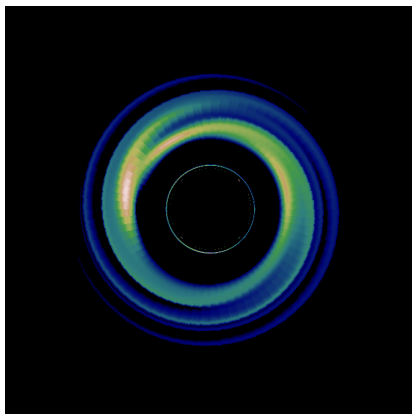
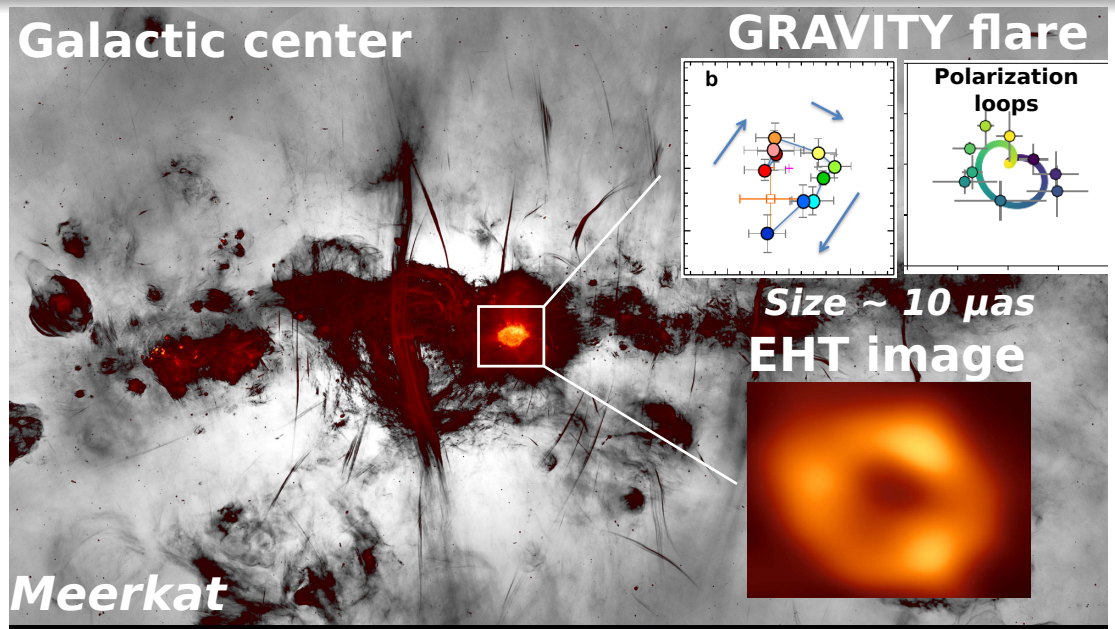
Polarization in general relativity: a probe of strong-field gravity?

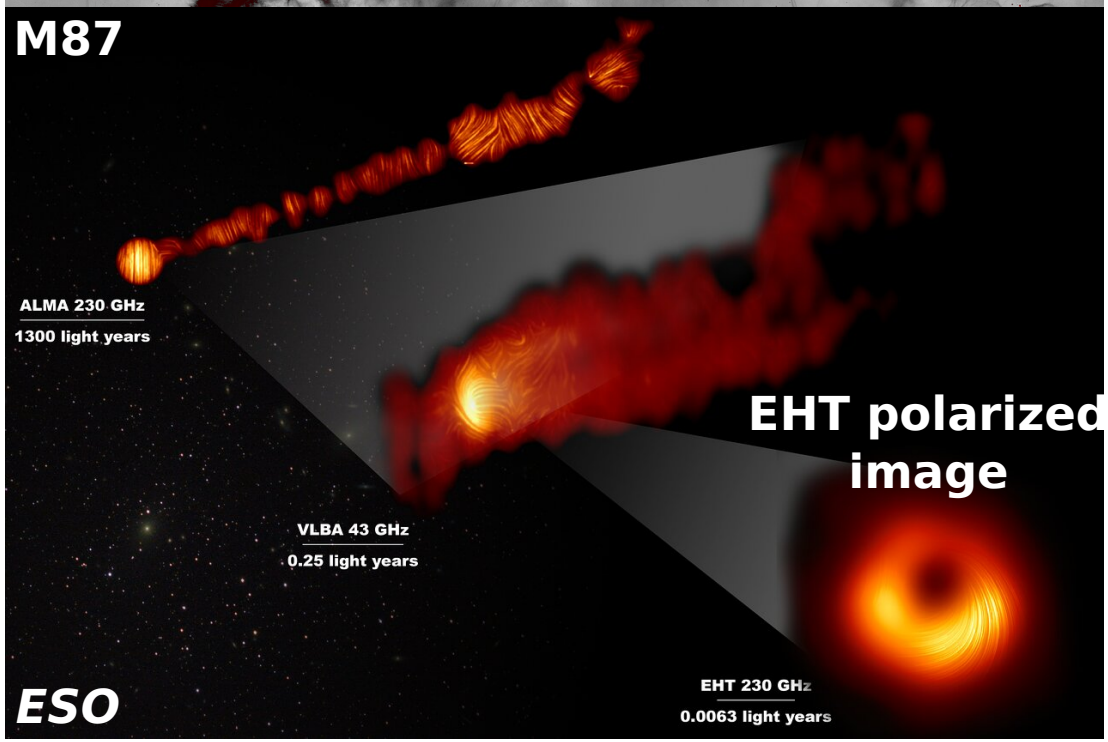
Frédéric Vincent[1]

in collaboration with:
N. Aimar, M. Wielgus, T. Paumard, G. Perrin

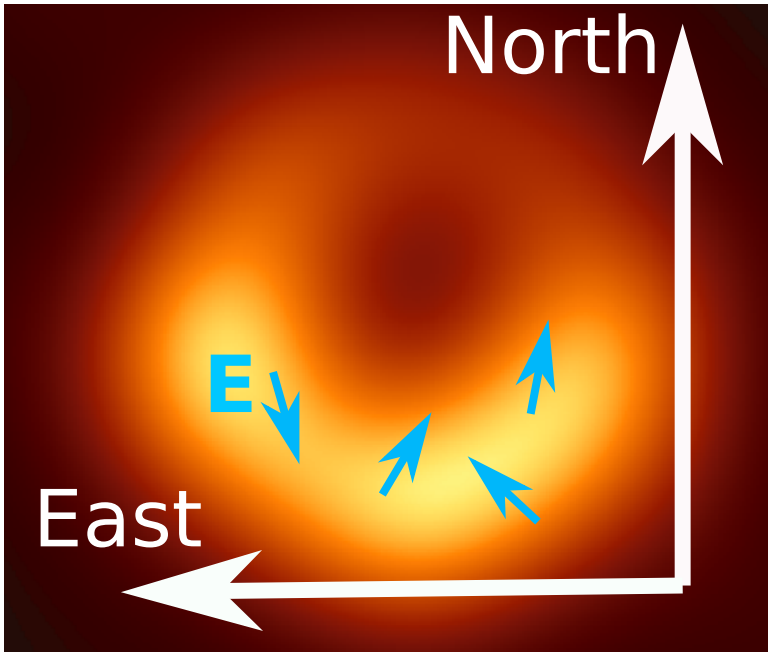
[1]CNRS/Observatoire de Paris/LESIA




Galactic center
GRAVITY flare
b
Polarization loops
Size ~ 10 μas
EHT image
Meerkat

