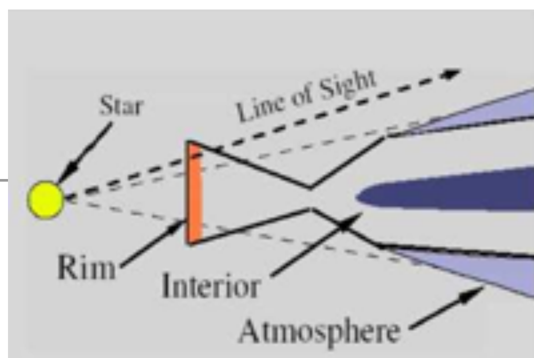
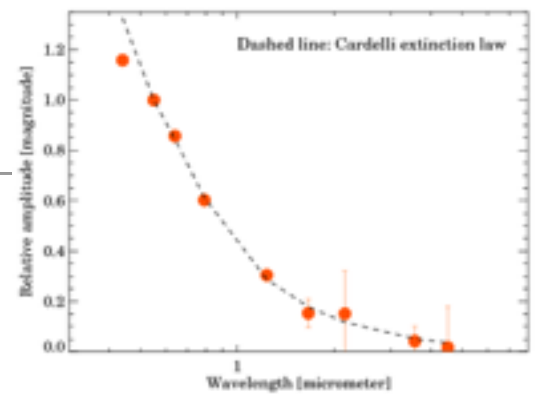
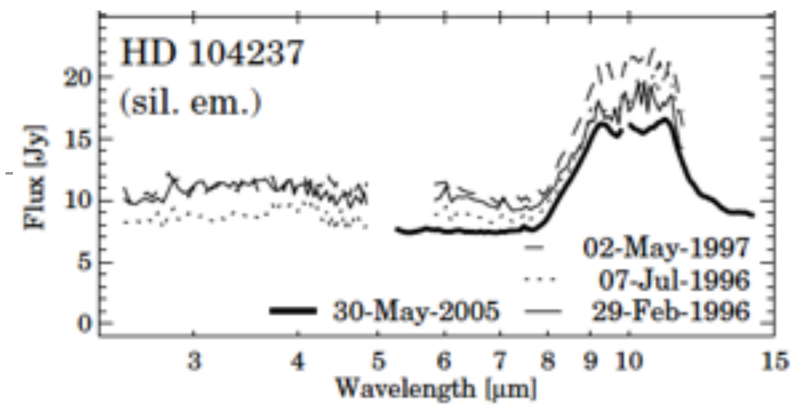
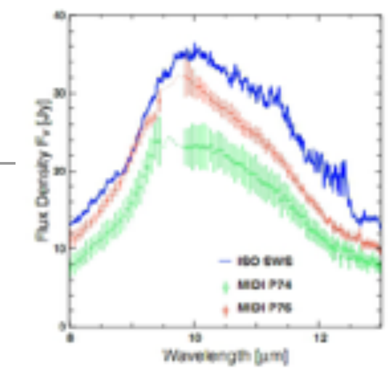
The 4th dimension of circumstellar disks: Infrared variability and disk structure of young stellar objects









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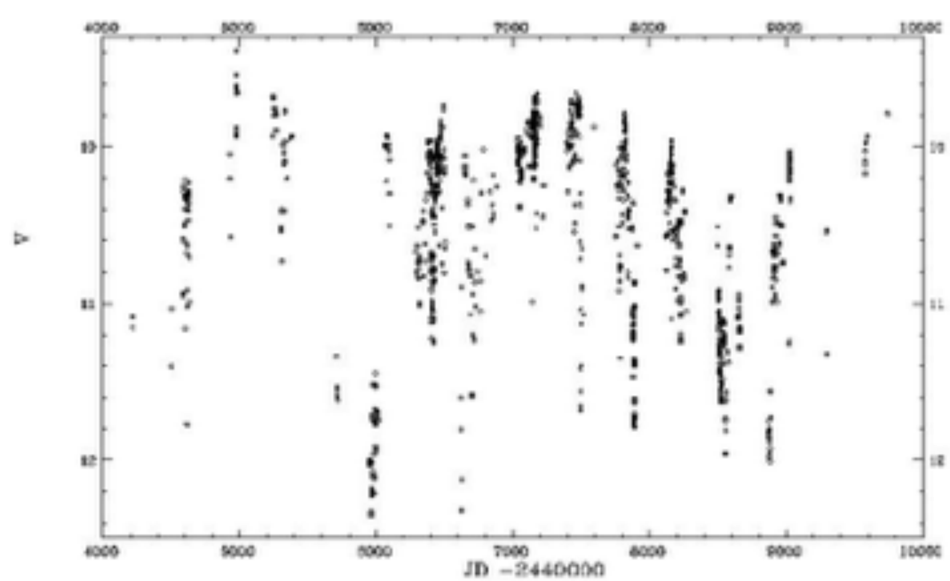
2016 December 13

Optical variability of YSOs

- YSOs are well-known about their optical and near-infrared variability. Three main classes of variability (Herbst et al. 1994):
- Type I - Cool spots: similar to sunspots, rotating for a few periods
- Type II - Hot spots or zones: variable veiling continuum arising in small transient hot regions where accretion energy is dissipated (periodic or irregular). Mainly later spectral type.
- Type III - Variable obscuration. Mainly earlier spectral type. Most studied type is the *UXor phenomenon:* protocometary clouds or protocomets (Grady et al. 2000), hydrodynamic fluctuation in the disk surface (Bertout 2000), puffed-up inner rim (Dullemond et al. 2003)

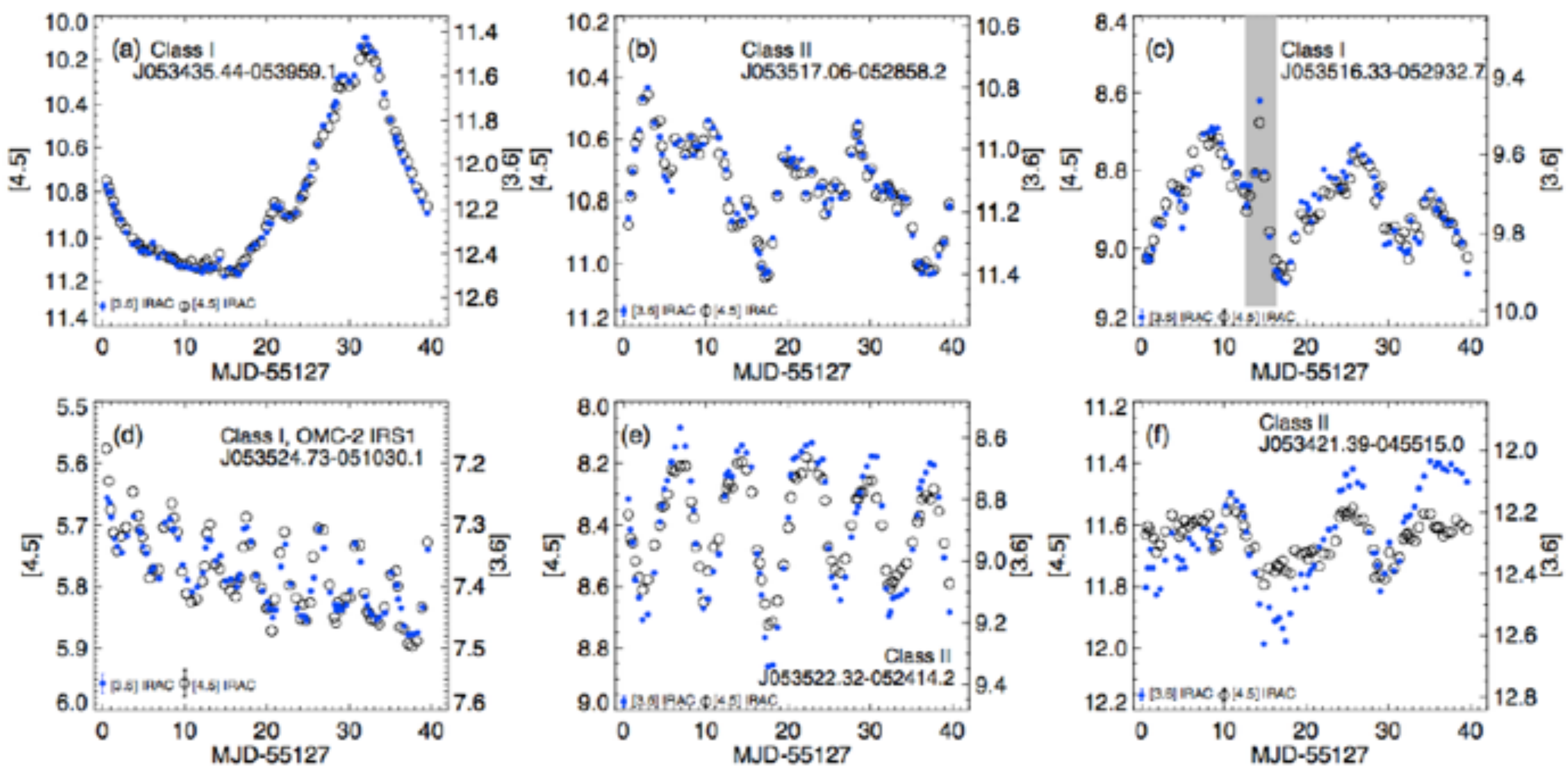


Type II-III are related to the disk!

Light curve of UX Ori

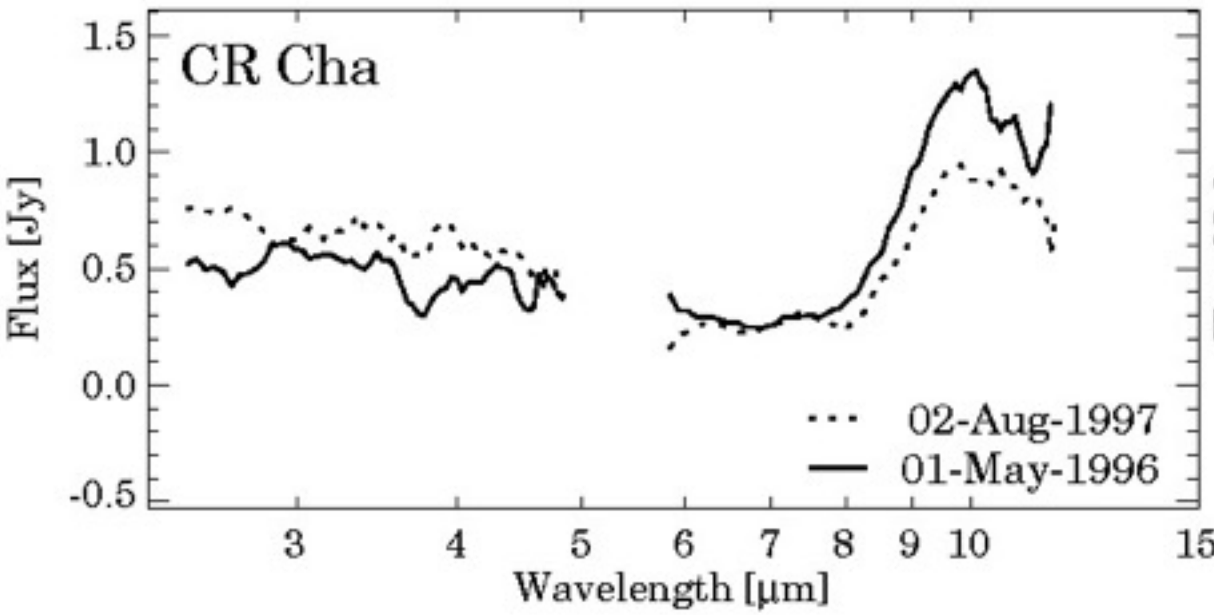
Infrared variability

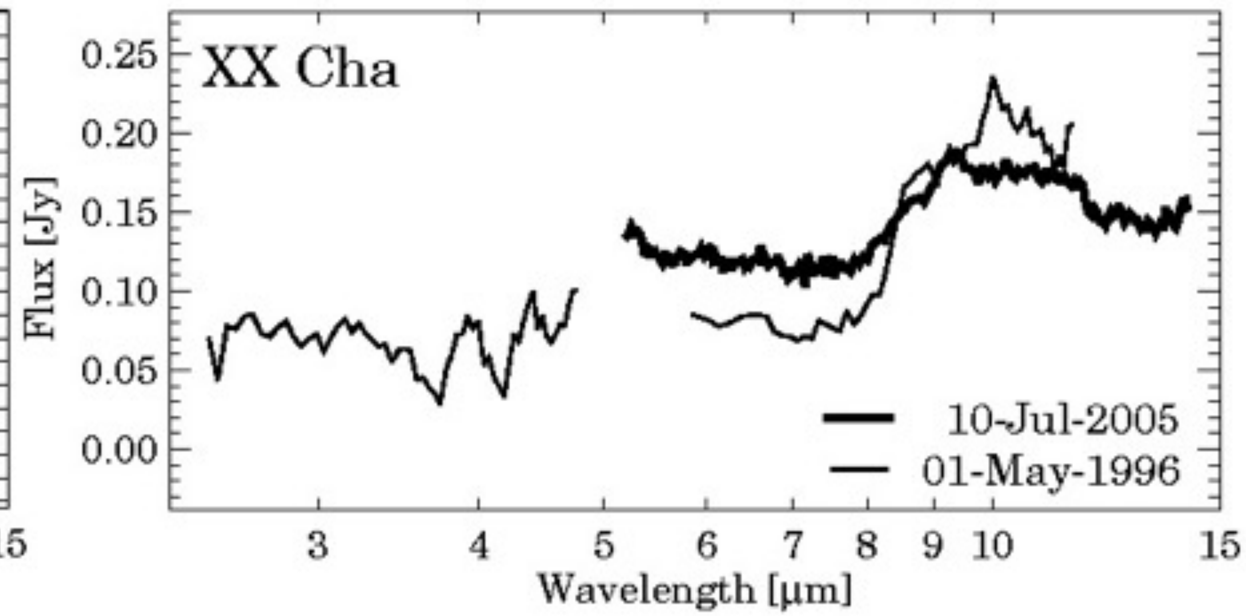
- The thermal infrared emission of the disks was traditionally assumed to be invariable (exceptions are eruptive stars)
- IRAS variability flag showed definite changes in several cases (Prusti & Mitskevich 1994)
- Recent mid-infrared photometric studies demonstrated that a large fraction of YSOs are also variable in the thermal infrared: up to 70-80% of YSOs are variable above the 0.1 mag (~10%) level at thermal infrared wavelengths (Barsony et al. 2005, Morales-Calderón et al., 2009, Luhman et al., 2010, ApJS 186, 111):

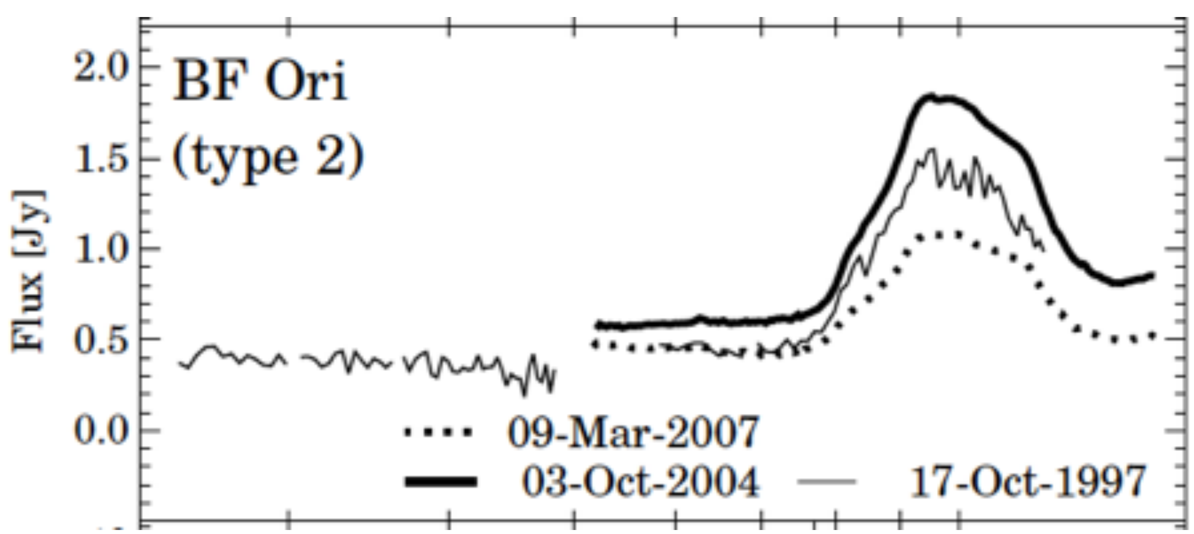


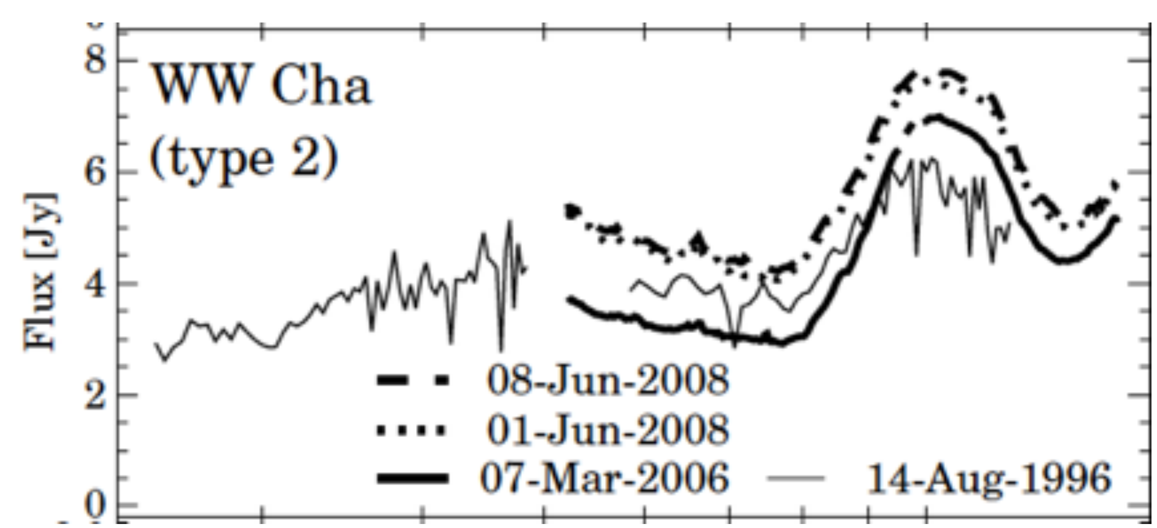
Infrared variability of YSOs

- Mid-IR spectral variability atlas (Kóspál et al. 2012):



