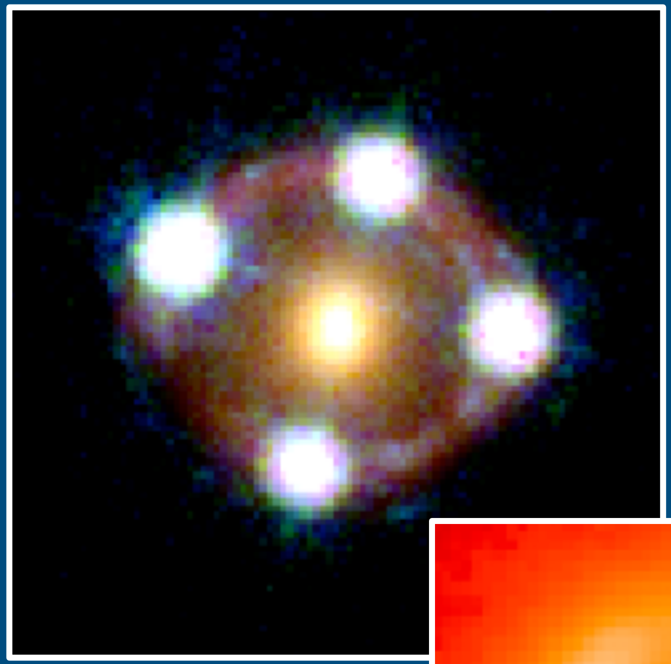
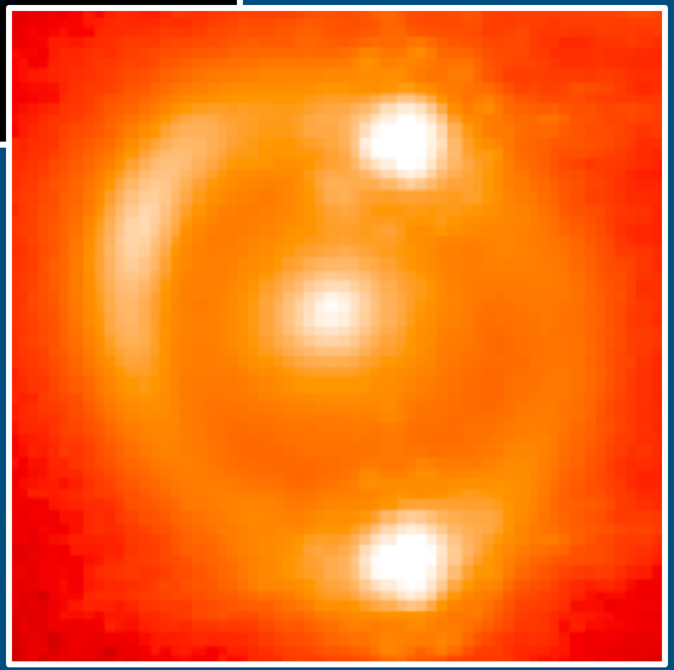
Time-delay cosmography: the present and the future



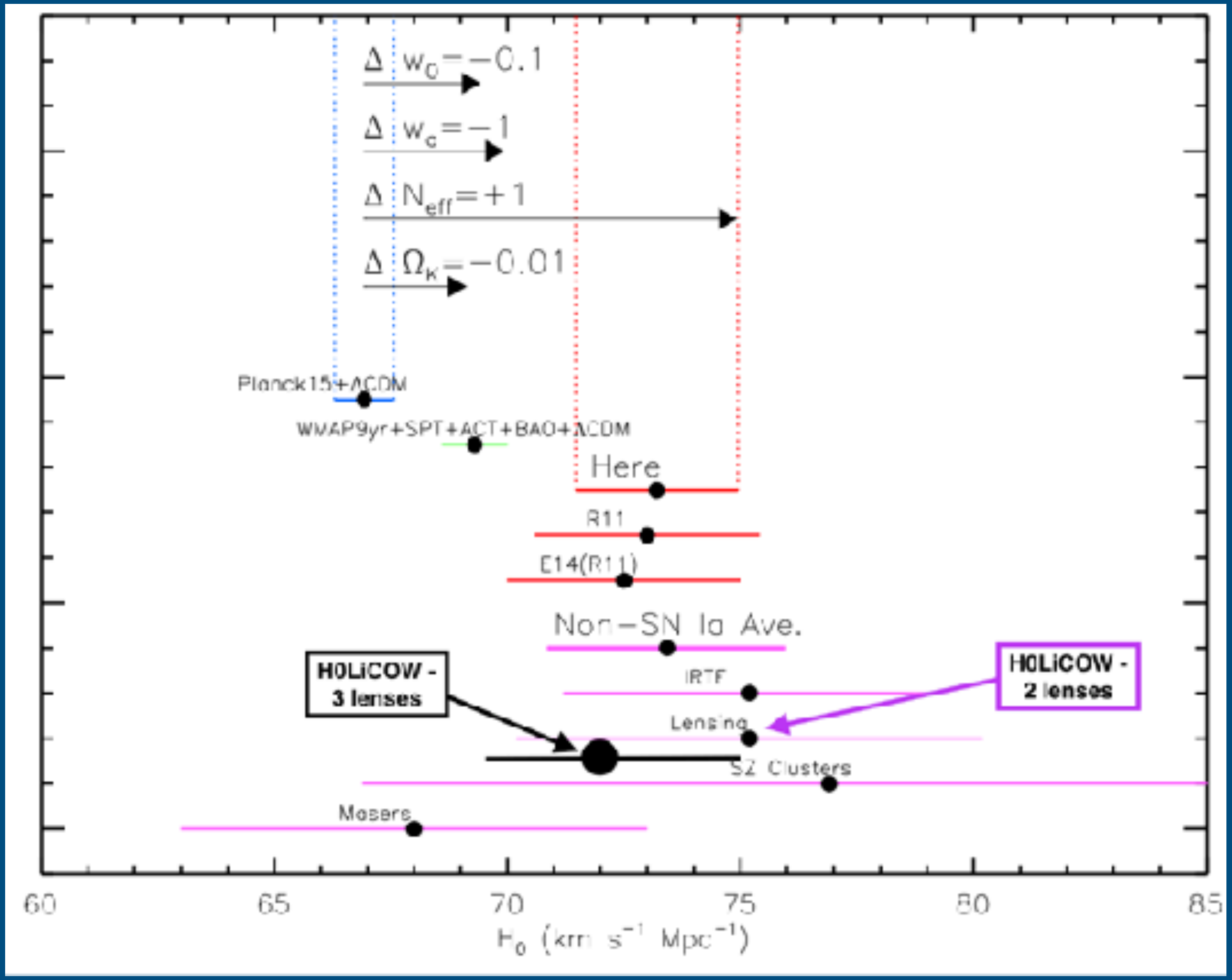


Simon Birrer
University of California, Los Angeles

presenting results from
H0LiCOW
COSMOGRAIL
STRIDES
collaborations

Shedding Light on the Dark Universe with Extremely Large Telescopes
ICTP, Trieste
July 3rd, 2018

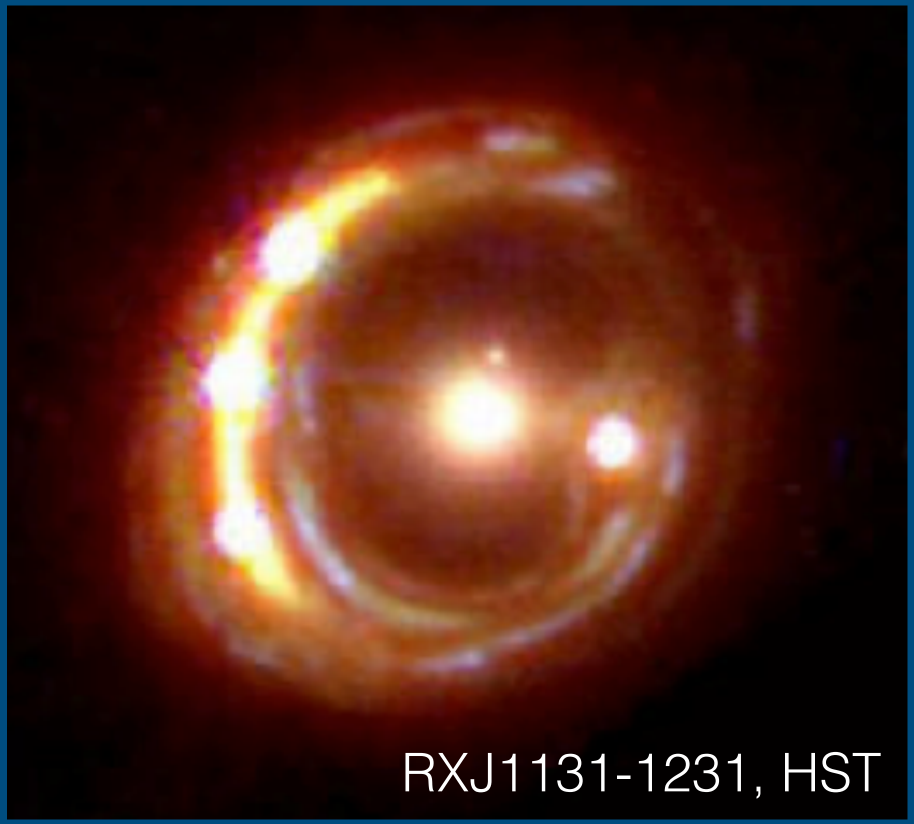
Value of the Hubble constant: New physics or unknown systematics?

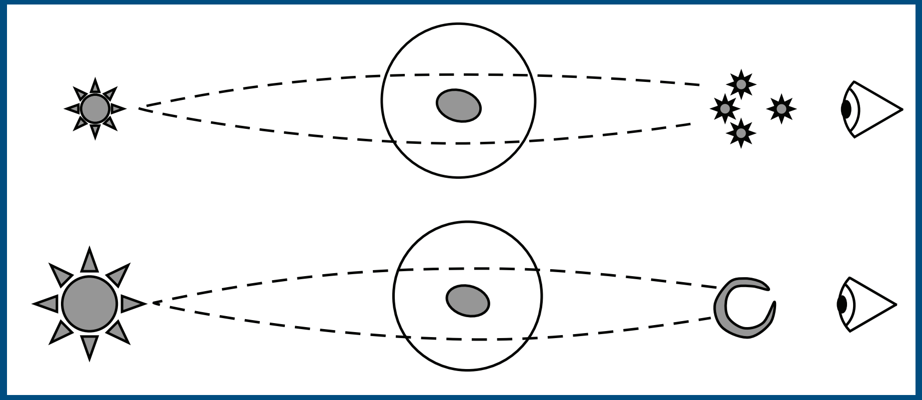


Riess+2016

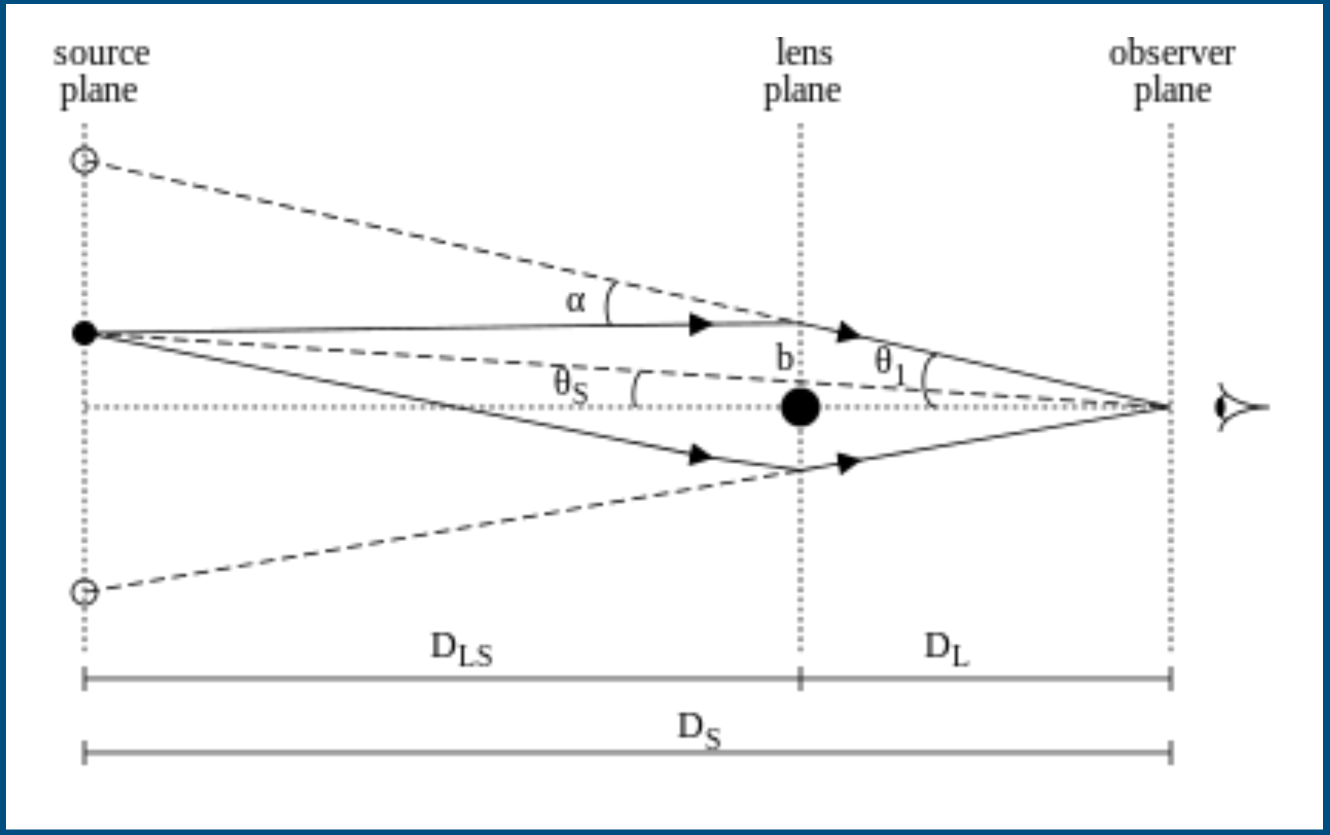
- H_0 measurements in combination with CMB parameters are a powerful probe of dark energy
- CMB analysis <u>assumes</u> flat ΛCDM (“standard model”)
- Indications of new physics will come from combination of CMB and lower-z probes
- Tension between CMB and distance ladder / SN (“Here” in figure)
- Need <u>independent</u> techniques to test for unknown systematics

