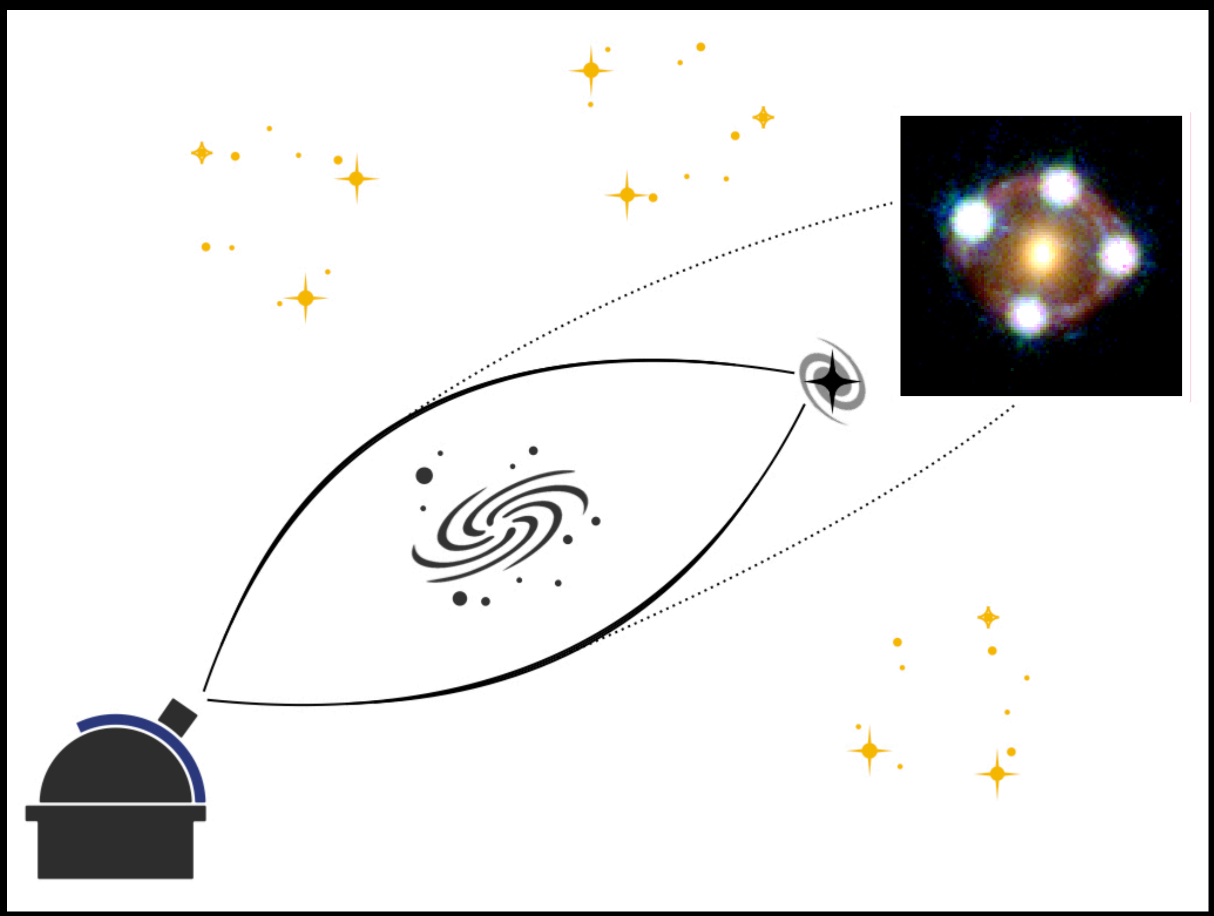
Strong Lensing Insights into the Hubble Tension



Kenneth Wong
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Kavli IPMU Lunch Seminar
April 19, 2022

科研費 KAKENHI

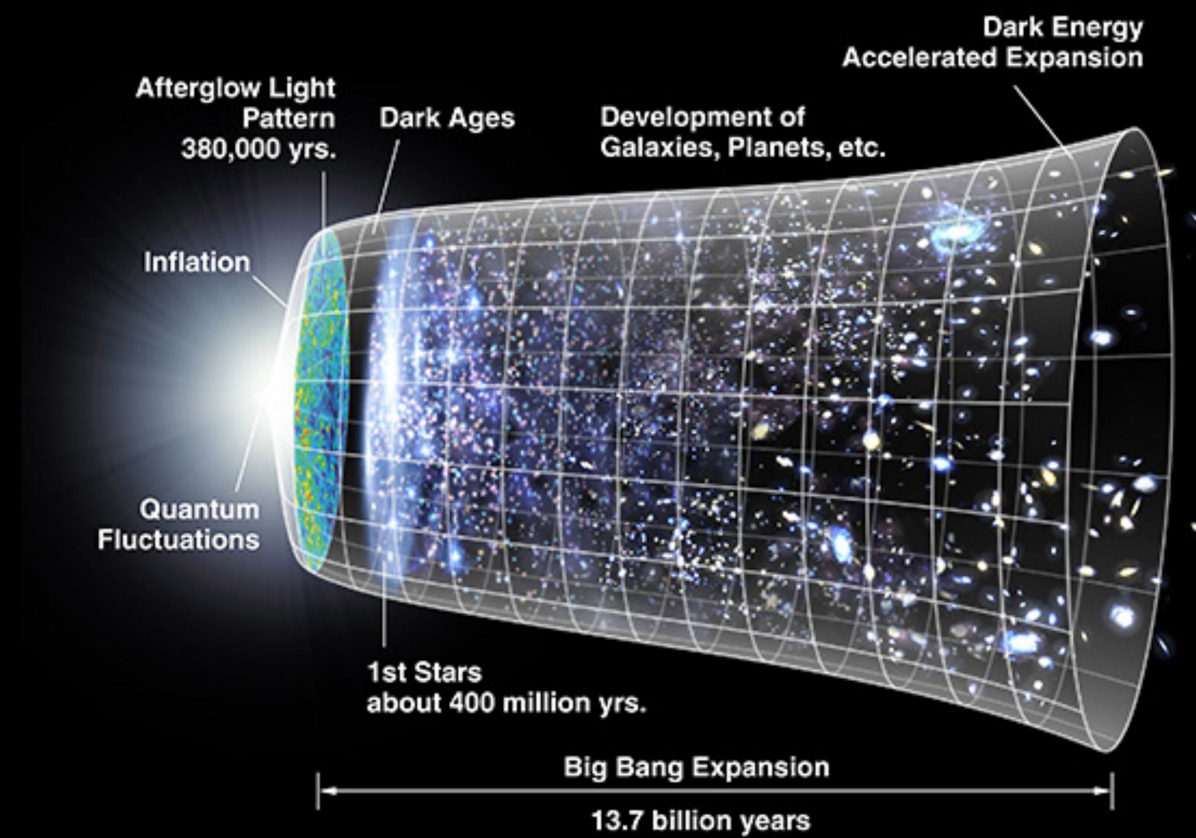
NAOJ

SUBARU TELESCOPE National Astronomical Observatory of Japan

The Standard Model of Cosmology

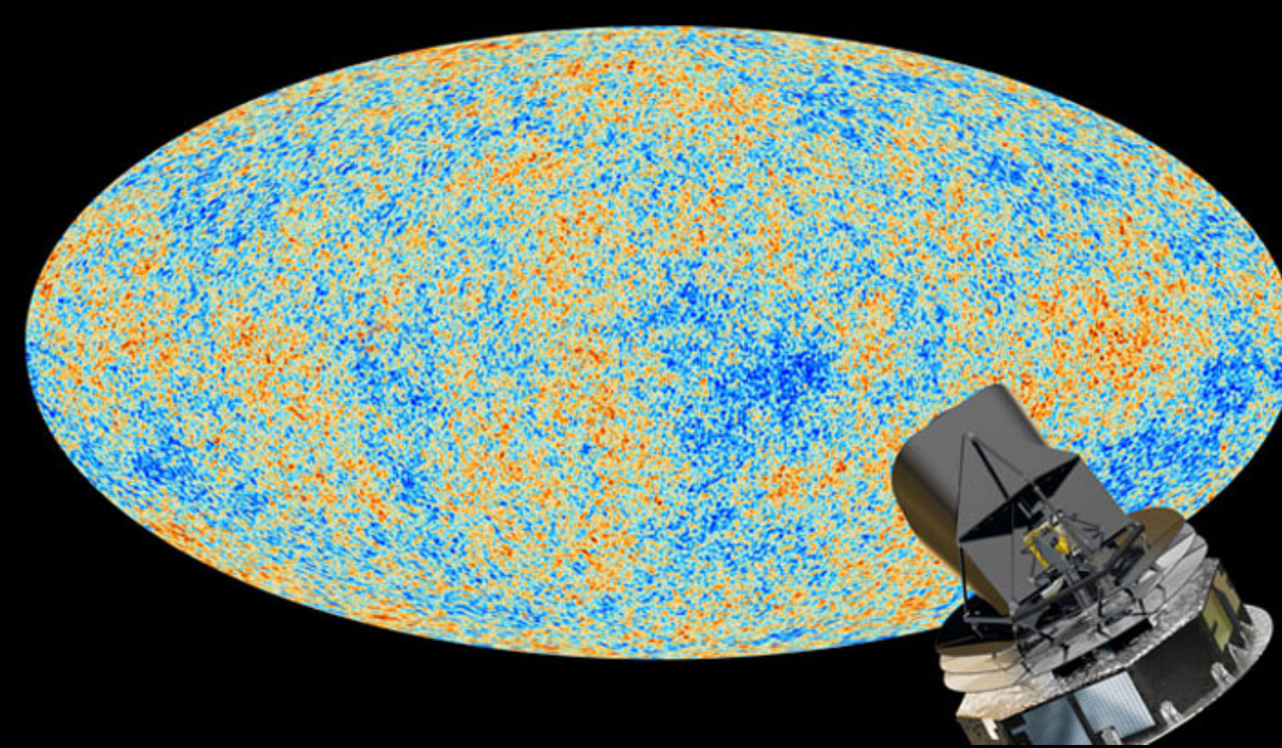
Standard model is the “flat ΛCDM” cosmology, where $\Omega_k = 1-\Omega_m-\Omega_\Lambda = 0$, $w = -1$

Very successful at explaining a variety of observations



Planck accurately measures cosmological parameters by observing the cosmic microwave background (CMB)

Planck observations do not directly constrain the Hubble constant (H_0) - must assume a cosmological model (e.g., flat ΛCDM)



The Hubble Tension

- Tension in early-Universe and late-Universe measurements of H_0
  - *Planck* CMB: 67.4 +/- 0.5 km/s/Mpc (assuming flat ΛCDM)
  - SH0ES (Cepheid distance ladder + type Ia SNe): 73.0 +/- 1.0 km/s/Mpc (Riess+2021)
- > 5σ discrepancy
  - systematic errors?
  - rejection of flat ΛCDM (i.e., new physics)?
- Independent measurements of H_0 are key

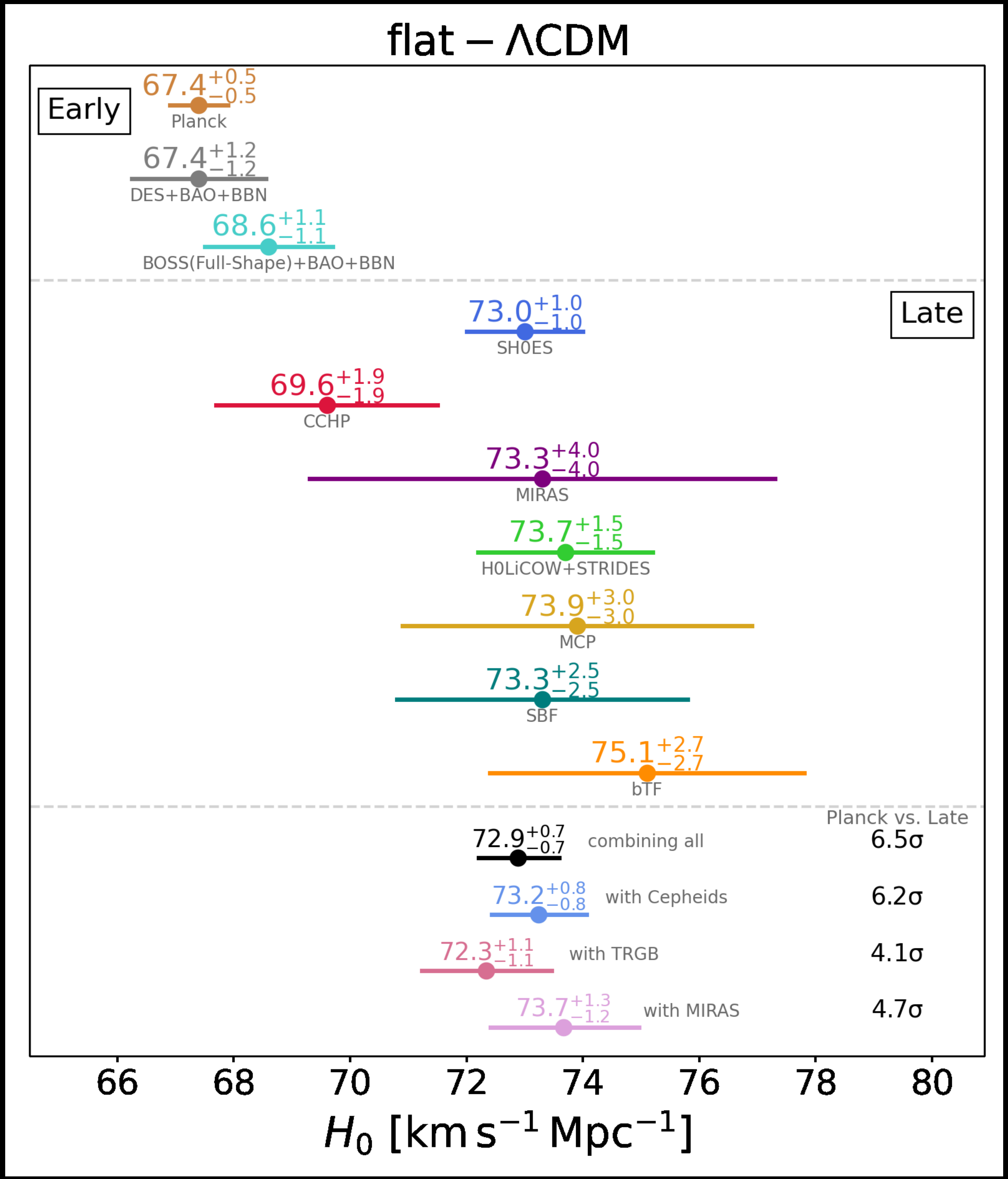
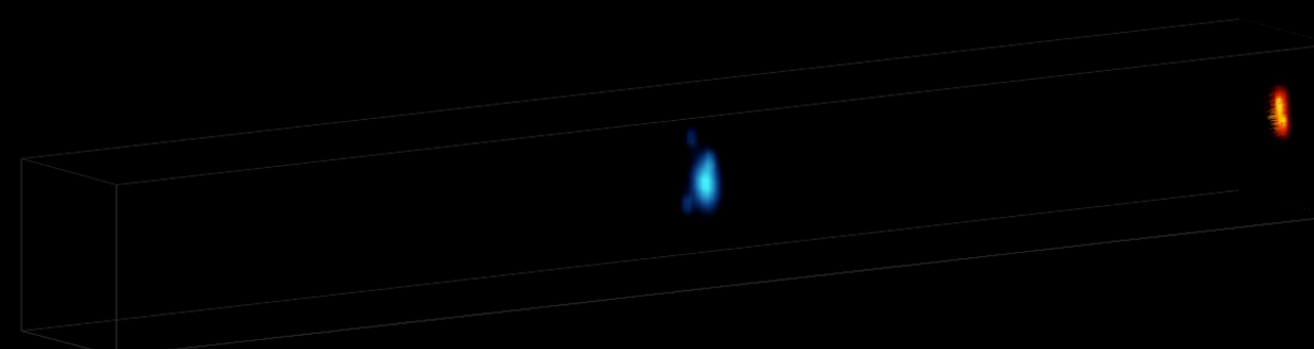


