TDCOSMO IV: Hierarchical time-delay cosmography - joint inference of the Hubble constant and galaxy density profiles

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PhD student

(Affiliations can be found after the references)

Accepted XXX. Received YYY; in original form ZZZ

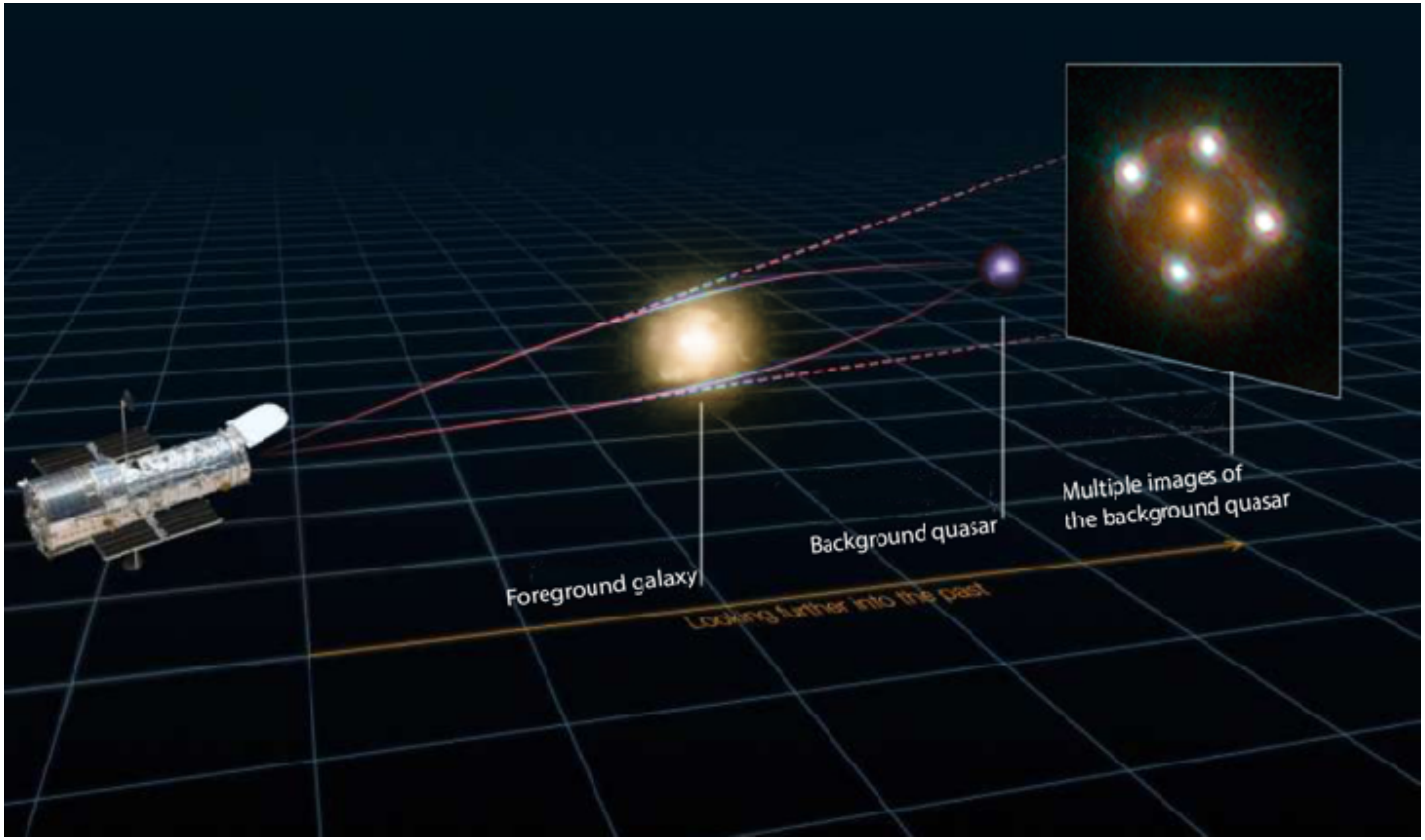
ABSTRACT

The H0LiCOW collaboration inferred via strong gravitational lensing time delays a Hubble constant value of $H_0 = 73.3^{+1.7}_{-1.8}$ km s^{-1}Mpc^{-1}, describing deflector mass density profiles by either a power-law or stars (constant mass-to-light ratio) plus standard dark matter halos. The mass-sheet transform (MST) that leaves the lensing observables unchanged is considered the dominant source of residual uncertainty in H_0. We quantify any potential effect of the MST with a flexible family of mass models that directly encodes it and are hence maximally degenerate with H_0. Our calculation is based on a new hierarchical Bayesian approach in which the MST is only constrained by stellar kinematics. The approach is validated on mock lenses generated from hydrodynamic simulations. We first apply the inference to the TDCOSMO sample of 7 lenses (6 from H0LiCOW) and measure $H_0 = 74.5^{+5.6}_{-6.1}$ km s^{-1}Mpc^{-1}.
Secondly, in order to further constrain the deflector mass density profiles, we add imaging and spectroscopy for a set of 33 strong gravitational lenses from the SLACS sample. For 9 of the 33 SLAC lenses, we use resolved kinematics to constrain the stellar anisotropy. From the joint hierarchical analysis of the TDCOSMO+SLACS sample, we measure $H_0 = 67.4^{+4.1}_{-3.2}$ km s^{-1}Mpc^{-1}. This measurement assumes that the TDCOSMO and SLACS galaxies are drawn from the same parent population. The **blind** H0LiCOW, TDCOSMO-only and TDCOSMO+SLACS analyses are in mutual statistical agreement. The TDCOSMO+SLACS analysis prefers marginally shallower mass profiles than H0LiCOW or TDCOSMO-only. Without relying on the form of the mass density profile used by H0LiCOW, we achieve a ∼5% measurement of H_0. While our new hierarchical analysis does not statistically invalidate the mass profile assumptions by H0LiCOW – and thus their H_0 measurement relying on those – it demonstrates the importance of understanding the mass density profile of elliptical galaxies. The uncertainties on H_0 derived in this paper can be reduced by physical or observational priors on the form of the mass profile, or by additional data. The full analysis is available here.

Validated! Blind! Public!

https://github.com/TDCOSMO/hierarchy_analysis_2020_public **arXiv:2007.02941**

Time-delay cosmography



credit: M. Millon

absolute scale

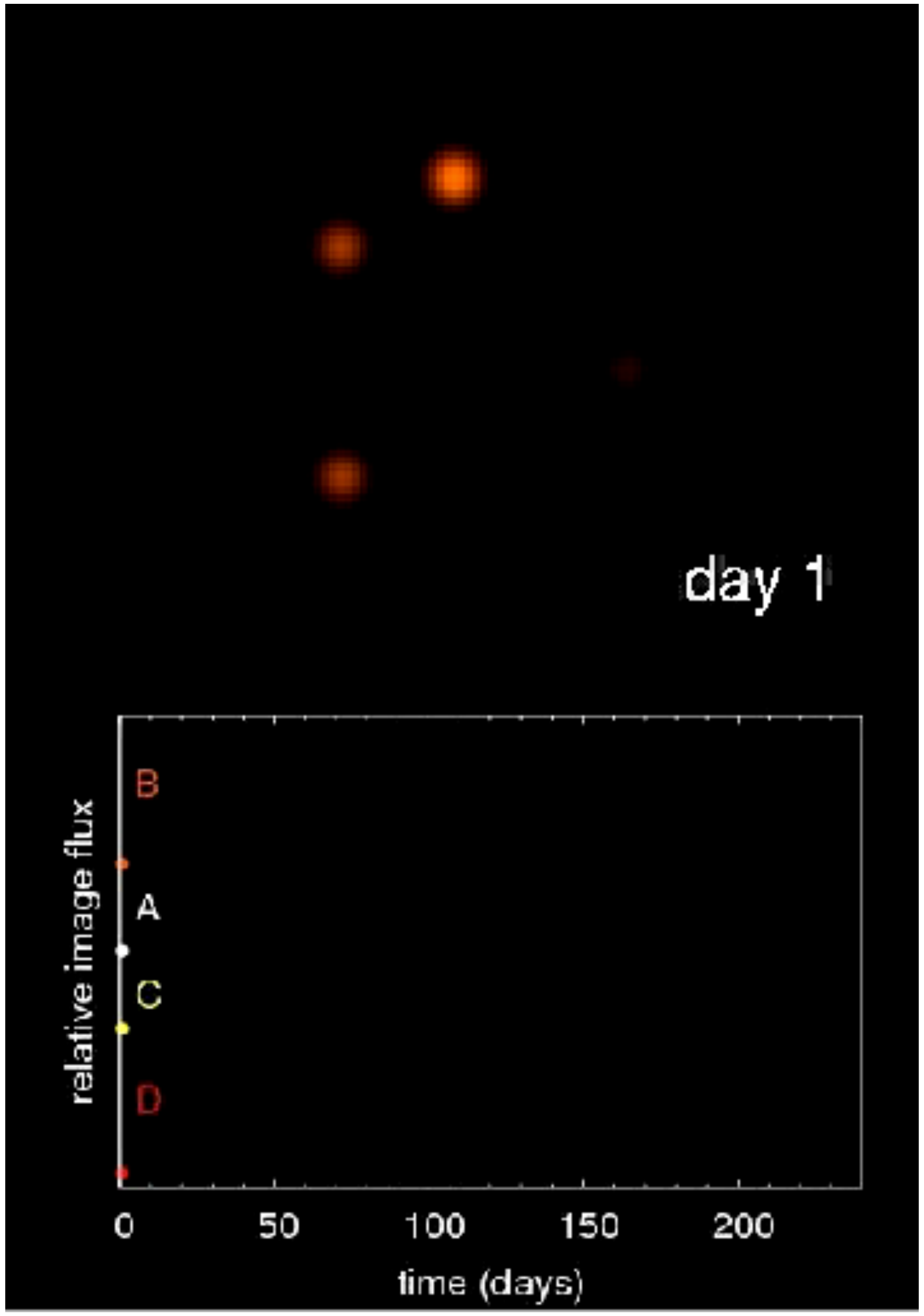
path difference

lensing potential

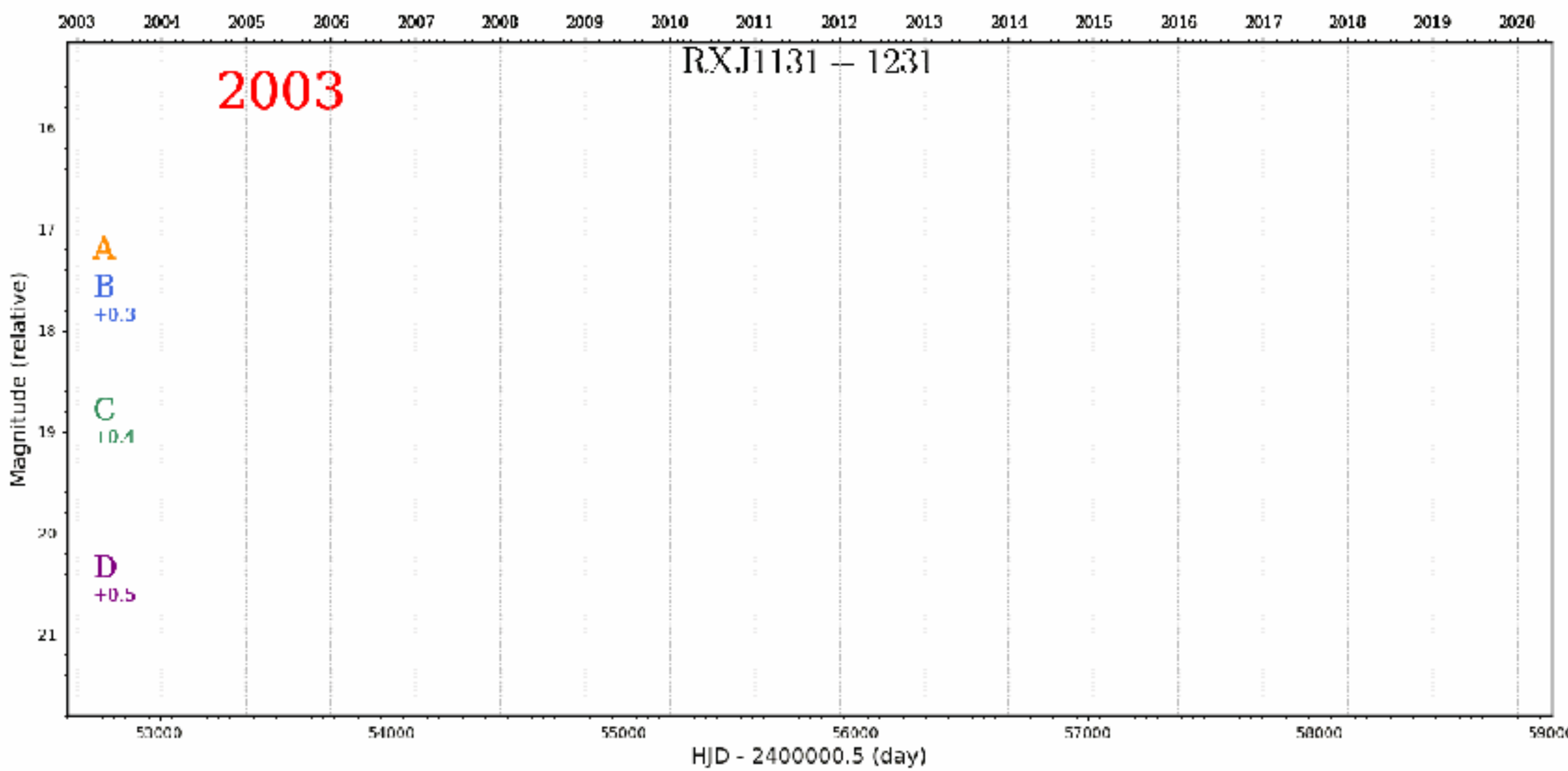
$$t(\boldsymbol{\theta}, \boldsymbol{\beta}) = \frac{(1 + z_\mathrm{d})}{c} \frac{D_\mathrm{d} D_\mathrm{s}}{D_\mathrm{ds}} \left[\frac{(\boldsymbol{\theta} - \boldsymbol{\beta})^2}{2} - \psi(\boldsymbol{\theta}) \right]$$

