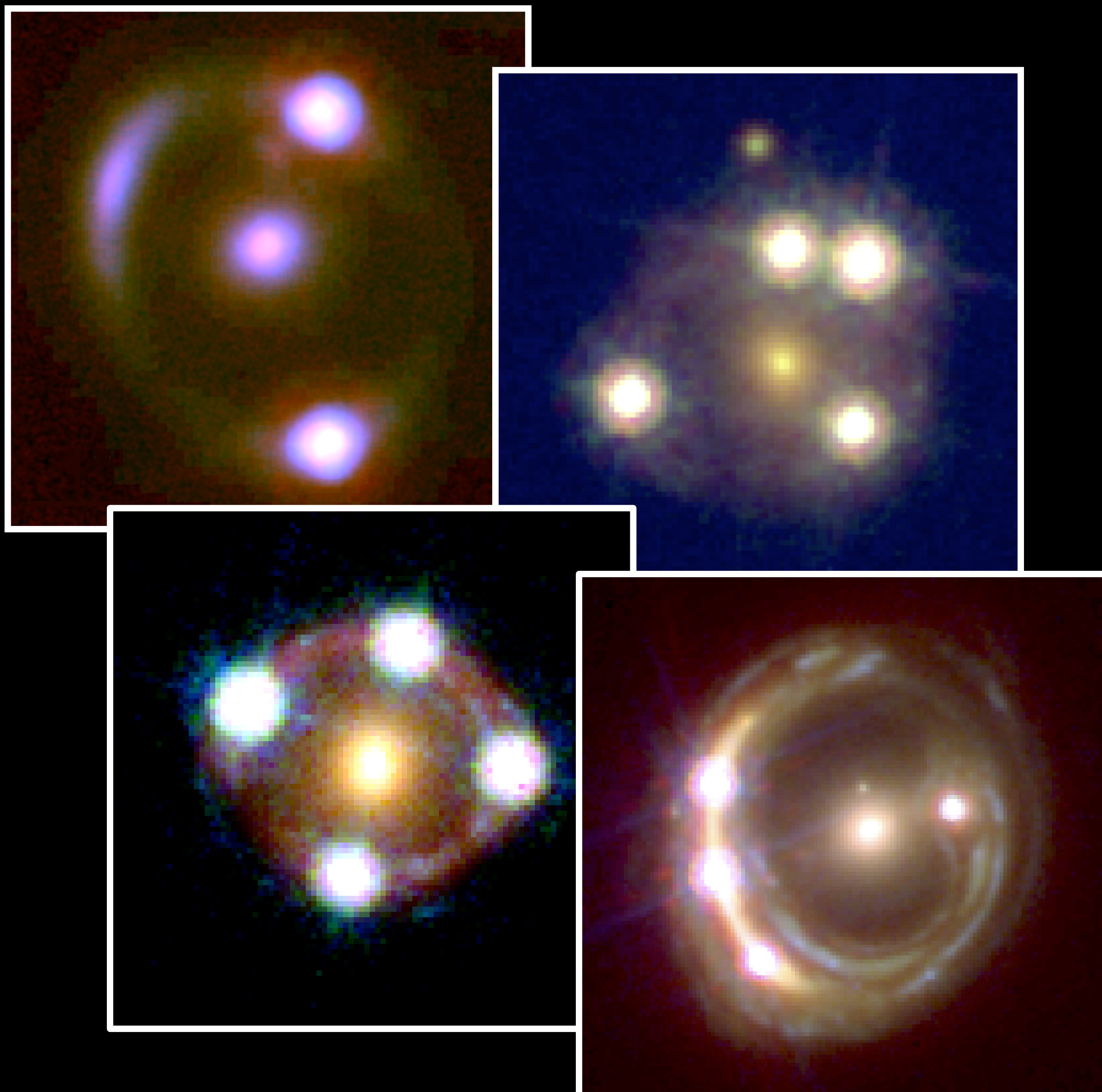
An Independent Measurement of H_0 from Lensed Quasars



