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# Optical Polarimetry Studies

*between Outburst and Quiescence of the X-ray Binary*

## V4641 Sagittarii

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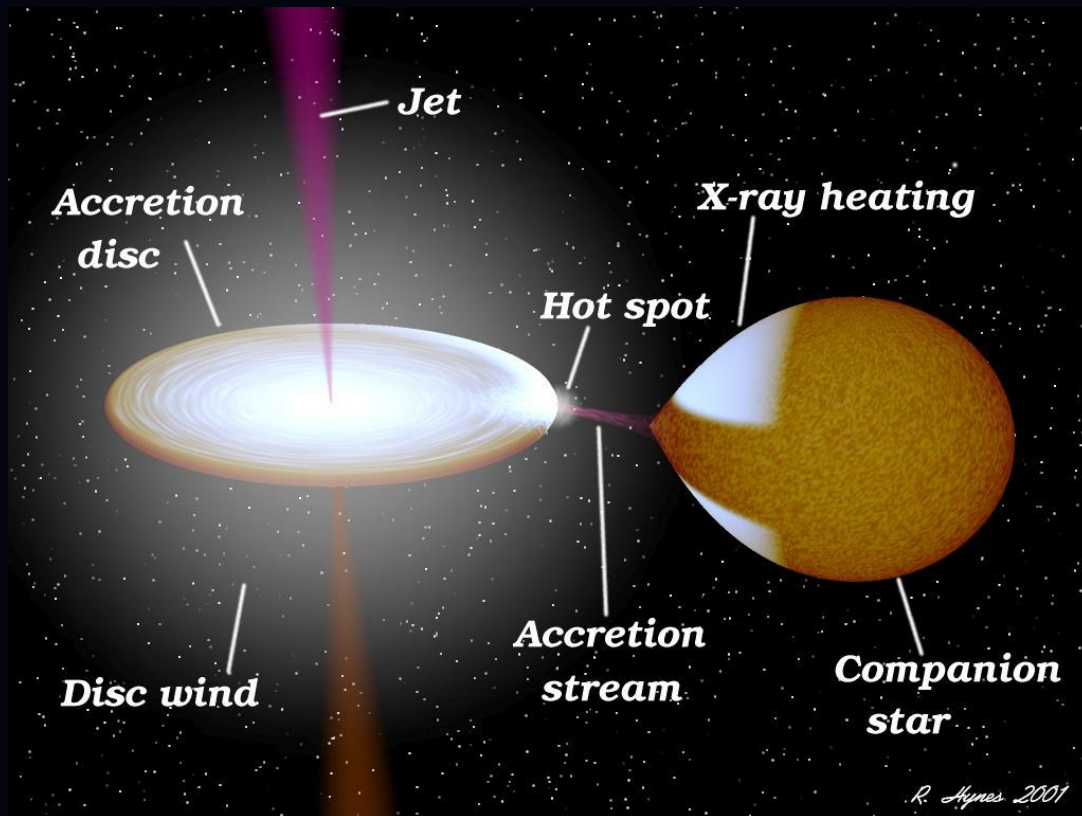
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Barcelona, 04/06/2026

*Maria Cristina Baglio  
Alessia Franchini  
Riccardo Brivio  
Kevin Alabarta Jativa  
Noah Grollmund*

# X-ray Binary Systems

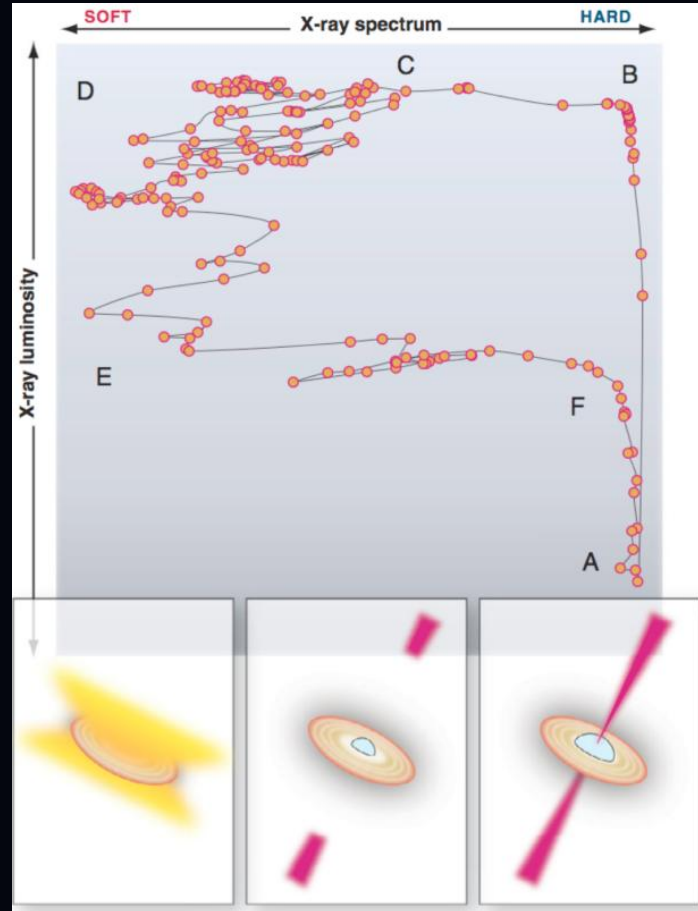
- **Low Mass X-ray Binary:** donor star + compact object (NS or BH)
- Mass transfer via L1 point forming an accretion disc
- **Emitting components:**
  - Radio: jet
  - Infrared: jet + outer disc
  - UV: inner disc + winds
  - X-rays: inner disc + winds + corona
  - Optical:
    - ✓ Companion star (thermal)
    - ✓ Outer disc (thermal)
    - ✓ Jet (synchrotron)
    - ✓ Winds (absorption/emission)
    - ✓ Corona (non-thermal tails)



# Hardness-Intensity Diagram

## Counter-clockwise hysteresis loop (q-plot)

- **A → B** Rise in Hard State: truncated disc + hot corona + compact jet; luminosity increases at high hardness
- **B → C** Hard-to-Soft Transition: disc expands inward; discrete jet ejections; spectrum softens rapidly
- **C → D** Soft State: full thin disc; thermal emission dominates; jet quenched; high luminosity
- **D → E** Soft State decay: luminosity decreases; disc remains extended; spectrum still soft
- **E → F** Soft-to-Hard Transition: at lower luminosity than B→C; disc truncates again
- **F → A** Return to Hard State quiescence: compact jet reforms; accretion rate drops



# Optical Polarimetry in LMXBs

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## Why polarimetry?

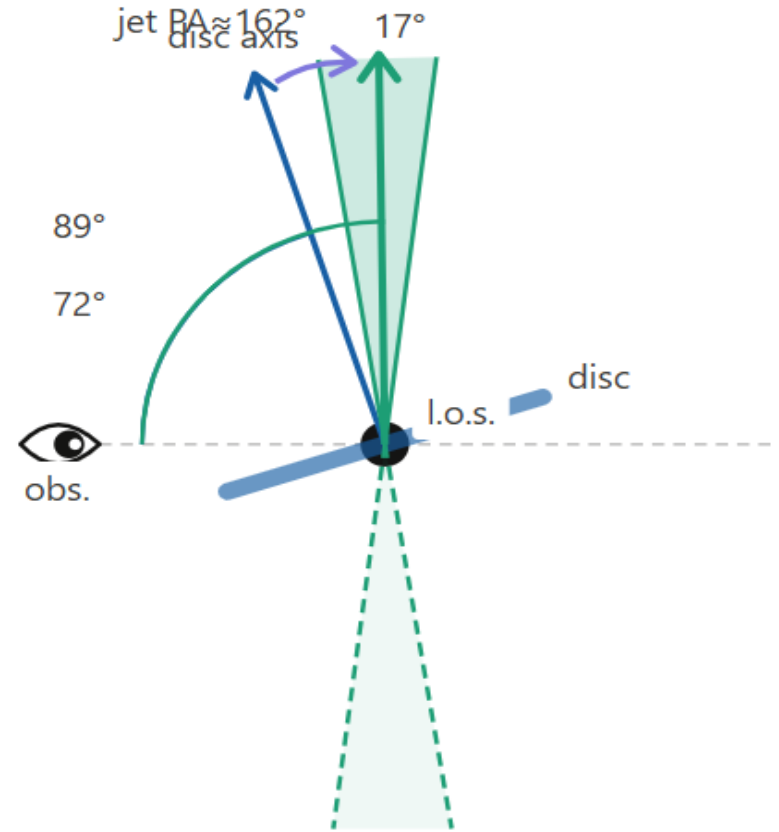
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Provides unique information on:

- Disentangling overlapping emission components
- System geometry
- Magnetic field structure
- Emission mechanisms: Thomson scattering, synchrotron, reflection

# V4641 Sagittarii

- Low-mass X-ray transient (LMXB) in the constellation of Sagittarius
- Distance:  $\sim 6.2$  kpc (MacDonald +2014)
- Black hole with  $M_2 \approx 6.4 M_\odot$
- Companion star con  $M_1 \approx 2.9 M_\odot$
- Orbital period:  $\sim 2.82$  days
- Optical magnitude in quiescence: 13 mag
- System inclination:  $i \sim 72^\circ$
- Confirmed relativistic jets
- Jet and axis aligned (Martí+2025 revision)
- Evidence of winds (spectroscopy)
- Funnel in the inner regions

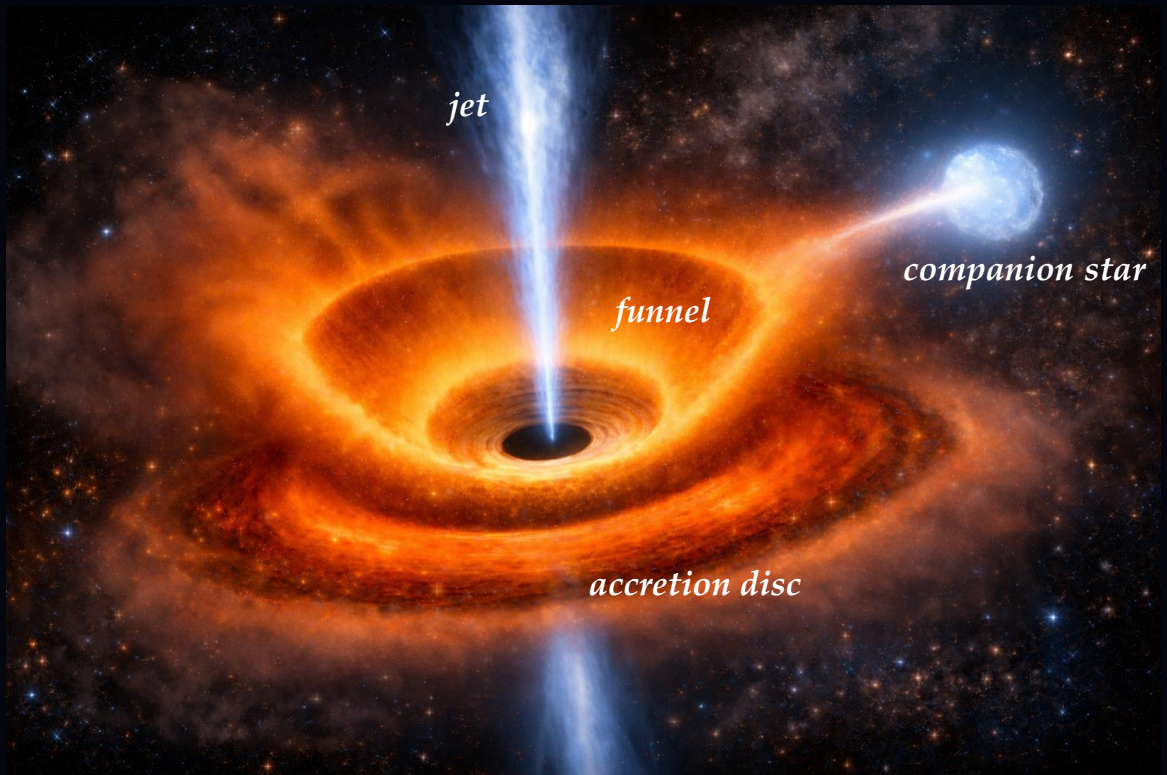


# Funnel Structure

- Radiation pressure carves a funnel structure in the innermost regions of the accretion disc
- Direct view is obscured, but a fraction of inner disc emission can hit the funnel walls
  - scattering toward the observer with a different polarization angle

## Why V4641 Sgr?

- Bright optical magnitude and low extinction
- Unique funnel geometry among LMXBs
- Partial obscuration → polarization signature accessible



# Instrumentation and Observations

## *Instrumentation*

*Telescope*

Very Large Telescope (ESO)  
(Cerro Paranal, Chile)

*Polarimeter*

FORS2, Half-Wave Plate



# Instrumentation and Observations

## Instrumentation

Telescope

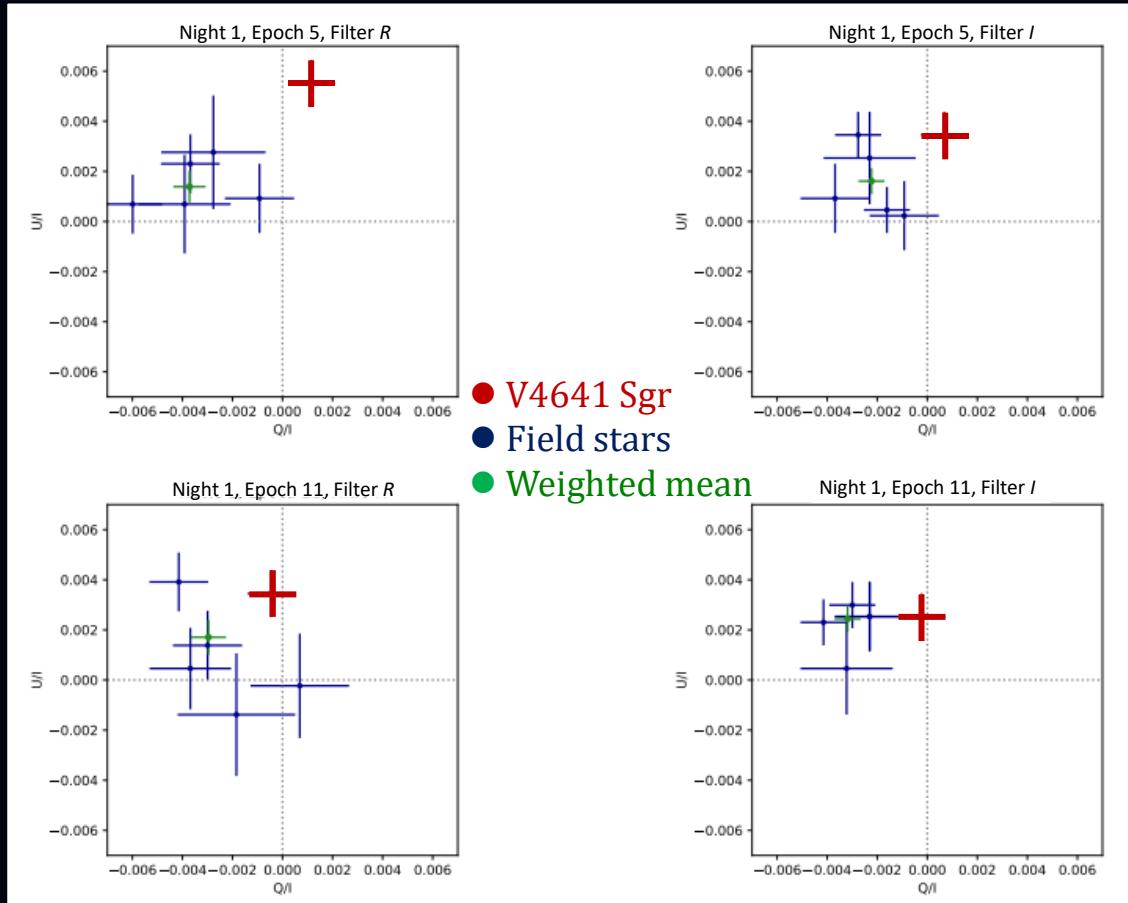
Very Large Telescope (ESO)  
(Cerro Paranal, Chile)

