# ALIGNMENT OF LIGHT AND MASS IN LENSING GALAXIES

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**Abstract**

Something

## 1 Introduction

### 1.1 Context/Background/Motivation

- Why interesting (lensing can constrain mass distribution (enclosed mass constraint independent from model with only few percent uncertainty e.g. Kochanek 1991?, Wambsganss & Paczyski 1994?), insights into structure formation)
- What is to be expected from theory (dm, alternative gravity)

### 1.2 Anything done before?

**Keeton et al. (1997)**: Look at 17 lenses at redshifts ranging between 0.1 and $\sim 1$. Sample consists of mainly passively evolving elliptical galaxies and a few spirals. Claim that generally projected light and dark matter distributions are strongly correlated and are not far out of alignment ($\lesssim 10°$), except in cases where there are strong external tidal perturbations (although misalignments are not necessary in these cases). 'Dark matter halos can be significantly flatter than the light (e.g., Sackett et al. 1994; Buote & Canizares 1994, 1996; also see the review by Sackett 1996)'. To reconstruct the mass they fit singular isothermal ellipsoid (SIE) lens models, which immediately give them the shape. Another model they use is a singular isothermal sphere (SIS) and some external tidal perturbation (shear). As already stated in Keeton et al. (1998), these models sometimes give a bad fit. To obtain a good fit, an another independent source of external shear is needed (external tidal perturbation). They also state that it is known that the lenses Q0957 + 561 (Young et al. 1980, Grogin & Narayan 1996), PG 1115 + 080 (Keeton & Kochanek 1997, Kundic et al. 1997a, Schechter et al. 1997, Tonry 1998), B1422 + 231 (Hogg & Blandford 1994, Kormann et al. 1994, Kundic et al 1997b, Tonry 1998) are subject to significant tidal perturbations by a nearby cluster, group or galaxy (also line-of-sight structure) (–¿ All lying in a environment? Ask Prasenjit). They find no obvious correlation in the axis ratios of the distributions.

**Keeton et al. (1998)**: They used SIEs for the reconstruction of 6 lenses. They find that for many lenses a model with two independent shears (e.g. SIE + 1 external shear) gives a much better fit. Additionally, the fits are much better than just trying to fit different radial mass distributions with the same number of degrees of freedom. Numerical simulations generally produce more elliptical and more triaxial dark matter halos than luminous galaxies (e.g. Warren et al. 1992; Dubinski 1992, 1994). They can however only compare 3 galaxies with eachother.

**Keeton (1998)**: Not sure whether everything was already covered in previous papers or not. He modelled observed lenses to determine their shapes and finds that the dark matter halos are generally aligned with the luminous part. Exceptions are however lenses with known tidal disruptions, where there can be a misalignment. He concludes that the halos were modified by interactions with the galaxies. He however does not state in the abstract how he modelled the lenses.

**Brainerd (2011)**:

**Koopmans et al. (2006)**: They use 15 massive field early-type galaxies selected from the SLACS Survey. To reconstruct the mass distribution (for total mass) they use a SIE mass model (Kormann et al. 1994) without external shear (they justify it by stating that an external shear was not required and also in hindsight as a small $\Delta\theta$ rms spread was reconstructed). The light distribution is based on the nonparametric source reconstruction method by Warren Dye 2003 and is described in Treu Koopmans 2004 and Koopmans 2005. They analyze then the misalignment between light and mass and find that the average difference is $\langle\Delta\theta\rangle = 0° \pm 3°$ with a rms spread of $10°$. For almost spherical SIEs, i.e. $q_{\rm SIE} > 0.75$ the rms spread is $13°$, for less spherical distributions, $q_{\rm SIE} < 0.75$, it is only $3°$. They conclude that this implies that dark matter is aligned with the stellar component on scales $\lesssim 4$ kpc. They also find using a theoretical formula for the external shear from Keeton et al. (1997) and assuming that there is no correlation between the galaxies and external shear orientations, they find that the average external shear has an upper limit of $\langle\gamma_{\rm ext}\rangle \lesssim 0.035$. They conclude therefore that the alignment of mass and light confirms that the external shear is very small and can be neglected. They state that significant external shear would in general cause a spread in $\Delta\theta$ if not accounted for in the models.