Kenneth Wong

on behalf of the H0LiCOW/TDCOSMO collaobration

Kavli IPMU Postdoc Colloquium Series

October 9, 2020

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

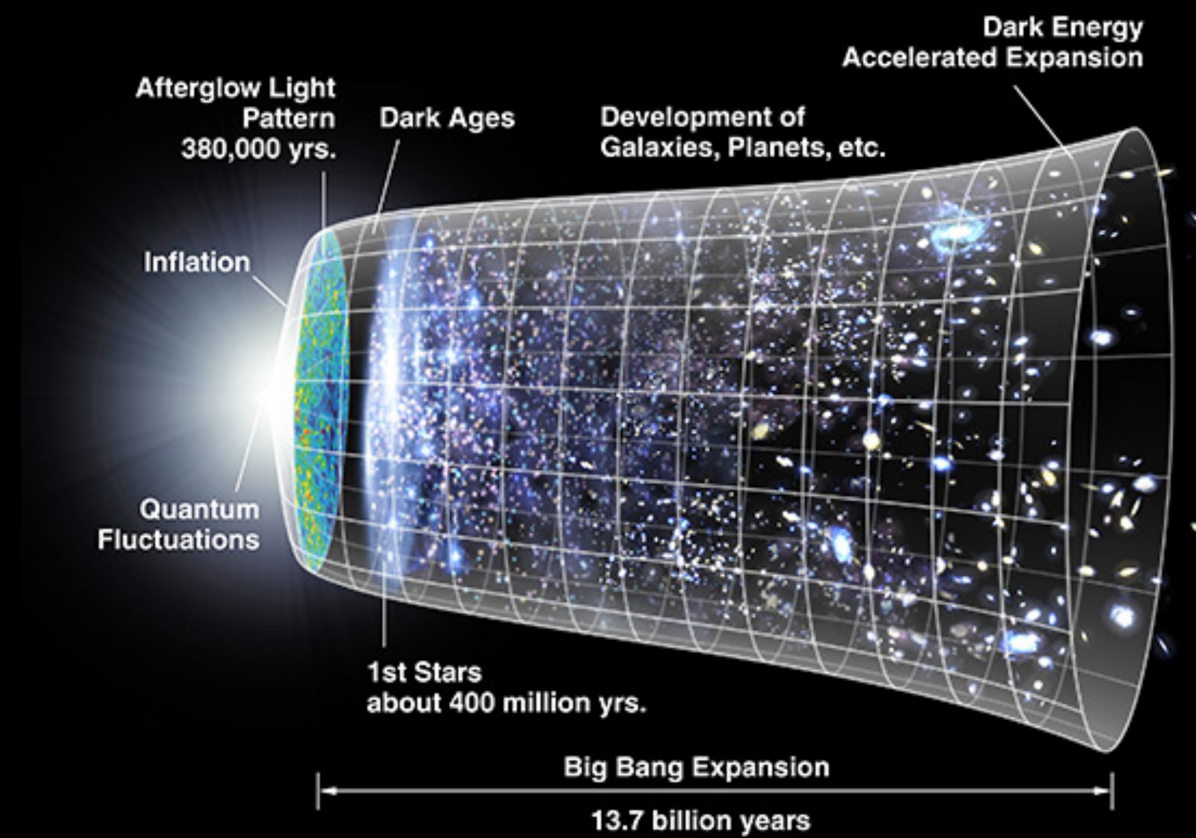
科研費 KAKENHI

東京大学 THE UNIVERSITY OF TOKYO

The Standard Model of Cosmology

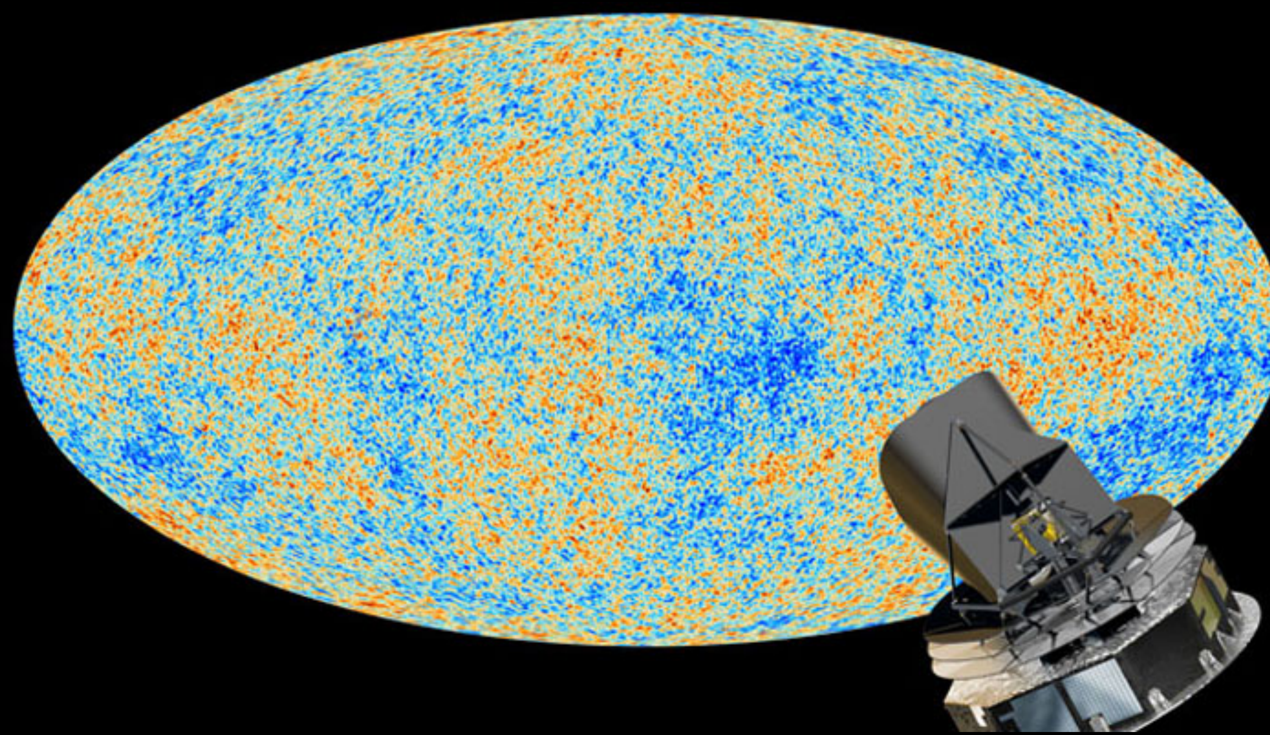
Standard model is the “flat ΛCDM” cosmology, where $\Omega_k = 1-\Omega_m-\Omega_\Lambda = 0$, $w = -1$

Very successful at explaining a variety of observations



Planck mission 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)



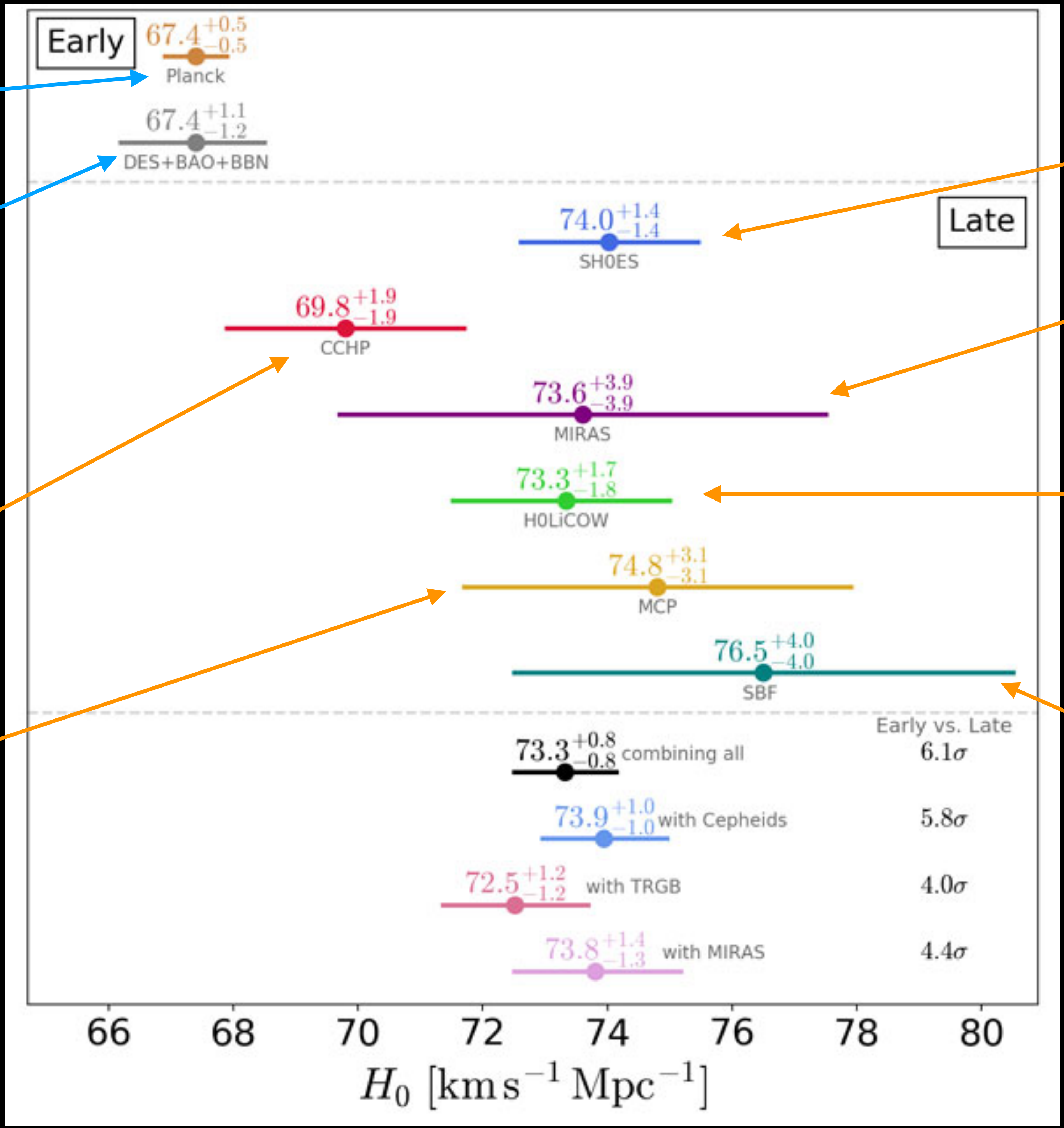
Recent Tension in H_0 Measurements

CMB

BBN anchor
(no CMB info)

TRGB calibration
of distance ladder

Water masers



Cepheid distance
ladder + SNe Ia

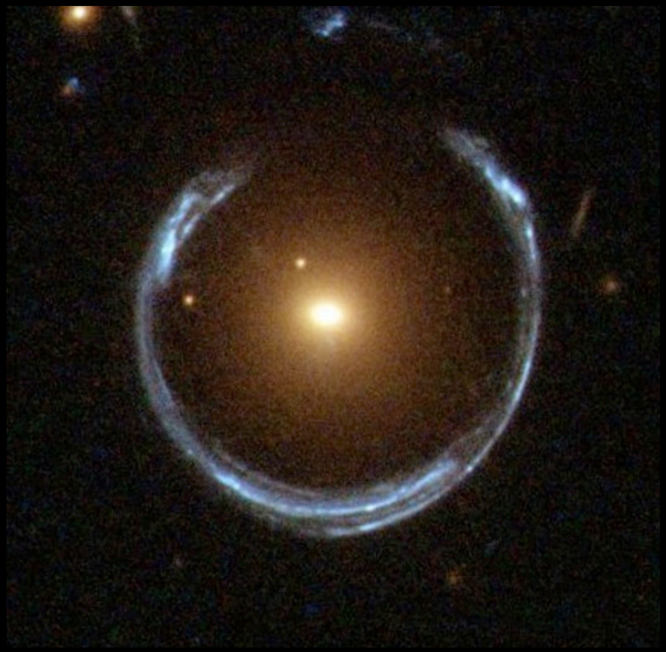
Mira calibration of
distance ladder

Time-delay cosmography

Surface
brightness
fluctuations

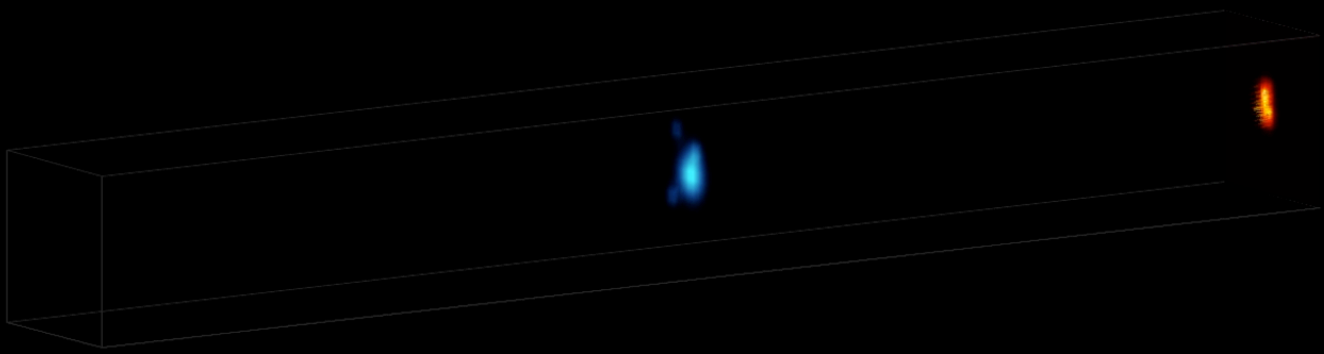
Verde, Treu, & Riess 2019 (image credit: V. Bonvin)

