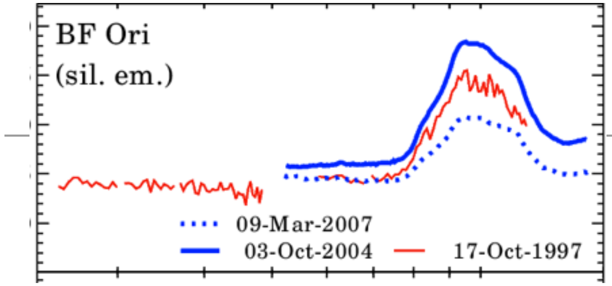
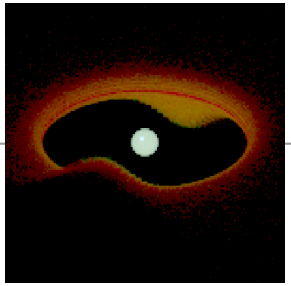
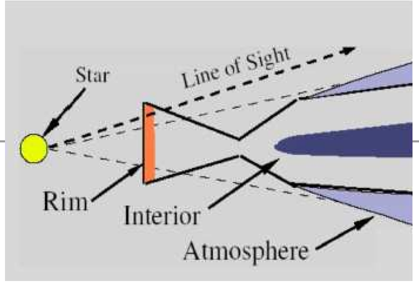
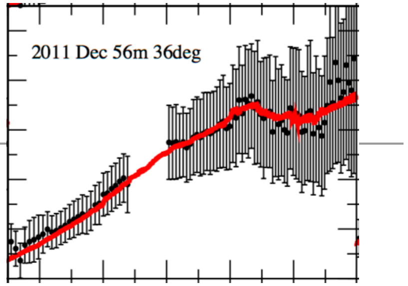
The 4th dimension of circumstellar disks: Infrared variability and disk structure of young stellar objects









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2017 November 15

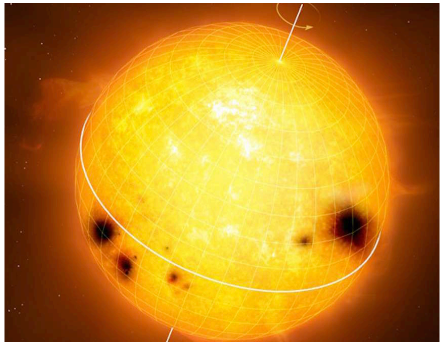
Optical variability of YSOs

- YSOs are well-known about their optical and near-infrared variability. Three main classes of variability (Herbst et al. 1994):

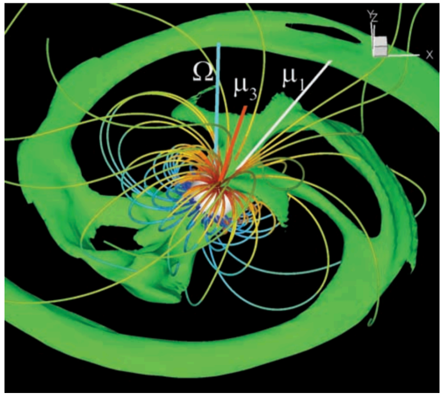
- **Type I** - Cool spots: similar to sunspots, rotating for a few periods

- **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. *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). *Dippers:* stable, but dynamic inner disk warp (Bouvier+ 2007)

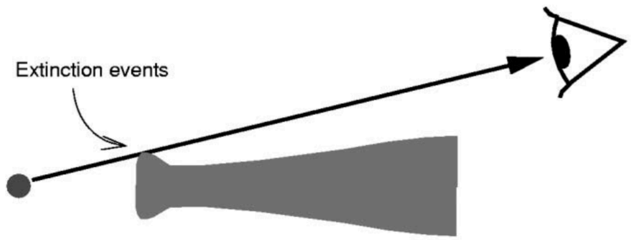


Credit: C. Garraffo

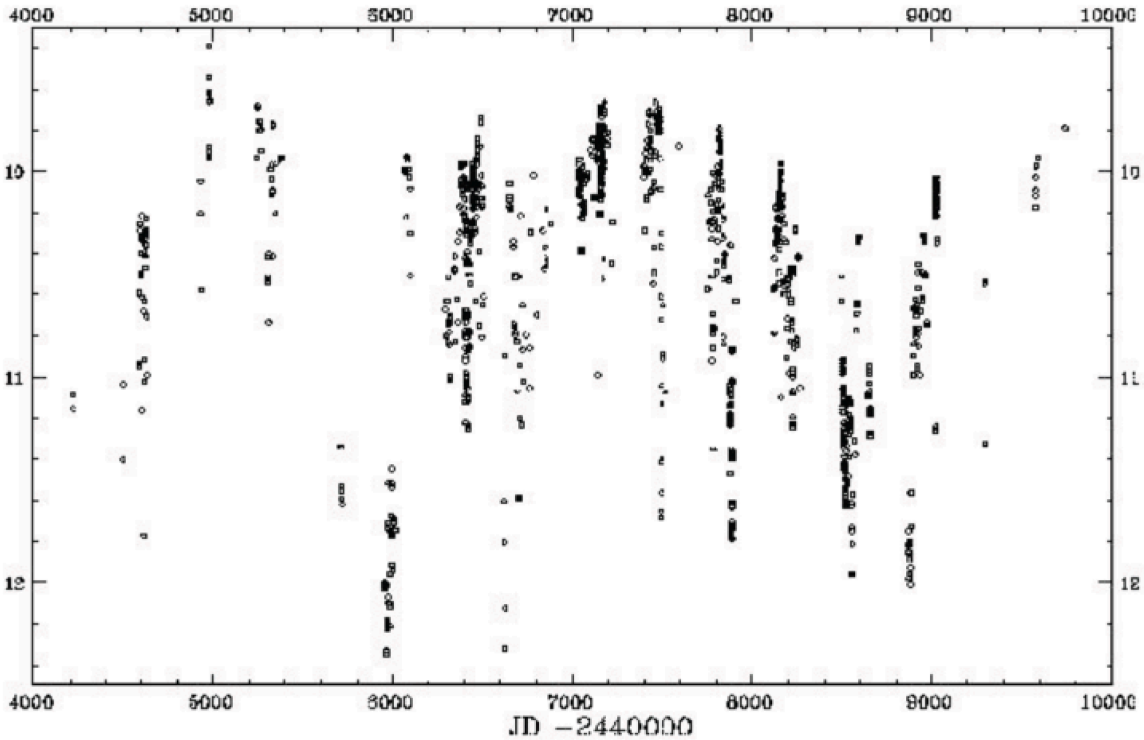


Credit: M. Romanova

UX Orionis phenomenon



Dullemond+2013

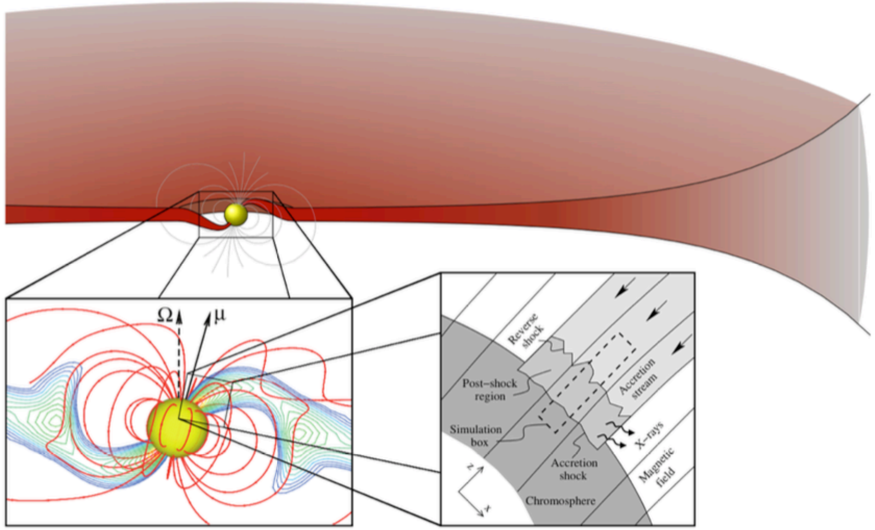


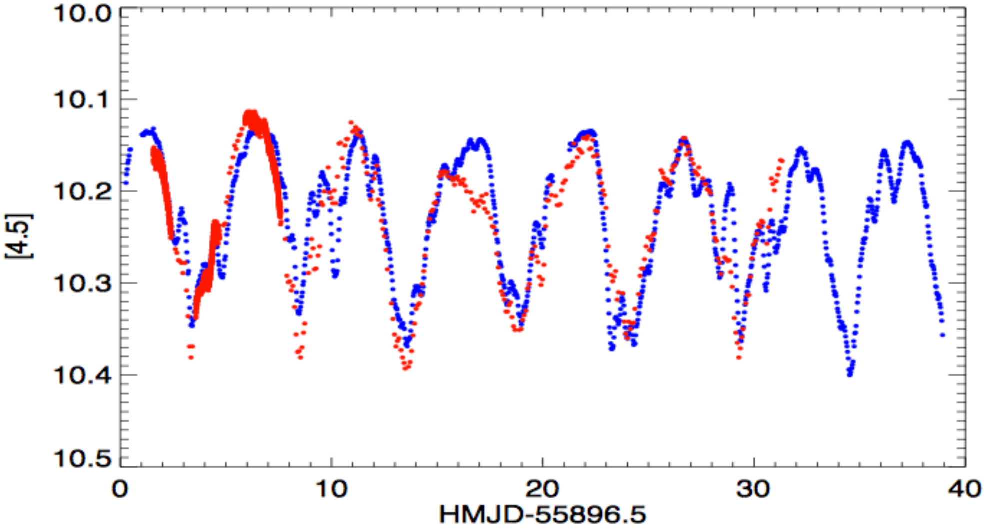
UX Ori-type variability

deep eclipses, blueing

the timescale is a typically a few weeks,

AA Tau phenomenon





AA Tau-type variability

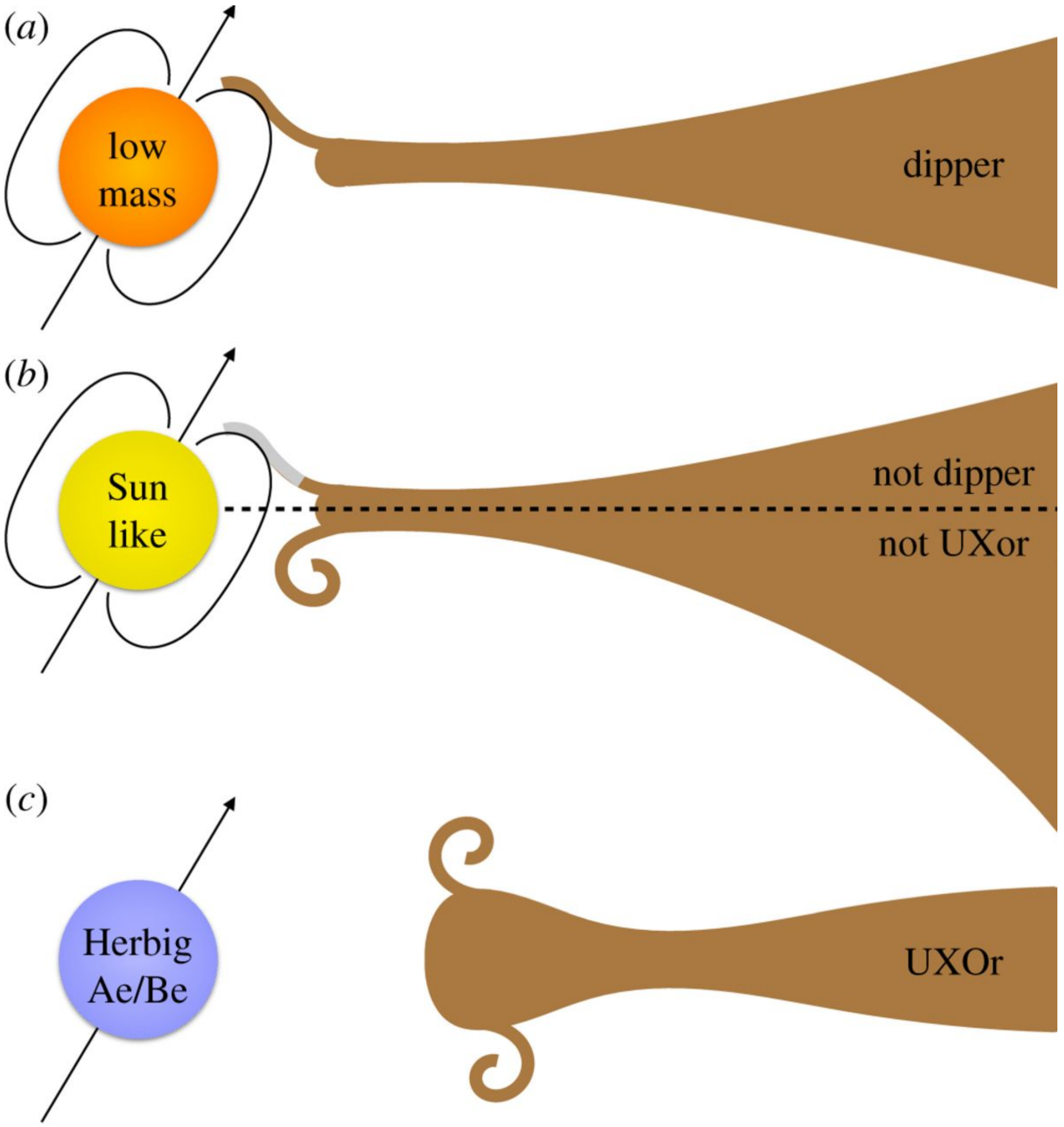
stable accretion funnel flow

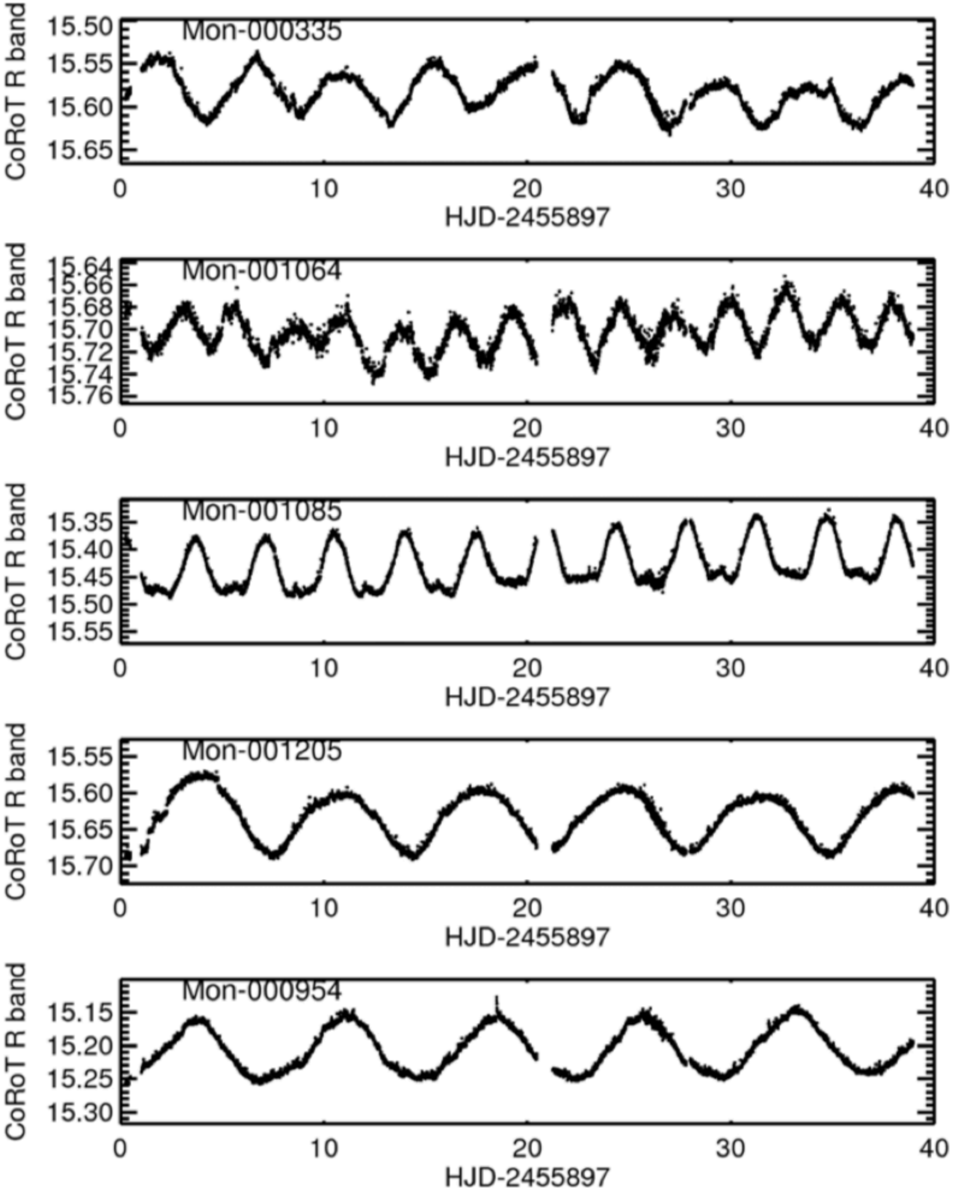
stable, but dynamic inner disk warp

But the warp is a caused by the magnetic field, and is at a radius of few R_{sun}.
Timescale is a few days/weeks only…

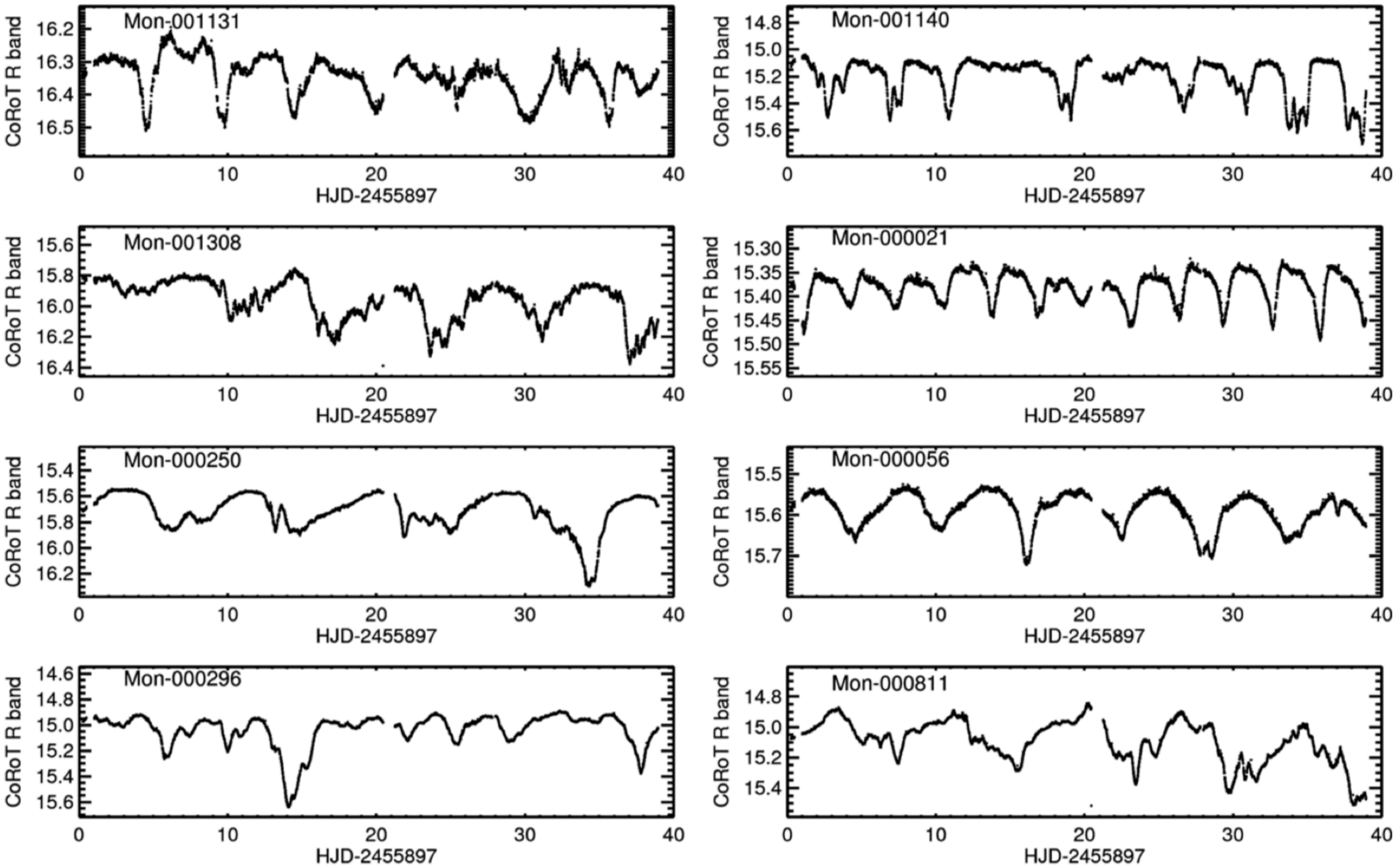
Possible origin of the dust clump: disk structure

Kennedy+ 2017

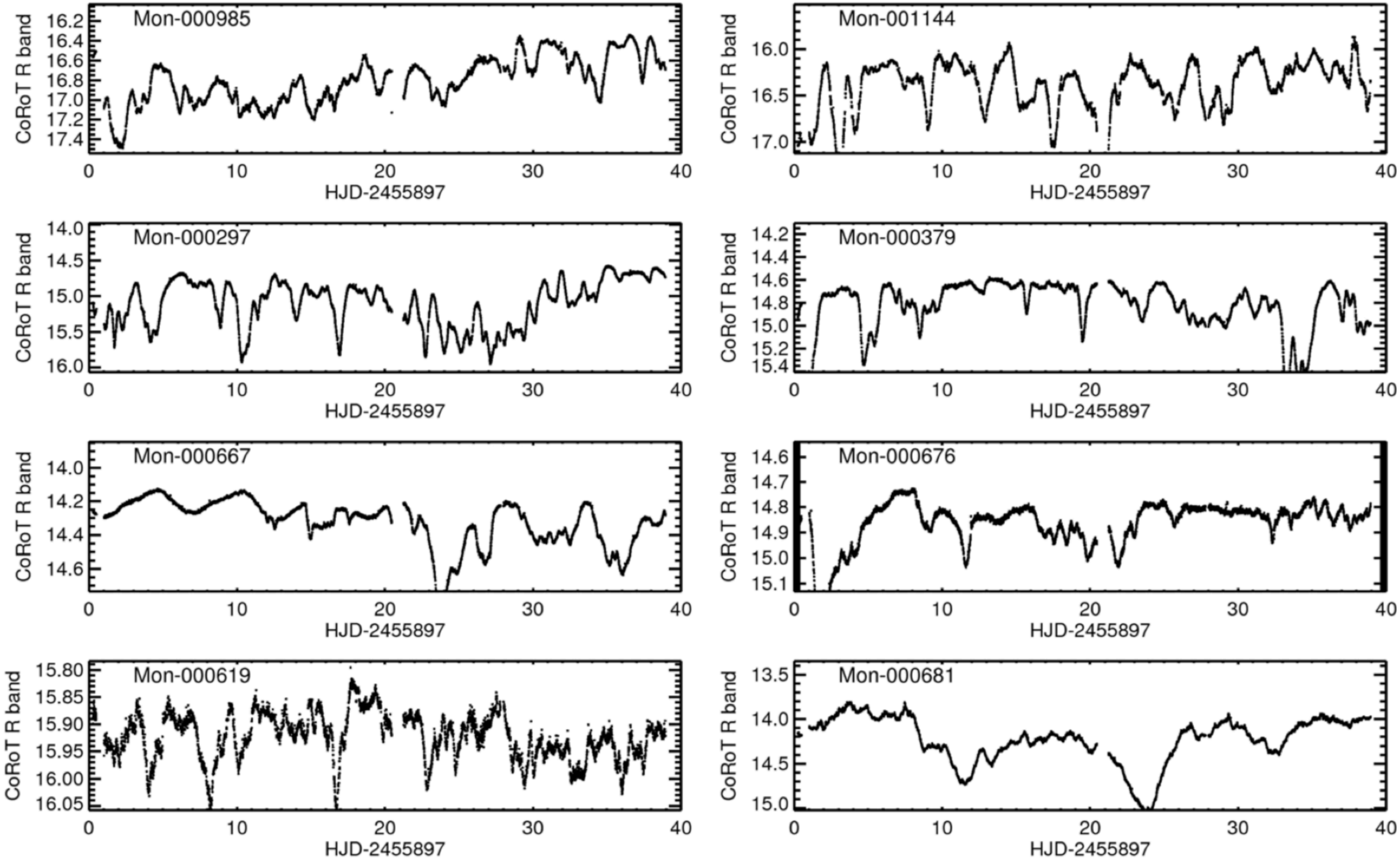




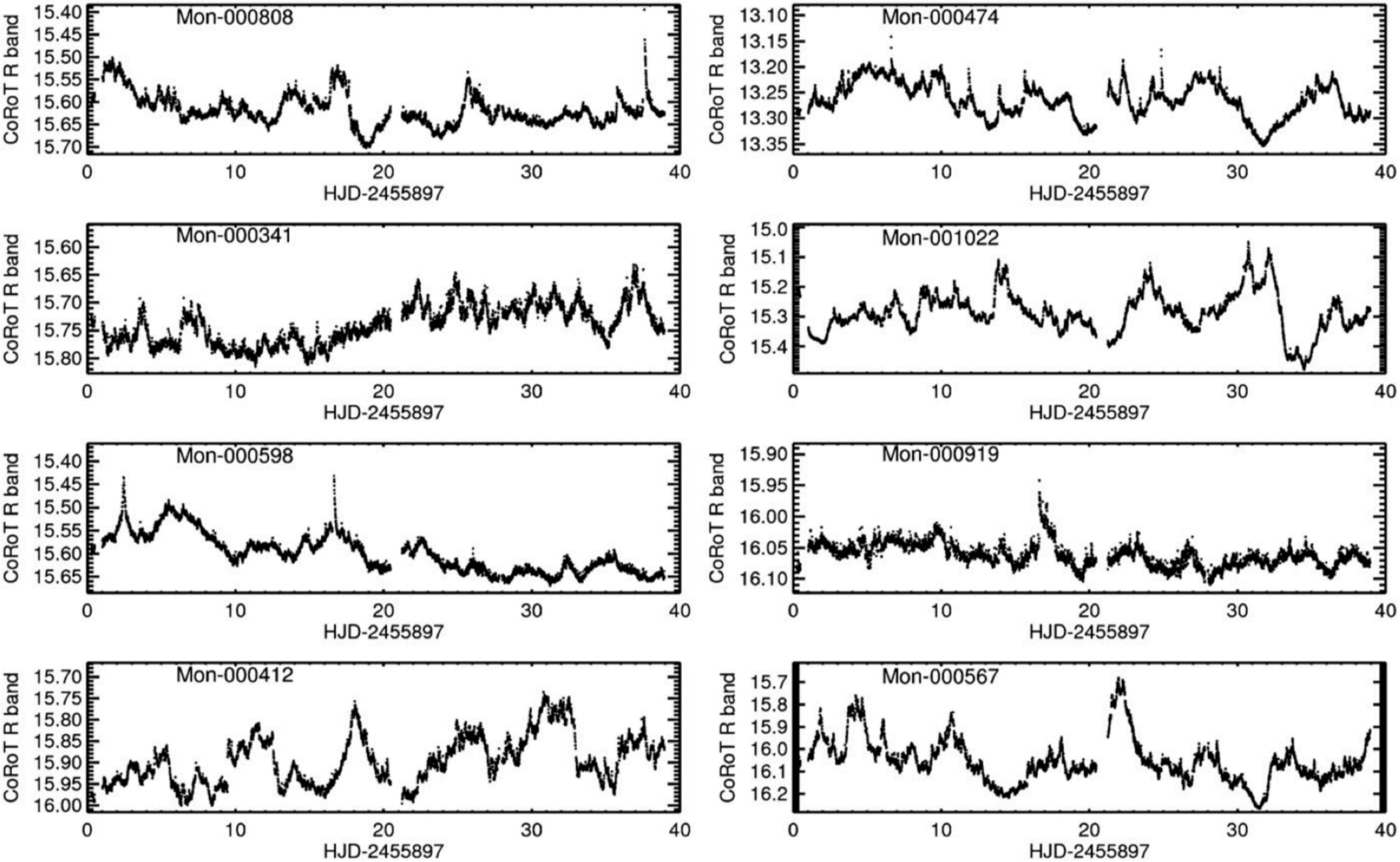
Periodic optical light curves: the most regular light curves in the entire disk-bearing data set. The weak infrared excesses, Hα, and low UV excesses of these objects suggest that they host cool magnetic spots, which appear in the light curves via rotational modulation (NGC 2264, Cody et al. 2014).