Strong gravitational lensing



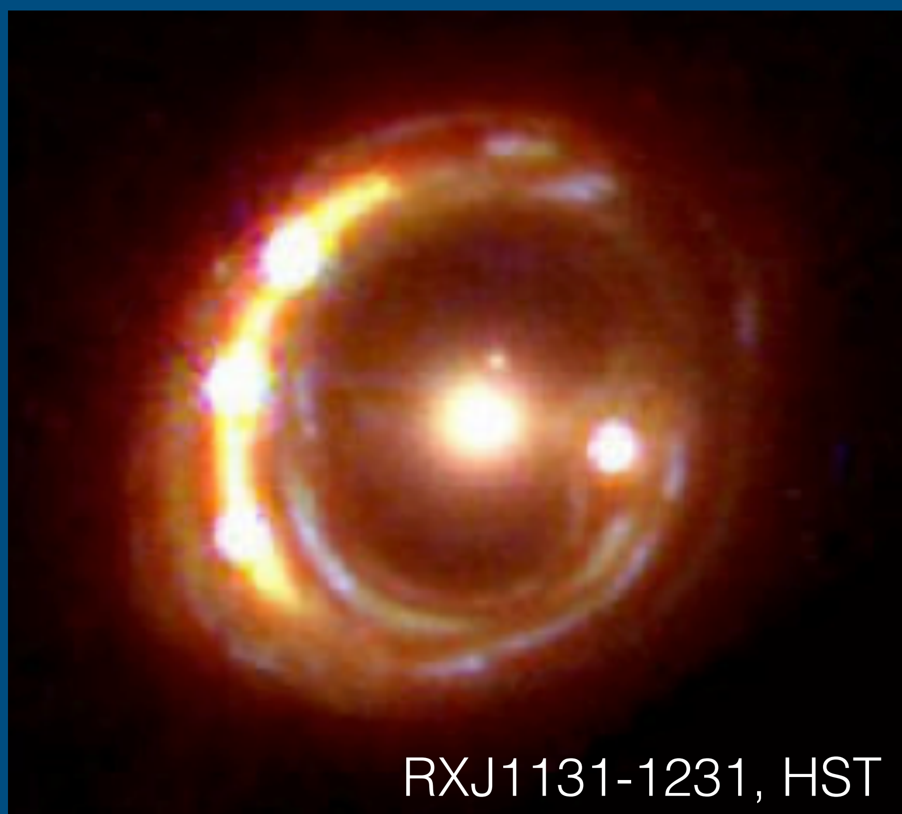


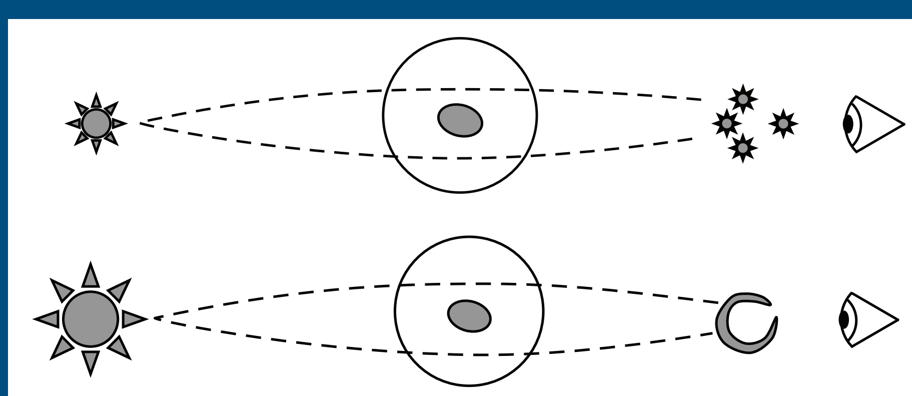
Observables:
image positions + **time delays**



Simon Birrer
H0LiCOW

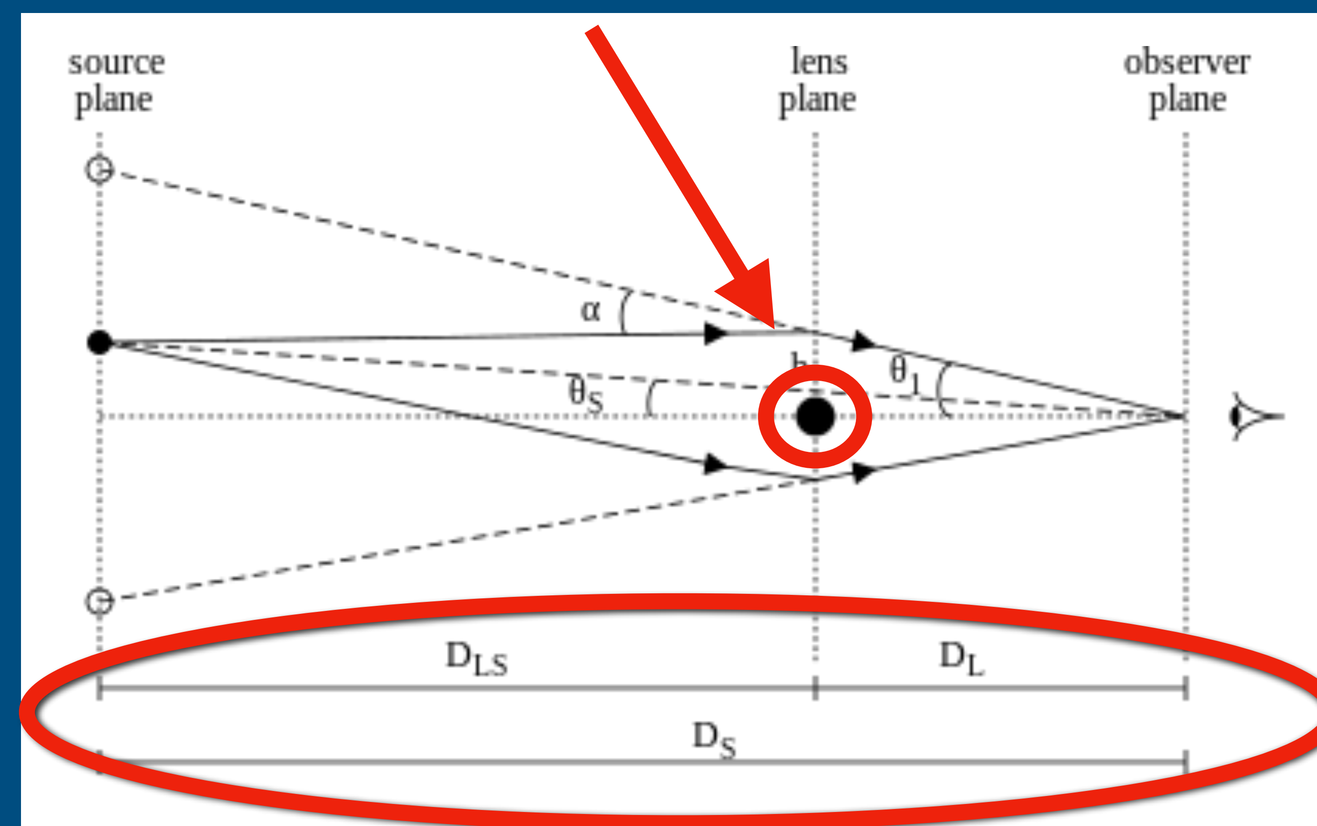
Strong gravitational lensing





Observables:
image positions + **time delays**

total mass

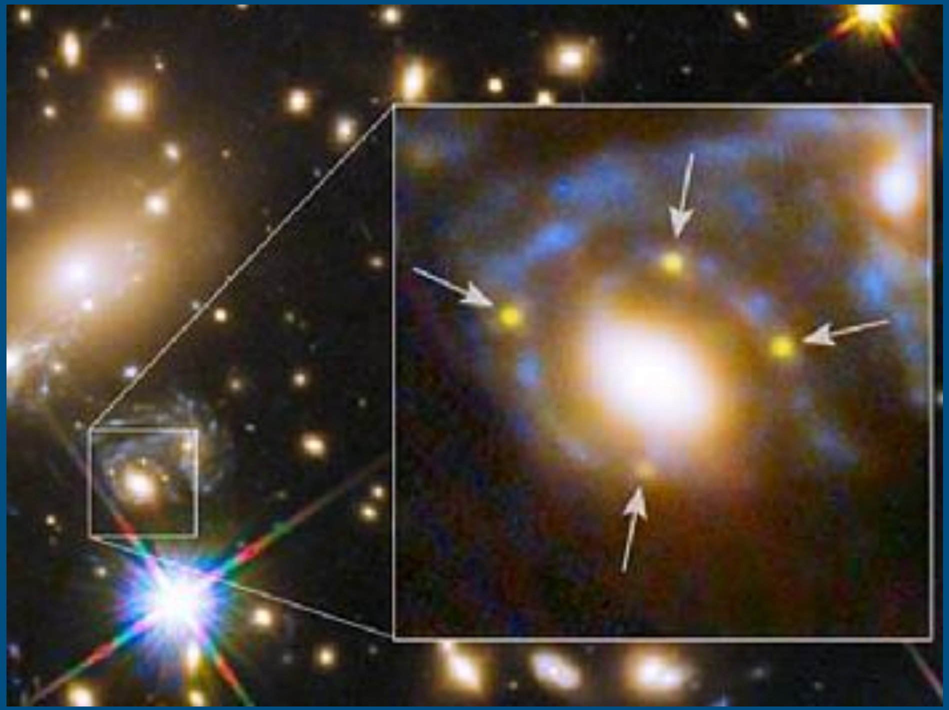


geometry

Simon Birrer
H0LiCOW

Time-delay cosmography

- Measure the “time delay” between the multiple images of a variable source (Quasar or SN)
- Model the mass distribution of the lens
- Characterise the line-of-sight perturbation to the geometric factors (external convergence κ_{ext})



SNe “Refsdal”

proposed by Refusal 1964

Time delay — Time-delay distance — Lens potential (from mass model)

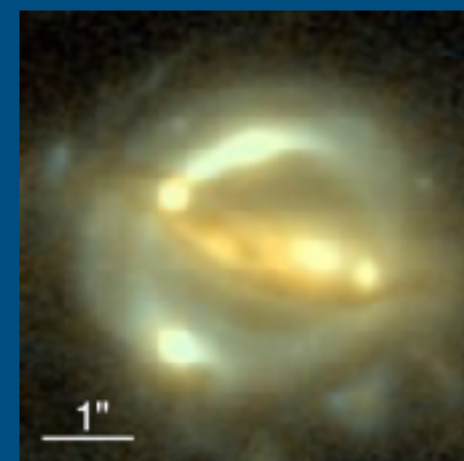
$$\Delta t \propto D_{\Delta t} \times \phi_{\mathrm{lens}} \Rightarrow D_{\Delta t} \propto \frac{1}{\mathbf{H_0}}$$

A very brief history of cosmology from gravitational lenses

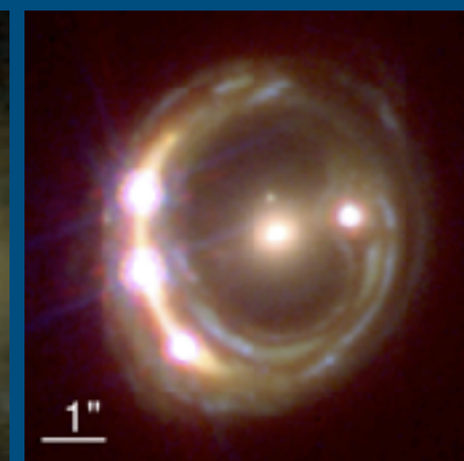
- **1979: First gravitational lens discovered**
- **1980s and early 90s:**
  - Only a few lenses known.
  - Time delays are very controversial
- **Mid 1990s – mid 2000s:**
  - Dedicated monitoring programs produce high-precision time delay measurements
  - Modeling makes unwarranted assumptions, giving big spread in derived values of H_0
- **Late 2000s – today:**
  - Improvements in modelling and data lead to first robust high precision measurements
  - Blind analysis to avoid confirmation bias
  - Three high-quality systems analysed so far as part of the H0liCOW program (Suyu et al. 2010, 2013, 2014; Bonvin et al. 2017)
  - Independent re-analysis of one system (Birrer et al. 2016)

