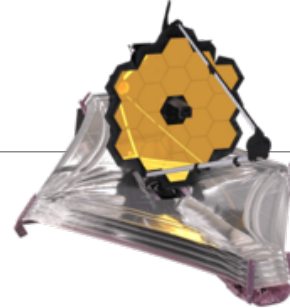
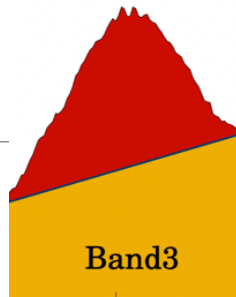


Optical-infrared variability as a new tool to explore inner disk structure and dynamics around young stars

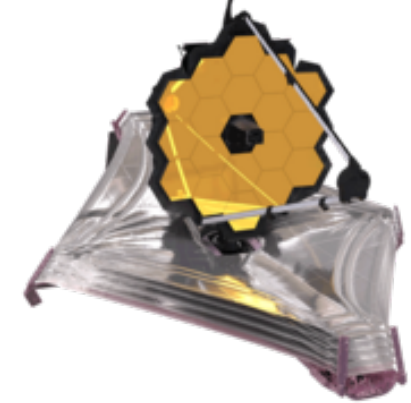
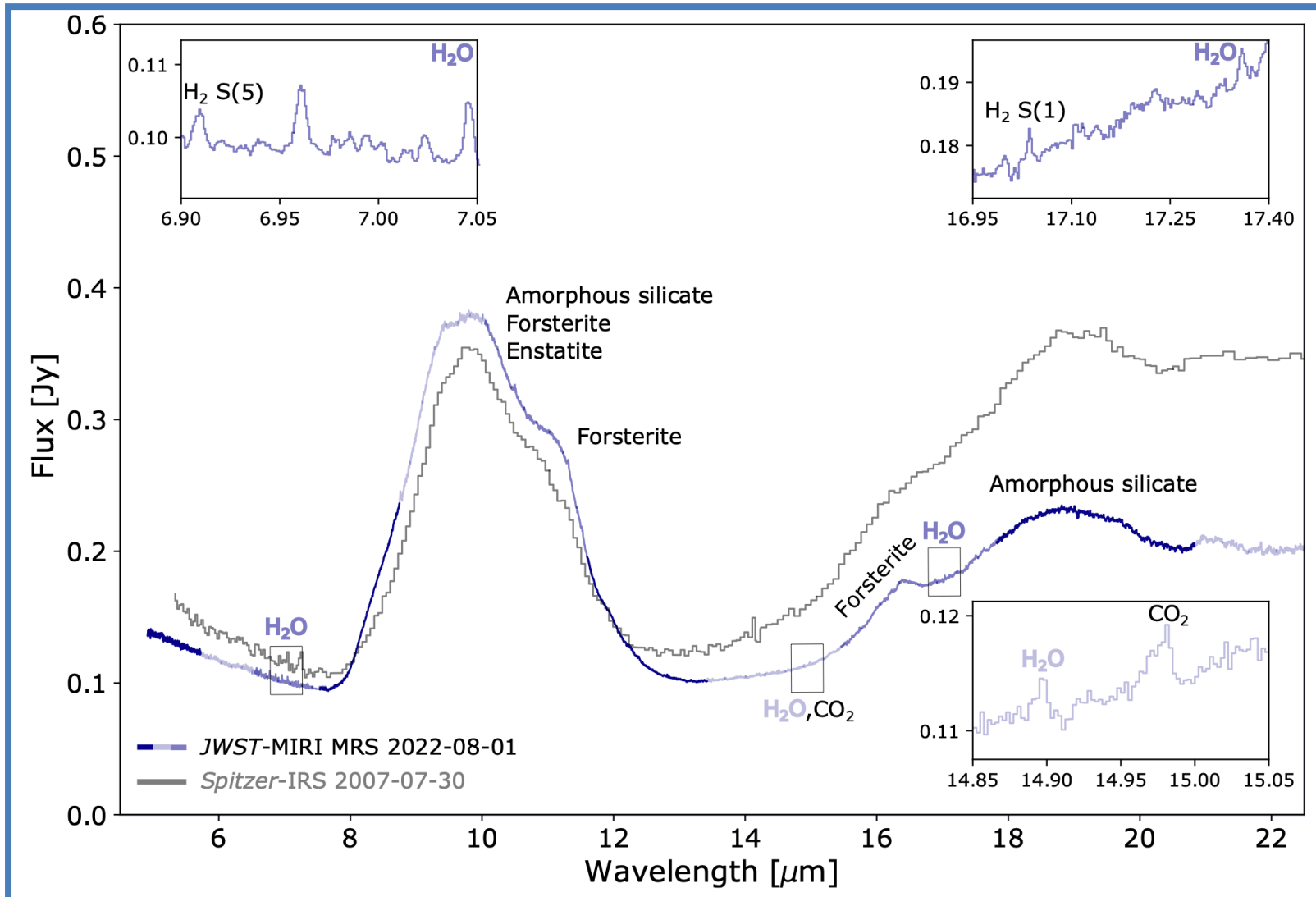


Péter Ábrahám
Konkoly Observatory, Budapest,



Ágnes Kóspál, Tímea Juhász, Claire Lykou, József Varga, Lis Zwicky

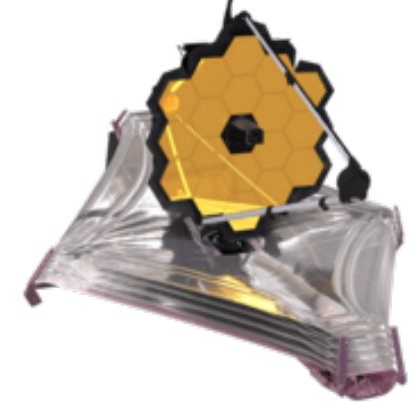
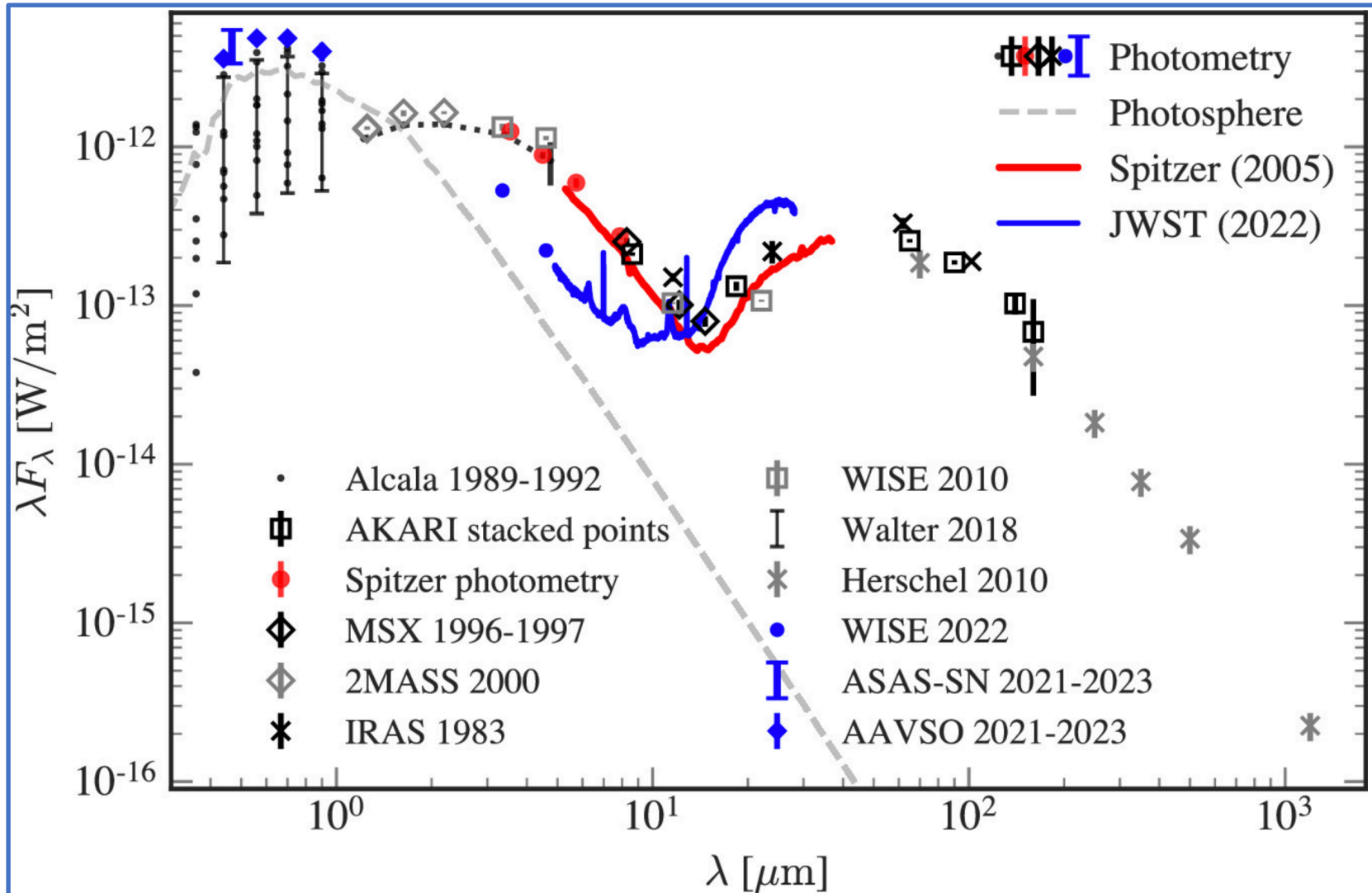
A surprise when you get your MIRI spectrum...



...and it disagrees with Spitzer

PDS 70 Perotti et al.
(Nature, 2023)

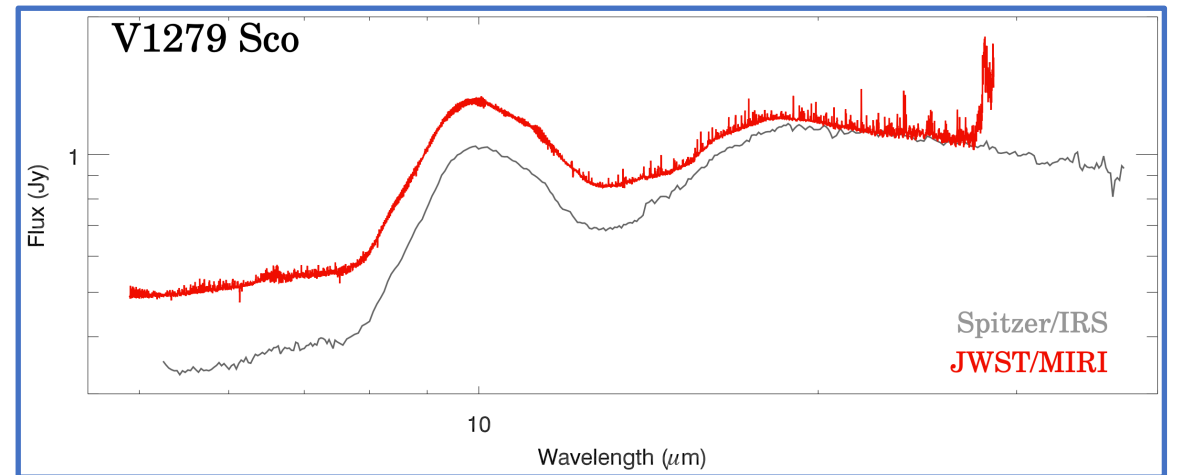
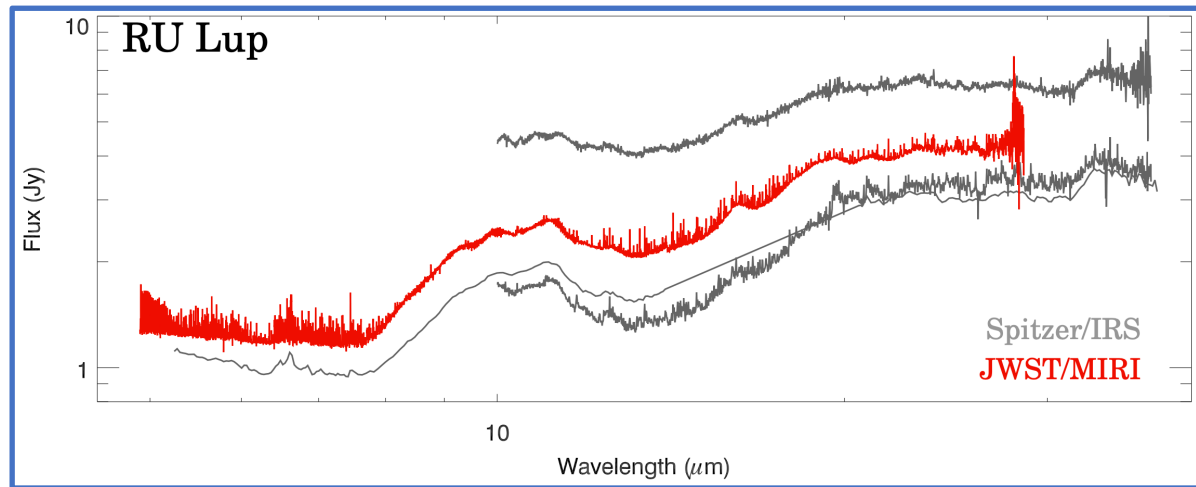
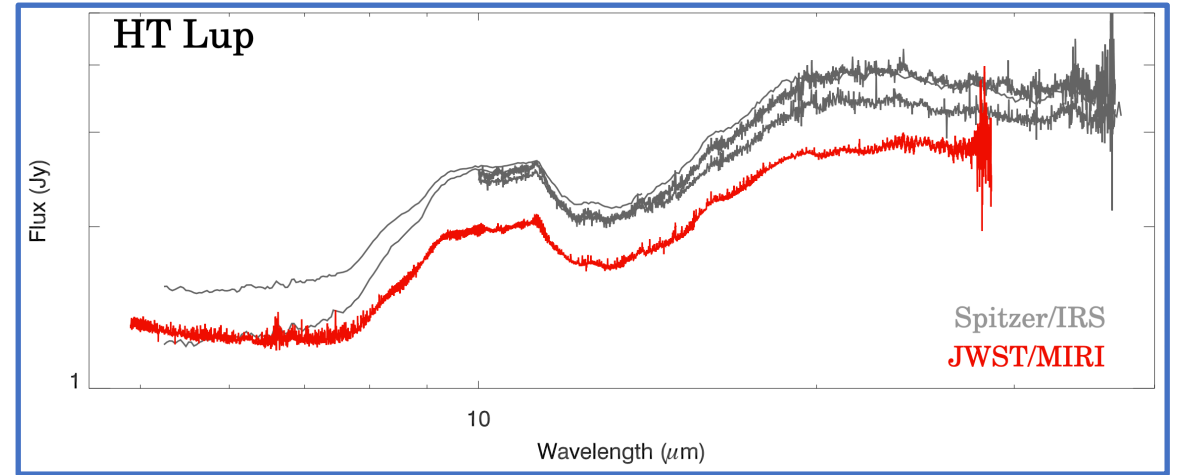
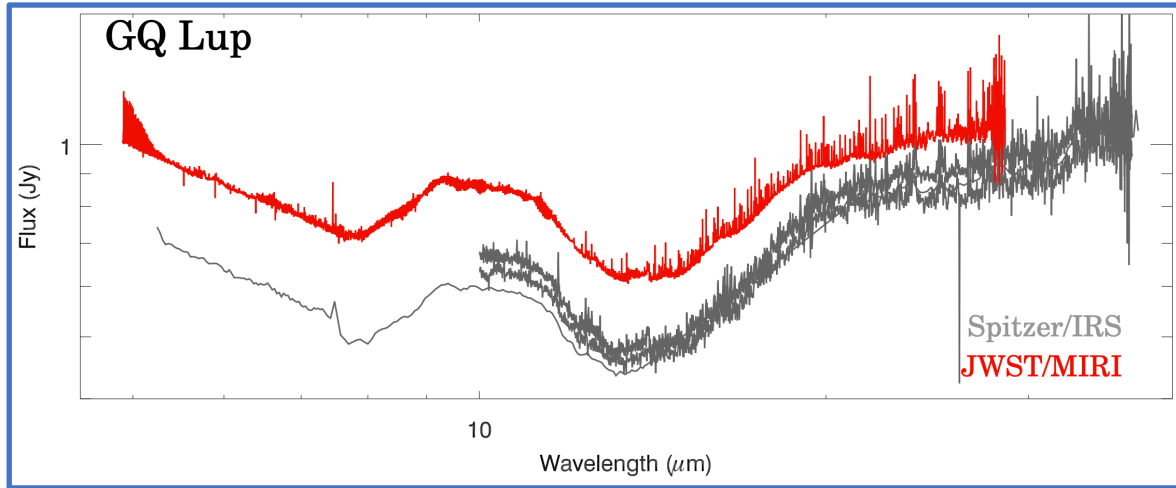
A surprise when you get your MIRI spectrum...



