The use of light polarization in weak-lensing inversions

by Audit E.,Simmons J. F. L., 1999

presented by
Nikos Mandarakas

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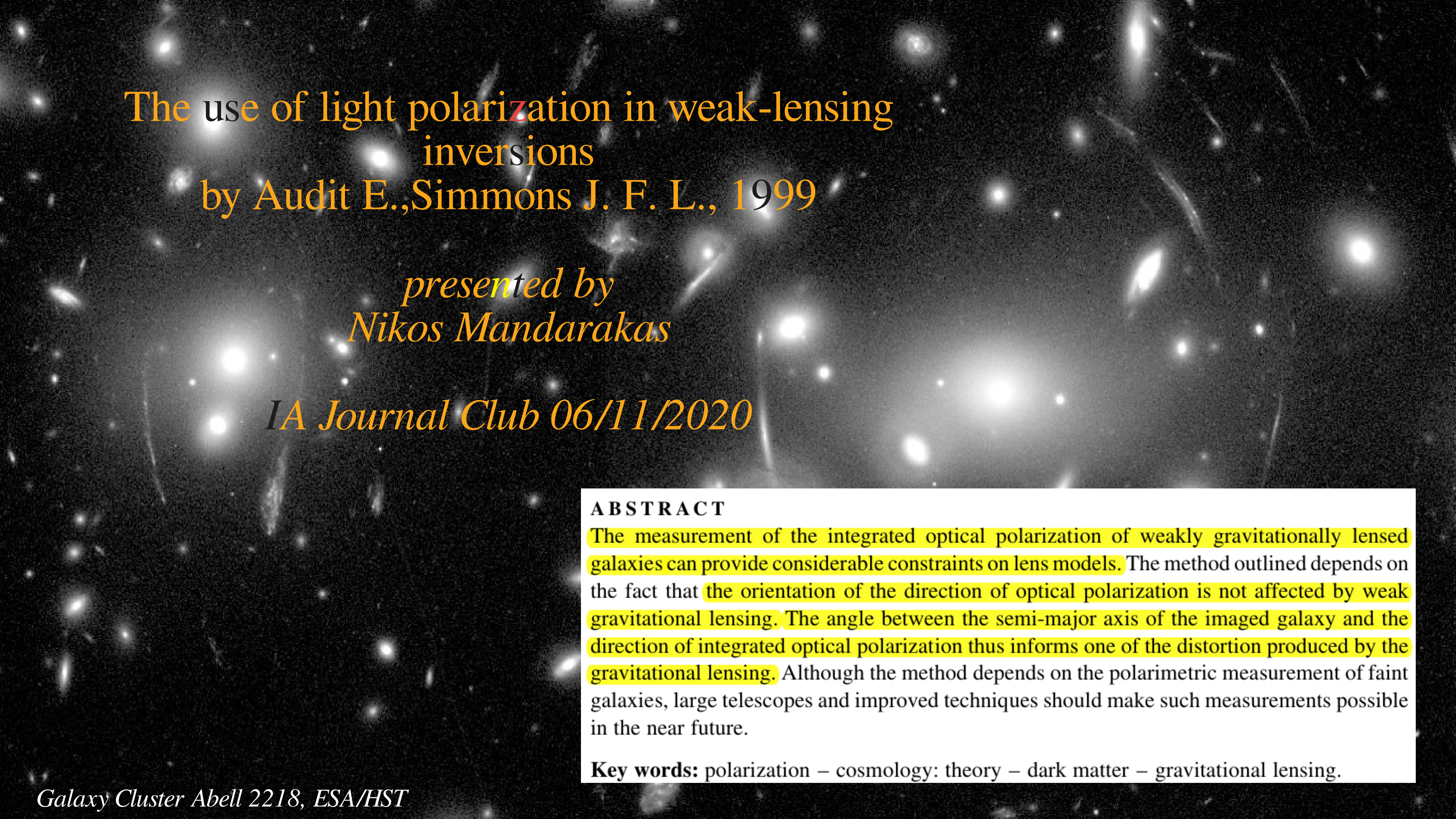
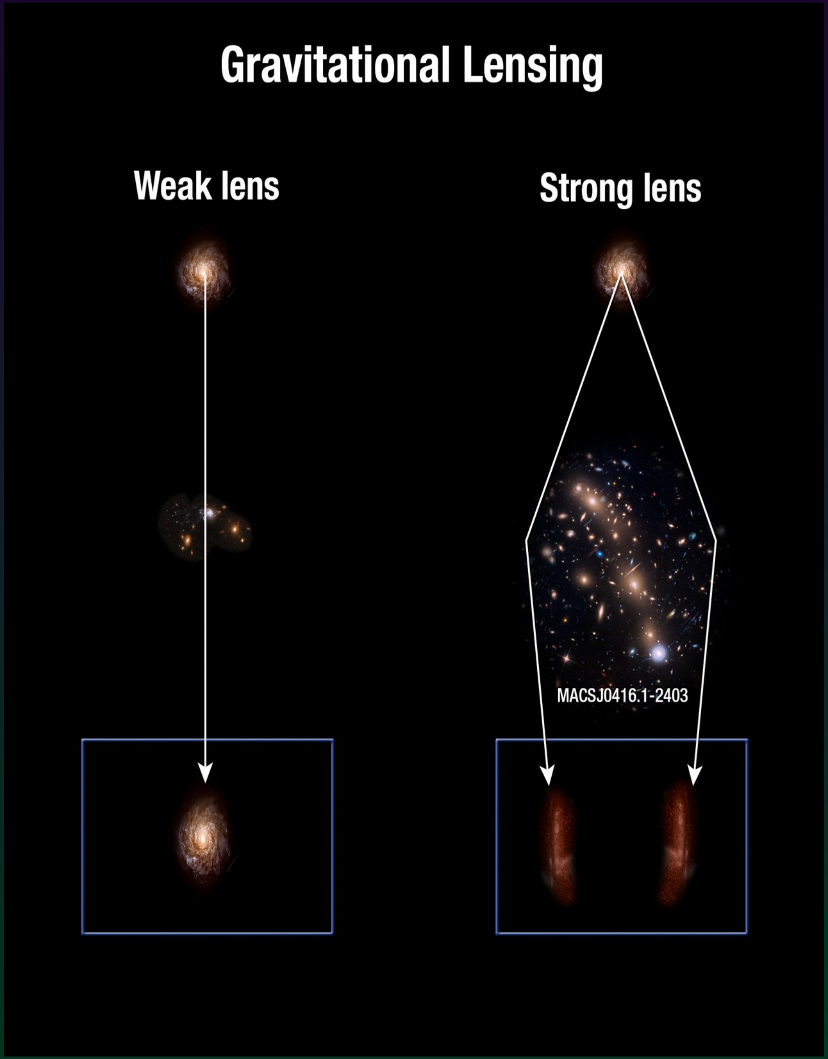
ABSTRACT

