Gravitational lensing measurements of the Hubble parameter: challenges and opportunities

Kfir Blum (Weizmann Institute)

KB, Castorina, Simonović, 2001.07182 KB, Teodori, 2105.10873 Teodori, KB, Castorina, Simonović, Soreq, 2201.05111



CAU-BSM Workshop 10/02/2022

H₀ tension



SNIa and gravitational lensing agree



TDCOSMO http://www.tdcosmo.org/projects.html

- H0LiCOW
- COSMOGRAIL
- STRIDES

- SHARP
- COSMICLENS



SNIa and gravitational lensing

A bit later: lensing out of the game?



SNIa and gravitational lensing

A bit later: lensing out of the game?

... agrees with CMB?



- 1. Recap: how lensing measures H0
- 2. Challenges: modeling degeneracy
- 3. Opportunities: galactic structure



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What is dark matter? Where are the missing baryons?

LSST: 100's of strongly lensed variable quasars Oguri, Marshall, 1001.2037



JWST: improved kinematics Yıldırım, Suyu, Halkola, 1904.07237 Birrer, Treu, 2008.06157



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-1223 (d) SDSS 1206+43



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Observables:

• Extended source image



Time delay Δt_{AB} 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 ${\rm HE\,}0435-1223$ Bonvin et al, 2016 -11.0 Magnitude (relative) -10.5 -10.0 -9.5 -9.0 53000 54000 55000 57000 56000 HID - 2400000.5 [dav]

Observables:

• Extended source image





$$\kappa(\vec{\theta}) = \frac{\Sigma(\vec{\theta})}{\Sigma_{\text{crit}}} = \frac{1}{2} \vec{\nabla}_{\theta} \cdot \vec{\alpha} = \frac{1}{2} \vec{\nabla}_{\theta}^{2} \psi$$
$$\Sigma_{\text{crit}} = \frac{d_{A}(z_{s}, 0)}{4\pi G d_{A}(z_{l}, 0) d_{A}(z_{s}, z_{l})}$$
$$\vec{\theta} = \vec{\beta} + \vec{\alpha}(\vec{\theta})$$

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$$\Delta t_{AB} = D_{\Delta t} \,\Delta \tau_{AB} \qquad \Delta \tau_{AB} = \frac{\overrightarrow{\theta}_A^2}{2} - \overrightarrow{\beta} \cdot \overrightarrow{\theta}_A - \psi(\overrightarrow{\theta}_A) - (A \leftrightarrow B)$$
$$D_{\Delta t} = (1 + z_l) \frac{d_A(z_l, 0) d_A(z_s, 0)}{d_A(z_s, z_l)}$$

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Extended source image



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$$\Sigma_{\text{crit}} = \frac{d_{A}(z_{s}, 0)}{4\pi G d_{A}(z_{l}, 0) d_{A}(z_{s}, z_{l})} \qquad D_{\Delta t} = (1 + z_{l}) \frac{d_{A}(z_{l}, 0) d_{A}(z_{s}, 0)}{d_{A}(z_{s}, z_{l})}$$

1. From the image, reconstruct a model $\kappa(\vec{\theta}), \vec{\beta} \rightarrow \Delta \tau$ 2. Given the model and Δt , extract $D_{\Delta t} = \frac{\Delta t}{\Delta \tau} \propto 1/H_0$ 2. Challenges: modeling degeneracy











Modelling *external* convergence





Rusu et al, 1607.01047 (H0LiCOW III)

Millon et al, 1912.08027 (TDCOSMO I)



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Weak lensing degeneracy:

$$H_0^{\text{uncorr}} = \frac{1 - \kappa^{\text{ls}}}{1 - \kappa^{\text{l}}} \frac{1}{1 - \kappa^{\text{s}}} H_0$$









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Birrer et al, 2007.02941 (TDCOSMO IV) Teodori, et al, 2201.05111







Rusu et al, 1607.01047 (H0LiCOW III)





Internal vs. External Convergence

Internal vs. External Mass Sheet Degeneracy

Schneider, Sluse, 1306.0901 KB, Castorina, Simonović, 2001.07182



Internal vs. External Convergence

Internal vs. External Mass Sheet Degeneracy

KB, Castorina, Simonović, 2001.07182 A core component in lens halos could solve lensing H0 tension.