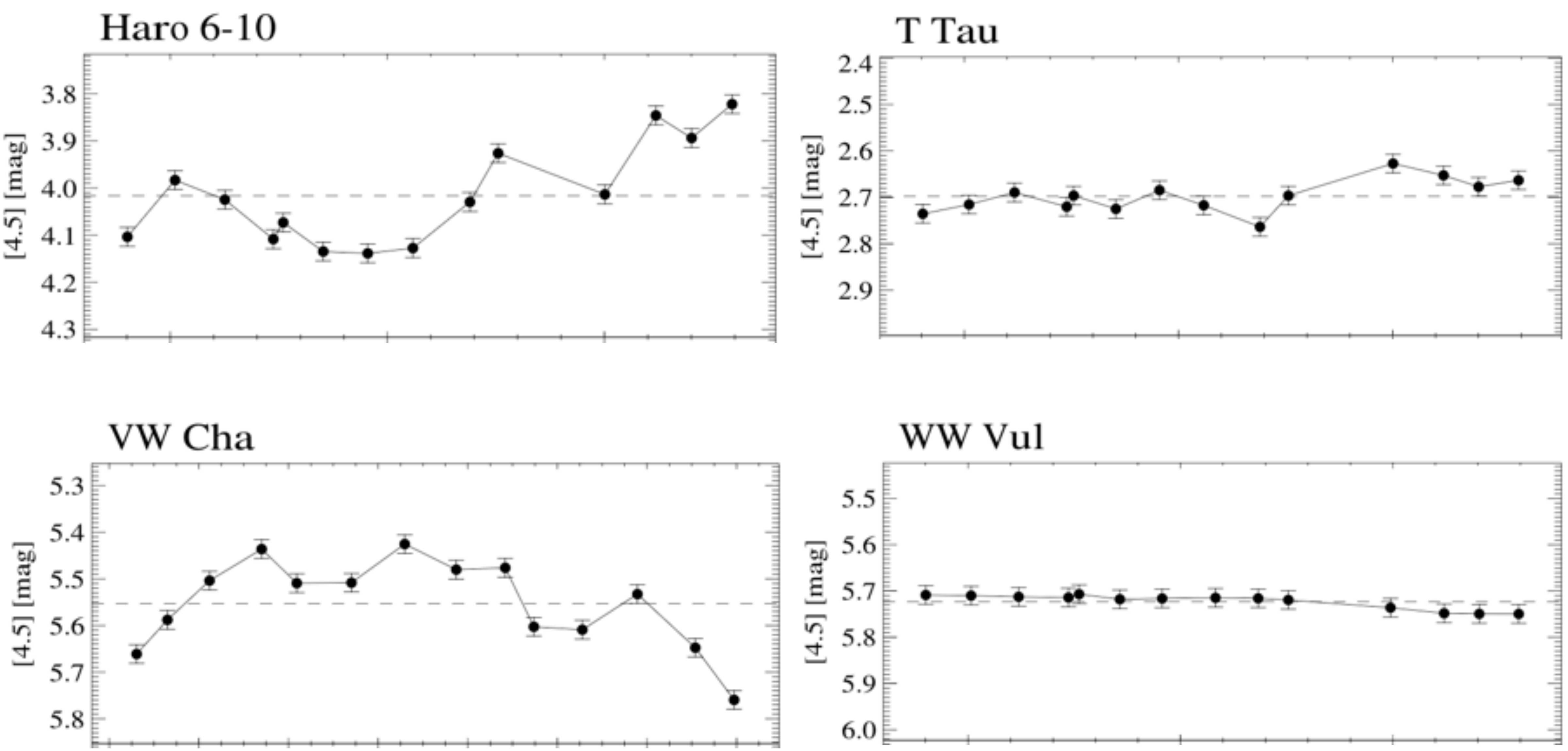






Infrared variability of YSOs

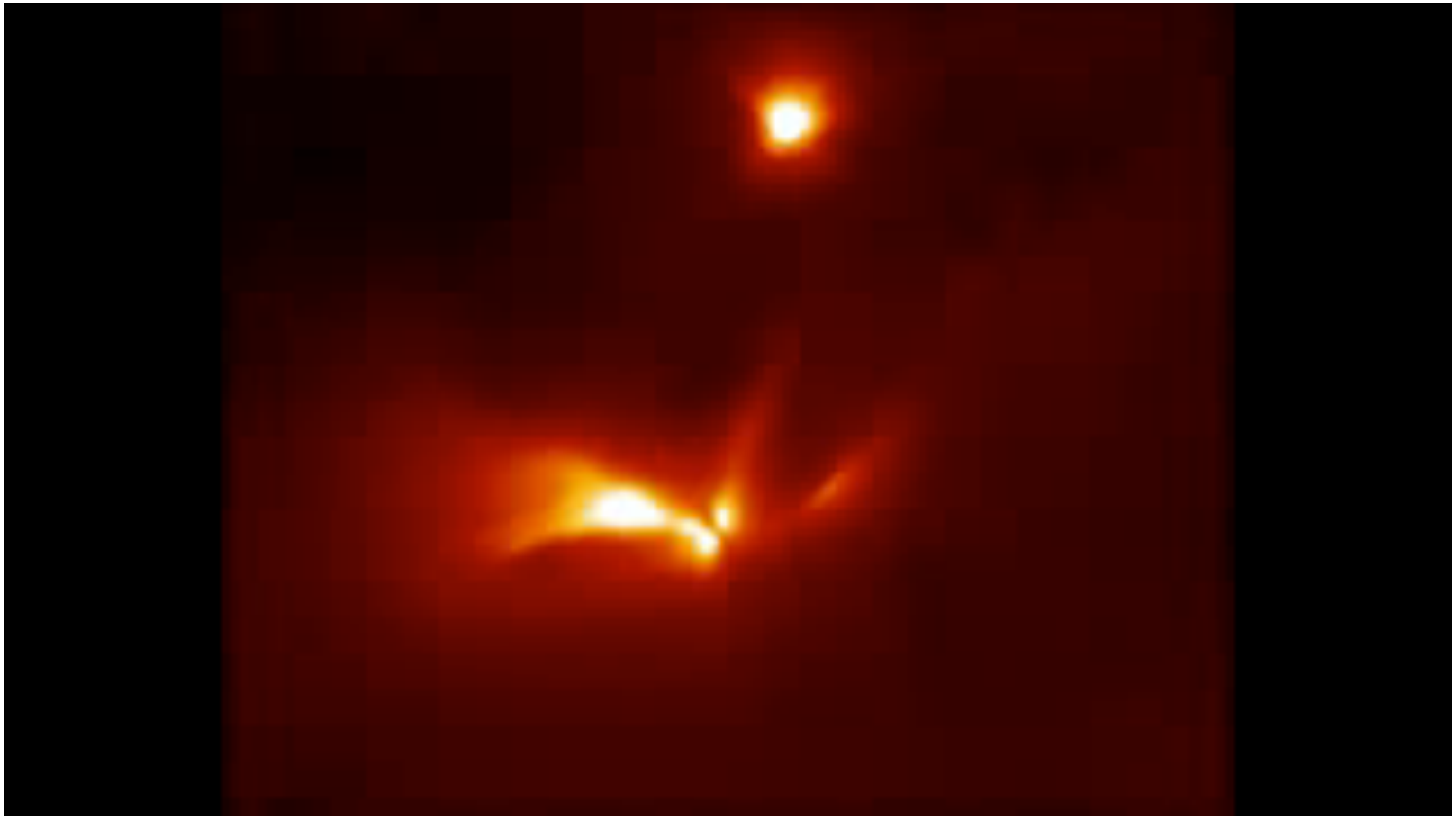
- Mid-infrared photometric monitoring with Spitzer (Ábrahám et al. in prep.)



Observable disk changes

In a simple view, YSO disks can:

- react on changing stellar illumination, e.g due to varying accretion

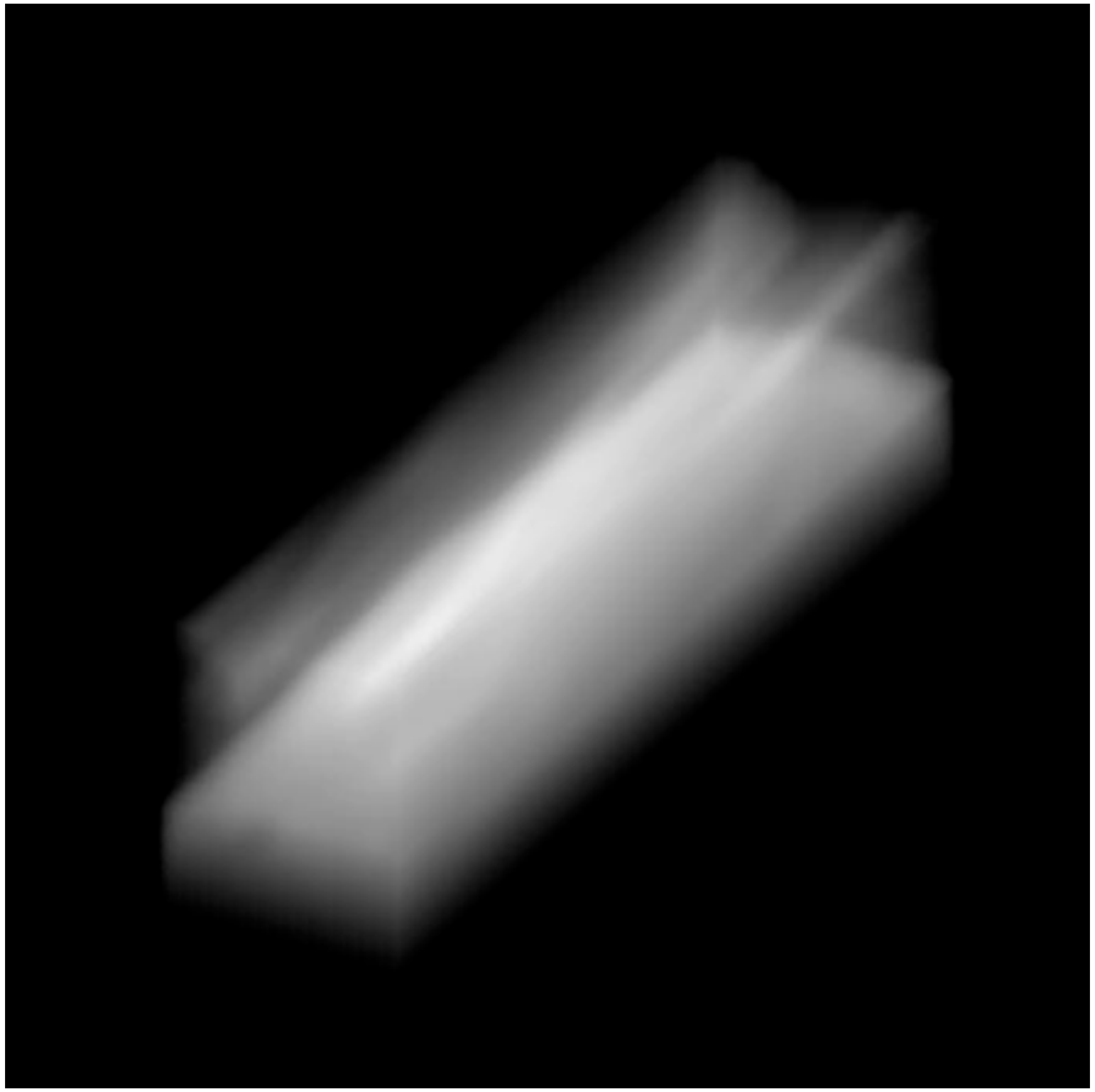


Muzerolle et al. Nature, 2013

Observable disk changes

In a simple view, YSO disks can:

- re-arrange their structure

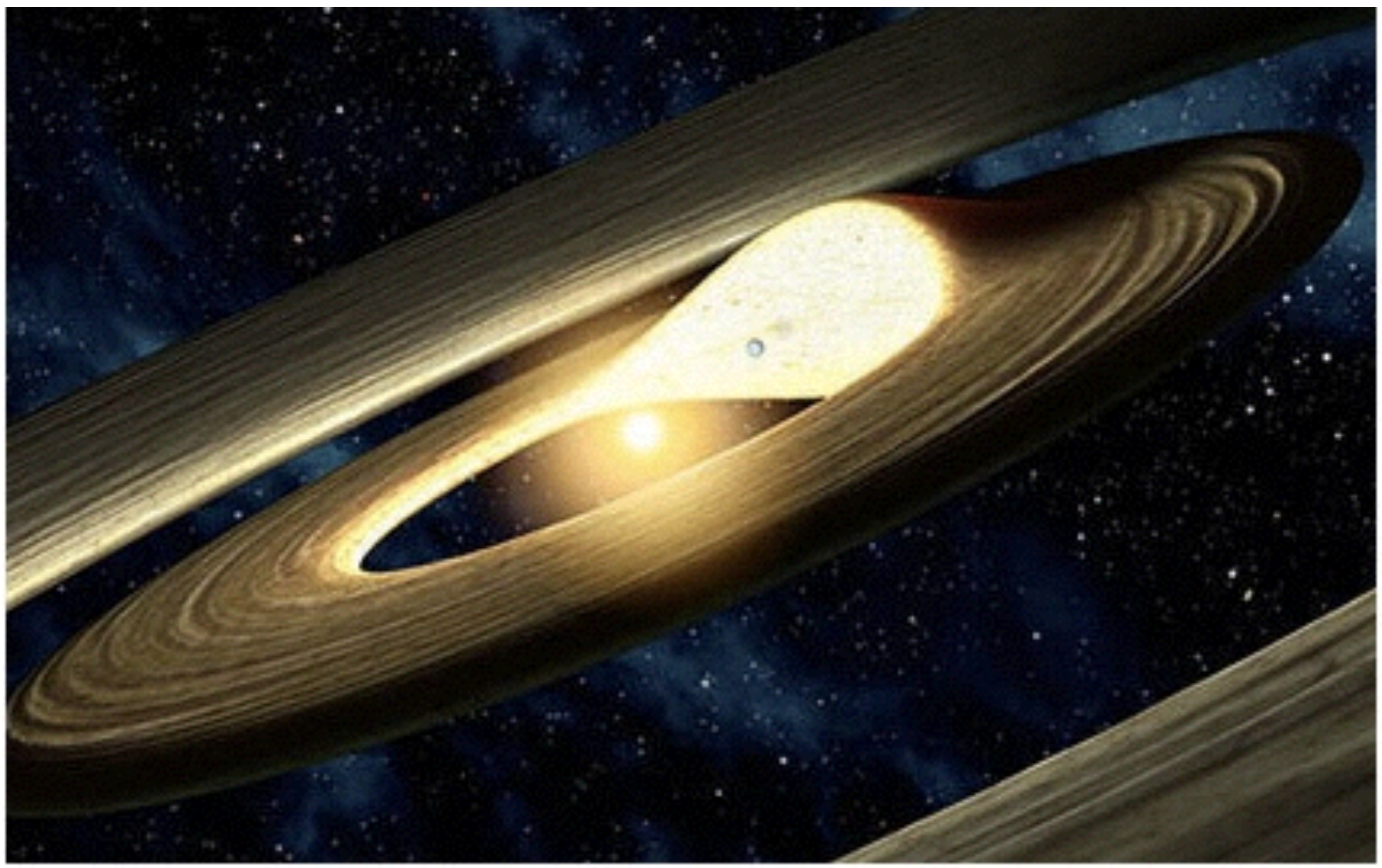


Turbulent motions lift up dust clouds in the disk atmosphere (Turner et al. 2010)

Observable disk changes

In a simple view, YSO disks can:

- temporarily eclipse the central star



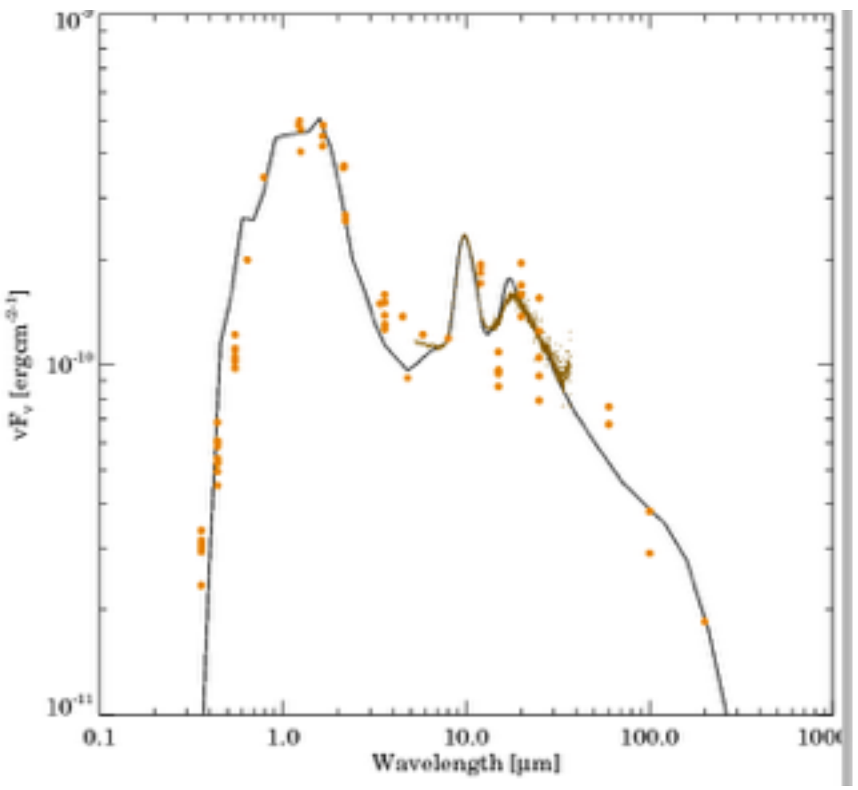
Muzerolle et al. 2009,
Flaherty et al. 2011

In reality, these effects may work in parallel.

Variability and disk structure

- **Both Type III optical variability (UXor phenomenon) and thermal infrared variability deliver information about disk structure.**
- **Two main avenues: (1) try to deduce disk parameters from the measurements in a model-independent way: (2) test disk models for temporal perturbations, and compare with observations.**
- **Possibility to study dynamical phenomena via determining timescales**
- **May we compile non-contemporoeus SEDs or interferometric observations?**

Methods?



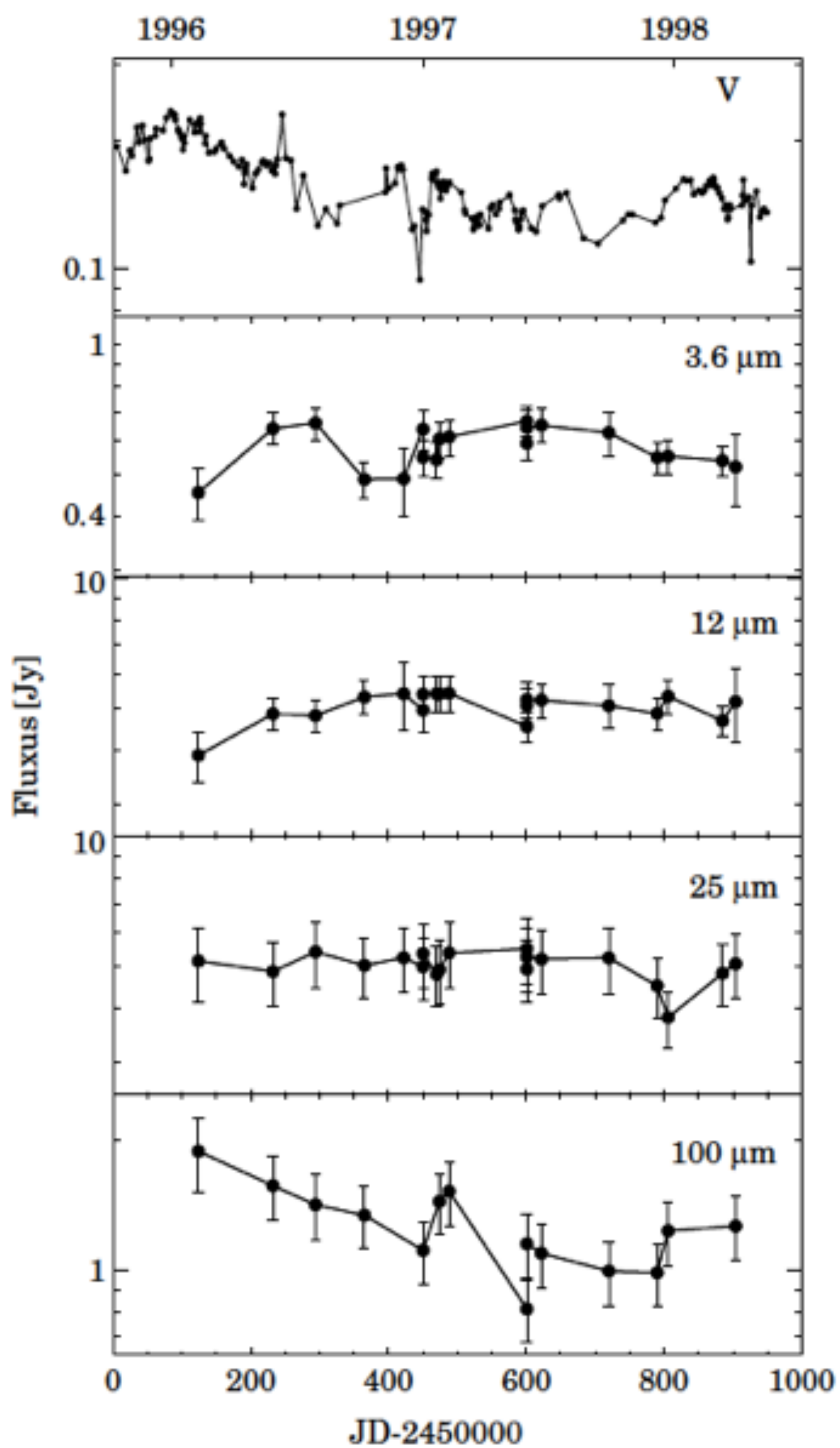
Available variability datasets

- IRAS variability flag (~half a year time difference)
- Infrared Space Observatory: monitoring of 5-6 UXors (e.g. SV Cep, Juhász et al. 2008)
- Ground based photometric or spectroscopic monitoring observations up to 10-20 micrometer (e.g. Sitko et al. 2008, Shenavrin et al. 2012)
- Spitzer Space Telescope (both cryogenic and post-He). Very accurate measurements!
- MIDI interferometric monitoring
- FIR: Herschel Space Observatory
- Optical: Kepler K2

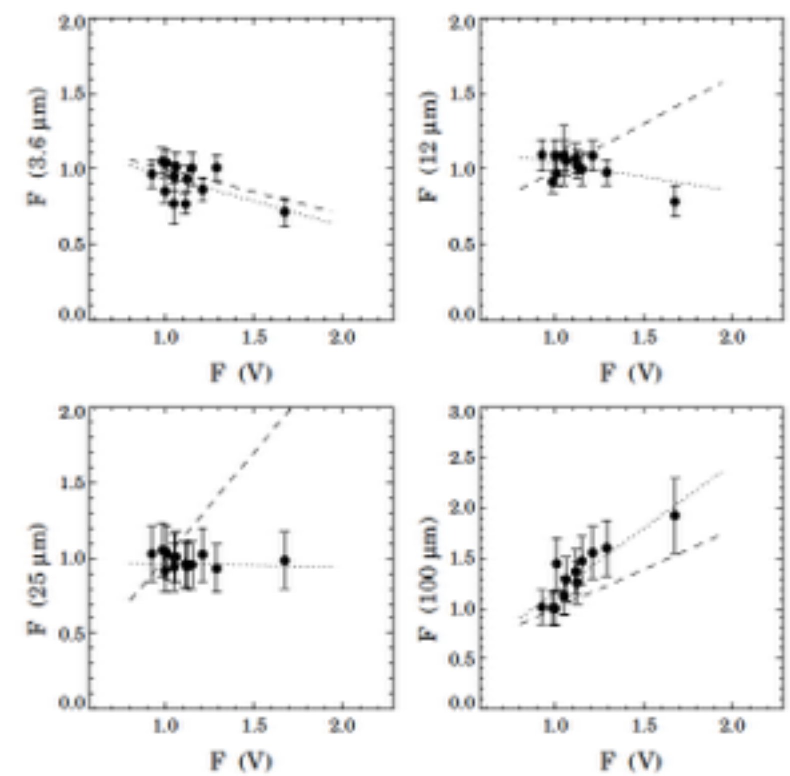
Credit: NASA/IPAC

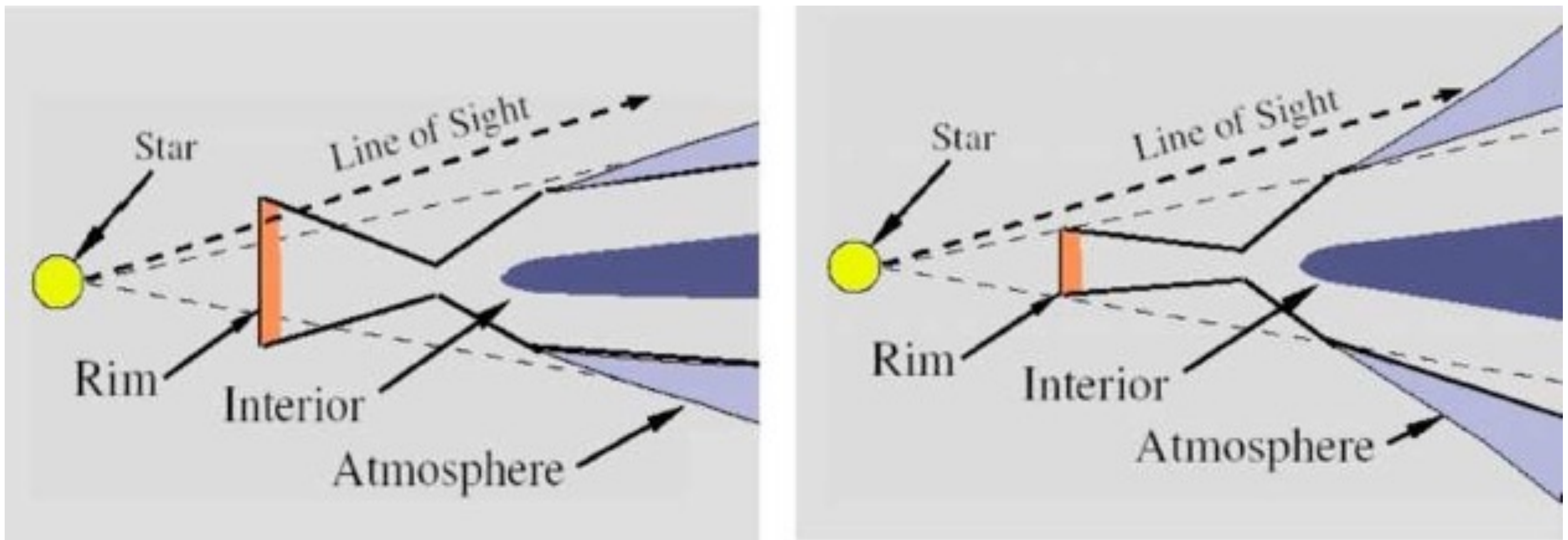
- Problem of 2015: very limited possibilities to observe (especially monitor!) in the mid- and far-infrared. Use archive data, wait for new instruments… for the era of JWST!!!!