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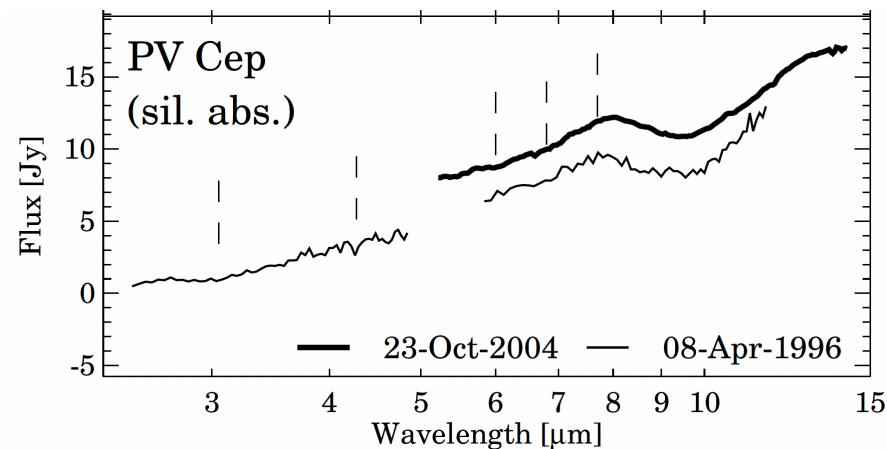
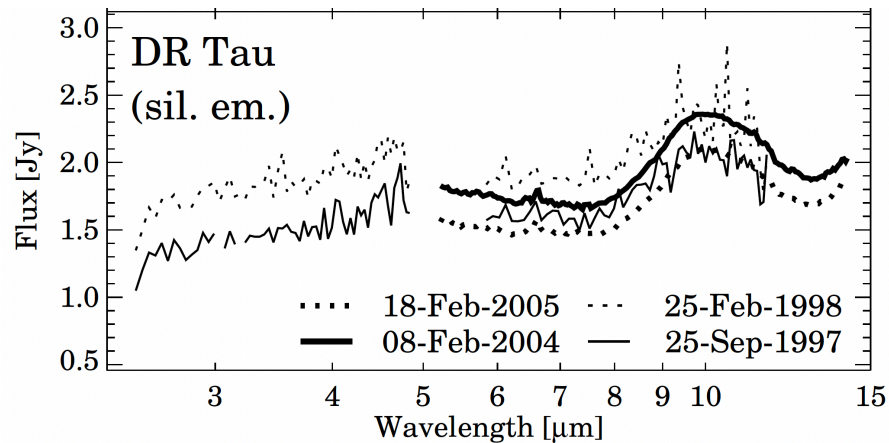
T Cha Xie et al. (2025)

Spitzer vs. JWST for T Tauri-type stars in Lupus



Mid-IR variability is interesting for me:

1. one needs to demonstrate that it is not an observation/calibration issue
2. determine the Incidence of mid-IR variability among YSOs
3. examine how different are YSOs in terms of mid-IR variability?
4. we may answer new type of questions about disk structure and dynamics
- +1 our group studied this phenomenon by comparing ISO and Spitzer



Kóspál et al. (2012)

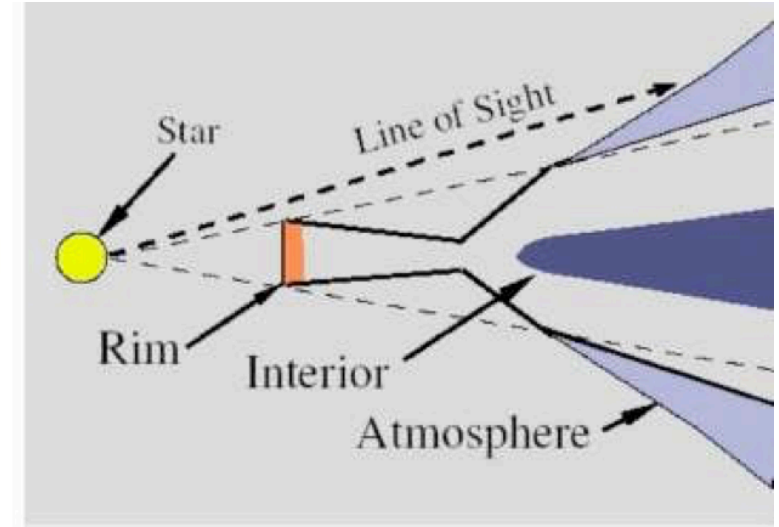
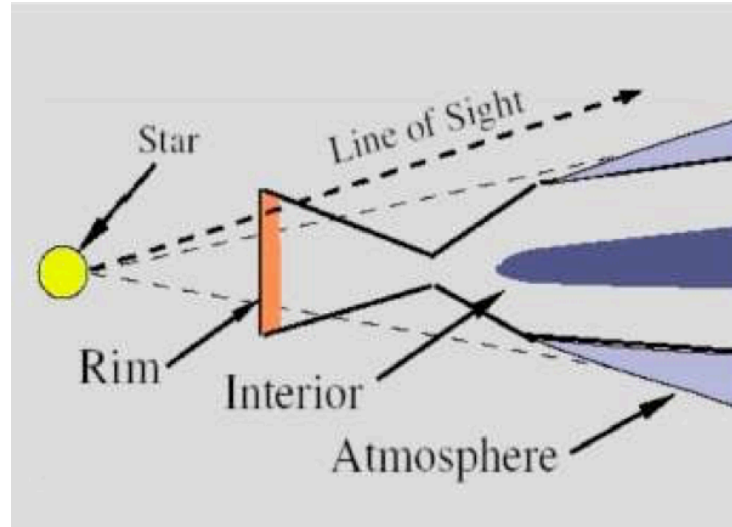
Physics behind mid-IR variability

Two actors: central star and circumstellar medium

Fluctuating luminosity of the star

Rearrangement of disk structure

Time-dependent shadows

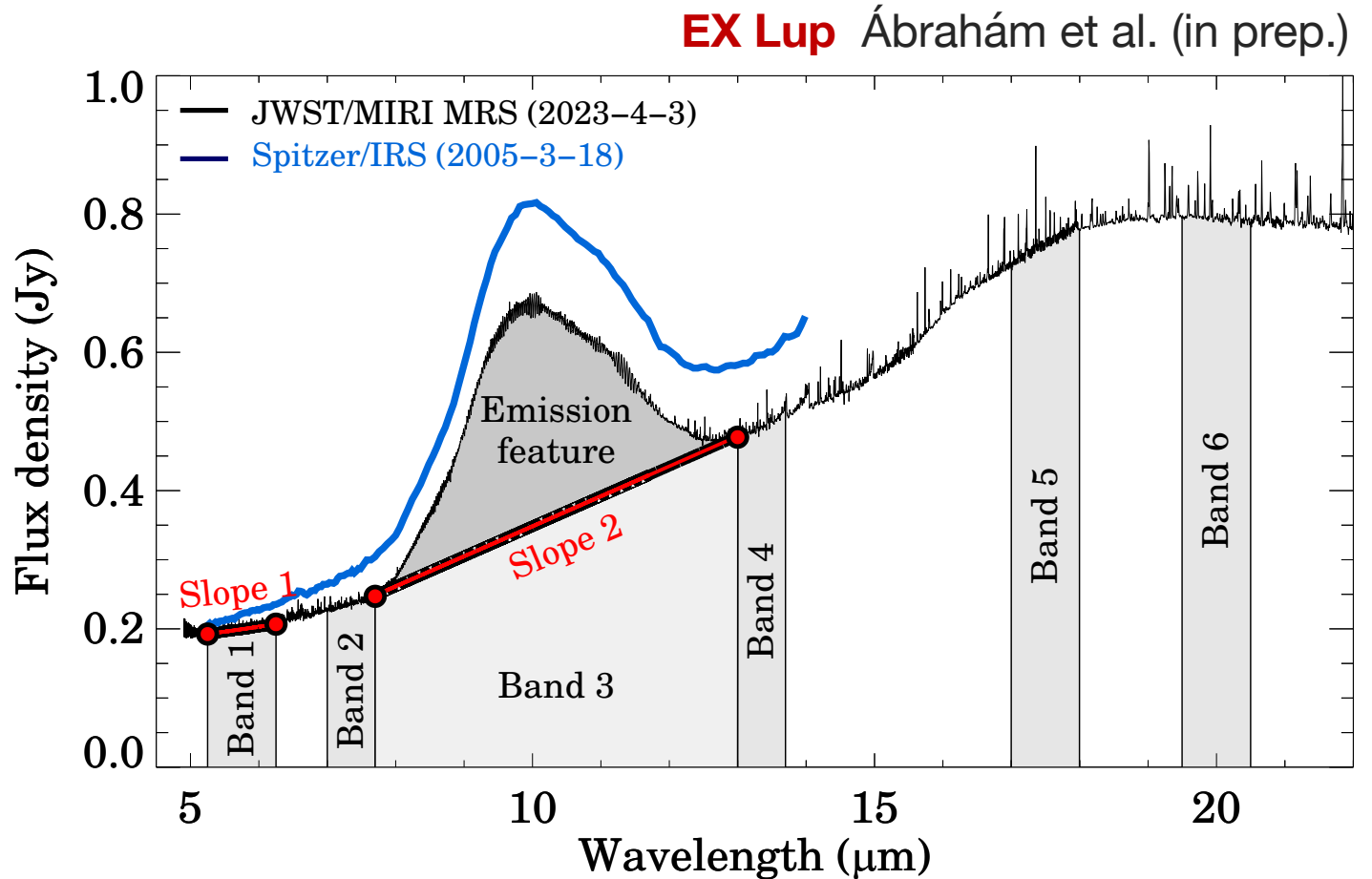


Juhász et al. (2008)

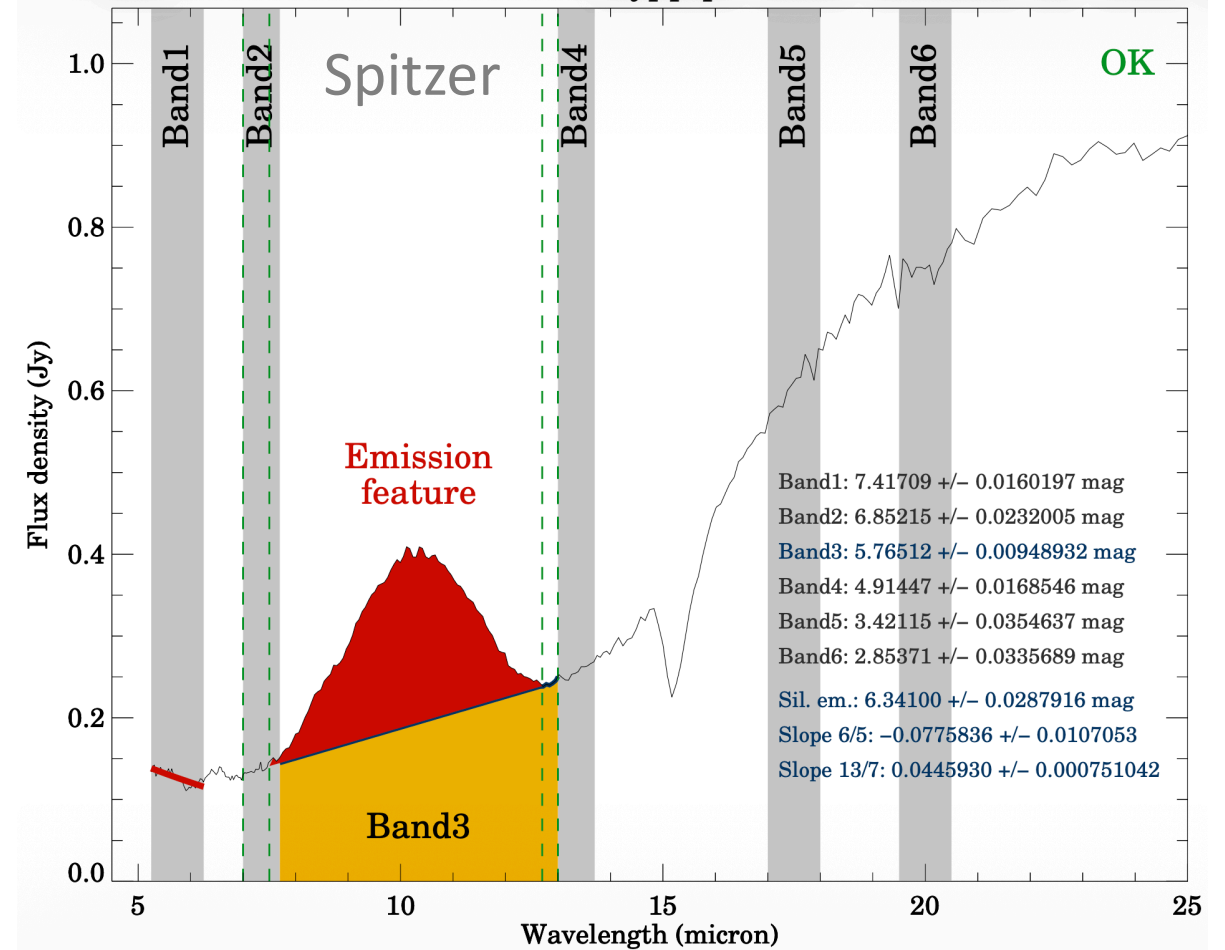
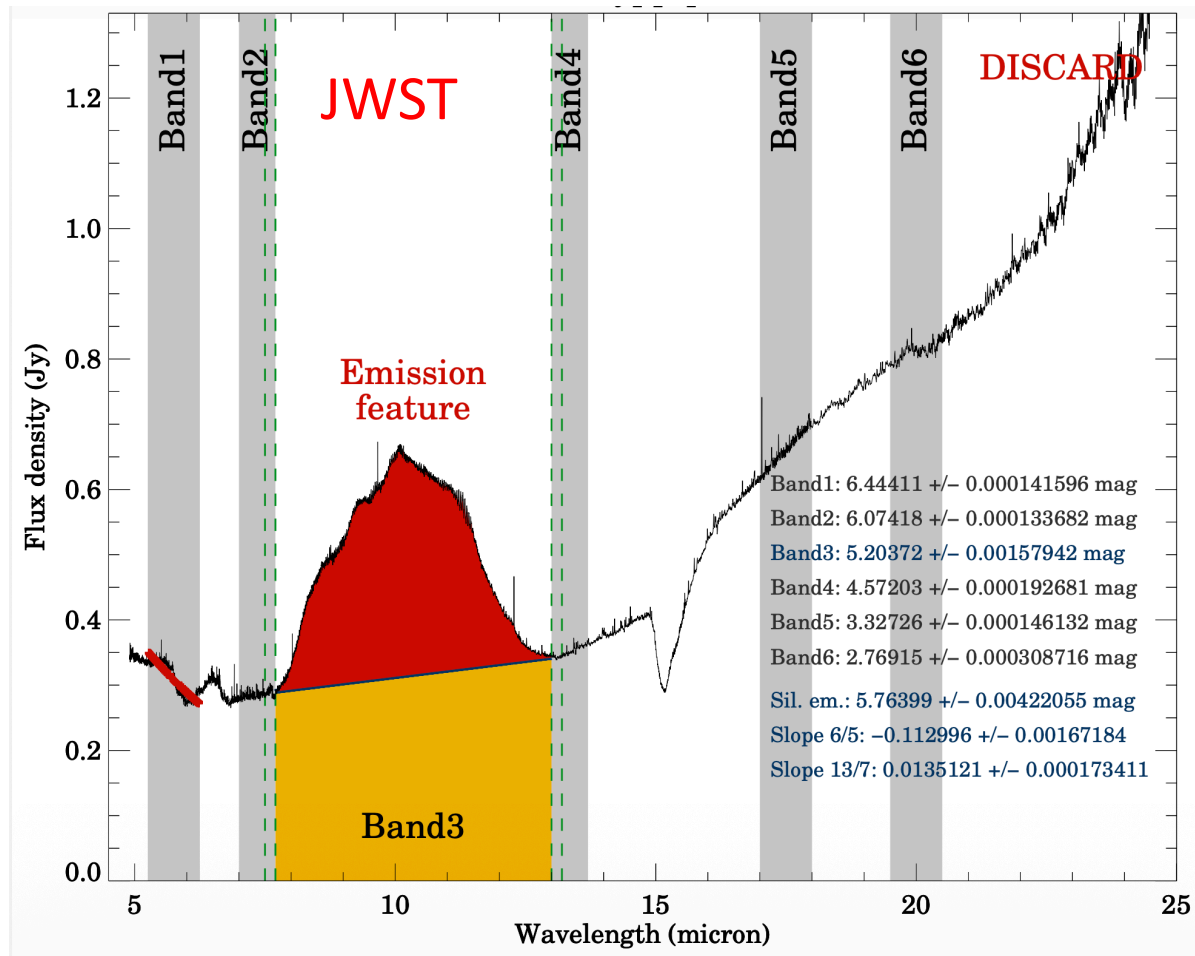
- **optical variability:** star, occulting material)
- **WISE W1/W2 variability:** changes in the hot inner edge of the disk
- **JWST-Spitzer 5-20 μm :** changes in disk area/illumination at several au radii
- Are inner disks more unsteady than we thought?
- Variation in disk chemistry and mineralogy?
- Are the birthplaces of terrestrial planets more dynamic than we thought?
- Impact on disk modeling: re-consider SED models based on multiepoch mid-IR data

