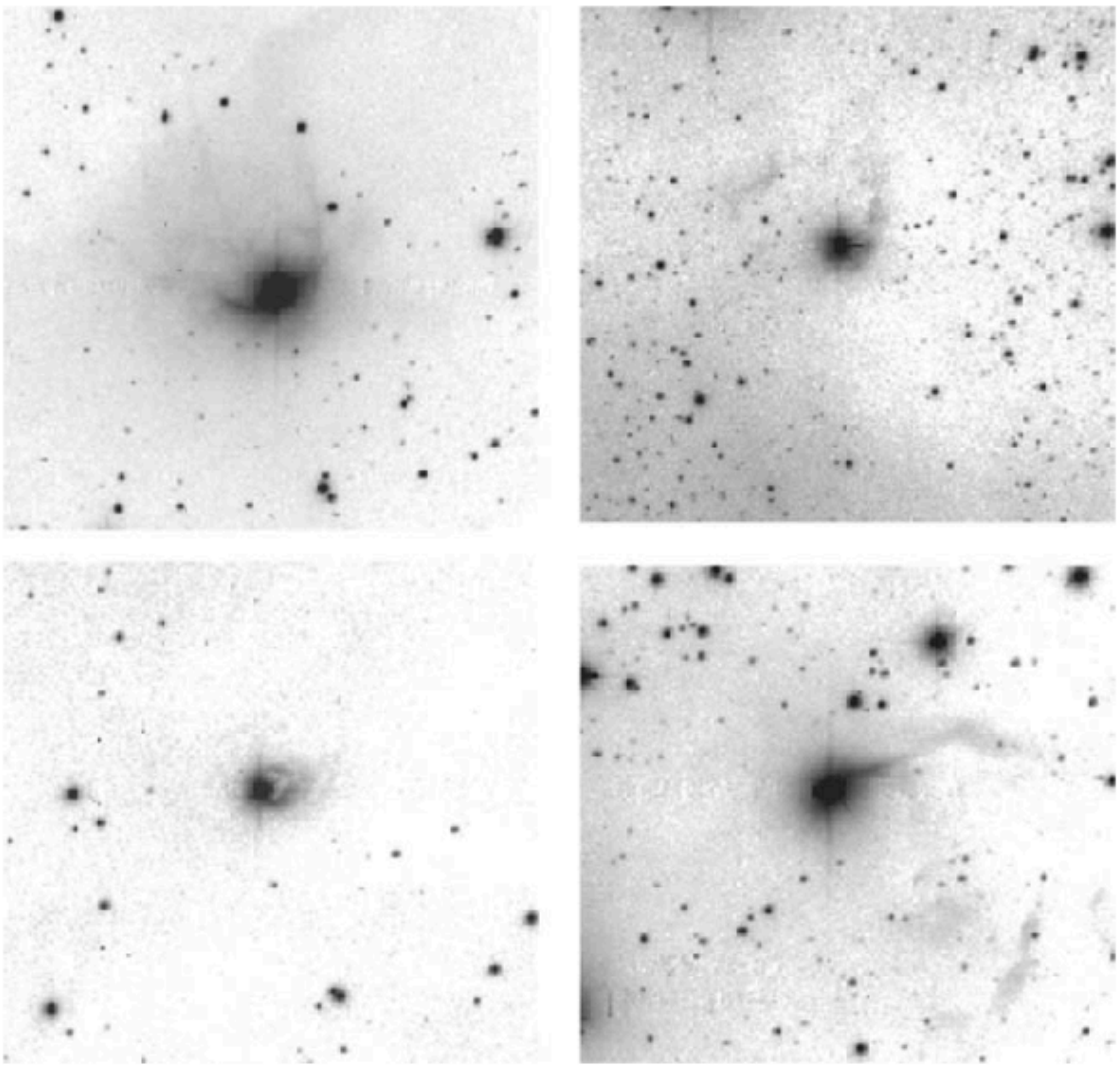
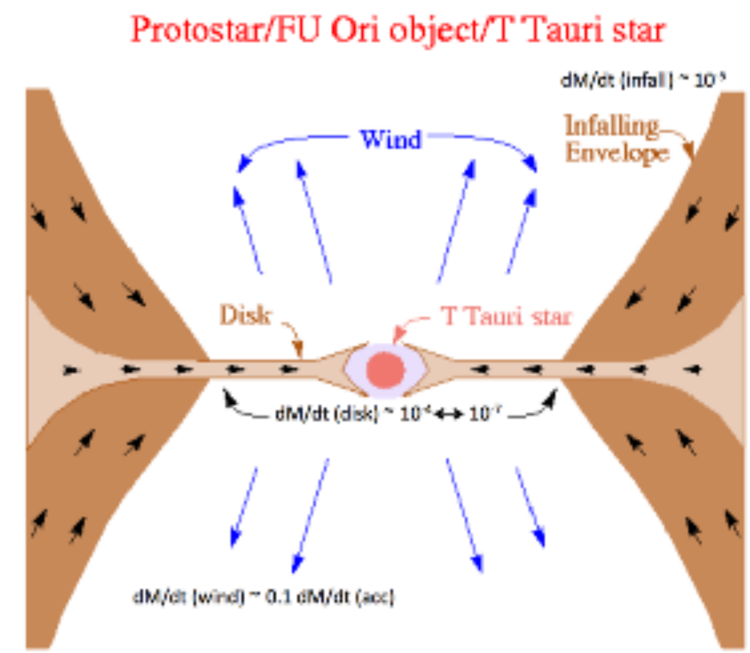
What can we learn from the light curves of young eruptive stars?

Péter Ábrahám
Konkoly Observatory

2017 November 29

FU Orionis-type stars (FUors)

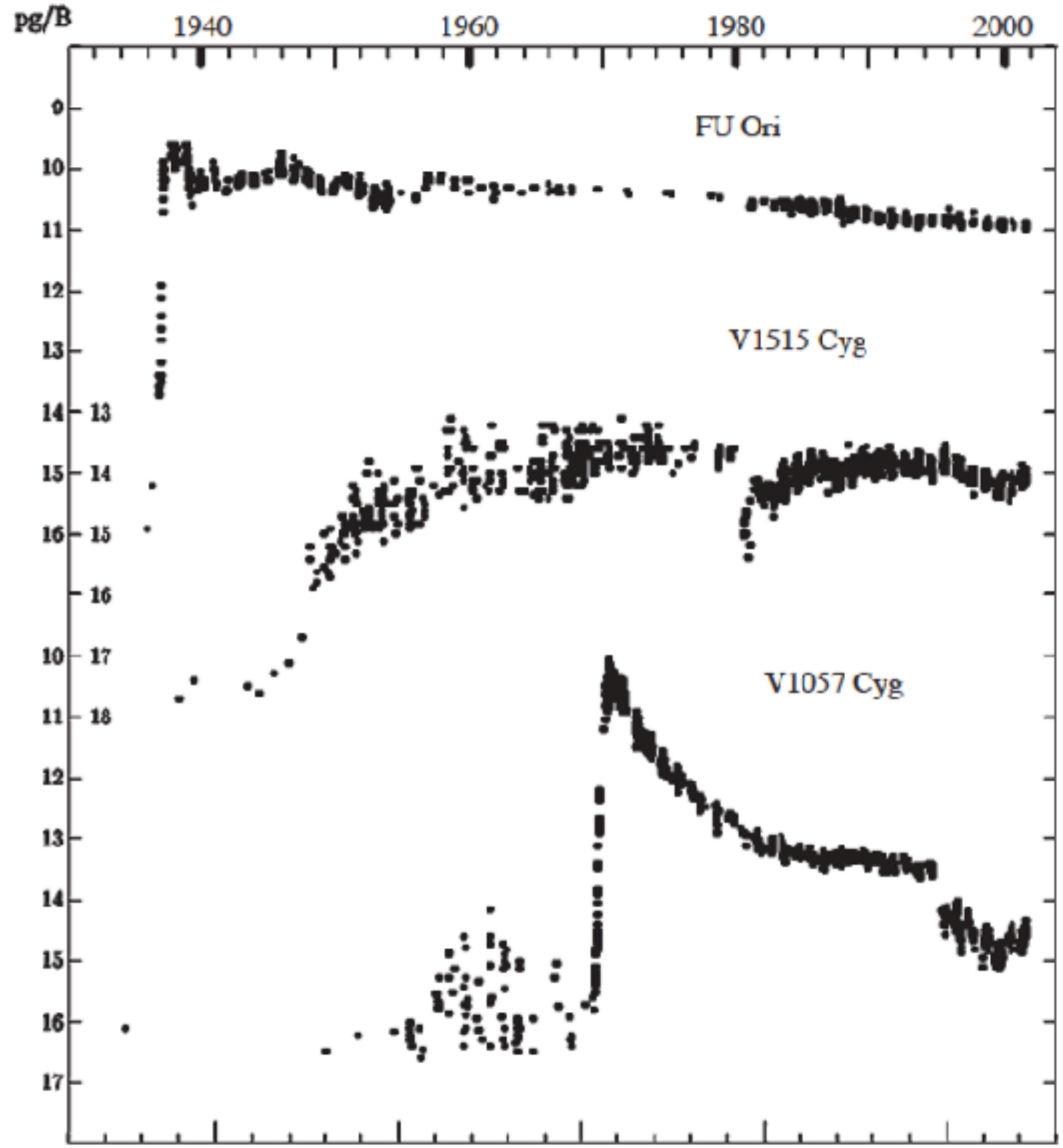




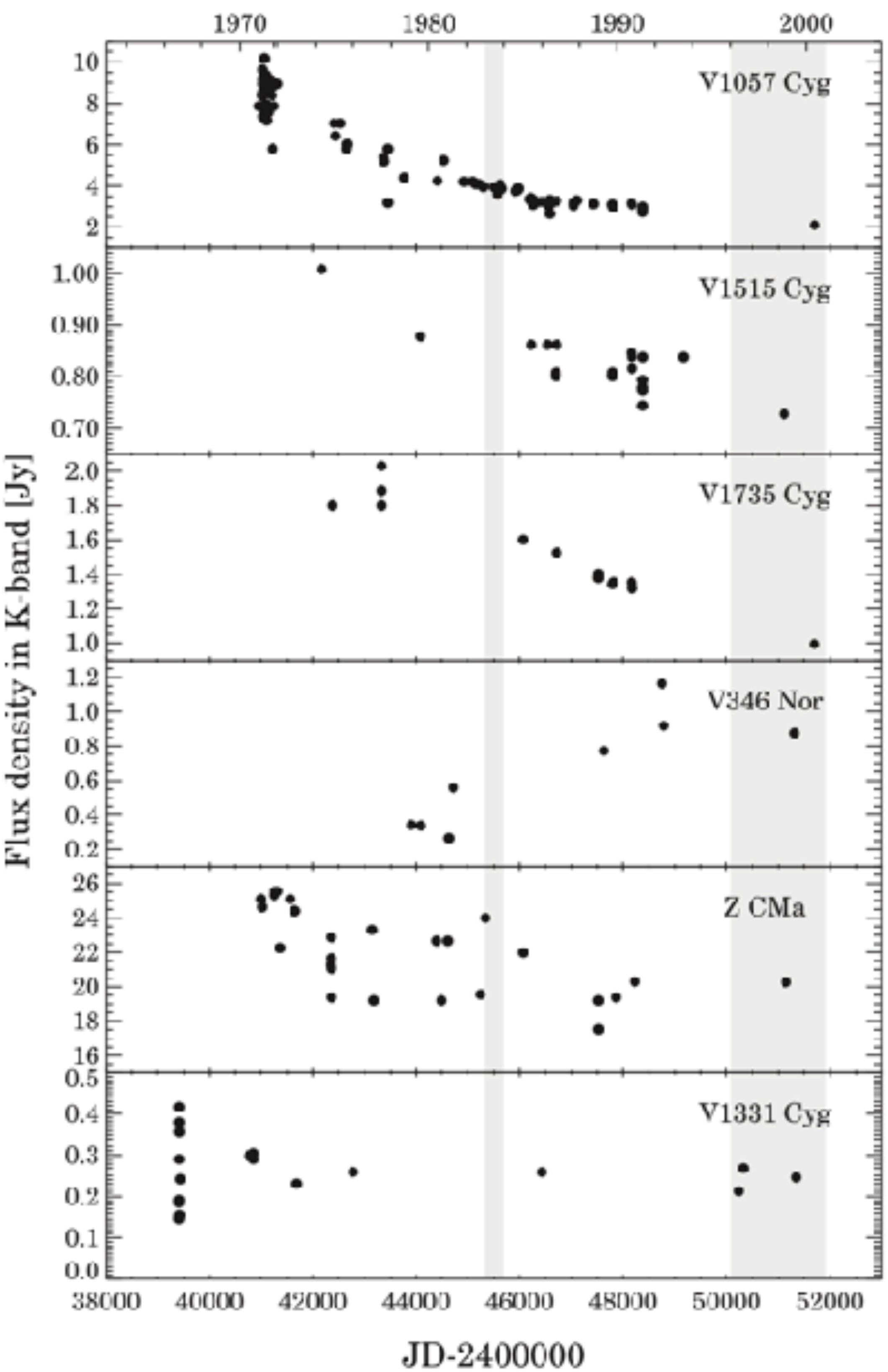
Young stars with large outburst (4-5^m) in optical light (Herbig 1966, 1977)

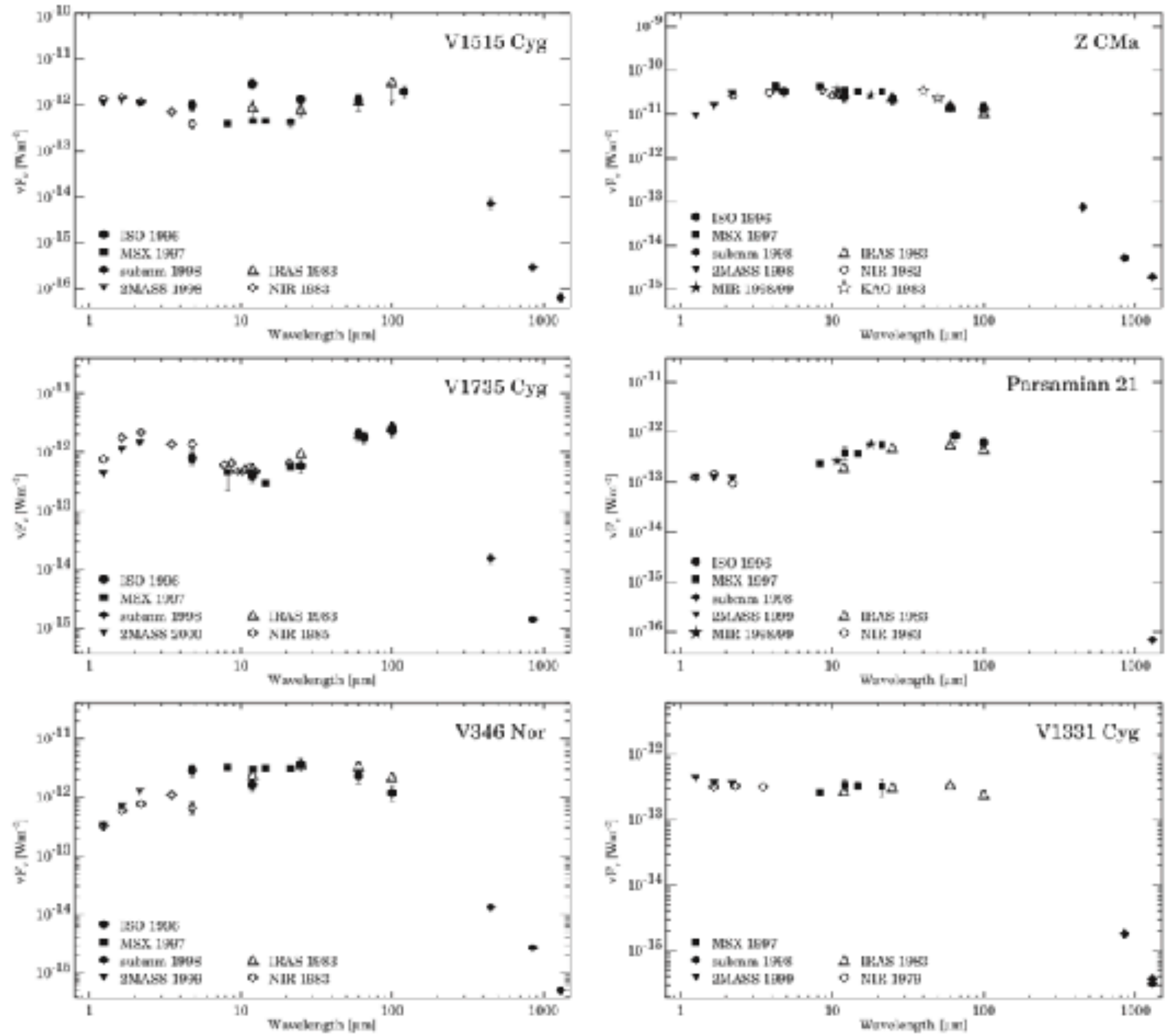
FU Ori-type young eruptive stars

- Light curve: long term evolution, initial brightening, plateau,???
- Physical instability in the system, leading to 1000x increased accretion
- Increased accretion up to 10^{-4} $M_{\odot} yr^{-1}$
- Physical mechanisms needed: (1) stops accretion to pile up material in the inner disk; (2) lets matter falling onto the star
- The outburst can be used to explore the disk (large illuminated area)



