l'Observatoire de Paris | LESIA
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

PSL UNIVERSITÉ PARIS

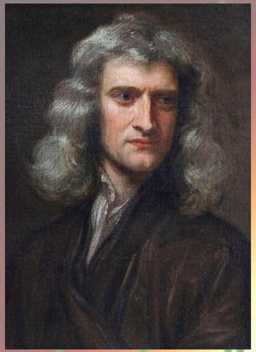
Synthetic polarized observables in curved space-time with the ray-tracing code Gyoto

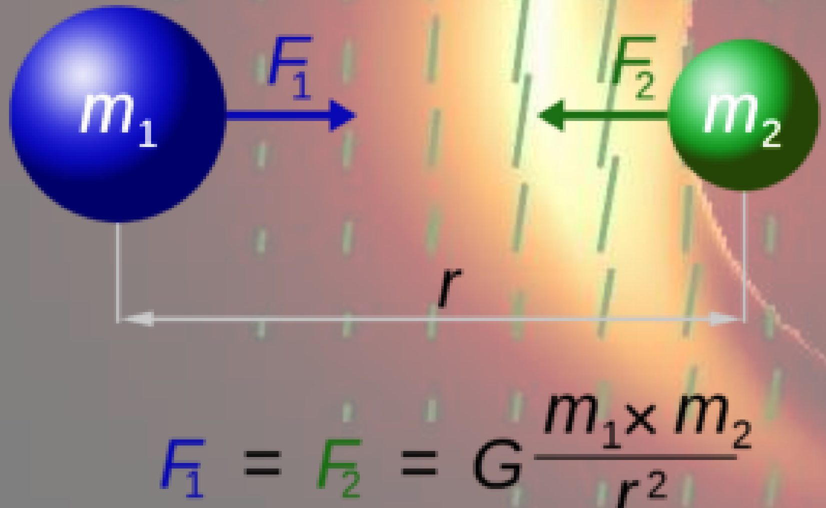
Journées PNHE 6-8 Septembre 2023

Institut d'Astrophysique de Paris

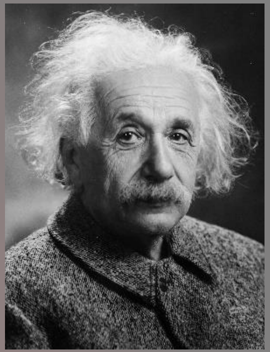
Nicolas Aimar, Thibaut Paumard, Frédéric Vincent, Eric Gourgoulhon, Guy Perrin

