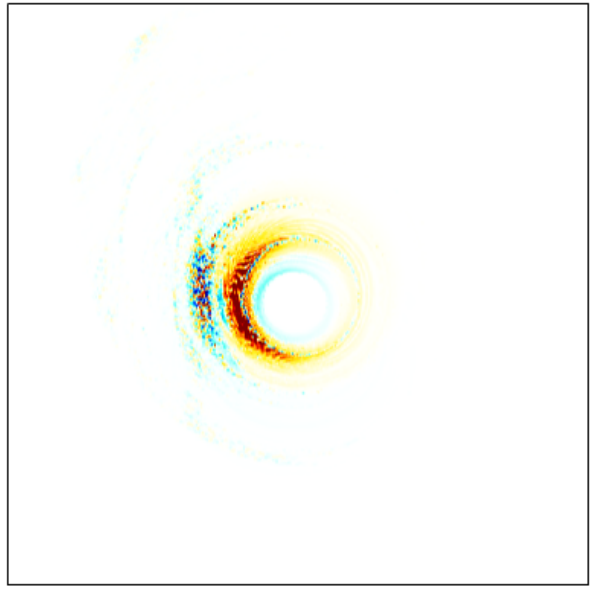
Polarization images around the supermassive black holes: Imprints of the magnetic field structure

(Tsunetoe et al. 2020, PASJ 72, 32;
Tsunetoe et al. 2021, subm. to PASJ, arXiv:2012.05243)

M87* Circular Polarization



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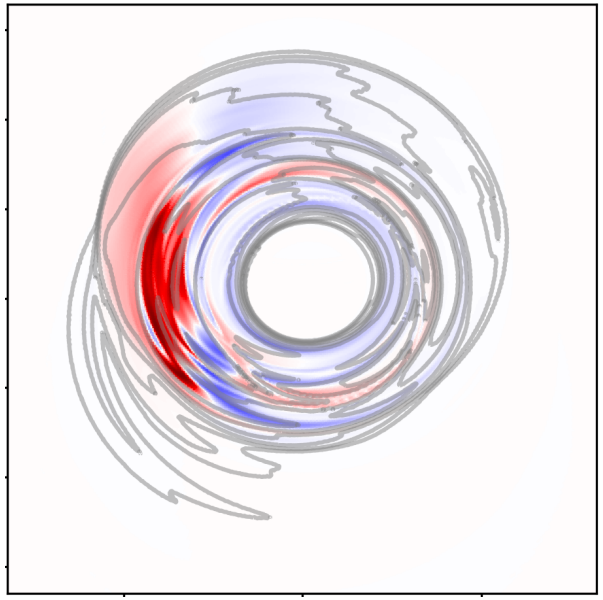
Sgr A* Circular Polarization



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Ken Ohsuga (U. of Tsukuba)
Tomohisa Kawashima (U. of Tokyo)
Kazunori Akiyama (MIT Haystack)

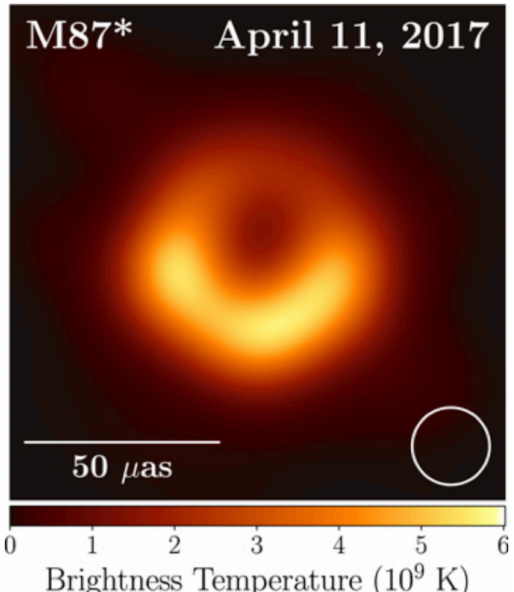
Observations of magnetically-driven jets

- **Driving mechanism of AGN jets: long-time enigma since early 20th century**
- **Blandford & Znajek process: modeling by magnetic fields**
  -> polarimetry: However, essential fields near the jet base are yet…

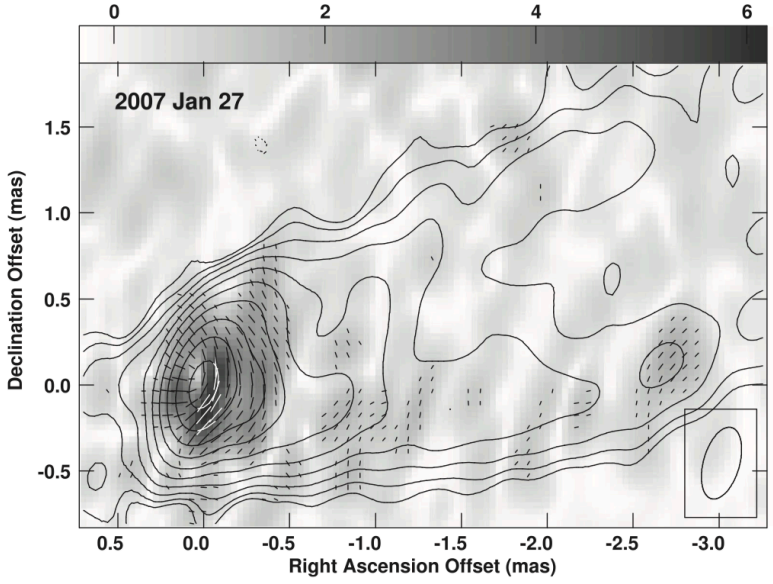
➢**New era of direct observations of SMBH by Event Horizon Telescope(EHT)**

➢**Survey of magnetic structure near BH by the EHT polarimetry**

M87* @230GHz, EHT Collaboration et al. 2019

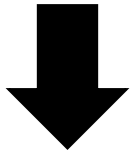


Linear Polarimetry of M87 @43GHz, Walker+2018



Our study: predict polarization images, and understand magnetic fields

- **Theoretical models of AGN jets :**
  General Relativistic Magneto-Hydro-Dynamics (GRMHD)



By post-process

This work

- **Implement polarimetric radiative transfer simulations**

➢ **Predict polarization images based on the models,**
directly compare with observations -> magnetic structures