Statistics on mid-IR variability of YSOs

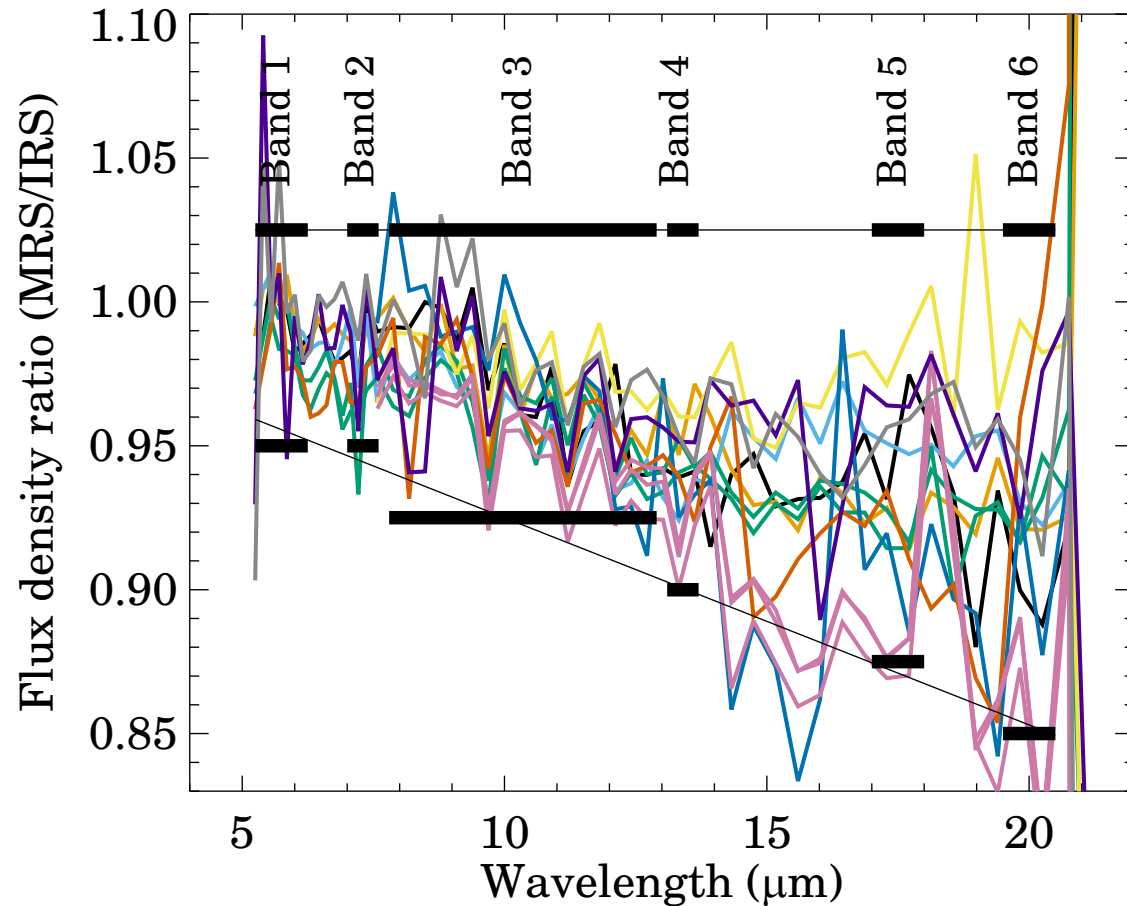
- Downloaded all publicly available JWST/MIRI MRS Cyc. 1-4 observations of YSOs from MAST
- Filtering for data quality, stitching
- Selected good data with silicate emission feature (105 spectra of 87 young stars, mainly Class II)
- Compared them with Spitzer IRS when available (downloaded from CASSIS)
- Defined 6 photometric bands, and computed synthetic magnitudes
- Timescales ≤ 15 -20 yrs



Photometric changes are found



Limits for invariability

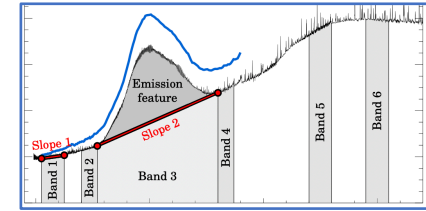
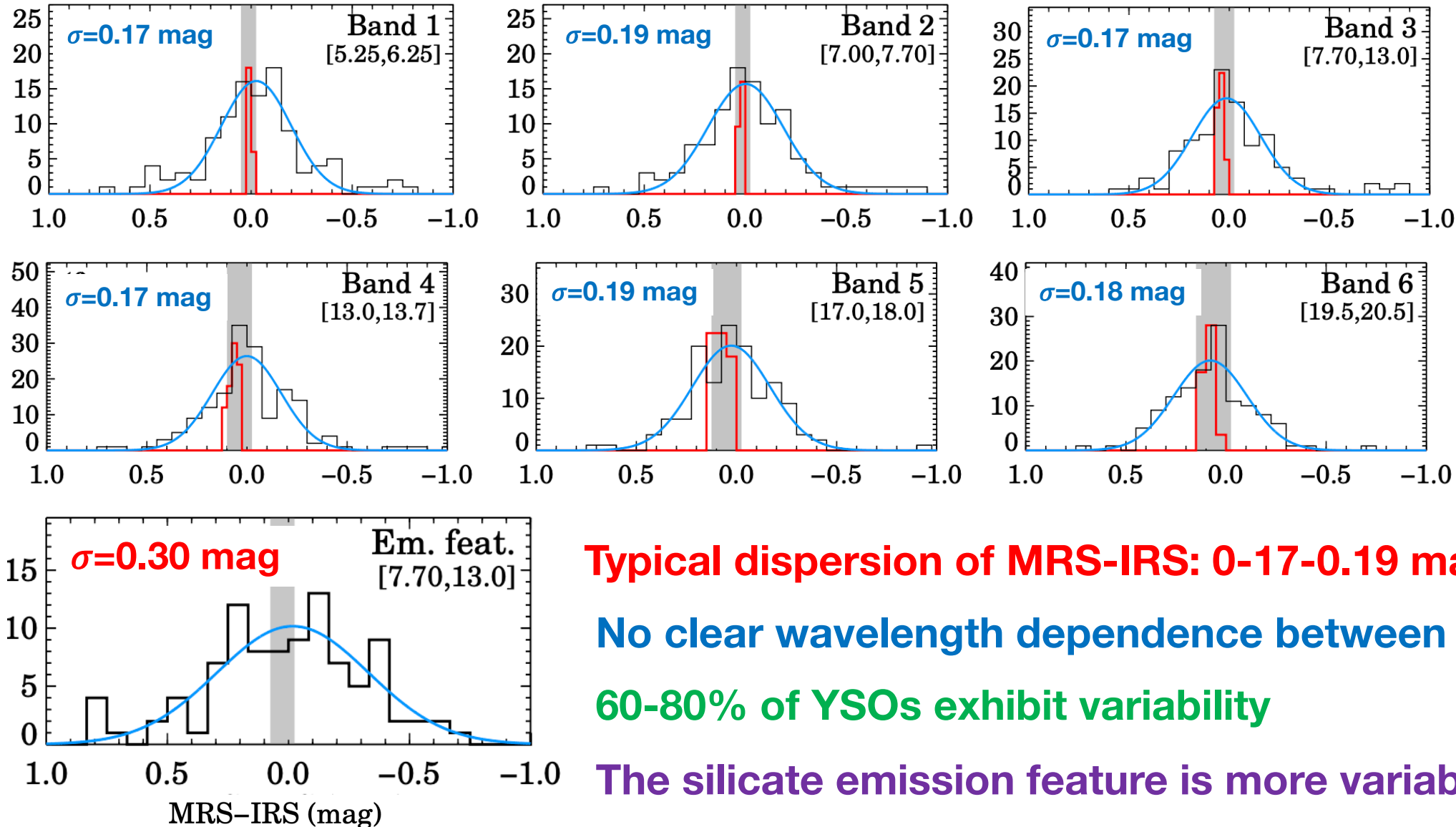


An object is variable when

$$F_{\nu}(\text{MRS})/F_{\nu}(\text{IRS}) \begin{cases} > 1.025 \\ \text{or} \\ < 0.997 - 0.0072 \lambda \end{cases}$$

General formula for the community, to be used in MRS/MIRI comparisons

Variability amplitude vs. wavelength



MRS-IRS mag
difference

Gray stripes:
calibrator stars

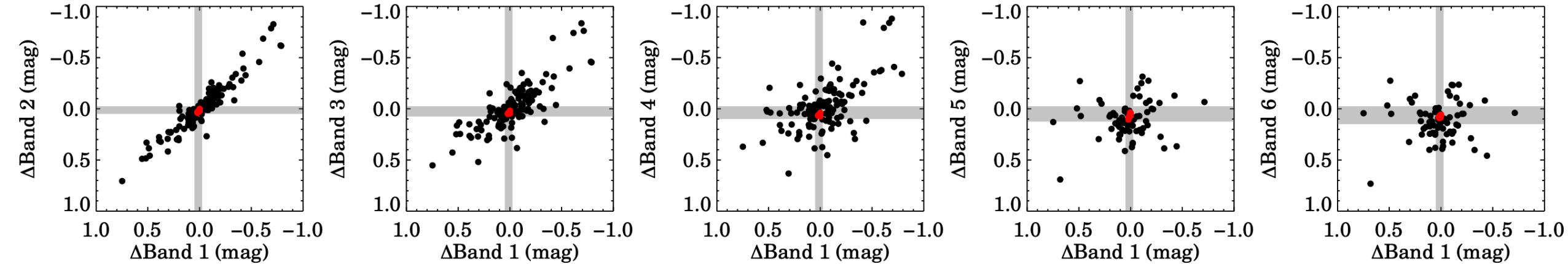
Typical dispersion of MRS-IRS: 0-17-0.19 mag

No clear wavelength dependence between 5-20 μ m

60-80% of YSOs exhibit variability

The silicate emission feature is more variable.