figure adapated from Verde, Treu, & Riess 2019

Gravitational Lensing

Animation credit: M. Mori

- Background object (source) magnified by foreground object (lens)
- Multiple images → create lens model
- Lensing effect depends on:
  - mass distribution of lens
  - line of sight structure
  - **cosmology**



Animation credit: Y. Hezaveh

Time-Delay Cosmography

- "time delay" between the multiple lensed images
  - due to different path length, gravitational potential
- Can determine "time-delay distance" $D_{\Delta t}$, inversely proportional to H_0
- One-step method to infer H_0, *independent of CMB and distance ladder*

Animation credit: M. Mori

Angular diameter distances $D \propto \frac{1}{H_0}$

$$t(\theta, \beta) = \underbrace{\frac{1}{c} \frac{D_d D_s}{D_{ds}} (1 + z_d)}_{D_{\Delta t}} \underbrace{\left[\frac{(\theta - \beta)^2}{2} - \psi(\theta) \right]}_{\Phi_{\mathrm{lens}}}$$

Time delay (observed)

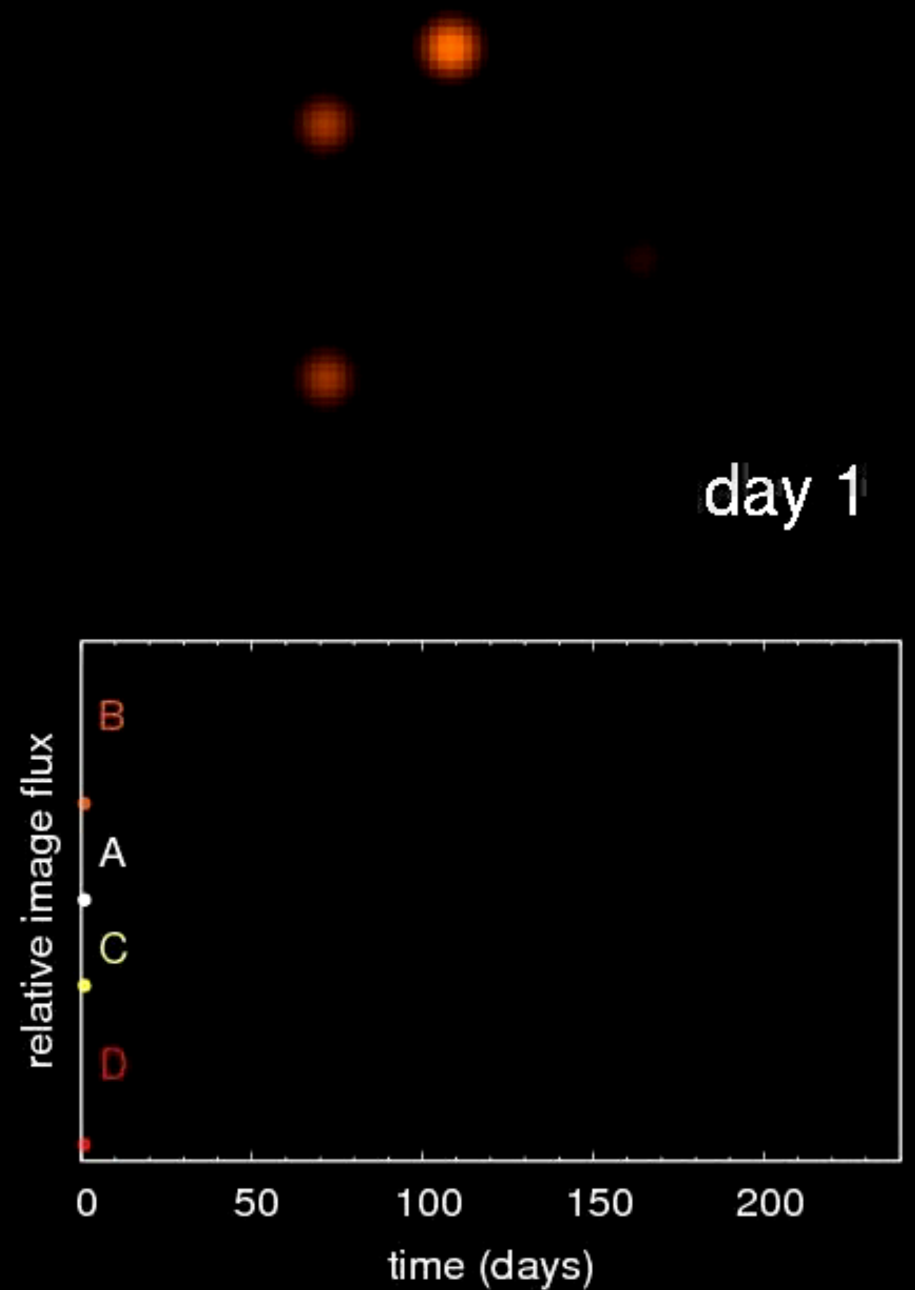
Time-delay distance

Fermat potential (from lens model)

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

Time-Delay Cosmography

- Lensed quasars
  - variable on short timescales (~days)
  - bright and easy to detect
- Monitoring of lensed quasars
  - measure brightness of images every night or every few nights
  - identical features in light curve correspond to same source event, but shifted in time
  - shift light curves until features overlap to determine time delay



Animation credit: C. Fassnacht, S. Suyu

Time-Delay Cosmography

- To constrain $D_{\Delta t}$, need:
  - Measured time delay (Δt)
  - Accurate lens model (to determine $\Phi_{\rm lens}$)
  - Estimate of mass along line of sight ($\kappa_{\rm ext}$; can bias $D_{\Delta t}$)
  - Lens galaxy velocity dispersion (break degeneracies in modeling; complementary constraints on cosmological parameters; e.g., Jee+2015, 2016)

Time delay (observed)

Time-delay distance

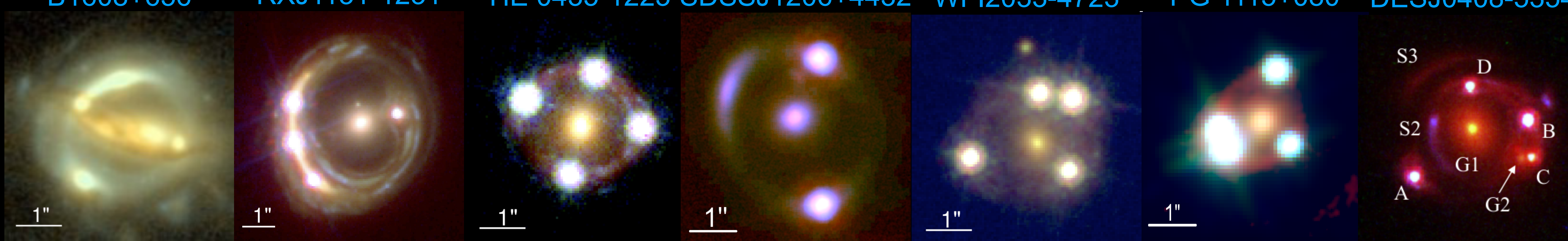
Fermat potential (from lens model)

$$\Delta t = \frac{D_{\Delta t}}{c} \times \Delta\Phi_{\rm lens} \Rightarrow D_{\Delta t} \propto \frac{1}{\mathbf{H_0}}$$

TDCOSMO / H0LiCOW

- TDCOSMO (formerly H0LiCOW; Suyu+2017) project has performed detailed analysis of several time-delay lenses
  - long term monitoring for accurate time delays
  - high-resolution imaging for detailed lens modeling
  - wide-field imaging/spectroscopy to characterize mass along LOS
  - spectroscopy to measure lens velocity dispersion
- Seven lenses analyzed to date (see Wong+2020, Shajib+2020, Birrer+2020 for latest results)

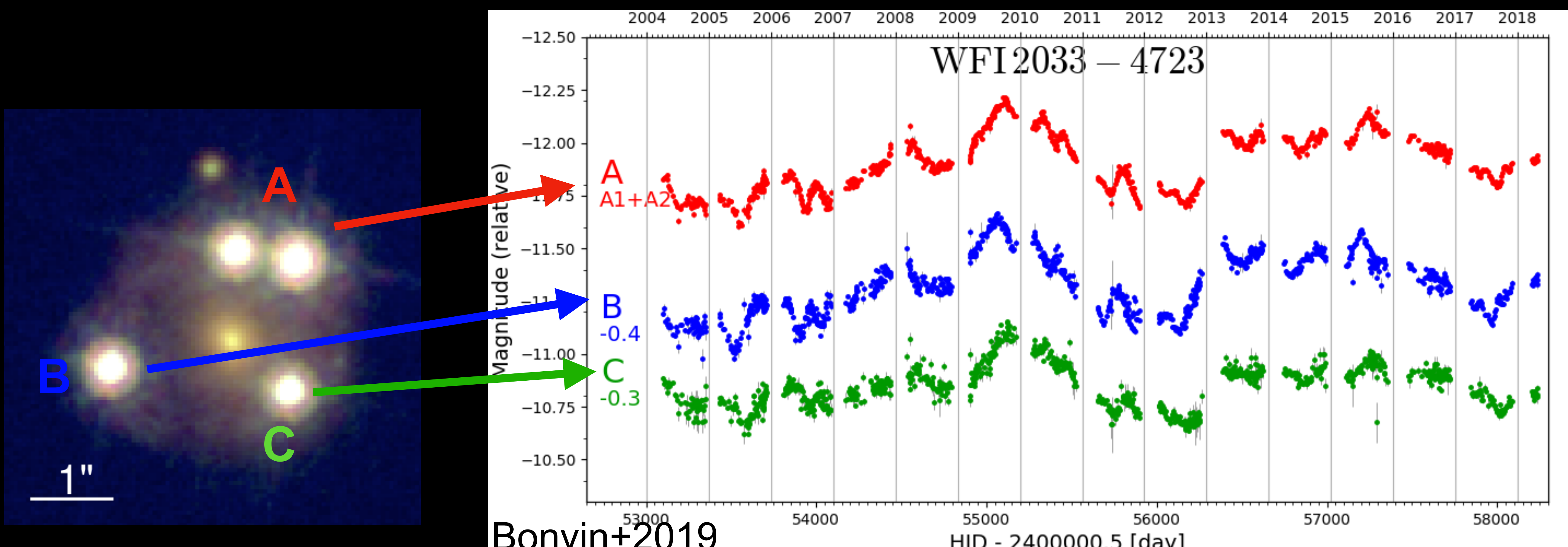
B1608+656 | RXJ1131-1231 | HE 0435-1223 | SDSSJ1206+4432 | WFI2033-4723 | PG 1115+080 | DESJ0408-5354



Suyu+2010, Jee+2019 | Suyu+2013,2014, Chen+2019 | Wong+2017, Chen+2019 | Birrer+2019 | Rusu+2020 | Chen+2019 | Shajib+2020