Polarimeter

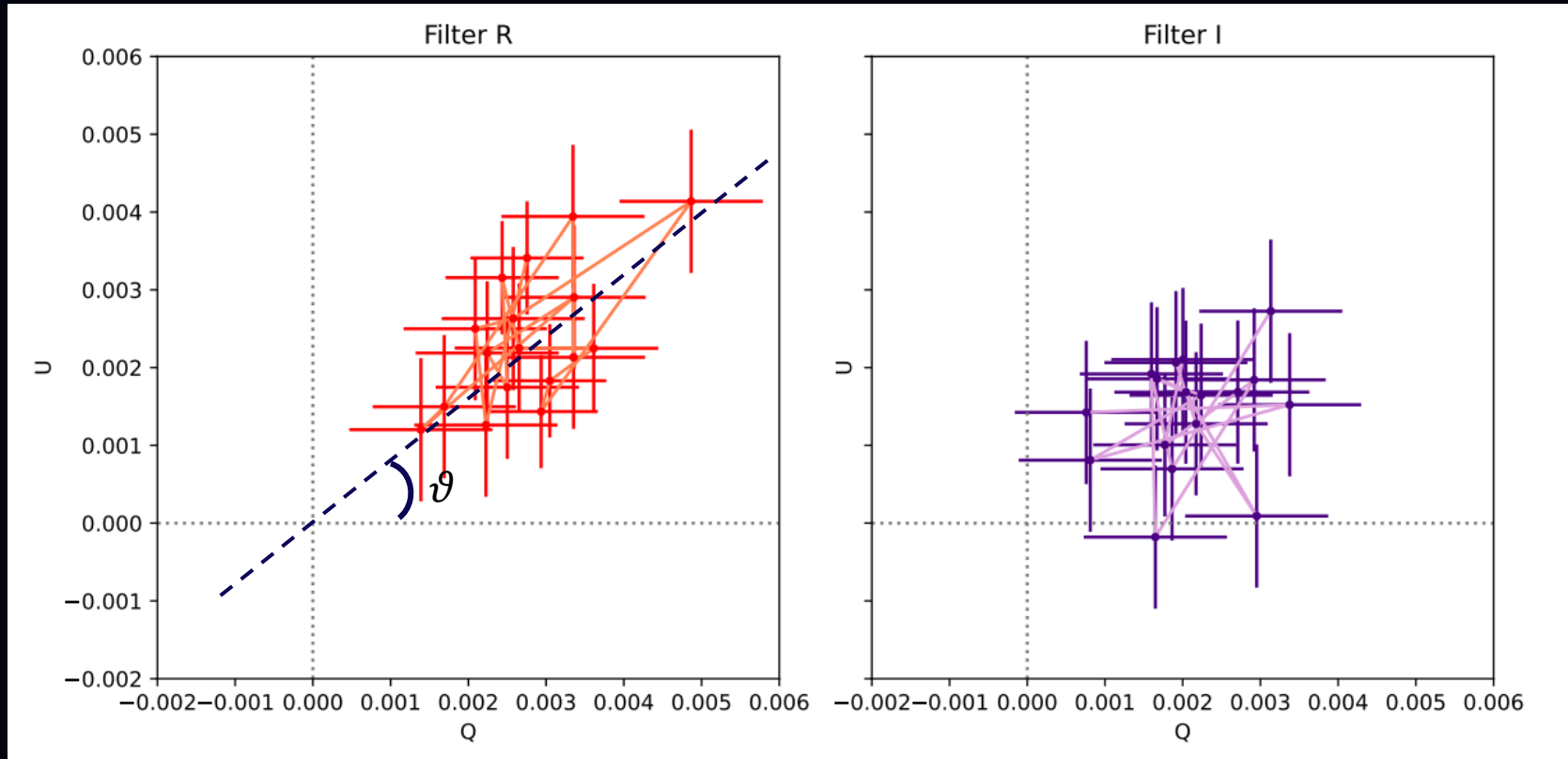
FORS2, Half-Wave Plate

Filter	Night 1	Night 2	Night 3	Quiesc.
<i>B</i>	--	1 epoch	1 epoch	1 epoch
<i>V</i>	--	1 epoch	1 epoch	1 epoch
<i>R</i>	17 epochs	1 epoch	1 epoch	1 epoch
<i>I</i>	17 epochs	1 epoch	1 epoch	1 epoch

# Results: Stokes Parameters

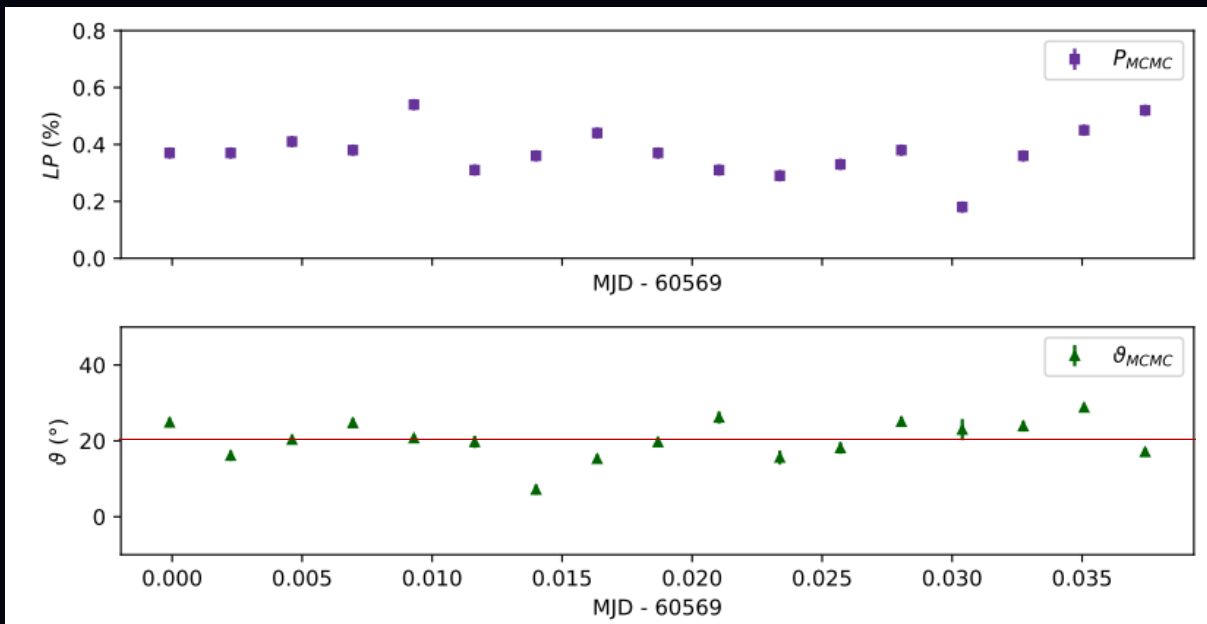
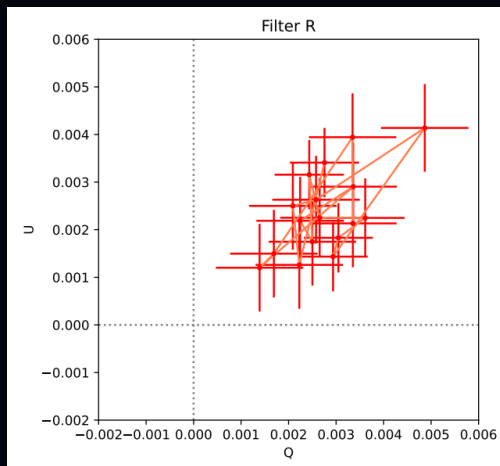


