Fast polarimetric imaging of Kerr black holes using a Schwarzschild approximation

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Latest Advances in X-ray Spectroscopy and Polarimetry

Introduction

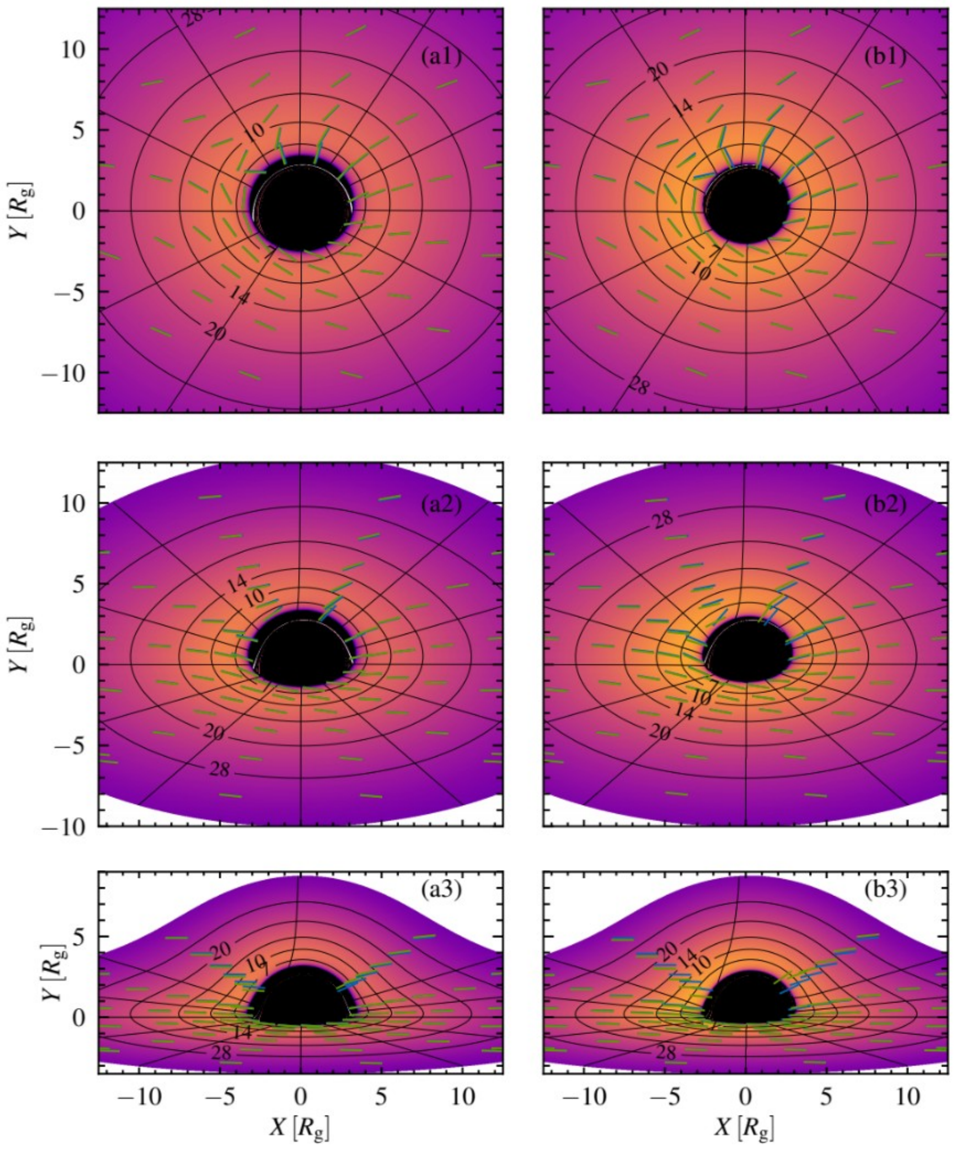
- Polarization carries information about the geometry of the flow and the space-time itself.
- The existance of the BHs spin affects the velocities in the flow, the effective temperature distribution, and the trajectories of light.
- The latter are affected mainly in the innermost parts of the flow. The Schwarzchild metric may give an approximation.
- It allows us to construct very simple and fast analytical method to model the polarization signatures from accretion discs around black holes, and to test various geometrial models.

