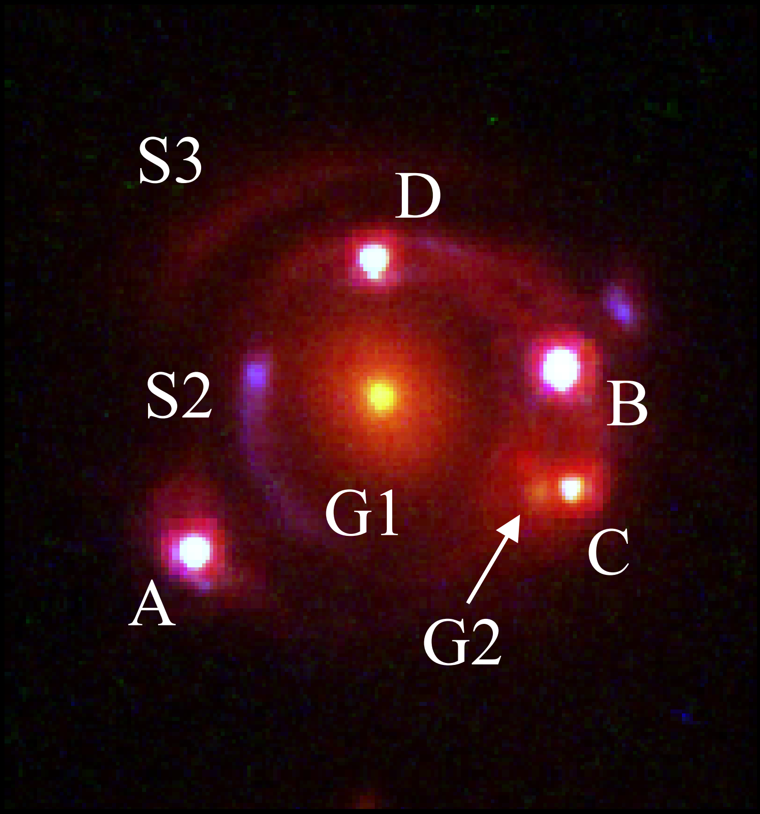
What's the universe made of? A strong gravitational lensing perspective

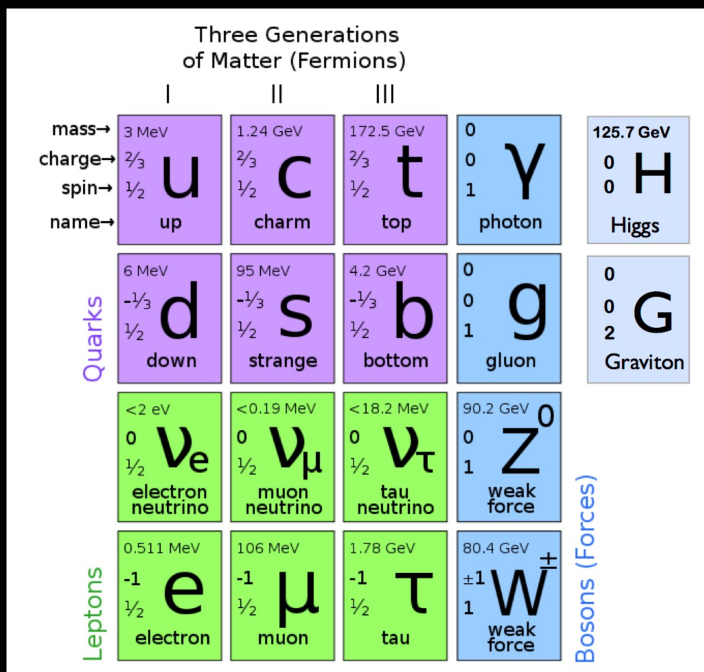


TOMMASO TREU
University of California Los Angeles

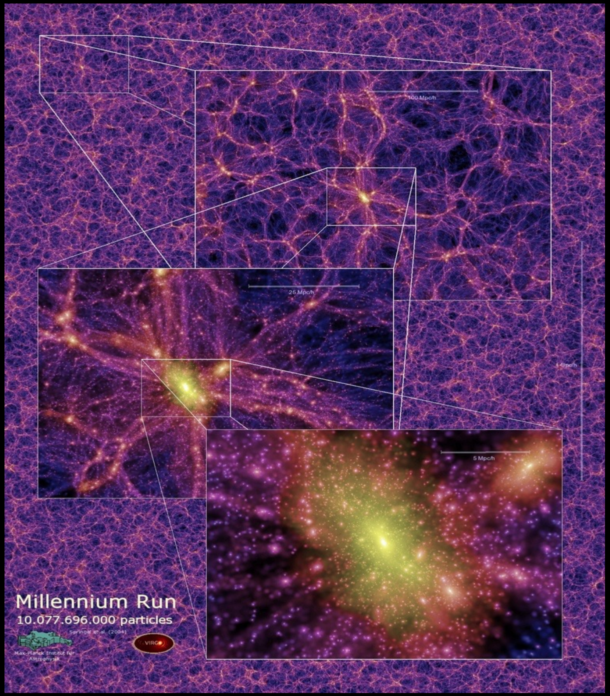
Outline

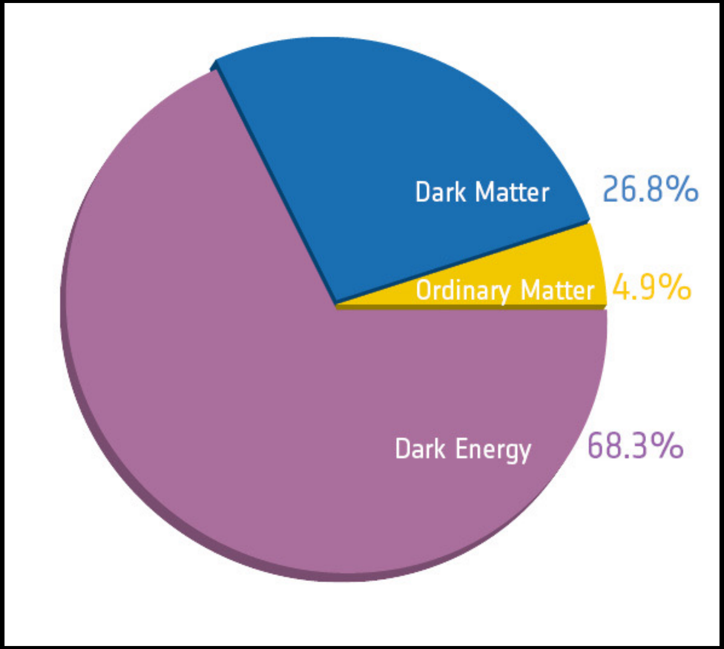
- Introduction.
  - The view from Earth
  - The view from space
- The expansion history of the universe
  - The Hubble tension
  - Time delay cosmography
- The nature of dark matter
  - Flux ratio anomalies
- Future outlook

The view from Earth: standard model of particle physics



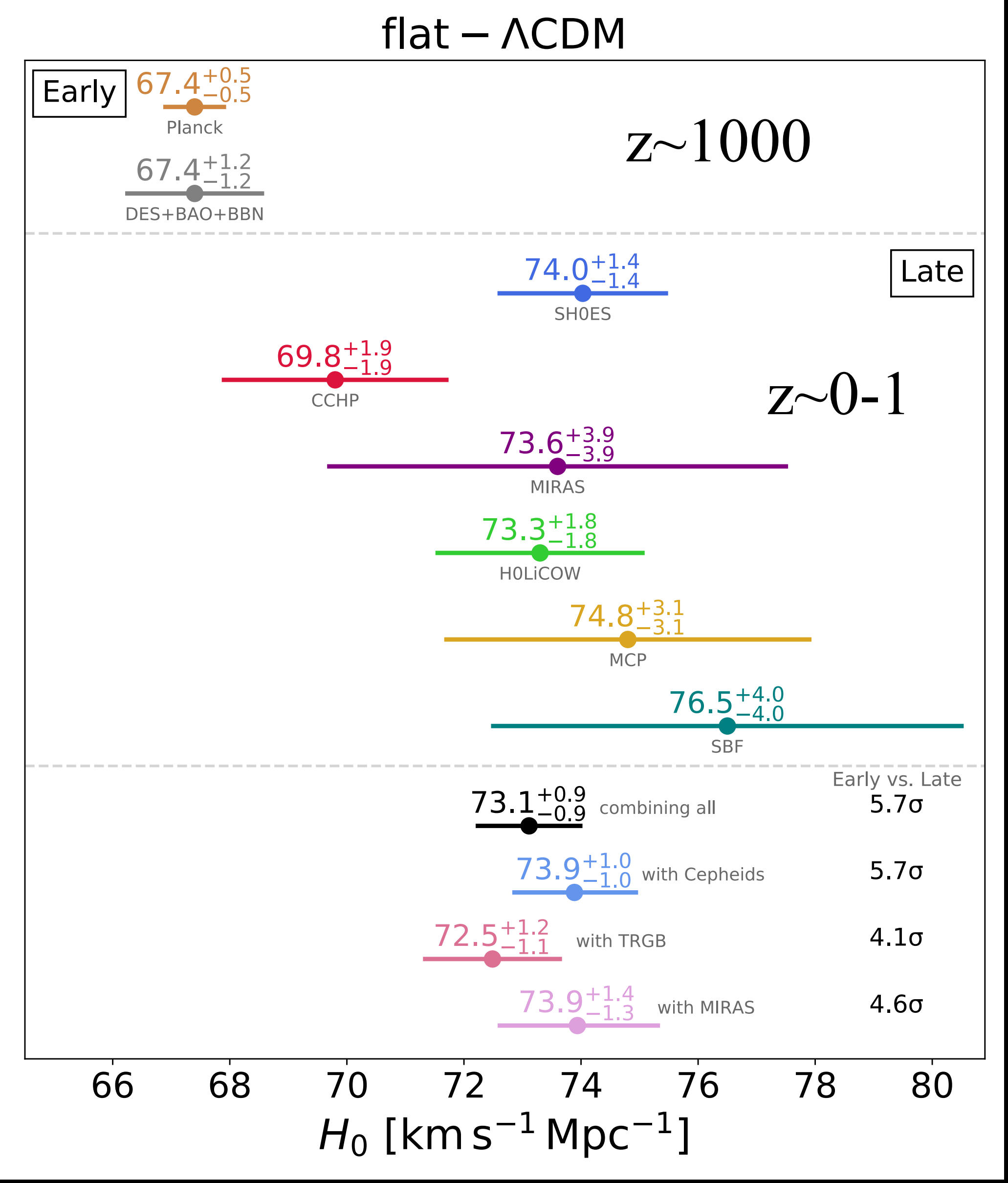
The Dark Universe





The expansion history of the universe

The H0 tension (2019)



Pre-recombination: >=2 independent methods

Dark matter/energy dominated era: 3-6 independent methods

Verde, Treu & Riess 2019

Why is this interesting?

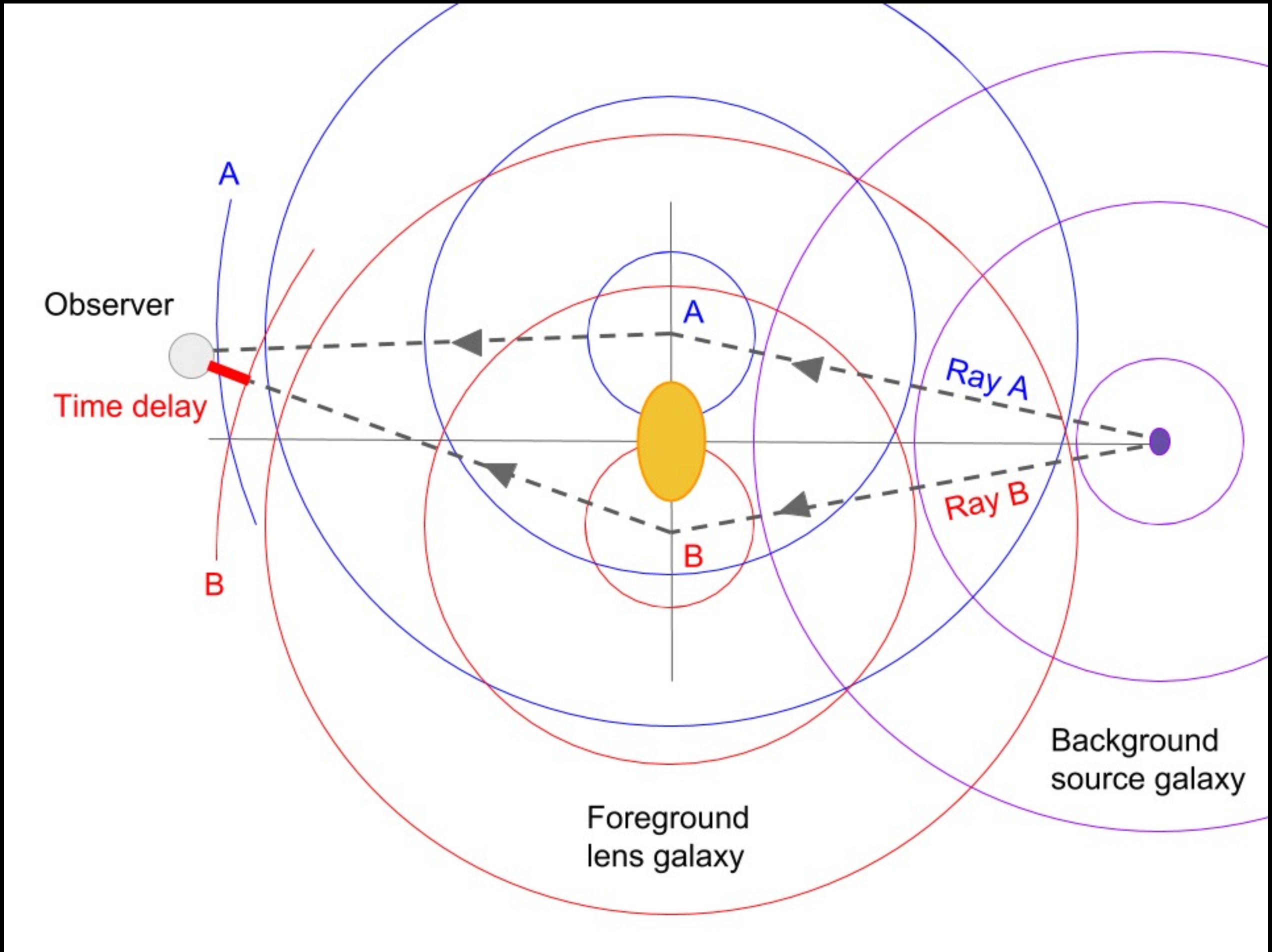
- Proves that LCDM is not a sufficient description of the universe
- Solutions have been proposed (e.g. early dark energy) but no clear idea has emerged that explains the tension away without breaking other constraints
- Little wiggle room to change expansion history after recombination, so focus is on pre-recombination physics
- Unless of course this is due to systematic errors in MULTIPLE MEASUREMENTS

Time delay cosmography

What is Gravitational Lensing?

Movie courtesy of Y. Hezaveh

Cosmography from time delays: how does it work?



Treu & Marshall 2016

Time delay distance in practice

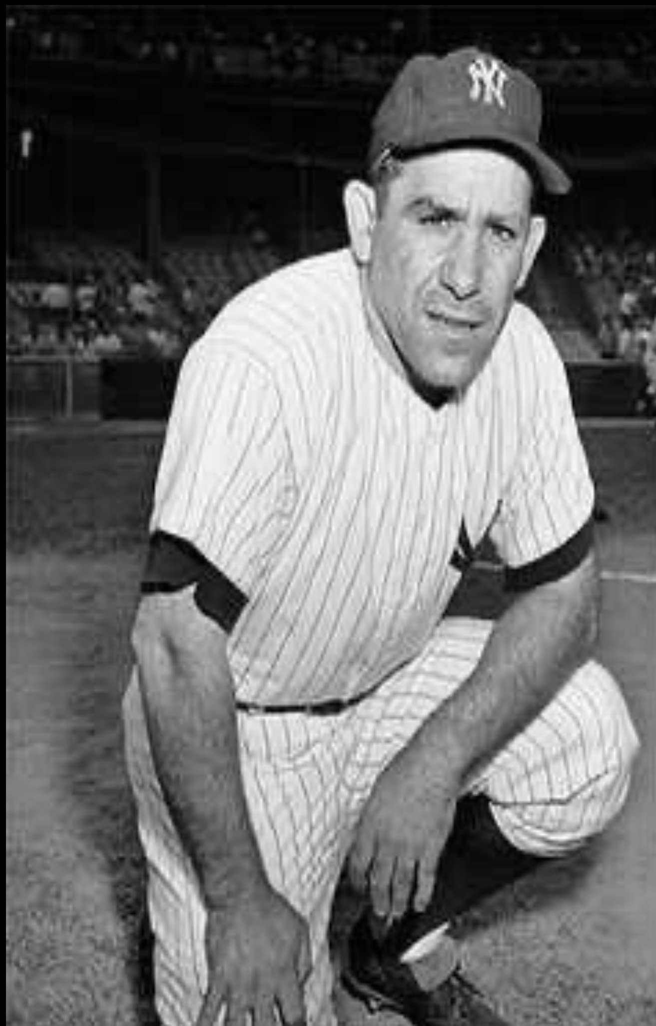
$$\Delta t \propto D_{\Delta t}(z_s, z_d) \propto H_0^{-1} f(\Omega_m, w, ...)$$

Steps:

- Measure the time-delay between two images
- Measure and model the potential
- Infer the time-delay distance
- Convert it into cosmlogical parameters

A brief history of time delay cosmography

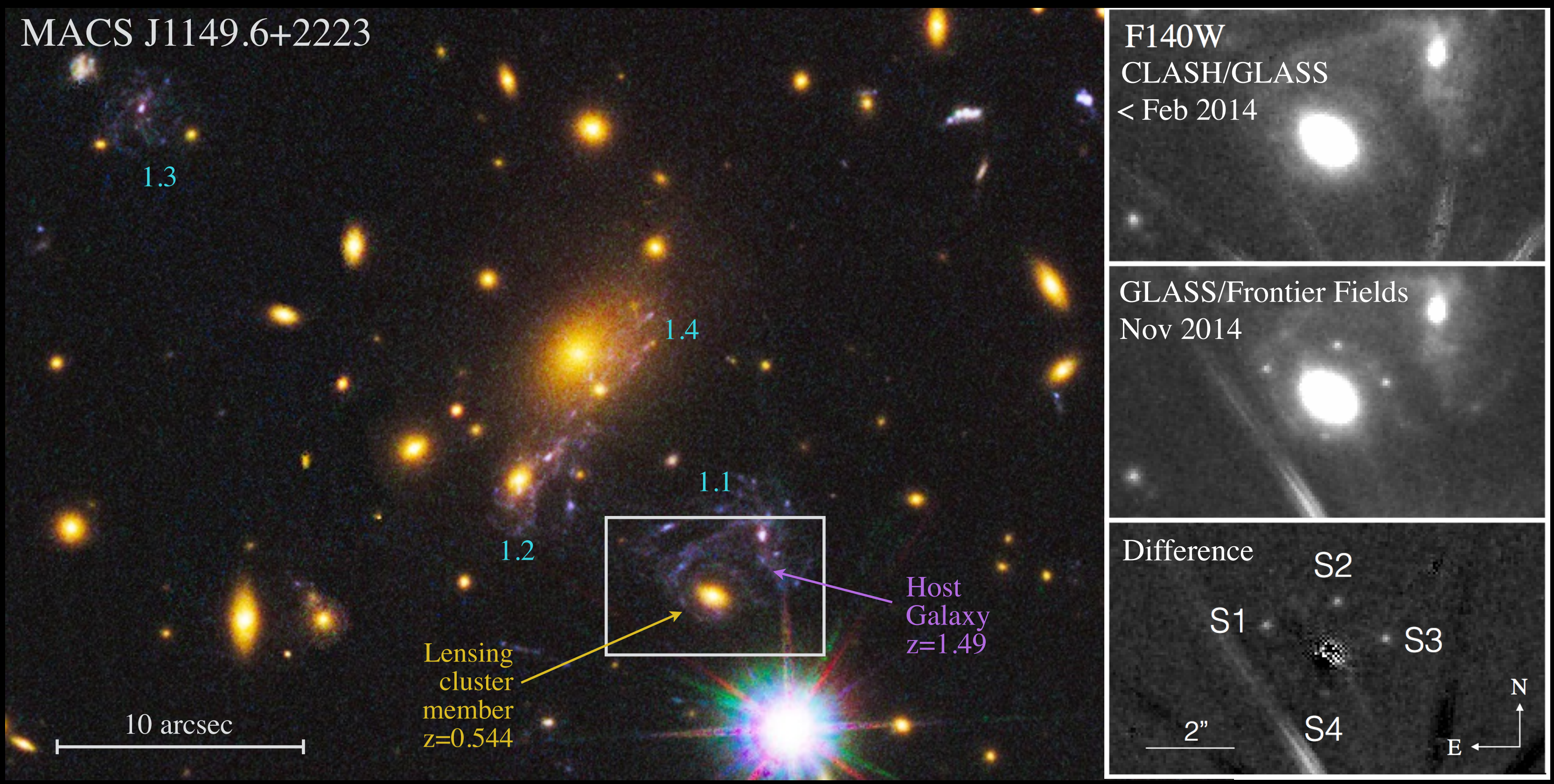
- 1964 Method proposed
- 70s First lenses discovered
- 80s First time delay measured
  - Controversy. Solution: improve sampling
- 90s First Hubble Constant measured
  - Controversy. Solution: improve mass models
- 2000s: modern monitoring (COSMOGRAIL, Fassnacht & others); stellar kinematics (Treu & Koopmans 2002); extended sources
- 2010s Putting it all together: precision measurements (6-7% from a single lens)
- 2014 first multiply imaged supernova discovered (50^{th} anniversary of Refsdal's paper)



"In theory there is no difference between theory and practice. In practice there is."