H_0 Lenses in COSMOGRAIL's Wellspring (H0LiCOW)

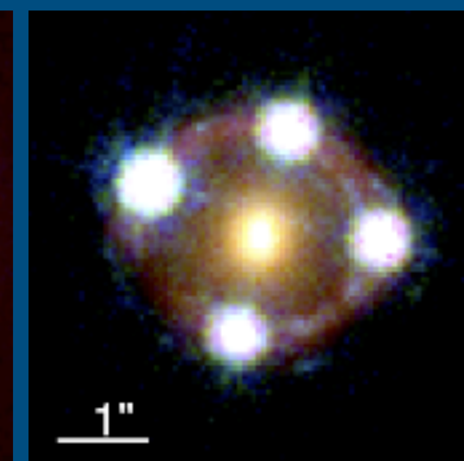
- Detailed analysis of several time-delay lenses (Suyu+2017)
  - long term monitoring from COSMOGRAIL (Courbin+2011) for accurate time delays
  - high-resolution *HST* imaging for detailed lens modelling
  - wide-field imaging/spectroscopy to characterise mass along LOS
- Goal is to constrain H_0 to ~few % precision
- First three lenses have been analysed (Suyu+2010, 2013; Wong+2017), three more to come this year (Birrer+, Rusu+, Wong+ in prep)



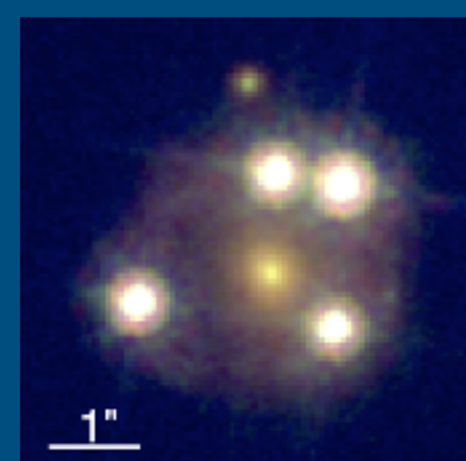
B1608+656



RXJ1131-1231



HE 0435-1223



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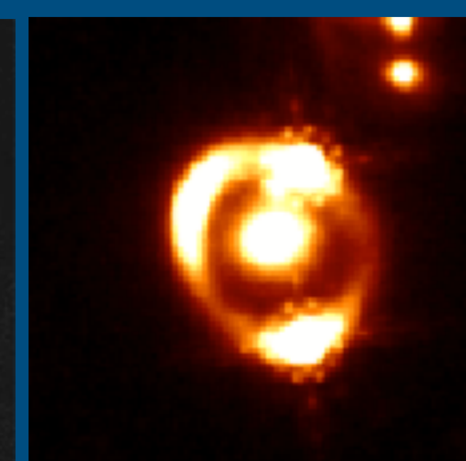
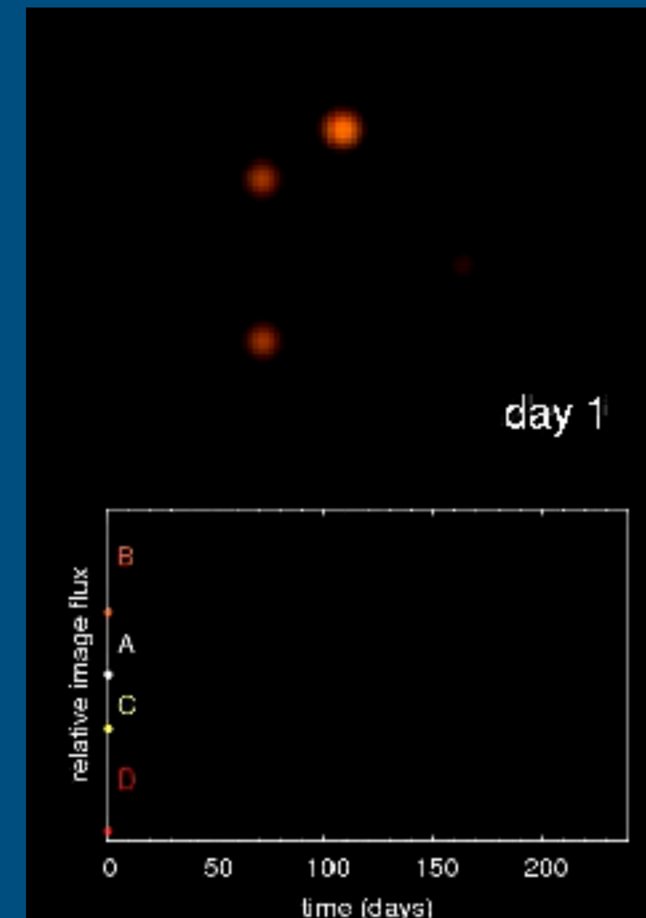
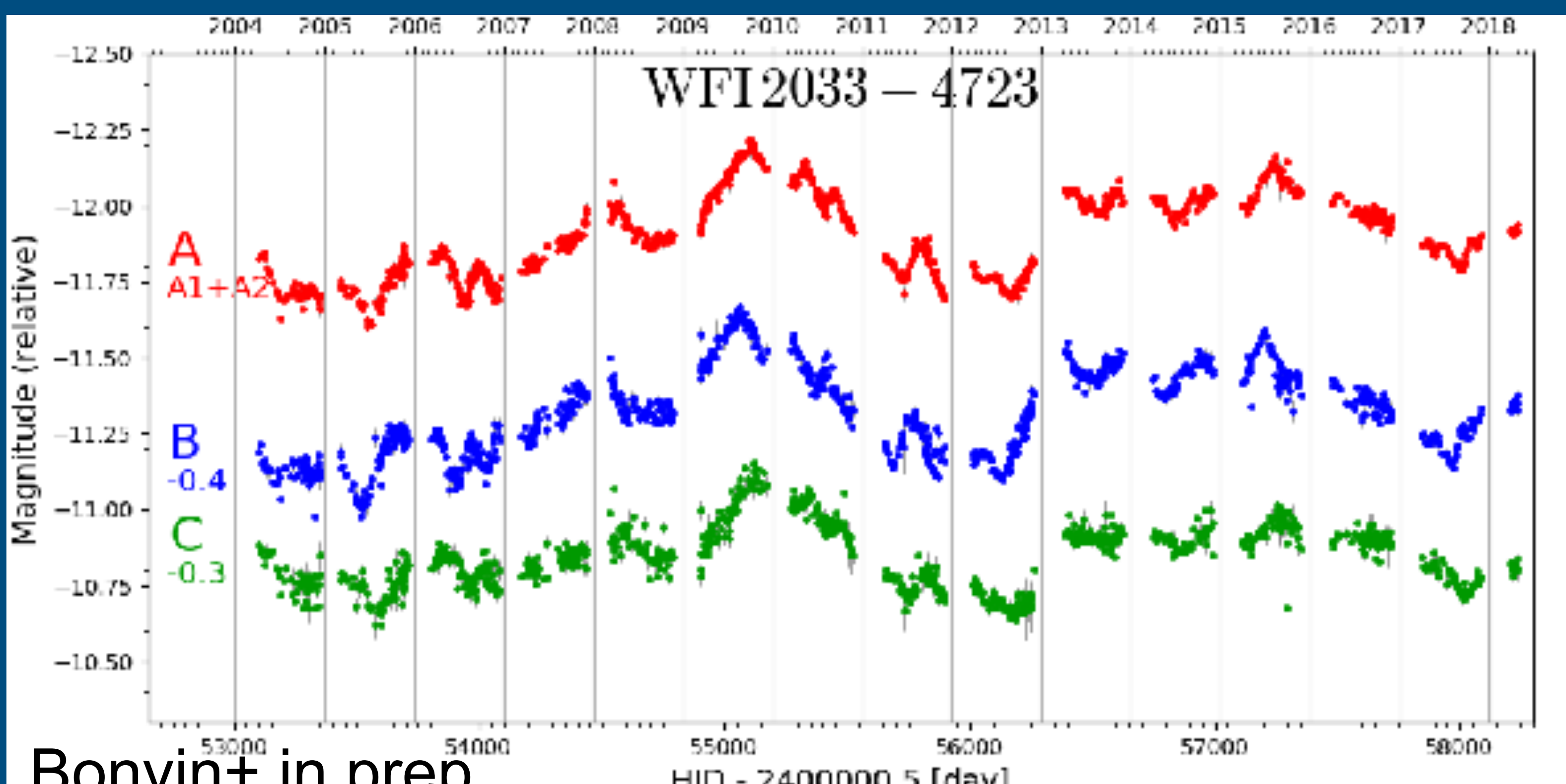

SDSS J1206+4432

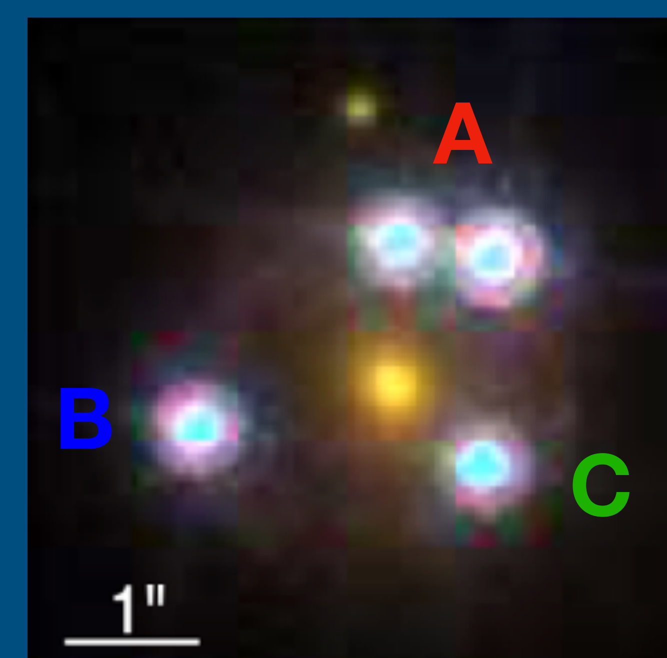
Time Delay Measurements

- COSMOGRAIL: long-term monitoring of time-delay lenses using small (1-m and 2-m) telescopes (Courbin+2011)
- Well-tested algorithms for time-delay measurements (Tewes+2013) provide precision to few percent or better
- Long time baselines needed to minimise effects of micro-lensing

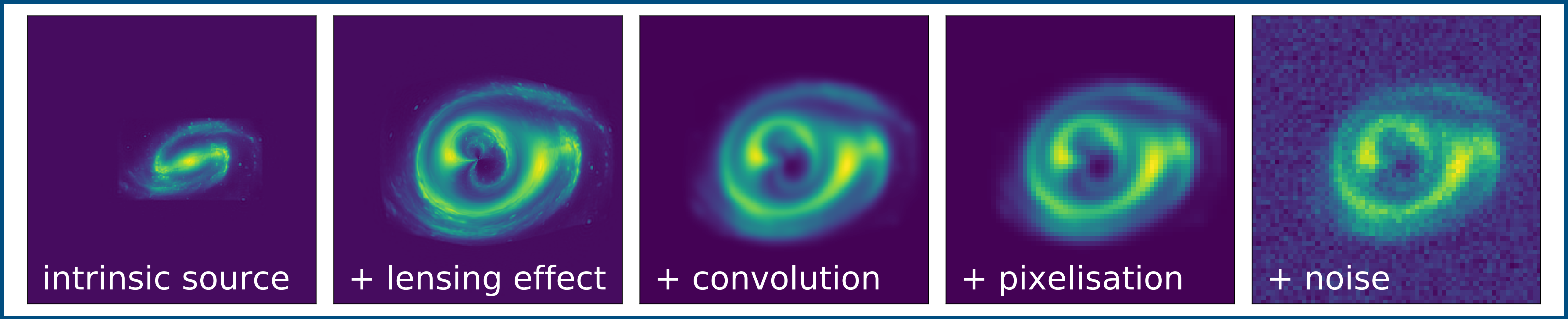




Bonvin+ in prep.

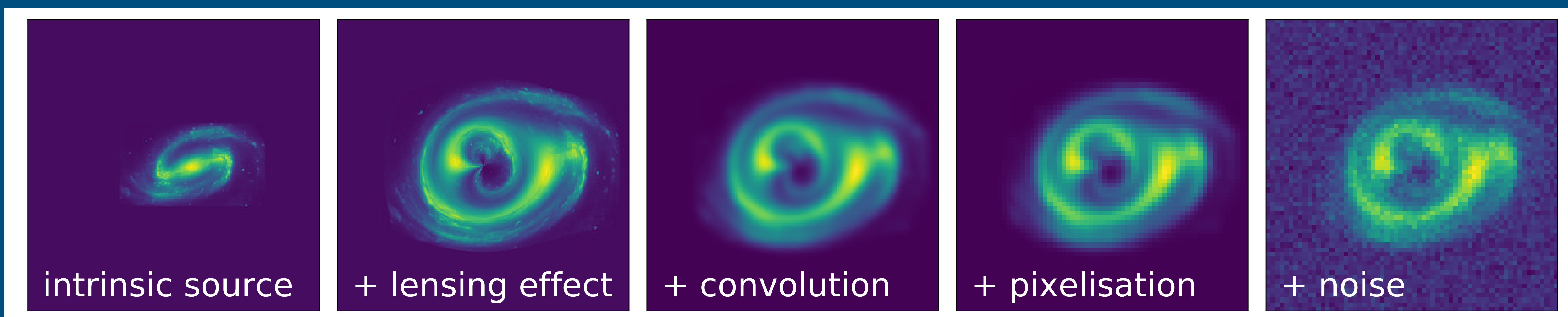


Modelling the lens: imagine



software available: `$pip install lenstronomy`
`https://github.com/sibirrer/lenstronomy`

Modelling the lens: imagine



a lot of nuisance!

that's what we care!

that's what we need to know!