Solving for geodesics in the Kerr metric

$$
(g_{ab}) = \begin{pmatrix} 1 - \frac{2Mr}{\rho^2} & 0 & 0 & \frac{2Mra\sin^2\theta}{\rho^2} \\ 0 & -\frac{\rho^2}{\Delta} & 0 & 0 \\ 0 & 0 & -\rho^2 & 0 \\ \frac{2Mra\sin^2\theta}{\rho^2} & 0 & 0 & -\sin^2\theta\left(r^2 + a^2 + \frac{2Mra^2\sin^2\theta}{\rho^2}\right), \end{pmatrix}
$$

A defined metric and the geodesic equation to solve numerically

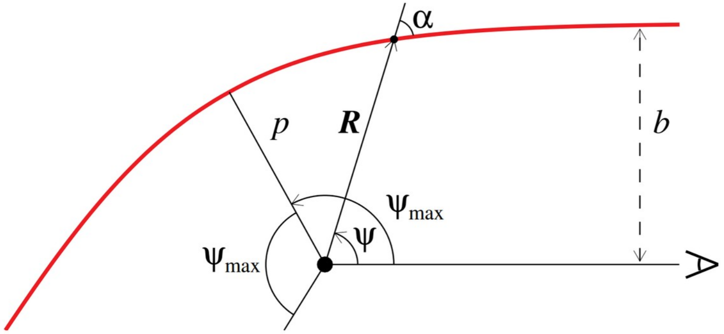
$$
\frac{\mathrm{d}u^a(\lambda)}{\mathrm{d}\lambda} = -\Gamma^a_{bc}u^b u^c + f^a
$$



a paper in preparation

Schwarzschild case

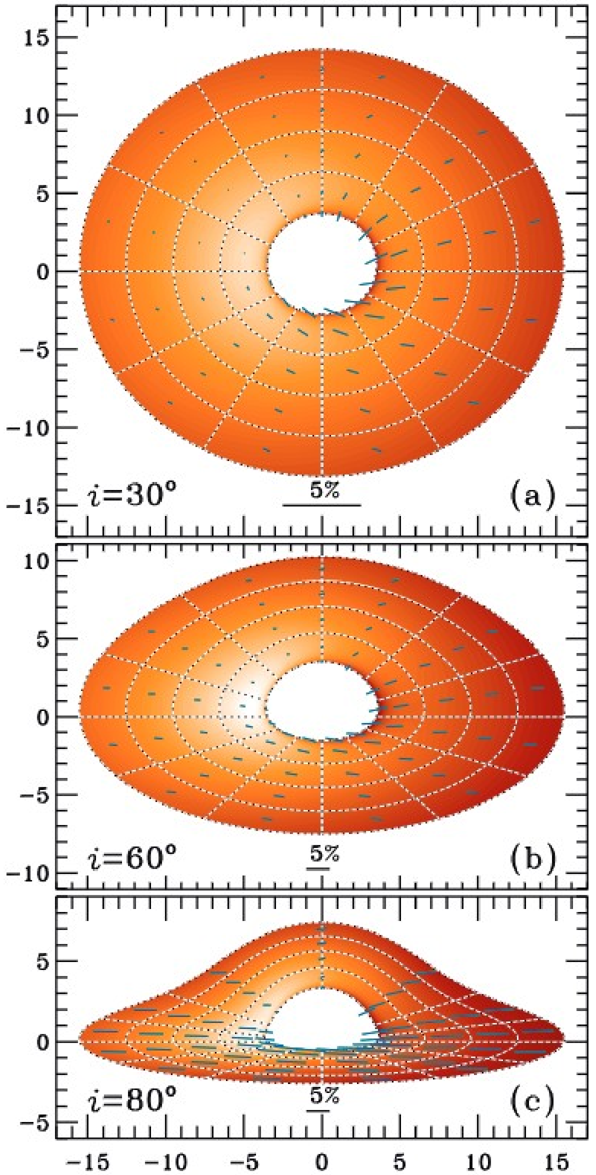
In the Schwarzschild metric the geodesics are planar and the endpoints of a light trajectory can be connected with an integral expression and an analytical approximation for it.