Monitoring and modeling of SV Cep



- B9-A0-type star
- ISOPHOT data
- Long-term variability
- Optical-MIR anticorr.
- Optical-FIR corr.
- Optical change: Av
- RT modeling: changing inner rim

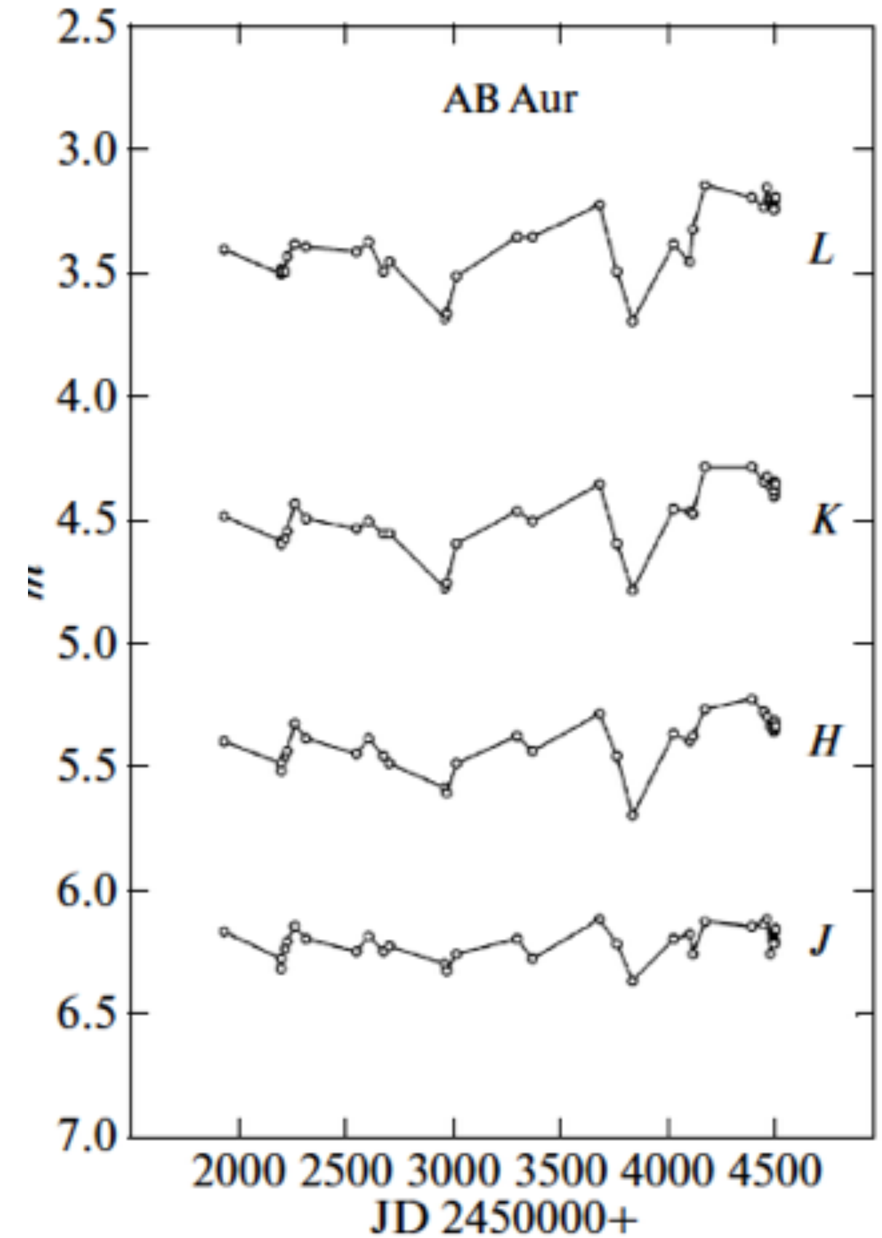


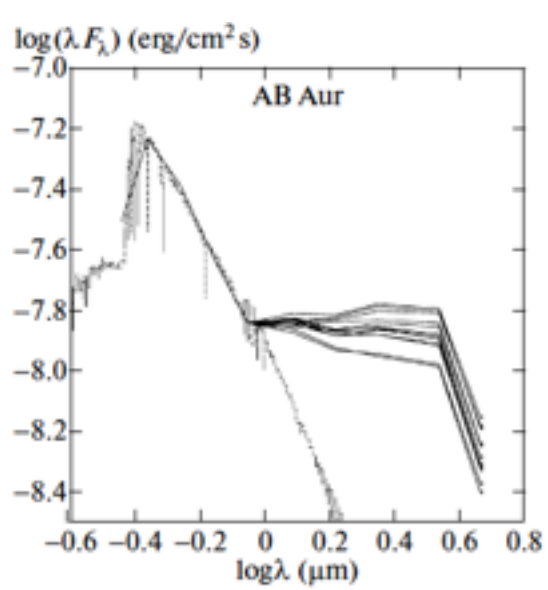


(Juhász, Prusti, Ábrahám, Dullemond 2008)

Disk variability with no luminosity change

- SV Cep indicated that infrared variability can occur even if the luminosity of the star is constant!
- Prediction: there might be many other Herbig stars, which are constant in the optical but variable in the infrared. AB Aur!
- It is the disk structure which changes, and we are not sure about the physical mechanisms. Inner disk instability? Planets?



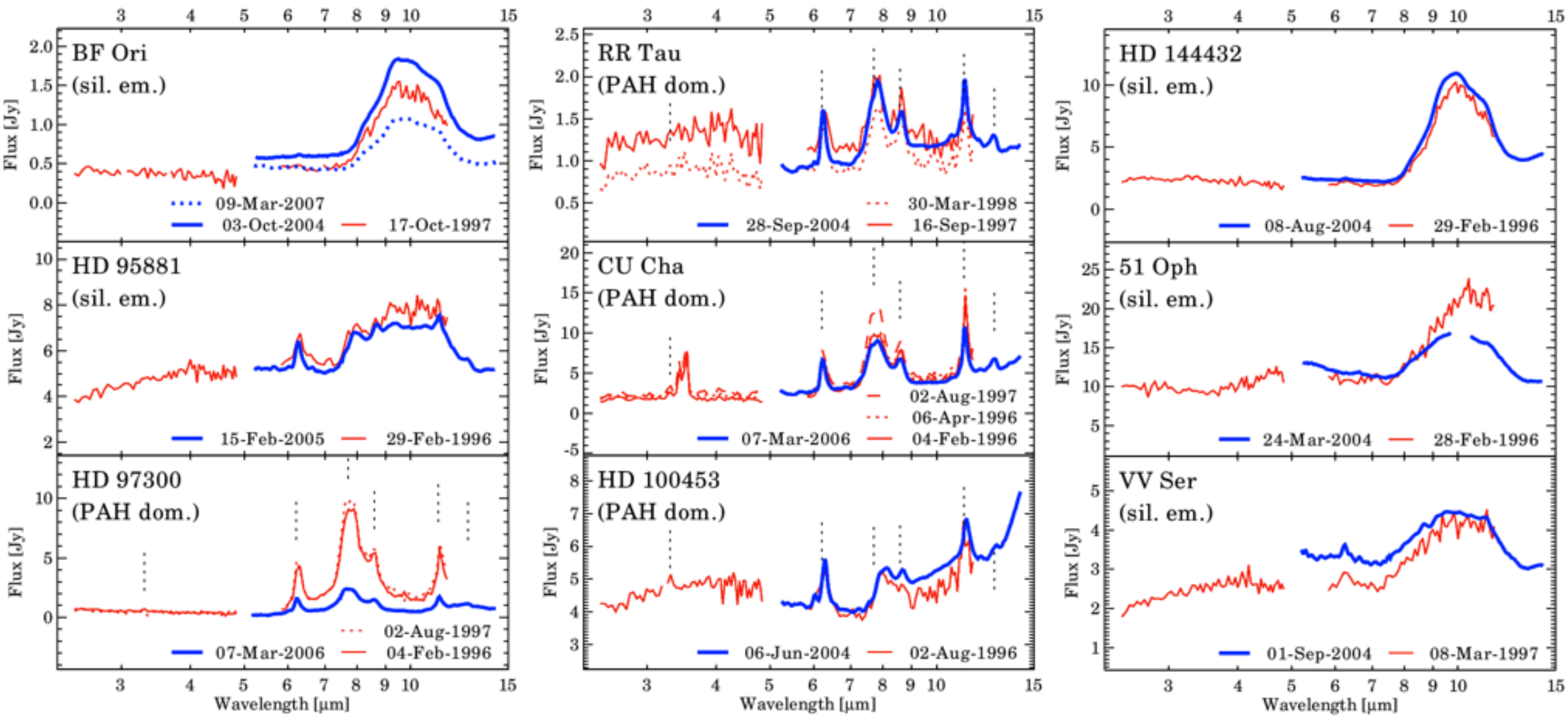


Shenavrin et al. 2012

Konkoly programs on infrared variability

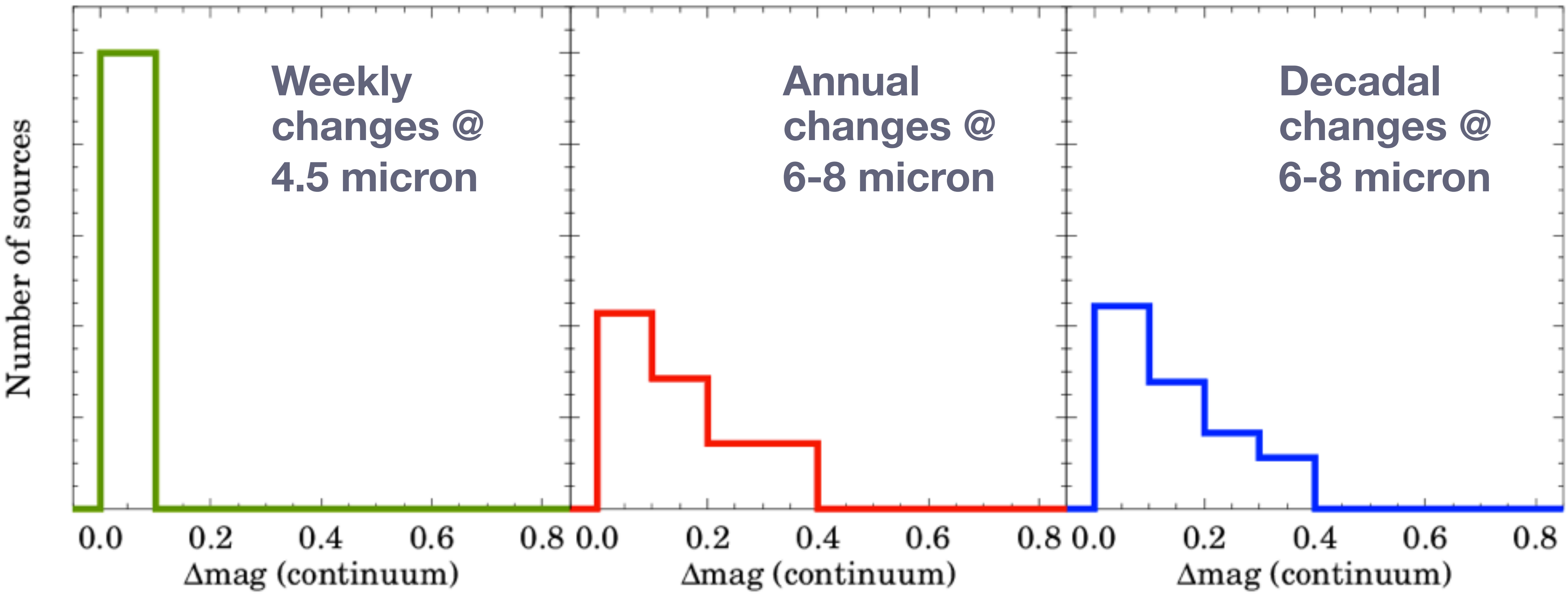
1. Mid-infrared spectral variability atlas (Kóspál, Ábrahám et al. 2012)
2. Konkolyvar: Spitzer warm-phase monitoring of 8 TTaus in Chamaeleon
3. Konkolyvar: Spitzer warm-phase monitoring of 8 Herbig Ae/Be stars
4. Herschel PACS variability study in the rho Oph region
5. VLTI/MIDI monitoring of Herbig and T Tauri stars
6. Kepler K2 optical monitoring of three Herbig Ae/Be stars in Ophiuchus
7. Variability of the 10 micron silicate feature during an eruption
8. Debris disk warm transient

Mid-infrared spectral variability atlas



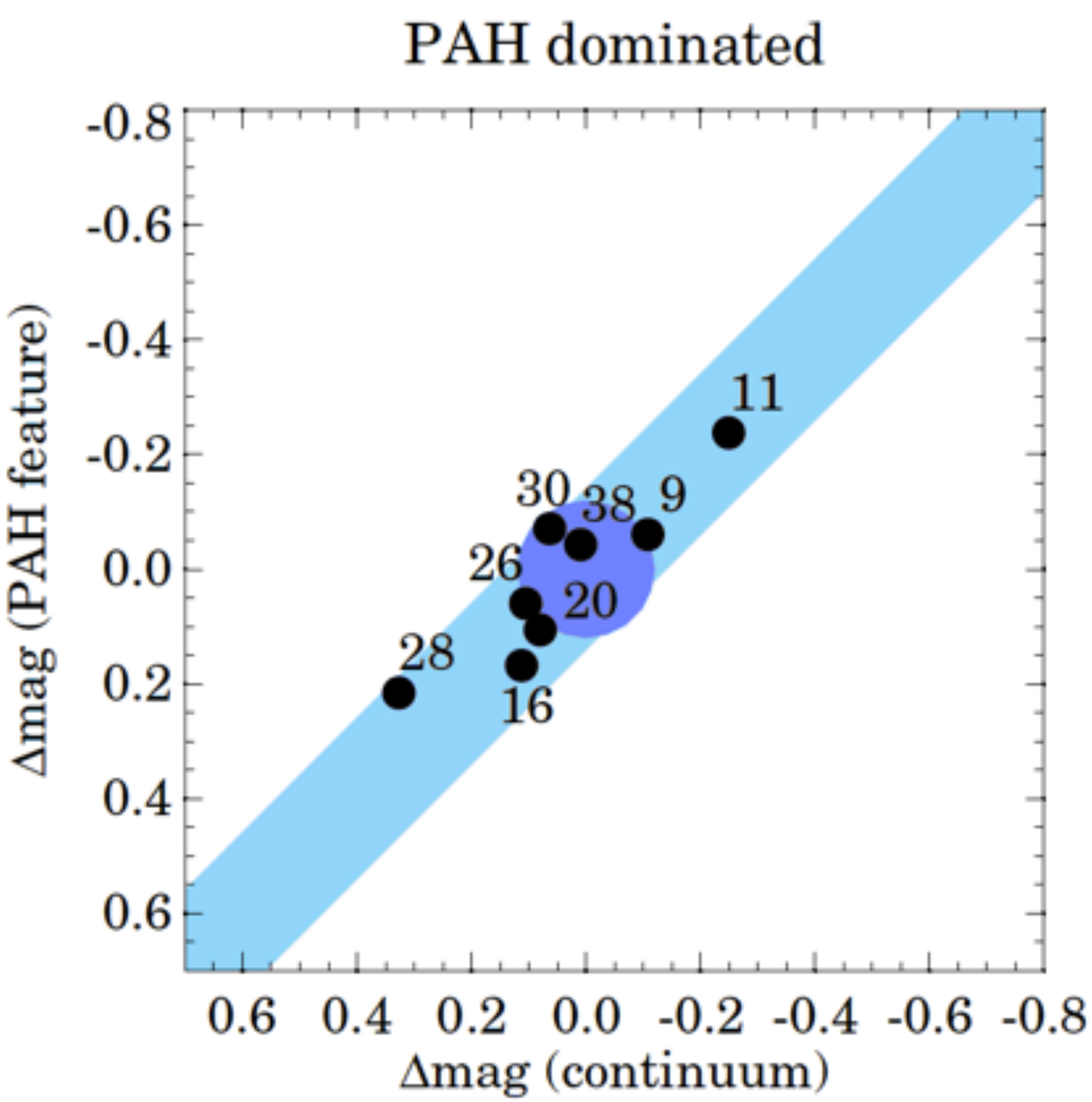
Kóspál et al. 2012

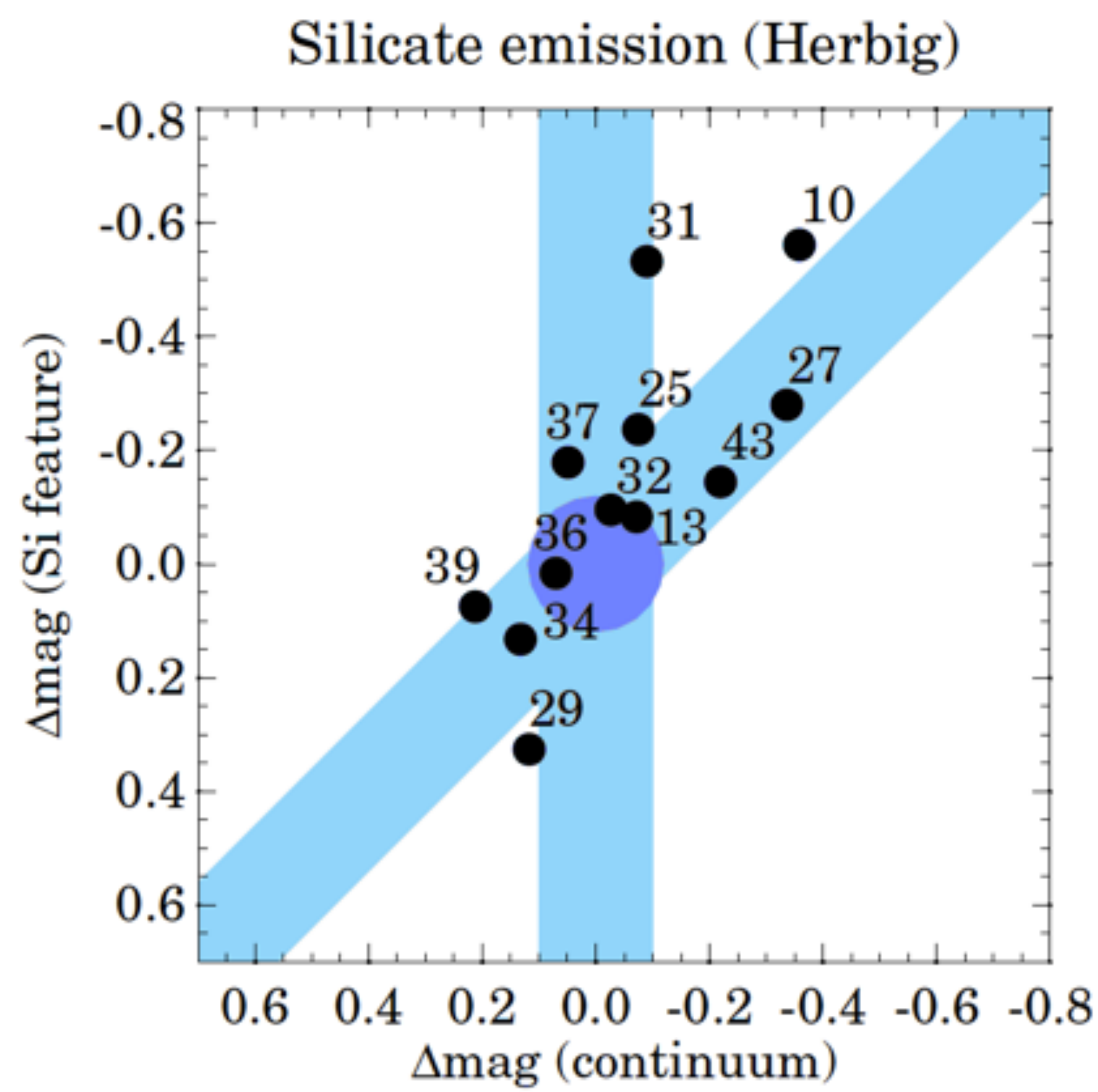
Weekly/annual/decadal variability timescales

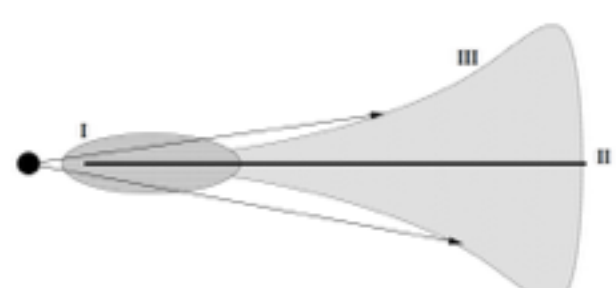


Typical MIR variability timescales in Herbig stars: week < t < year.
Typical dynamical timescale of the inner disk.

