Could quasar lensing time delays hint to cored dark matter halos, instead of H_0 tension?

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The time delay measured between the images of gravitationally lensed quasars probes a combination of the angular diameter distance to the source-lens system and the mass density profile of the lens. Observational campaigns to measure such systems have reported a determination of the Hubble parameter H_0 that shows significant tension with independent determination based on the cosmic microwave background (CMB) and large scale structure (LSS). We show that lens mass models that exhibit a cored component, coexisting with a stellar cusp, probe a degenerate direction in the lens model parameter space, being an approximate mass sheet transformation. This family of lens models has not been considered by the cosmographic analyses. Once added to the model, the cosmographic error budget should become dependent on stellar kinematics uncertainties. We propose that a dark matter core coexisting with a stellar cusp could bring the lensing measurements of H_0 to accord with the CMB/LSS value.

I. INTRODUCTION AND MAIN RESULT

There appears to be a tension between measurements of the Hubble parameter H_0 based on the classic cosmic distance ladder method and measurements obtained through a fit of the standard ΛCDM model to the CMB or LSS data (for a summary, see [1]). The SH0ES collaboration [2] reported $H_0 = 74.03 \pm 1.42$ km/s/Mpc using supernovae calibrated with Cepheids. This result is more than 4σ discrepant with the best fit ΛCDM value given by the Planck collaboration $H_0 = 67.36 \pm 0.54$ km/s/Mpc [3], or with H_0 measurements obtained from galaxy clustering and galaxy lensing data [4–7], that are independent of but agree with the CMB result. The tension is not so strong in the analysis of a supernova sample calibrated with the tip of the red giant branch, that gives $H_0 = 69.8 \pm 0.8(\text{stat}) \pm 1.7(\text{sys})$ km/s/Mpc [8]. On the other hand, a third, alternative method to constrain H_0 independently of both the distance ladder and cosmological perturbation theory, is provided by measurements of time delays in strongly lensed systems [9–11]. The H0LiCOW collaboration [12] used the time delays between multiple images of strongly lensed galaxies hosting a quasar to obtain $H_0 = 73.3^{+1.7}_{-1.8}$ km/s/Mpc [12–16], achieving 2.5% precision with a central value in agreement with SH0ES. Combining the SH0ES and H0LiCOW measurements, the result is in more than 5σ tension with CMB/LSS data.

Given the importance of these results to cosmology, it is worth investigating them from every angle. In this paper we focus on the lensing time delay ("cosmography") measurements. It is well known that lensing analyses are subject to systematic uncertainty associated with the choice of the family of models used to reconstruct the lens potential [17–25]. The H0LiCOW collaboration is, of course, well aware of this problem, and had taken measures to mitigate it by considering different families of lens models. Nevertheless, H0LiCOW systems probe the baryonic-dominated inner part of the lens, where theoretical understanding of the mass profile is limited to challenging N-body simulations. Moreover, given that we do not know what makes-up the dark matter, its distribution on galactic scales could exhibit unexpected features. With these issues in mind, the question we address in this paper is: could a feature in the mass density profile of H0LiCOW lenses bring the cosmographic result for H_0 to agree with the CMB/LSS value? Another way to phrase this question could be to accept, tentatively and for the purpose of the exercise, the CMB/LSS value of H_0; and then ask, given this hypothesis, what would the cosmography data teach us about the inner structure of galaxies.

We believe that we have found an interesting answer to this question. To summarise, we find that if one took the simple power law (PL) density models, shown by H0LiCOW to provide a good fit to the lensing data, and then added a core component *in addition to* the PL, then: (i) the lensing reconstruction problem should be equally well solved by the PL+core models as it is for the pure PL; and (ii) the addition of comparable cores to all H0LiCOW lenses would systematically shift the inferred cosmographic value of H_0 downwards in all systems, in accord with the fact that all of the systems analysed by the standard H0LiCOW analysis pipeline consistently hint to high H_0.

The cores we need are a moderate deformation of the nominal profile: at the Einstein radius (translating to a few kpc for H0LiCOW systems, where the lenses are massive elliptical galaxies), the core component need only make-up 10% or less of the total enclosed mass of the lens. Outside of the Einstein radius the relative core contribution could become larger, potentially reaching as much as $\mathcal{O}(1)$ of the mass and opening a possible way to constrain our solution with detailed kinematic modelling. However, current lensing data do not constrain very well the outer extent of the core.