Time-delay cosmography

- If source is variable, there is a “time delay” between the multiple images
- Allows to probe absolute distances of the source-lens-observer configuration
- Provides a physical anchor of the scales at intermediate redshifts, *independent of CMB and distance ladder*



credit: S. Suyu, C. Fassnacht

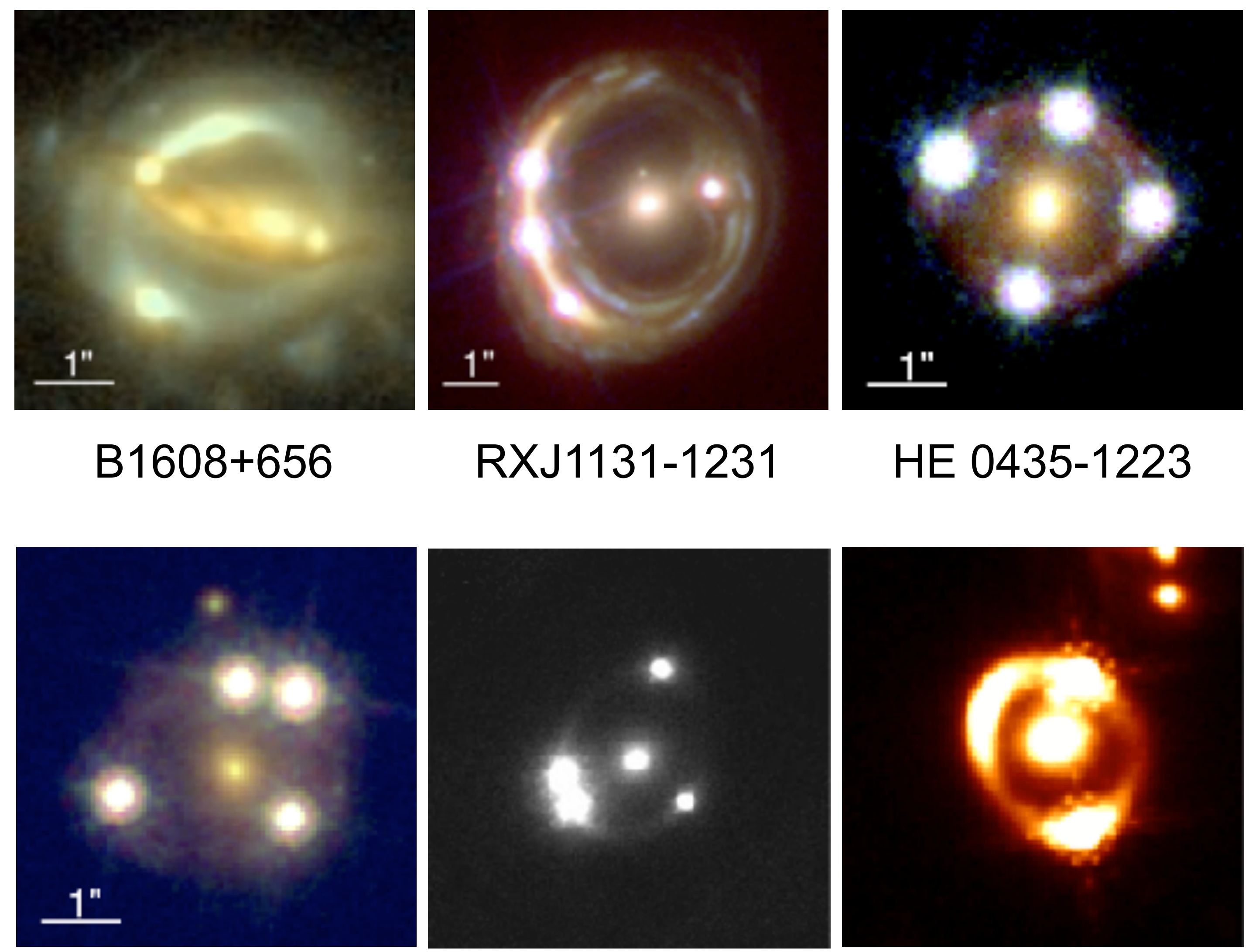


credit: F. Courbin, M. Millon

TDCOSMO project

(H0LiCOW+COSMOGRAIL+ STRIDES+SHARP)

- Detailed analysis of several time-delay lenses (Suyu+2017)
  - long term monitoring from COSMOGRAIL (Courbin+2011) or VLA (Fassnacht+2002) for accurate time delays
  - high-resolution *HST* or AO imaging for detailed lens modeling
  - wide-field imaging/spectroscopy to characterize mass along LOS
- Goal is to constrain H_0 to ~few % precision
- Seven lenses have been analyzed (Suyu+2010, 2013; Wong+2017, Birrer+2019, Rusu+2019, Chen+2019, Shajib+2019), more coming

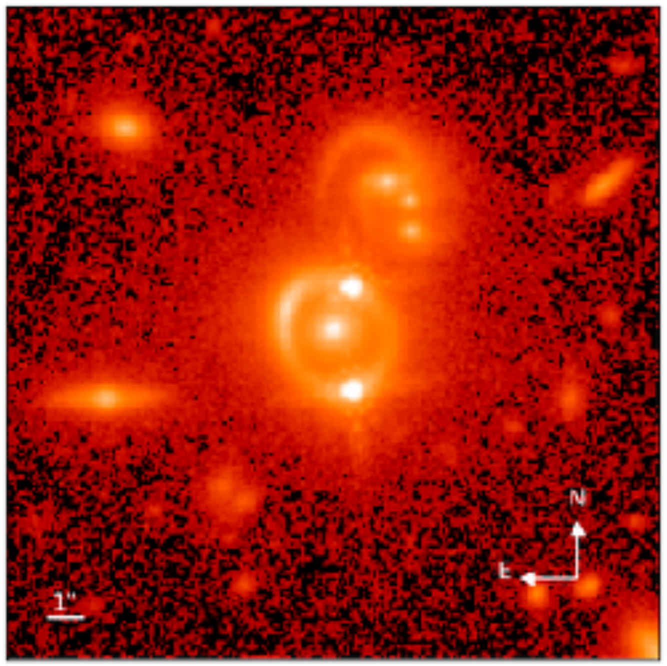


B1608+656 | RXJ1131-1231 | HE 0435-1223

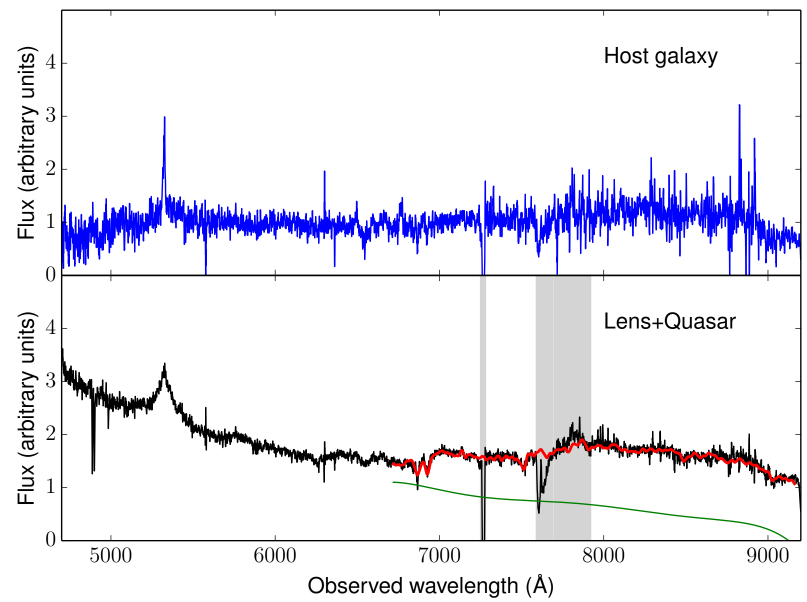
WFI2033-4723 | PG1115+080 | SDSS J1206+4432

Single lens - multiple data sets

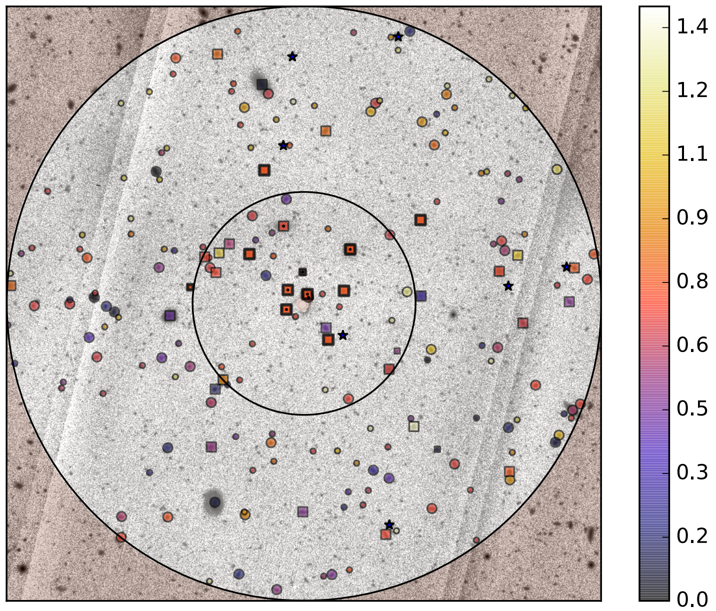
high resolution image

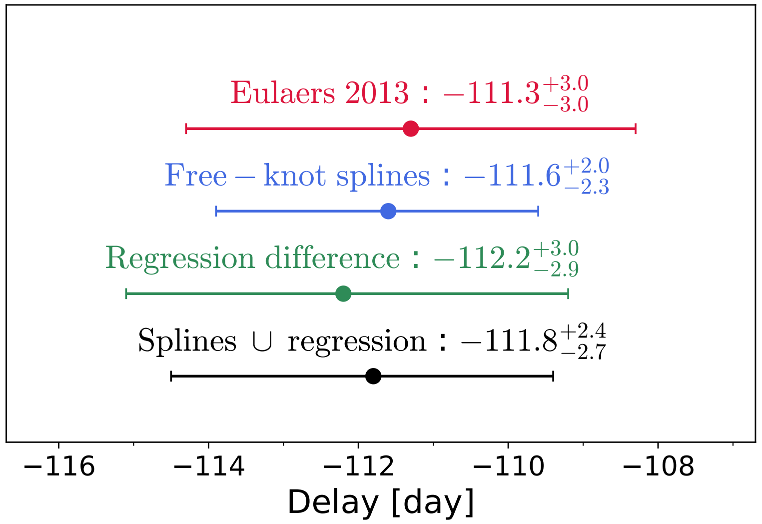


stellar kinematics



line of sight





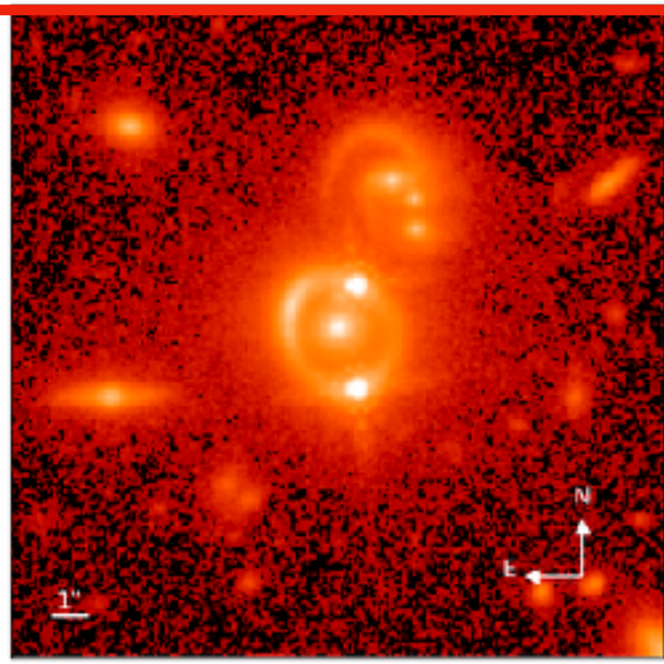
$$P(\boldsymbol{d}_{\mathrm{J1206}}|D_{\mathrm{d,s,ds}}) = P(\Delta t_{AB}|D_{\mathrm{d,s,ds}}) \times P(\sigma^{\mathrm{P}}|D_{\mathrm{d,s,ds}}) \times P(\boldsymbol{I}_{HST}|D_{\mathrm{d,s,ds}}) \times P(\boldsymbol{d}_{\mathrm{env}}|D_{\mathrm{d,s,ds}})$$

