STAR
Space sciences, Technologies and Astrophysics Research

LIÈGE université

H_0 using strongly lensed quasars: Results and perspectives from the H0LICOW project

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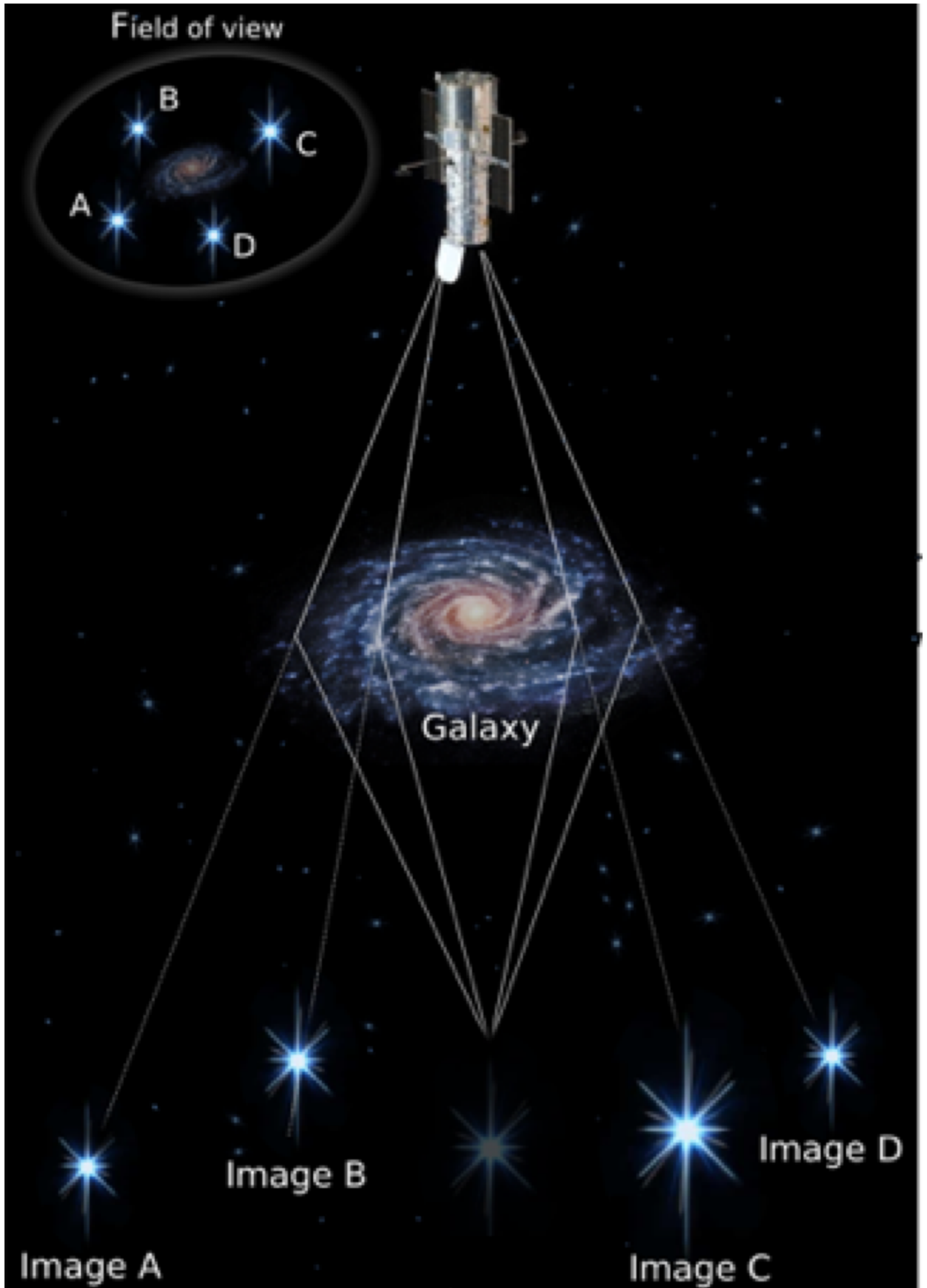
Representing the
H0LiCOW collaboration

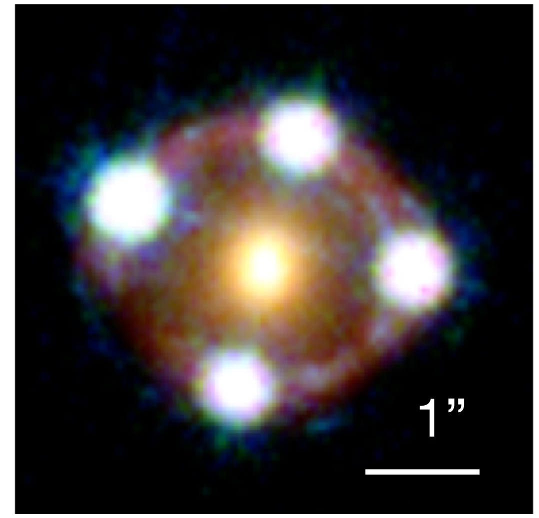
European Commission

erc
European Research Council
Established by the European Commission

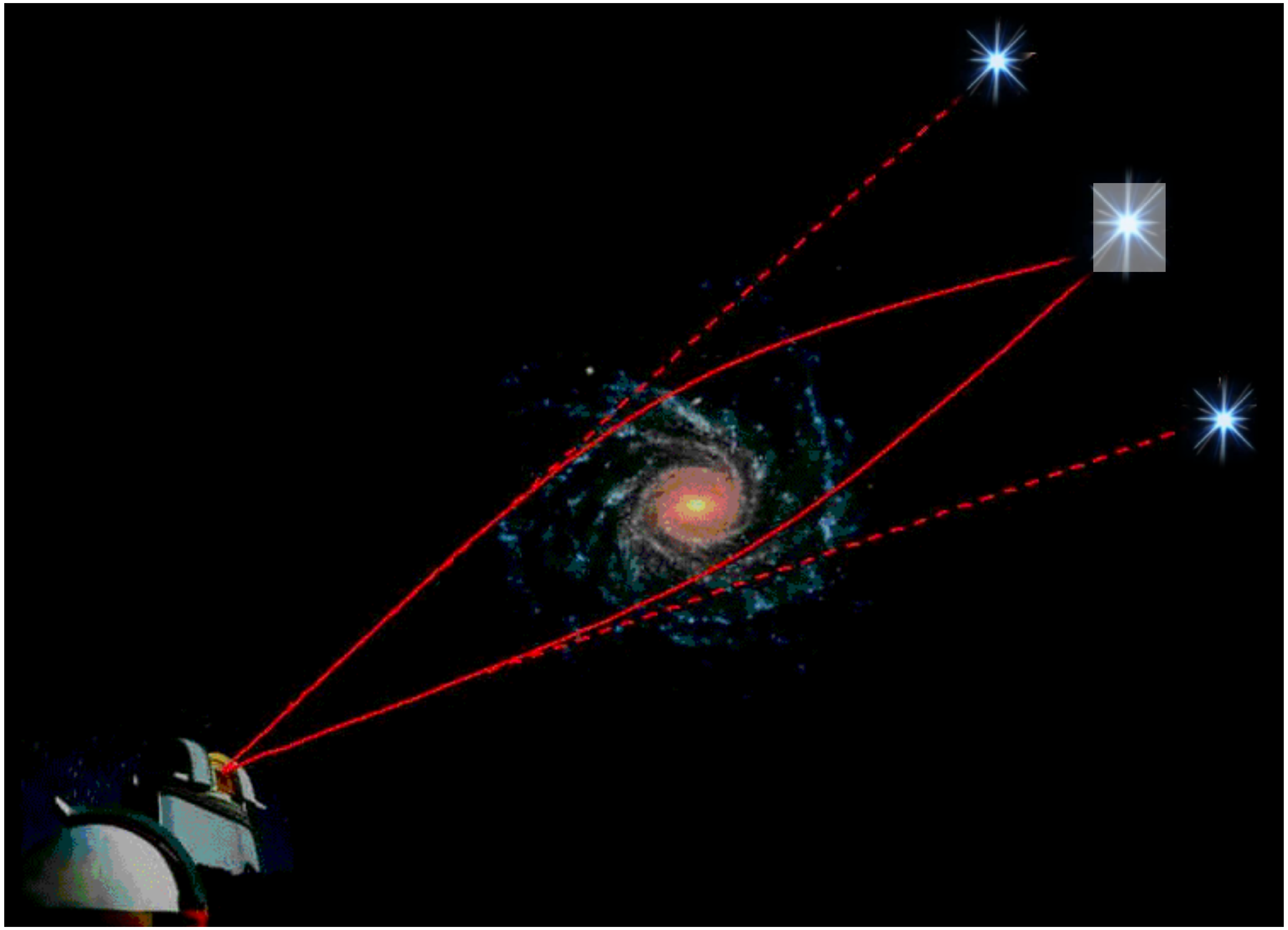
Sesto, Concordance and challenges in Cosmology, Feb. 19th 2019

Gravitational lensing





Cosmology with time delays



For cosmography, we need:

(1) time delays

(2) lens mass model

(3) mass along line of sight

[(4) Combine with σ_{lens} to determine D_L (e.g. Jee+ 2015)]

z_L ≡ lens redshift

$$\Delta t = \frac{1}{c}(1+z_L)\frac{D_L\, D_S}{D_{LS}} \cdot \Delta\left(\frac{1}{2}|\vec{\theta} - \vec{\beta}|^2 - \psi_{2D}\right)$$