Decadal infrared brightness evolution





IRAS (1983) vs. ISO (2005-08)

(Ábrahám, Kóspál et al. 2004)

V1515 Cyg: dust condensation in wind

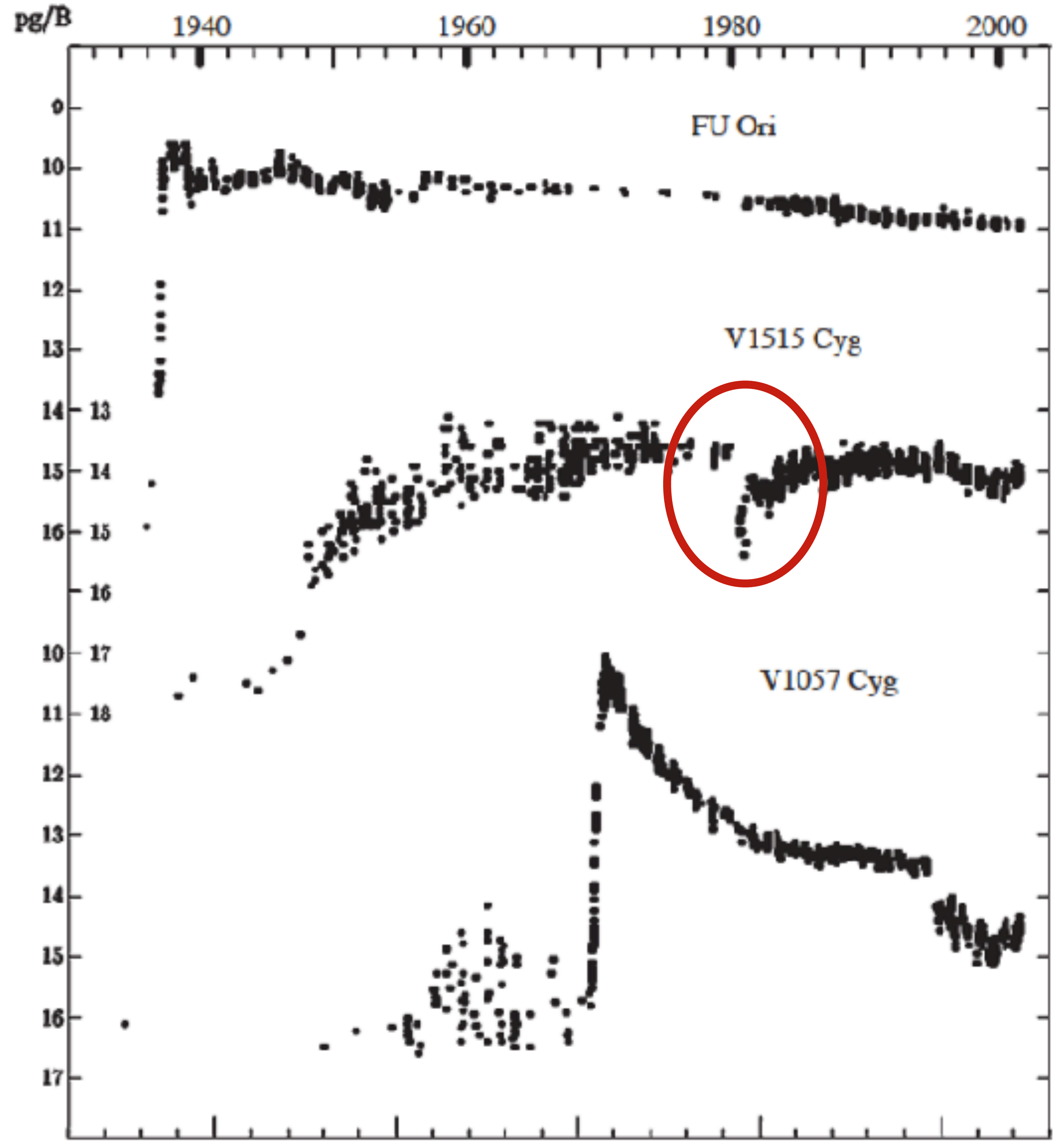
The 1980 optical photometric minimum is interpreted as a dust condensation event in the outflowing wind of V1515 Cyg.

The slow recovery from the minimum was caused by expansion of the dust cloud in the wind.

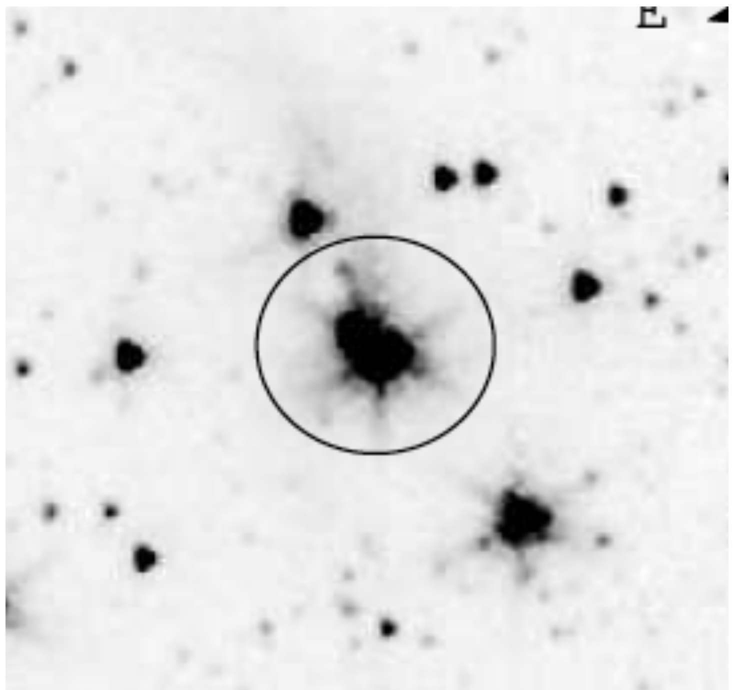
Dust formation occurred in material with a temperature of 500-700 K at a radial distance of (1-2)x10^{15} cm from the mass-losing source.

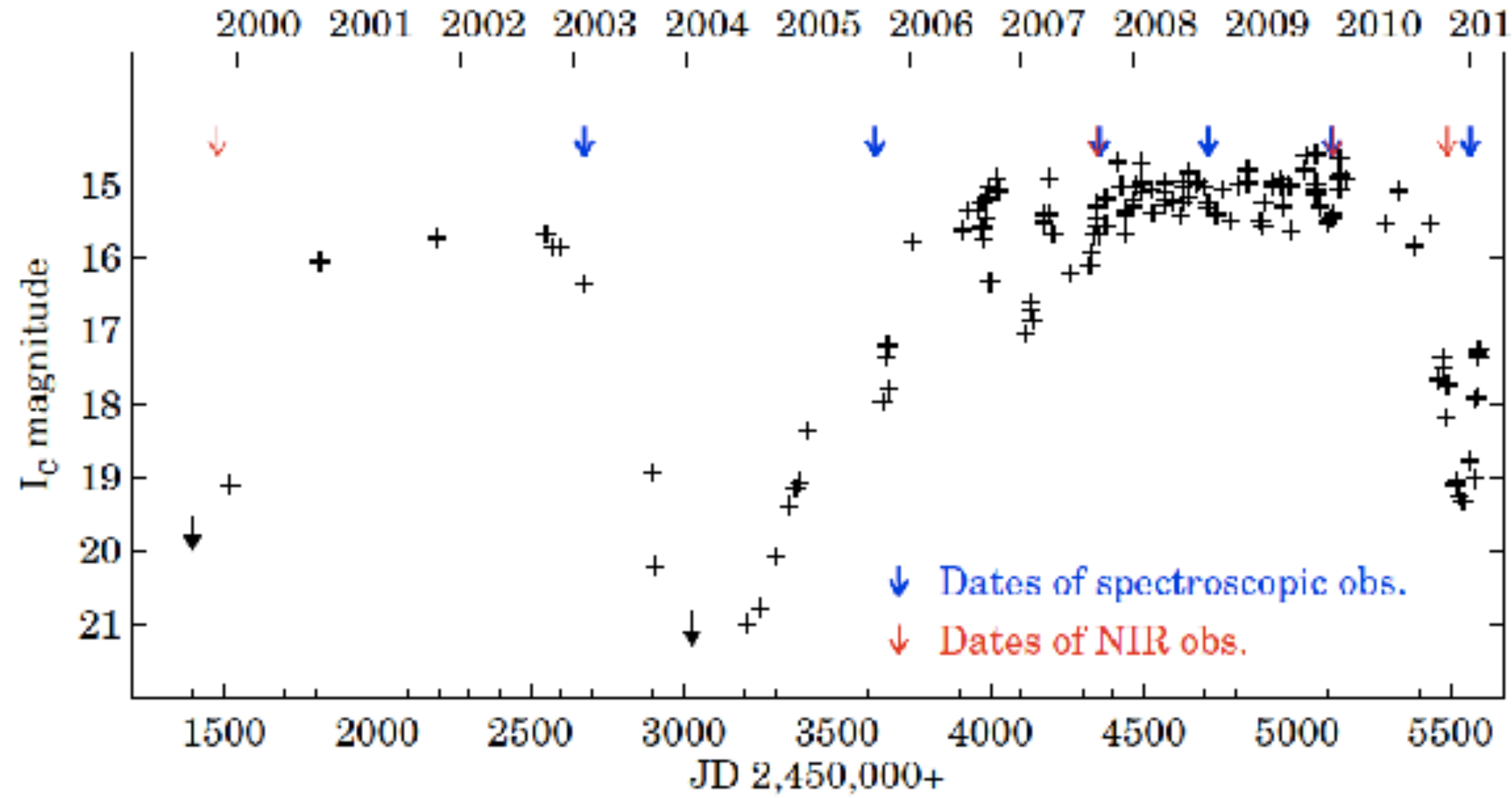
A mass-loss rate of (1-3)x10^{-5} solar masses per year can produce the conditions required for dust formation in the wind of V1515 Cyg.

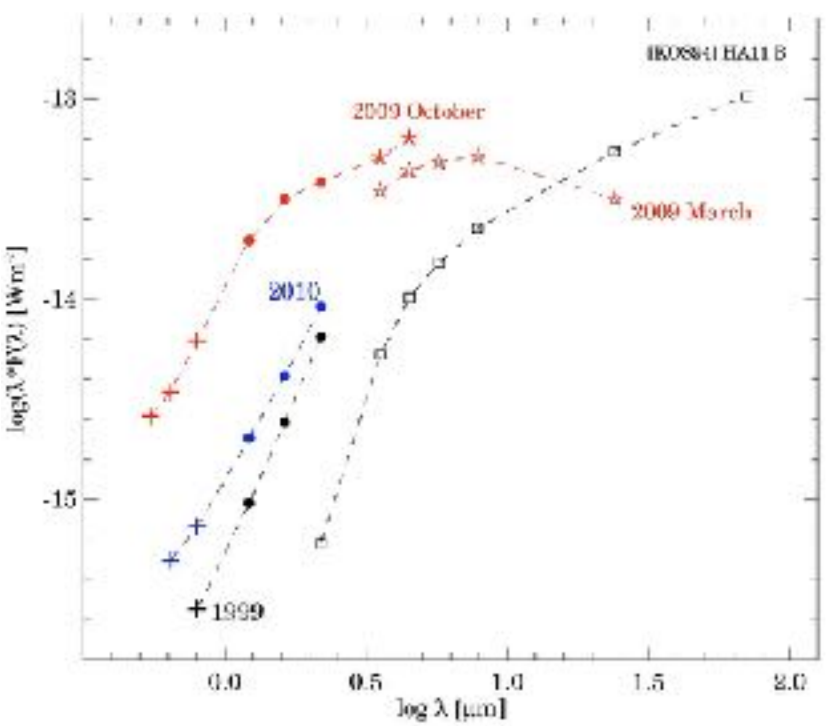
(Kenyon et al. 1991)

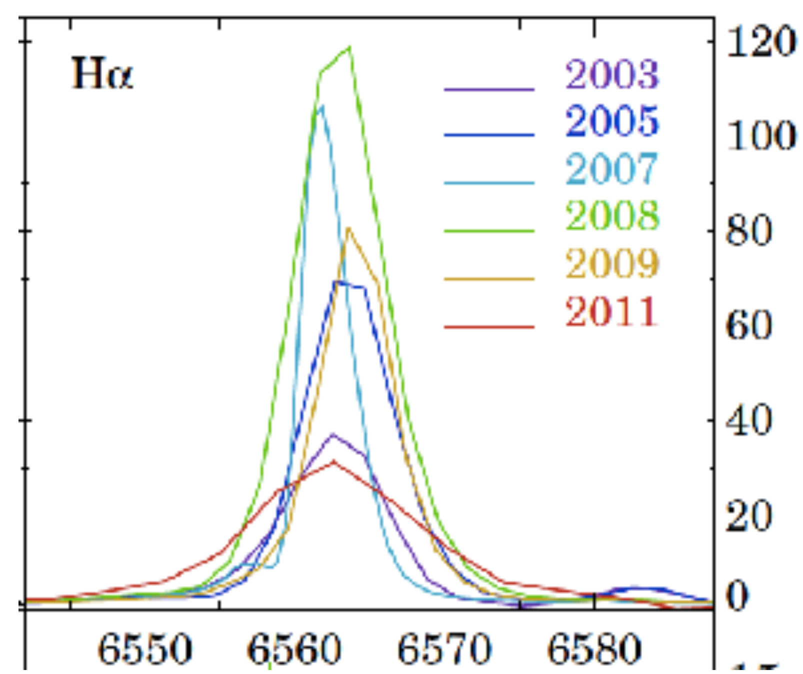


[KOS94] Ha 11 (2006-2010)