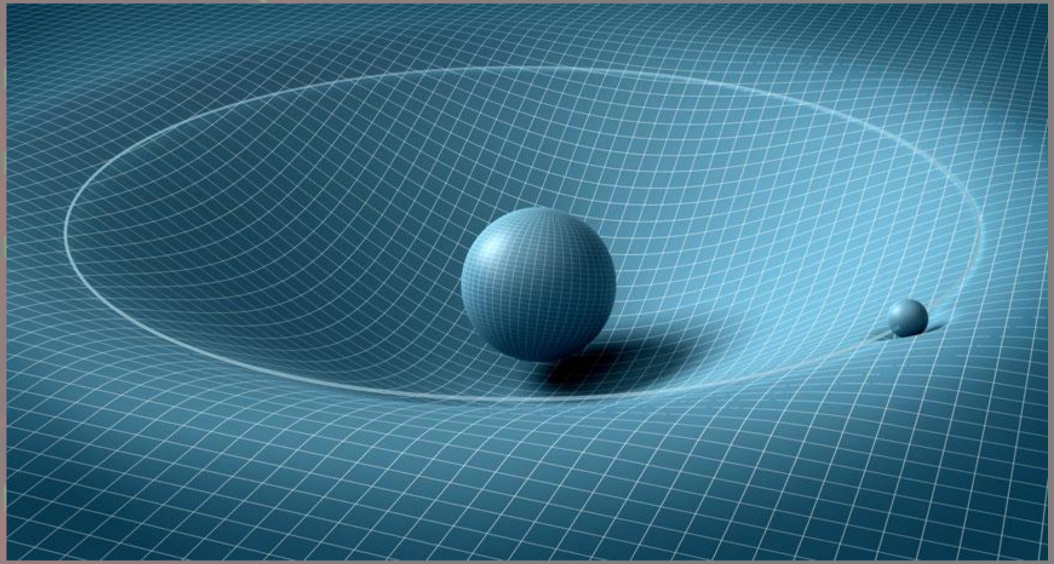
I. Introduction



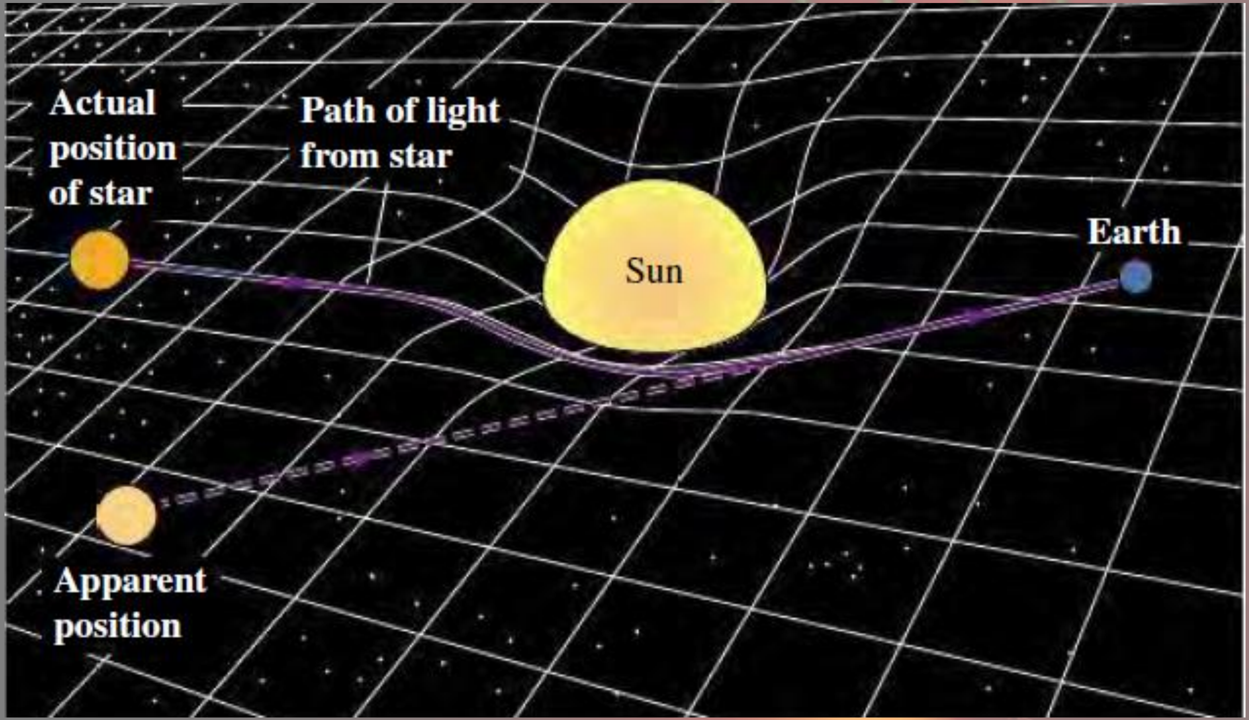


Credits : EWT

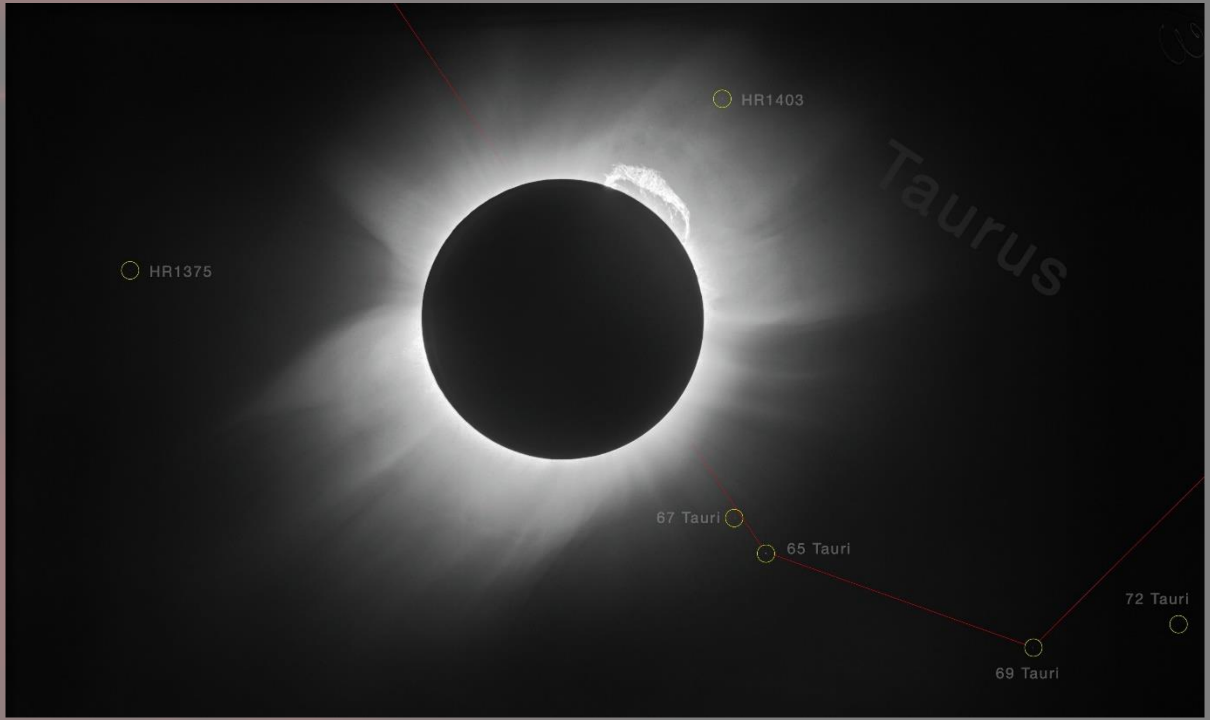




Credits : Science News

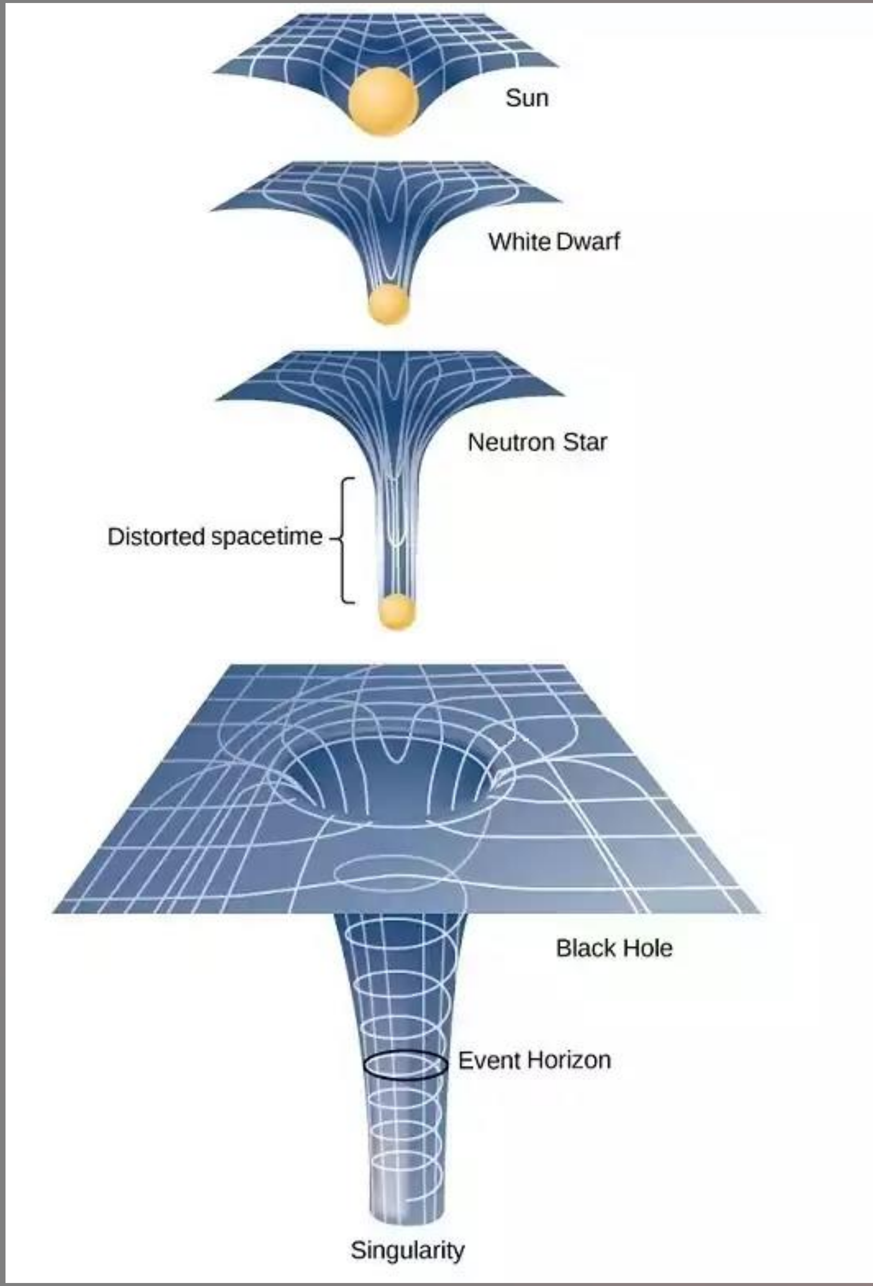


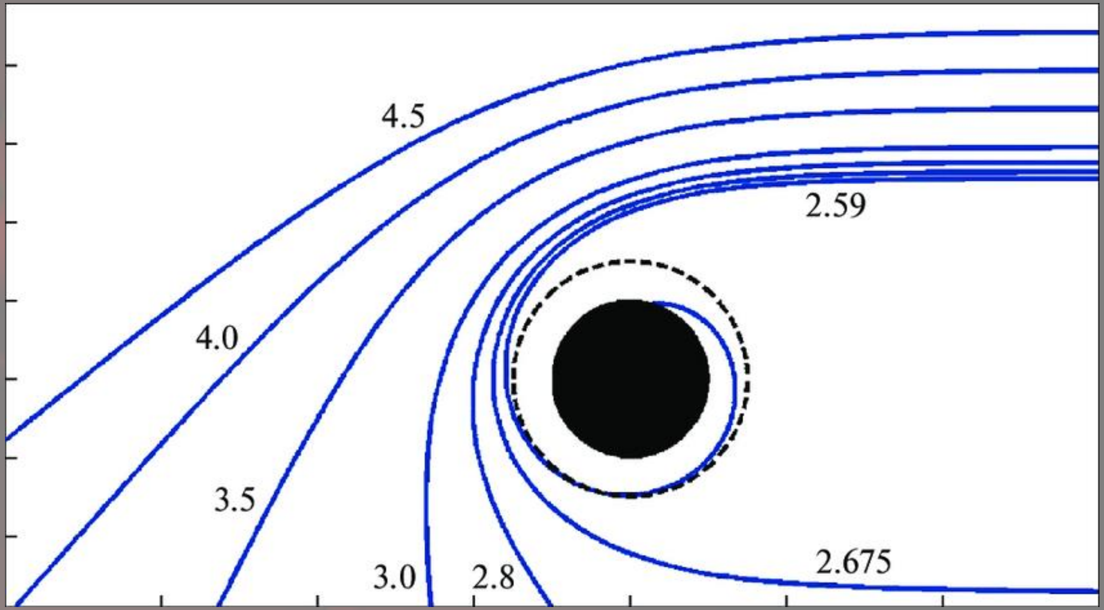
Light bending due to curvature of space-time.



Total solar eclipse of 1919.

Credits : ESO/Landessternwarte Heidelberg-Königstuhl/F. W. Dyson, A. S. Eddington, &; C. Davidson





Bugaev, M. & Novikov, I. & Repin, S. & Shelkovnikova, A.. (2021)

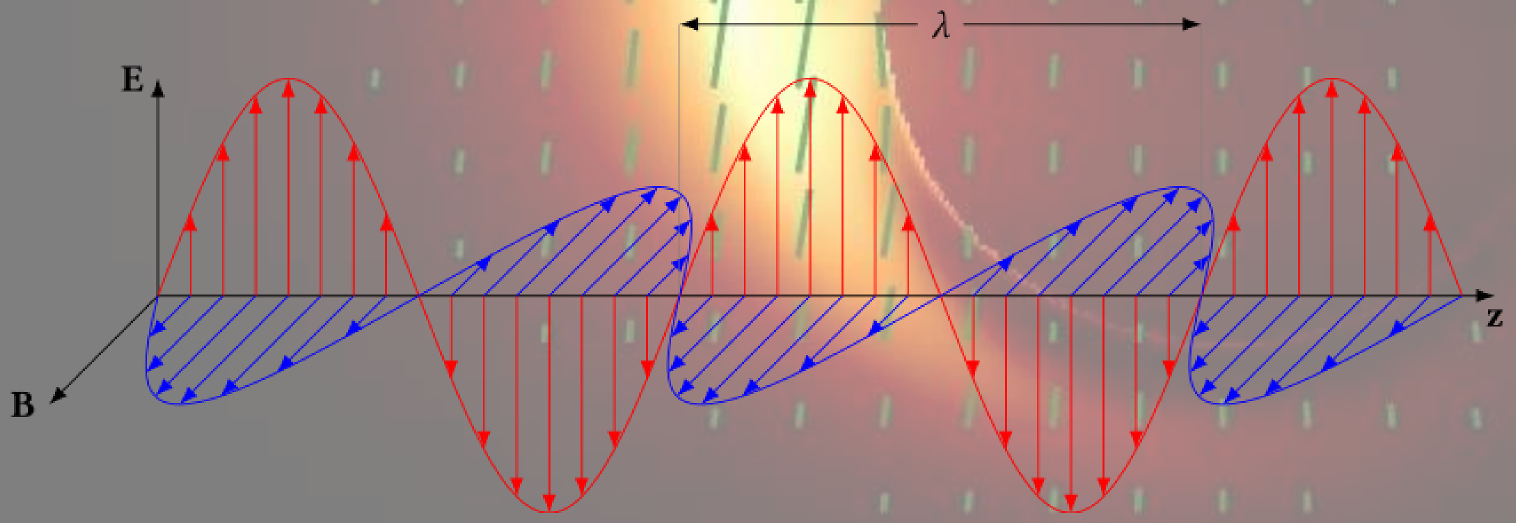
II. Polarisation

Definition : *The polarisation vector* ***F*** *of an electromagnetic wave is the vector orthogonal to the direction of propagation* ***k*** *and to the magnetic vector* ***B****.*

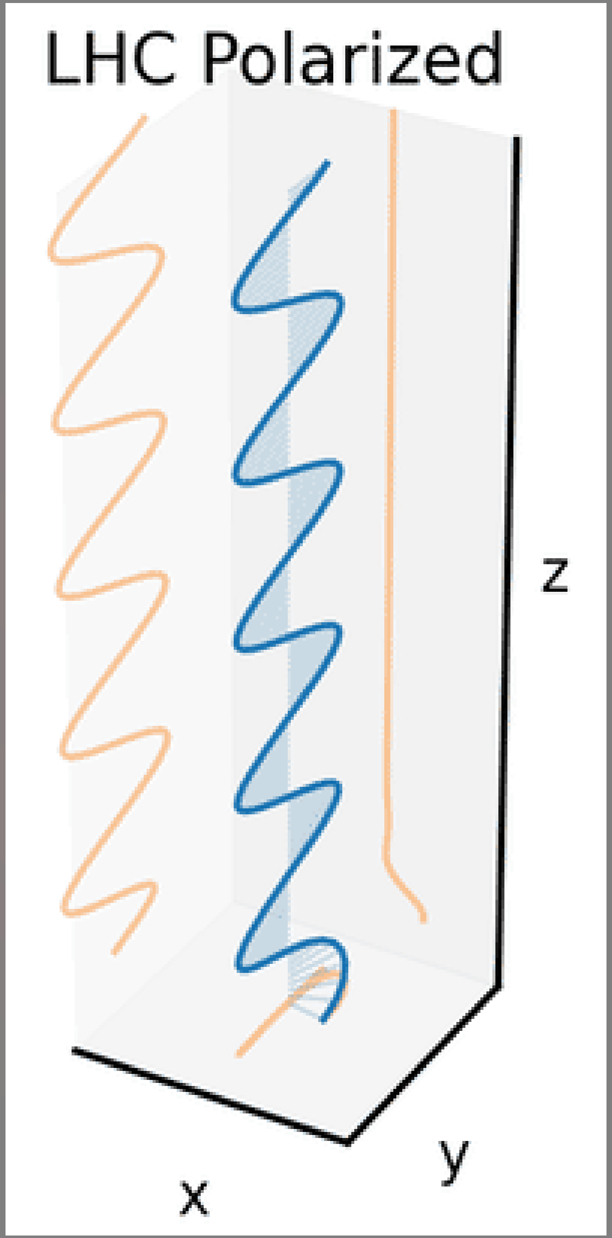
⇒ $\mathbf{F} = \mathbf{k} \times \mathbf{B}$