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**

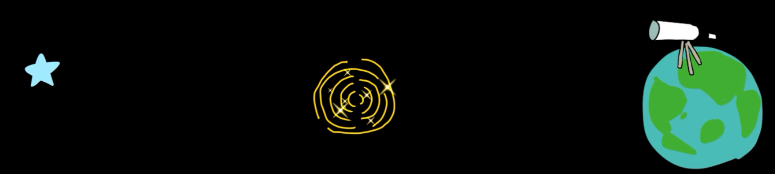


Animation credit: Y. Hezaveh

Time-Delay Cosmography

- There is a "time delay" between the multiple variable lensed images
  - due to different path length, gravitational potential at different images
- 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*

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



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

Animation credit: M. Mori

Time delay (observed)

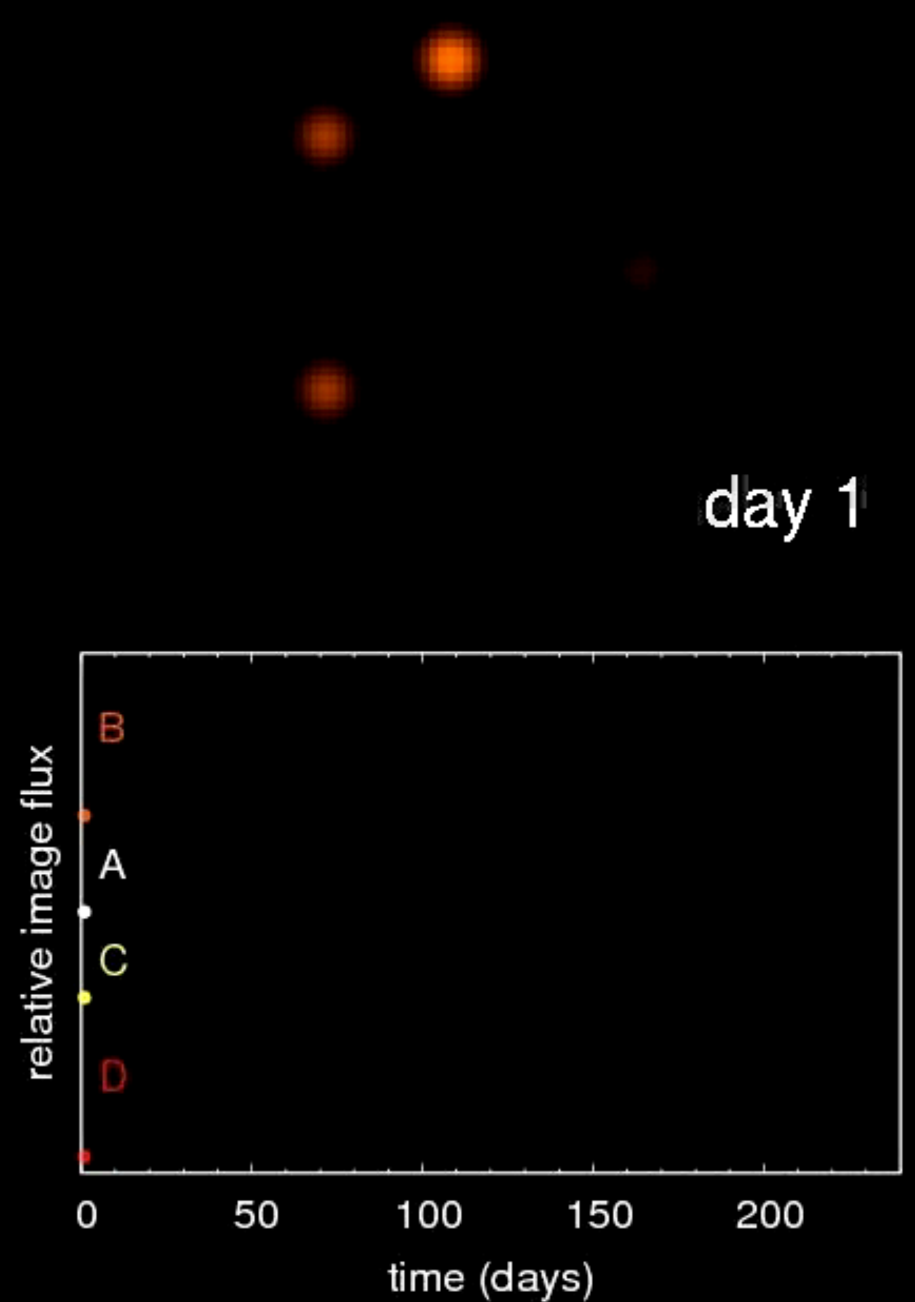
Time-delay distance

Fermat potential (from lens model)

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

Cosmology with Lensed Quasars

- Lensed quasars
  - variable on short timescales (~days)
  - bright and easy to detect
- Measure time delay by monitoring lensed quasars over time
  - identical features in light curve correspond to same source event, but shifted in time



Animation credit: C. Fassnacht, S. Suyu

Cosmology with Lensed Quasars

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

Time delay (observed)

Time-delay distance

Fermat potential (from lens model)

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

H0LiCOW / TDCOSMO

- H_0 Lenses in COSMOGRAIL's Wellspring (H0LiCOW; Suyu+2017) project has performed detailed analysis of several time-delay lenses
  - long term monitoring from COSMOGRAIL (Courbin+2005), VLA (Fassnacht+2002) 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
- New umbrella collaboration: TDCOSMO
  - H0LiCOW + COSMOGRAIL + STRIDES + SHARP + other collaborators
- Seven lenses analyzed to date (see Wong+2020, Millon+2020a for latest results)