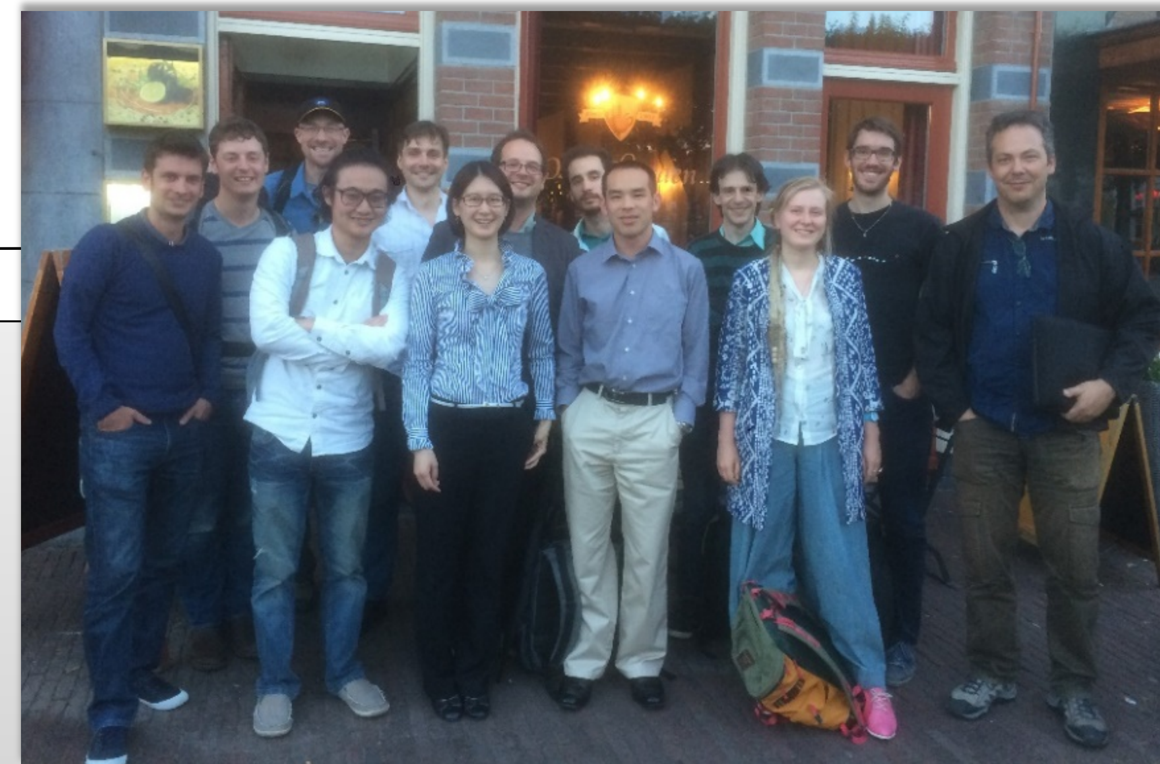
$D_{\Delta t} \propto 1/H_0$

Astrometry of the images

Source positions (unconstrained)

Gravitational potential (at the image)

H0LICOW



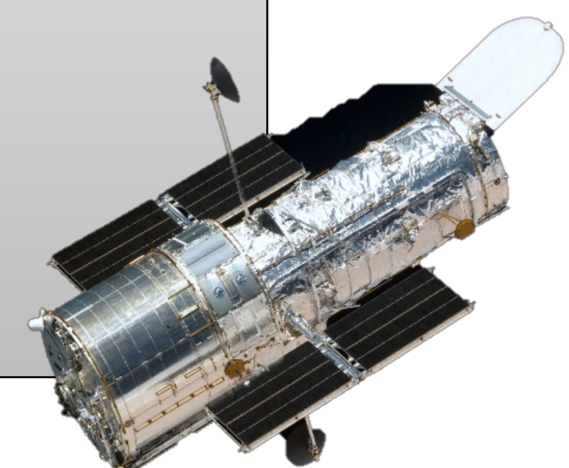
H_0 Lenses **I**n the **CO**SMOGRAIL's **W**ellspring (PI S. Suyu – MPA/U.Munich):

Turn accurate Δt into time delay distance

$$\Delta t \propto \frac{1}{H_0} \cdot f\,(\text{geometry, mass distribution})$$

Immediate scientific objective:

Reach < 3.5% accuracy on H_0 with a small sample of systems.



Challenges

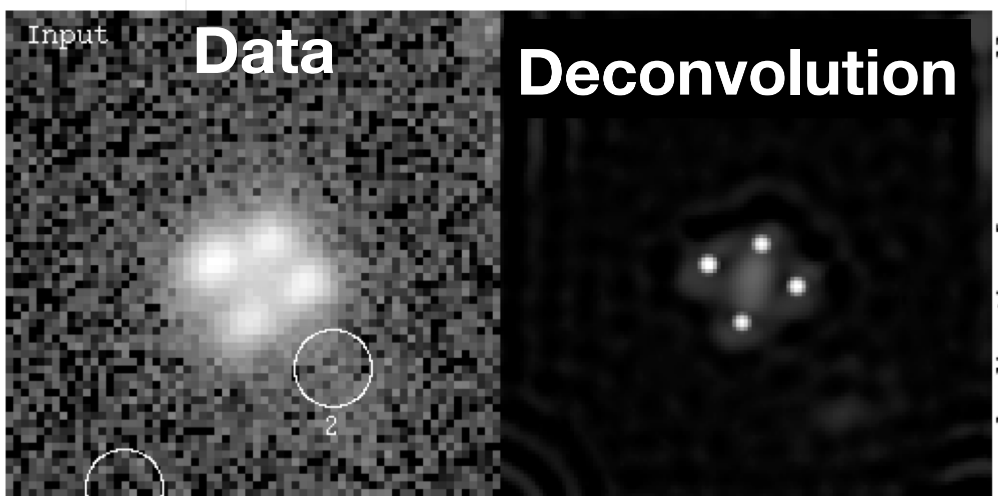
(1) time delays

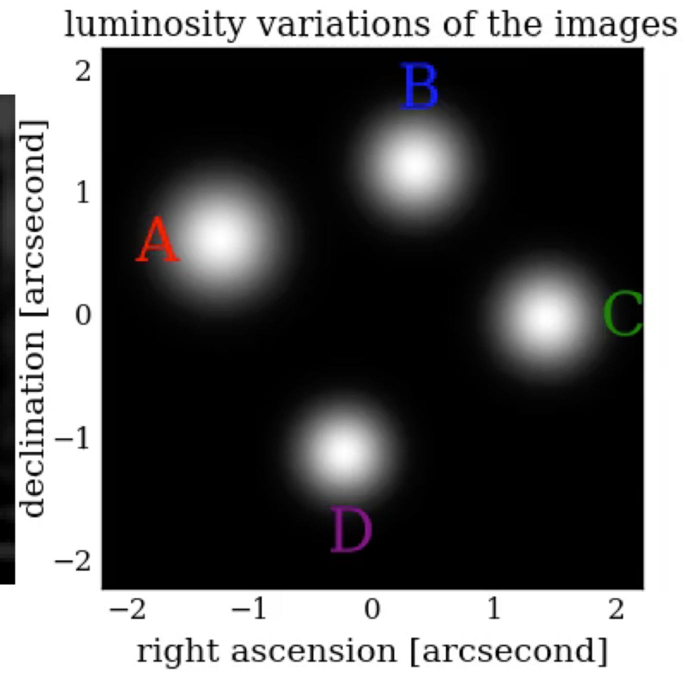
(2) lens mass model

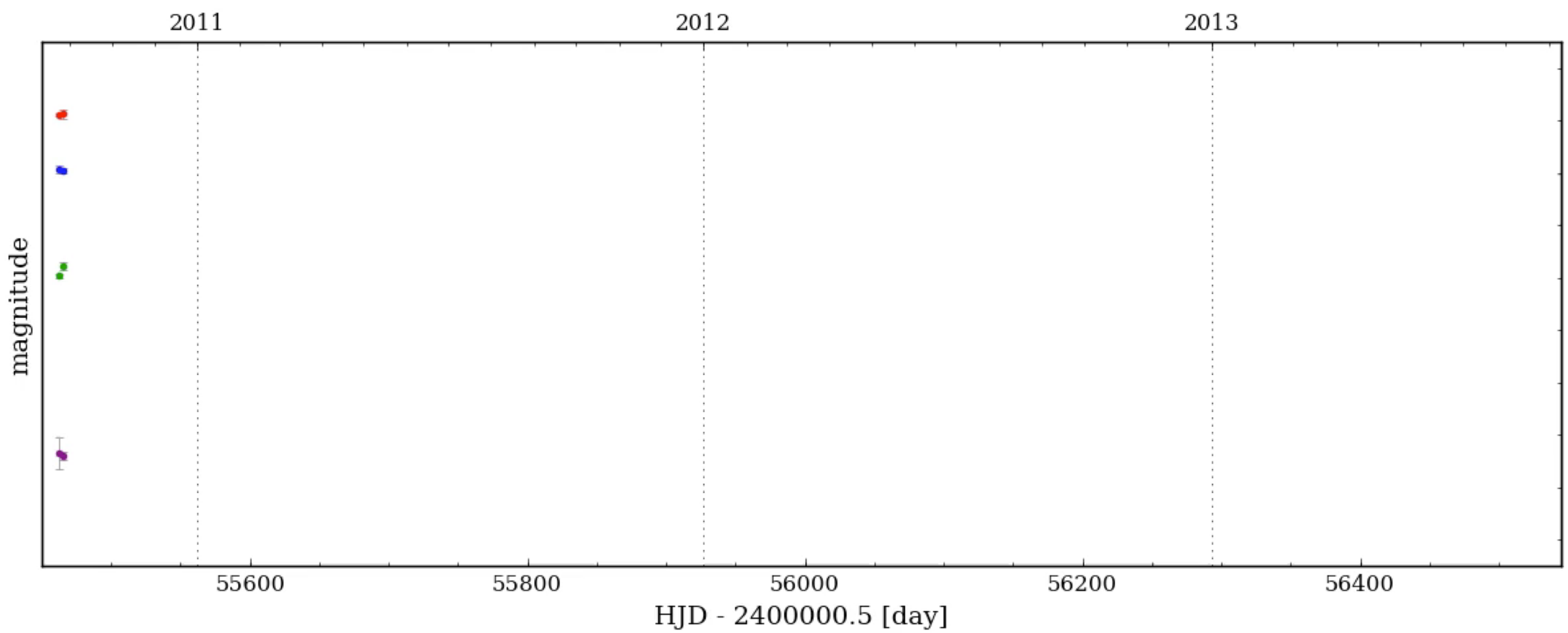
(3) mass along line of sight

[(4) Combine with σ_{lens} to determine D_L]