Single-source lensing data cannot distinguish a pure PL profile from PL+core, because moving along the PL+core family of models (as we shall define it in Sec. II) is an approximate mass sheet transformation (MST) [17]. Therefore, PL+core models probe a flat direction in the likelihood for H_0. Stellar kinematics could, in principle, break the mass sheet degeneracy (MSD) [26–30]. However, as mentioned above, to solve the H_0 tension we need an effect of no more than 10% in enclosed mass within θ_E. Constraining this with stellar kinematics would not be trivial and would suffer from systematic uncertainties related to, e.g., the velocity anisotropy modelling. Furthermore, kinematics modelling uncertainties would come to dominate the determination of H_0, which should be revised [25]. Perhaps another potential way to resolve the MSD would be to have multiple sources lensed by the same object, as is usually the case in lensing by galaxy clusters [31, 32].

It is worth pointing out that we are not aware of the presence of PL+core profiles in N-body simulations. In this sense, introducing them is an ad-hoc solution of the (cosmographic contribution to) the H_0 tension. But we are also not aware of observational data that excludes such profiles. If one accepts PL+core profiles and interprets the PL as a stellar cusp, then the question arises what is the core made of. Since the inner part of the lenses is baryon-dominated, we do not know at this point if the core is some baryonic structure (gas?), or dark matter. It is exciting to speculate that the H_0 tension could actually hint to new constraints on the nature of the dark matter, perhaps along the lines of models such as [33] or [34].

This paper is organized as follows. In Sec. II we show that adding an inner core component, on top of a (rescaled) cusp component, is an approximate MST. We give some simple examples, estimate the MSD breaking effects, and introduce λPL models as a family of models that is expected to probe a flat direction in cosmographic measurements of H_0. In Sec. III we consider as input the CMB/LSS measurement of H_0 and use it to estimate the required morphology of H0LiCOW lenses. In Sec. IV we discuss our findings, and the possibility that the (cosmographic part of the) H_0 tension might actually hint to a core component, perhaps due to dark matter, coexisting with a stellar cusp in galaxies.

II. ADDING A CORE TO A STELLAR CUSP IS A MASS SHEET TRANSFORMATION

Lensing analyses [12–16] take as input a brightness map defined on the image plane, spanned by coordinates $\vec{\theta}$, and constrain the deflection angle $\vec{\alpha}(\vec{\theta})$ given by

$$\vec{\alpha}(\vec{\theta}) \;=\; \frac{1}{\pi}\int d^2\theta' \,\frac{(\vec{\theta}-\vec{\theta}')}{|\vec{\theta}-\vec{\theta}'|^2}\kappa(\vec{\theta}') \tag{1}$$

via solving the lens equation

$$\vec{\beta} \;=\; \vec{\theta}-\vec{\alpha}(\vec{\theta}), \tag{2}$$

where $\vec{\beta}$ parametrizes positions on the source plane. The deflection angle is obtained by integration over the convergence,

$$\kappa(\vec{\theta}) \;=\; \frac{\Sigma(\vec{\theta})}{\Sigma_c}, \tag{3}$$

$$\Sigma_c \;=\; \frac{D_s}{4\pi G D_l D_{ls}}. \tag{4}$$

Here $\Sigma(\vec{\theta})$ is the projected surface mass density of the lens and D_s, D_l, D_{ls} are the angular diameter distances from the source to the observer, from the lens to the observer, and from the source to the lens.

Given multiple images of a quasar contained in the host galaxy, one constructs the time delay Δt_{ij} between quasar images $\vec{\theta}_i$ and $\vec{\theta}_j$,

$$\Delta t_{ij} \;=\; \mathcal{D}\Delta\tau_{ij}, \tag{5}$$

$$\Delta\tau_{ij} \;=\; \frac{\vec{\alpha}^2(\vec{\theta}_i)-\vec{\alpha}^2(\vec{\theta}_j)}{2}+\psi(\vec{\theta}_j)-\psi(\vec{\theta}_i), \tag{6}$$

$$\mathcal{D} \;=\; (1+z_l)\frac{D_s D_l}{D_{ls}}, \tag{7}$$

where

$$\psi(\vec{\theta}) \;=\; \frac{1}{\pi}\int d^2\theta' \kappa(\vec{\theta}')\ln|\vec{\theta}-\vec{\theta}'|. \tag{8}$$

If one has a model of $\kappa(\vec{\theta})$, then it can be used to calculate $\Delta\tau_{ij}$ in Eq. (6). Given a measurement of Δt_{ij}, one can extract $\mathcal{D}=\Delta t_{ij}/\Delta\tau_{ij}$ and thus $H_0 \propto 1/\mathcal{D} \propto \Delta\tau_{ij}/\Delta t_{ij}$.