Yogi Berra

A real life example

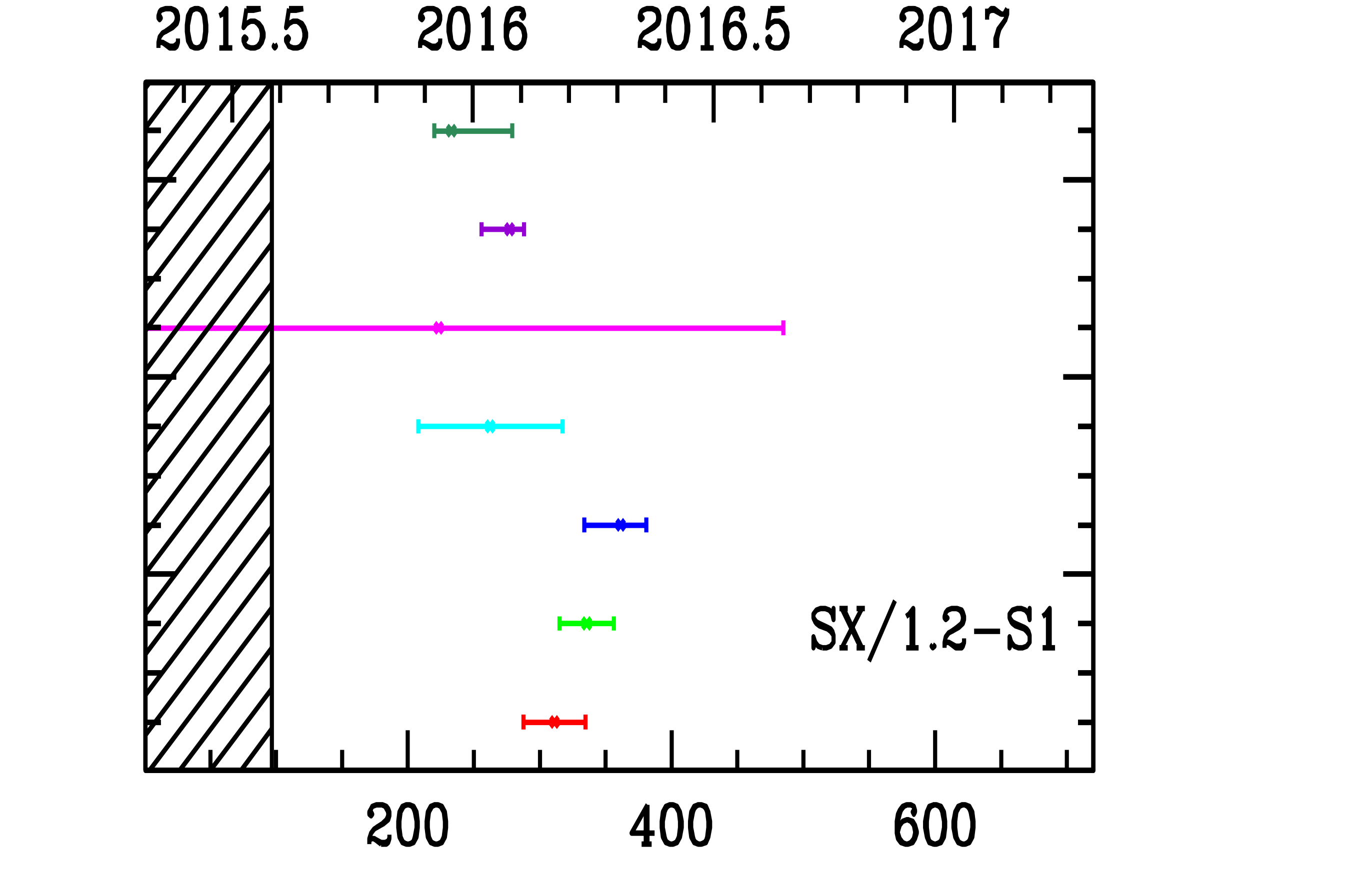


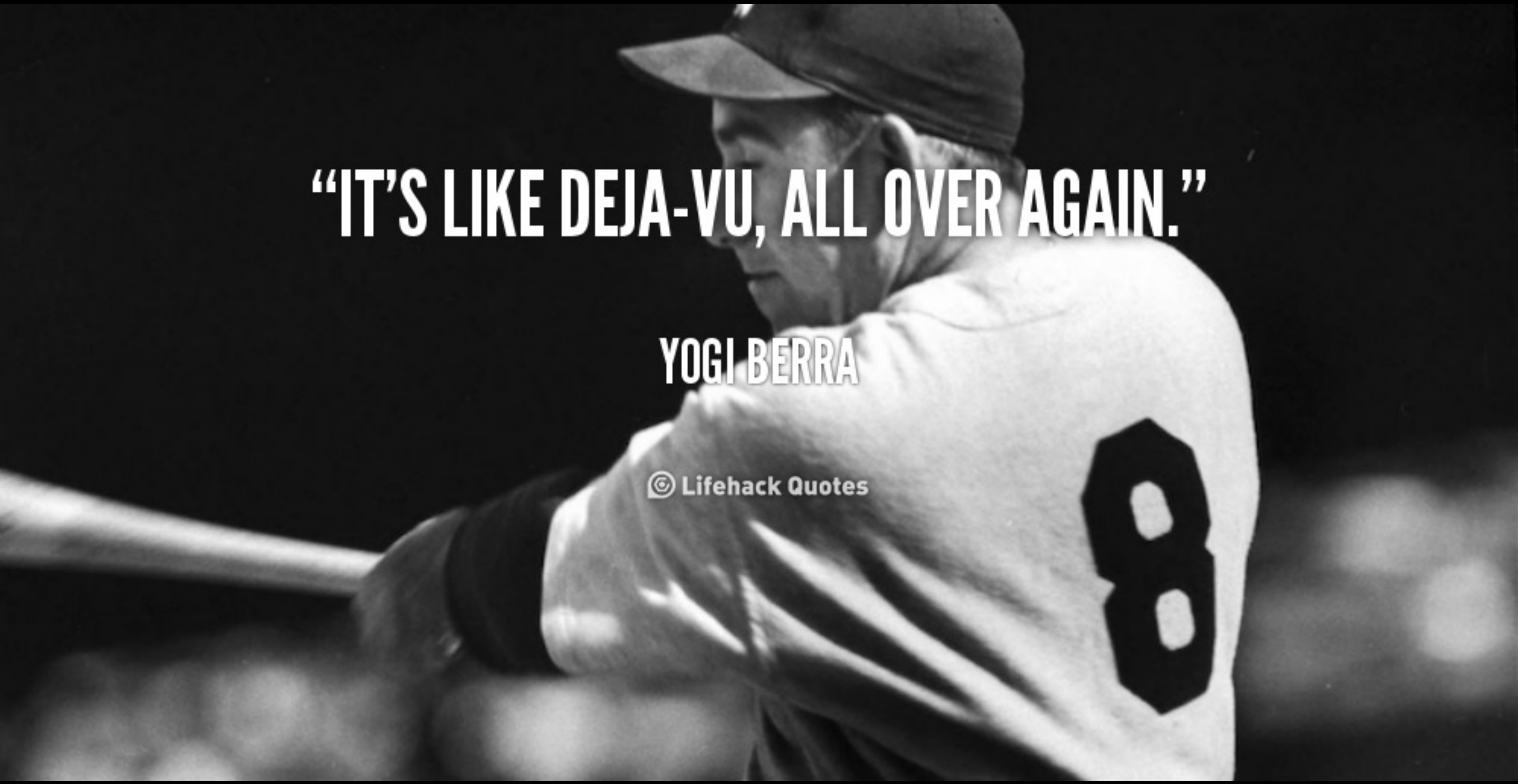
Kelly, Rodney, Treu et al. 2015

"REFSDAL" MEETS POPPER: COMPARING PREDICTIONS OF THE RE-APPEARANCE OF THE MULTIPLY IMAGED SUPERNOVA BEHIND MACSJ1149.5+2223

T. Treu[1,28], G. Brammer[2], J. M. Diego[3], C. Grillo[4], P. L. Kelly[5], M. Oguri[6,7,8], S. A. Rodney[9,10,29], P. Rosati[11], K. Sharon[12], A. Zitrin[13,29], I. Balestra[14], M. Bradač[15], T. Broadhurst[16,17], G. B. Caminha[11], A. Halkola, A. Hoag[15], M. Ishigaki[7,18], T. L. Johnson[12], W. Karman[19], R. Kawamata[20], A. Mercurio[21], K. B. Schmidt[22], L.-G. Strolger[2,23], S. H. Suyu[24], A. V. Filippenko[5], R. J. Foley[25,26], S. W. Jha[27], and B. Patel[27]

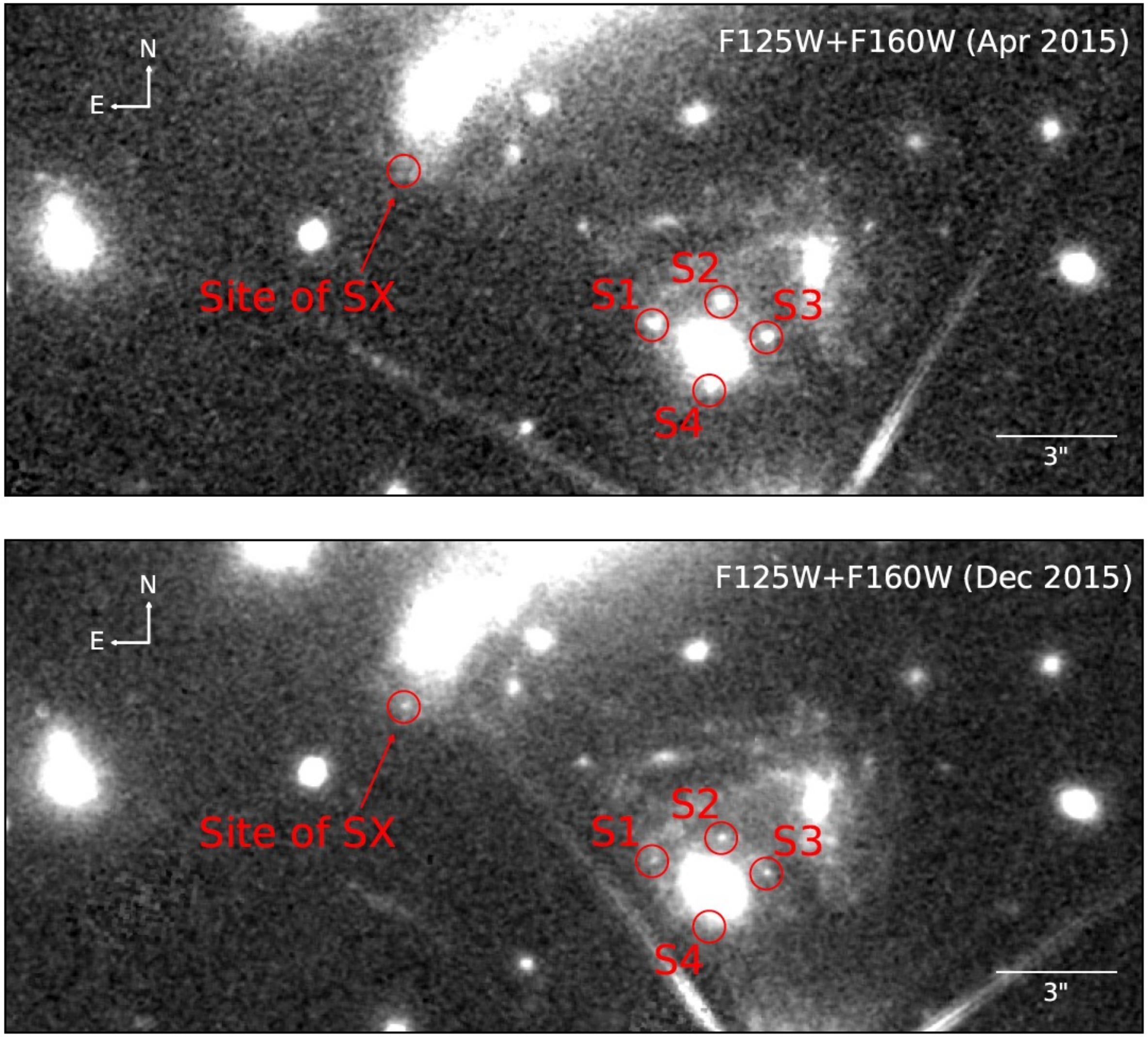
Received 2015 October 19; accepted 2015 November 24; published 2016 January 20




"IT'S LIKE DEJA-VU, ALL OVER AGAIN."
YOGI BERRA
Lifehack Quotes

DÉJÀ VU ALL OVER AGAIN: THE REAPPEARANCE OF SUPERNOVA REFSDAL

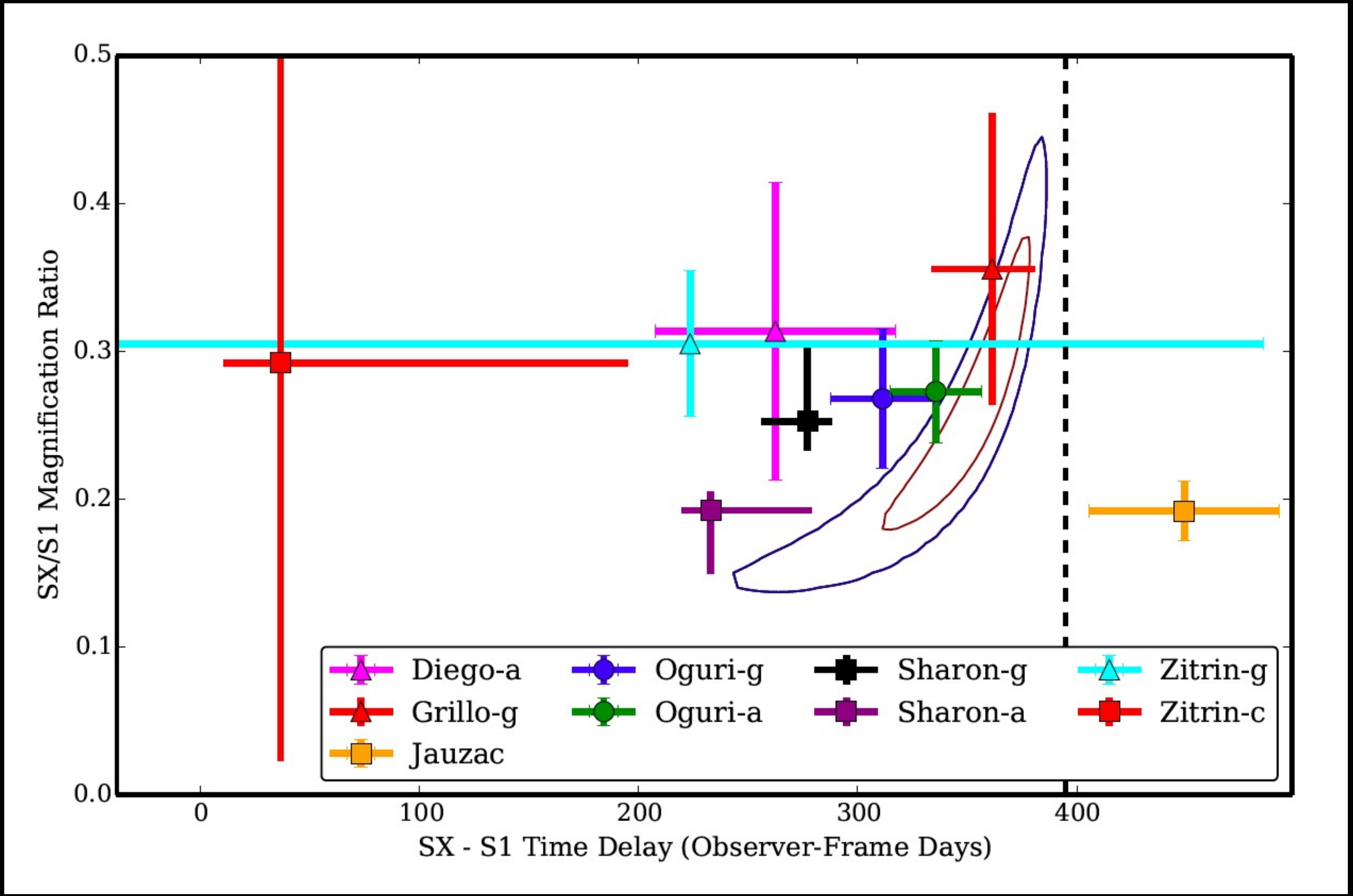
P. L. Kelly[1], S. A. Rodney[2], T. Treu[3,4], L.-G. Strolger[5], R. J. Foley[6,7], S. W. Jha[8], J. Selsing[9], G. Brammer[5], M. Bradač[10], S. B. Cenko[11,12], O. Graur[13,14], A. V. Filippenko[1], J. Hjorth[9], C. McCully[15,16], A. Molino[17,18], M. Nonino[19], A. G. Riess[20,5], K. B. Schmidt[16,21], B. Tucker[22], A. von der Linden[23], B. J. Weiner[24], and A. Zitrin[25,26]



DÉJÀ VU ALL OVER AGAIN: THE REAPPEARANCE OF SUPERNOVA REFSDAL

P. L. Kelly[1], S. A. Rodney[2], T. Treu[3,4], L.-G. Strolger[5], R. J. Foley[6,7], S. W. Jha[8], J. Selsing[9], G. Brammer[5], M. Bradač[10], S. B. Cenko[11,12], O. Graur[13,14], A. V. Filippenko[1], J. Hjorth[9], C. McCully[15,16], A. Molino[17,18], M. Nonino[19], A. G. Riess[20,5], K. B. Schmidt[16,21], B. Tucker[22], A. von der Linden[23], B. J. Weiner[24], and A. Zitrin[25,26]

Draft version 2015/12/16



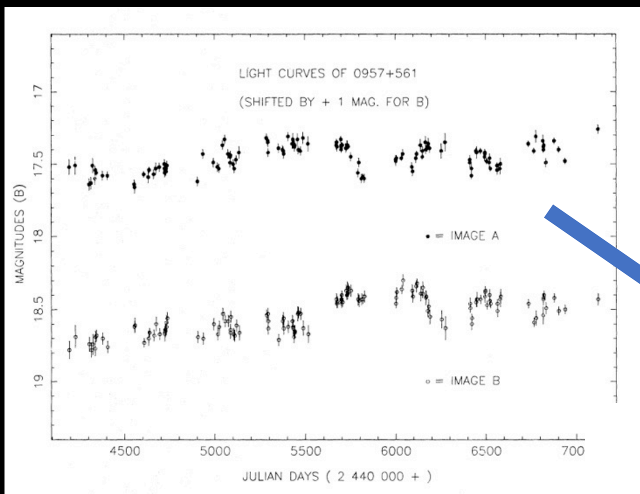
H0 measurement from Refsdal is almost done!