**Treu et al. (2009)**: They look at 70 lenses from the SLACS Survey, mostly early-type galaxies (62), 6 disk galaxies, and 2 have ambiguos morphology. They again fit a SIE without external shear and compare the position angles of the distributions. They argue that the stellar contribution is significant at the scales they test and therefore they expect no misalignment if there is no significant external potential. Also the contrary should hold that the rms amplitude of the misalignment is a measure of the external perturbing potential (Keeton et al. (1997); Koopmans et al. (2006)). They find that the correlation between alignment and local resp. global environment is significant. They do not expect a simple relation between these. However, in general lenses in overdense environments will be more likely to be affected by nearby companions, which causes a misalignment (external perturber located in a random direction). They estimate again that external shear of order 0.05-0.06 is needed to match the results.

**Gavazzi et al. (2012)**: They use 16 massive early-type galaxies from SL2S (only 2 are quads). They reconstruct the lens mass with a SIE. They only add an external shear when more information is available. To find the intrinsic source light distribution they try to minimize a $\chi^2$ (they have an observed, pixelated light distribution). All in all, they use a MCMC technique to find the best-fitting 9-parameter-model (6 from light, 3 from SIE (ellipticity, position angle, Einstein radius). They find that stellar and mass ellipticities are tightly correlated (think it is reasonable as light makes up a significant part) with the exception of a few outliers (some basically spherical mass distributions, and one case where the stars are almost round and the mass is flatte -¿ state that source of ellipticities seems to be external shear associated with a satellite). The scatter they find in the ellipticities ratio is however larger than it is in the SLACS sample, which is also at a lower redshift. This is probably due to a much more significant role played by external shear. They also find reasonable alignment between light and mass, the scatter is however larger than for the SLACS sample. For almost round mass distributions the scatter is 25°, for less round distributions it is still 18°. Again the calculate the required average external shear and find (independent of including the round lenses or not) $\langle\gamma_{\rm ext}\rangle = 0.12 \pm 0.05$. This is significantly larger than what they found for the SLACS lenses. They think that it is likely due to the environment of the lenses (Auger et al. (2007); Treu et al. (2009); Auger 2008; Wong et al. (2011)).

**Lehár et al. (2000)**:

### 1.3 New here

- Statistics
- Free-form (explain advantages of free-form over parametric modelling (Saha & Williams (2004), Lubini & Coles (2012), Coe et al. (2008)), cite GLASS (Lubini & Coles (2012))
- group versus stellar misalignment with dm halo

## 2 Data

- SPS (Ignacio Ferreras, Dominik, etc. (Leier et al. (2011)))
- Write why specifically these lenses were chosen, where they're from
- Bundle information in tables (especially what input data was used for the lenses)

| Lens | $z_L$ | Group/Cluster centroid | | Other galaxy | | Galaxy type | Environment | References |
|---|---|---|---|---|---|---|---|---|
| | | $\Delta\alpha$ (") | $\Delta\delta$ (") | $\Delta\alpha$ (") | $\Delta\delta$ (") | | | |
| Q0047 | 0.48 | $3.6 \pm 15.6$ | $43.2 \pm 28.8$ | | | Early-type | G(9) | Wong et al. (2011) |
| Q0142 | 0.49 | | | | | Early-type | - | Lehár et al. (2000) |
| MG0414 | 0.96 | | | $-0.385$ | 1.457 | Early-type | 1 | Schechter & Moore (1993) |
| B0712 | 0.41 | | | 47 | $-91$ | Early-type | 1 | Fassnacht & Lubin (2002) |
| HS0818 | 0.39 | | | | | see below | 1 | aaaaaaaaa |
| RXJ0911 | 0.77 | $-12.0$ | $-39.8$ | | | Early-type | C | Morgan et al. (2001) |
| BRI0952 | 0.63 | | | | | Early-type | - | aaaaaaaaa |
| Q0957 | 0.36 | 4.8 | 2.1 | | | Early-type | C | Chartas et al. (1998) |
| LBQS1009 | 0.87 | | | | | Early-type | - | aaaaaaaaa |
| B1030 | 0.60 | | | $-9.78$ | 8.54 | Early-type | 1 | Lehár et al. (2000) |
| HE1104 | 0.73 | | | | | Early-type | - | aaaaaaaaa |
| PG1115 | 0.31 | $-10.8 \pm 21$ | $-3.6 \pm 15.6$ | | | Early-type | G(13) | Wong et al. (2011) |
| B1152 | 0.439 | | | | | Unknown | - | see below |
| B1422 | 0.34 | $61.2 \pm 25.2$ | $-10.8 \pm 23.4$ | | | Early-type | G(17) | Wong et al. (2011) |
| SBS1520 | 0.72 | | | | | Early-type | G(4) | see below |
| B1600 | 0.41 | $-8.44286$ | $-1.48571$ | | | Late-type | G(7) | Auger et al. (2007) |
| B1608 | 0.63 | $-0.697246$ | 7.96956 | | | Both | G(8) | Fassnacht et al. (2006) |
| MG2016 | 1.01 | | | | | Early-type | C(69) | Toft et al. (2003) |
| B2045 | 0.87 | | | | | Early-type | - | Fassnacht et al. (1999) |
| HE2149 | 0.60 | $-36.6$ | 14.2 | | | Early-type | G | Williams et al. (2006) |
| Q2237 | 0.04 | | | | | Late-type | - | see below |