2. Challenges: modeling degeneracy



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	H_0	$\lambda = 67/H_0$	γ	$ heta_E$ ["]	$ heta_s$ ["]	lens redshift z_l	ref
RXJ1131	$76.1^{+3.6}_{-4.3}$	$0.88^{+0.06}_{-0.04}$	1.98	1.6	19	0.295	Chen et al. (2016)
PG1115	$83.0^{+7.8}_{-7.0}$	$0.81\substack{+0.07 \\ -0.07}$	2.18	1.1	17	0.311	Chen et al. (2019)
HE0435	$71.7^{+5.1}_{-4.6}$	$0.93\substack{+0.07 \\ -0.06}$	1.87	1.2	10	0.4546	Chen et al. (2019)
DESJ0408	$74.6^{+2.5}_{-2.9}$	$0.9\substack{+0.03\\-0.03}$	2	1.9	13	0.6	Shajib et al. (2019)
WFI2033	$72.6^{+3.3}_{-3.5}$	$0.92^{+0.05}_{-0.04}$	1.95	0.9	11	0.6575	Rusu et al. (2019)
J1206	$67.0^{+5.7}_{-4.8}$	$1^{+0.08}_{-0.08}$	1.95	1.2	4.7	0.745	Birrer et al. (2019)

What do we learn about galaxies if we add CMB/LSS prior?

Expect evidence for core component, reflecting precision on H0

KB, Castorina, Simonović, 2001.07182 KB, Teodori, 2105.10873



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Mock inference using power-low model.

Truth has H₀=67.4 km/s/Mpc, and a 10% core!



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Expect evidence for core component, reflecting precision on H0

KB, Teodori, 2105.10873 Could reach $> 2\sigma$ per system





A step towards covering internal M\$D (no CMB prior) :

Birrer et al 2020 (TDCOSMO IV)

		ιv				10			
			$ heta_x$						
Data sets			$H_0 [{\rm km \ s^{-1} Mpc^{-1}}]$	$\lambda_{\rm int,0}$	$lpha_{\lambda}$	$\sigma(\lambda_{\rm int})$	<i>a</i> _{ani}	$\sigma(a_{\rm ani})$	$\sigma_{\sigma^{\mathrm{P}},\mathrm{sys}}$
TDCOSMO-	-only		$74.5^{+5.6}_{-6.1}$	$1.02^{+0.08}_{-0.09}$	$0.00^{+0.07}_{-0.07}$	$0.01^{+0.03}_{-0.01}$	$2.32^{+1.62}_{-1.17}$	$0.16^{+0.50}_{-0.14}$	_
TDCOSMO	$+ \ \mathrm{SLACS}_{\mathrm{IFU}}$		$73.3^{+5.8}_{-5.8}$	$1.00^{+0.08}_{-0.08}$	$-0.07^{+0.06}_{-0.06}$	$0.07^{+0.09}_{-0.05}$	$1.58^{+1.58}_{-0.54}$	$0.15_{-0.13}^{+0.47}$	-
TDCOSMO	$+ \mathrm{SLACS}_{\mathrm{SDS}}$	S	$67.4_{-4.7}^{+4.3}$	$0.91^{+0.05}_{-0.06}$	$-0.04^{+0.04}_{-0.04}$	$0.02^{+0.04}_{-0.01}$	$1.52^{+1.76}_{-0.70}$	$0.28^{+0.45}_{-0.25}$	$0.06^{+0.02}_{-0.02}$
TDCOSMO	$+ \mathrm{SLACS}_{\mathrm{SDS}}$	S+IFU	$67.4^{+4.1}_{-3.2}$	$0.91^{+0.04}_{-0.04}$	$-0.07^{+0.03}_{-0.04}$	$0.06^{+0.08}_{-0.04}$	$1.20^{+0.70}_{-0.27}$	$0.18_{-0.15}^{+0.50}$	$0.06^{+0.02}_{-0.02}$

KB, Castorina, Simonovic 2020

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RD, Custoffild, Shifoliovic 20								
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``Internal MSD" (and a CMB prior) may require a non-minimal density profile.



Why would galaxies be non-minimal?



Why should galaxies have a core component?

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Why should galaxies have a core component?