$$\psi(R,\alpha) = \int_R^\infty \frac{\mathrm{d}r}{r^2}\left[\frac{1}{b^2} - \frac{1}{r^2}\left(1 - \frac{R_S}{r}\right)\right]^{-1/2}$$

[Poutanen, J. (2020)]: $$x = (1-u)y\left(1 + \frac{u^2y^2}{112} - \frac{e}{100}uy(\ln(1-y/2)+y/2)\right)$$

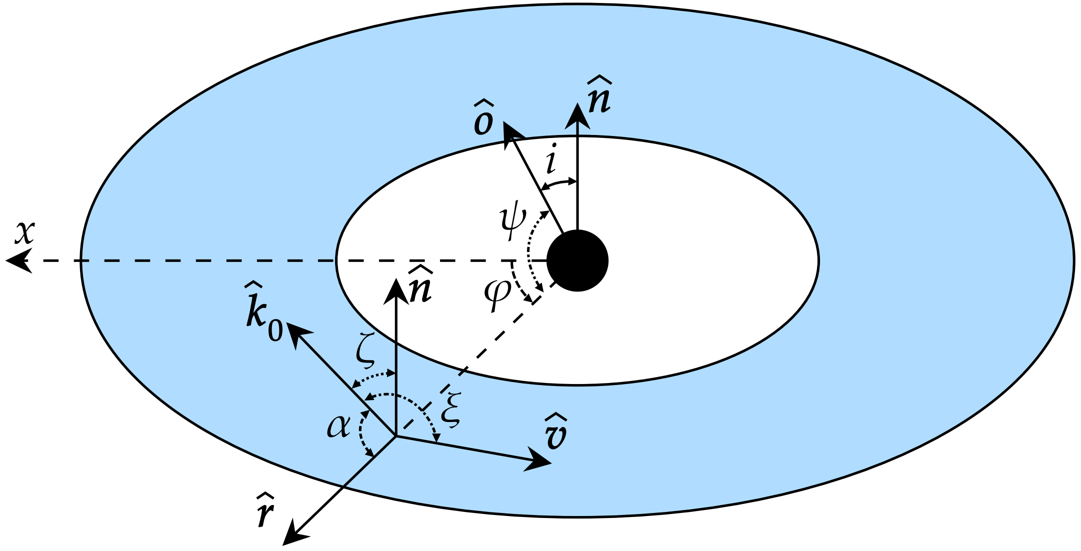
where $x = 1 - \cos\alpha$, $y = 1 - \cos\psi$, and $u = 2/r$.



Loktev et al. (2021)

The disk model and the polarization rotation

As an example we consider a simple thin equatorial disk geometry.



Polarization frame rotations:

$$\tan\chi^{\mathrm{SR}} = -\beta\,\frac{\cos\alpha\cos\zeta}{\sin^2\zeta - \beta\cos\xi}$$

$$\tan\chi^{\mathrm{GR}} = \frac{\cos i \sin\phi}{\cos\phi + b^{-1}\sin i}$$

where $$b = \frac{\cos\alpha - \cos\psi}{1 - \cos\alpha\cos\psi}$$

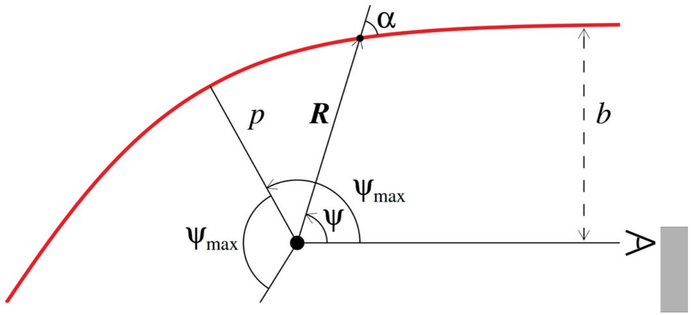
$$\chi^{\mathrm{tot}} = \chi^{\mathrm{SR}} + \chi^{\mathrm{GR}}$$