The pixelated stellar mass maps we use here was reconstructed by Leier (2011). For each pixel the surface brightness was compared with stellar mass-to-light ratios, which were determined by populations synthesis model. Details for this method can be found in Leier (2011), Ferreras et al. (2005), Ferreras et al. (2008).

Here some comments about the environments of the lenses in the sample.

**Q0047-2808**: Wong et al. (2011) find a group of 9 members, spectroscopically confirmed. According to Warren et al. (1996) it is a luminous early-type galaxy.

**Q0142-100**: The required external shear is comparable to the cosmic LSS-contribution, and it also seems to be a passively evolving early-type galaxy according to Lehár et al. (2000) and confirmed by Eigenbrod et al. (2007).

**MG0414+0534**: According to Tonry & Kochanek (1999) the lens seems to be a passively evolving early-type galaxy. Schechter & Moore (1993) find a luminous satellite galaxy north-west of the lens. The position data of this object was taken from CASTLES.

**B0712+472**: According to Fassnacht & Lubin (2002) potentially only one other galaxy 102" to the south-east at a similar redshift. There is however a group of 10 galaxies at a lower redshift. According to Fassnacht & Cohen (1998) the spectrum is typical for an early-type galaxy.

**HS0818+1227**: According to Hagen & Reimers (2000) one galaxy, which seems to be at the same redshift, can be found near the lens. In roughly the same direction, two other brighter galaxies can be found a bit farther away. However, no further inquiries were made whether they all belong to the same group or not. There are also a couple of fainter ones, which could potentially be group members. TO DO: Get relative position of nearest galaxy! More or less everybody lists HS0818 as an early-type, however noone states a source for their belief.

**RXJ0911+0551**: According to Morgan et al. (2001) the lens lies on the outskirts of a cluster environment. The cluster seems to be rather complex and not spherical, and it possibly is not dynamically relaxed. The X-ray emission analysis yields a temperature of 2.3 keV. There is also a satellite galaxy to the north-west direction (Kneib et al. (2000)). The lens is a almost circular early-type galaxy (Sluse et al. (2012)). Time delay: $\Delta t_{BA} = 146 \pm 4$ (Hjorth et al. (2002); CASTLES: BD-delay, here BA-delay).

**BRI0952-0115**: Lens possibly part of smaller system (of 2 or 3 other galaxies), which is found at a slightly higher redshift, according to Eigenbrod et al. (2007). Surely group found in Momcheva et al. (2006) is at a lower redshift than the lens as the redshift estimate $z = 0.41$ was used. Eigenbrod et al. (2007) however find that the redshift is more likely to be $z = 0.632$. In Lehár et al. (2000) it is found that required external shear can be explained easily by a cosmic contribution. Lehár et al. (2000), and later on confirmed by Eigenbrod et al. (2007), find that it seems to be a typical early-type galaxy. TO DO: Why is the such a hugely different redshift estimate in Table 4 of Momcheva et al. (2006)? Reason: In Lehár et al. (2000) this redshift is listed as the lens redshift. −¿ Correct redshift used in analysis?