$$P(\boldsymbol{d}_{\mathrm{J1206}}|D_{\mathrm{d,s,ds}}) = \int P(\boldsymbol{I}_{HST}|\boldsymbol{\xi}_{\mathrm{lens}}, \boldsymbol{\xi}_{\mathrm{light}})P(\boldsymbol{\xi}_{\mathrm{lens}}, \boldsymbol{\xi}_{\mathrm{light}}) \times P(\boldsymbol{d}_{\mathrm{env}}|\kappa_{\mathrm{ext}})P(\kappa_{\mathrm{ext}}) \times P(\Delta t_{AB}|D_{\mathrm{d,s,ds}}, \boldsymbol{\xi}_{\mathrm{lens}}, \boldsymbol{\xi}_{\mathrm{micro}}, \kappa_{\mathrm{ext}}) \times P(\sigma^{\mathrm{P}}|D_{\mathrm{d,s,ds}}, \boldsymbol{\xi}_{\mathrm{lens}}, \boldsymbol{\xi}_{\mathrm{light}}, \kappa_{\mathrm{ext}}, \beta_{\mathrm{ani}}) d\boldsymbol{\xi}_{\mathrm{lens,light,micro}} d\kappa_{\mathrm{ext}} d\beta_{\mathrm{ani}}$$

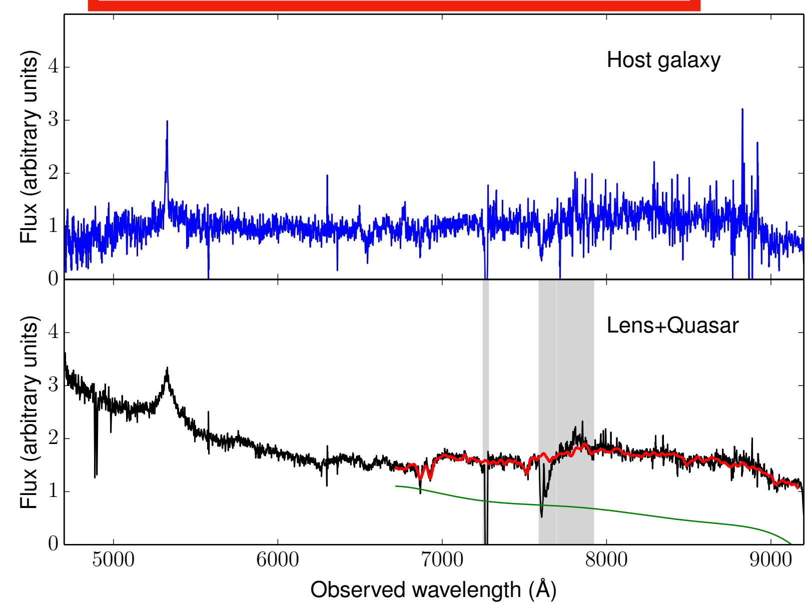
example of Birrer+2019; see also Suyu+2010,2013, Wong+2017, Chen+2020, Rusu+2020, Shajib+2020

Single lens - multiple data sets

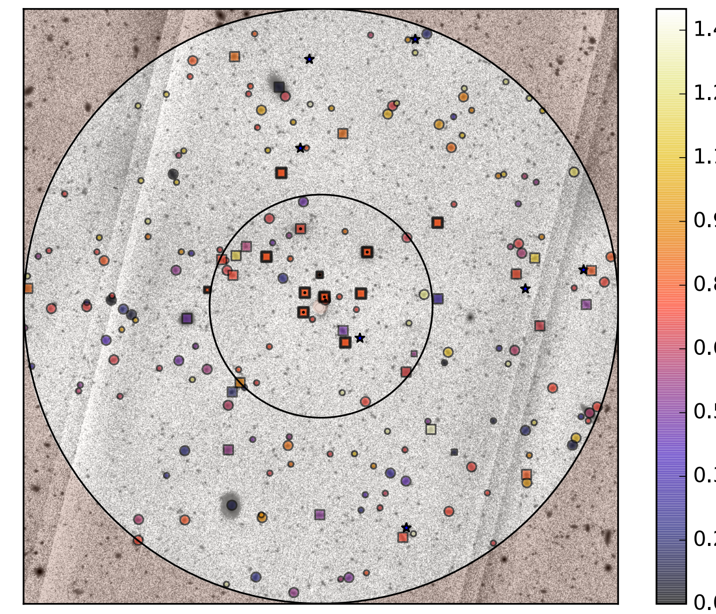
high resolution image

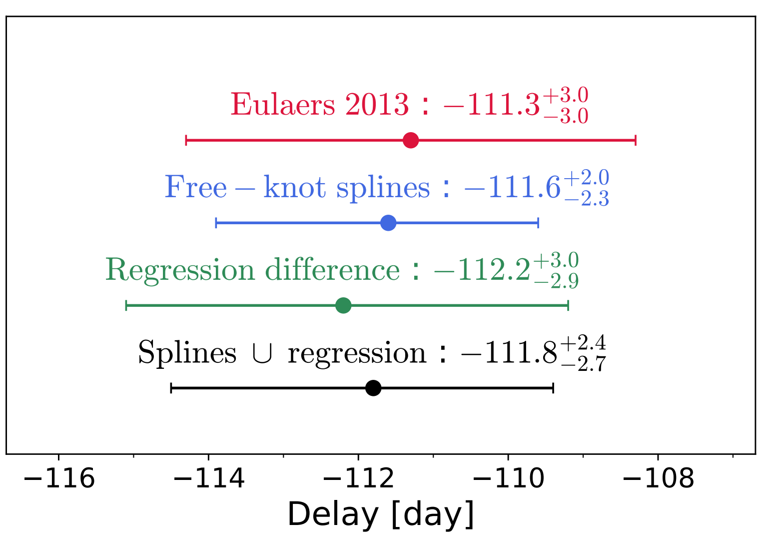


stellar kinematics



line of sight





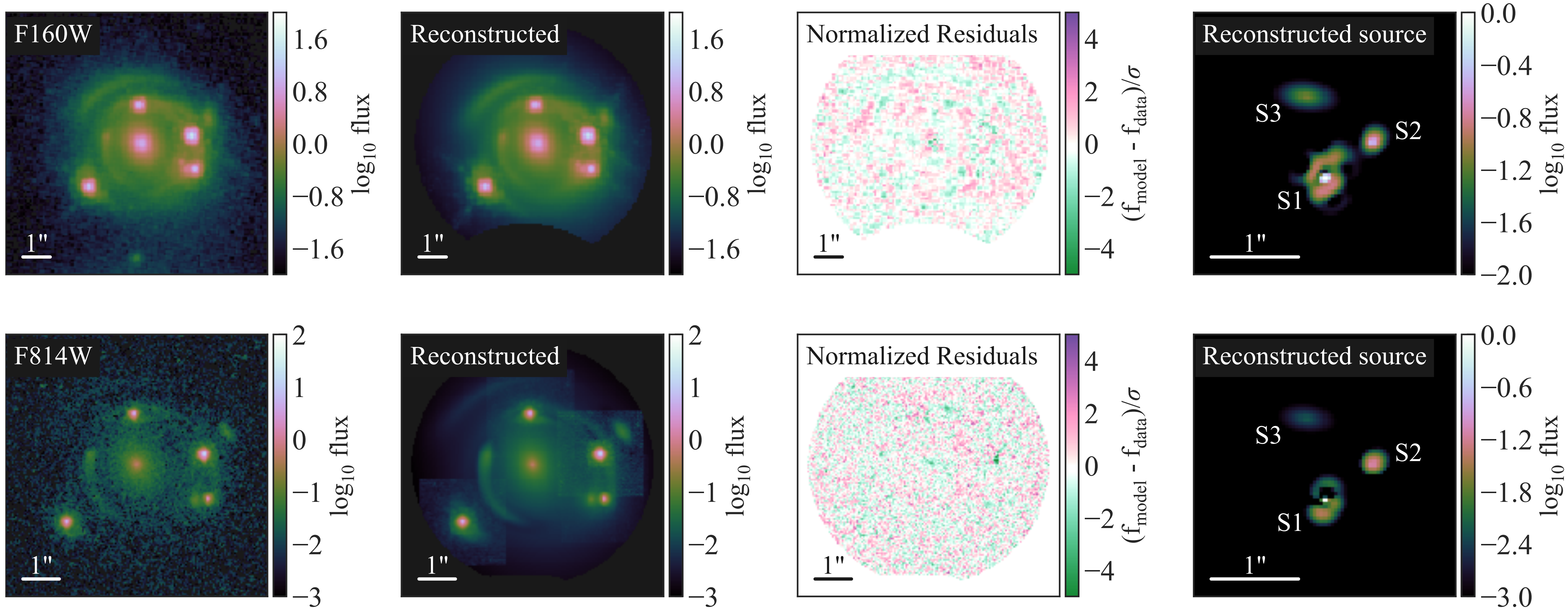
$$P(\boldsymbol{d}_{\rm J1206}|D_{\rm d,s,ds}) = P(\Delta t_{AB}|D_{\rm d,s,ds}) \times P(\sigma^{\rm P}|D_{\rm d,s,ds}) \times P(\boldsymbol{I}_{HST}|D_{\rm d,s,ds}) \times P(\boldsymbol{d}_{\rm env}|D_{\rm d,s,ds})$$

$$P(\boldsymbol{d}_{\rm J1206}|D_{\rm d,s,ds}) = \int P(\boldsymbol{I}_{HST}|\boldsymbol{\xi}_{\rm lens},\boldsymbol{\xi}_{\rm light})P(\boldsymbol{\xi}_{\rm lens},\boldsymbol{\xi}_{\rm light}) \times P(\boldsymbol{d}_{\rm env}|\kappa_{\rm ext})P(\kappa_{\rm ext}) \times P(\Delta t_{AB}|D_{\rm d,s,ds},\boldsymbol{\xi}_{\rm lens},\boldsymbol{\xi}_{\rm micro},\kappa_{\rm ext}) \times P(\sigma^{\rm P}|D_{\rm d,s,ds},\boldsymbol{\xi}_{\rm lens},\boldsymbol{\xi}_{\rm light},\kappa_{\rm ext},\beta_{\rm ani})d\boldsymbol{\xi}_{\rm lens,light,micro}d\kappa_{\rm ext}d\beta_{\rm ani}$$

example of Birrer+2019; see also Suyu+2010,2013, Wong+2017, Chen+2020, Rusu+2020, Shajib+2020