Current trends in YSO variability

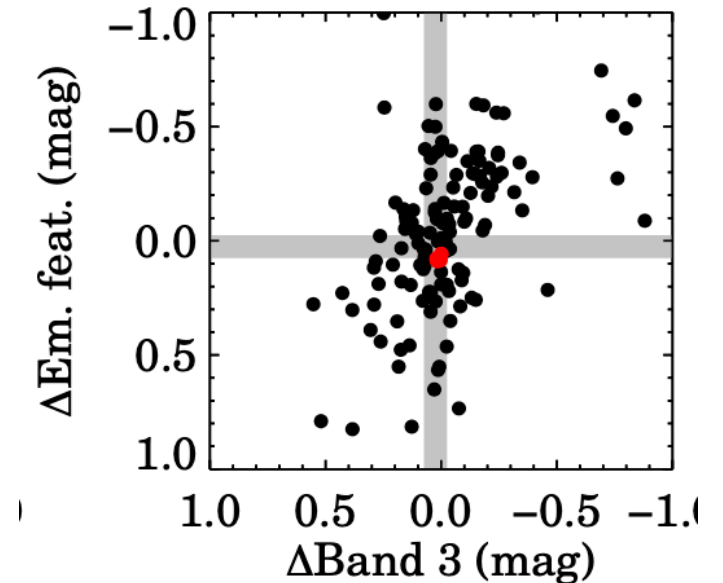


Nearby wavelength bands change synchronized

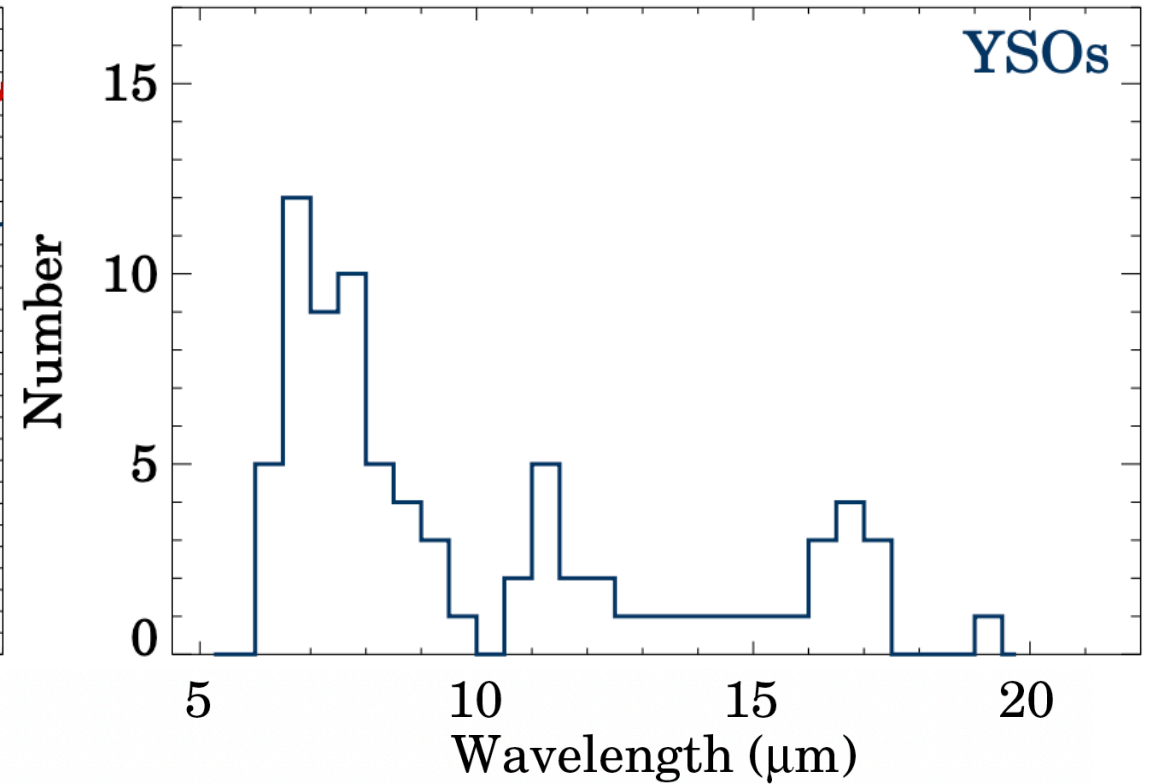
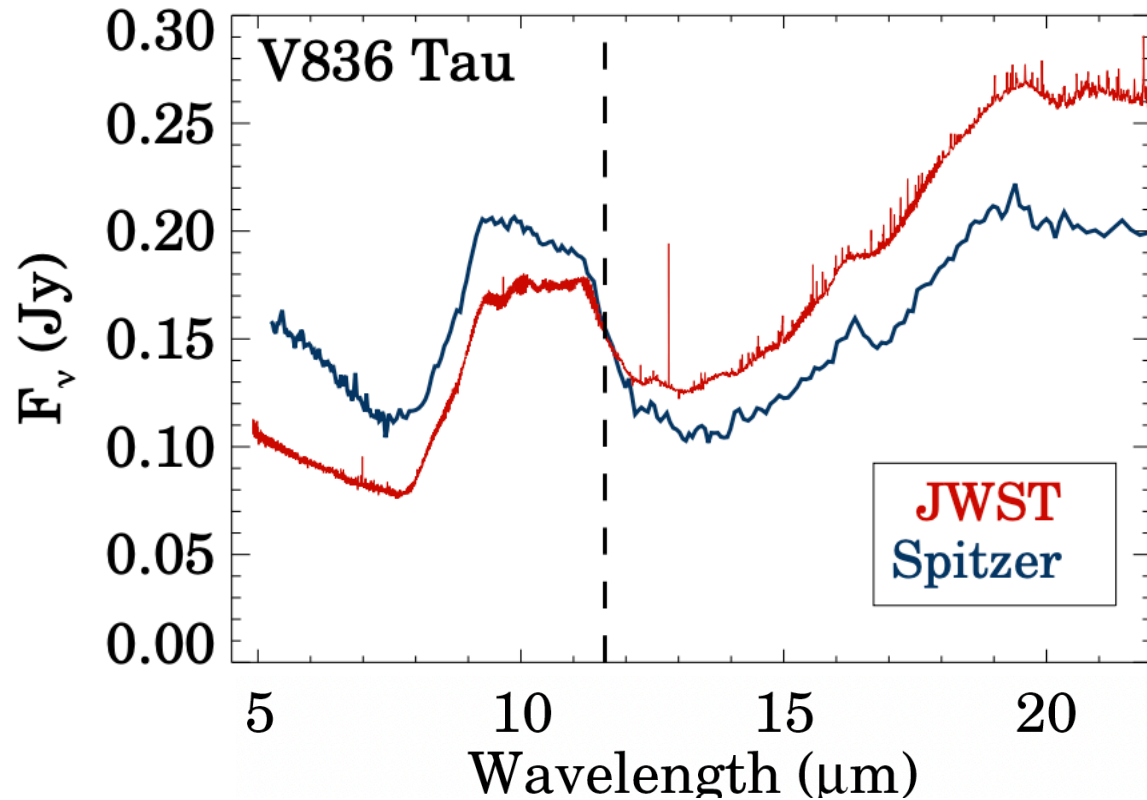
With increasing wavelengths, variations are less correlated

5 vs. 20 μm : 60% correlations, 40% anti-correlations

Silicate feature: weak correlation with its continuum flux,
very few anti-correlation



Seesaw variability

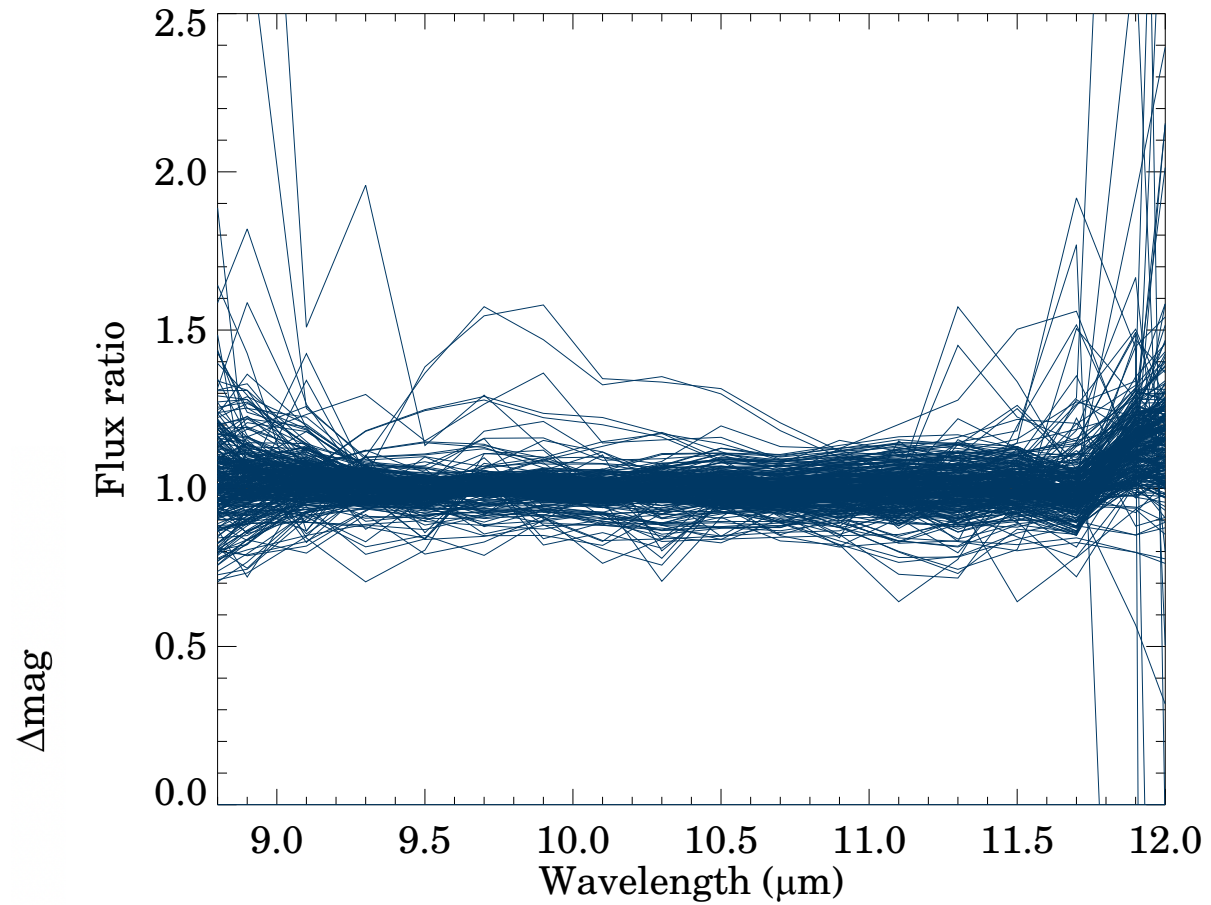


Peak at 7-8 μm (not only because of DQ Tau)

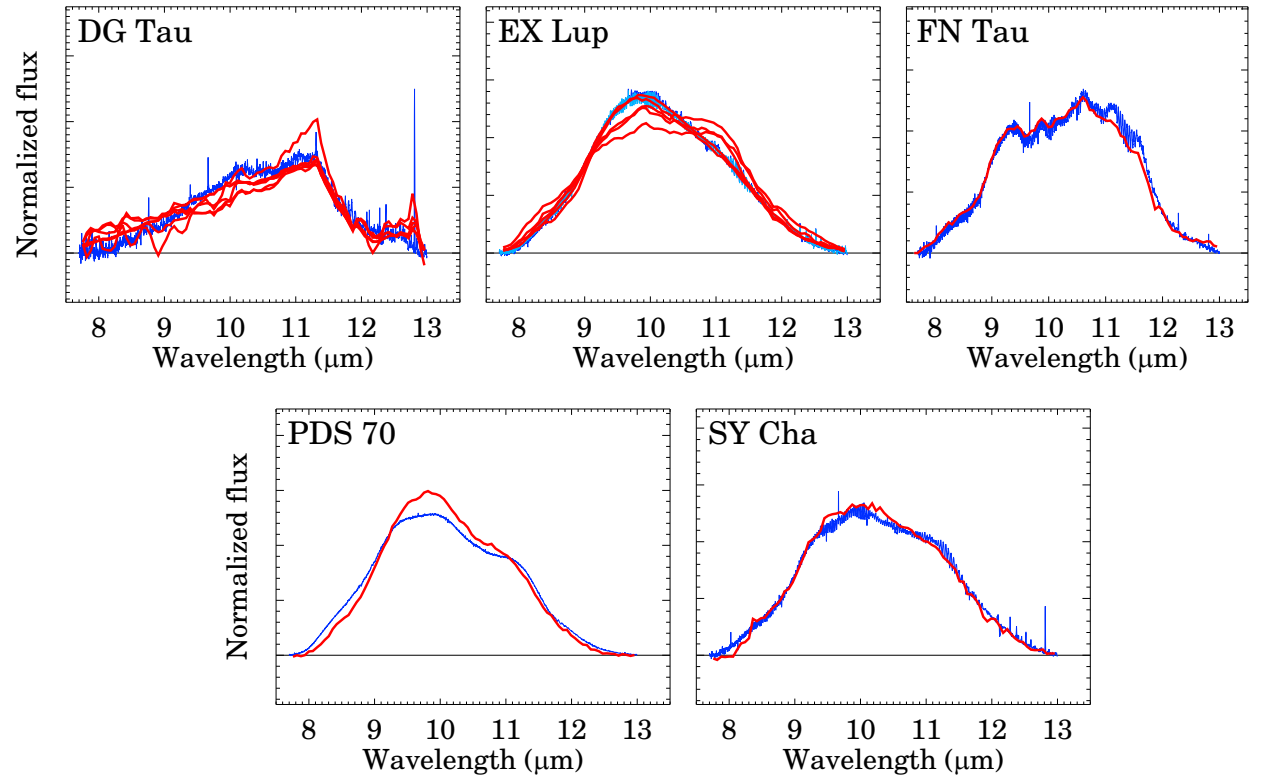
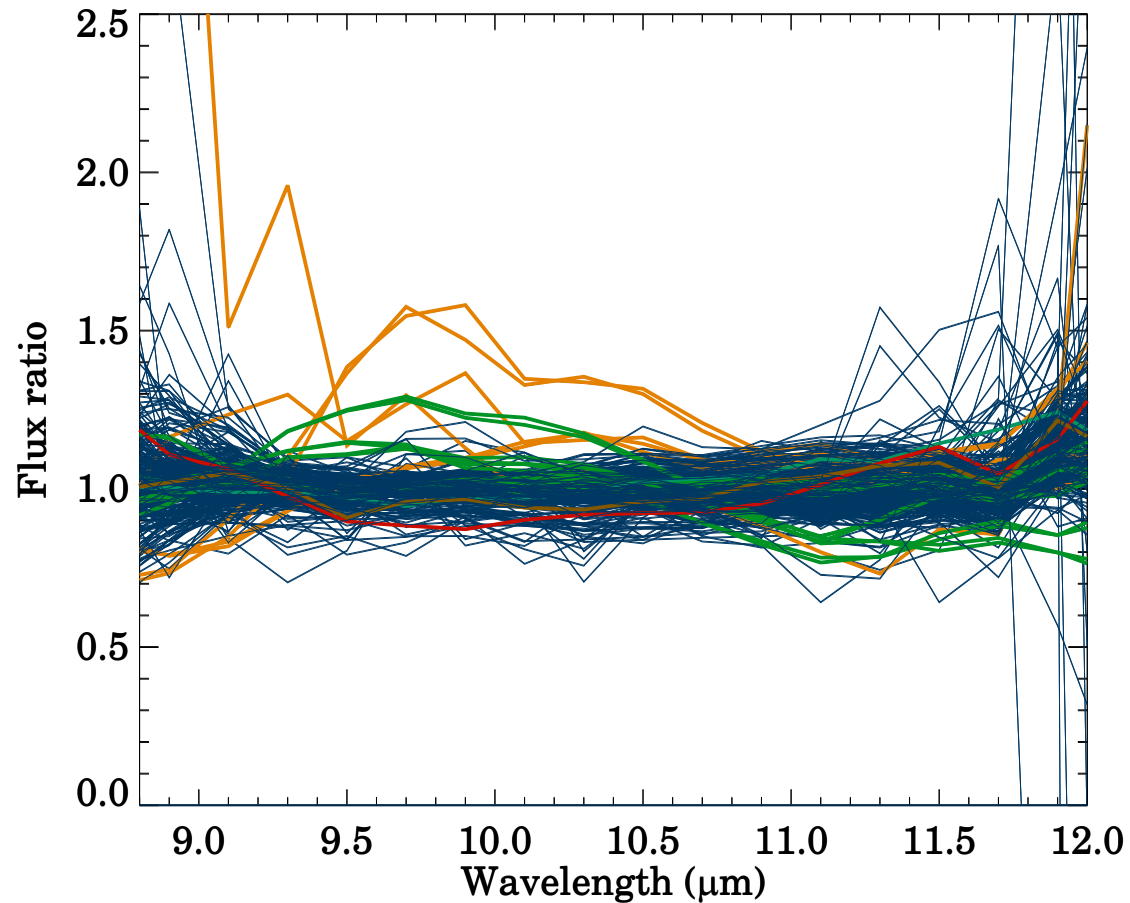
Interpreted by a time-dependent shadow cast by the inner rim on the outer disk.

Many disks are illuminated by redder stellar light (romantic sunset). Effect on chemistry?