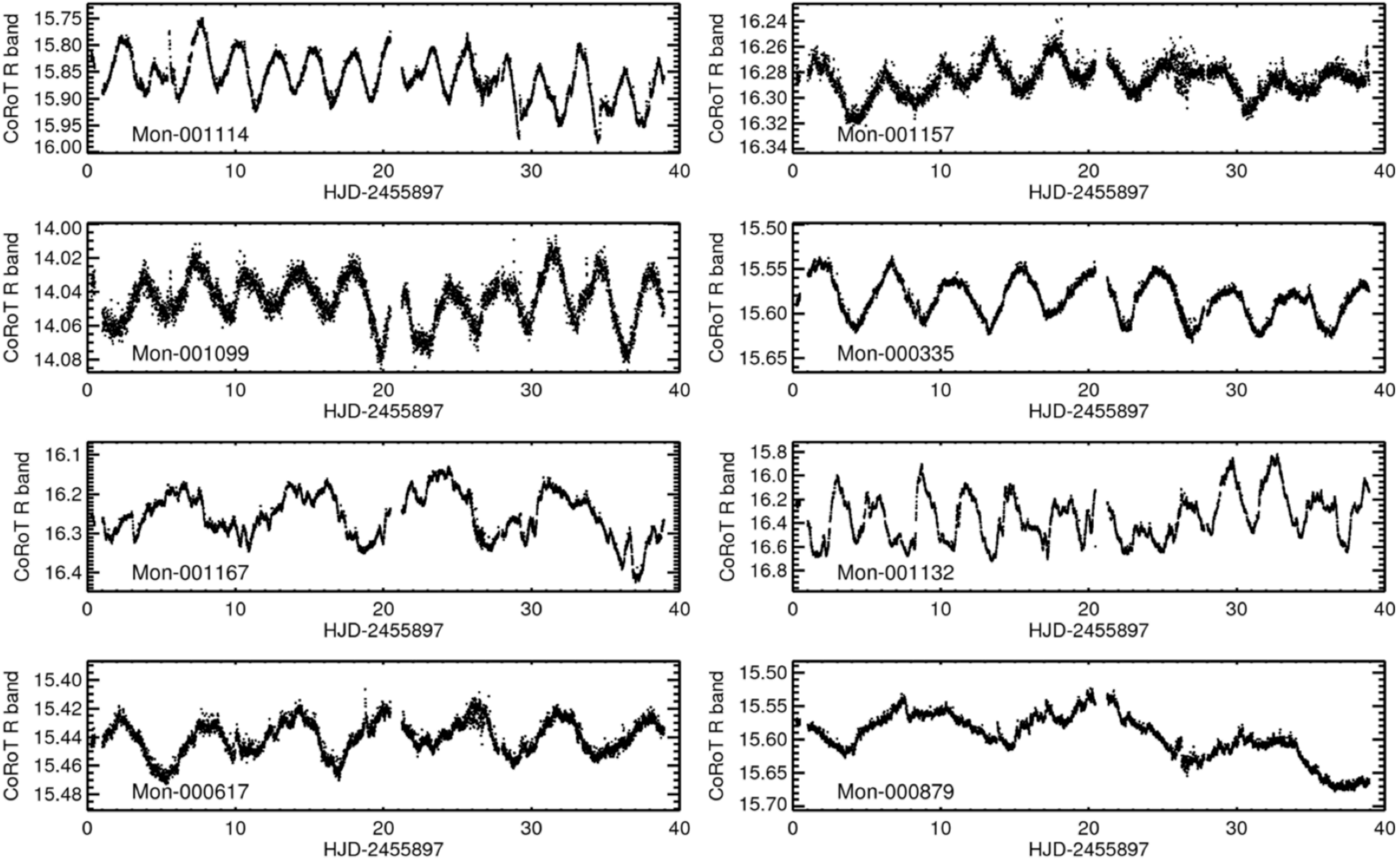
Periodic optical dippers: fading events that repeat regularly, albeit with different amplitudes (NGC 2264, Cody et al. 2014).



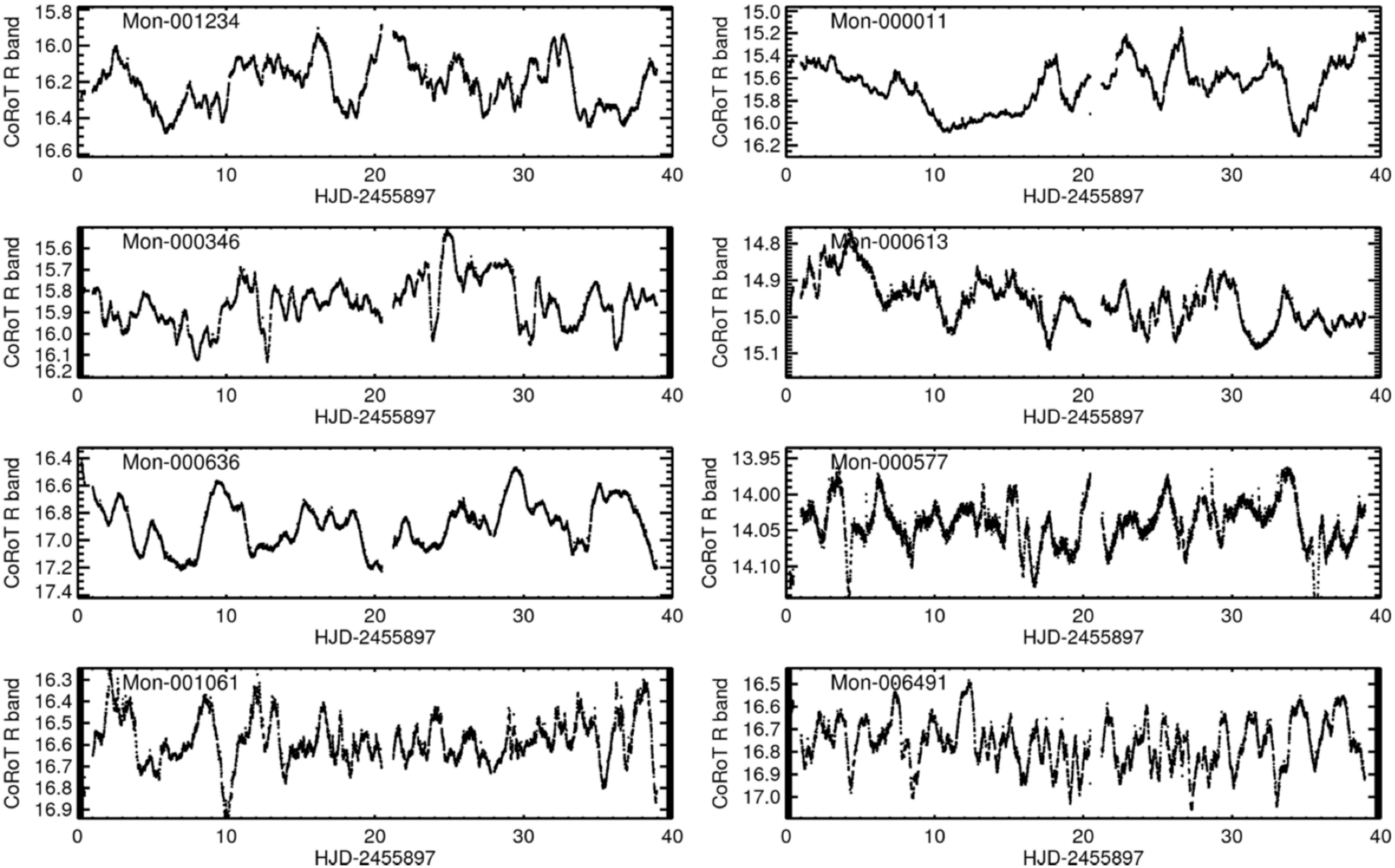
Aperiodic optical dippers: prominent fading events with no detectable periodicity (NGC 2264, Cody et al. 2014).



Optical bursters: short-duration flux increases in the optical. The events seen here may represent accretion bursts; some repeat regularly, while others are aperiodic (NGC 2264, Cody et al. 2014).

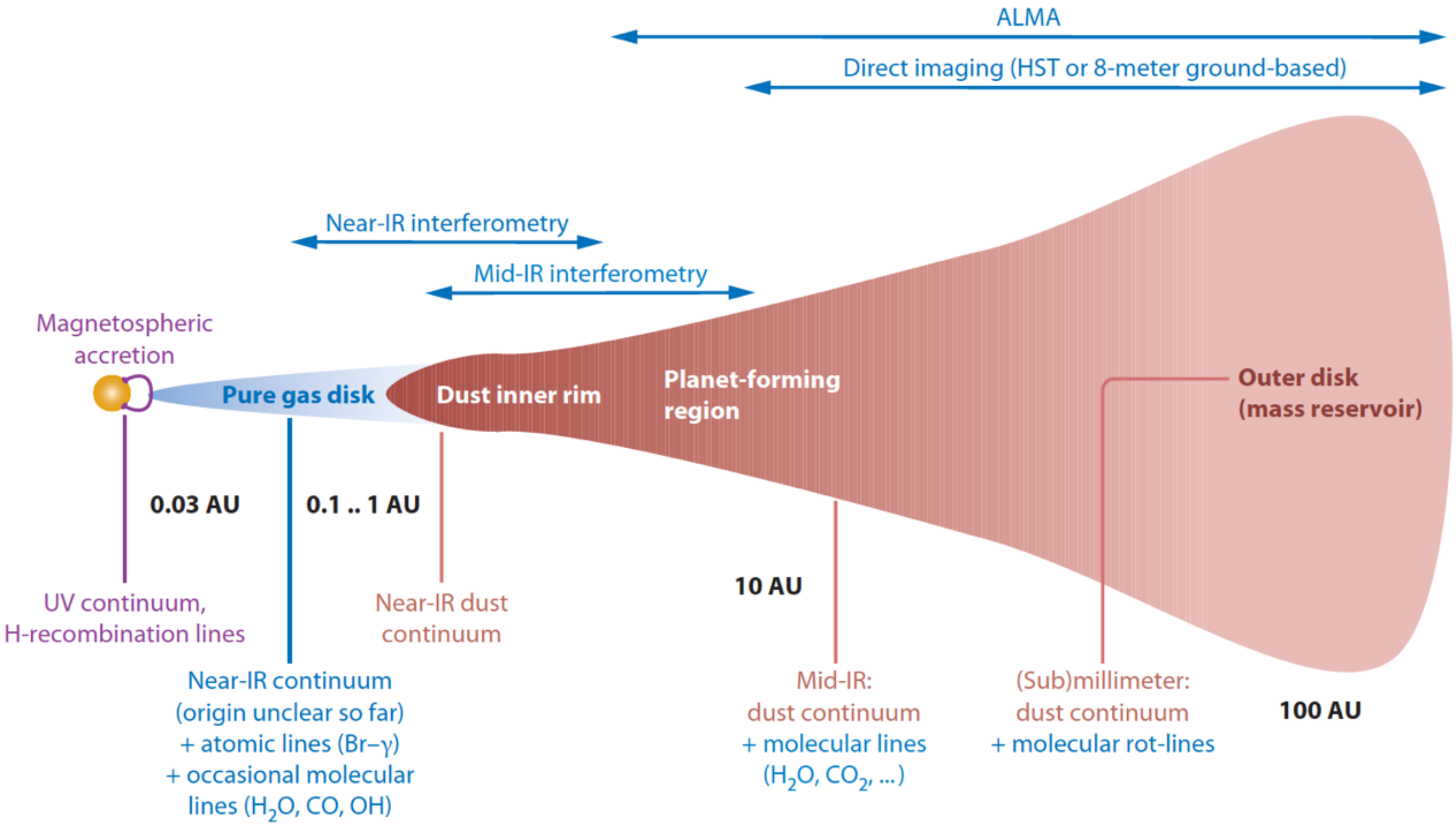


Quasi-periodic optical variability: regular repetition, but amplitudes and shapes change from one cycle to the next (NGC 2264, Cody et al. 2014).



Stochastic optical light curves: no detectable periodicity, nor any preference for fading or brightening events (NGC 2264, Cody et al. 2014).

Motivation

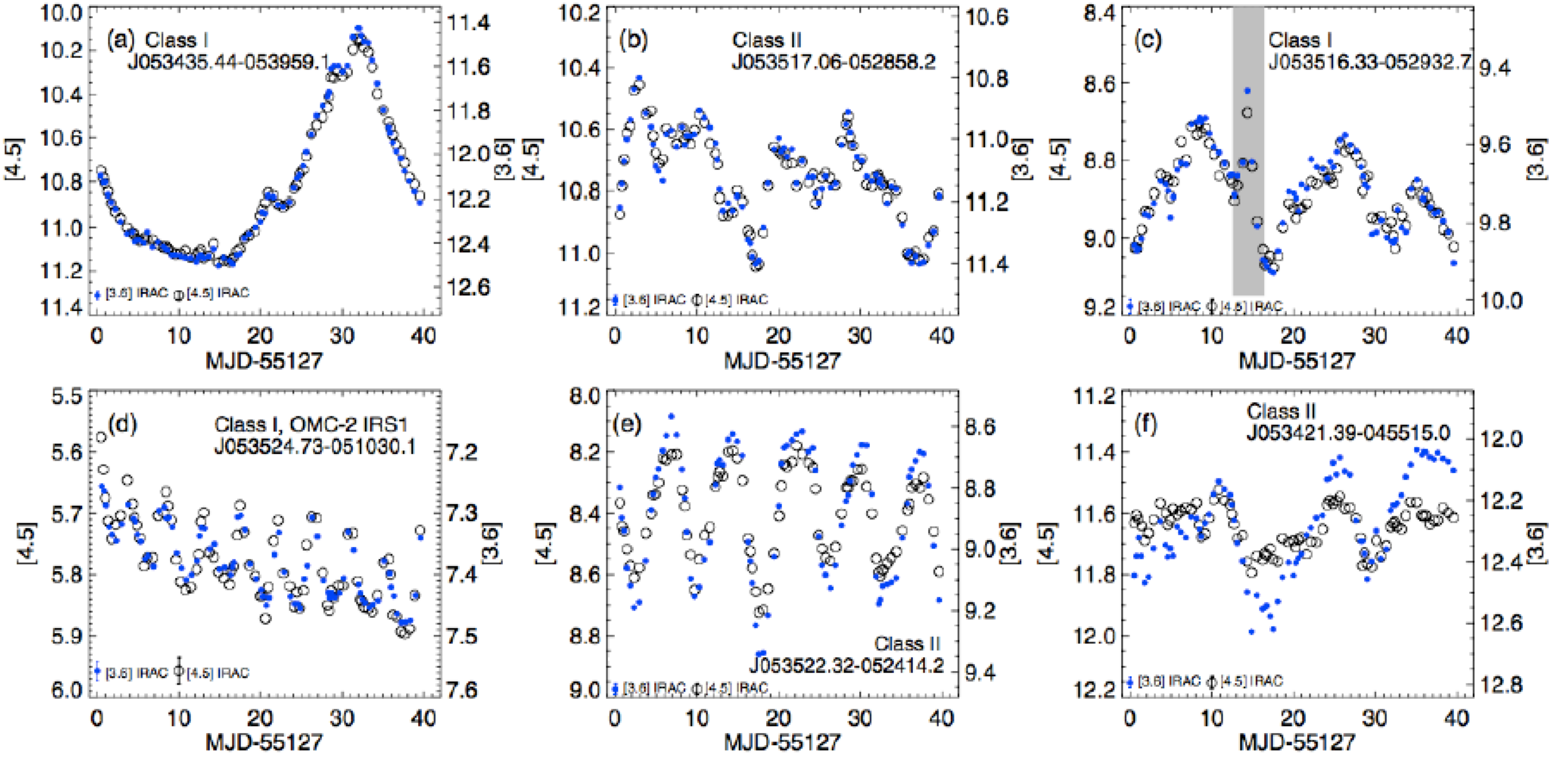


Dullemond & Monnier (2010)

Mid-IR flux is the thermal dust emission in the inner disk, and its variability carries information from the planet-forming zone

Infrared monitoring observations

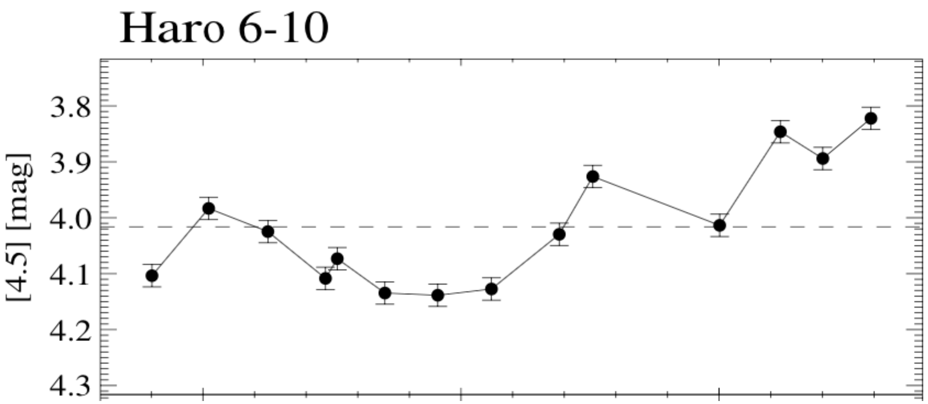
- **Thermal infrared: more difficult to obtain accurate light curves**
- IRAS variability flag showed definite changes in several cases (Prusti & Mitskevich 1994)
- **Ground- and space-based mid-infrared photometric studies**: up to 70-80% of YSOs are variable above the 0.1 mag (~10%) level (e.g. Barsony et al. 2005, Morales-Calderón et al., 2009, Luhman et al., 2010)

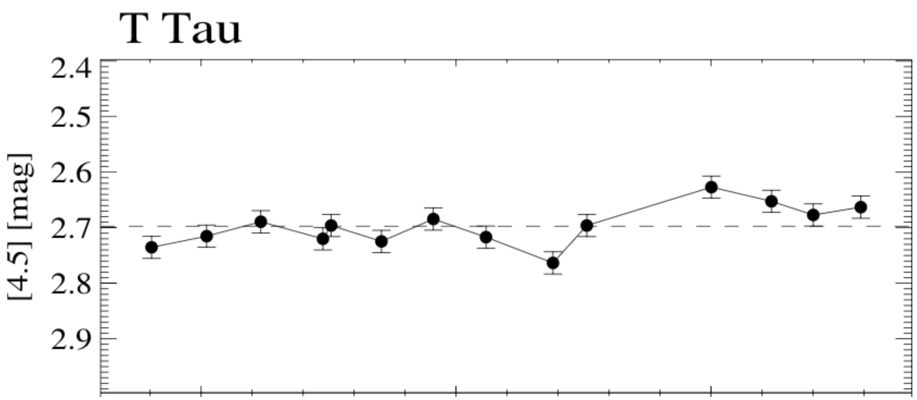


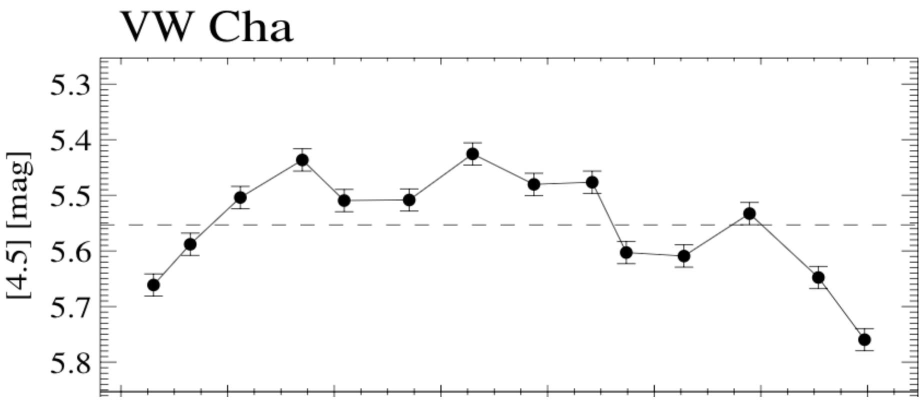
Morales-Calderón+ 2009

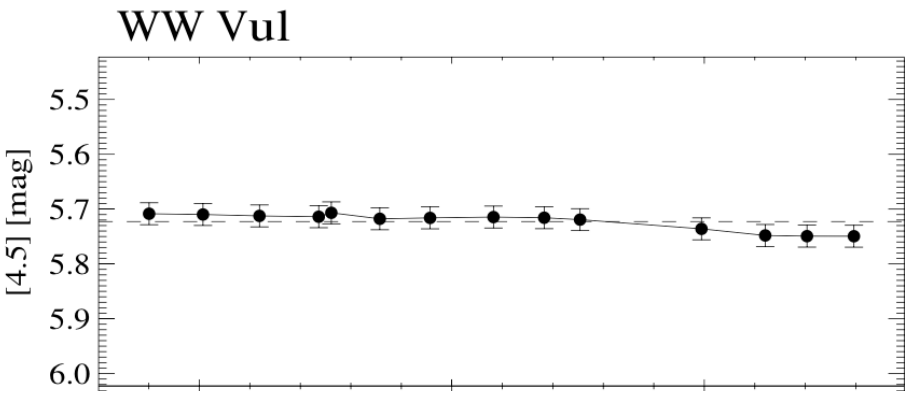
Infrared variability of YSOs

- Mid-infrared photometric monitoring with Spitzer (Konkolyvar project)

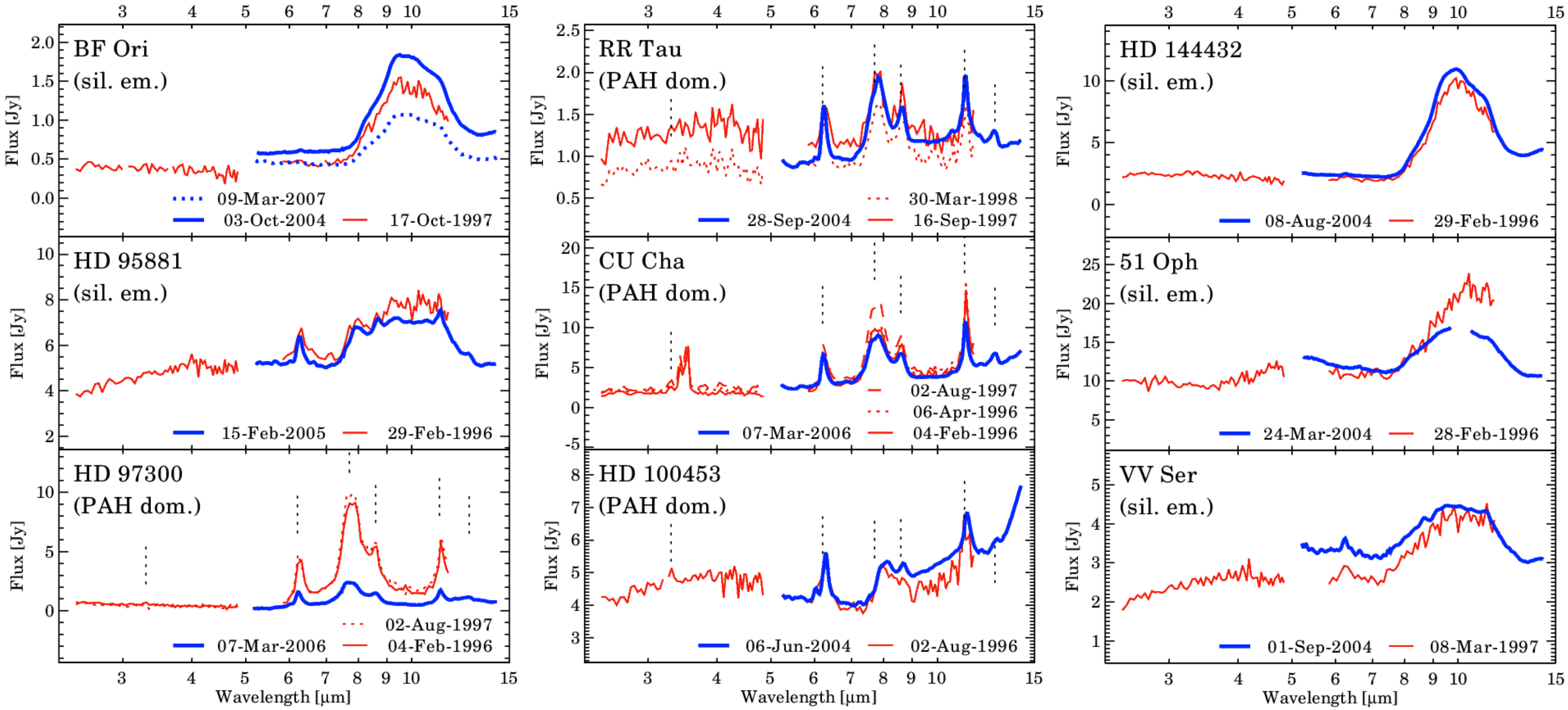

Haro 6-10


T Tau


VW Cha


WW Vul

Mid-infrared spectral variability atlas



Comparison of ISOPHOT-S and Spitzer spectra: many young objects are variable, both in silicate feature and continuum (Kóspál et al. 2012).

Infrared disk variability is now observationally proven.

What can we learn from mid-infrared variability?