- **Especially, focus on Circular Polarization (CP)!!**

Radiative Transfer eq:

$$\frac{\mathrm{d}}{\mathrm{d}\lambda}\boldsymbol{I} = \boldsymbol{j} - \boldsymbol{K}\boldsymbol{I}$$

- Stokes parameters $\boldsymbol{I}$

$$\boldsymbol{I} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

I: Total intensity

Q, U: Linear polarization (**LP**)

V: Circular polarization (**CP**)

- Synchrotron emissivities $\boldsymbol{j}$

$$\boldsymbol{j} = \begin{bmatrix} j_I \\ j_Q \\ j_U \\ j_V \end{bmatrix}$$

j_I, j_Q, j_U: Dominant by beaming

j_V: **CP emission: weak**

- Radiative matrix $\boldsymbol{K}$

Faraday rotation of LP vector

$$\boldsymbol{K} = \begin{bmatrix} \alpha_I & \alpha_Q & \alpha_U & \alpha_V \\ \alpha_Q & \alpha_I & \rho_V & \rho_U \\ \alpha_U & -\rho_V & \alpha_I & \rho_Q \\ \alpha_V & -\rho_U & -\rho_Q & \alpha_I \end{bmatrix}$$

Synchrotron self-absorption

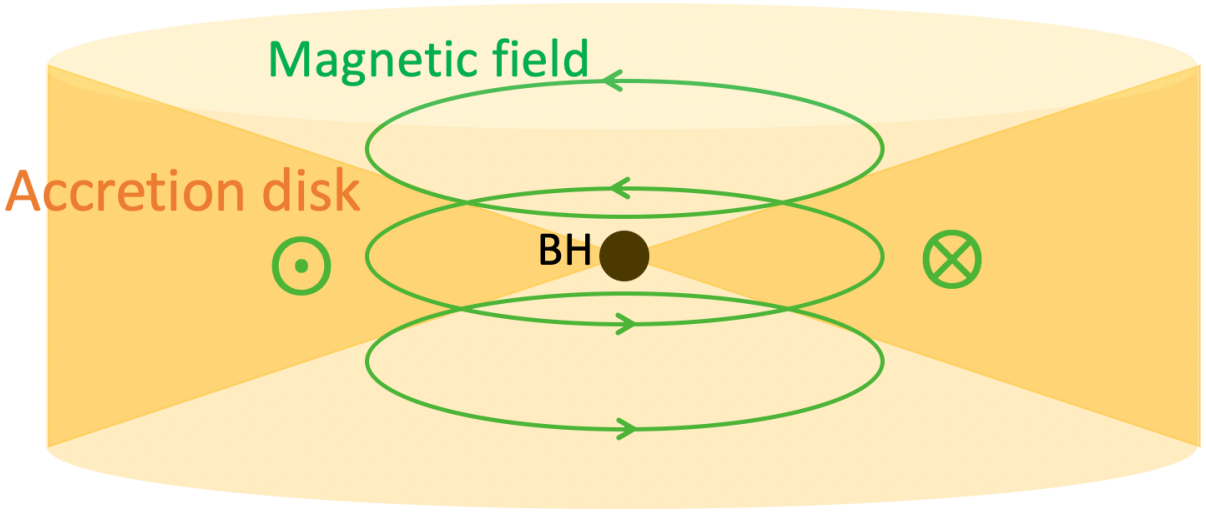
Faraday conversion LP↔CP

Our viewpoint

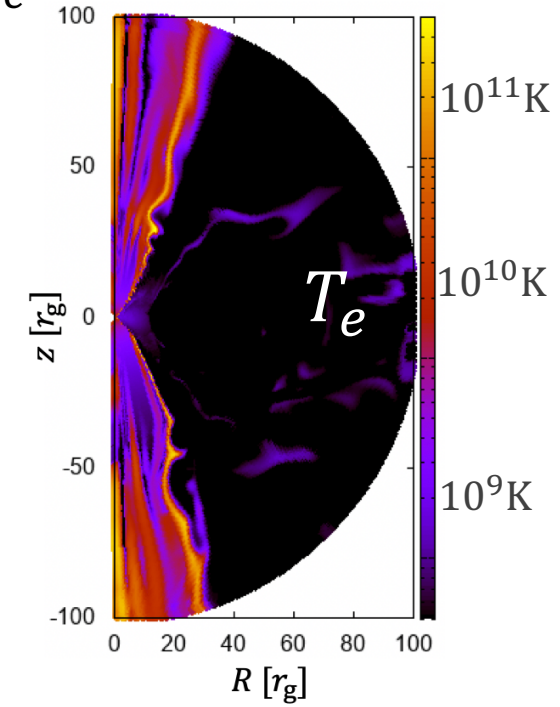
- **CP can increase near the BH by Faraday conv. (coeff: $\rho_Q, \rho_U \propto B^2 T_\mathrm{e}$)**
- **CP obs. -> magnetic field near the BH**

Models for M87* & Sgr A*

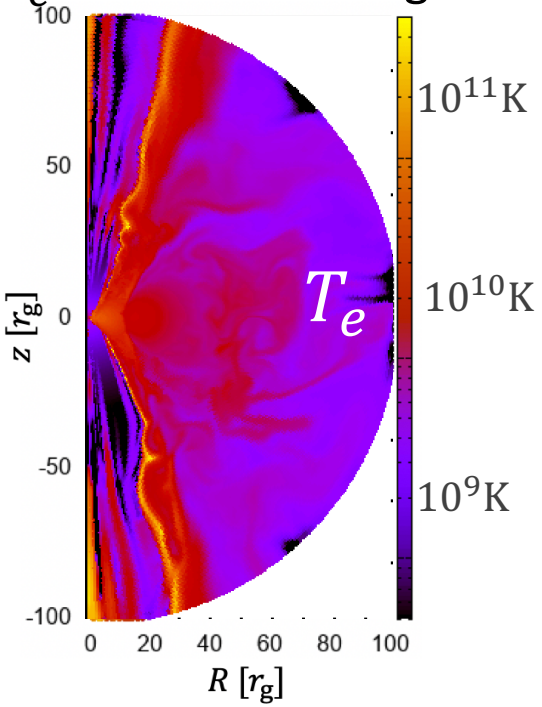
- **Nakamura et al. 2018: axi-symmetric GRMHD models**
  - **Magnetically driven jet with BH spin of $a = 0.9M_{BH}$**
- **M87* model: $T_e \approx T_p$ in the jet, $T_e \approx T_p/100(\sim 10^8\mathrm{K})$ in the disk; jet>disk**
- **Sgr A* model: $T_e \approx T_p$ in the jet, $T_e \approx T_p/2(\sim 10^{10}\mathrm{K})$ in the disk; jet<disk**