The measurement of the integrated optical polarization of weakly gravitationally lensed galaxies can provide considerable constraints on lens models. The method outlined depends on the fact that the orientation of the direction of optical polarization is not affected by weak gravitational lensing. The angle between the semi-major axis of the imaged galaxy and the direction of integrated optical polarization thus informs one of the distortion produced by the gravitational lensing. Although the method depends on the polarimetric measurement of faint galaxies, large telescopes and improved techniques should make such measurements possible in the near future.

Key words: polarization – cosmology: theory – dark matter – gravitational lensing.



Galaxy Cluster Abell 2218, ESA/HST



https://frontierfields.org/

Weak lensing Basics

- Slight distortions in apparent size,orientation, ellipticity
- Affects galaxies and CMB

Why is it important

- Sensitive to all gravitating matter
- Gives direct measurement of matter distribution
- Probe of dark matter

Basics of galactic polarization
Optical regime

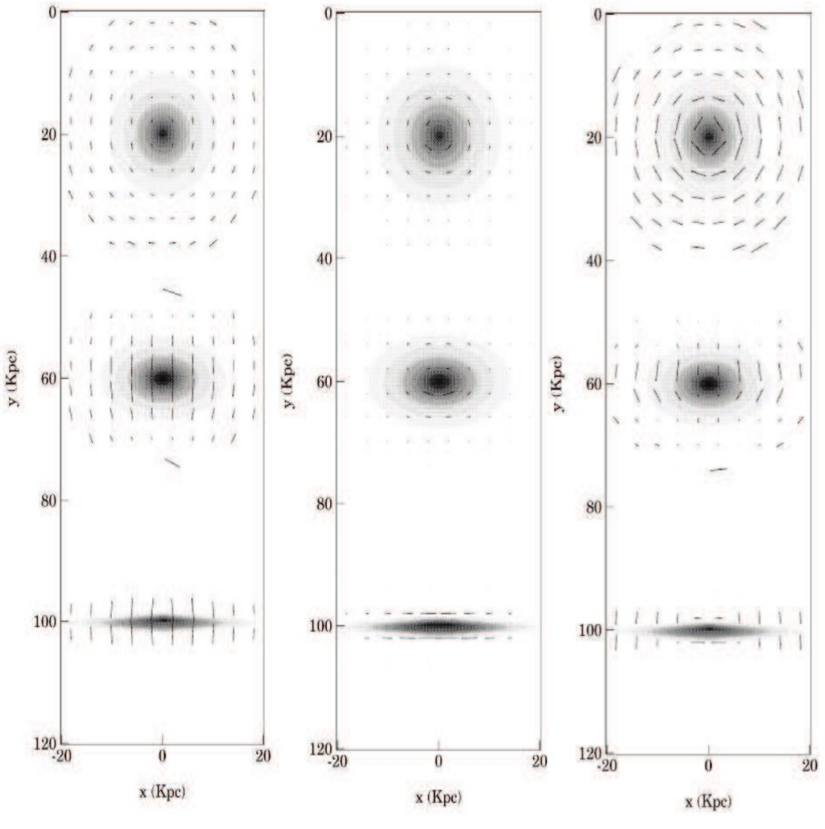
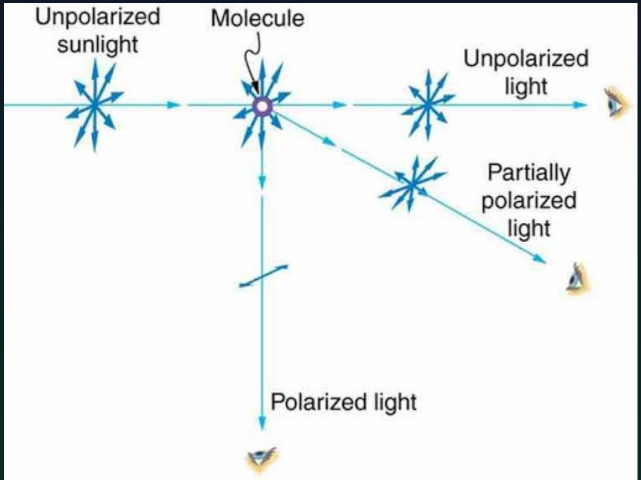
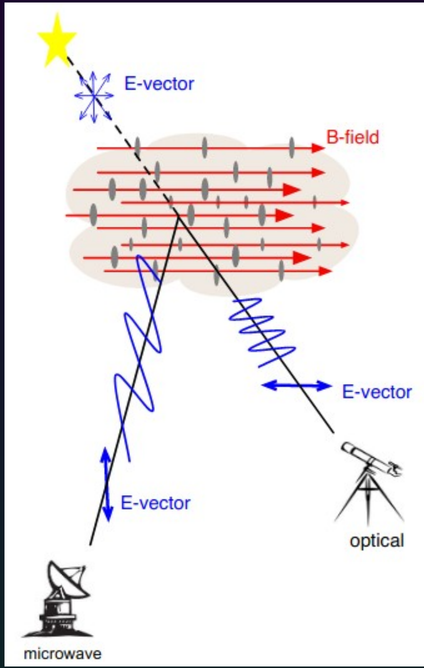