I. Measuring time-delays



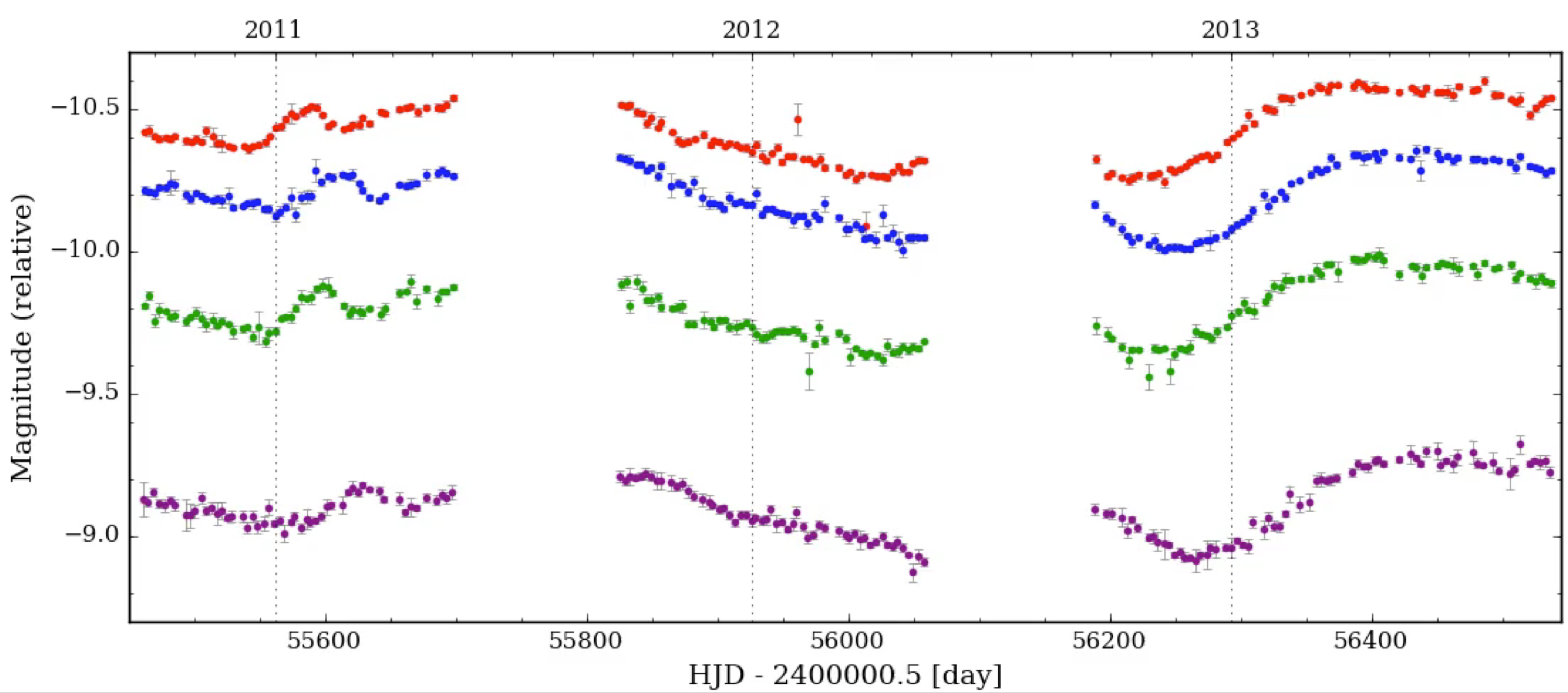




[Credit: V. Bonvin]

I. Measuring time-delays

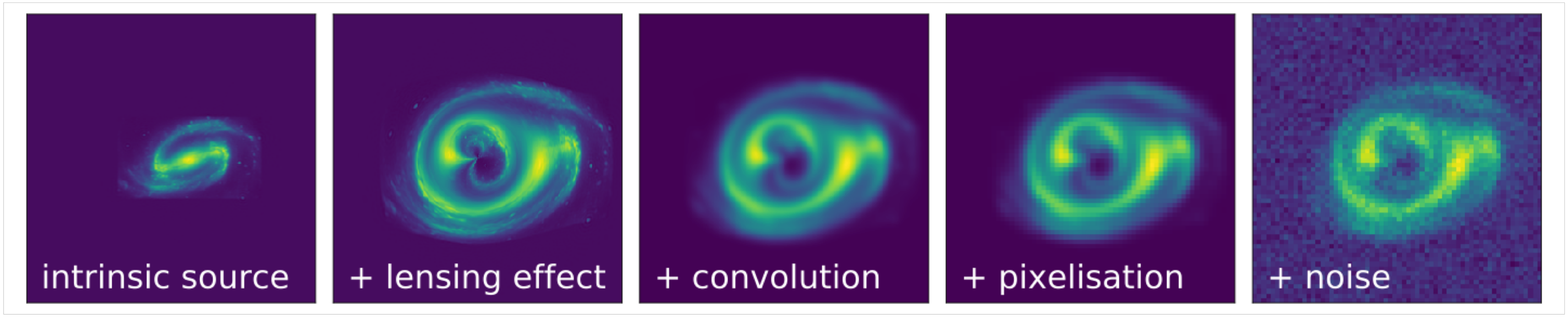
$$\frac{\sigma_{\Delta t}}{\Delta t} \leq 3\%$$



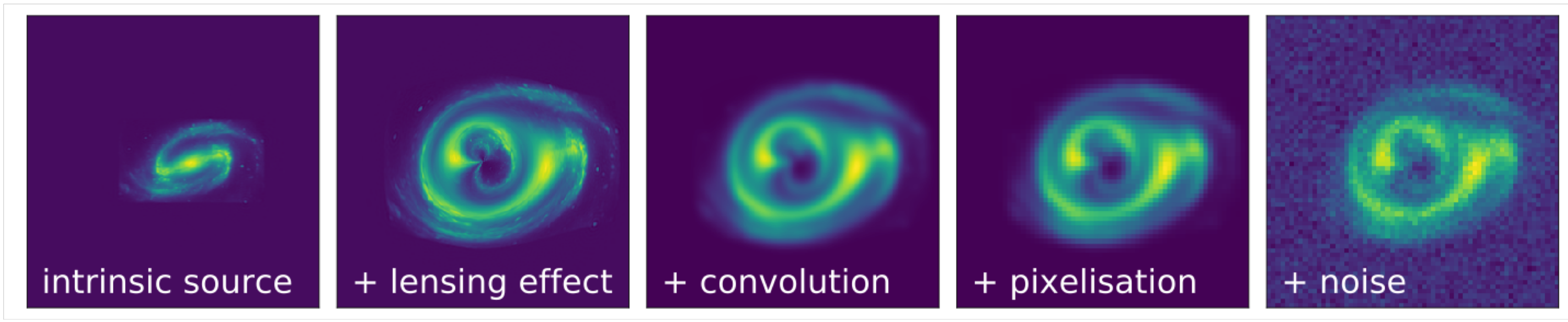
Not always as straightforward as it looks due to microlensing (modelled using free-knots spline systems)

[Credit: V. Bonvin]

II. Lens modeling



II. Lens modeling



a lot of nuisance!

that's what we care!

that's what we need to know!

?

$$\phi(\vec{\theta}, \vec{\beta}) = \left(\frac{1}{2}(\vec{\theta} - \vec{\beta})^2 - \psi(\vec{\theta}) \right)$$

Analytical lens mass model
Source model ((non)-parametric)
PSF blurring

Likelihood

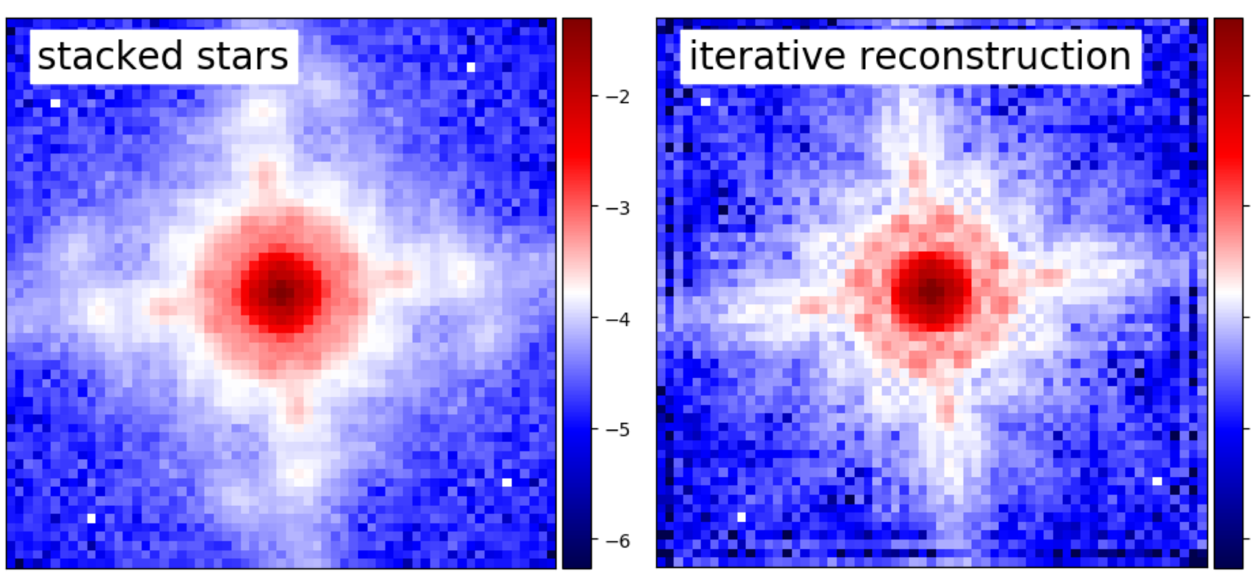
MCMC sampling

Two different codes:

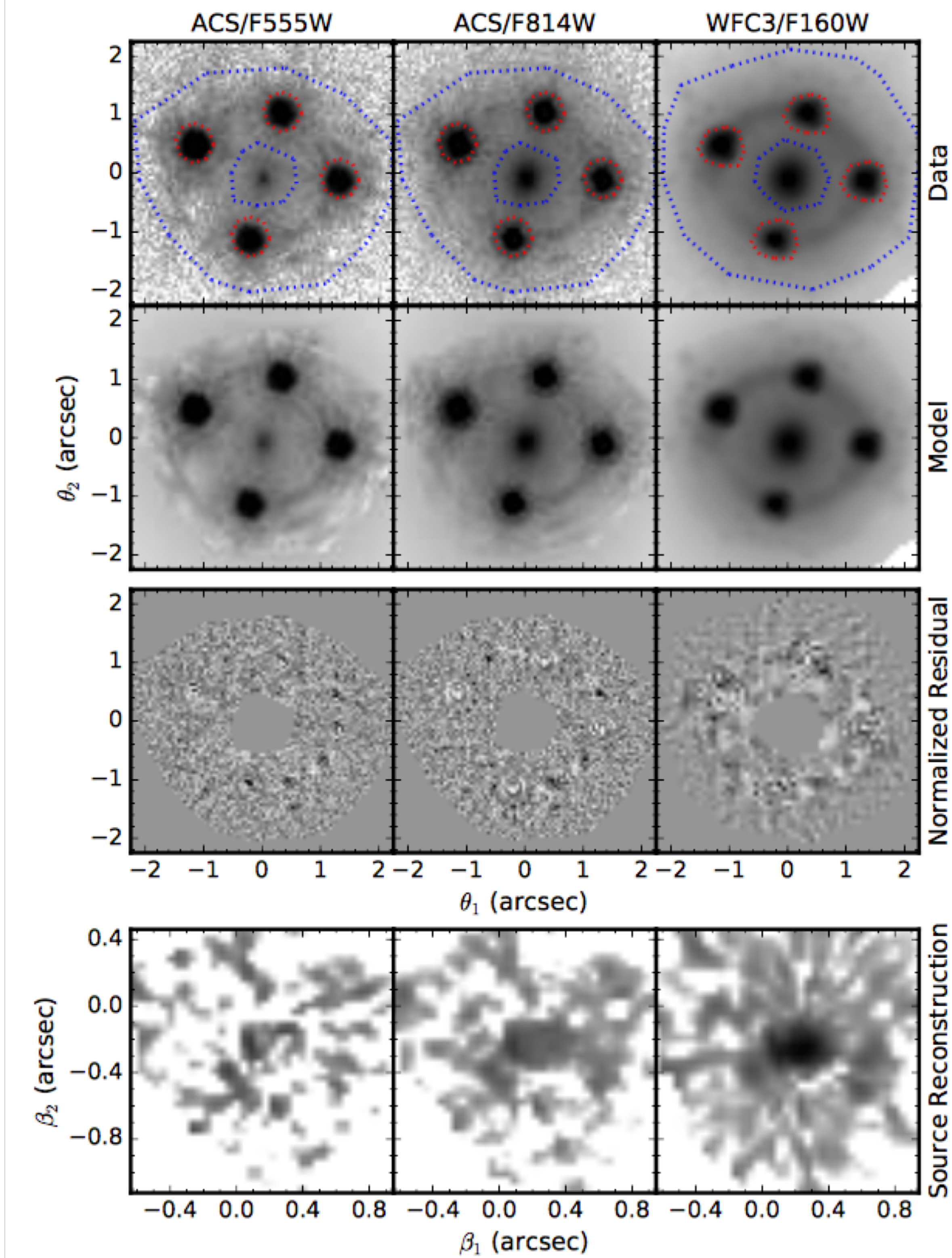
- GLEE (Suyu and Halkola 2010)
- Lenstronomy (Birrer and Amara 2010) – validated on J1131-1231 and HE 0435-1223
  `https://github.com/sibirrer/lenstronomy`