T_e distribution in M87*



T_e distribution in Sgr A*



CP amplification near the BH

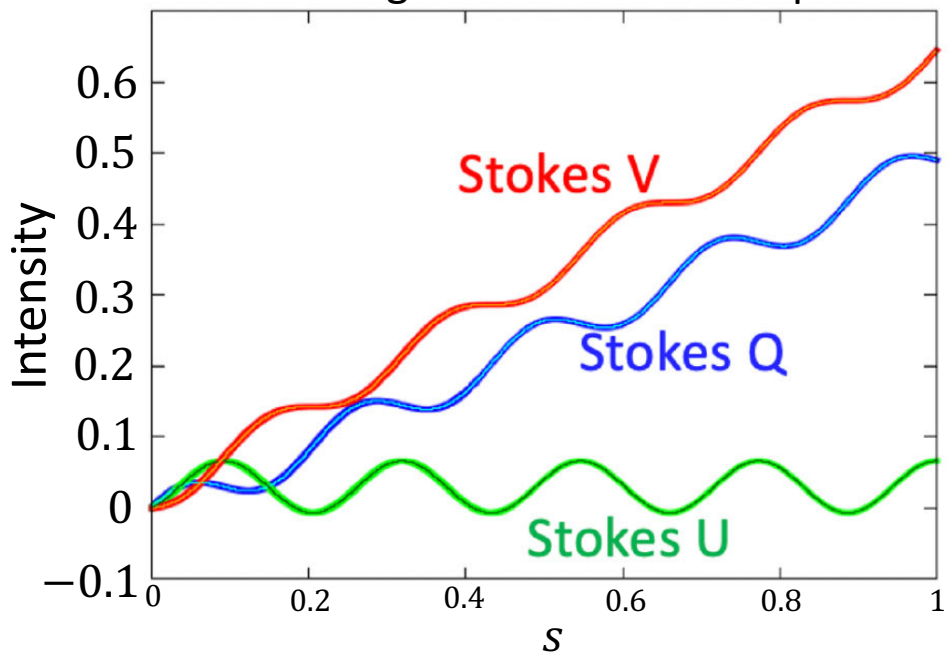
- **Near the BH: Hot electrons** $(T_e > 10^{10}\mathrm{K})$ **+ strong magnetic fields**
  -> **Faraday conversion rate ~ Faraday rotation rate**
- **Propagation of the CP: Stokes** $V \propto j_{LP} \rho_{\mathrm{rot.}} \rho_{\mathrm{conv.}} s$ ← Path length

The LP emissivity

Coefficients of Faraday rot. & conv.

(see Tsunetoe et al. 2020 for detail)

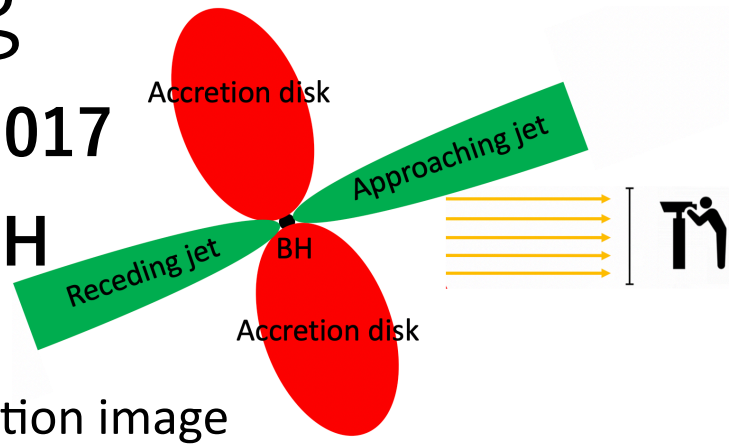
Co-increasing of the LP & CP components



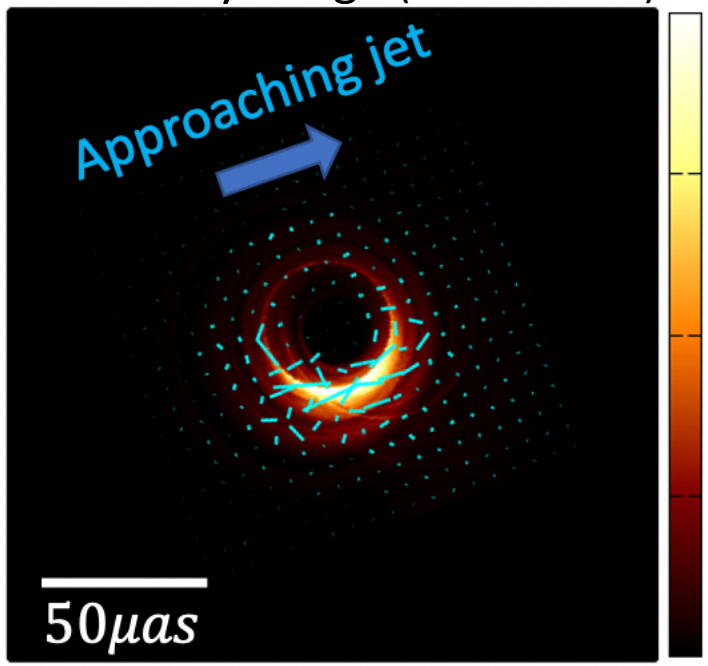
(test calculation with proper coefficients)

M87* CP image: positive ring

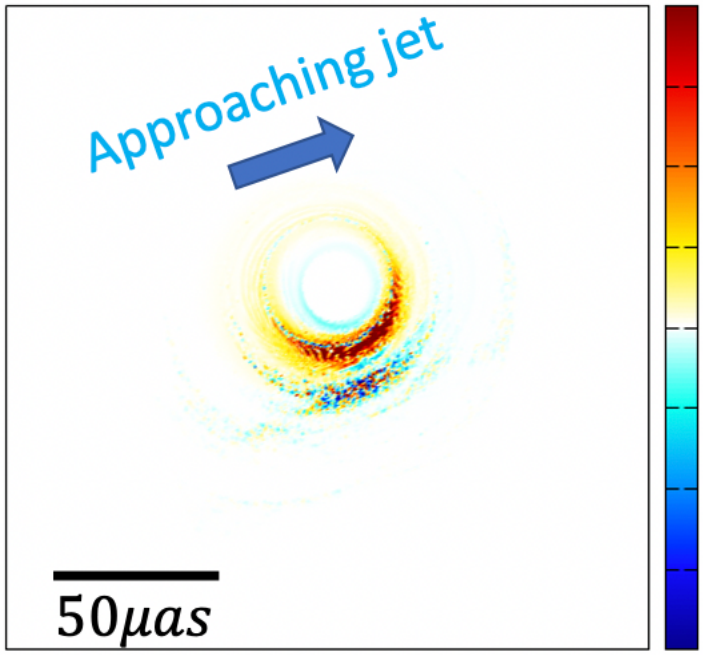
- **Inclination $i = 160^{\circ}$, the shadow consistent with EHT2017**
- **CP: amplified by ordered magnetic fields near the BH**
  -> a ring feature with positive sign