# Results: Short-term Variability of Stokes Parameters



# Results: Polarization with $S(\varphi)$ Parameter

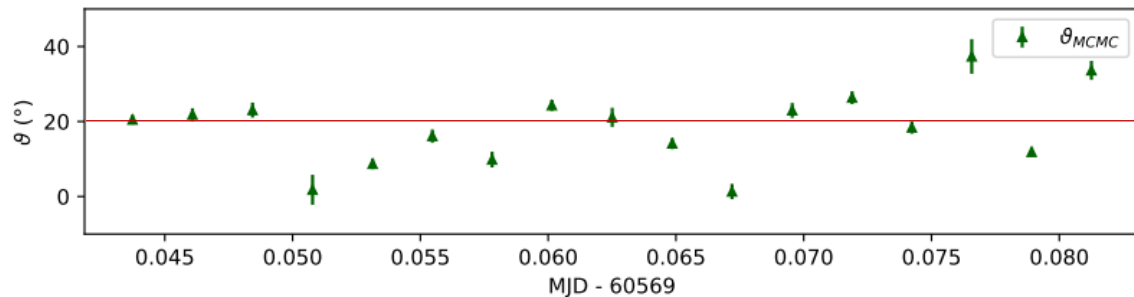
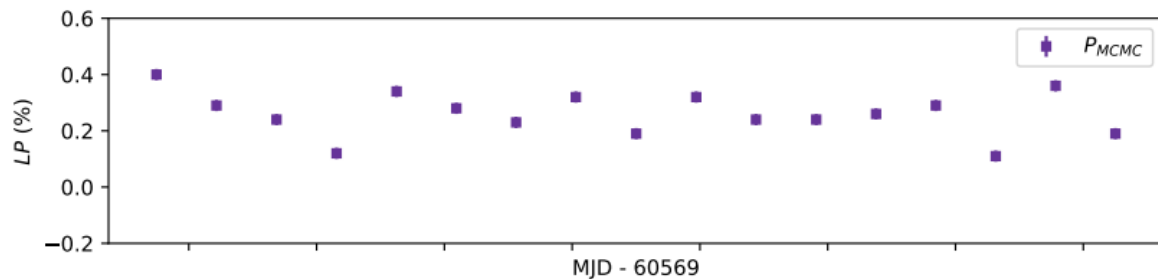
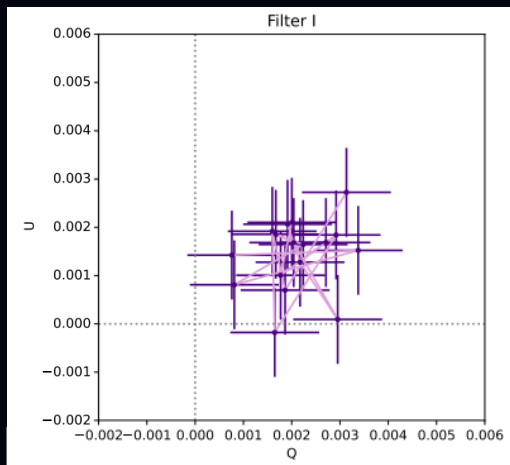
Night 1  
Filter R



LP: variable  
 $\theta$ : not variable

# Results: Polarization with $S(\varphi)$ Parameter

Night 1  
Filter I



$LP$ : variable  
 $\vartheta$ : variable

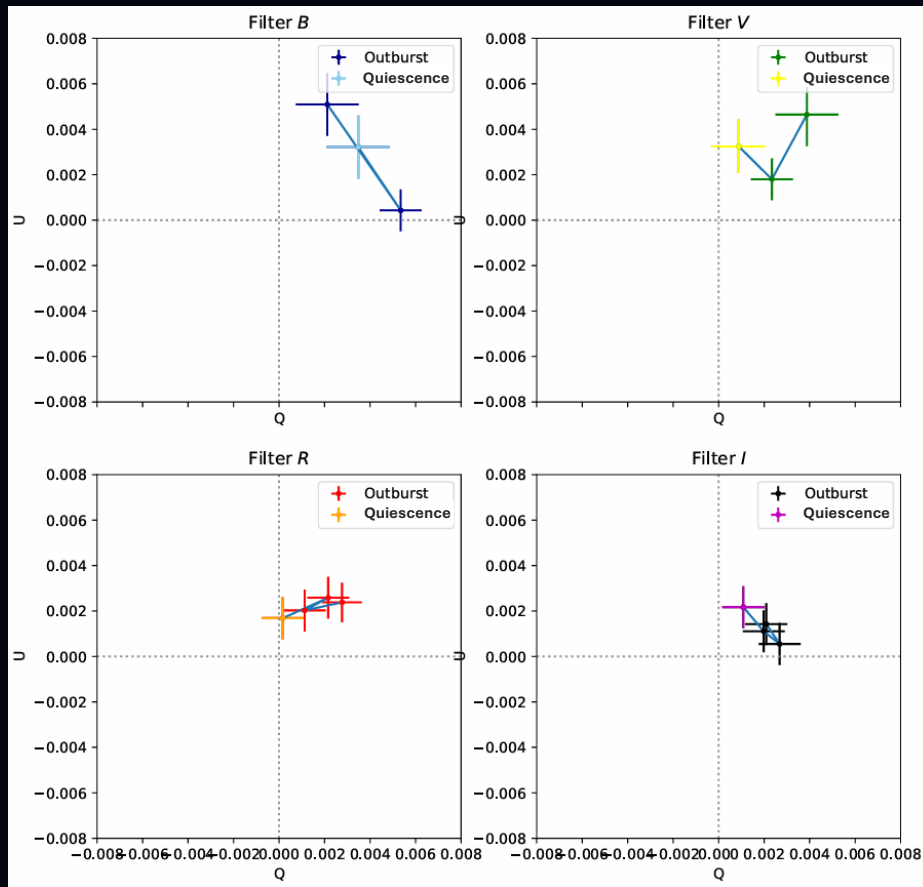
# Results: Long-term Variability of Stokes Parameters

## Filter B:

- Outburst and quiescence compatible
- No shift

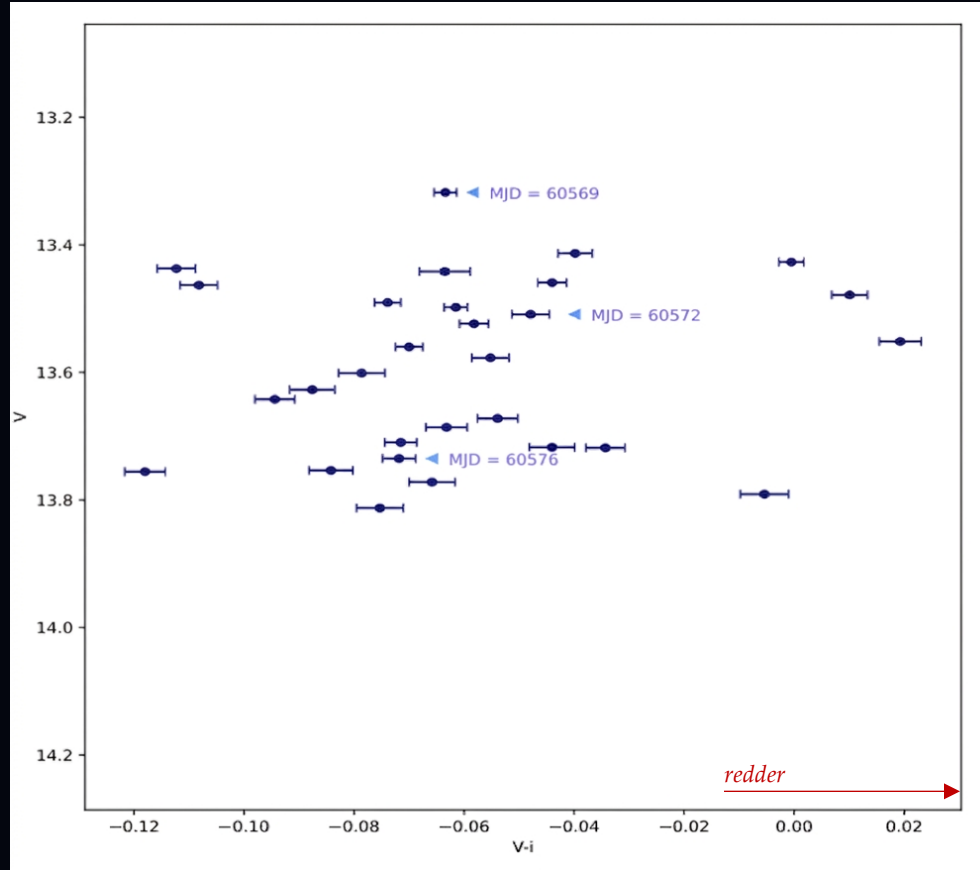
## Filter V, R e I:

- Slight shift compared to quiescence
- Diagonal trajectory  $\rightarrow$  both polarization degree and angle vary