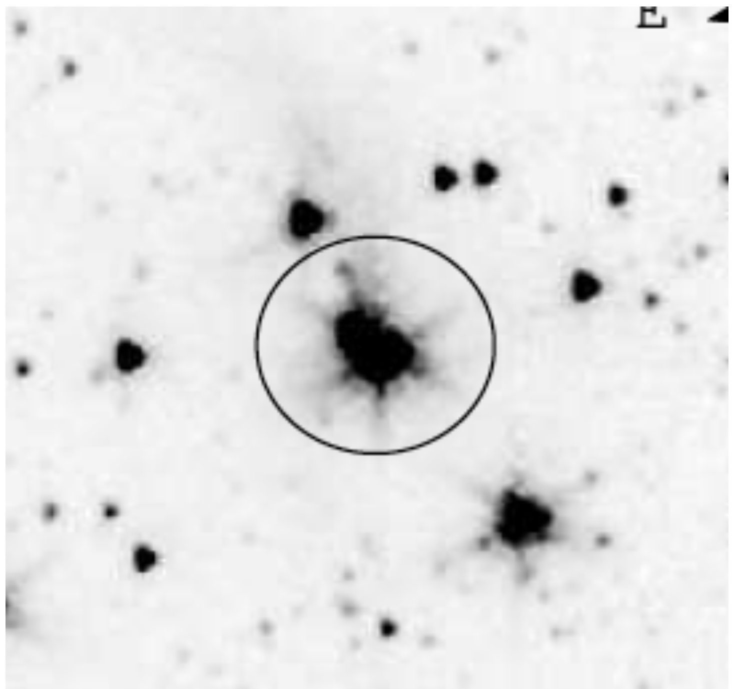


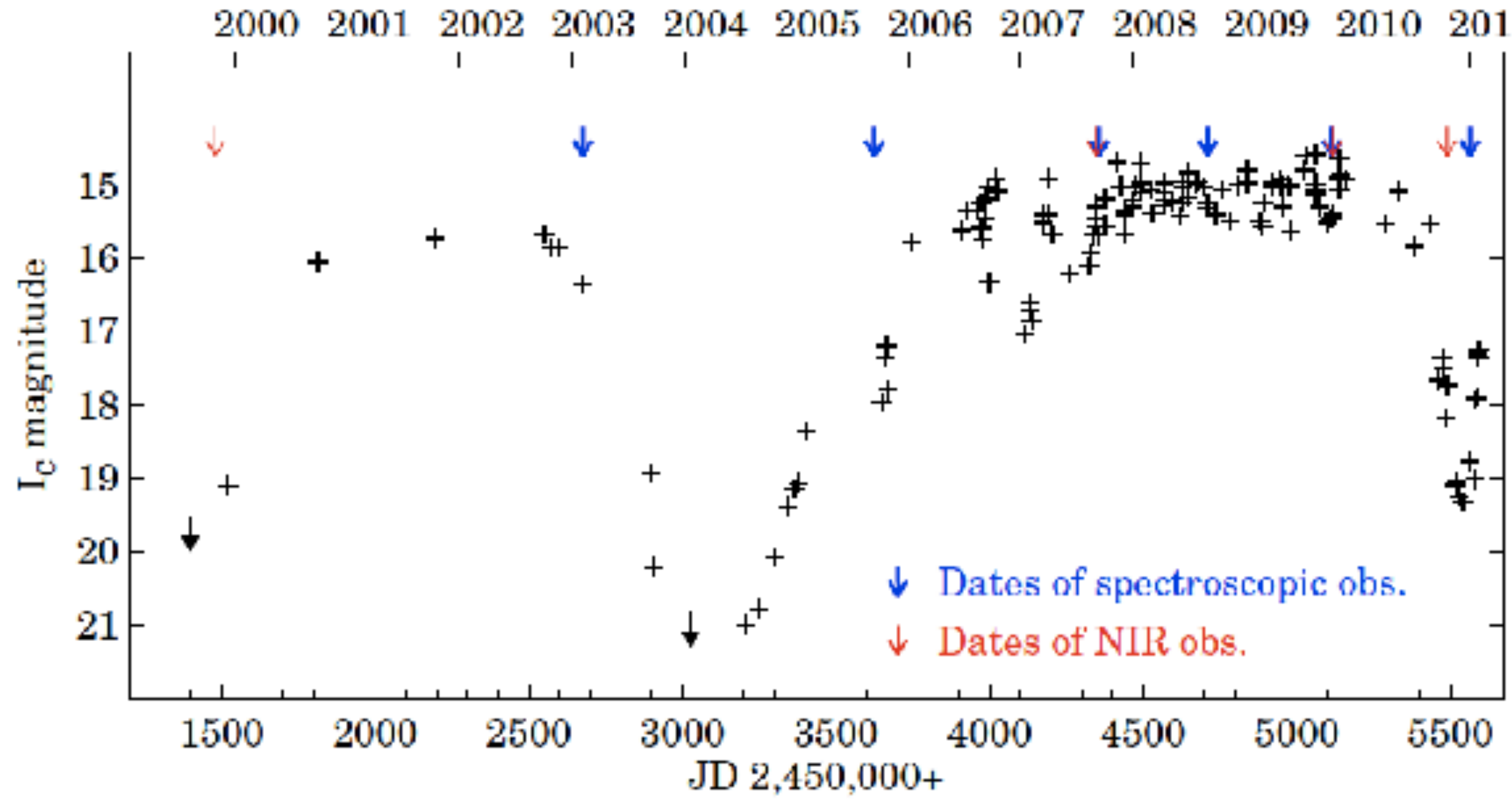


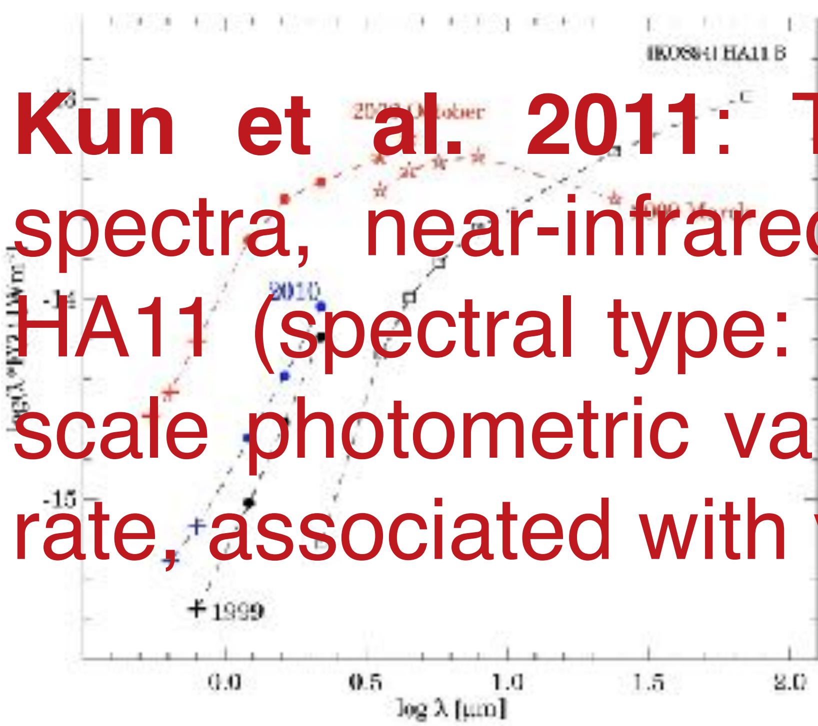


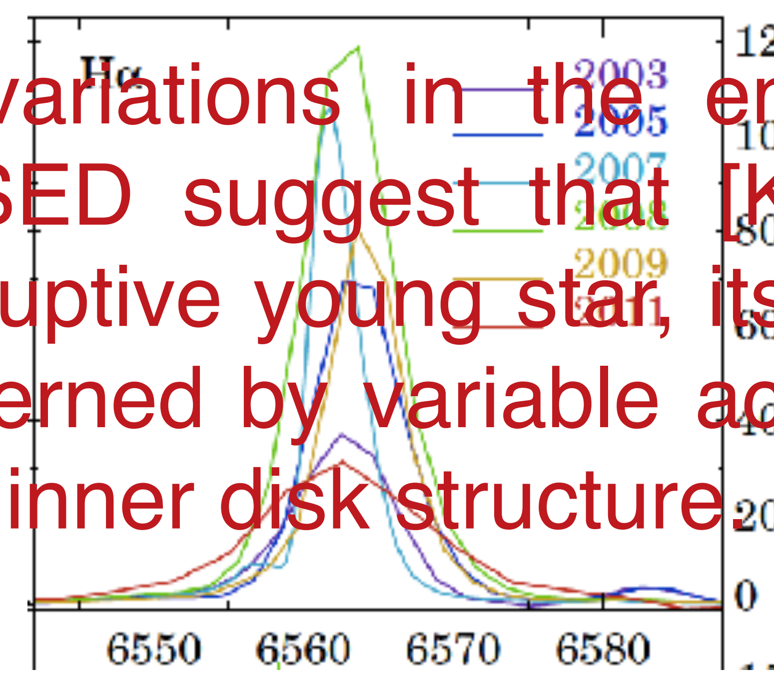
Kun et al. (2011)

[KOS94] Ha 11 (2006-2010)





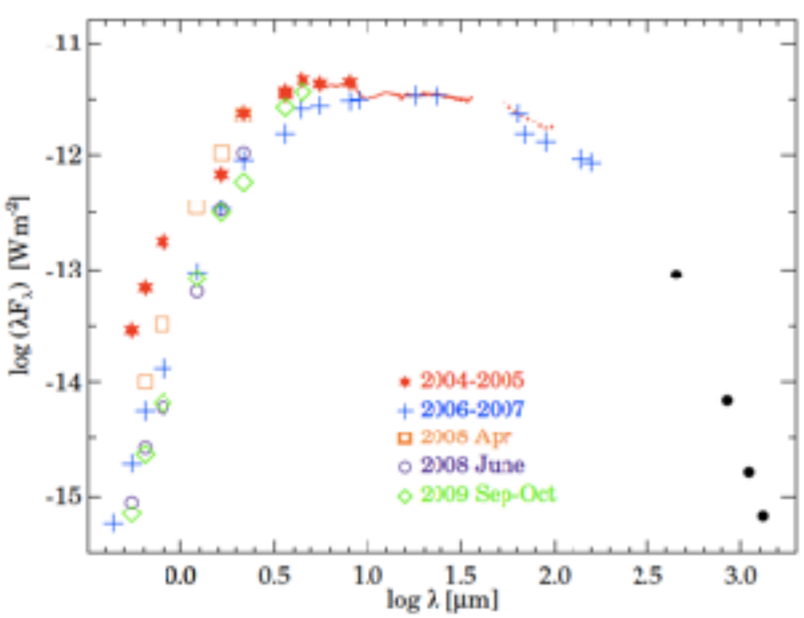


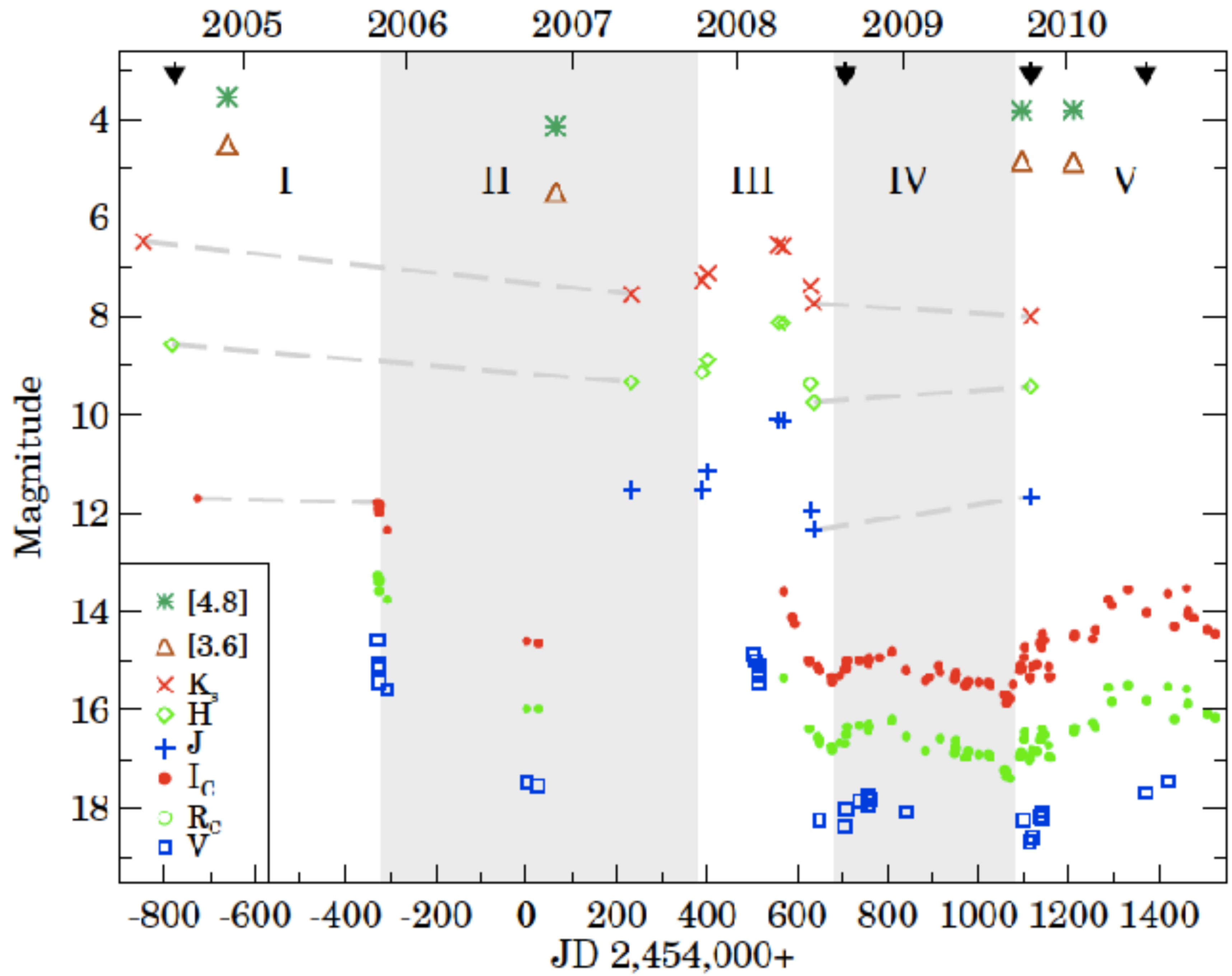


Kun et al. 2011: The observed variations in the emission spectra, near-infrared colors, and SED suggest that [KOS94] HA11 (spectral type: K7-M0) is an eruptive young star, its large-scale photometric variations are governed by variable accretion rate, associated with variations in the inner disk structure.