The MSD comes from the fact that if the lensing reconstruction problem Eq. (2) is solved by a model for $\kappa(\vec{\theta})$, along with a model for the source position $\vec{\beta}$, then the reconstruction problem is also solved equally well by the alternative MST model[1]

$$\kappa_\lambda(\vec{\theta}) \;=\; \lambda\kappa(\vec{\theta}) + 1 - \lambda, \tag{9}$$
$$\vec{\beta}_\lambda \;=\; \lambda\vec{\beta}, \tag{10}$$

leaving $\vec{\theta}$ unchanged. While the lensing image plane geometry is invariant under the MST, the time delay is not invariant and it is easy to verify that $\Delta\tau_{ij,\lambda} = \lambda\Delta\tau_{ij}$. This means that if we measure H_0 from some model κ, then the MST model κ_λ would give $H_0 \to (\Delta\tau_{ij,\lambda}/\Delta\tau_{ij})\, H_0 = \lambda H_0$.

The actual reconstruction problem of H0LiCOW deals with an extended source model, given by a map of the brightness $I_s(\vec{\beta})$ on multiple source plane pixels. Under an MST, the distortion matrix $A_{ij}(\vec{\theta}) = \partial\beta_i/\partial\theta_j$ is rescaled to $A_{\lambda,ij}(\vec{\theta}) = \lambda A_{ij}(\vec{\theta})$, which means that the magnification $\mu = 1/\mathrm{det}A$ becomes $\mu_\lambda = \mu/\lambda^2$. Importantly, the relative magnification between images is unchanged. For H0LiCOW systems the precise intrinsic luminosity of the source is unknown, so absolute magnification cannot be measured. Thus extended source information does not mitigate the MSD.

The "mass sheet" in MSD refers to the $1-\lambda$ term in Eq. (9) which is a constant convergence term and thus it acts as a $\vec{\theta}$-independent mass sheet. H0LiCOW took careful measures to account for the MSD due to external convergence $\kappa_{\rm ext}$ (see dedicated discussions in [12–16]). This was done by using numerical simulations to estimate the cumulative contributions of mass along the line of sight in the field of the lens systems. However, a cored density profile (3D density $\rho \sim$ const) extending over a finite radius R_c, and dropping quickly afterwards, can also give κ that is constant inside[2] $\theta \lesssim \theta_c = R_c/D_l$. Thus, if the images in the lensing data only extend over angles $\theta < \theta_c$, then the addition of a cored density component, with κ_c that is constant inside θ_c, is (i) an approximate MST, if it is done alongside a rescaling of the previous κ model, and (ii) is not equivalent to an external convergence term.

To make things more concrete we define the λPL family of profiles:

$$\kappa_\lambda(\vec{\theta}) \;=\; \lambda\kappa_{\rm PL}(\vec{\theta}) + (1-\lambda)\kappa_{\rm c}(\vec{\theta}). \tag{11}$$

Here, we take $\kappa_{\rm PL}$ to represent the elliptic PL profile as used by H0LiCOW to successfully model the lensing data in their systems[3]. The $\kappa_c(\vec{\theta})$ term is chosen to satisfy $\kappa_c(\vec{\theta}) \approx 1$ for $\theta < \theta_c$ and to fall faster than $\kappa_{\rm PL}$ at $\theta > \theta_c$. We do not need to assume that $\kappa_c(\vec{\theta})$ is isotropic, but in what follows for simplicity we will.