Intensity image (+ LP vectors)



Circular Polarization image



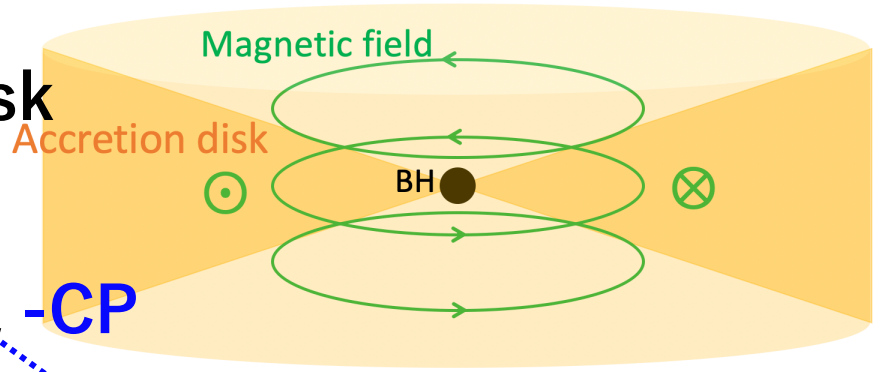
Positive CP
(right-handed CP)

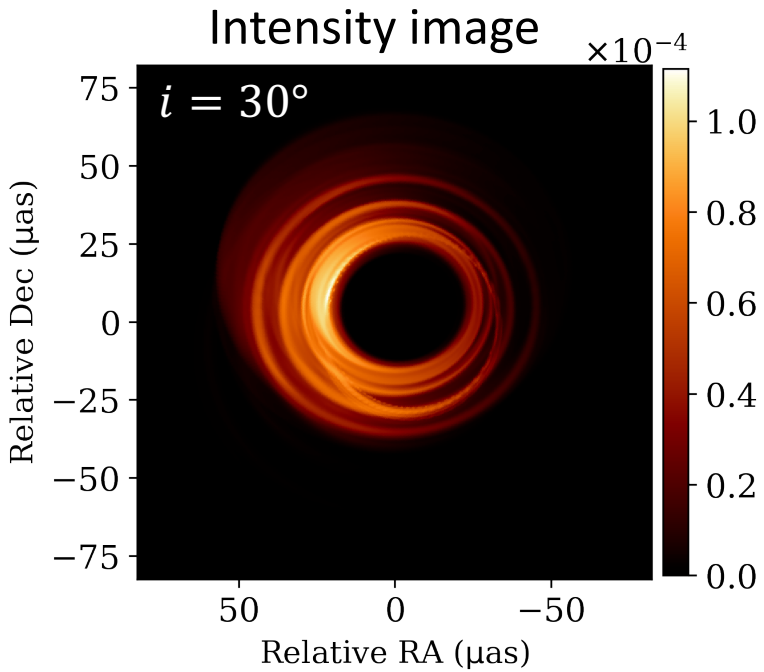
Negative CP
(left-handed CP)

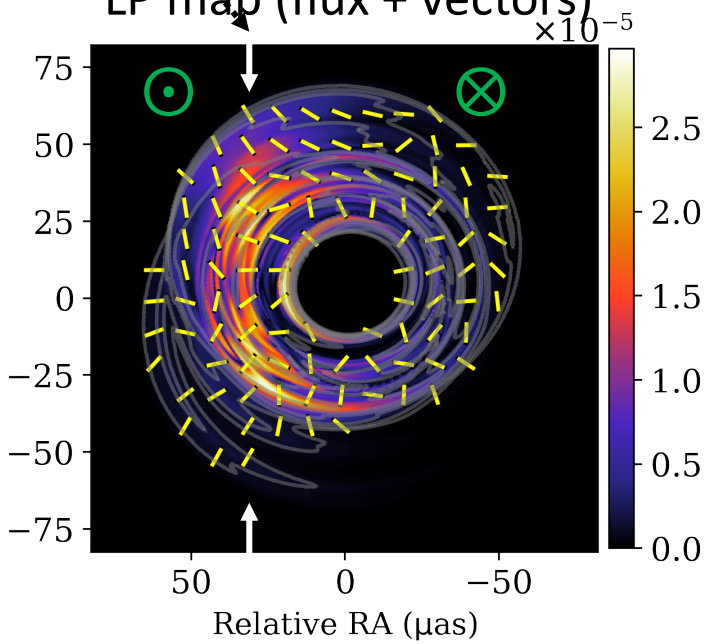
➢ **CP ring: trace of hot plasma & ordered fields!!**

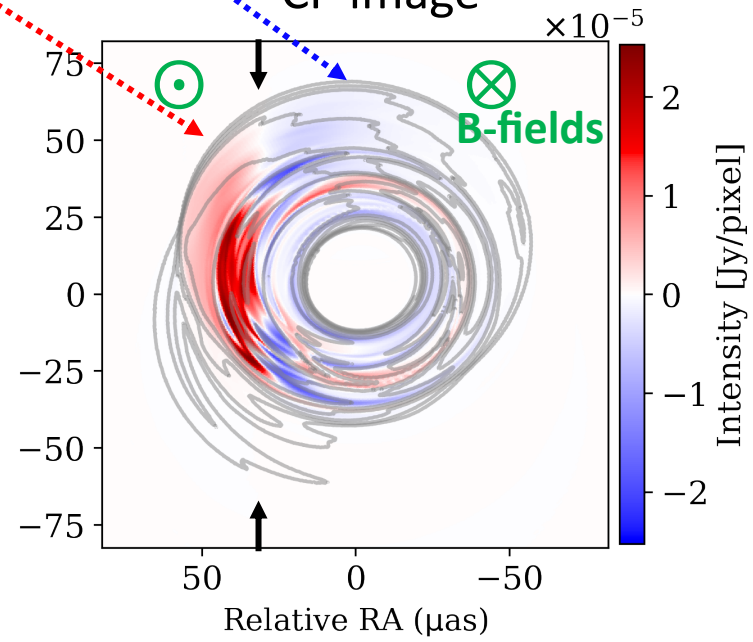
Sgr A* CP image: sign-change

- $i = 30°$: **ring feature, broad emission from hot disk**
- **CP: amplified like M87*, but + in right, - in left**
- **LP: bright along the 'separatrix' between +CP & -CP**