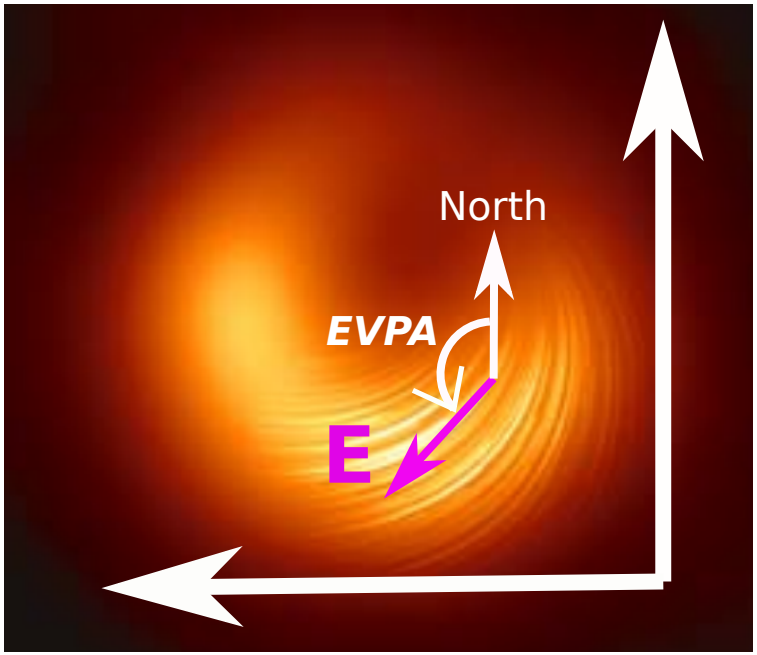

M87
ALMA 230 GHz
1300 light years
EHT polarized image
VLBA 43 GHz
0.25 light years
EHT 230 GHz
0.0063 light years
ESO

Non-polarized



$I = E^2$

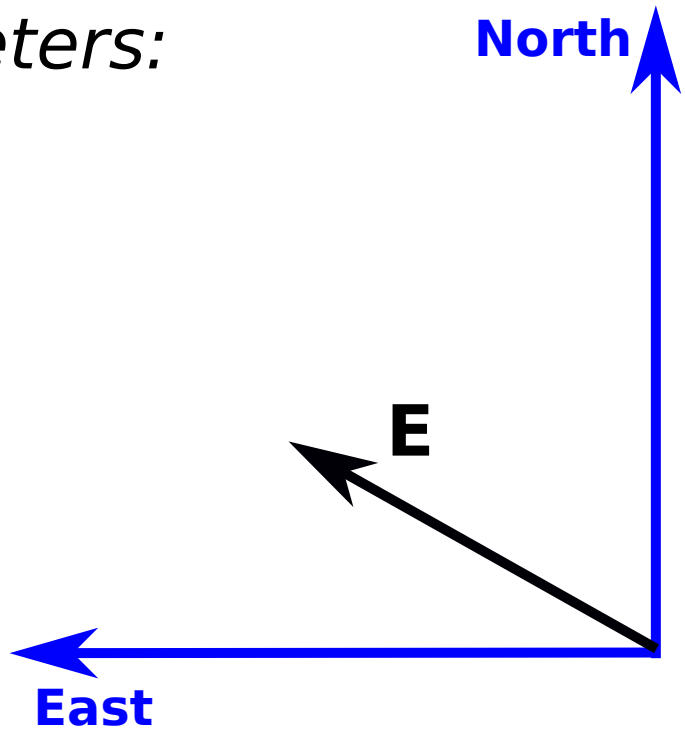
Polarized



$I = E^2$
+EVPA

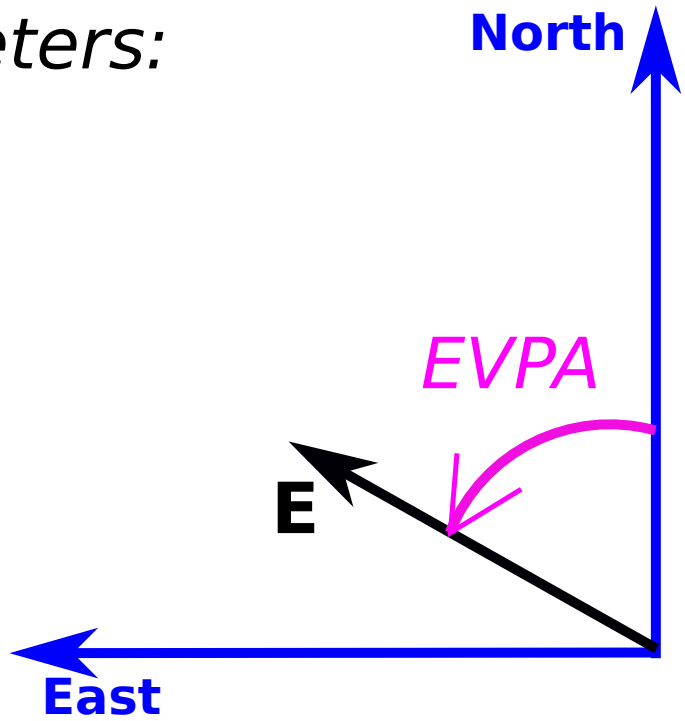
Stokes parameters:

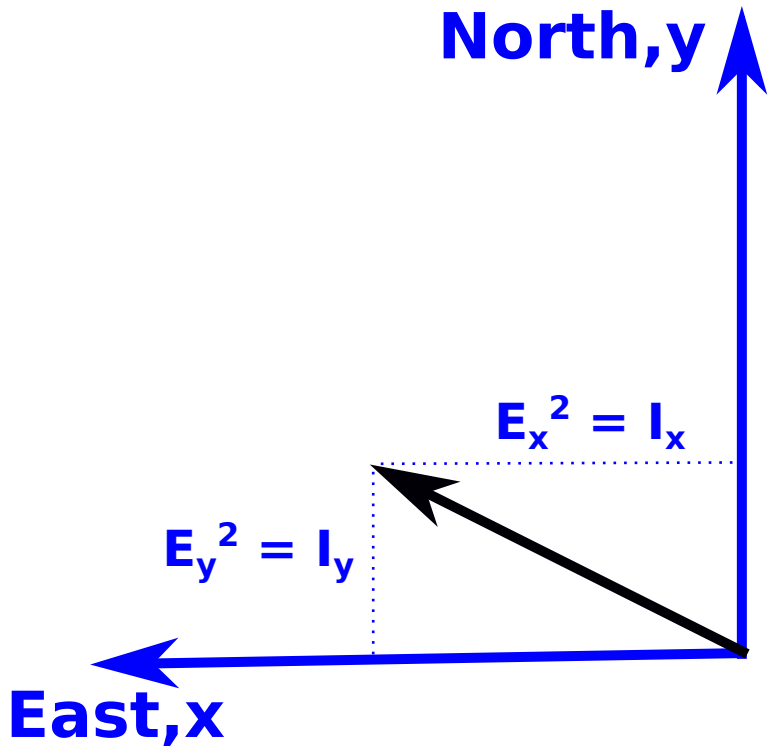
$$I = E^2$$



Stokes parameters:

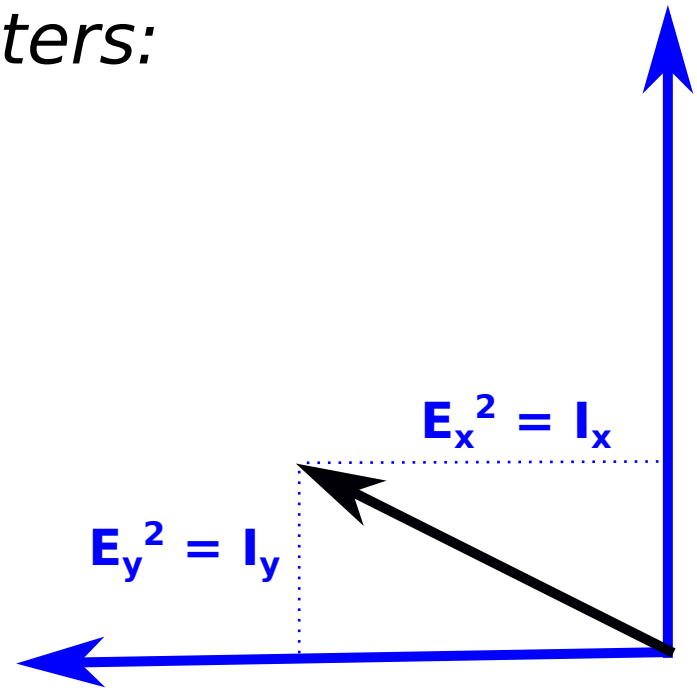
$$I = E^2$$

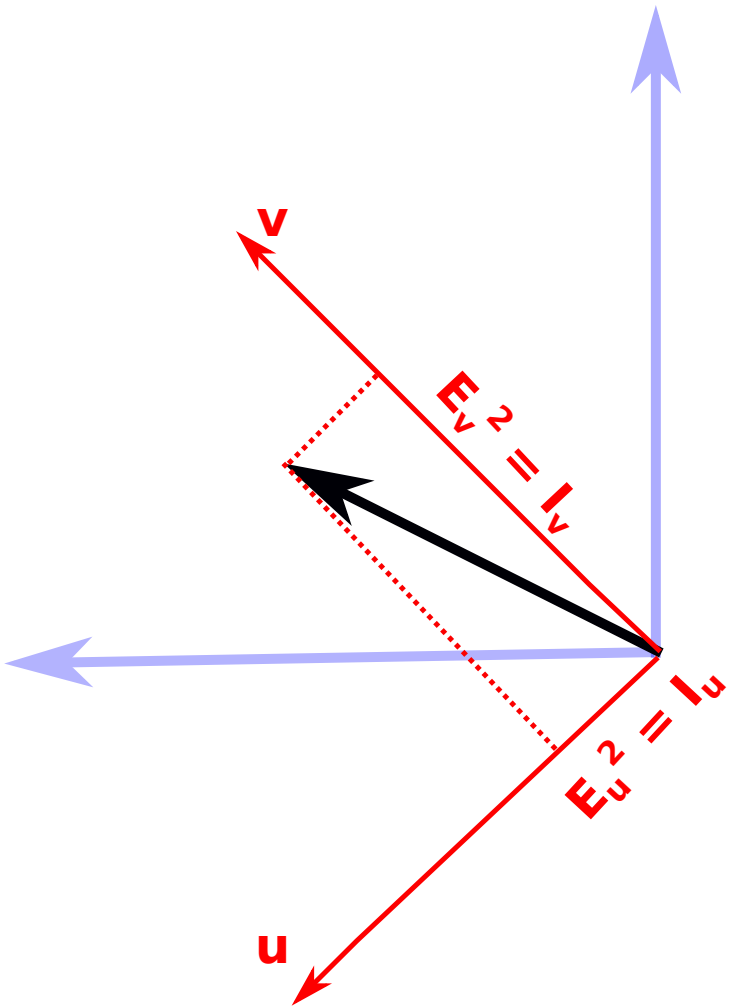



North,y
$E_x^2 = I_x$
$E_y^2 = I_y$
East,x

Stokes parameters:

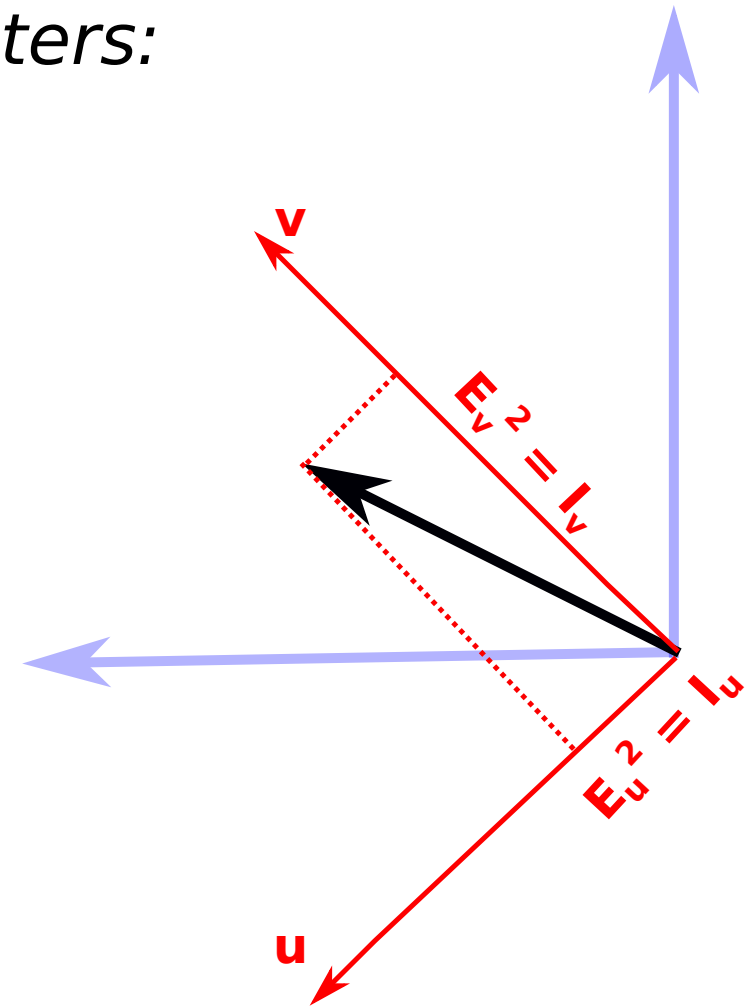
$$Q = I_x - I_y$$

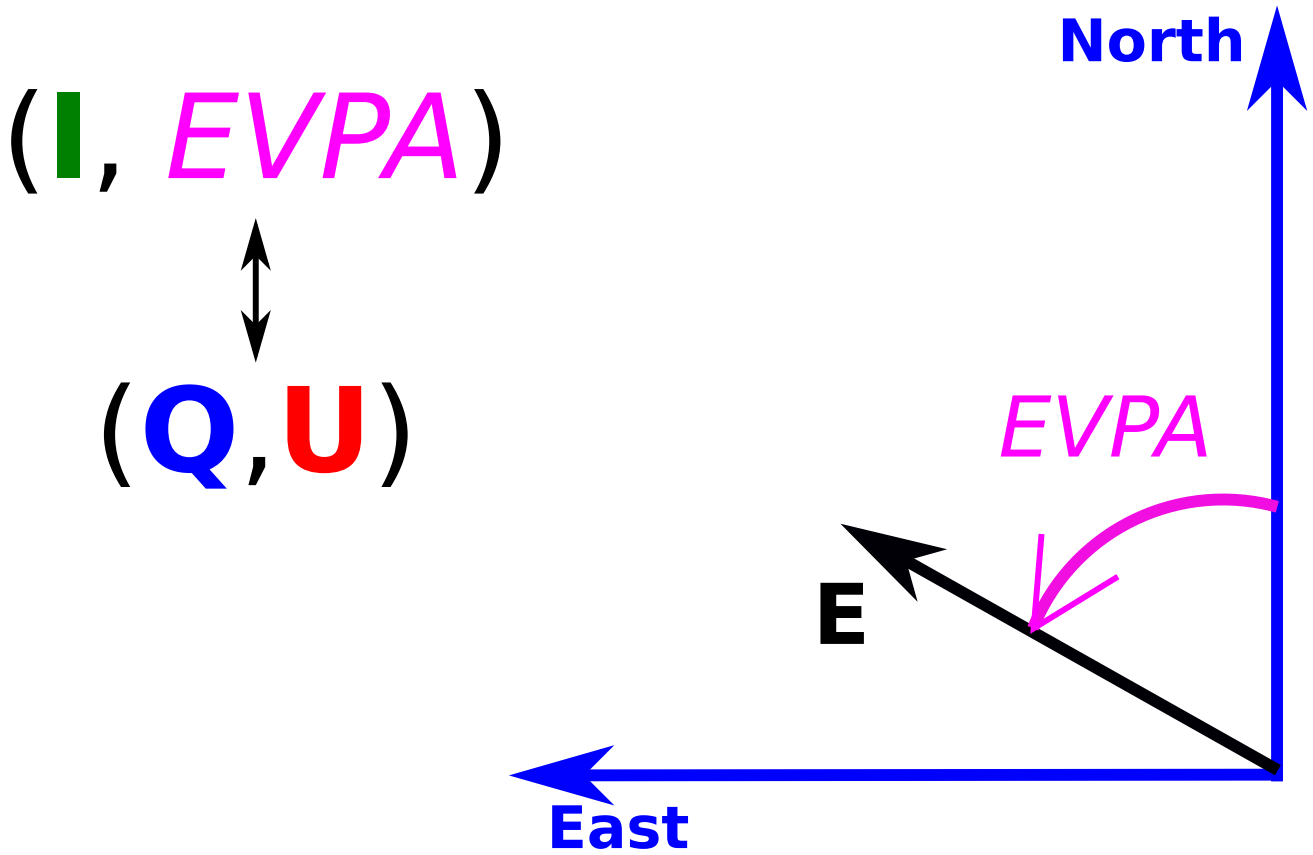



v
$E_v^2 = I_v$
$E_u^2 = I_u$
u

Stokes parameters:

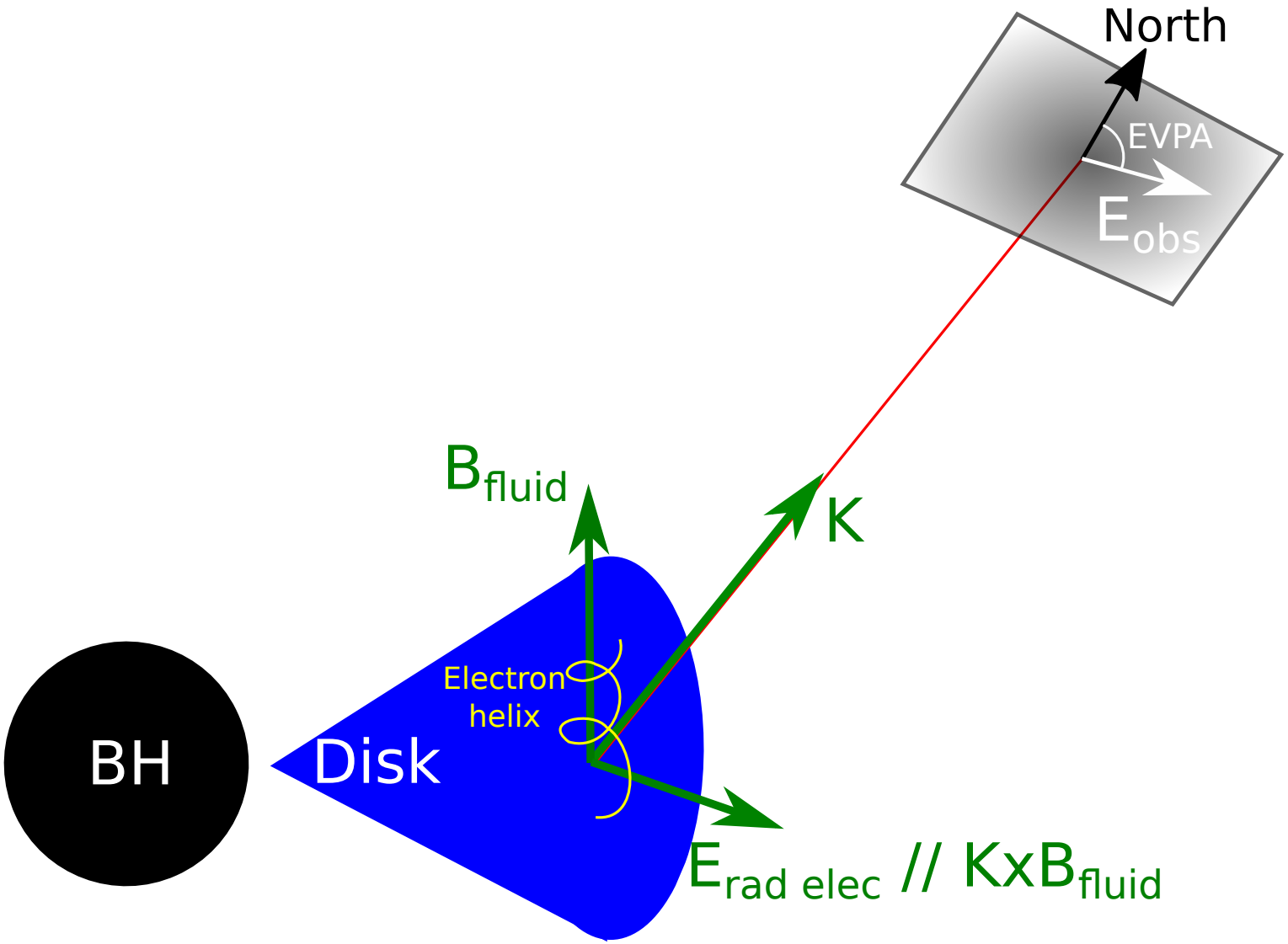
$$U = I_u - I_v$$



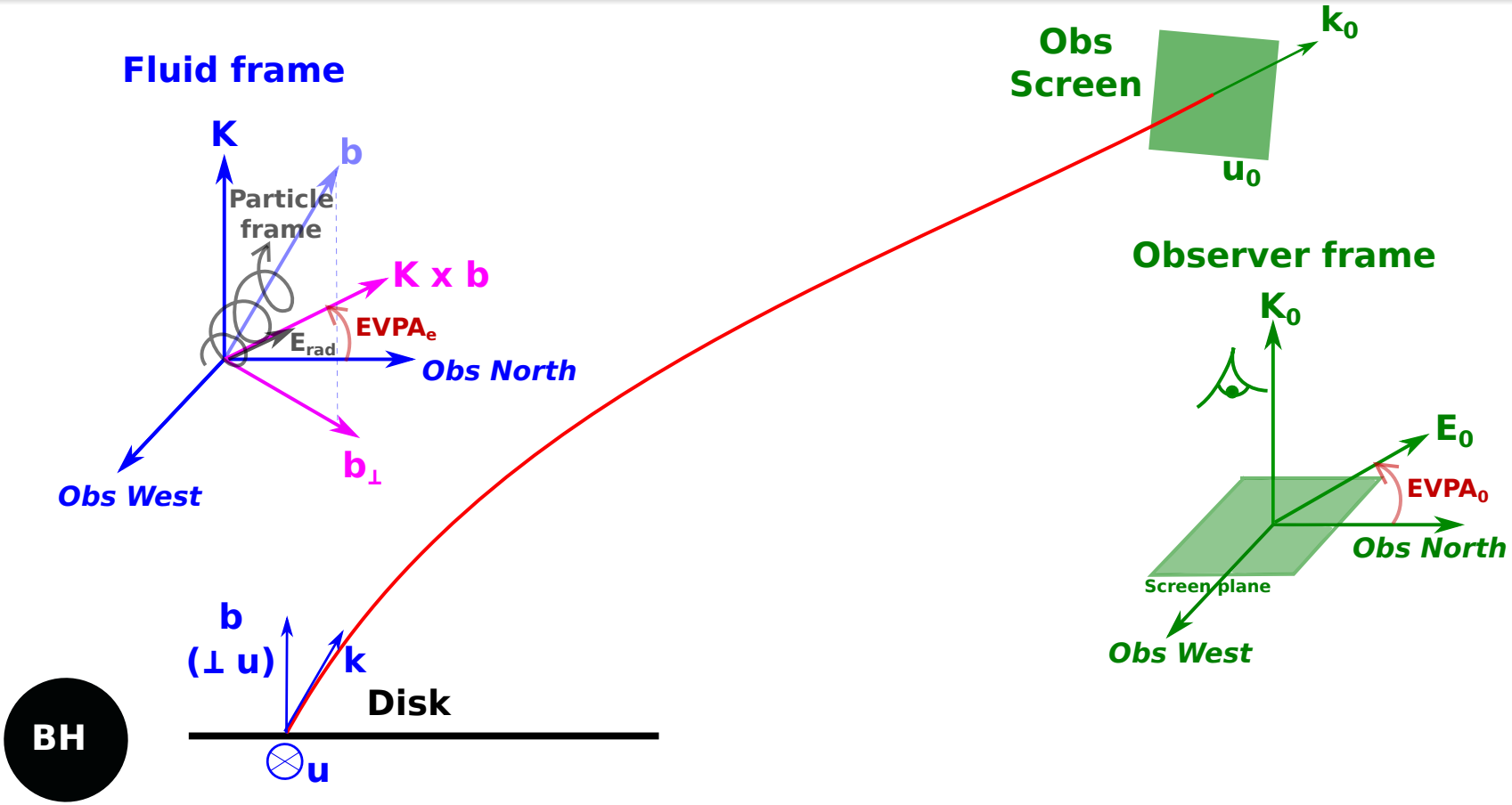


Linear polarization Stokes parameters

- (Q, U), easily observable, encode $(I, EVPA)$
- $I^2 = Q^2 + U^2$, EVPA = $1/2 \operatorname{atan}(U/Q)$
- Full linear polarization information

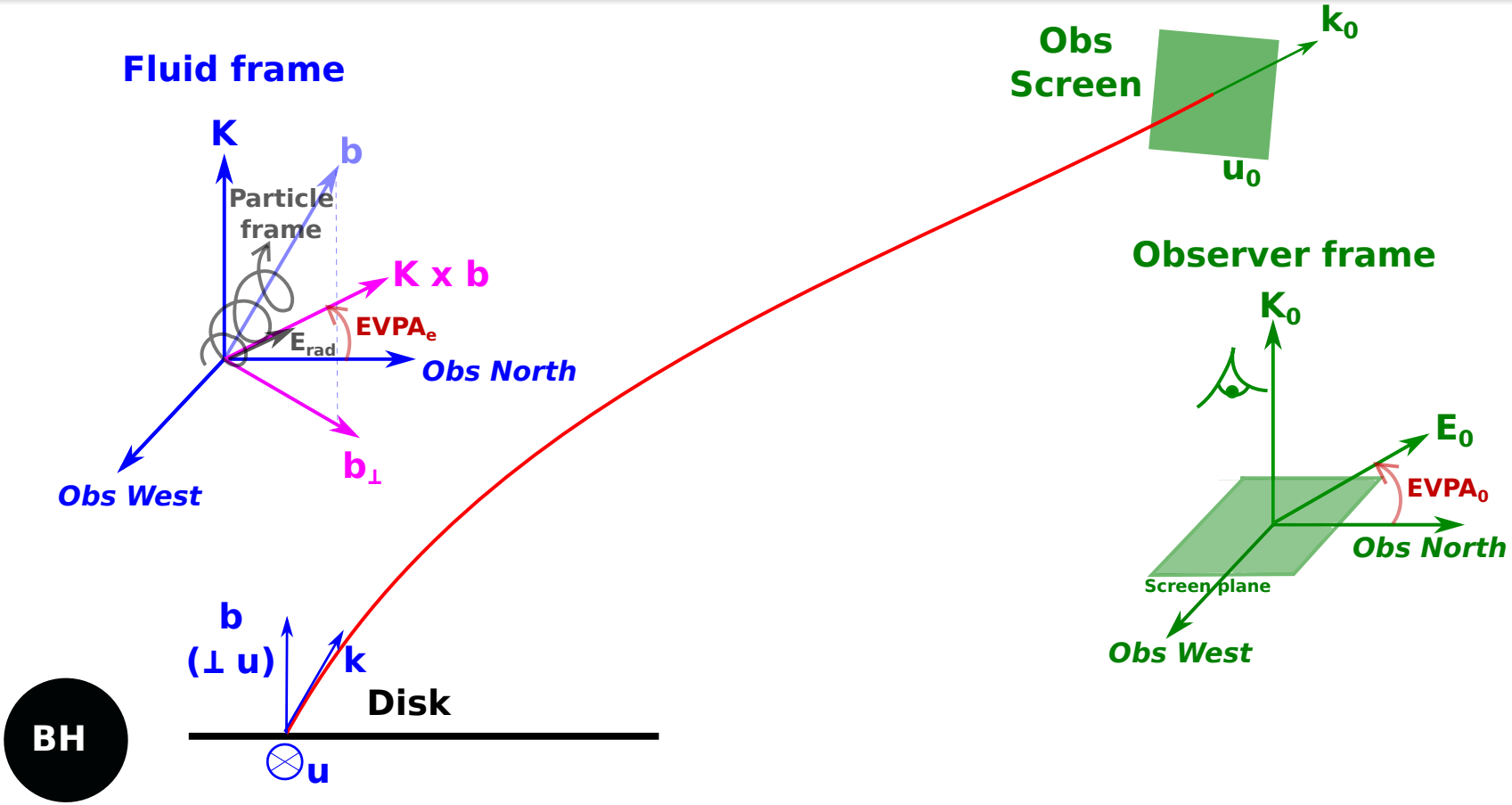


EVPA → B field orientation



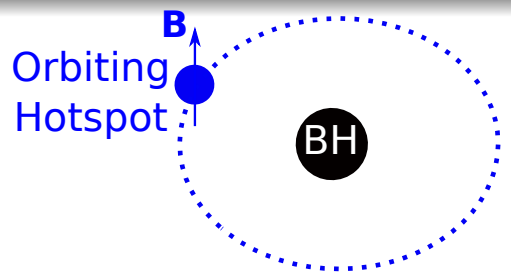
Polarization in GR

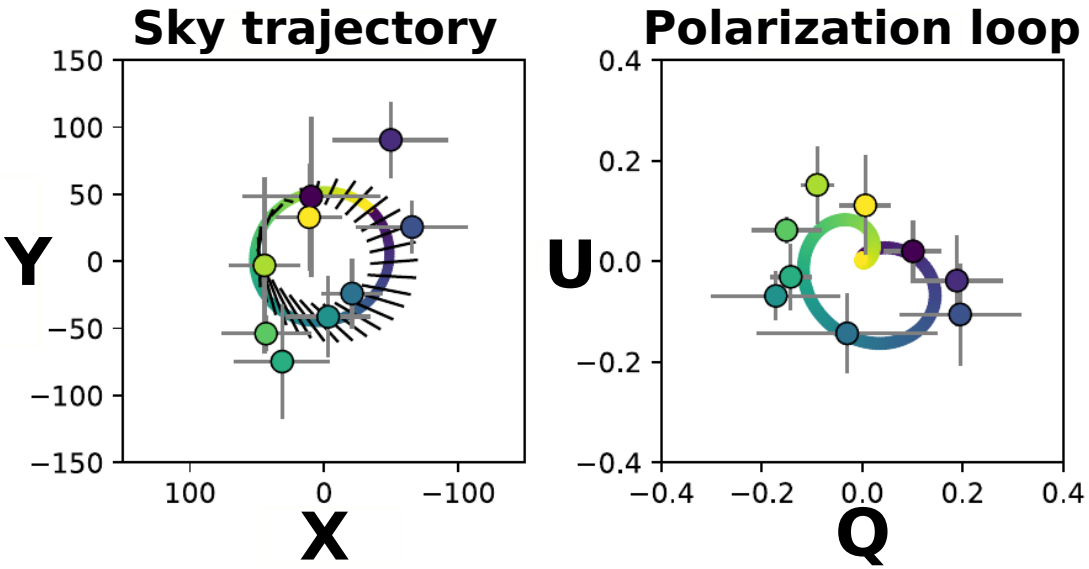
- Parallel transport
- Synchrotron frame $(\mathbf{K}, \boldsymbol{b}_\perp, \mathbf{F})$, observer frame $(\mathbf{K}, \boldsymbol{w}, \mathbf{n})$
- Rotated by EVPA (including curvature effect)