Origin of the variability:

changing accretion heating

changing irradiation by the central source

structural changes in the inner disk (absorbing and emitting surface)

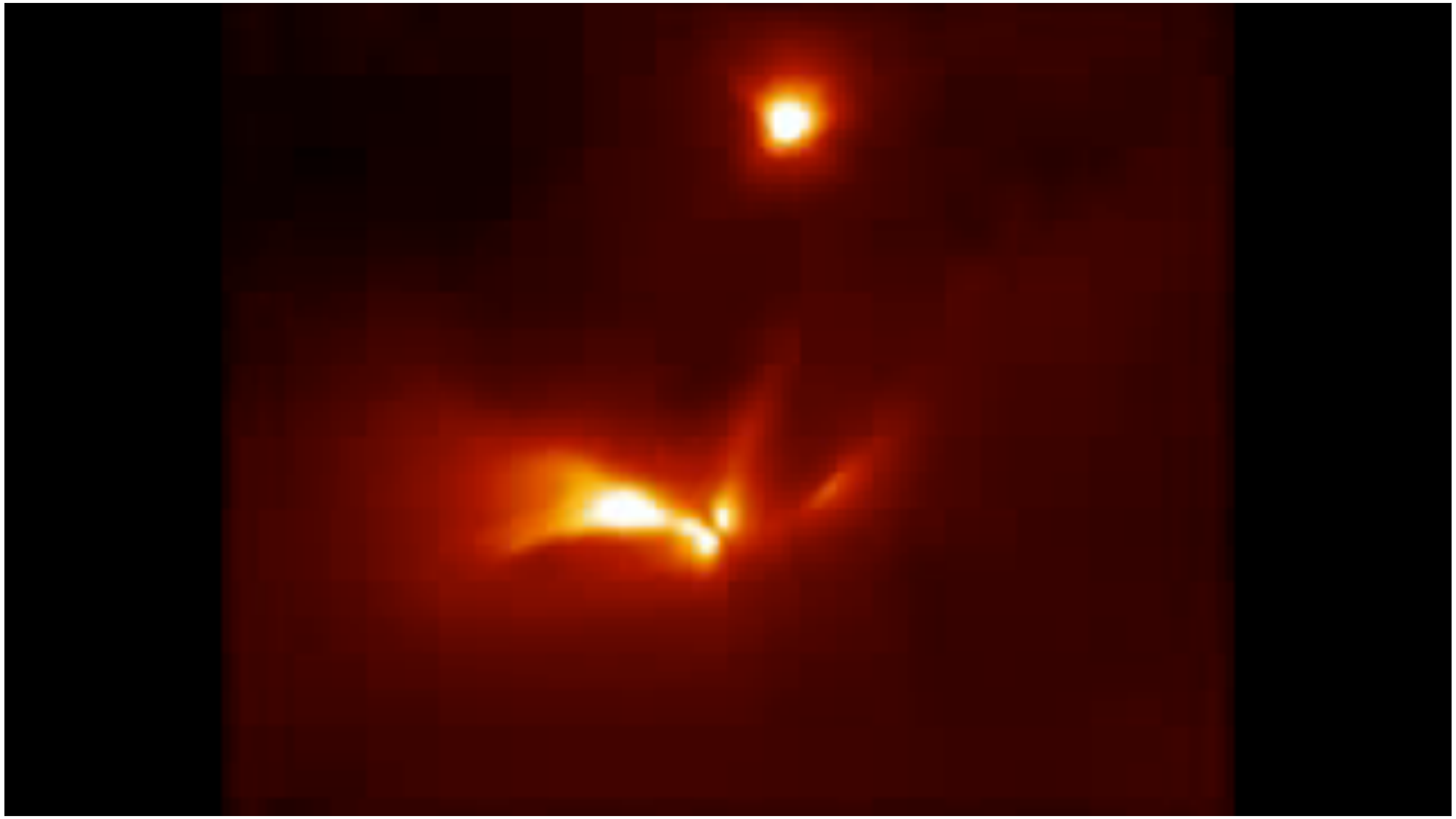
In order to understand variability, we need:

- optical monitoring of the star (irradiation changes)
- analysis of the time-dependent, infrared disk flux (amplitude, periodicity, wavelength dependence…)
- multiepoch images at mid-infrared wavelengths

Observable disk changes

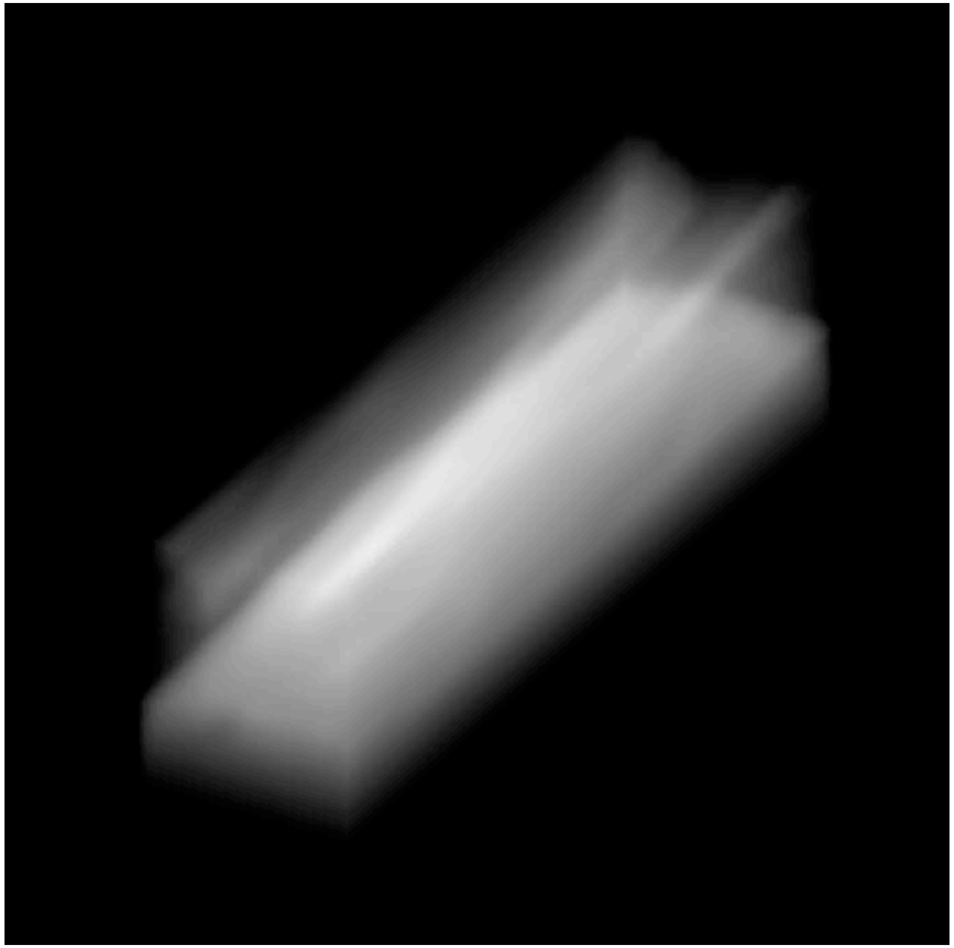
In a simple view, YSO disks can:

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



Muzerolle et al. Nature, 2013

Physics of structural changes



Turner et al. (2010): time-varying, magnetically-supported disk atmosphere. Turbulence caused by accretion.

<u>Can explain:</u>

- variability uncorrelated with visible-light changes,
- foreground extinction that recurs on timescales of weeks
- excesses over the stellar photosphere too large to explain by reprocessing in a hydrostatic circumstellar disk.

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.

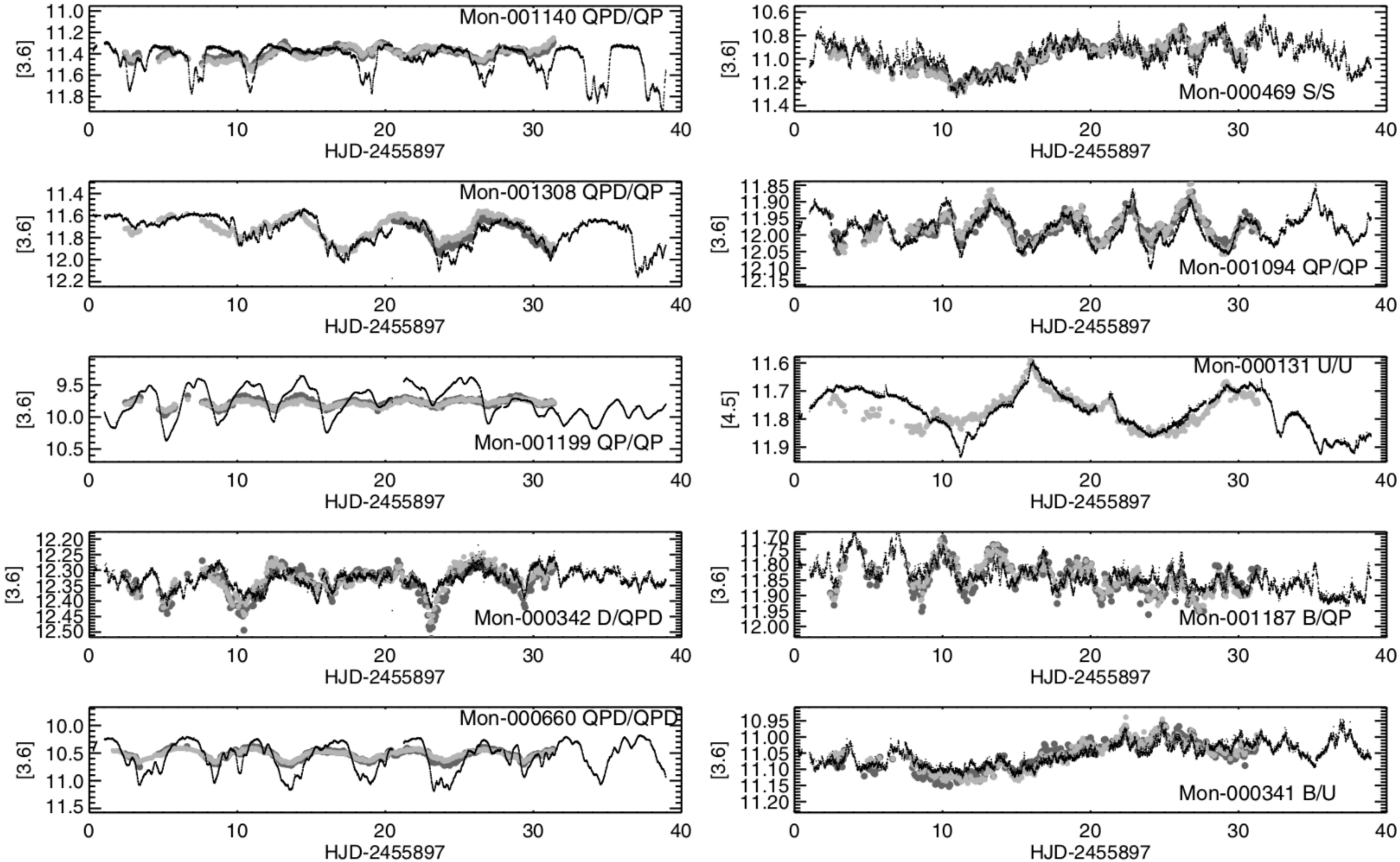


Figure 37. Light curves with correlated optical and infrared behavior. Small black points are *CoRoT* data, light gray points are 3.6 μm data, and dark gray points are 4.5 μm data (sometimes hidden behind the 3.6 μm points). Labels show the Mon ID along with the optical and infrared morphologies, respectively; morphology abbreviations are the same as in Table 4.

(NGC 2264, Cody et al. 2014).

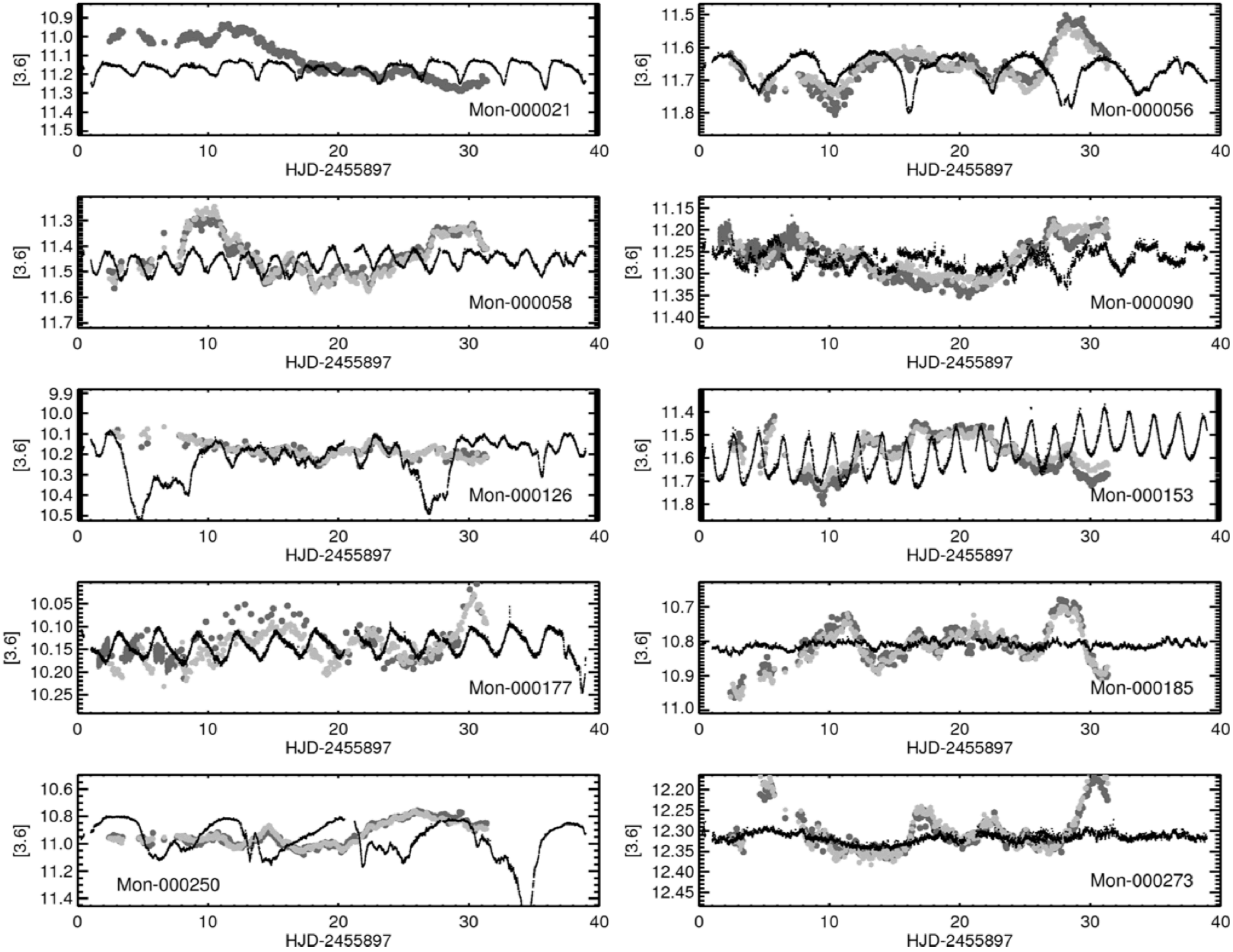


Figure 38. Light curves with uncorrelated optical and infrared behavior. Small black points are *CoRoT* data, light gray points are 3.6 μm data, and dark gray points are 4.5 μm data (sometimes hidden behind the 3.6 μm points).

(62%, NGC 2264, Cody et al. 2014).

Variability and disk structure

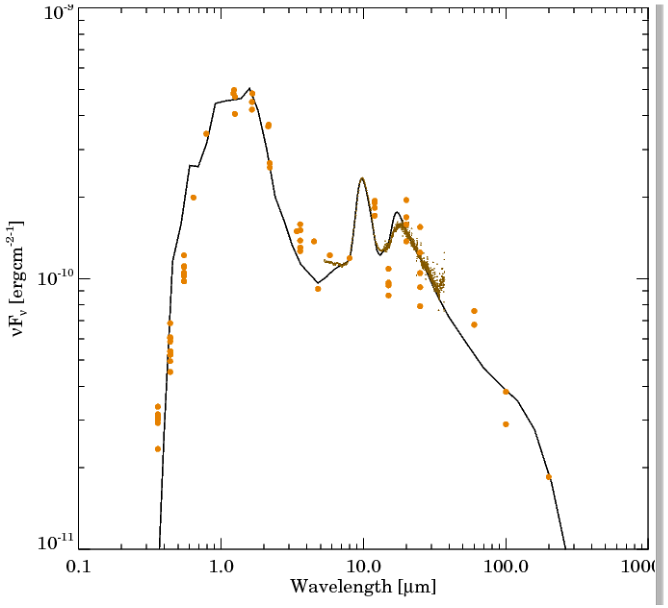
- Both Type III optical variability (UXor phenomenon) and thermal infrared variability deliver information about disk structure.

- 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-contemporeous SEDs or interferometric observations?

Methods?



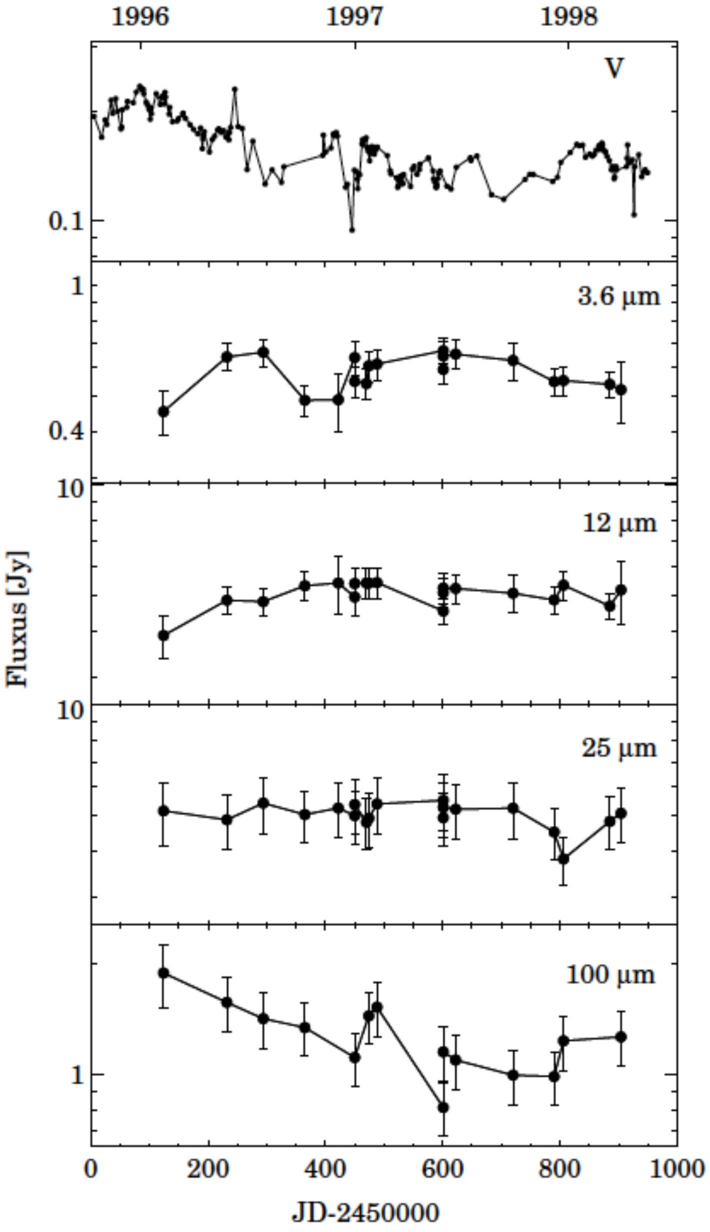
Available variability datasets

- 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

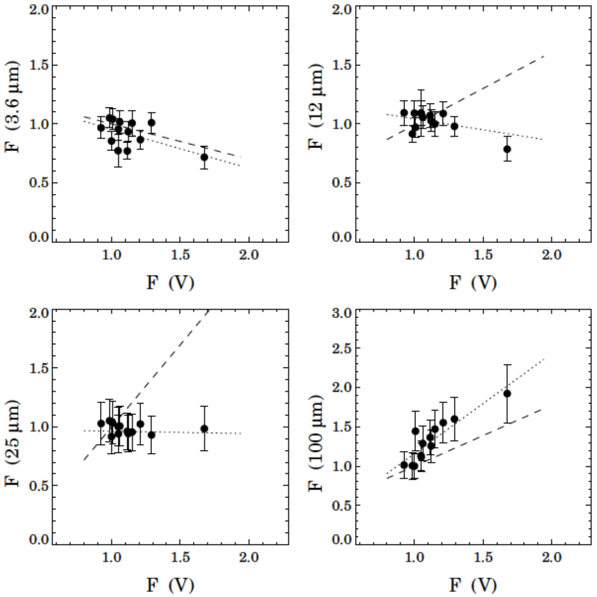
Credit: NASA/IPAC

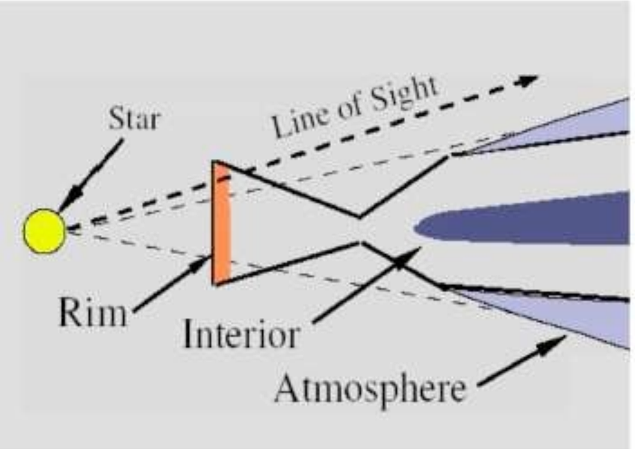
- Problem of 2017: very limited possibilities to observe (especially monitor!) in the mid- and far-infrared. Use archive data, wait for new instruments… for the era of JWST!!!!

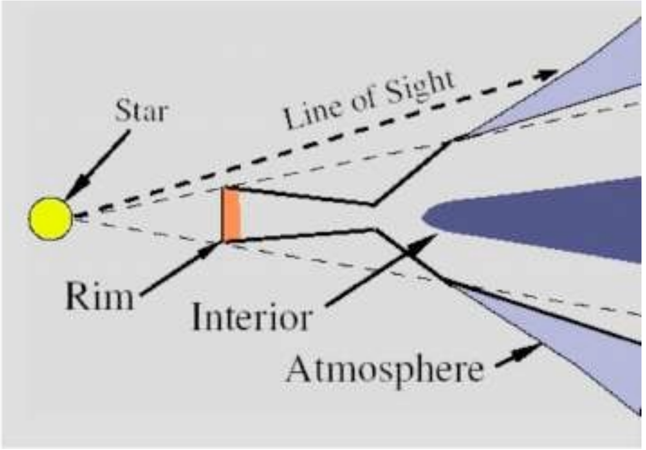
Monitoring and modeling of SV Cep



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



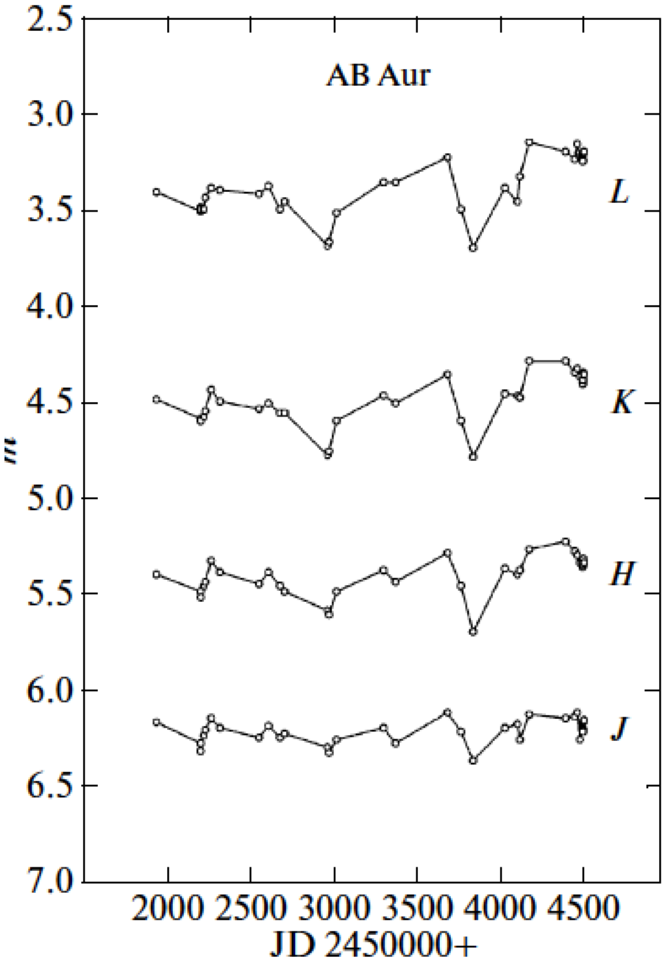


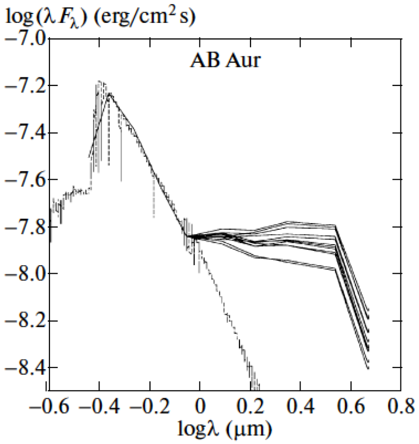


(Juhász, Prusti, Ábrahám, Dullemond 2008)

Disk variability with no luminosity change

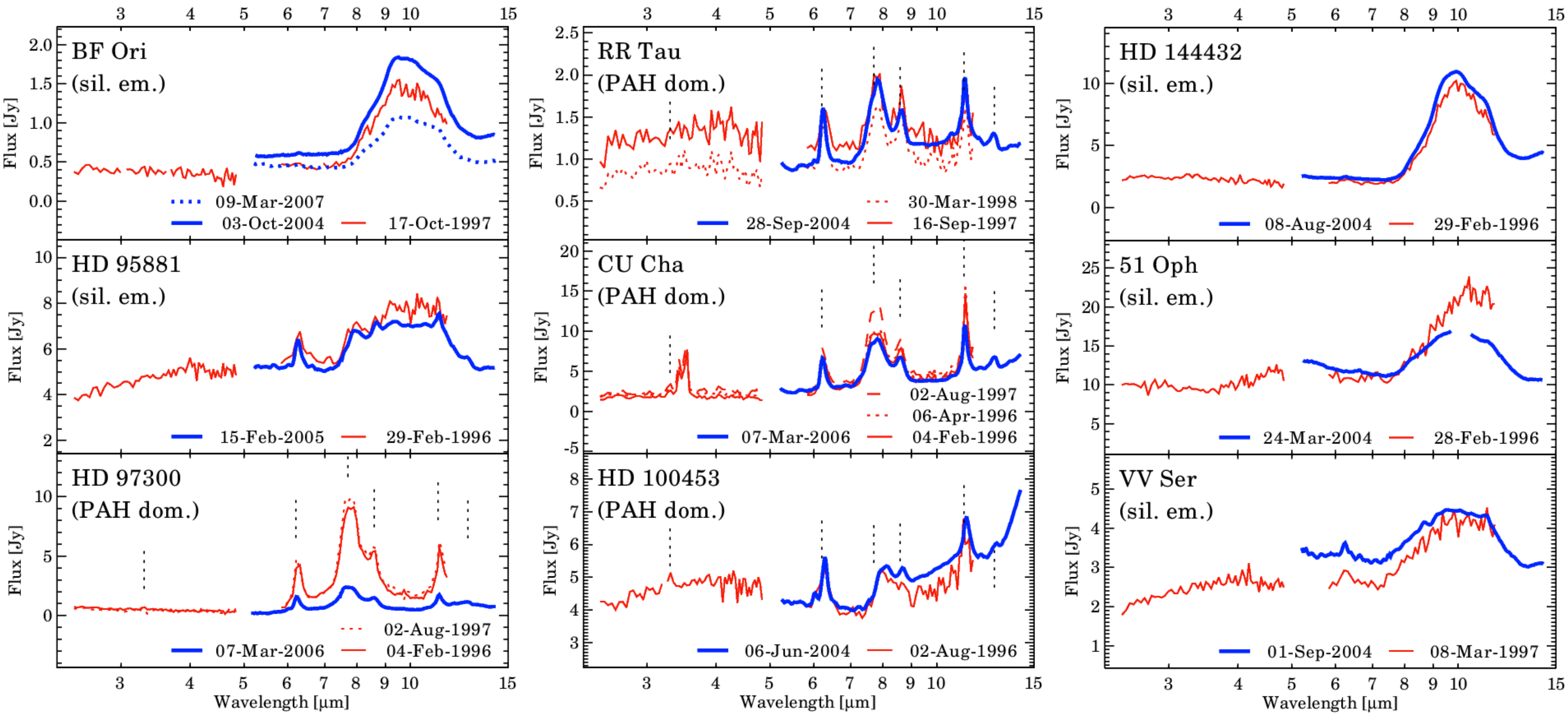
- **SV Cep indicated that infrared variability can occur even if the luminosity of the star is constant!**
- **Prediction: there might be many other Herbig stars, which are constant in the optical but variable in the infrared. AB Aur!**
- **It is the disk structure which changes, and we are not sure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