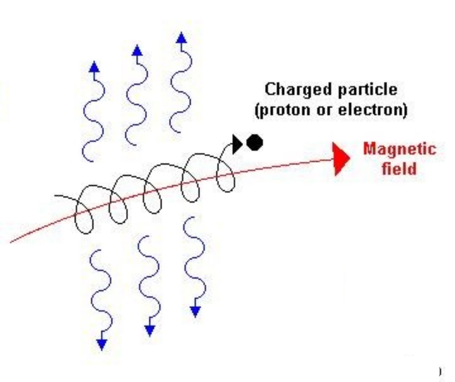
Figure 2. Model outputs assuming scattering only (left), dichroism only (middle) and both mechanisms (right). All figures taken from Wood (1997).

- Scattering
- Dichroic absorption
- Synchrotron

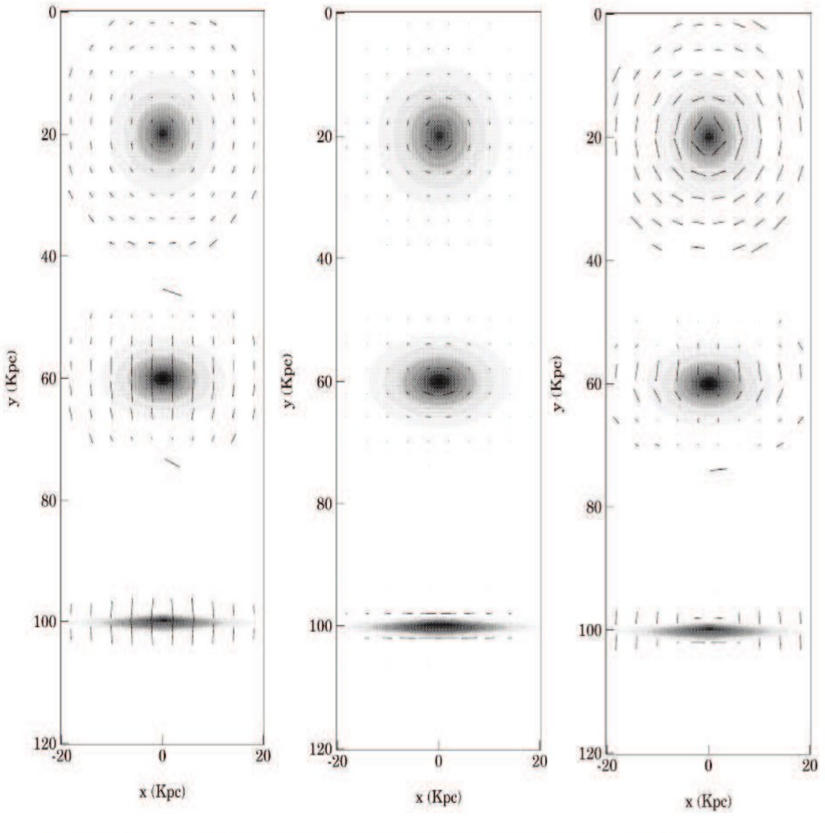




Tassis et al., 2018



Basics of galactic polarization
