Measuring the Hubble-Lemaitre constant H_0 from Gravitational Lensing

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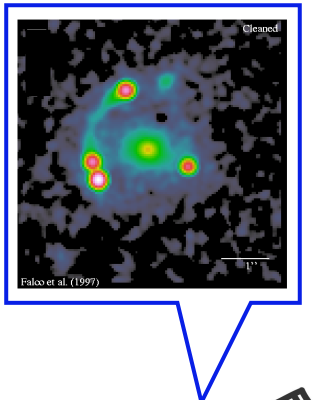
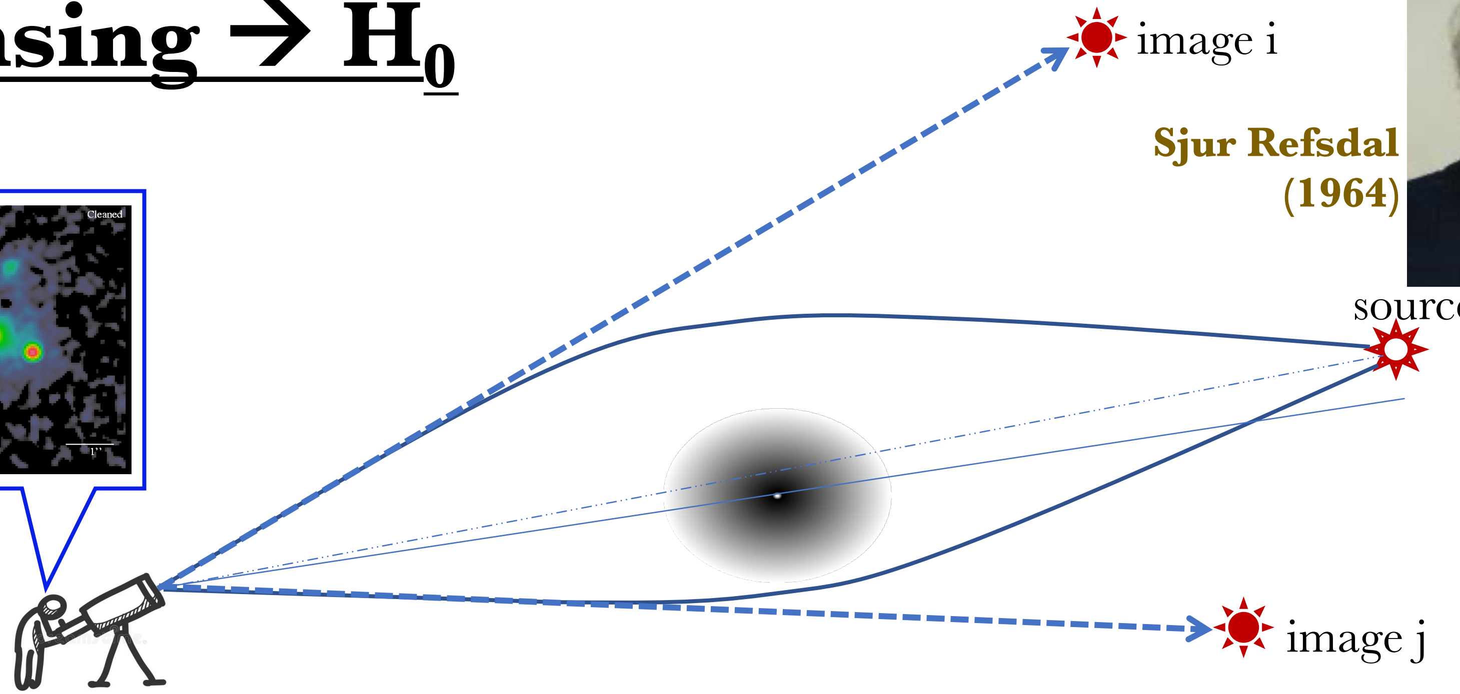
Lensing → H_0





Sjur Refsdal (1964)