Effects on dust properties



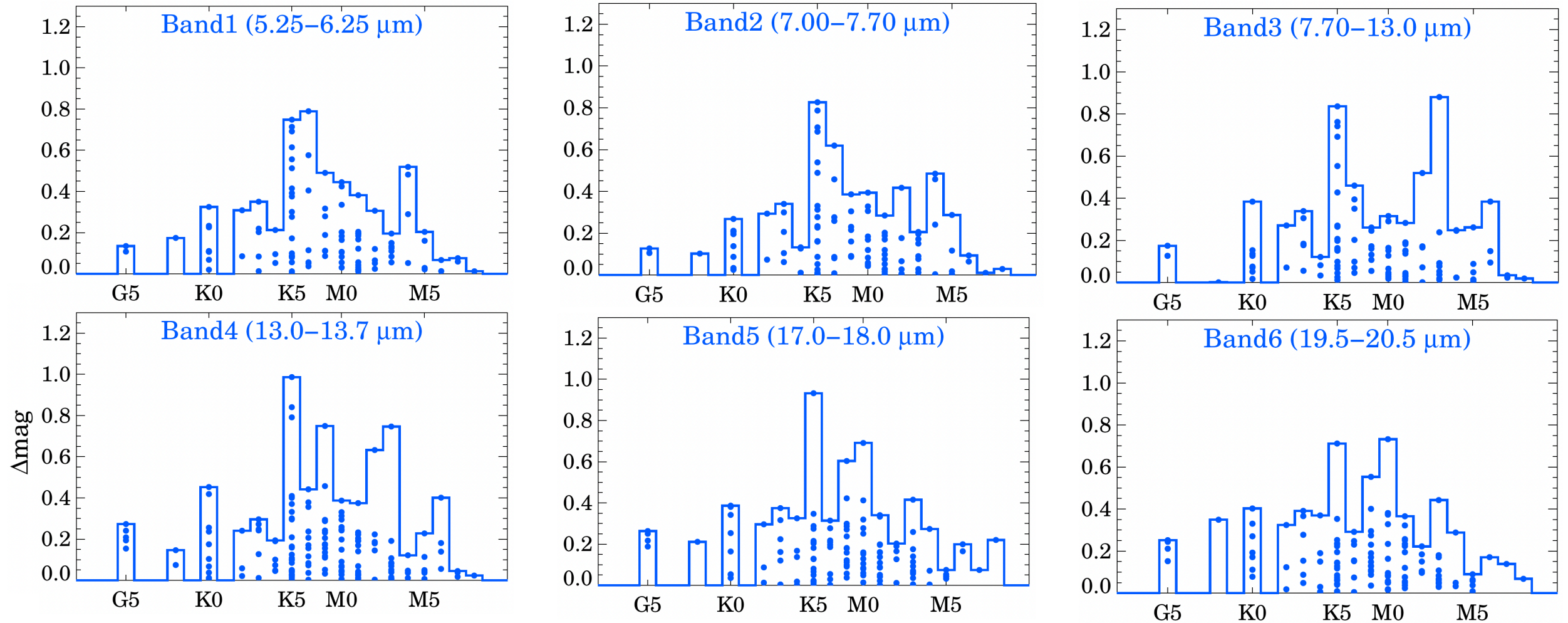
Effects on dust properties



Feature shapes are very stable

Deviating cases are mostly known objects

Variability over spectral types



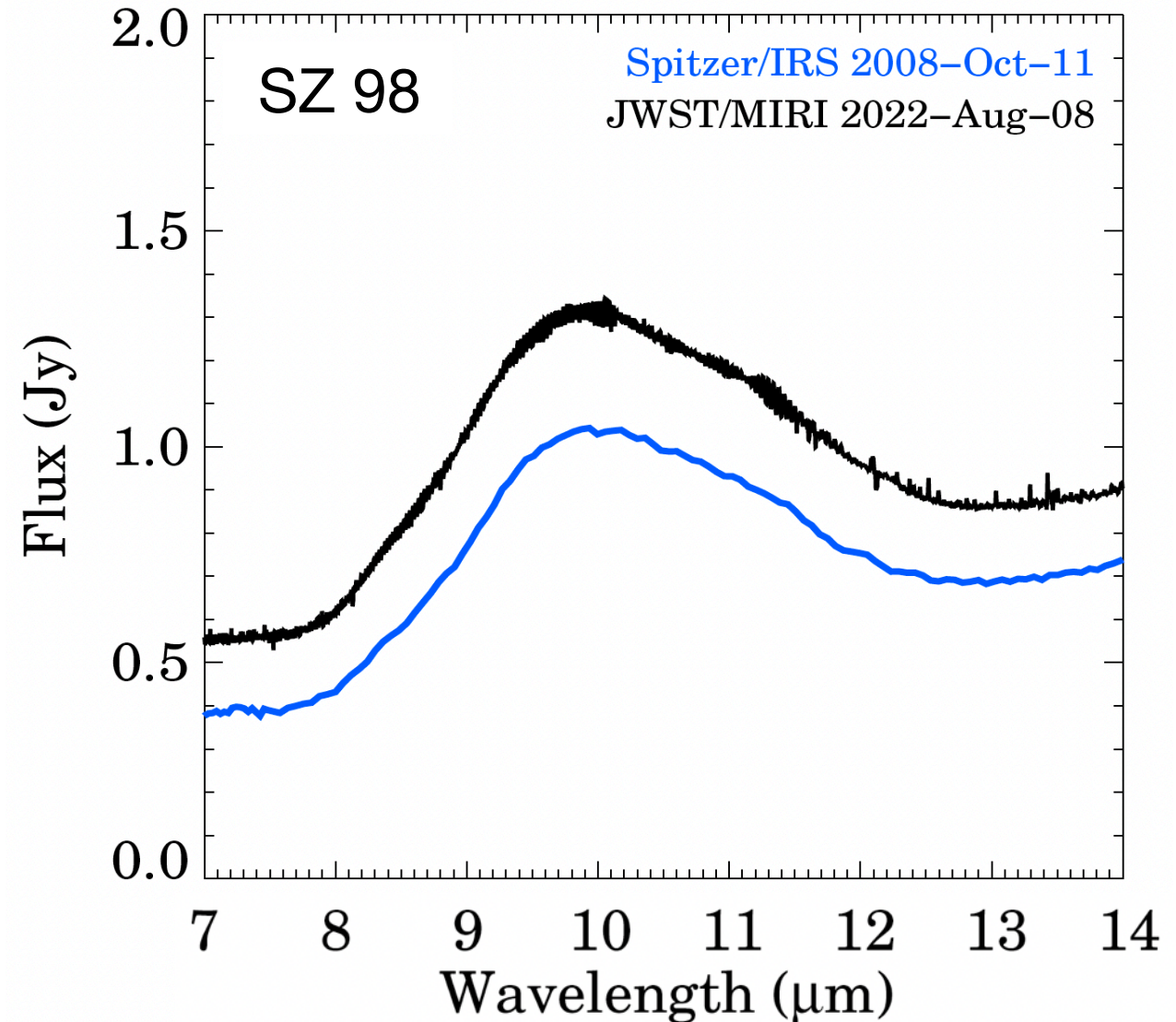
Variability peaks at K5-M0 spectral types.

Earlier sp. types vary more at longer lambda

Real timescales

Spitzer-JWST time difference: 15-20 yrs
What is the real timescale of variability?

Monitoring of 4 Class II stars (GQ Lup, HT Lup, RU Lup, SZ 98 a.k.a V1279 Sco) with VLT/VISIR in 3-4 epochs. Cadence: 2-3 weeks.



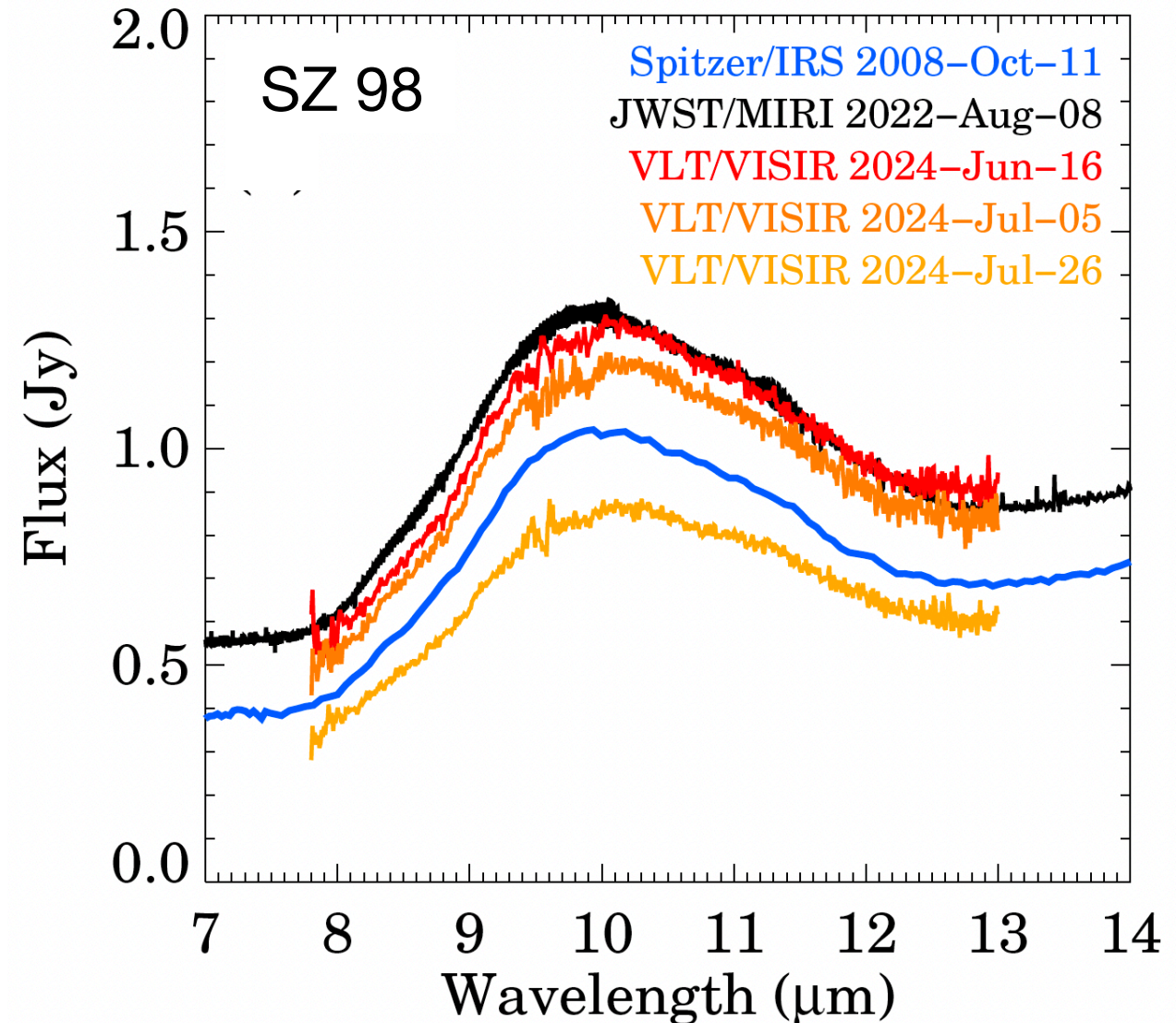
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Flux variations match (or exceed) the Spitzer-JWST difference

Timescale is not necessarily 15 yrs, but can be a few weeks only



Real timescales

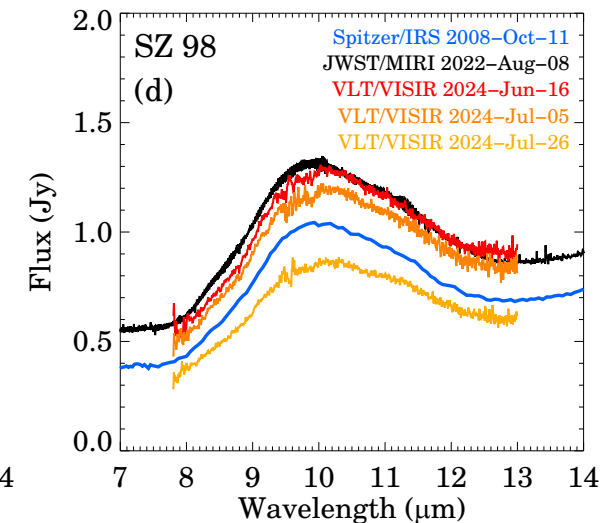
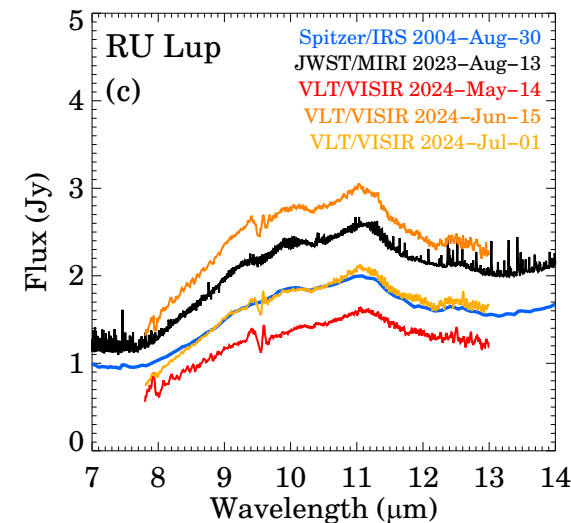
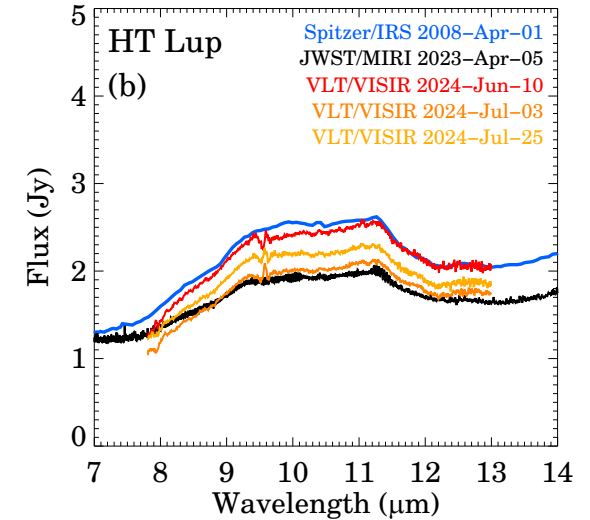
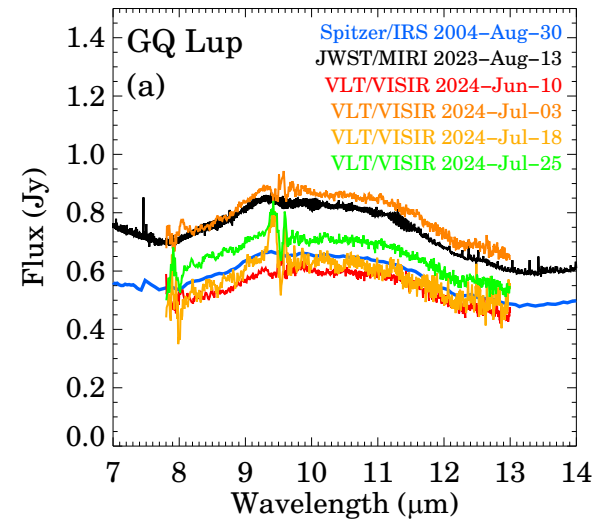
Spitzer-JWST time difference: 15-20 yrs
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Flux variations match (or exceed) the Spitzer-JWST difference

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All four Class II stars showed the same trend