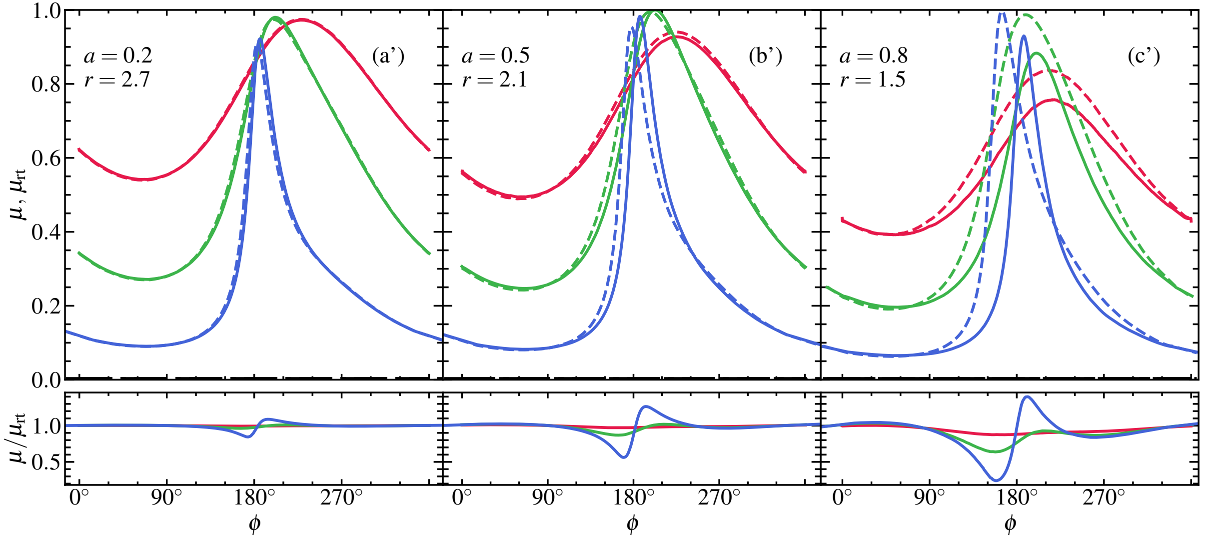
Loktev et al. (2021)

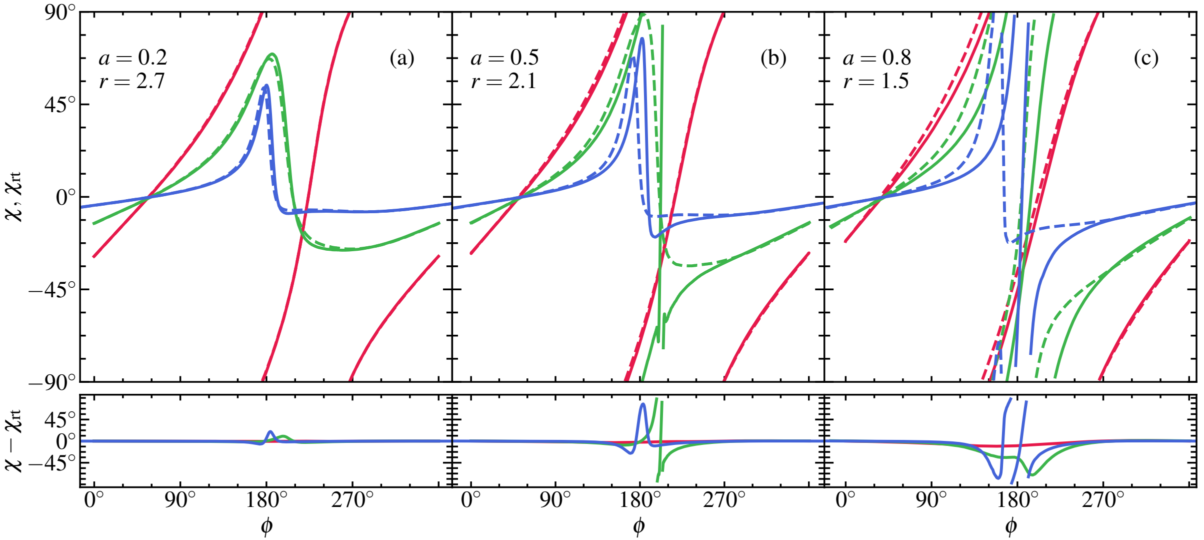
At the innermost orbit

Higher spins and smaller inner radius - the errors arehigher.