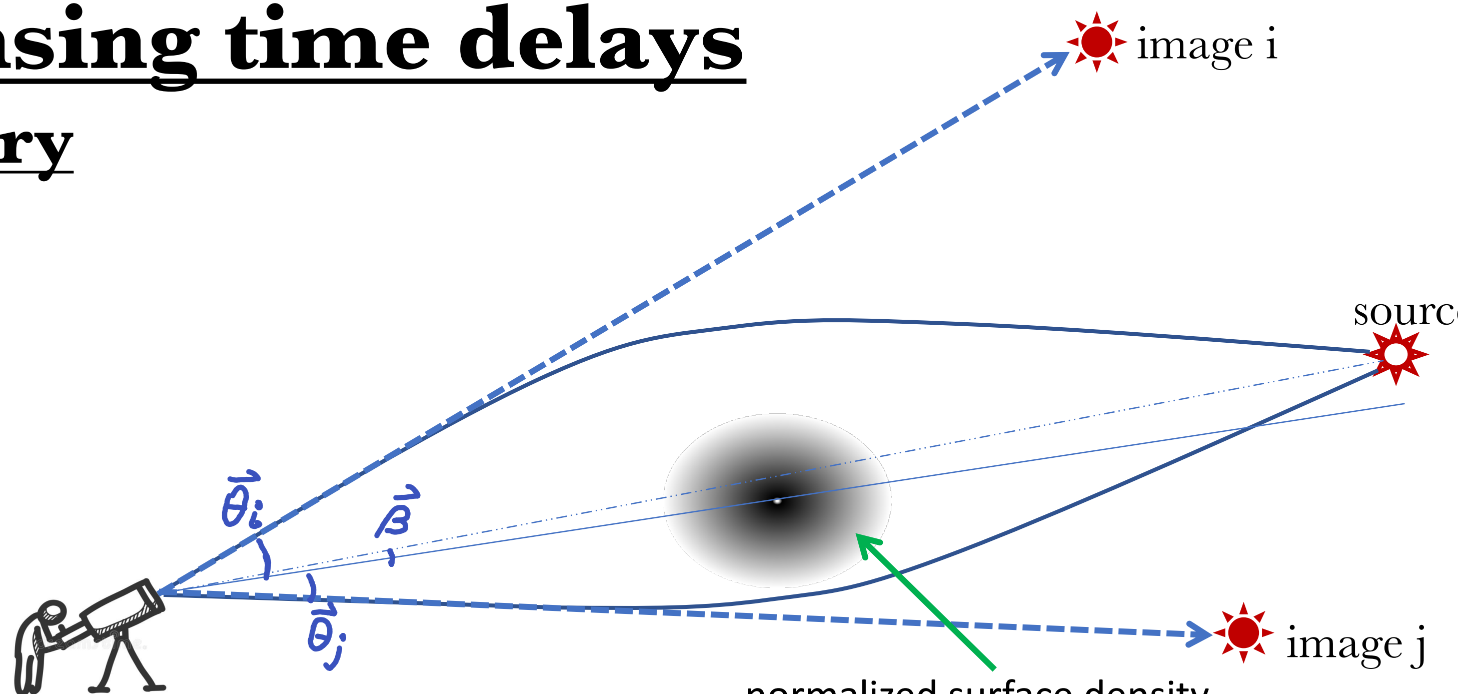
H_0 is a property of global cosmology, and has units of 1/time;
since light travel spans cosmological distances, light travel time will depend on H_0

Light travel time from the source through different geodesics (observed as images) is the sum of two contributions

- ***geometrical*** – path length related to the angular location of image on the sky
- ***gravitational*** – integrated Newtonian potential along the line of sight (Shapiro)