II. Lens modeling

- 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

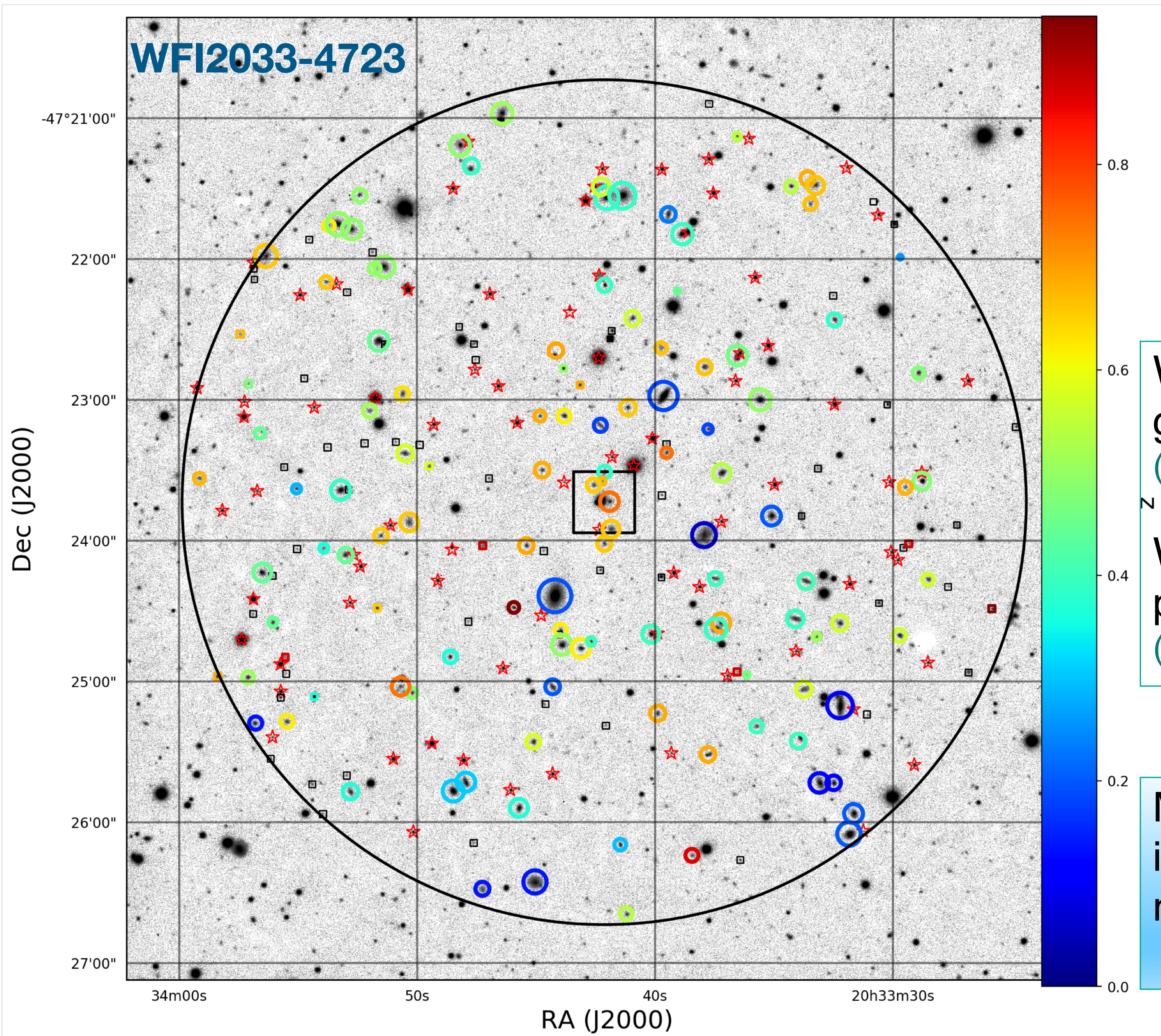


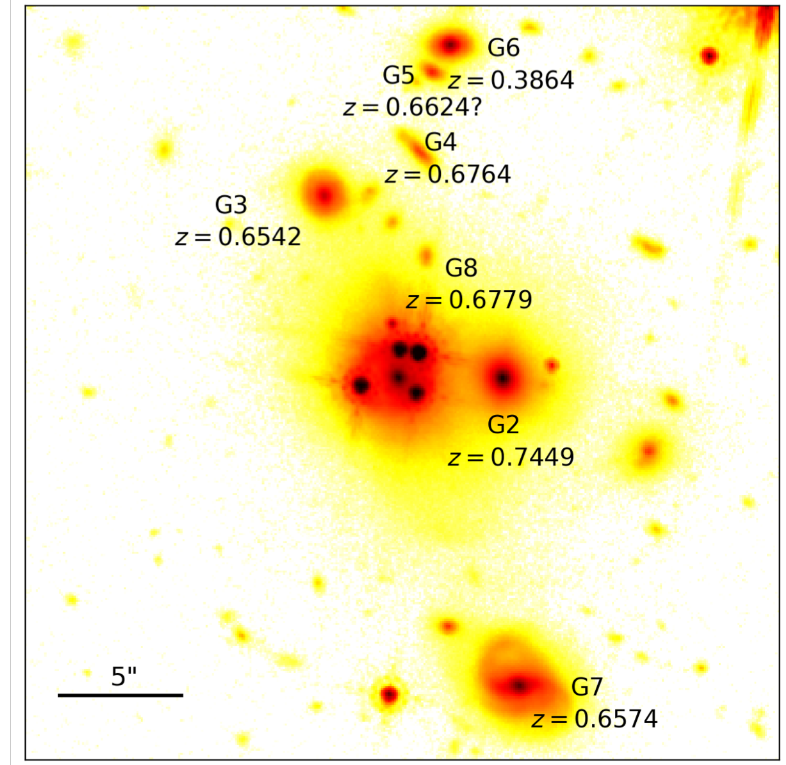
Birrer+ 2019, 1809.01274



Wong+2017
1607.01403

III. Lens environment





Wide-field spectroscopy for group identification
(Sluse+ 2017 - 1607.00382; 2019)

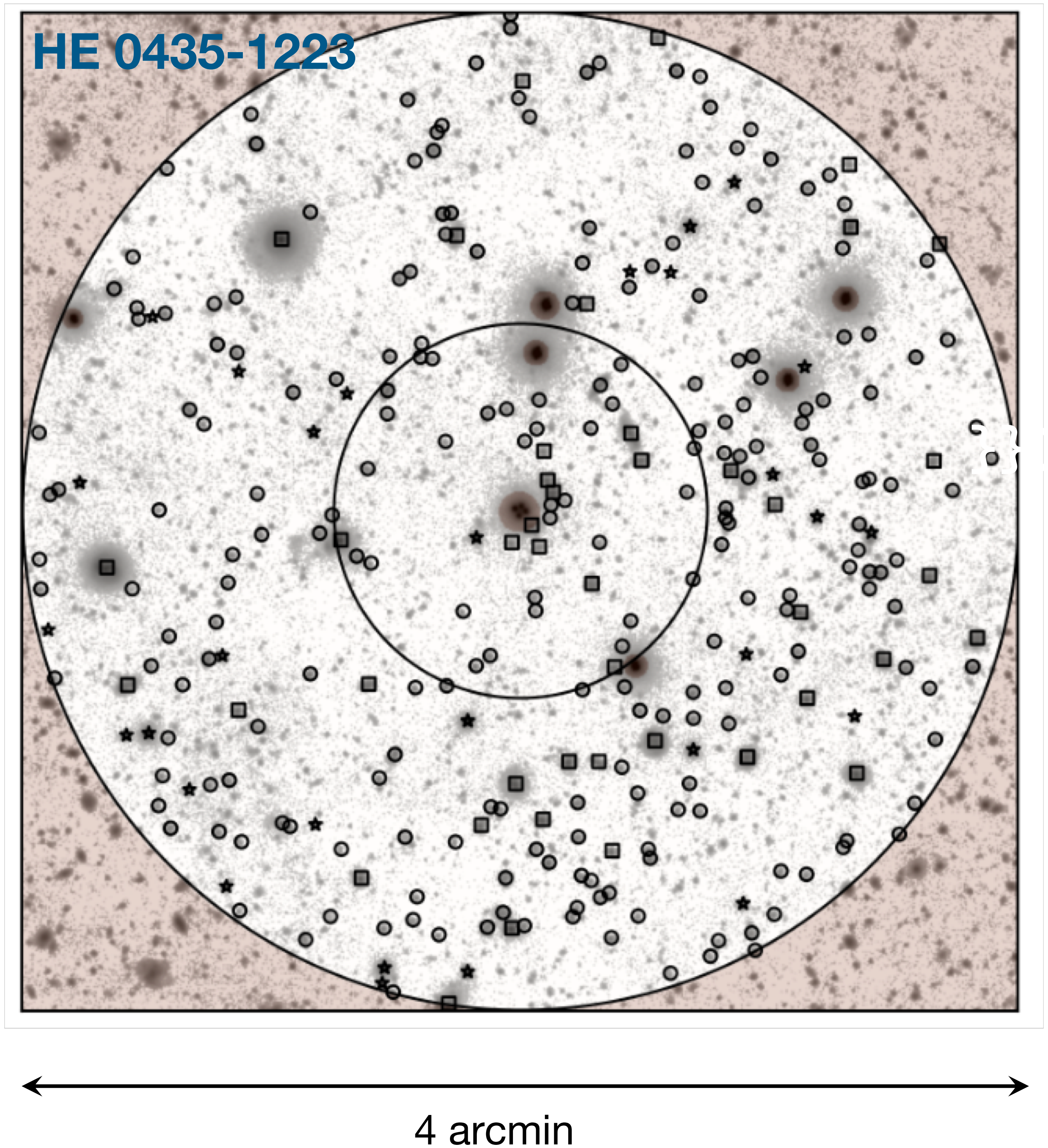
Wide-field multi-λ imaging for photo-z and stellar masses
(Rusu+ 2017 - 1607.01047)