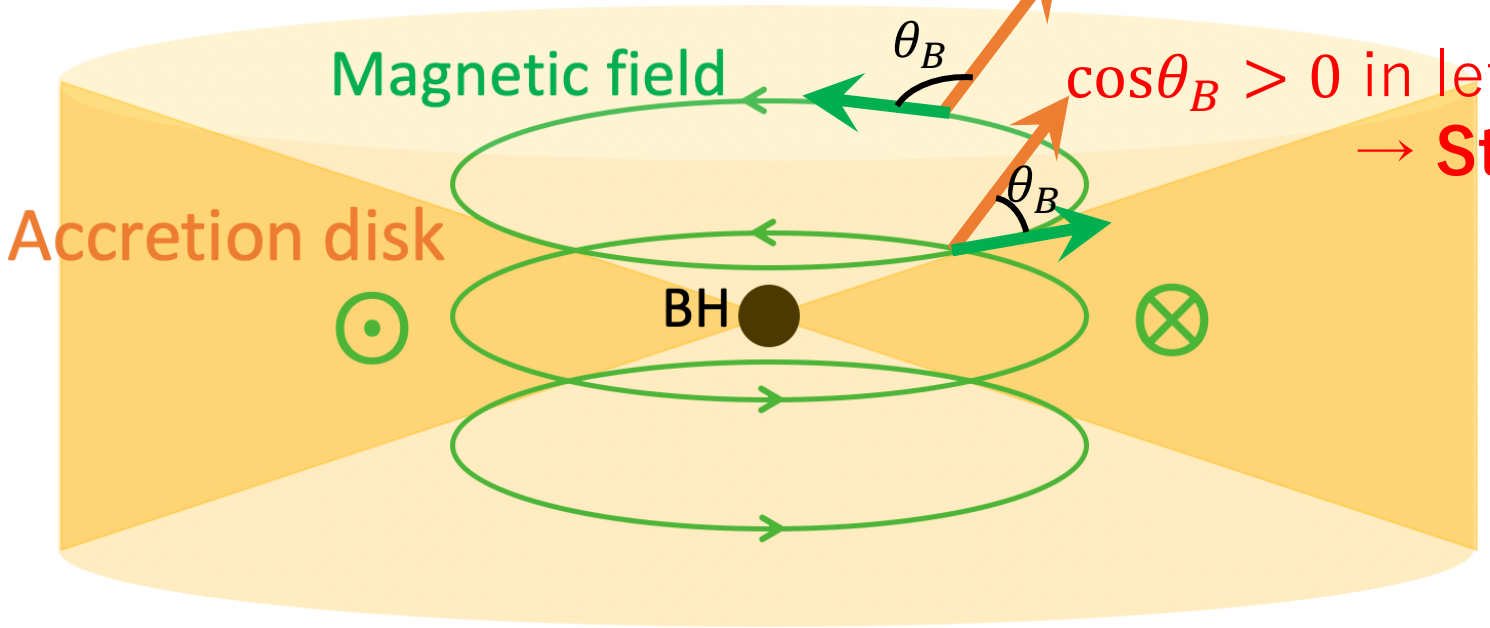


Sign-changing CP & bright LP: toroidal fields

- **CP: depends on the angle θ_B between B-field vs LoS**

  Stokes $V \propto j_{\mathrm{LP}} \rho_{\mathrm{rot.}} \rho_{\mathrm{conv.}} s \propto \cos\theta_B$

$\cos\theta_B < 0$ in right→ **Stokes V<0**

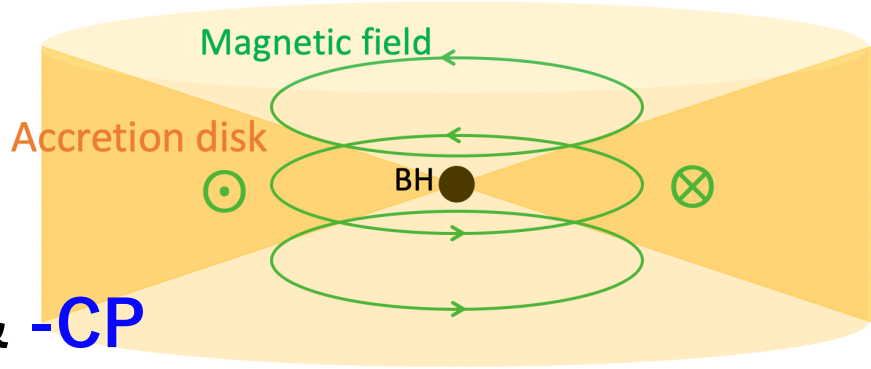


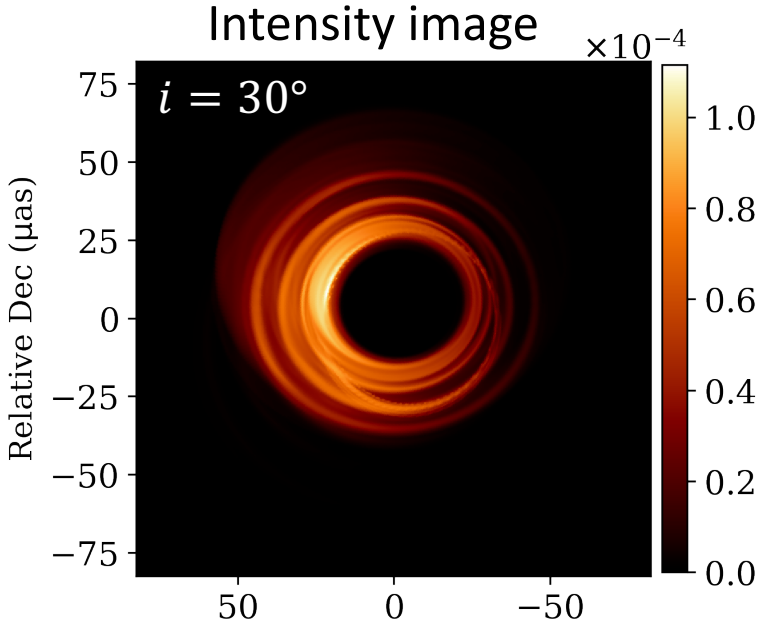
- **LP flux: Faraday rotation $\rho_{\mathrm{rot.}} \propto \cos\theta_B \approx 0$ on the separatrix**