Lensing time delays

theory



normalized surface density distribution in the lens

arrival time
not observed

$$t(\vec{\theta}) = \frac{(1+z_l)}{c}\frac{D_l D_s}{D_{ls}}\left[\frac{1}{2}(\vec{\theta}-\vec{\beta})^2 - \frac{1}{\pi}\int d\vec{\theta}' \, \kappa(\vec{\theta}') \ln|\vec{\theta}'-\vec{\theta}|\right]$$

angular distances — geometrical — gravitational

$$D = \frac{c}{H_0} fcn(\Omega's, w)$$

lens mass model $\tau(\vec{\theta})$

observed time delay between images i and j

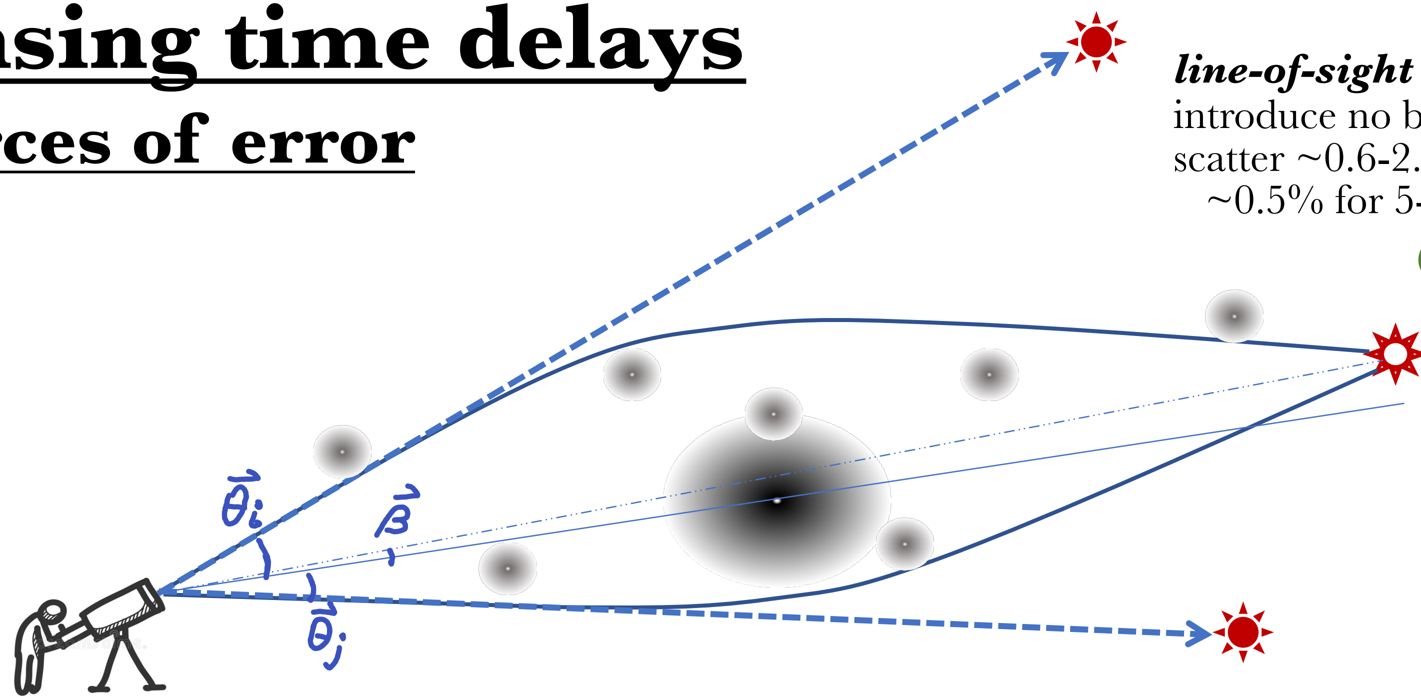
$$\Delta t = t(\vec{\theta}_i) - t(\vec{\theta}_j) \;\Rightarrow\; \Delta t \propto \frac{\Delta \tau}{H_0}$$

Lensing time delays

sources of error

line-of-sight subhalos
introduce no bias to H_0
scatter ~0.6-2.4% for 1 lens
~0.5% for 5-6 lenses

(Gilman+2020)