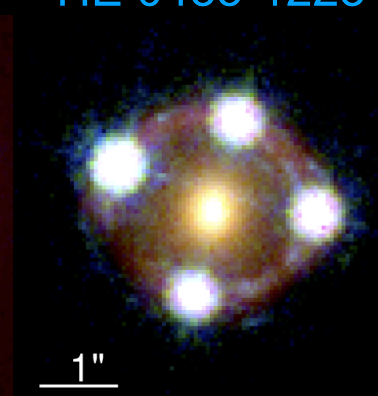
B1608+656

Suyu+2010
Jee+2019

RXJ1131-1231

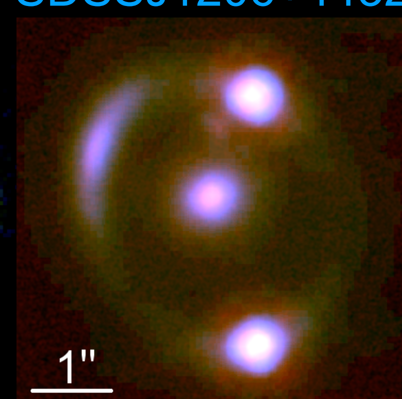
Suyu+2013,2014
Chen+2019

HE 0435-1223



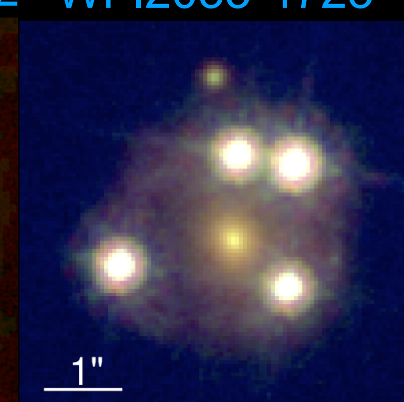
Wong+2017
Chen+2019

SDSSJ1206+4432



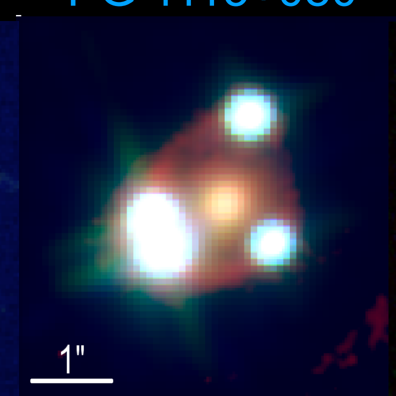
Birrer+2019

WFI2033-4723



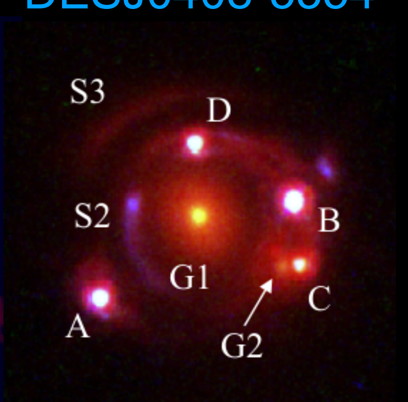
Rusu+2020

PG 1115+080



Chen+2019

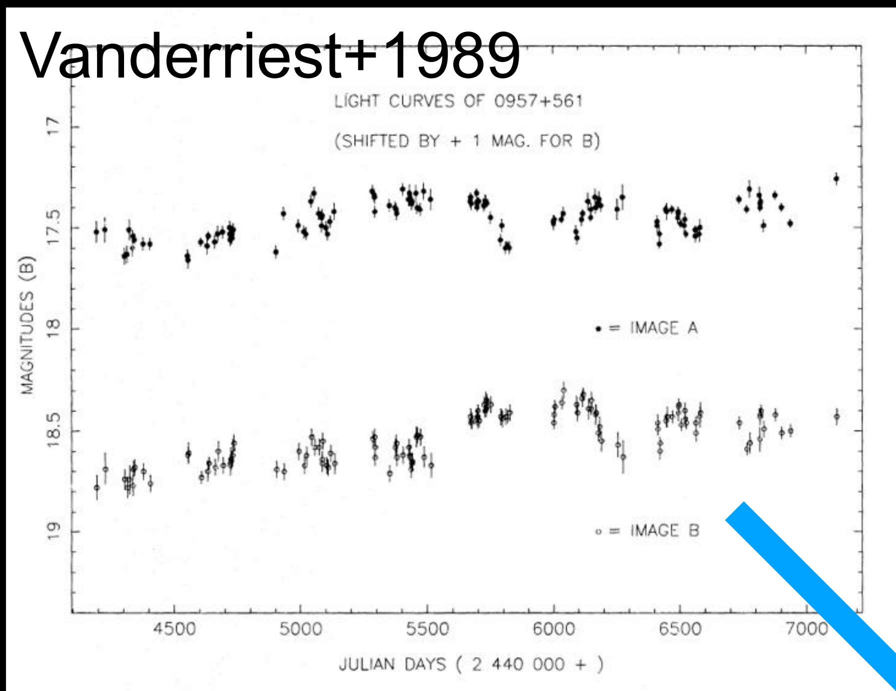
DESJ0408-5354

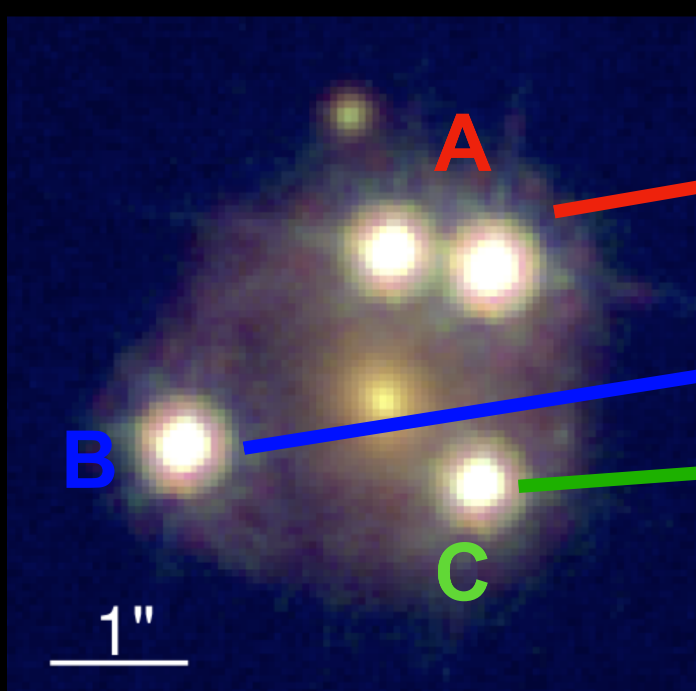


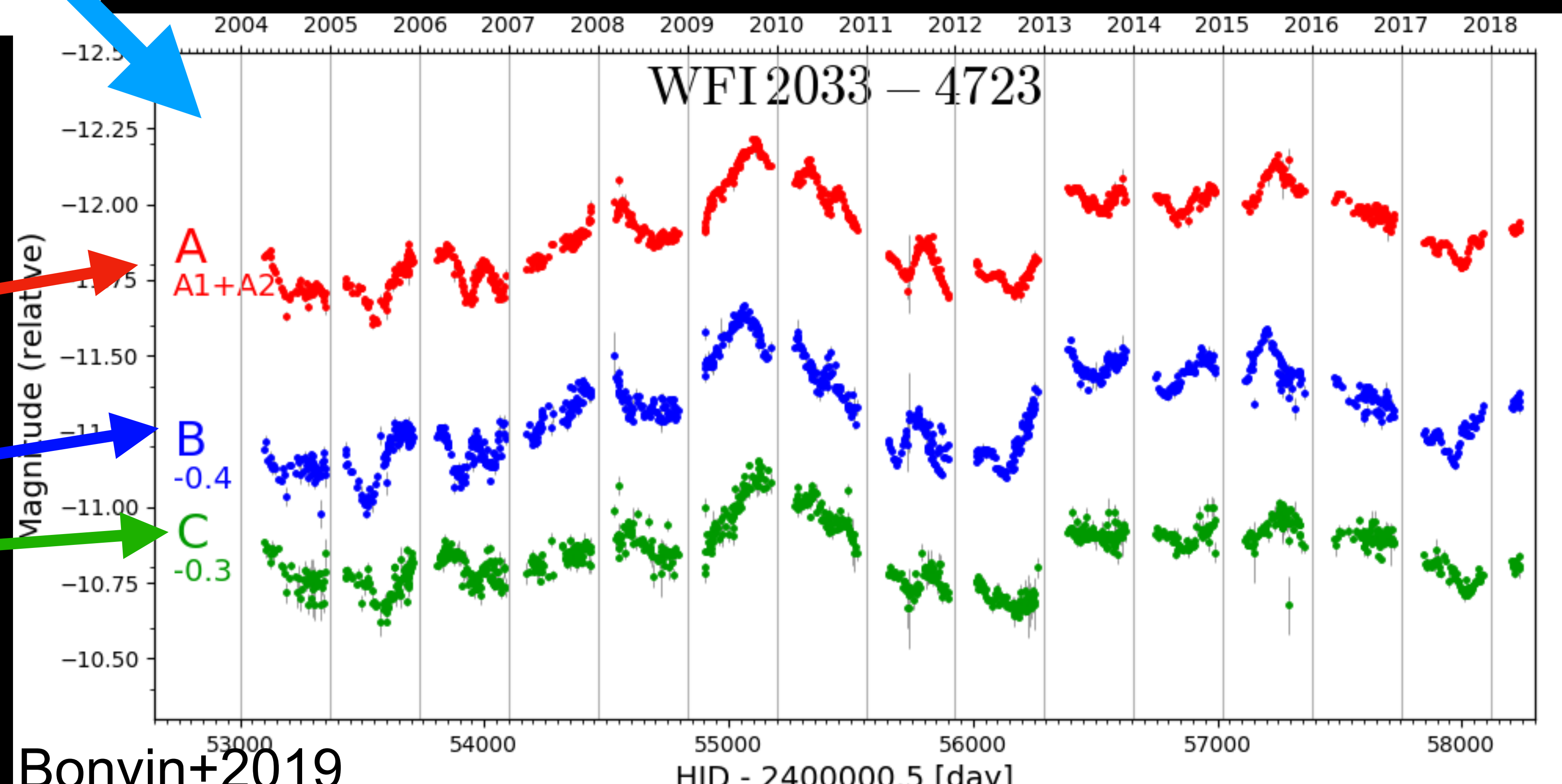
Shajib+2020

Time Delay Measurements

- COSMOGRAIL: 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)