Forward modeling in action

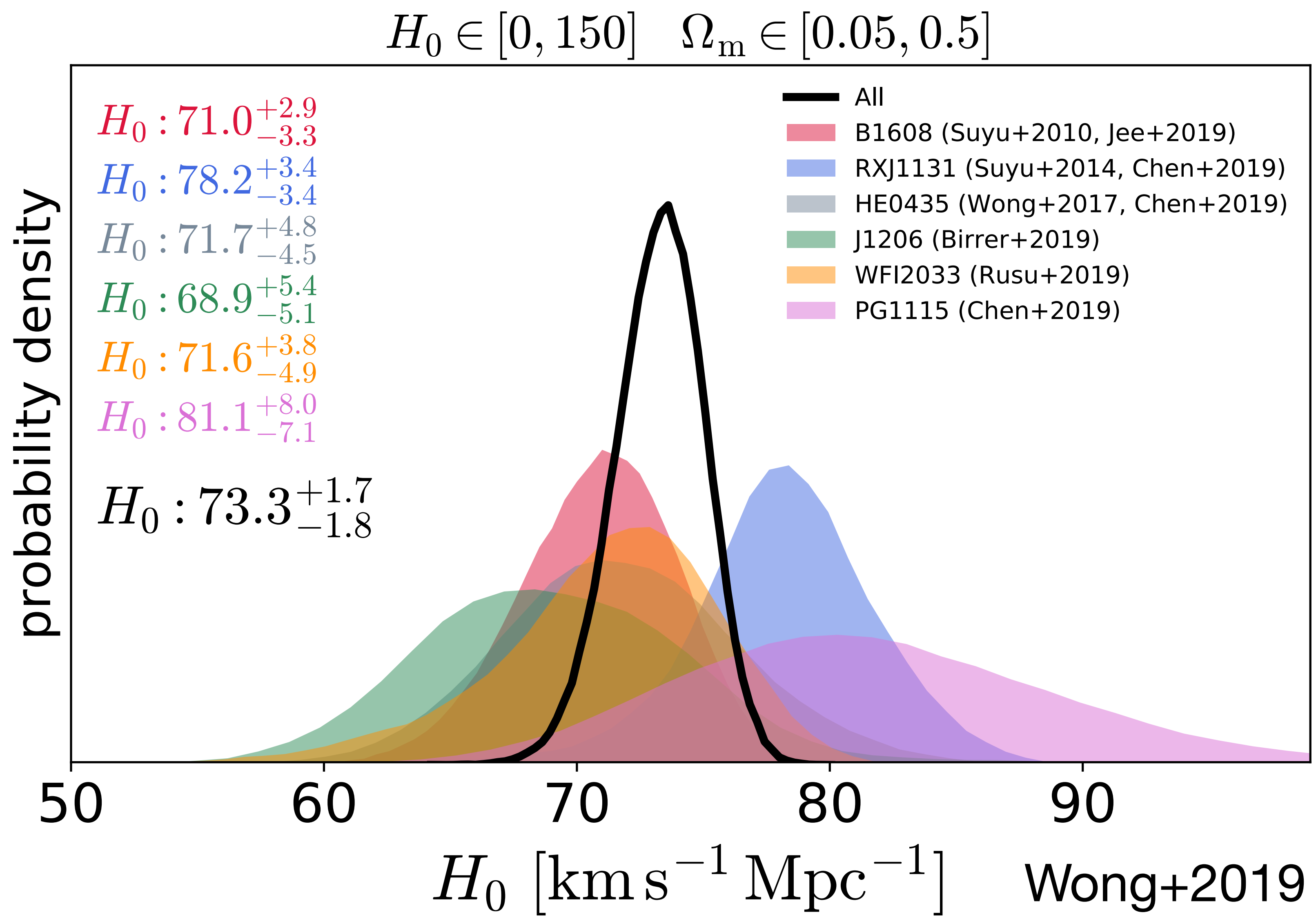
STRIDES: A 3.9 per cent measurement of the Hubble constant from the strong lens system DES J0408−5354



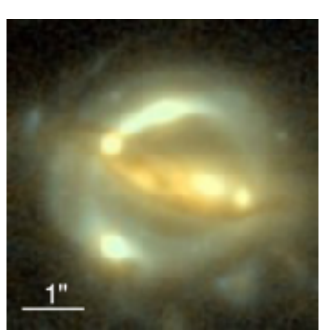
- Data vector ~3 x 10^4 (likelihood defined on pixel level)
- Nonlinear parameters: ~60
- Linear parameters: ~100
- Nested sampling of nonlinear parameter space while reconstruction the source each time
- No substructure being modeled (yet)

Shajib, SB+ 2019 STRiDES collaboration

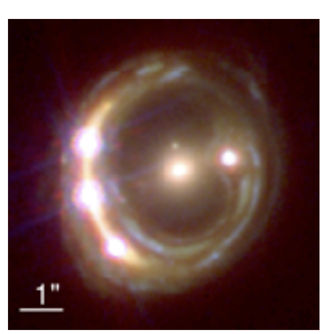
Previous results from the H0LiCOW collaboration



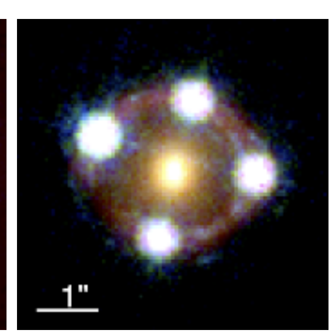
assuming:
- **independence**
- **mass profile family**



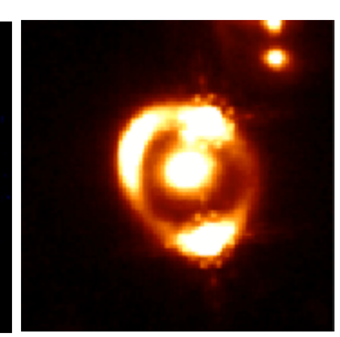
B1608+656

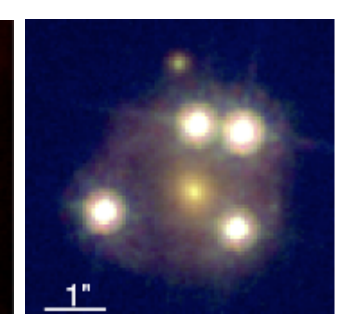


RXJ1131-1231

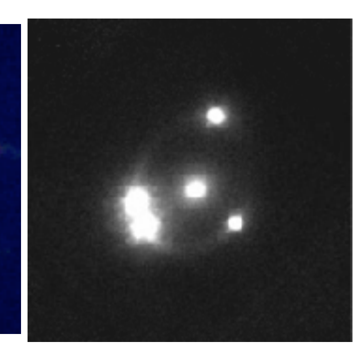


HE 0435-1223

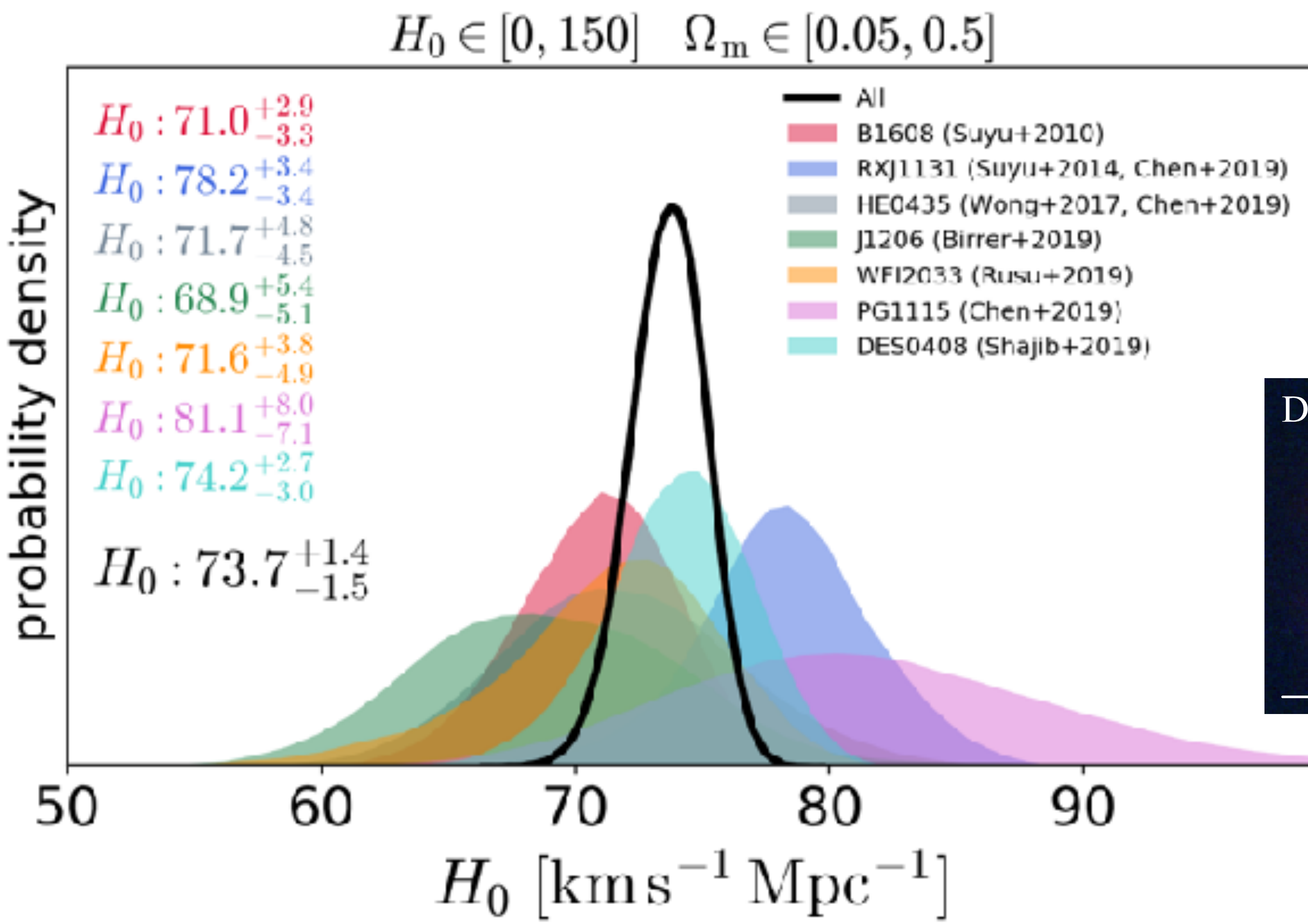

SDSS J1206+4432



WFI2033-4723

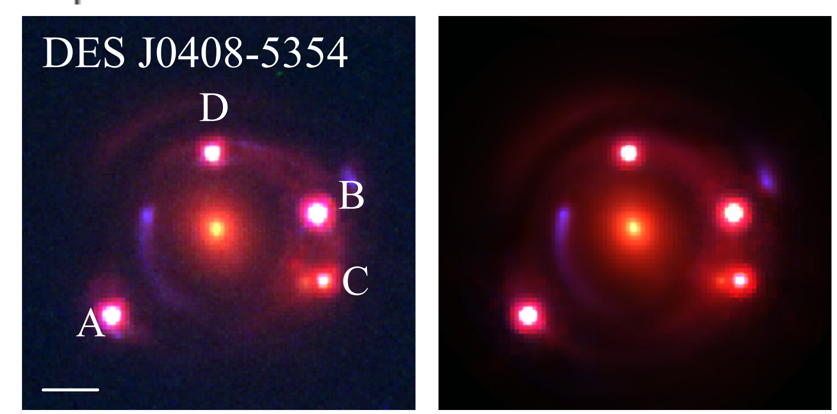

PG1115+080

Previous results from the H0LiCOW+STRIDES collaboration

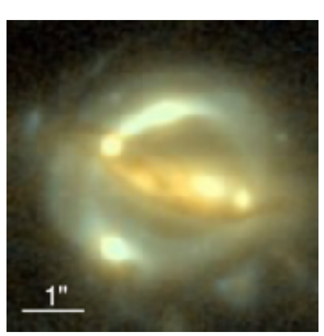


assuming:

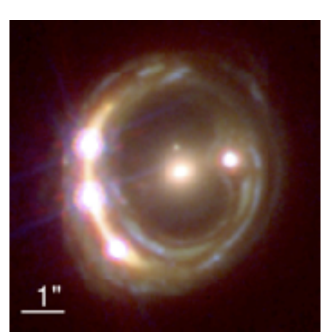
- **independence**
- **mass profile family**