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observed time delays
1-10%

(Millon+2020a,b Bonvin+2019)

cosmological parameters, Ω
small, <0.1%

lens plane mass models
main source of uncertainties
few% --10% or larger

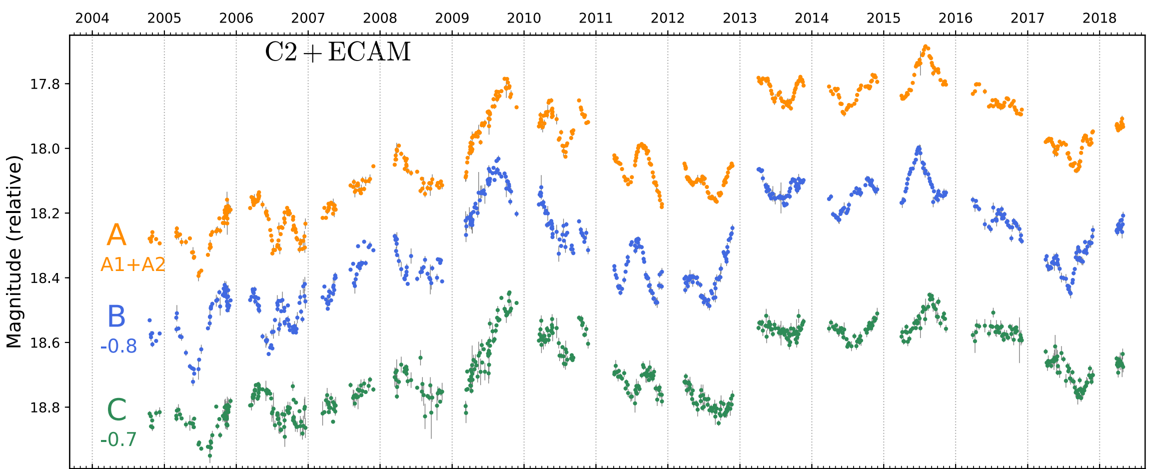
Measuring time delays

COSMOGRAIL

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

A dedicated program
to measure time delays
(Meylan & Courbin+)

Quasar image flux vs. time



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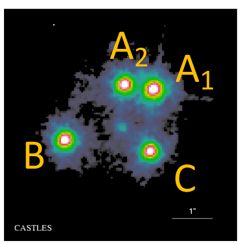
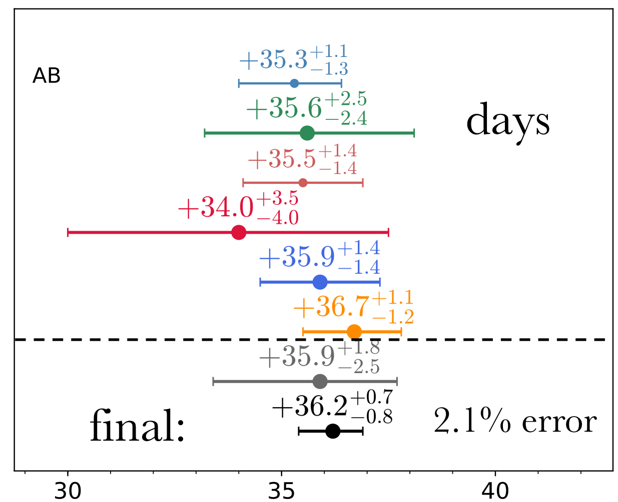
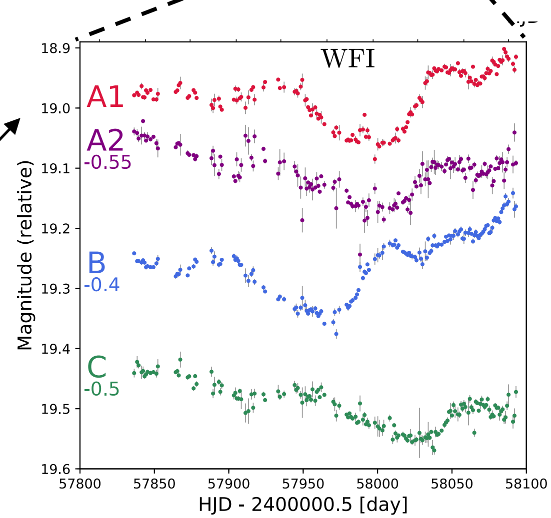


time delay from
different estimators



different instruments
on 1-2m class telescopes



(Bonvin+2019)