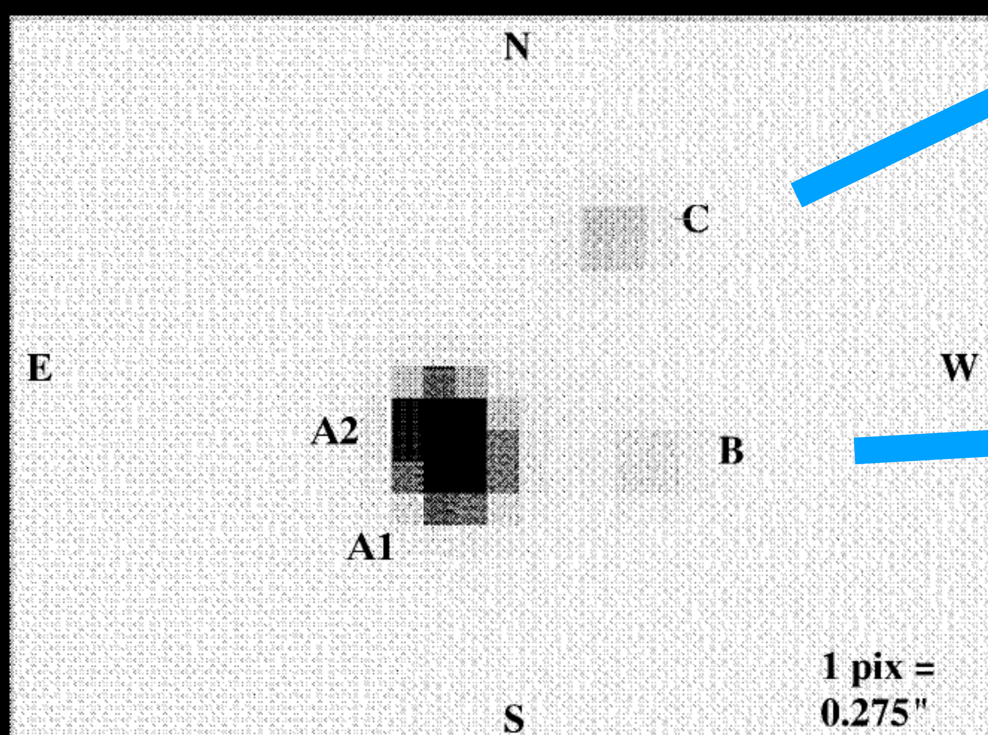




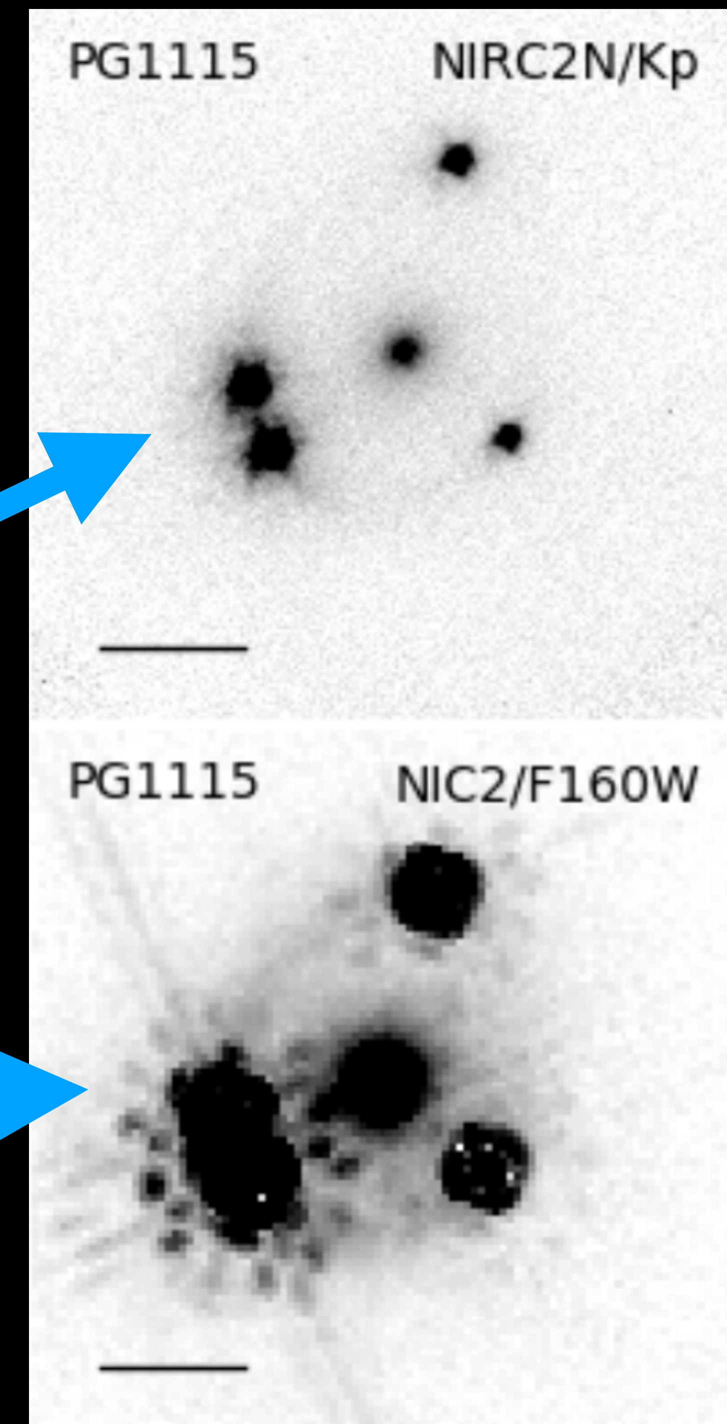


Lens Modeling

- 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



Schechter+1997

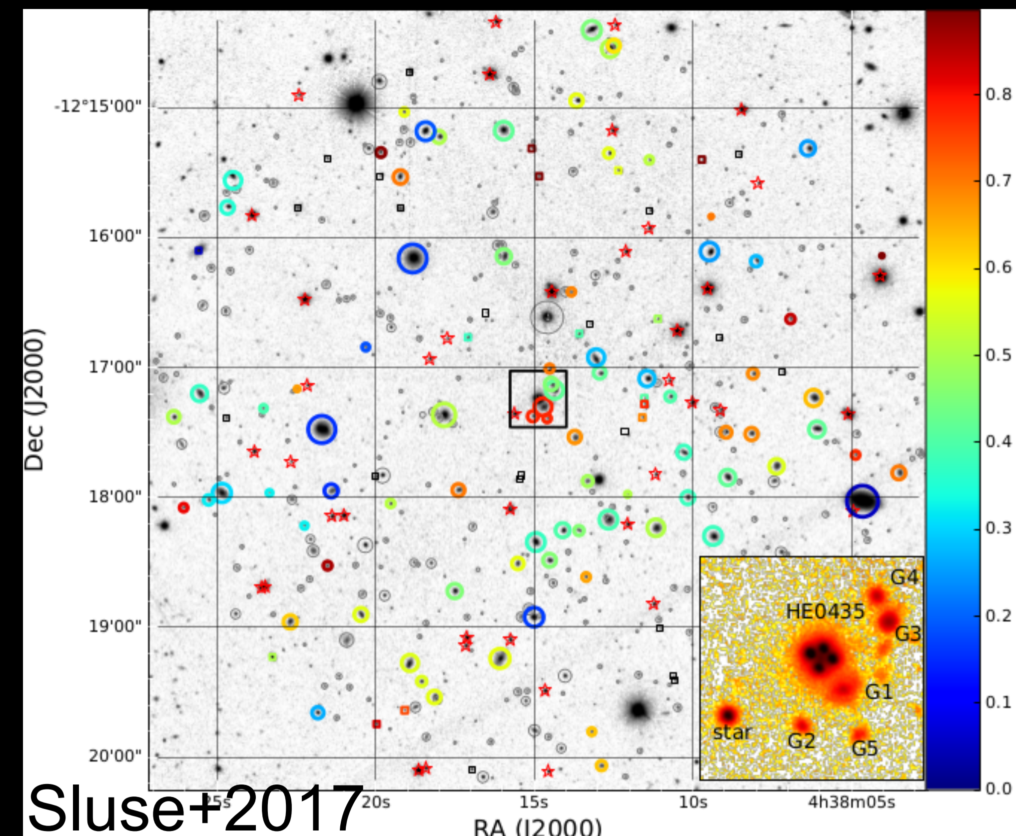


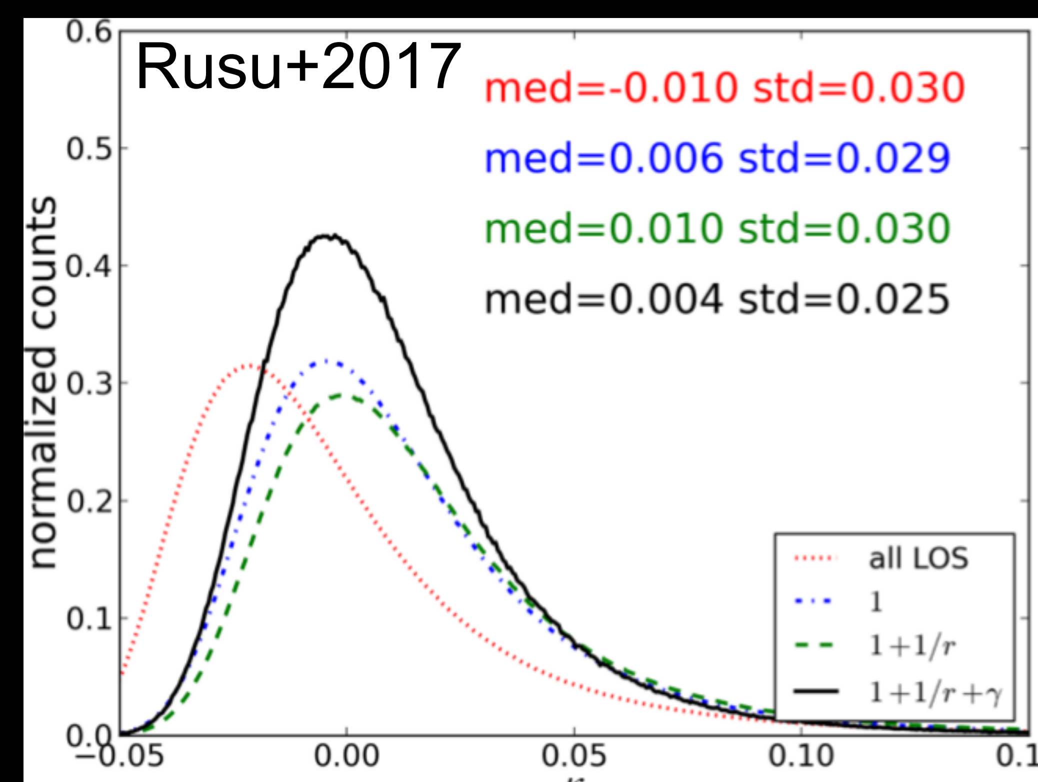
Chen+2019

Mass Along the Line of Sight

Animation credit: M. Mori

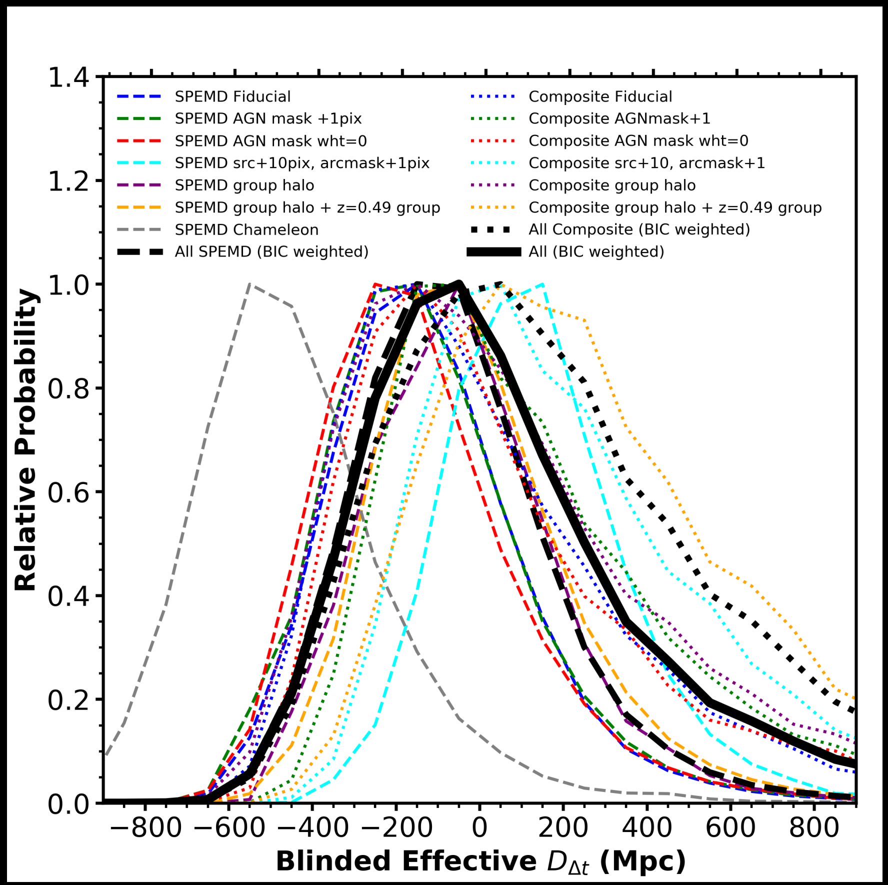
- Lenses lie in overdense LOS due to local lens environment (e.g., Fassnacht+2011; Wong+2018)
- Some strong perturbers need to be included explicitly in lens model (e.g., Wilson+2016; McCully+2017; Sluse+2017)
- Estimate effect of weaker perturbers using weighted galaxy number counts calibrated by simulations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