Mid-infrared spectral variability atlas

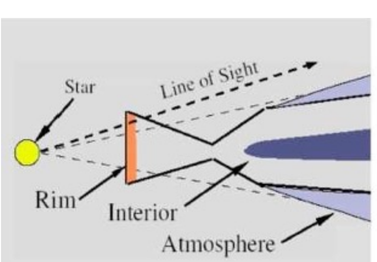


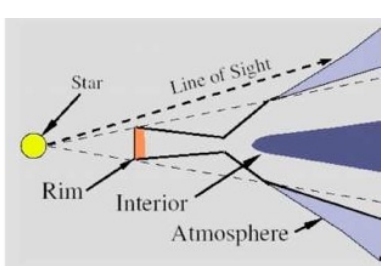


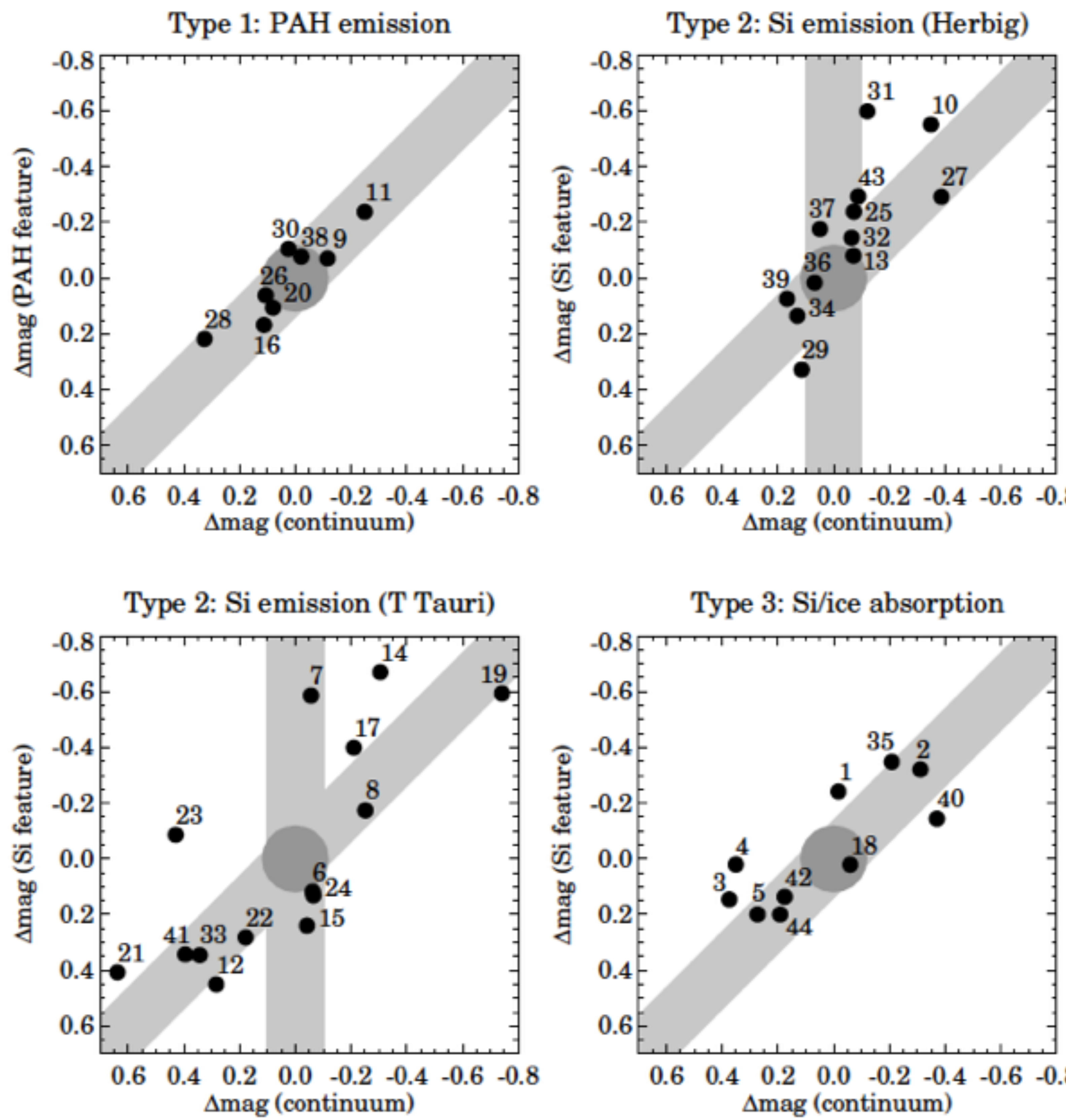


Kóspál et al. 2012

Mid-infrared spectral variability atlas



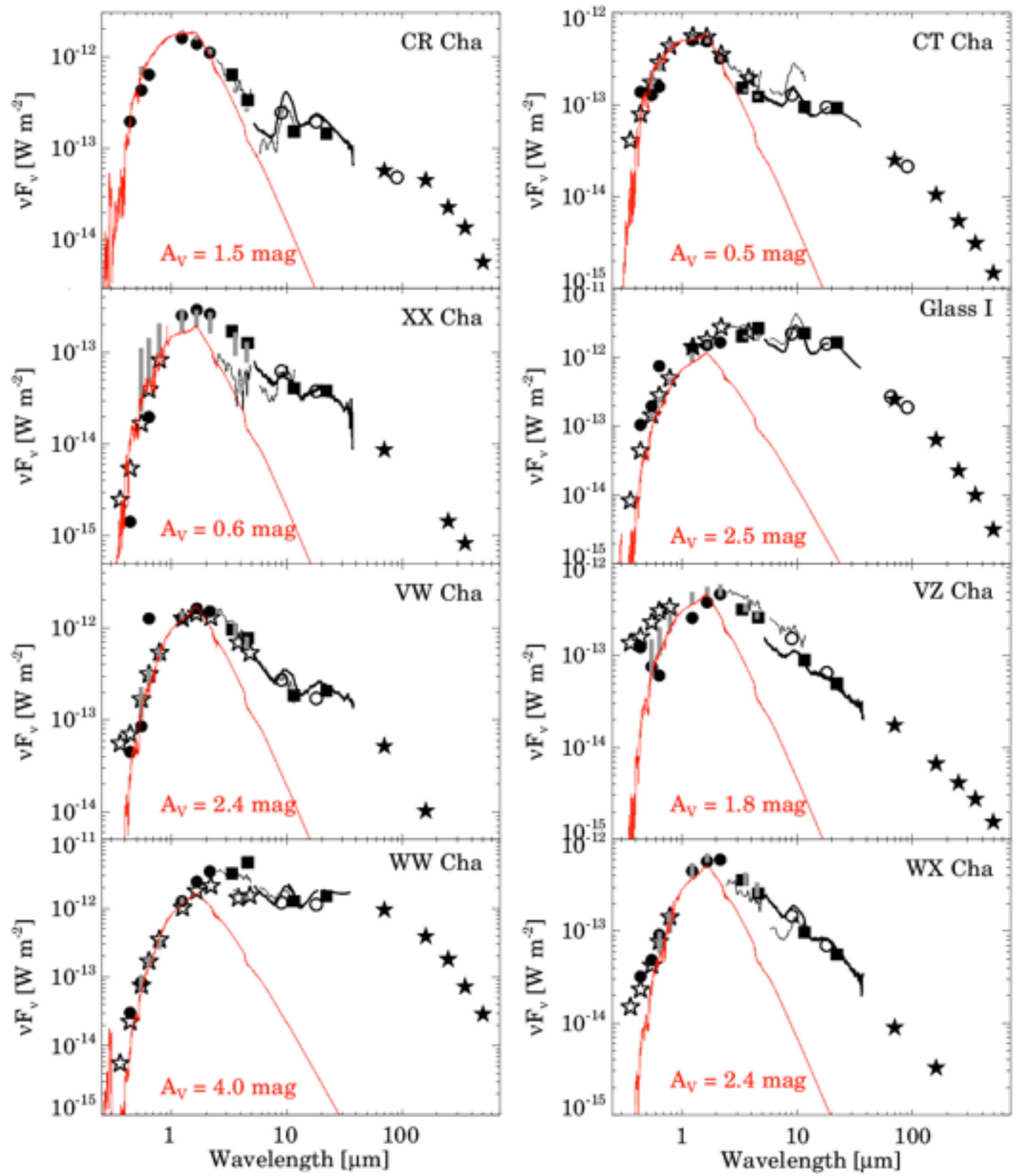




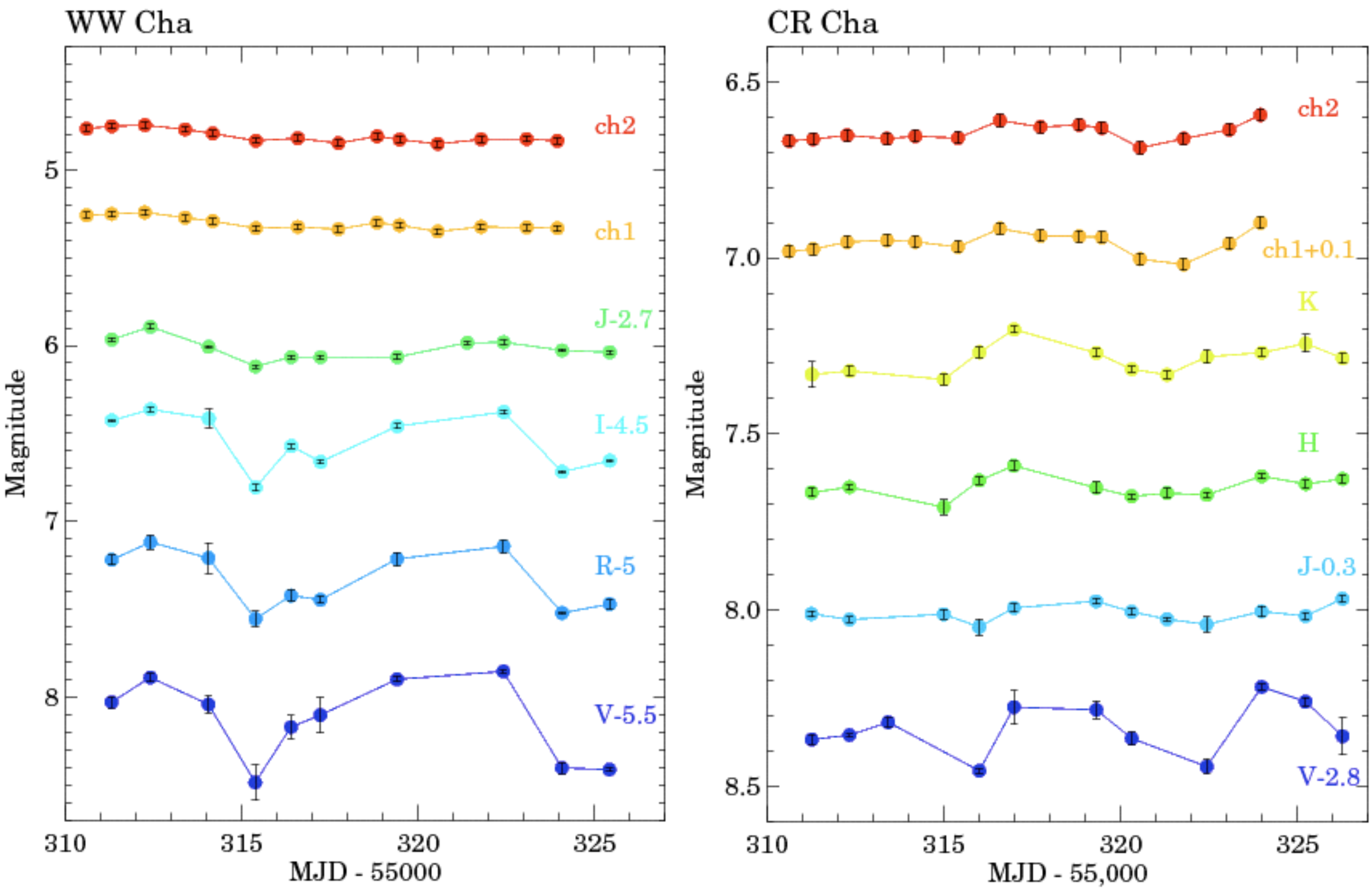
Optical-infrared monitoring of 8 T Tau stars

Source list	
CR Cha	VW Cha
CT Cha	VZ Cha
Glass I	WW Cha
VW Cha	XX Cha

Observations (2010 May)
Spitzer: 14-days monitoring at 3.6 and 4.5μm, 1-day cadence
JHKs: REM robotic telescope, La Silla,
Optical VRI: REM, La Silla



Light curves



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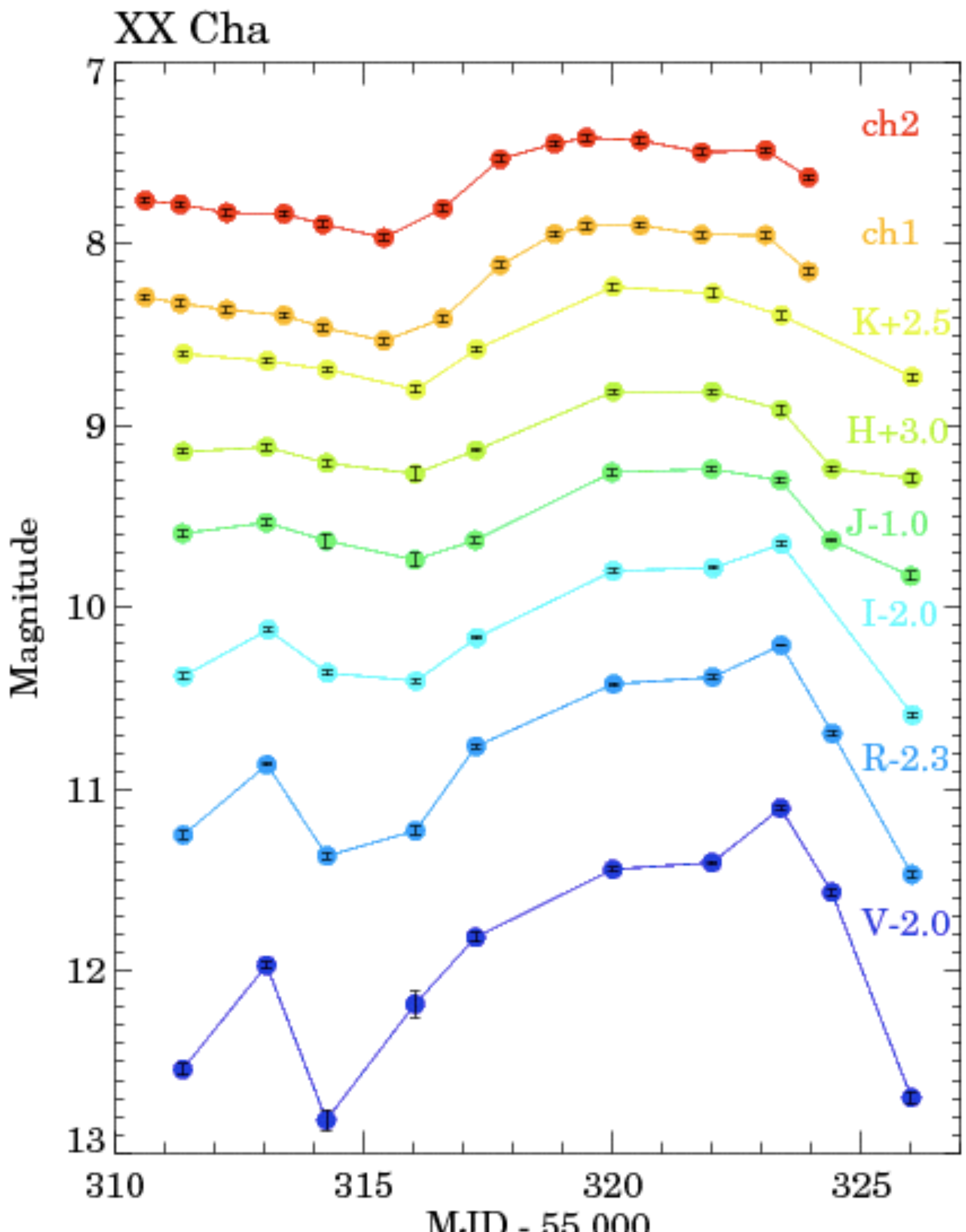
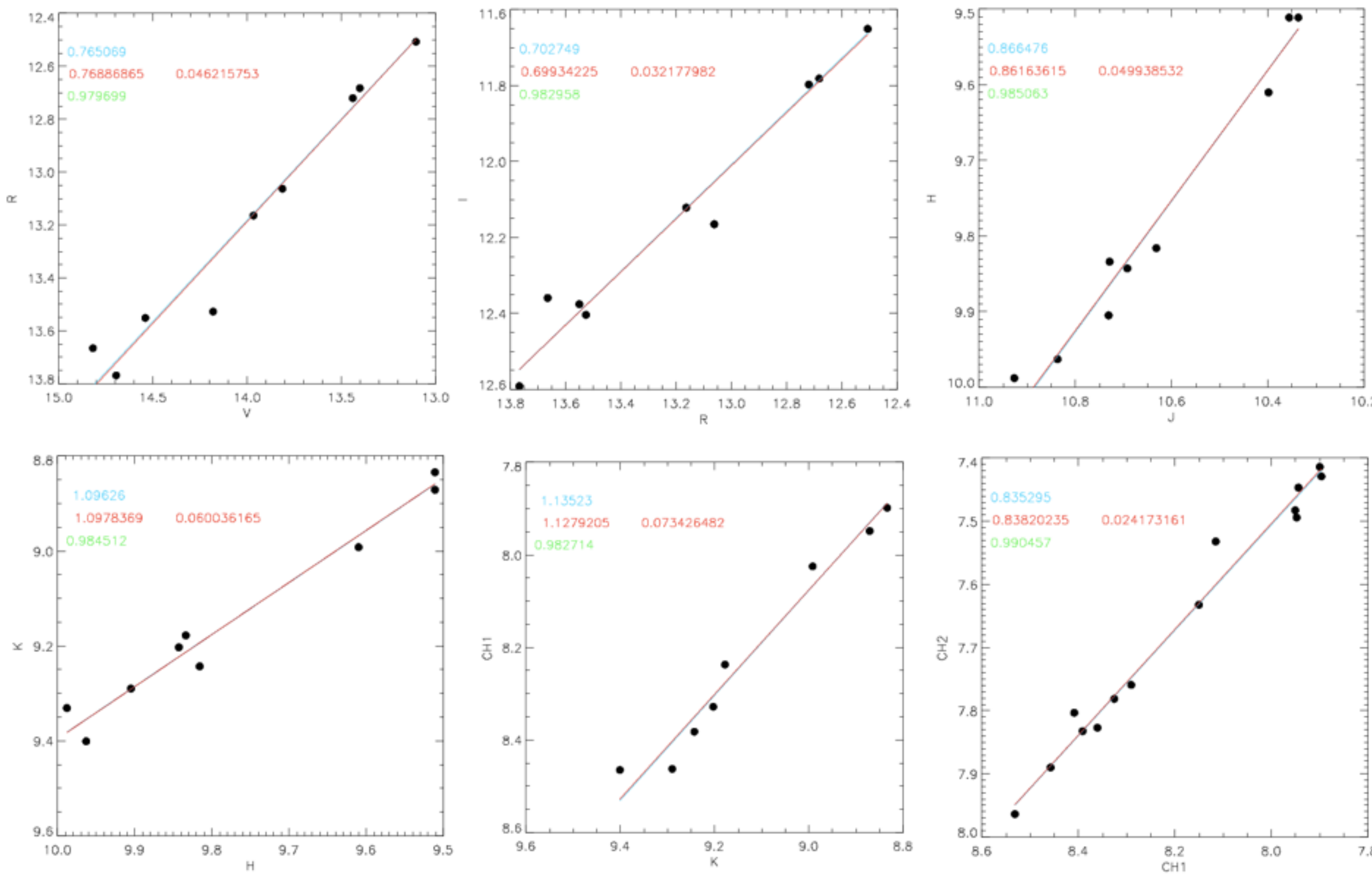
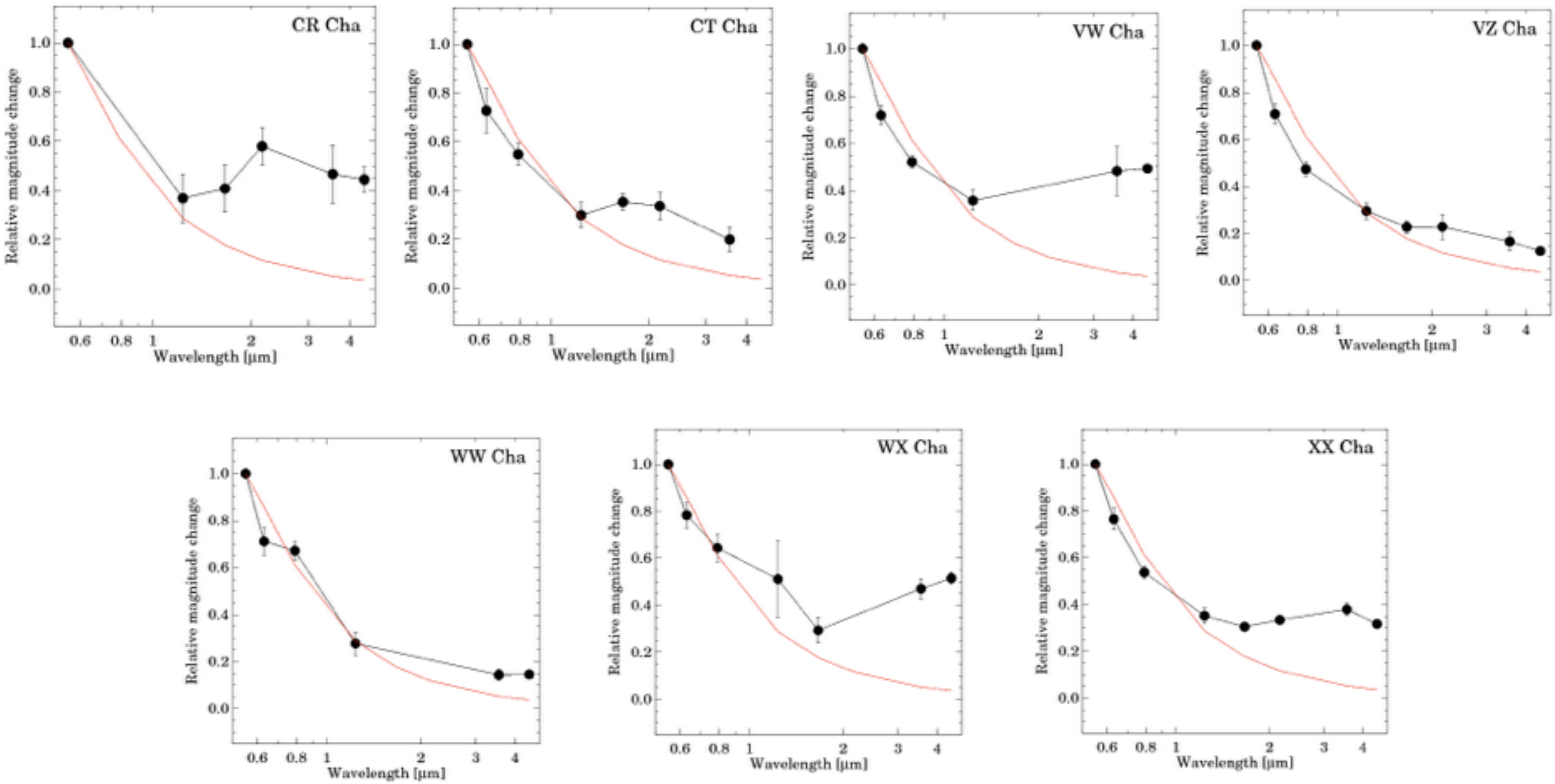