?

$$\phi(\vec{\theta},\vec{\beta}) \equiv \left[\frac{(\vec{\theta}-\vec{\beta})^2}{2} - \psi(\vec{\theta})\right]$$

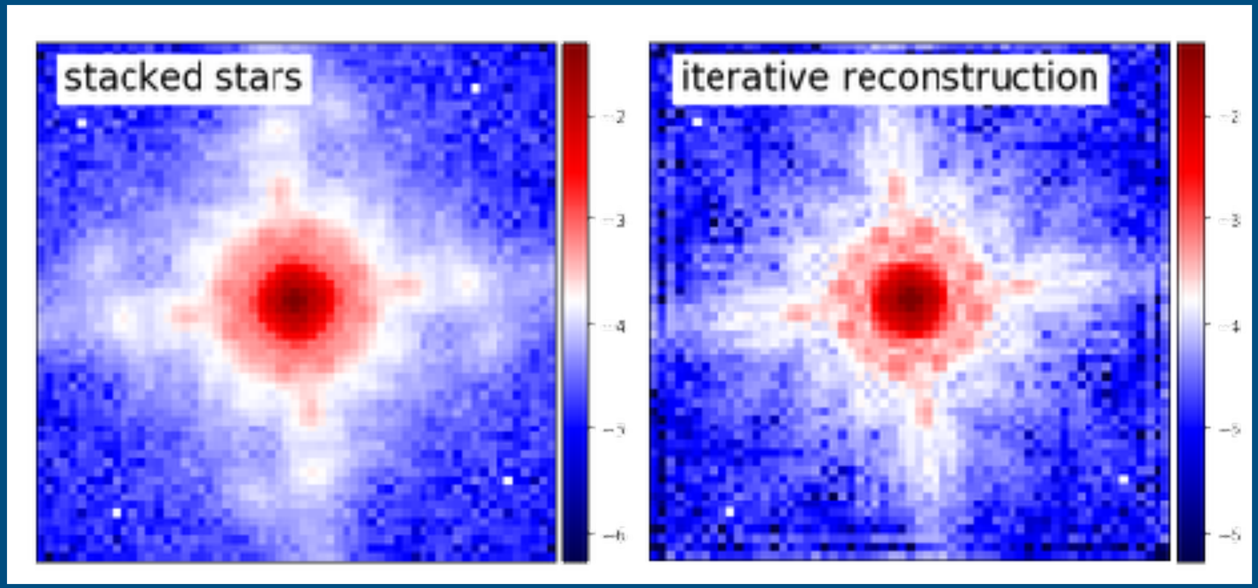
geometric delay

gravitational delay

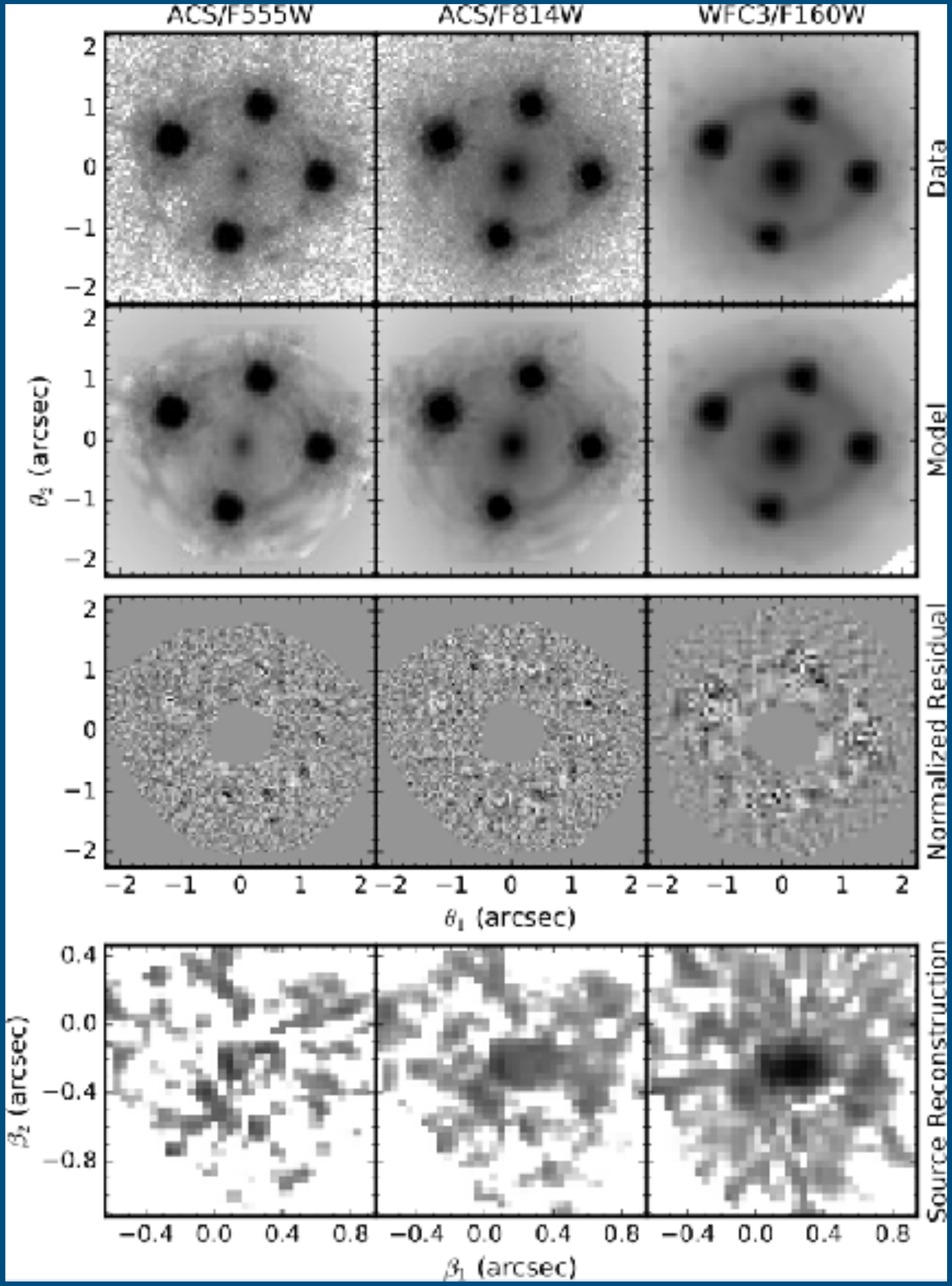
software available: `$pip install lenstronomy`
`https://github.com/sibirrer/lenstronomy`

Modelling the lens: imagine

- High-resolution imaging needed to model quasar host galaxy (so far primary HST)
- Adaptive PSF correction using quasar images (e.g. Chen+2016, Wong+2017, Birrer+2017)
- provides few % uncertainty on H_0

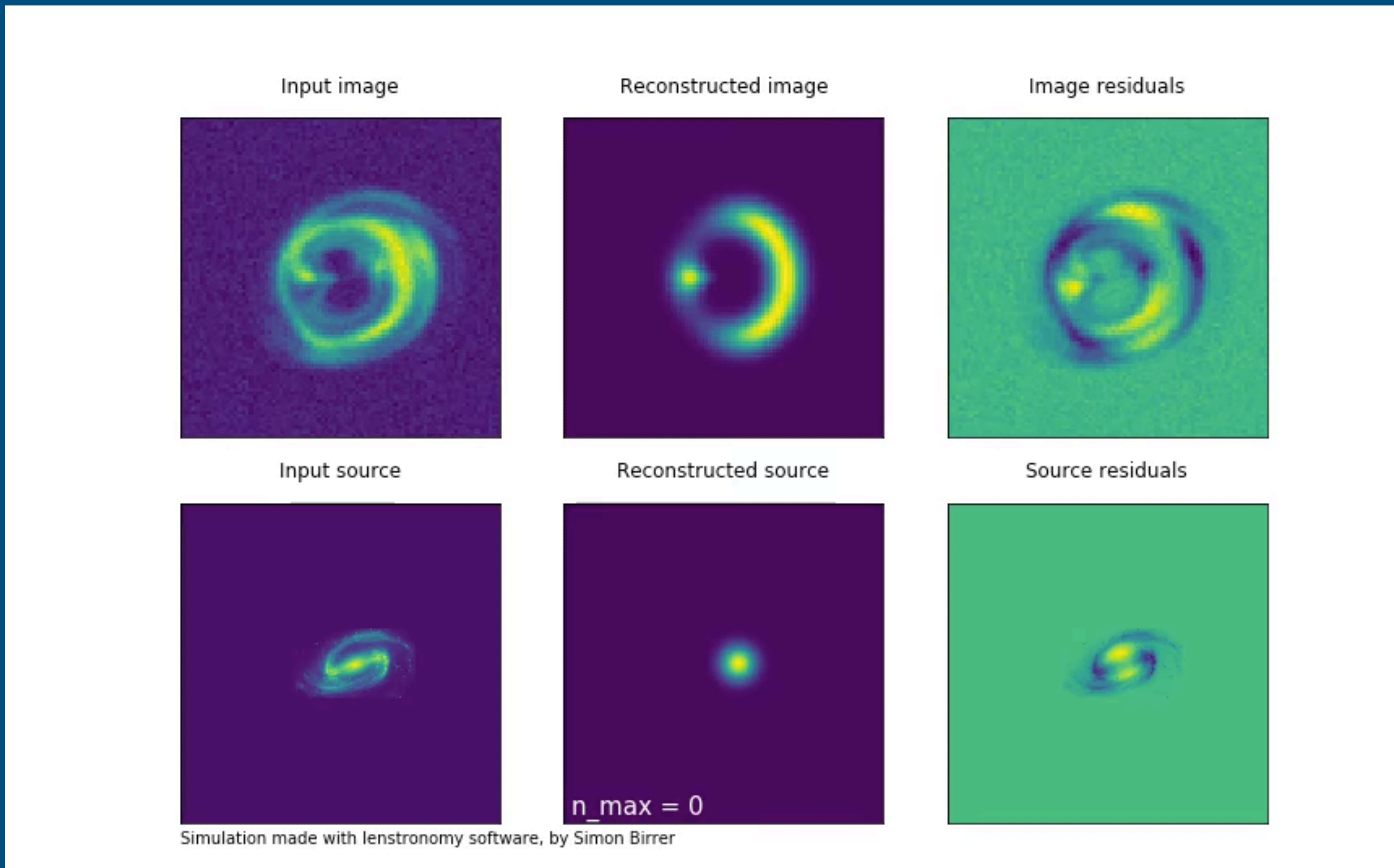


Birrer+ in prep



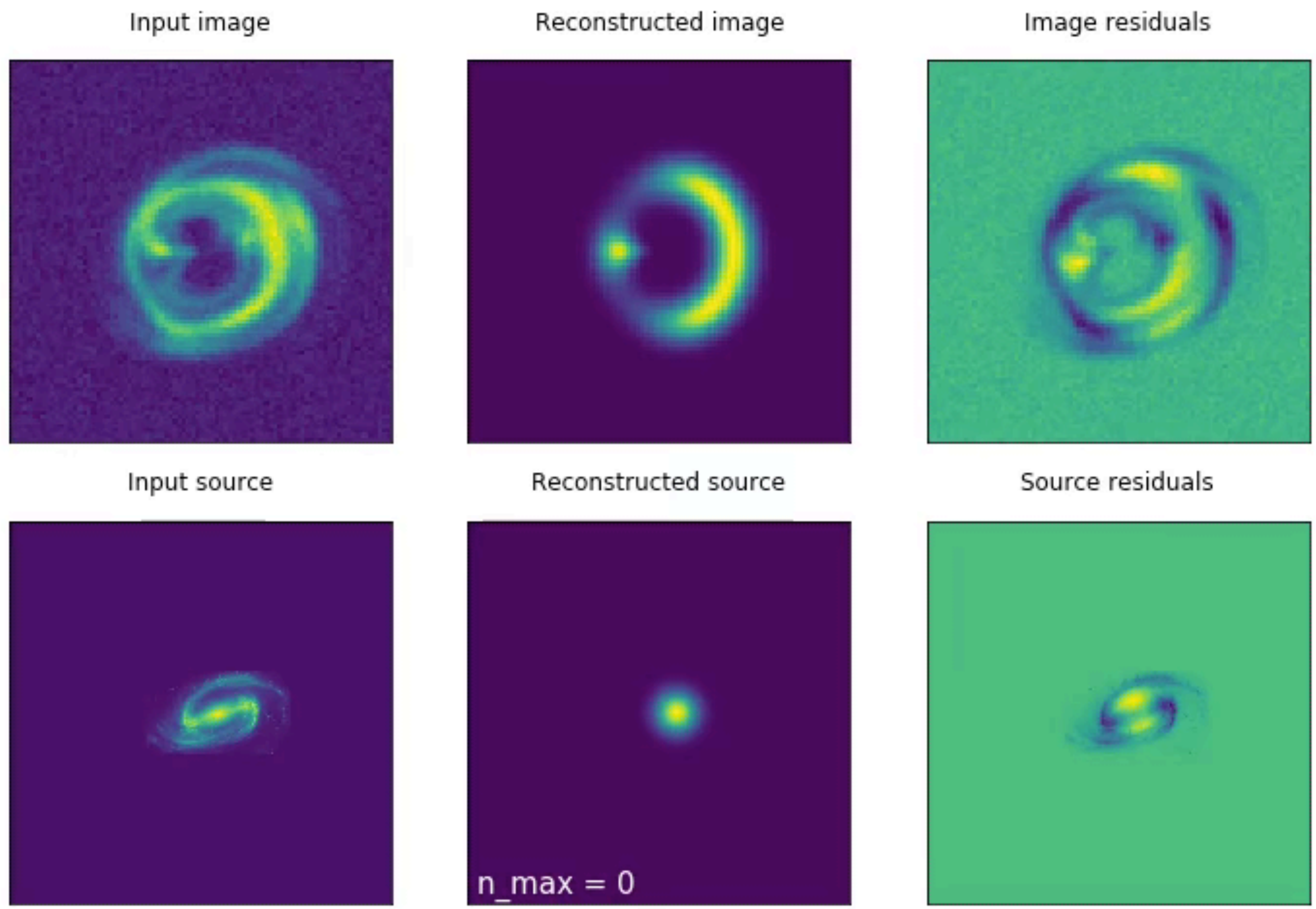
Wong+2017

source reconstruction: example with perfect lens model



software available: `$pip install lenstronomy`
`https://github.com/sibirrer/lenstronomy`