Time Delay Measurements

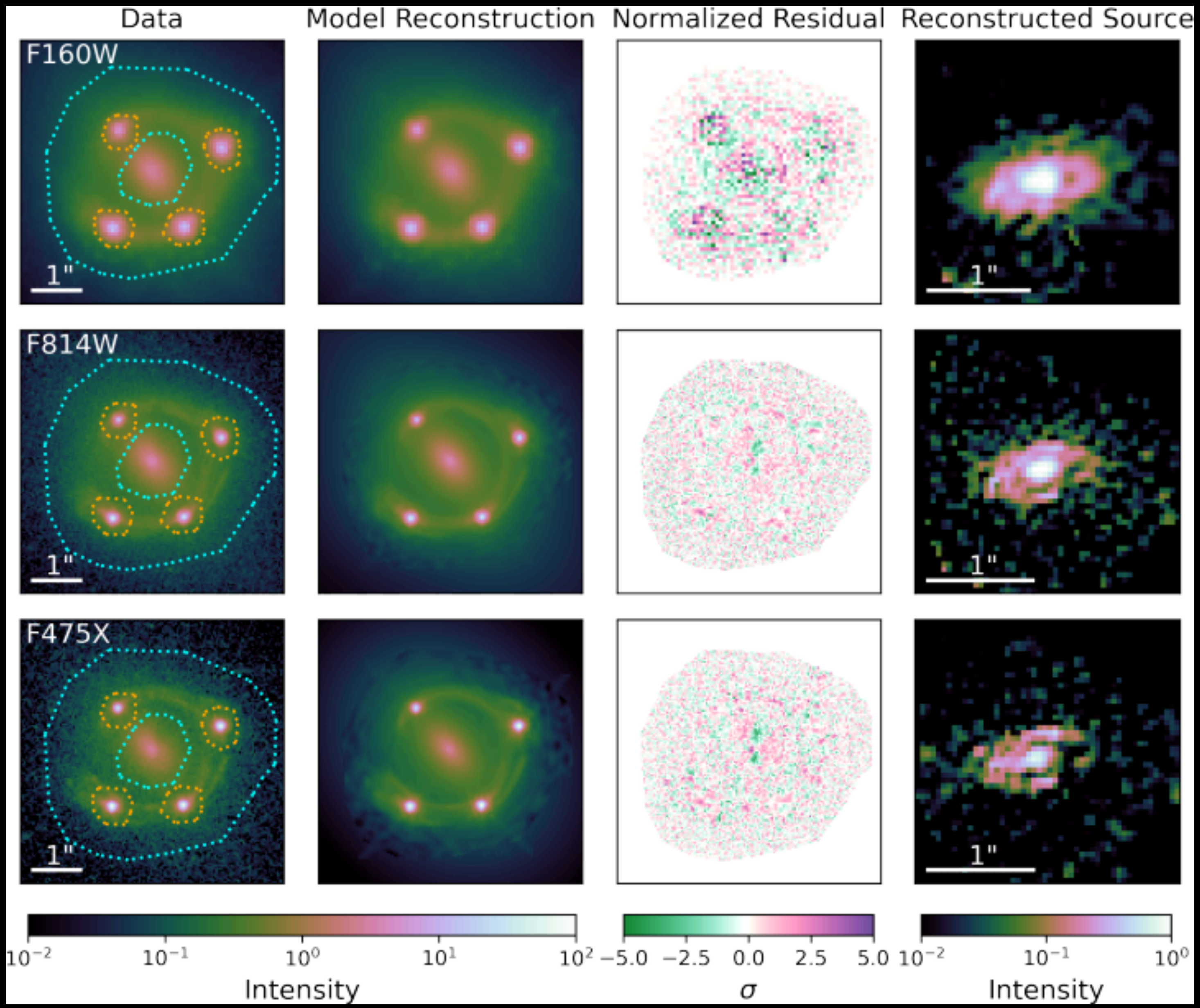
- Long-term monitoring of time-delay lenses using small (1-m and 2-m) telescopes (Courbin+2011; Bonvin+2017)
- Well-tested algorithms for time-delay measurements (Tewes+2013)
- Long time baselines needed to minimize effects of microlensing (but high-cadence monitoring possible; Courbin+2018, Millon+2020b)



Bonvin+2019

Lens Modeling

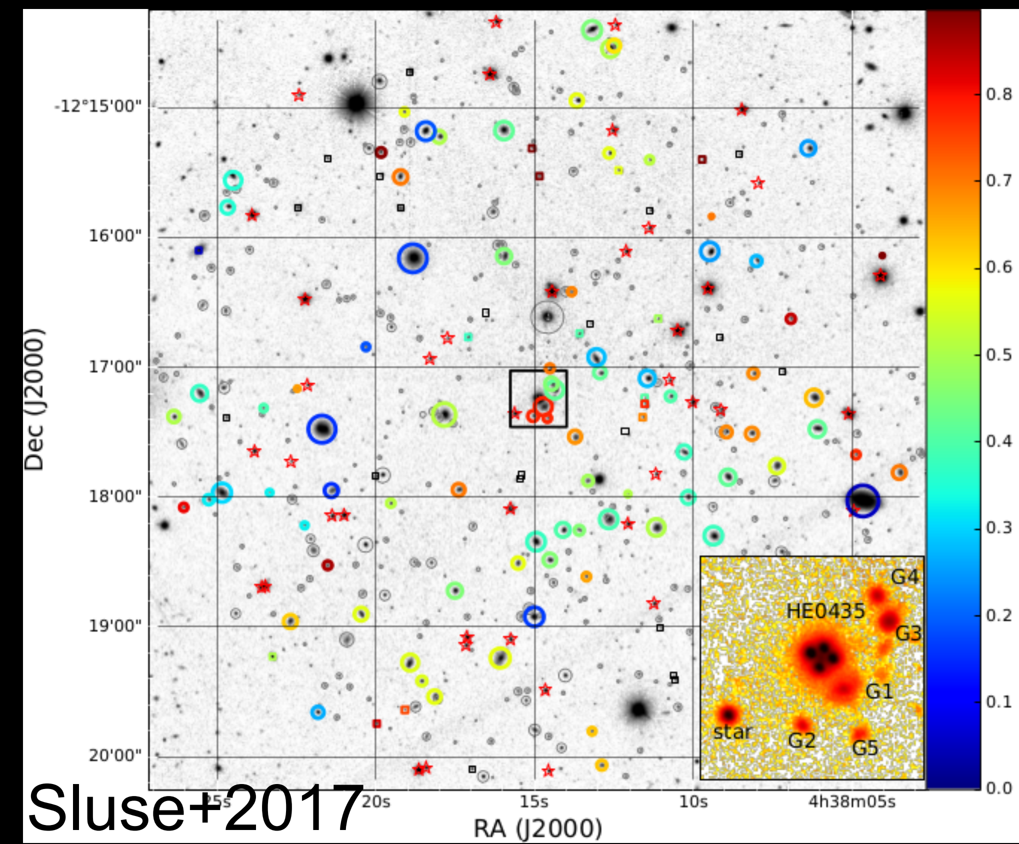
- Accurate lens model using deep *HST* and AO imaging
- High resolution needed to model quasar host galaxy
- Adaptive PSF correction using quasar images (e.g. Chen+2016)
- Incorporate velocity dispersion of lens galaxy to reduce model degeneracies
- Assume either elliptical power-law or stars+NFW (composite) model and combine results

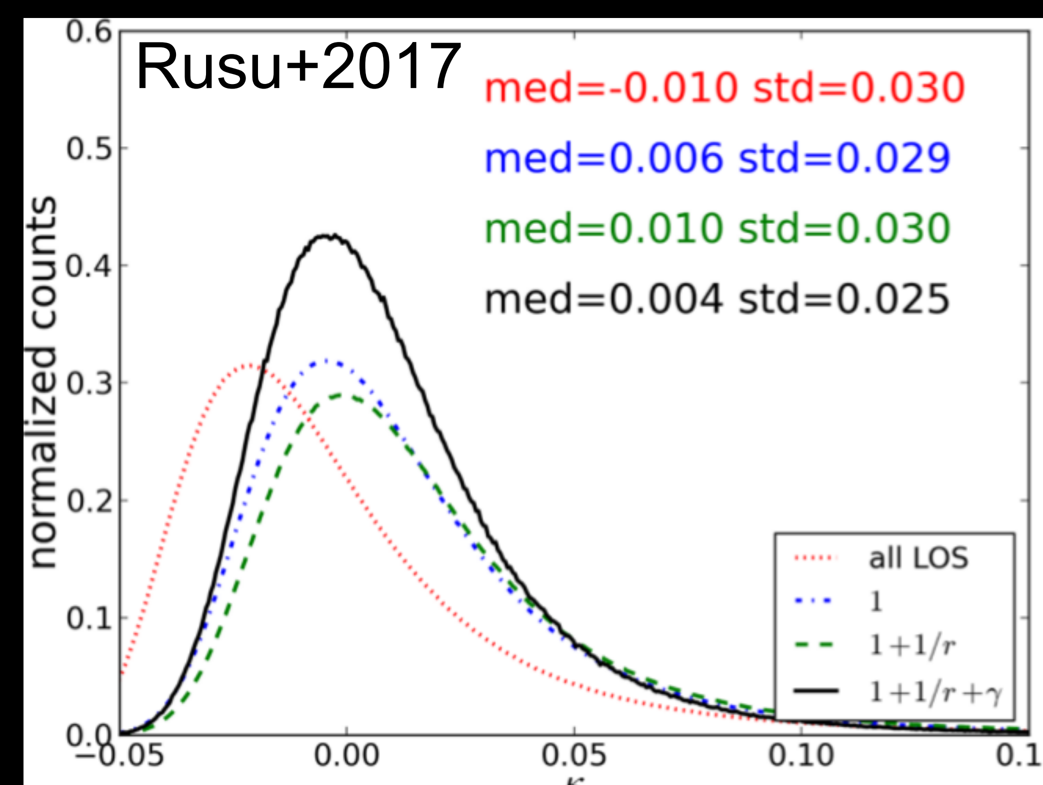


Shajib, Wong et al. 2022

Mass Along the Line of Sight

Animation credit: M. Mori

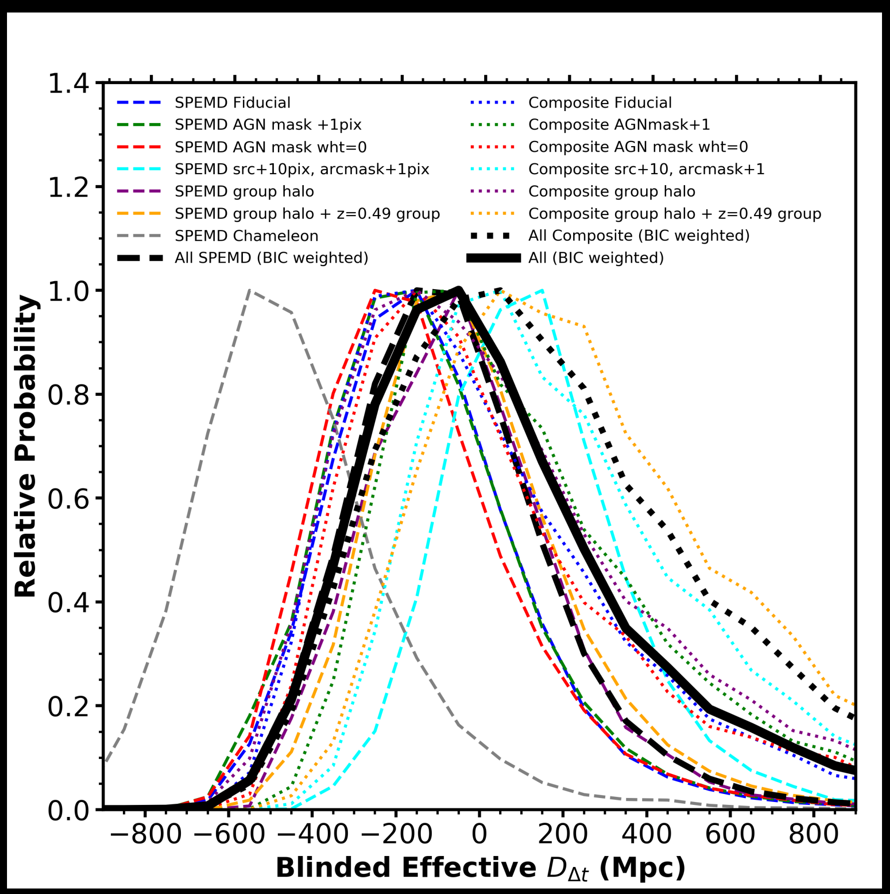


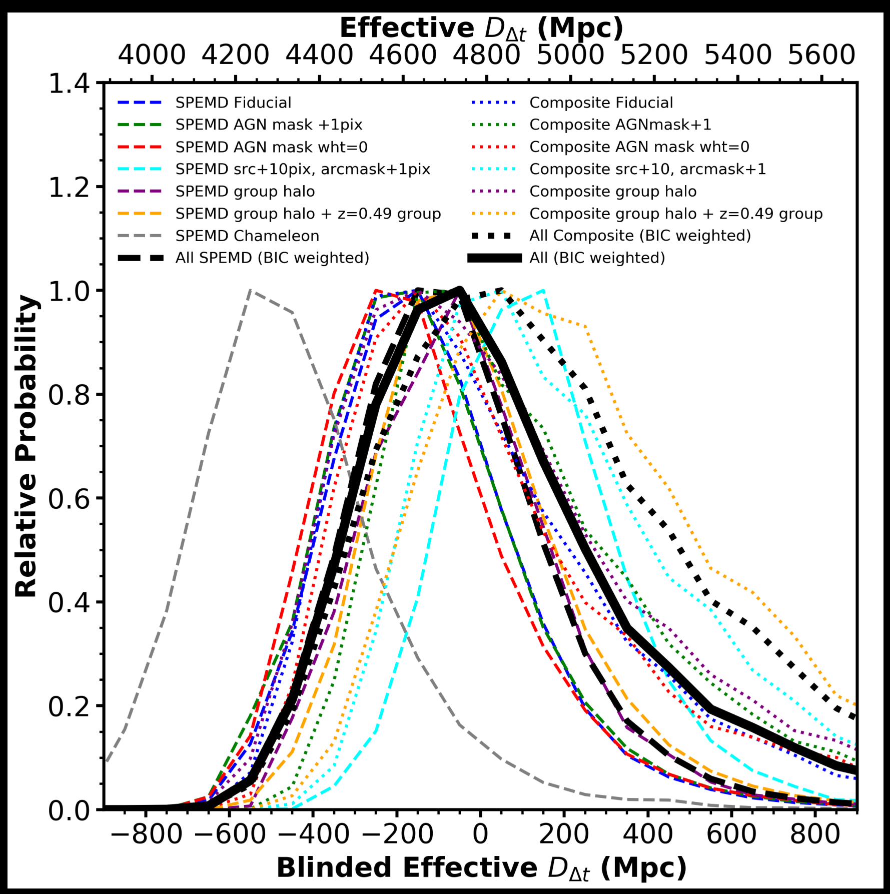


- Lenses lie in overdense LOS due to local lens environment (e.g., Fassnacht+2011; Wong+2018)
- Some strong perturbers need to be included explicitly in lens model (e.g., Wilson+2016; McCully+2017; Sluse+2017)
- Estimate effect of weaker perturbers using weighted galaxy number counts calibrated by simulations (e.g., Greene+2013; Rusu+2017,2020)
- Independent weak lensing analysis agrees with weighted number counts method (Tihhonova+2018,2020)