The most drastic - at azimuth about 180°
(behind the black hole)
At the front – not so much.



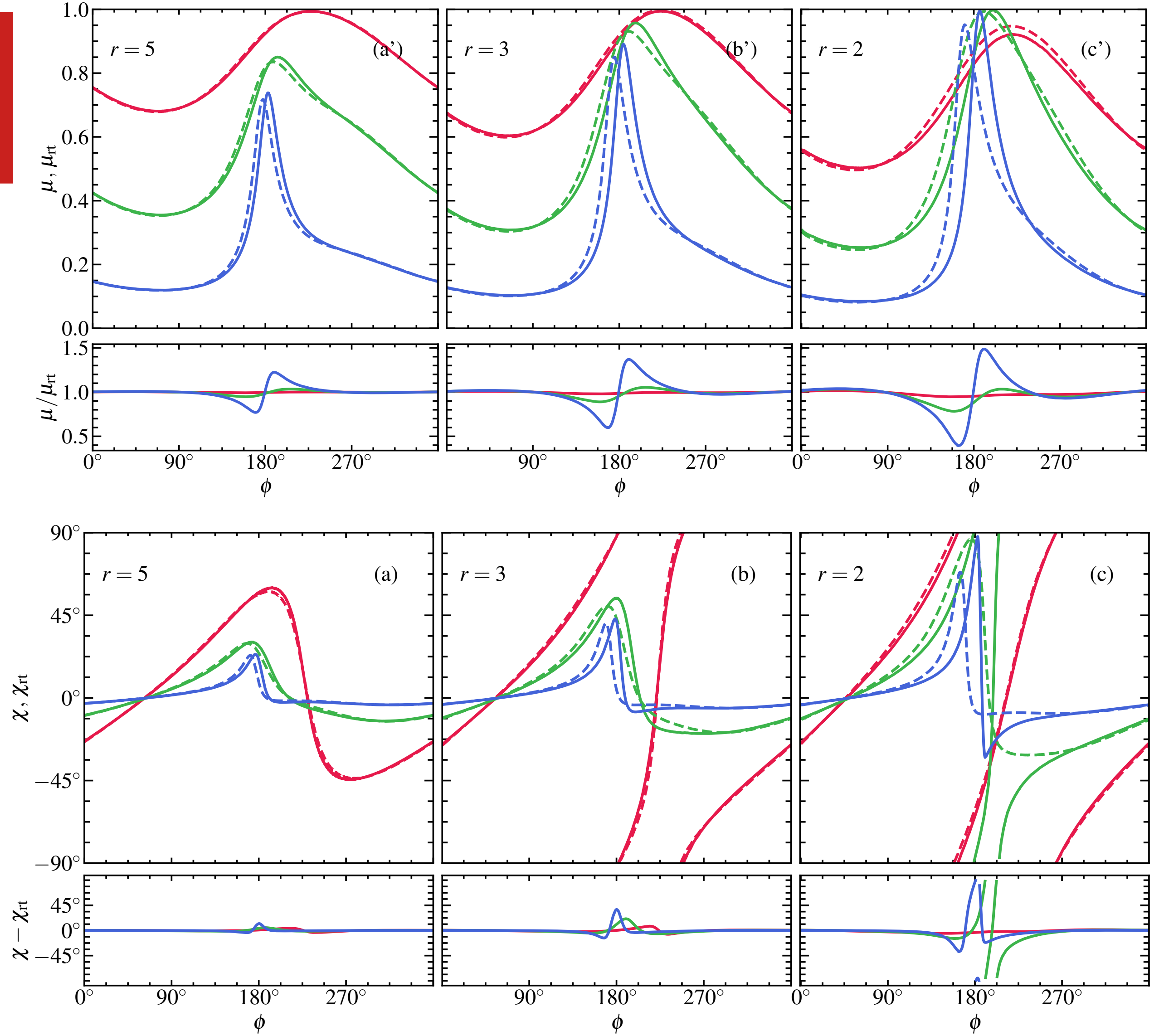




At wider orbits

At wider orbits the spin does not affect the light trajectories as much.

For moderate inclinations, the approximatons works especially well.