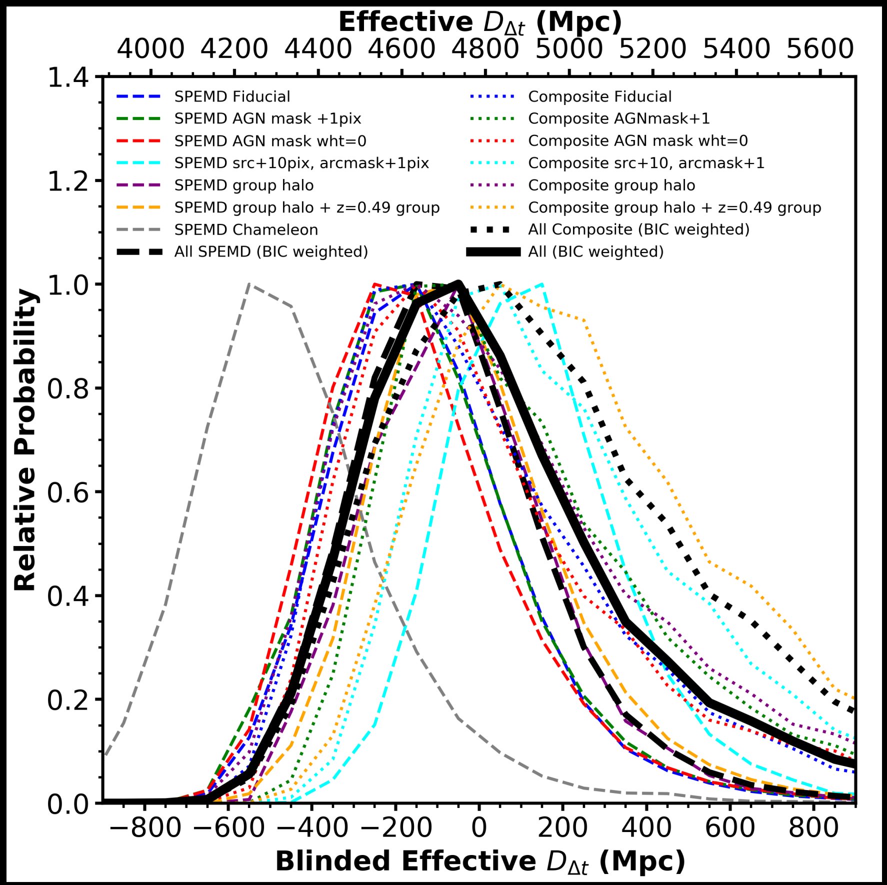




Blind Analysis

- 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

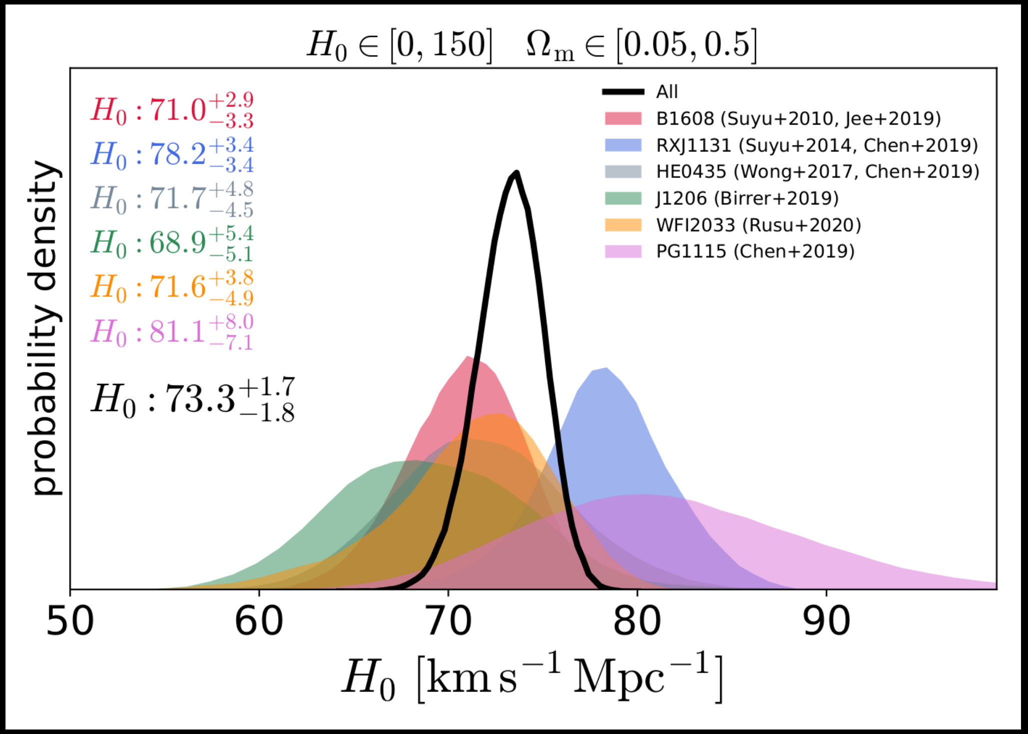




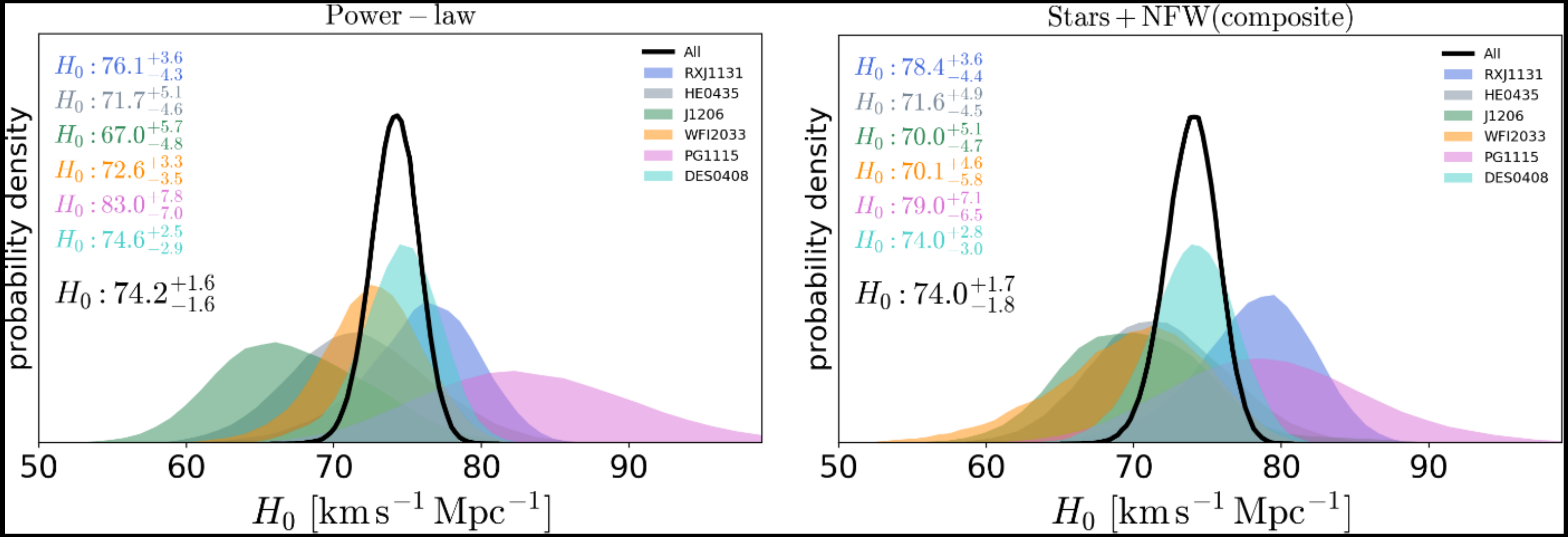
Rusu+2020

Latest TDCOSMO Results

- Combined result: ~2% precision on H_0 for flat ΛCDM, in >3σ tension with *Planck*
- Power-law and composite (stars+NFW) lens mass models give consistent results
- Spread of PDFs for individual lenses suggests no evidence for unaccounted systematics