Kun et al. (2011)

PV Cep (< 2006)





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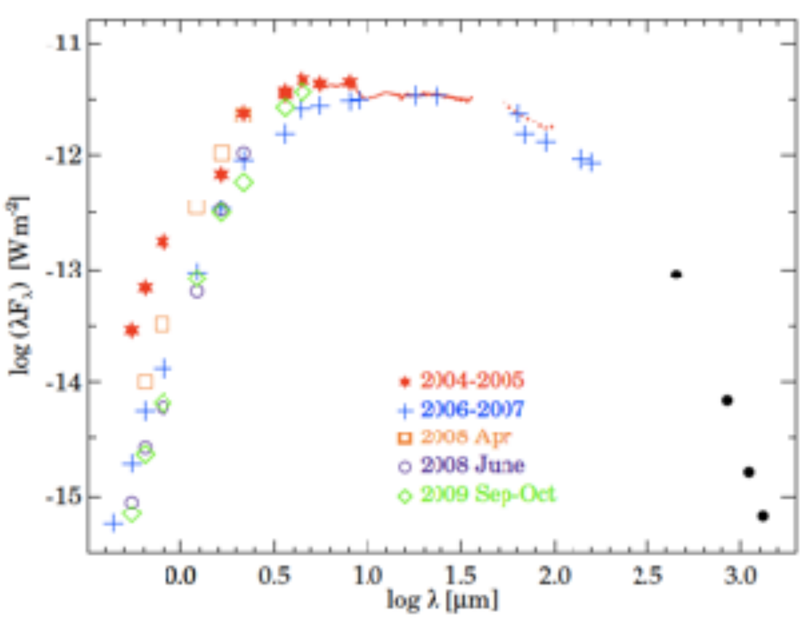

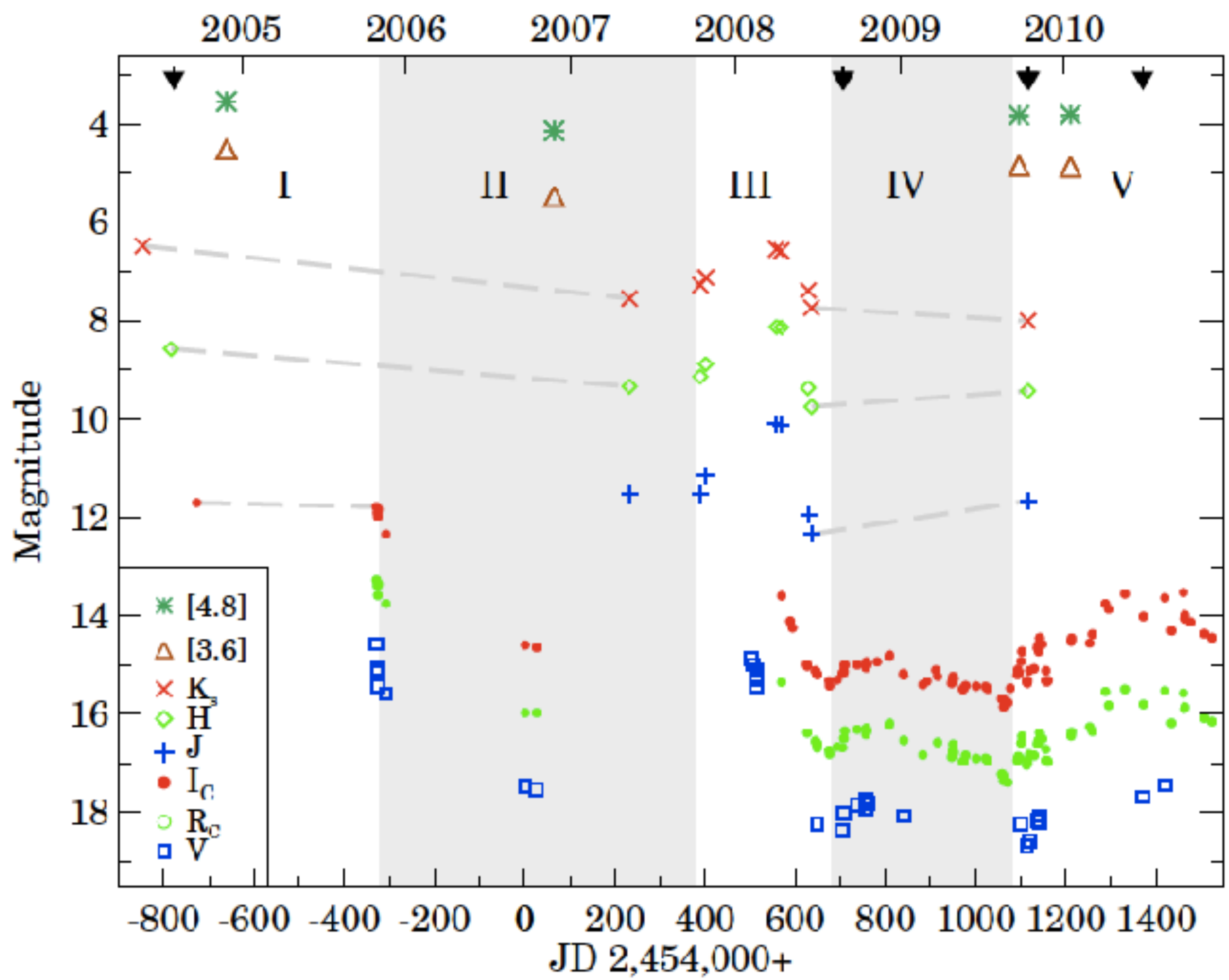

- Kun+ 2011: Inner disc rearrangement revealed by dramatic brightness variations in the young star PV Cep

Open questions

Why does the extinction change?
Is it caused by the outburst?
Is the dust evaporated by the heat of the outburst?

To answer these questions, we need to study those objects where the extinction changes are particularly large, and the effect is very well visible.

Our target

image credit: Anna Morris (www.eprisephoto.com)

Our target

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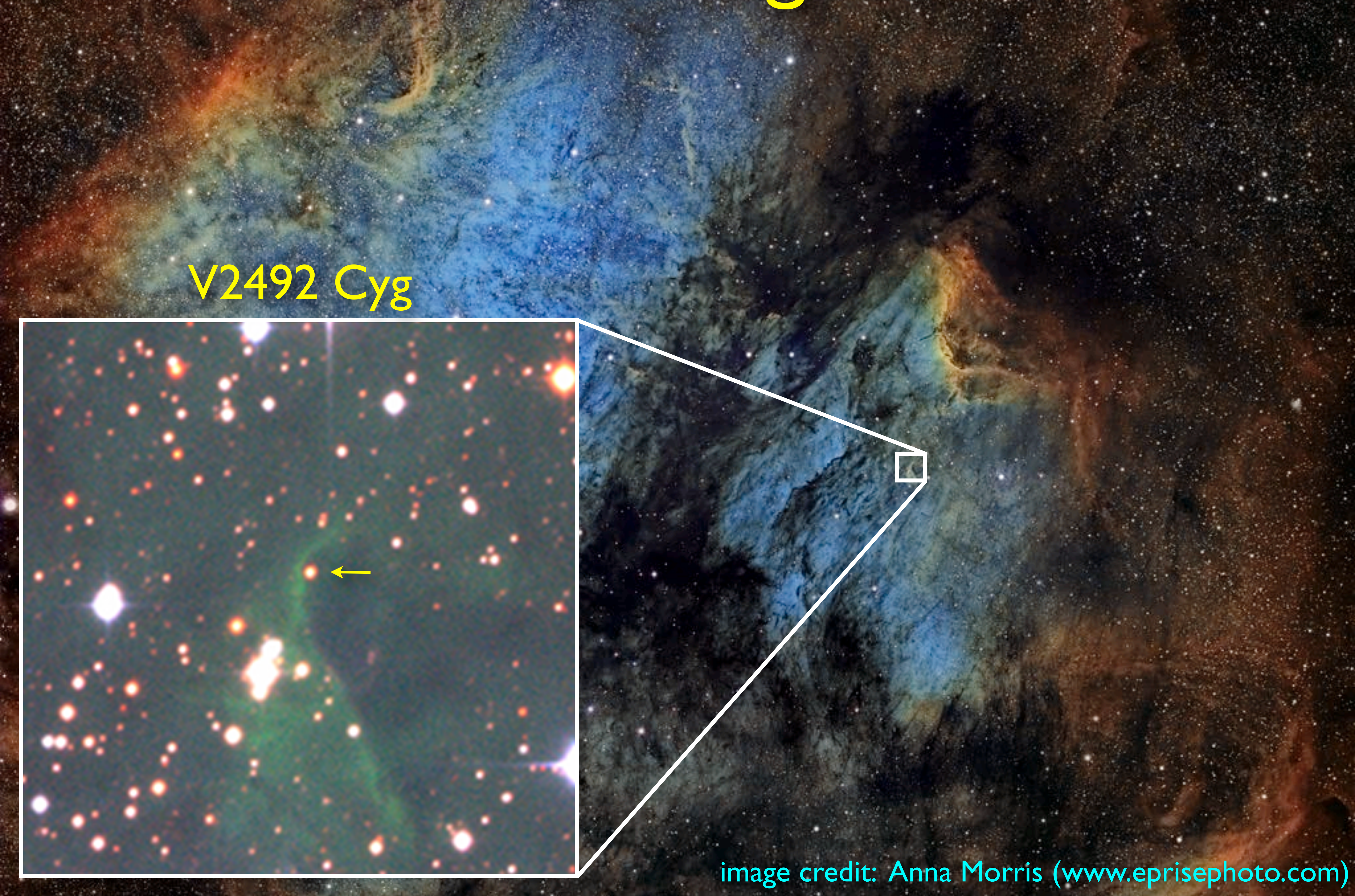
Our target

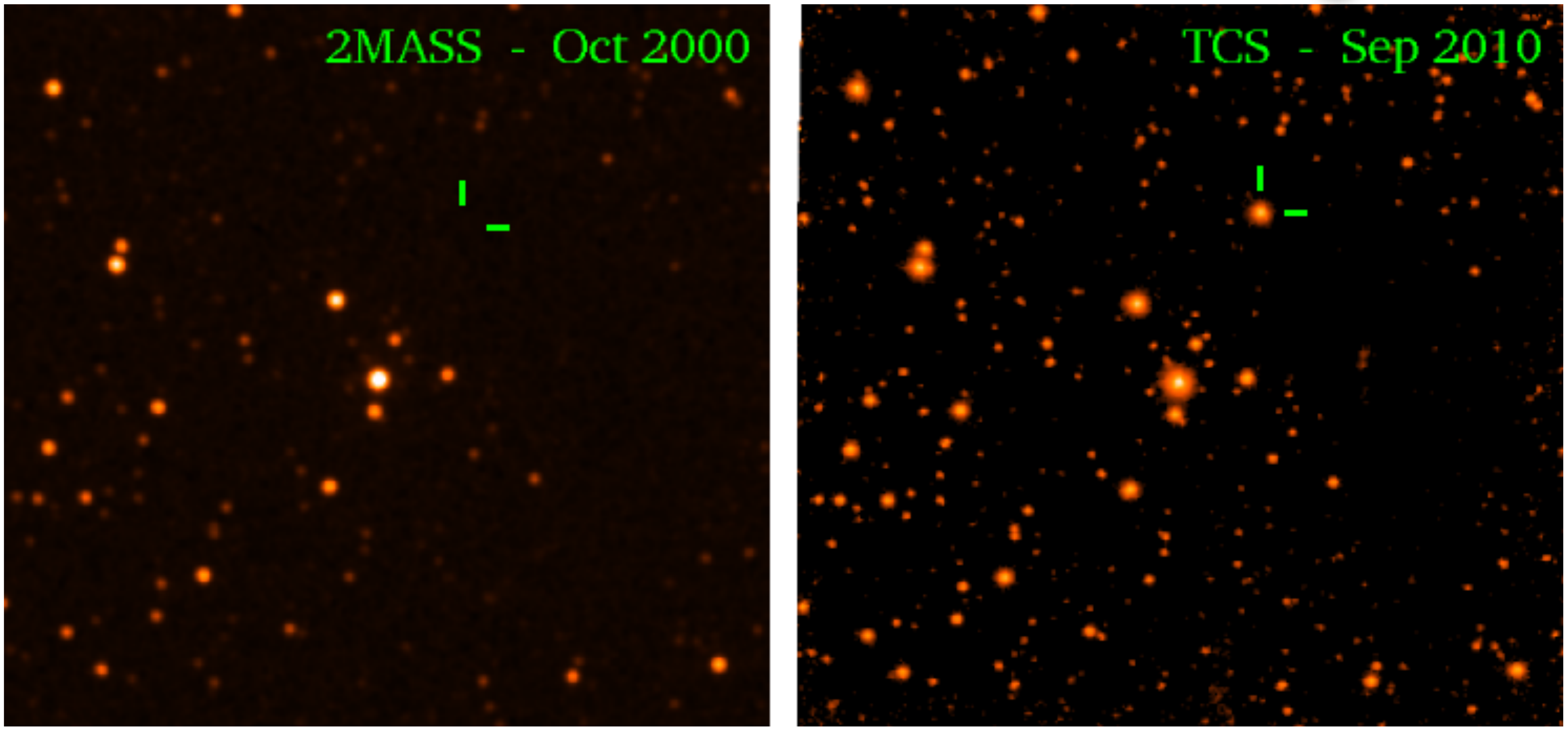


Why is V2492 Cyg so special?

Huge outburst amplitudes: ΔJ = 7.9 mag

ΔH = 6.7 mag

ΔKs = 4.8 mag



Observations: BVRI imaging

Piszkéstető Mountain Station

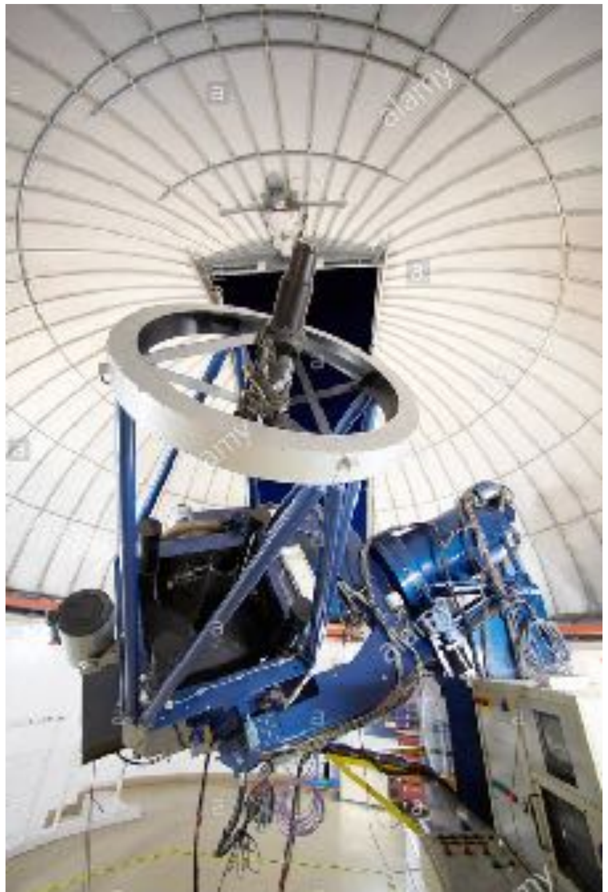
1m *RCC, 60/90/180cm Schmidt*

CCD camera

Teide Observatory

IAC-80 (85 cm Cassegrain)