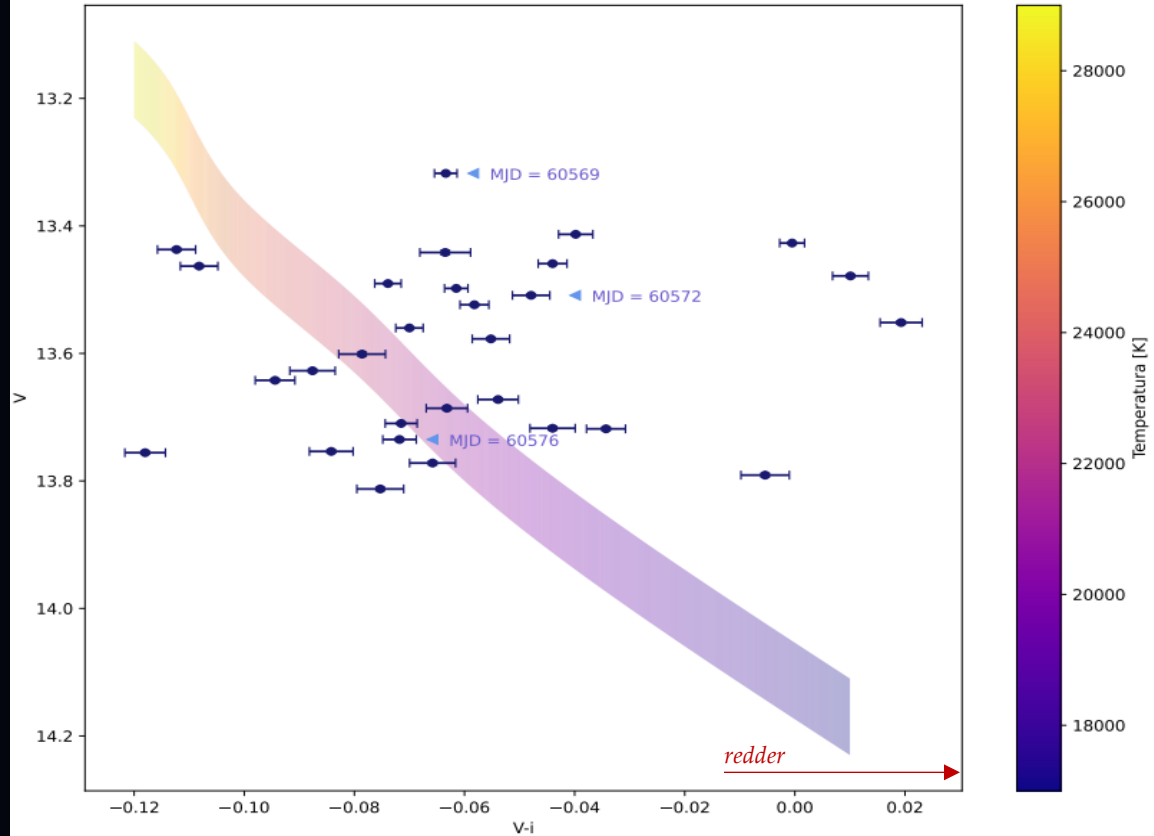
# Results: Color-Magnitude Diagram

- V4641Sgr LCO monitoring ~50 days before and after our observation



# Results: Color-Magnitude Diagram

- V4641Sgr LCO monitoring
  - Chromatic band: blackbody for the accretion disk
  - Low temperatures: R-J tail
  - High temperatures: peak of spectrum
- Increase in optical luminosity  $\rightarrow$  increase in effective temperature
- Outliers: jet - negligible

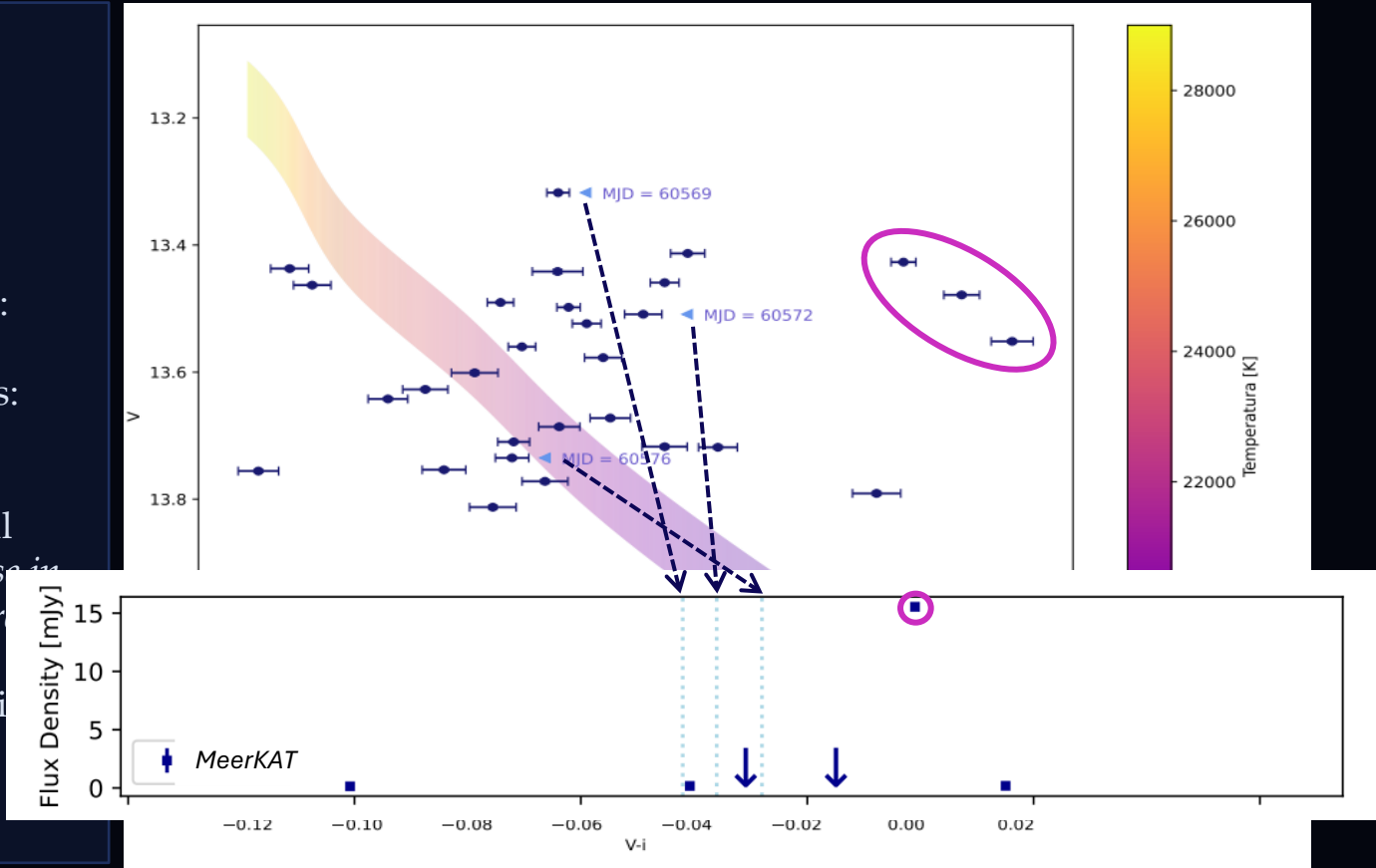


# Results: Color-Magnitude Diagram

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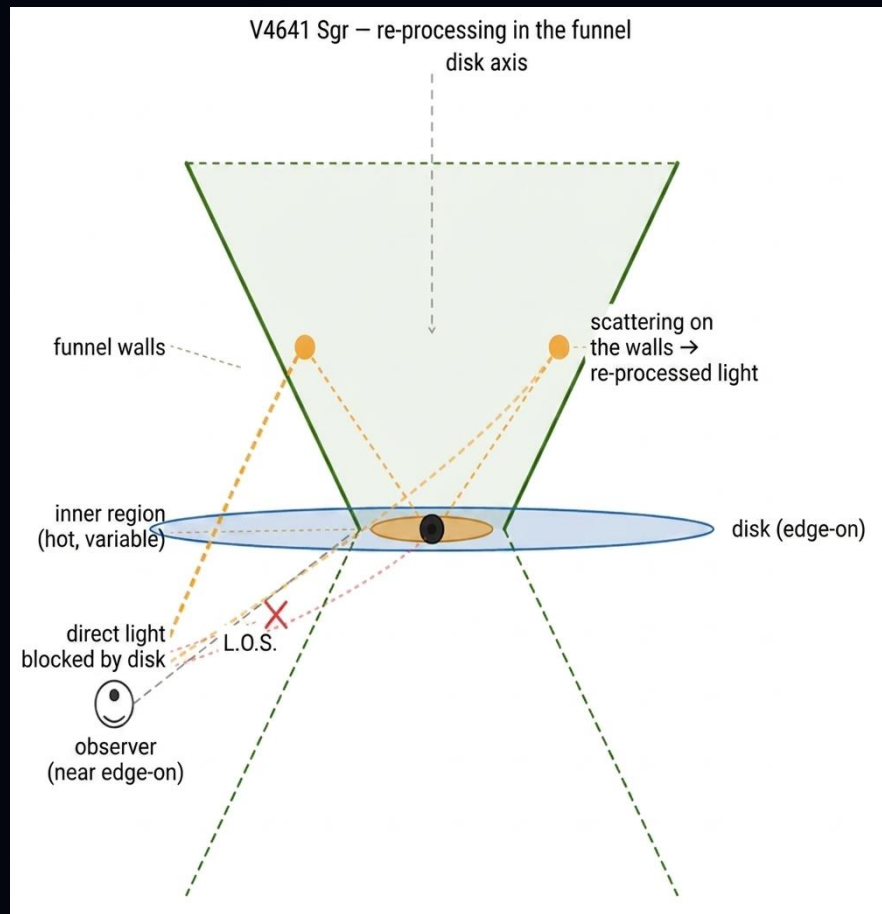
# Interpretation