In general, **1-10%** and
can be improved upon
with further observations

Modeling constraints

quasar image positions

quasar time delays

quasar image flux ratios *If due to stars or LCDM subhalos, then does not constrain lens models*

host galaxy's extended Einstein ring *Often low S/N, low spatial resolution; shape of source unknown*

Modeling constraints

subject to lensing degeneracies

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- quasar time delays
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Mass Sheet Degeneracy

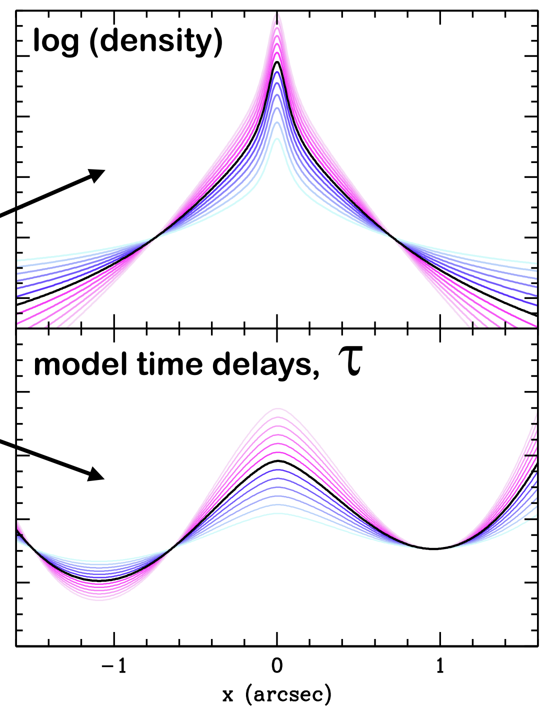
changes steepness of density profile

changes time delays

(Gorenstein+1988
Saha 2000)

$$\Delta t \propto \frac{\Delta \tau}{H_0}$$

MSD has a linear affect on derived H_0



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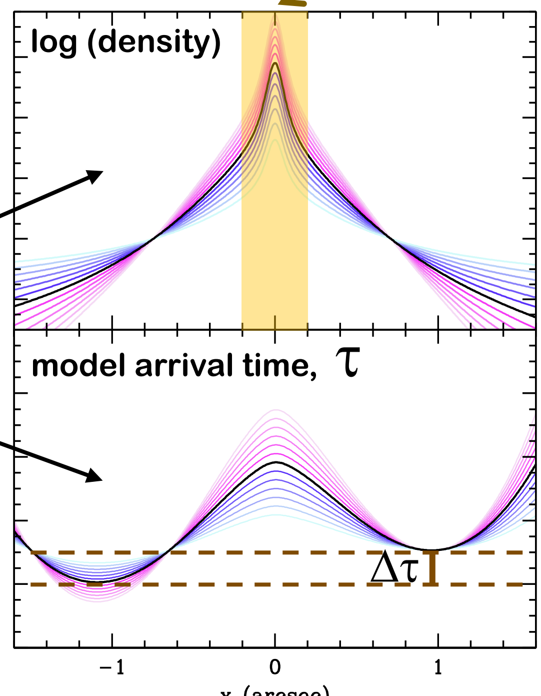

knowing mass density at center will break MSD

→ **stellar kinematics** (velocity dispersion measures mass)

(Gronin & Narayan 1996
Treu & Koopmans 2002
H0LiCOW papers)

Modeling constraints

subject to lensing degeneracies:

- quasar image positions
- quasar time delays
- quasar image flux ratios — *If due to stars or LCDM subhalos, then does not constrain lens models*
- host galaxy's extended images – ring — *Often low S/N, low spatial resolution; shape of source unknown*

kinematics of the lensing galaxy

Kinematic priors have a significant impact **(Birrer+2016)**

Using kinematics can result in bias **(Gomer & LLRW 2020)**

Unresolved kinematics has limited power to constrain the mass profiles **(Birrer+2020)**