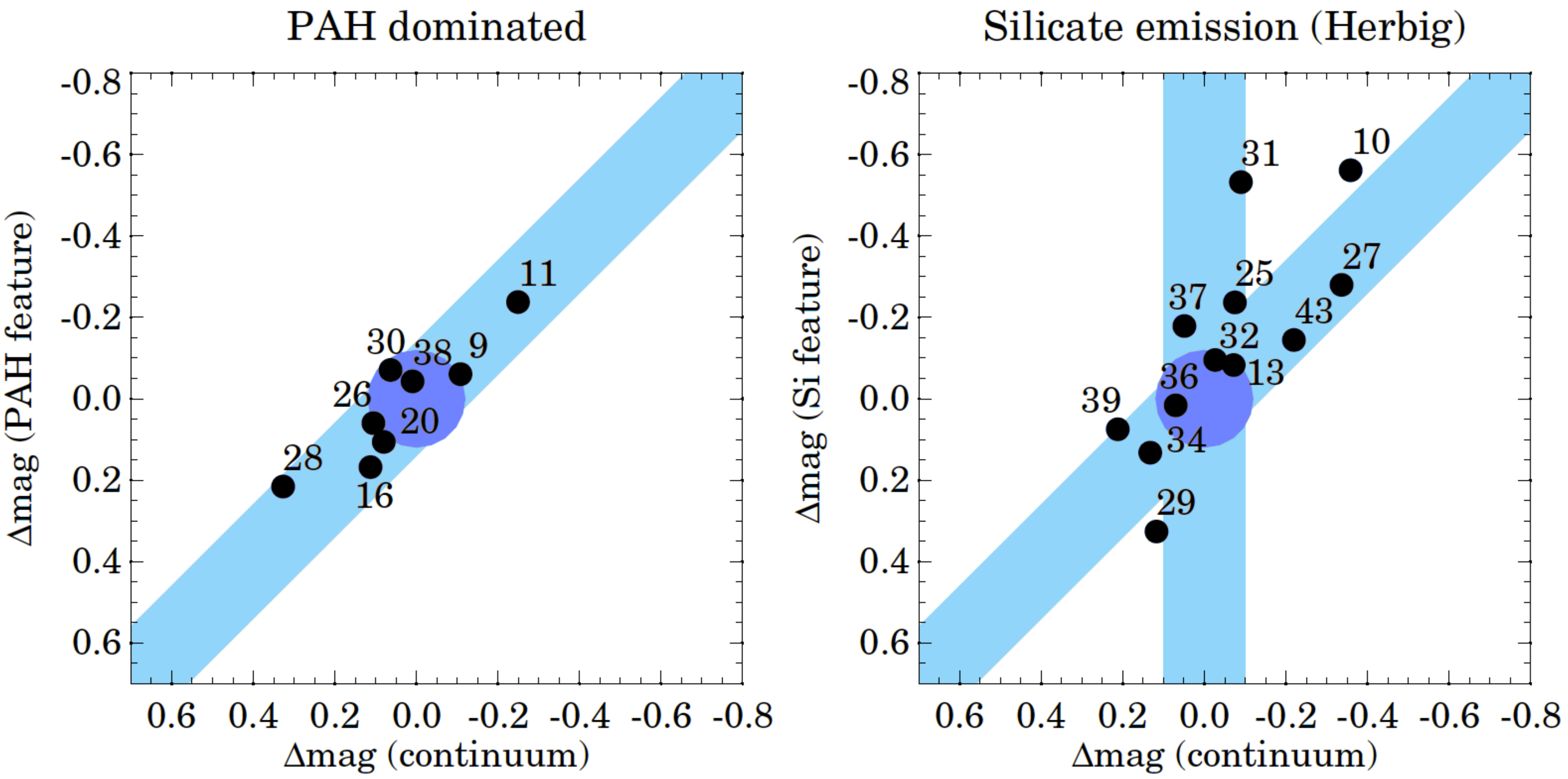
Shenavrin et al. 2012

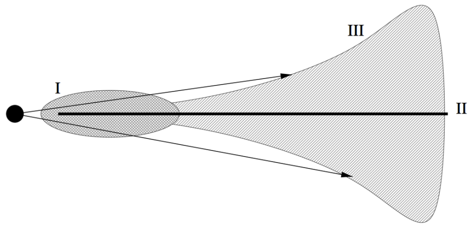
Mid-infrared spectral variability atlas



Kóspál et al. 2012

Mid-infrared spectral variability atlas





Kóspál et al. 2012

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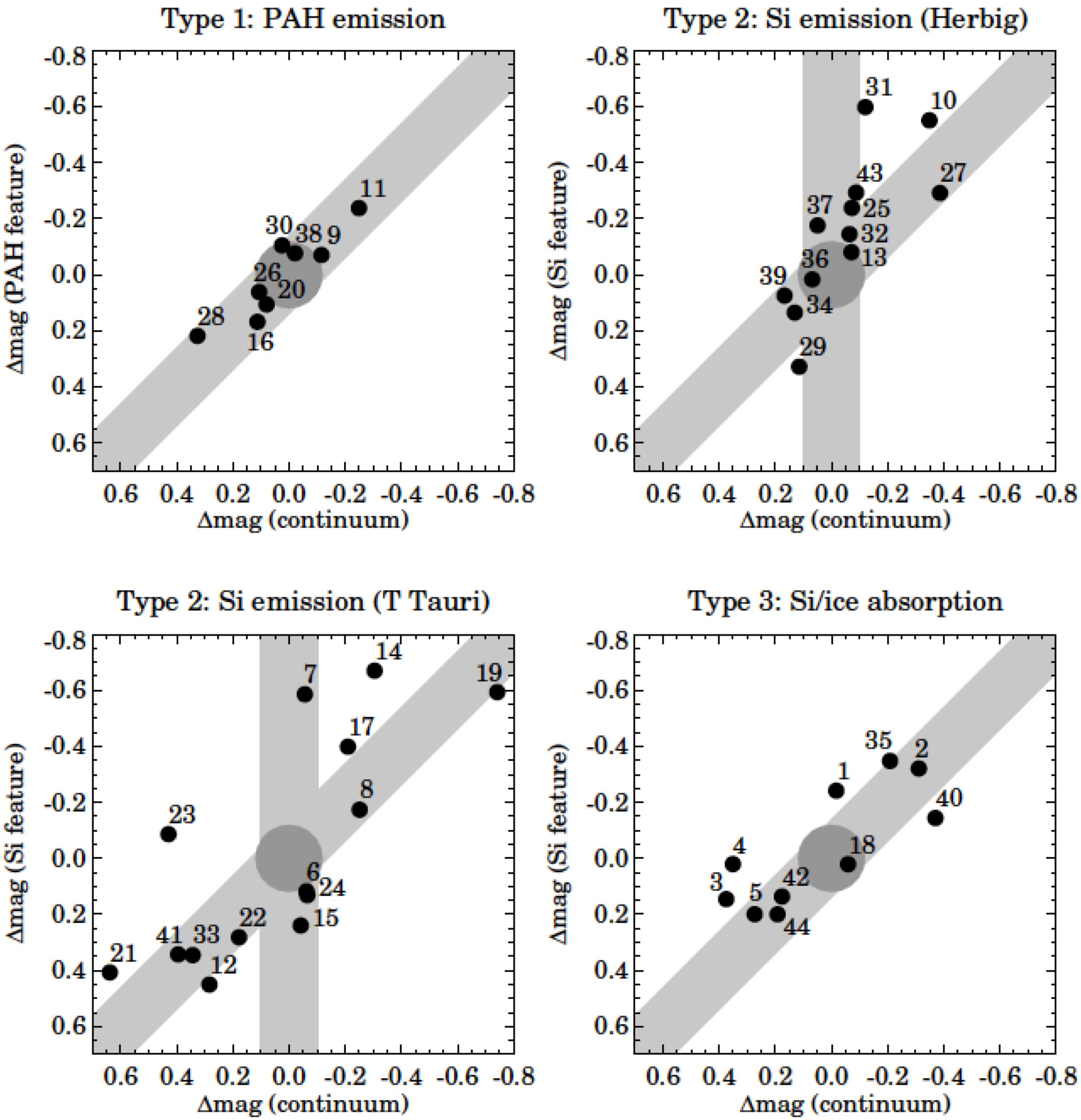
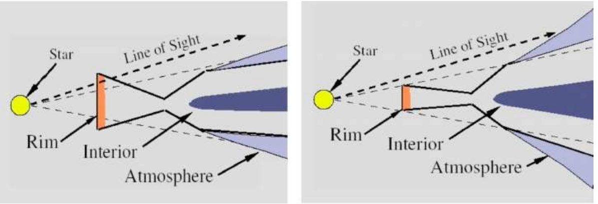


Type 1: PAH emission

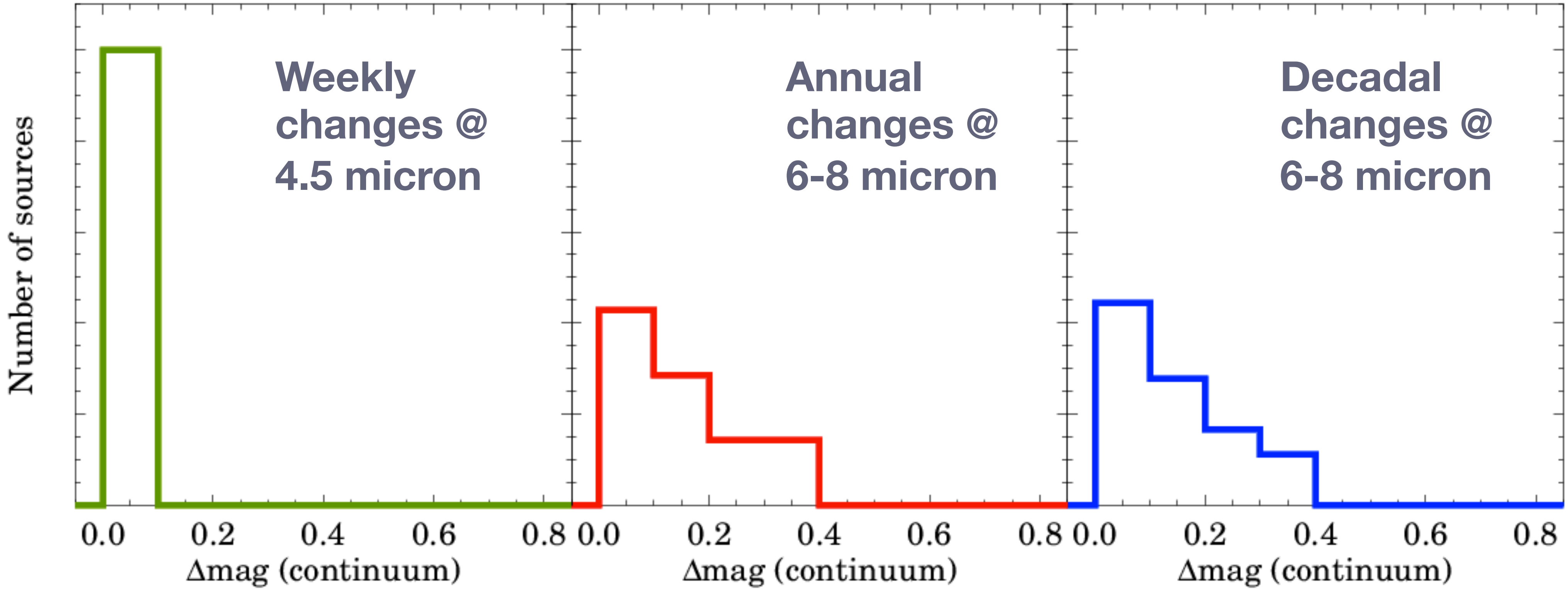
Type 2: Si emission (Herbig)

Type 2: Si emission (T Tauri)

Type 3: Si/ice absorption



Weekly/annual/decadal variability timescales

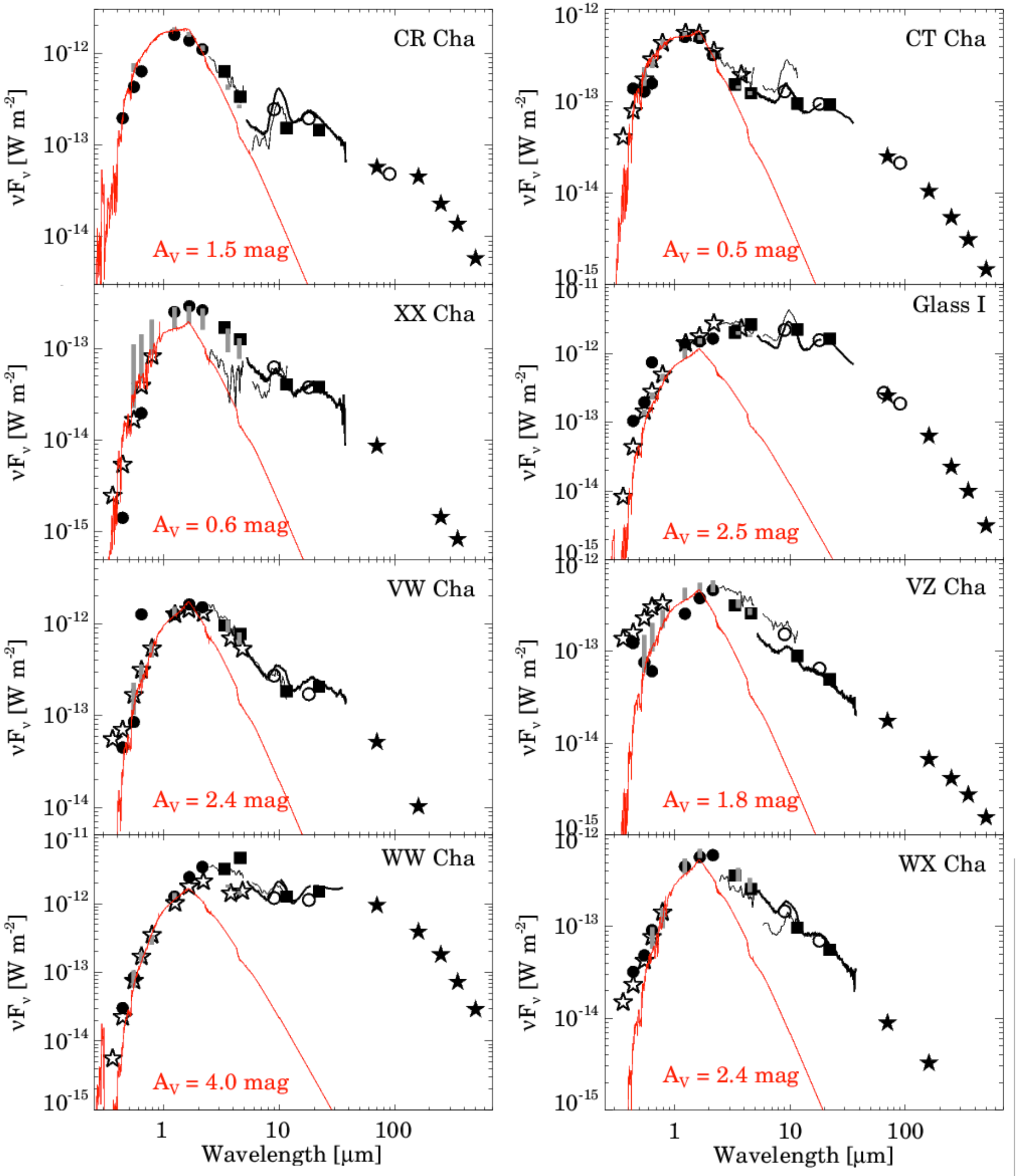


Typical MIR variability timescales in Herbig stars: week < t < year.
Typical dynamical timescale of the inner disk.

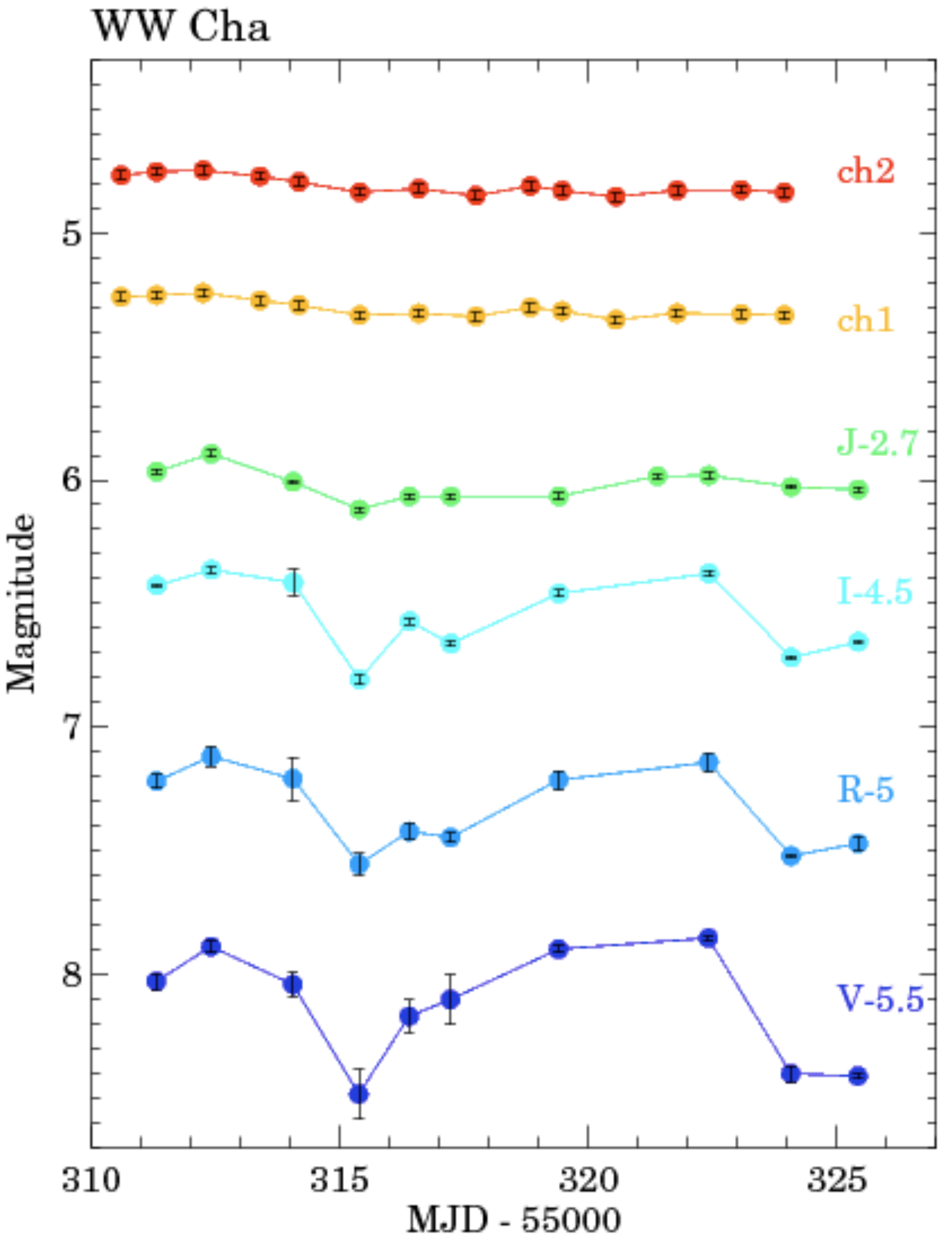
Optical-infrared monitoring of 8 T Tau stars

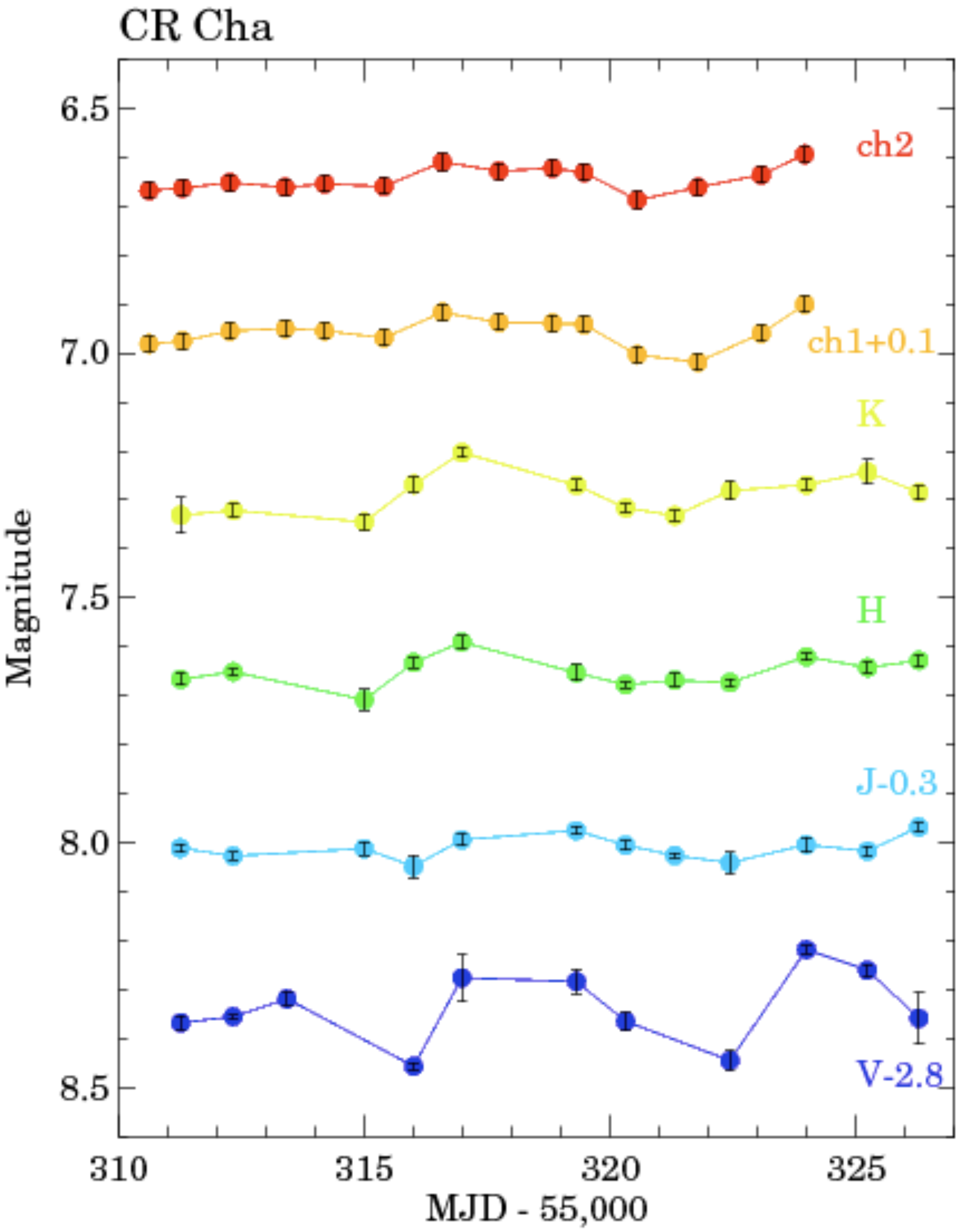
Source list	
CR Cha	VW Cha
CT Cha	VZ Cha
Glass I	WW Cha
VW Cha	XX Cha