Massive groups and galaxies included explicitly in the mass model

→ Multi-plane models

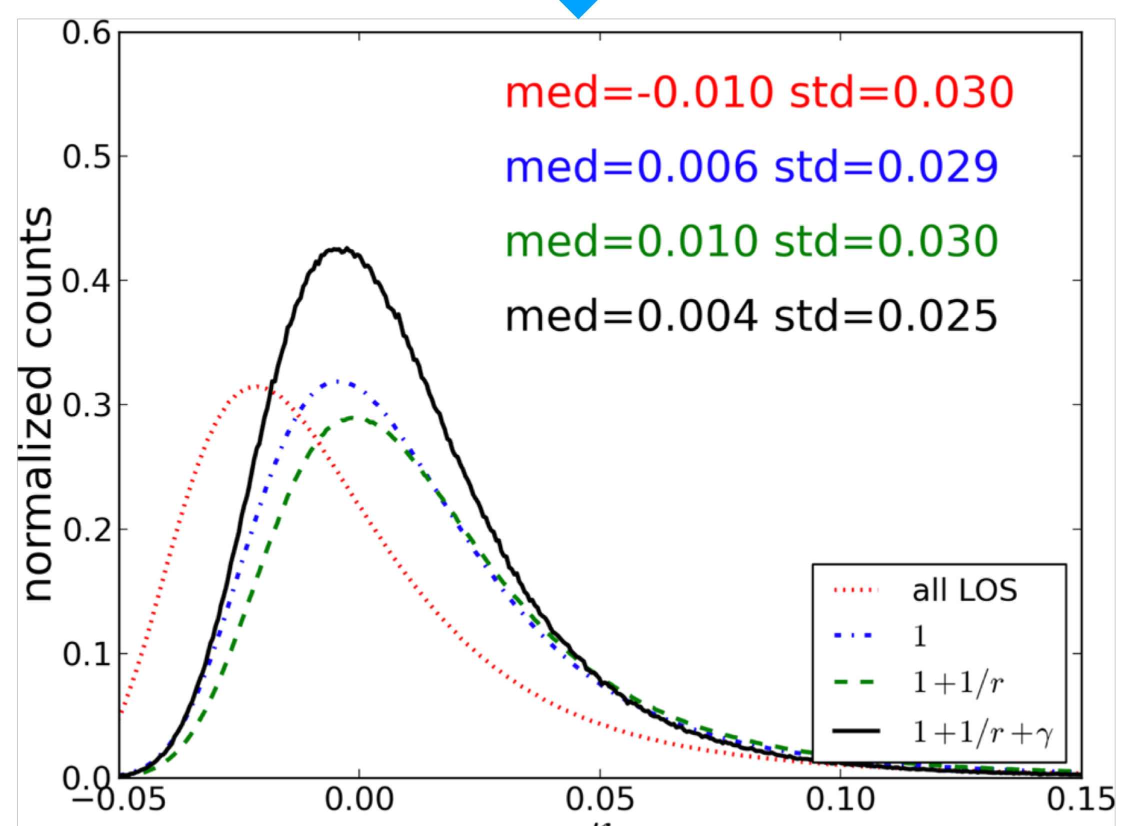
III. Lens environment

$$D_{\Delta t}^{\rm true} = \frac{D_{\Delta t}^{\rm model}}{(1-\kappa_{\rm ext})}$$



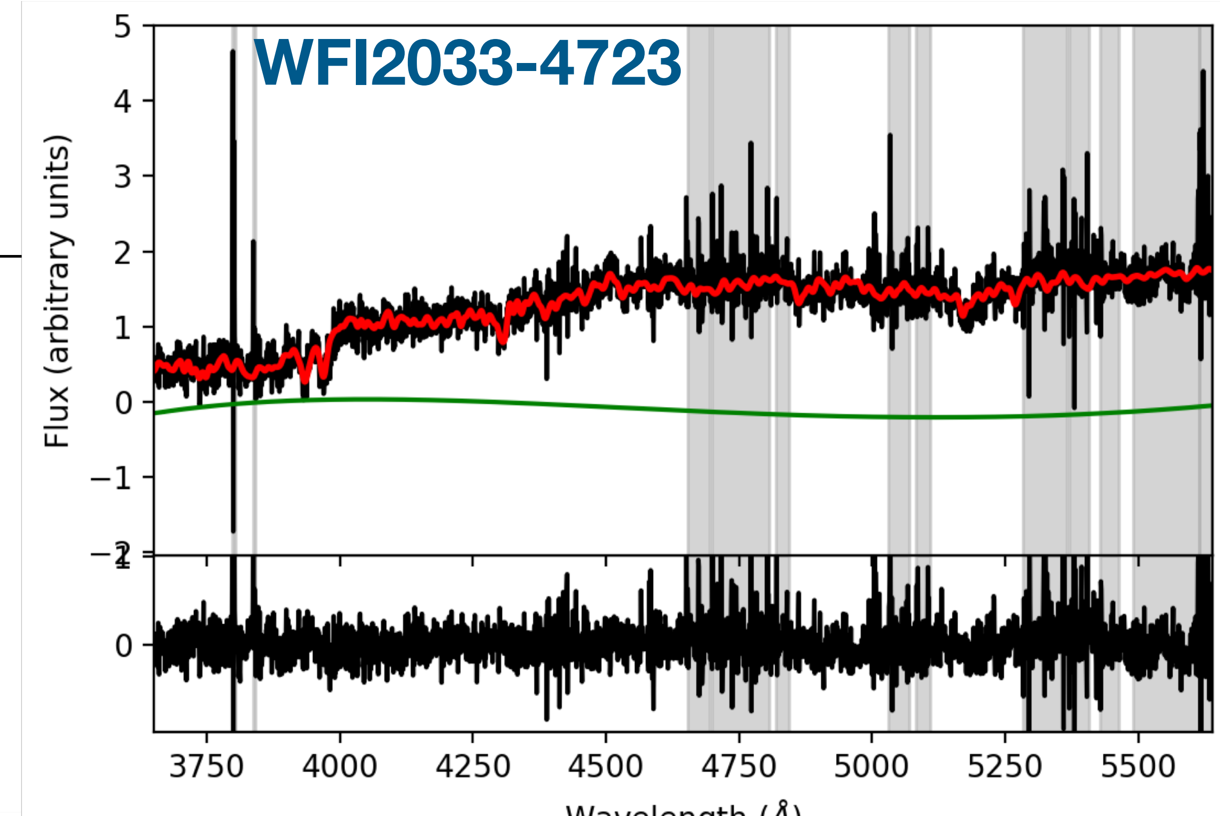
Statistical contribution using weighted number counts: field from simulations with same over-density as data allow us to derive $P(\kappa_{\rm ext}$ I overdensity)

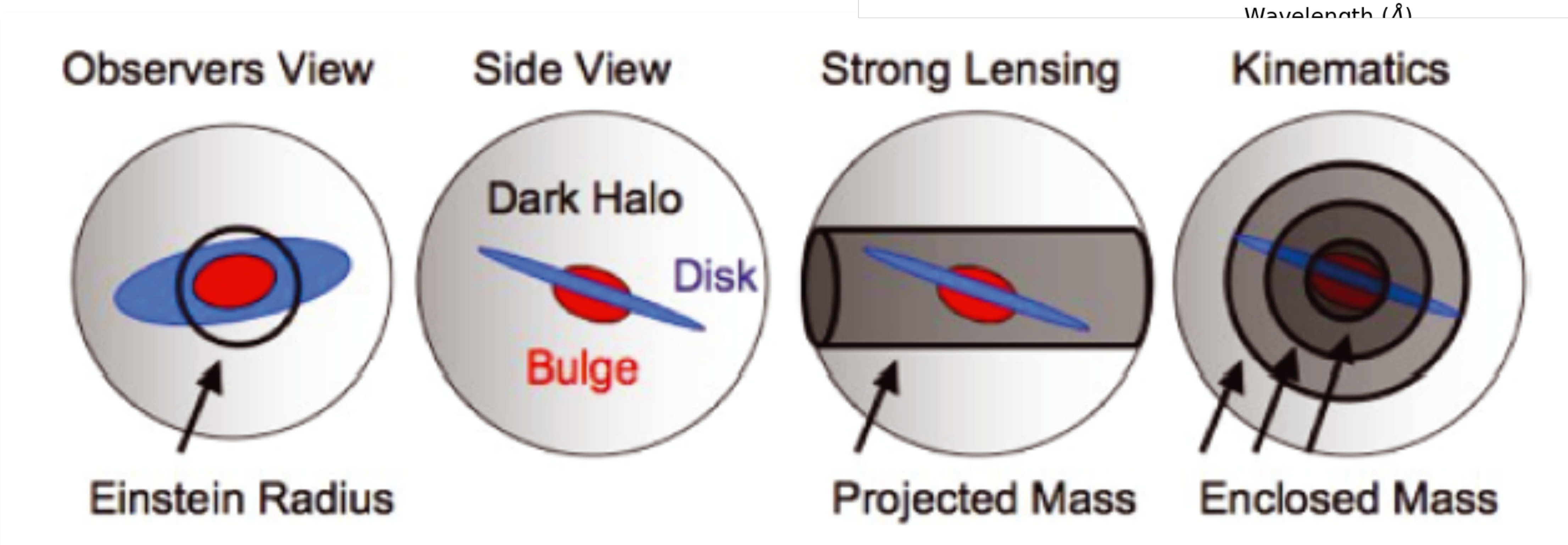
N_{gal} in data
N_{gal} in ref. fields (CFHTLS)
N_{gal} in Millenium Simulations