CCD camera

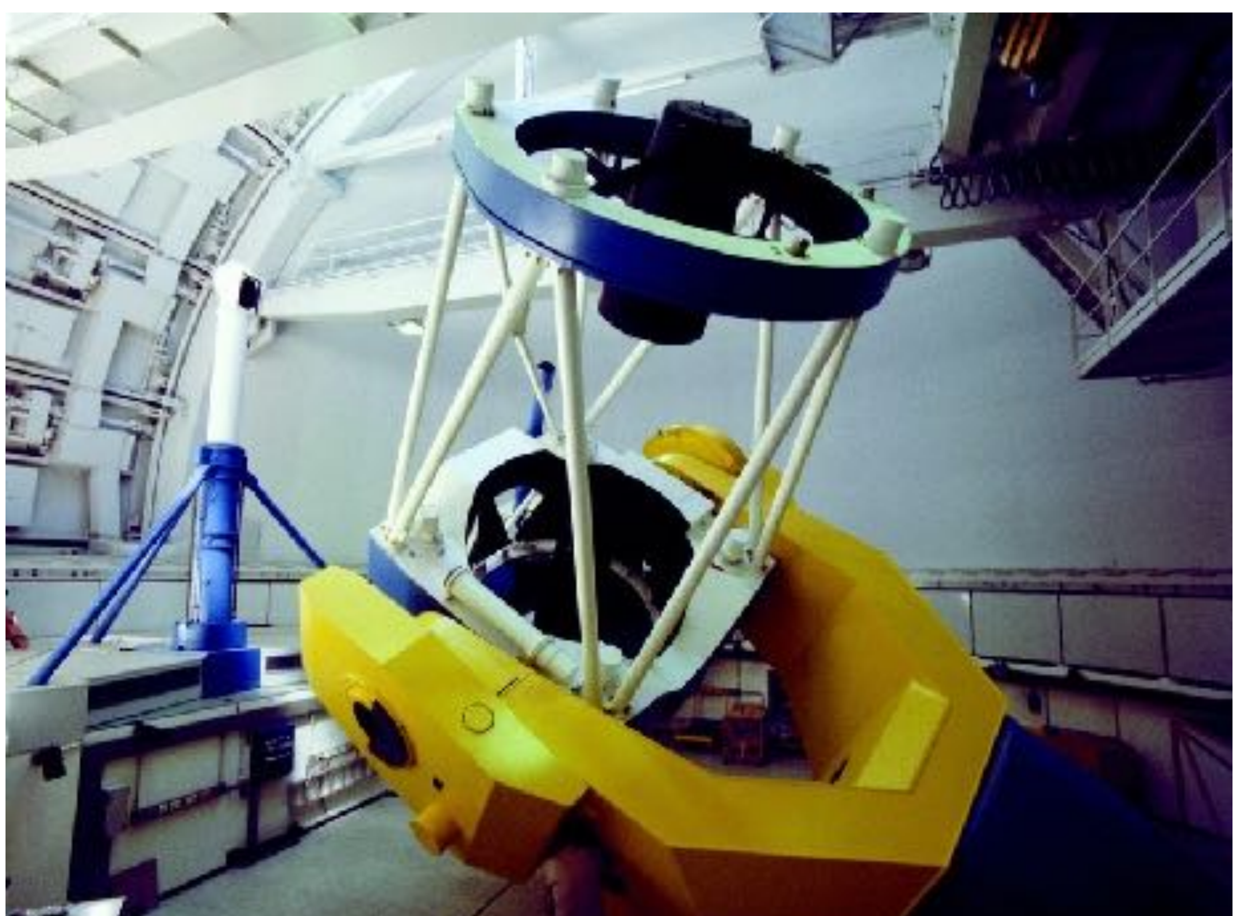


Observations: optical spectroscopy

Roque de Los Muchachos Observatory
La Palma

10.4m Gran Telescopio Canarias

OSIRIS tunable imager and spectrograph, 5575-7685 AA, R=2475



Calar Alto Observatory

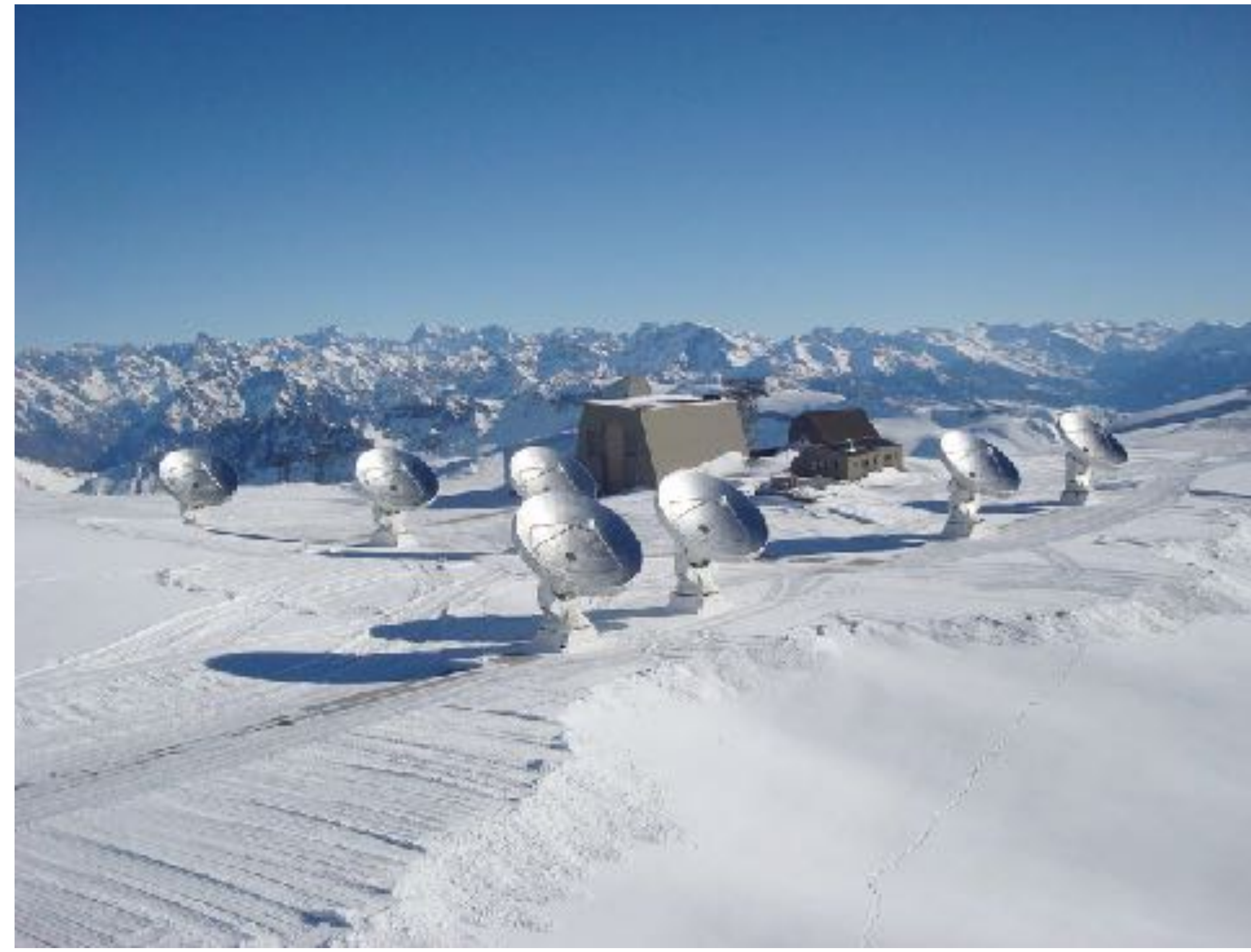
2.2m Cassegrain

CAFOS, 5800-9000 AA, R=3500

Observations: millimeter wavelengths

IRAM 30m single dish
Granada

45.8” beam



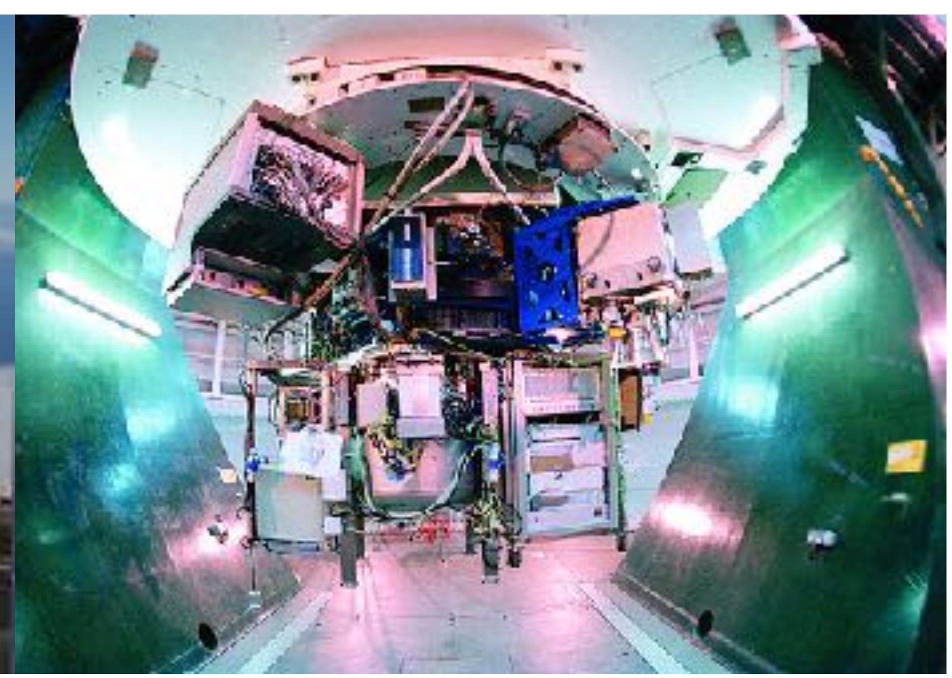
NOEMA (PdBI)
Plateau de Bure, Hautes-Alpes 7 antennas, 15m each, $^{13}CO(1\text{-}0)$, $C^{18}O(1\text{-}0)$, 2.7mm continuum, 4.2”x2.8” beam

Observations: near-IR imaging & spectroscopy

Teide Observatory
Tenerife

Telescopio Carlos Sanchez (152 cm)

CAIN3 camera, JHKs filters



Roque de Los Muchachos Observatory
La Palma

William Herschel Telescope (4.2 m)

LIRIS instrument, long-slit spectra, R=550-700; 2500

Observations: near-IR imaging & spectroscopy

Teide Observatory
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Telescopio Carlos Sanchez (152 cm)

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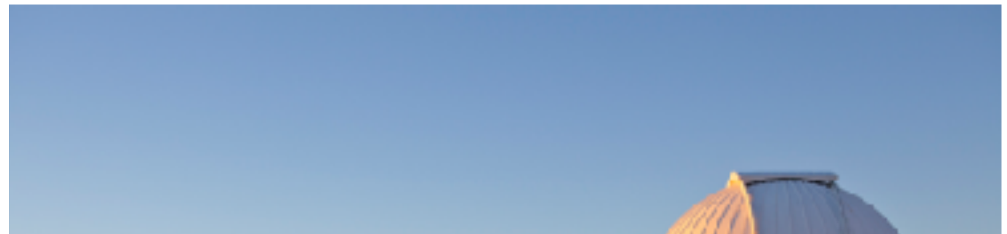

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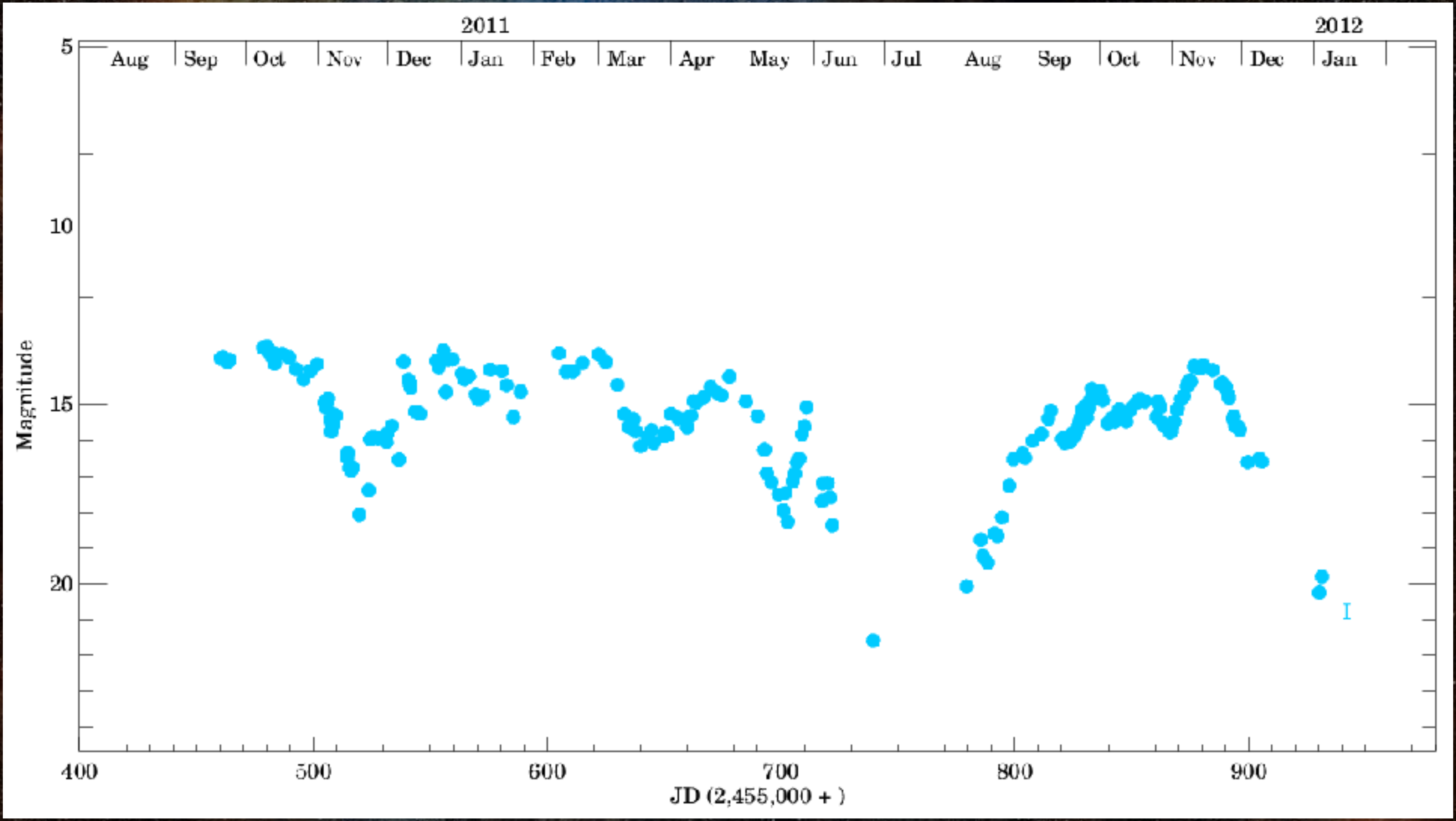
LIRIS instrument, long-slit spectra, R=550-700; 2500

Why is V2492 Cyg so special?