Modern time delay cosmography

Cosmography with strong lenses: the 4 problems solved

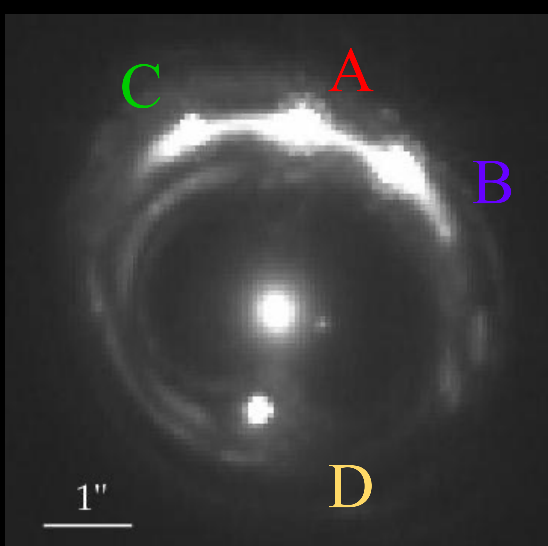
- Time delay – 2-3 %
  - Tenacious monitoring (e.g. Fassnacht et al. 2002); COSMOGRAIL (Meylan/Courbin)
- Astrometry – 10-20 mas
  - Hubble/VLA/(Adaptive Optics?)
- Lens potential (2-3%)
  - Stellar kinematics/Extended sources (Treu & Koopmans 2002; Suyu et al. 2009)
- Structure along the line of sight (2-3%)
  - Galaxy counts and numerical simulations (Suyu et al. 2010)
  - Stellar kinematics (Koopmans et al. 2003)

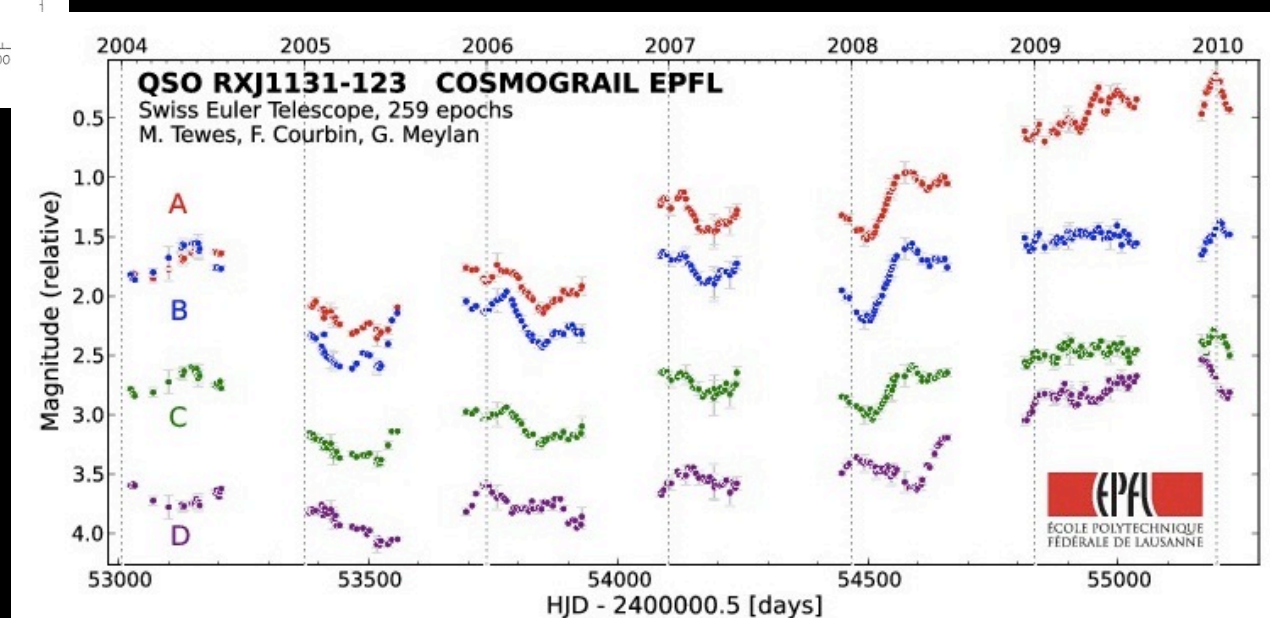
Cosmography with strong lenses: measuring time delays



Vanderriest et al. 1989

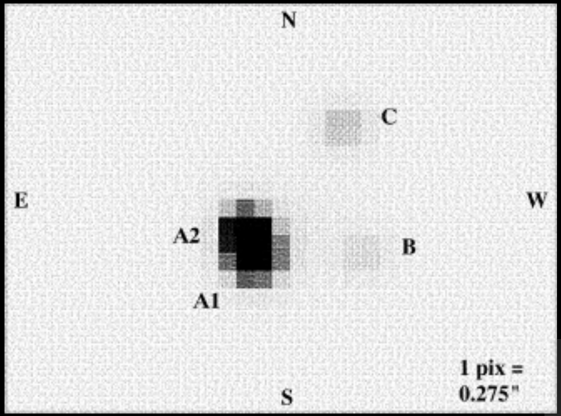
COSMOGRAIL: better data & better techniques



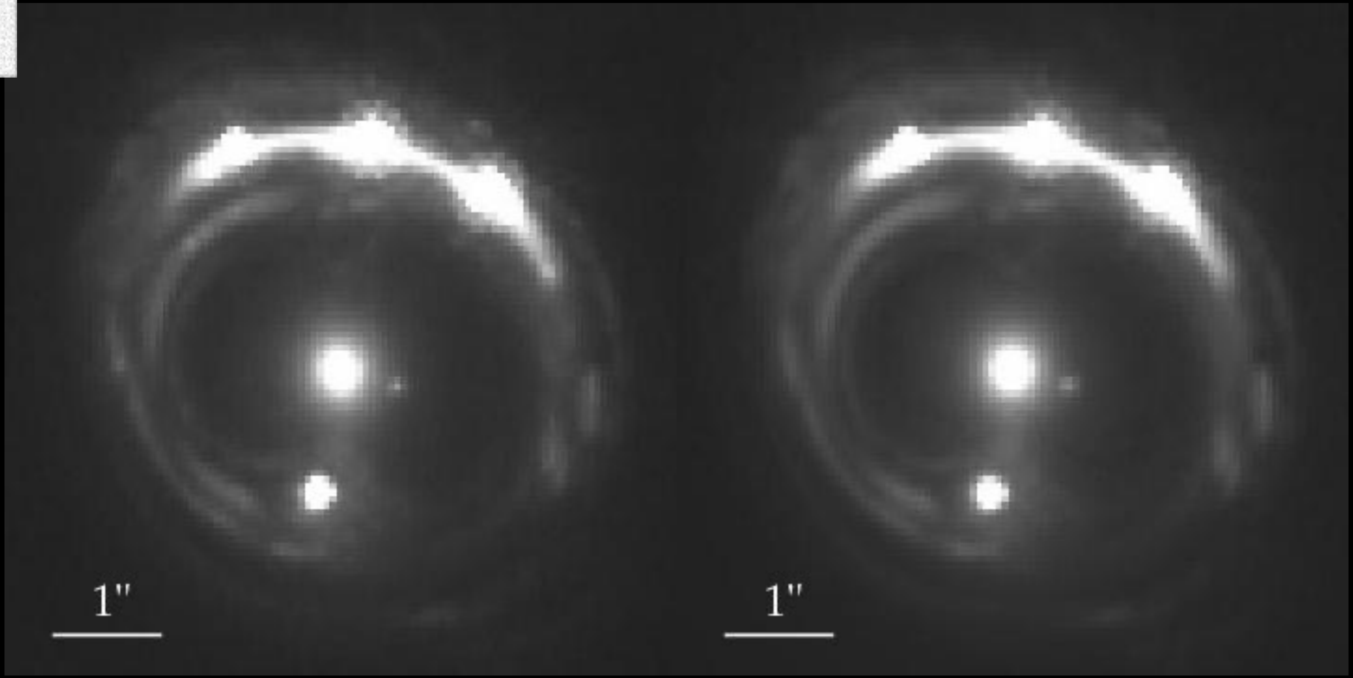


Cosmography with strong lenses: measuring the lens potential

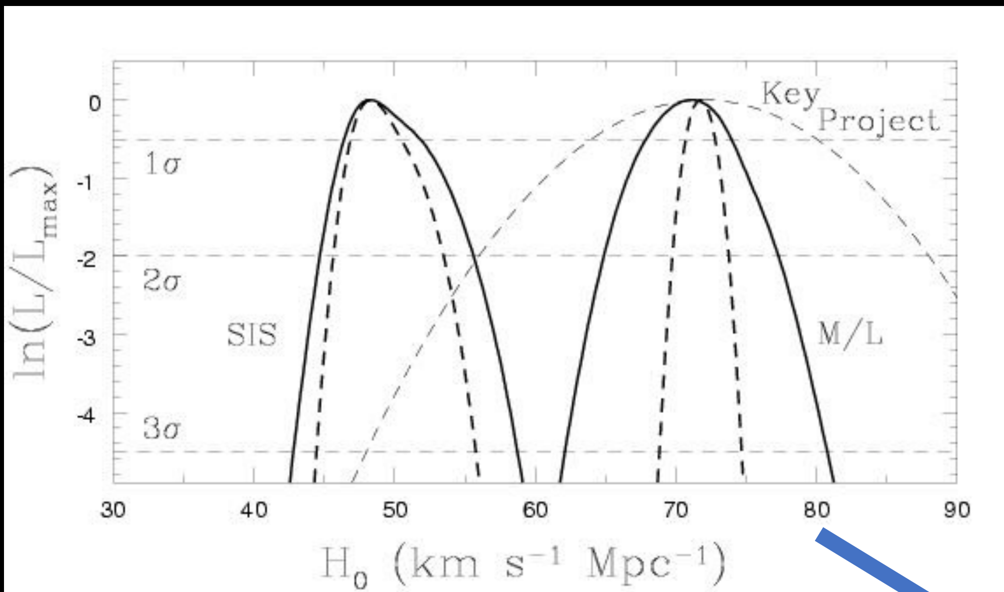
Schechter et al. 1997

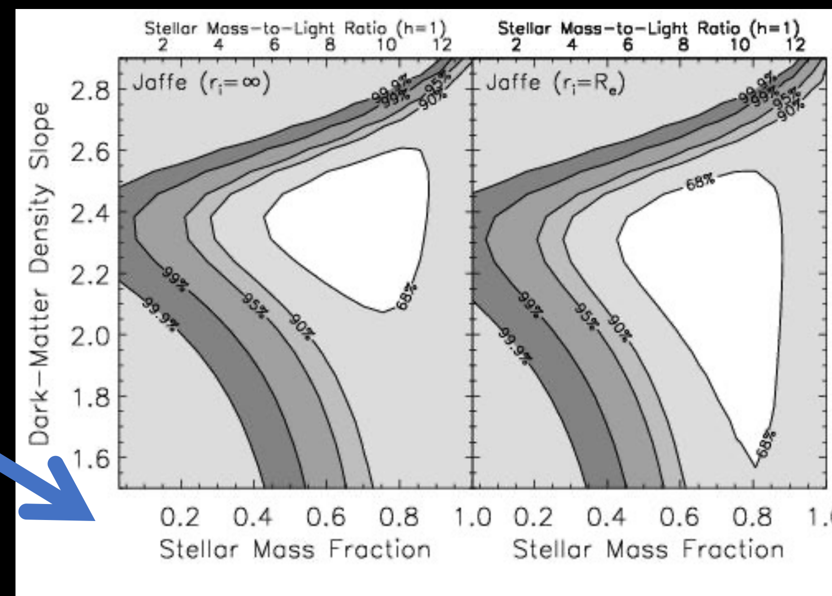


Host galaxy reconstruction; Suyu et al. 2012



Cosmography with strong lenses: measuring the lens potential

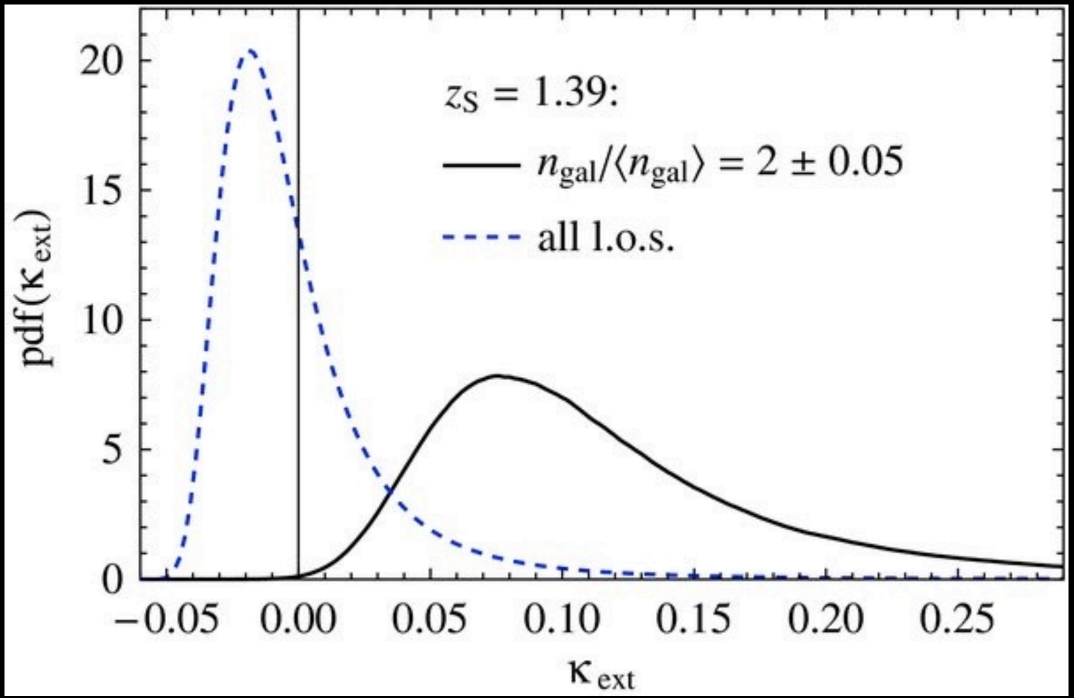




Stellar kinematics: Treu & Koopmans 2002

Cosmography with strong lenses: Structure along the line of sight

???

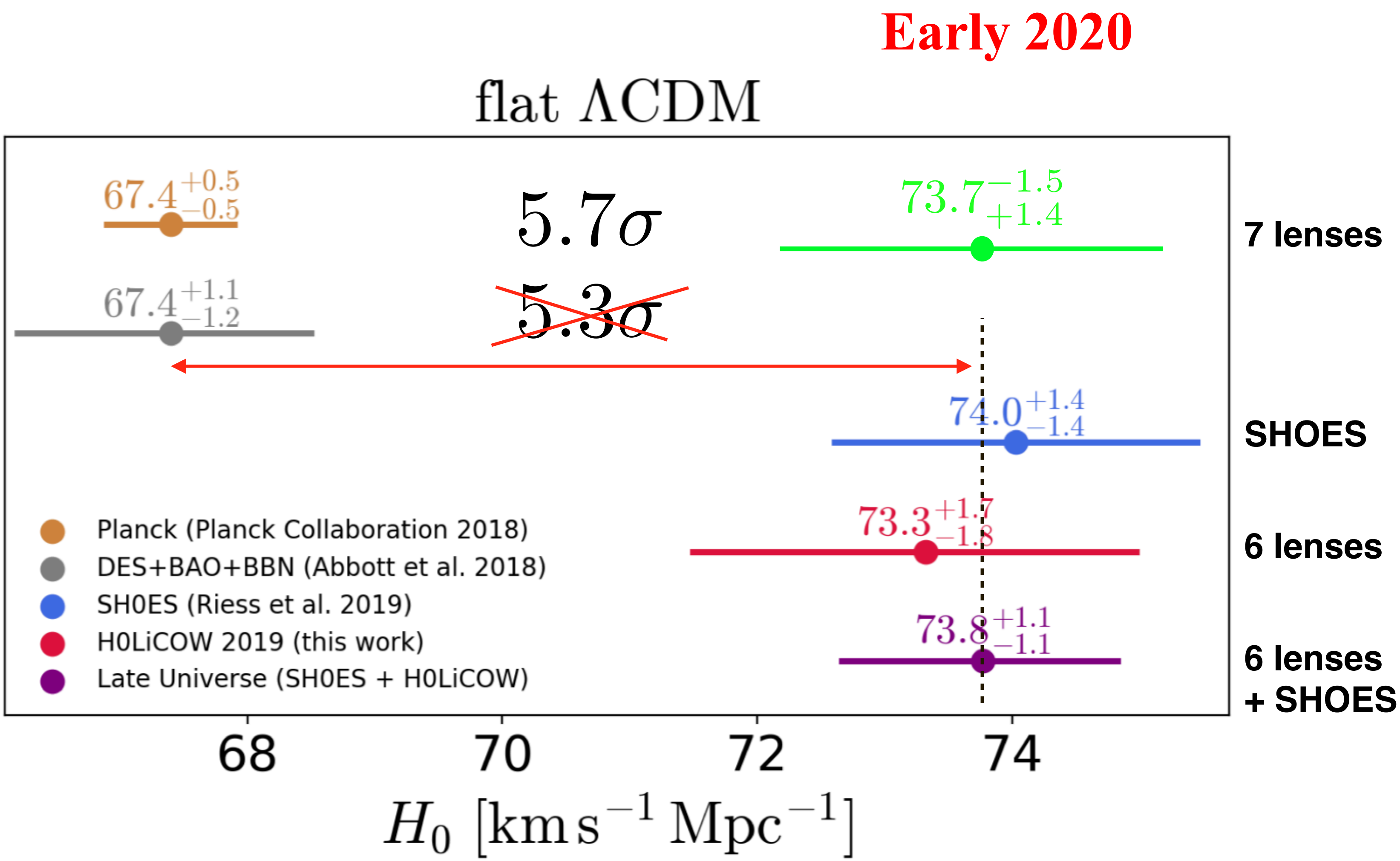


Suyu et al. 2010

Methodology - Blindness

- Blinding is the most effective way to avoid experimenter bias and discover unknown unknowns
- Refsdal is a rare example of a true blind test in astronomy
- “Blindness” can be achieved for example via software, by removing the average of the posterior pdf during the measurement and only revealing the average/peak just prior to publication.
    - Unblinded results are published without correction.

Cosmology Results for 7 Lenses in flat lambda-CMD



Now combining SHOES with 7 lenses

Revisiting assumptions

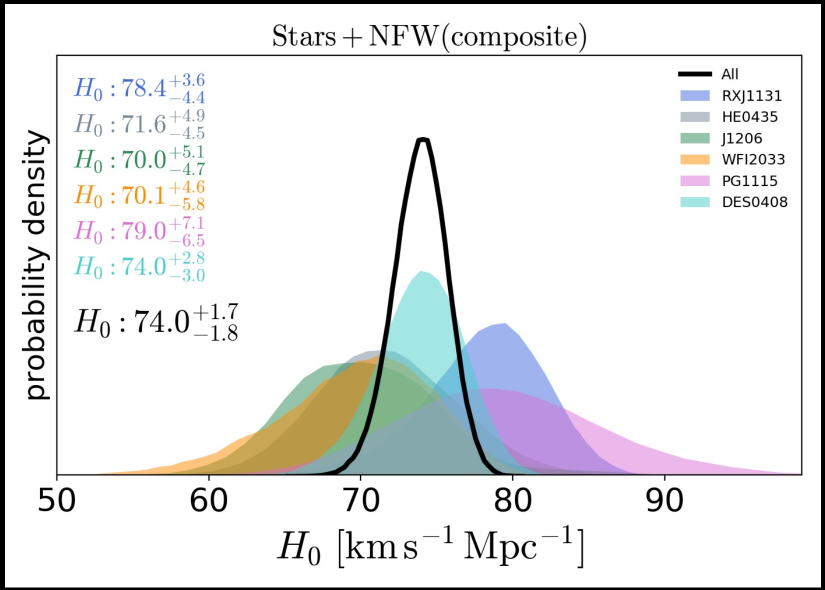
Mass profile assumption

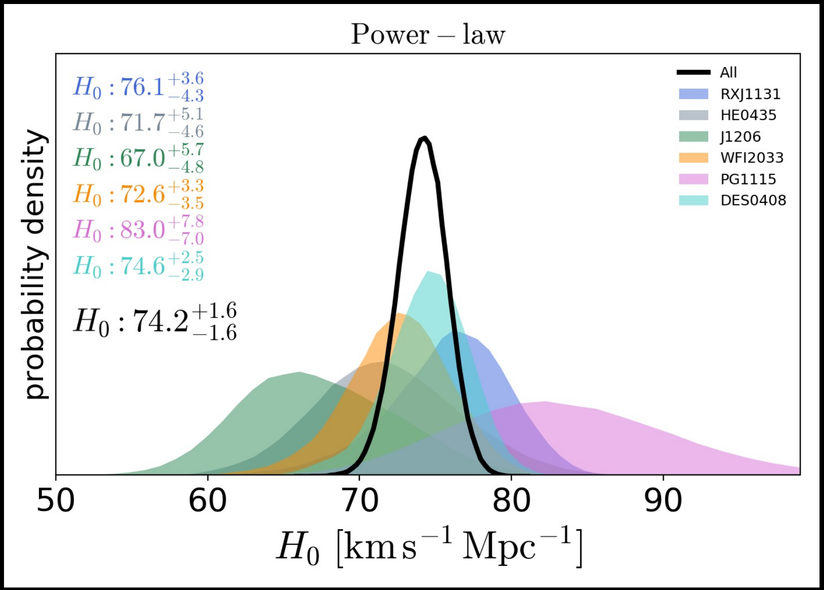
- Power law or stars (M/L) + NFW
- Assumptions consistent with observations (X-ray, dynamics, lensing, statellites) and theory (numerical simulations)