In vacuum : $\mathbf{F} = \pm \mathbf{E}$ (the electric field)

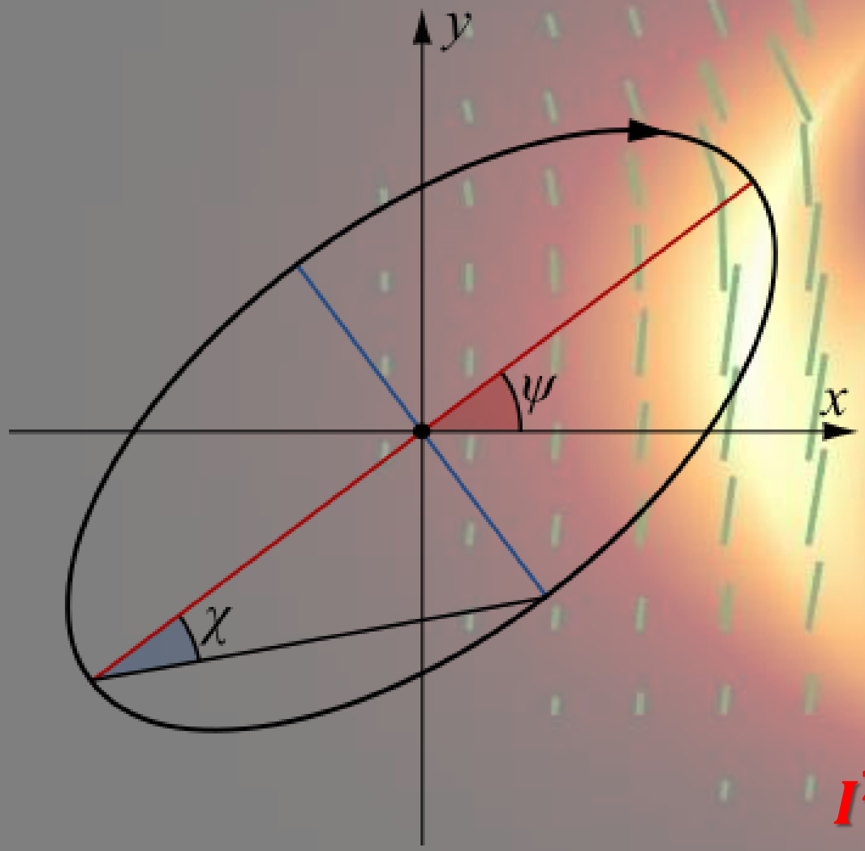
In plasma : $\mathbf{F} \neq \mathbf{E}$



Credit : SuperManu, Wikimedia Commons



II. Polarisation



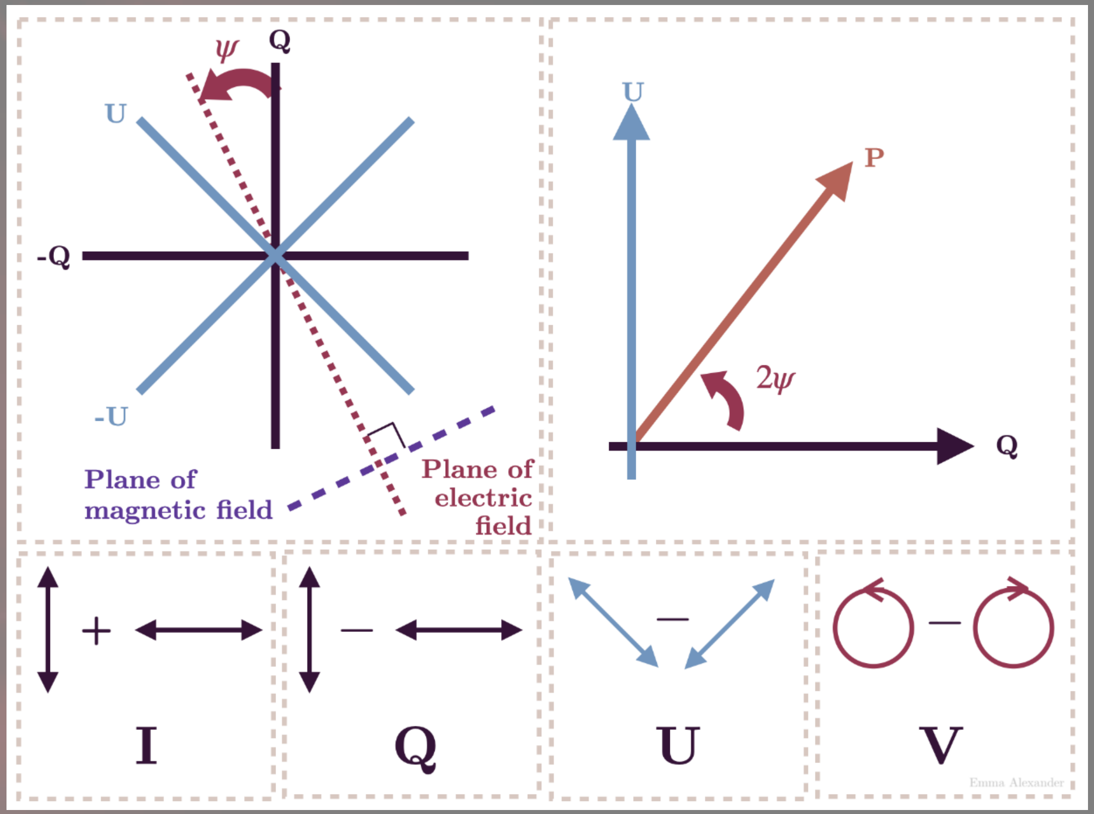
I : *total intensity*

$$Q = Ip\cos 2\psi \cos 2\chi$$
$$U = Ip\sin 2\psi \cos 2\chi$$
$$V = Ip\sin 2\chi$$

$$I = |E_x|^2 + |E_y|^2$$
$$Q = |E_x|^2 - |E_y|^2$$
$$U = 2Re(E_x E_y^*)$$
$$V = -Im(E_x E_y^*)$$