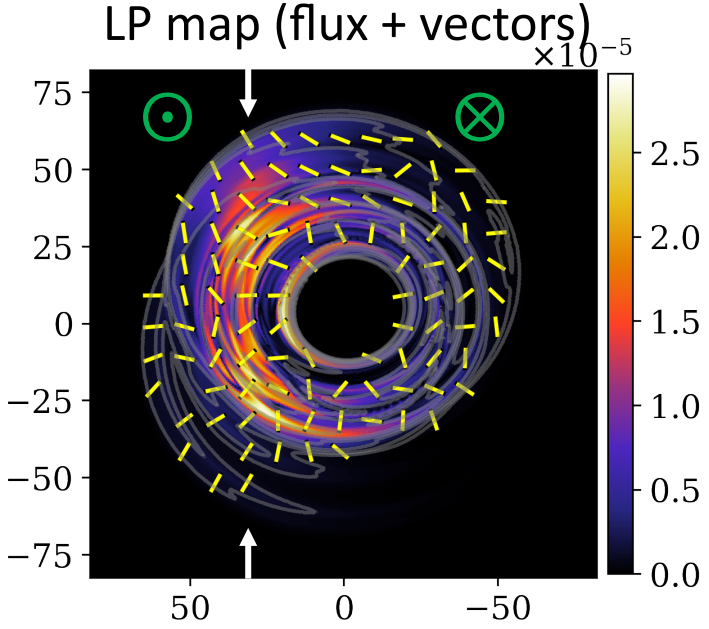
  →the original components can survive (no depolarization)

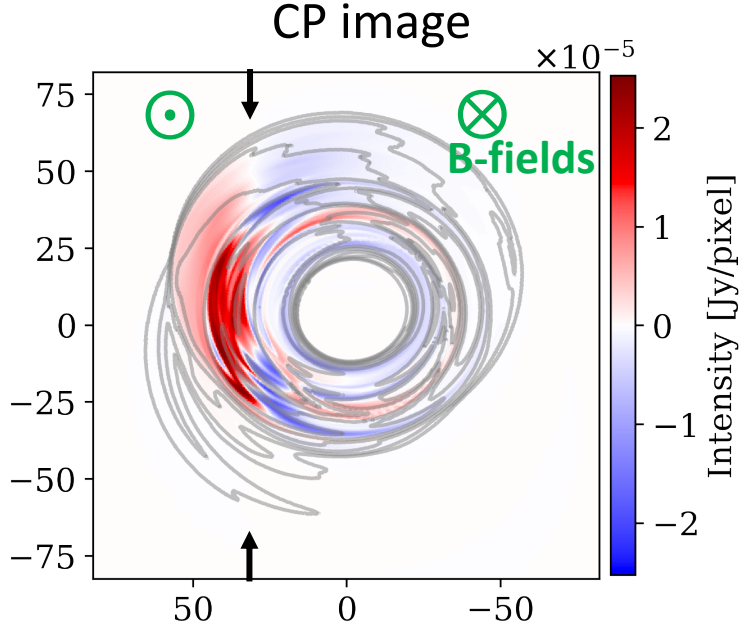
Sgr A* CP image: sign-change

- $i = 30°$: **ring feature, broad emission from disk**
- **CP: amplified like M87*, but + in right, - in left**
- **LP: bright along the 'separatrix' between +CP & -CP**