As a first example, consider the 3D cored density profile $\rho_c(r) = \frac{2}{\pi}\Sigma_c R_c^3 (R_c^2 + r^2)^{-2}$, where Σ_c is the critical density of Eq. (4). The convergence for this profile is $\kappa_c(\vec{\theta}) = \left(1 + \frac{\theta^2}{\theta_c^2}\right)^{-\frac{3}{2}} = 1 - \frac{3\theta^2}{2\theta_c^2} + \mathcal{O}\left(\frac{\theta^4}{\theta_c^4}\right)$ and it induces the deflection angle $\vec{\alpha}_c(\vec{\theta}) = \hat{\theta}\frac{2\theta_c^2}{\theta}\left(1 - \left(1 + \frac{\theta^2}{\theta_c^2}\right)^{-\frac{1}{2}}\right) = \vec{\theta}\left(1 - \frac{3\theta^2}{4\theta_c^2} + \mathcal{O}\left(\frac{\theta^4}{\theta_c^4}\right)\right)$. Obviously, using this κ_c in Eq. (11) gives an approximate MSD inside of $\theta < \theta_c$. We can estimate the corrections to the MSD by comparing the Einstein angle θ_E for $\kappa_{\rm PL}$ and the Einstein angle $\theta_{E\lambda}$ for κ_λ in Eq. (11). For simplicity, in this exercise we take $\kappa_{\rm PL}$ to be isotropic and given by $\kappa_{\rm PL}(\vec{\theta}) = \frac{3-\gamma}{2}\frac{\theta_E^{\gamma-1}}{\theta^{\gamma-1}}$, for which the deflection angle is $\vec{\alpha}_{\rm PL}(\vec{\theta}) = \frac{\theta_E^{\gamma-1}}{\theta^{\gamma-1}}\vec{\theta}$. In the limit $\theta_c \to \infty$, the MSD is exact and $\theta_E = \theta_{E\lambda}$. For finite θ_c we find $\theta_{E\lambda} = \theta_E + \delta$, with $\delta = -\frac{3}{4(\gamma-1)}\frac{1-\lambda}{\lambda}\frac{\theta_E^2}{\theta_c^2} + \mathcal{O}\left(\frac{\theta_E^4}{\theta_c^4}\right)$. From the form of δ we can infer the parametric dependence of the breaking of the MSD. The corrections to the image plane geometry enter at order θ^2/θ_c^2, and if $\lambda \approx 1$ (that is, if we only add a small core) are further suppressed by a factor $1-\lambda$. Note that for real systems H0LiCOW find $\gamma \approx 2$ so $1/(\gamma-1) \approx 1$ (see Tab. I).

More generally, if in Eq. (11) we use an isotropic core component that can be expanded as $\kappa_c = 1 + a\theta^2/\theta_c^2 + ...$ at $\theta < \theta_c$, then the leading order image plane corrections to the MSD at $\theta < \theta_c$ scale as $(1-\lambda)\theta^2/\theta_c^2$. This scaling remains true also when the baseline term $\kappa_{\rm PL}$ (or whatever other baseline model is considered, e.g. a composite stellar cusp+NFW model) is anisotropic.

As another example, consider the 3D cored Navarro-Frenk-White (NFW) density profile,

$$\rho_{\rm cNFW}(r) \;=\; \frac{\rho_0}{(R_c + r)(R_s + r)^2}, \tag{12}$$

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[1] We note that the MST represents a subset of a more general set of transformations that leave the lens equation invariant [19].

[2] Here and elsewhere $\theta = |\vec{\theta}|$.

[3] The elliptic PL profile is referred to as SPEMD in [12–16].

