Strong Gravitational Lensing in the Era of Big Data
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The "External" Shears In Strong Lens Models

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Abstract. The distribution of mass in galaxy-scale strong gravitational lenses is often modelled as an elliptical power law plus 'external shear', which notionally accounts for line-of-sight galaxies and cosmic shear. We argue that it does not, using three lines of evidence from the analysis of 54 galaxy-scale strong lenses: (i) strong lensing external shears do not correlate with weak lensing; (ii) the measured shear magnitudes in strong lenses (which are field galaxies) are too large (exceeding 0.05) for their environment and; (iii) the external shear position angle preferentially aligns or anti-aligns with the mass model position angle, indicating an internal origin. We argue the measured strong lensing shears are therefore systematically accounting for missing complexity in the canonical elliptical power-law mass model. If we can introduce this complexity into our lens models, this will further lensing studies of galaxy formation, dark matter and Cosmology.

Keywords. Strong lensing, galaxies

Strong gravitational lens modeling necessitates the assumption of a mass model for the lens galaxy, in order to trace light from the image-plane to the source-plane. Typically, a power-law mass distribution, often with a fixed slope for isothermality, is assumed. This represents the total mass of the lens galaxy, including stars and dark matter.

In addition to this mass model, strong lens models frequently incorporate an external shear term. Conventionally, this term is thought to account for the lensing effects of nearby line-of-sight galaxies surrounding the lens of interest. It is a common refrain in lens modeling literature to acknowledge the inclusion of this external shear term, as exemplified by the quote from a paper by the author of this section (Nightingale 2019), "Both of the mass models above include an external shear term, which accounts for the contribution of line-of-sight structures to the strong lensing signal."

However, a closer examination of the literature over the past few decades suggests that the external shear in strong lens models might not actually represent the influence of nearby line-of-sight galaxies. This doubt arises from several findings, including the alignment of shear position angles with the lens mass model position angles (Witt 1997), a lack of correlation between shears derived from lens modeling and environmental or weak lensing studies (Wong 2011), and inconsistencies in the lens models of observed quadruply imaged quasars (Gomer 2021). Notably, (Keeton 1997), a frequently cited source when introducing the external shear in a lens model, highlights themselves that "the secondary shear must also be dominated by the primary lens galaxy rather than external perturbations," casting doubt on the external shear's origin. However, it's crucial to acknowledge that these studies often work with limited sample sizes, preventing conclusive determinations.

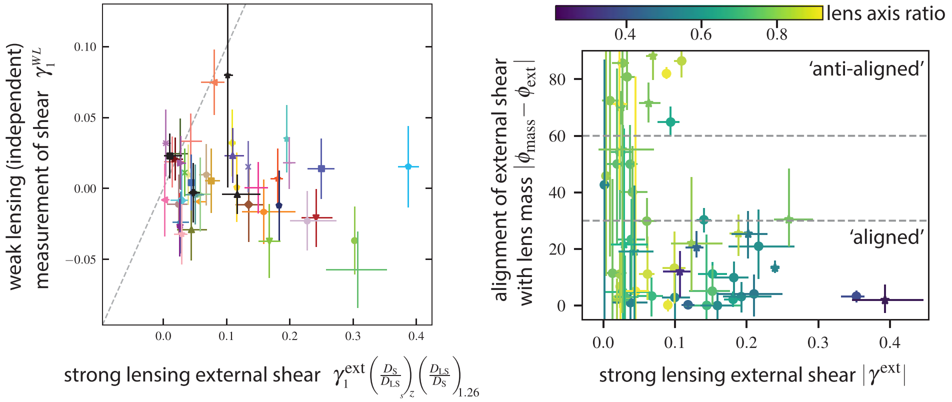

Figure 1. Left Panel: Values of the shear along the lines of sight to 39 galaxy-galaxy lenses, independently measured using strong lensing 'external' shear $\gamma^{\rm SL}$ and weak lensing $\gamma^{\rm WL}$. Strong lensing shears do not correlate with weak lensing shears and go to magnitudes in excess of 0.05. **Right Panel:** Relative orientation of the strong lensing 'external' shear and the major axis of the lens mass, in 54 galaxy-galaxy lenses. In both cases, most of the shears are suspiciously aligned ($\phi_{\rm mass}^{\rm PL+ext} - \phi_{\rm ext}^{\rm PL+ext} \leq 30°$) or anti-aligned ($\phi_{\rm mass}^{\rm PL+ext} - \phi_{\rm ext}^{\rm PL+ext} \geq 60°$) with the lens mass distribution. Points are coloured by the best-fit axis ratio of the lens mass distribution. Highly elliptical lenses often lead to high values of $\gamma_{\rm ext}$.

We presented the results of (Etherington 2023), offering compelling evidence that the shears inferred in strong lens models are predominantly of internal origin. The findings are based on the comprehensive analysis of (Etherington 2022), who performed uniform modeling of 54 strong lenses from the SLACS (Bolton 2008) and BELLS-GALLERY (Shu 2016) samples, using the open-source lens modeling software `PyAutoLens` (Nightingale 2015; Nightingale 2018; Nightingale 2021). The lens modeling assumes an elliptical power-law mass model with external shear, and is supplemented with weak lensing analysis of the SLACS sample that are compared with the strong lens models.