Stellar kinematics: "The resulting total density profiles were found well described by a nearly-isothermal power law $\rho_{tot}(r)\propto r^{-\gamma}$ from $R_e/10$ to at least $4R_e$ (Cappellari 2016)”

X-RAY: “We show that the conspiracy between the baryonic (Sersic) and dark matter (Navarro–Frenk–White/Einasto) components required to maintain a power-law *total* mass distribution naturally predicts an anti-correlation between a and R_e that is very close to what is observed.” (Humphrey & Buote 2010)

Mass profile assumption





Millon et al. 2020

Relaxing Assumptions

Time Delay Cosmography (TDCOSMO) – H_0 determination

No assumption on the radial mass density profile of the lens galaxy

Galaxies are described by power law/stars+NFW mass profile

$73.3^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1}
H0LiCOW

$74.0^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1}
TDCOSMO (NFW + stars/constant M/L)

$74.2^{+1.6}_{-1.6}$ km s^{-1} Mpc^{-1}
TDCOSMO (power-law)

Assuming SLACS lenses and TDCOSMO lenses share the same anisotropy property

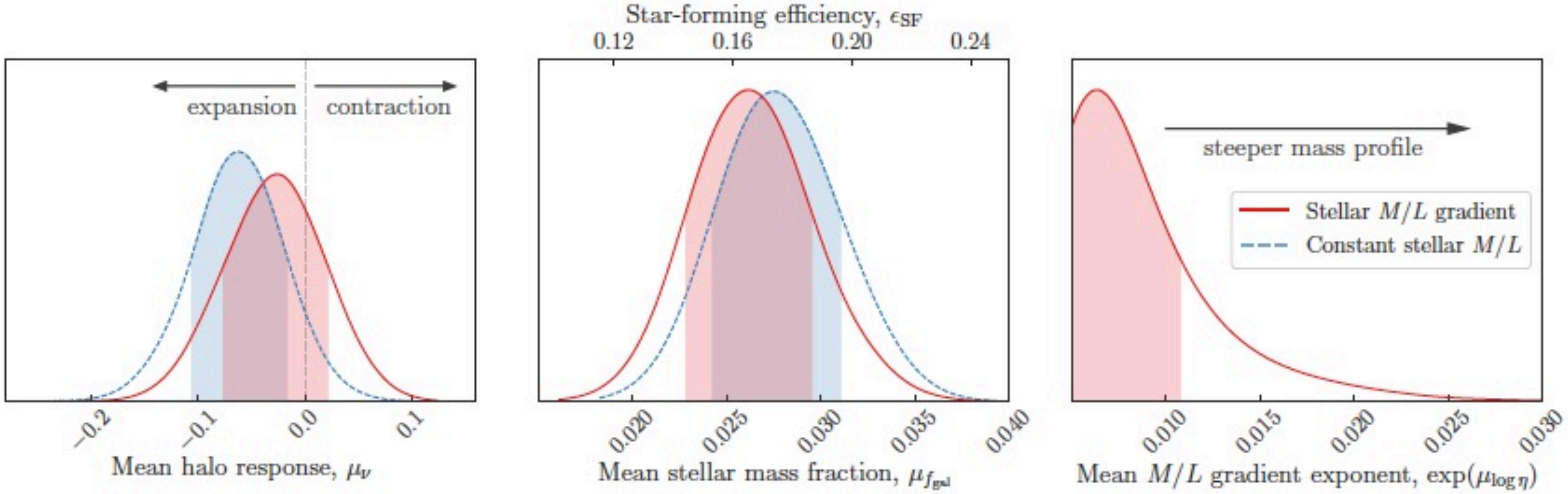
$73.3^{+5.8}_{-5.8}$ km s^{-1} Mpc^{-1}
TDCOSMO+SLACS$_{IFU}$ (anisotropy constraints from 9 SLACS lenses)

Assuming SLACS lenses and TDCOSMO lenses share the same anisotropy and radial mass density property

$67.4^{+4.1}_{-3.2}$ km s^{-1} Mpc^{-1}
TDCOSMO+SLACS$_{SDSS+IFU}$ (anisotropy and profile constraints from SLACS)

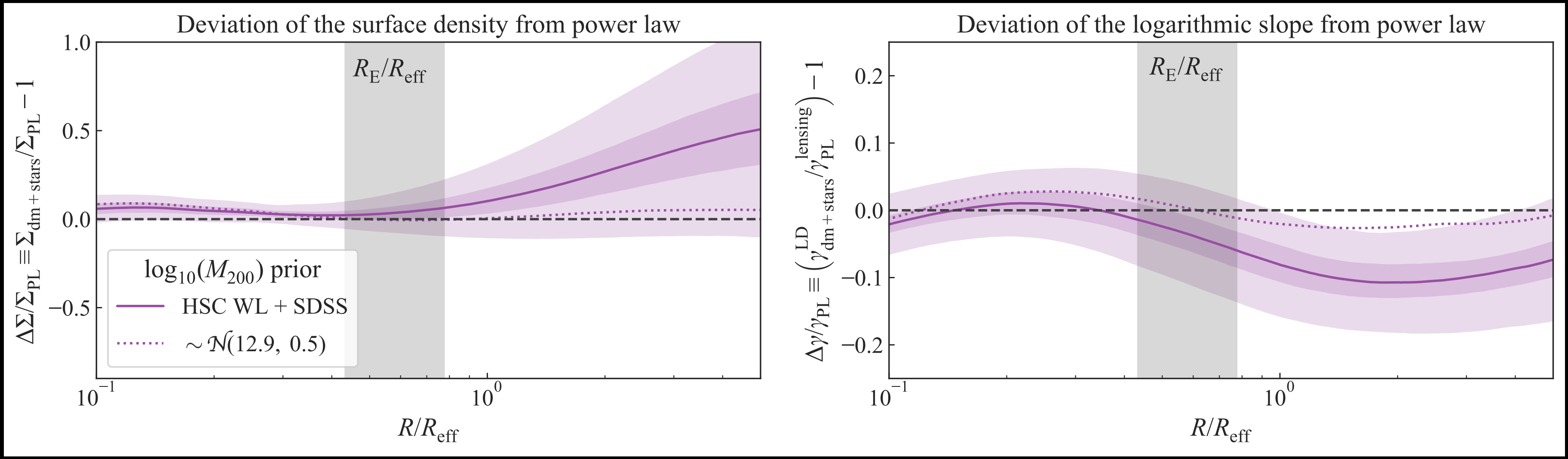
Birrer et al. 2020
Millon et al. 2020
Shajib et al. 2020
Wong et al. 2020
Chen et al. 2019

Generalizing



Shajib, TT et al. 2021

Total mass density profile



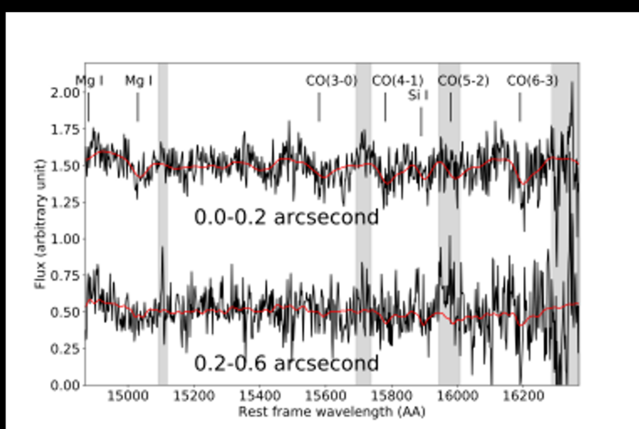
Very similar to power law (close to isothermal)
But with current data wiggles cannot be ruled out

Shajib, TT et al. 2021

A general way forward

Current scenario	resolution	$\delta\sigma_\star/\sigma_\star$	FWHM	R_{spec}/R_{eff}	N_{bin}	δH_0	+50 δH_0	+50IFU δH_0
7 TDCOSMO-5%	unresolved	5%	0.″8	-	1	8.5%	7.0%	2.7%
7 TDCOSMO+O-IFU	resolved	5%	0.″8	2	3	4.7%	2.9%	2.6%
7 TDCOSMO+AO-IFU	resolved	5%	0.″1	1	10	4.7%	3.0%	2.5%
7 TDCOSMO+JWST-IFU	resolved	3%	0.″1	2	10	3.5%	2.6%	2.6%
Future scenario							+200 δH_0	+200IFU δH_0
40 TDCOSMO-5%	unresolved	5%	0.″8	-	1	7.3%	7.1%	1.2%
40 TDCOSMO+O-IFU	resolved	5%	0.″8	2	3	2.0%	1.3%	1.2%
40 TDCOSMO+AO-IFU	resolved	5%	0.″1	1	10	2.0%	1.4%	1.2%
40 TDCOSMO+ELT-IFU	resolved	3%	0.″02	3	30	1.5%	1.2%	1.2%

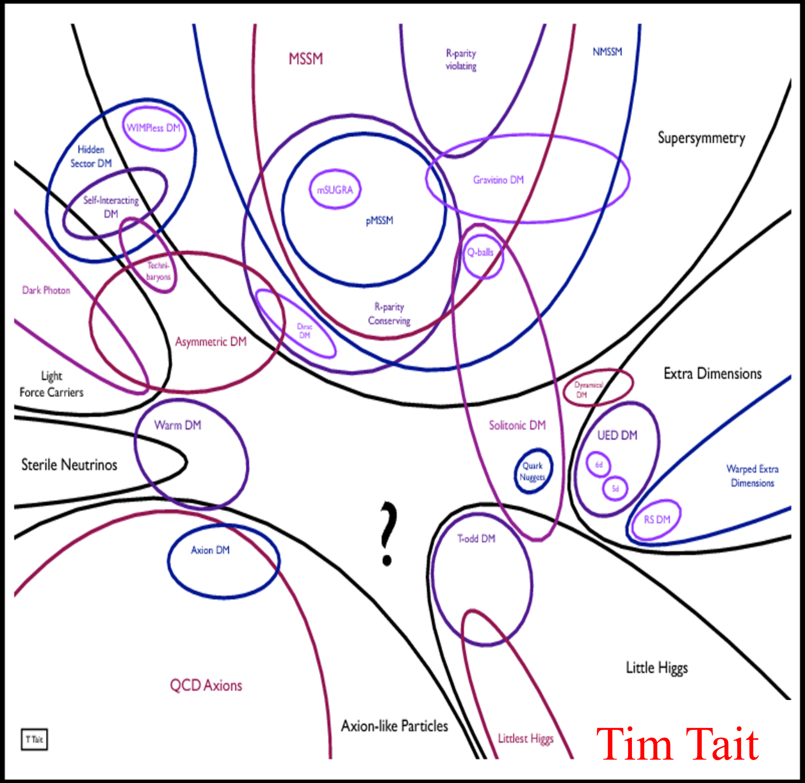
Birrer & Treu 2021



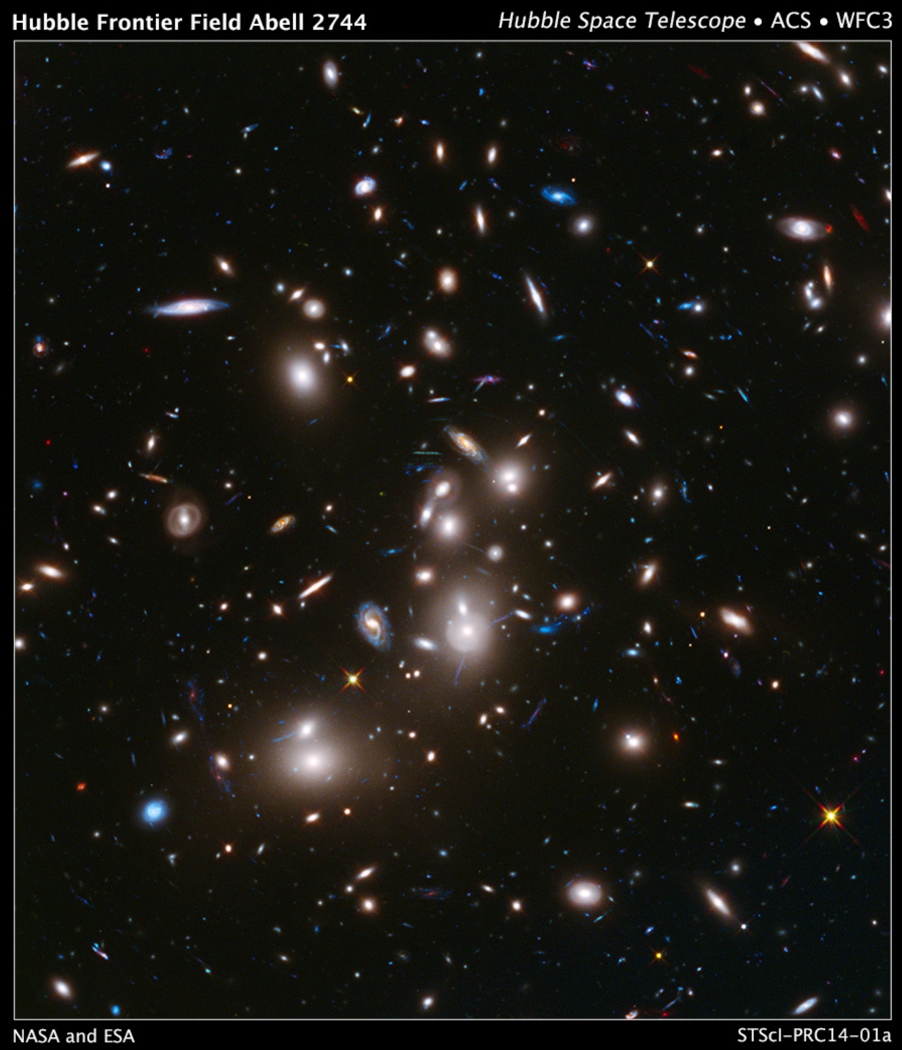
Incredibly hard for Keck+OSIRIS!!
(Shajib et al. 2021)
Need JWST (approved cycle1!) or better AO

What’s dark matter?