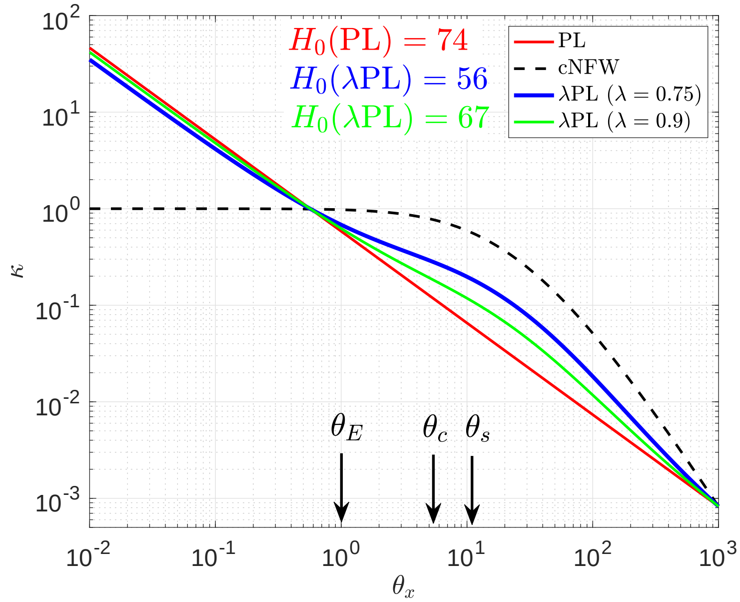

FIG. 1: Convergence for the λPL example of Fig. 2, with $\lambda = 0.75$ (blue) and $\lambda = 0.9$ (green). The $\lambda = 1$ pure PL case is shown in red, and the cNFW profile is shown in dashed black. A value of $\lambda \approx 0.9$ would bring the H0LiCOW determination of H_0 down to the CMB/LSS value. Note that for H0LiCOW lenses, both lensing and kinematics data reach outward only slightly beyond θ_E, and never constrain angles around the value of θ_c chosen in this example.

which contains 1 extra parameter R_c, defining the core, in addition to the usual NFW density ρ_0 and scale radius R_s. The convergence κ_{cNFW} can be computed analytically but is not particularly illuminating. With proper normalization such that $\kappa_{\mathrm{cNFW}}(0) = 1$ it has the correct characteristics to function as κ_c in Eq. (11). We show κ_{cNFW} by the dashed black line in Fig. 1. We have set $\theta_s = R_s/D_l = 11$ and $\theta_c = 0.5\,\theta_s$, indicated by arrows at the bottom of the plot.

To illustrate the MSD, in Fig. 2 we calculate the lensing geometry and time delays for a toy model of a quasar sitting in an extended host galaxy. To make things simple we replace the extended host by a circle on the source plane, centred on the quasar. We first do the lensing exercise for a pure PL model with slope $n = 1.95$ and ellipticity parameter $q = 0.8$, similar to typical H0LiCOW systems. The source plane host "galaxy" is shown by the red circle in the top panel (source plane). The "quasar" is denoted by magenta cross. The lensed images are shown by red lines in the bottom panel (image plane). (It is difficult to see these lines because they lie underneath the green lines of the λPL model, as explained below.) We calculate the dimensionless time delays $\Delta\tau_{ij}$ at the quasar image positions and show them next to the bottom panel (magenta, titled PL). The convergence for this PL model (along the θ_x axis) is shown by the red line in Fig. 1. We have chosen the PL normalisation such that $\theta_E \approx 1$.

Next, we consider a λPL model with $\lambda = 0.75$. The convergence for this λPL model is shown by the blue line in Fig. 1. The source plane host model as given by the MSD is shown by the green circle in the top panel of Fig. 2. The quasar is shown by the blue cross. The images are shown by the green line and blue crosses in the bottom panel. As expected, they sit *almost* on top of the pure PL. The time delays for the λPL model images are shown next to the bottom panel (blue, titled λPL). As expected the λPL time delays satisfy $\Delta\tau_{ij,\lambda} \approx \lambda\Delta\tau_{ij}$.

III. IF WE ASSUME H_0 FROM CMB/LSS, WHAT DO WE LEARN ABOUT H0LICOW LENSES?

If one used the toy example of Fig. 2 to measure H_0, and if, assuming the pure PL model, one found, for example, $H_0 = 74$ km/s/Mpc, then we expect that the λPL model with $\lambda = 0.75$ would give acceptable likelihood with $H_0 \approx 56$ km/s/Mpc. Our choice of λ in this example is, of course, an exaggeration. To solve the H_0 tension we only need $\lambda \approx 0.9$. In Tab. I we collect some key numbers for six H0LiCOW systems. Taking $H_0 \approx 67$ km/s/Mpc to represent the CMB/LSS measurement, we show in the third column the value of λ that is required to bring the cosmographic H_0 from each system down to the CMB/LSS value.

Noting that H0LiCOW found adequate fits to the lensing reconstruction with the PL model, and given an estimate of λ for each system from Tab. I, we can use Eq. (11) with some model for κ_c to investigate the implied physical shape of