- Variability on ~1 week timescale
- Optical and infrared light curves are similar, and are in the same phase
- The amplitudes change with wavelength: always highest in the V-band, and decrease between R and J
- In the infrared two types of behaviour: the amplitude of the flux change either decreases towards longer wavelengths, or exhibits a minimum in the J or H band

Scatter plots: XX Cha



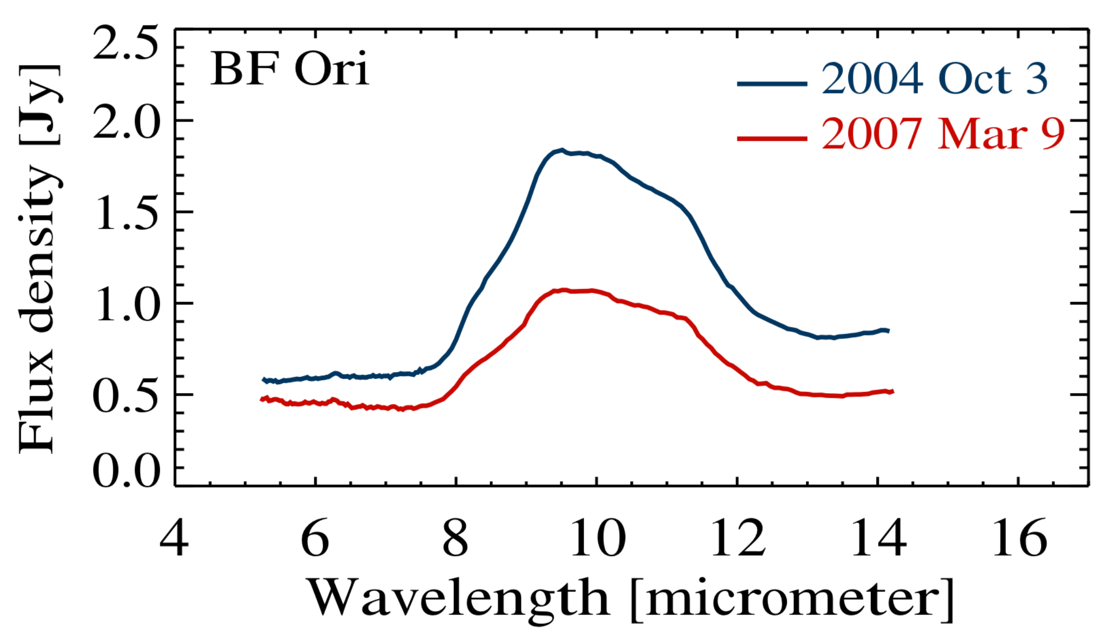
Relative magnitude changes

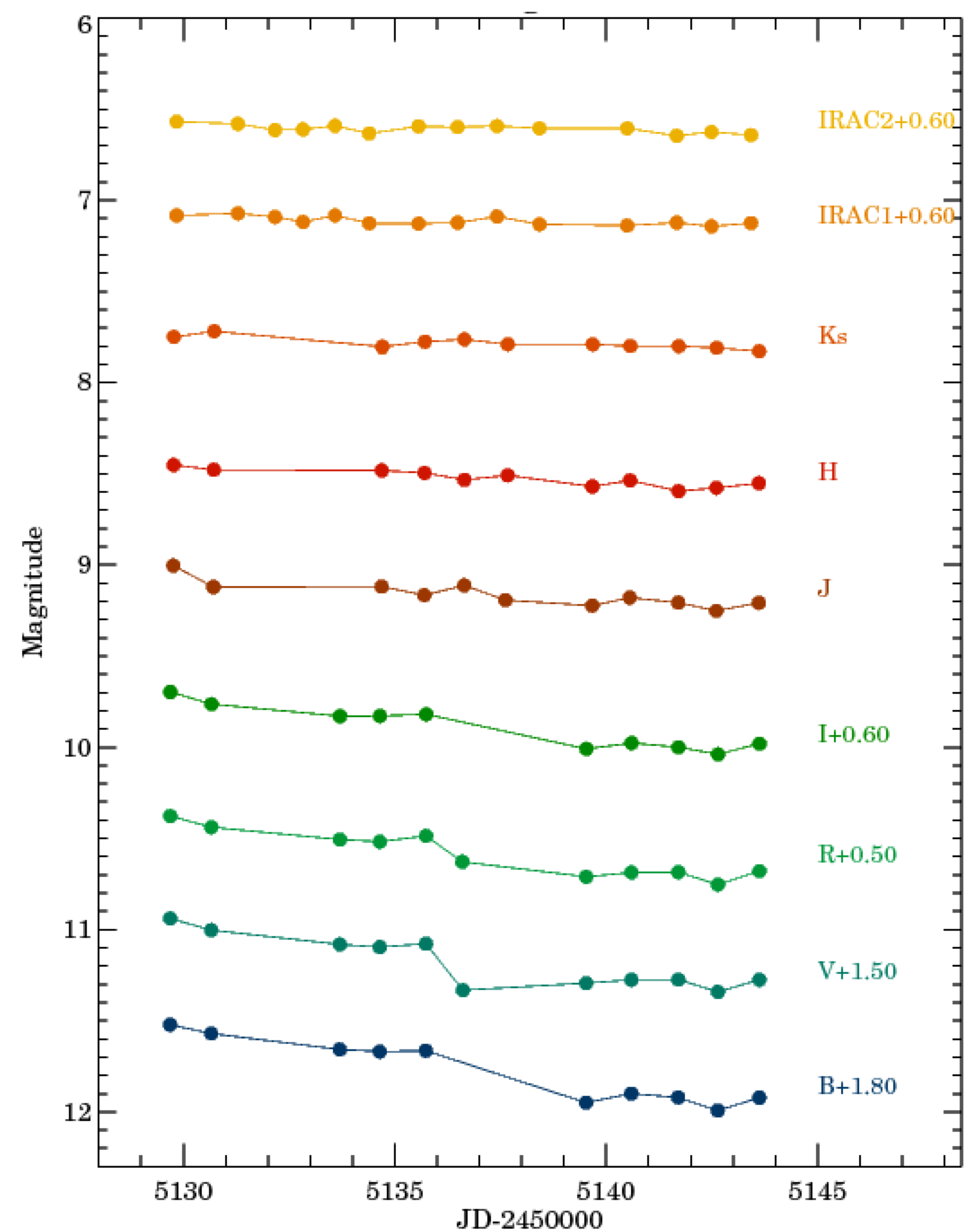


Variable extinction (red line) can be excluded

MID-INFRARED SPECTRAL VARIABILITY

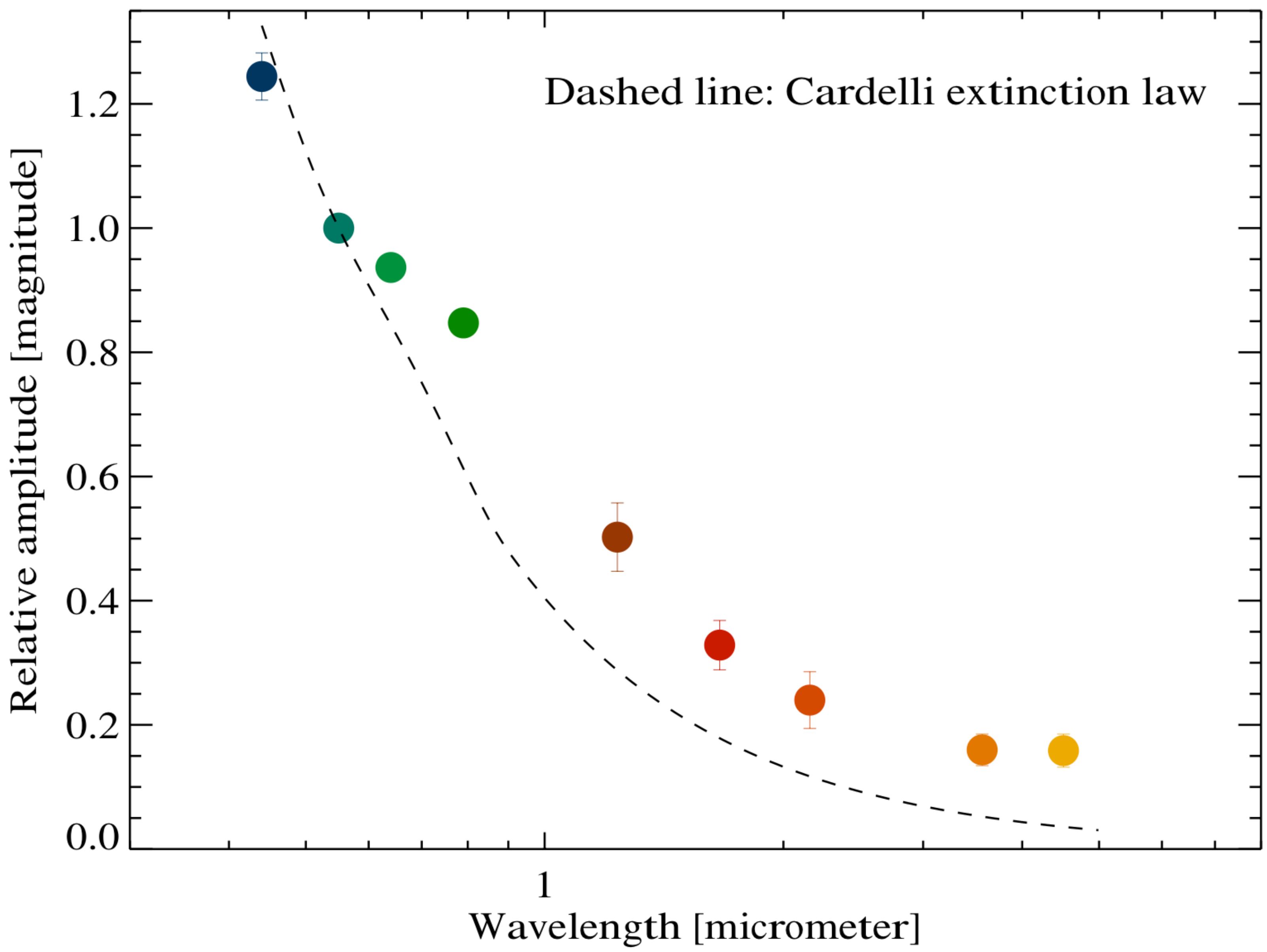
- Kóspál et al. (2012) reported that two Spitzer/IRS spectra of BF Ori, taken with a 2.5 year time difference, have significantly changed.
- In order to follow up this finding at shorter wavelengths, we monitored BF Ori at BVRIJHK and Spitzer/IRAC 3.6 and 4.5μm, for 14 days in 2009 October.





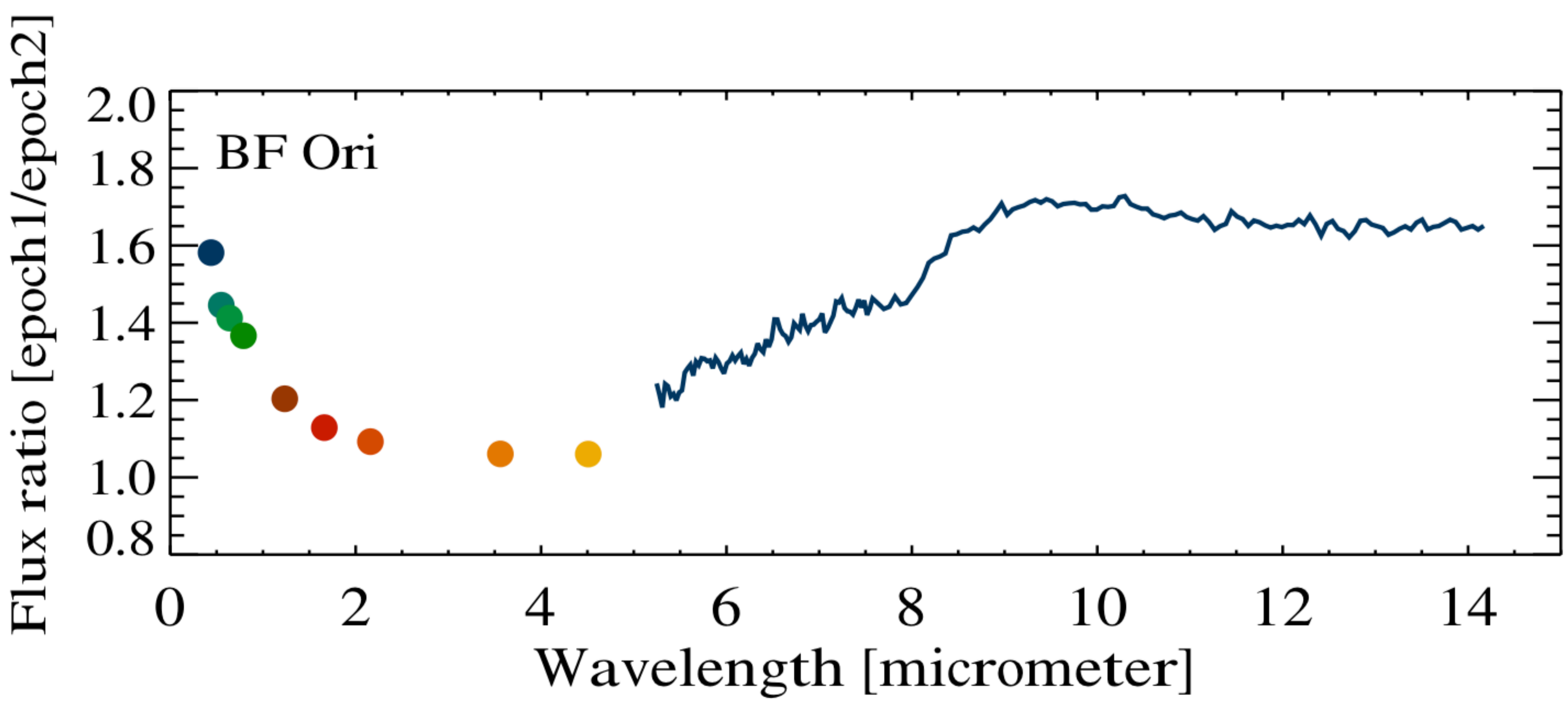
MID-INFRARED SPECTRAL VARIABILITY

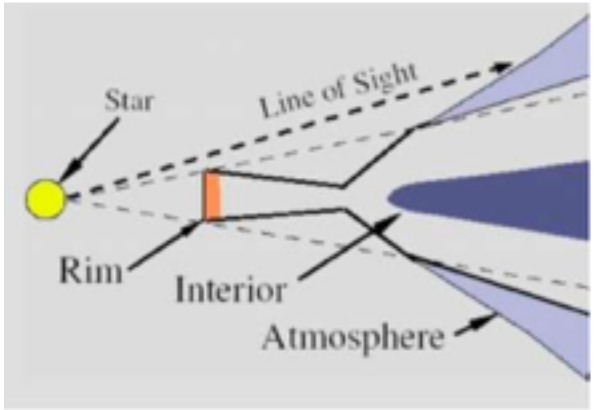
- **A general fading trend was observed. We computed variability amplitudes, normalized to the V-band.**



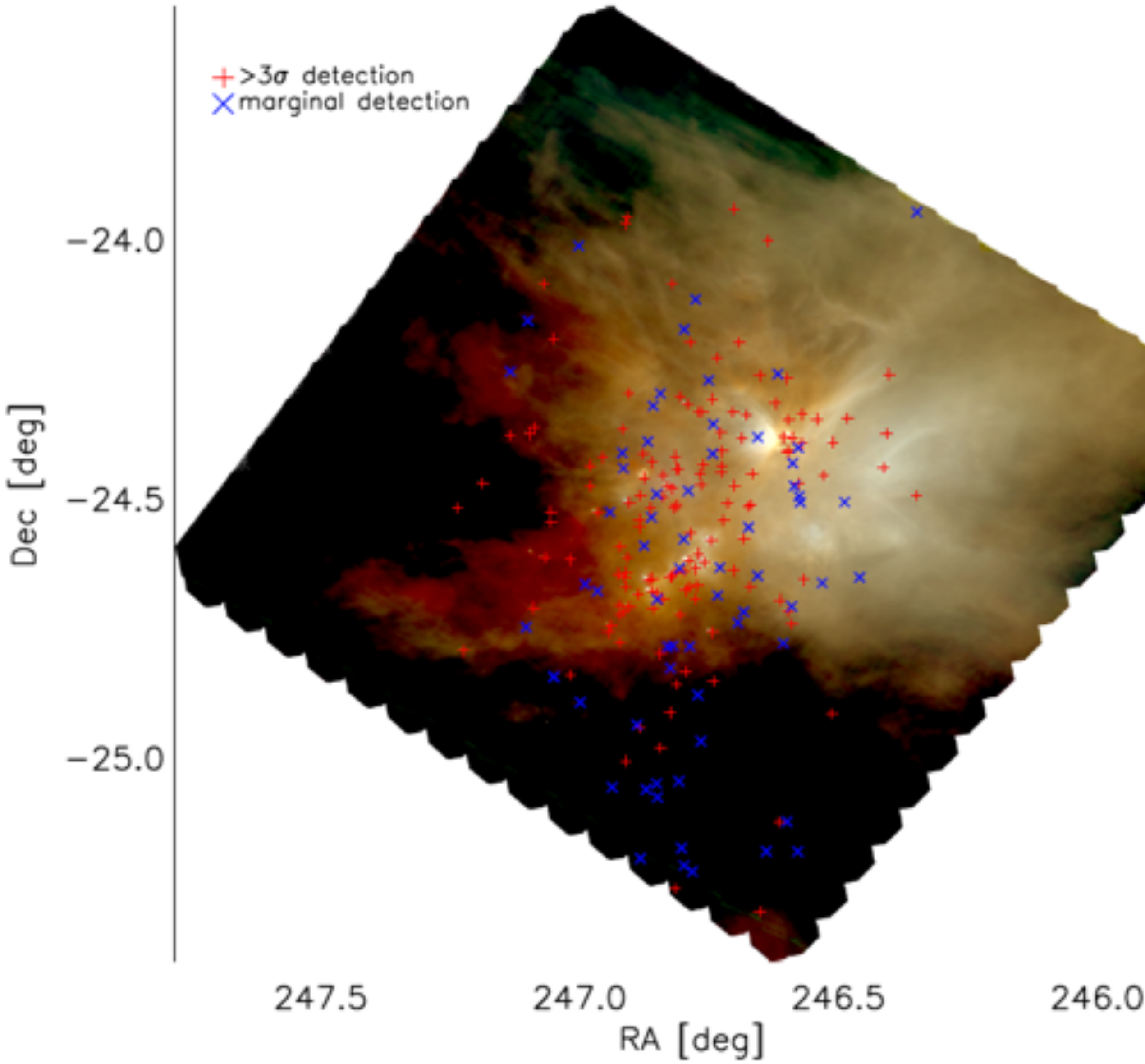
MID-INFRARED SPECTRAL VARIABILITY

- Using the ASAS database, we could determine V-magnitudes for the epochs of the Spitzer spectra. 2004 Oct 3: V = 10.7 mag; 2007 Mar 9: V = 11.1 mag.
- Assuming that the obtained normalized variability amplitude curve is representative for the star at any time, from the V-band difference we predicted optical/near-infrared magnitude differences between the two Spitzer epochs, and supplemented them with the ratio of the two Spitzer/IRS spectra:





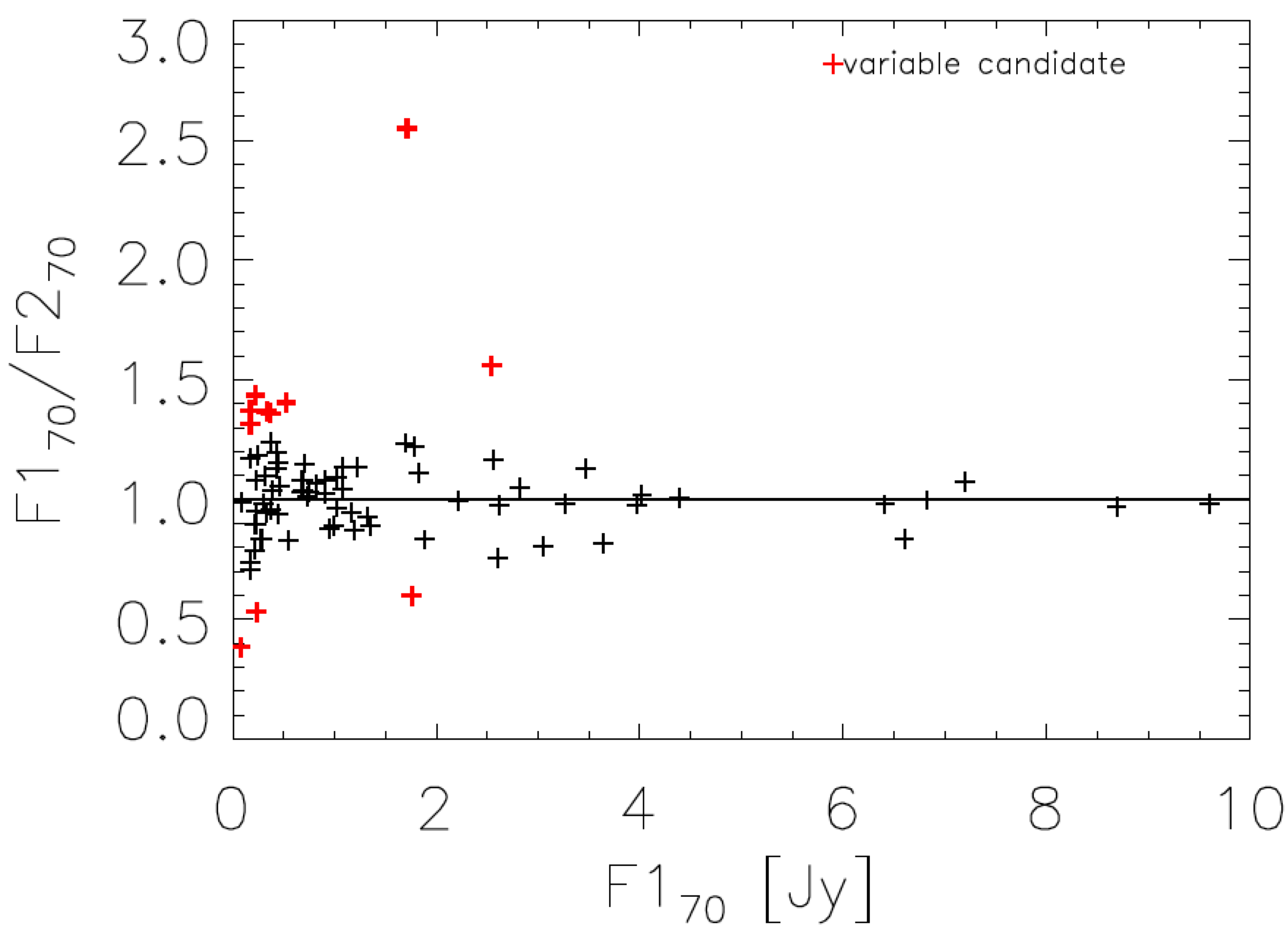
Far-infrared variability in rho Ophiuchi



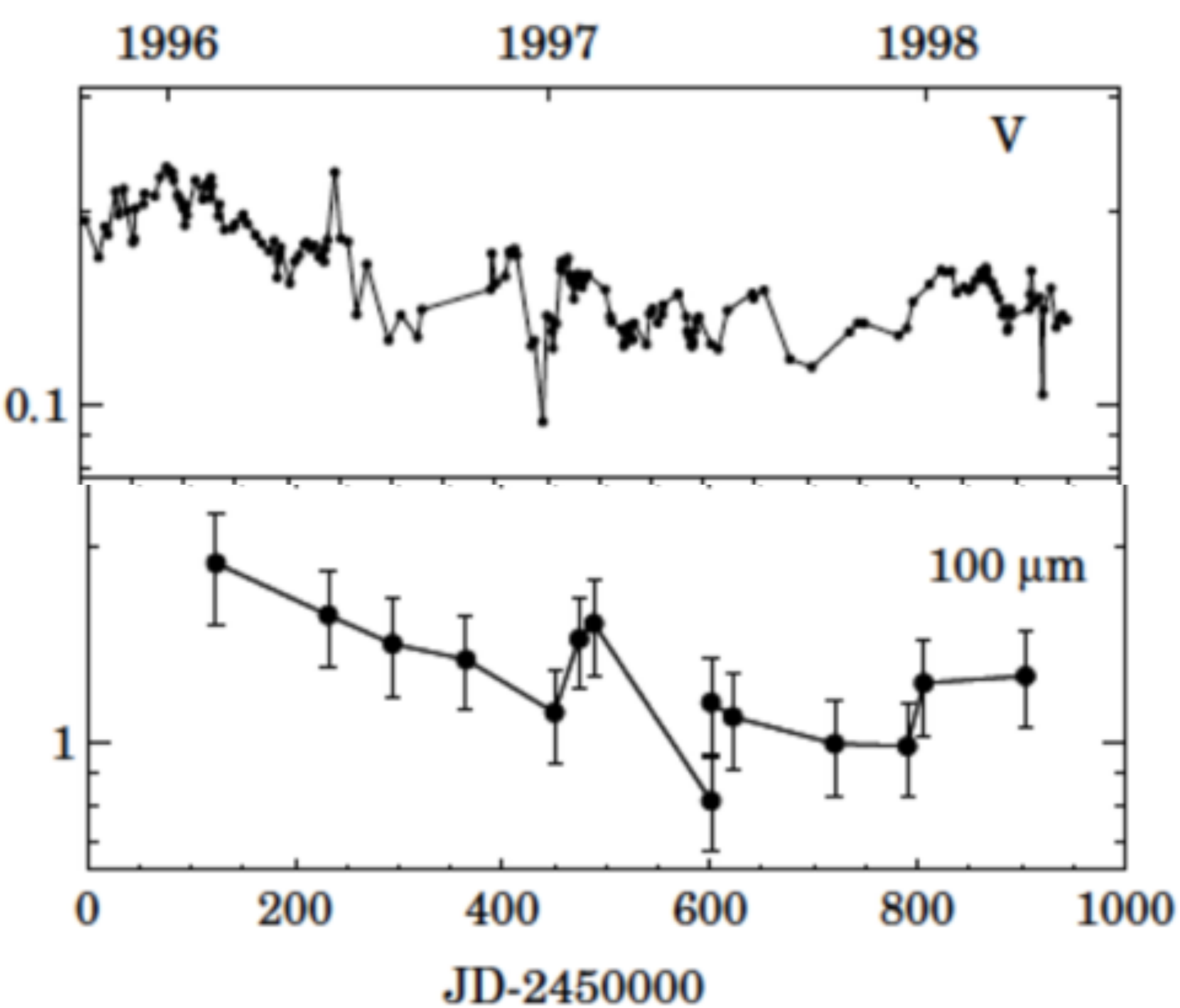
Total number of YSOs: 458		
70 μm detections	Significant (> 3 sigma)	Marginal (1 < sigma < 3)
Spitzer MIPS	11	
Gould Belt Survey	115	56
Our PACS observations	141	65
160 μm detections	Significant (> 3 sigma)	Marginal (1 < sigma < 3)
Spitzer MIPS	0	
Gould Belt Survey	93	37
Our PACS observations	94	35

Far-infrared variability in rho Ophiuchi

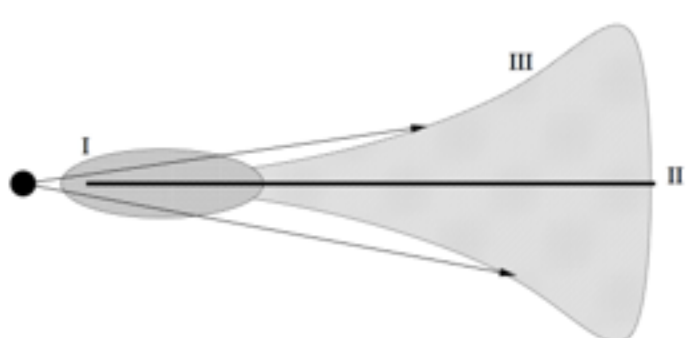
- We compared the 70 µm fluxes of 89 YSOs detected both in the Herschel Gould Belt Survey and in our observations.
- In 11 cases (12 %) the flux difference between the two epochs, separated by about 2 years, exceeded 30% (marked in red in the figure)
- These sources are strong candidates for far-infrared variability.



Far-infrared variability: screen effect?

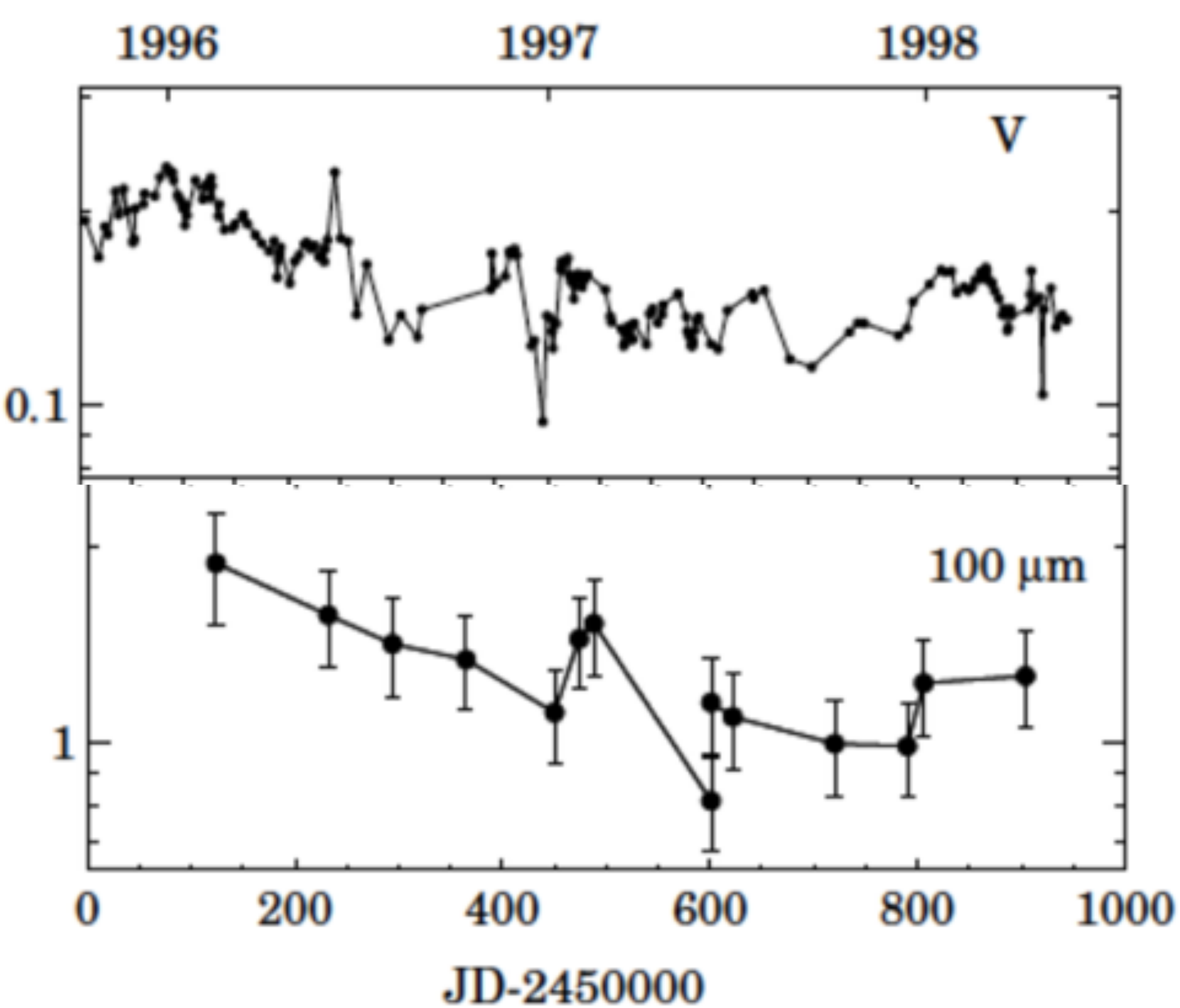


- **SV Cep**: correlation between optical and FIR fluxes
- The outer disk responds to the changing radiation from the central source
- It is the optically thin component, and it must be well visible from the centre (flared disk geometry)



FIR variability can be used to study processes in the inner disk

Far-infrared variability: screen effect?



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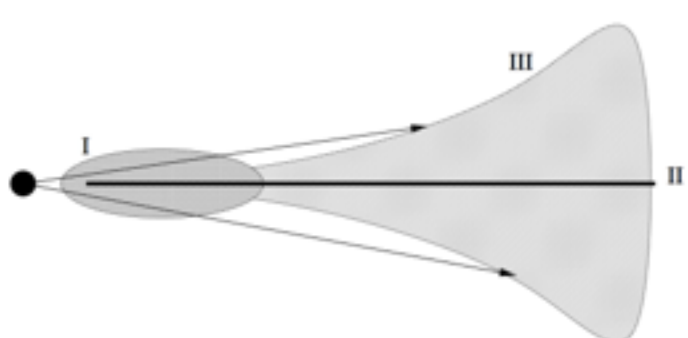
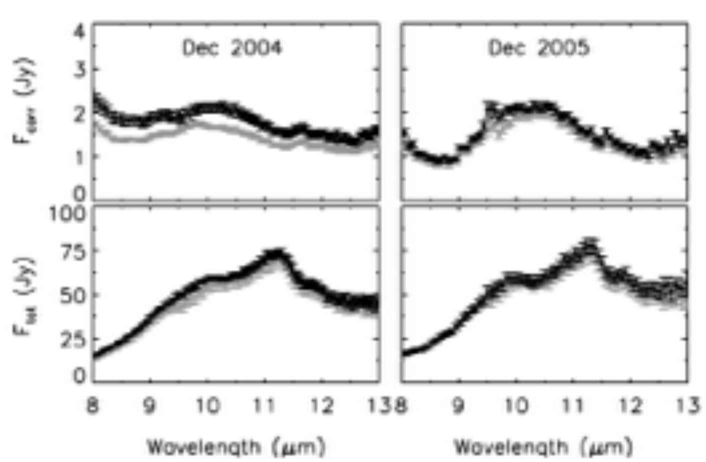


FIR variability can be used to study processes in the inner disk

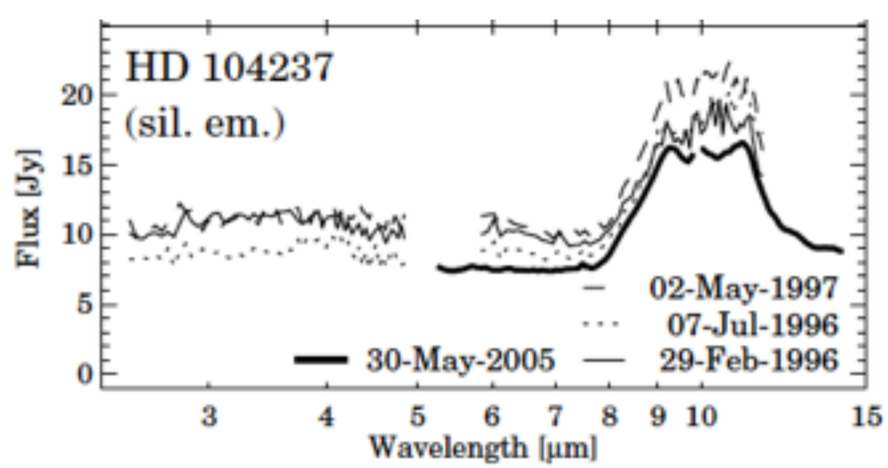
A systematic interferometric variability program

- ESO proposal (Grellmann et al., Ábrahám et al.): monitoring VLTI/ MIDI + UVES/H-alpha observations (~10 per target)
- Accepted targets: HD 100546 (reported MIDI variability, Panic et al.); HD 163296 (infrared variability with a pivot point, Sitko et al.); HR 5999, HD 104237 (Kóspál et al., 2012, significant mid-IR spectral variability around 10 μm).
- Proposed targets: AB Aur, HD 50138

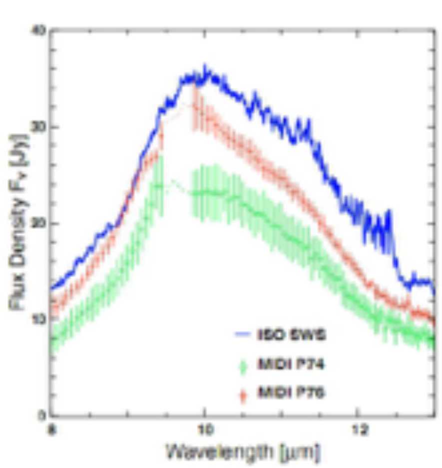
Goal: study re-arrangements in the inner regions; check if image reconstruction with Matisse could be performed