Structure function

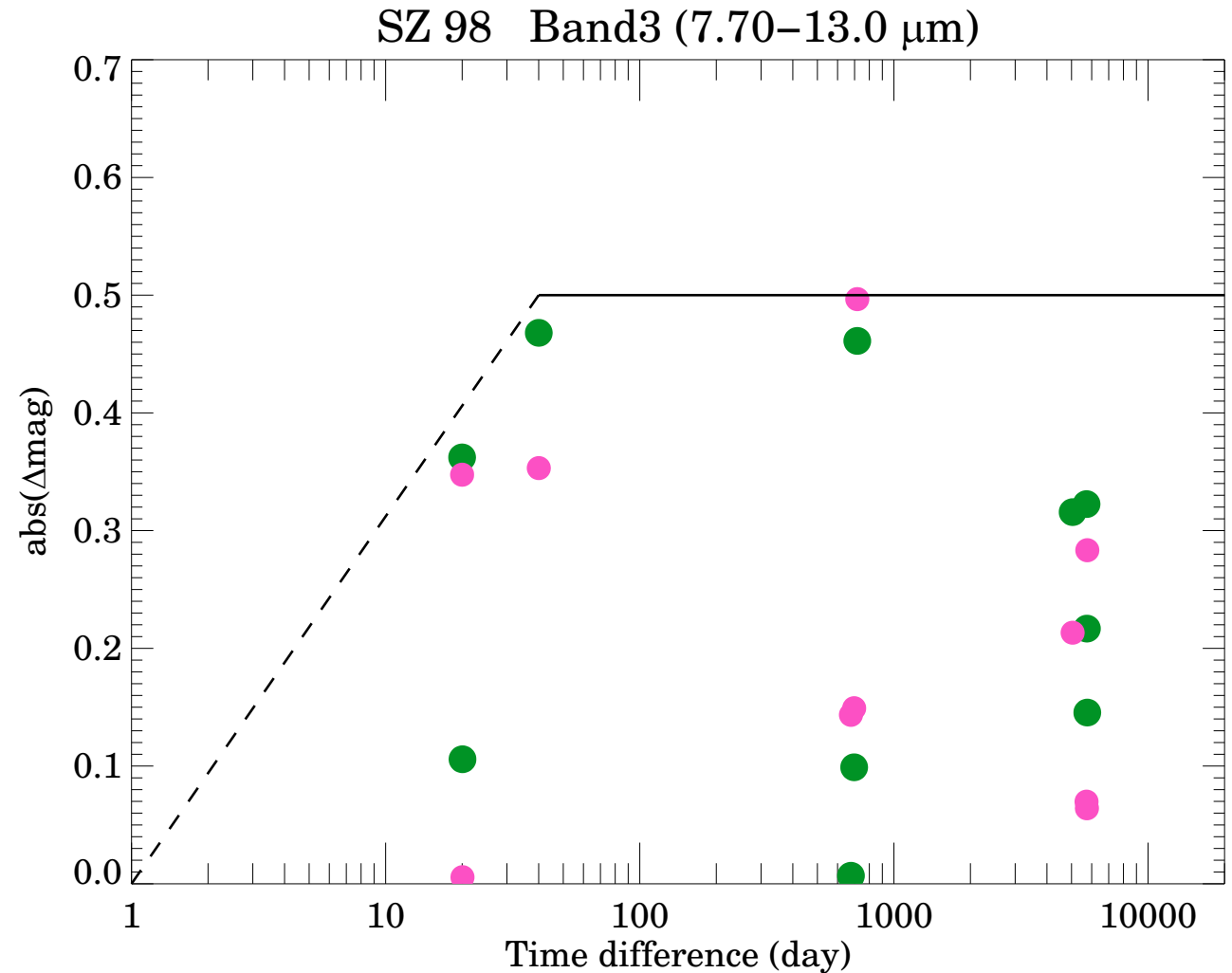
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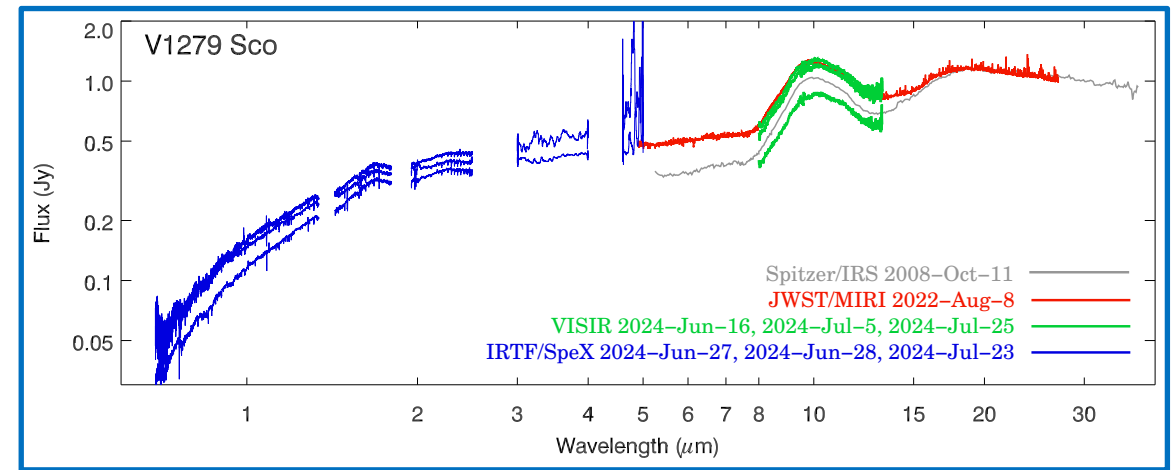
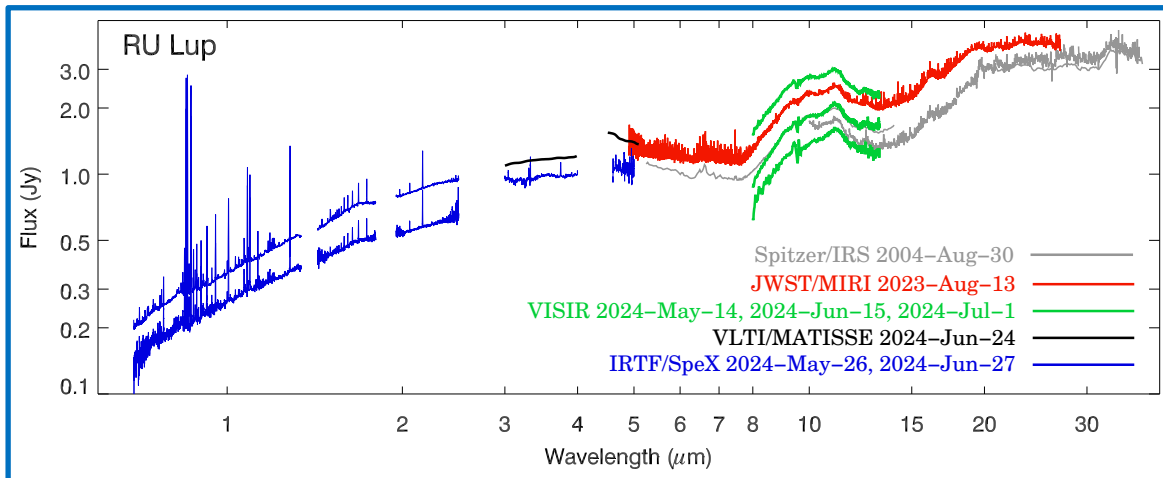
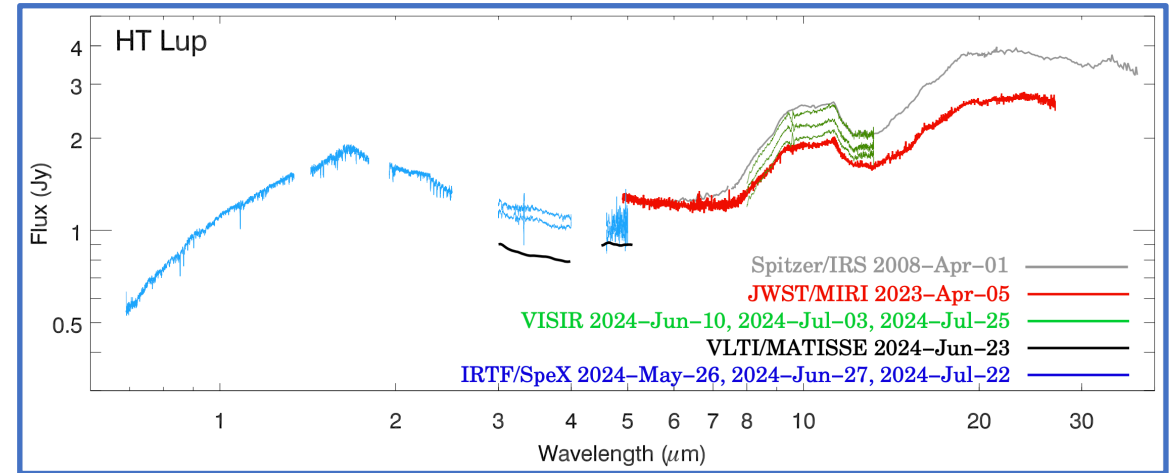
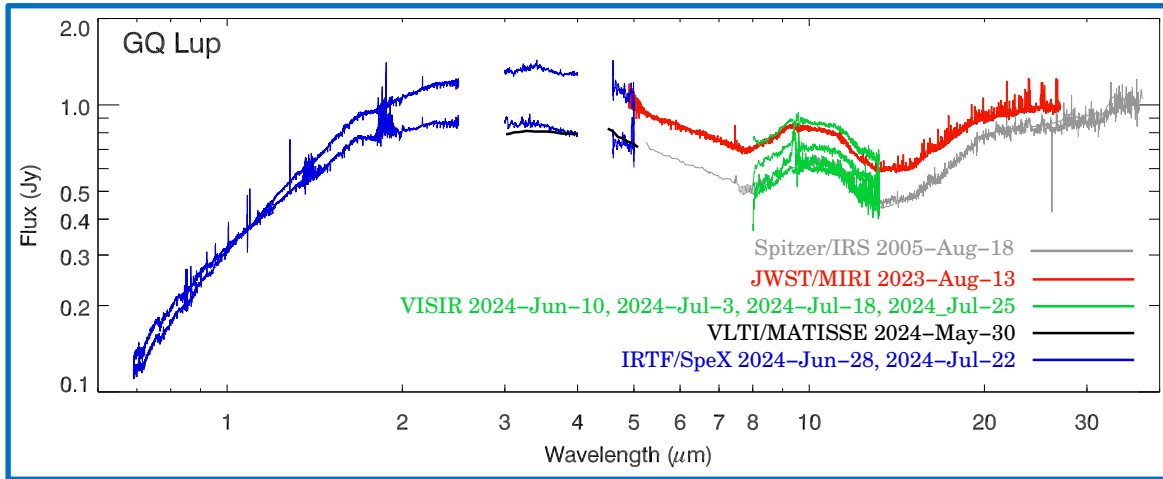
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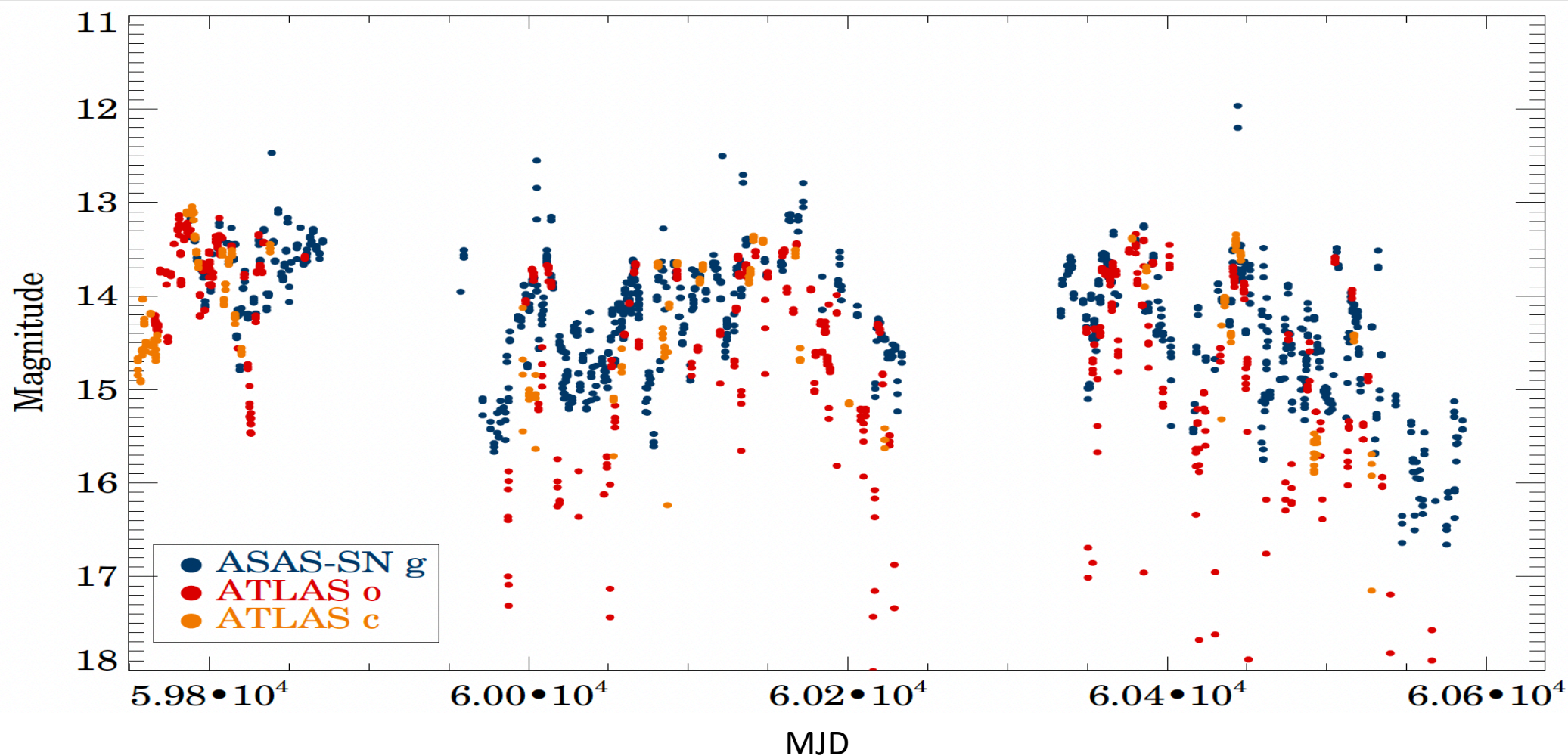


I. Variability of disk components



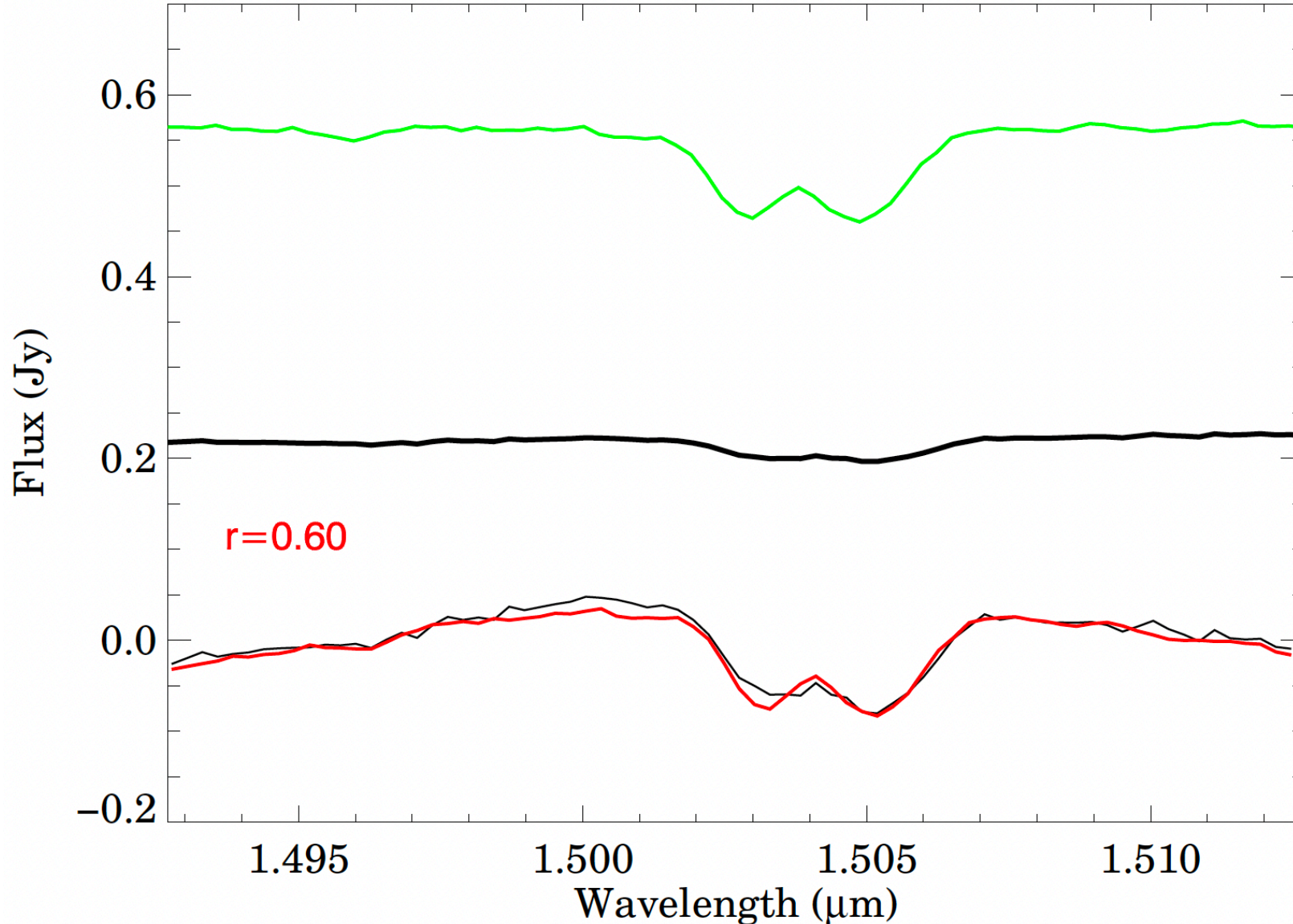
Infrared monitoring of 4 young stars in 2024 May-July. JWST/MIRI: publicly available archive data from MAST (PI: A. Banzatti, C. Salyk). IRTF/SpeX and ESO/VISIR: our own observations (PI: P. Ábrahám).