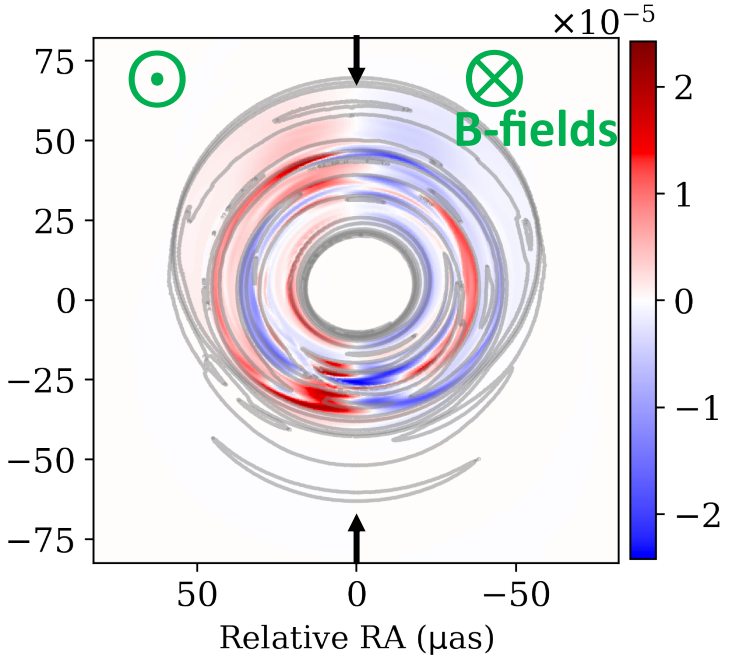




➢ **CP separatrix & LP flux -> toroidal magnetic field!!**

Left-leaning separatrix?
-Relativistic effect by disk rotation

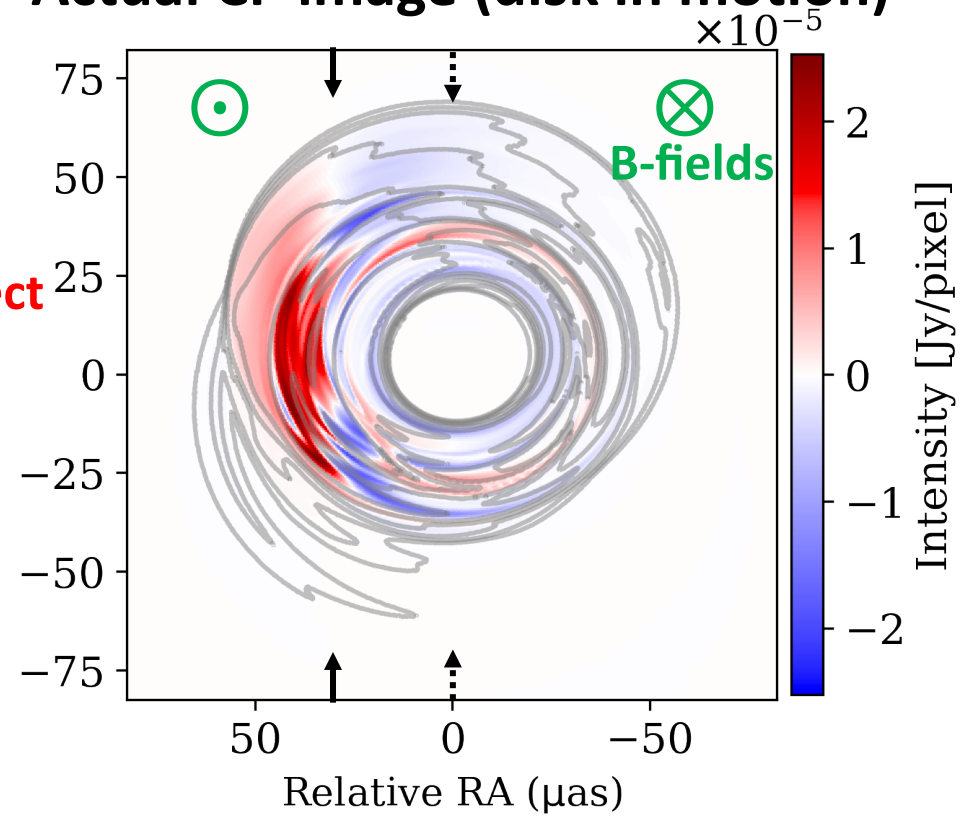
If the disk was not in motion



Relativistic aberration effect
by the disk motion

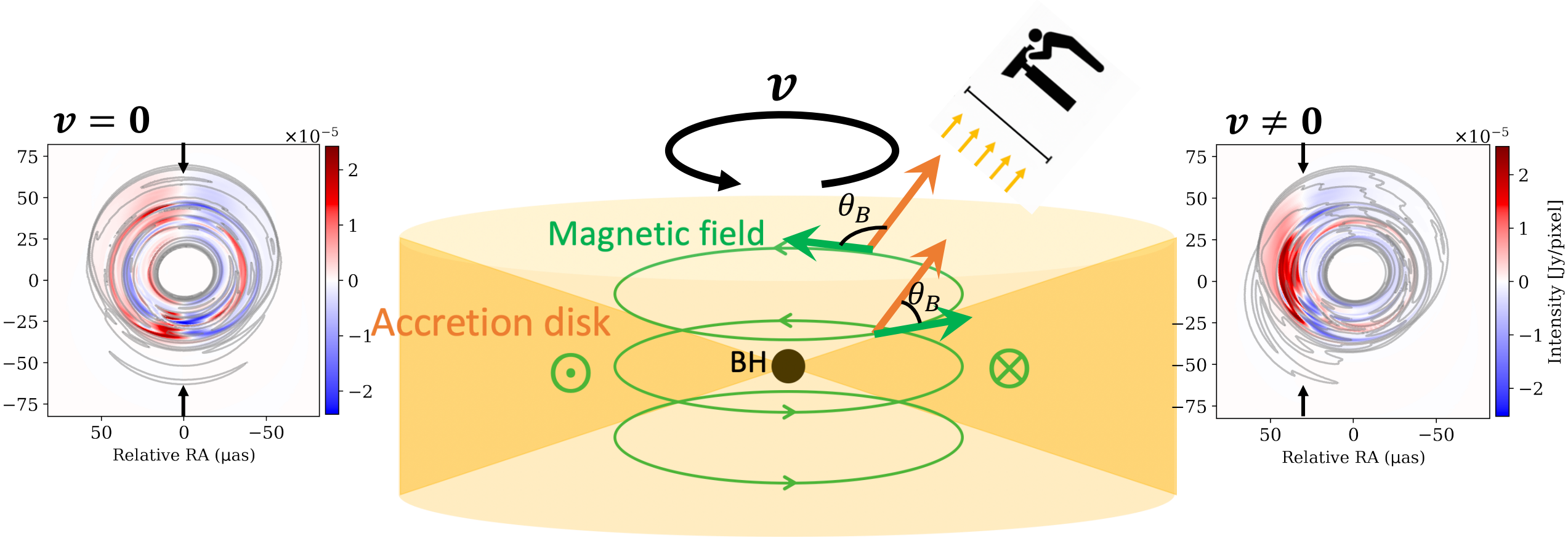
Actually…

Actual CP image (disk in motion)



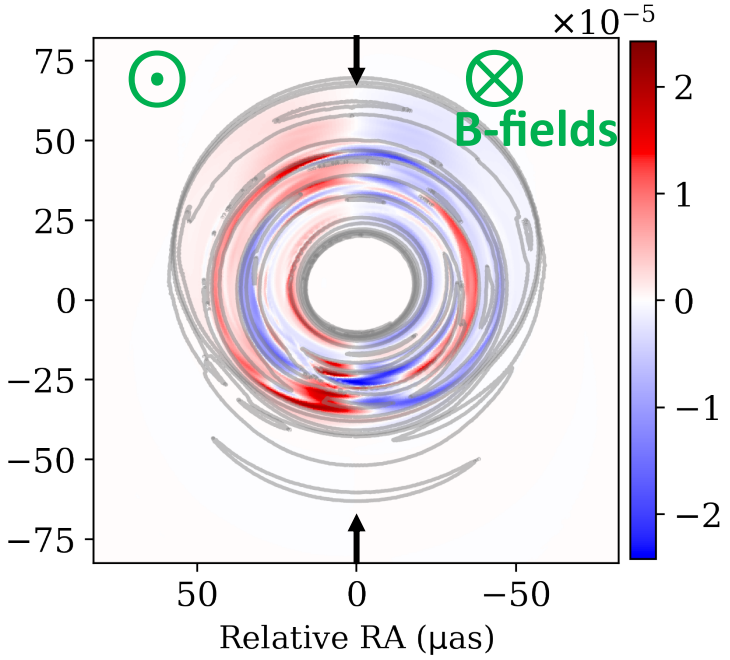
Relativistic aberration effect by disk motion