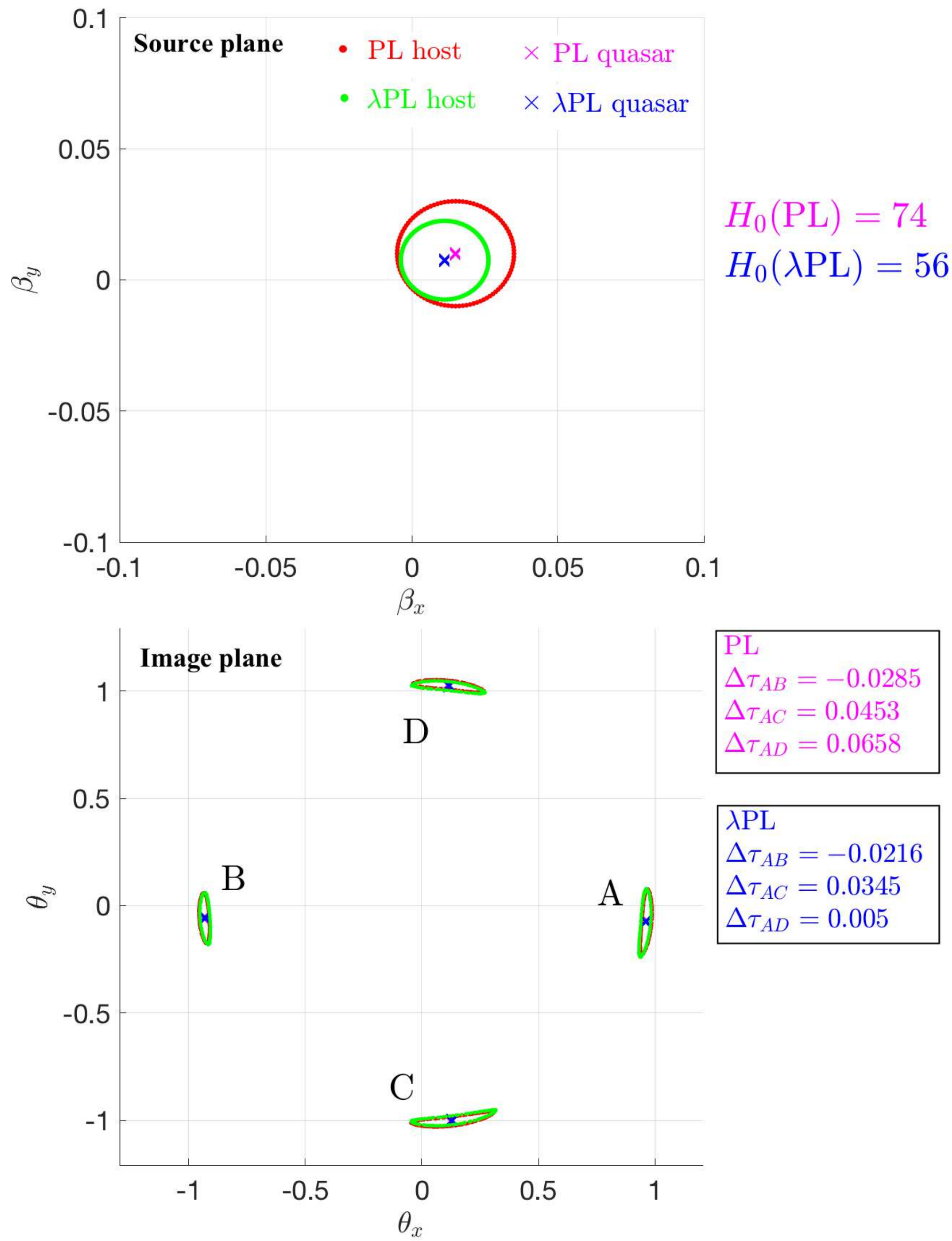

FIG. 2: Example of PL-core MST for $\lambda = 0.75$. **Top:** Source plane. **Bottom:** Image plane. Dimensionless time delays in inset.

the lens galaxies. In Fig. 3 we show the results of this exercise for five systems[4], where we use $\kappa_{\rm cNFW}$ with $\theta_s = 11''$ and $\theta_c = 5.5''$ to play the role of κ_c. For simplicity we ignore the ellipticity q of the PL component. Including it would shift the PL line by a constant factor of $q^{\frac{\gamma-1}{2}}$ if we project along the θ_x direction, or $q^{-\frac{\gamma-1}{2}}$ if we project along θ_y, without adjusting κ_c. Typical H0LiCOW lenses have $q \sim 0.8$ and $\gamma \sim 2$.

[4] The 6th system – J1206 [14] – has $\lambda = 1 \pm 0.08$, so while it would admit a $\lambda \sim 0.92$ core it is also consistent with no core component.