Blind Analysis

- H_0 and related quantities blinded throughout analysis
  - avoid confirmation bias
  - discover unknown systematics
- Blindness can be implemented by subtracting median of posterior PDF during analysis
- Unblind only after analysis completed, agreement by all coauthors
- Unblinded results published without any further modification





Rusu+2020

Latest TDCOSMO Results

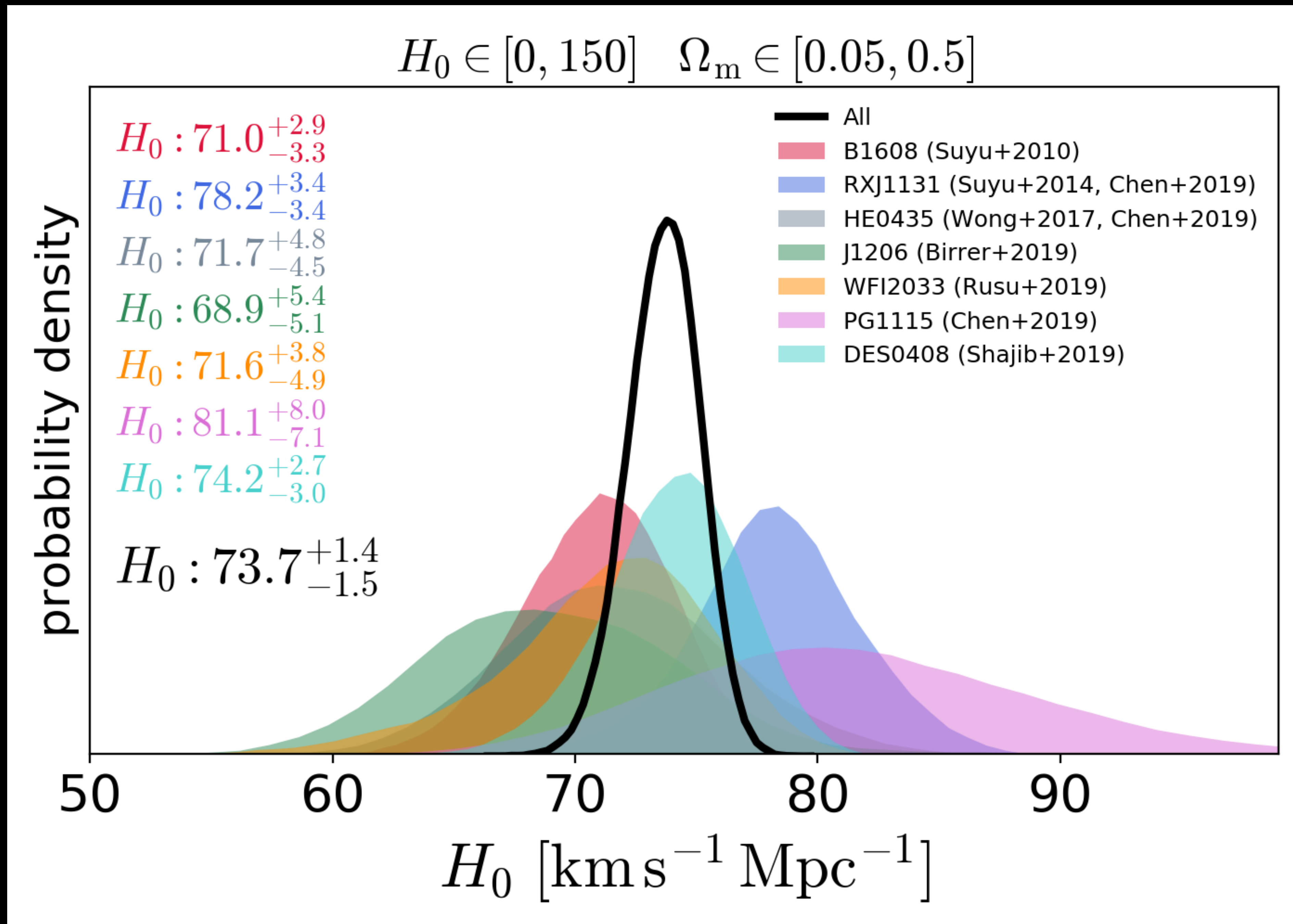


figure adapted from Wong+2020

Combined result: ~2% precision on H_0 for flat ΛCDM, in >4σ tension with *Planck*

Latest TDCOSMO Results

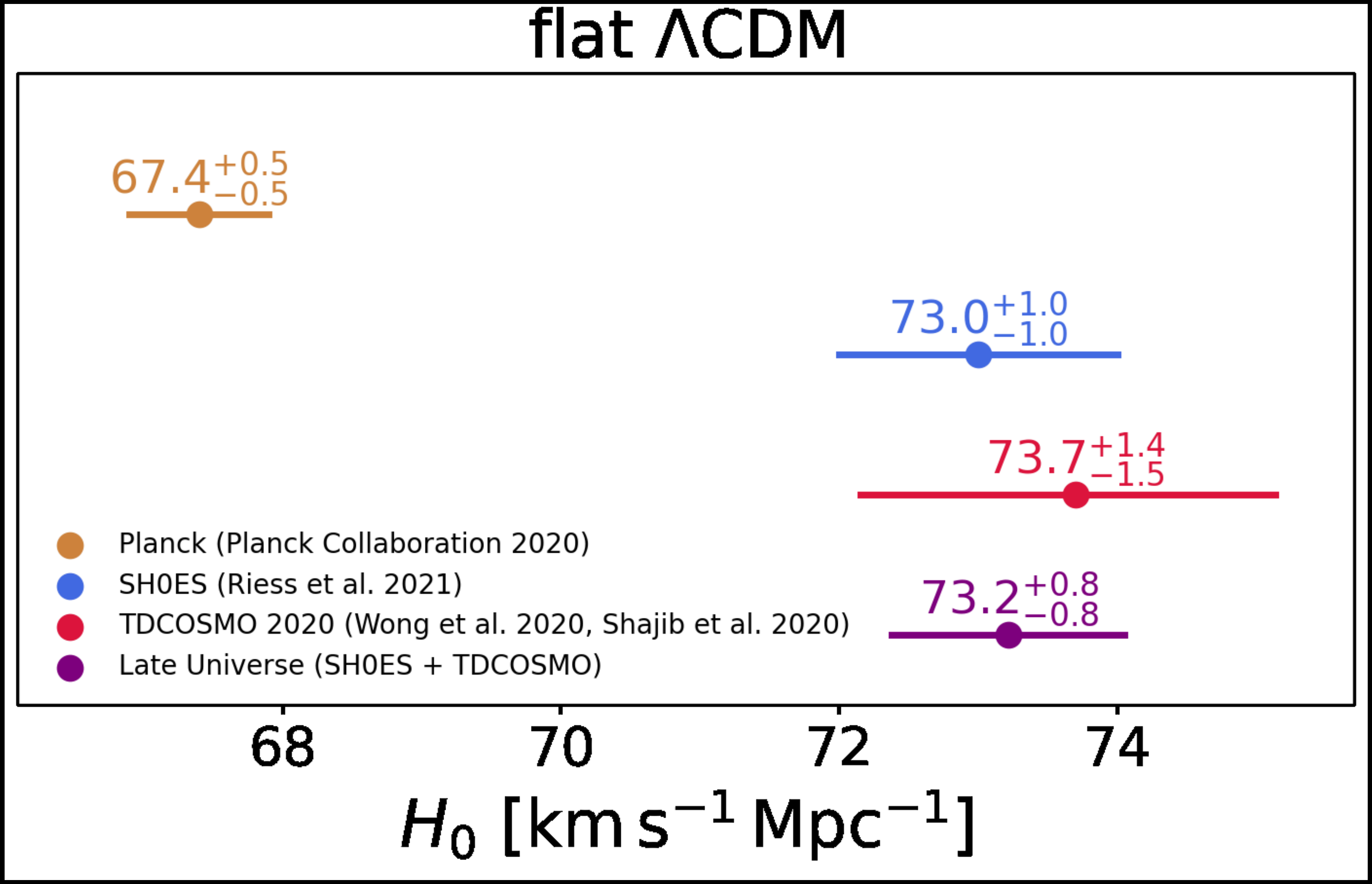


figure adapted from Wong+2020

>4σ tension between TDCOSMO and *Planck*

Combined with SH0ES, >6σ tension between early and late-Universe probes

What next? Systematic error checks

- Spread of PDFs for individual lenses suggests no evidence for unaccounted systematics (Millon+2020)
- Could there be systematics that bias the results as a whole?

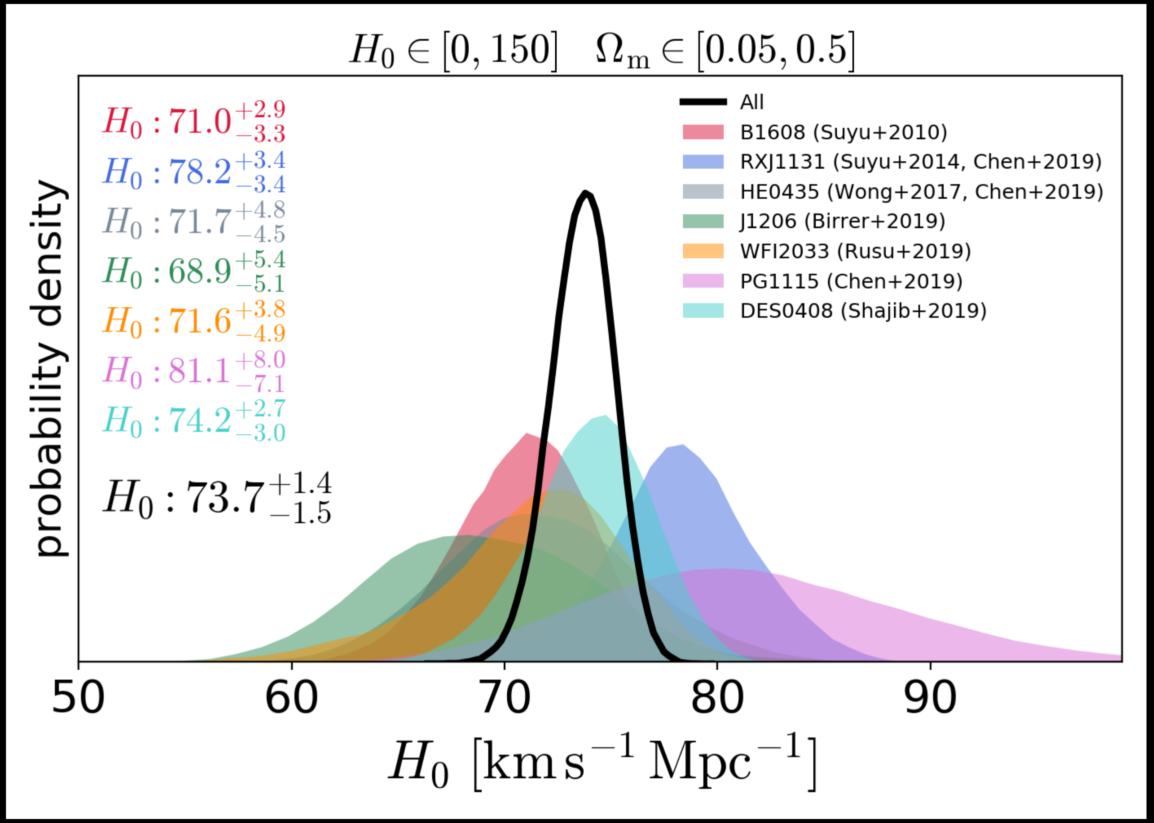
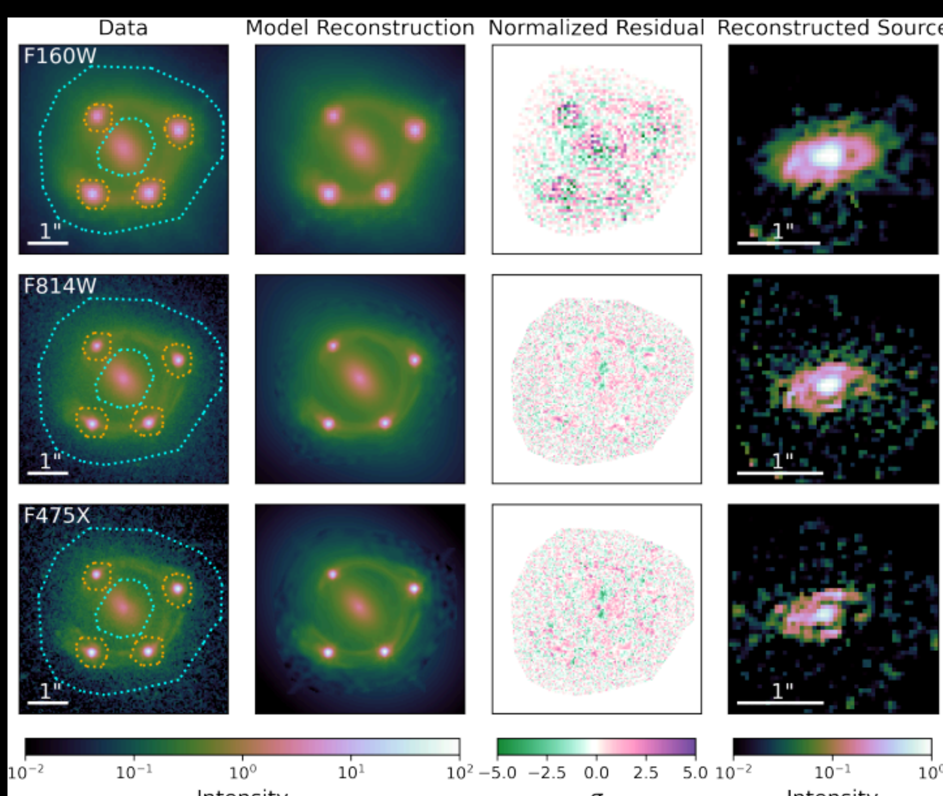