Optical regime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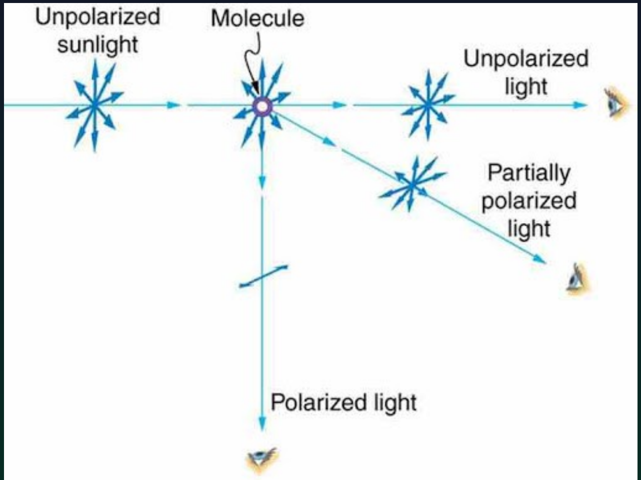
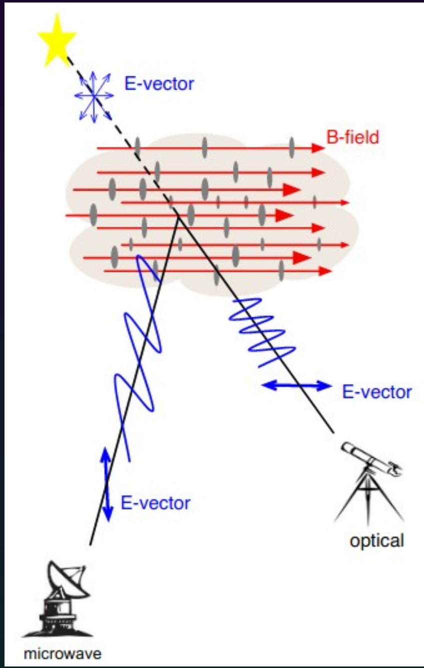
- ~~Synchrotron~~





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Basics of galactic polarization
Optical regime

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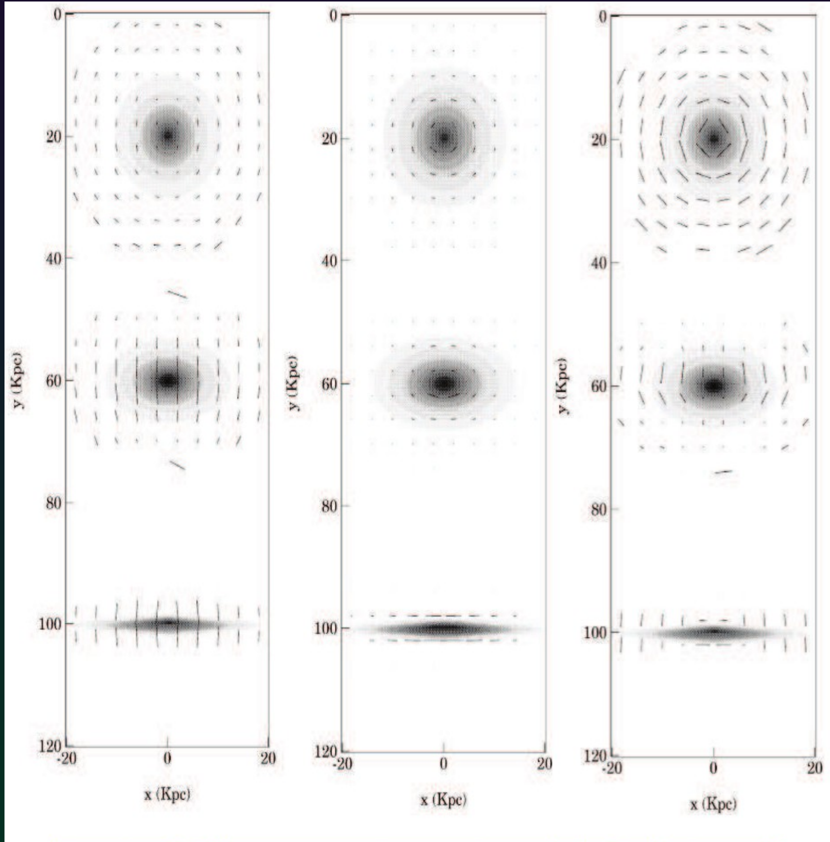