$$\boldsymbol{I^2 \geq Q^2 + U^2 + V^2}$$

Stokes parameters



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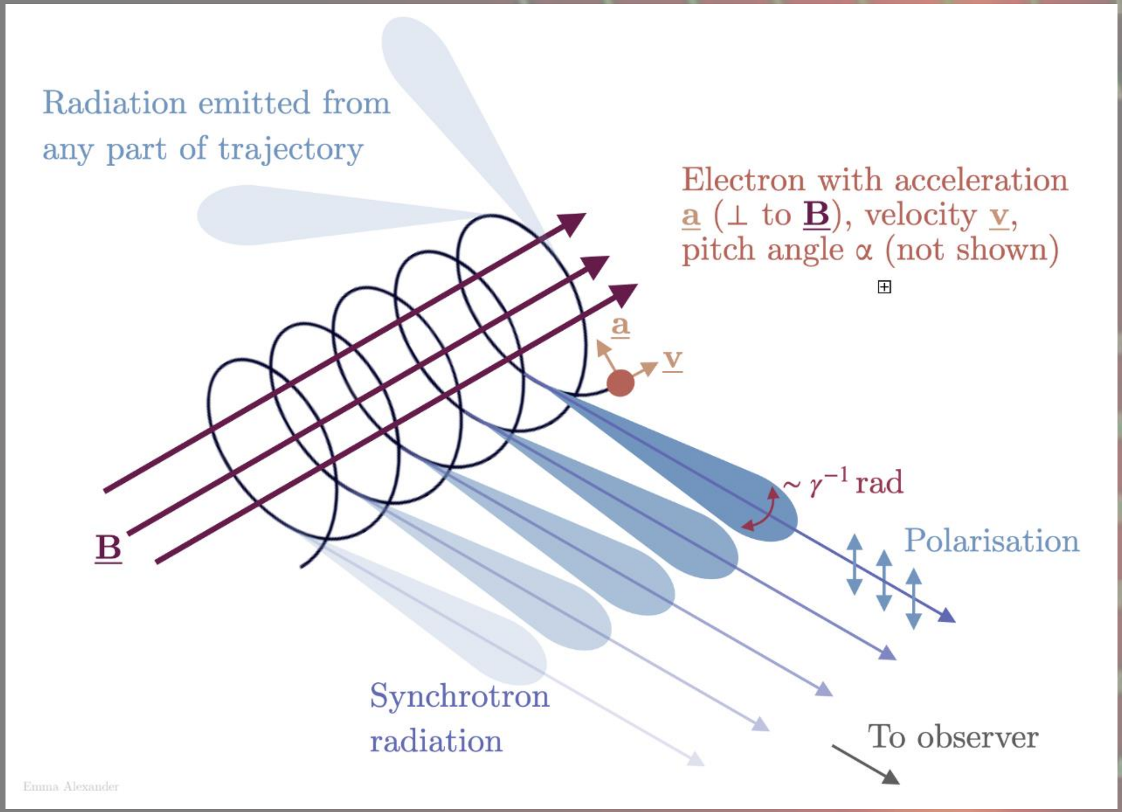
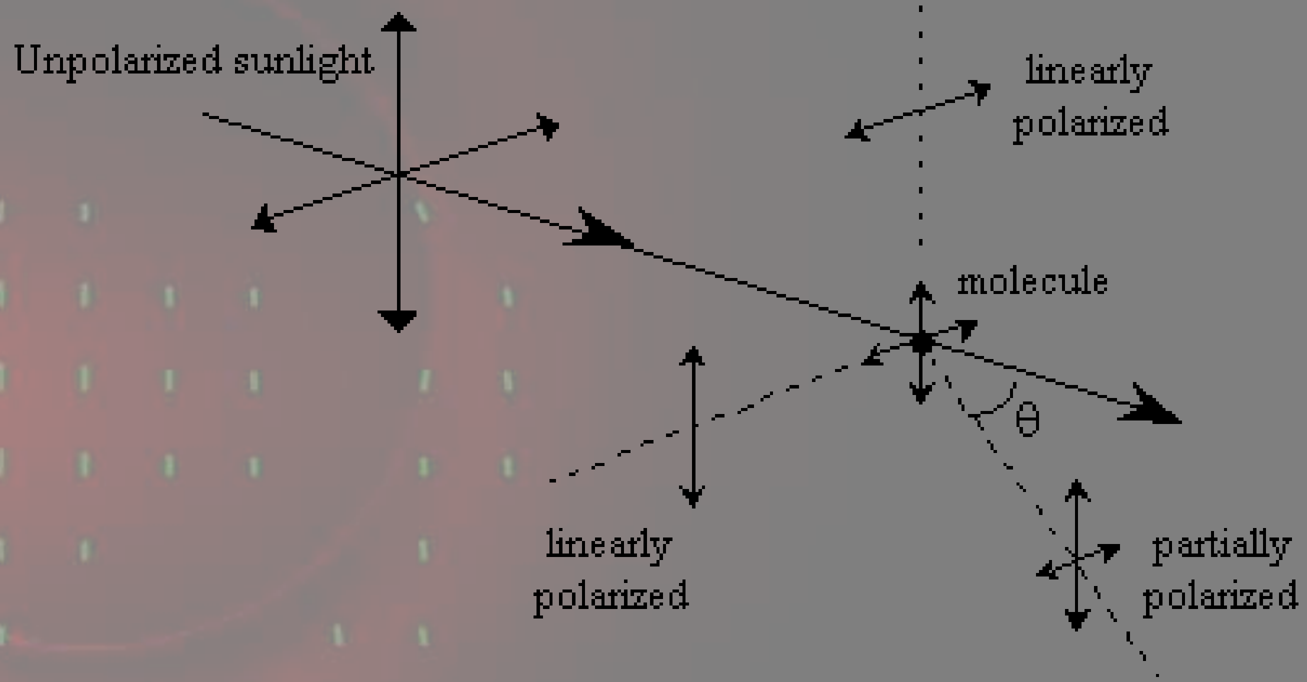
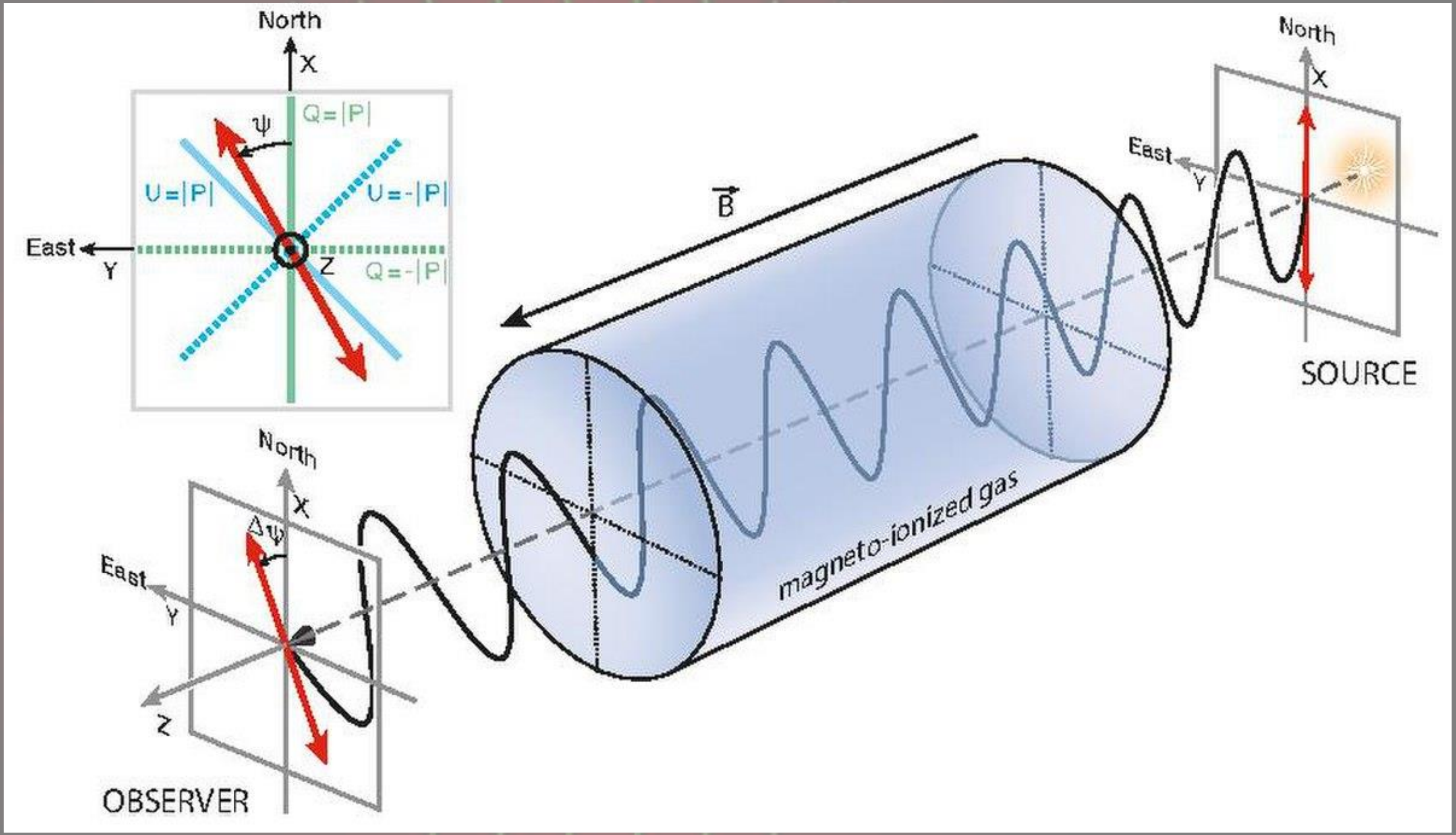


Diagram of synchrotron radiation. Credit : Emma Alexander



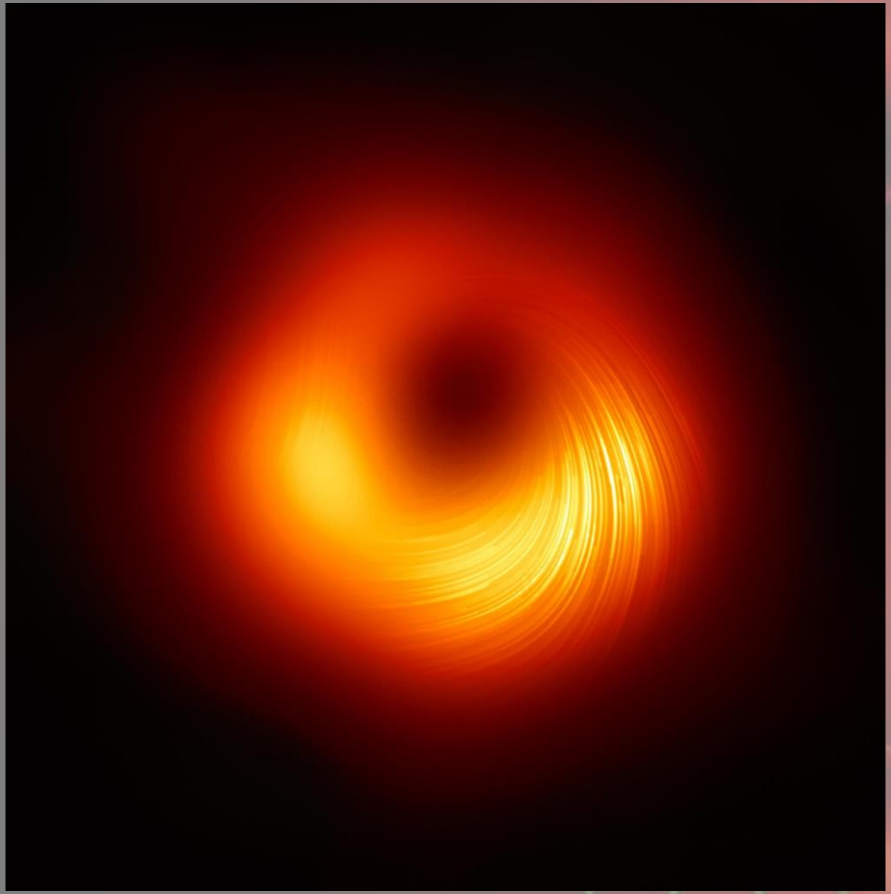
Polarisation by scattering. Credit : Harvard Natural Sciences Lecture Demonstrations

II. Polarisation

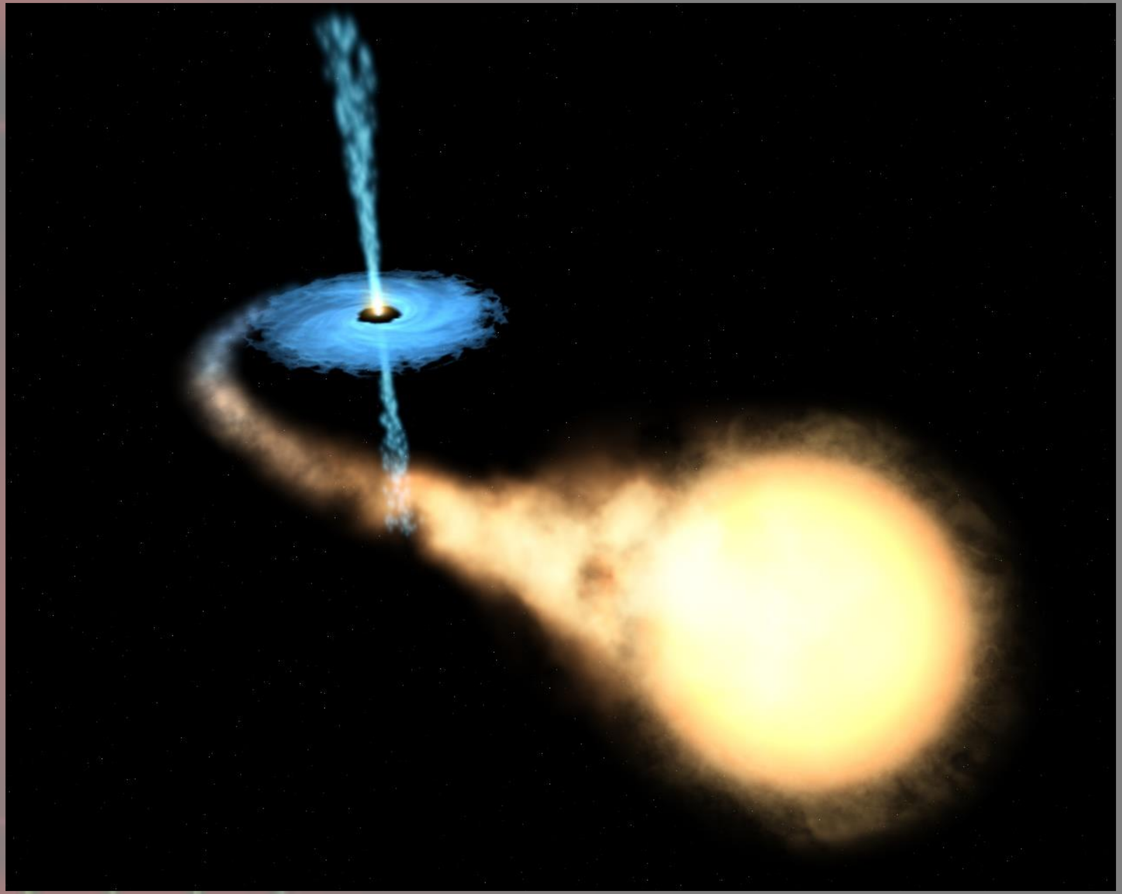


Faraday rotation by an ionised media. Credit : Ferrière K. et al (2021)