Why not? (What is dark matter?) Can think of several reasons. ``Internal MSD" (and a CMB prior) may require a non-minimal density profile.



Why would galaxies be non-minimal?



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Why not? (What is dark matter?) Can think of several reasons.

Dark matter not boring NFW? ...a little bit of ultralight dark matter?



KB, Teodori, 2105.10873

20 % of total DM, $m = 2.5 \times 10^{-25} \text{ eV}$

Dynamical relaxation consistent at O(1). Cosmology OK.

Summary

Lensing H0 sensitive to galaxy profile at few % level: Unexpected feature in the galaxy profile, or fundamental breakdown of ACDM?

Weak lensing: include all segments of line of sight. Lacking in published results. Likely few % bias on H0.

Teodori, et al, 2201.05111

Adding a core to a density profile is an approximate MSD. 10% core solves the lensing H0 tension?

KB, Castorina, Simonović 2001.07182

Could point to interesting dark matter dynamics. If we go there, may as well adopt CMB (*or SNIa*!) prior on H0.

Ultralight DM (axion-like):

Vanilla vacuum misalignment. Dynamically makes a core. Correct ballpark to solve lensing H0 tension, if 10^{-25} eV $\leq m \leq 10^{-24}$ eV Dynamical relaxation consistent at O(1) level.

Thank you!

KB, Teodori 2105.10873



Xtra

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Birrer et al, 2007.02941 (TDCOSMO IV) Teodori, et al, 2201.05111



0.4





Cappellari et al, 1504.00075

$$\rho_{\rm DM}(r) = \rho_{\rm s} \left(\frac{r}{r_{\rm s}}\right)^{\alpha} \left(\frac{1}{2} + \frac{1}{2}\frac{r}{r_{\rm s}}\right)^{-\alpha - 3}.$$
 (3)

Our models have seven free parameters. Some are poorly constrained but are not of interest here. They are just "nuisance parameters," marginalized out to derive the total mass profiles studied here. The parameters are (i) the inclination *i*; (ii) the anisotropy $\beta_z \equiv 1 - \sigma_z^2 / \sigma_R^2$, with σ_z and σ_R the stellar dispersion in cylindrical coordinates, for the MGE Gaussians with $\sigma_j < R_e$; (iii) the anisotropy for the remaining Gaussians at larger radii; (iv) the stellar $(M/L)_{\text{stars}}$; (v) the break radius of the dark halo, constrained to be $10 < r_s < 50$ kpc; (vi) the halo density ρ_s at r_s ; and (vii) the dark halo slope α for $r \ll r_s$.



Cappellari et al, 1504.00075

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A friend:

...a cored structure of the kind you propose would be difficult to exclude from measurements of the stellar kinematics. Part of the reason is the mass profile-velocity anisotropy degeneracy. Another part is simply that no one has tried: most modelers fit the system to a small number of components (stars, gas, dark matter, central black hole) with constant mass-to-light ratio and none of these look like the core you propose. It would be straightforward for some of the modelers to try adding cores.

I suppose some critics will say that your **cores are ad hoc**, but I think they are **less ad hoc than most of the modifications to cosmology needed to explain the Hubble discrepancy!**



Ultralight DM as a solution of the lensing H₀ tension:



Dynamical relaxation consistent at O(1), can become a bottleneck:

$$\tau \sim \frac{\sqrt{2}}{12\pi^3} \frac{m^3 \sigma^6}{G^2 \rho^2 \ln \Lambda}$$

(But see Eggemeier, Niemeyer 2019, Chen et al 2020, Schwabe et al 2020; for effect of background density.)

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E. Di Valentino et al 2103.01183

CMB with Planck

Balkenhol et al. (2021), Planck 2018+SPT+ACT : 67.49 ± 0.53 Pogosian et al. (2020), eBOSS+Planck $\Omega_m H^2$: 69.6 ± 1.8 Aghanim et al. (2020), Planck 2018: 67.27 ± 0.60 Aghanim et al. (2020), Planck 2018+CMB lensing: 67.36 ± 0.54 Ade et al. (2016), Planck 2015, $H_0 = 67.27 \pm 0.66$