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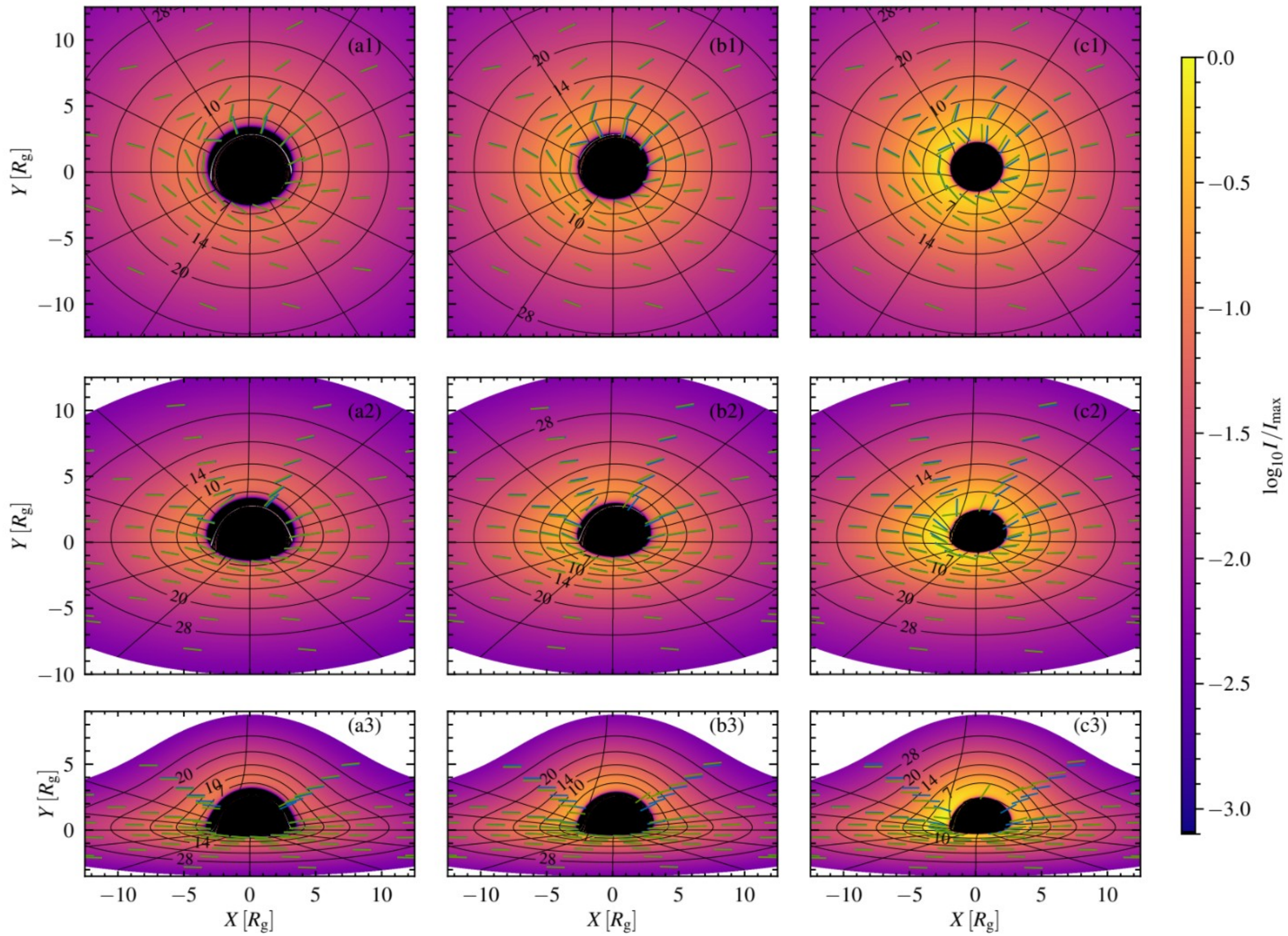
Images