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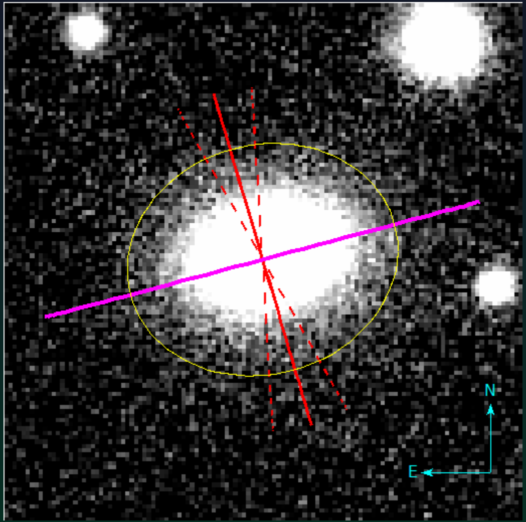

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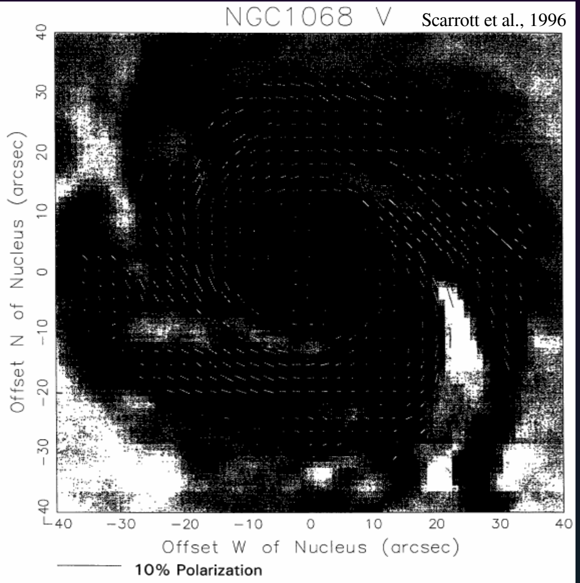


FIG. 1. A polarization map of NGC 1068 [Sb(rs)]. In the non-nuclear regions the orientation of the polarization vectors form a spiral pattern in both the arm and interarm regions. This pattern can be explained in terms of a magnetic field with a spiral configuration and polarization produced by dichroic extinction.

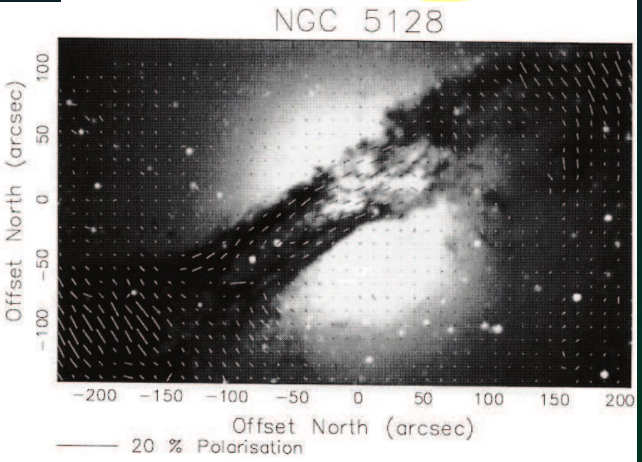


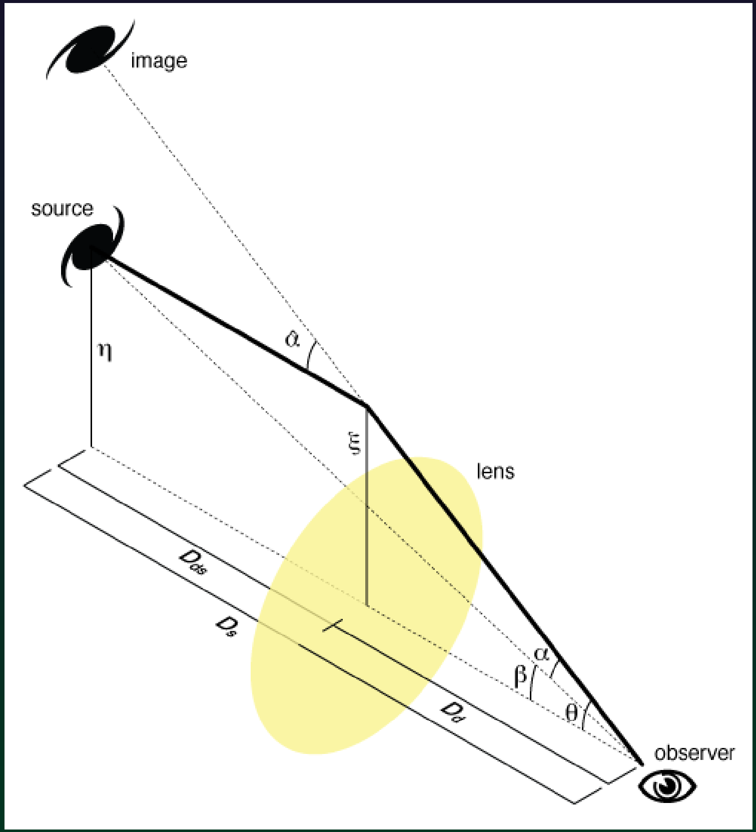
Figure 3. Optical polarization of NGC 5128 (Scarrott et al. 1996). Note the dichroic polarization along the dust lane, scattering of light far from the nucleus, and polarization null points at the transition.