Peculiar light curve



Kóspál et al. (2011), Kóspál et al. (in prep.), AAVSO

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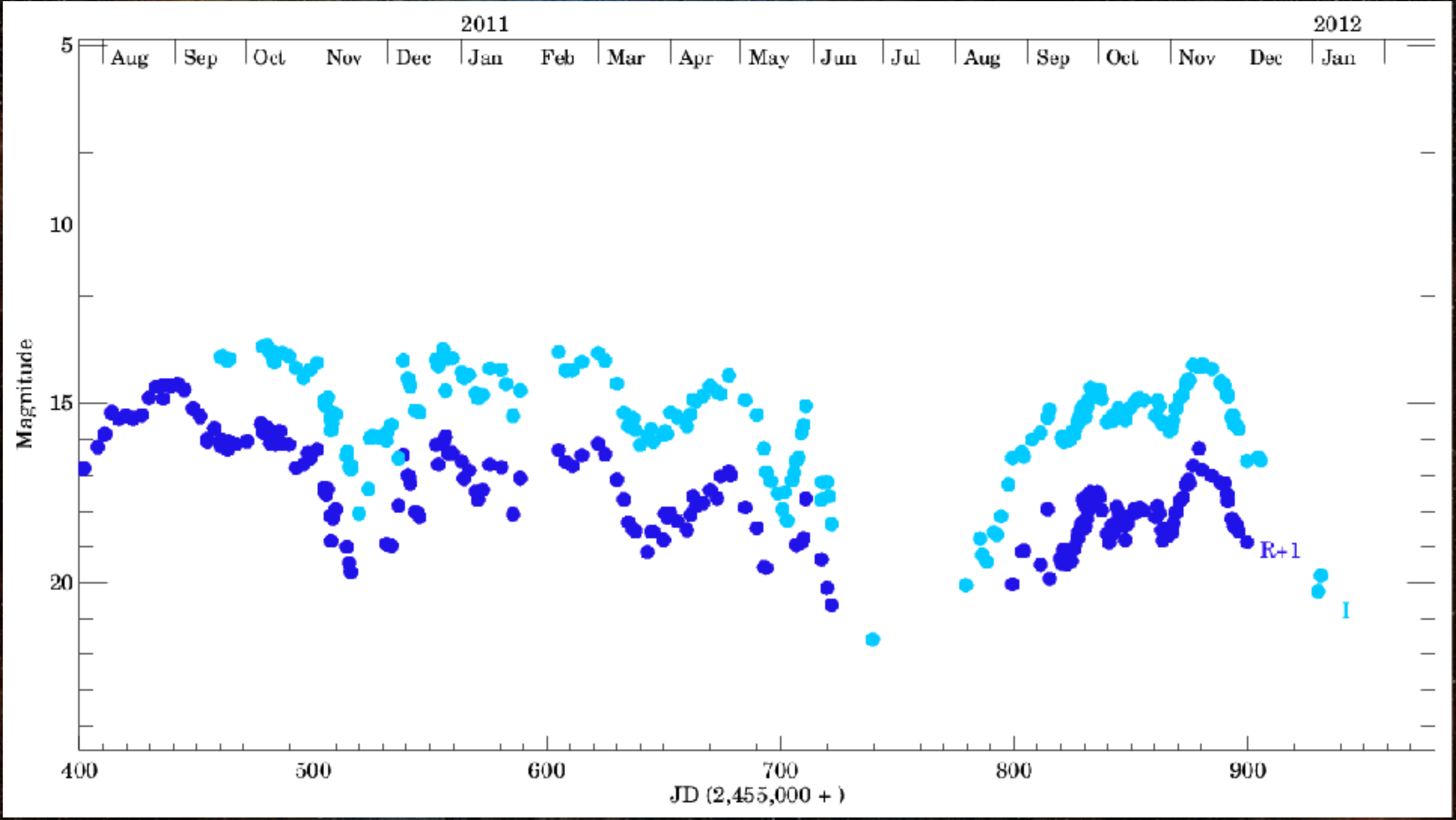

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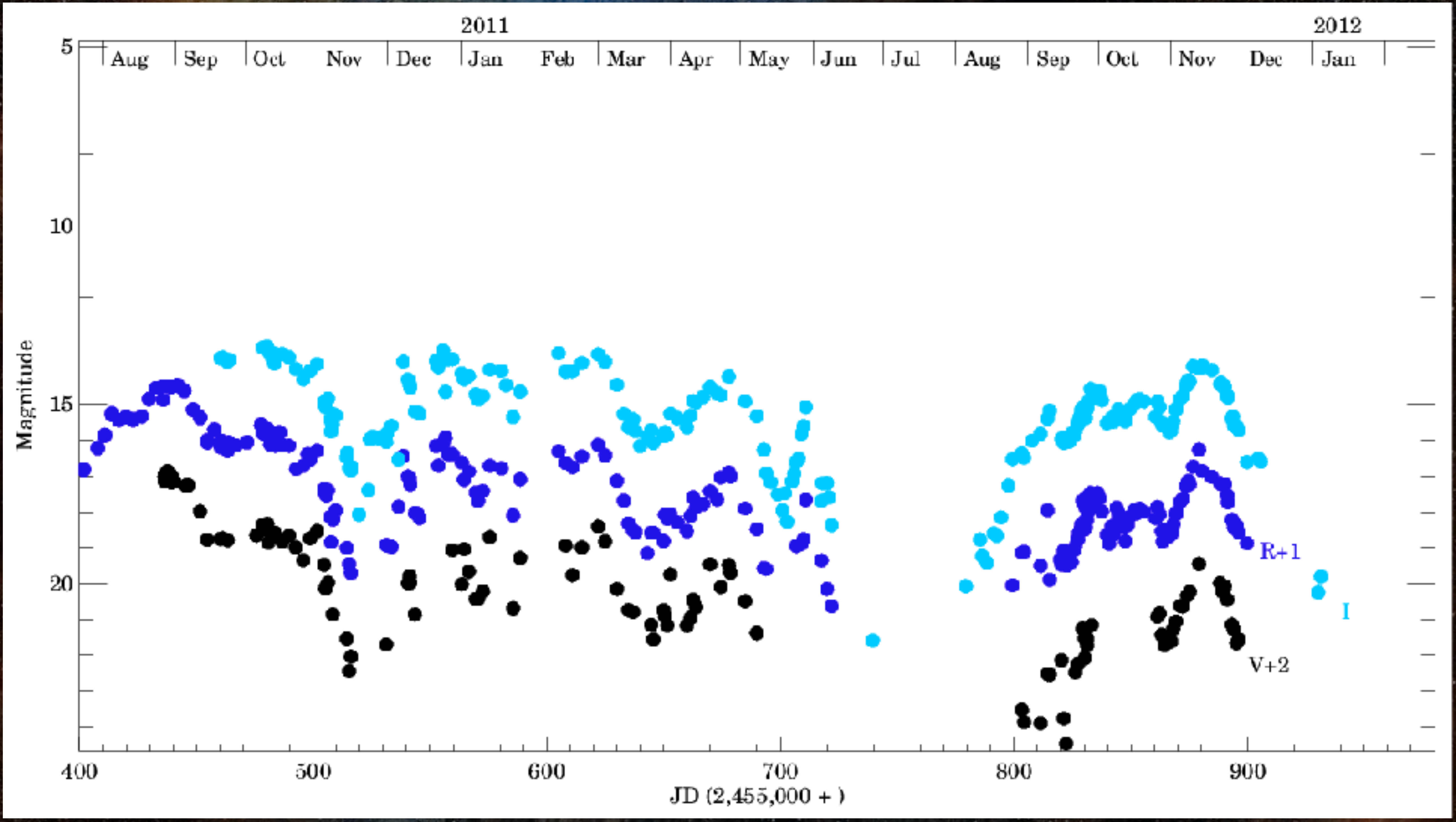

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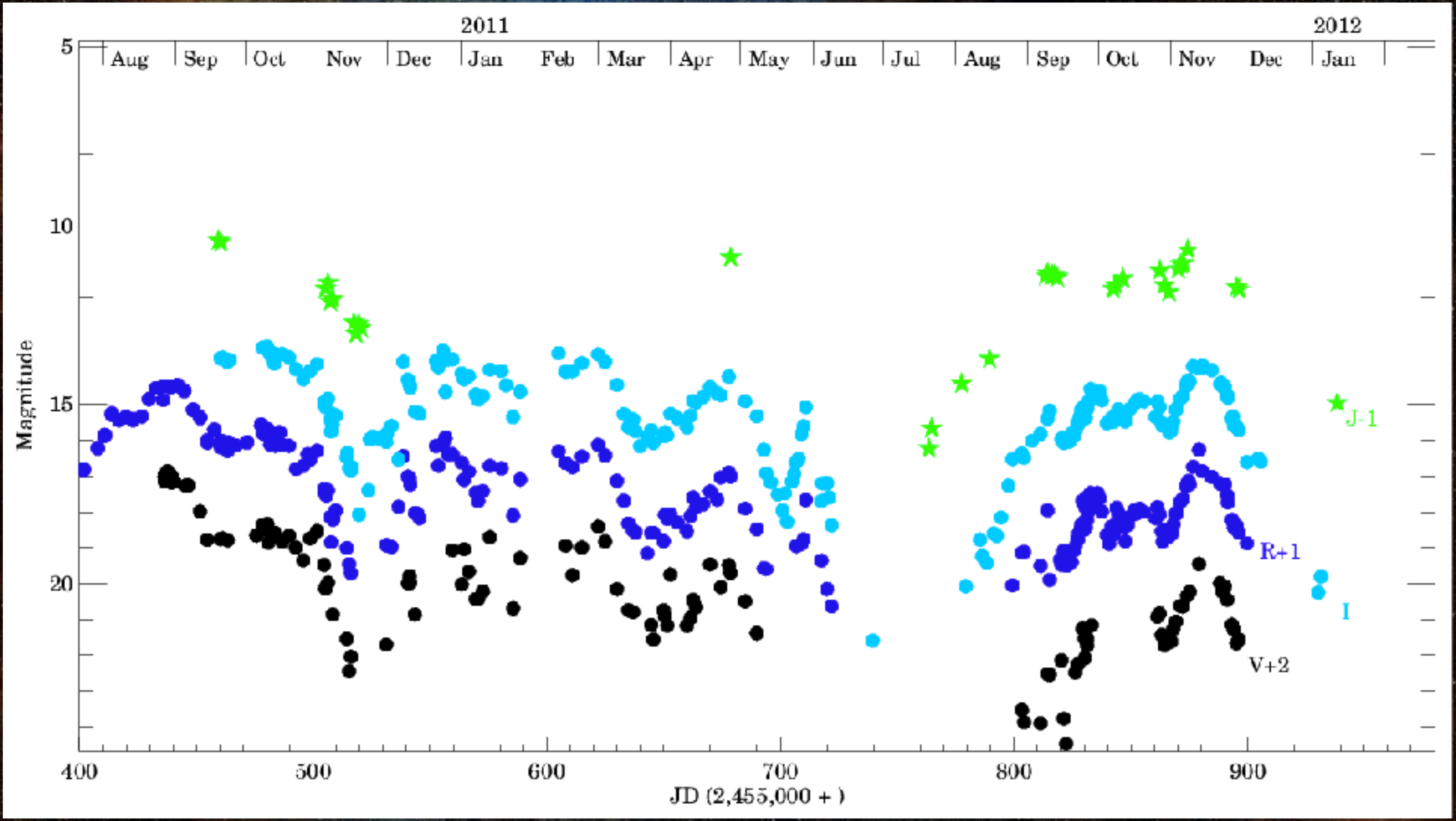

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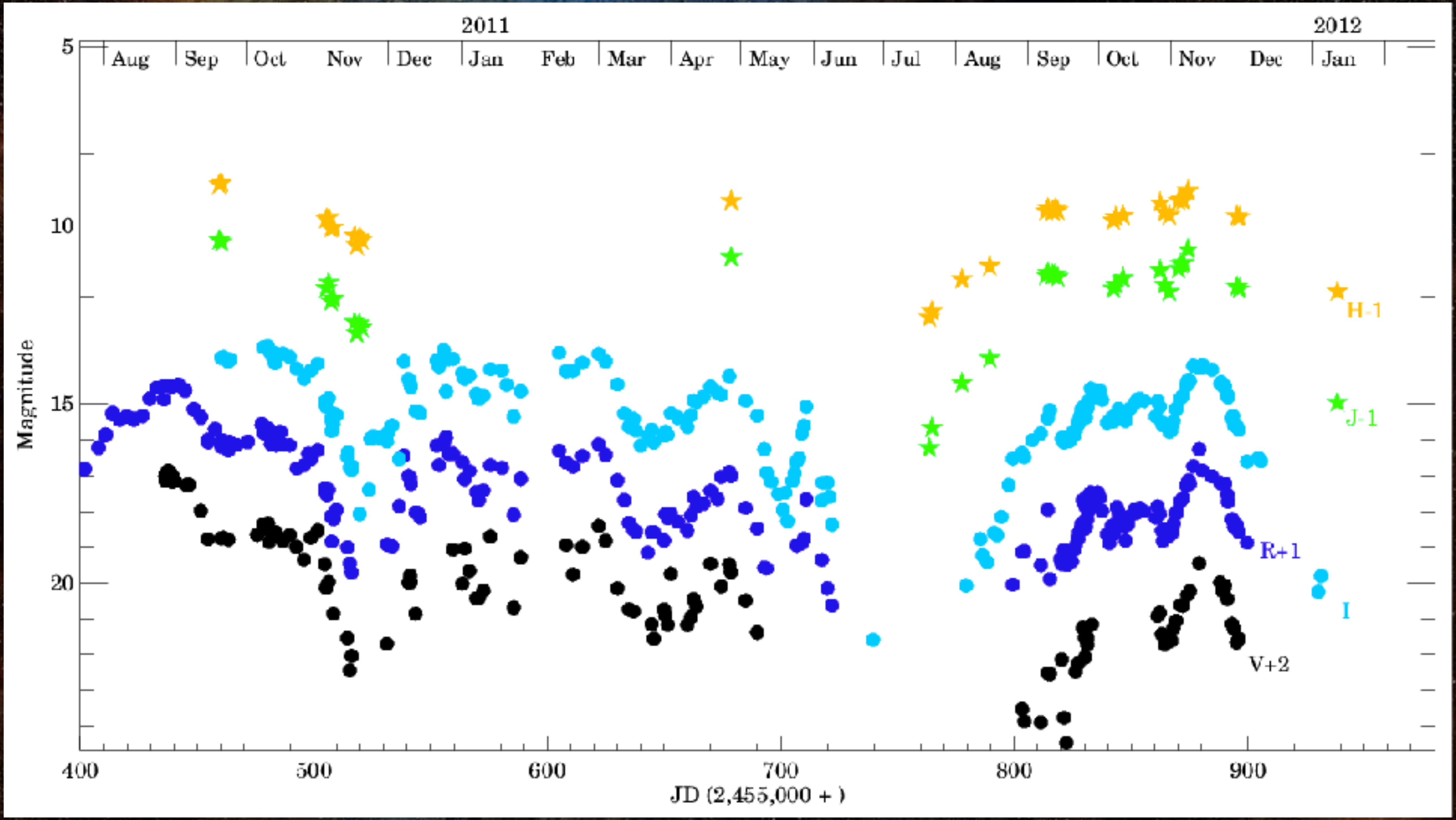