- **Plasma in relativistic bulk motion: Stokes V & Faraday rot.** $\propto (\boldsymbol{k} - \boldsymbol{v}) \cdot \boldsymbol{B} = \boldsymbol{k} \cdot \boldsymbol{B} - \boldsymbol{v} \cdot \boldsymbol{B}$
- **Thus, take a negative value where** $\boldsymbol{k} \perp \boldsymbol{B}$ **(~ in the central line of the CP image)**



Left-leaning separatrix:
Relativistic effect by disk rotation

If the disk was not in motion



Relativistic aberration effect
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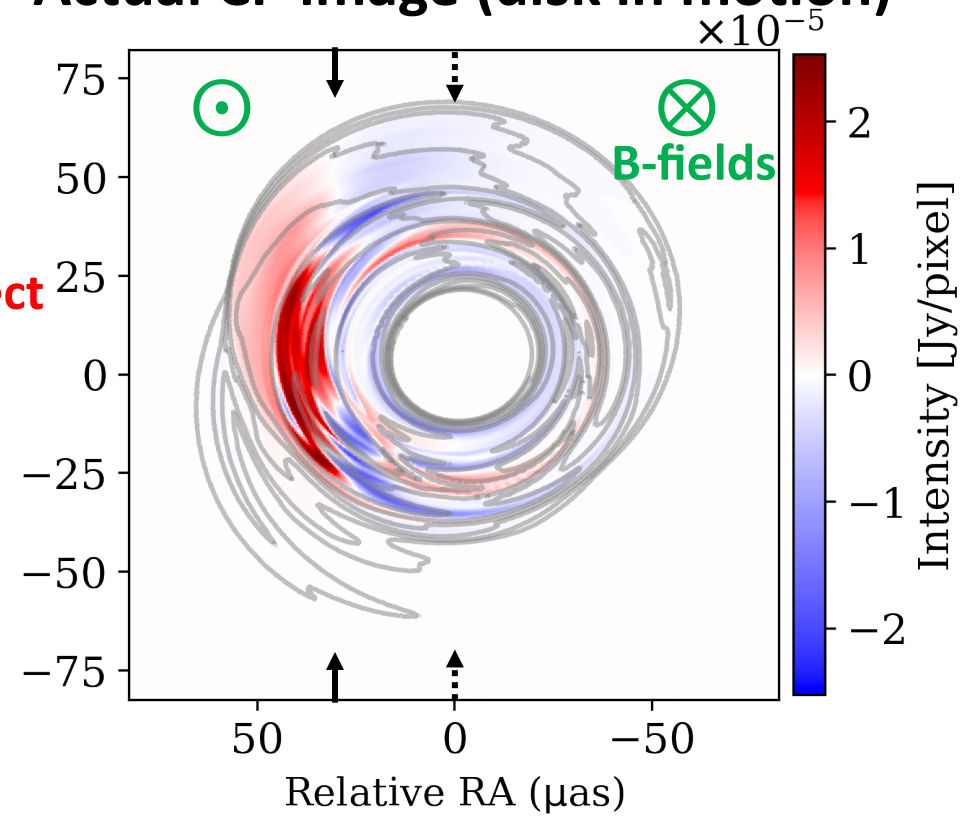
Actually…

Actual CP image (disk in motion)



The CP separatrix -> magnetic fields + disk motion!!

Why no sign-change in M87* model?

- **Face-on$(i = 160°)$ case & cold disk**

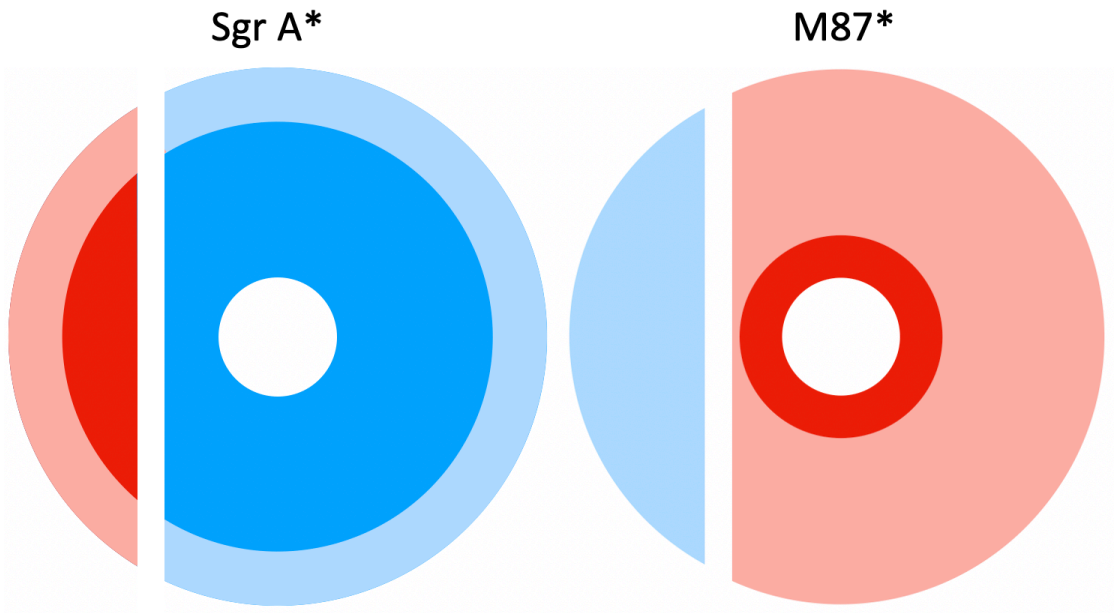
  →emission limited to narrow region near the BH (with positive CP)

  →the left side with negative CP: weak emission

- **Sign reversal between Sgr A*$(i = 30°)$ & M87* $(i = 160°)$:**

  magnetic fields' reversal between the north- & south-hemisphere

Pictures for the CP images for Sgr A* & M87*



Summary

- **CP amplified near the BH: trace of jet-driving B-fields**

Tsunetoe et al. 2020

- **M87: compact ring, consistent with EHT2017**
- **Positive ring in CP: hot electron + ordered B-fields**

no sign-change because of narrow emission

Tsunetoe et al. 2021

- **Sgr A*: broad emission from hot disk**
- **The CP separatrix + LP flux: evidences of toroidal B-fields**

left-leaning due to relativistic motion of the disk

➢**Recent & Future works: 3D effects & time-variability**