figure adapted from Wong+2020

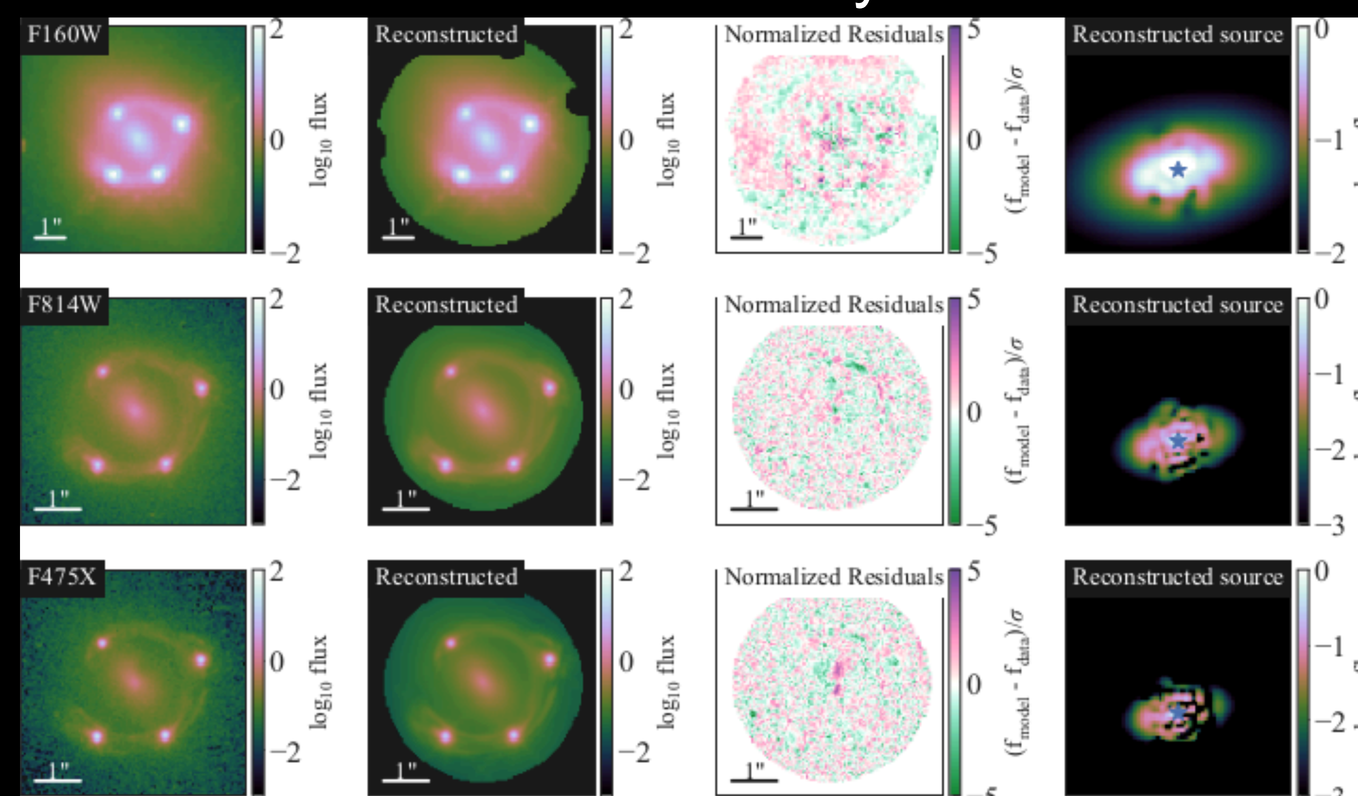
Lens Modeling Codes

- TDCOSMO lenses have been modeled using one of two codes
  - GLEE (Suyu & Halkola 2010; Suyu+2012)
  - Lenstronomy (Birrer+2015; Birrer & Amara 2018)
- Main differences are in source plane reconstruction (parametrized vs. pixelated) and PSF error handling
- Model lens WGD2038 with both codes to predict time delays (Shajib, Wong et al. 2022)
  - two teams agreed on dataset and basic model parameters beforehand
  - results blinded to other team until models completed

GLEE



Lenstronomy

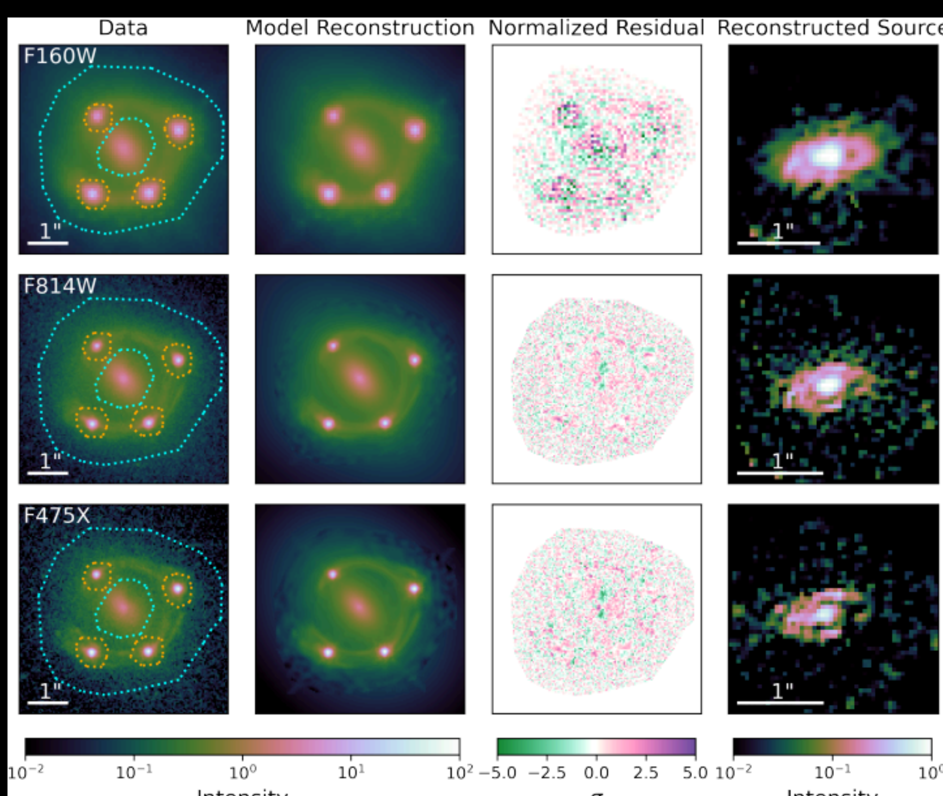


Shajib, Wong, et al. 2022

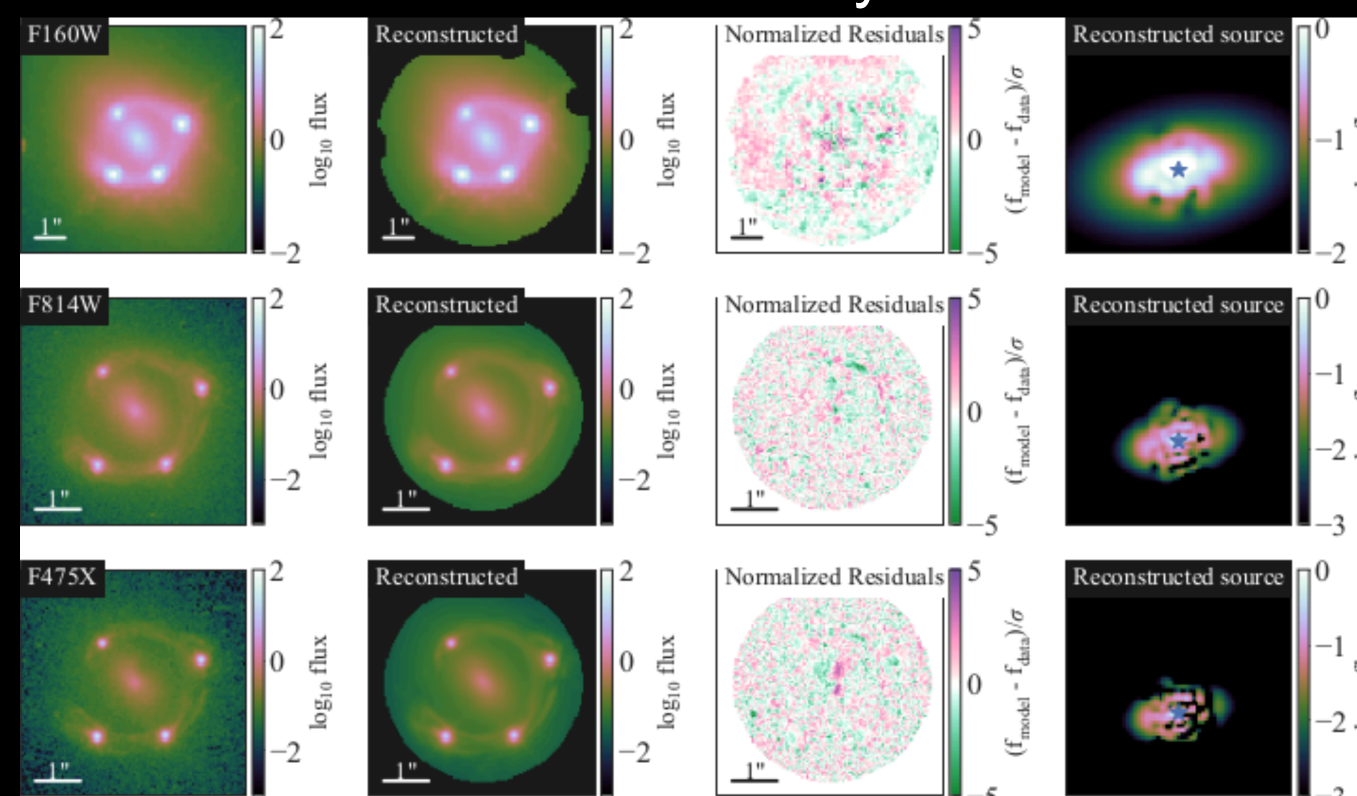
Lens Modeling Codes

- Unblinded time delays consistent within ~1.2σ for power-law model
- Both teams found irregularities in composite model before unblinding
- Some differences in other parameters before kinematics/κ_{ext} folded in
  - e.g., power-law slope
- PSF reconstruction a possible systematic
  - teams exchanged PSFs post-unblinding, found better agreement in power-law slope
  - should subsample PSF for IR band (GLEE team did this, Lenstronomy did not)
- Future time delay measurement of WGD2038 will test model accuracy