Supplement MIRI/Spitzer with optical/NIR data



Ideally, extinction and accretion (veiling) are measured simultaneously!

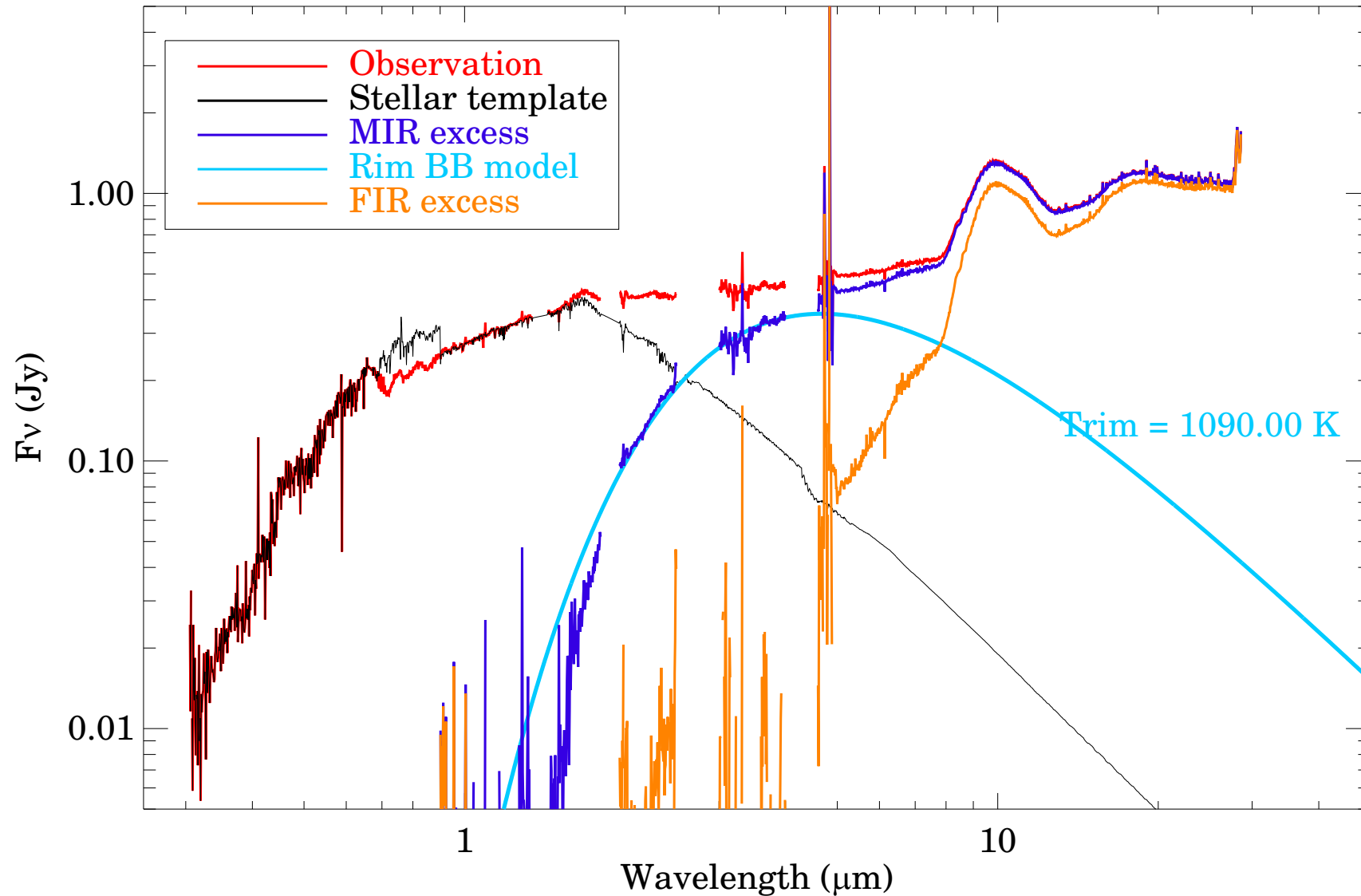
Near-IR spectra: veiling and A_v can be measured



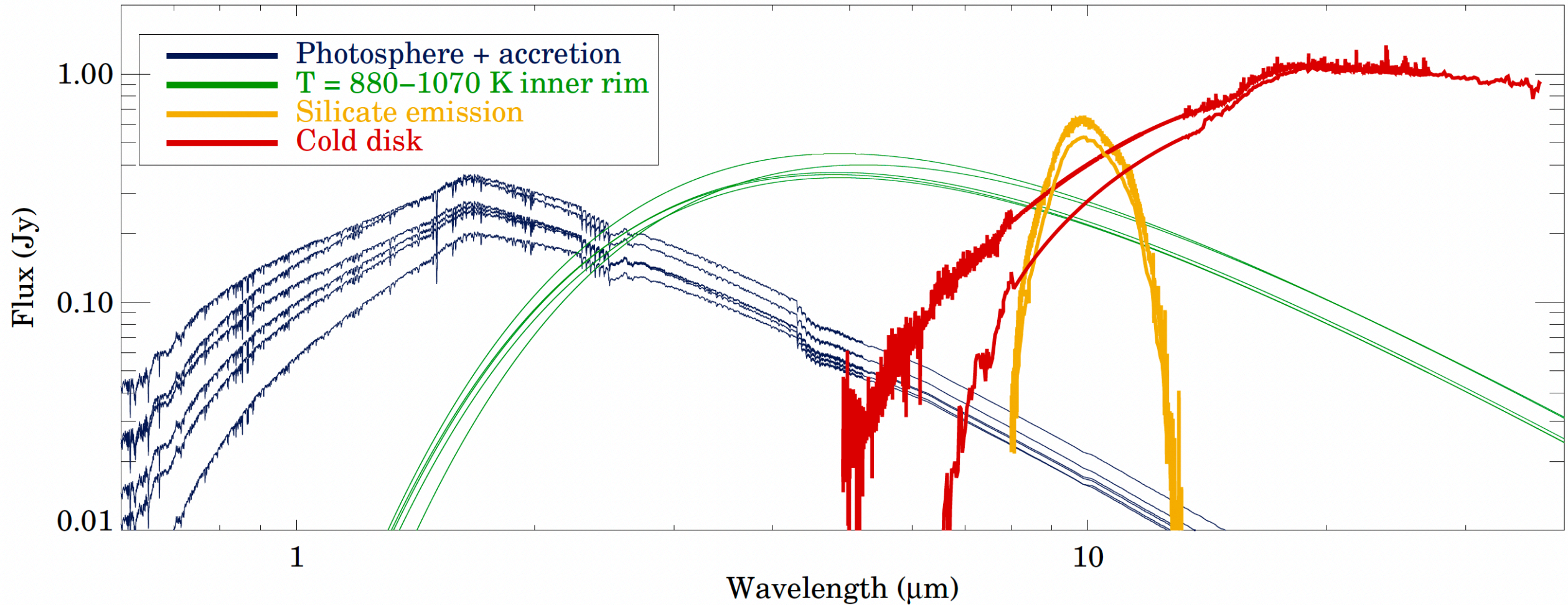
Comparing absorption lines of Sz 98 with the non-accreting Class III star TWA 6. The lines in Sz 98 are shallower.

From the wavelength dependence of the veiling values A_v extinction is determined,

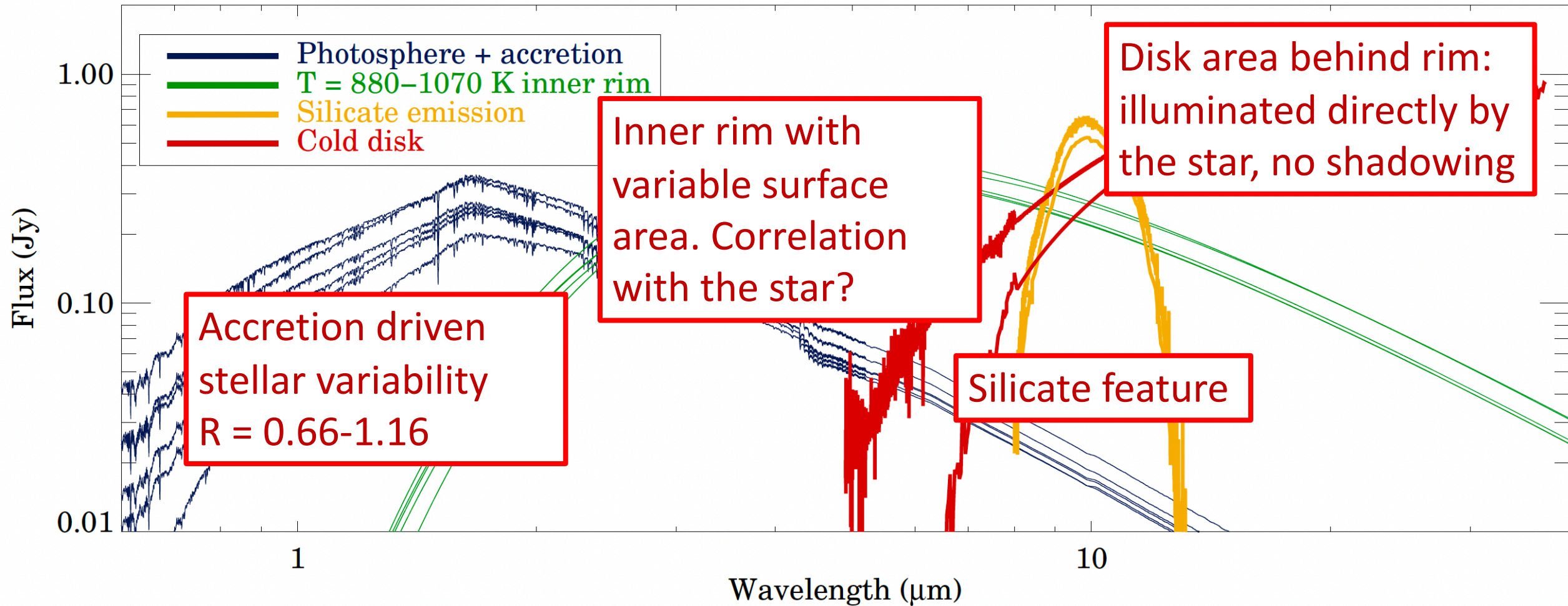
Disk components in the time domain



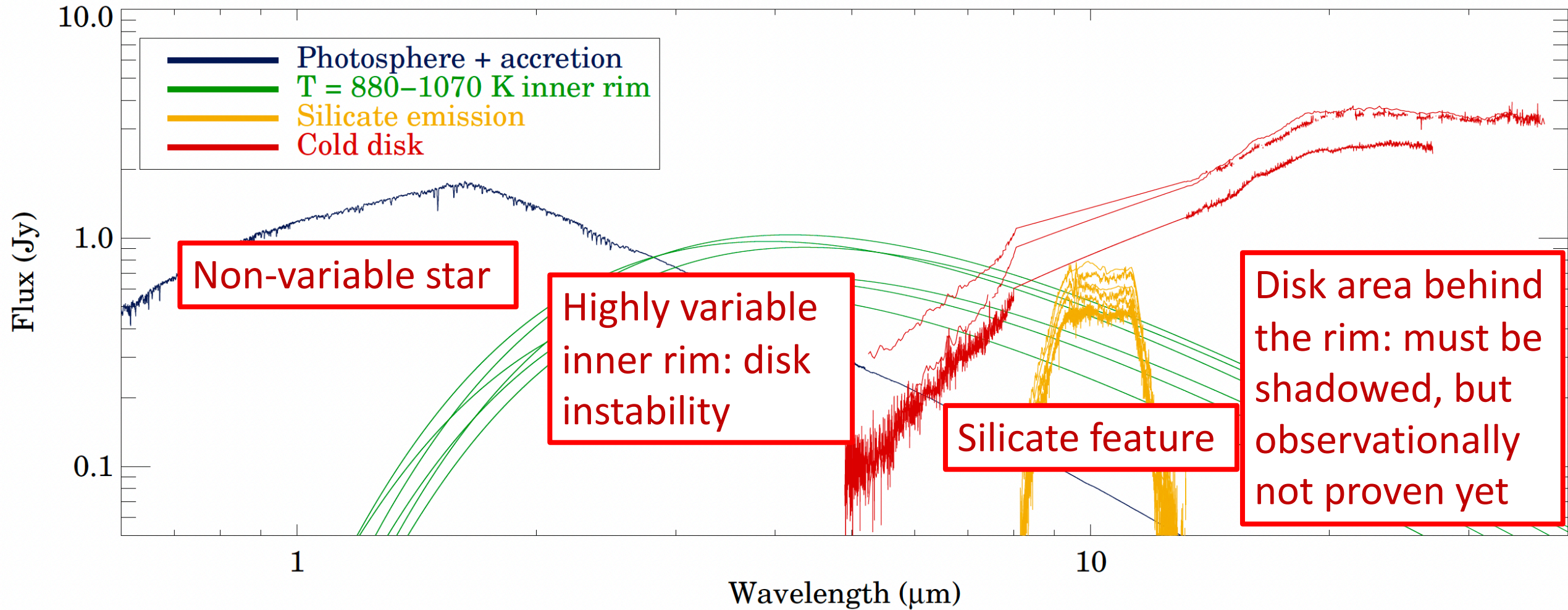
Sz 98: decomposition of the variable SED



Sz 98: decomposition of the variable SED



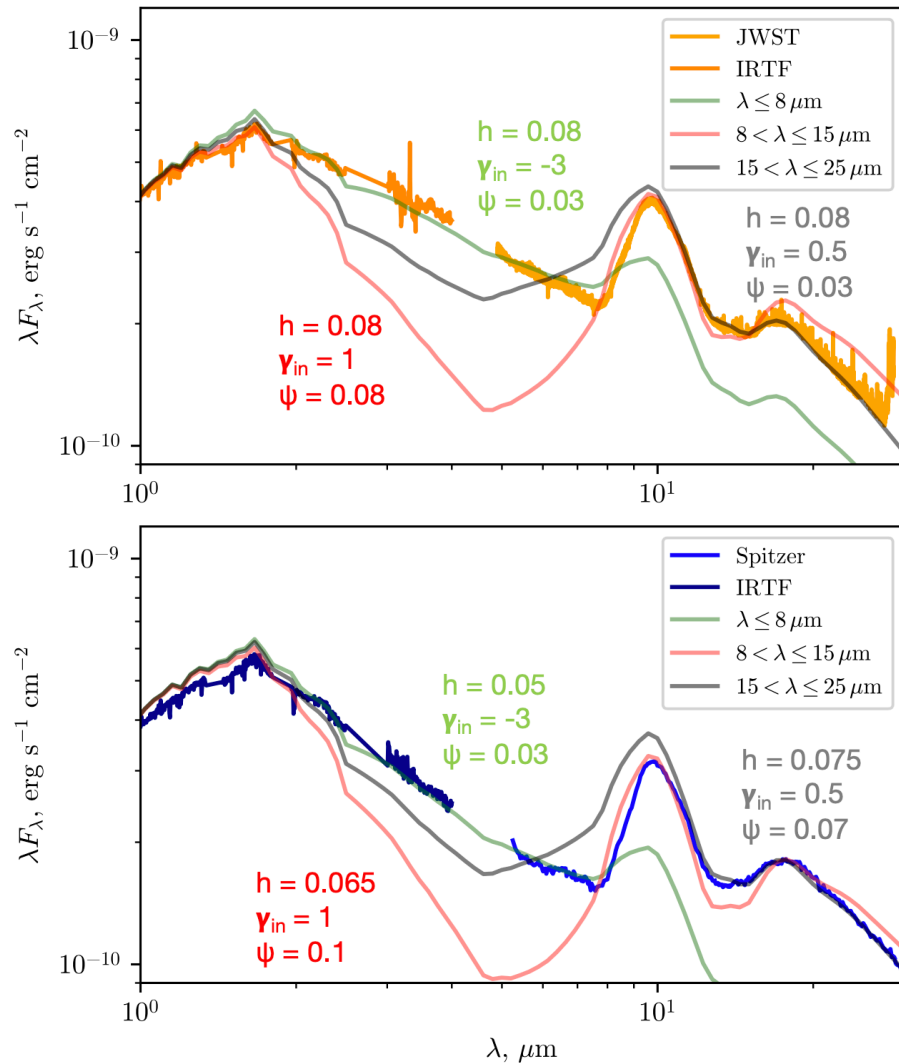
HT Lup: fluctuating irradiation is excluded



Changes in inner rim surface by 87% in ~6 months: strong constraints for dynamics.