BUT: spatially resolved kinematics can be useful **(Yildirim+2020)**

Other degeneracies:

generalization of MSD **(Schneider & Sluse 2014)**

monopole degeneracy **(Saha 2000, Liesenborgs+2012)**

shape degeneracies **(Saha & LLRW 2006)**

Lens mass modeling

Lensing data not sufficient to generate a unique lens model
Need additional assumptions – prior knowledge about galaxies

1 mass component:
elliptical power law
with fixed or variable
slope + tidal term

HOLiCOW (Suyu+2014, Chen+2019, Wong+2017, 2019, Birrer+2019, Rusu+2019)

5-6

2 mass components:
baryons & DM
+ tidal term
+ nearby gals

9-15

2 offset mass comp.:
baryons & DM
+ tidal term
+ nearby gals

(Nightingale+2018 Gomer & LLRW 2018, 2021 LLRW & Zegeye 2020)

14-17

pixellated
free-form
+ tidal term

PixeLens / Glass (Saha+2006, Coles 2008, Denzel+2021)

~100

 # parameters

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H0LiCOW (Suyu+2014, Chen+2019, Wong+2017, 2019, Birrer+2019, Rusu+2019)		(Nightingale+2018 Gomer & LLRW 2018, 2021 LLRW & Zegeye 2020)	**PixeLens / Glass** (Saha+2006, Coles 2008, Denzel+2021)
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 # parameters

more priors

many degeneracies
broken artificially

uncertainties underestimated?

(optimistic)

Need different modeling philosophies as cross-checks

fewer priors

allow wider range of
degenerate models

uncertainties overestimated?

(cautious)

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5-6 → **9-15** → **14-17** → **~100** → **# parameters**

shape degeneracies

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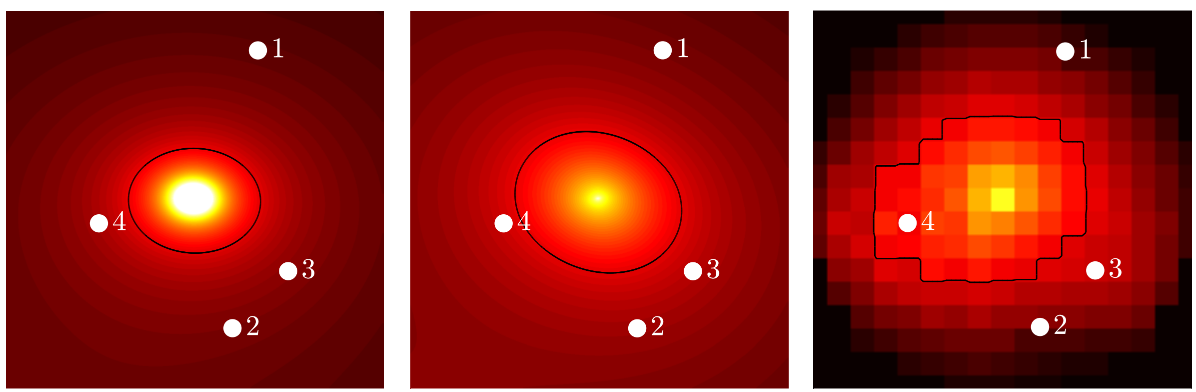

Rusu+2020 | **Barrera & LLRW (in prep)** | **Denzel+2021**

H0LiCOW does not reproduce quasar image positions to ~5 σ

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**(Nightingale+2018
Gomer & LLRW 2018, 2021
LLRW & Zegeye 2020)**