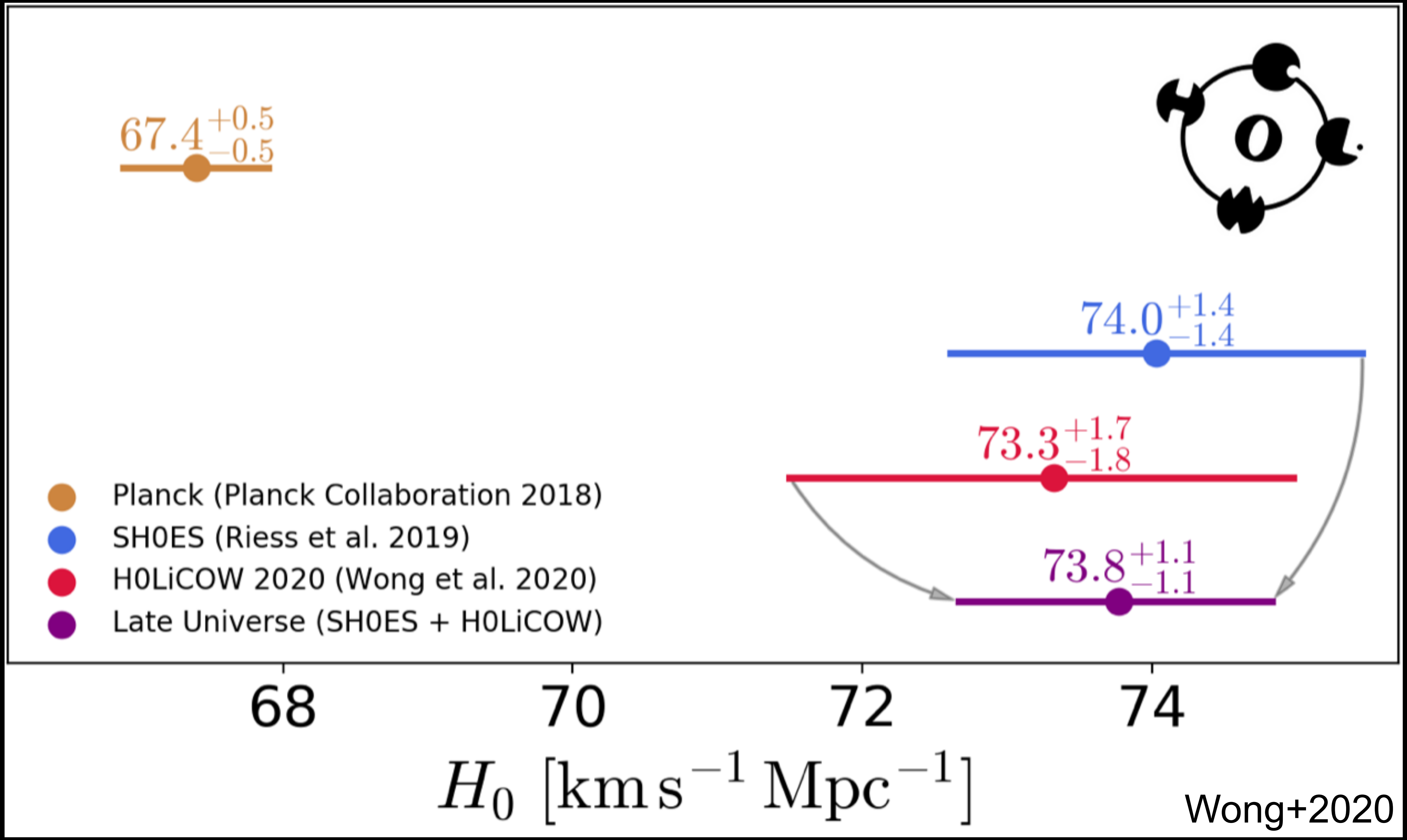


Wong+2020



Millon+2020a

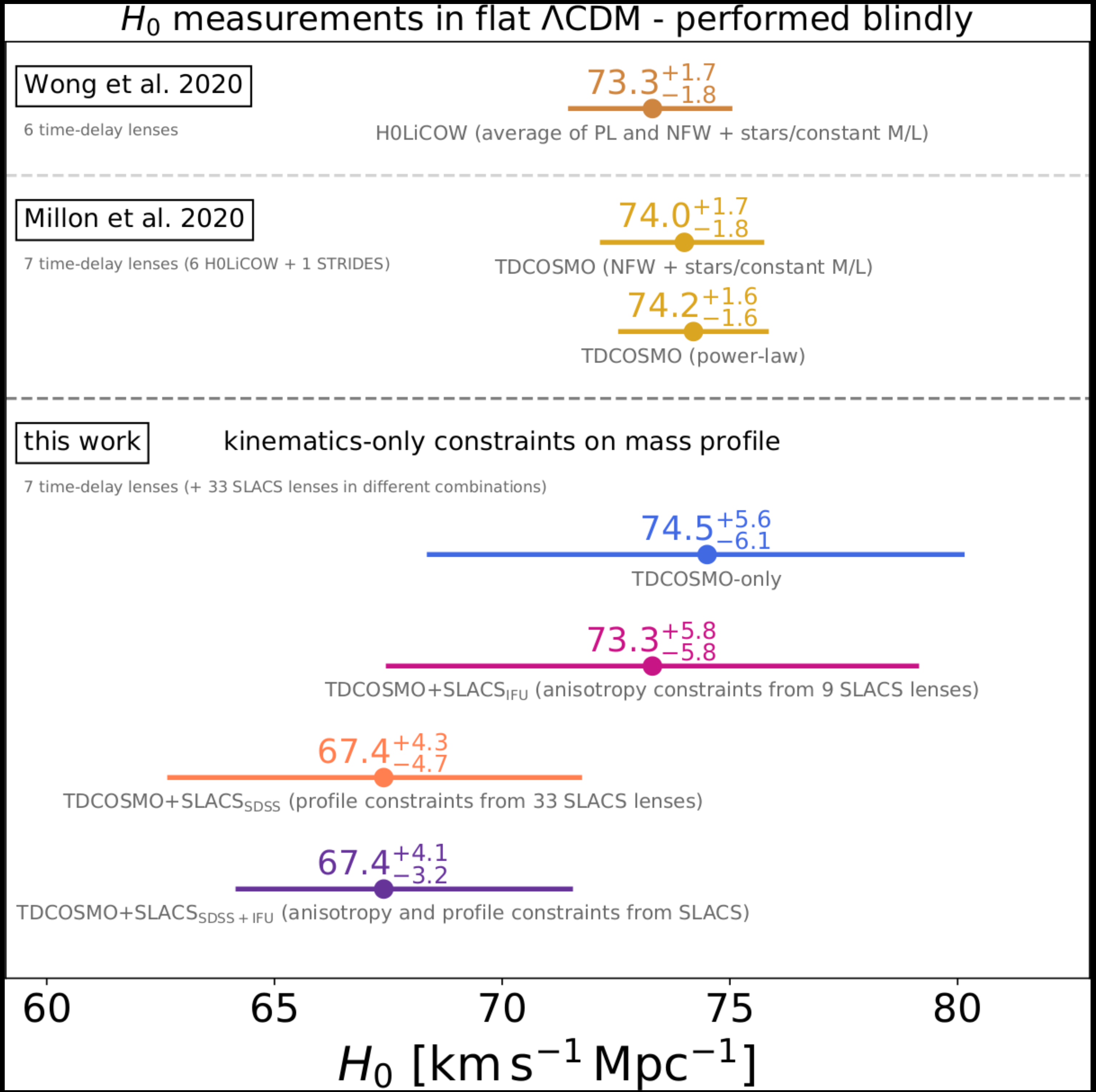
Tension between Early and Late-Universe Probes



3.1σ tension between H0LiCOW and Planck CMB results
Combined with SH0ES, 5.3σ tension between early and late-Universe probes

TDCOSMO Hierarchical Analysis

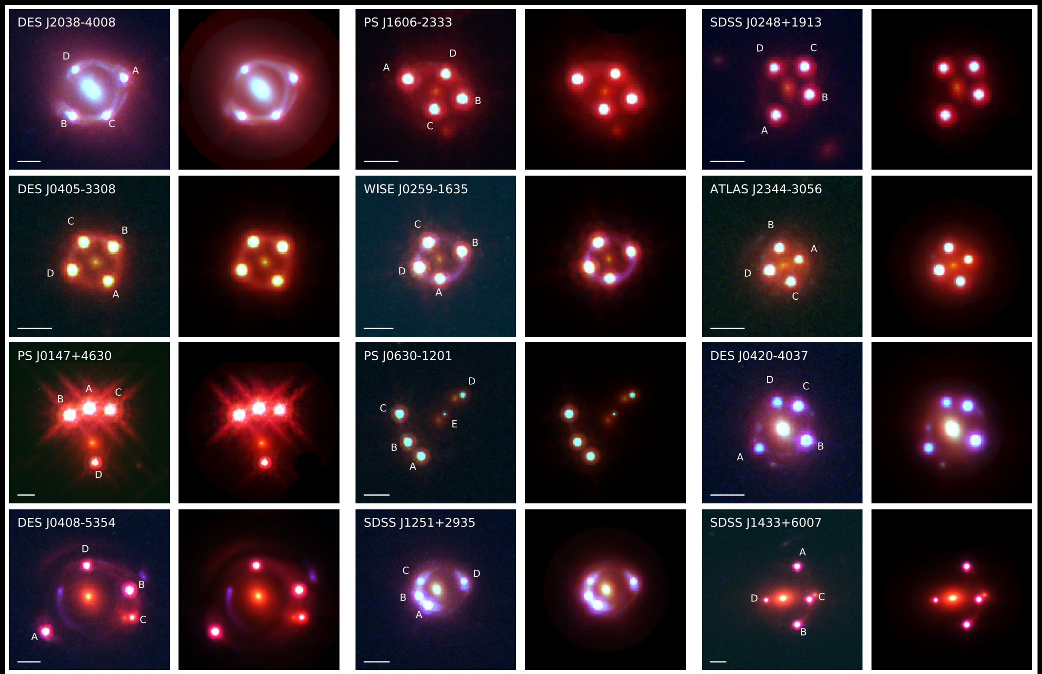
- H0LiCOW/TDCOSMO uses physical and well-motivated lens mass profiles
- Potential systematic: mass sheet transform (i.e., deviation from power law or stars+DM)
- New analysis relaxes assumptions on mass profile, use kinematics to constrain mass (Birrer+2020)
- Joint Bayesian hierarchical analysis of TDCOSMO lenses combined with mass profile constraints from 33 SLACS (Bolton+2006) lenses
- Maximally conservative, but assumes similarity between TDCOSMO and SLACS lenses: ~5% constrain on H_0



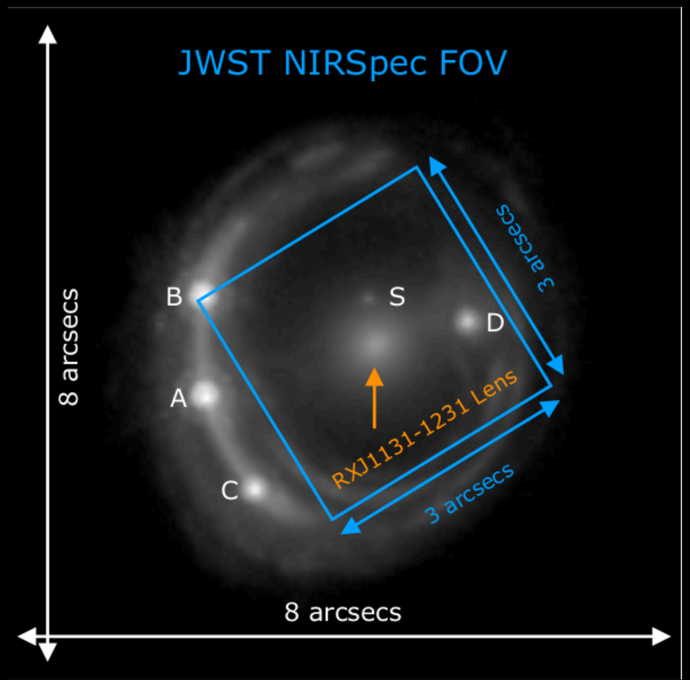
Birrer+2020

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 (e.g., Yidirim+ in prep.)
  - increasing sample size of time-delay lenses (discovery, monitoring, follow-up)
- Adding external data sets
  - external lensing sample precisely matching TDCOSMO (redshift, morphology, etc.)
  - increase sample size of lenses in general (e.g., Rubin Observatory, Euclid, Roman Observatory)
  - add kinematic information from local elliptical galaxies (e.g., SAURON, ATLAS3D)
- Challenge ourselves
  - improve simulations for better validation
  - blind analysis challenges
  - keep analysis blind
  - open source



Shajib+2018



Yildirim+ 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 >3σ tension with *Planck* CMB value
- Hierarchical analysis using external datasets, relaxed assumptions on mass profile gives ~5% precision on H_0 in flat ΛCDM
- Future developments will push toward a ~1% constraint
  - larger lens samples
  - resolved kinematics
  - more external datasets
  - improved simulations

TDCOSMO Collaboration

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