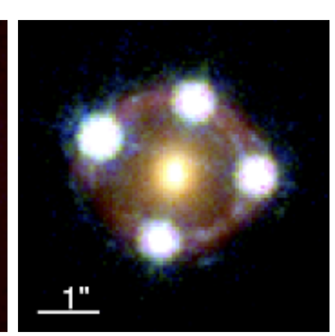
Shajib, SB+ 2020



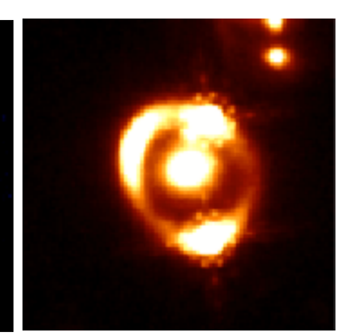
B1608+656



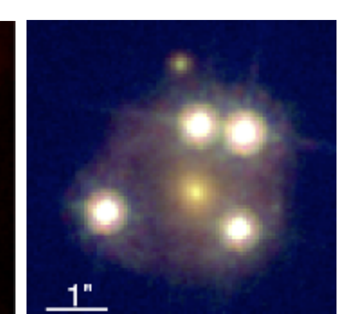
RXJ1131-1231



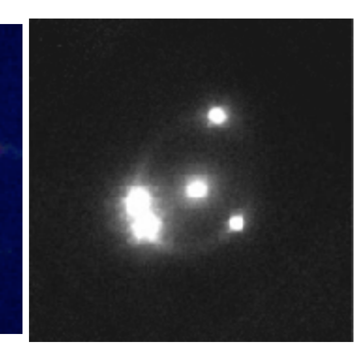
HE 0435-1223



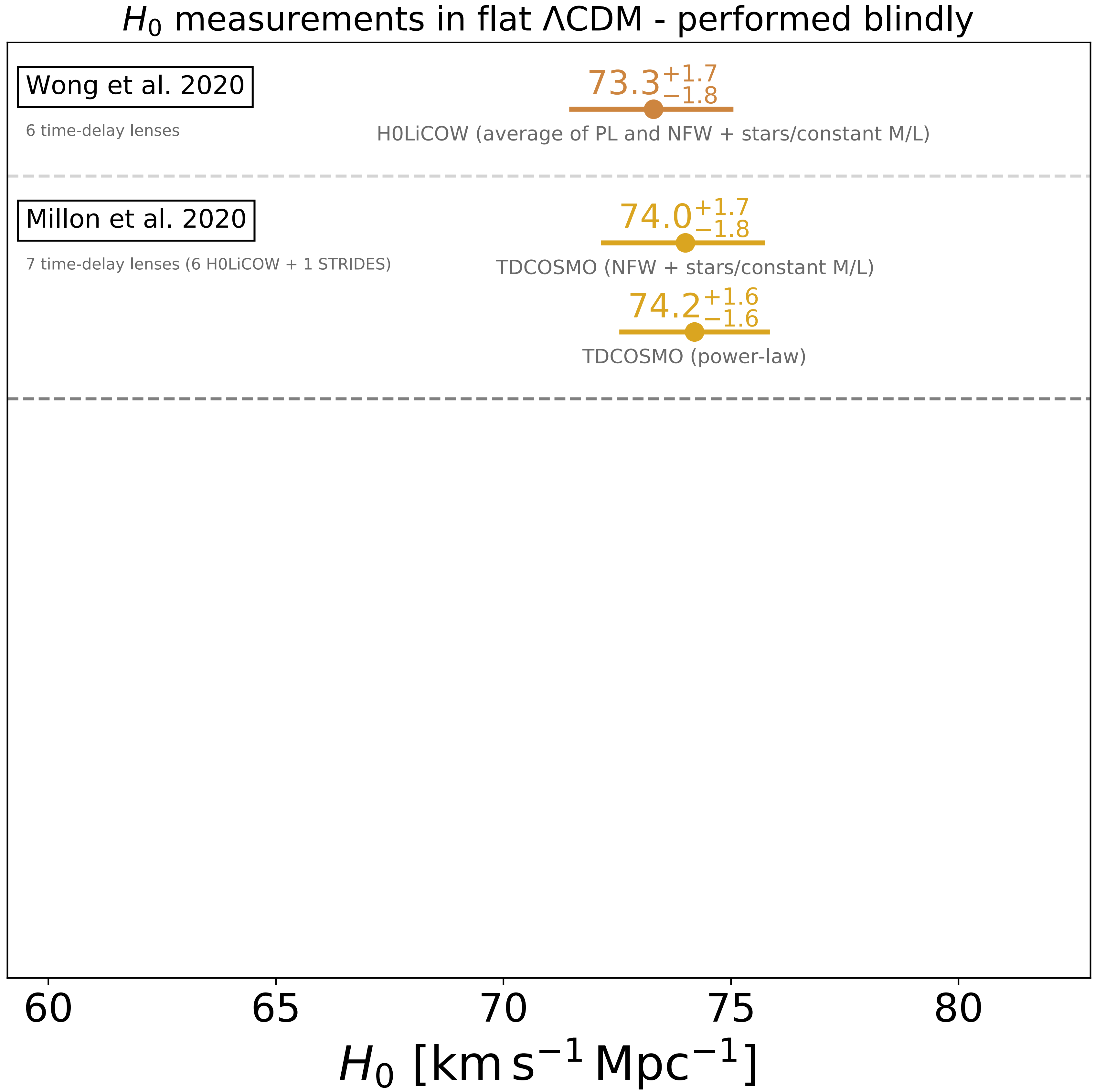
SDSS J1206+4432



WFI2033-4723

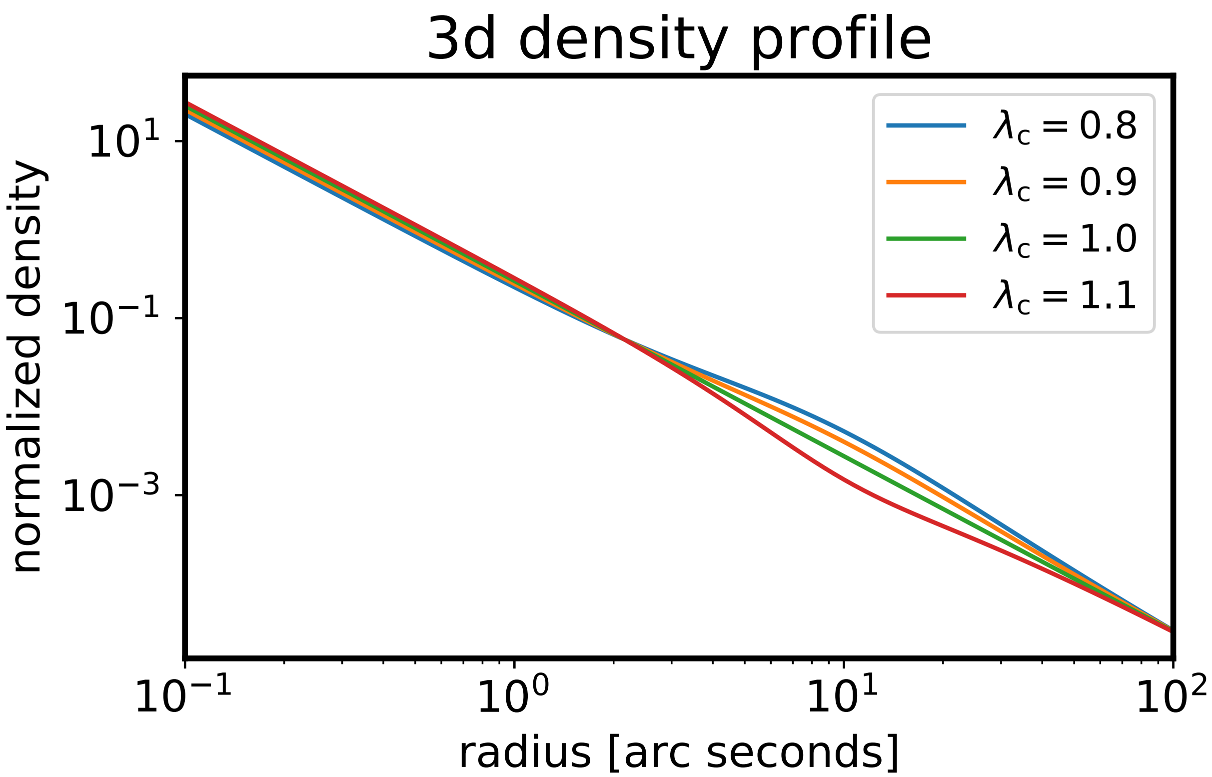


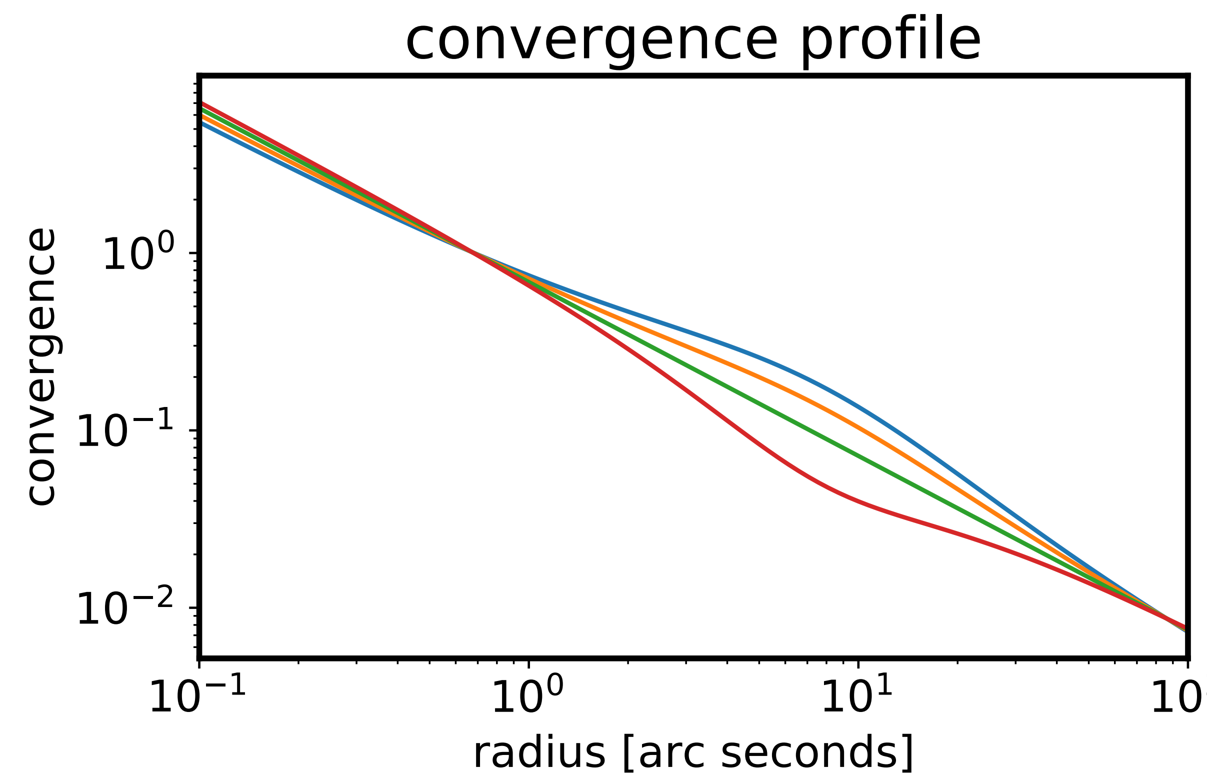
PG1115+080



H_0 measurements in flat ΛCDM - performed blindly
Wong et al. 2020
6 time-delay lenses
$73.3^{+1.7}_{-1.8}$
H0LiCOW (average of PL and NFW + stars/constant M/L)
Millon et al. 2020
7 time-delay lenses (6 H0LiCOW + 1 STRIDES)
$74.0^{+1.7}_{-1.8}$
TDCOSMO (NFW + stars/constant M/L)
$74.2^{+1.6}_{-1.6}$
TDCOSMO (power-law)
60
65
70
75
80
H_0 [km s^{-1} Mpc^{-1}]

"mass-sheet degeneracy" (Falco 1985)





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

$$\lambda\boldsymbol{\beta} = \boldsymbol{\theta} - \lambda\boldsymbol{\alpha}(\boldsymbol{\theta}) - (1 - \lambda)\boldsymbol{\theta}$$

$$\kappa_{\lambda}(\theta) = \lambda \times \kappa(\theta) + (1 - \lambda)$$

$$H_{0\,\lambda} = \lambda H_0$$

Gorenstein+1988, Kochanek 2002, Saha&Williams 2006,
Kochanek 2006, Read+2007, Schneider&Sluse 2013/2014,
Coles+2014, Xu+2016, Birrer+2016, Unruh+2017,
Sonnenfeld 2018, Wertz+2018, Kochanek 2020a, b,Blum+2020