EVPA IS UNALTERED BY GRAVITATIONAL LENSING

It follows from a linear expansion of equation (2) that, in the weak regime, an elliptical source (i.e. elliptical isophotes) will be transformed into an elliptical image (Kochanek 1990). The relation

- Source: $S = (\lambda_s, \Delta\lambda_s, \alpha_s)$
- Image: $I = (\lambda_i, \Delta\lambda_i, \alpha_i)$
- Lens: $\mathcal{L} = (\kappa, \gamma, \theta)$

α: orientation of ellipse
$(\lambda \pm \Delta\lambda)^{1/2}$: major (minor) axis length
θ: angle between lens center and image
κ: convergence
γ: shear



https://en.wikipedia.org

$$\Delta\lambda_s S_s = (\kappa^2 - \gamma^2) S_i \Delta\lambda_i, \quad (6)$$
$$\lambda_s = \lambda_i(\kappa^2 + \gamma^2) + 2\Delta\lambda_i \kappa\gamma C_i, \quad (7)$$
$$\lambda_s \pm \Delta\lambda_s C_s = (\lambda_i \pm \Delta\lambda_i C_i)(\kappa \pm \gamma)^2, \quad (8)$$
$$\Delta\lambda_s C_s = 2\kappa\gamma\lambda_i + \Delta\lambda_i C_i(\kappa^2 + \gamma^2), \quad (9)$$
where we have defined $C_x = \cos 2(\alpha_x - \theta)$ and $S_x = \sin 2(\alpha_x - \theta)$.

↓

$$\Delta l_s S_s = (1 - \Gamma^2) S_i \Delta l_i, \quad (10)$$
$$l_s = (1 + \Gamma^2) + 2\Delta l_i \Gamma C_i, \quad (11)$$
$$l_s \pm \Delta l_s C_s = (1 \pm \Delta l_i C_i)(1 \pm \Gamma)^2, \quad (12)$$
$$\Delta l_s C_s = 2\Gamma + \Delta l_i C_i(1 + \Gamma^2), \quad (13)$$
where $\Delta l_i = \Delta\lambda_i/\lambda_i$, $l_s = \lambda_s/(\kappa^2\lambda_i)$, $\Delta l_s = \Delta\lambda_s/(\kappa^2\lambda_i)$ and $\Gamma = \gamma/\kappa$.

https://en.wikipedia.org

Simulation

- Fix a lens model, i.e. $\kappa(x,y)$, $\gamma(x,y)$, $\theta(x,y)$ in the lens plane
- Generate sample of background galaxies with random position angle and ellipticity assuming uniform distribution
- Try to reconstruct the lens parameters from the images.

A spherical lens model (fixed θ)

$$\kappa = \frac{1}{2}\Phi_0\left(d^{-3/2} + d^{-1/2}\right)$$

$$\gamma = \frac{1}{2}\Phi_0\left(d^{-3/2} - d^{-1/2}\right)$$

where $d = [1 + (r/r_0)^2]$ and r is the distance to the lens centre. In addition to the values of r_0 and Φ_0, the coordinates of the centre of symmetry introduce two further parameters. The centre of the lens can be inferred in various ways (see for example Kochanek 1990) and we shall assume in the rest of this article that it is already known. We have used a lens with $r_0 = 1$ and $\Phi_0 = 0.9$ (Fig. 3).

Assume pairs of r_0, Φ_0,
Assume image parameters are measured exactly
Infer α_s from EVPA

→ χ^2 minimization over the lens parameters → Determination of (r_0,Φ_0)

With measured polarization

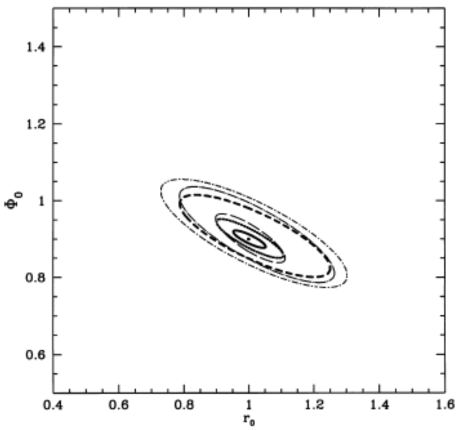


Figure 4. This figure shows the ellipses of the (r_0, Φ_0) plane which contain 70 per cent of the reconstructed points. The solid line is for ($N = 50$, $\epsilon = 2$ per cent), the dotted for ($N = 50$, $\epsilon = 5$ per cent), the short-dashed for ($N = 50$, $\epsilon = 10$ per cent), the long-dashed for ($N = 20$, $\epsilon = 2$ per cent), the dot–short-dashed for ($N = 20$, $\epsilon = 5$ per cent) and the dot–long-dashed for ($N = 10$, $\epsilon = 2$ per cent).