In Figure 1, we present three key pieces of evidence suggesting that the dominant contributor to the shears in strong lens models is not an external signal from nearby line-of-sight galaxies but something else entirely:

- **Lack of Correlation Between Strong and Weak Lensing Shears:** We begin by examining the absence of correlation between strong and weak lensing shears. Weak lensing measurements, which capture shear on larger environmental scales, are expected to closely resemble external shears. The left panel of Figure 1 compares the strong lensing shear $\gamma_1^{\rm SL}$ with the weak lensing shear $\gamma_1^{\rm WL}$. This reveals no such correlation between strong lensing shear ($\gamma_1^{\rm SL}$) and weak lensing shear ($\gamma_1^{\rm WL}$). This discrepancy implies that the strong lens shear is measuring an entirely different phenomenon.
- **Excessive Shear Magnitudes:** We then delve into the issue of shear magnitudes. Strong lenses typically exist in field environments where shear magnitudes should never exceed 0.05, as shear of such magnitude is usually only encountered in galaxy clusters. The x-axis of the right panels of Figure 1 show $\gamma^{\rm ext}$, the inferred shear magnitudes of the strong lens models fitted to all 54 lenses. It shows that approximately half of the lenses in the sample exhibit shear magnitudes exceeding 0.05, with over a quarter exceeding 0.1. These values are far too large for galaxies inhabiting field environments.
- **Alignment of Strong Lensing Shear Position Angles with Mass Model:** The final piece of evidence centers on the alignment of strong lensing shear position angles with the mass model's position angles. If the shear were indeed external, we would expect no correlation with internal mass model parameters. The y-axis of the right panel shows

the of Figure 1 shows the absolute difference of the position angle in degrees of the power-law mass model and strong lens model external shear. A value of 0° indicates the two are aligned, which occurs in ~ 13 lenses, another ~ 5 lenses show anti-alignment with a value of 90°, and the overall lens samples clusters towards these values. The strong lens model external shear is tightly coupled to the lens mass models, indicating an internal origin.

Collectively, these lines of evidence suggest that the primary contributor to the external shears measured in strong lens models is not a genuine external shear from nearby line-of-sight galaxies. Instead, it appears to be driven by other factors, which are yet to be definitively identified. It is expected that a genuine external shear signal from the surrounding environment is present in every strong lens, it is simply sub-dominant to these other factors.

This raises the fundamental question of what the dominant contributor to the measured strong lensing shears might be. (Etherington 2023) argue that the simplicity of the elliptical power-law mass model commonly assumed for lens galaxies is inadequate. This model assumes that the mass distribution can be described by isodensity contours with a single axis ratio and position angle, failing to account for complexities like radial twists in the mass profile and boxiness/diskiness in iso-density contours. Recent simulations and studies support this view, showing that complex mass features, such as boxiness, diskiness, and mass twists, can affect shear measurements in lens models (Cao 2020; VanDeVyvere 2022a; VanDeVyvere 2022b).

At present, we lack a definitive explanation for why strong lens models yield these apparently "external shears." Emphasis must now shift towards understanding the aspects of real lens galaxy's mass distributions that the power-law mass model fails to capture. Looking ahead, this pursuit serves two vital purposes.

Firstly, these "external shears" underlie the lens models used in critical areas of strong lens research, such as dark matter substructure (Vegetti 2014) and Hubble constant measurements (Suyu 2016). The absence of a clear understanding of what these shears represent could introduce unexpected systematics into analyses, with it being established that lens models can trade-off different forms of complex in ways that may bias cosmological measurements (Kochanek 2021) (see also the mass sheet transformation (Schneider 2014)). Ensuring that our models accurately represent the physical systems they are meant to describe is essential for robust analyses, and this is evidently not yet the case for strong lens models.

Secondly, despite the current uncertainty regarding the origin of "external shears," they represent a detected signal worthy of further scientific investigation. We anticipate that this signal results from a combination of complex mass structures within the lens, such as boxiness, diskiness, mass twists, and centroid offsets. Once we decipher this signal, it could offer profound insights into the mass structure of high-redshift galaxies, enriching our understanding of galaxy formation and evolution models. Additionally, a true external shear signal ought to be present in every strong lens observation, which contains cosmologically valuable information, particularly when combined with wide-field weak lensing cosmological surveys (Birrer 2017; Hogg 2022). By comprehending the source of the "external shear," we can unlock the potential to measure the true external shear in each lens, thereby advancing cosmological endeavors.

In conclusion, we implore authors of strong lens papers to refrain from characterizing the external shear in their models as merely "accounting for nearby line-of-sight galaxies." Instead, we encourage them to acknowledge its role in shaping the internal mass complexity of the lens. This shift in perspective will not only rectify a misconception prevalent throughout the literature but also guide us toward a deeper comprehension of the underlying physical nature of the lens galaxies we scrutinize.

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