GLEE



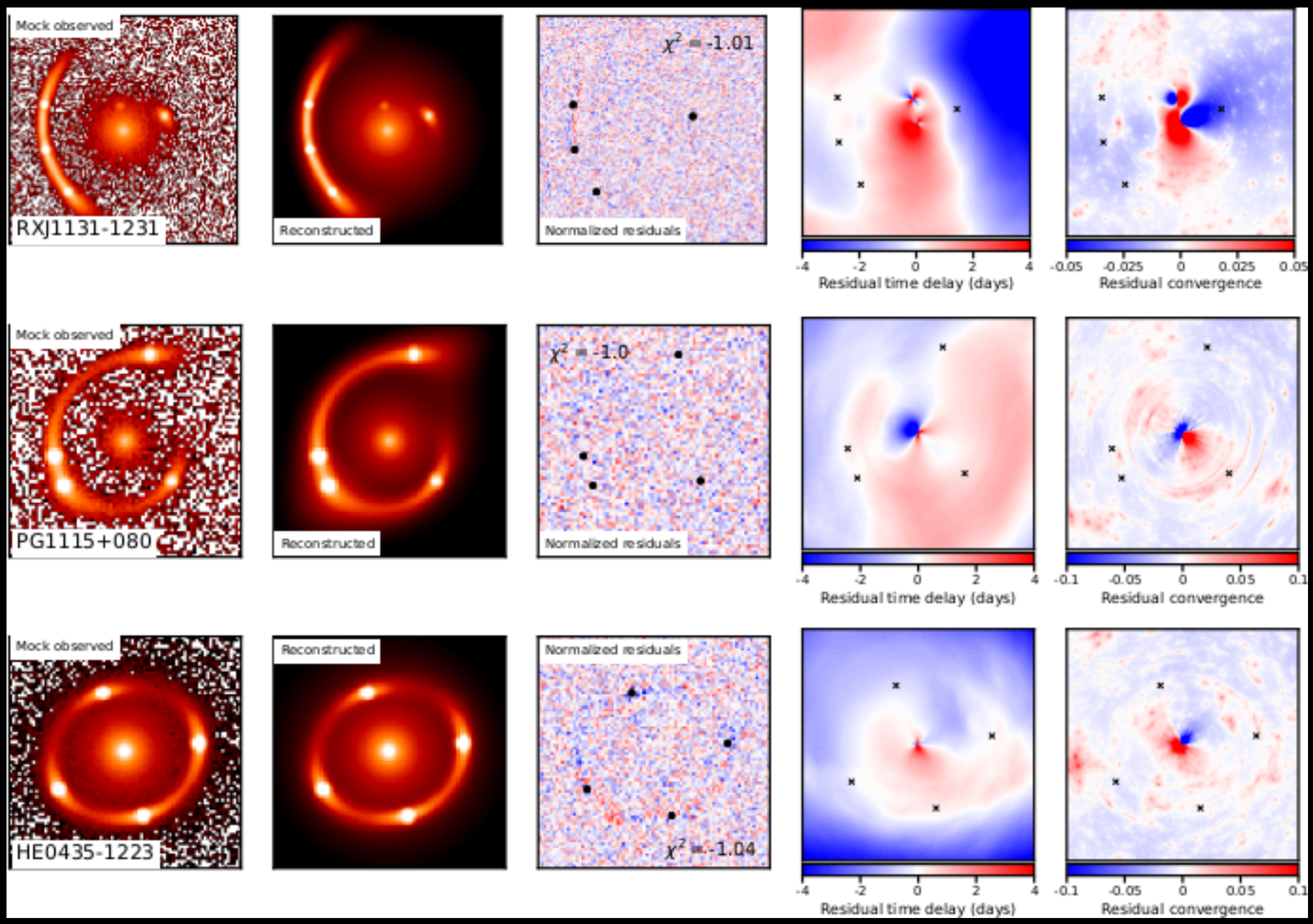
Lenstronomy



Shajib, Wong, et al. 2022

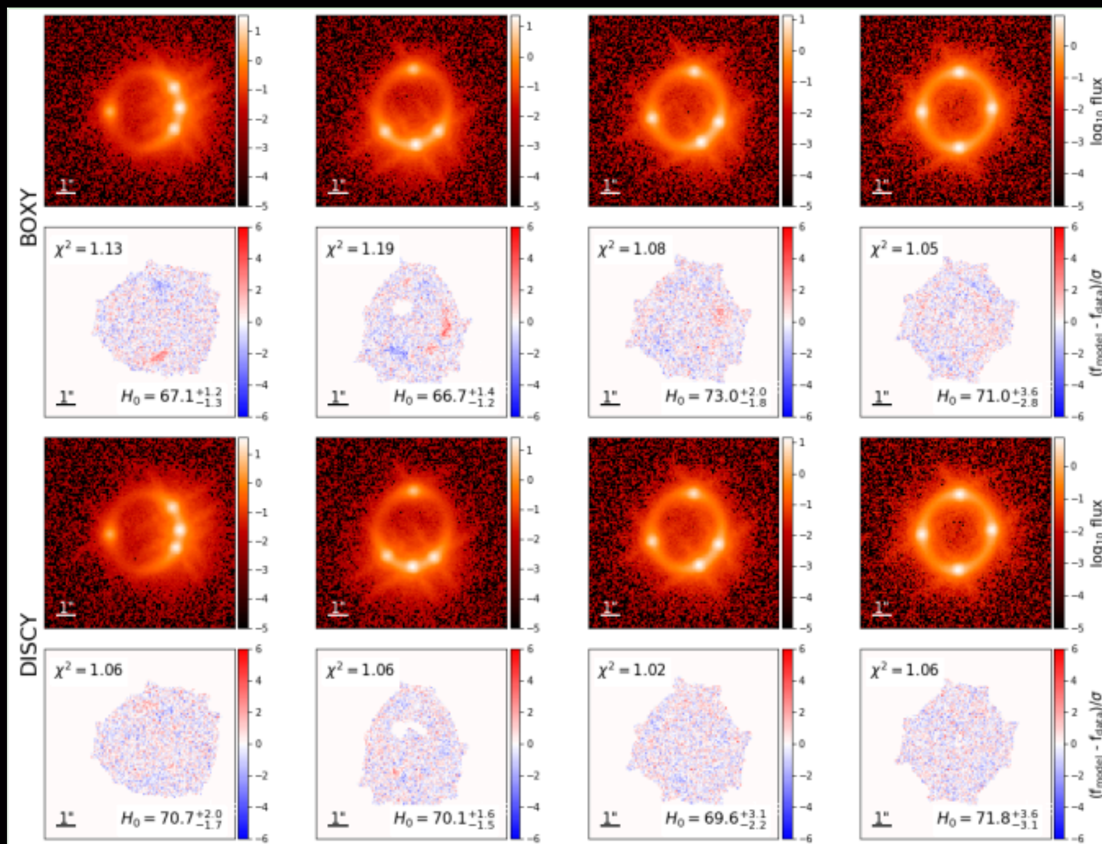
Dark Matter Substructure

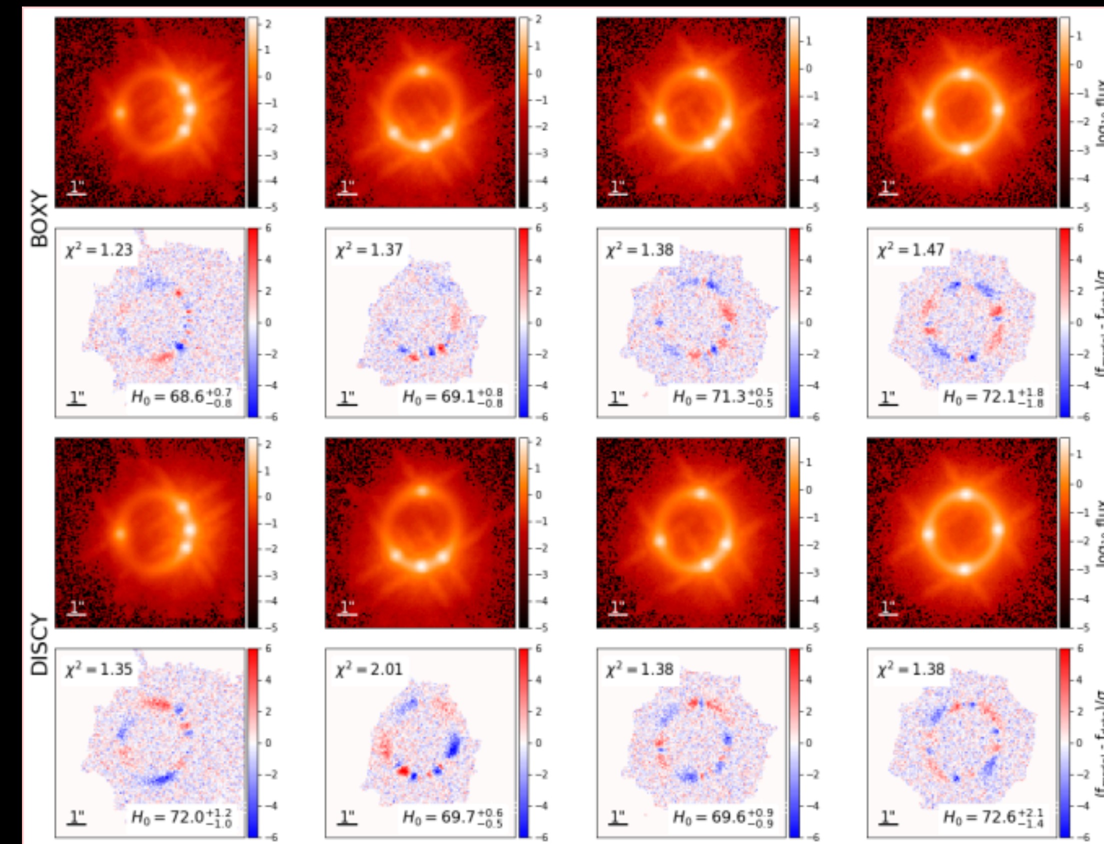
- Dark matter subhalos / satellite galaxies can perturb lens potential
- Strong lensing is a promising technique to constrain DM substructure (e.g., Nierenberg+2014, 2017; Hezaveh+2016; Gilman+2019)
- Effect on time delays?
  - analysis of mock lenses w/ substructure shows bias < 0.3%, ~0.5% scatter in overall H_0 constraint (Gilman+2020)



Gilman+2020

Higher-order Multipoles in Lens Galaxies

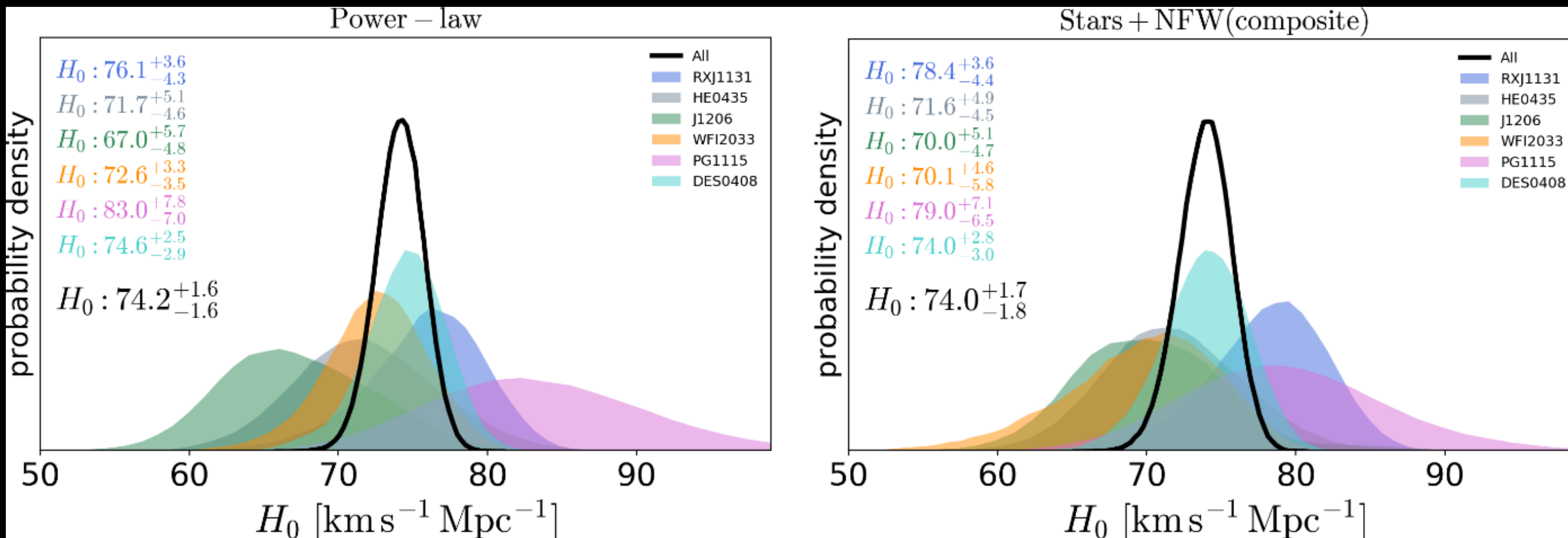




van de Vyvere+2022

- Test effect of higher-order multipoles (i.e. boxyness/discyness) in lens galaxies (van de Vyvere+2022)
- Mock boxy/discy lenses fit with standard elliptical profiles - what is the effect?
- H_0 can be biased, but should see strong residuals if S/N high enough
- TDCOSMO lenses are high-S/N and show low residuals (i.e., no evidence for additional complexity in lens structure)

Power-law vs. Composite Profiles



Millon+2020

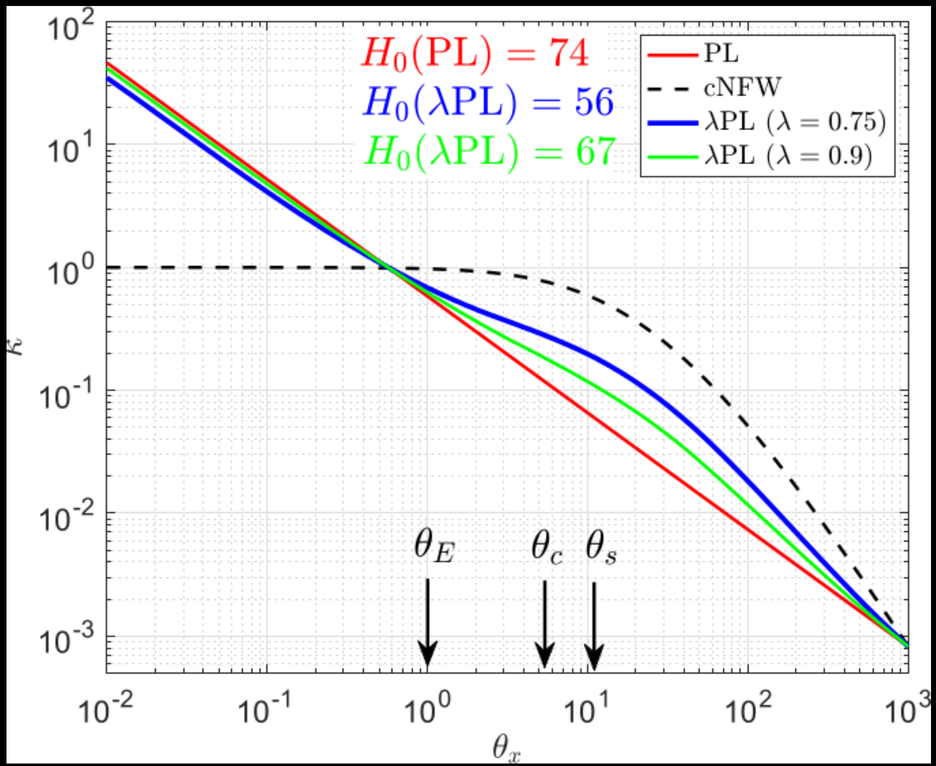
TDCOSMO models assume either elliptical power-law or stars+NFW (composite) profile and marginalize over both

Both model types give consistent results (Millon+2020)