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

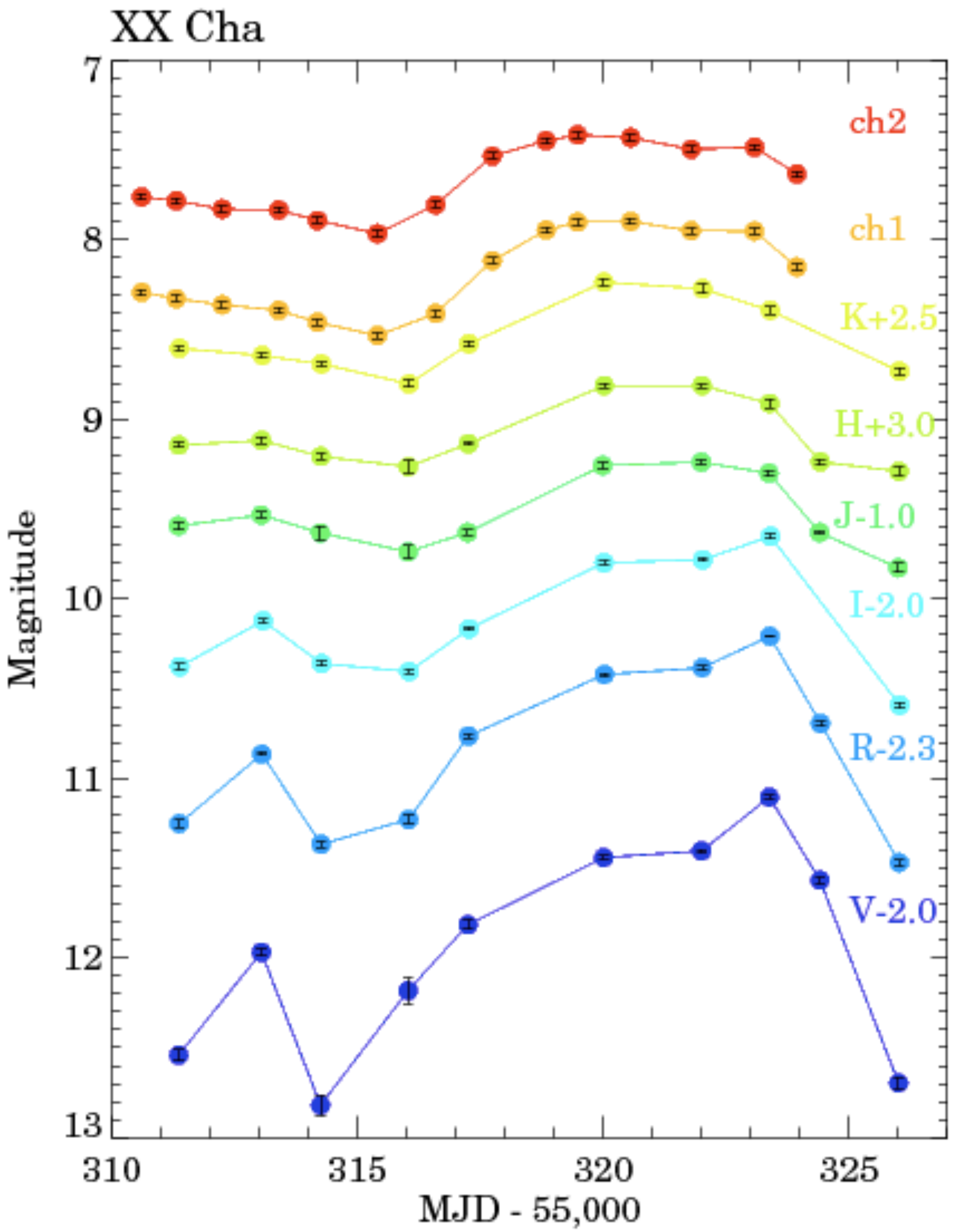


Light curves



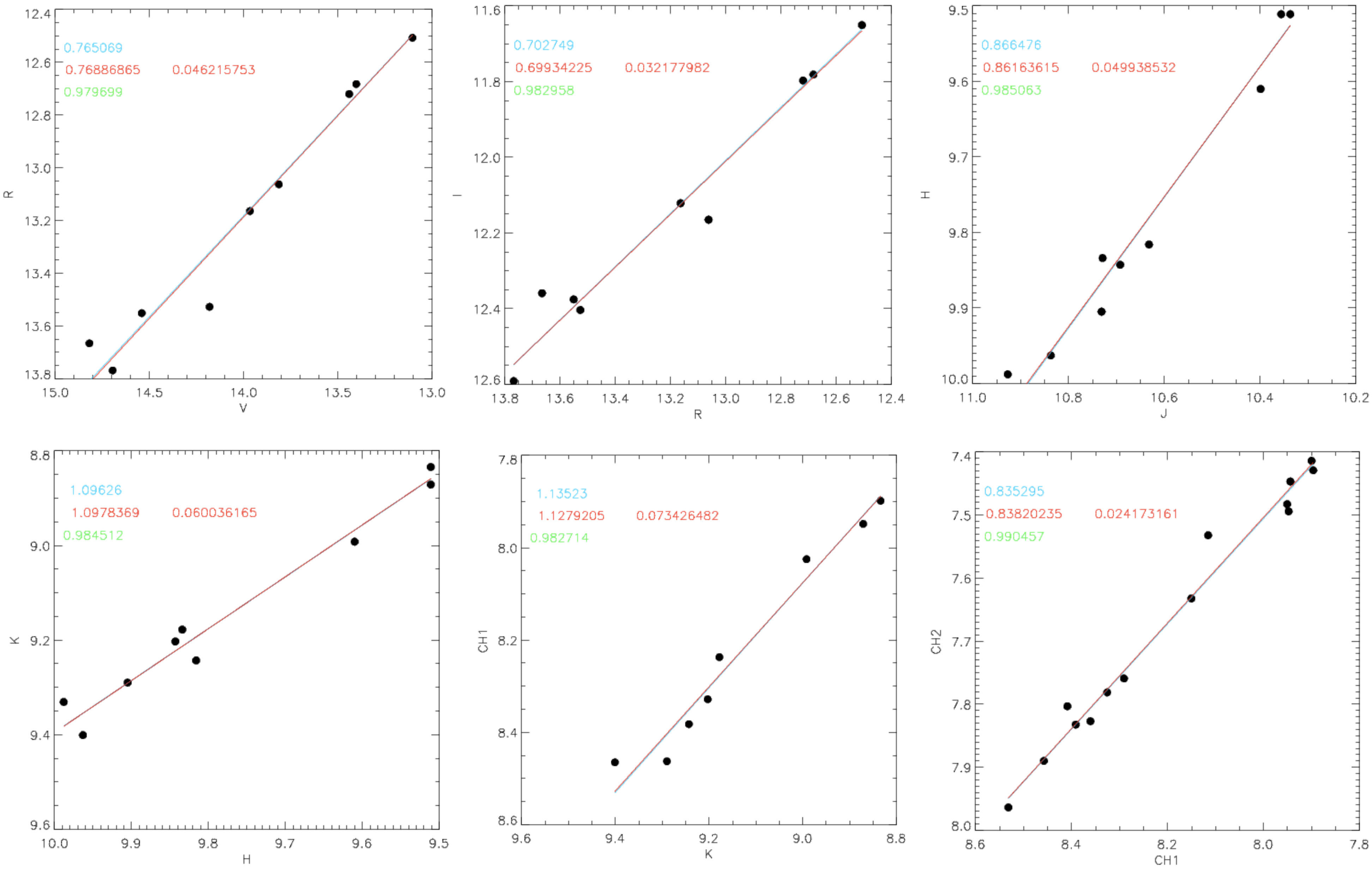


Light curves

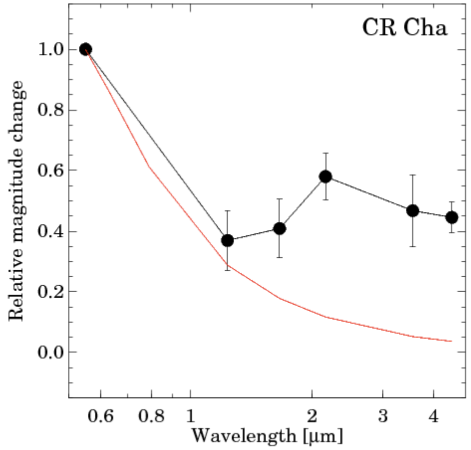


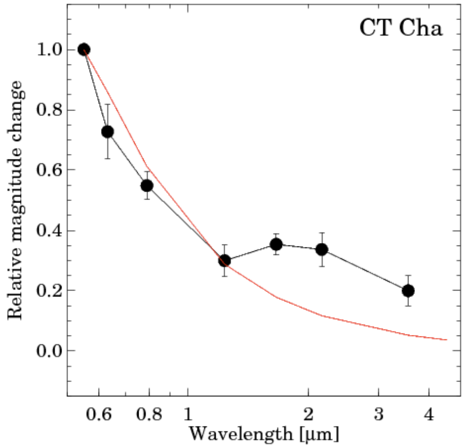
- Variability on ~1 week timescale
- Optical and infrared light curves are similar, and are in the same phase
- The amplitudes change with wavelength: always highest in the V-band, and decrease between R and J
- In the infrared two types of behaviour: the amplitude of the flux change either decreases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

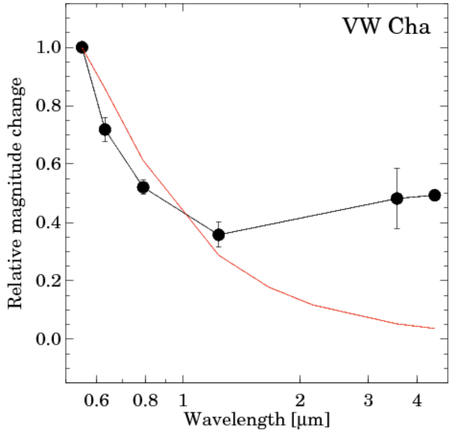
Scatter plots: XX Cha

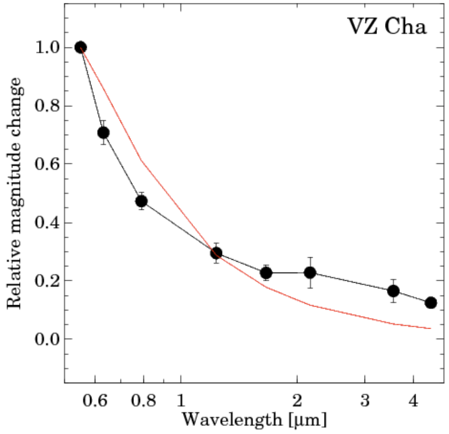


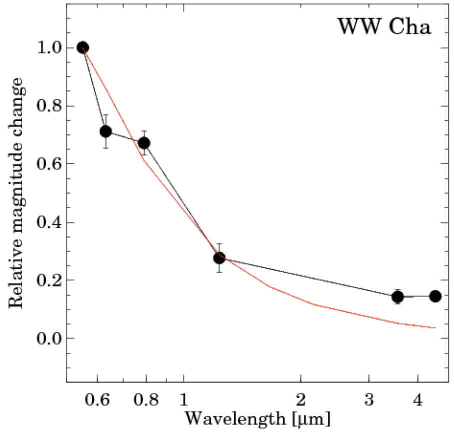
Relative magnitude changes

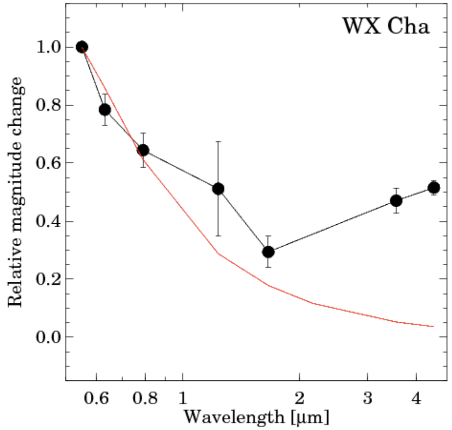


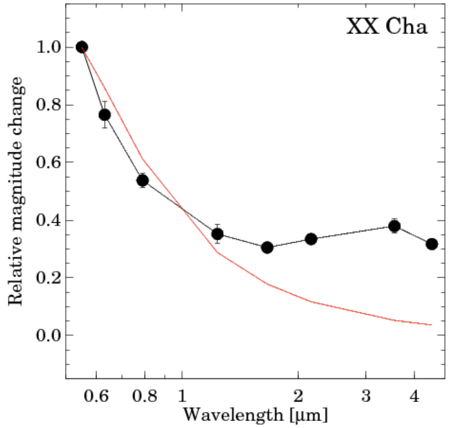










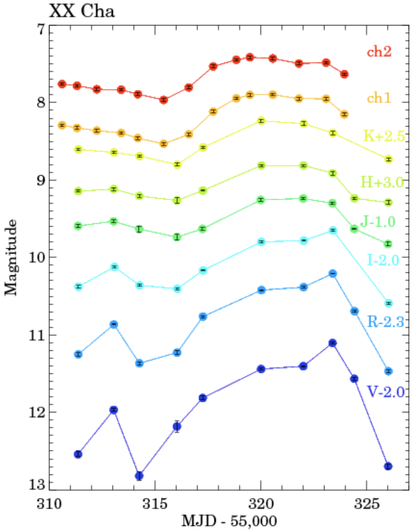


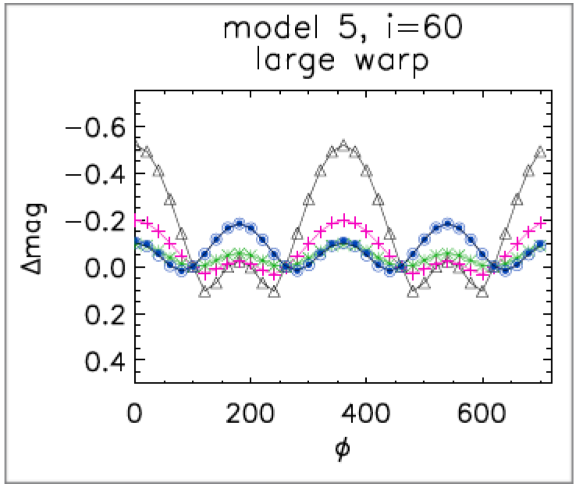
Variable extinction (red line) can be excluded

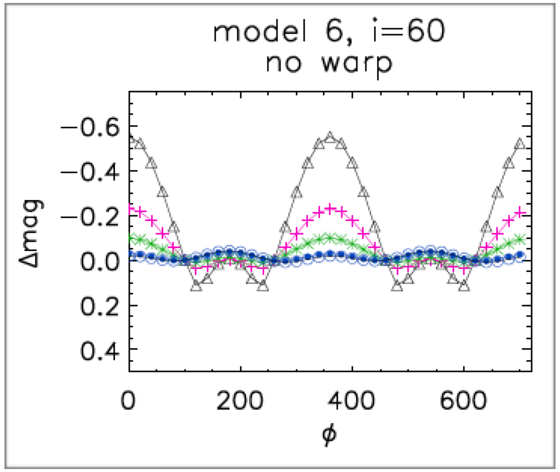
Rotating hotspots + warped disk model

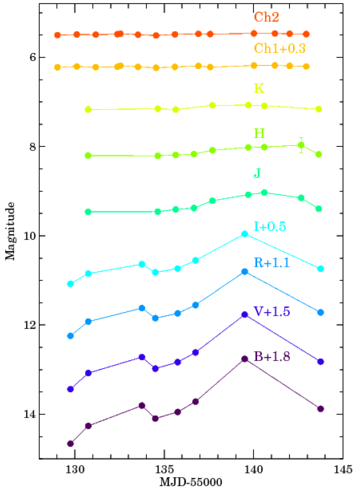
XX Cha

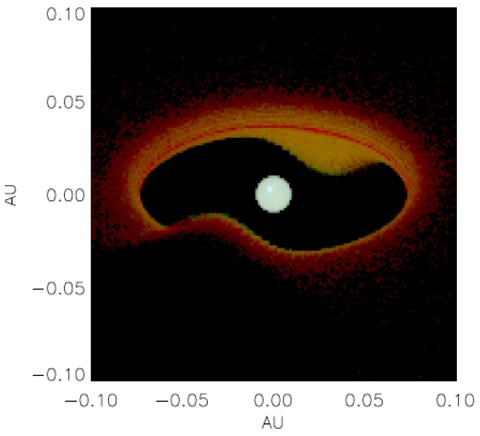
RR Tau











No warp

Geometrical model: star + 2 hot spots + truncated disk + two warps/no warp (Kesseli et al. 2016)

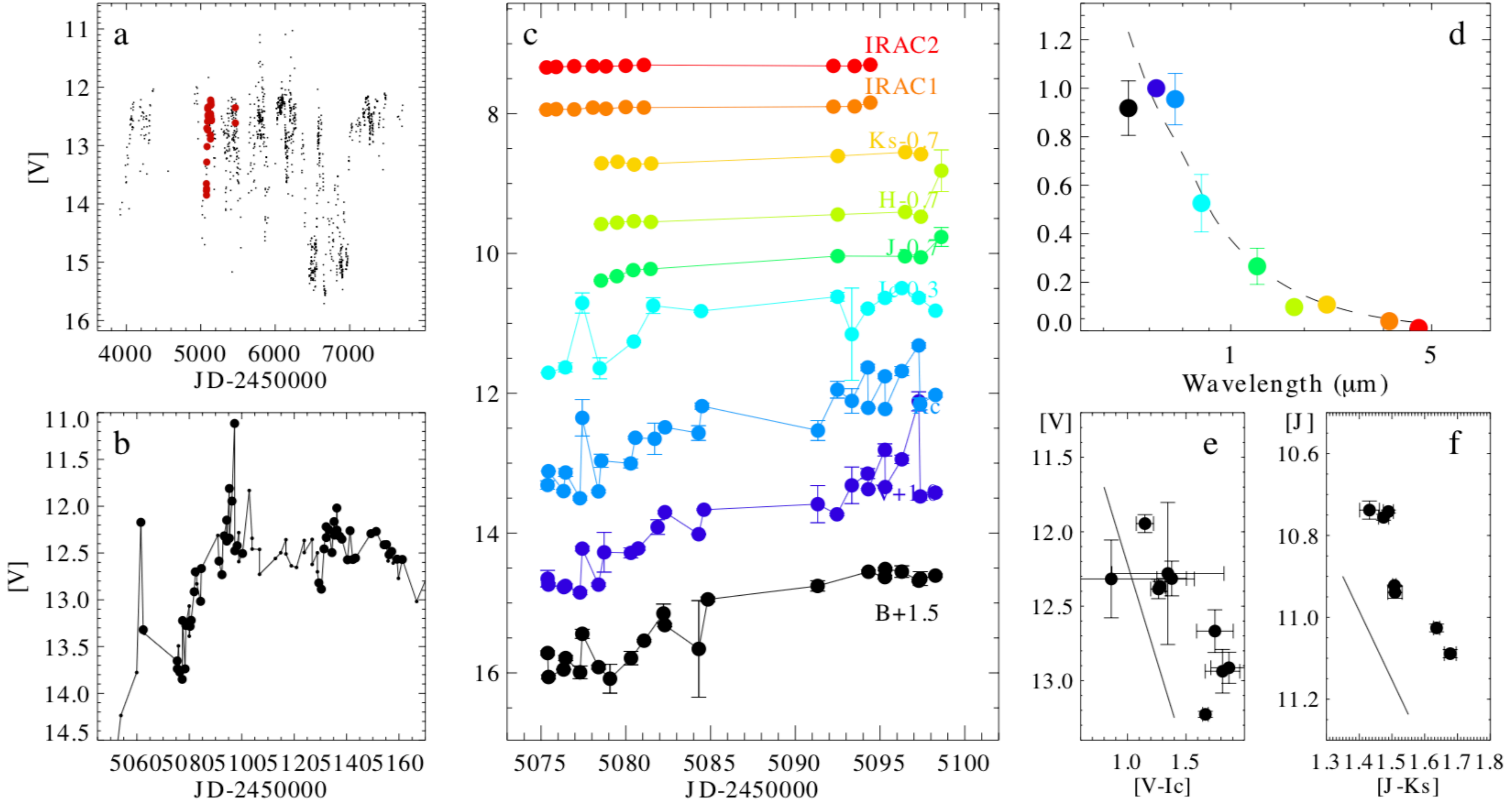
Herbig Ae/Be disks

Sample: 8 variable Herbig Ae/Be stars (BF Ori, RR Tau, UX Ori, V517 Cyg, SV Cep, VV Ser, VX Cas, WW Vul)

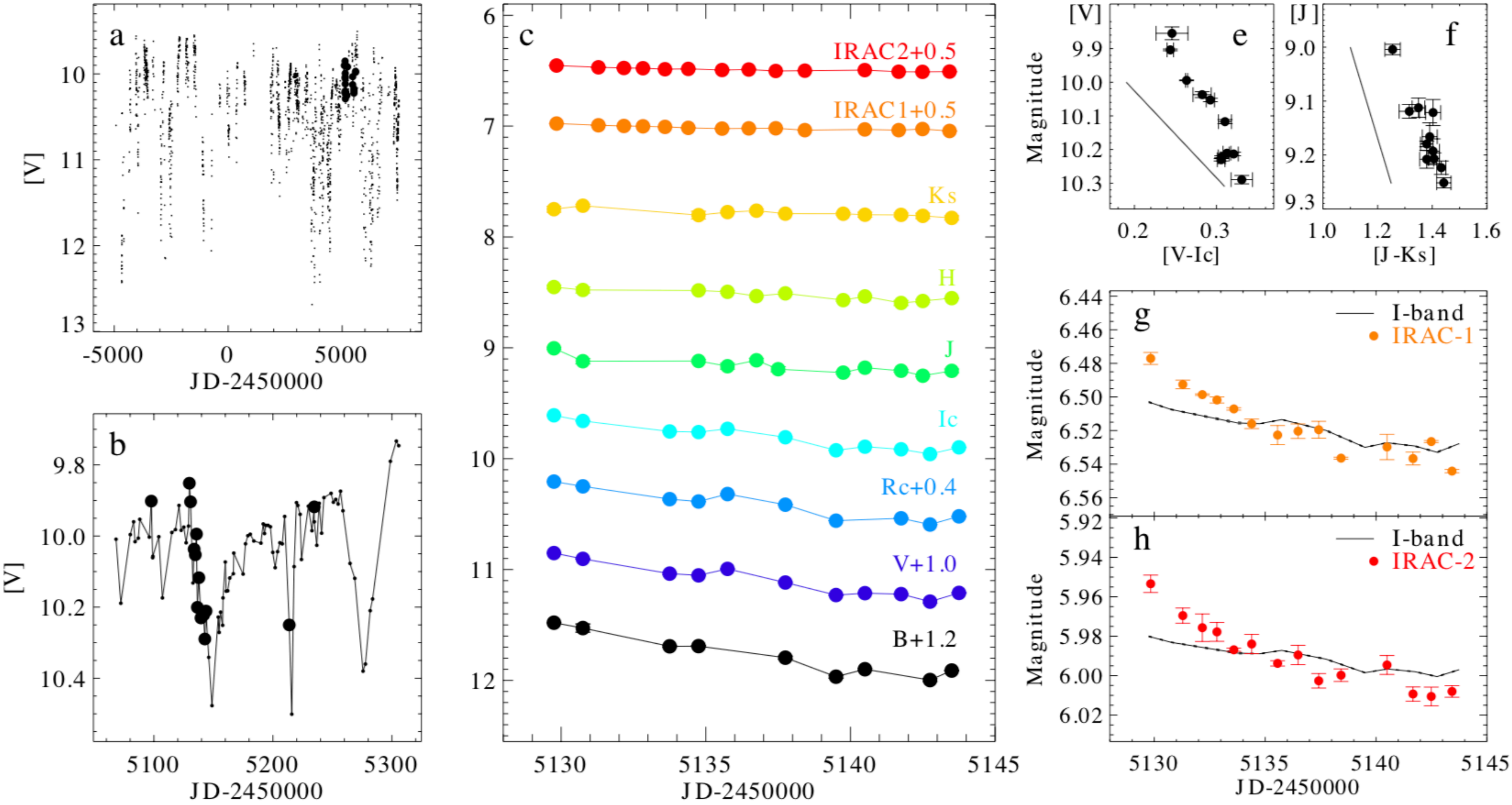
- BVRIJHK[3.6][4.5] 14 epochs monitoring in 2009

Science goals: study of the origin of variability

V517 Cyg


a
[V]
11
12
13
14
15
16
4000
5000
6000
7000
JD-2450000
b
[V]
11.0
11.5
12.0
12.5
13.0
13.5
14.0
14.5
5060
5080
5100
5120
5140
5160
JD-2450000
c
IRAC2
IRAC1
Ks-0.7
H-0.7
J-0.7
I-0.3
Ic
V+1
B+1.5
8
10
12
14
16
5075
5080
5085
5090
5095
5100
JD-2450000
d
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1
5
Wavelength (μm)
e
[V]
11.5
12.0
12.5
13.0
1.0
1.5
[V-Ic]
f
[J]
10.6
10.8
11.0
11.2
1.3
1.4
1.5
1.6
1.7
1.8
[J-Ks]

BF Ori


a
[V]
10
11
12
13
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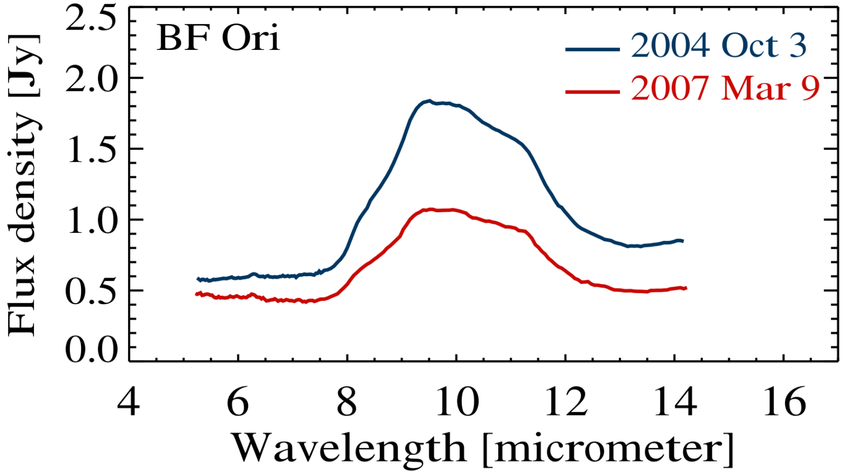
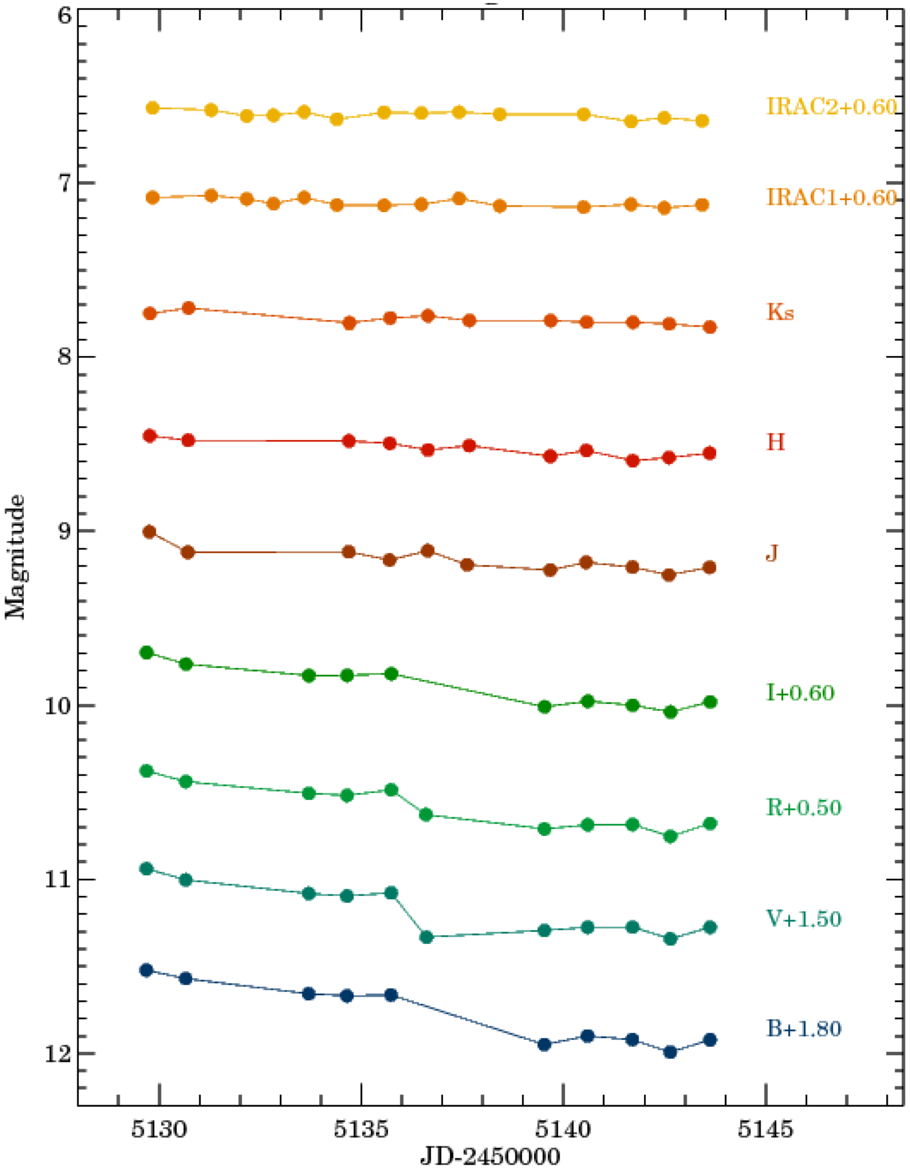
0
5000
JD-2450000
b
[V]
9.8
10.0
10.2
10.4
5100
5200
5300
JD-2450000
c
6
7
8
9
10
11
12
IRAC2+0.5
IRAC1+0.5
Ks
H
J
Ic
Rc+0.4
V+1.0
B+1.2
5130
5135
5140
5145
JD-2450000
e
[V]
Magnitude
9.9
10.0
10.1
10.2
10.3
0.2
0.3
[V-Ic]
f
[J]
9.0
9.1
9.2
9.3
1.0
1.2
1.4
1.6
[J-Ks]
g
Magnitude
I-band
IRAC-1
6.44
6.46
6.48
6.50
6.52
6.54
6.56
h
Magnitude
I-band
IRAC-2
5.92
5.94
5.96
5.98
6.00
6.02
5130
5135
5140
5145
JD-2450000