II. Polarisation



Polarised Image of M87*. Credit : EHT Collaboration



Artist view of X-ray binaries. Credit : ESA/Hubble

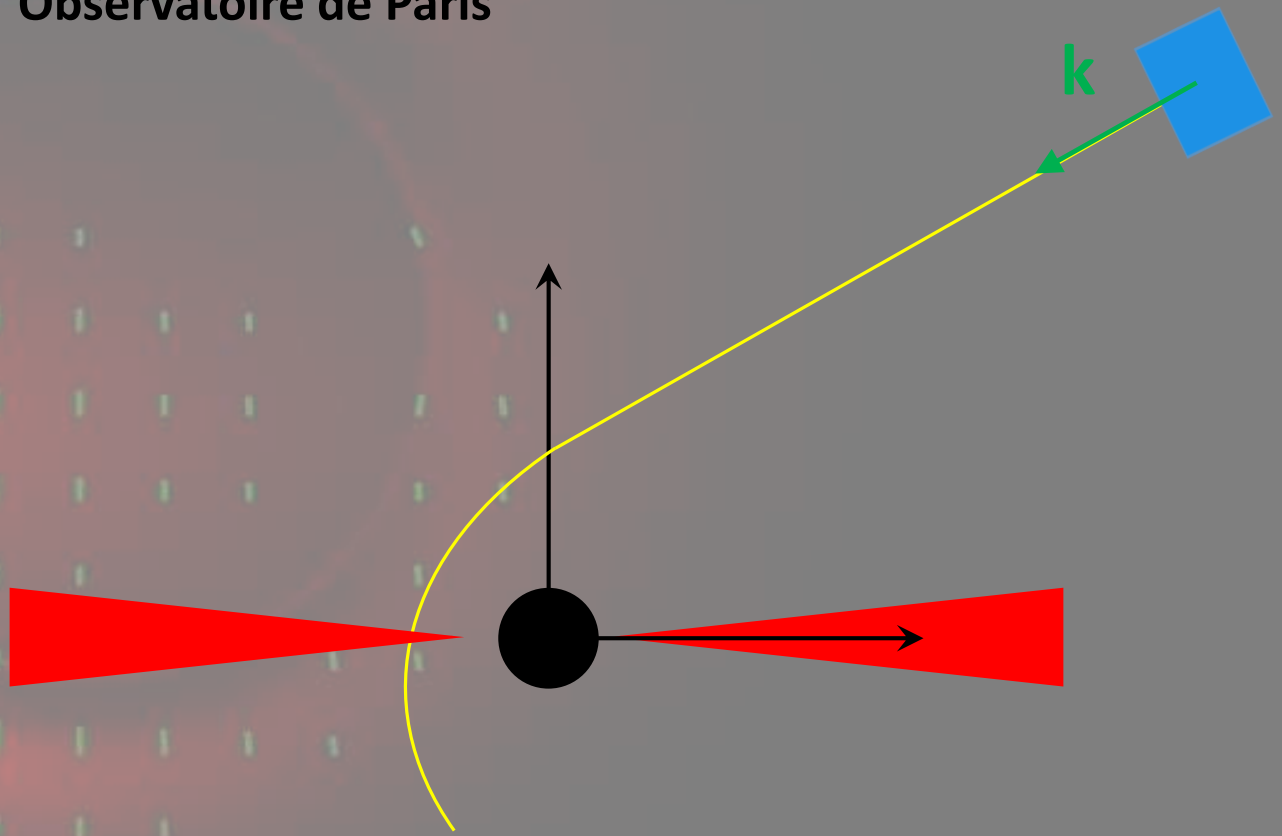
III. Polarisation and ray-tracing with GYOTO

1. Principle of backward ray-tracing

GYOTO : the General relativitY Orbit Tracer of Observatoire de Paris

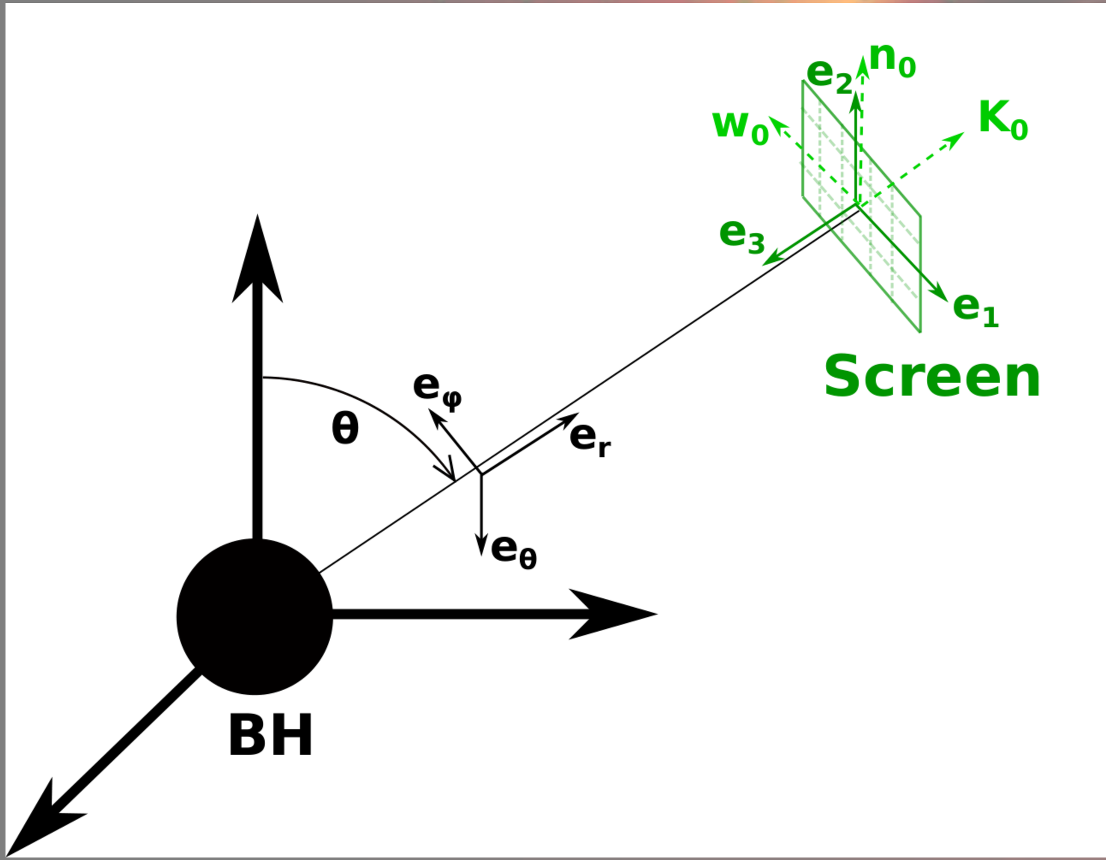
Scenery :

- *Metric*
  - Coordinate system, mass, spin
- *Screen*
  - Position, spectrometer, number of pixels
- *Astrobj*
  - Emitting region
- Photons



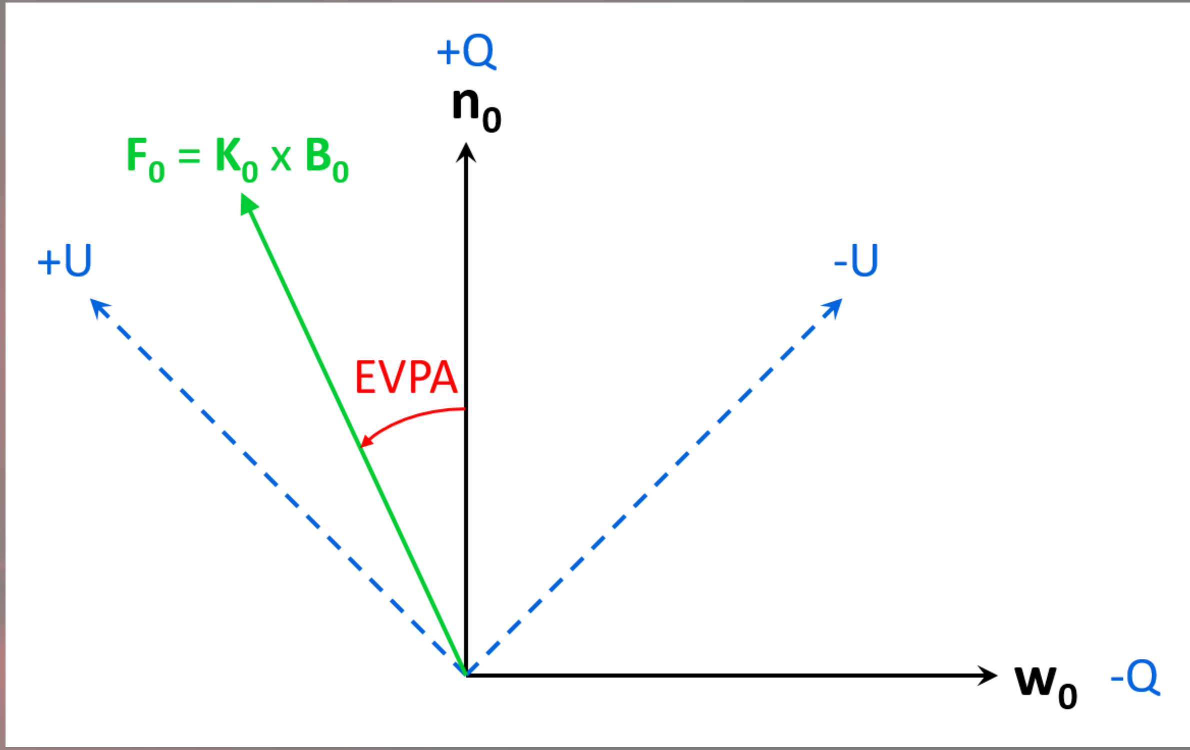
III. Polarisation and ray-tracing

2. Polarised ray-tracing



Aimar N., Paumard T., Vincent F. et al. (in prep)