Novikov & Thorne disck

Black-body spectra

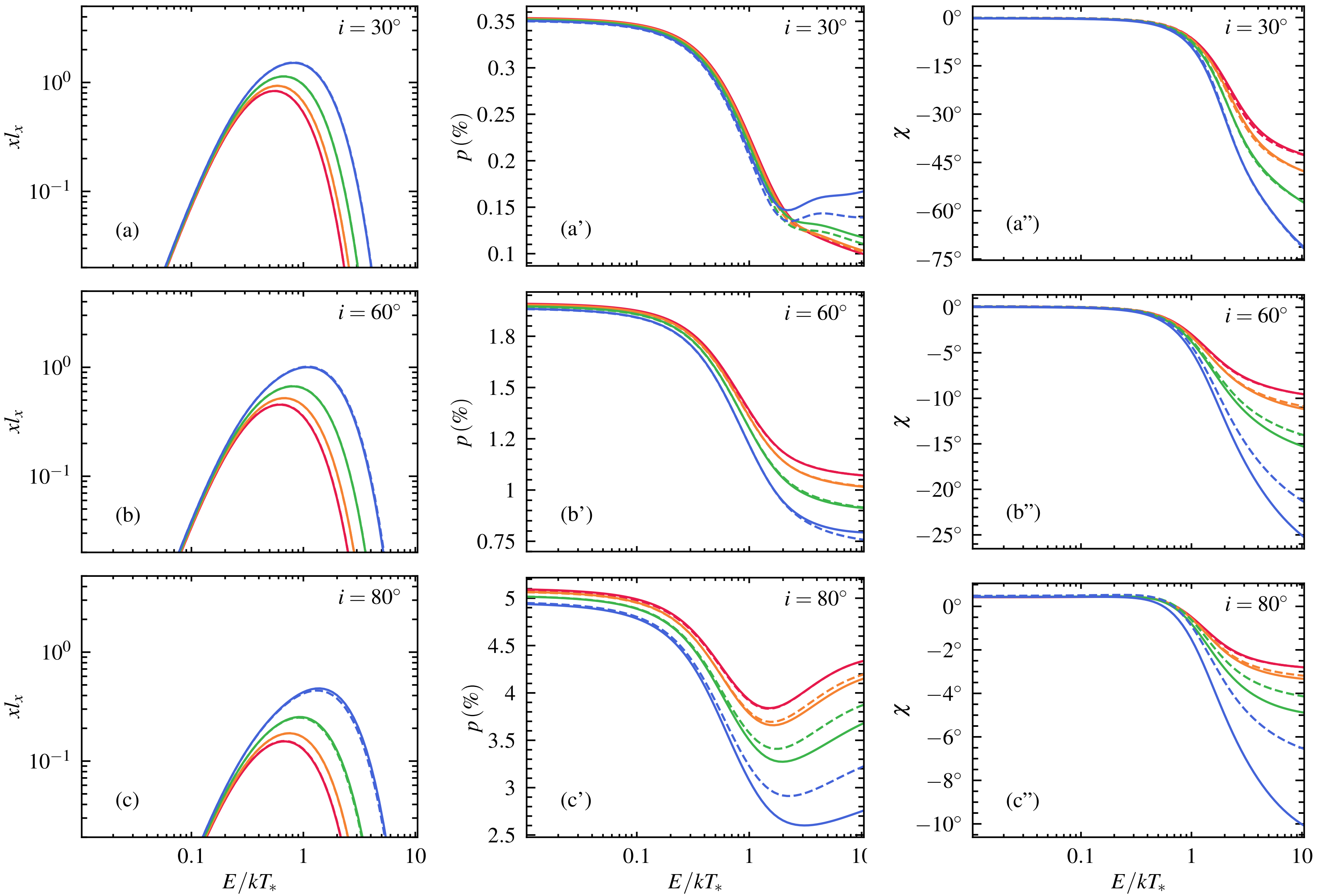
Chandresekhar angular and polarization profile for pure electron scattering atmosphere



Spectra

The spins

$a =$
0 (red),
0.2 (orange),
0.5 (green),
0.8 (blue)



Conclusions

- The method allows us to compute the observable X-ray polarization quickly (100 times faster than numerical ray tracing computation).

- Schwarzschild approximation can be applied to a Kerr black hole for fast computation, while $a<0.8$, or $i<80^{o}$, or large inner radius, etc.

- This approximation is useful for spectral fitting, for testing various geometries of the flow the images are computed on the spot.

The end

Thank you