source reconstruction: example with missing (sub)-structure

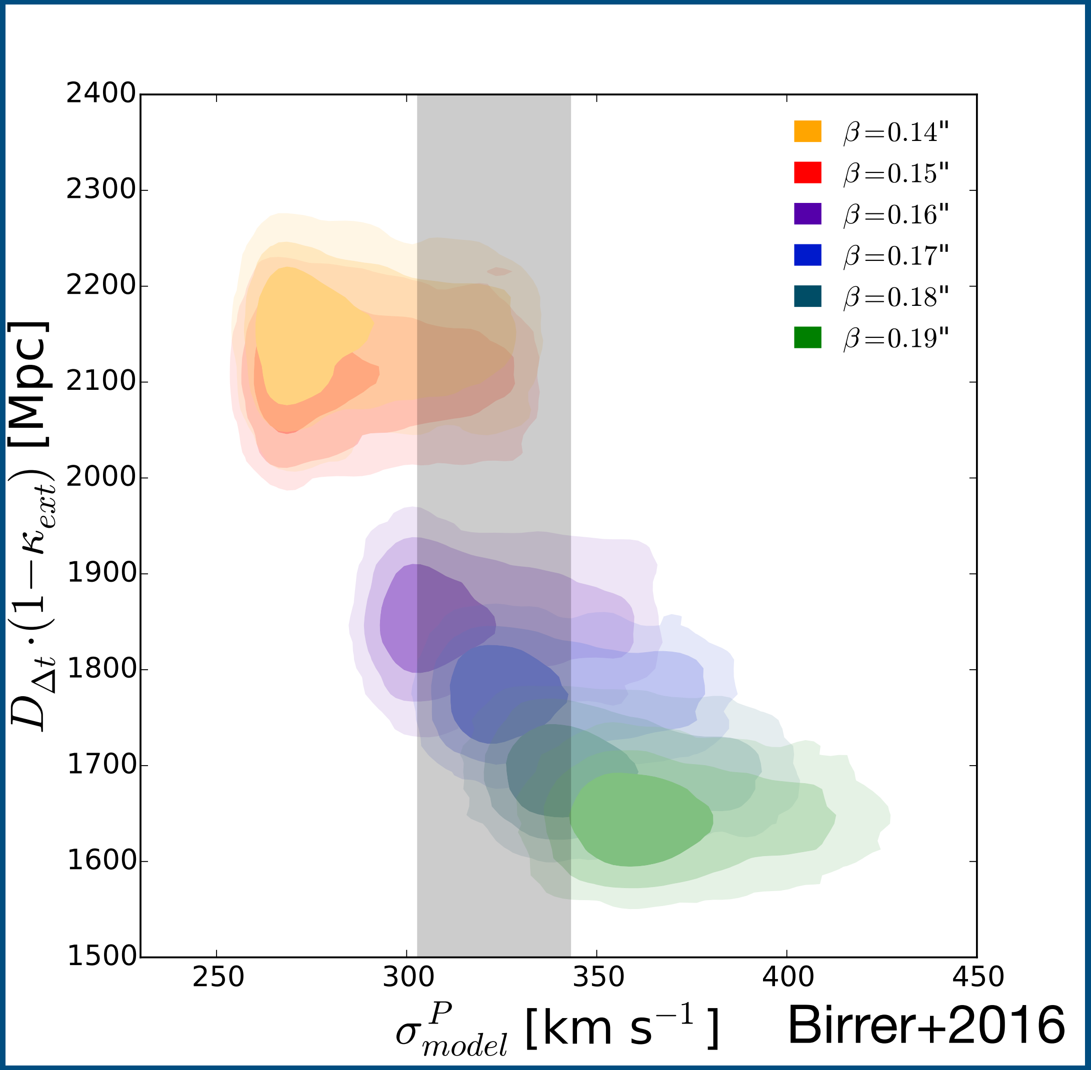


Simulation made with lenstronomy software, by Simon Birrer

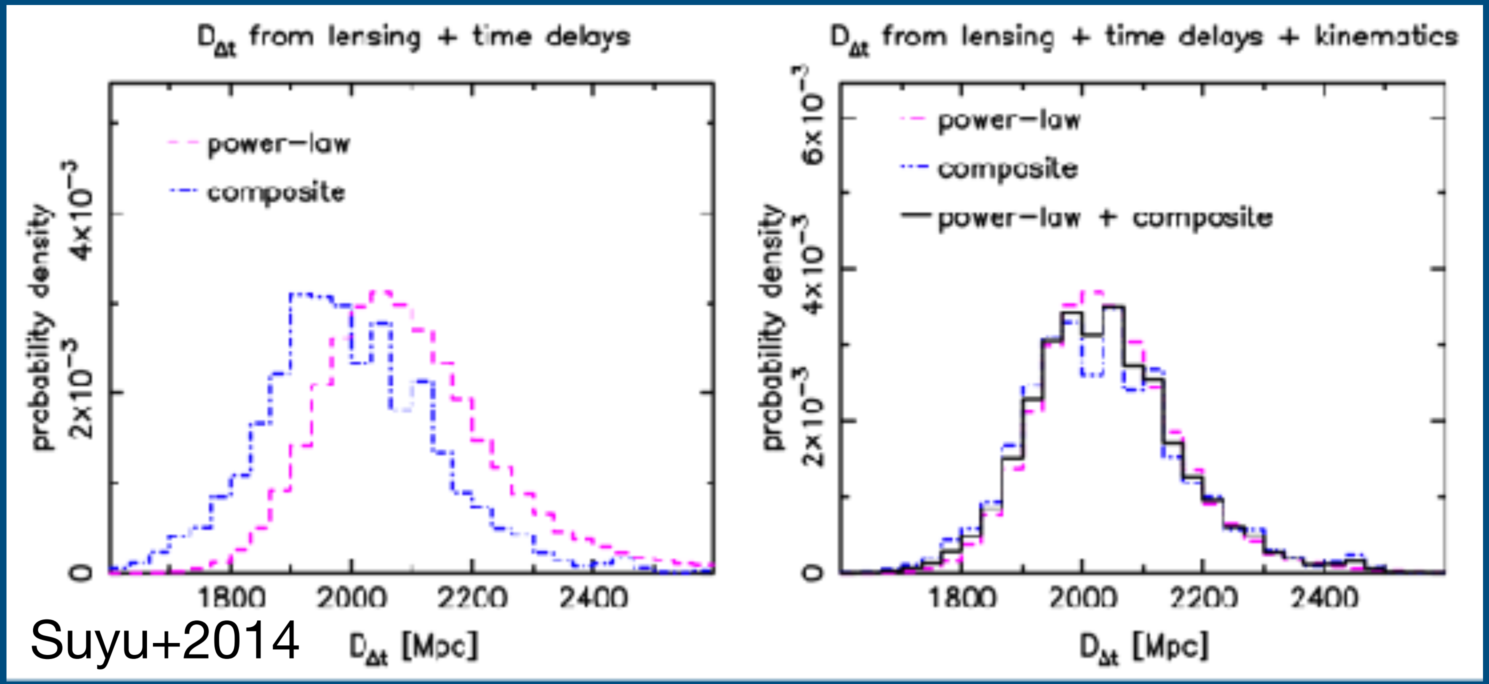
software available: `$pip install lenstronomy`
`https://github.com/sibirrer/lenstronomy`

Modelling the lens: spectroscopy

- Stellar velocity dispersion of lensing galaxy breaks additional degeneracies
- e.g., when comparing a simple power-law mass model with a more complex NFW+stellar composite model (Suyu+2014, Wong+2017)
- e.g., mapping the source position transform (Birrer+2016)



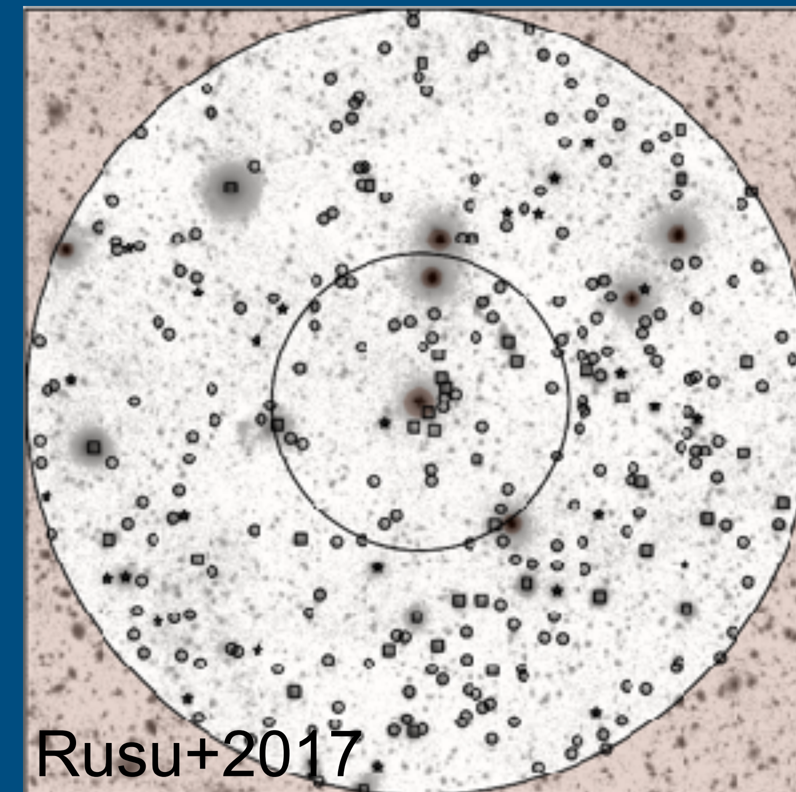
Birrer+2016



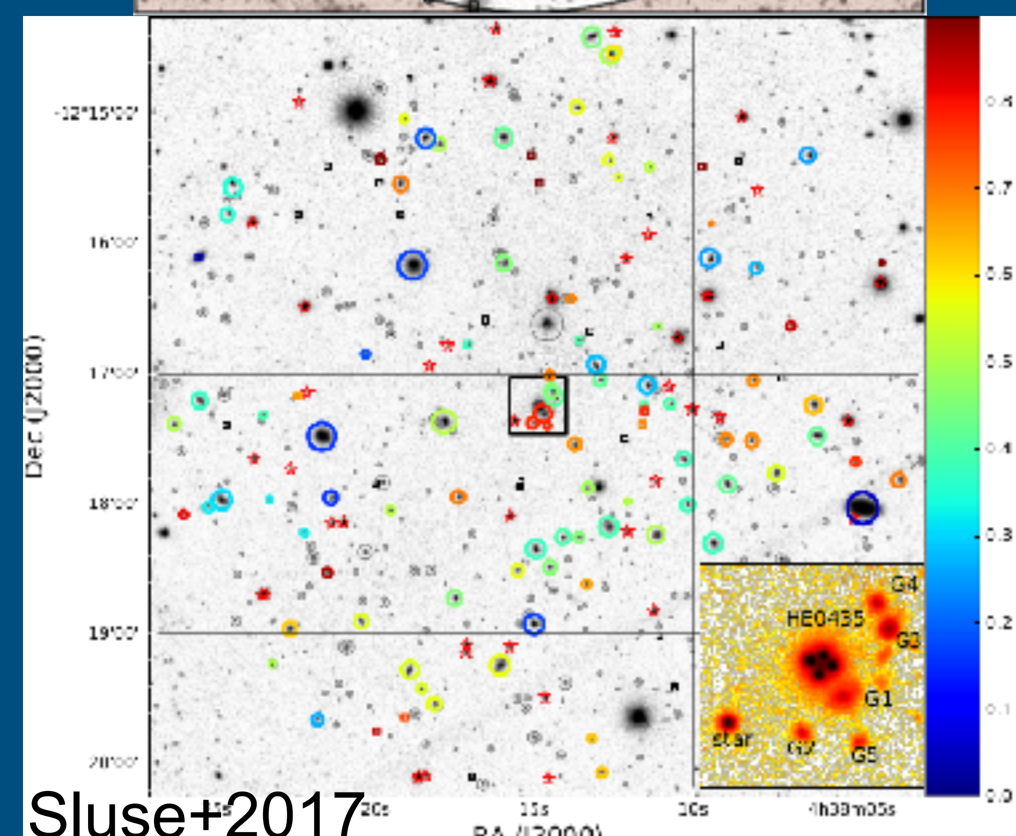
Suyu+2014

Mass Along the Line of Sight

- Angular diameters are perturbed by large scale structure relative to the homogeneous prediction
- Compare relative galaxy number counts to cosmological simulations to calibrate κ_{ext} (e.g., Fassnacht+2011; Greene+2013; Suyu+2010,2013)
- Deep multi-band imaging to get photometric redshift and stellar masses to reconstruct line of sight mass distribution (Rusu+2017)
- Multi-object spectroscopy to characterise nearby galaxies, groups (Sluse+2017)
- Independent κ_{ext} constraint using weak lensing data (Tihhonova+2018)