MID-INFRARED SPECTRAL VARIABILITY

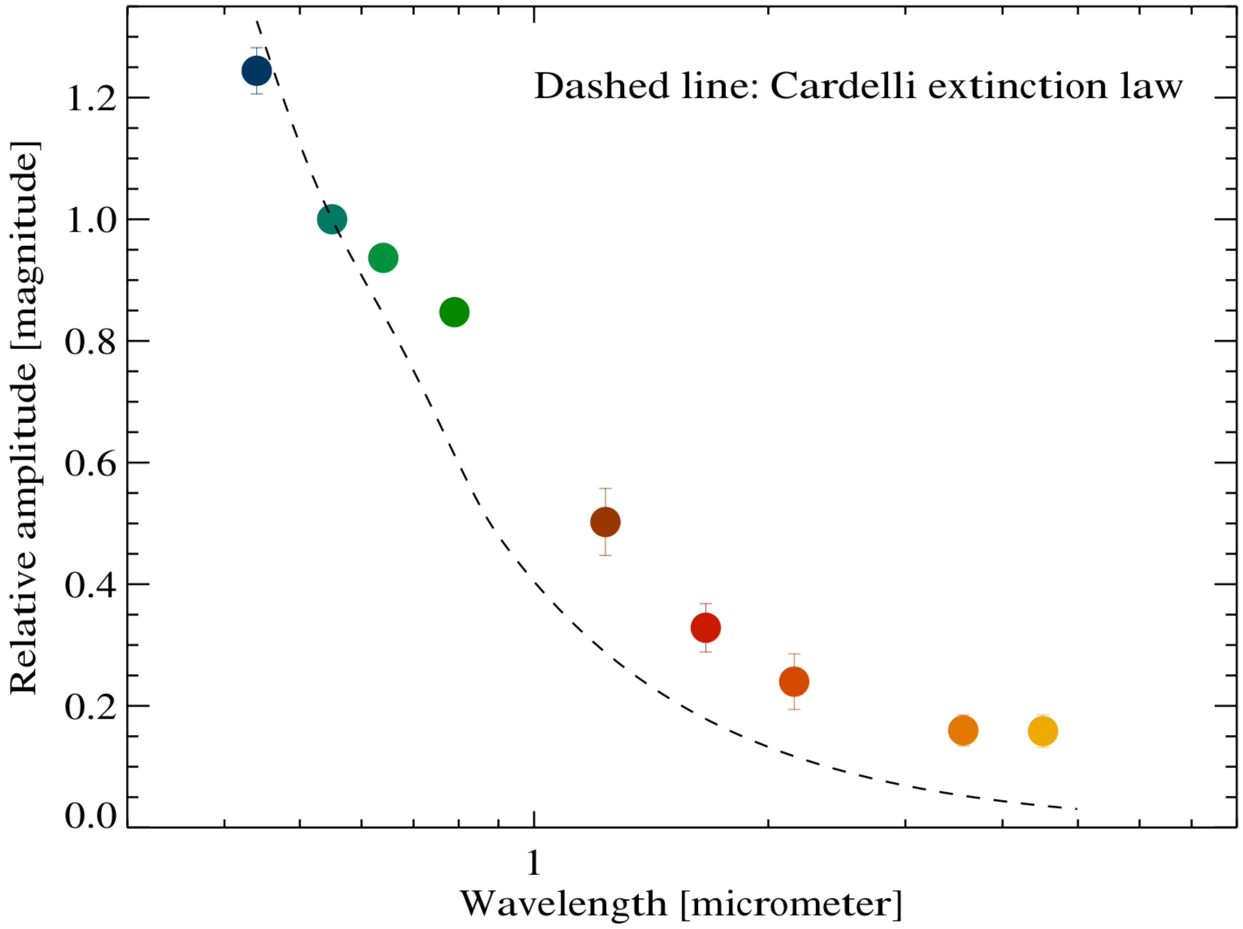
- **Kóspál et al. (2012) reported that two Spitzer/IRS spectra of BF Ori, taken with a 2.5 year time difference, have significantly changed.**
- **In order to follow up this finding at shorter wavelengths, we monitored BF Ori at BVRIJHK and Spitzer/IRAC 3.6 and 4.5µm, for 14 days in 2009 October.**





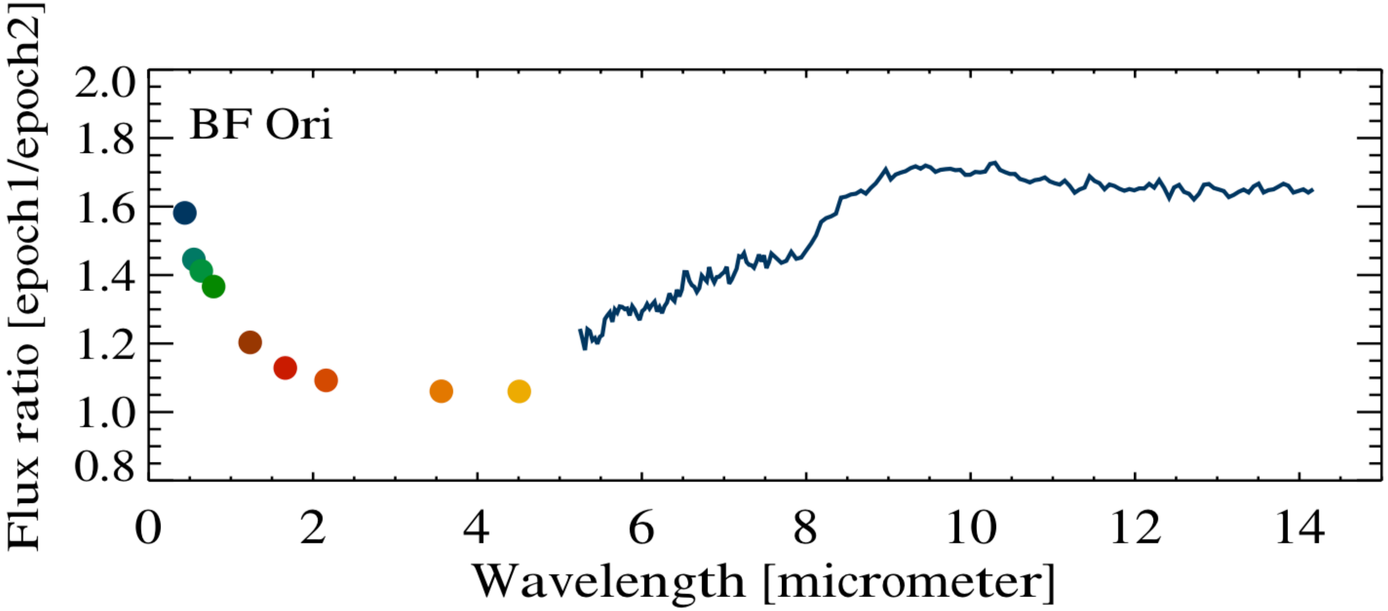
MID-INFRARED SPECTRAL VARIABILITY

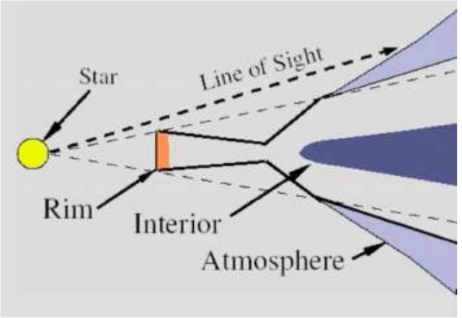
- **A general fading trend was observed. We computed variability amplitudes, normalized to the V-band.**



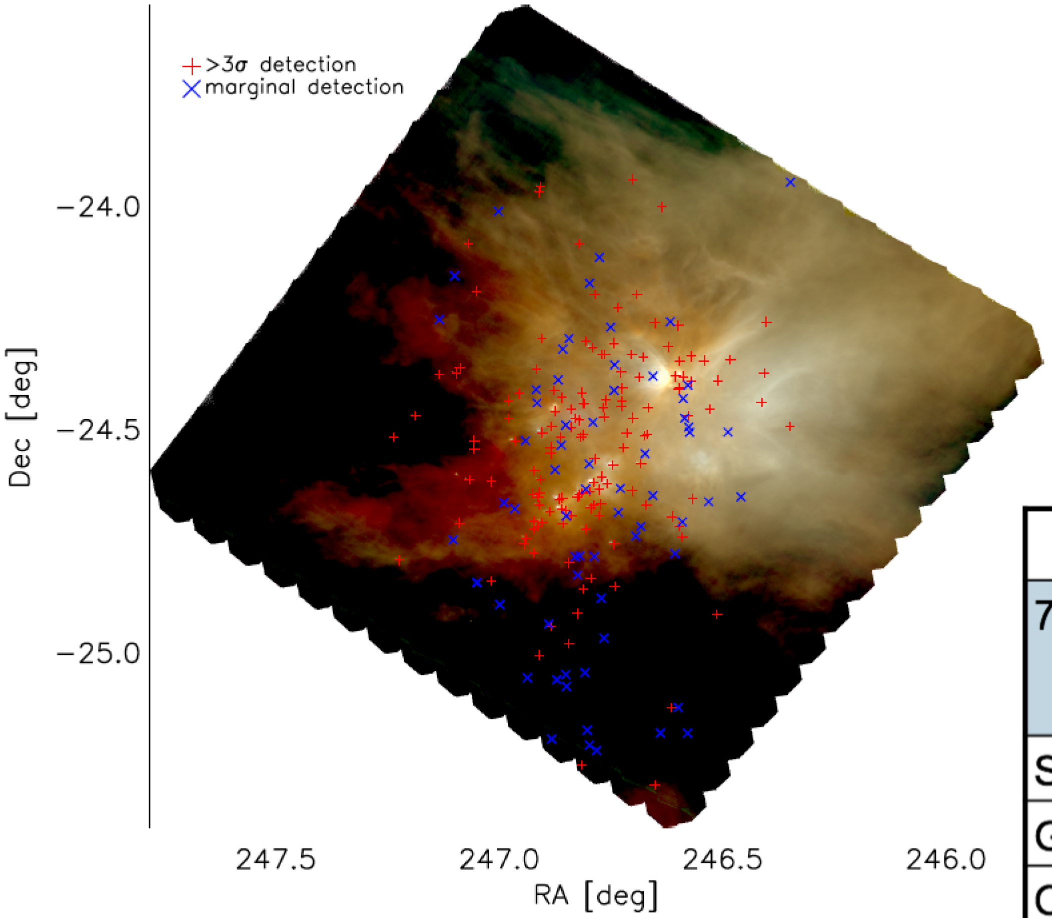
MID-INFRARED SPECTRAL VARIABILITY

- **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:**





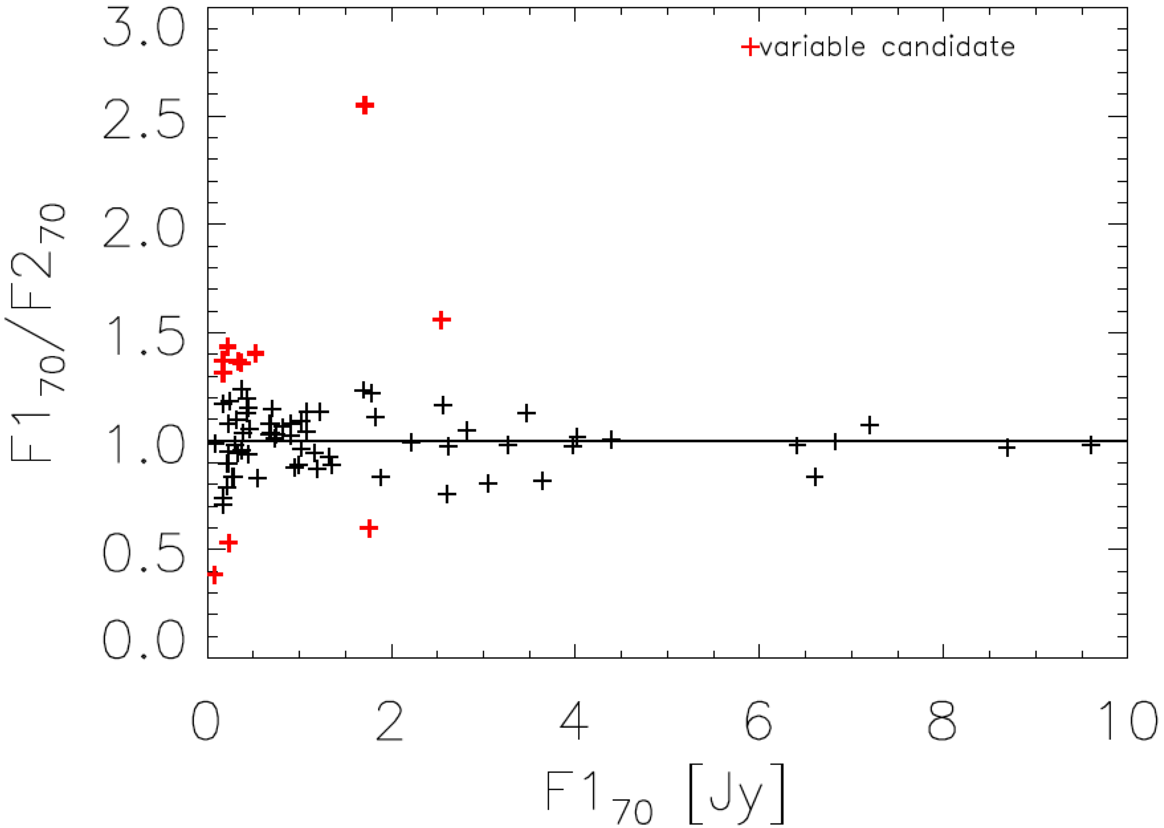
Far-infrared variability in rho Ophiuchi



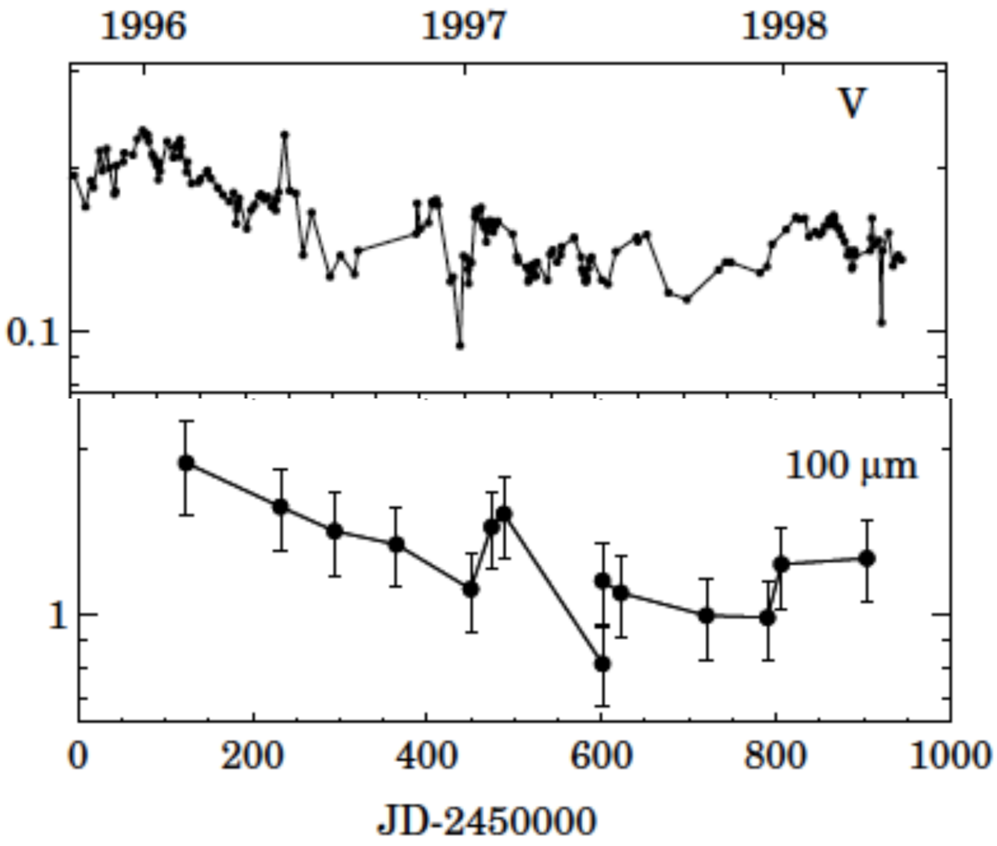
Total number of YSOs: 458		
70 µm detections	Significant (> 3 sigma)	Marginal (1 < sigma < 3)
Spitzer MIPS	11	
Gould Belt Survey	115	56
Our PACS observations	141	65
160 µm detections	Significant (> 3 sigma)	Marginal (1 < sigma < 3)
Spitzer MIPS	0	
Gould Belt Survey	93	37
Our PACS observations	94	35

Far-infrared variability in rho Ophiuchi

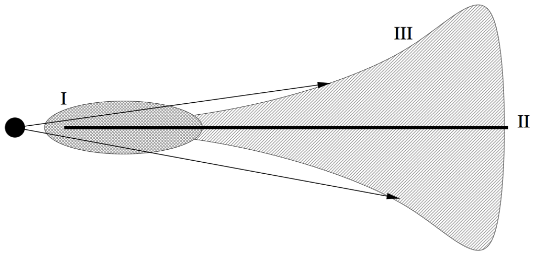
- We compared the 70 µm fluxes of 89 YSOs detected both in the Herschel Gould Belt Survey and in our observations.
- In 11 cases (12 %) the flux difference between the two epochs, separated by about 2 years, exceeded 30% (marked in red in the figure)
- These sources are strong candidates for far-infrared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



Far-infrared variability: screen effect?

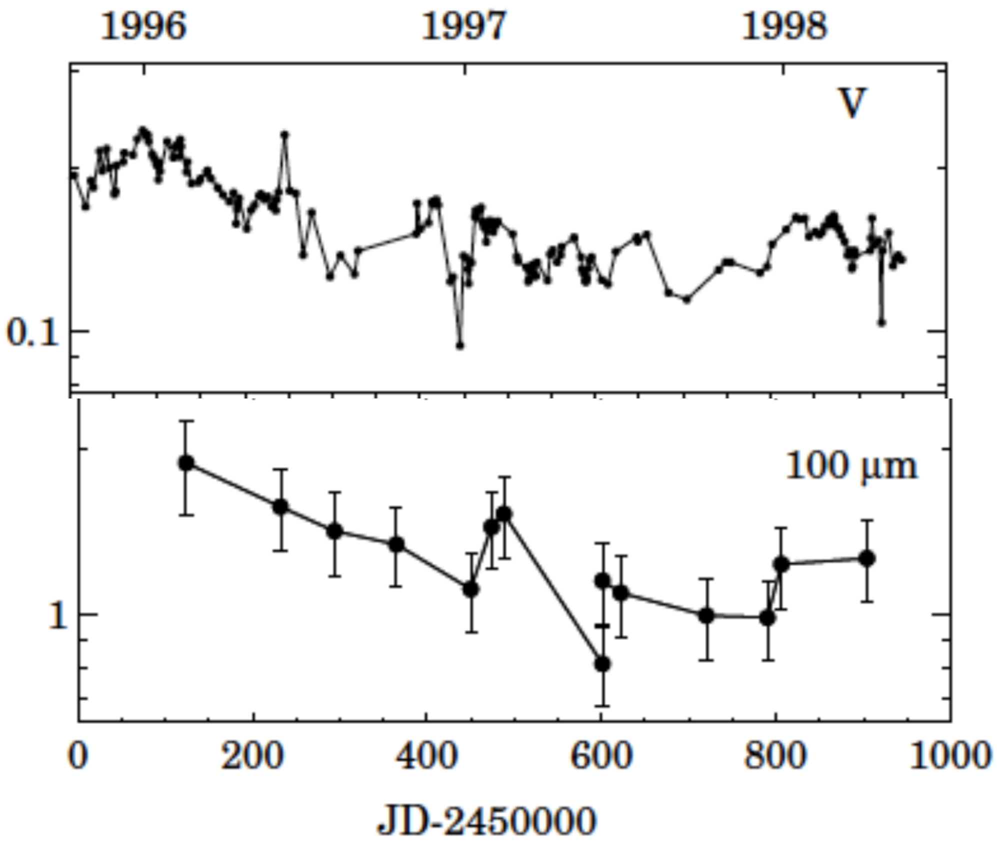


- **SV Cep**: correlation between optical and FIR fluxes
- The outer disk responds to the changing radiation from the central source
- It is the optically thin component, and it must be well visible from the centre (flared disk geometry)



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

Far-infrared variability: screen effect?



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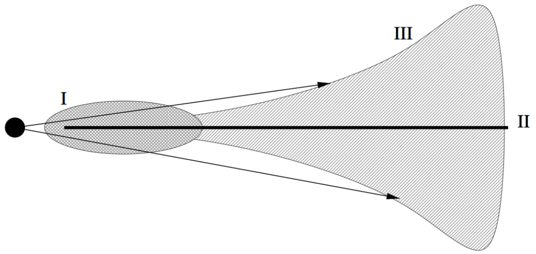
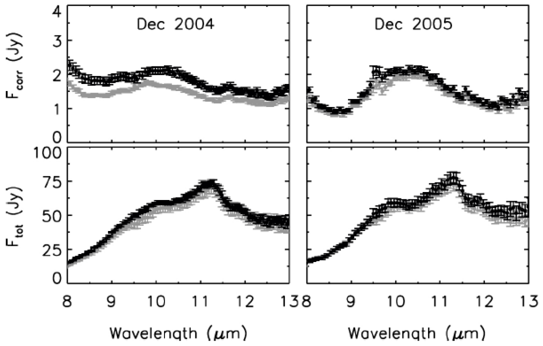


FIR variability can be used to study processes in the inner disk

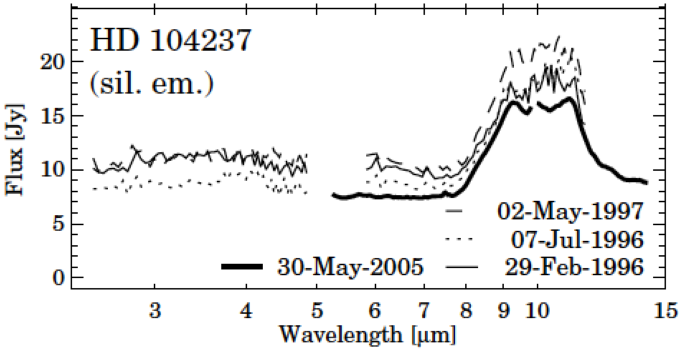
A systematic interferometric variability program

- **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**

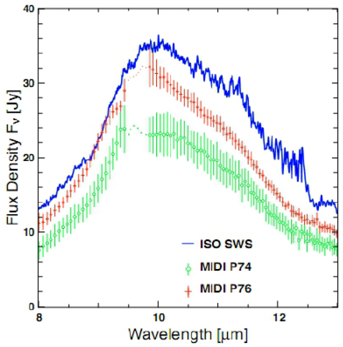
Goal: study re-arrangements in the inner regions; check if image reconstruction with Matisse could be performed



Panic et al. 2014

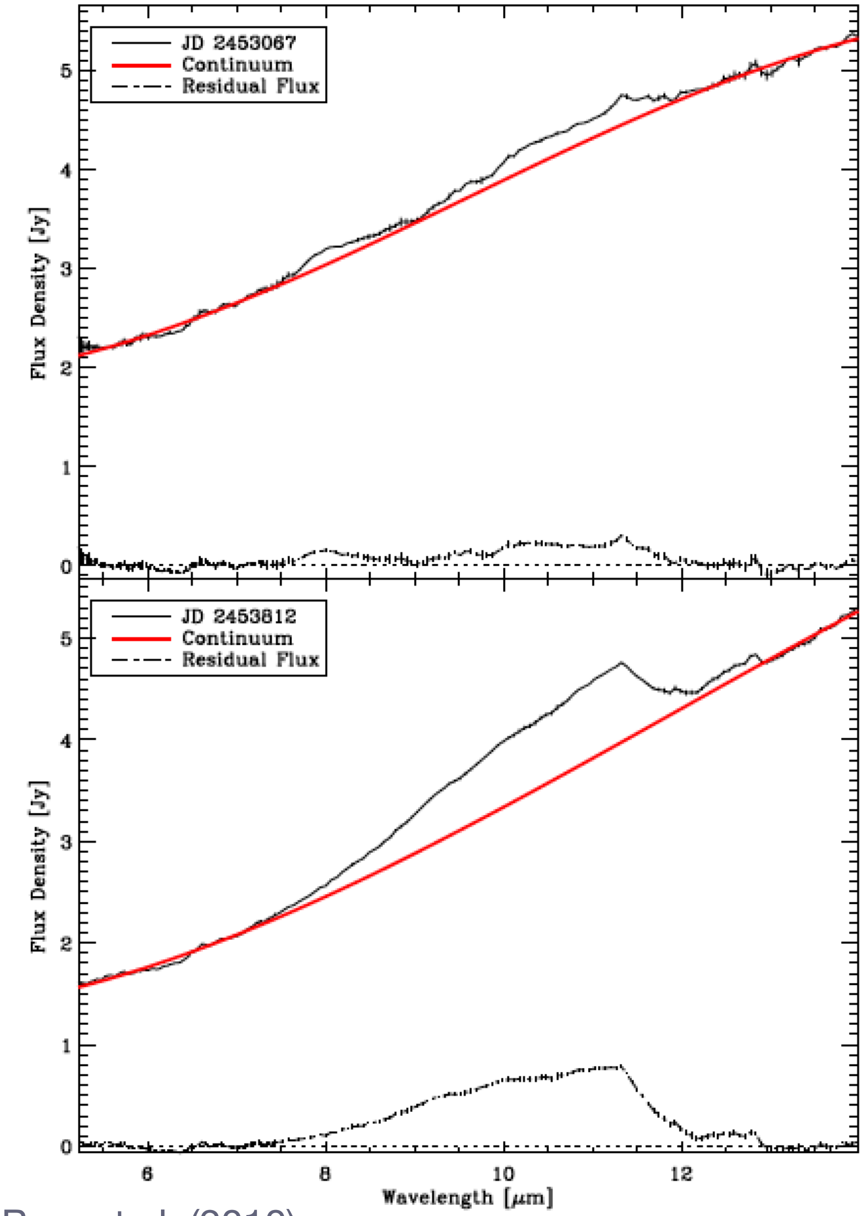


Kóspál et al. 2012



Di Folco et al. 2009

An interferometric monitoring: DG Tau



Bary et al. (2010)