Panic et al. 2014

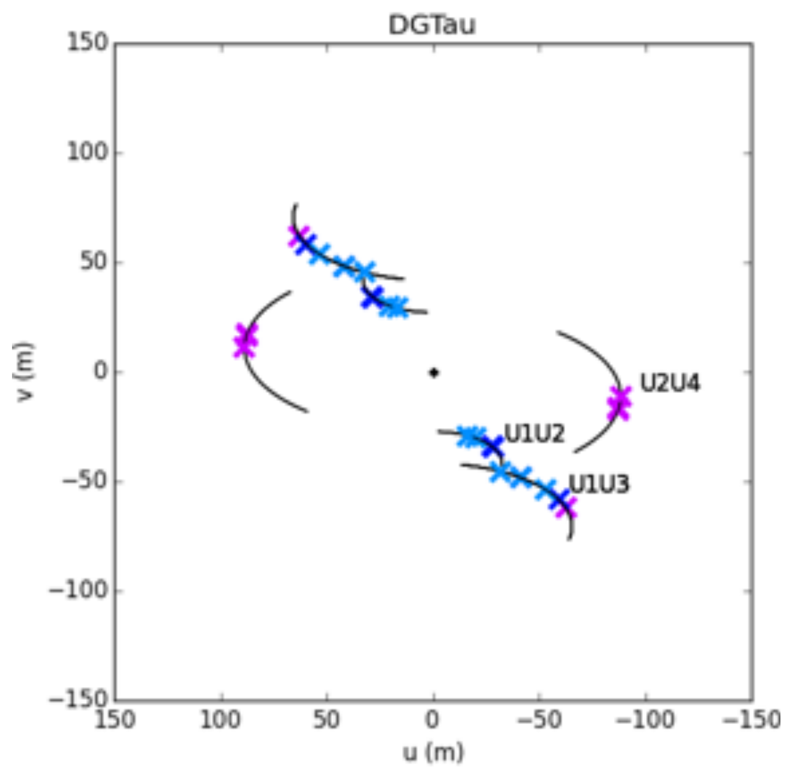


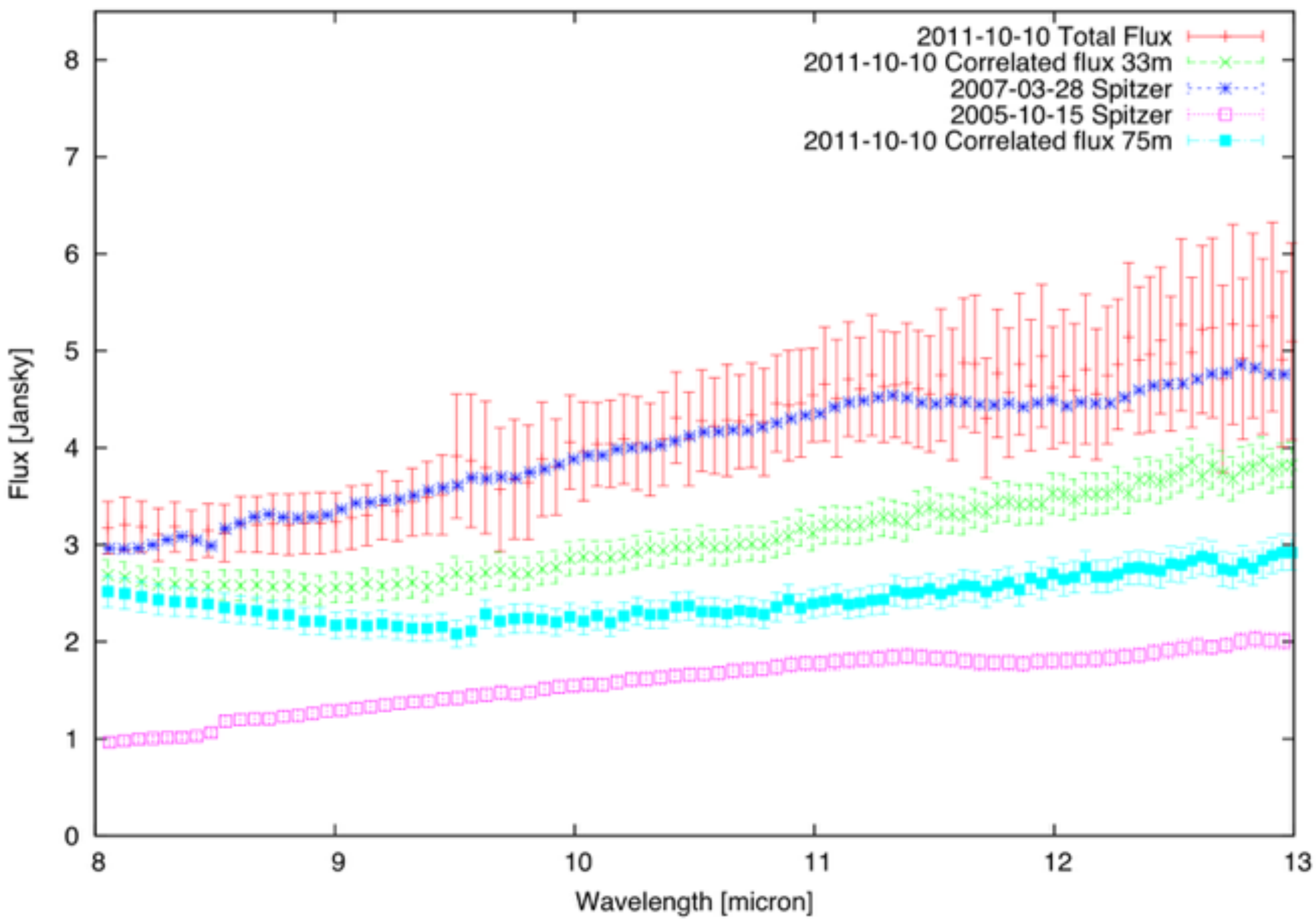
Kóspál et al. 2012



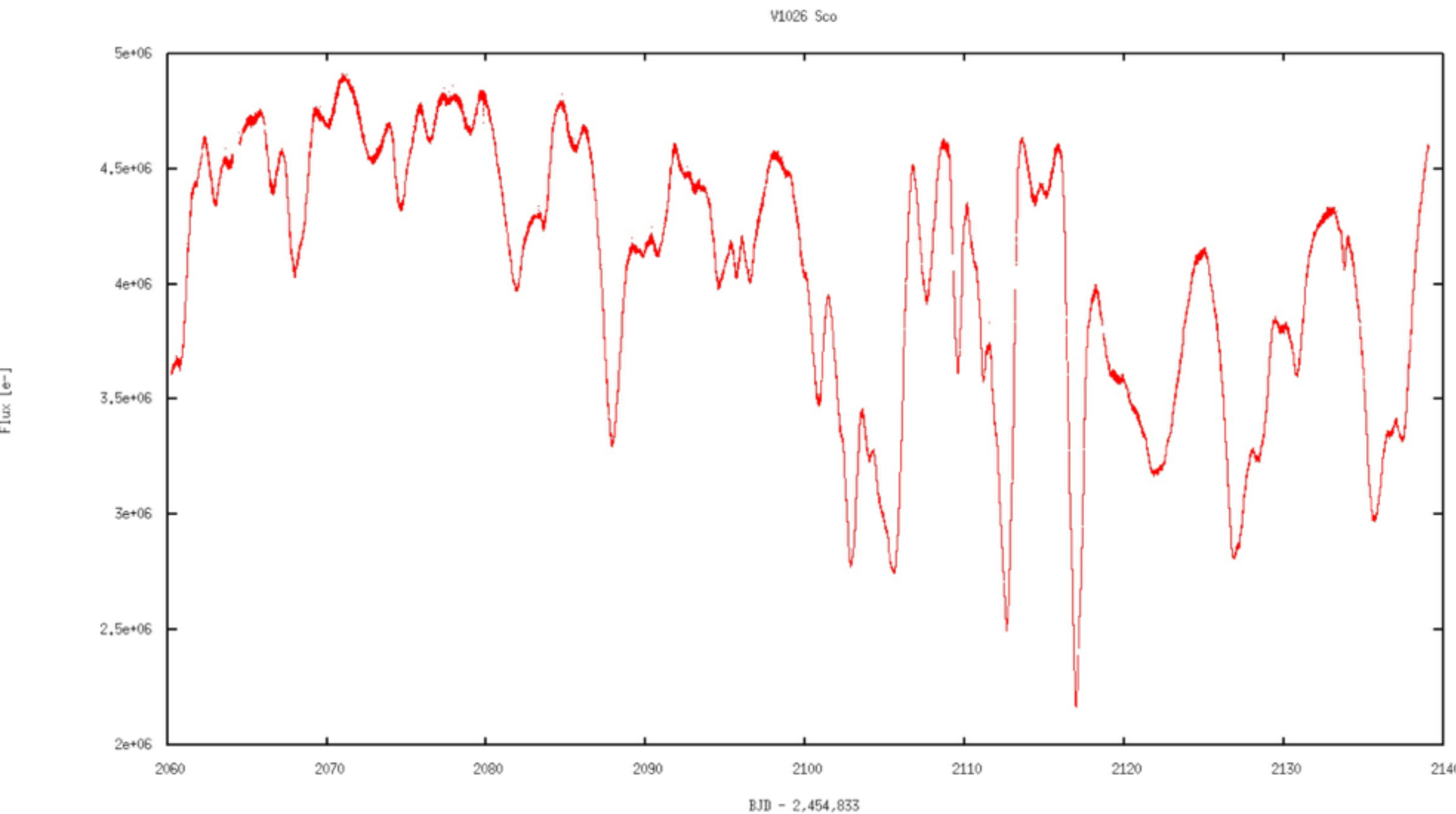
Di Folco et al. 2009

An interferometric variability program: DG Tau

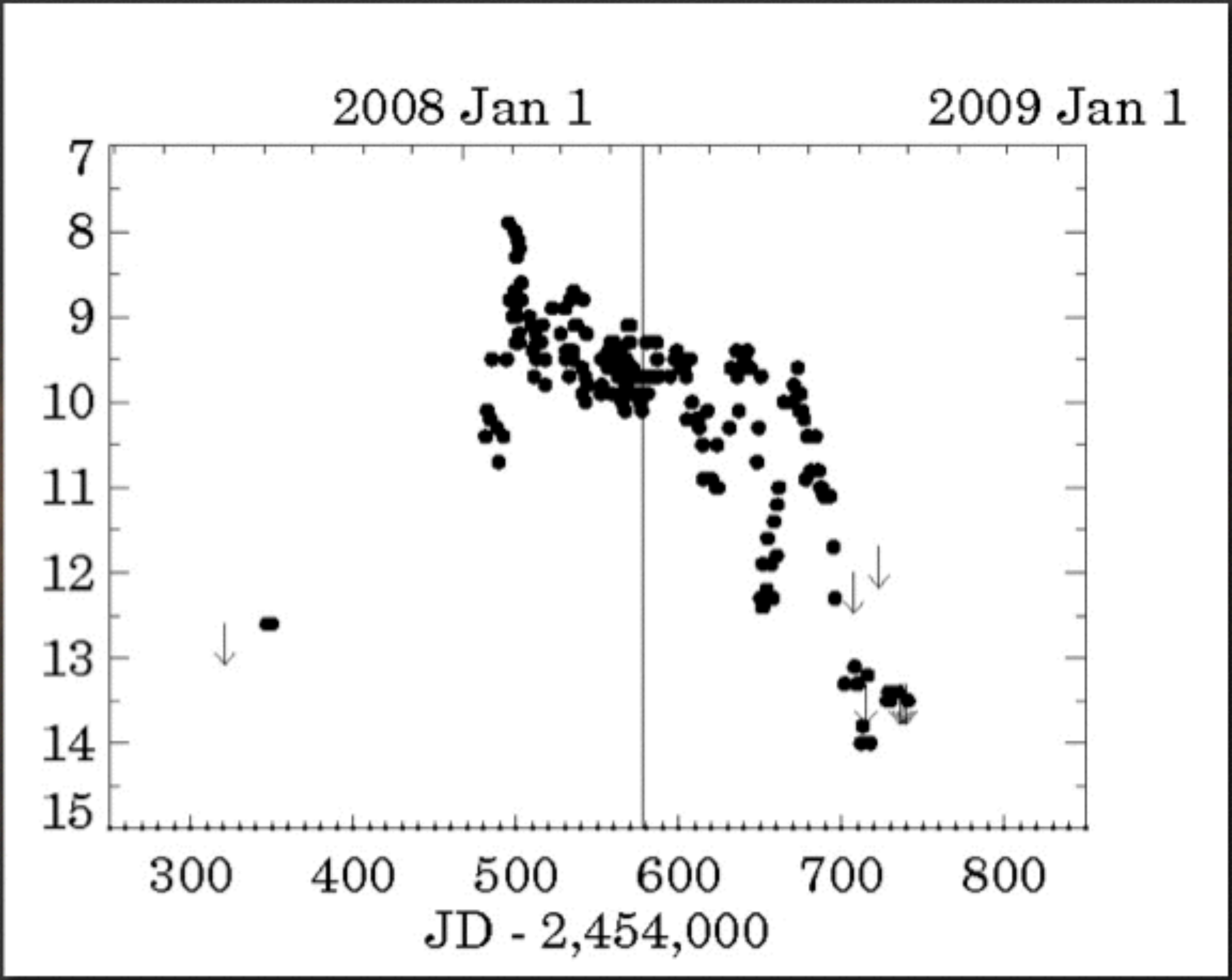




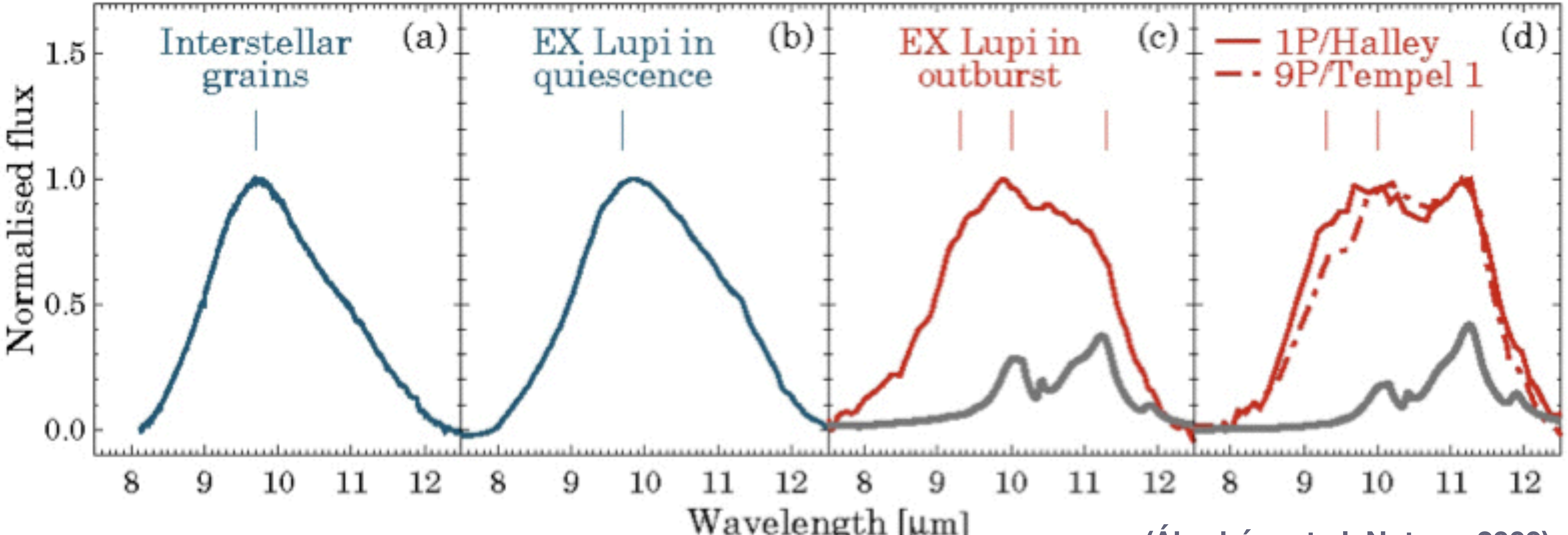
Kepler variability study



A Cosmic Laboratory: EX Lupi



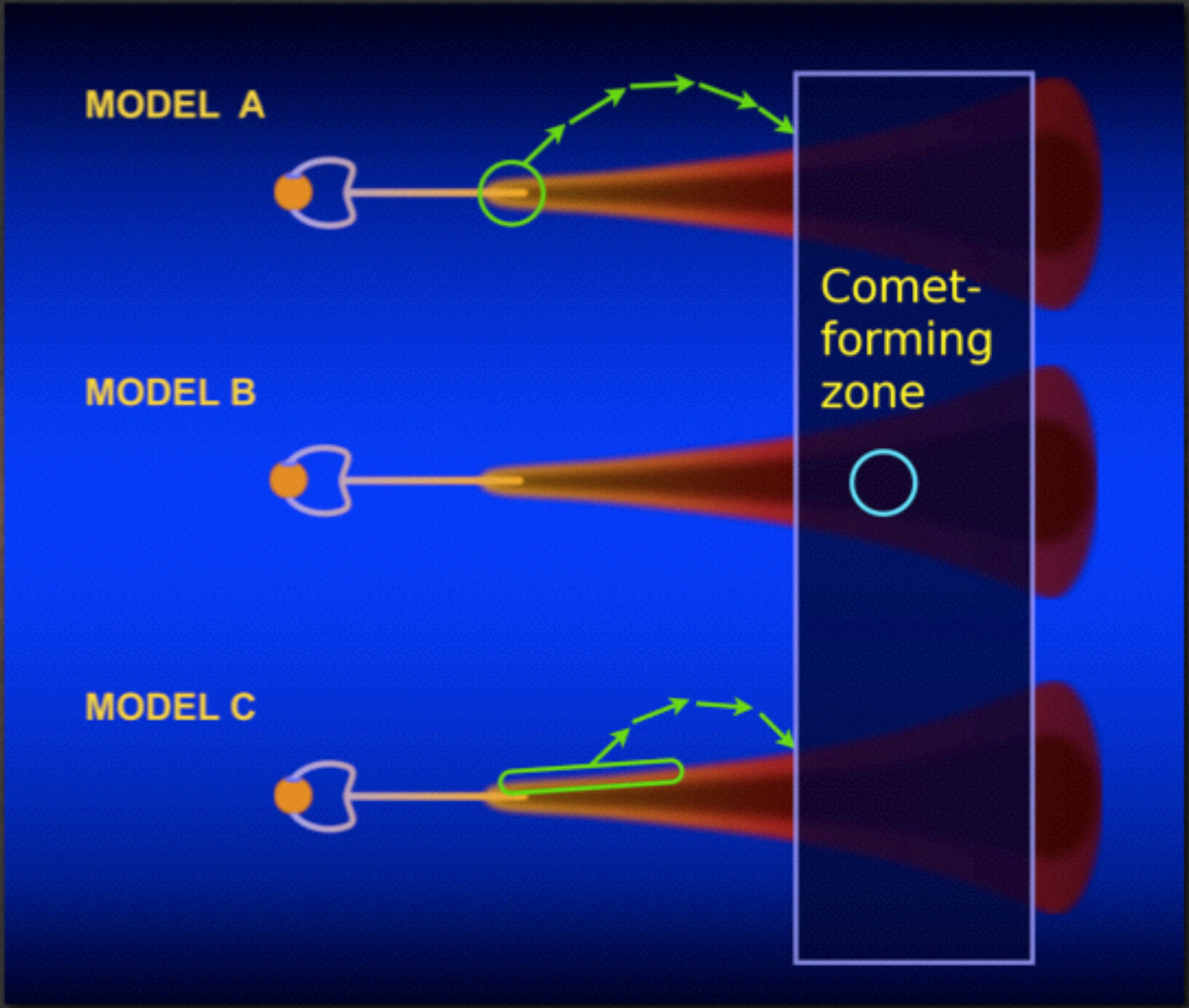
Dust in EX Lupi's disk



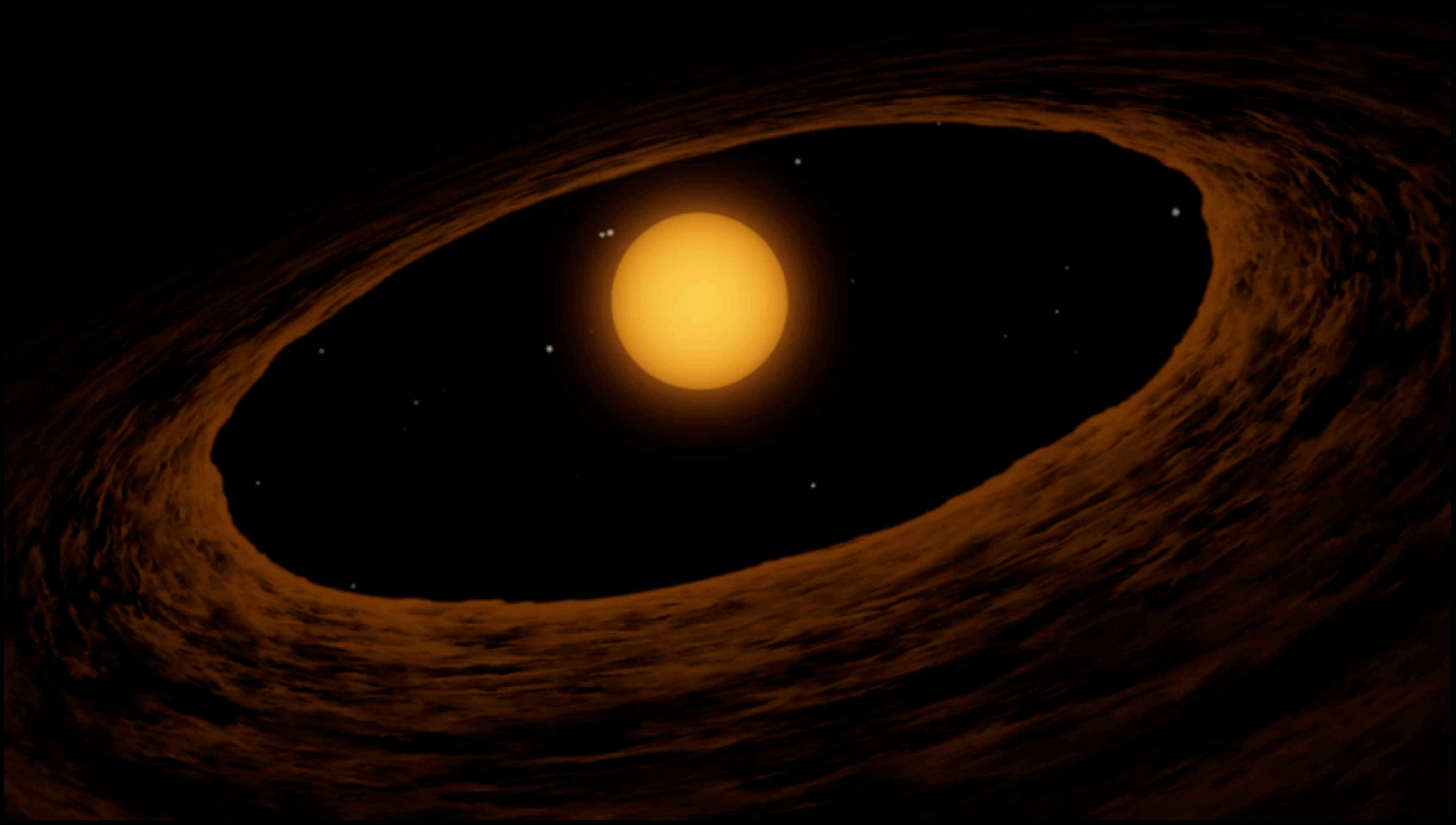
(Ábrahám et al. Nature, 2009)

Ongoing crystal-formation?

Crystal formation in EX Lup



Figures by A. Juhász



Radiative transfer modeling

consequence of the extinction of optical radiation in a flared disk viewed at large inclination angle.