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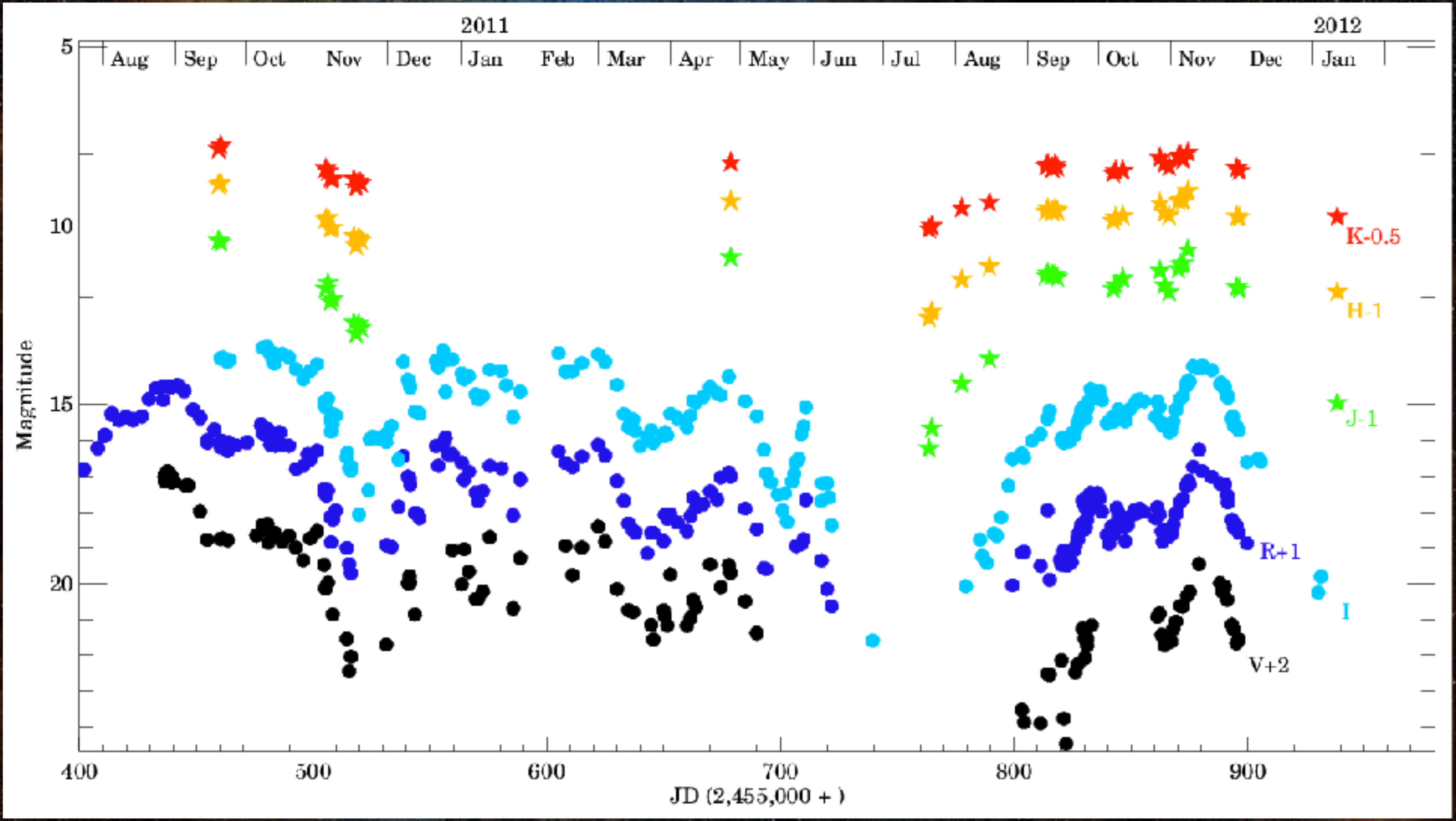

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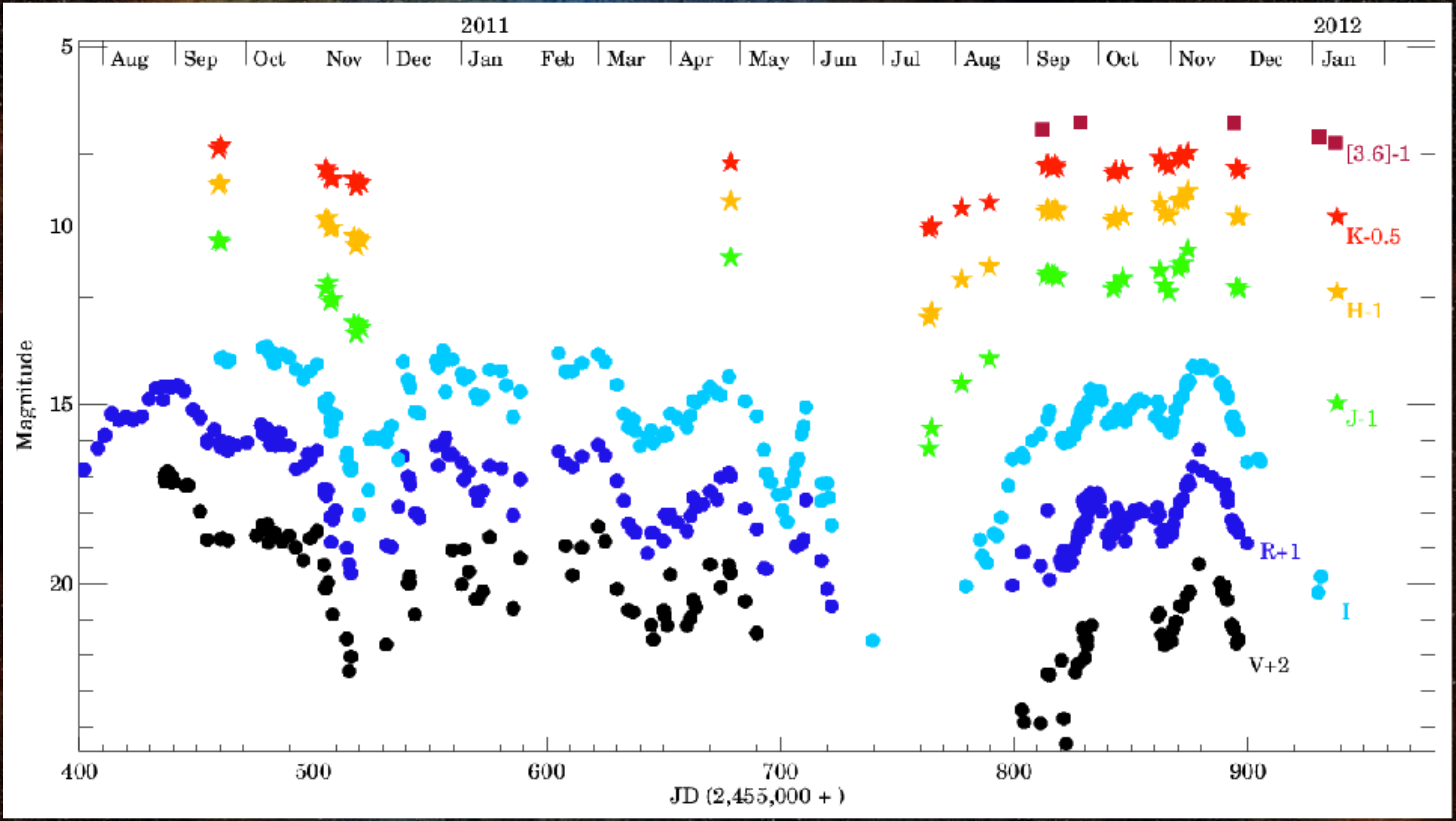

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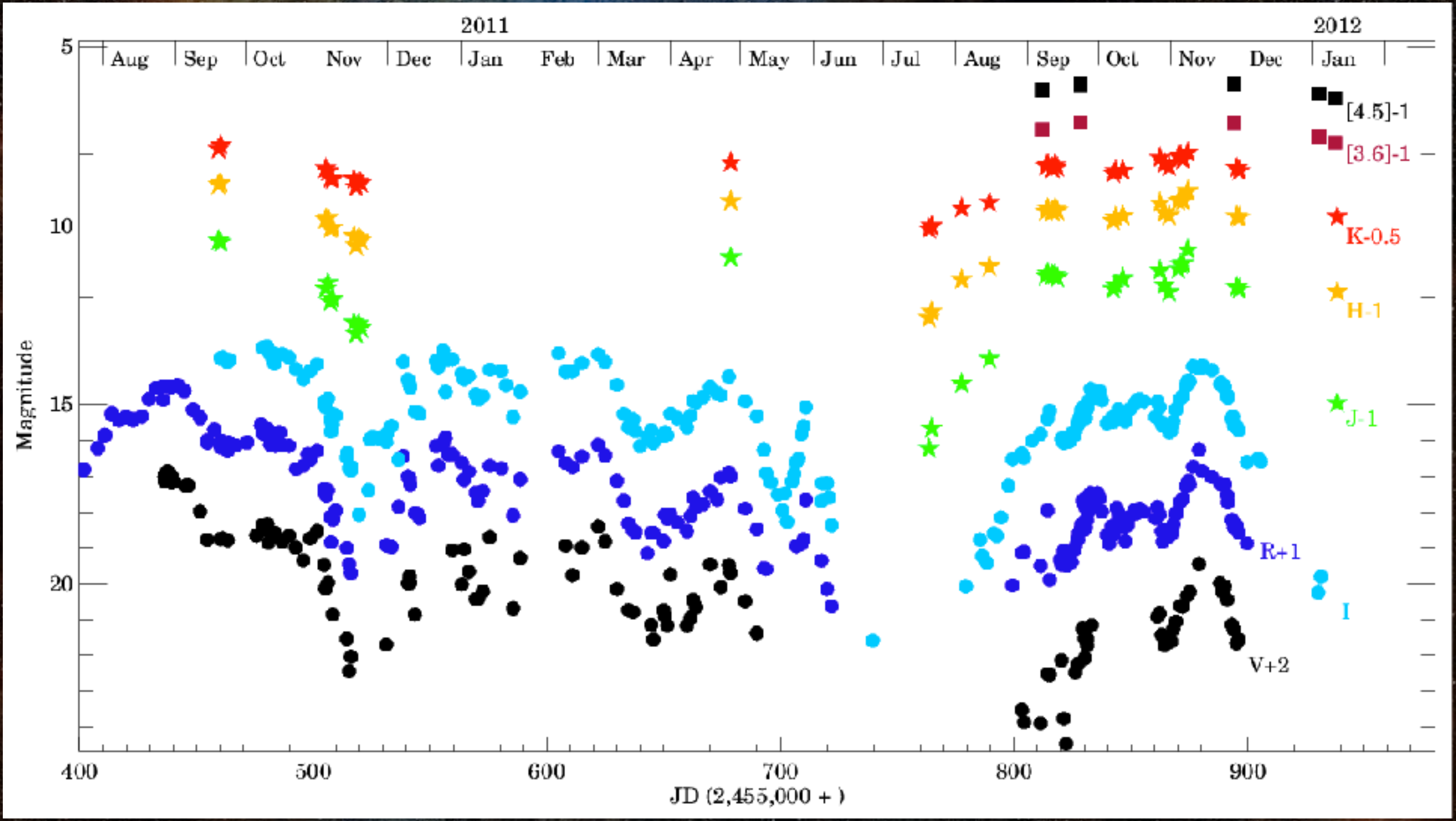

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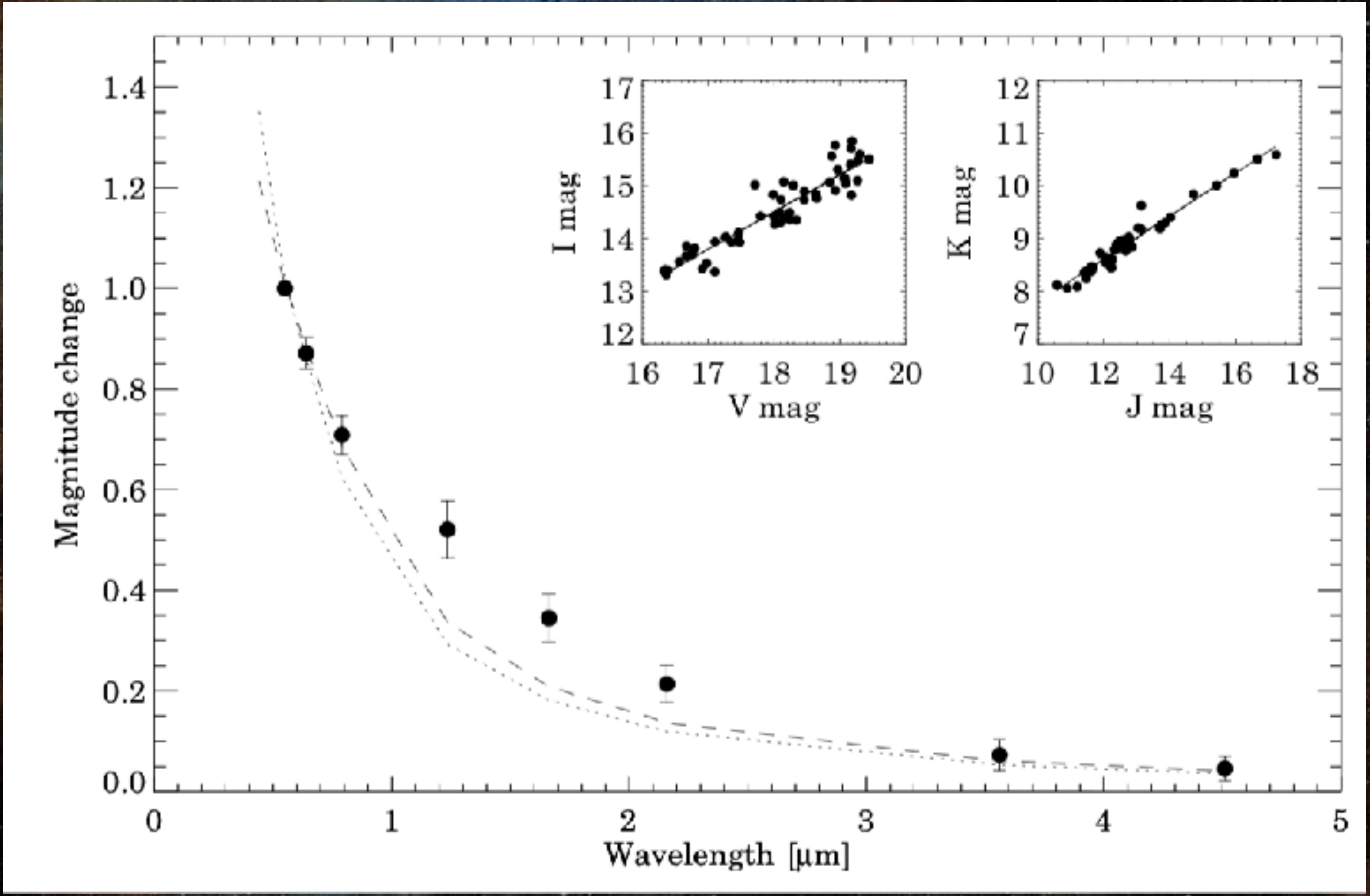
Why is V2492 Cyg so special?