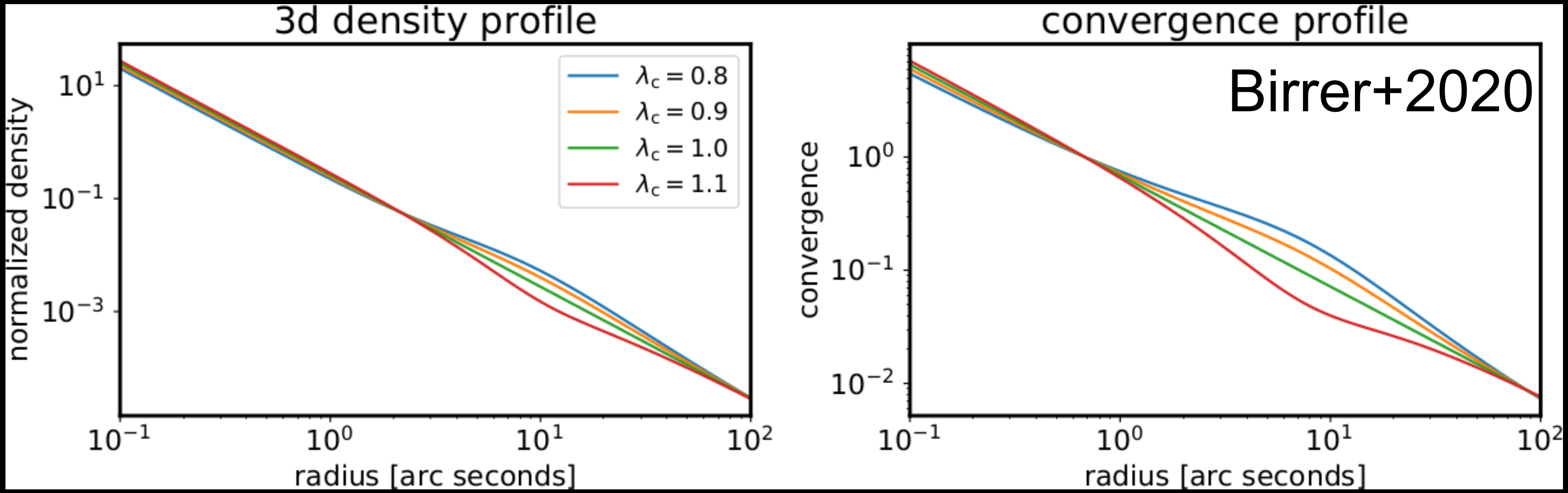
We believe these mass profiles are well-motivated, but…

Mass-Sheet Transform (MST)

- Modification of the density profile of the lens by a multiplicative factor λ
  - rescales the time delay and source position, leaving all other observables invariant
  - fundamental degeneracy in lensing (e.g., Falco+1985, Schneider & Sluse 2013,2014)
- Can be due to either/both an external mass sheet (κ_{ext} or κ_s) or a modification of the lens mass profile λ_{int}
- Can be broken with observables related to intrinsic source size, magnification, or lensing potential (e.g., kinematics) OR by assuming a mass profile (e.g., power-law)

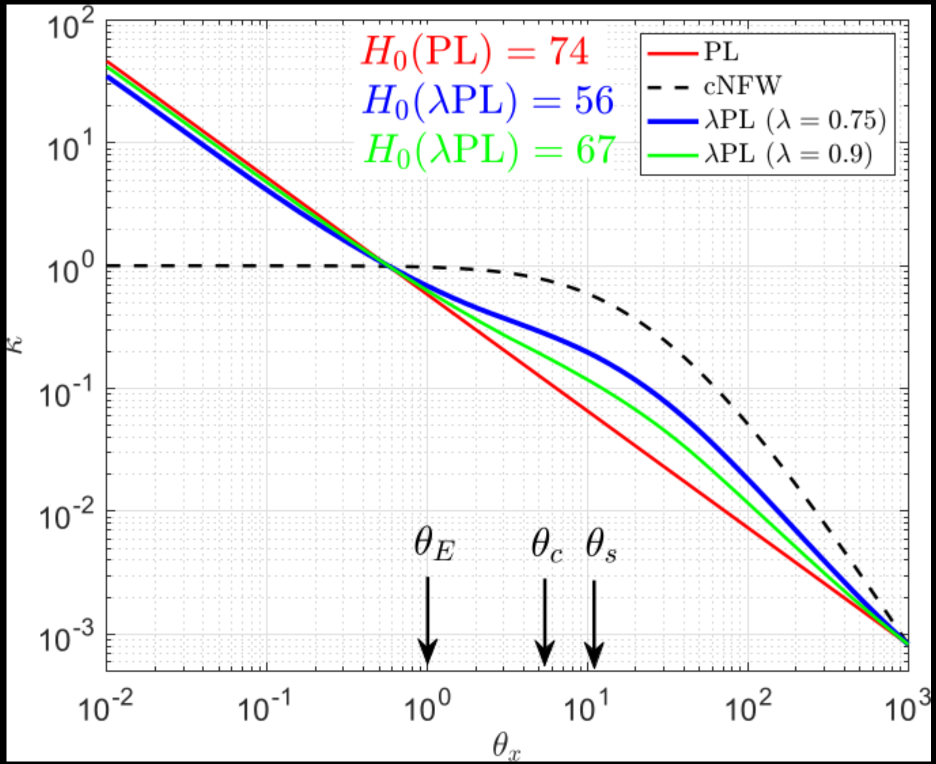


Blum+2020

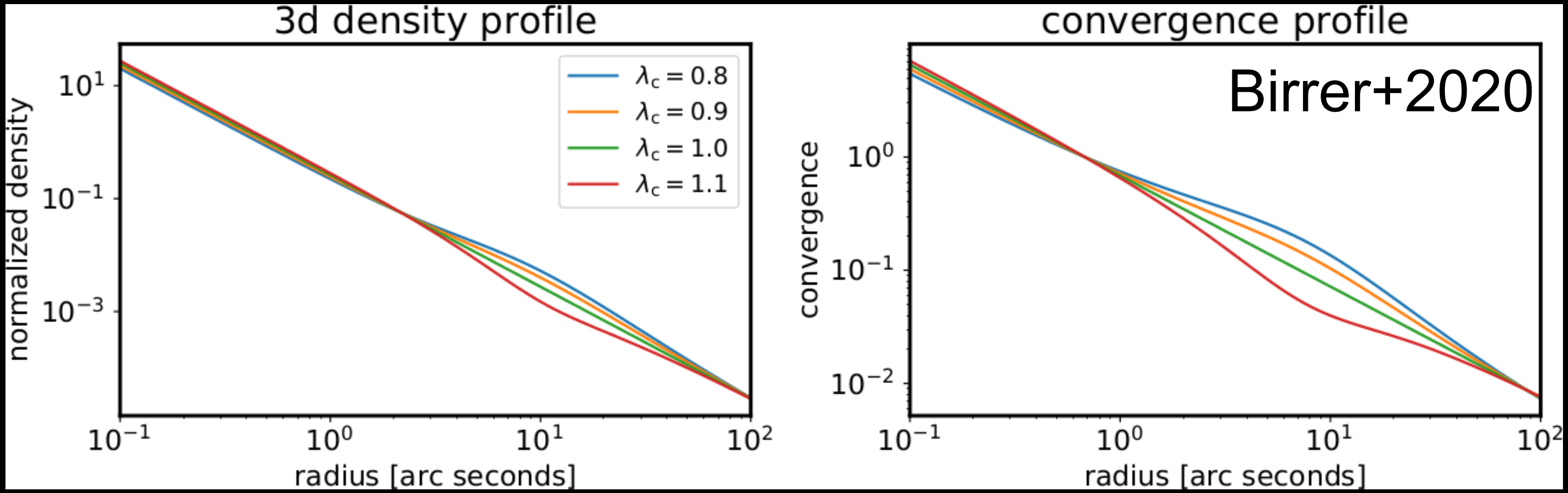


Mass-Sheet Transform (MST)

- TDCOSMO results depend on assumption of power-law or composite (stars+DM) profile (Kochanek+2020a,b)
  - physical and well-motivated
  - relaxing this assumption, we can only constrain H_0 to precision of velocity dispersion measurement (~5-10%)
- Additional cored NFW component can act as an approximate MST (Blum+2020)
  - core radius must be quite large (at least 3x Einstein radius)



Blum+2020

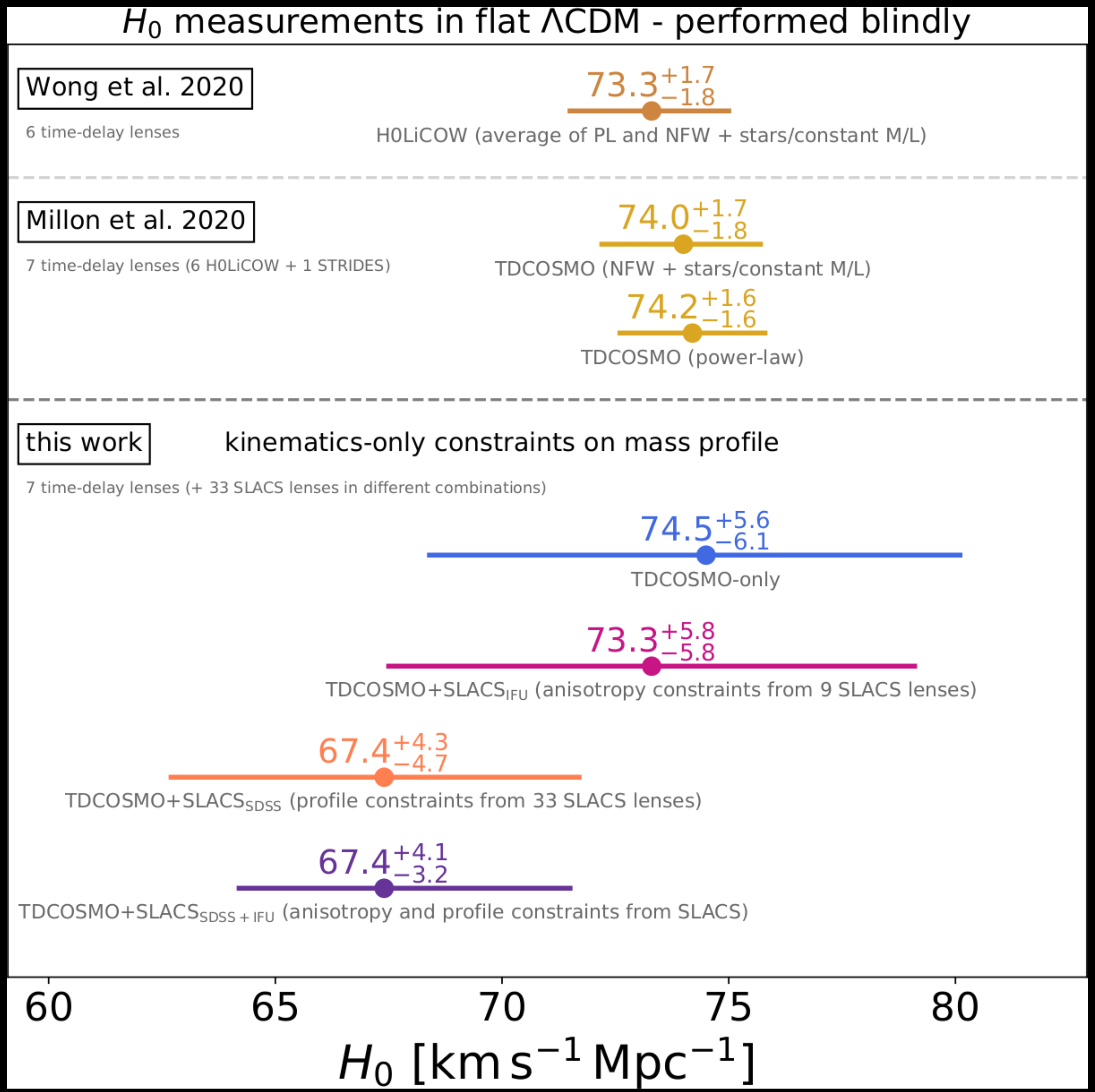


Bayesian Hierarchical Inference

- Reanalysis of TDCOSMO lenses using Bayesian hierarchical model (Birrer+2020)
  - internal MST parameters are encoded in analysis as hyperparameters
  - maximally conservative, mass profile constrained only from kinematics
  - freedom to bring in external datasets to constrain galaxy structure hyperparameters
- Use external sample of lenses from SLACS (Bolton+2006)
  - assumes TDCOSMO and SLACS lenses drawn from same parent population

Hierarchical Model Results

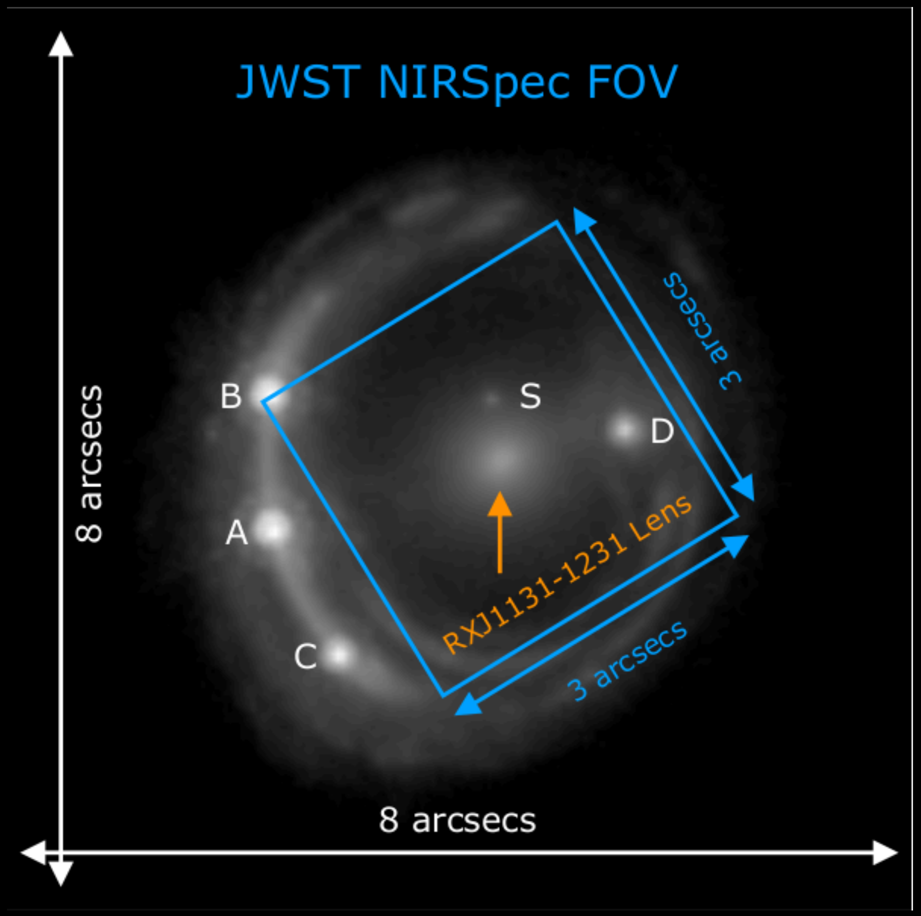
- Maximally conservative approach gives H_0 = 74.5 (-6.1/+5.6) km s^{-1} Mpc^{-1}
  - ~8% precision
- Adding SLACS lenses gives lower λ_{int} (i.e., shallower mass profile)
- Assuming TDCOSMO and SLACS lenses are drawn from same parent population, H_0 = 67.4 (-3.2/+4.1) km s^{-1} Mpc^{-1}
  - ~5% precision, central value lower but still consistent with original constraint
- Key questions:
  - is MST physical? (i.e., is it reasonable to assume galaxies are described by a power-law or stars+DM model)?
  - are TDCOSMO & SLACS lenses drawn from same parent population?
  - can degeneracy be broken with additional observations?