TDCOSMO IV: Hierarchical time-delay cosmography - joint inference of the Hubble constant and galaxy density profiles

assumptions

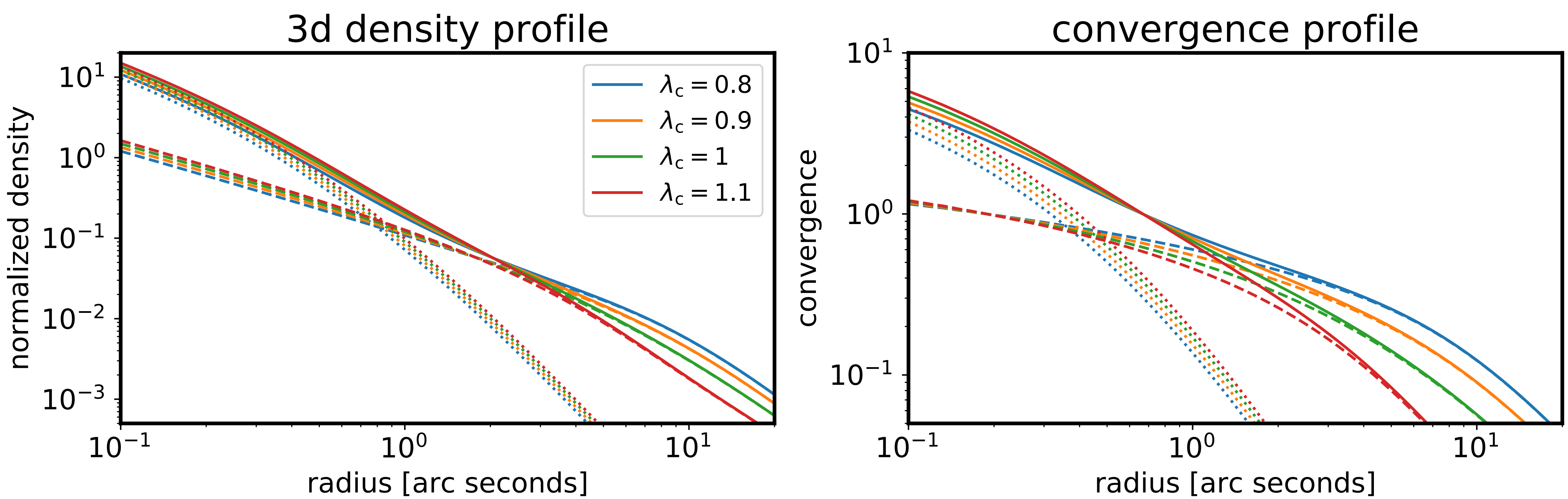
+

data

assumptions

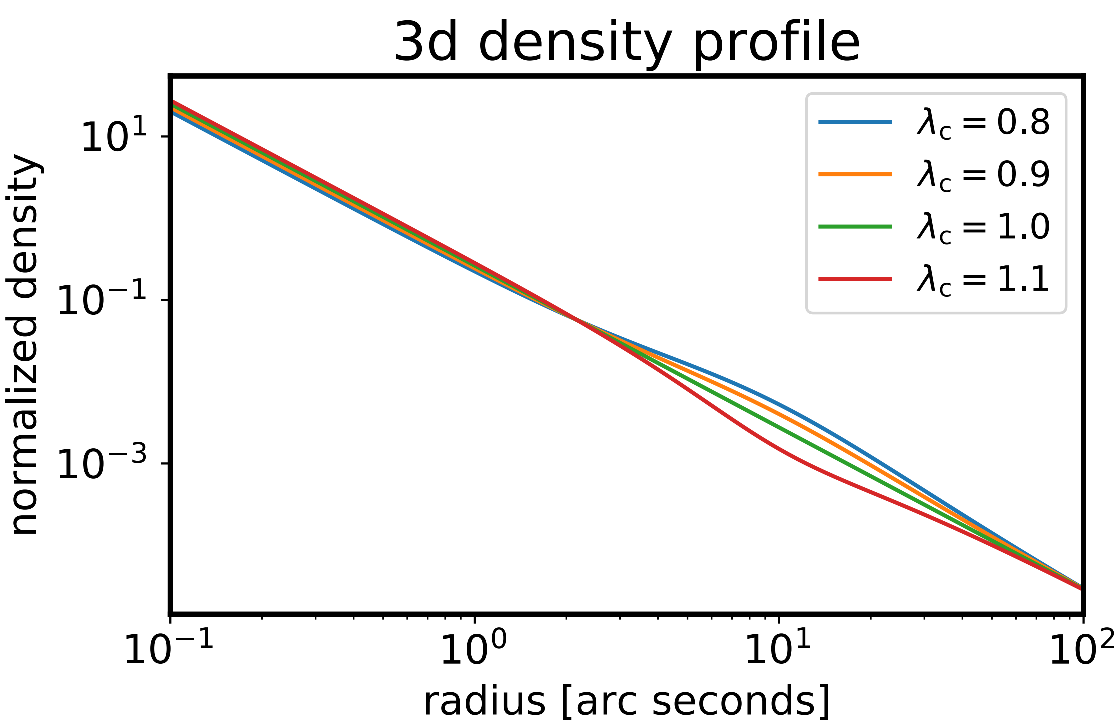
+

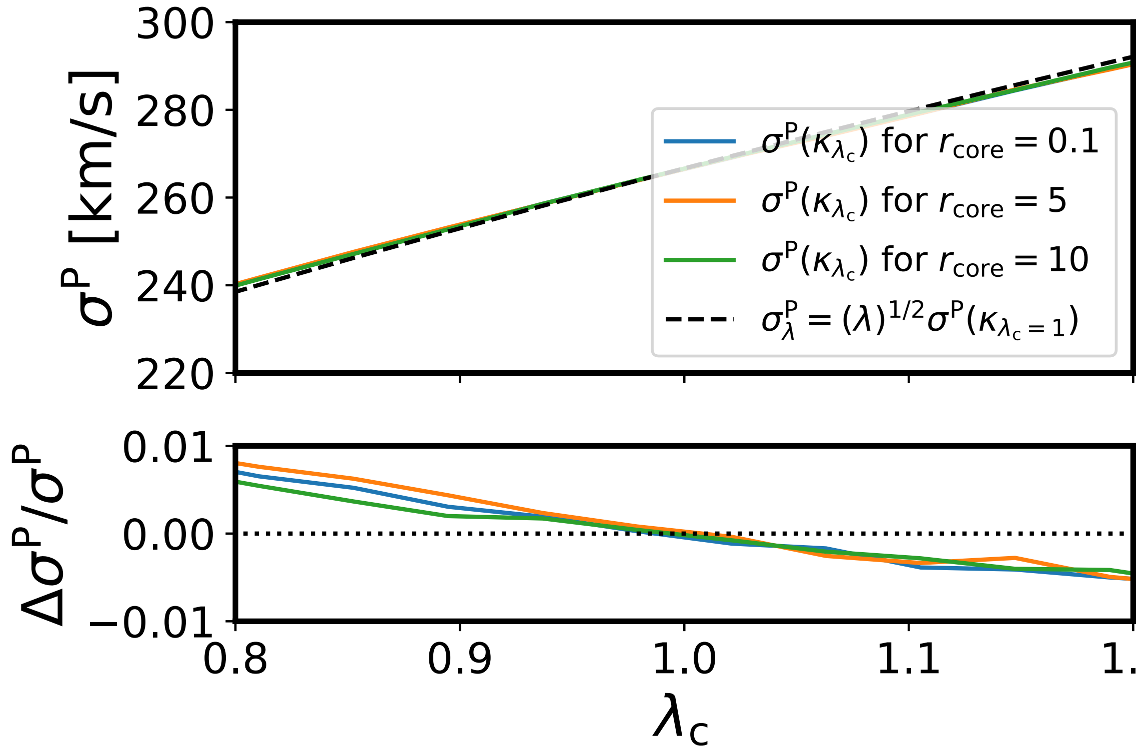
data



$$t(\boldsymbol{\theta}, \boldsymbol{\beta}) = \frac{(1 + z_\mathrm{d})}{c} \frac{D_\mathrm{d} D_\mathrm{s}}{D_\mathrm{ds}} \left[\frac{(\boldsymbol{\theta} - \boldsymbol{\beta})^2}{2} - \psi(\boldsymbol{\theta}) \right]$$

Velocity dispersion measurements of the deflector galaxy can break the mass-sheet degeneracy

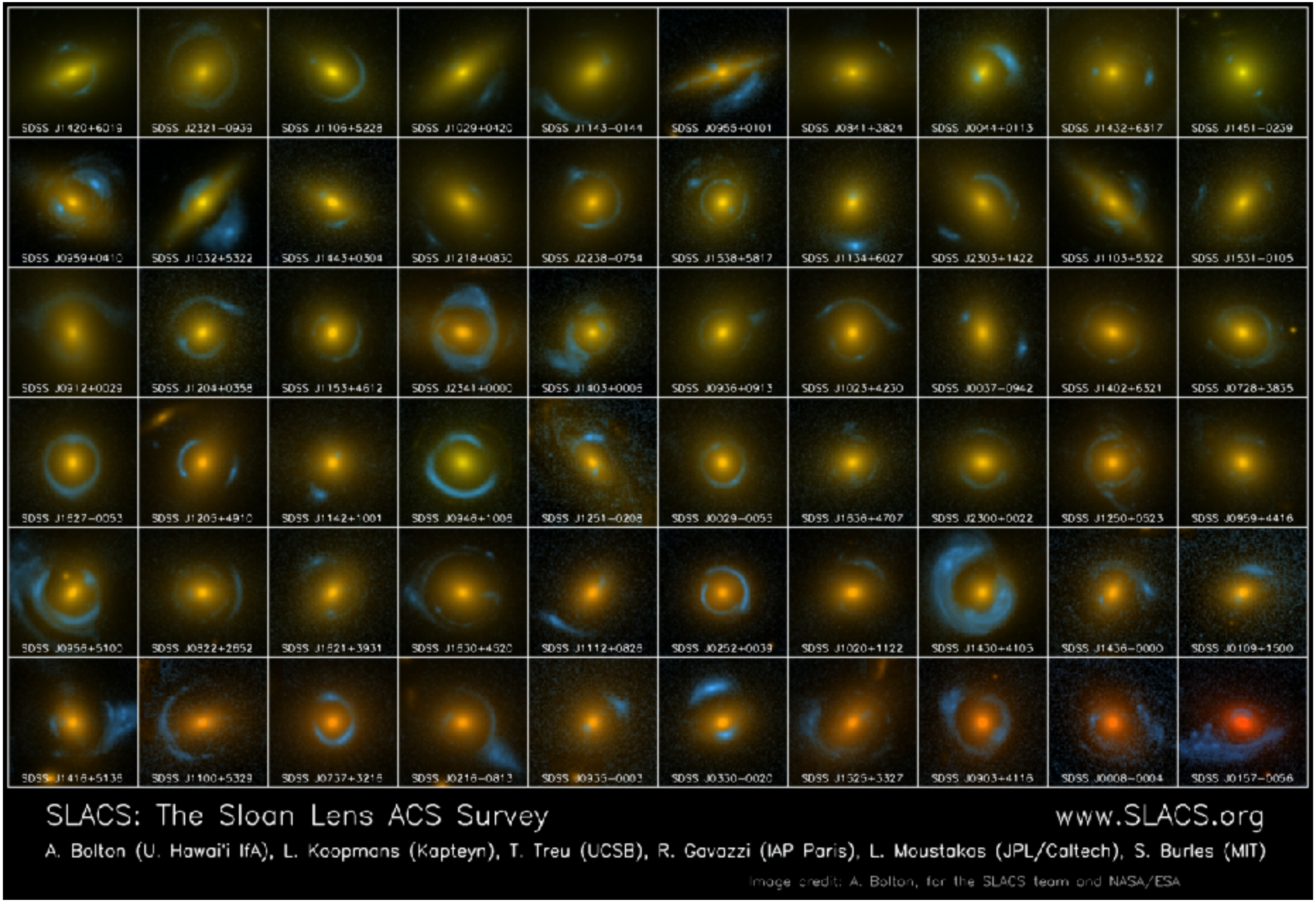




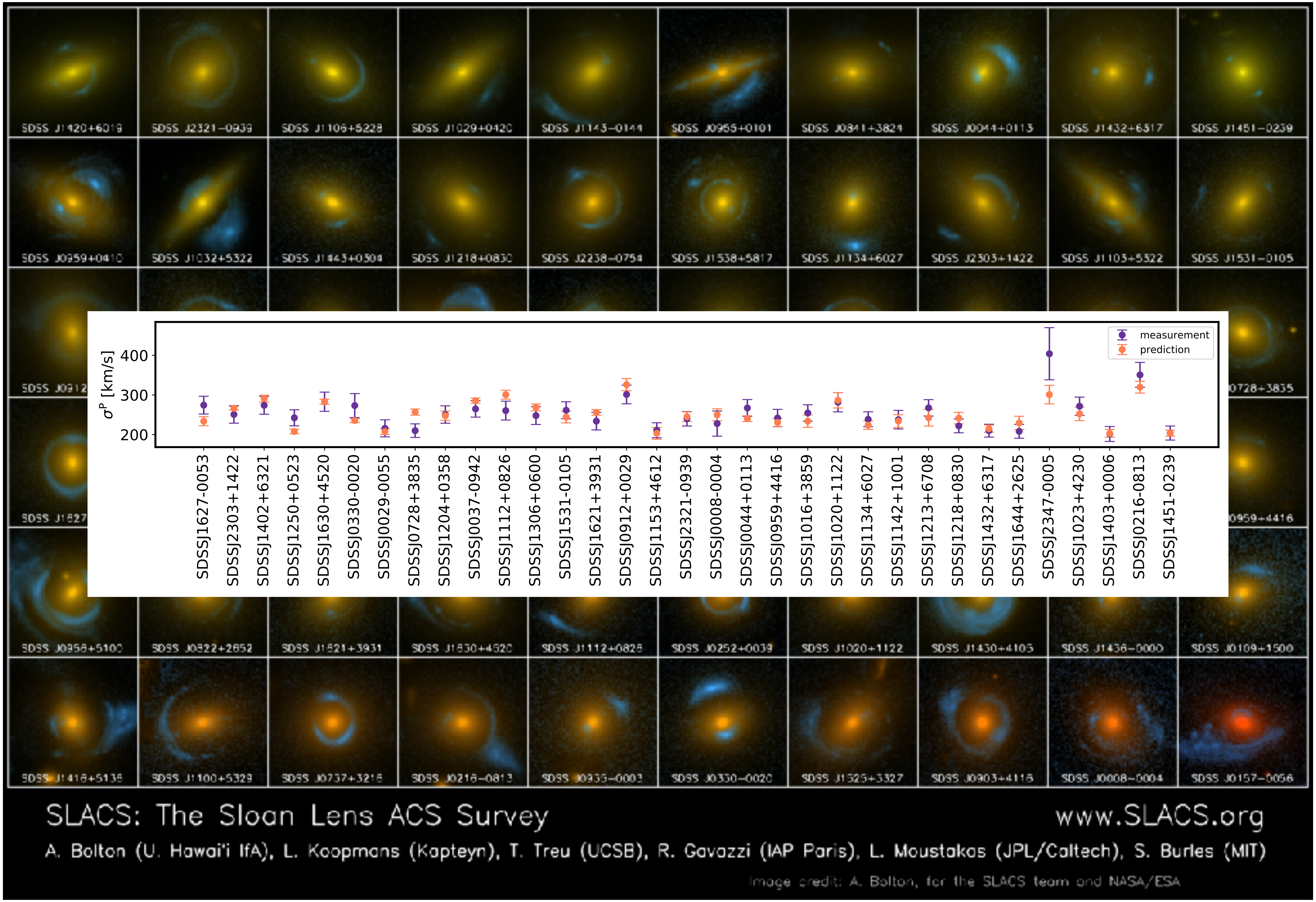
$$\kappa_\lambda(\theta) = \lambda \times \kappa(\theta) + (1 - \lambda)$$