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Without measured polarization

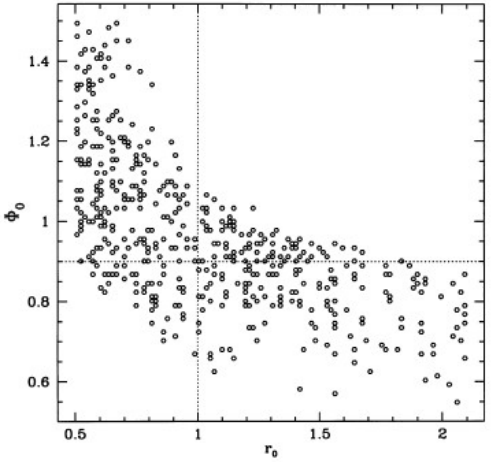

Figure 6. Each point in this figure gives the couple (r_0, Φ_0) reconstructed from a sample of 500 galaxies without using the information given by the polarization. (There are no points outside this square because, during the minimization process, we limited the variation of r_0 to [0.5, 2.1] and that of Φ_0 to [0.4, 1.5].)

An arbitrary spherical lens model (fixed θ)

Assume spherically symmetric lens, known center (as before)

↓

θ is known

Measure EVPA

↓

α_s is known

↓

$$(C_i S_s + S_i C_s)\Delta l_i \Gamma^2 + 2S_s\Gamma + (C_i S_s - S_i C_s)\Delta l_i = 0$$

If there is no measurement in error and the lens is really spherical, local Γ can be determined exactly **USING ONLY 1 GALAXY**

$$C_x = \cos 2(\alpha_x - \theta) \text{ and } S_x = \sin 2(\alpha_x - \theta)$$

Introduce a random error – test for 10000 galaxies

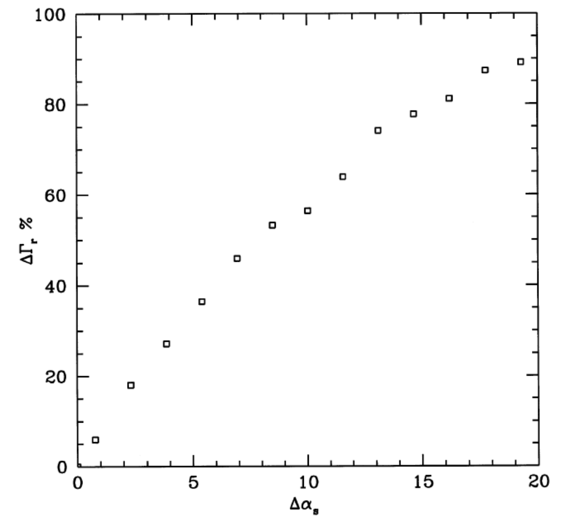

Figure 7. The average error, expressed in per cent, in the reconstructed value of Γ as a function of the error of the orientation, α_s, of the source galaxy, expressed in degrees. One can see that if α_s is given with better than 5° precision then the error in Γ is less than 30 per cent.

- Generate 2 samples of galaxies with a Gaussian error distribution with σ=2.5°, 5°

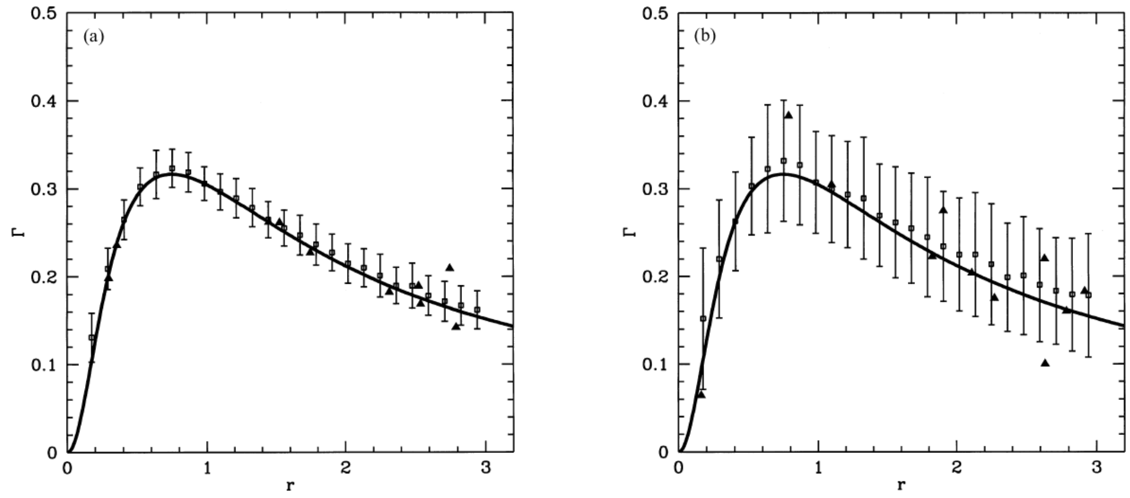

Figure 8. This figure shows the value and the error (squares) of the parameter Γ as a function of radius. The bars are 95 per cent error bars. The filled triangles correspond to the values found for 10 randomly selected galaxies. The left (right) diagram corresponds to a population of galaxies with a $1-\sigma$ dispersion of 2.5° (5°) in the measure of α_s.