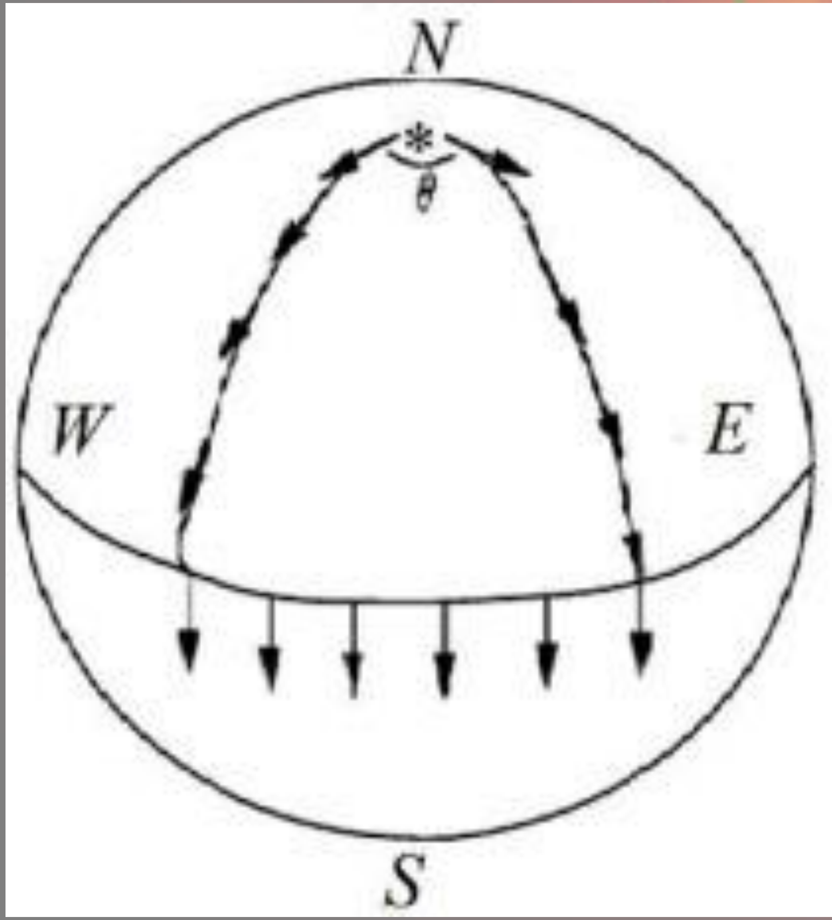
- Observer polarisation basis



PhD. Thesis Aimar N. (2023)

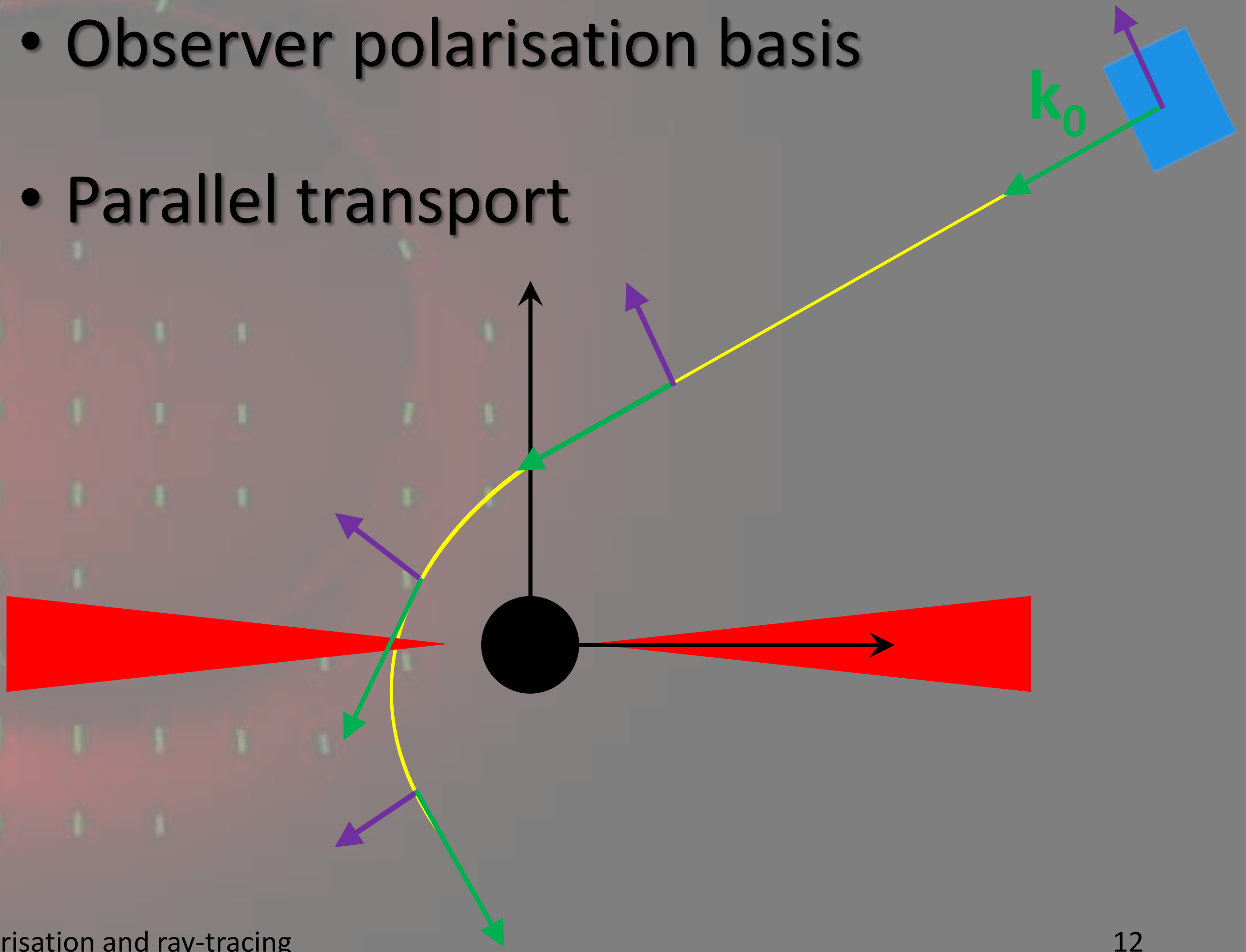
III. Polarisation and ray-tracing

2. Polarised ray-tracing



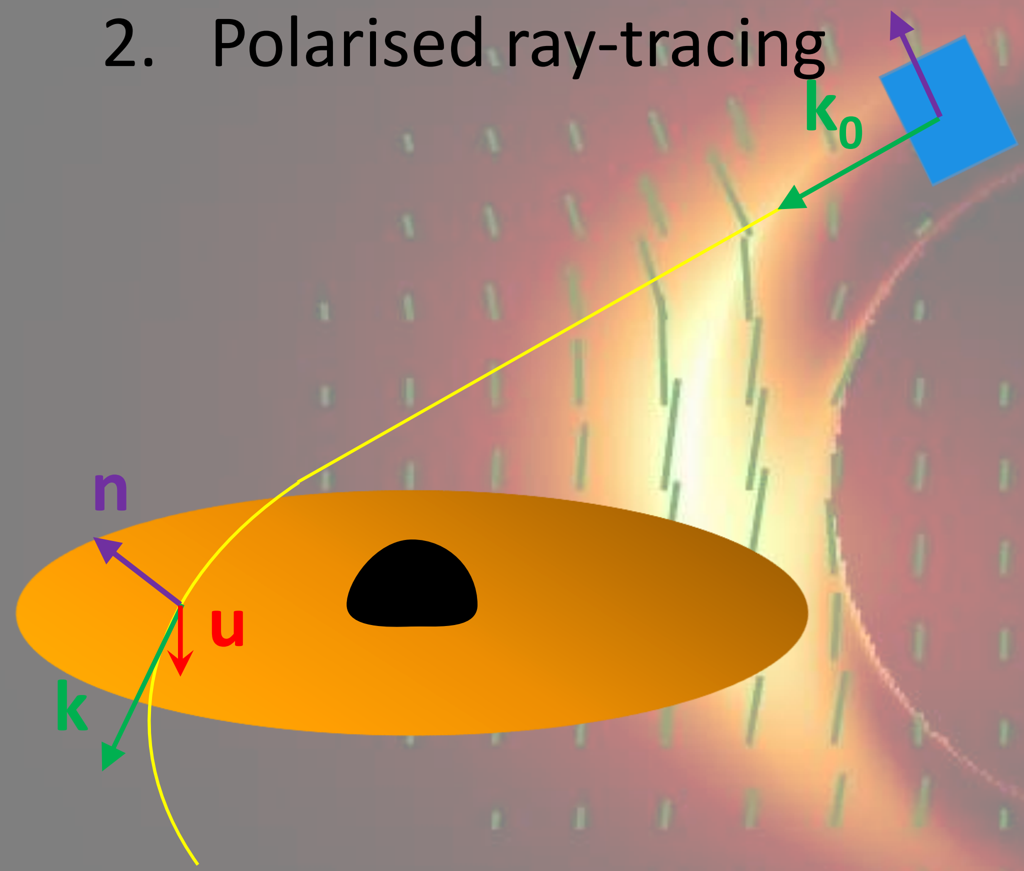
Henri Bourlès, 2019
Fundamentals of Advanced Mathematics V3