$$H_{0\,\lambda} = \lambda H_0$$

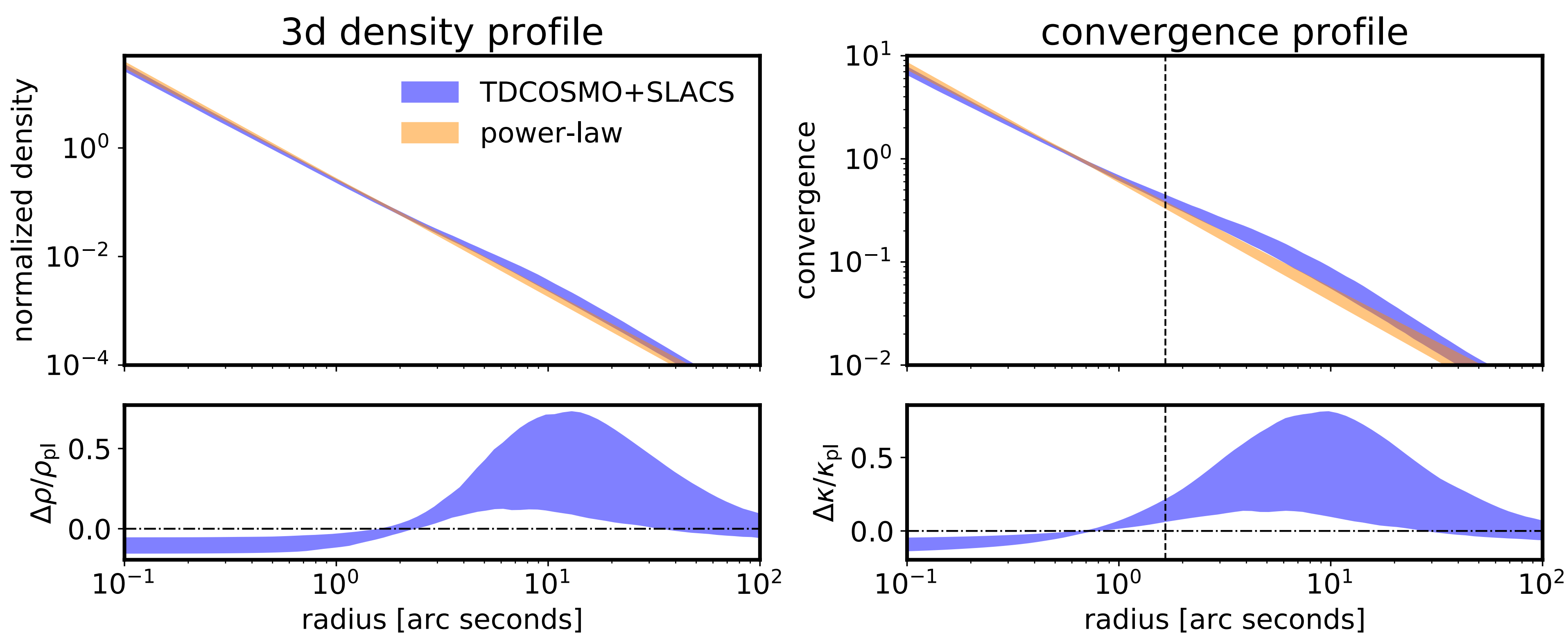
Constraining galaxy density profiles with lensing and kinematics