- With few galaxies with measured polarization, determination of Γ function is possible
  - If 2 galaxies at similar radii are used, the hypothesis of sphericity can be tested

Arbitrary lenses

- No assumptions about the lens → θ is unknown
- If EVPA is measured → α_s is known → 4 unknowns (l_s,Δl_s,Γ,θ) but 3 equations

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→

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where $\Delta l_i = \Delta\lambda_i/\lambda_i$, $l_s = \lambda_s/(\kappa^2\lambda_i)$, $\Delta l_s = \Delta\lambda_s/(\kappa^2\lambda_i)$ and $\Gamma = \gamma/\kappa$.

- If 2 galaxies can be associated with the same Γ,θ → 6 unknowns with 6 equations
- Take 2 galaxies with angular separation << angular diameter of lens → Assume same gravitational potential

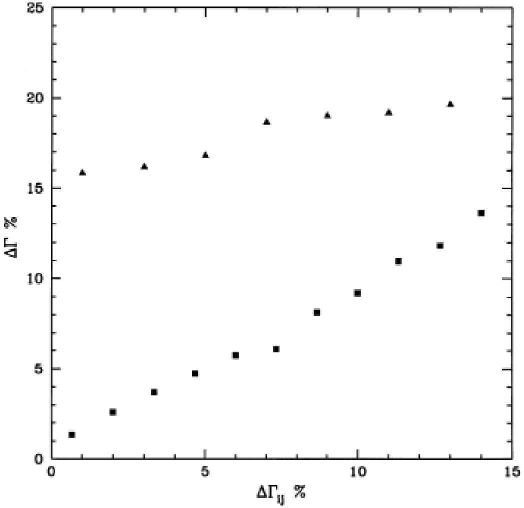

Figure 9. Error in Γ plotted against the difference between Γ^{g_1} and Γ^{g_2} (see text) for galaxies for which α_s is measured exactly (squares) and a standard deviation of 2.5° (triangles).

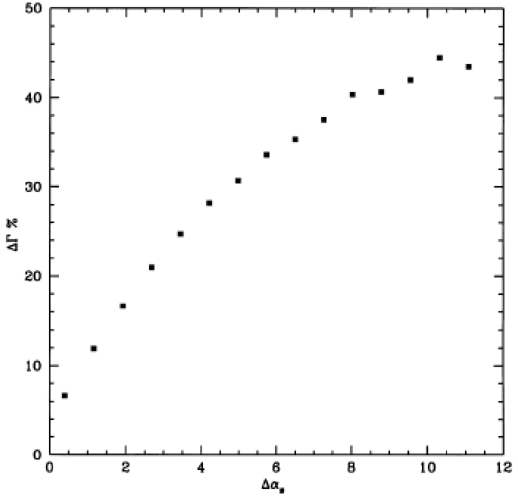

Figure 10. Error in Γ plotted against the average error in α_s.

- One pair of galaxies can constrain Γ
- More pairs of galaxies can constrain Γ more!!

Determine κ,γ from Γ= γ/κ

$$\lambda_s = \kappa^2 \left[\lambda_i(1+\Gamma^2) + 2\Delta\lambda_i \Gamma C_i\right] = a\kappa^2$$

- Use a subset Q of galaxies which have the same κ → $\kappa^2 = \bar{\lambda}_s/\bar{a}$

together or because of some symmetry (all the galaxies can be used and not only those with a measured polarization), we obtain $\kappa^2 = \bar{\lambda}_s/\bar{a}$, where $\bar{a}$, the average of a over the subset S, can be computed using the image and the reconstructed values of Γ and θ (which are equal for all galaxies in S). The average of λ_s, $\bar{\lambda}_s$, cannot be computed because the intrinsic brightness of the sources are not known, but, as the source galaxies (and therefore their properties) are uniformly distributed in the source plane, $\bar{\lambda}_s$ should be constant (independent of the set S chosen) if the average is taken over a sufficiently large number of galaxies. Therefore we can arbitrarily set $\bar{\lambda}_s = 1$ for the whole subset of galaxies. This allows us to compute $\tilde{\kappa} = 1/\bar{a}$ and $\tilde{\gamma} = \Gamma\tilde{\kappa}$ which are proportional to κ and γ respectively, the proportionality factor being a constant throughout

Take-home message

- EVPA is unaltered by weak lensing
- EVPA is a marker of the orientation of the source
- EVPA can be used to derive info on the lensing potential that would be difficult/impossible to obtain otherwise
- Reduces uncertainties of lens parameters – can break degeneracy when data of many objects are available

Thank you


LETS SEE WHO'S
REALLY BEHIND CORONA VIRUS
COULD GRAVITATIONAL LENSING BE RESPONSIBLE?