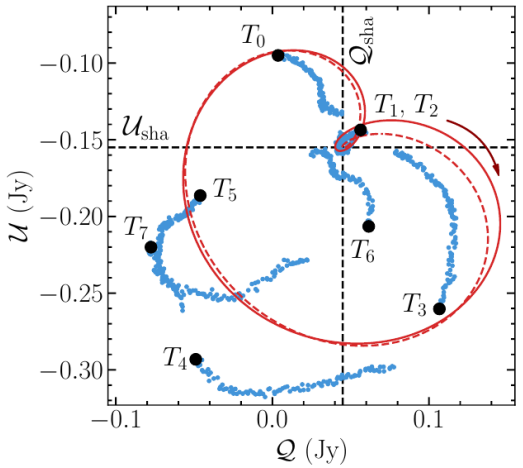
Polarization in GR

- $\mathcal{I} = (I, Q, U, V)$, Stokes parameters vector in obs frame
- $\mathrm{d}\mathcal{I}/\mathrm{d}s = \mathcal{J}(\chi) - \mathcal{K}(\chi)\mathcal{I}$, χ=EVPA
- Details: **Aimar+23** (soon online), polarized GYOTO code





GRAVITY Coll. 2023

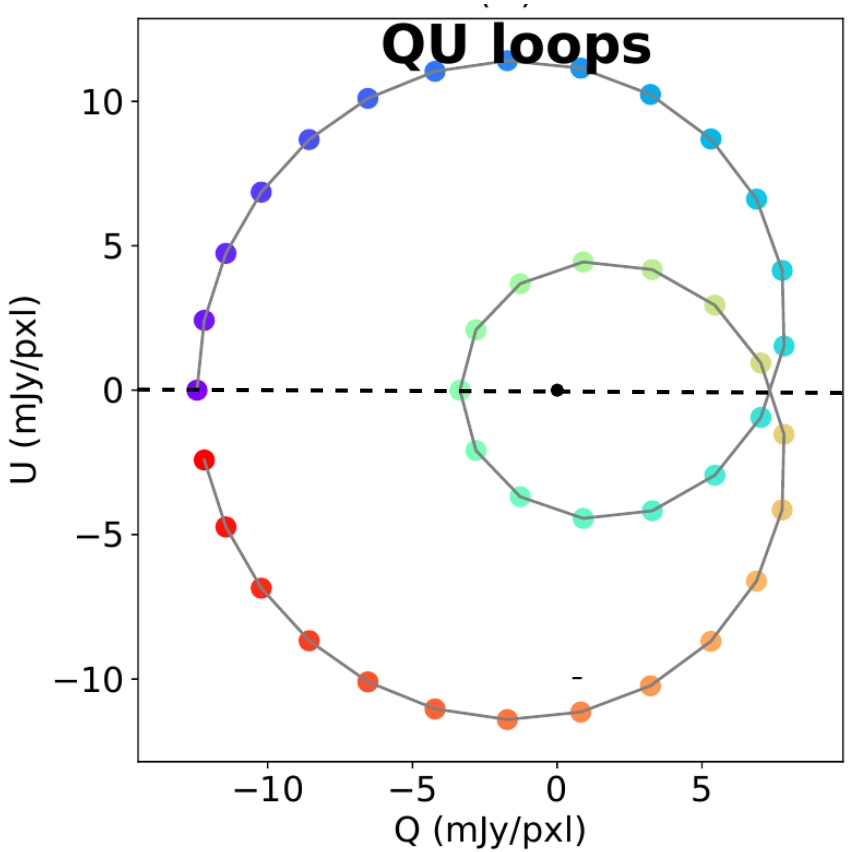


ALMA/Wielgus+22

Observed polarized flares

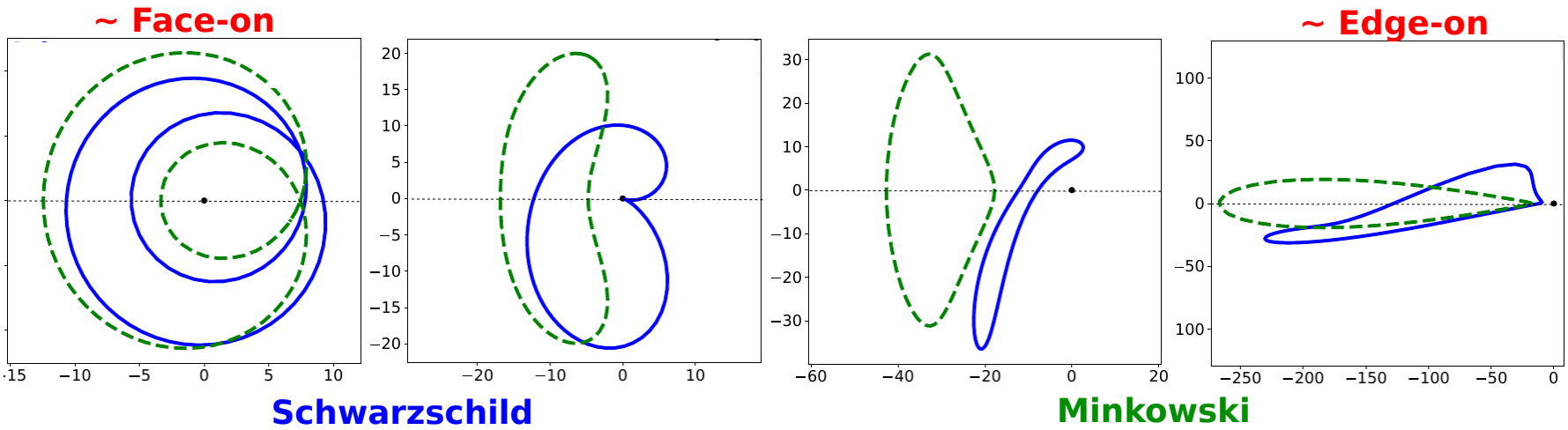
- Orbiting “hot spot”
- Track in linear polarization plane: **QU loops**
- Impact of GR?

Minkowski / vertical B



Flat-space QU loops

- Minkowski QU loops are very similar to Kerr
- Specific property: **Mirror symmetry**