pixellated
free-form
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**PixeLens / Glass
(Saha+2006,
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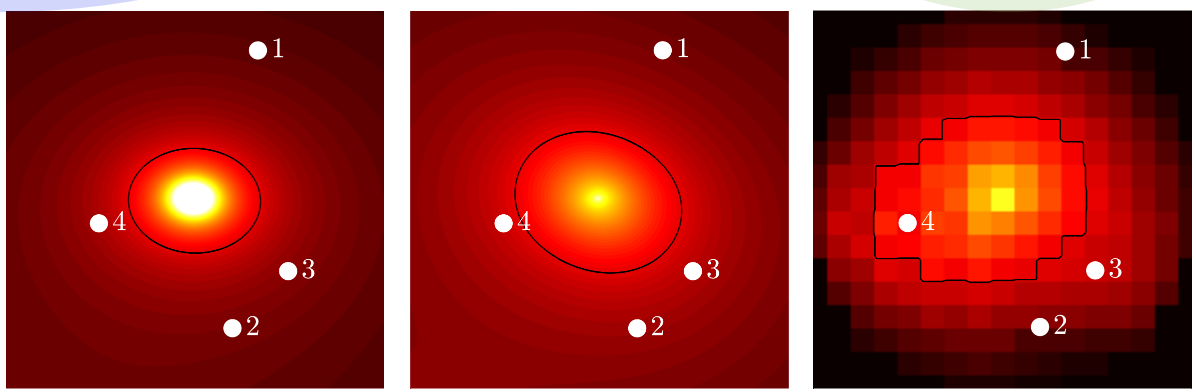
5-6 **9-15** **14-17** **~100** **# parameters**

parametric **free-form**

shape degeneracies

WFI 2033-4723



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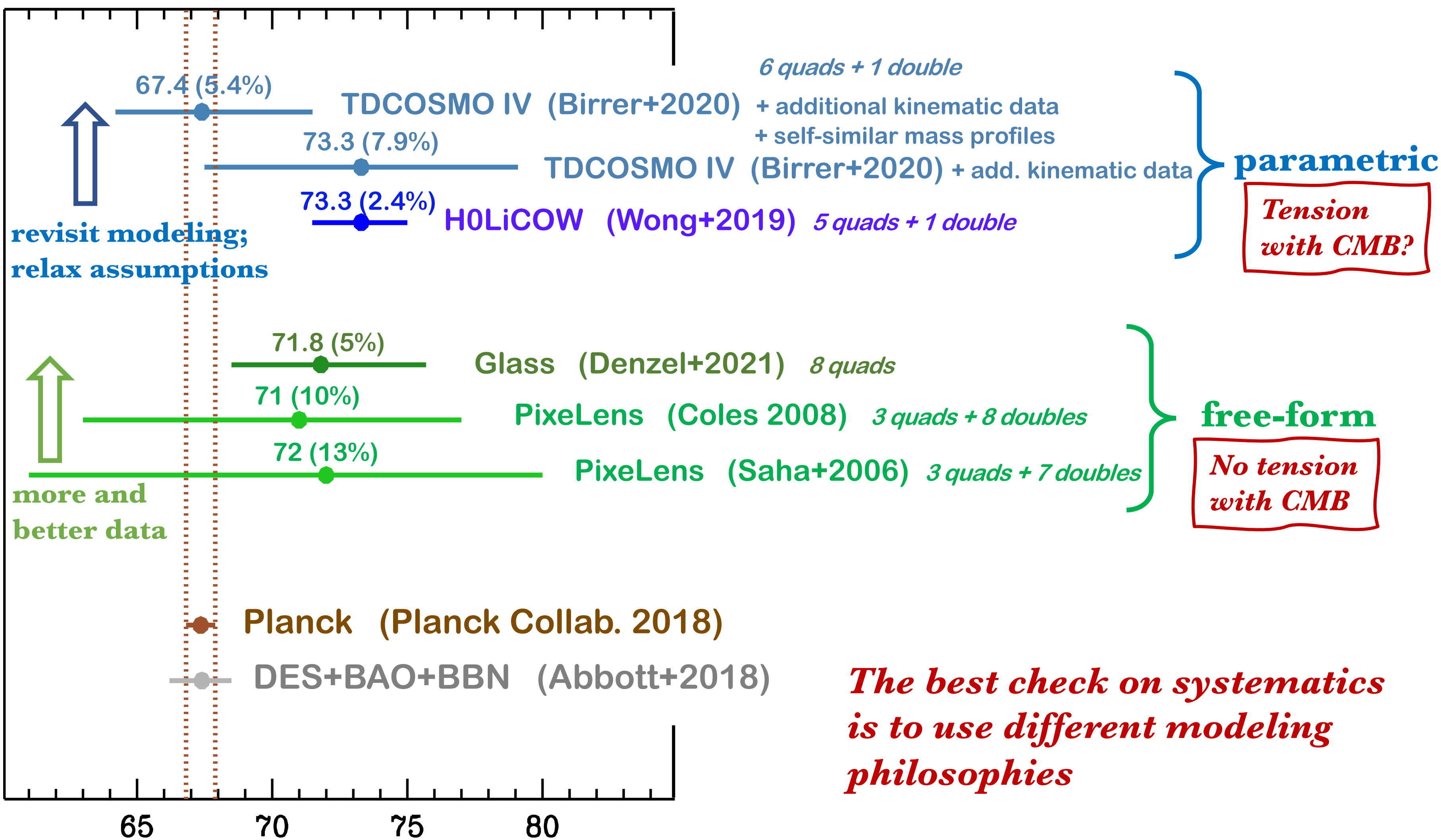
Results for H_0