K6V-type classical T Tauri star

Relatively high accretion rate

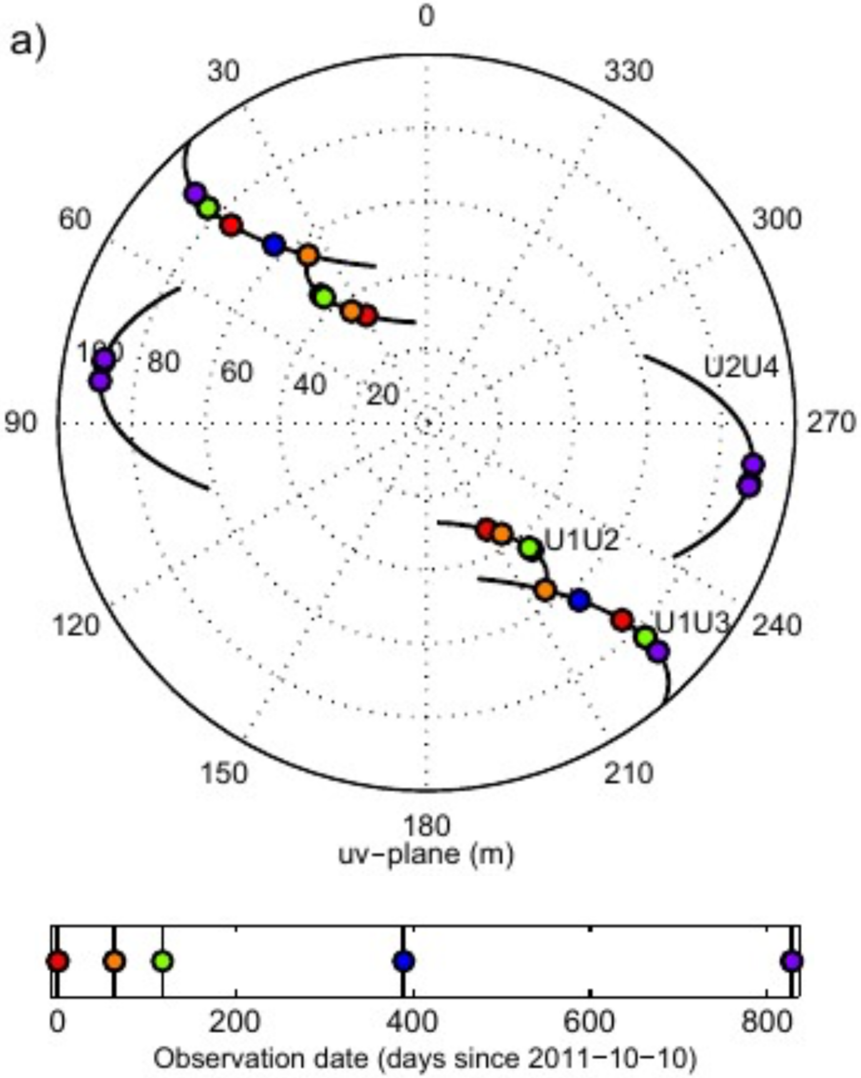
CARMA: R_{out} = 70-80 au, inclination=28 deg, mass=0.01-0.07 M_{sun} (Isella et al. 2010)

Spitzer: strongly variable 10 micron silicate feature and continuum (Bary et al. 2009)

The feature may completely disappear

No explanation for the variability yet

DG Tau: MIDI observations



- Dedicated observing program with VLTI/MIDI
- In total, 12 interferometric observations
- Low-resolution 8-13um spectra
- Most observations have the same position angle

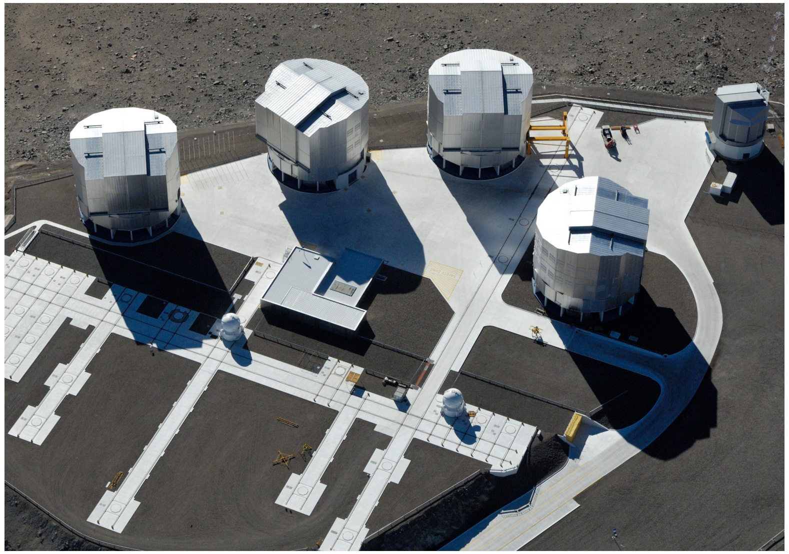
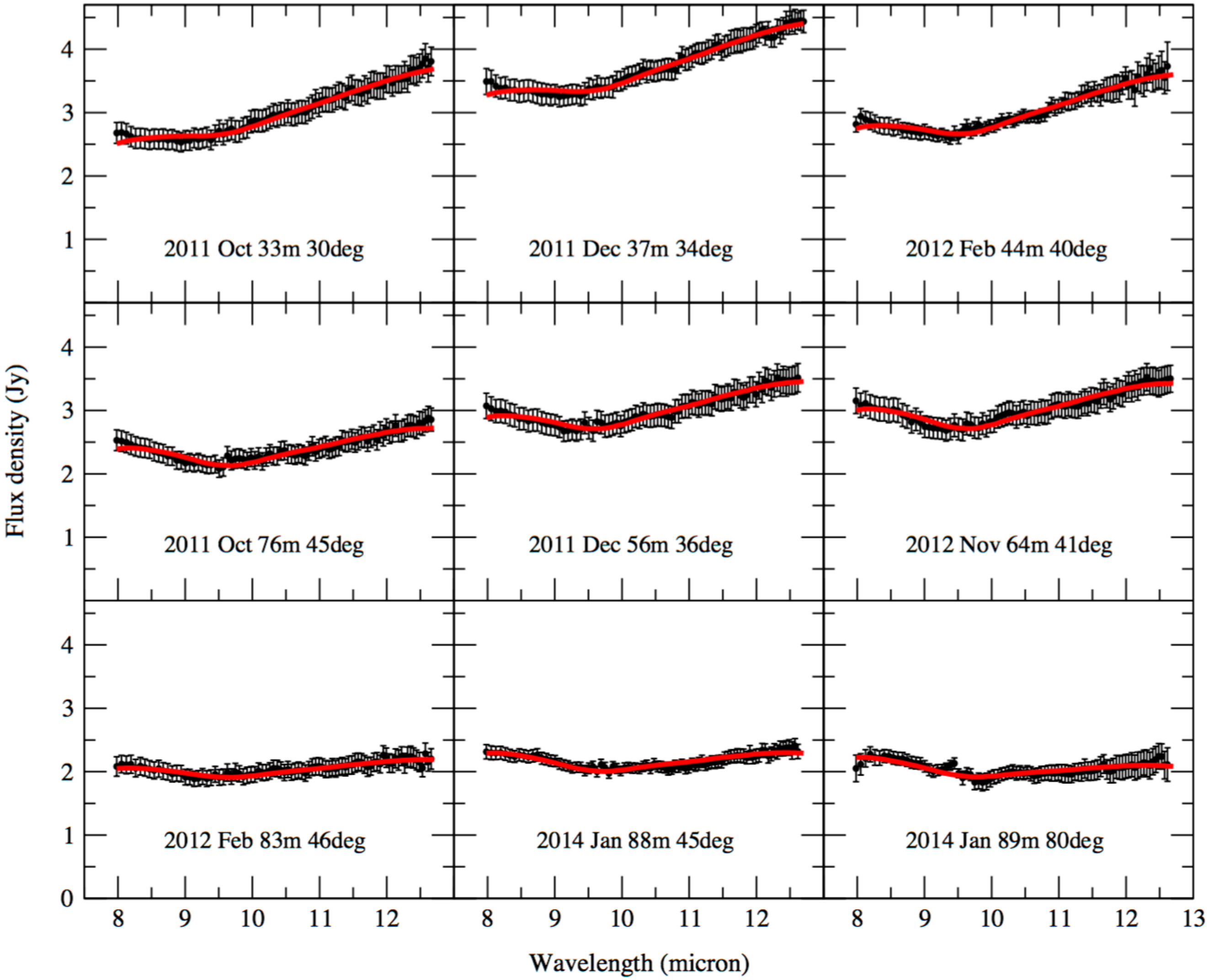


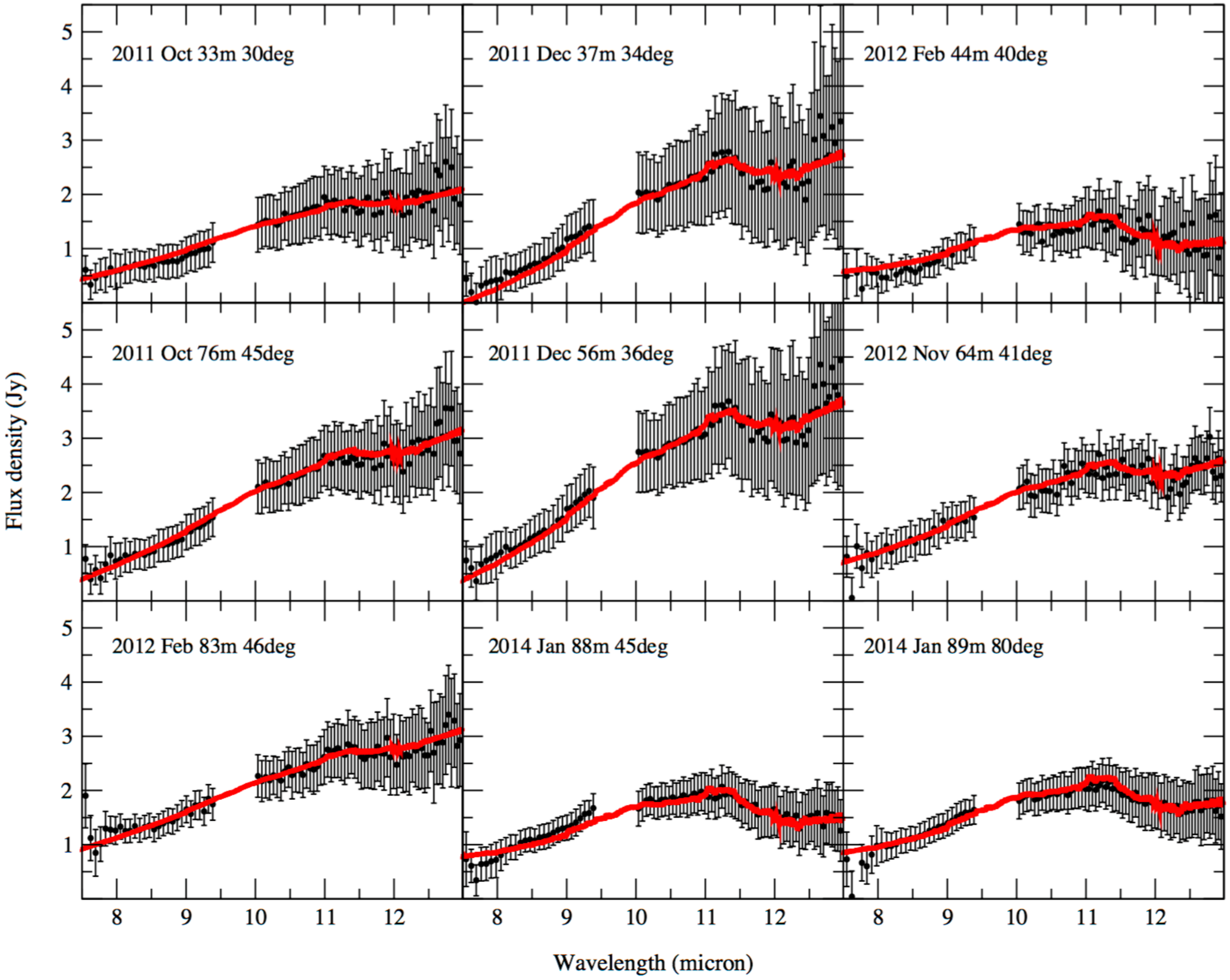
Image: ESO

DG Tau: correlated spectra (<1-2 au)



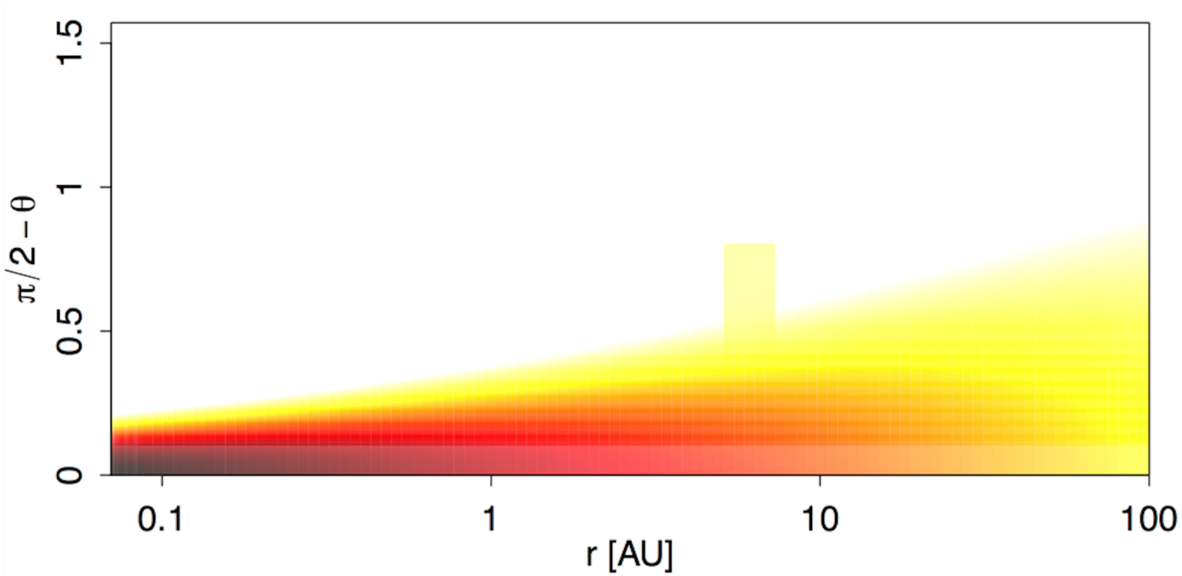
- varying continuum
- absorption feature
- small amorphous silicate grains
- no time variability in the feature
- very different from the total flux spectrum

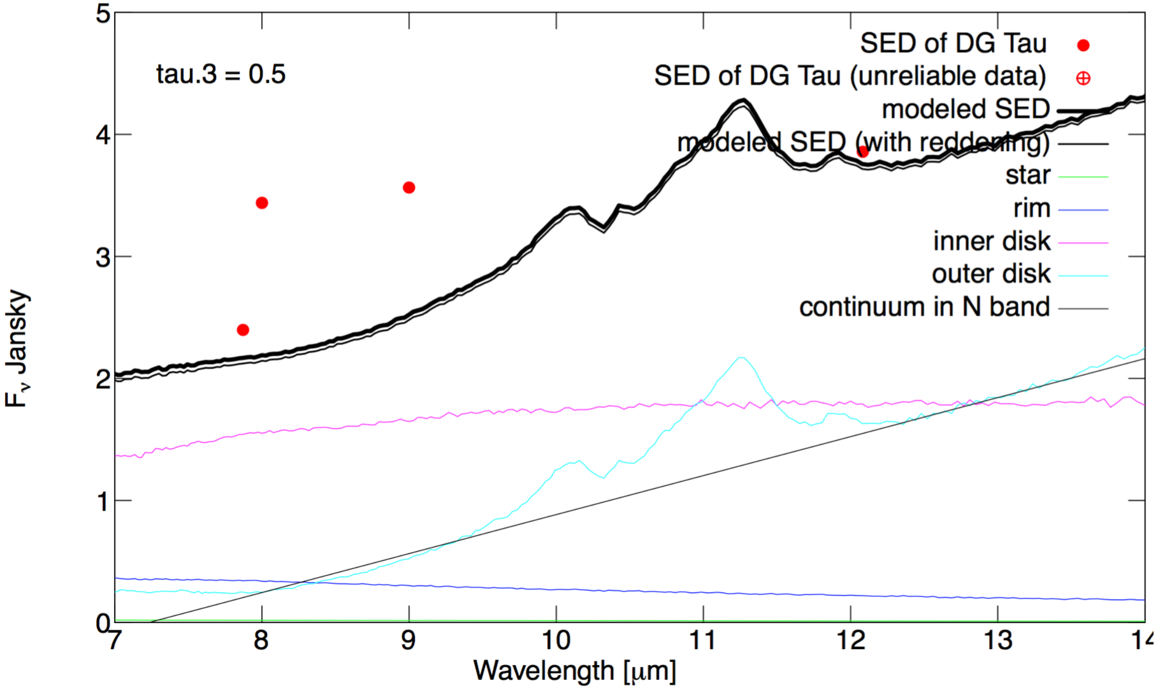
DG Tau: uncorrelated spectra (>2-5 au)



- varying continuum
- emission feature
- crystalline silicate grains
- strongly variable feature
- dominates the total spectrum

DG Tau: modeling

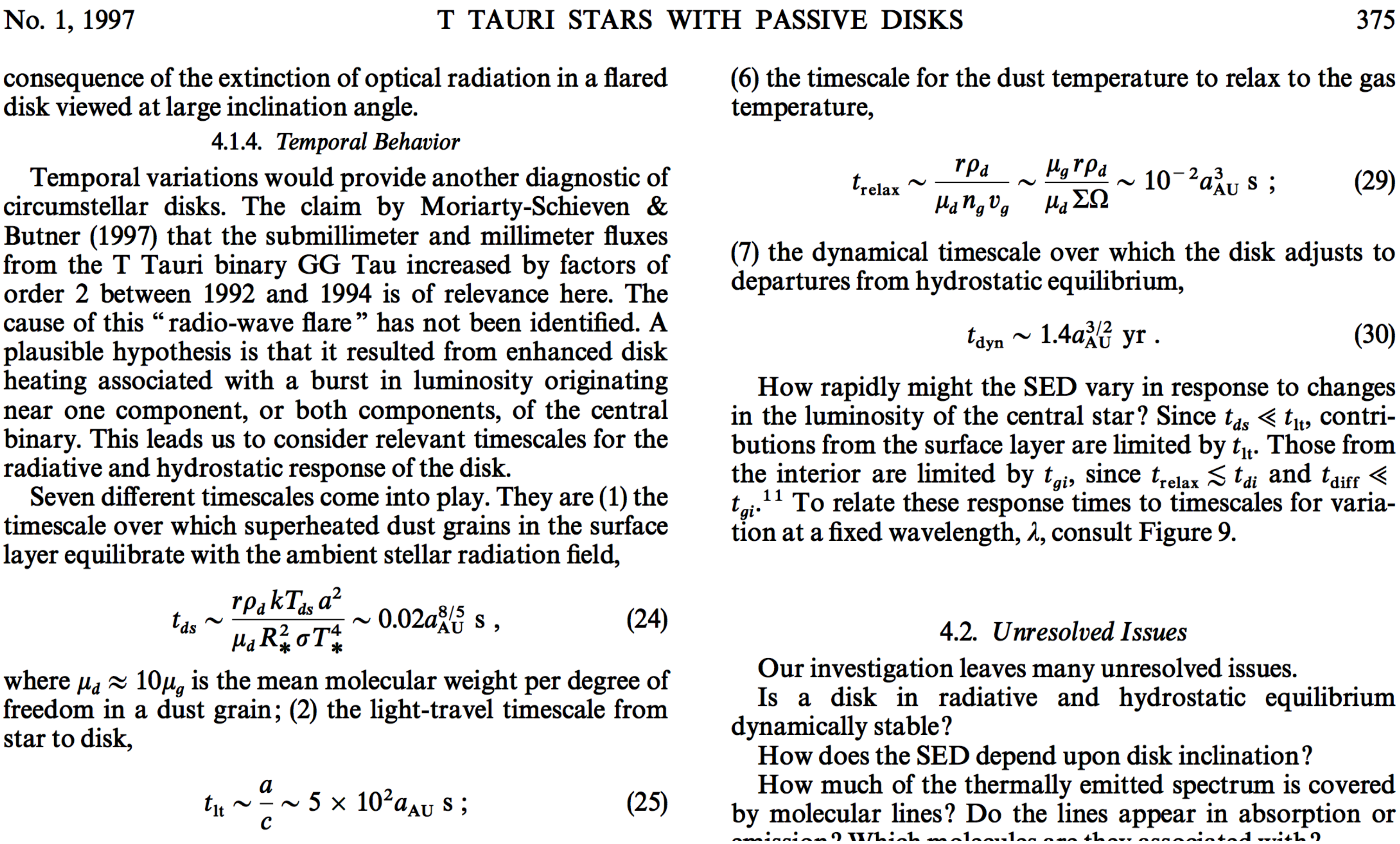




- optically thin dust cloud above the disk atmosphere
- Hale-Bopp like crystal composition
- can reproduce variable emission feature in the uncorrelated spectrum
- But: short timescales, hinting at irradiation changes?

Why do crystalline particles exist at 5 au, but not in the inner disk?!

Radiative transfer modeling



No. 1, 1997 T TAURI STARS WITH PASSIVE DISKS 375

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,

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

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,

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

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

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

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

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

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.

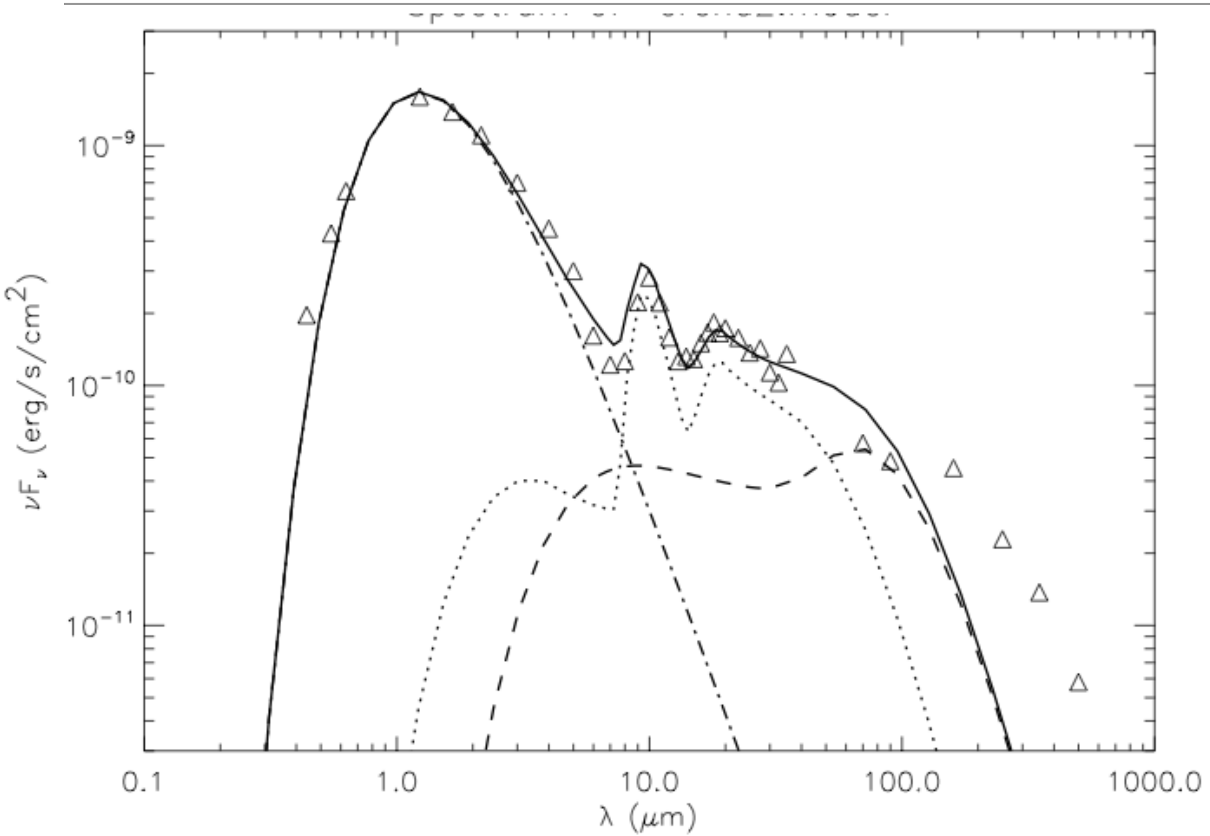
Is a disk in radiative and hydrostatic equilibrium dynamically stable?

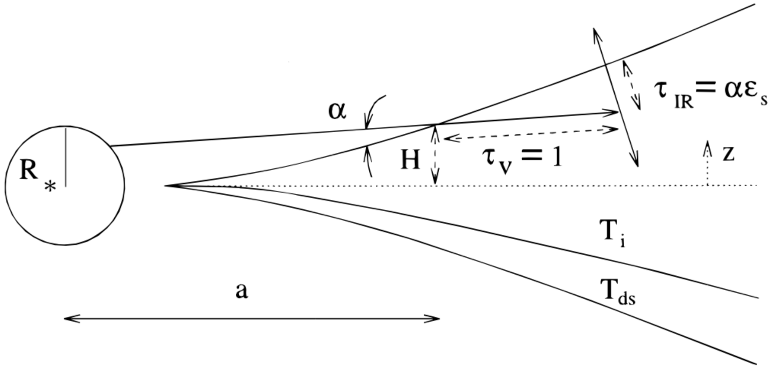
How does the SED depend upon disk inclination?