Rusu+ 2017 - 1607.01047; Greene et al. 2013 – 1303.3588

IV. Lens kinematics

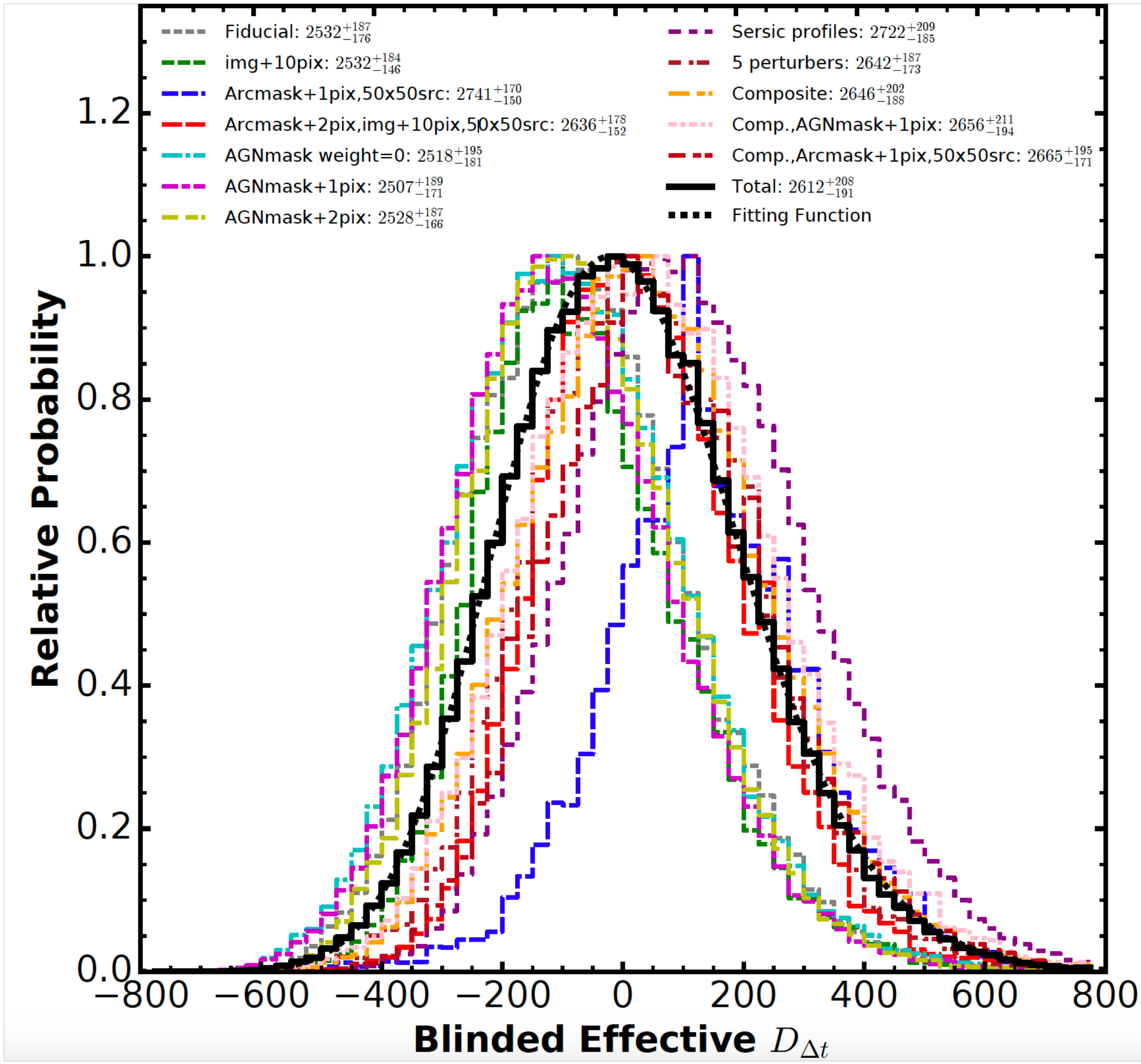




Dynamical mass M_{dyn} within R_{eff} and strong lensing mass $M(<R_E)$

Important to break degeneracies between models / provides estimate of D_L

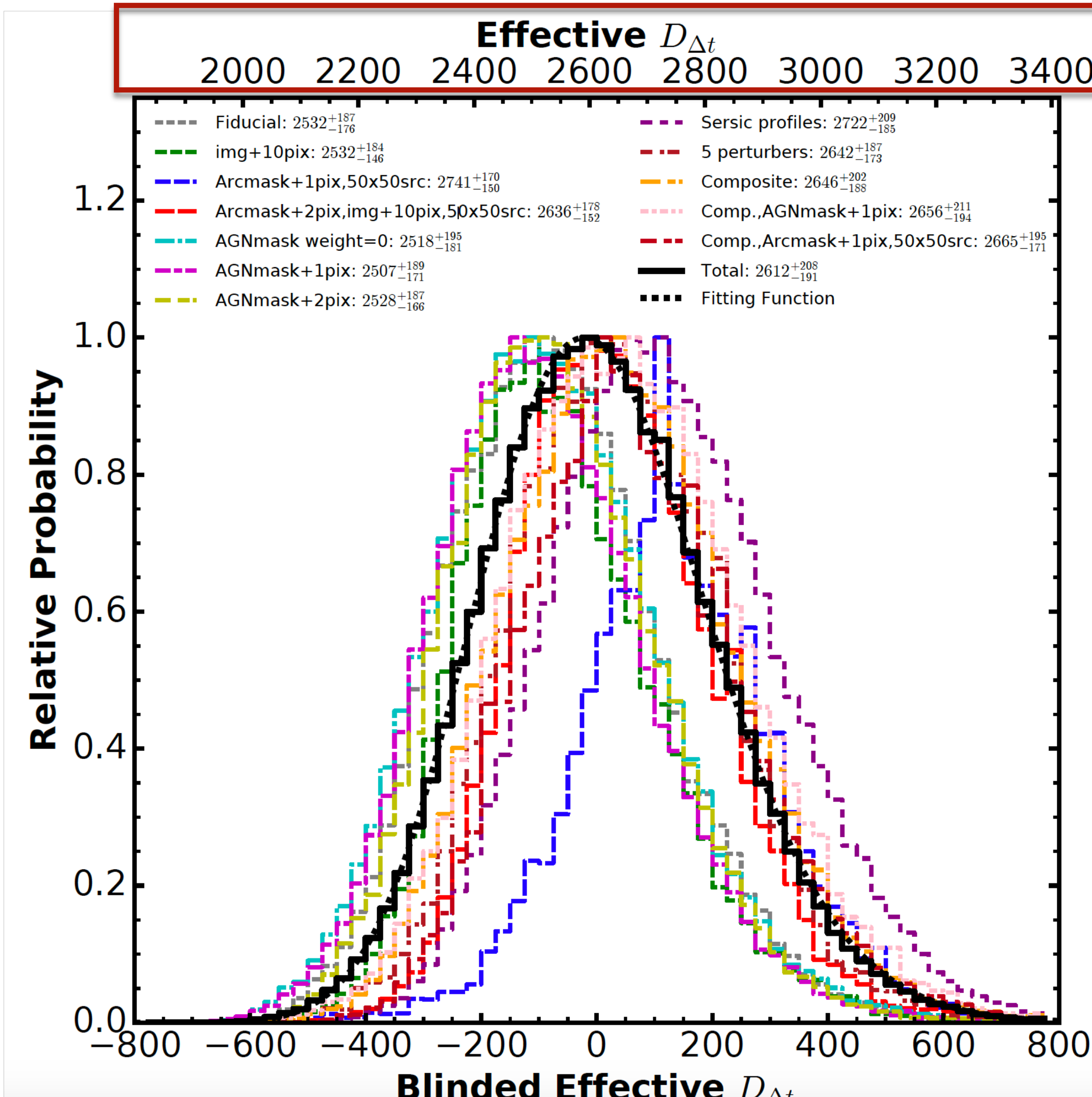
Blind analysis



Since the analysis of J1131-1231 (Suyu+2013), the analysis is carried out blind. This slide illustrates blindness in action (for HE0435-1223, Wong+ 2017 ; H0LICOW IV)

Throughout analysis, cosmological distances and parameters are offset from median, i.e., blinded

Blind analysis



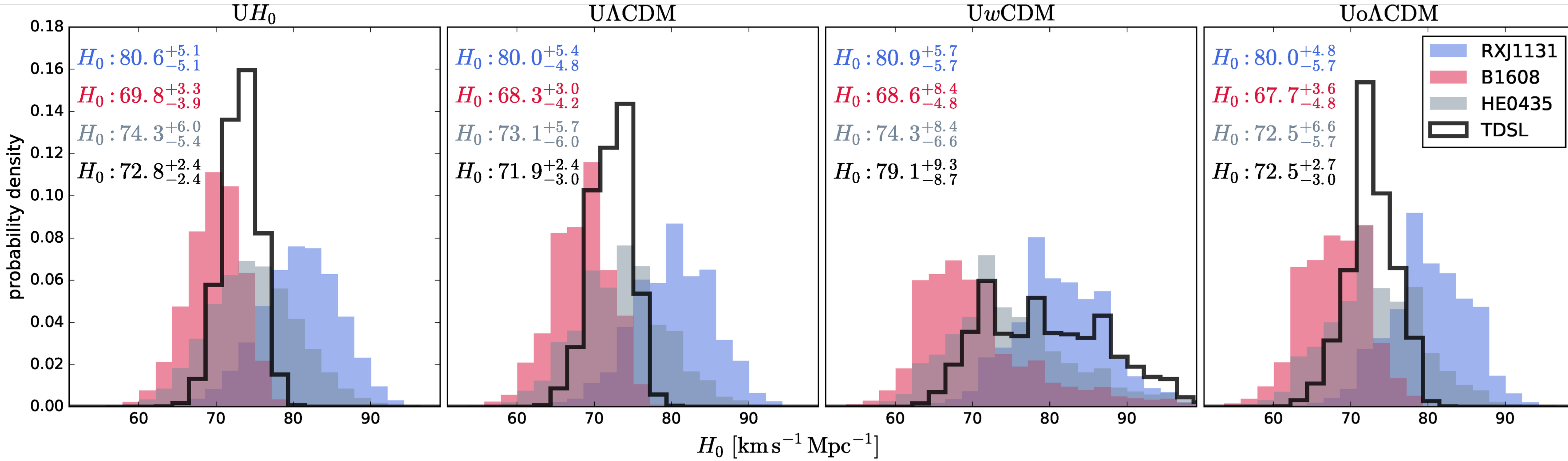
Throughout analysis, cosmological distances and parameters are offset from median, i.e., blinded

The collaboration agreed: when we unblind, publish $D_{\Delta t}$ without modification

- Scheduled unblinding telecon on June 2nd 2017
- Scheduled second telecon on June 16th 2017
- Typical relative uncertainty from one system of 8%

Note that from J1206 (HOLICOW IX), we weight models based on their BIC

Cosmology results from 3 lenses



Flat ΛCDM cosmology	Flat ΛCDM cosmology	Flat wCDM cosmology	Non-flat ΛCDM cosmology
$\Omega_\mathrm{m} = 1 - \Omega_\Lambda = 0.32$	$\Omega_\mathrm{m} = 1 - \Omega_\Lambda$	H_0 uniform in [0, 150]	$\Omega_\mathrm{m} = 1 - \Omega_\Lambda - \Omega_\mathrm{k} > 0$
H_0 uniform in [0, 150]	H_0 uniform in [0, 150]	Ω_de uniform in [0, 1]	H_0 uniform in [0, 150]
	Ω_m uniform in [0, 1]	w uniform in [−2.5, 0.5]	Ω_Λ uniform in [0, 1]
			Ω_k uniform in [−0.5, 0.5]