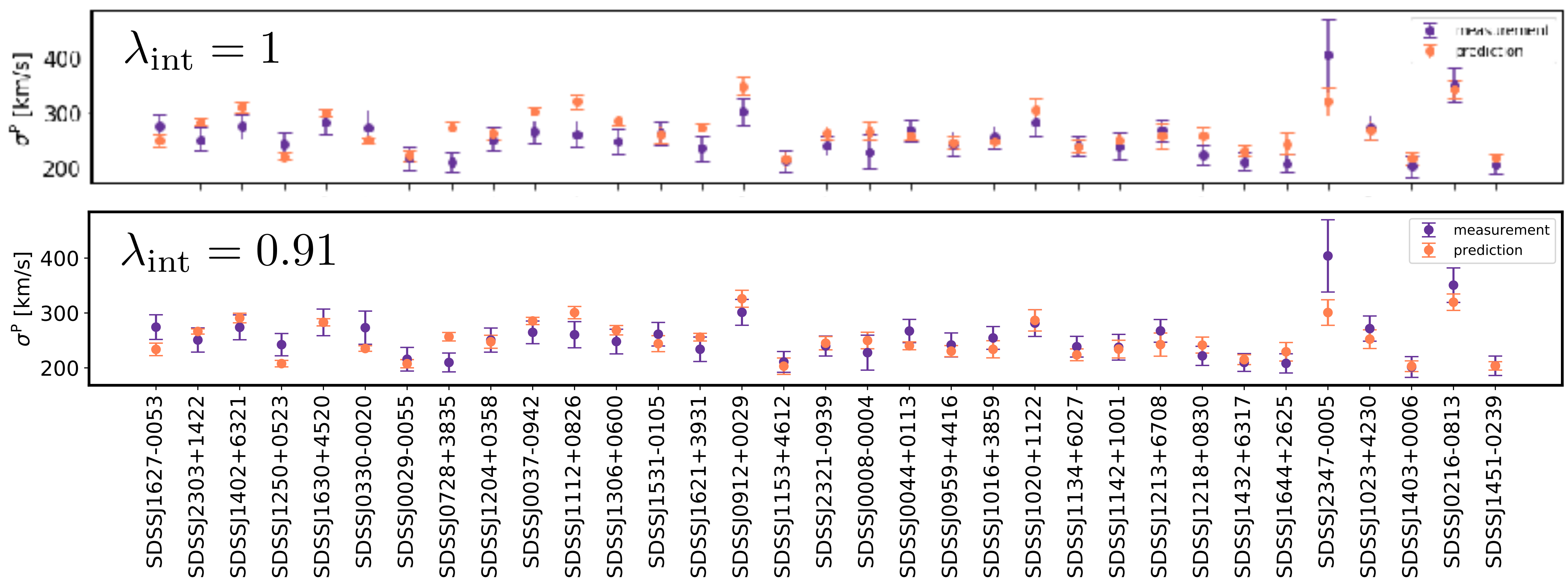


Constraining galaxy density profiles with lensing and kinematics

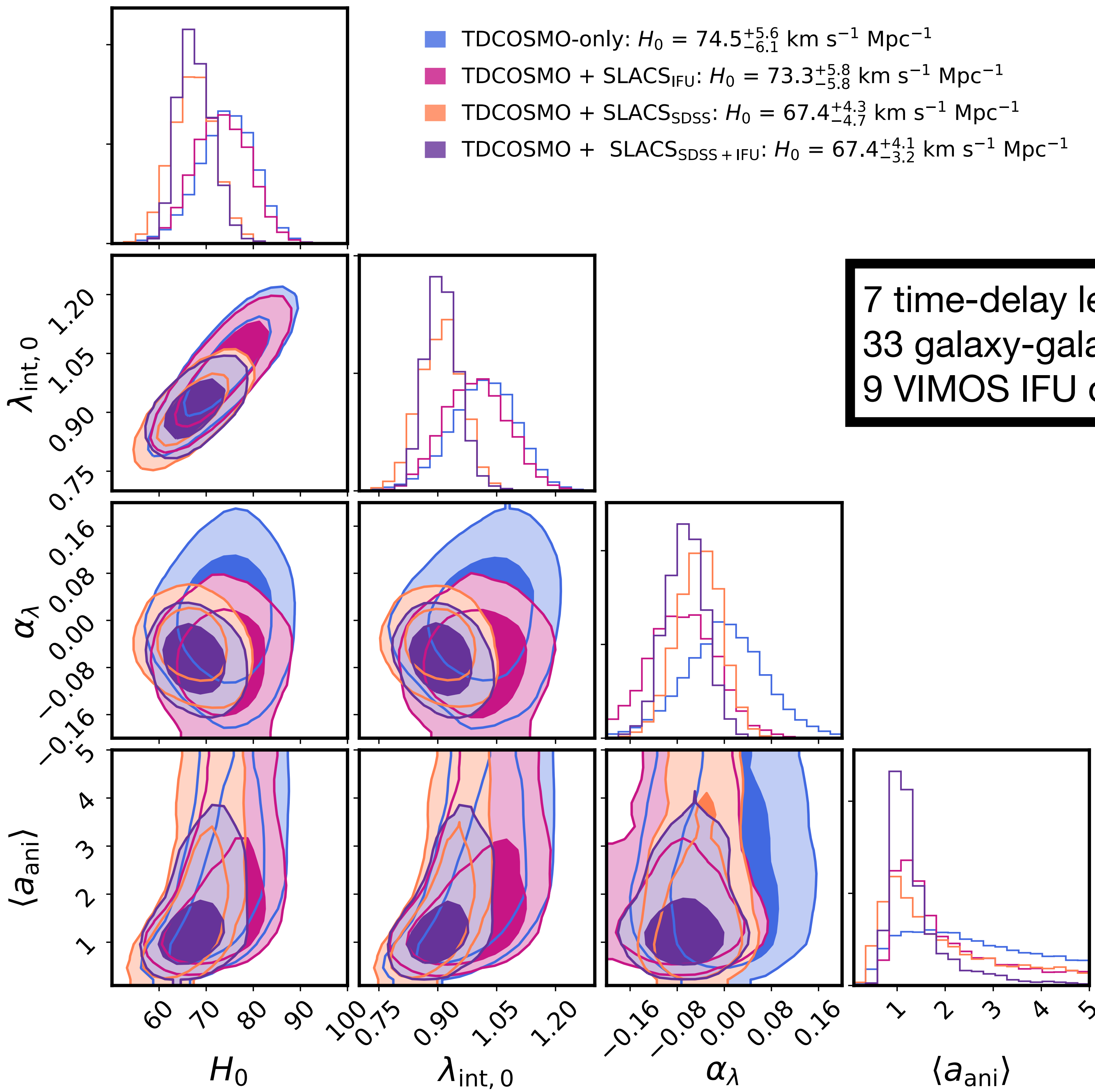


Constraining galaxy density profiles with lensing and kinematics

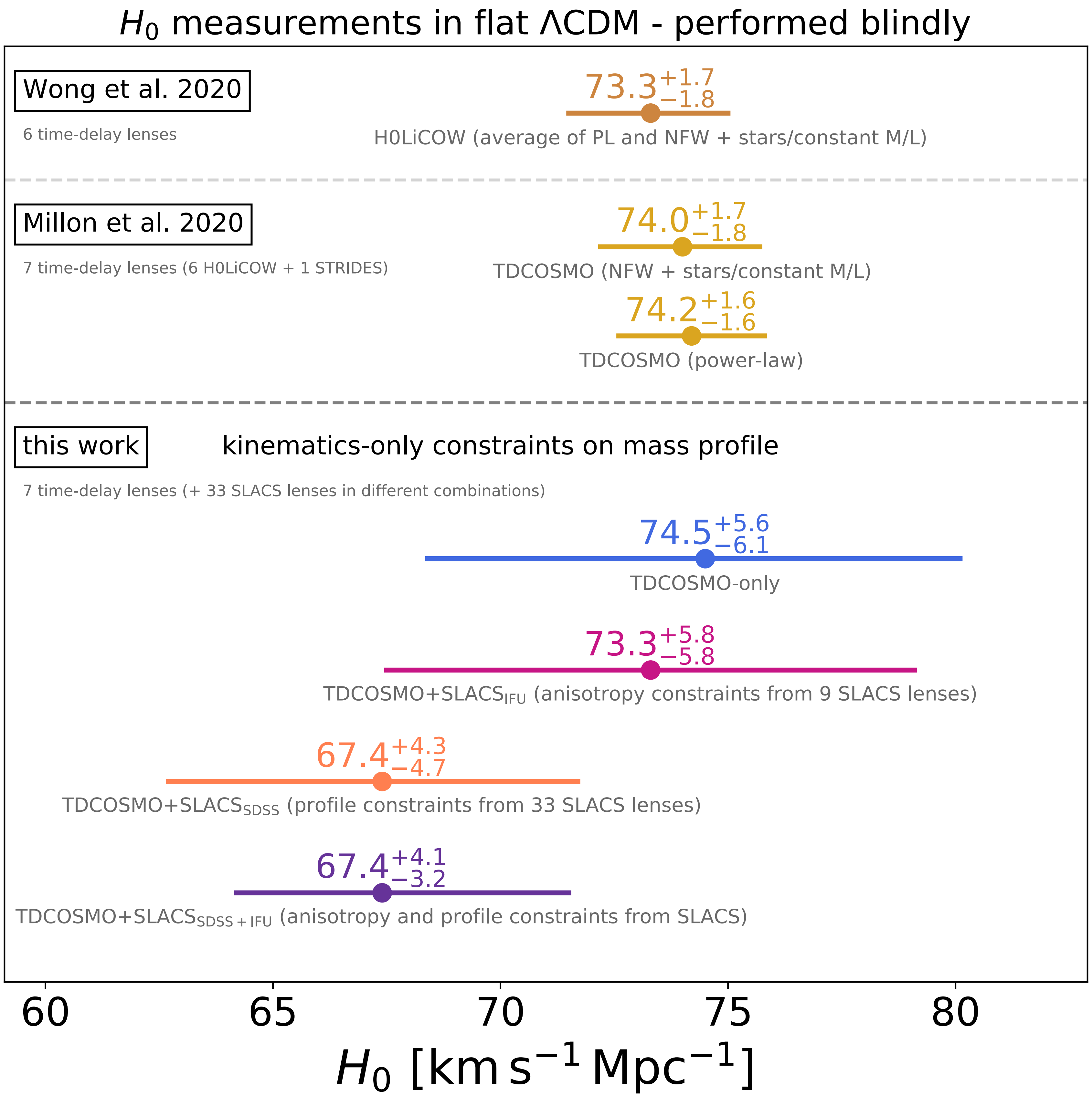




Joint hierarchical analysis of H0, galaxy density profiles and stellar anisotropy



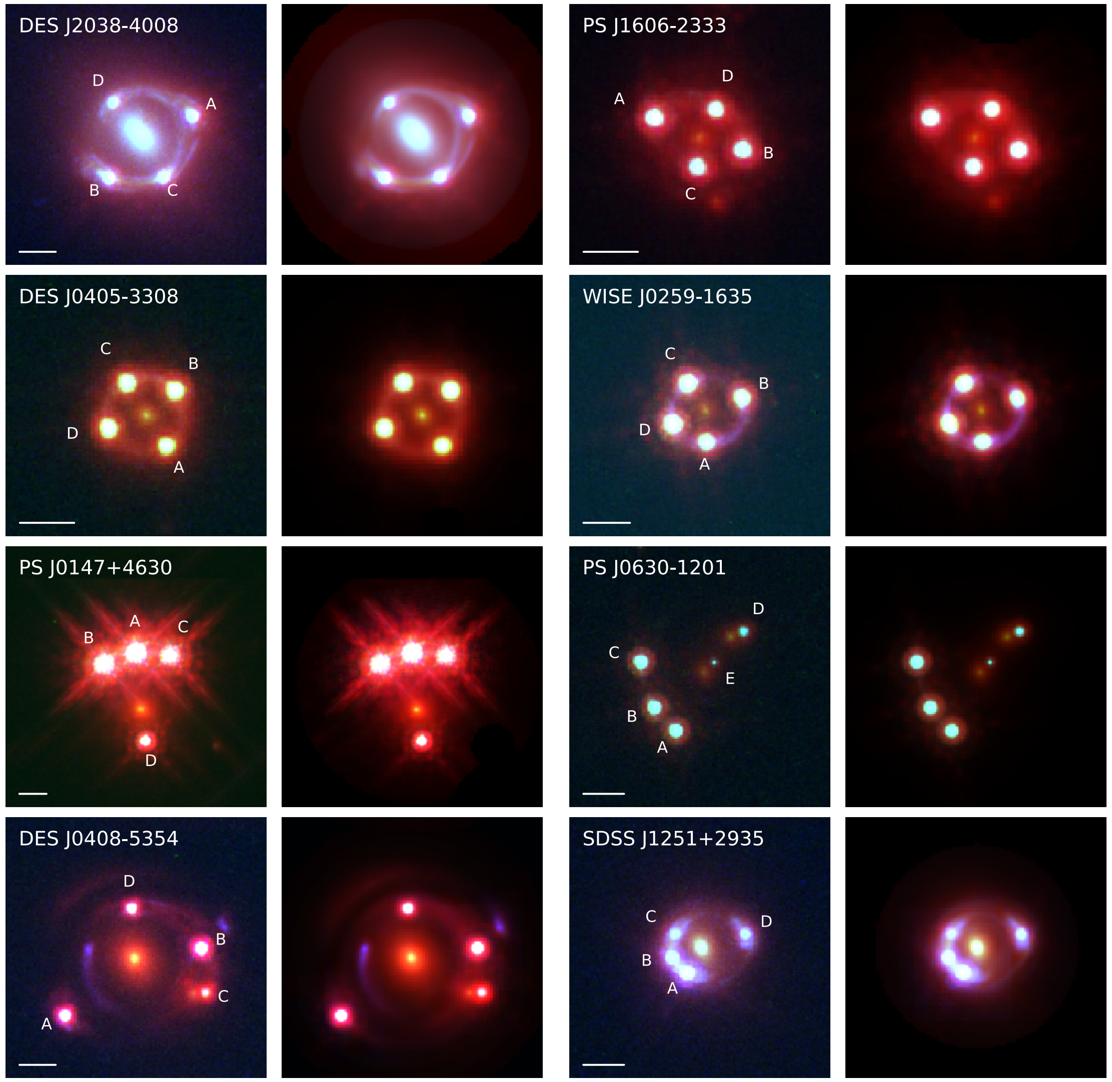
7 time-delay lenses from TDCOSMO
33 galaxy-galaxy lenses from SLACS
9 VIMOS IFU data sets



Birrer et al. 2020

Way forward 1:
data on time delay lenses

- spatially resolved stellar kinematics
  (i.e. VLT MUSE, Keck KCWI)
- improving kinematics measurement and modeling
  (mitigating errors on the population level)
- increase sample size of time-delay lenses
  (discovery, monitoring, high-resolution imaging, spectroscopy)

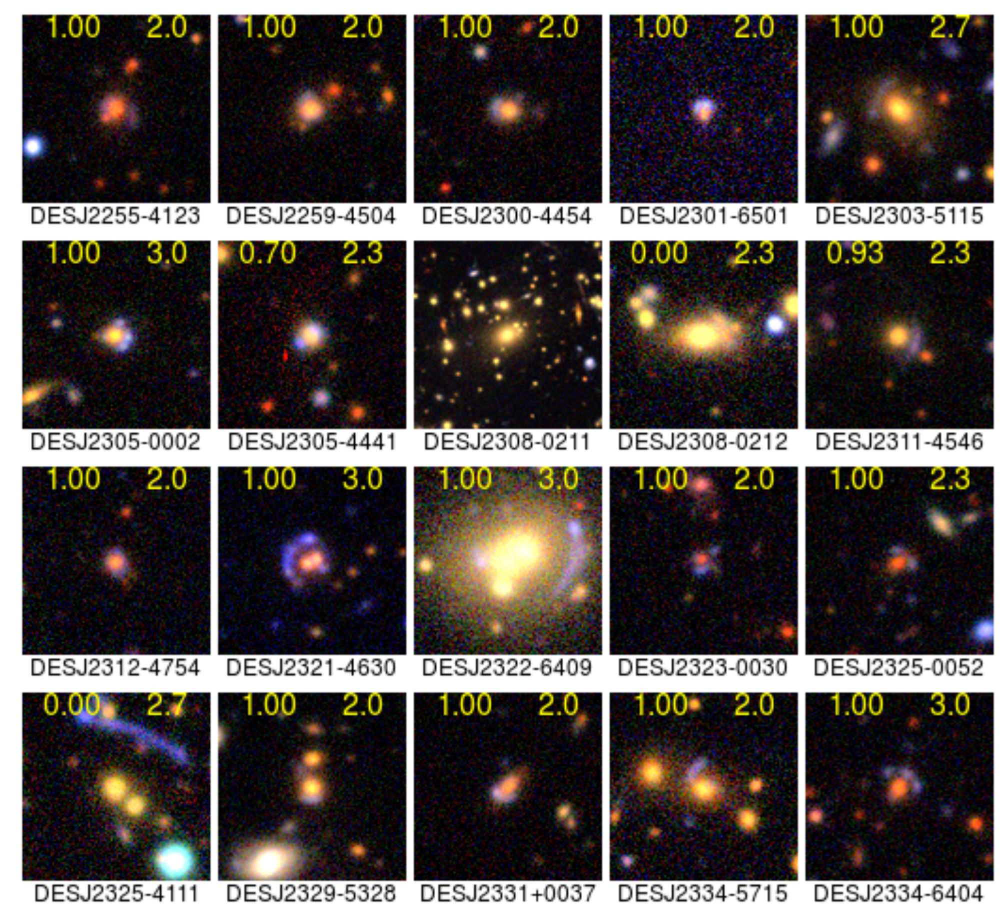


Shajib, SB+2018, STRIDES collaboration

see also Birrer & Treu 2020, arXiv:2008.06157, Yildirim et al in prep, Chen et al. in prep

Way forward 2: adding external data sets

- external lensing sample matching precisely TDCOSMO
  (same redshift, deflector morphology etc)
- increase sample size of galaxy-galaxy lenses
  (Rubin Observatory, Euclid, Roman Observatory will discover 10'000+ lenses - which to follow up?)
- add kinematic information from local elliptical galaxies
  (SAURON, ATLAS3D, …)



Jacobs+2019, DES collaboration

see also Birrer & Treu 2020, arXiv:2008.06157

Way forward 3: challenge yourself!

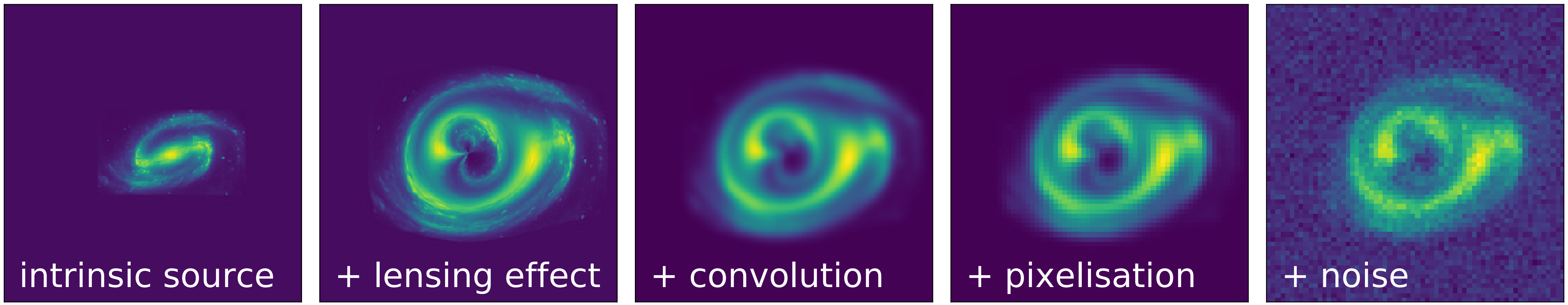
- Improve simulation products for better validation
  (full line-of-sight ray-tracing)
- Blind analysis challenges
  (blind data challenges for the community - as realistic as possible)
- Keep analysis blind!
  (continue assessing systematics regardless of the outcome of the experiment - challenge our intuition and assumptions)
- Open source
  (provide the full end-to-end analysis open source)

public software

sibirrer / lenstronomy

Unwatch 11 | Star 47 | Fork 24

Code | Issues 8 | Pull requests 2 | Actions | Projects | Wiki | Security | Insights | Settings



pypi package 1.3.0 | build passing | docs passing | coverage 97% | license MIT | arXiv 1803.09746

Full software, scripts and data released for Birrer+19, 20

The development is coordinated on GitHub and contributions are welcome. The documentation of `lenstronomy` is available at readthedocs.org and the package is distributed over PyPI.

Installation

```
$ pip install lenstronomy --user
```

https://github.com/sibirrer/lenstronomy