**Q0957+561**: The lens is a cD galaxy lying close to the center of a cluster with a high sprial galaxy-fraction (e.g. Garrett et al. (1992), Angonin-Willaime et al. (1994), Chartas et al. (1998)). As listed in table 3 of Keeton et al. (2000), the position angles to the center of the cluster of earlier lens reconstructions range between 51.8 deg and 67.8 deg measured north-through-east. Judging 'by hand' from the center of the X-ray emission measured by Chartas et al. (1998), we find $\Delta\alpha = 4.8''$ and $\Delta\delta = 2.1''$, which corresponds to a position angle of 66.4 deg, consistent with the values listed above. Shalyapin et al. (2012) measure the time delay in the g- and r-band. They find $\Delta t_{BA} = 416.5 \pm 1.0$ in the g-band, $\Delta t_{BA} = 420.6 \pm 1.9$ in the r-band. So, they find a three-day lag between these two bands and the two estimates do not agree at the $2\sigma$-level. They argue that this effect can be accounted for by the presence of a substructure and chromatic dispersion (light propagation time increases with decreasing wavelength). TO DO: Better measure of the cluster center? Time delay?

**LBQS1009-0252**: Lehár et al. (2000) find that it is probably an early-type galaxy. According to Faure et al. (2004), there is no significant galaxy overdensity near the lens.

**B1030+074**: As noted by Xanthopoulos et al. (1998) it appears to have some substructure. Lehár et al. (2000) conclude that they are two distinct galaxies. The main one is an red, early-type galaxy. The other component seems to be fitted well by an exponential disk galaxy. They also conclude that no firm statements about the environment can be made. Although there is another galaxy nearby, it is too blue to be an early-type galaxy and thus they cannot estimate its shear contribution. TO DO: No error on position of G1 in Lehár et al. (2000)?

**HE1104-1805**: Lehár et al. (2000) find that it is probably an early-type galaxy (also Courbin et al. (2000)). They also seem to find a group environment. Faure et al. (2004) however rather think that their photometric redshift measurement indicate that these galaxies are at a higher redshift and rather associated with the source. As it is also listed in Faure et al. (2004), modelling of the lens, parametric and free-form, requires strong external shear. Time delay: $\Delta t_{AB} = 162.2^{+6.3}_{-5.9}$ (Morgan et al. (2008); here BA-delay).

**PG1115+080**: Environments analyzed by Momcheva et al. (2006) and Wong et al. (2011). Lying in a small group of 13 members. The lens is an early-type galaxy (Yoo et al. (2005)). Grant et al. (2004) detect X-ray emission from the corresponding group at temperature 0.8 keV. Time delays: Barkana (1997) find $\Delta t_{AC} = 13.3^{+0.9}_{-1.0}$ and $\Delta t_{BA} = 11.7^{+1.5}_{-1.6}$, Tsvetkova et al. (2010) find however $\Delta t_{AC} = 12.0^{+2.4}_{-2.0}$ and $\Delta t_{BA} = 4.4^{+3.2}_{-2.4}$ (here actually BA- and CD-delay).

**B1152+200**: Not much seems to be known about the environment. The lens galaxy type is not known. According to Toft et al. (2000) however, its color is consistent with a late-type or an irregular galaxy.

**B1422+231**: Momcheva et al. (2006) find totally 16 spectroscopically confirmed member galaxies of the group. Using newer data, Wong et al. (2011) find an additional member. Grant et al. (2004) detect X-ray emission from the corresponding group at temperature 1.0 keV. According to Impey et al. (1996) the lens is an early-type galaxy. Although there are measured time delays by Patnaik & Narasimha (2001), they are probably not to trust too much as they deviate quite a bit from theoretical expectations in Raychaudhury et al. (2003). An accurate measurement of the time delays probably requires time delay measurements on the scale of hours.