The best check on systematics is to use different modeling philosophies

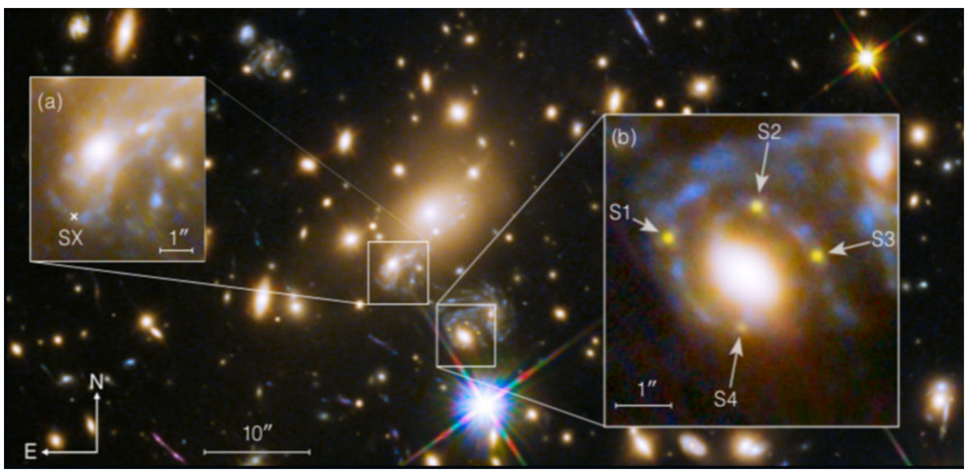
In the near future!

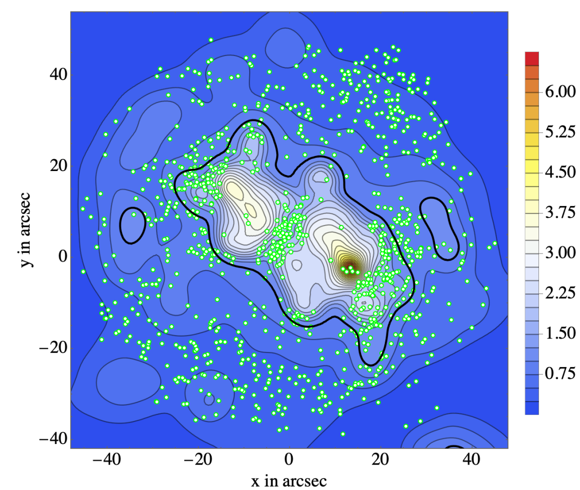
New variable sources: Multiply imaged supernova SN Ia, GRBs, fast radio bursts will make it easier to measure time delays & characterize lens galaxy. Type Ia Supernova will aide in breaking the mass sheet degeneracy.

Goobar+2017
Suyu+2018, 2020
Zitrin & Eichler 2018
Grillo+2018
Wagner+2019
Ding+2021
etc…

Cluster lenses: Mass distribution is more complicated, but clusters have more lensed images!

1% possible with 500-1000 images





5 images of supernova Refsdal

(Kelly+2015, 2016)

(Ghosh+2020)