A theorist's view

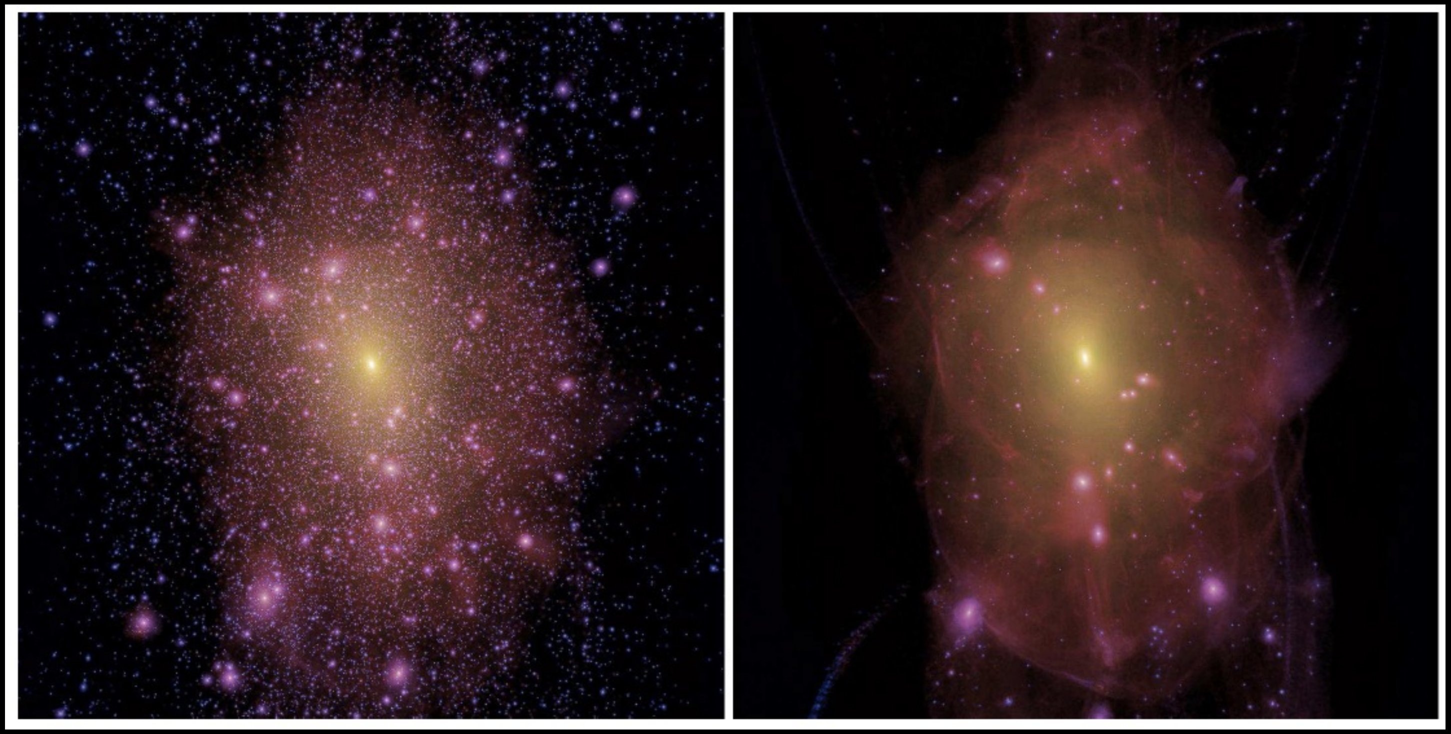


An observer's view



Satellites as a probe of The NATURE OF DARK MATTER

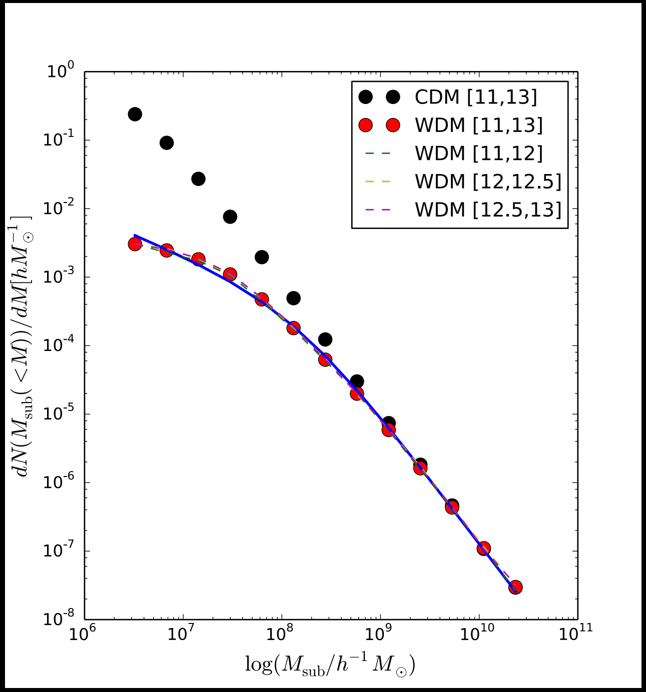
Warm Dark Matter



Free streaming ~kev scale thermal relic

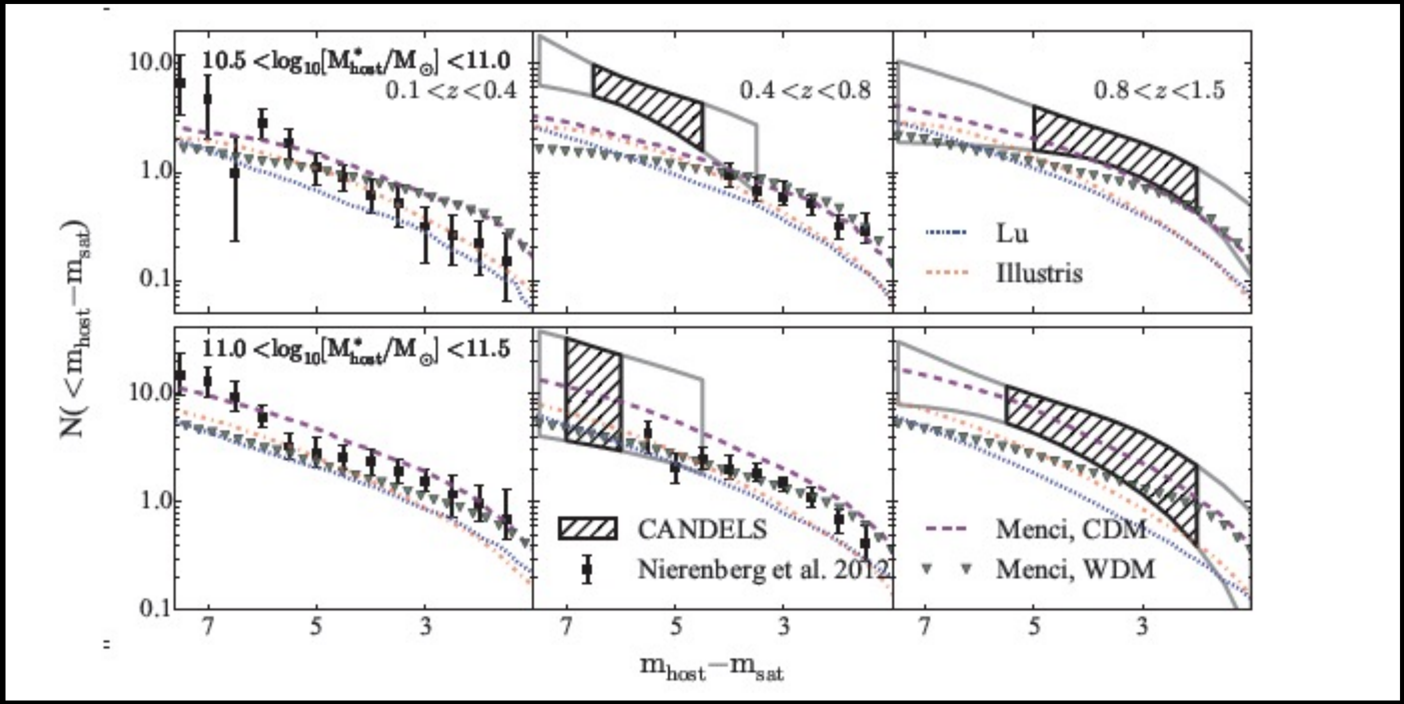
Lovell et al. 2014

Dark satellites in CDM vs WDM



Li et al. 2016; Nierenberg et al. 2013

Luminous Satellites in CDM vs WDM



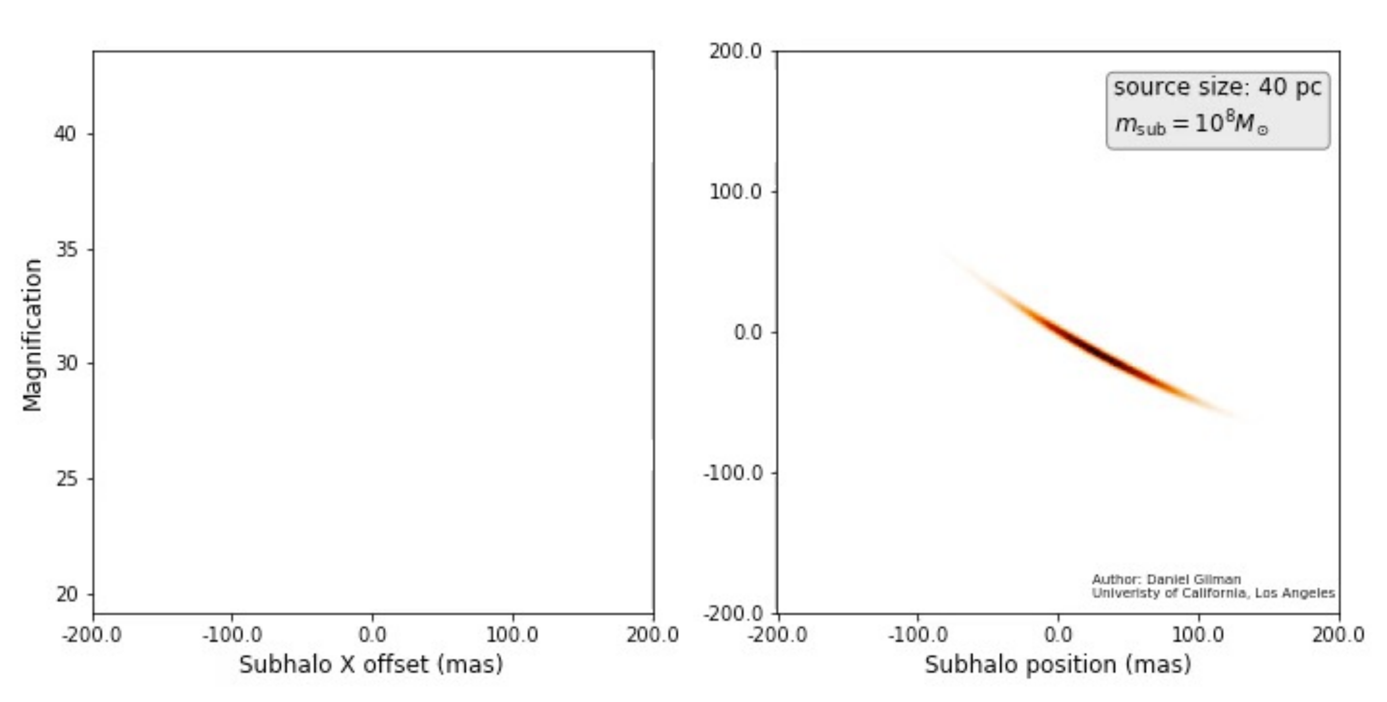
Nierenberg, Treu, Menci et al. 2016

“Missing satellites” and lensing

- Strong lensing can detect satellites based solely on mass!
- Satellites are detected as “anomalies” in the gravitational potential ψ and its derivatives
  - ψ'' = Flux anomalies
  - ψ' = Astrometric anomalies
  - ψ = Time-delay anomalies

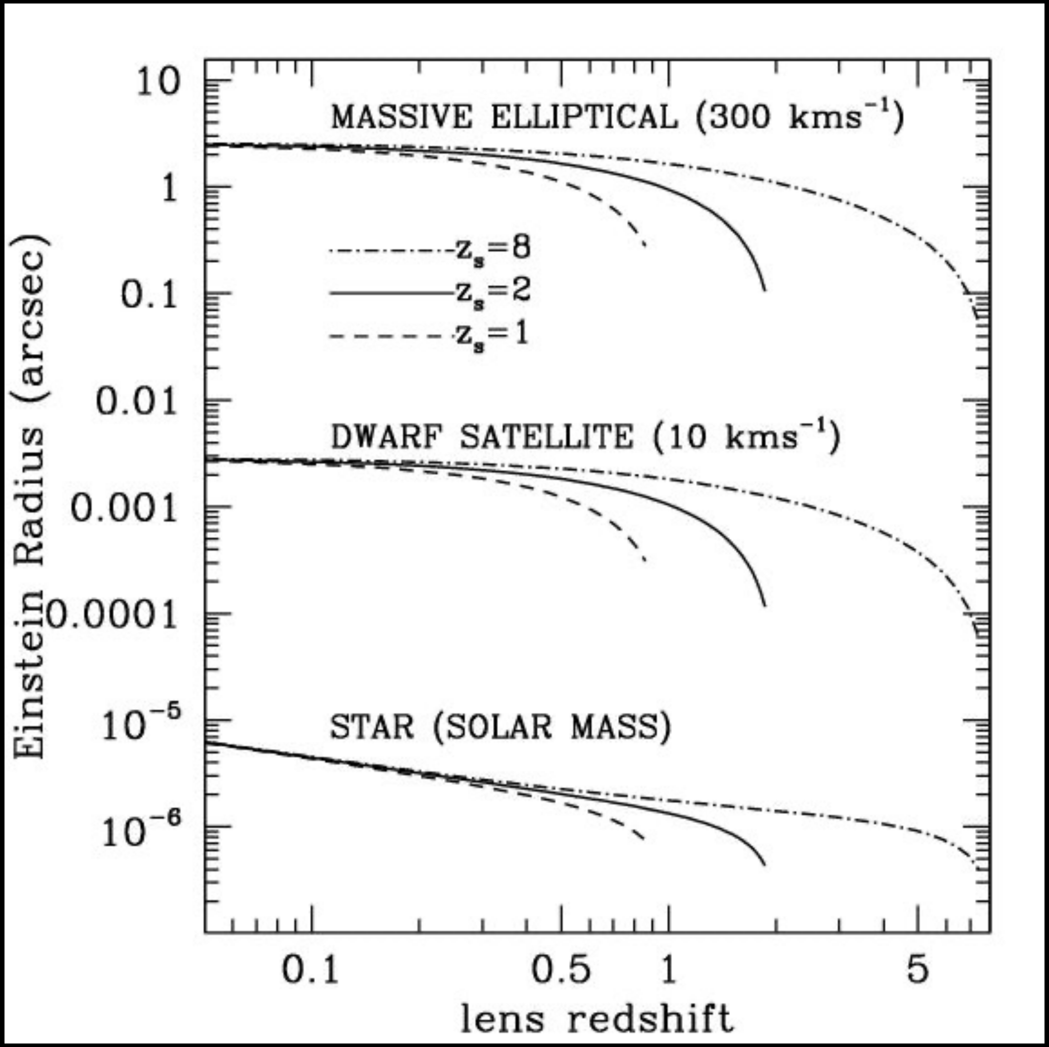
– **Natural scale is a few milliarcseconds. Astrometric perturbations of 10mas are expected**

“Missing satellites” and lensing



Courtesy of D.Gilman

“Missing satellites” and lensing



Treu 2010

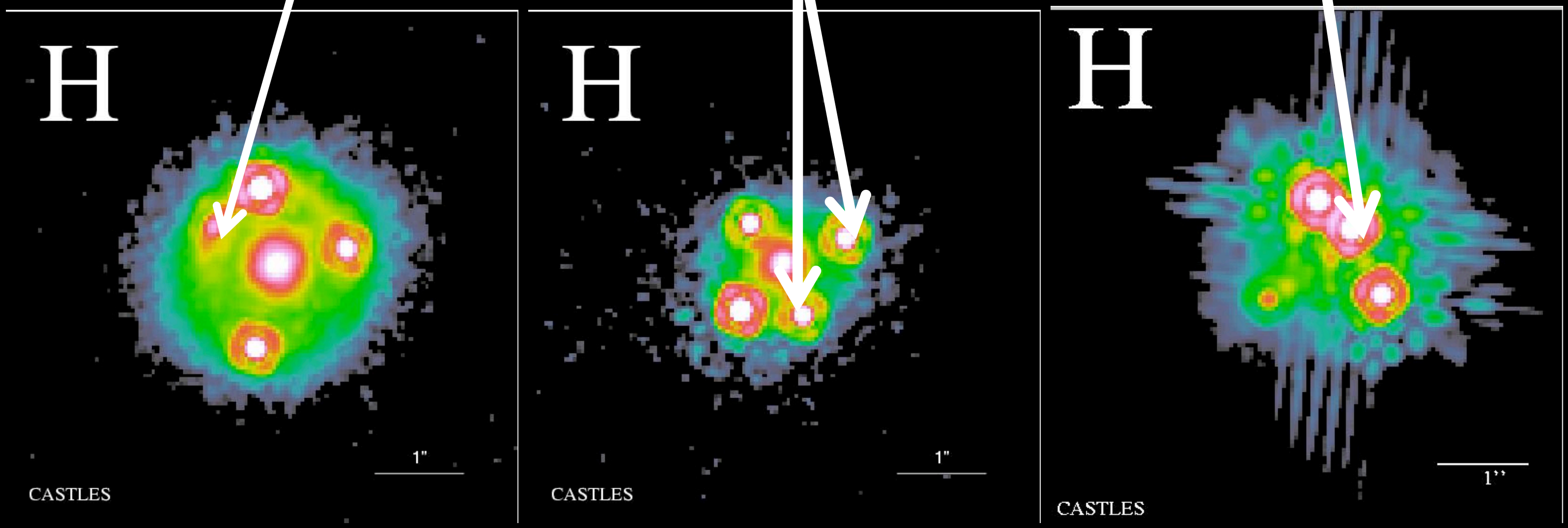
Flux Ratio Anomalies

A smooth mass distribution would predict:

This to be 100x brighter

These to be 2x brighter

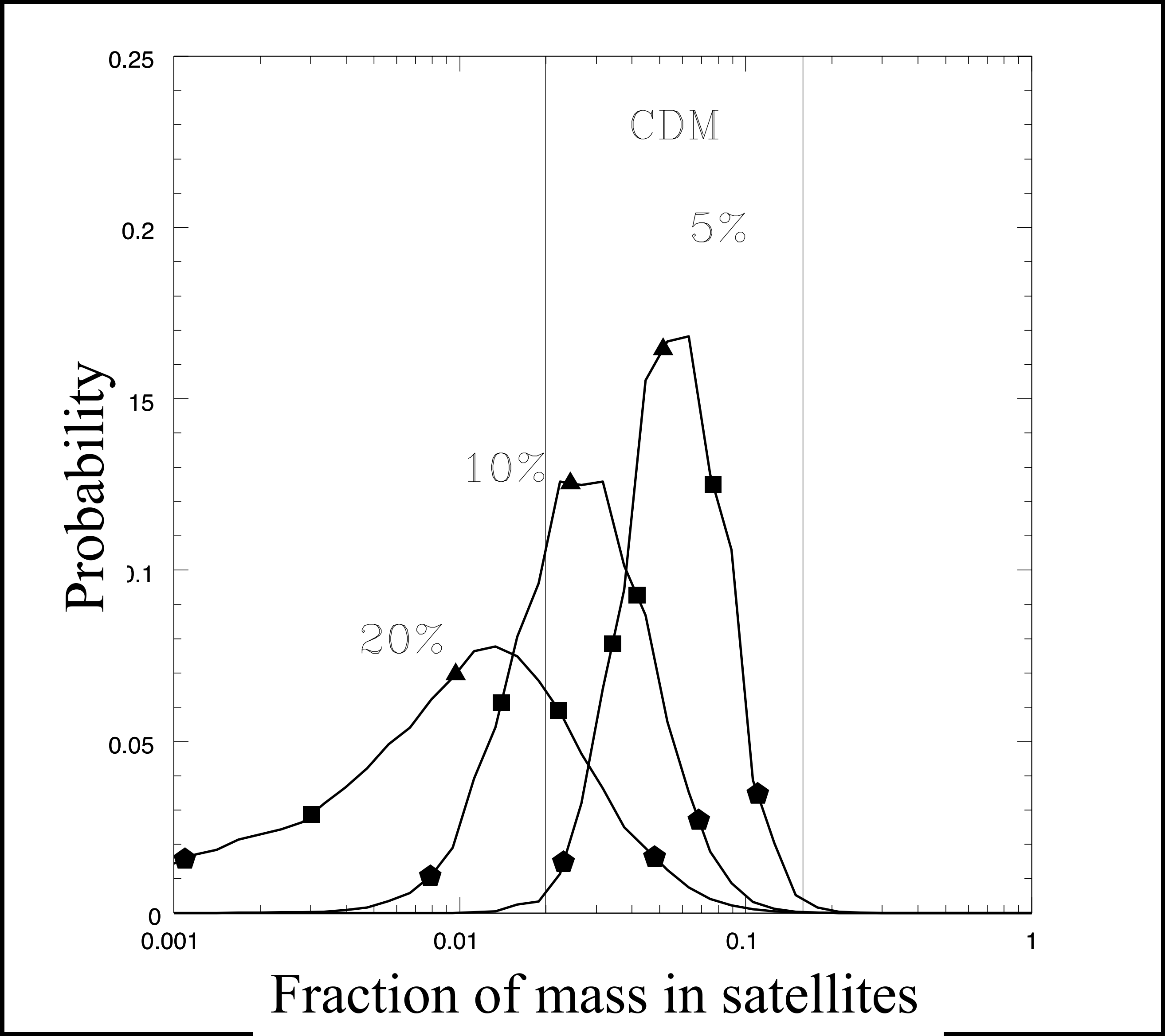
This to be 10% brighter



What causes this the anomaly?

1. Dark satellites?
2. Astrophysical noise (i.e. microlensing and dust)?

Anomalies detected in 7 radio lenses

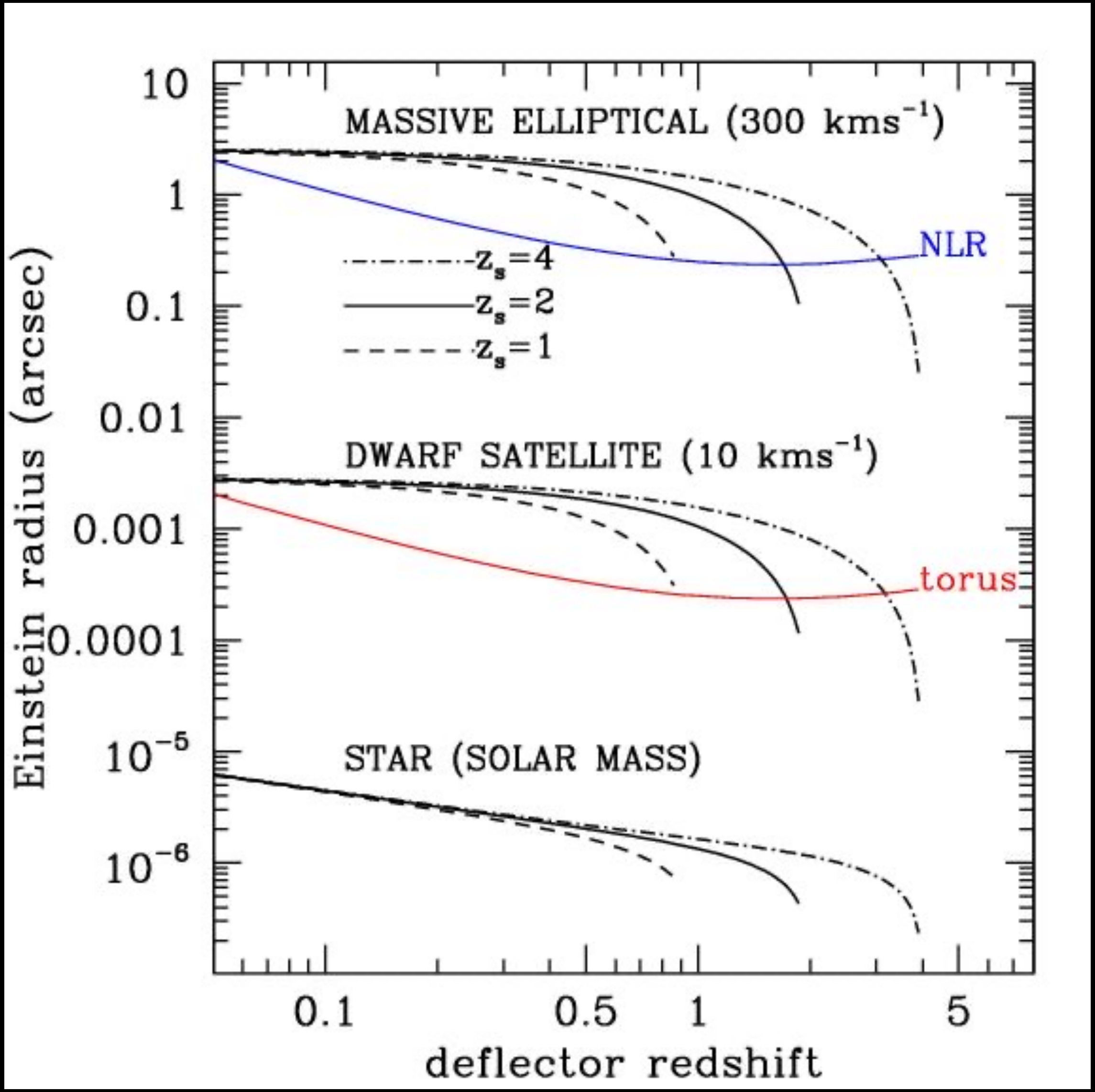


Dalal and Kochanek 2002

How do we make progress?