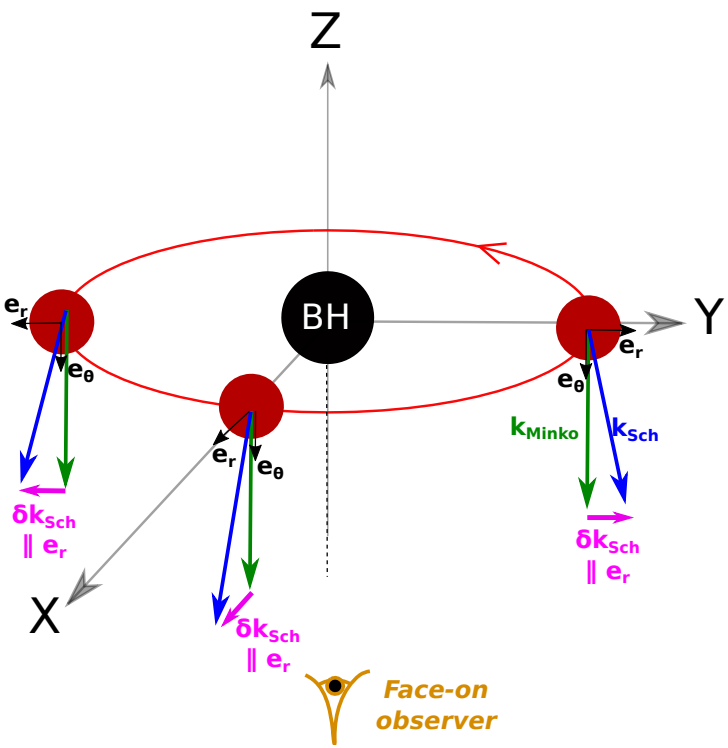
Minkowski vs. Schwarzschild

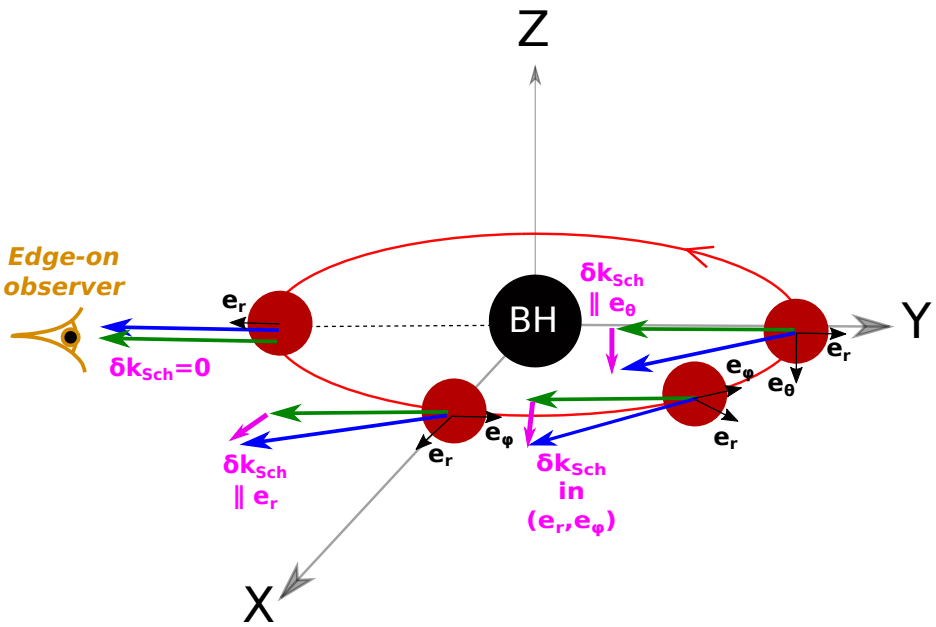
- **Mirror symmetry broken in Sch** with inclination.
- Due to **light bending**
- $\rightarrow$ *Specifically GR feature = mirror asymmetry*
- *Quantifying curvature?*

