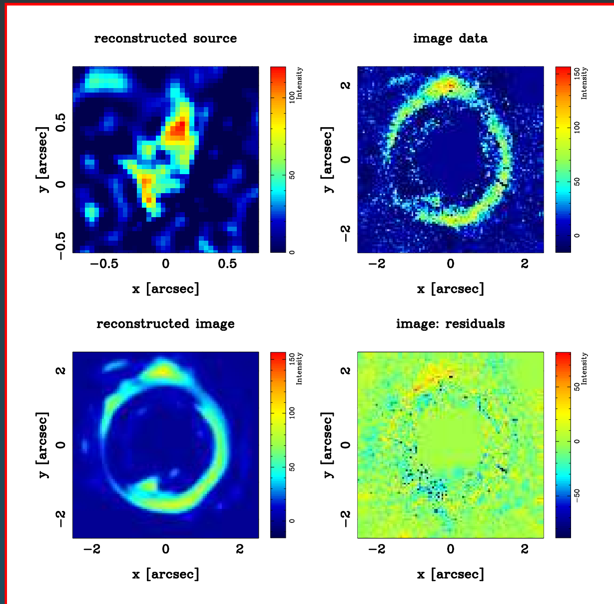



reconstructed distribution function



# J2321−097: preliminary analysis

**Lensing + Dynamics**

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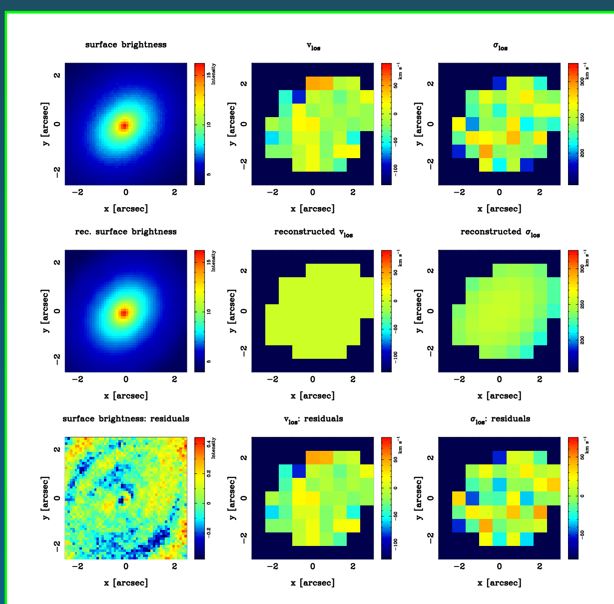



$$\rho(R,z) \propto \frac{1}{(R_c^2 + R^2 + z^2/q^2)^{\gamma}}$$

Best model:

- inclination: 36°
- position angle: 139°
- lens strength $\alpha_0 = 0.47$
- slope: $\gamma = 2.04$
- $q = 0.51$
- $R_c \sim 0$

# Summary

- High-quality data set of high-resolution VIMOS/IFU observations on 17 SLACS lenses
  $\Rightarrow$ two-dimensional maps of $\overline{v}_{\mathrm{los}}$ and $\sigma_{\mathrm{los}}$

- Complemented by "mock-IFU" observations from Keck on 13 systems (Treu, Gavazzi)

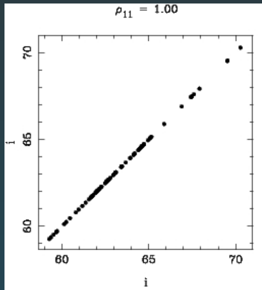
- CAULDRON: Self-consistent combined lensing and dynamics analysis in a Bayesian framework (Matteo Barnabè, Léon Koopmans)

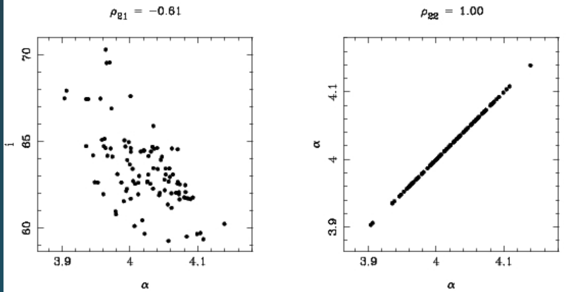
- Extensively tested on simulated "data"

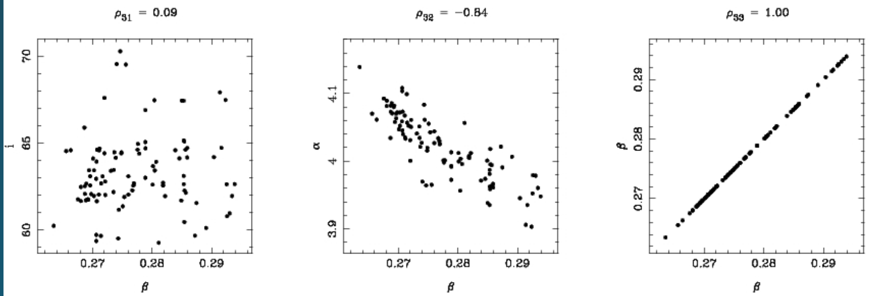
- Application to real data is only starting

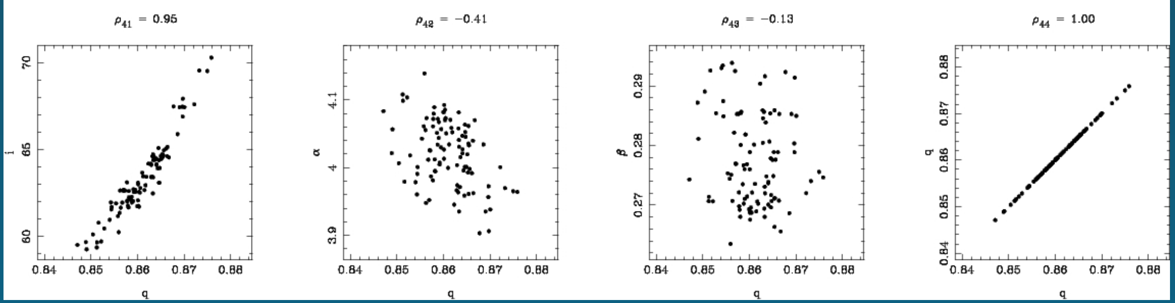
- Watch this place!

# Model uncertainties




- 100 random realizations of the test data
- as expected, sets $(i, q)$ and $(\alpha, \beta)$ are significantly correlated
- recovered parameters are quite tightly constrained (95% confidence levels)

| | median | 95% CL | $\eta_{\text{true}}$ |
|---|---|---|---|
| $i$ | 63.0 | 59.5…69.5 | 60 |
| $\alpha_0$ | 4.02 | 3.94…4.10 | 4.05 |
| $\beta$ | 0.276 | 0.266…0.293 | 0.280 |
| $q$ | 0.861 | 0.849…0.873 | 0.850 |

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