TABLE I: Lens systems from [35]. Values for H_0 (in km/s/Mpc) are from the PL fit (Fig. 6 in [35]). Approximate values for the PL index γ, the Einstein radius θ_E, and the NFW scale θ_s were read from PL and composite NFW+stellar fits reported by papers in the last column.

	H_0	$\lambda = 67/H_0$	γ	θ_E ['']	θ_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	[36]
PG1115	$83.0^{+7.8}_{-7.0}$	$0.81^{+0.07}_{-0.07}$	2.18	1.1	17	0.311	[15]
HE0435	$71.7^{+5.1}_{-4.6}$	$0.93^{+0.07}_{-0.06}$	1.87	1.2	10	0.4546	[15]
DESJ0408	$74.6^{+2.5}_{-2.9}$	$0.9^{+0.03}_{-0.03}$	2	1.9	13	0.6	[37]
WFI2033	$72.6^{+3.3}_{-3.5}$	$0.92^{+0.05}_{-0.04}$	1.95	0.9	11	0.6575	[38]
J1206	$67.0^{+5.7}_{-4.8}$	$1^{+0.08}_{-0.08}$	1.95	1.2	NA	0.745	[14]

We would like to make two clarifications regarding Fig. 3.

The first point to note, is that the particular shape of the profiles at angles $\theta > \theta_E$ is probably poorly constrained by the lensing data. Despite the fact that H0LiCOW utilises extended host information, in practice the host image pixels do not exceed $\theta \lesssim 1.5\theta_E$ or so. As we have seen, the impact of the edge of the core component, which breaks the MSD, enters the image plane geometry at order $(1-\lambda)\theta^2/\theta_c^2$. The λ values needed to sort out the H_0 tension imply $1-\lambda \approx 0.1$ or so for most systems; even for the most deviant system (PG1115) we have $1-\lambda \approx 0.2$. This means that $\theta_c \gtrsim 3\theta_E$ would be enough to bring the MSD-breaking deformation down to the 1% level for most systems. Moreover, in a real analysis, some of this deformation would probably be absorbed by the fitting for the source plane host parameters. A full-fledged analysis à-la H0LiCOW, fitting λPL models to the real data, would be needed to truly quantify the level of the degeneracy. At this point, however, we emphasize that the shape of the profiles in Fig. 3 at $\theta > \theta_E$ comes from our particular choice of κ_c in this example, and is not necessitated by the data.

The second point has to do with fine tuning. In all of the systems in Fig. 3, the pure PL curve intersects the inferred λPL curve very close to θ_E. Since θ_E is a projected parameter of the source-lens-observer system, while the core we speculate here is an intrinsic parameter of the lens, this triple intersect may look at first sight fine-tuned. However, this is not the case. To see this, consider the possibility that the λPL models are in fact the truth. In this case, a H0LiCOW analysis looking for a pure PL fit would find a best-fit pure PL solution that is the MST of the λPL truth; in other words, it would necessarily find the solid PL line, which would necessarily intersect the λPL very near the same θ_E.

IV. DISCUSSION AND SUMMARY

Lensing data alone cannot resolve the mass sheet degeneracy. Therefore, we think that the likelihood function in the cosmographic measurement of H_0 would have a very flat (albeit not completely flat) direction, corresponding to the effective MST λ parameter of λPL models. The H0LiCOW collaboration could thoroughly test this hypothesis on the real data. The λPL models do not require more fitting parameters than, for example, the composite stars+NFW models considered already by H0LiCOW.

Stellar velocity data do resolve the MSD and could constrain λPL models. Probably too large variations over the pure PL, in terms of the total enclosed mass, are not allowed by the stellar velocity data. However, we doubt that stellar velocity data can test an λPL model with $\lambda \approx 0.9$. Either way, if the systematic uncertainty comes to be dominated by the stellar velocity modelling, then the significance of the H_0 tension would need to be revised. In this respect, we agree with the recent discussion of Kochanek [25].

It would be very interesting, if indeed H0LiCOW has detected a core component in the lens galaxies. We are not aware of such cores in standard N-body simulations. Perhaps they could arise if, for example, the dark matter sector contains a component of ultralight [33] or self-interacting [34] dark matter. On the other hand, since typical H0LiCOW lenses have $\theta_E \ll \theta_s$ (inferred in their composite stars+NFW models), it is clear that the lensing data probe the inner part of the lens halo where baryons either dominate the dynamics or at least make a large impact on it, making the simulations challenging. From this point of view, a detection of λPL profiles with $\lambda \approx 0.9$ could be turned into a goal to explain. Before we venture to more speculations, though, it would be reassuring to see a dedicated lensing/time delay analysis that tests λPL models on the real data.