4.1.4. *Temporal Behavior*

Temporal variations would provide another diagnostic of circumstellar disks. The claim by Moriarty-Schieven & Butner (1997) that the submillimeter and millimeter fluxes from the T Tauri binary GG Tau increased by factors of order 2 between 1992 and 1994 is of relevance here. The cause of this "radio-wave flare" has not been identified. A plausible hypothesis is that it resulted from enhanced disk heating associated with a burst in luminosity originating near one component, or both components, of the central binary. This leads us to consider relevant timescales for the radiative and hydrostatic response of the disk.

Seven different timescales come into play. They are (1) the timescale over which superheated dust grains in the surface layer equilibrate with the ambient stellar radiation field,

$$t_{ds} \sim \frac{r \rho_d k T_{ds} a^2}{\mu_d R_*^2 \sigma T_*^4} \sim 0.02 a_{\rm AU}^{8/5} \text{ s} , \quad (24)$$

where $\mu_d \approx 10\mu_g$ is the mean molecular weight per degree of freedom in a dust grain; (2) the light-travel timescale from star to disk,

$$t_{\rm lt} \sim \frac{a}{c} \sim 5 \times 10^2 a_{\rm AU} \text{ s} ; \quad (25)$$

(6) the timescale for the dust temperature to relax to the gas temperature,

$$t_{\rm relax} \sim \frac{r \rho_d}{\mu_d n_g v_g} \sim \frac{\mu_g r \rho_d}{\mu_d \Sigma \Omega} \sim 10^{-2} a_{\rm AU}^3 \text{ s} ; \quad (29)$$

(7) the dynamical timescale over which the disk adjusts to departures from hydrostatic equilibrium,

$$t_{\rm dyn} \sim 1.4 a_{\rm AU}^{3/2} \text{ yr} . \quad (30)$$

How rapidly might the SED vary in response to changes in the luminosity of the central star? Since $t_{ds} \ll t_{\rm lt}$, contributions from the surface layer are limited by $t_{\rm lt}$. Those from the interior are limited by t_{gi}, since $t_{\rm relax} \lesssim t_{di}$ and $t_{\rm diff} \ll t_{gi}$.[11] To relate these response times to timescales for variation at a fixed wavelength, λ, consult Figure 9.

4.2. *Unresolved Issues*

Our investigation leaves many unresolved issues.

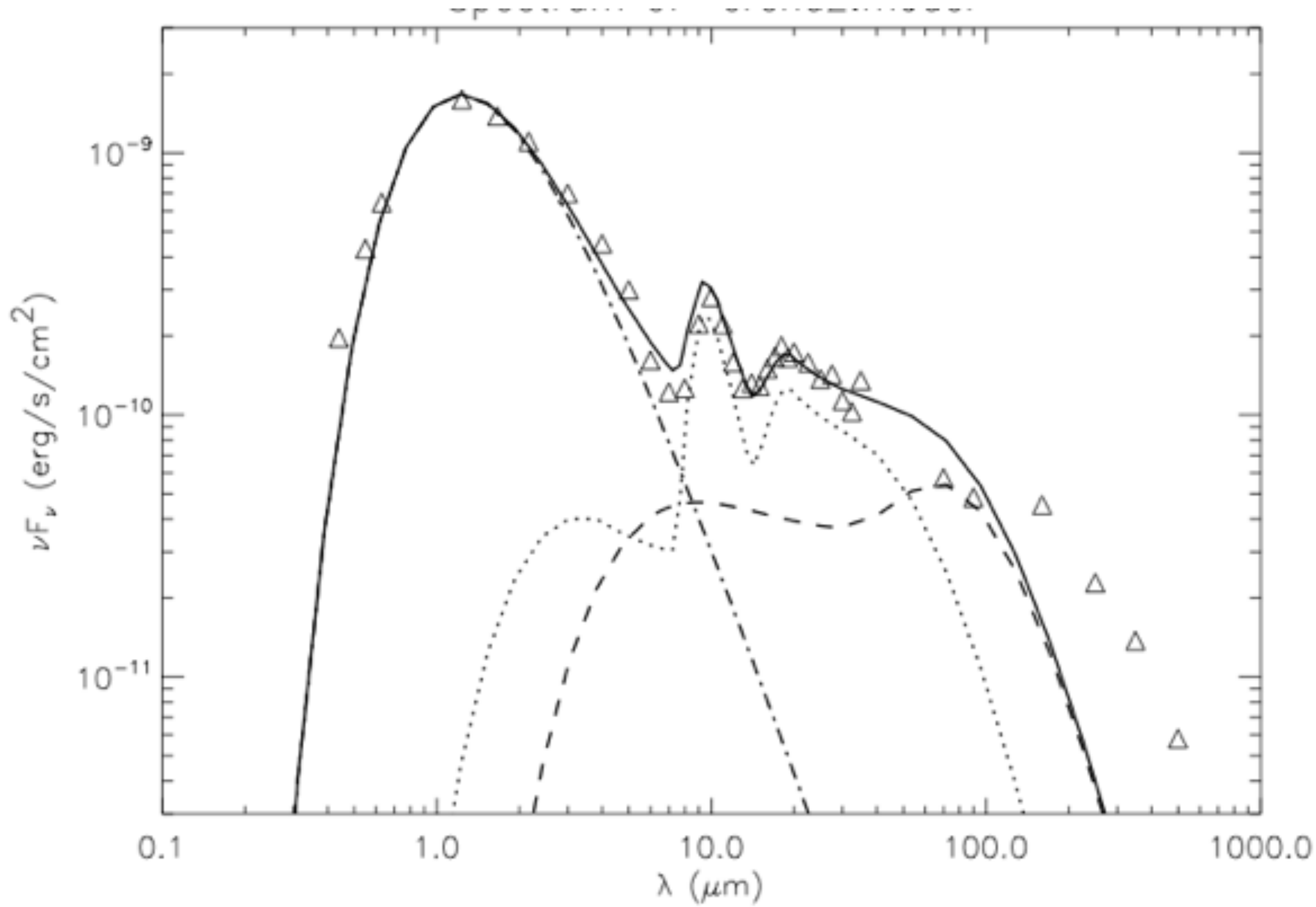
Is a disk in radiative and hydrostatic equilibrium dynamically stable?

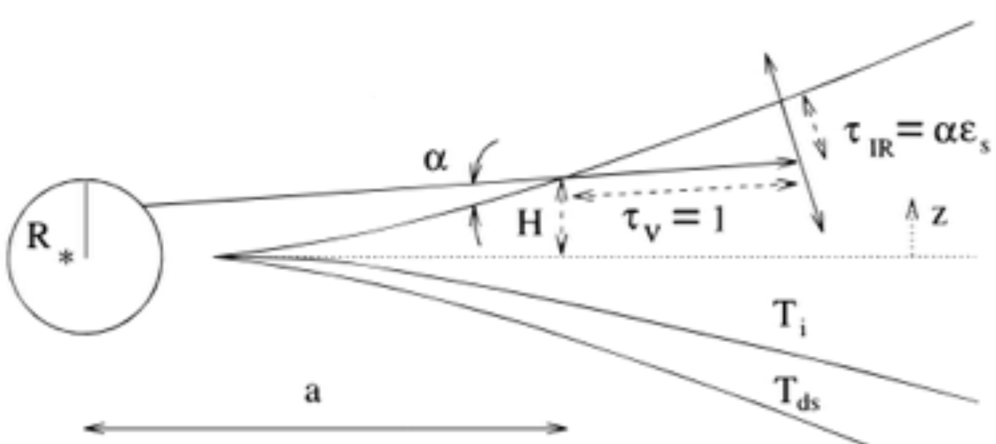
How does the SED depend upon disk inclination?

How much of the thermally emitted spectrum is covered by molecular lines? Do the lines appear in absorption or emission? Which molecules are they associated with?

Chiang & Goldreich, 1997

Radiative transfer modeling

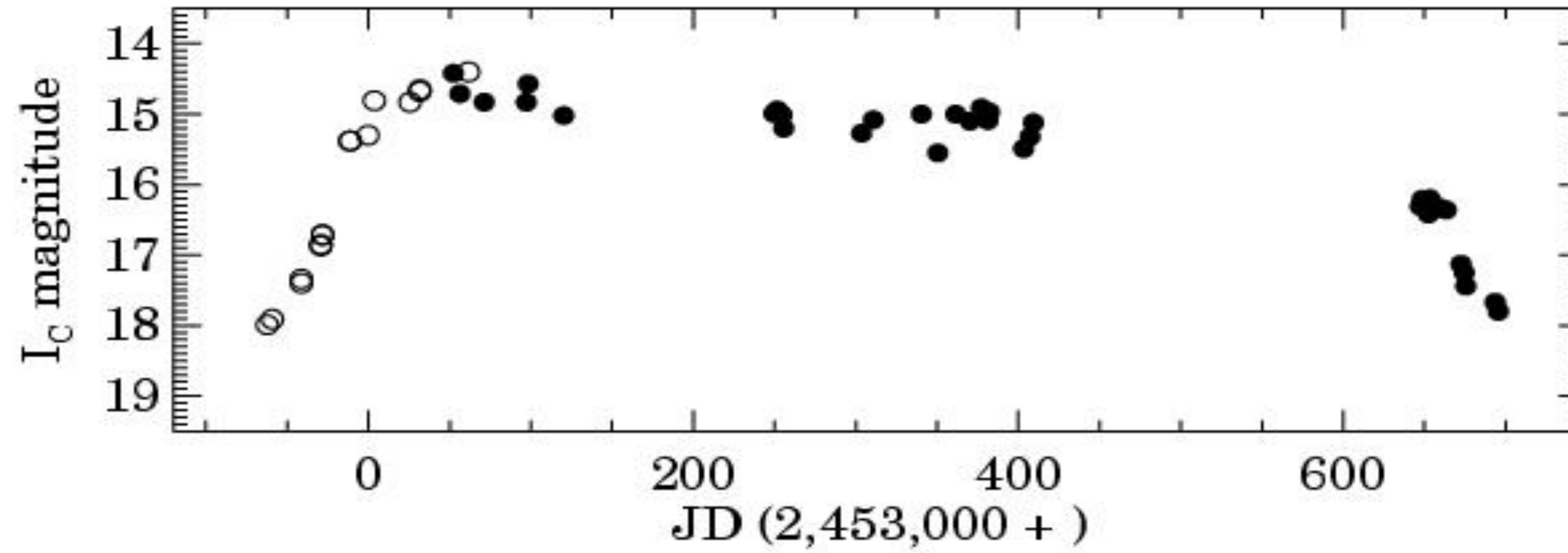


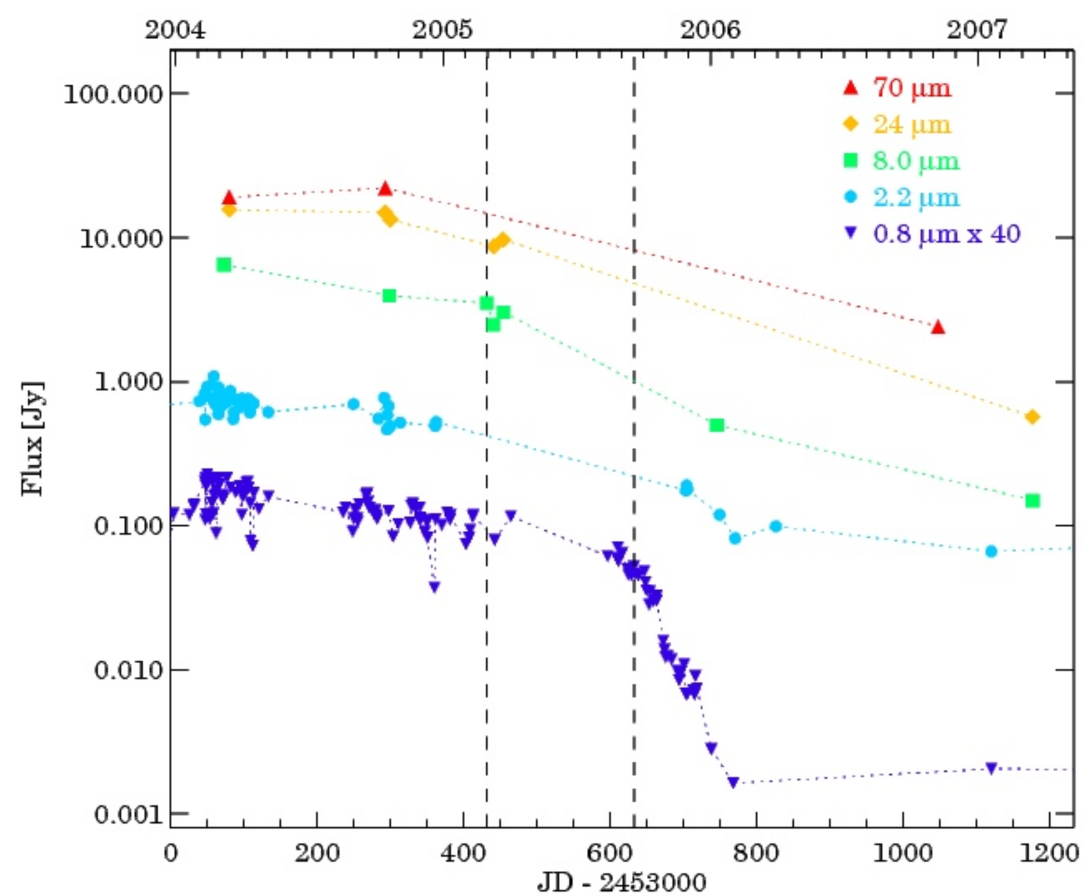


Chiang & Goldreich, 1997

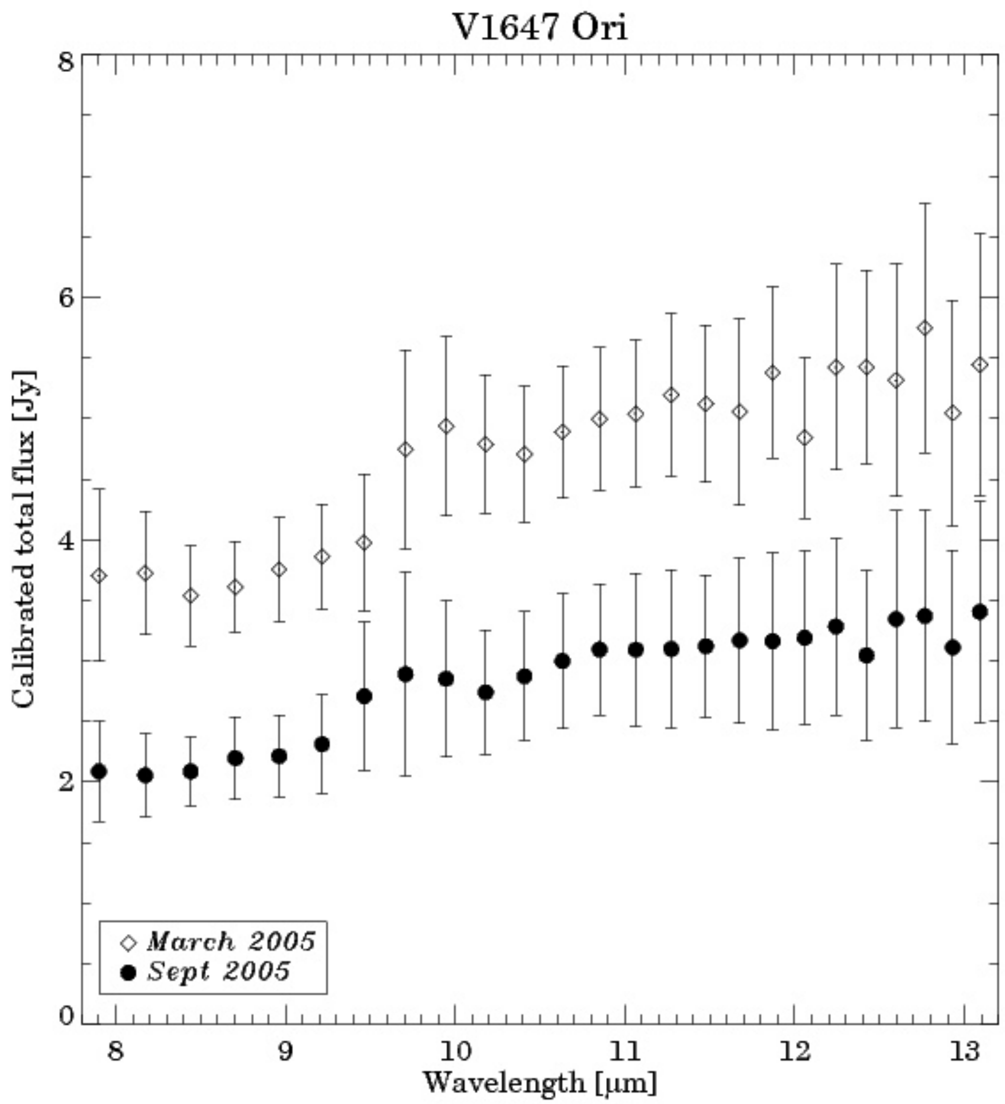
The 2004-06 outburst of V1647 Ori

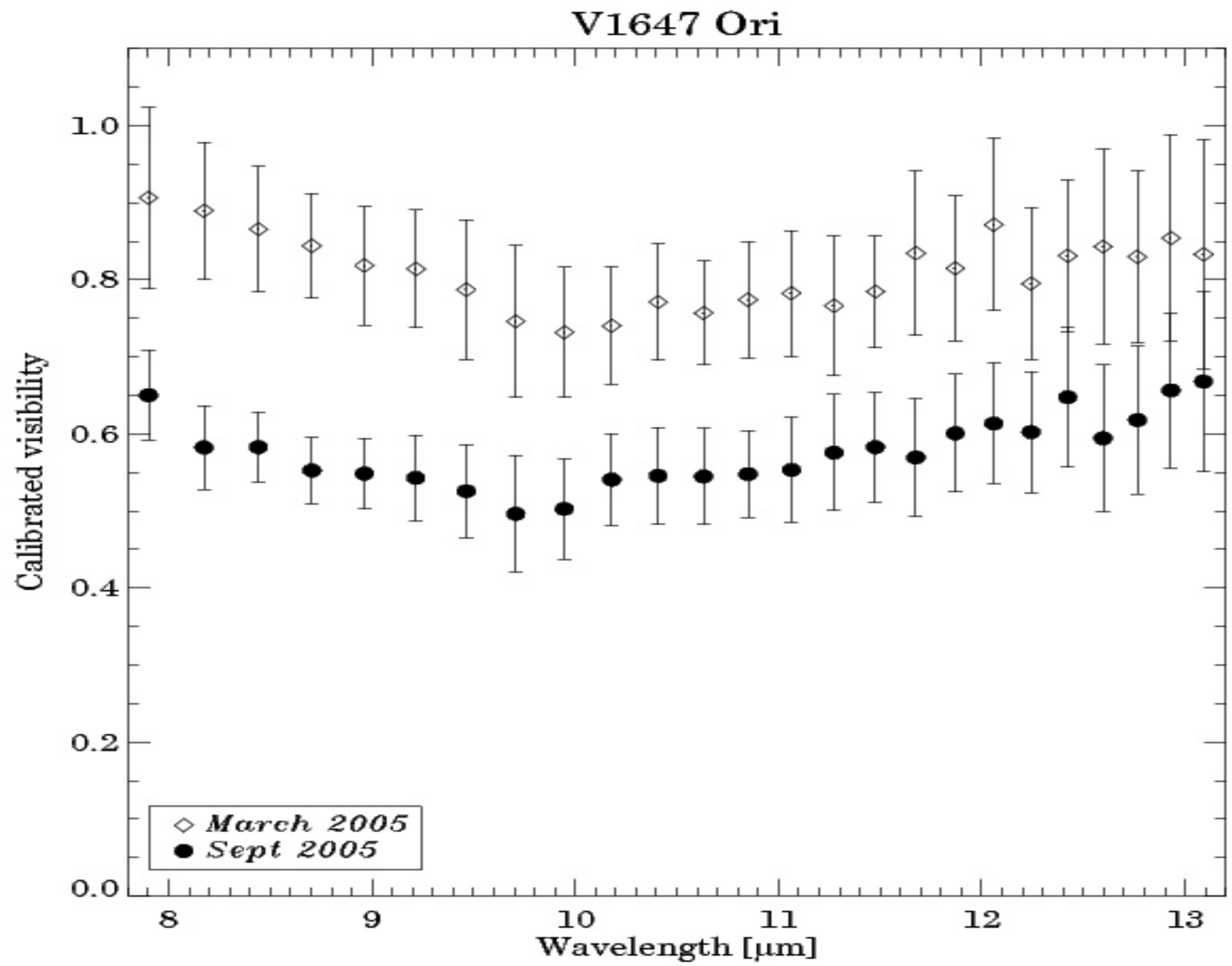
Reipurth & Aspin (2004)





The 2004-06 outburst of V1647 Ori





Reipurth & Aspin (2004)

Radiative transfer modeling

- Disk structure is usually modeled using time-independent radiative transfer codes

- In the case of changing central illumination, different parts of the disk may adapt to the new irradiation conditions with different pace

- At short wavelengths the disk responses immediately

- **At longer wavelengths part of the disk emission is originating from below the optical photosphere, due to lower IR opacity**

- Inclusion of this effect into RT codes might help to interpret situations of rapidly changing illumination (e.g. outbursts)

The 4th dimension of circumstellar disks

- Disk variability, in particular its wavelength dependence, carries new type of independent information on disk structure (*response of a perturbed system*)
- Deduce structural information directly (disk tomography), or constrain disk models
- Information on dynamical processes
- **Only few works have been completed so far, methodology is yet to be developed and consolidated**
- Our dream: carry out a comprehensive, observational and theoretical, exploration of the time domain in circumstellar disk studies
- Potentially high impact on many aspects of our knowledge on the formation of stars and planets
- Time domain astronomy was identified as one of the five Science frontier discovery areas in the 2010-20 US Decadal Survey
- All these might become popular with JWST