## Scattering in the accretion disk

- $\vartheta$  consistent with the disk axis
- CMD: polarimetric epochs on the blackbody theoretical track
- Systematic shift between outburst and quiescence: inner regions depleted in quiescence
- Issue: elongation in  $R$ , stability in  $I$

## Reprocessing on the walls of the funnel

- Elongation of the Stokes parameter distribution on short timescales in  $R$  but not in  $I$
- Scatter in the CMD



# Conclusions

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- ✓ The dominant polarization component in V4641 Sgr originates from Thomson scattering in the **accretion disk** – both in outburst and in quiescence
- ✓ Rapid variability during night 1:
  - Band *R*: *LP* varies,  $\vartheta$  stable
  - Band *I*: *LP* varies,  $\vartheta$  varies → presence of a second polarized component
- ✓ Second component: **funnel!**
  - Reprocessing of inner accretion flow radiation on the walls of the funnel, on short timescales
  - $\tau \propto \lambda^{-1}$  → suppressed at shorter wavelengths

Combining optical polarimetry with X-ray precision:

**WFI:** Simultaneous inner disk variability characterization.

**X-IFU:** Direct mapping of disk wind geometry to build quantitative models.

Thank You!

# Polarimetry: Formalism

## Stokes Parameters

The vector (I, Q, U, V) describes the polarization state.  
The linear polarization degree is:

$$LP = \sqrt{\frac{Q^2 + U^2}{I}}.$$

The polarization angle is:

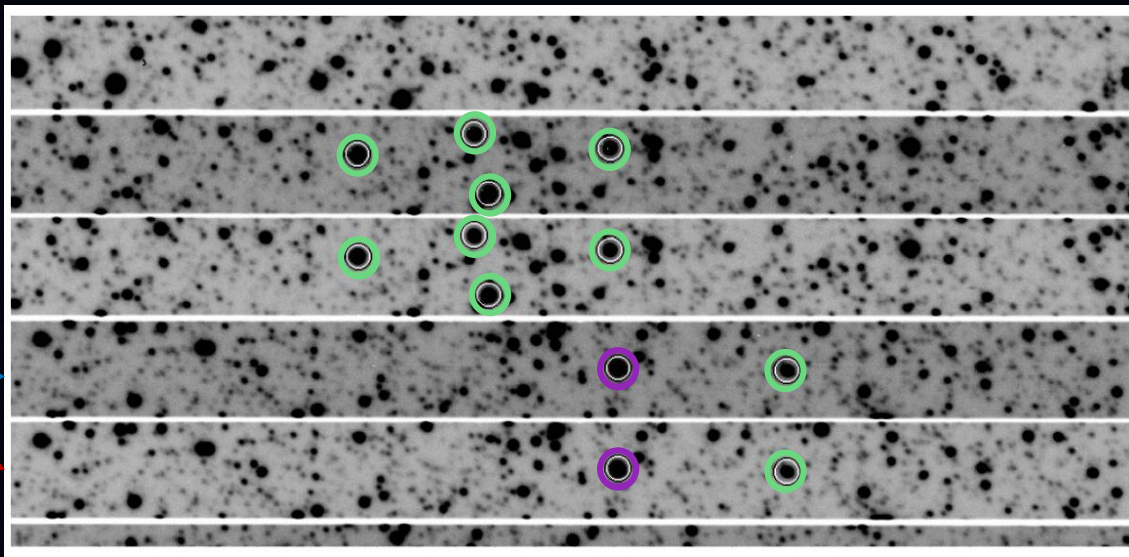
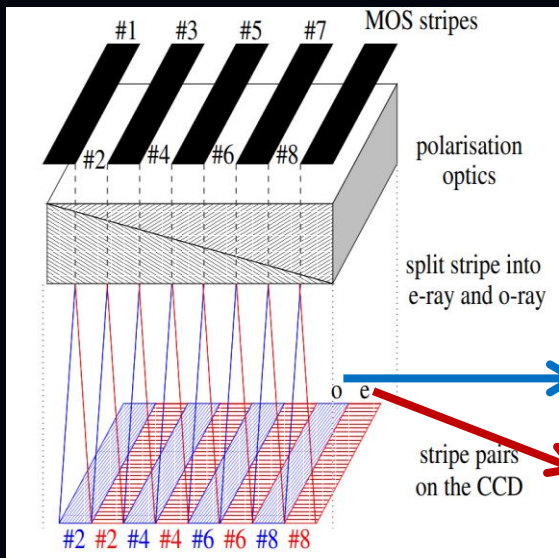
$$\vartheta = \begin{cases} \frac{1}{2} \arctan\left(\frac{U}{Q}\right) & U > 0, Q > 0 \\ 90^\circ + \frac{1}{2} \arctan\left(\frac{U}{Q}\right) & U < 0, Q > 0 \\ 90^\circ + \frac{1}{2} \arctan\left(\frac{U}{Q}\right) & U > 0, Q < 0 \\ 180^\circ + \frac{1}{2} \arctan\left(\frac{U}{Q}\right) & U < 0, Q < 0. \end{cases}$$

## $S(\varphi)$ Parameter

$S(\varphi)$  is the intensity of radiation transmitted through an ideal linear polarizer whose transmission axis forms an angle  $\varphi$  with the reference axis of the coordinate system.

$$S(\varphi) = \frac{1}{2} [I + Q \cos(2\varphi) + U \sin(2\varphi)]$$

# Strumentation and Observations



○ V4641 Sgr  
○ Field Stars

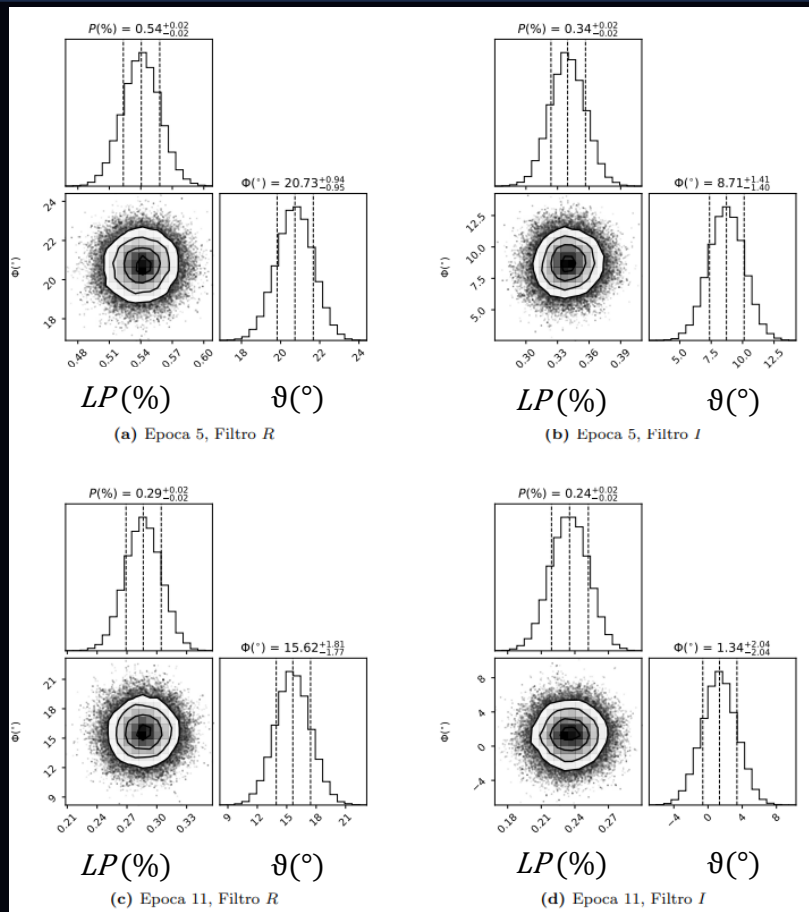
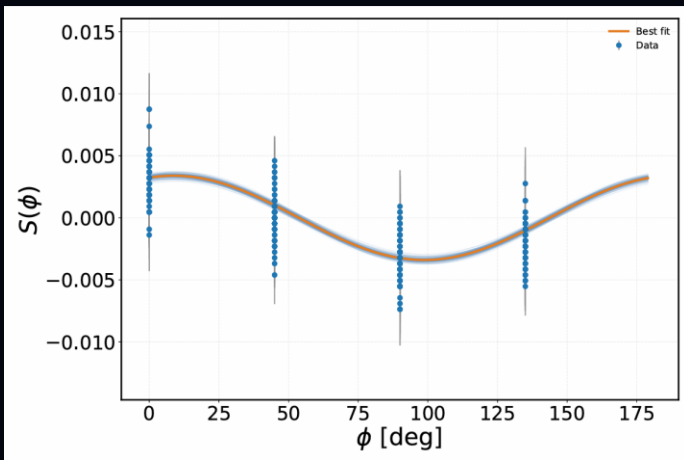
# Results: Polarization with $S(\varphi)$ Parameter