II. Radiative transfer modeling (L. Zwicky, PhD)

V1279 Sco



We run a grid of simple vertical structure models:

$$\rho = \rho_0 \exp\left(-\frac{z^2}{2H^2}\right)$$

$$H = hR \left(\frac{R}{R_c}\right)^\psi$$

The inner disk is smoothed with exponential taper:

$$\Sigma \propto \exp\left[-\left(\frac{R_{c,\text{in}}}{R}\right)^{2-\gamma_{\text{in}}}\right]$$

$R_{c,\text{in}}$ is calculated from R_{min} where density drops to 10^{-24} g/cm³. R_{min} is a model parameter, and we choose it to be near sublimation radius. For V1279 Sco $R_{\text{min}} = 0.1$ au. For RU Lup $R_{\text{min}} = 0.15$ au.

YSO parameters:

V1279 Sco

$d = 156.2$ pc (Gaia)
 $A_V = 2.19$
 $R_c = 148$ au (Long+2022)
 $M_{\text{dust}} = 120 M_\oplus$ (Xin+2023)
 $i = -47.1^\circ$ (Ansdell+2018)

RU Lup

$d = 157.5$ pc (Gaia)
 $A_V = 0.9$
 $R_{\text{disk}} = 62$ au (Xin+2023)
 $M_{\text{dust}} = 159 M_\oplus$ (Xin+2023)
 $i = 0^\circ$ (Ansdell+2016)

Stellar spectra of both:
 XShooter + IRTF +
 BTSettle (Allard 2014)

Dust sublimation per
 Flock+2019

Dust opacities:
 (approximate,
 we do not fit the feature here)

optool
 (Dominik+2021)

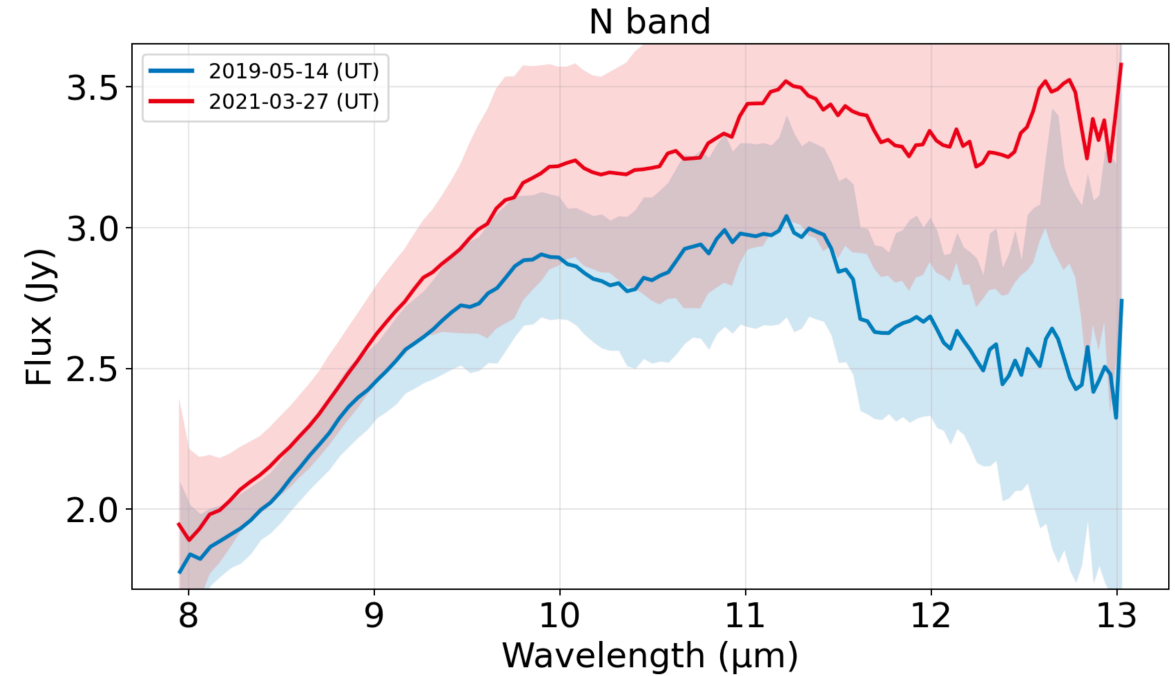
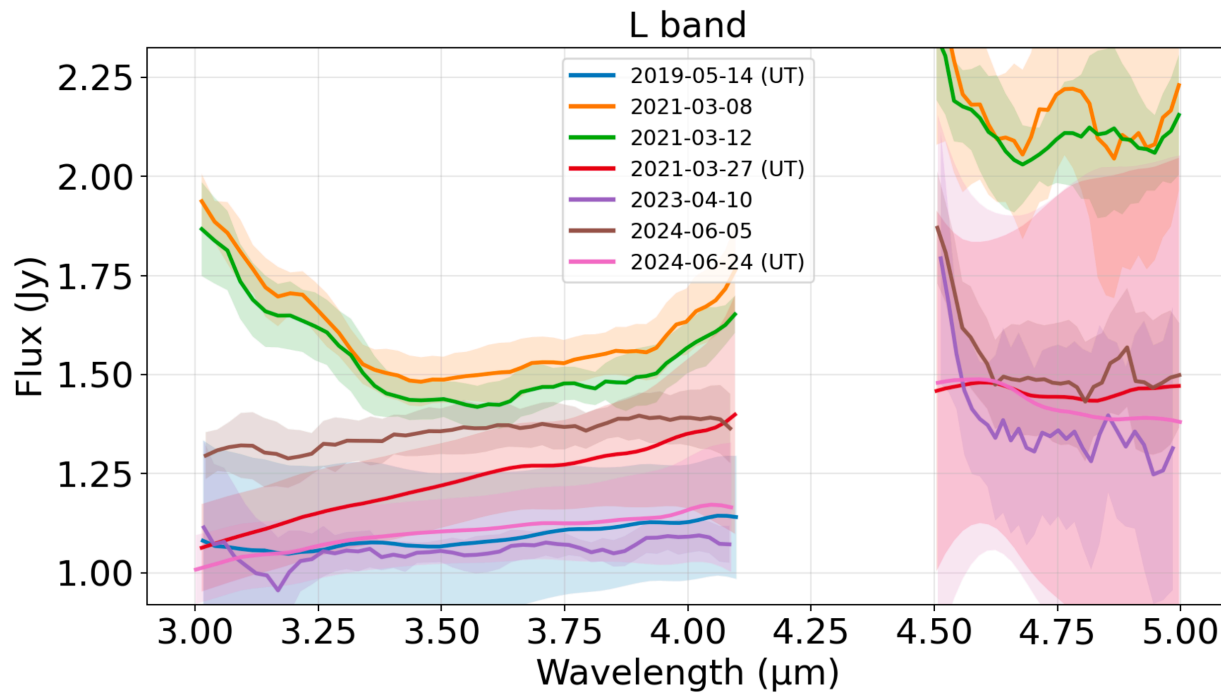
Parametric disk setup:

DiskCheF
 (on GitLab)

Radiative transfer:

RADMC-3D
 (Dullemond+2012)

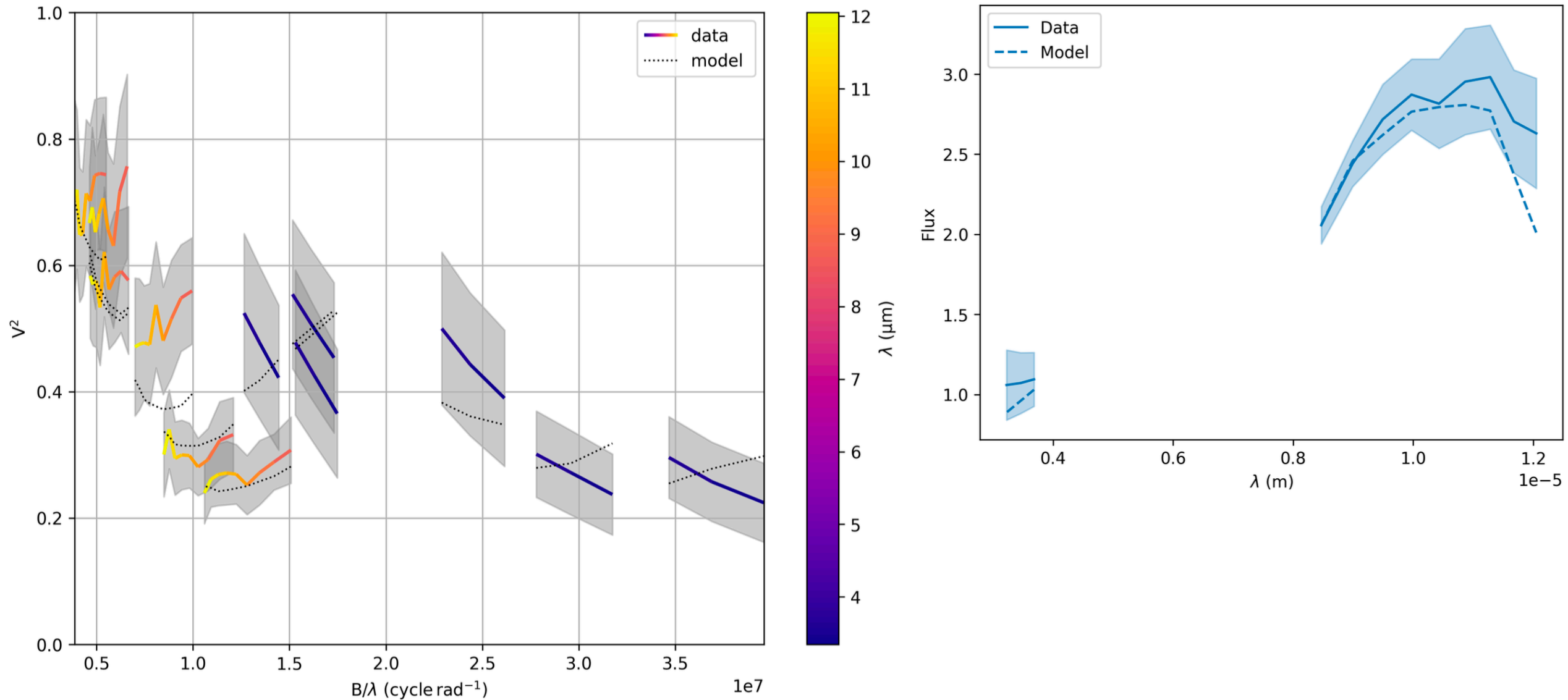
III. Interferometry with VLT/MATISSE (T. Juhász)



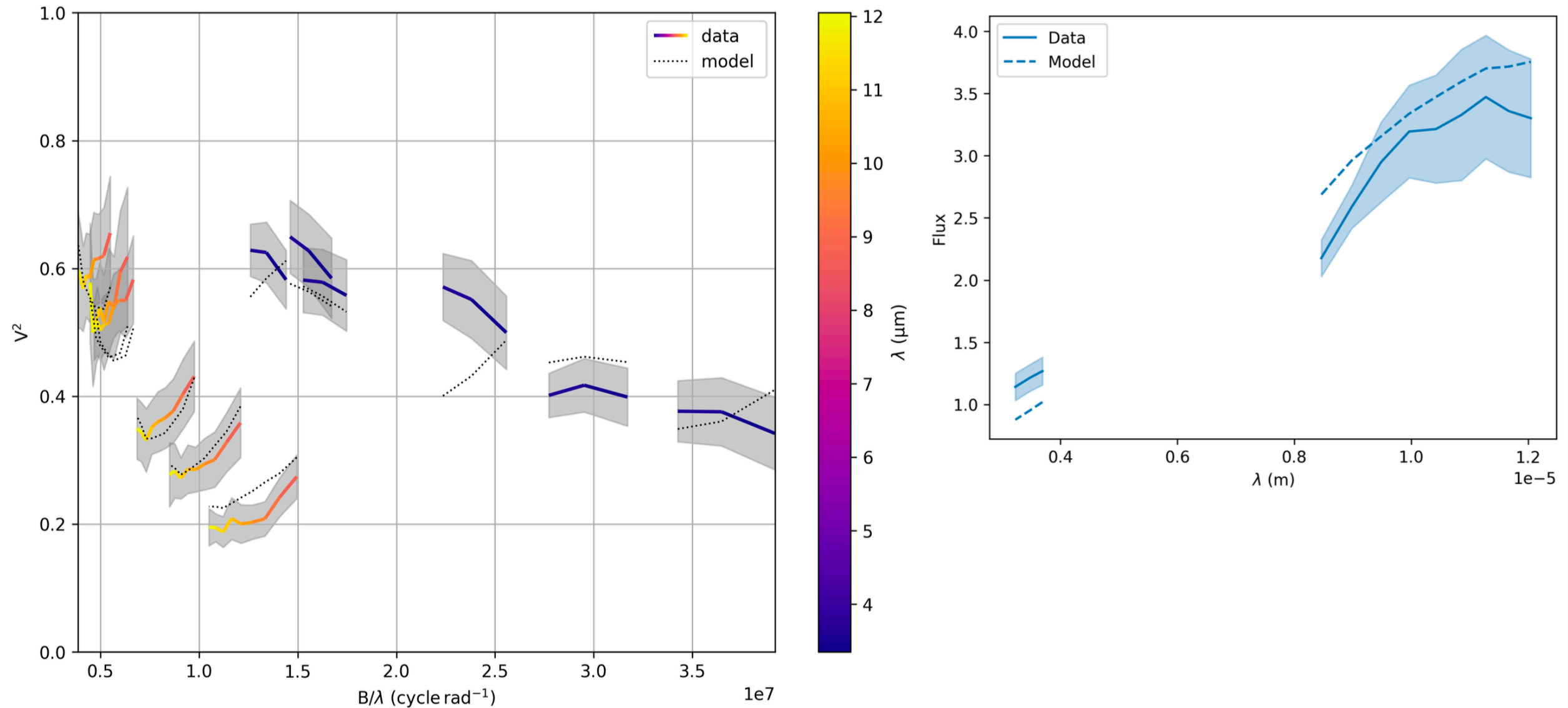
Changing relative contributions from different star+disk regions affects the source's brightness distribution, and thus visibilities and closure phases.

Can we see such changes in RU Lup?

Oimodeler fits of MATISSE data from 2019



Oimodeler fits of MATISSE data from 2021



Conclusions and wishes

A large part of YSOs are variable at mid-IR wavelengths

Timescales are a few weeks: hint for shadowing

Physical explanation methods:

- Decomposition of multi-epoch SEDs
- RT modeling of multi-epoch SEDs
- Multi-epoch infrared interferometry

With JWST we could enter the time domain, let's do it!

Conclusions and wishes

A large part of YSOs are variable at mid-IR wavelengths

Timescales are a few weeks: hint for shadowing

Physical explanation:

- Decomposition of multi-epoch SEDs
- RT modeling of multi-epoch SEDs
- Multi-epoch infrared interferometry

With JWST we could enter the time domain, let's do it!

My lesson and Xmas wish: Santa pls. give me data simultaneously with each and every JWST/MIRI measurement! It will make the world a much better place!



Thomas at Konkoly Observatory (Budapest)



2025 Sep-Dec

Good memories



Piszkéstető Mountain Station



Explaining silicates...



Thanks Thomas, and come back!

My questions



- **Question 1:** how do the stellar accretion luminosity and the luminosity of the different disk components (inner rim, silicate feature, outer disk) correlate? Do stellar luminosity changes provide enough energy for disk variability?
- **Question 2:** what is going on in systems where the star is constant but the disk varies? Energy source of the variability?!
- **Question 3:** how could we convince the JWST TAC to monitor YSOs with MIRI?

Thanks for your attention!