1. Larger samples
2. High precision photometry and astrometry
3. Avoid microlensing
4. Including contribution of the line of sight

Dusty Torus and Narrow Line Region Are not affected by microlensing

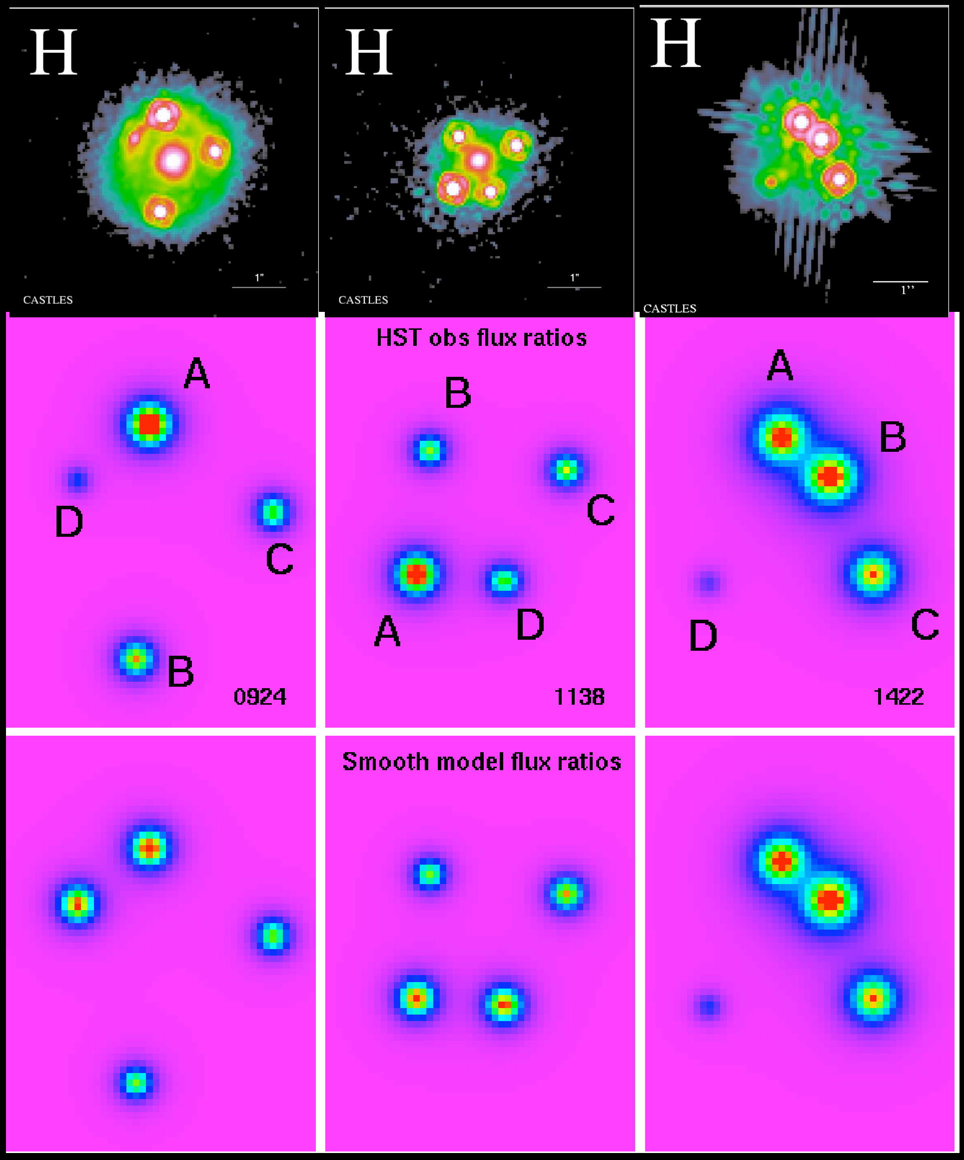


Narrow line flux ratios of lensed AGN

Benefits:
1. Confirm/eliminate microlensing

2. High resolution spectroscopy rules out wavelength-dependent suppression (e.g. dust)

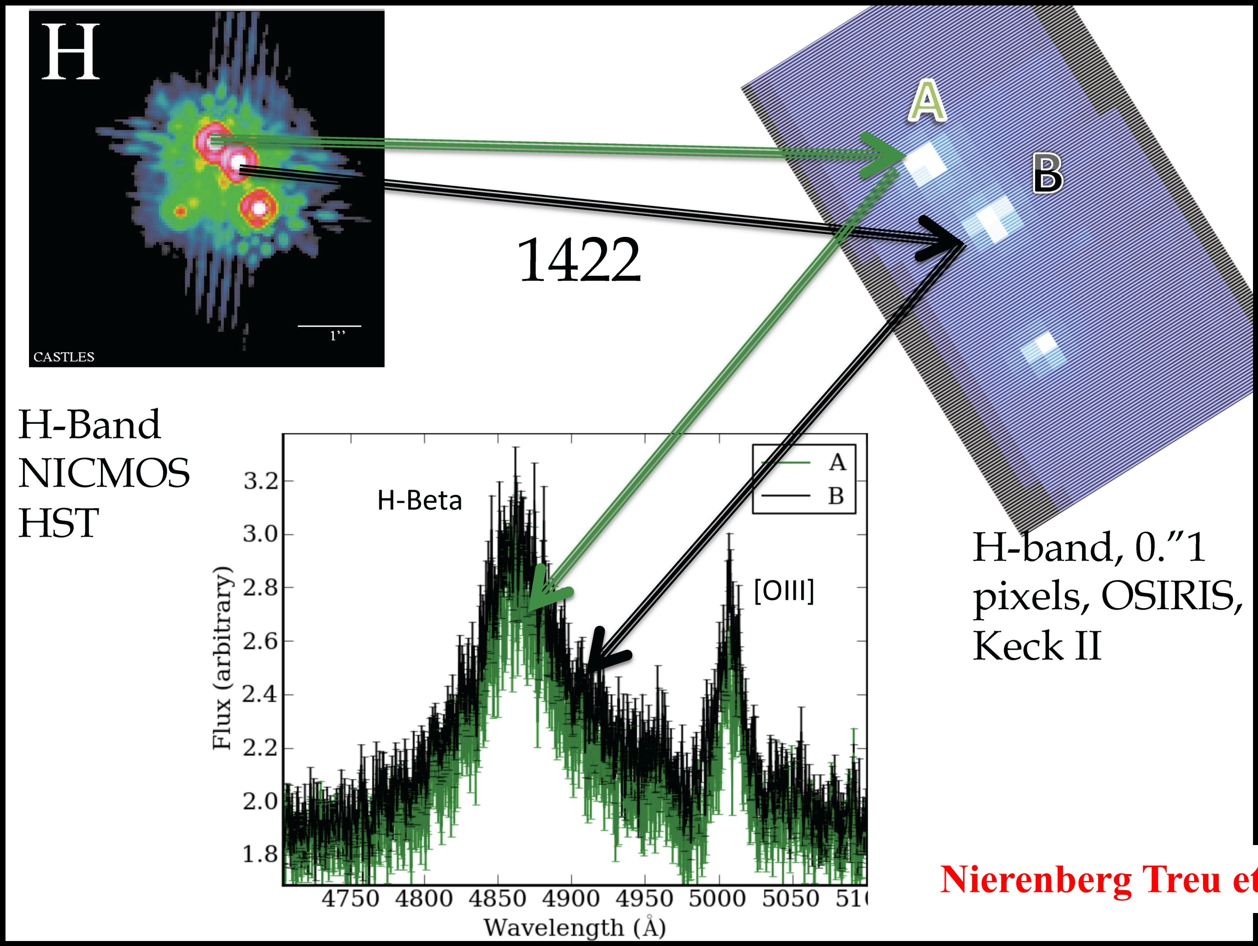
3. Excellent astrometry and photometry



If the anomaly is from substructure…

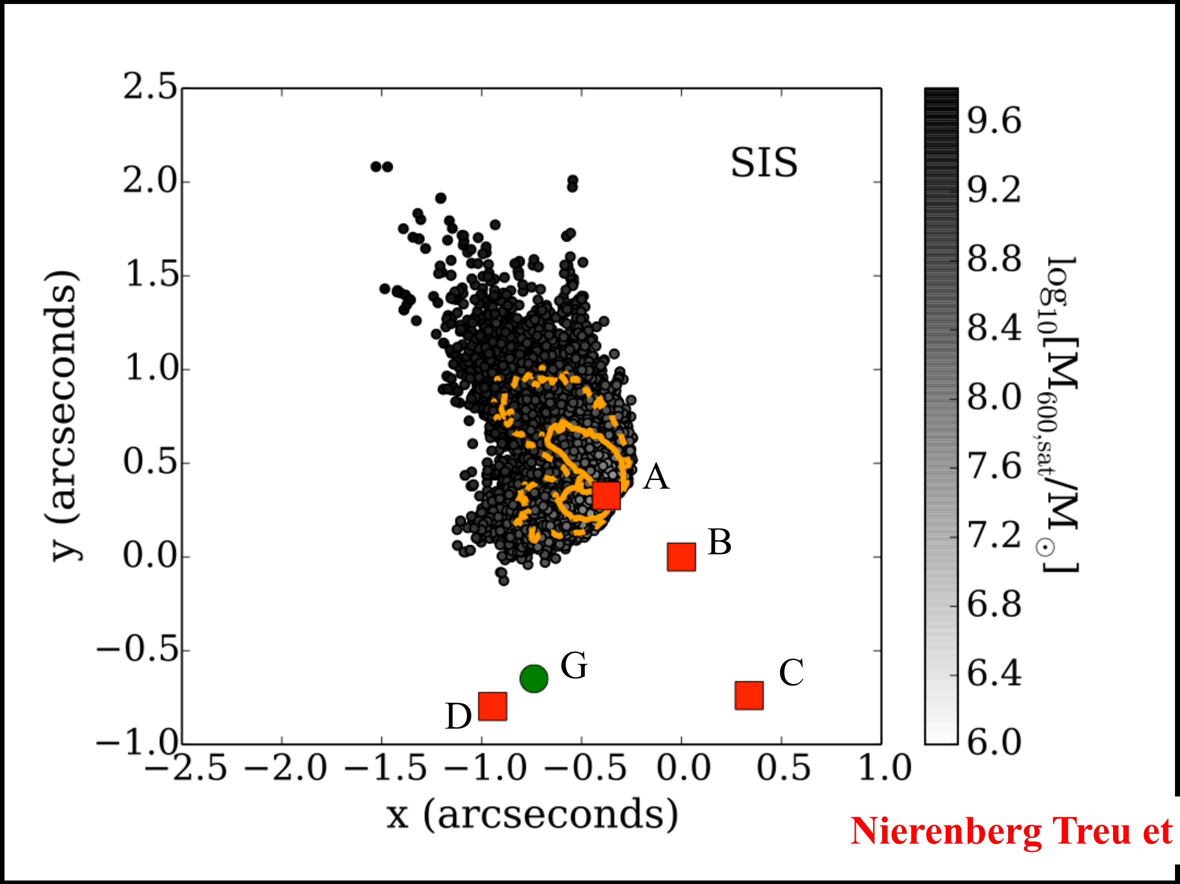
If the anomaly is from microlensing…

OSIRIS detection of substructure



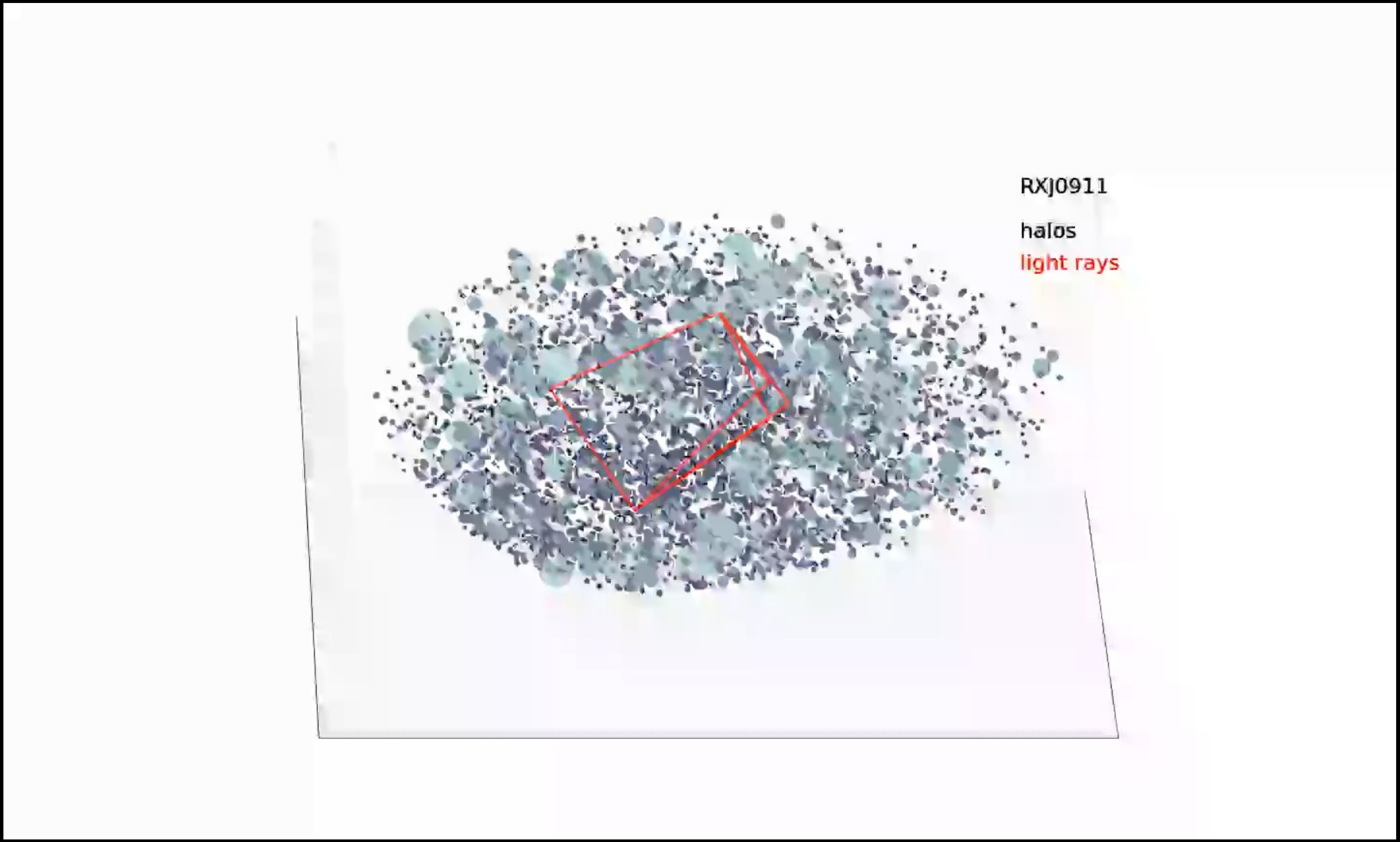
Nierenberg Treu et al 2014

OSIRIS detection of substructure



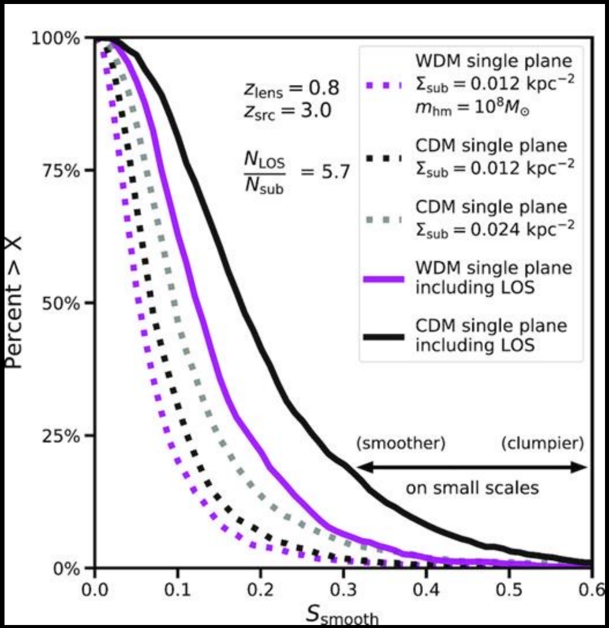
Nierenberg Treu et al 2014

The full problem in 3D

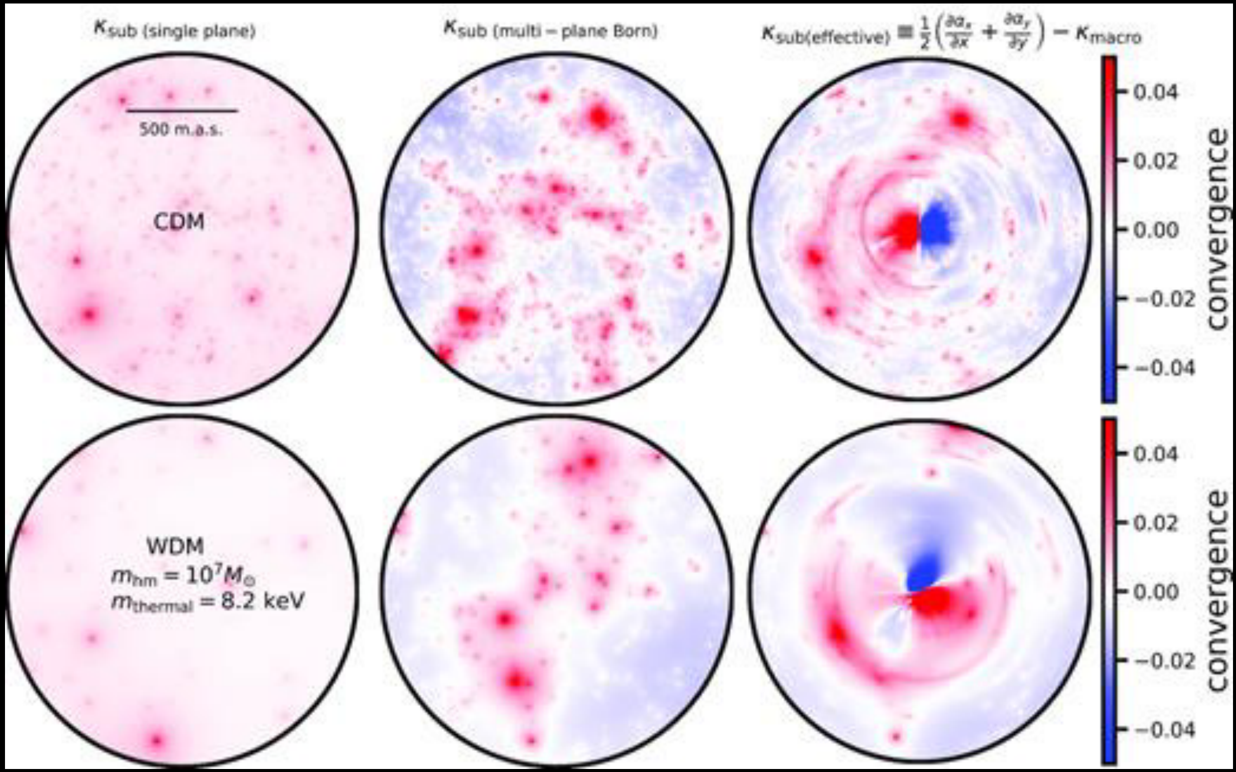


Courtesy of Daniel Gilman

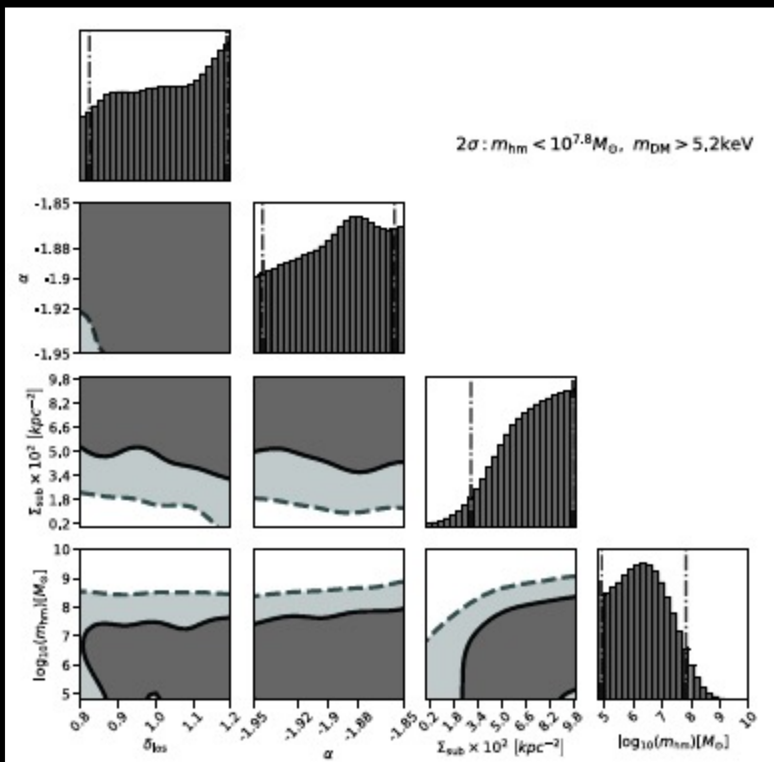
Flux ratio anomalies: statistical treatment including LOS