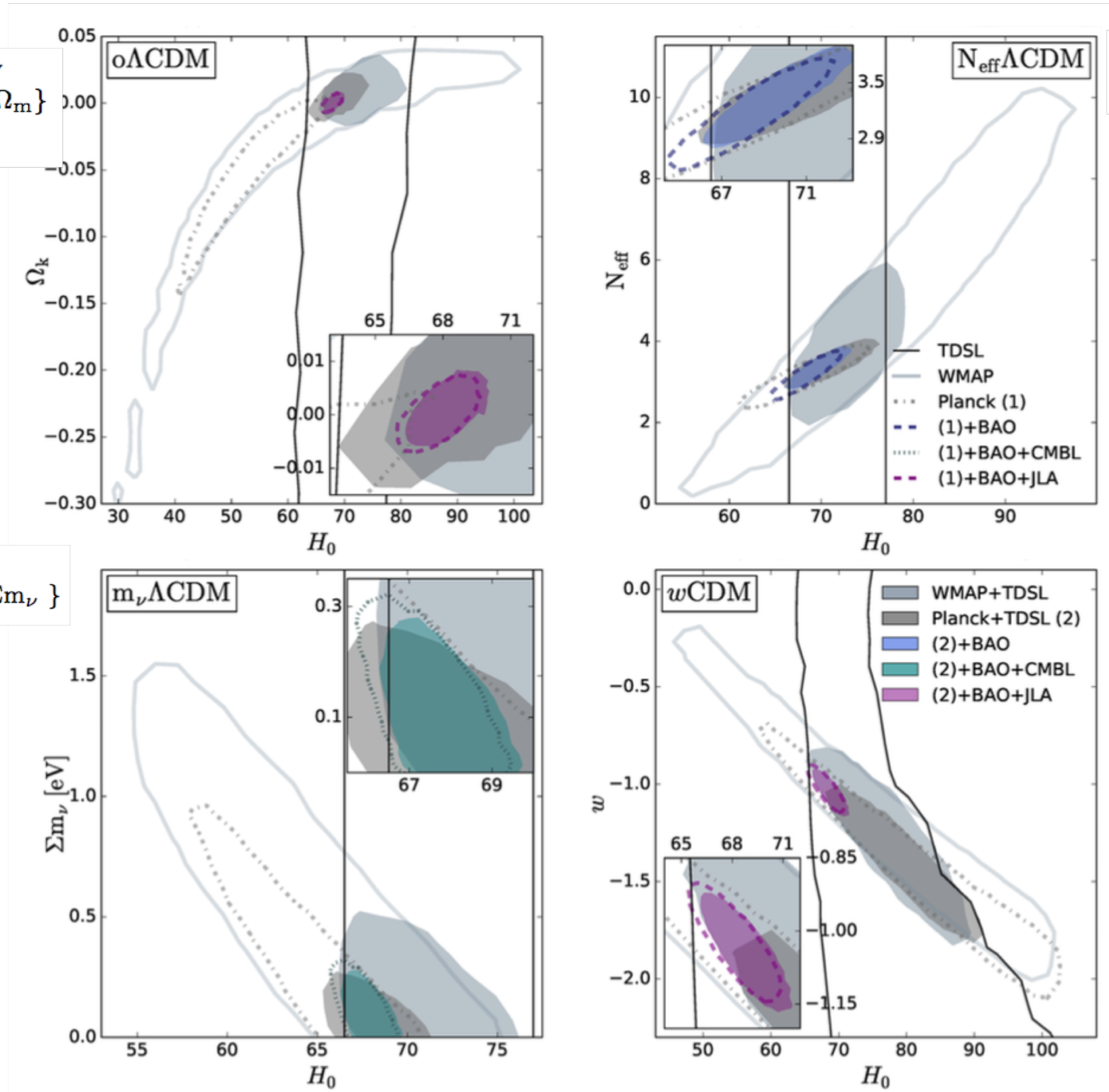
	UH_0	UΛCDM		UwCDM			UoΛCDM		
	H_0	H_0	Ω_Λ	H_0	Ω_de	w	H_0	Ω_Λ	Ω_k
TDSL	$72.8^{+2.4}_{-2.4}$	$71.9^{+2.4}_{-3.0}$	$0.62^{+0.24}_{-0.35}$	$79.1^{+9.3}_{-8.7}$	$0.72^{+0.19}_{-0.34}$	$-1.79^{+0.94}_{-0.49}$	$72.5^{+2.7}_{-3.0}$	$0.51^{+0.28}_{-0.30}$	$0.1^{+0.3}_{-0.3}$

Bonvin+ 2017 - 1607.01790
MNRAS, 465, 4914 (H0LICOW V)

Cosmology results from 3 lenses

Non-flat ΛCDM cosmology
WMAP/Planck for $\{H_0, \Omega_\Lambda, \Omega_m\}$
$\Omega_k = 1 - \Omega_\Lambda - \Omega_m$

Flat ΛCDM cosmology
WMAP/Planck for $\{H_0, \Omega_\Lambda, N_{eff}\}$



Flat ΛCDM cosmology
WMAP/Planck for $\{H_0, \Omega_\Lambda, \Sigma m_\nu\}$

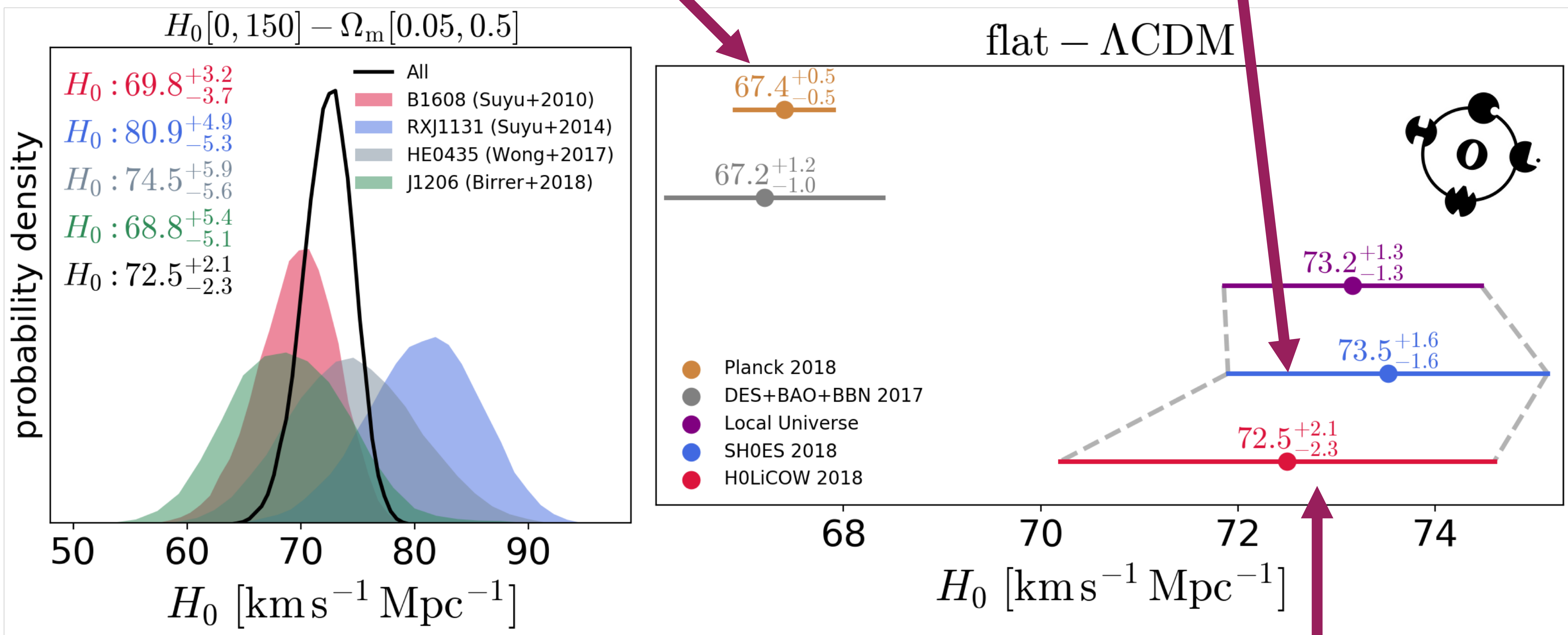
Flat wCDM cosmology
Planck for $\{H_0, w, \Omega_{de}\}$

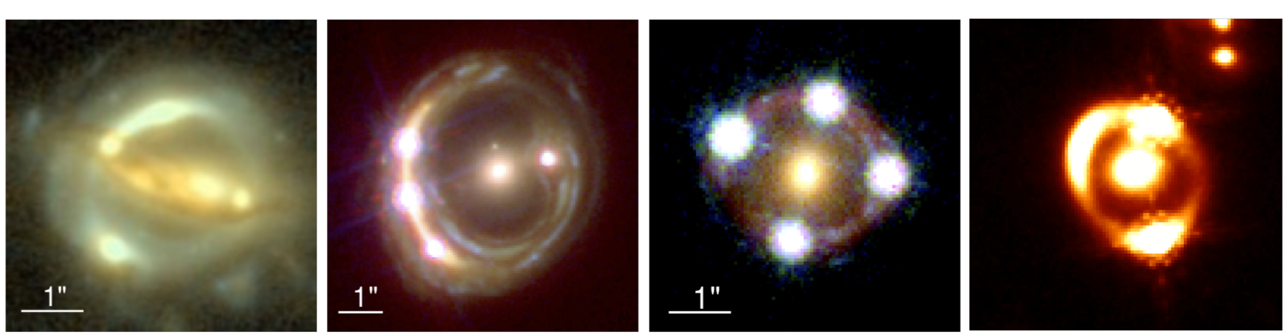
Bonvin+ 2017 - 1607.01790
MNRAS, 465, 4914 (H0LICOW V)

Lastest results from H0LICOW

Planck (CMB)

Distance Ladder/Type Ia Supernovae



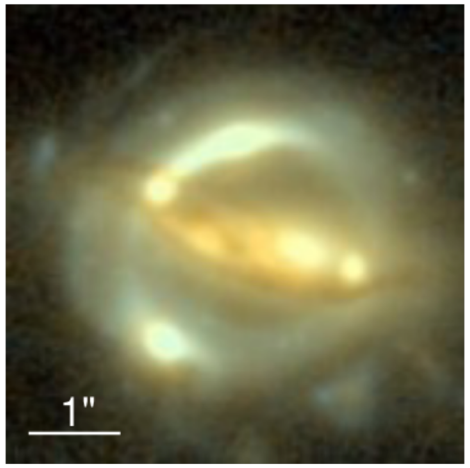


H0LiCOW (gravitational lensing)