- Observer polarisation basis
- Parallel transport



III. Polarisation and ray-tracing

2. Polarised ray-tracing



- Observer polarisation basis
- Parallel transport
- Projection in the emitting region

$$\boldsymbol{n}' = \boldsymbol{n} + \alpha\, \boldsymbol{k}, \quad \alpha = -\frac{\boldsymbol{n}\cdot\boldsymbol{u}}{\boldsymbol{k}\cdot\boldsymbol{u}}$$

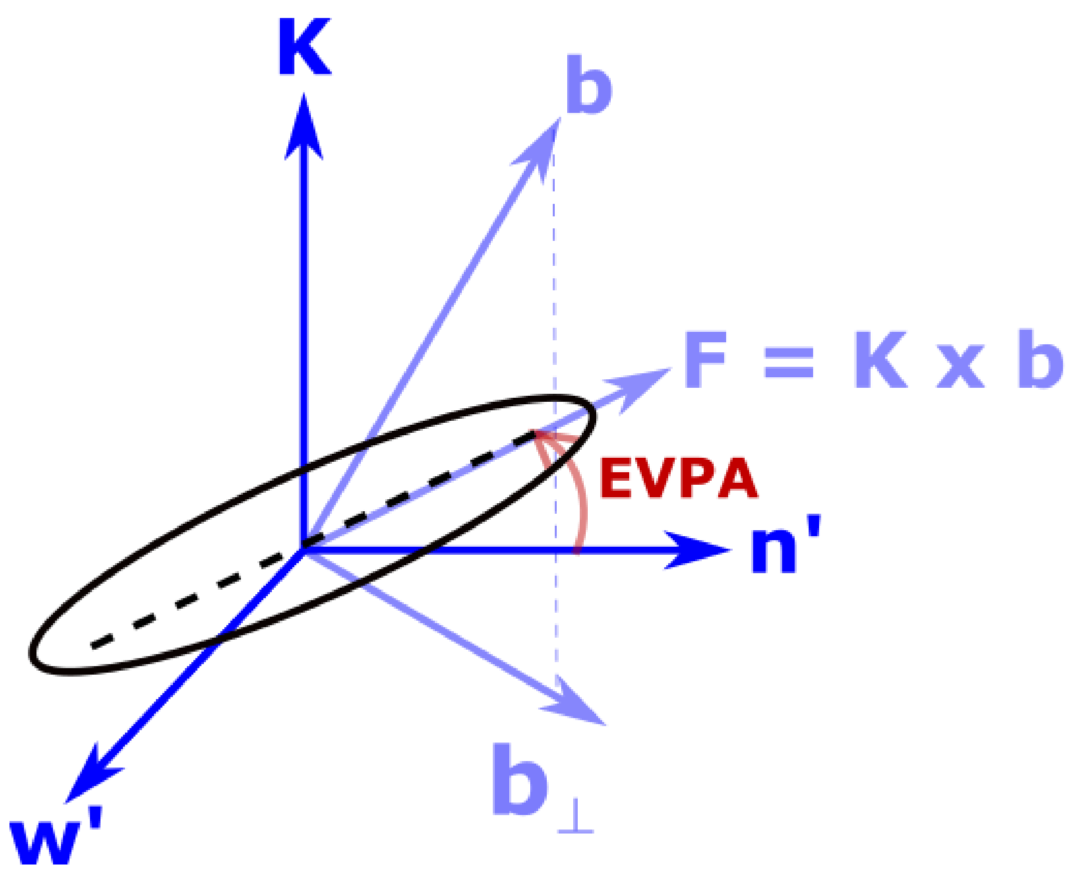
$$\boldsymbol{w}' = \boldsymbol{w} + \beta\, \boldsymbol{k}, \quad \beta = -\frac{\boldsymbol{w}\cdot\boldsymbol{u}}{\boldsymbol{k}\cdot\boldsymbol{u}}$$

$$\boldsymbol{K} = \boldsymbol{k} + (\boldsymbol{k}\cdot\boldsymbol{u})\boldsymbol{u}$$

$$(\boldsymbol{n}, \boldsymbol{w}, \boldsymbol{k}) \underset{\perp_{\boldsymbol{u}}}{\rightarrow} (\boldsymbol{n}', \boldsymbol{w}', \boldsymbol{K})$$

III. Polarisation and ray-tracing

2. Polarised ray-tracing

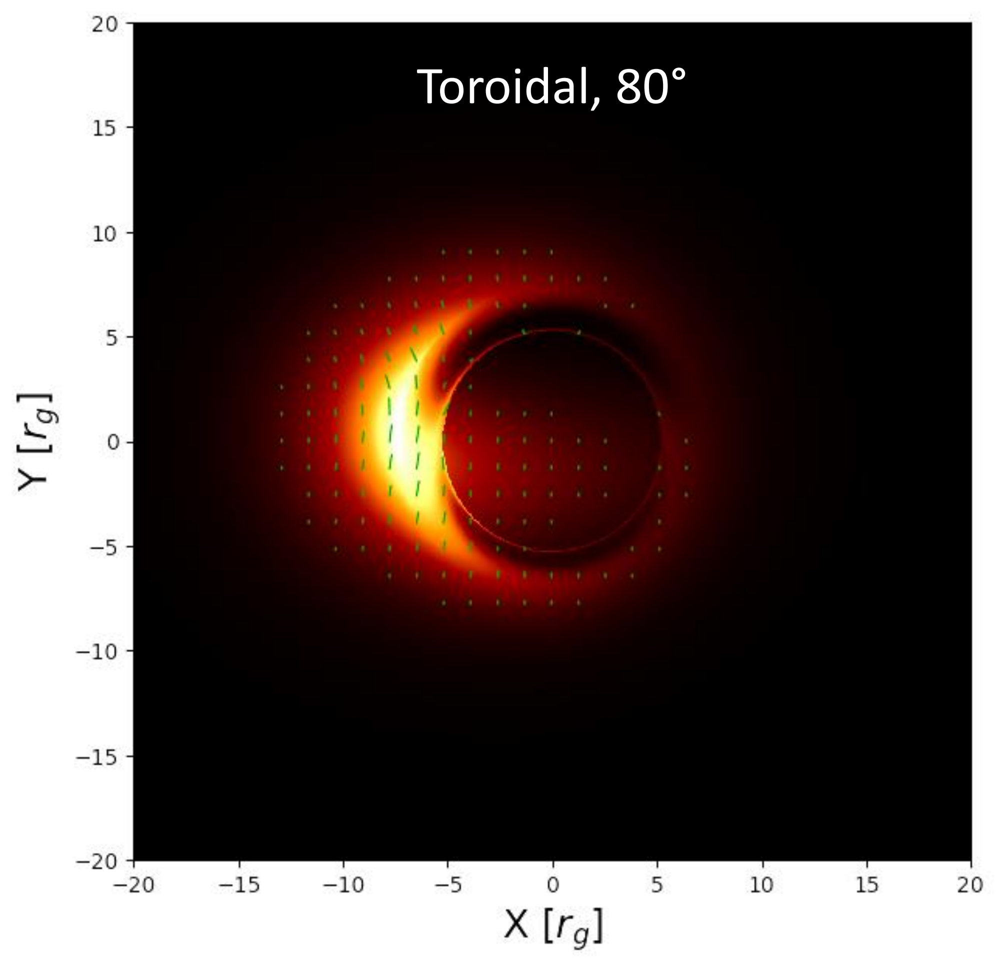


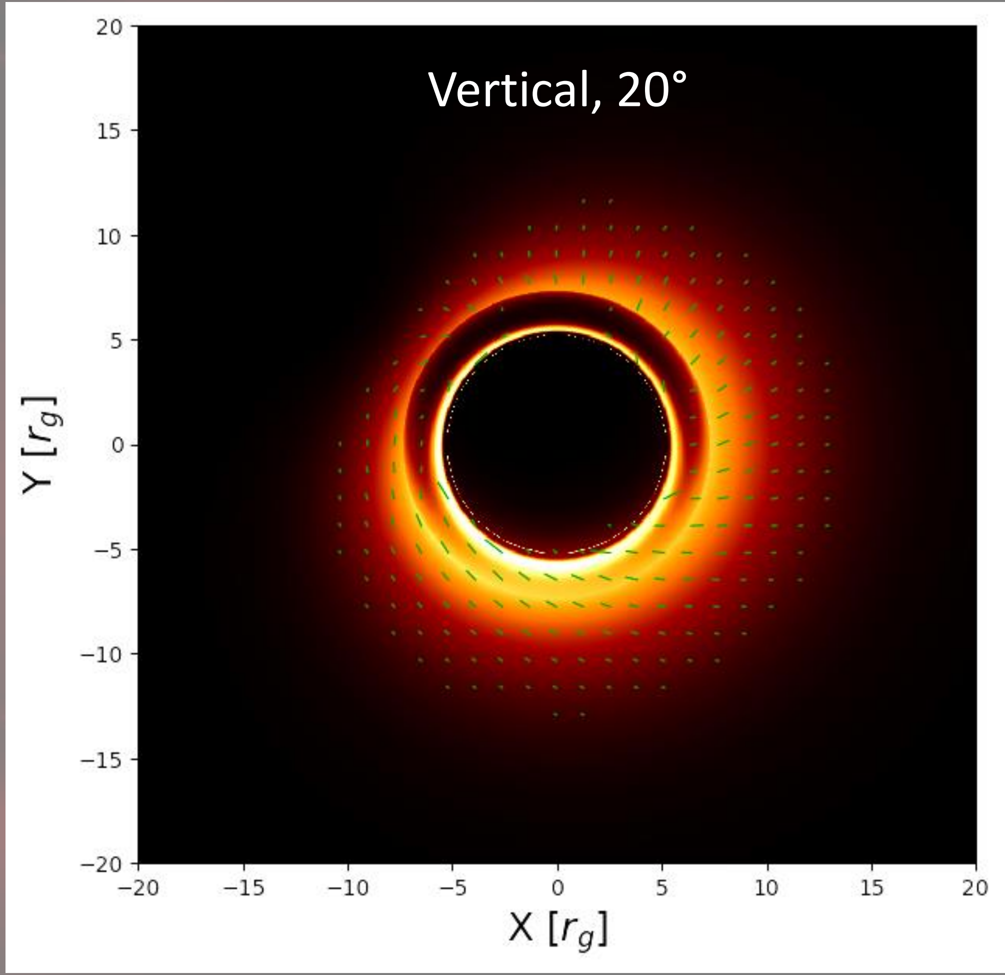
Aimar N., Paumard T., Vincent F. et al. (in prep)