Filtro	Notte 1			Notte 2		
	$LP(\%)$	$\vartheta(^{\circ})$	$UL(\%)$	$LP(\%)$	$\vartheta(^{\circ})$	$UL(\%)$
$B$	–	–	–	$0.26^{+0.17}_{-0.17}$	$13.06^{+18.75}_{-19.69}$	$< 0.83$
$V$	–	–	–	$0.52^{+0.07}_{-0.07}$	$27.90^{+3.90}_{-3.71}$	–
$R$	$0.37 \pm 0.02$	$20.37 \pm 1.47$	–	$0.28 \pm 0.02$	$35.11^{+1.73}_{-1.71}$	–
$I$	$0.26 \pm 0.02$	$18.43 \pm 2.28$	–	$0.29 \pm 0.02$	$9.11^{+1.62}_{-1.66}$	–
Filtro	Notte 3			Quiescenza		
	$LP(\%)$	$\vartheta(^{\circ})$	$UL(\%)$	$LP(\%)$	$\vartheta(^{\circ})$	$UL(\%)$
$B$	$0.55 \pm 0.16$	$10.65^{+8.32}_{-8.60}$	–	$0.26 \pm 0.17$	$23.94^{+17.63}_{-19.25}$	$< 1.12$
$V$	$0.41 \pm 0.07$	$17.46^{+4.59}_{-4.58}$	–	$0.12 \pm 0.08$	$42.77^{+16.24}_{-22.26}$	$< 0.63$
$R$	$0.33 \pm 0.02$	$20.01^{+1.42}_{-1.40}$	–	$0.29 \pm 0.02$	$27.49^{+1.67}_{-1.65}$	–
$I$	$0.21 \pm 0.02$	$14.32^{+2.05}_{-2.06}$	–	$0.30 \pm 0.02$	$31.11^{+1.43}_{-1.44}$	–

$$S(\varphi) = LP \cos(\vartheta - \varphi)$$

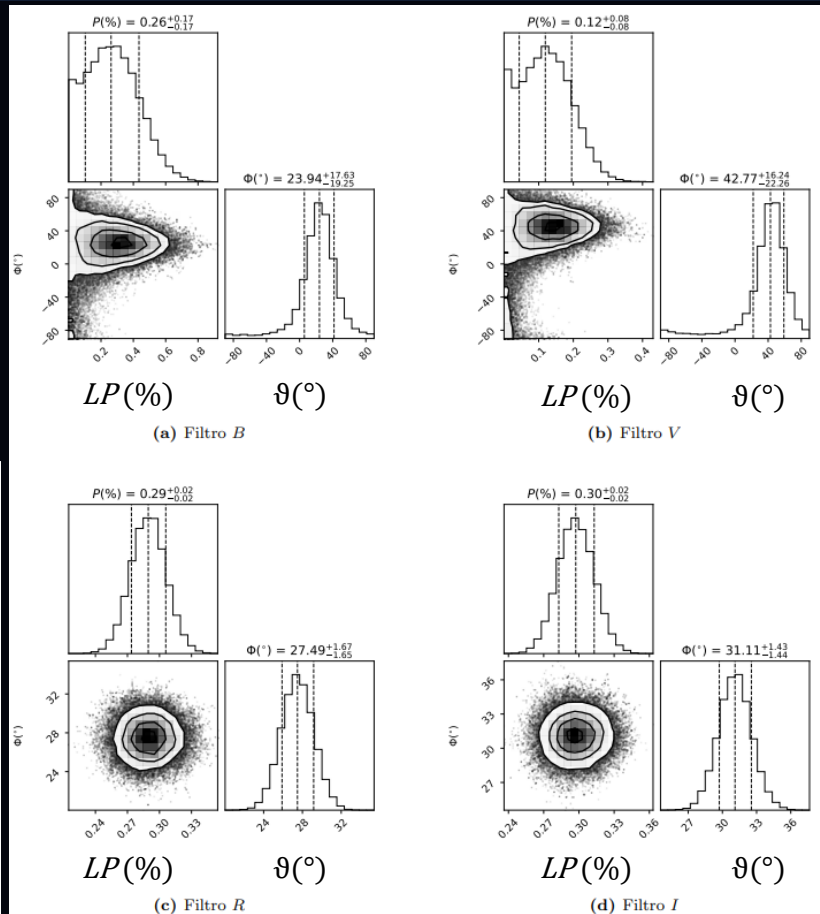
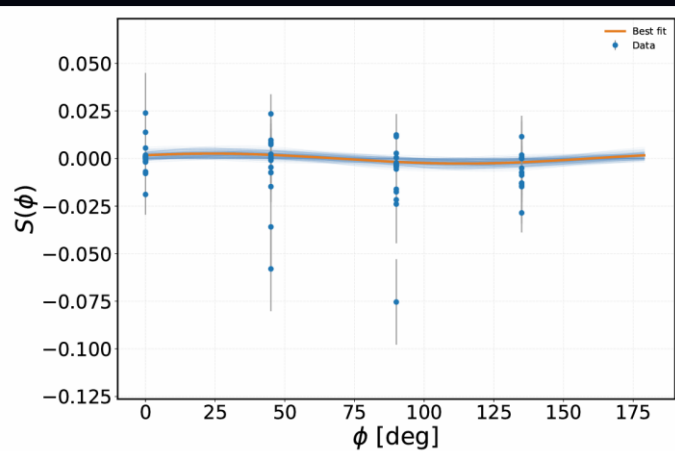
# Results: Polarization with $S(\phi)$ Parameter

Night 1  
Epoch 5 e 11  
Filters  $R$  e  $I$



# Results: Polarization with $S(\varphi)$ Parameter

Quiescence  
Filters  $B, V, R, I$



# Results: Energy Distribution

Intrinsic emission:  
 $F_{int}(\lambda) \propto \lambda^{-\alpha}$ .