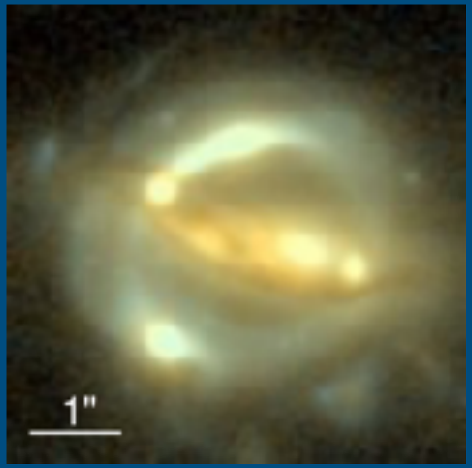


Rusu+2017



Sluse+2017

Latest H0LiCOW Results



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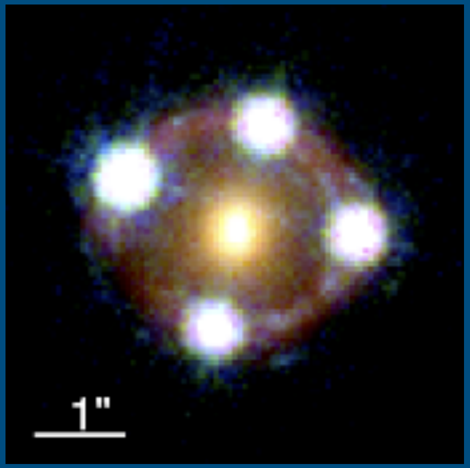
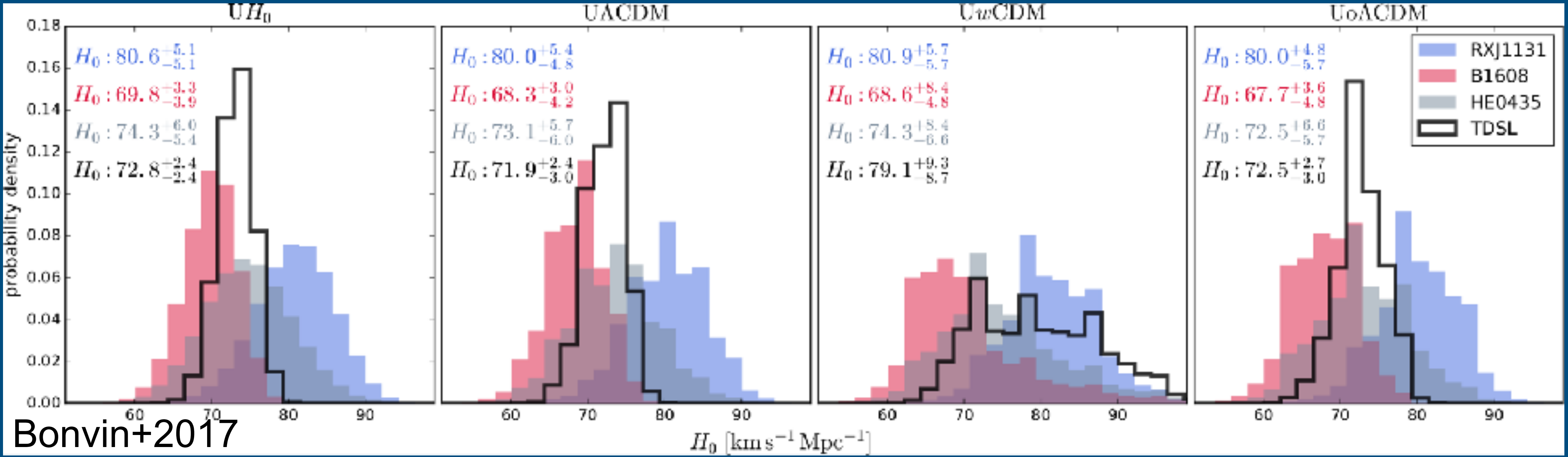


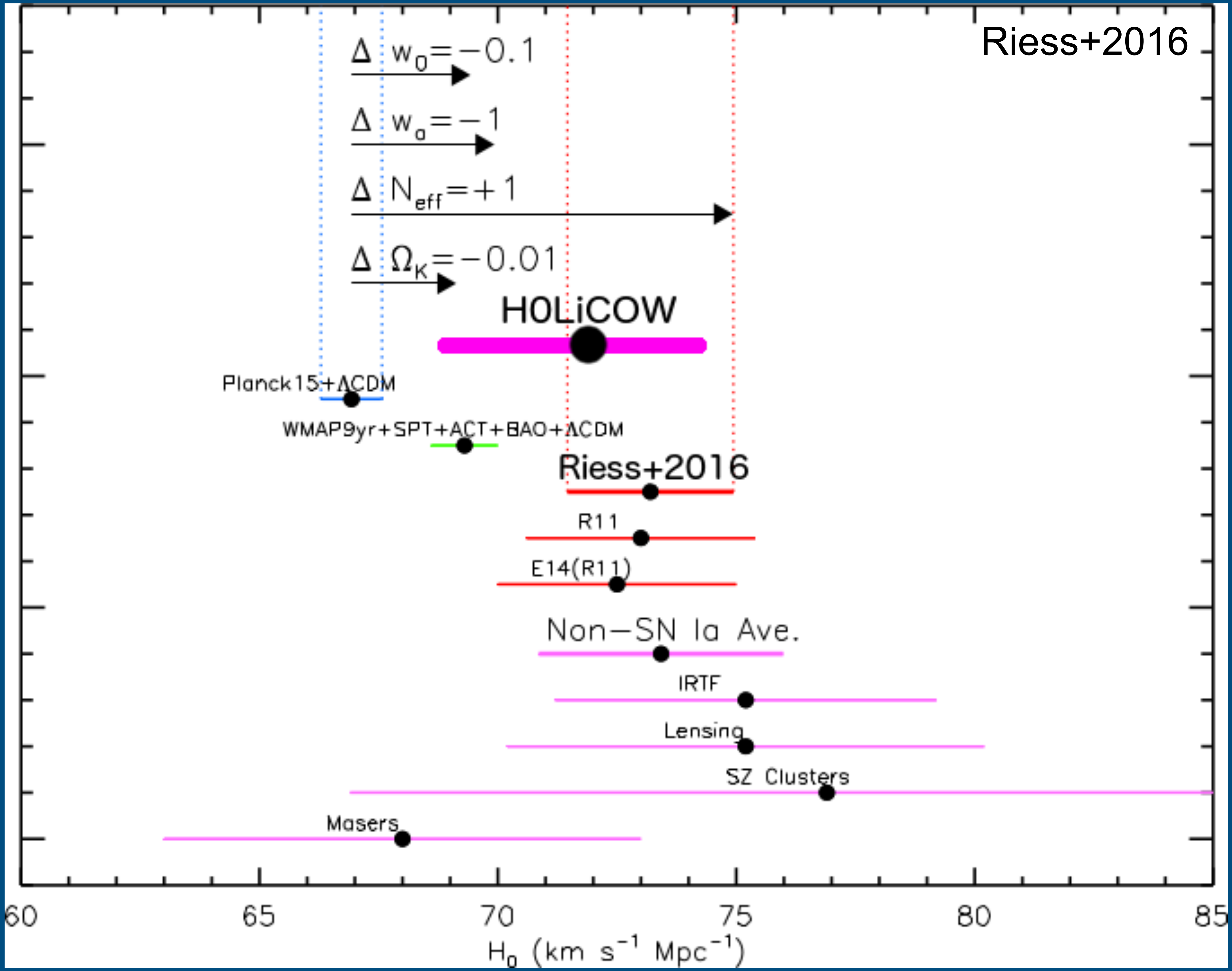
HE 0435-1223



~3.8% precision on H_0 from 3 H0LiCOW lenses

$H_0 = 71.9^{+2.4}_{-3.0}$ km/s/Mpc for flat ΛCDM cosmology

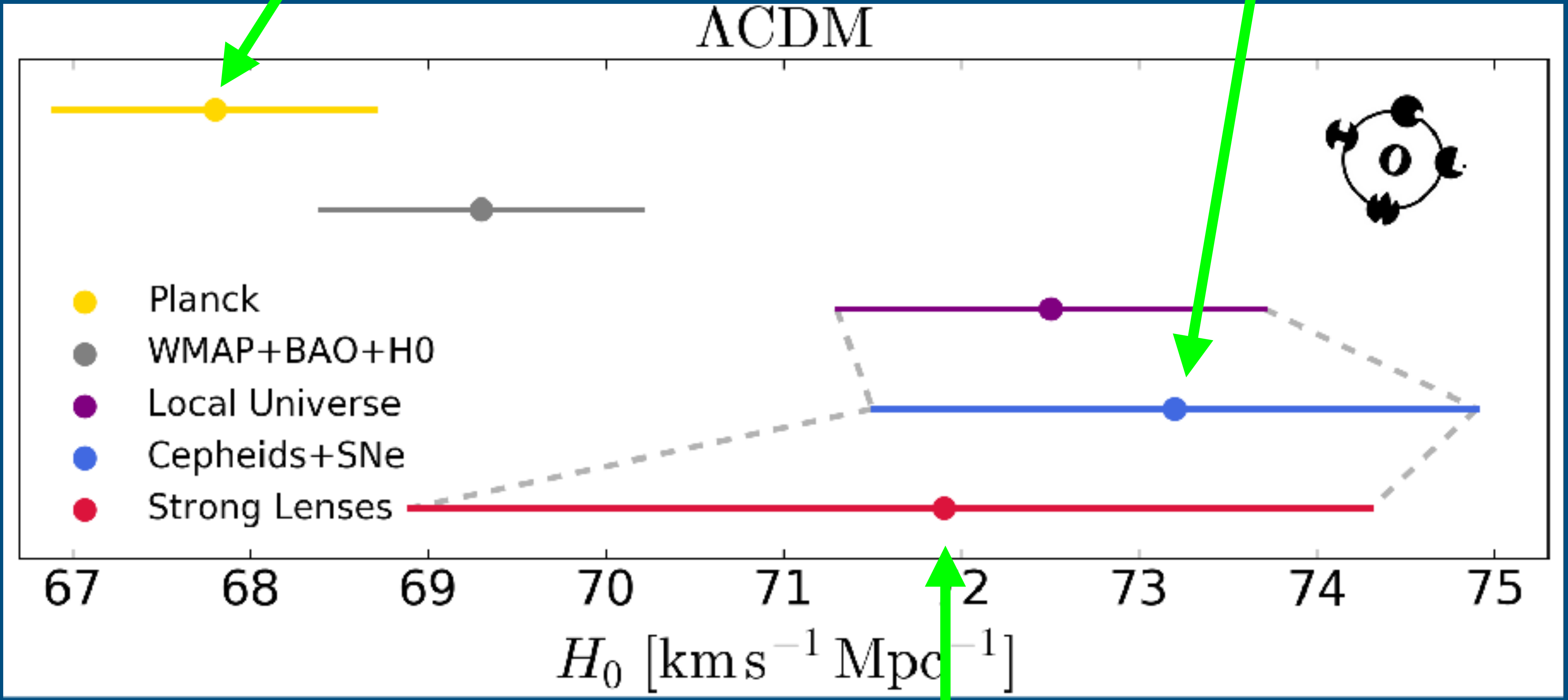
Latest H0LiCOW Results



Latest H0LiCOW Results

Planck (CMB)

Distance Ladder/Type Ia Supernovae



H0LiCOW (gravitational lensing)