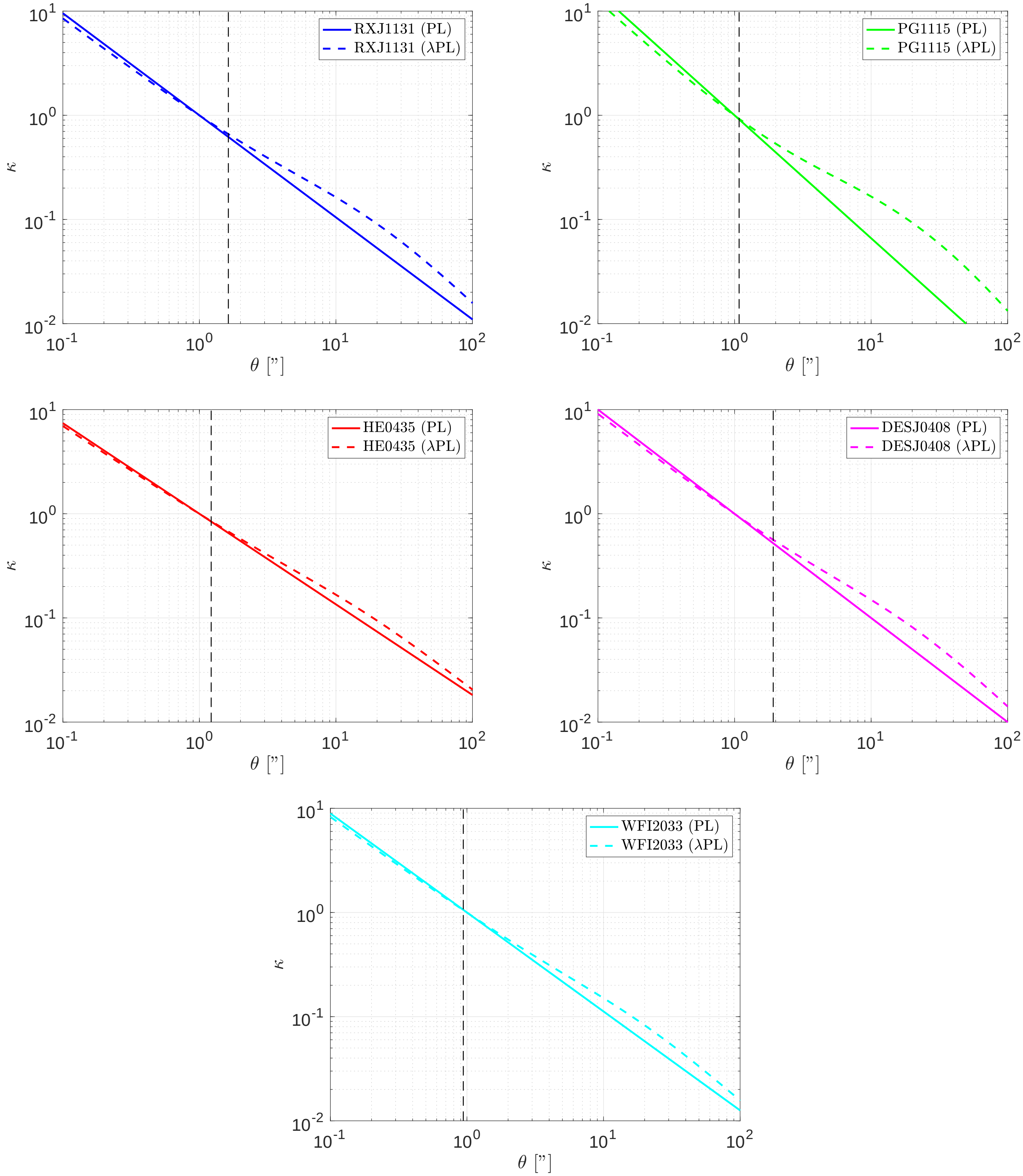

FIG. 3: Inferred κ profiles (1D projection) for the lenses in Tab. I. The vertical dashed line shows θ_E for each system.

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