Night 1:

$$\alpha = 0.51 \pm 0.32$$

Night 2:

$$\alpha = 0.21 \pm 0.34$$

Night 3:

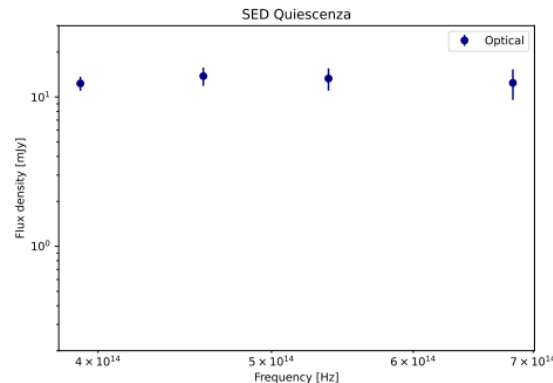
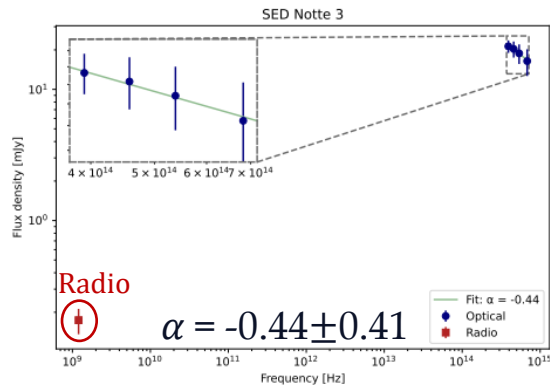
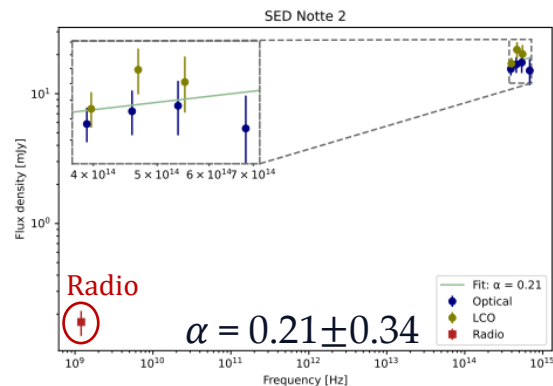
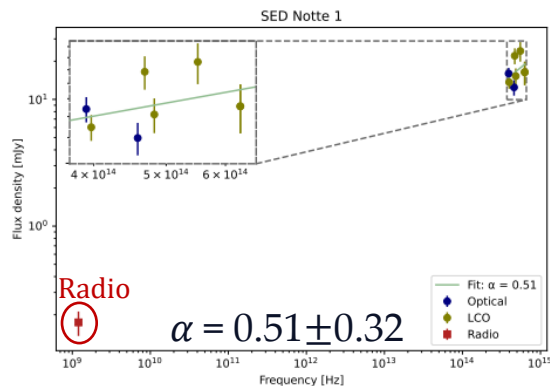
$$\alpha = -0.44 \pm 0.41$$

Quiescence:

no , blackbody

Radio da

Grollmund+2026

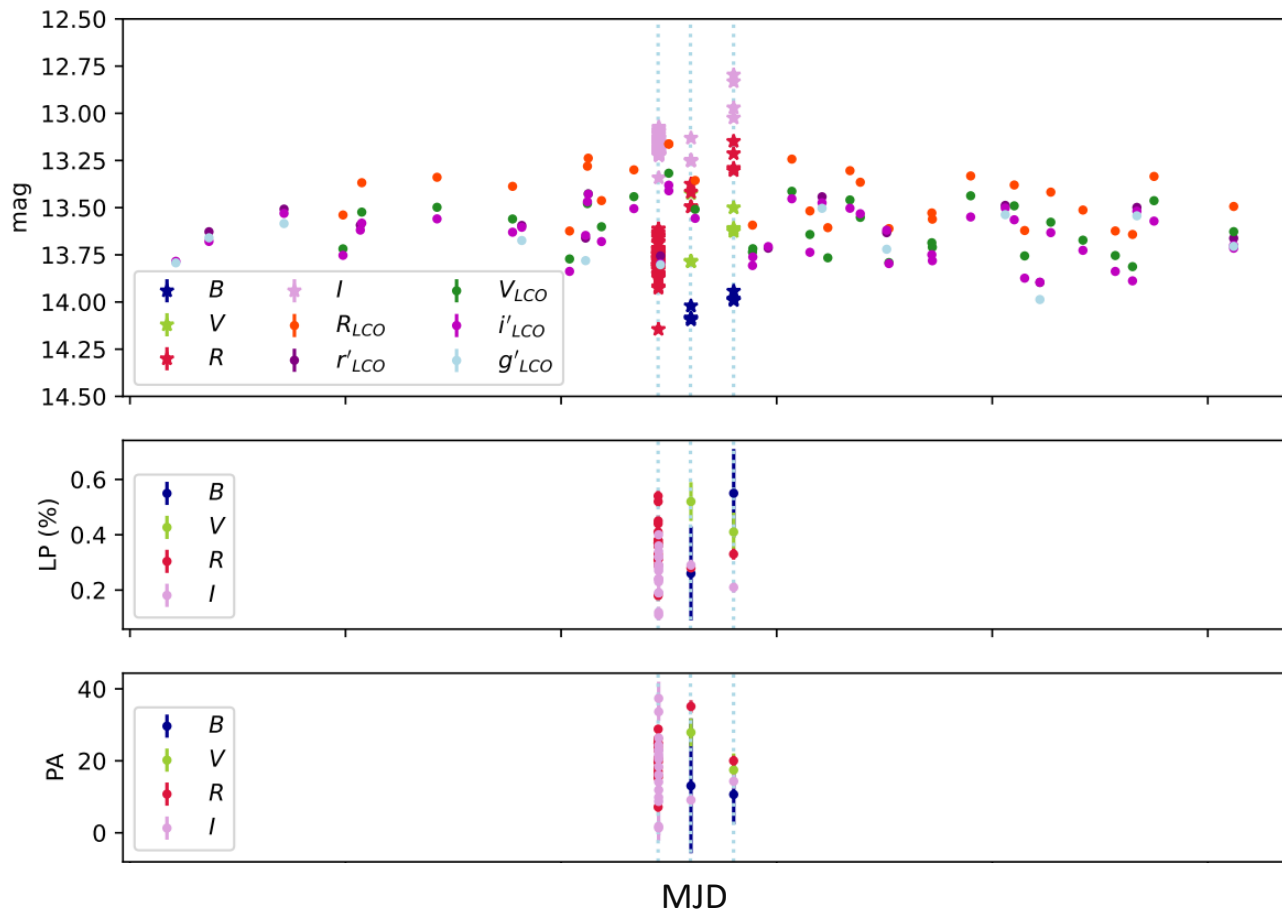


# Results: Multi-band plot

□ Lightcurve with VLT ★ and LCO ● (~50 days before and after)

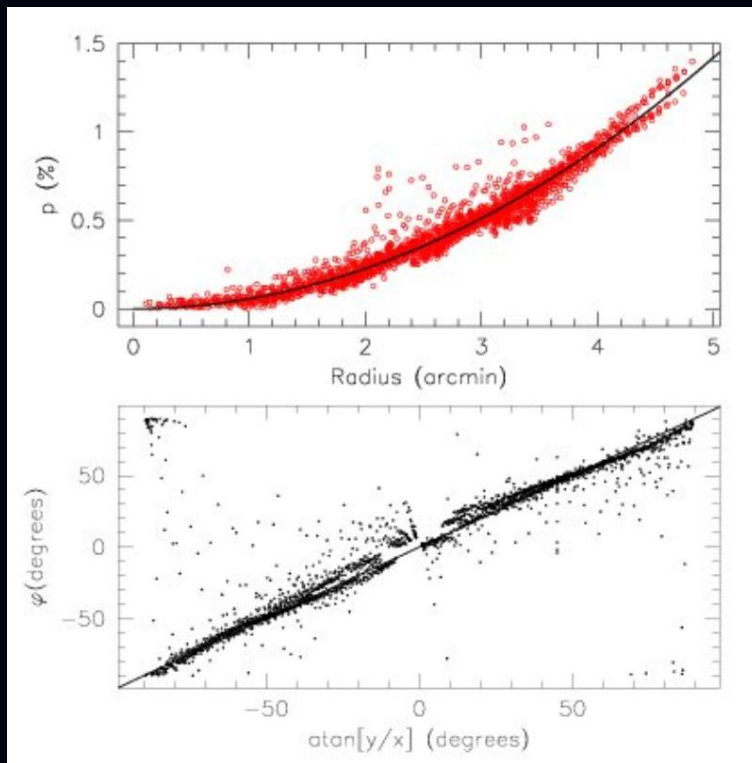
□ Linear Polarization Degree ( $LP$ )

□ Polarization Angle ( $\vartheta$ )



# CCD

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# Possible Scenarios

## Companion Star

- No variability
- Brighter disk
- Indirect polarization from Thomson scattering
- Angle aligned with the disk axis

## Jet

- Oriented  $\sim 90^\circ$  with respect to the l.o.s.
- If it were a jet, we should see  $\sim 10\%$
- Effective jet contribution  $\sim 0.07\%$
- Confirmation from the CMD

## Winds

- Thomson Scattering
- Massive presence in V641Sgr
- Compatible values but incompatible angles