Simon Birrer
H0LiCOW

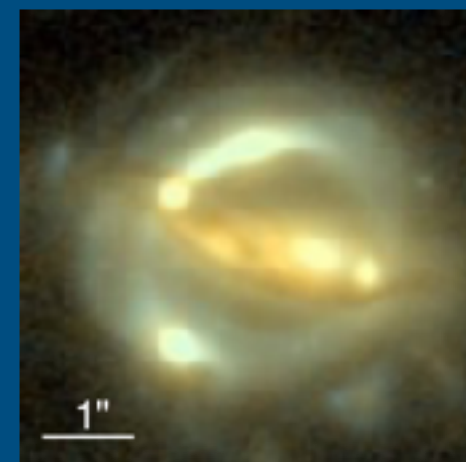
Trieste, 3 July 2018

Error budget

- Right now we are getting ~6-7% precision per lens system
- Three main contributions, all at roughly the same level (a few percent from each)
  - Time delay measurements (Δt)
  - Mass distribution in the primary lensing galaxy and its local environment (ψ)
  - Line-of-sight mass distribution (κ_{ext})
- Two ways to improve precision:
  - increase sample size: sqrt(N) statistics
  - more precise individual measurements: total sample can be reduced by more than a factor of two and allows for systematics check

The near future of Time Delay Cosmology

- Three additional H0LiCOW lenses to be completed this year, more to come in the future
- Improvement/refinement of analysis
  - alternative lens modeling codes
  - ground-based AO data
  - high-cadence monitoring (Courbin+2017)



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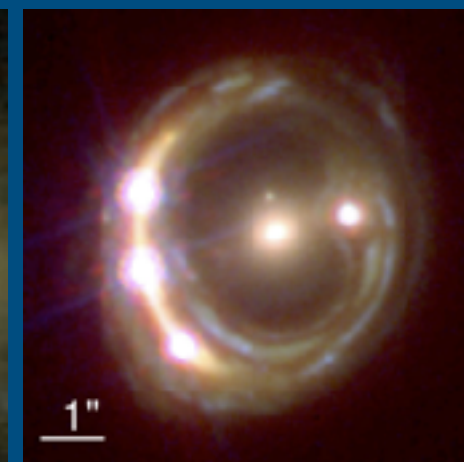

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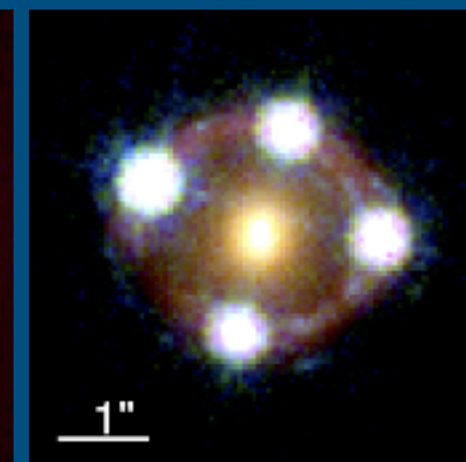
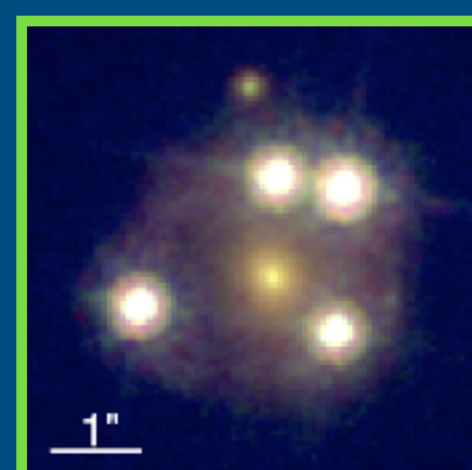


HE 0435-1223



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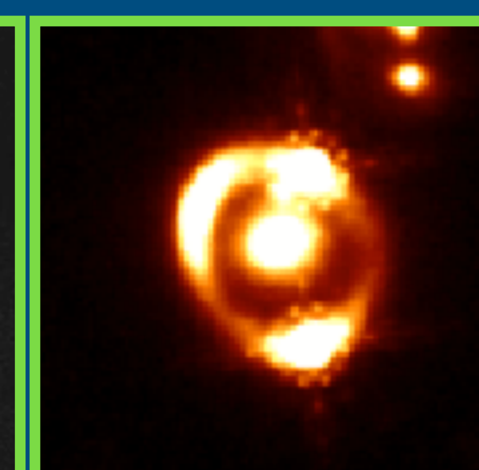
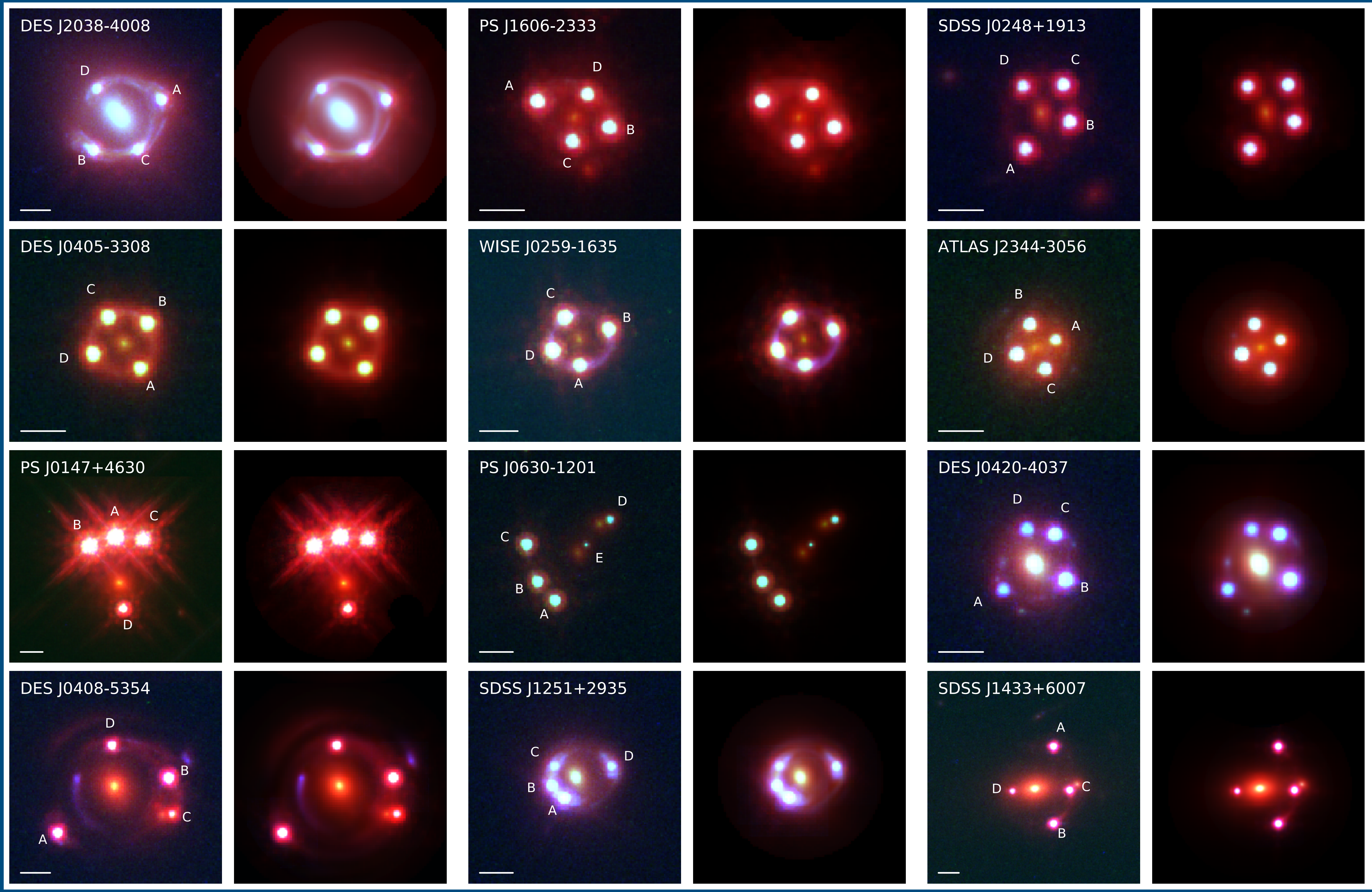

SDSS J1206+4432

Increasing the sample size…

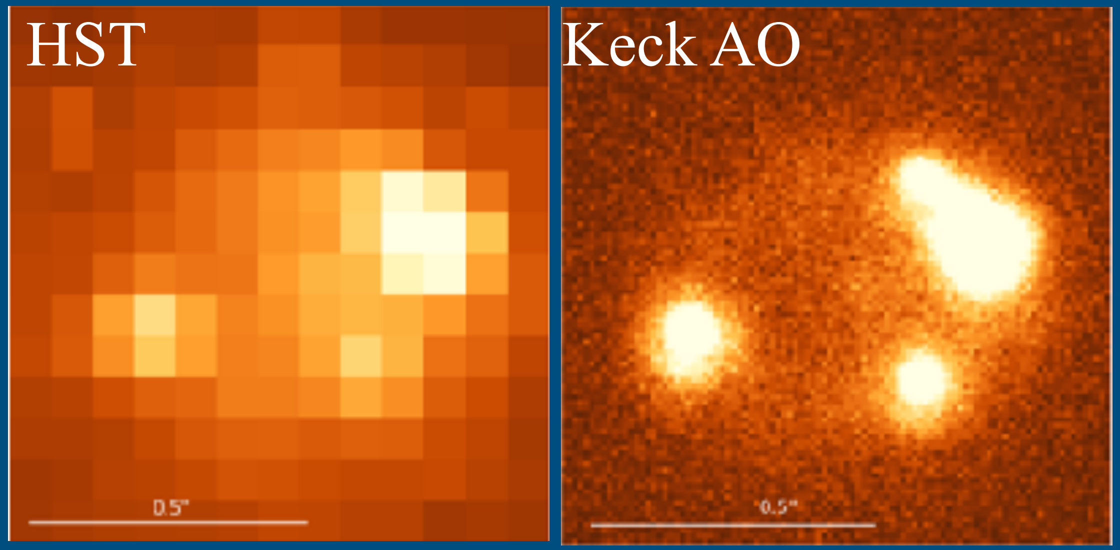


…and follow them up!

Shajib, Birrer+ (DES internal review), modelling with lenstronomy
discovered: Agnello+, Ostrovski+, Lemon+, Schechter+, Oguri+ and the **STRIDES collaboration**

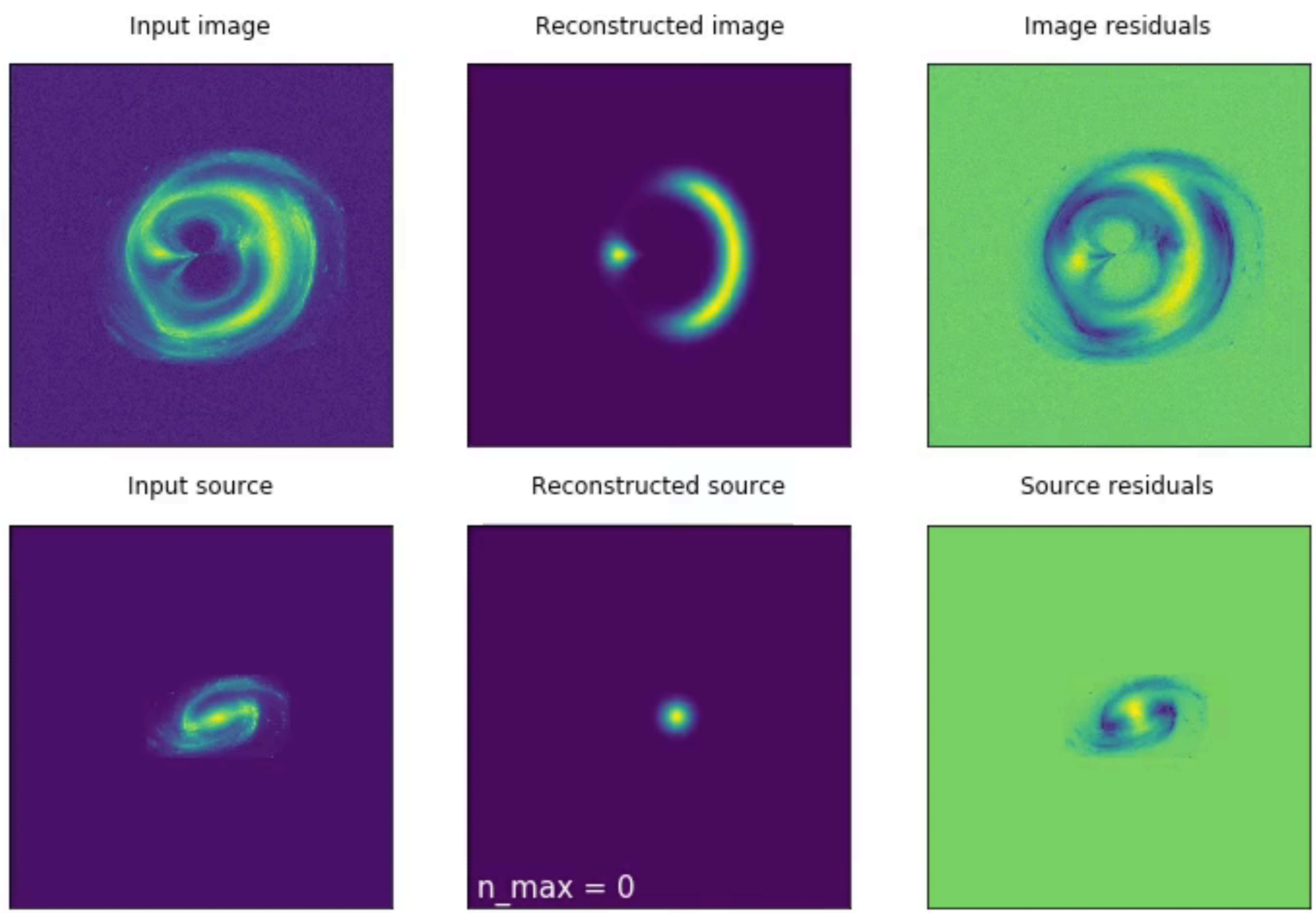
Improving lens model precision

- Resolving the lensed AGN host galaxy in the radial direction is a key to improving the lens modelling
- Keck AO vs. HST has shown improvements in modelling precision
  - Lagattuta+2010, Vegetti+2012, Chen+2016
- Can expect fast improvements in resolution with ELTs
- Caveat: Requires an extremely well characterized PSF