**SBS1520+530**: There is some uncertainty about the redshift of the galaxy. Burud et al. (2002b) find that their spectroscopic redshift estimate of the galaxy is consistent with $z = 0.71$, which was measured first by Chavushyan et al. (1997). Both however also measured a system at $z = 0.82$. Burud et al. (2002b) however conclude that it does not seem to be associated with the lens. Auger et al. (2008) find another system at $z = 0.76$. They argue that this system is more likely to be the lens, and the foreground system at $z = 0.71$ just a local perturber. The data however does not seem to be conclusive. Auger et al. (2008) also find and spectroscopically confirm 3 groups in the line of sight. One is at $z = 0.716$, with 5 members and the centroid position: $\alpha = 15 : 21 : 48.16$, $\delta = 52 : 53 : 19.5$. Another one at $z = 0.758$, with 13 members and $\alpha = 12 : 21 : 38.22$, $\delta = 52 : 55 : 23.1$. Another one is at the higher redshift $z = 0.818$ with 10 members. Including the lens would change these positions. The lens seems to be an early-type galaxy, possibly with a disc (Auger et al. (2008)). Time delay: $\Delta t_{BA} = 125.8 \pm 2.1$ (Eulaers & Magain (2011); here also BA-delay). TO DO: Dominik has used a lower redshift. Implications for the stellar population synthesis? Redo analysis at a higher redshift.

**B1600+434**: The lens is a nearly edge-on late-type galaxy (Jaunsen & Hjorth (1997)). No significant X-ray emission was detected from the surrounding group (Dai & Kochanek (2005)). According to Auger et al. (2007), the lens lies in a group with at least seven members, which all seem to be late-type galaxies. The centroid of the group is not luminosity-weighted in the table. Time delay: $\Delta t_{AB} = 51 \pm 2$ (Burud et al. (2000); here BA-delay). TO DO: No error on position estimate in paper? −¿ What should the error estimate for the centroid be? Add environment image?

**B1608+656**: The environment and the mass distribution along the line of sight have been analyzed by Fassnacht et al. (2006). All data points to a galaxy merger, so we could as well talk about 9 group members. A luminosity weighted measure was taken to find the group centroid. No errors are given, but as a comparision the median centroid is listed: $\Delta\alpha = 12.5$, $\Delta\delta = 21.6506$. Along the line of sight, there seem to be four other groups. No significant X-ray emission was detected from the surrounding group (Dai & Kochanek (2005)). According to Surpi & Blandford (2003) the galaxy G1 is an early-type galaxy which disrupted probably a late-type galaxy G2. Time delays: $\Delta t_{AB} = 31.5^{+2}_{-1}$, $\Delta t_{CB} = 36.0 \pm 1.5$, $\Delta t_{DB} = 77.0^{+2}_{-1}$ (Fassnacht et al. (2002); here BA-, CA-, DA-delay). TO DO: Errors? Add environment image?

**MG2016+112**: The environments were analyzed by Toft et al. (2003). They find a cluster-environment with photometrically 69 probable galaxies. Most galaxies are close to the lens and many lie in a south-east direction. It seems to be a giant elliptical (e.g. Lawrence et al. (1984), Schneider et al. (1986)). TO DO: Add environment image?

**B2045+265**: To the west of the lens, Fassnacht et al. (1999) find that there may be galaxies in a group at the same redshift as the lens McKean et al. (2007) find evidence for a dwarf satellite galaxy, which would be needed to be included in the analysis. Although Fassnacht et al. (1999) initially classified the galaxy as a late-type Sa galaxy, McKean et al. (2007) find that it is more probable to be an elliptical galaxy as the velocity dispersion is higher than the characteristic velocity dispersion. Furthermore, the source redshift is relatively low compared to the lens redshift, which requires the deflector to have a large dark matter halo. The galaxy is well fitted by a de Vaucouleurs profile. TO DO: Add environment image? Get position of the group?

**HE2149-2745**: According to Eigenbrod et al. (2007) the spectrum is typical for an early-type galaxy. Although initial redshift estimations of Wisotzki et al. (1996) found a probable redshift rang of $\equiv 0.2 - 0.5$ (also see Kochanek et al. (2000)). Burud et al. (2002a) find by cross-correlating the lens spectrum with a template spectrum of an elliptical galaxy that the redshift probably lies in the range $0.49 \leq z \leq 0.60$. They then conclude that the most likely redshift is $z = 0.495 \pm 0.01$. Eigenbrod et al. (2007) however find, that it is more likely to be $z = 0.603 \pm 0.001$. This would make the lens part of a group at this redshift found by Momcheva et al. (2006) of probably 3 other members (kinematically not confirmed). They also find 2 groups at lower redshifts. Williams et al. (2006) calculated a luminosity weighted centroid position. Time delay: $\Delta t_{BA} = 103 \pm 12$ (Burud et al. (2002a); here also BA-delay). TO DO: Change redshift from 0.50 to 0.60 in the calculations.