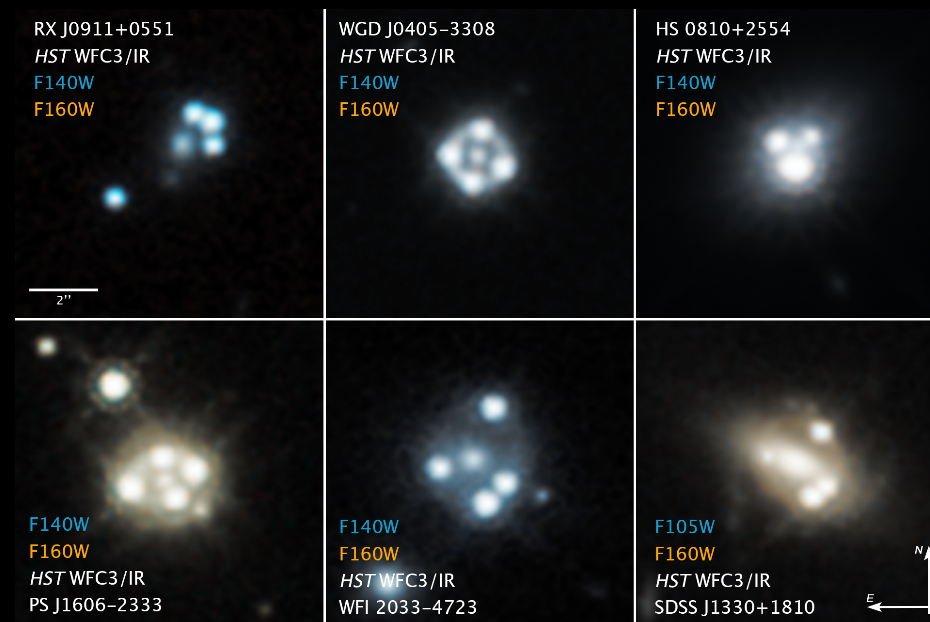


Gilman, Birrer, Treu et al. 2019



Flux ratio anomalies: RESULTS

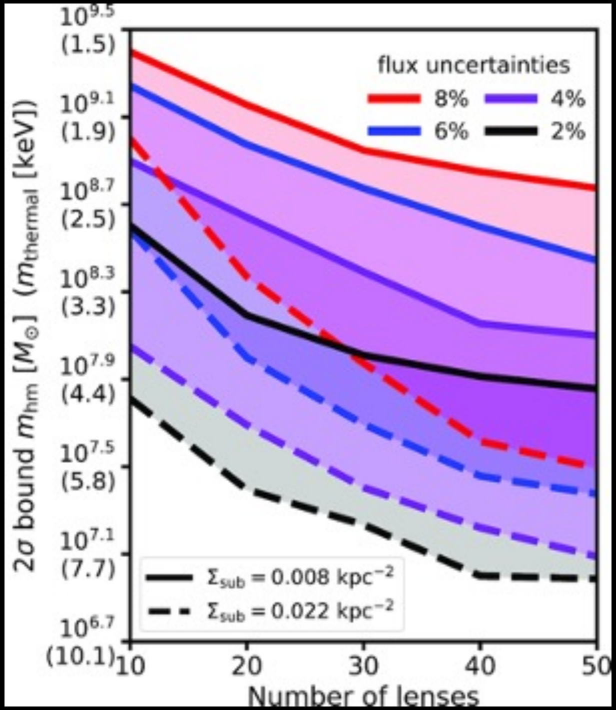




Gilman, Birrer, Treu et al. 2020
Nierenberg, Gilman, Treu et al. 2020

Flux ratio anomalies: Future Prospects 1

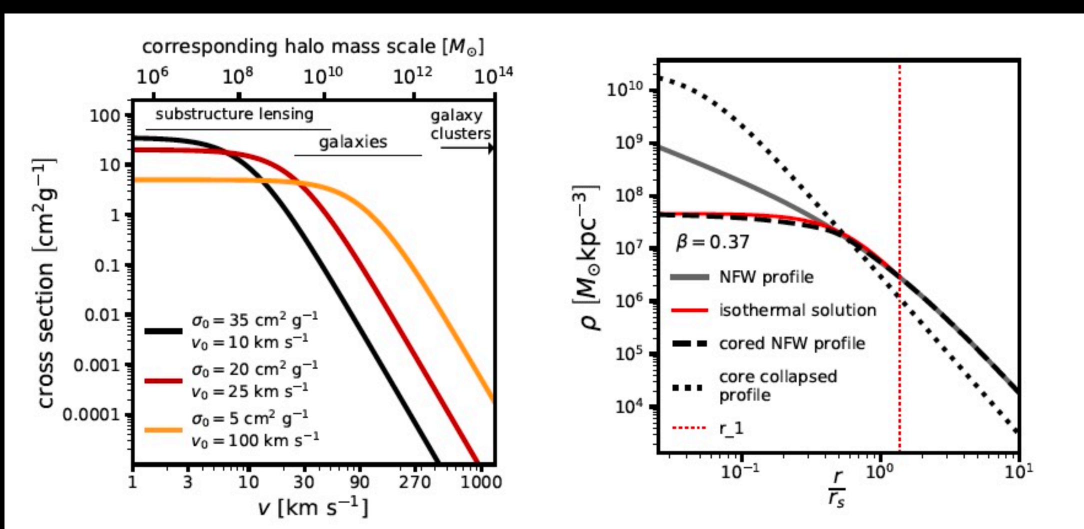
- Narrow line flux ratio anomalies can currently be studied for 20 systems
- Many more systems are being discovered and will be discovered
- Large telescopes with AO will provide spectroscopic follow-up and emission line flux ratios
- **JWST will be revolutionary by allowing MID-IR measurements (cycle-1 program approved!)**

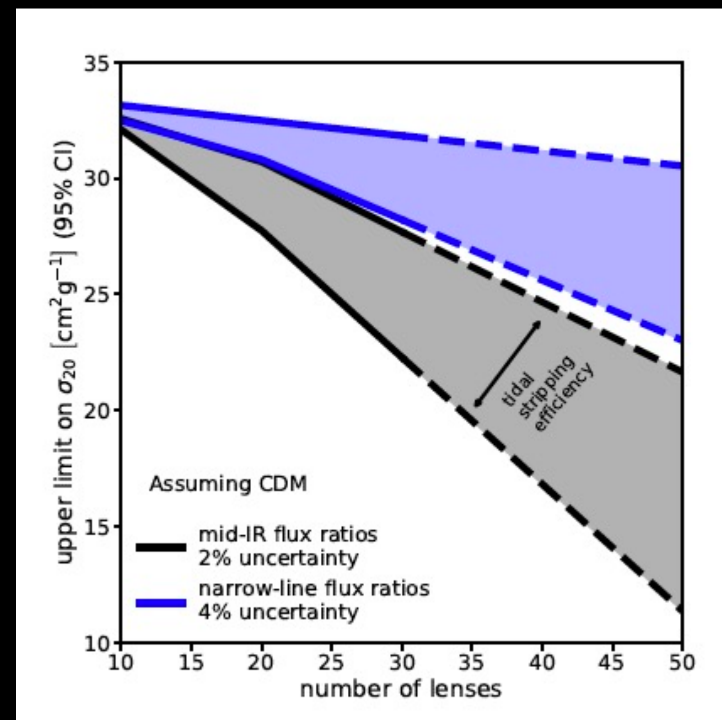


Flux ratio anomalies: Future Prospects 2

- As new systems are discovered one can explore new models, e.g. self-interacting dark matter

$$\sigma\left(\sigma_0, v_0, v\right) = \sigma_0 \left(1 + \frac{v^2}{v_0^2}\right)^{-2}$$



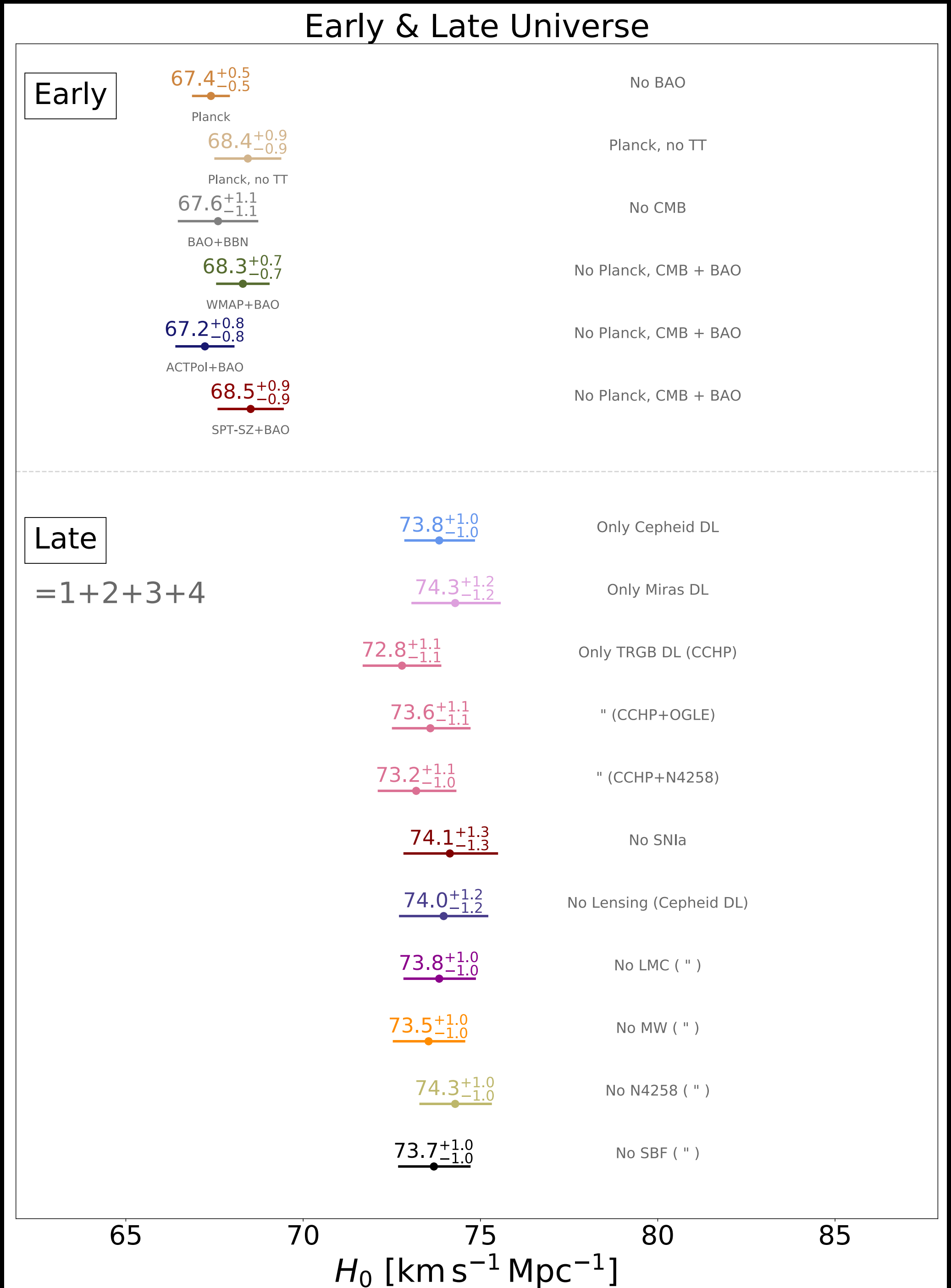


Gilman et al. 2021

Summary

- The H_0 tension indicates a major departure from LCDM
  - Given the stakes, multiple independent measurements are needed.
  - Gravitational Time delays are a powerful one-step method that can quickly reach 2% precision with resolved kinematics
- The nature of dark matter is unknown, many alternatives to CDM are viable
  - Lensing provides unique insights on the small scale structure
    - CDM passed the test so far
  - Many more stringent tests of broad classes of DM models are possible

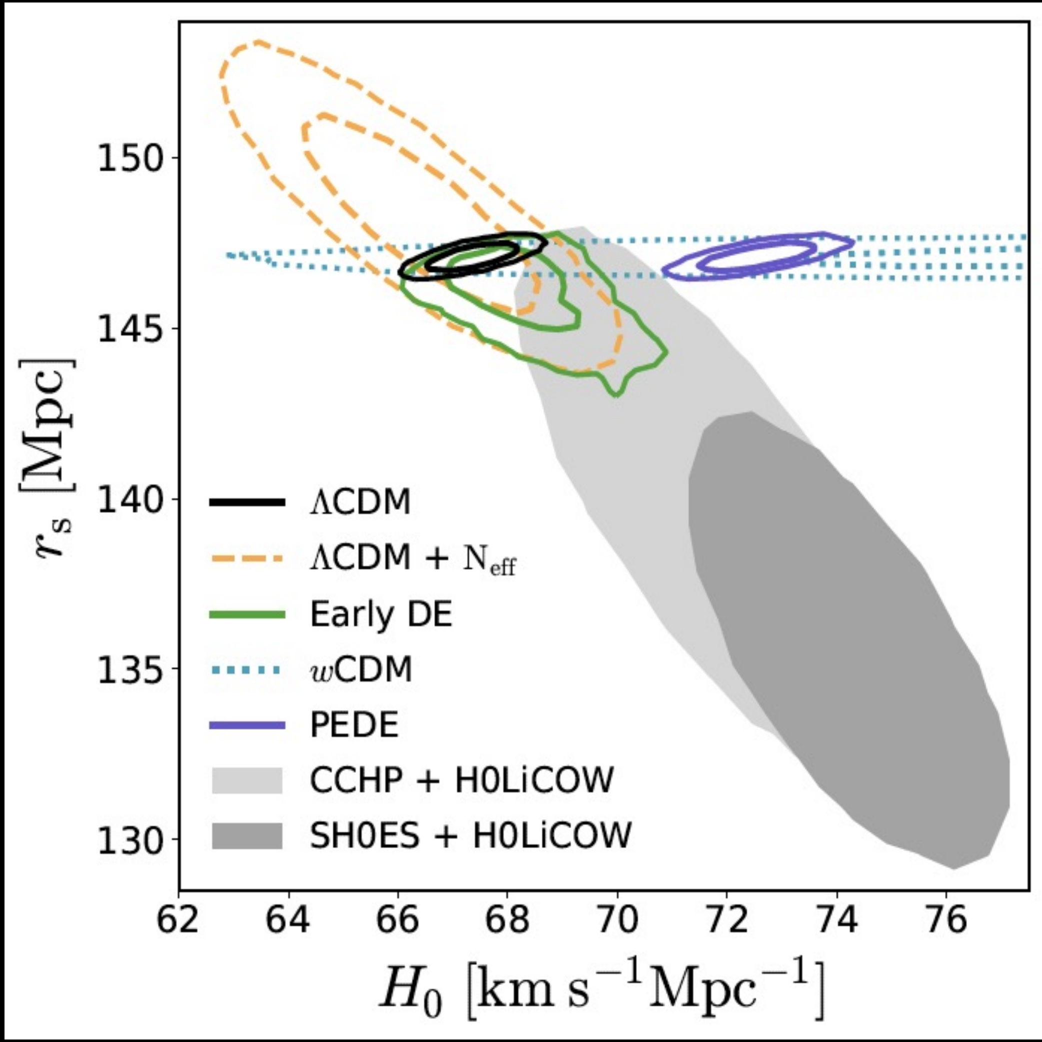
Backup slides



The tension is there even without Planck and including CCHP TRGB

Courtesy of A.Riess

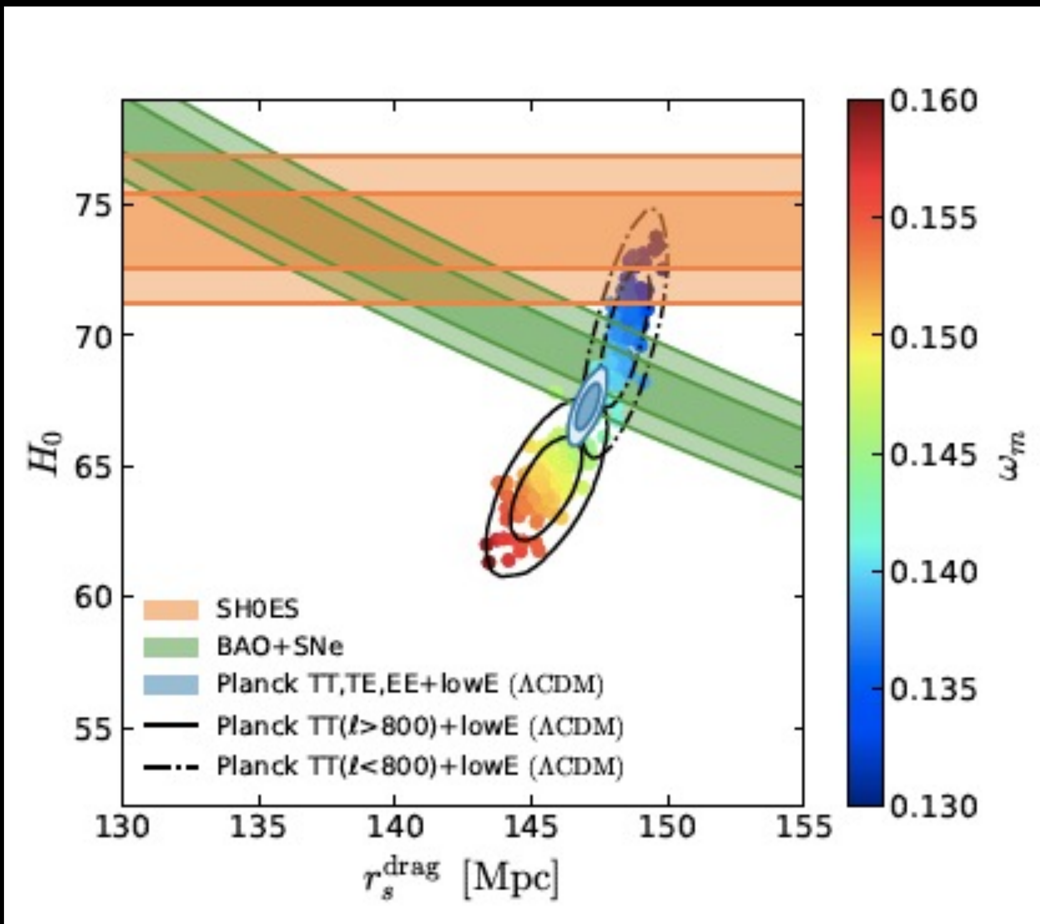
How do we solve it? 1



- Make the sound horizon shorter
- New relativistic particle?
- Early Dark Energy?