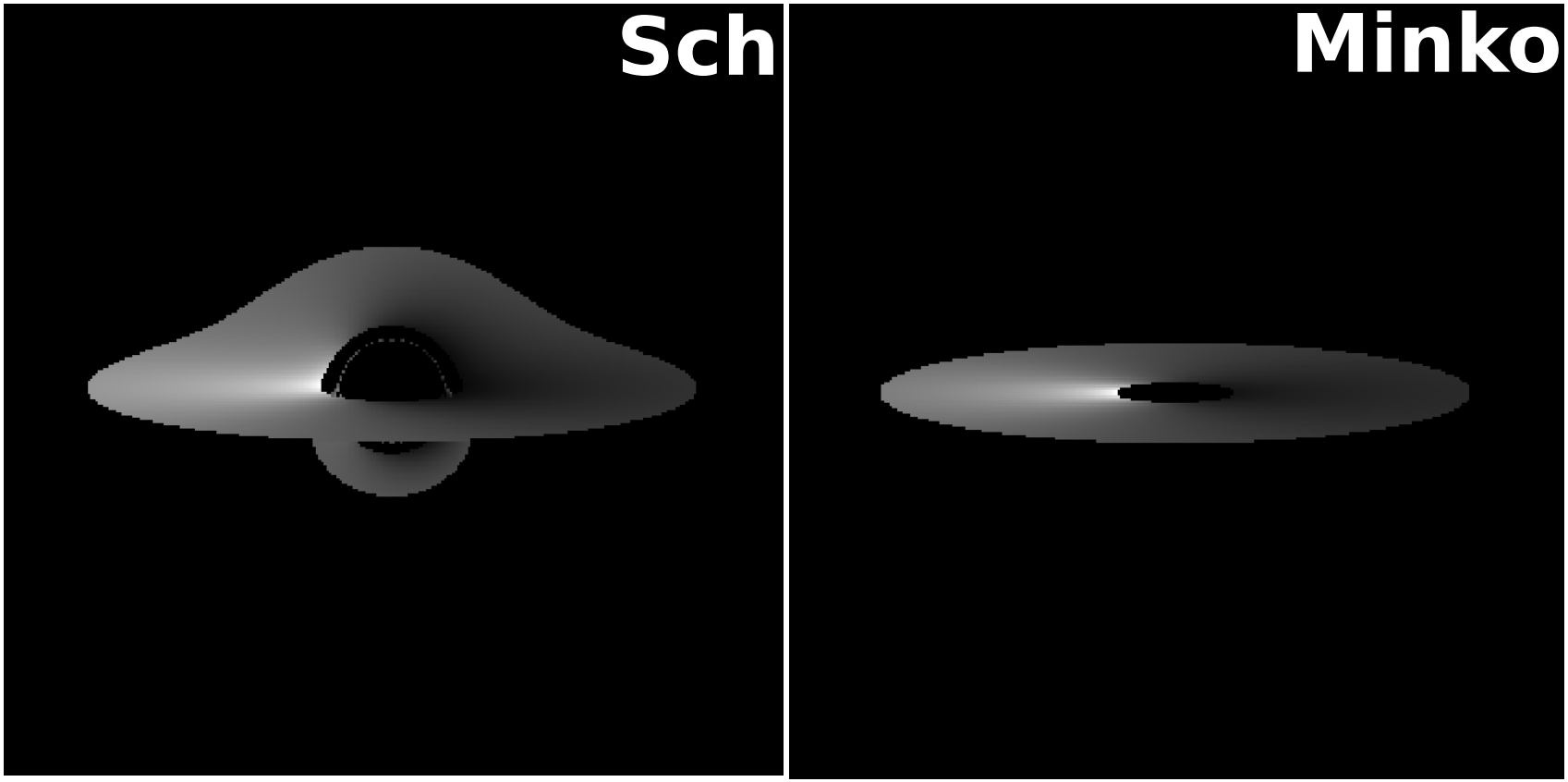
Conclusions

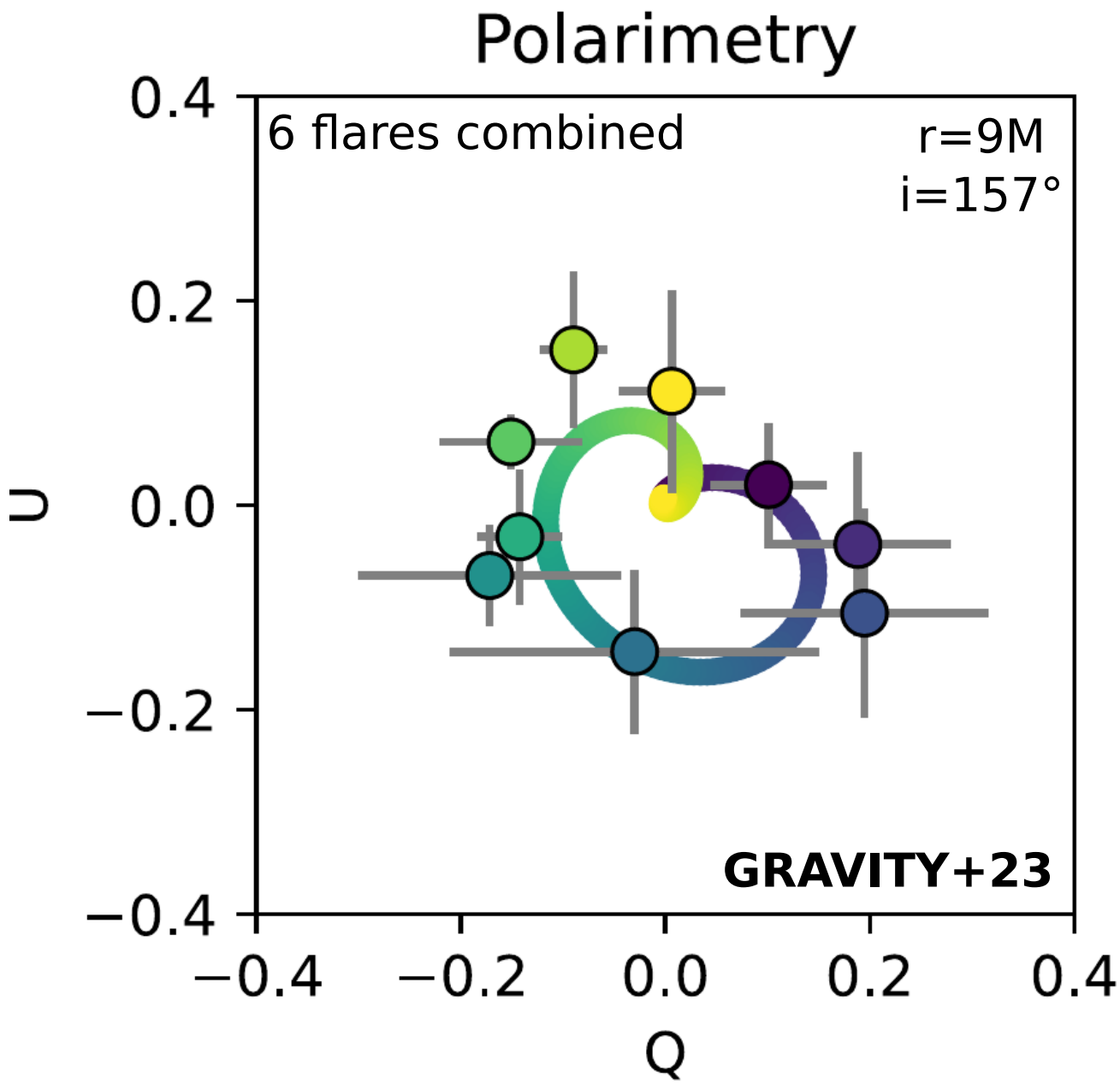
- Polarized radiative transfer = **crucial tool for plasma**
- Now routinely integrated in raytracing codes
- Hot spots QU loops: **light bending causes asymmetry**
- Path to quantifying curvature?
- **Caveats**: equatorial motion, axisymmetry of velocity and physical quantities, time-independence of emission $\rightarrow$ **check robustness**
- Other gravity constraints with polarization: photon rings (Himwich+20)

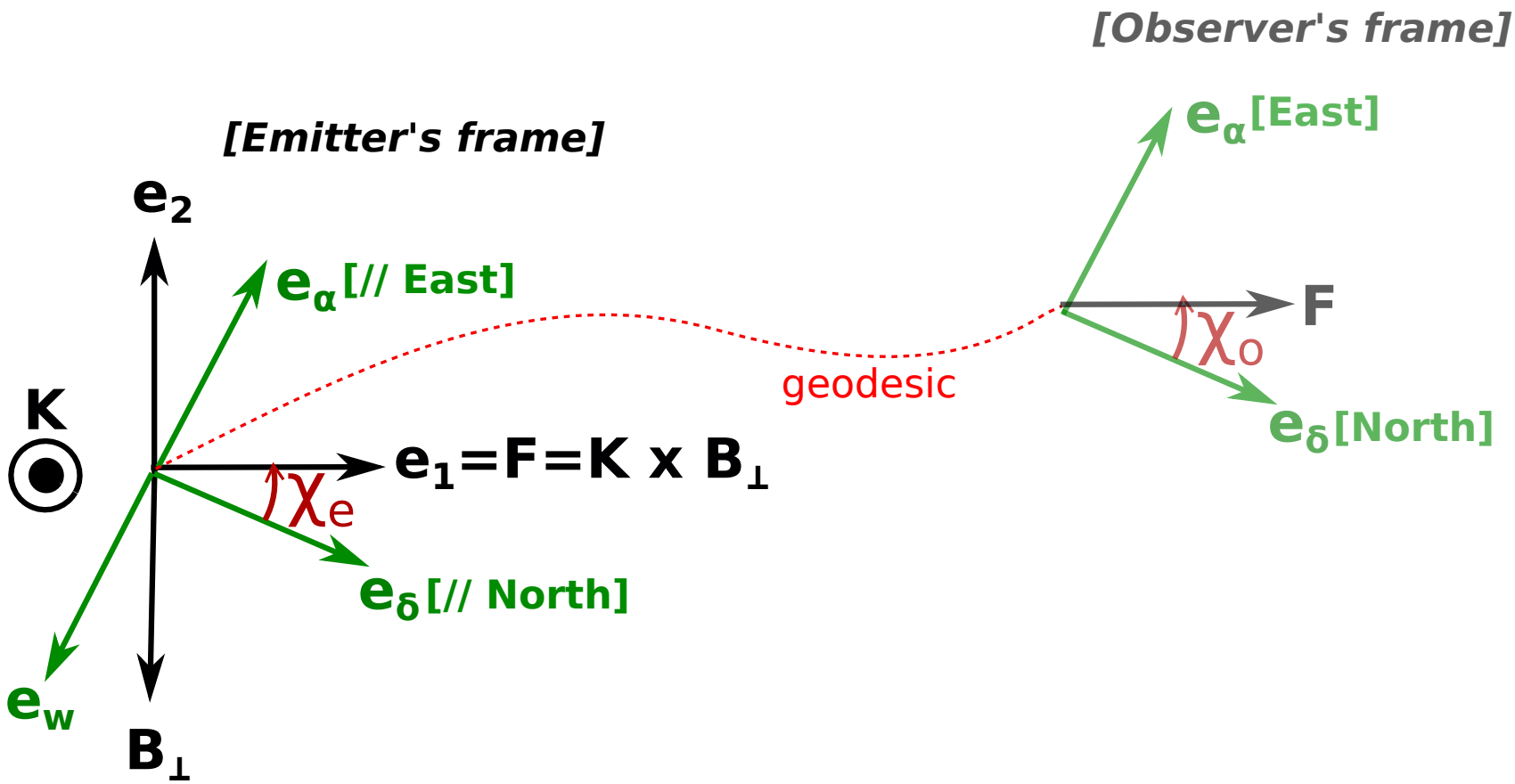
- Details: Vincent+23 arxiv/2309.10053; Aimar+23 in prep.


Z
Y
X
BH
e_r
e_θ
k_{Minko}
k_{Sch}
$\delta k_{Sch} \parallel e_r$
$\delta k_{Sch} \parallel e_r$
$\delta k_{Sch} \parallel e_r$
Face-on observer


Edge-on observer
$\delta k_{Sch}=0$
Z
Y
X
BH
e_r
e_θ
e_φ
$\delta k_{Sch} \parallel e_\theta$
$\delta k_{Sch} \parallel e_r$
δk_{Sch} in (e_r, e_φ)


Sch
Minko


Polarimetry
6 flares combined
r=9M
i=157°
GRAVITY+23
U
Q
0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4


[Observer's frame]
e_α[East]
F
χ_o
e_δ[North]
geodesic
[Emitter's frame]
e_2
e_α[// East]
K
e_1=F=K x $B_\perp$
χ_e
e_δ[// North]
e_w
$B_\perp$