CMB without Planck

Dutcher et al. (2021), SPT: 68.8 ± 1.5 Aiola et al. (2020), ACT: 67.9 ± 1.5 Aiola et al. (2020), WMAP9+ACT: 67.6 ± 1.1 Zhang, Huang (2019), WMAP9+BAO: $68.36^{+0.53}_{-0.52}$ Hinshaw et al. (2013), WMAP9: 70.0 ± 2.2

No CMB, with BBN

D'Amico et al. (2020), BOSS DR12+BBN: 68.5 ± 2.2 Philcox et al. (2020), P_t +BAO+BBN: 68.6 ± 1.1 Ivanov et al. (2020), BOSS+BBN: 67.9 ± 1.1 Alam et al. (2020), BOSS+eBOSS+BBN: 67.35 ± 0.97

$P_{I}(k) + CMB$ lensing

Philcox et al. (2020), $P_{l}(k)$ +CMB lensing: 70.6⁺³₋₅₀

Cepheids – SNIa

Riess et al. (2020), R20: 73.2 ± 1.3 Breuval et al. (2020): 72.8 ± 2.7 Riess et al. (2019), R19: 74.0 ± 1.4 Camarena, Marra (2019): 75.4 ± 1.7 Burns et al. (2018): 73.2 ± 2.3 Dhawan, Jha, Leibundgut (2017), NIR: 72.8 \pm 3.1 Follin, Knox (2017): 73.3 \pm 1.7 Feeney, Mortlock, Dalmasso (2017): 73.2 ± 1.8 Riess et al. (2016), R16: 73.2 ± 1.7 Cardona, Kunz, Pettorino (2016), HPs: 73.8 ± 2.1 Freedman et al. (2012): 74.3 ± 2.1

TRGB – SNIa

Soltis, Casertano, Riess (2020): 72.1 ± 2.0 Freedman et al. (2020): 69.6 ± 1.9 Reid, Pesce, Riess (2019), SH0ES: 71.1 ± 1.9 Freedman et al. (2019): 69.8 ± 1.9 Yuan et al. (2019): 72.4 ± 2.0 Jang, Lee (2017): 71.2 ± 2.5

Miras – SNIa Huang et al. (2019): 73.3 ± 4.0

Masers

Pesce et al. (2020): 73.9 ± 3.0

Tully – Fisher Relation (TFR) Kourkchi et al. (2020): 76.0 ± 2.6 Schombert, McGaugh, Lelli (2020): 75.1 ± 2.8

Surface Brightness Fluctuations

Blakeslee et al. (2021) IR-SBF w/ HST: 73.3 ± 2.5 Khetan et al. (2020) w/ LMC DEB: 71.1 ± 4.1

de Jaeger et al. (2020): 75.8^{+5.2}₋₄₉

HII galaxies

Fernández Arenas et al. (2018): 71.0 ± 3.5

Lensing related, mass model – dependent

Denzel et al. (2021): 71.8⁺³ Birrer et al. (2020), TDCOSMO+SLACS: 67.4^{+4,1}, TDCOSMO: 74.5^{+5,0} Millon et al. (2020), TDCOSMO: 74.2 ± 1.6 Baxter et al. (2020): 73.5 ± 5.3 Qi et al. (2020): 73.6^{+1.8}_{-1.6} Liao et al. (2020): 72.8 $^{+1.6}_{-1.7}$ Liao et al. (2019): 72.2 ± 2.1 Shajib et al. (2019), STRIDES: 74.2⁺² Wong et al. (2019), H0LiCOW 2019: 73.3+ Birrer et al. (2019), HOLICOW 2019, 75.3-1 Bonvin et al. (2018), HOLICOW 2018: 72.5⁺²/₋₂ Bonvin et al. (2016), HOLICOW 2016: 71.9⁺³/₋₃ **Optimistic average**

Di Valentino (2021): 72.94 ± 0.75 Ultra – conservative, no Cepheids, no lensing Di Valentino (2021): 72.7 ± 1.1

GW related

Gayathri et al. (2020), GW190521+GW170817: 73.4^{+6.9} Mukherjee et al. (2020), GW170817+ZTF: 67.6⁺⁴ Mukherjee et al. (2019), GW170817+VLBI: 68.3⁺⁴ Abbott et al. (2017), GW170817+72B1. $00.5_{-4.5}$

H₀ tension