**Q2237+030**: There seems to be no information available on the environment. According to Yee (1988) the lens is a barred spiral.

Further information about the sample can be found in Leier (2011), Leier et al. (2011), and Sluse et al. (2012).

## 3 Methods

### 3.1 GLASS

- Explain GLASS briefly

We use the new free-form lens modelling framework *GLASS* (Lubini & Coles (2012)). As its predecessor *PixeLens* (Saha & Williams (2004)), it reconstructs a pixelated mass map of a lens reproducing the image positions perfectly. In this case, the arrival time surface for a source at position $\boldsymbol{\theta}_S$ taking the geometric and Shapiro contributions into account can be calculated using (Saha & Williams (1997))

$$\tau(\boldsymbol{\theta}) = \frac{1}{2}|\boldsymbol{\theta}|^2 - \boldsymbol{\theta} \cdot \boldsymbol{\theta}_S - \sum_n \kappa_n \psi_n(\boldsymbol{\theta}), \tag{1}$$

where $\kappa_n$ is the surface mass density in the n-th pixel rescaled by the critical density $\Sigma_{crit}$ and $\psi_n$ is the contribution to the gravitational potential by this pixel.

According to Fermat's principle, lensed images appear where the arrival time surface takes on extremal values $\nabla\tau(\boldsymbol{\theta}) = 0$. Thus we have to solve the following equation

$$\boldsymbol{\theta} - \boldsymbol{\theta}_S - \sum_n \kappa_n \alpha_n = 0, \tag{2}$$

where $\alpha_n$ is the contribution to the bending angle of the n-th pixel. Therefore, to reconstruct the lens, i.e. finding $\{\kappa_n\}$, this linear equation has to be solved. Additional constraints on the lens like individual time delays between images and all priors are also linear. The problem is highly underconstrained, so the solution domain is a high-dimensional polytope.

The dimension of the solution space usually exceeds $\gtrsim 100$ why sophisticated sampling methods are required. Here *GLASS* and *PixeLens* differ. Coles (2008) and Lubini & Coles (2012) show that *PixeLens* does not produce uncorrelated random samples. They propose a new sampling algorithm. They prove that generic high-dimensional volumes indeed are sampled in a much more uniform way. Models in *GLASS* are generated using a MCMC-method with a Metropolis-Hastings algorithm. A new step $x_{i+1}$ of the Markov chain is accepted with the probability

$$\alpha = \min\left(1, \frac{P(x_{i+1})Q(x_i, x_{i+1})}{P(x_i)Q(x_{i+1}, x_i)}\right), \tag{3}$$

where $P(x)$ is the probability distribution samples are drawn from, and $Q(x_i, x_{i+1})$ is the proposal density. It is special in mass modelling that all the valid mass configurations have the same probability, thus $P$ is a constant $\equiv 1$. For Markov chains $Q$ has to be symmetric. It is usually taken to be a multivariate Gaussian $\mathcal{N}(x, \hat{\boldsymbol{\Sigma}})$, where $\hat{\boldsymbol{\Sigma}}$ is an estimate of the true covariance matrix $\boldsymbol{\Sigma}$. In principle it could be estimated by an adaptive chain during the random walk, but then the chain is no longer Markovian as it loses the reversibility property. Therefore, first an initial adaptive burn-in phase is run to get an good estimate $\hat{\boldsymbol{\Sigma}}$, before the real MCMC random walk. Many models can thus be generated and the solution space sampled. The estimation of the covariance matrix is refined in *GLASS* such that models are much less correlated. Further details and tests of the method can be found in Lubini & Coles (2012) and (((citation needed of Jonathan's fake data paper))).

Priors: Reference cosmology, chosen priors, etc.

### 3.2 Shape measure

- Explain shape measure
- Link to tests on fake data
- Include one plot of fake data test

To get a rough estimate of the shape we use the inverse of the moment of inertia tensor we can compute of the mass map. Its eigenvectors and eigenvalues track the shape of the mass distribution. This seemingly crude measure was tested on fake data.

— Need to expand —

## 4 Results

- Show some examples (stellar and dm contour plots, image of lens, arrival time surface, included mass)
- Show money plots
- Comment on a few lenses

## 5 Conclusion

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