Lagattuta+2010

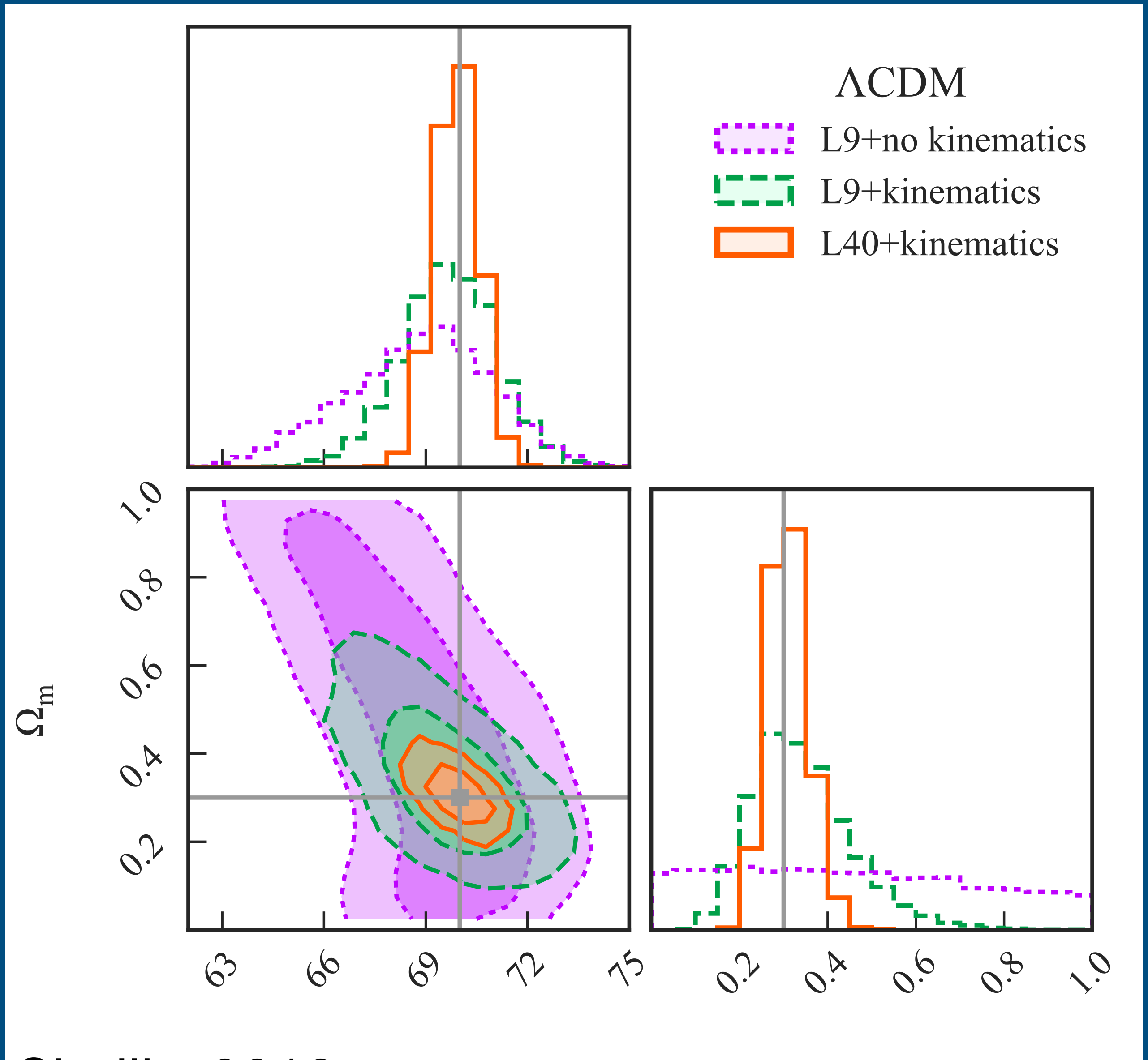
Improving lens model precision



Simulation made with lenstronomy software, by Simon Birrer

Improving lens model precision

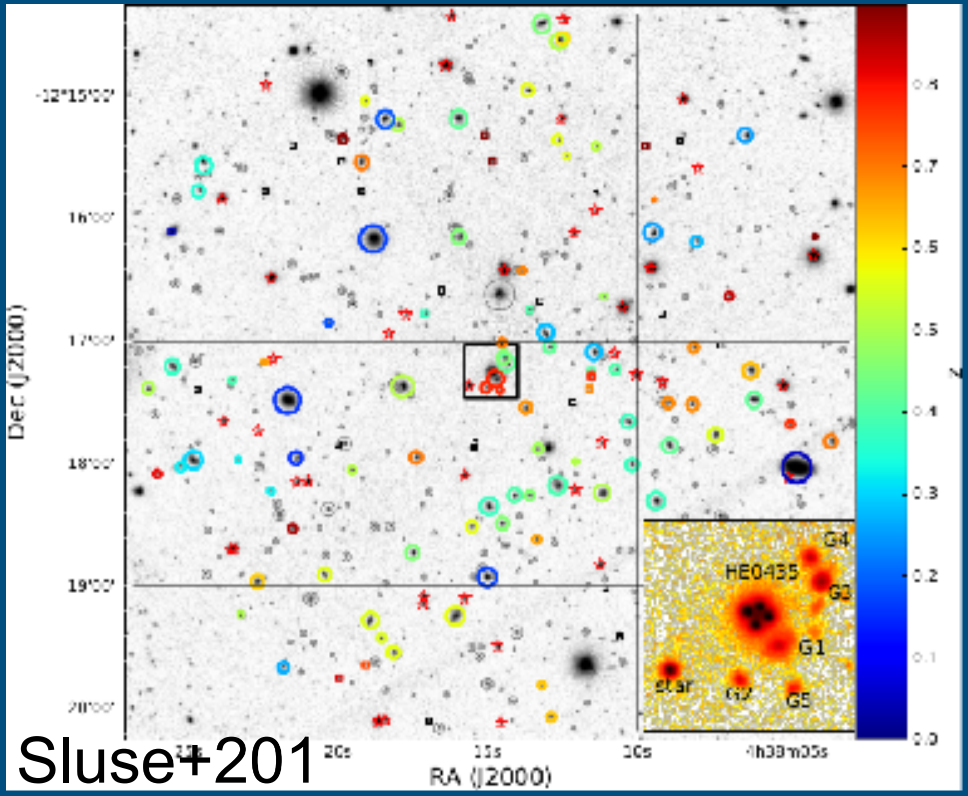
- Resolved 2-d kinematic information for the lensing galaxy can provide a big improvement in the precision of the lens modelling
- Observations are challenging on a 8-10m class ground-based telescope
- ELT are designed to provide resolved kinematic maps of high redshift galaxies

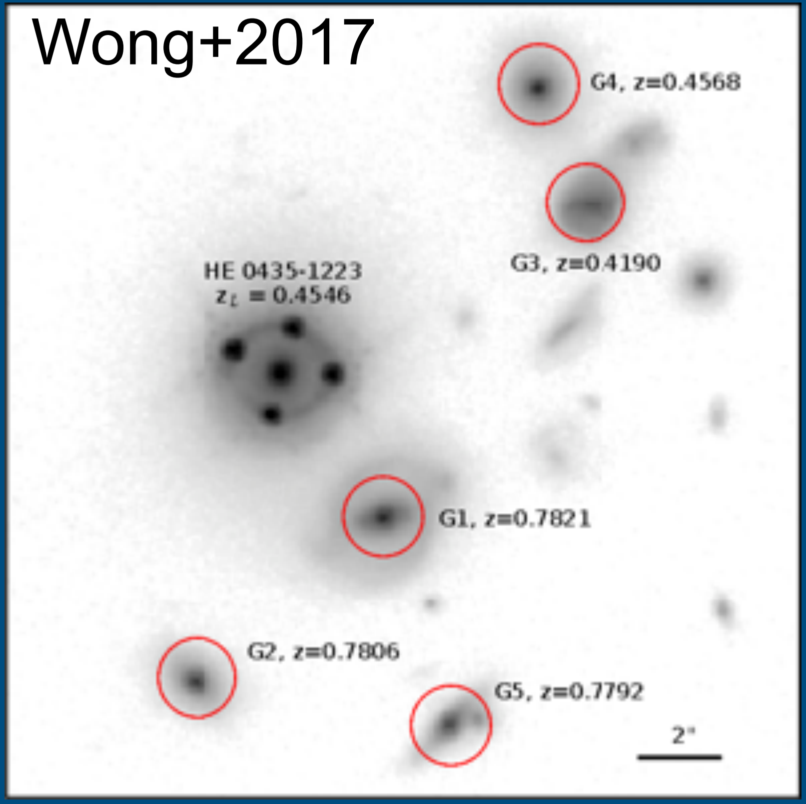


Shajib+2018

κ_{ext}: Improving the LOS constraints

- Wide-field and deep imaging from new sky surveys (e.g., LSST, HSC, possibly DES) will give requisite photometric data.
- Multiplexing spectroscopic follow-up with ELTs could improve LOS galaxy and group/ cluster mass estimates



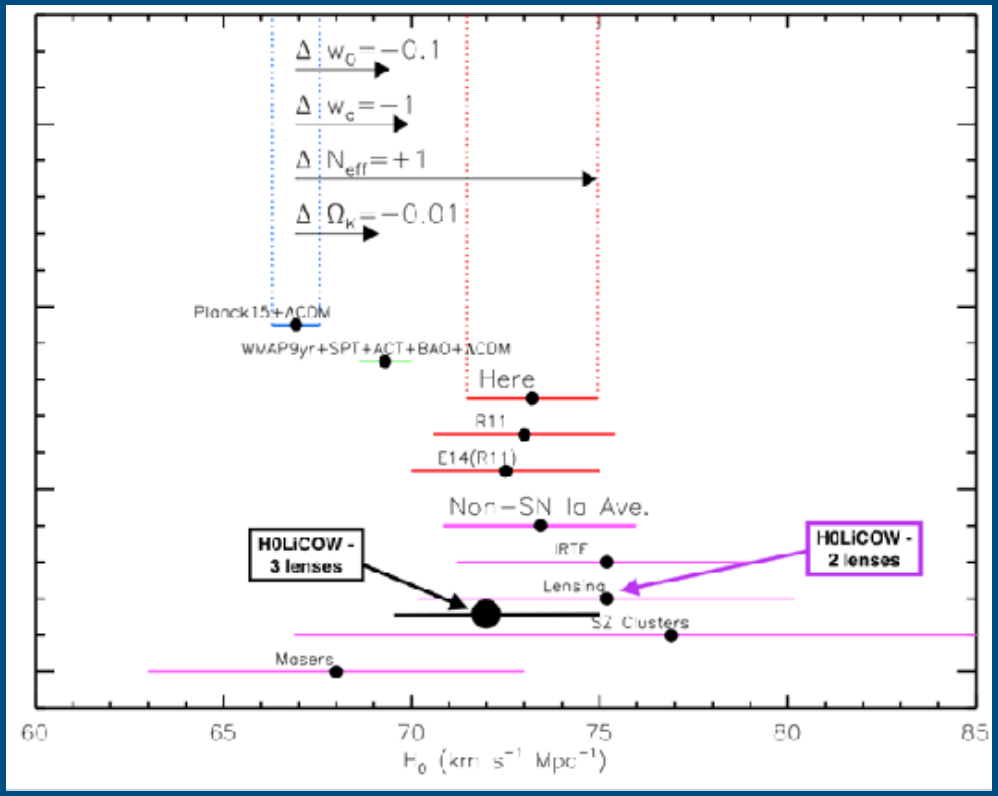


Δt: Time delay measurement possibilities

- Continuation of monitoring programs with 1-2m class telescopes
  - Including purchasing of telescope time explicitly for monitoring
  - Requires several years of data to overcome microlensing
- Intensive short-term monitoring with 8-10m class telescopes
- LSST provides 10 years of lensed quasar monitoring “for free”
  - Time delay challenges to see how cadence and multiple filters impact the ability to measure delays at high enough precision

Time-delay strong lensing

- Time delay cosmology tests the standard ΛCDM model, in an independent fashion from other distance-scale techniques
- Current 3-lens H0liCOW sample already gives better than 4% precision on H_0
- With ELTs and larger sample sizes, we can aim for ~1% precision (or better?) on H_0



Simon Birrer
H0LiCOW