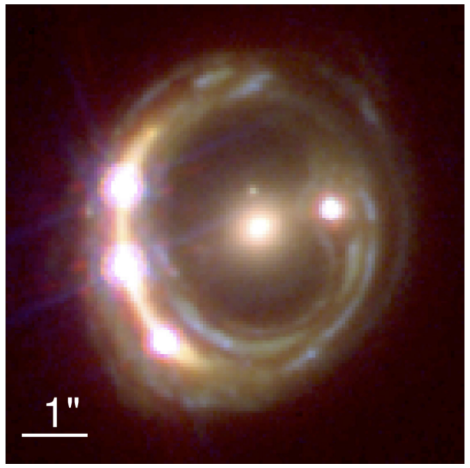
Birrer+ 2019 , 1809.01274

The near future of time delay cosmography

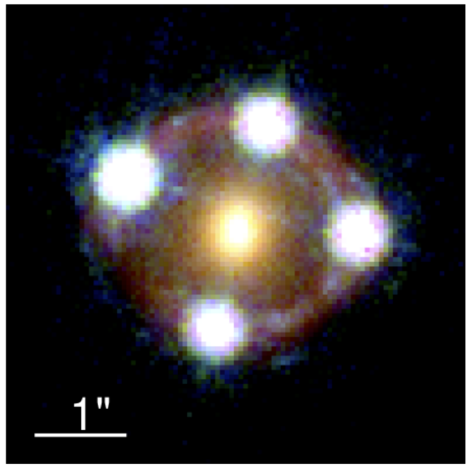
- Two additional H0LiCOW lenses to be completed in few months time
- Improvement/refinement of analysis
  - Alternative lens modeling codes
  - ground-based AO data
  - high-cadence monitoring (Courbin+2017)
  - Emulate full analysis chain



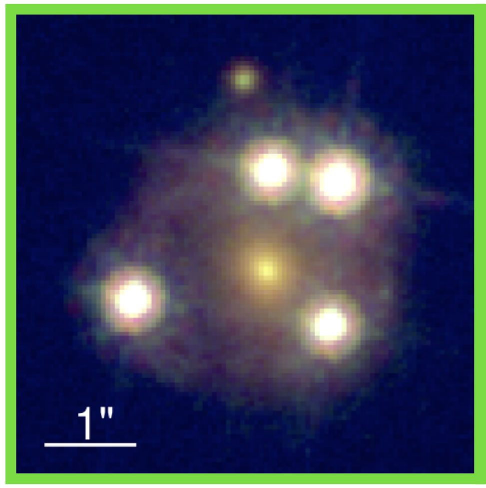
B1608+656



RXJ1131-1231

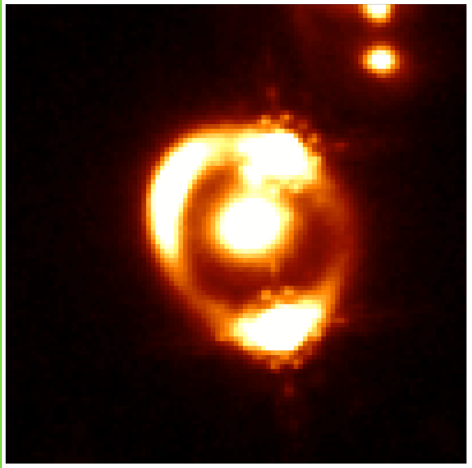


HE 0435-1223



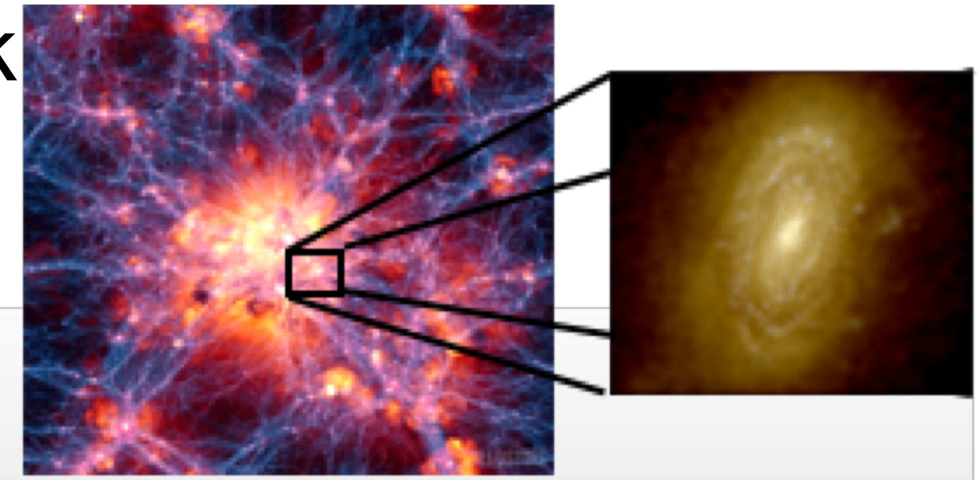
WFI2033-4723

PG1115+080



SDSS J1206+4432

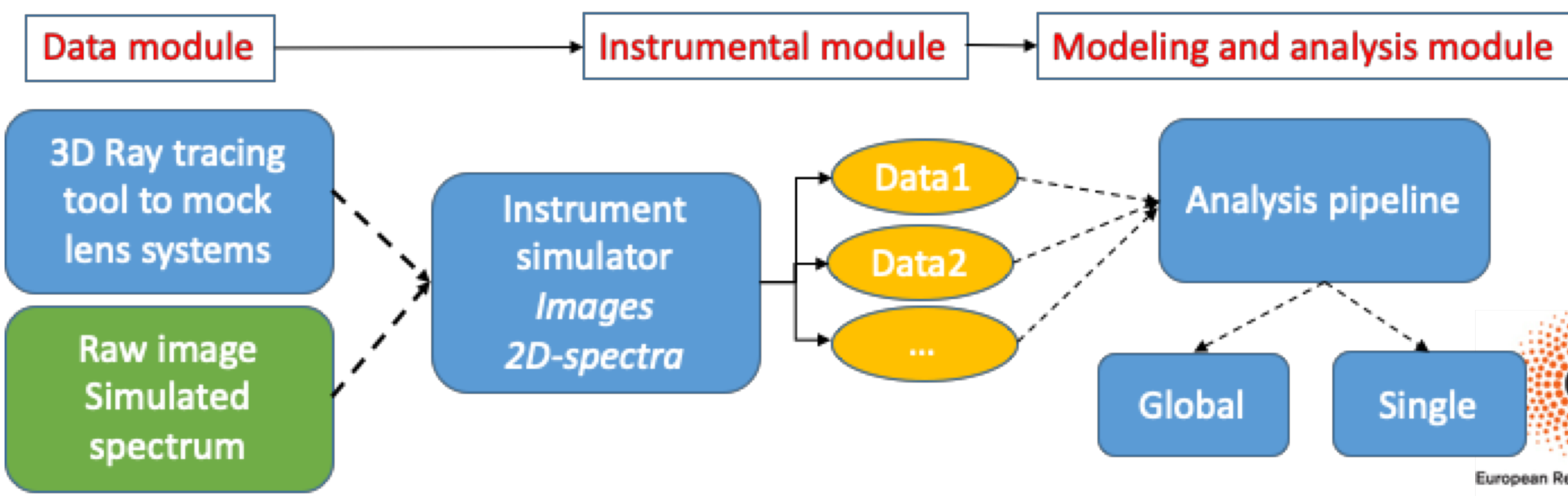
COSMICLENS' end-to-end simulation and analysis framework



Main goal:

Mock lens systems based on hydrodynamic simulated galaxies to test modeling strategies used in H0LICOW and mitigate impact of model degeneracies

Secondary goal:
Modular/versatile tool to mock data obtained with various telescopes and instruments (Euclid, JWST, VLT, ...), but also emulate the analysis chain to optimize the observational set-up (How many objects ? Compare various analysis strategies ? ...)



Summary and outlook

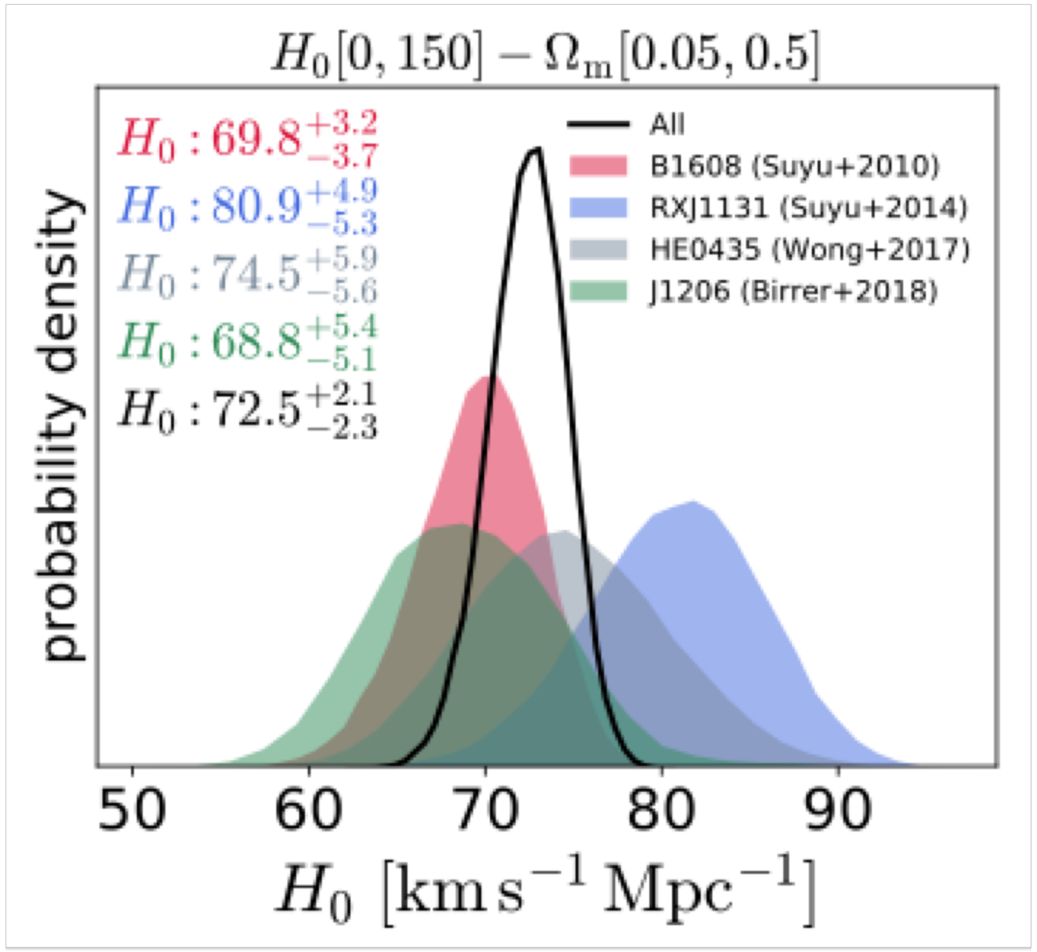
Precision on H_0:

- H0LiCOW 4 lenses: 3.1 %
- H0LiCOW 6 lenses: 2.x %
- H0LiCOW 40 lenses: ~1.0%

Accuracy:

- Time-delay lens modeling challenge underway
- Different lens modeling codes
- Blinded analysis
- Re-analysis encouraged (software and analysis scripts available for Birrer+2018)
- COSMICLENS (incl. Δt, new models, end to end simulator)
- ...

$$H_0 = 72.5^{+2.1}_{-2.3}\, km\, s^{-1}\, Mpc^{-1}$$



$D_{\Delta t}$ chains available from `http://www.h0licow.org`