- Observer polarisation basis
- Parallel transport
- Projection in the emitting region
- Emitter polarisation vector and radiative transfer
  - Emission, absorption, rotation coefficients

III. Polarisation and ray-tracing

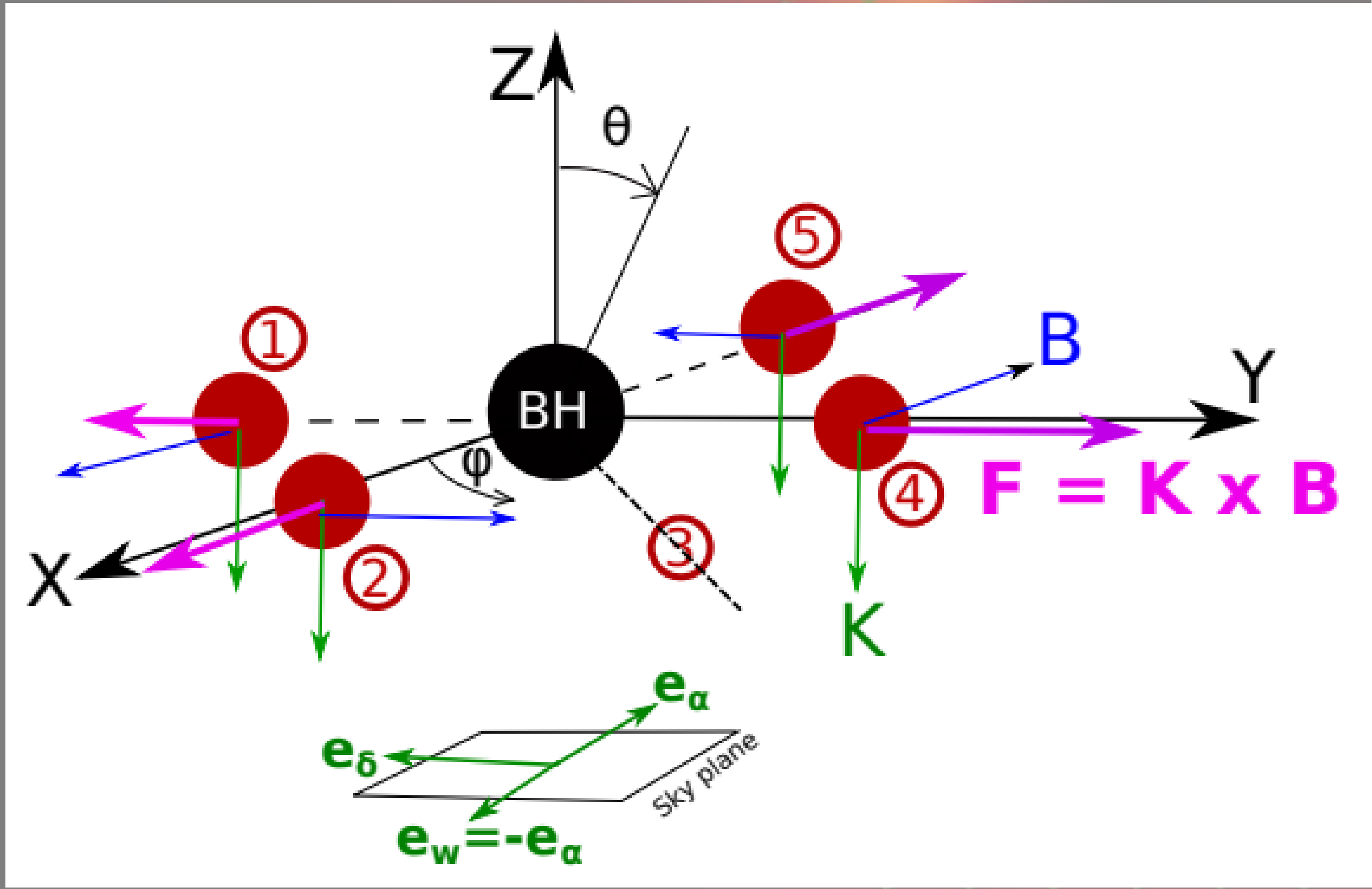
3. Polarisation observables : **Images with polarisation vectors**

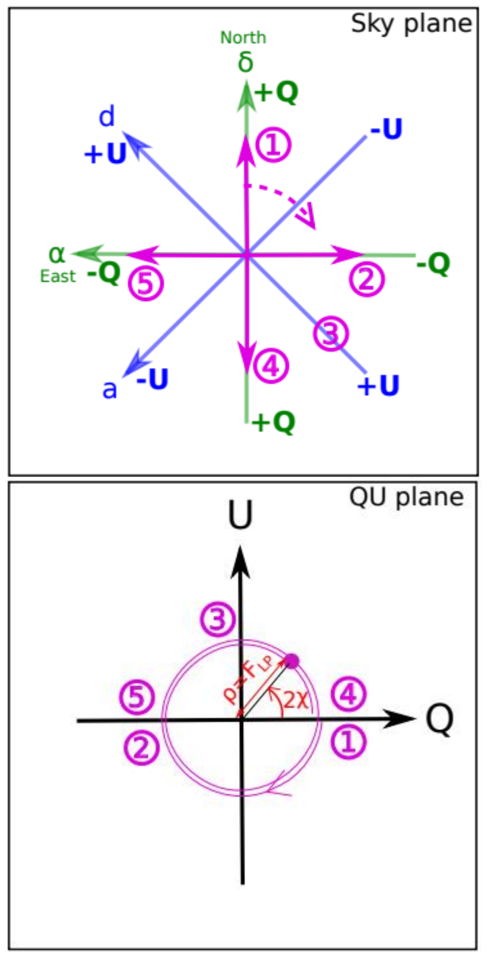




III. Polarisation and ray-tracing

3. Polarisation observables : **Q-U loops**





Example :

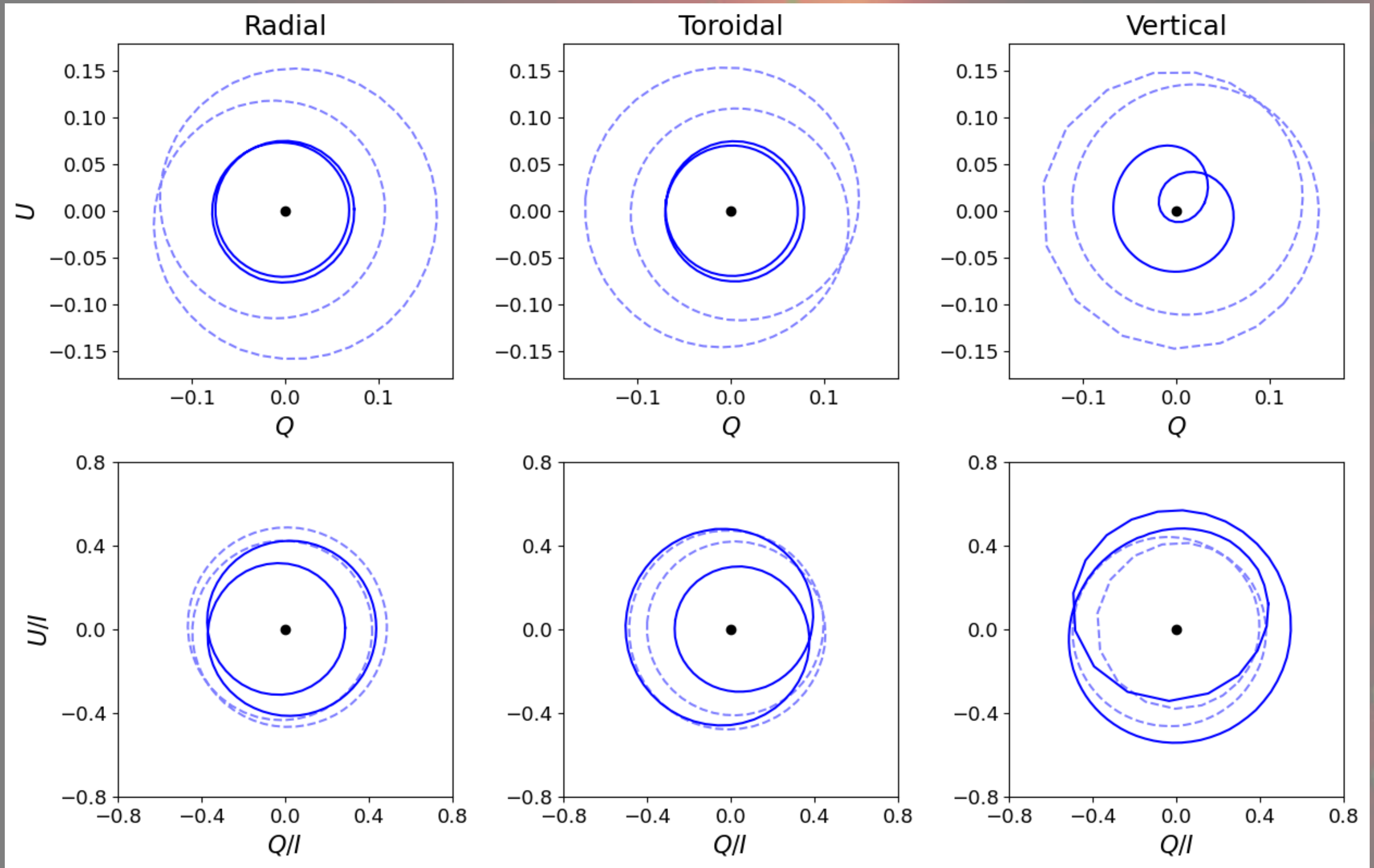
- Equatorial orbit
- Toroidal B field
- Face-on
- Minkowski metric

⇒ Double QU loop

Vincent F. et al. (in prep, soon submitted)

III. Polarisation and ray-tracing

3. Polarisation observables



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<u>Examples :</u>

- **Equatorial** orbit @ 11 r_g
- Inclination : **20°**
- **Schwarzschild** metric
- Various B field configurations
- **Thermal** synchrotron (full lines)
- **Kappa** synchrotron (dashed lines)

Conclusion

- **Ray-tracing** in necessary to compute **images, LC or spectra** of very compact objects (black holes, or black holes like objects)
- Polarisation of light is an important observable in many wavelength (radio, IR and X-ray)
- **GYOTO** is now able to compute **polarisation in any given metric**
- We can generate **synthetic observables** (polarised images, QU loops, polarimetry, …)
- Polarisation can constrain physical properties and **space-time**