Arendse et al 2019

How do we solve it? 2

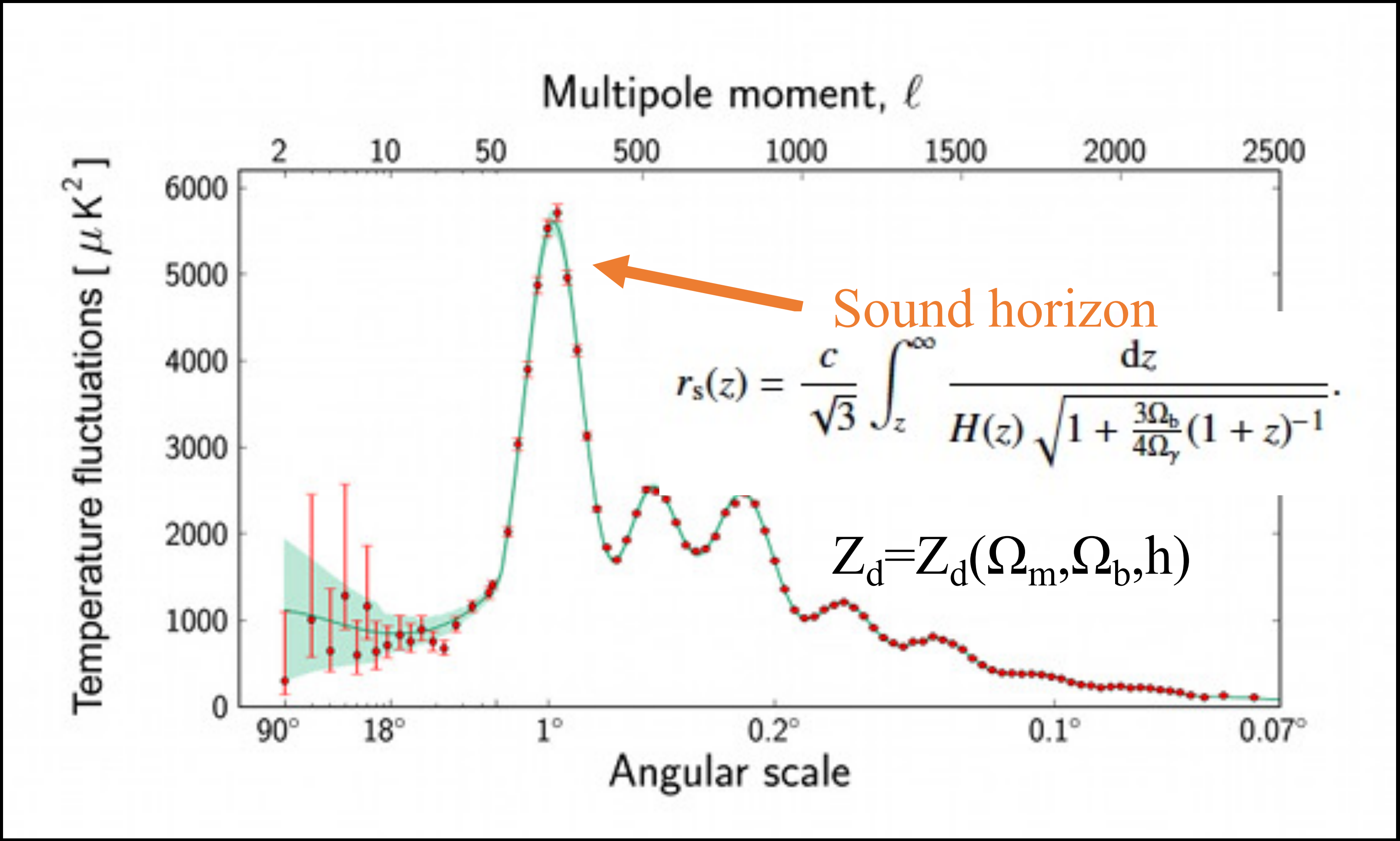


- Increase expansion rate just before recombination
  - New relativistic particle?
  - Early Dark Energy?
- There may be already a signature of this effect in CMB data, although at low significance

Knokx & Millea 2019

Early Universe

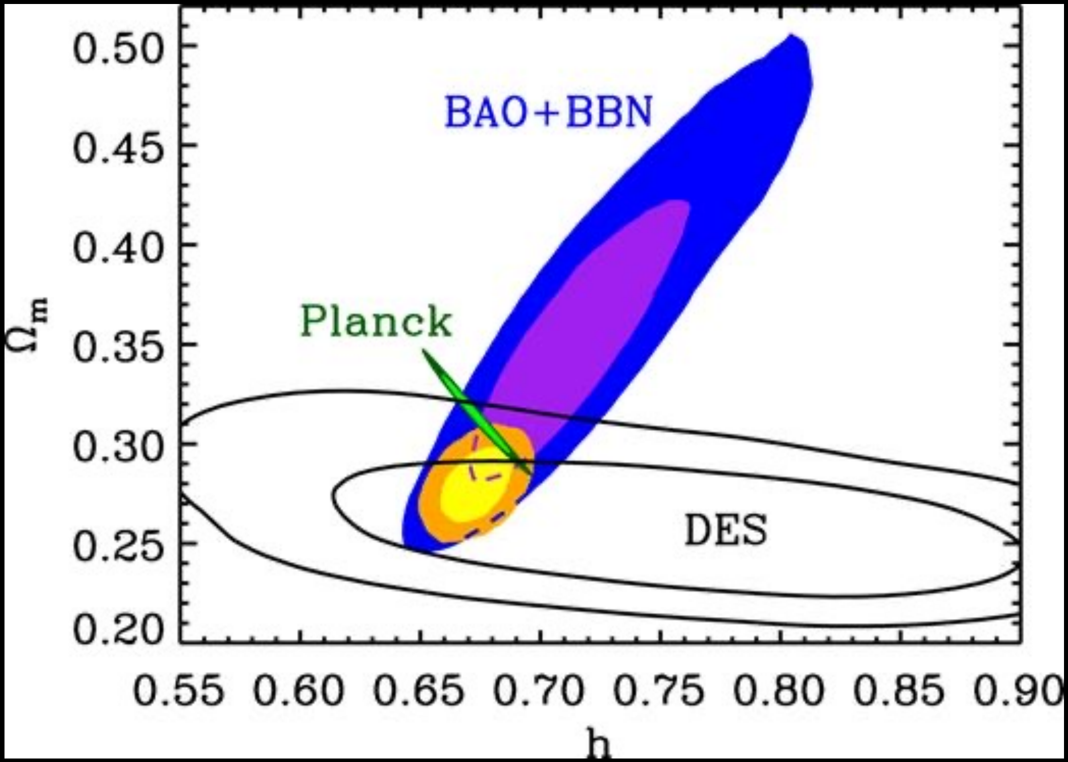
Cosmic Microwave Background and H0



The height and location of the peaks contain all the relevant data

Early-Universe H0 Alternative

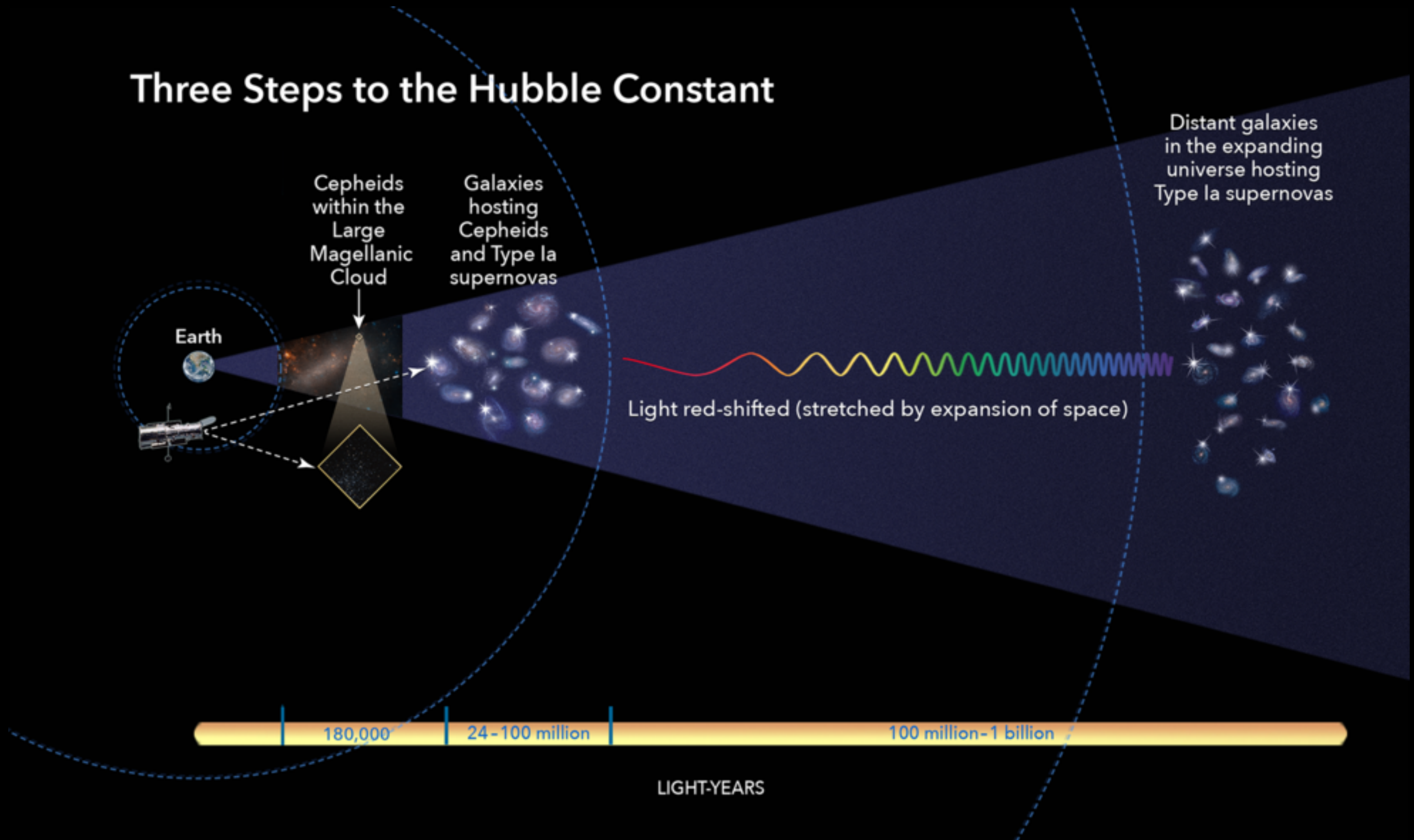
- Baryonic Acoustic Oscillations determine the angular size of the sound horizon as a function of redshift
- Absolute calibration requires
  - $\Omega_b h^2$ (D/H abundance)
  - Ω_m–h (e.g. clustering and weak lensing)



Abbott et al 2018; see Addison et al 2013, 2017

Late Universe

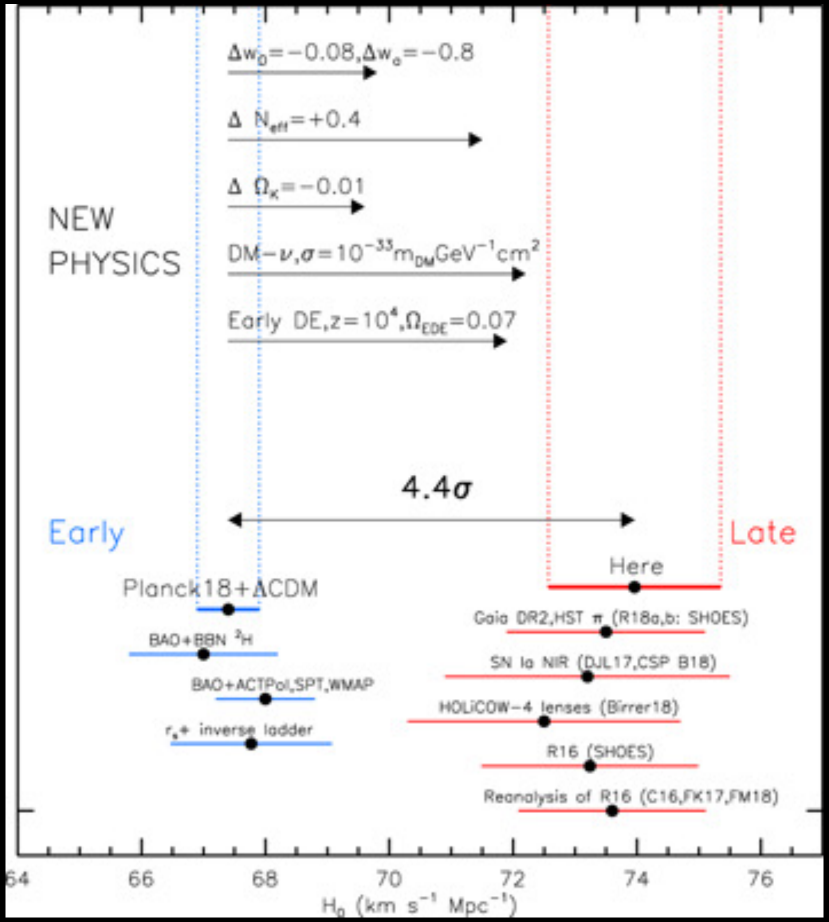
Local distance ladder(s)



Steps of modern ladder(s)

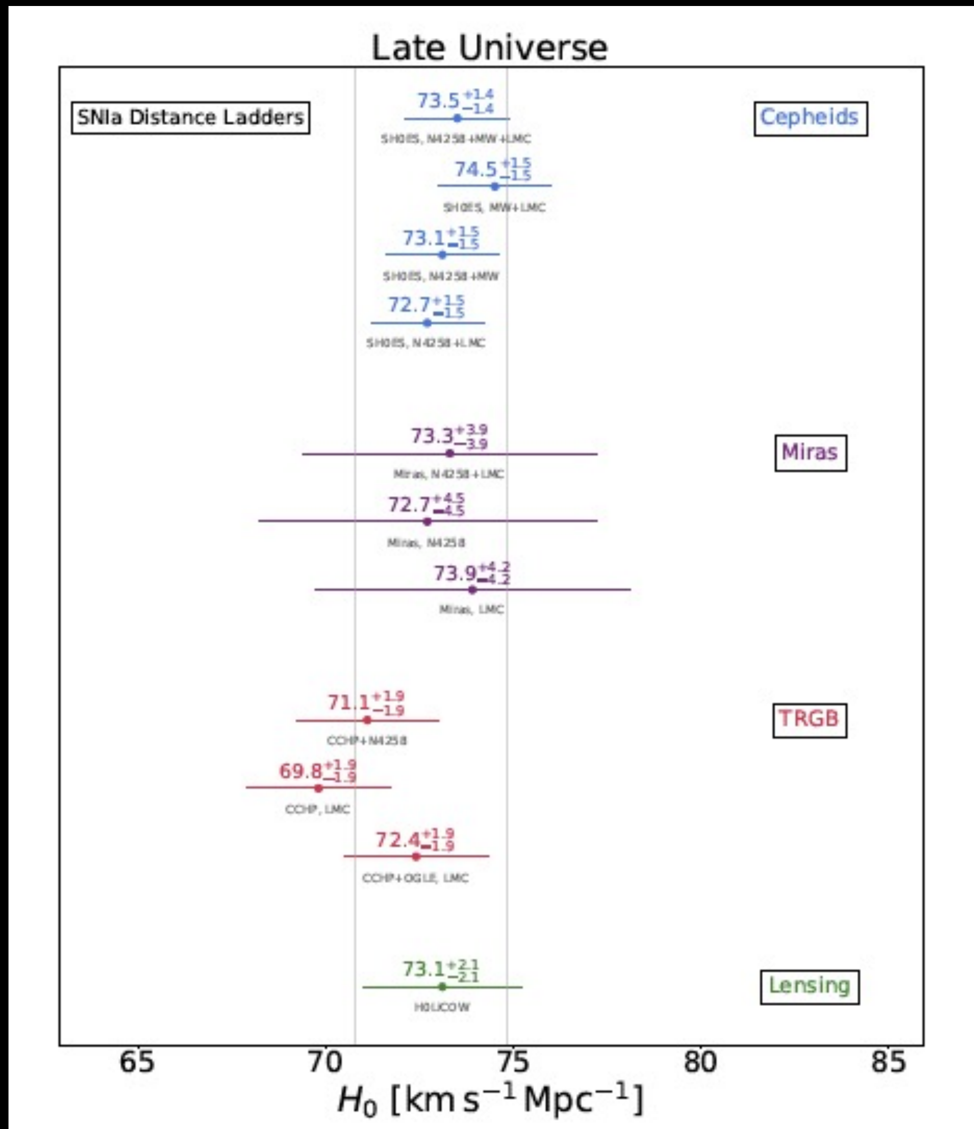
- Parallax or other method to determine absolute distance to first relative distance indicator
- Relative distance indicator that is bright enough to reach a volume containing enough Supernovae Ia
  - Cepheids
  - Tip of the red giant branch
  - Miras
- Relative distance indicator bright enough to reach into the Hubble Flow
  - SN Ia

SHOES (Cepheid based)



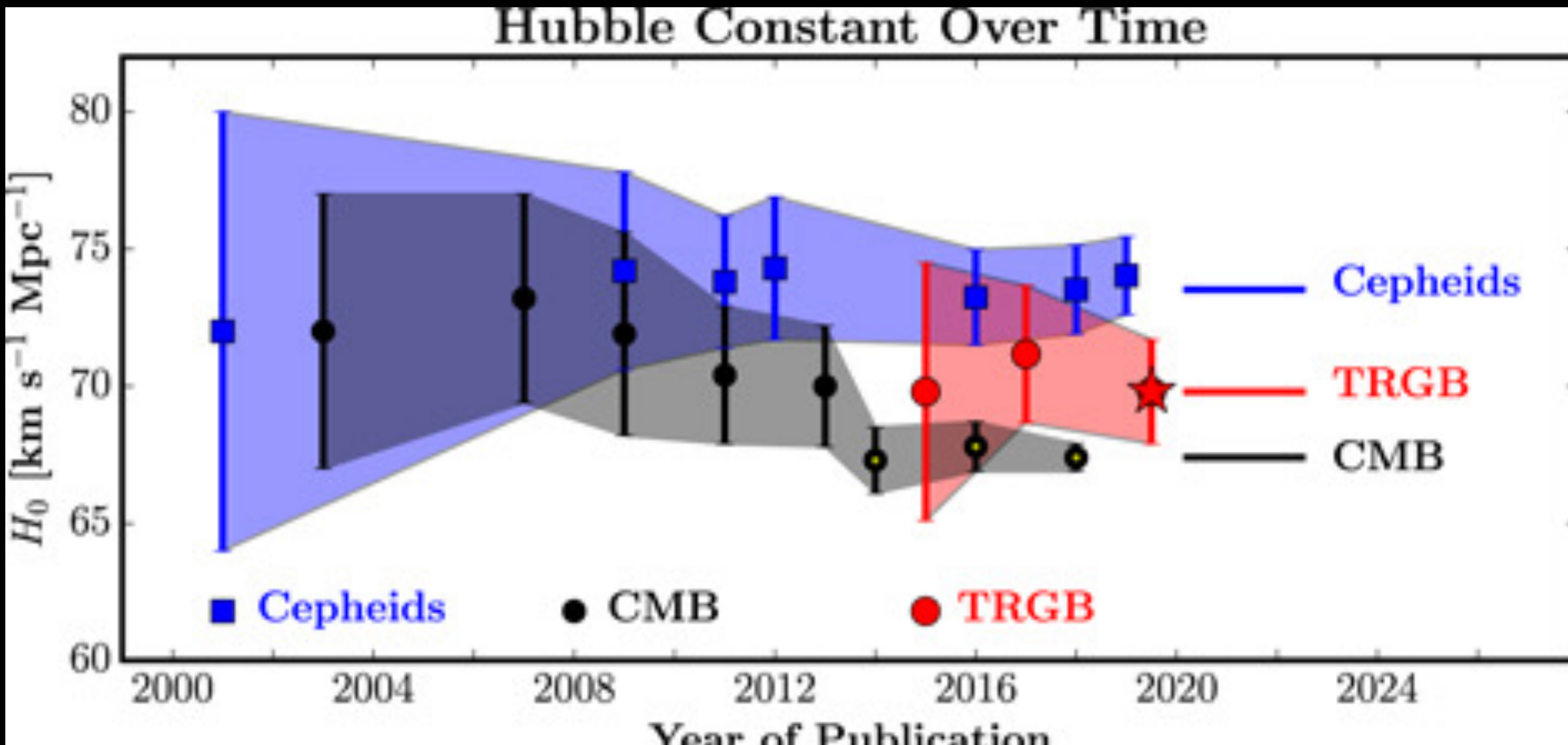
Riess et al. 2019

SHOES (MIRA based)



Huang et al. 2019

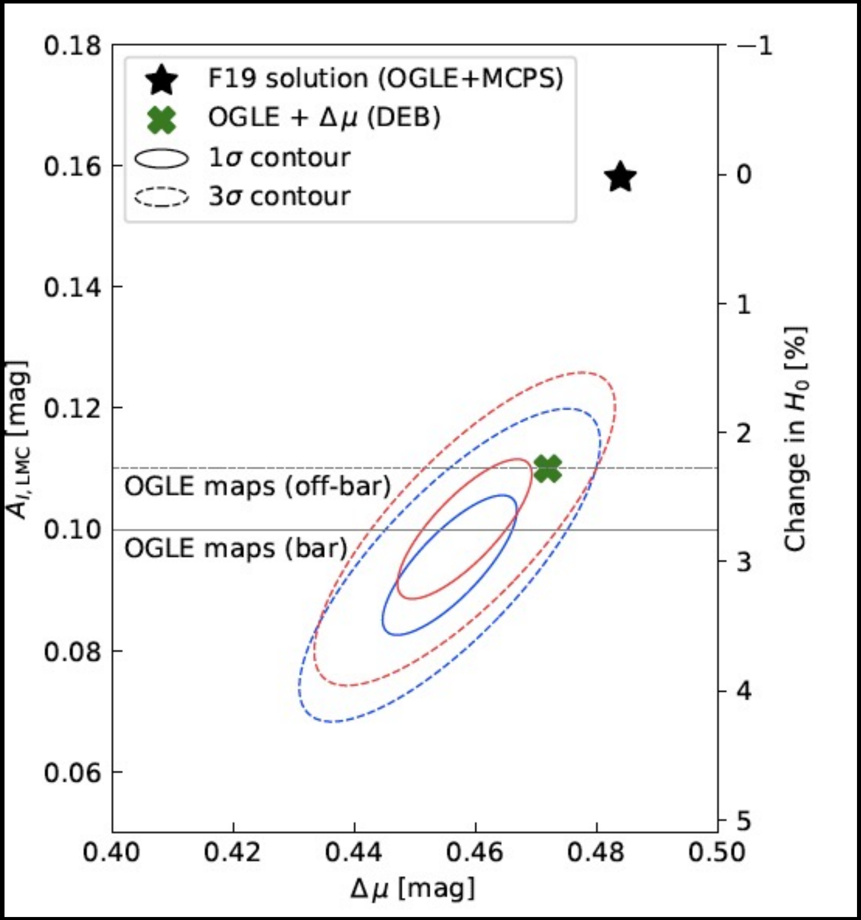
CCHP (TRGB based)



H_0 = 69.8 ± 0.8 (±1.1% stat) ± 1.7 (±2.4% sys) km s^{-1} Mpc^{-1}

Freedman et al. 2019

SHOES (TRGB based)



$$H_0 = 72.4 \pm 2.0 \text{ km s}^{-1}\text{ Mpc}^{-1}$$

Yuan et al. 2019

Dust is hard!
Using NGC4258 (low extinction) megamaser distance as calibrator instead of LMC, yields 71.1+-1.9 (Reid, Pesce & Riess 2019)