Birrer+2020

Resolved Kinematics

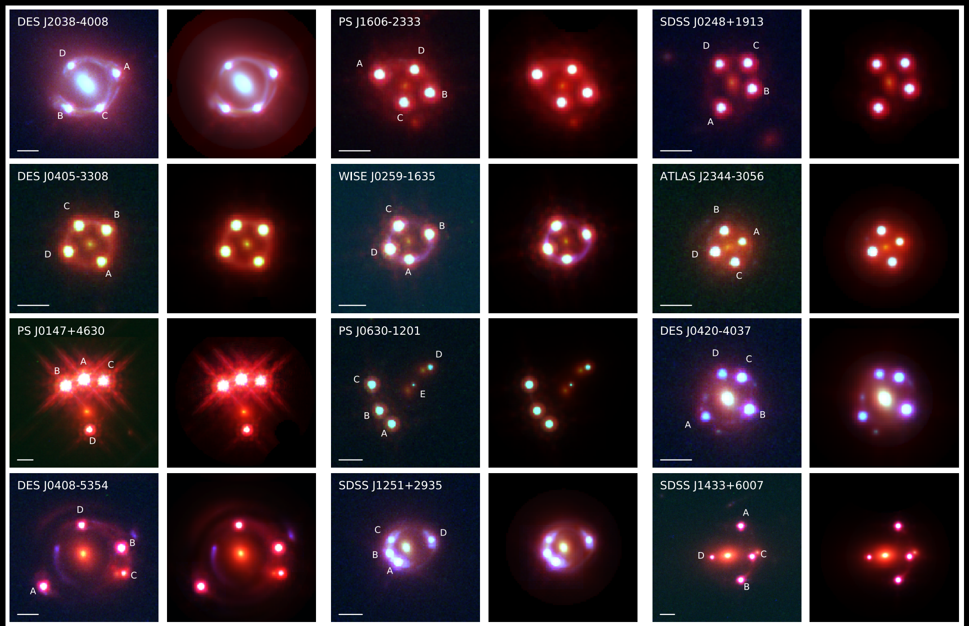
- MST can be broken with resolved kinematics from IFU observations (Yildirim+2020,2021)
- Mock lens tests show *JWST* IFU data could lead to ~4% constraint per lens
- Upcoming *JWST*/NIRSpec cycle 1 program has been approved for this purpose
- Can constrain MST from TDCOSMO lenses alone, without needing to use external datasets



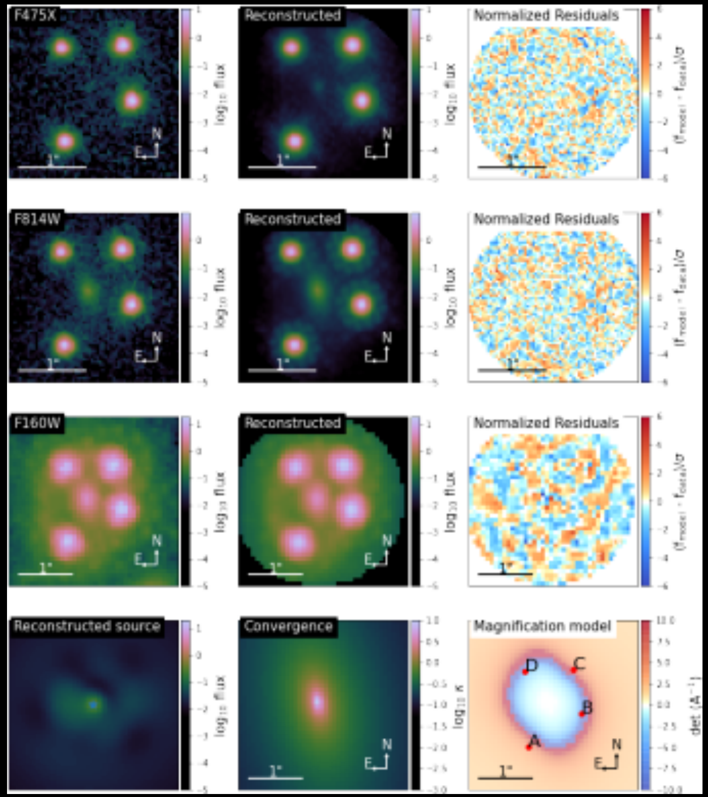
Yildirim+2021

Future of Time-Delay Cosmography

- Goal: 1% precision on H_0
- More data on time-delay lenses
  - spatially-resolved stellar kinematics (e.g., VLT/MUSE, Keck/KCWI, JWST/NIRSpec)
  - improving kinematics measurement and modeling
  - increasing sample size of time-delay lenses (discovery, monitoring, follow-up)
- Testing and controlling for systematic uncertainties
  - more detailed investigation of lens mass profiles
  - multiple modeling approaches (Shajib, Wong et al. 2022)
- Analysis of large future lens samples
  - LSST will eventually discover ~hundreds or ~thousands of lensed quasars for time-delay cosmography
  - develop lens search methods on large imaging surveys (e.g., DES, HSC)
  - develop automated modeling techniques (Schmidt+ in prep.; Ertl+ in prep.)



Shajib+2018



Schmidt+ in prep.

Summary

- Time-delay cosmography measures H_0 completely independent of CMB and distance ladder/SNe
- Latest TDCOSMO results attain ~2% precision on H_0 in flat ΛCDM
  - consistent with SH0ES SNe Ia + distance ladder
  - in >4σ tension with *Planck* CMB value
- Hierarchical analysis using external datasets, relaxed assumptions on mass profile gives ~5% precision on H_0 in flat ΛCDM
  - assumes external lenses from SLACS are similar to TDCOSMO lenses
  - IFU data with upcoming *JWST* observations will break degeneracy
- Tests for systematic uncertainties
  - differences in lens modeling codes
  - DM substructure, higher-order multipoles in lens mass profile
- Future developments will push toward a ~1% constraint
  - larger lens samples
  - automated lens modeling

TDCOSMO Collaboration

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Timo Anguita
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Simon Birrer
Roger Blandford
Vivien Bonvin
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Gabriel Caminha
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Stefan Taubenberger
Tommaso Treu
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Lyne Van de Vyvere
Patrick Wells
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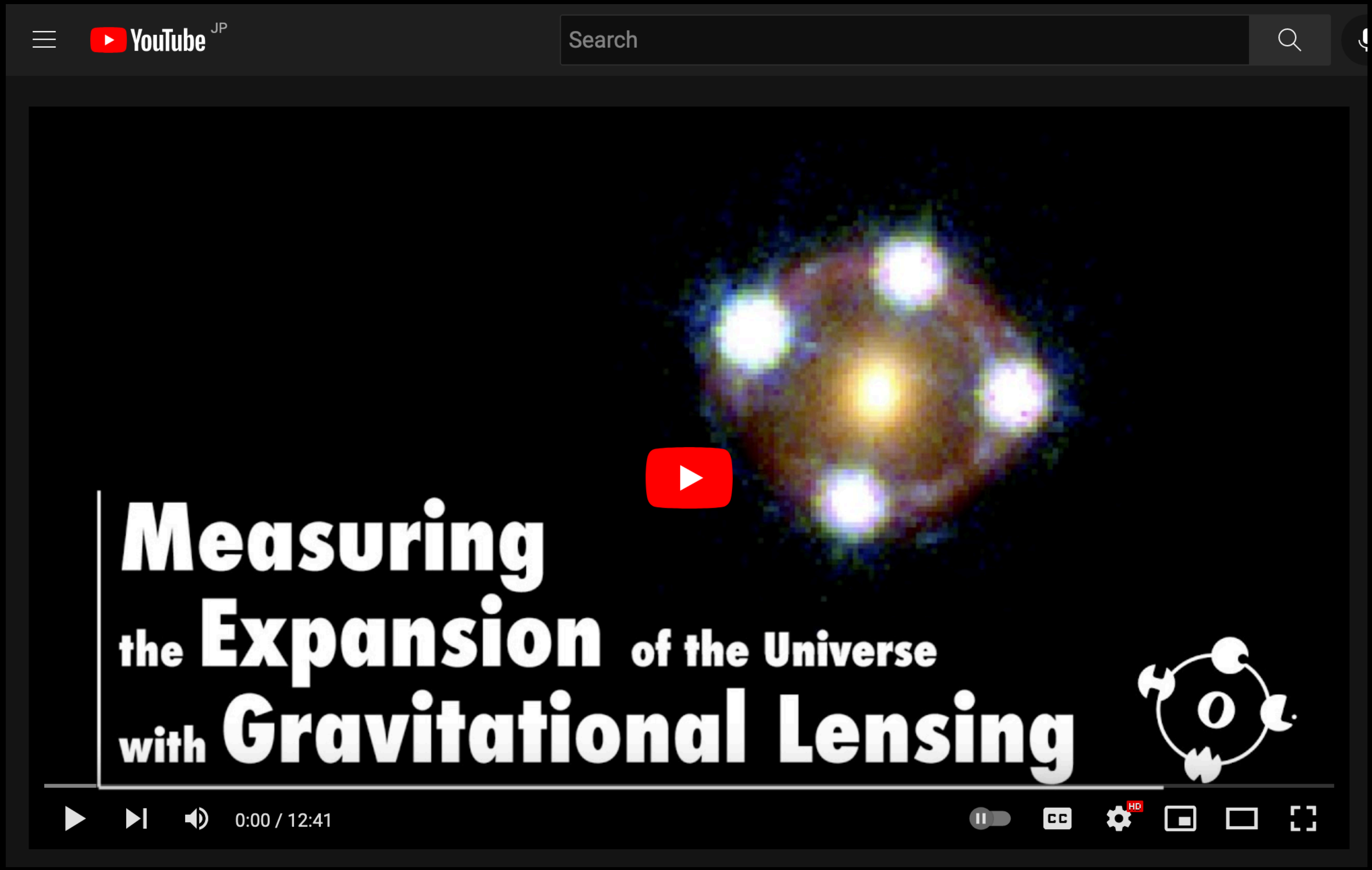
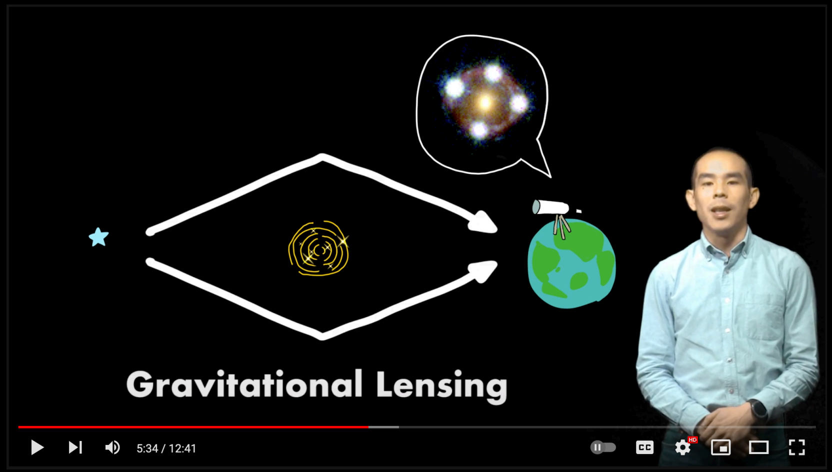
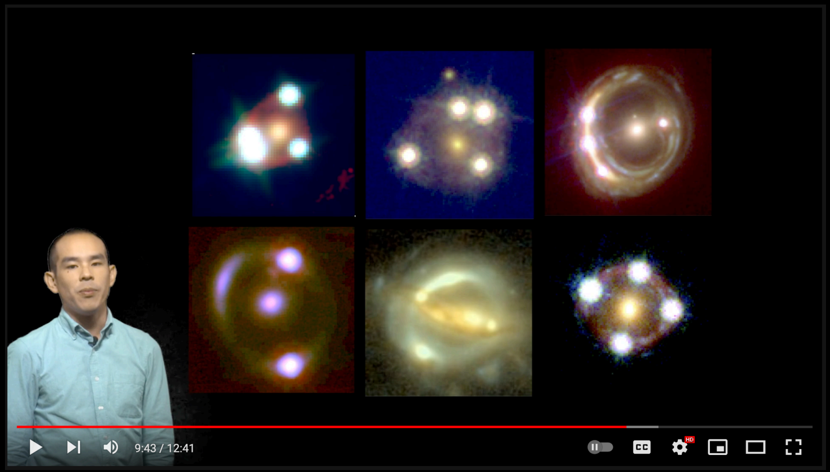
Akın Yıldırım

http://www.tdcosmo.org

We're on YouTube!







search "h0licow" on YouTube (it should be the first result)

Interested in public education/outreach in Tokyo?

contact me (kcwong19@gmail.com)