How much of the thermally emitted spectrum is covered by molecular lines? Do the lines appear in absorption or

Chiang & Goldreich, 1997

Radiative transfer modeling

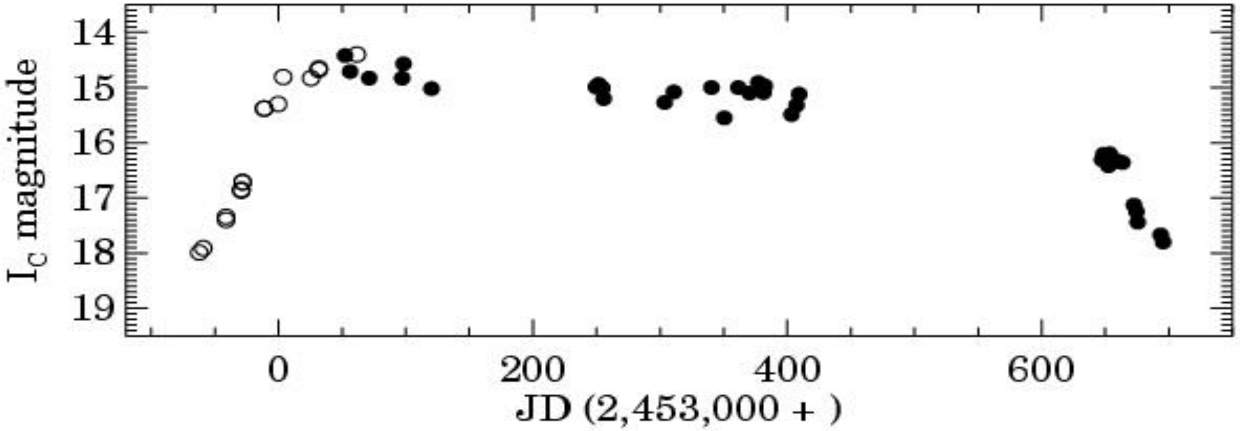


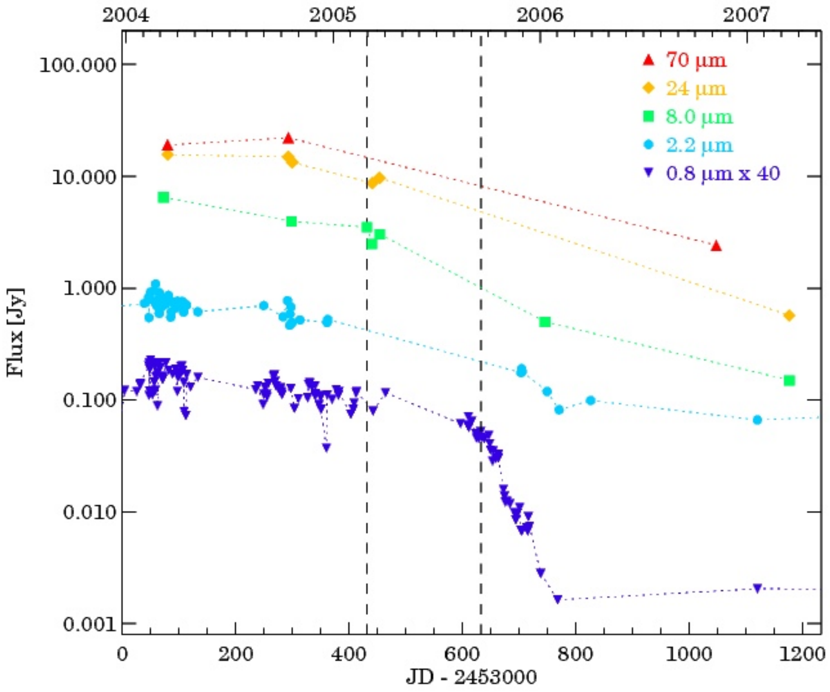


Chiang & Goldreich, 1997

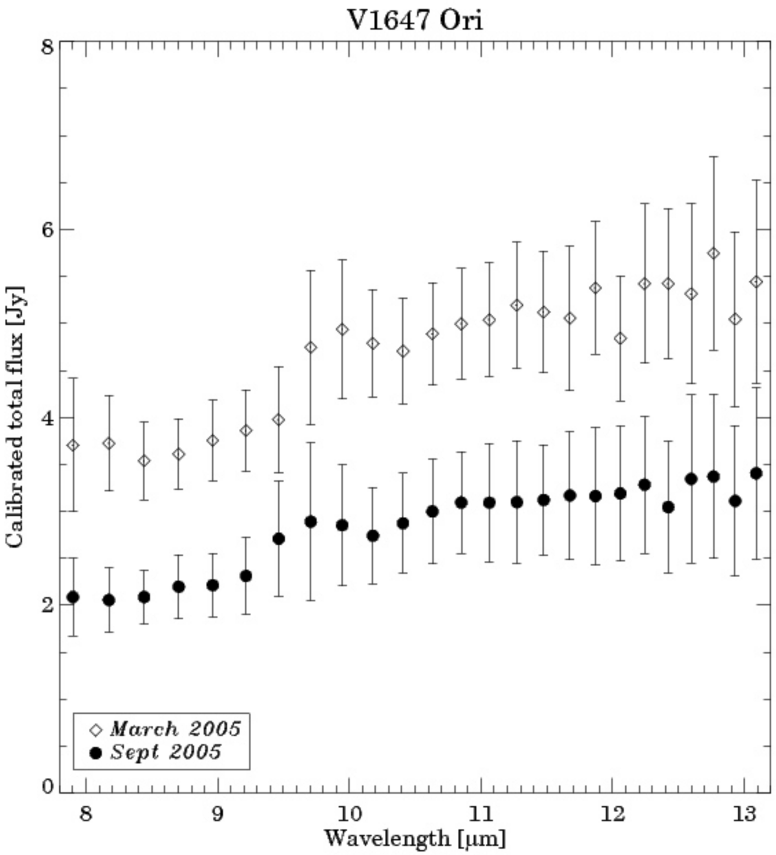
The 2004-06 outburst of V1647 Ori

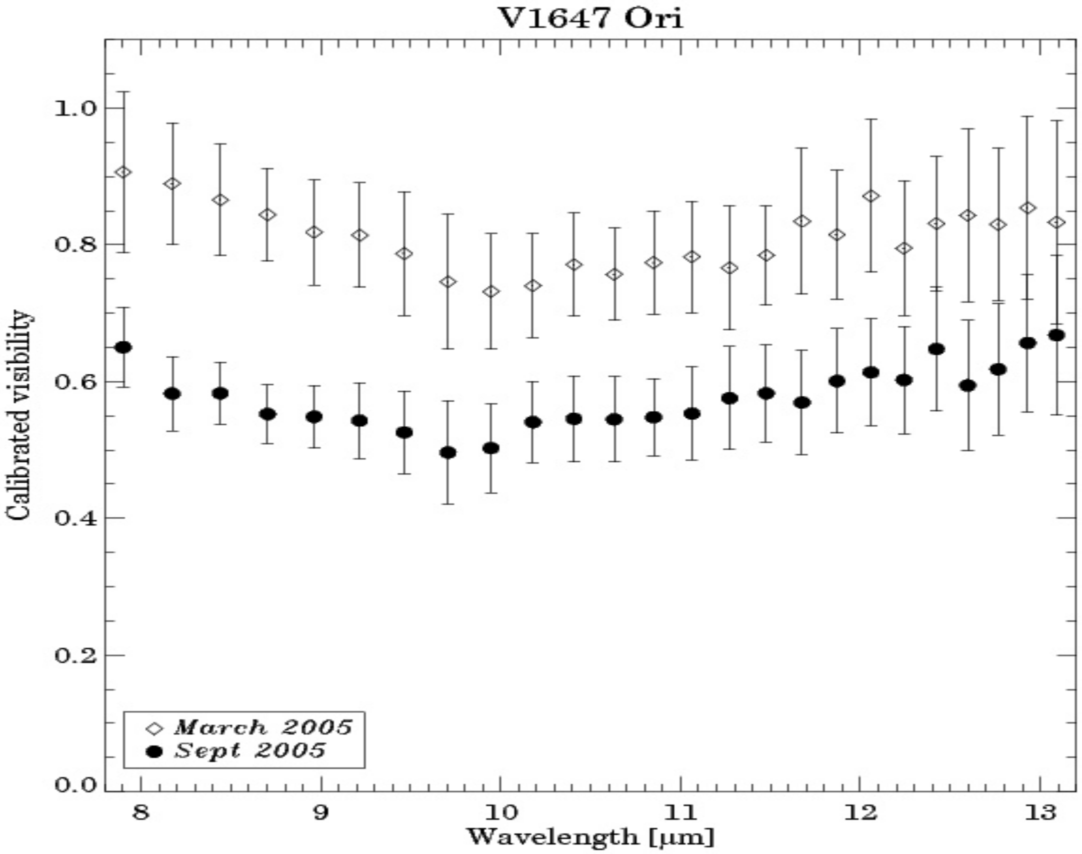
Reipurth & Aspin (2004)





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)

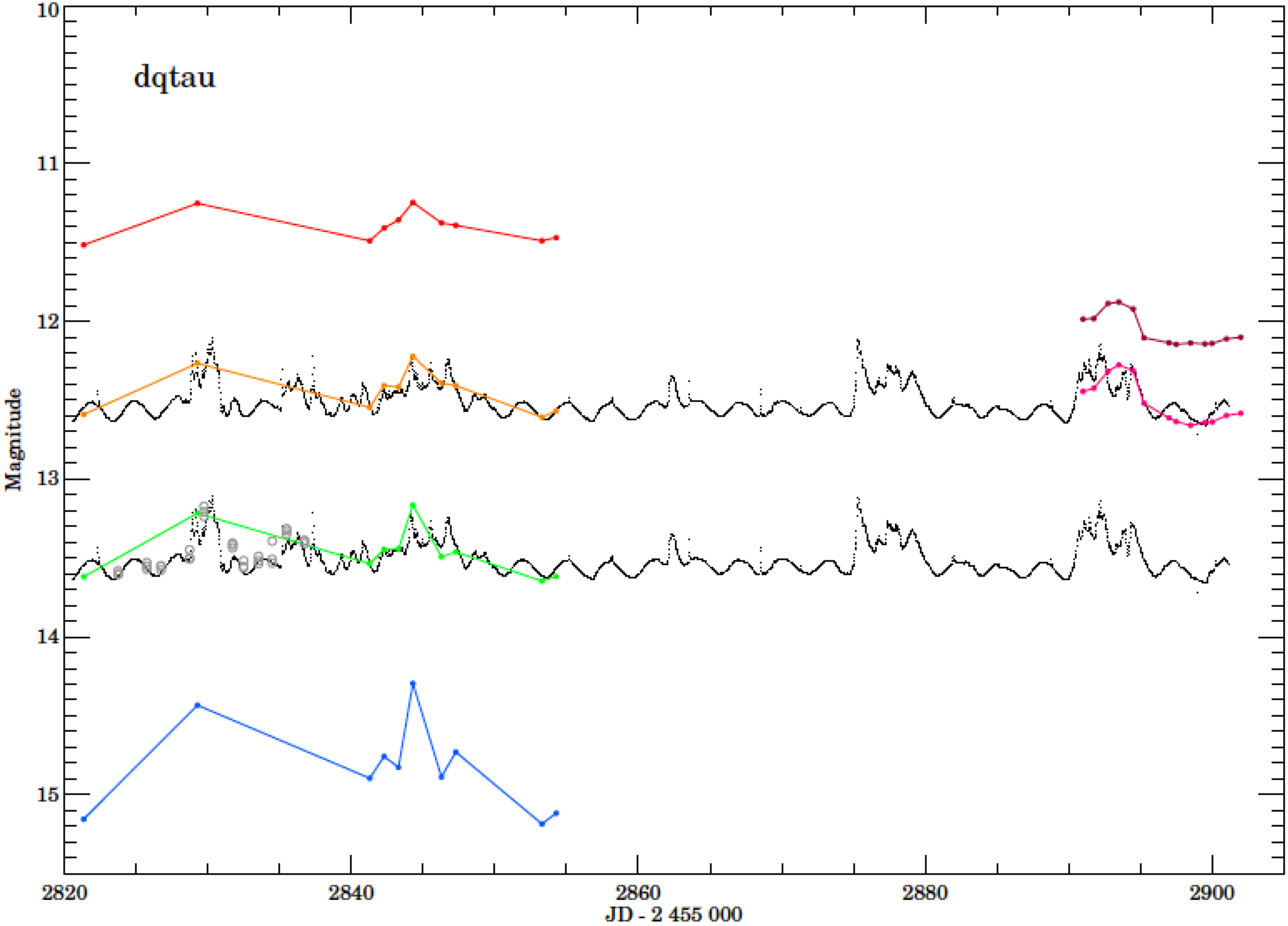
Kepler-Spitzer project

Sample: 7 strongly accreting YSO (DQ Tau, DR Tau, Haro 6-10, HL Tau, L1551 IRS 5, UZ Tau, XZ Tau)

- Kepler K2 light curve for 3 months
- BVRI photometry from Piszkéstető (Gabriella Zsidi)
- Spitzer 3.6 um, 4.5 um, 14 data points in 12 days
- BVRIJHK[3.6][4.5] 14 epochs monitoring in 2009 (Gabriella Zsidi, Zsófia Szabó)

Science goals: study of accretion process, star-disk interaction

In collaboration with the institute’s K2 group (Róbert Szabó)


dqtau
Magnitude
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15
2820
2840
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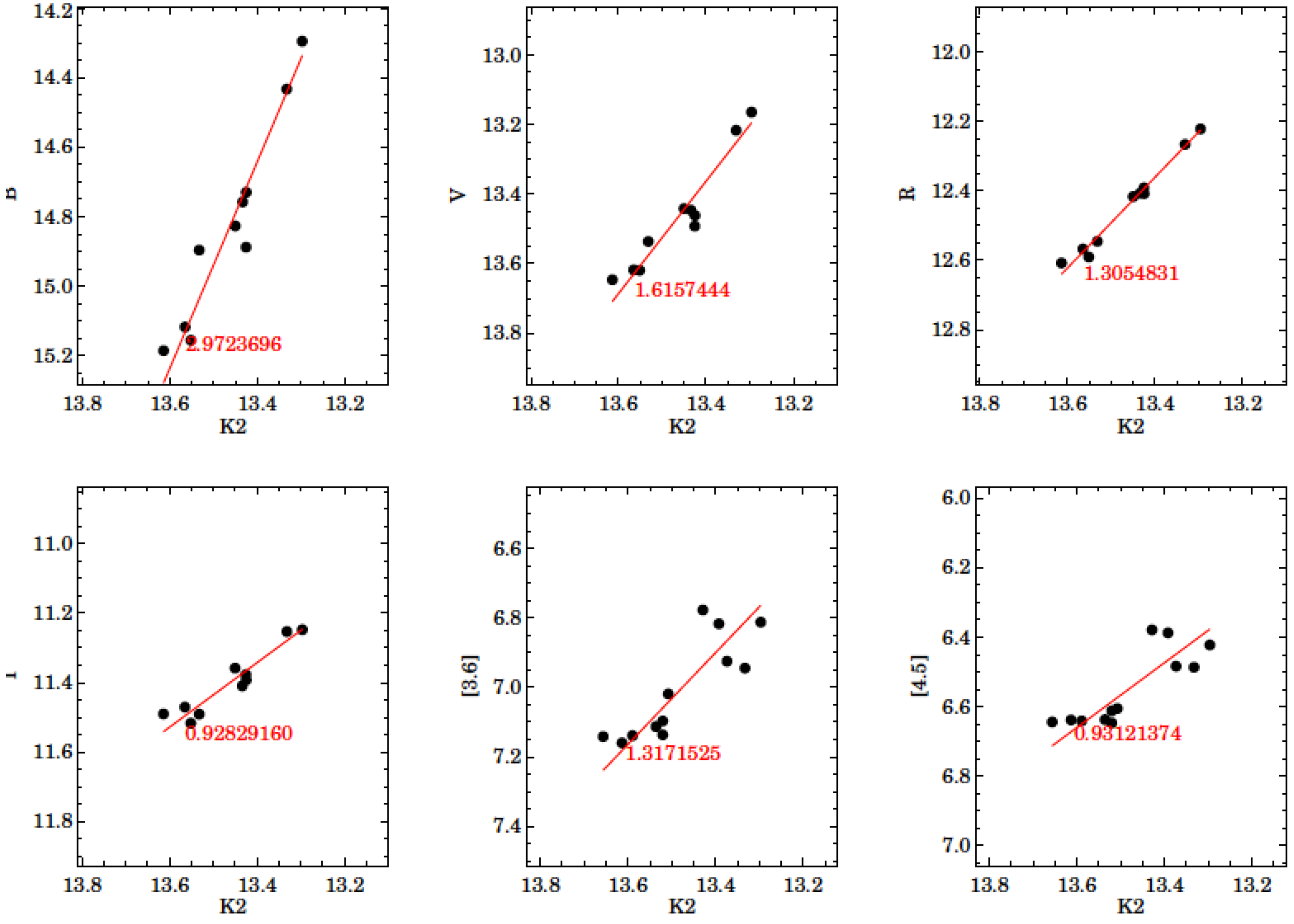
2880
2900
JD - 2 455 000


B
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14.4
14.6
14.8
15.0
15.2
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K2
13.8
13.6
13.4
13.2
V
13.0
13.2
13.4
13.6
13.8
1.6157444
K2
R
12.0
12.2
12.4
12.6
12.8
1.3054831
K2
I
11.0
11.2
11.4
11.6
11.8
0.92829160
K2
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6.6
6.8
7.0
7.2
7.4
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K2
[4.5]
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6.4
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6.8
7.0
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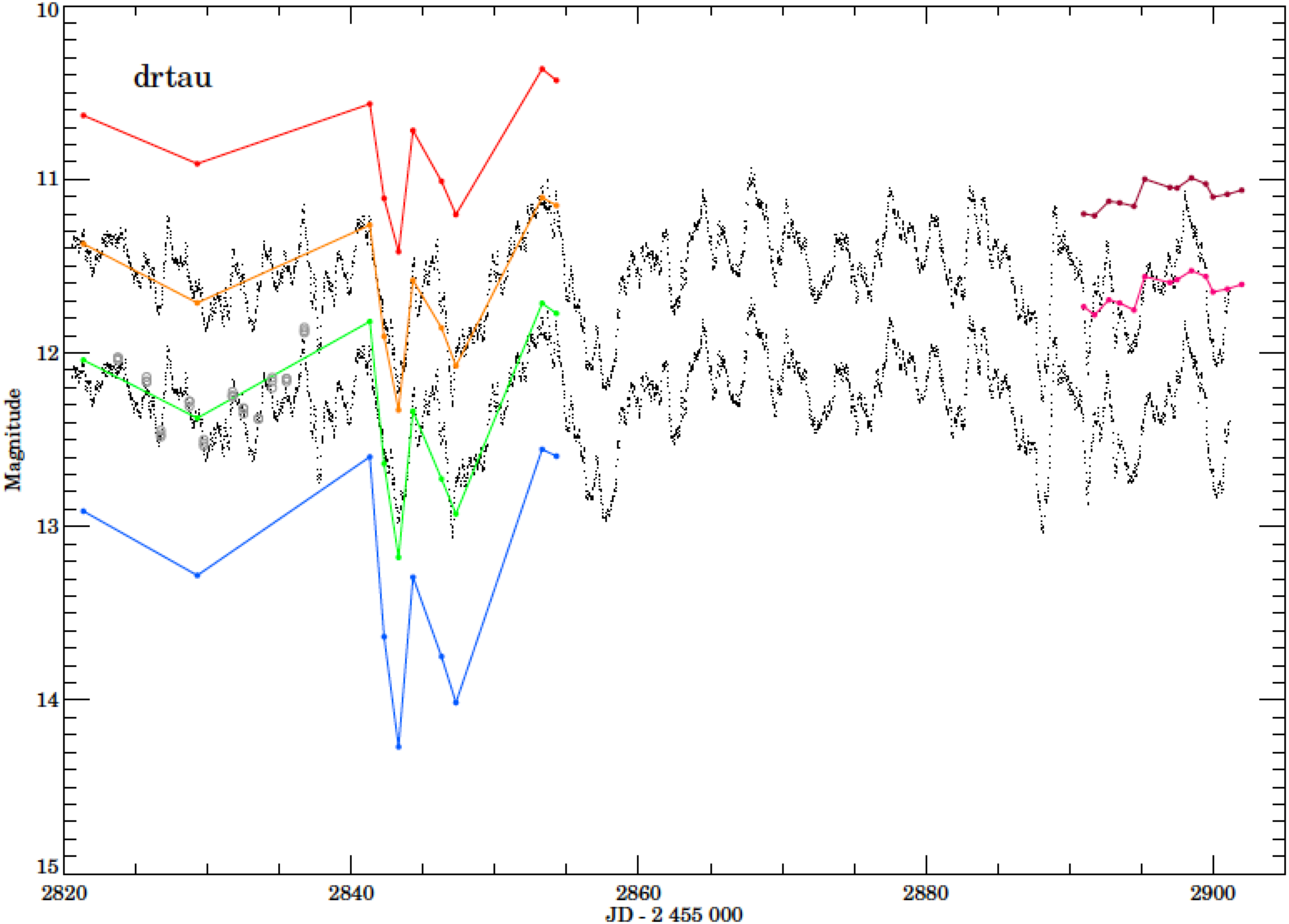
K2


drtau
Magnitude
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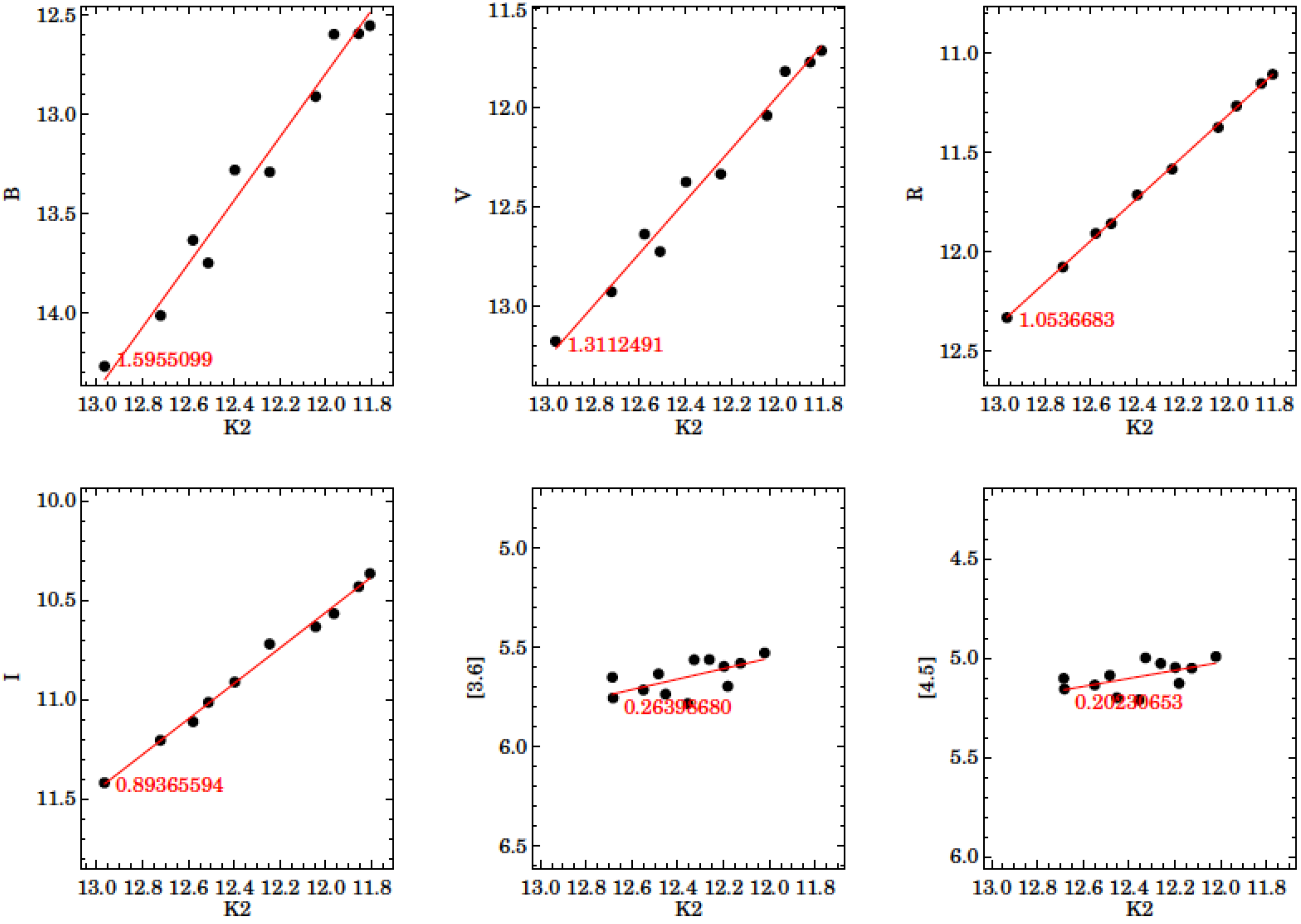
JD - 2 455 000


B
12.5
13.0
13.5
14.0
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K2
V
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13.0 12.8 12.6 12.4 12.2 12.0 11.8
K2
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11.5
12.0
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1.0536683
13.0 12.8 12.6 12.4 12.2 12.0 11.8
K2
I
10.0
10.5
11.0
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0.89365594
13.0 12.8 12.6 12.4 12.2 12.0 11.8
K2
[3.6]
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5.5
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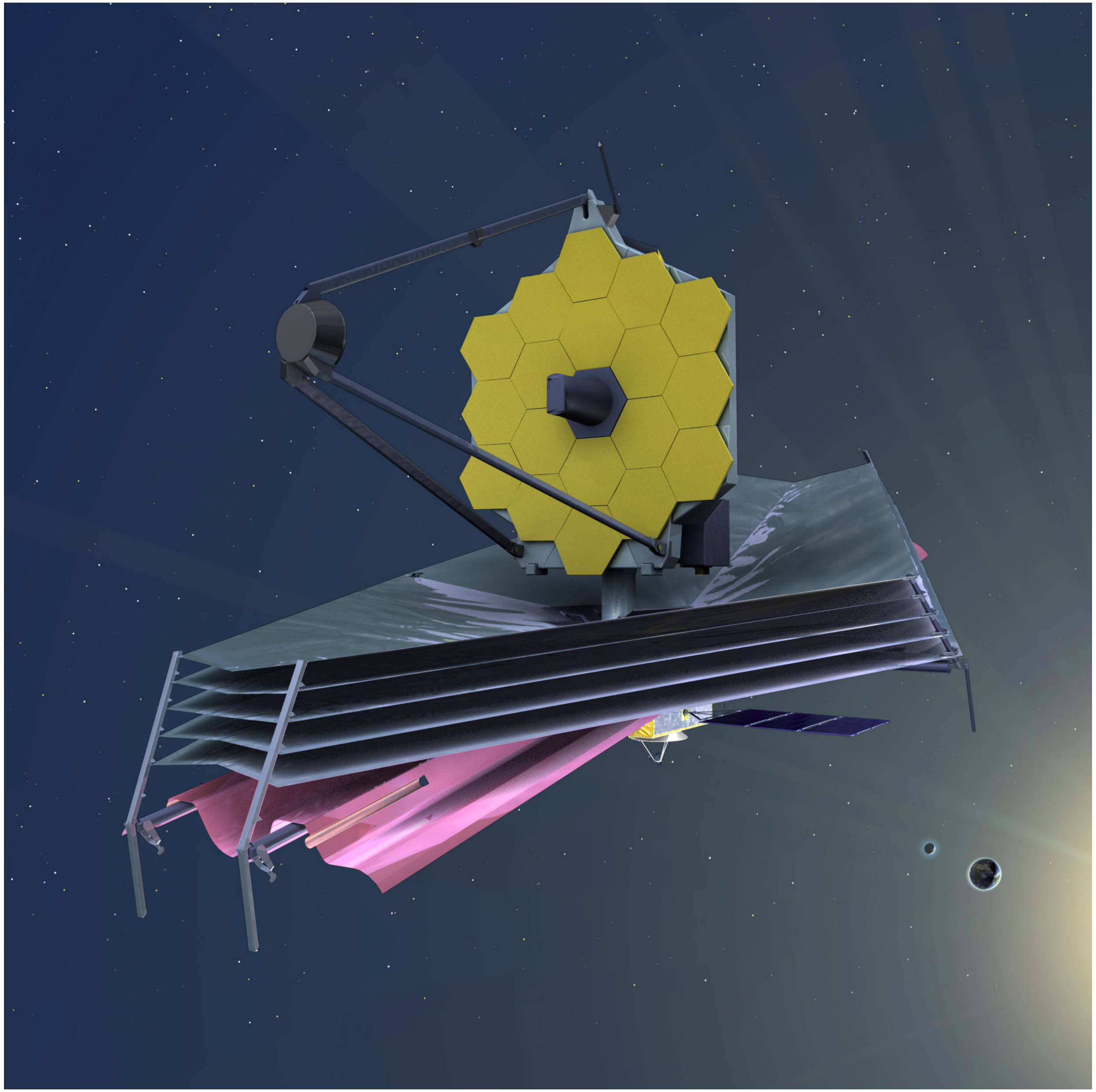
6.5
0.26398680
13.0 12.8 12.6 12.4 12.2 12.0 11.8
K2
[4.5]
4.5
5.0
5.5
6.0
0.20230653
13.0 12.8 12.6 12.4 12.2 12.0 11.8
K2

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

JWST



- **Near InfraRed Camera (NIRCam)**
- **Near InfraRed Spectrograph (NIRSpec)**
- **Mid-InfraRed Instrument (MIRI)**
- **Fine Guidance Sensor and Near InfraRed Imager and Slitless Spectrograph (FGS/NIRISS)**