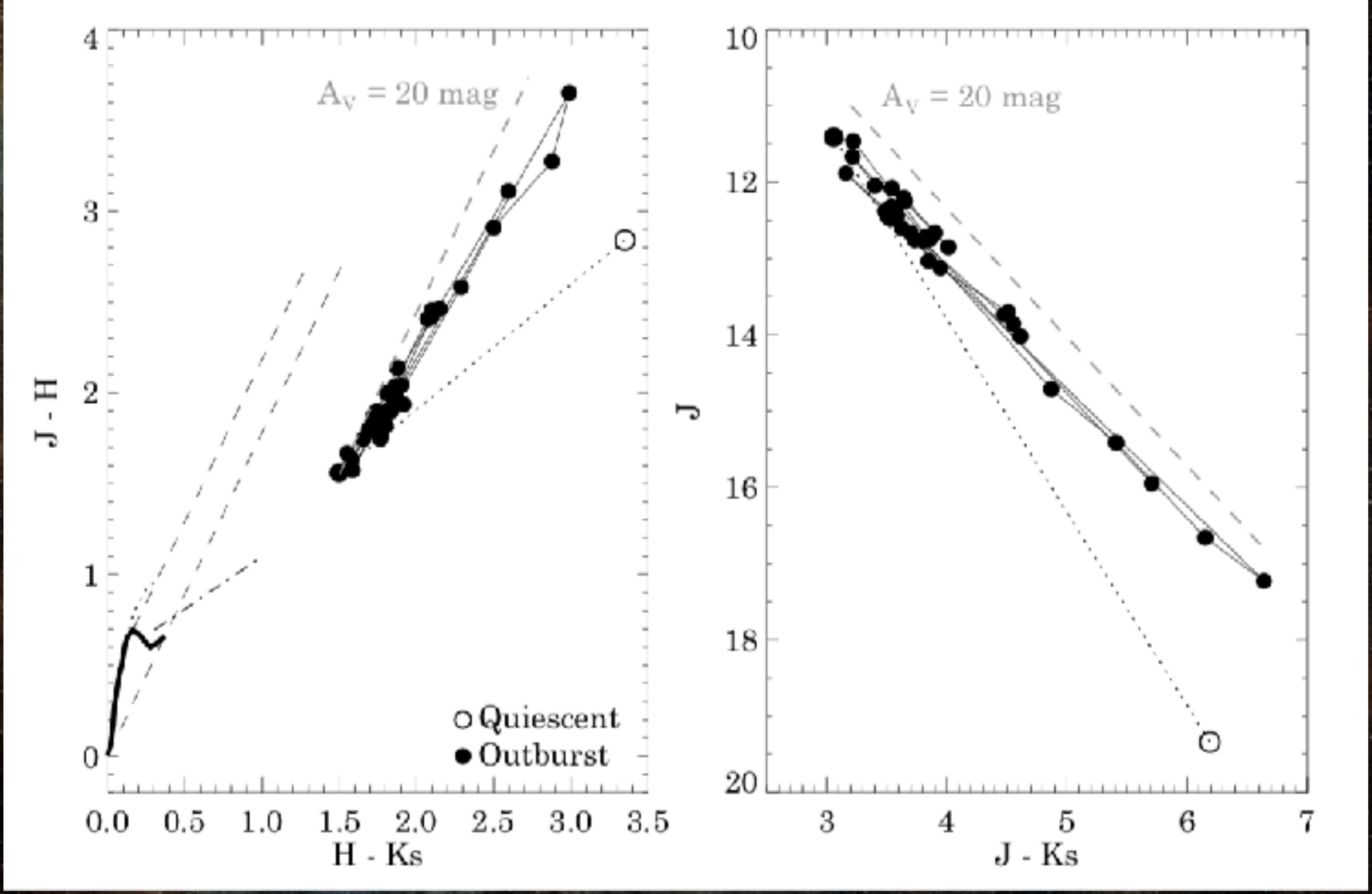
Peculiar color changes



Kóspál et al. (2013)

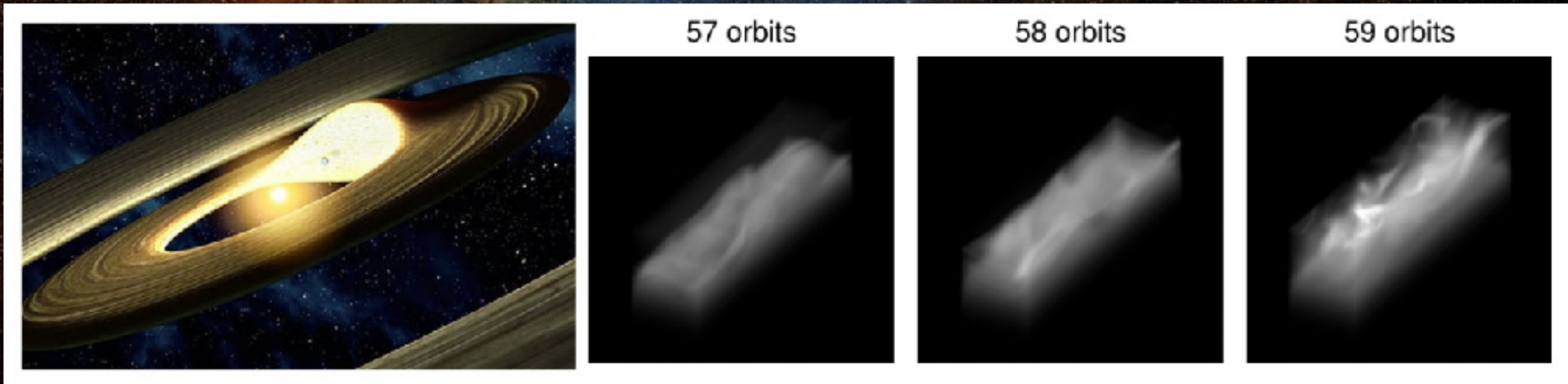
Why is V2492 Cyg so special?

Peculiar color changes



Kóspál et al. (2013)

Possible reasons for flux changes



Muzerolle et al. (2009)
Flaherty et al. (2011)

Turner et al. (2010)

Existing dust cloud/ lump in the disk orbits the star

Due to turbulence/magnetic activity, dust clouds are lifted off the surface of the disk

Let’s look for far-infrared flux variations!

What do we expect?

Pre-existing, orbiting dust cloud/lump

$\Downarrow$

Constant far-infrared flux

Forming/disappearing dust cloud/lump

$\Downarrow$

Variable far-infrared flux

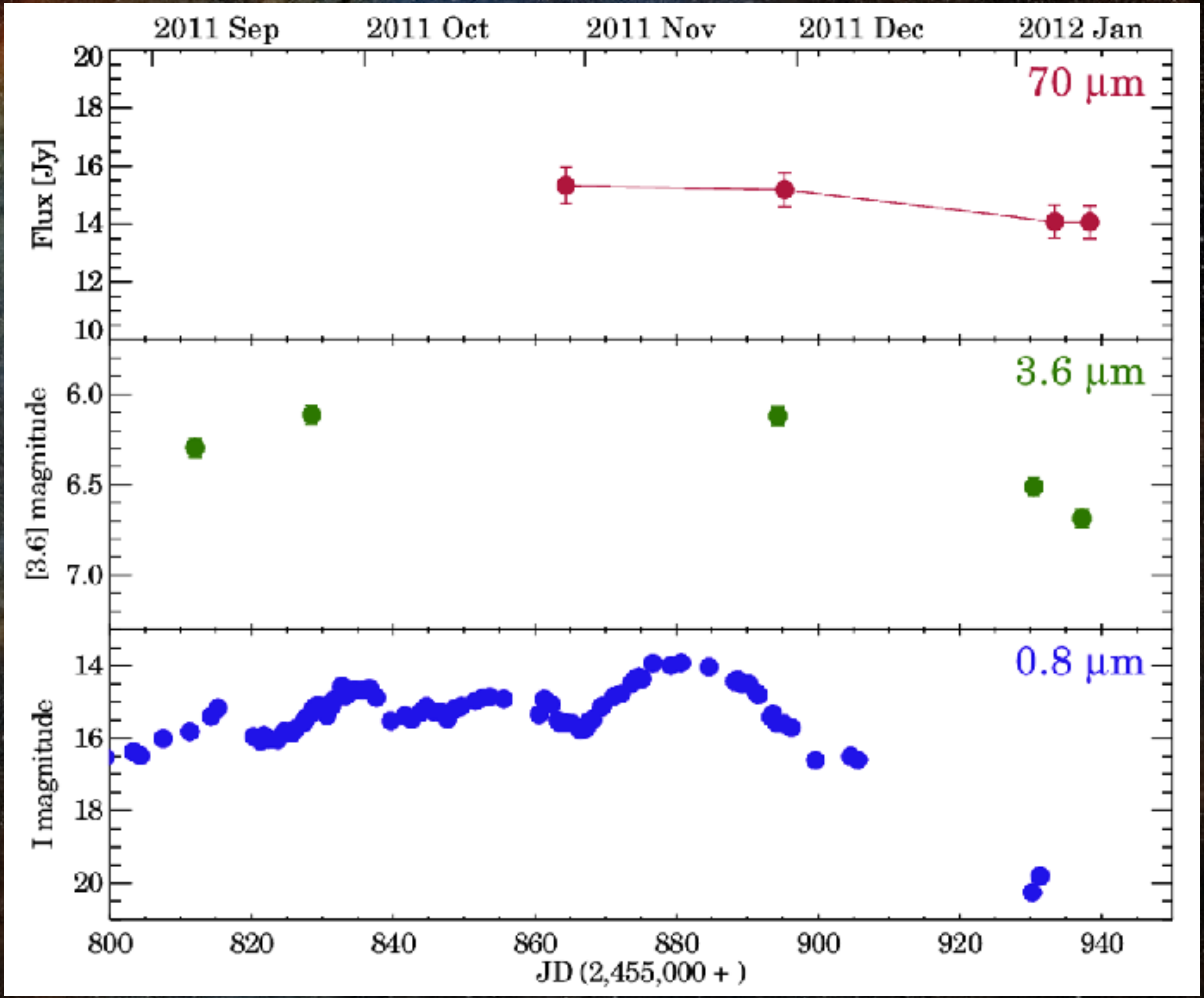
PV Cep

Herschel DDT monitoring of V2492 Cyg (coordinated with Spitzer)

Date	Instrument	Wavelength
2011-Oct-29	PACS	70, 160
2011-Nov-29	PACS	70, 100, 160
2012-Jan-03	SPIRE	250, 350, 500
2011-Jan-06	PACS	70 160
2011-Jan-11	PACS	70, 160

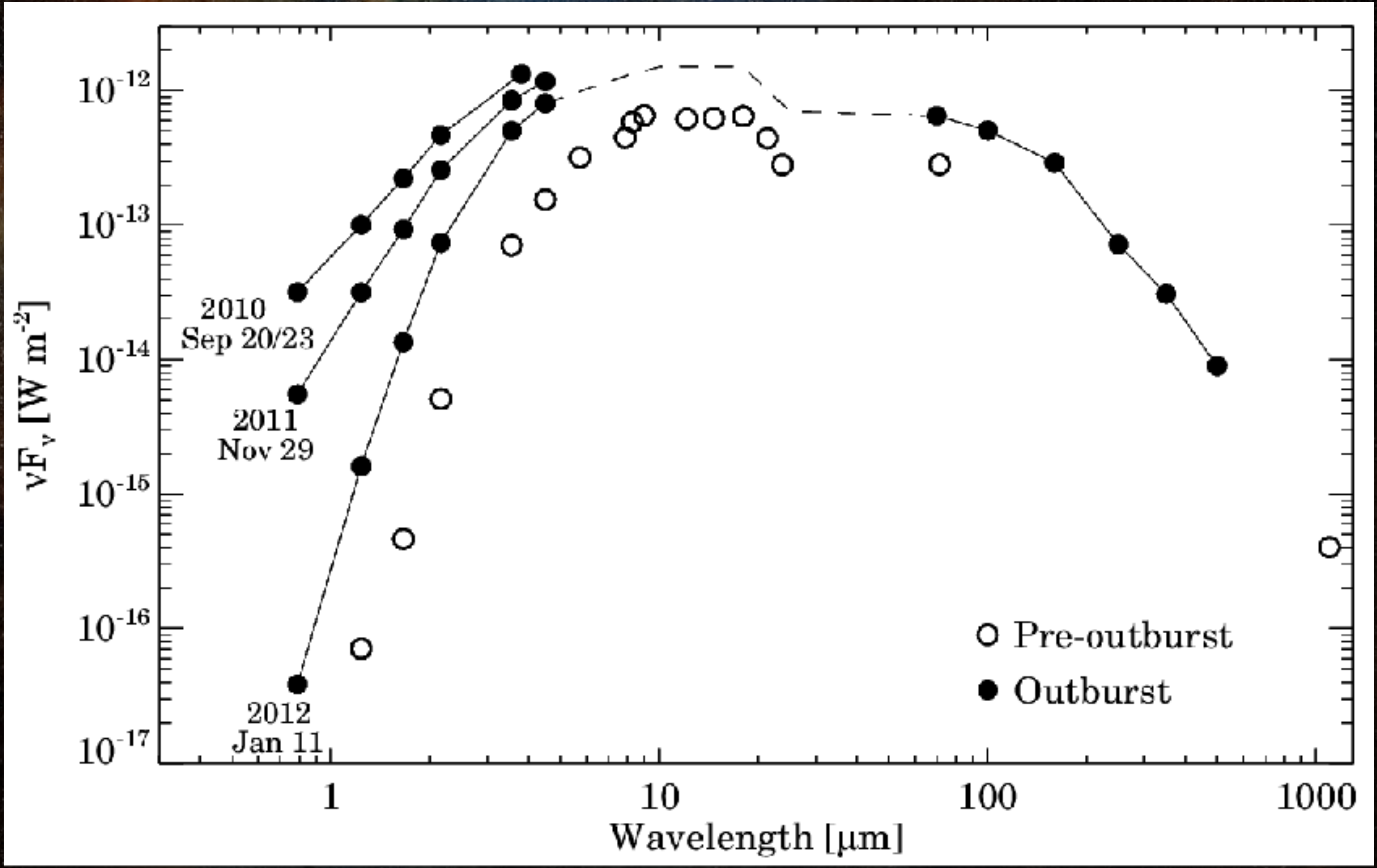
PV Cep

FIR light curves of V2492 Cyg



Kóspál et al. (in prep.)

SED of V2492 Cyg



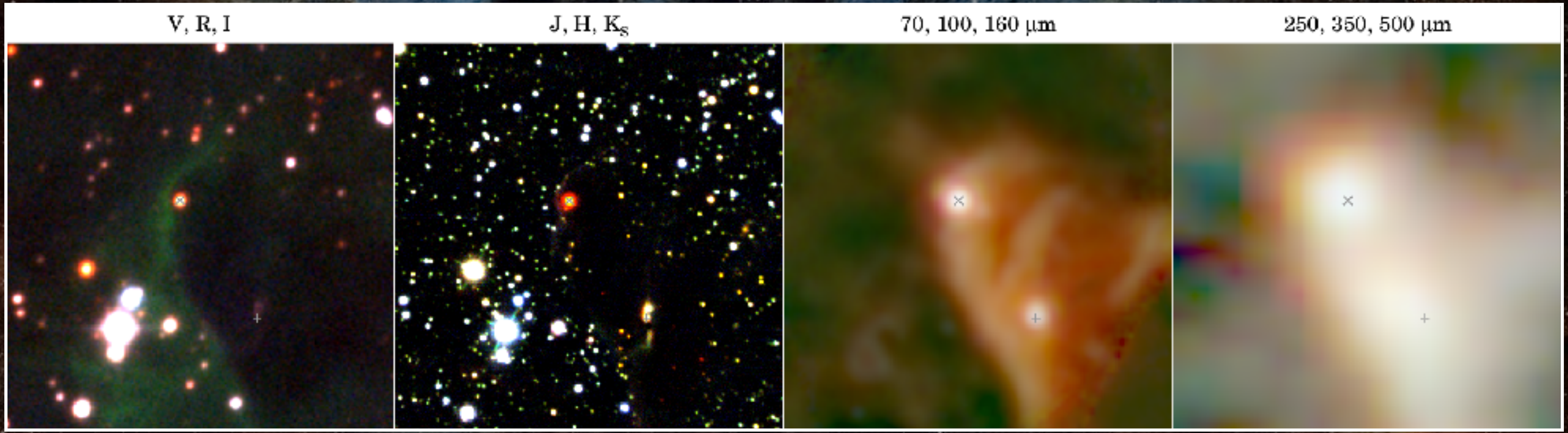
Kóspál et al. (2011), Kóspál et al. (in prep.)

Summary

- V2492 Cyg went into outburst reaching a peak around August 2010
- Since then, the optical-infrared light curves show signs of changing extinction (ΔA_V = 20 mag, Δ(column density) = 0.07 g cm^{-2}) → dust inhomogeneities/clouds/lumps in the inner disk
- We performed a co-ordinated Spitzer-Herschel monitoring to see if there is any indication for changing illumination of the outer disk/envelope
- The 70 μm monitoring shows constant flux → favors the model of an orbiting dust cloud in the system

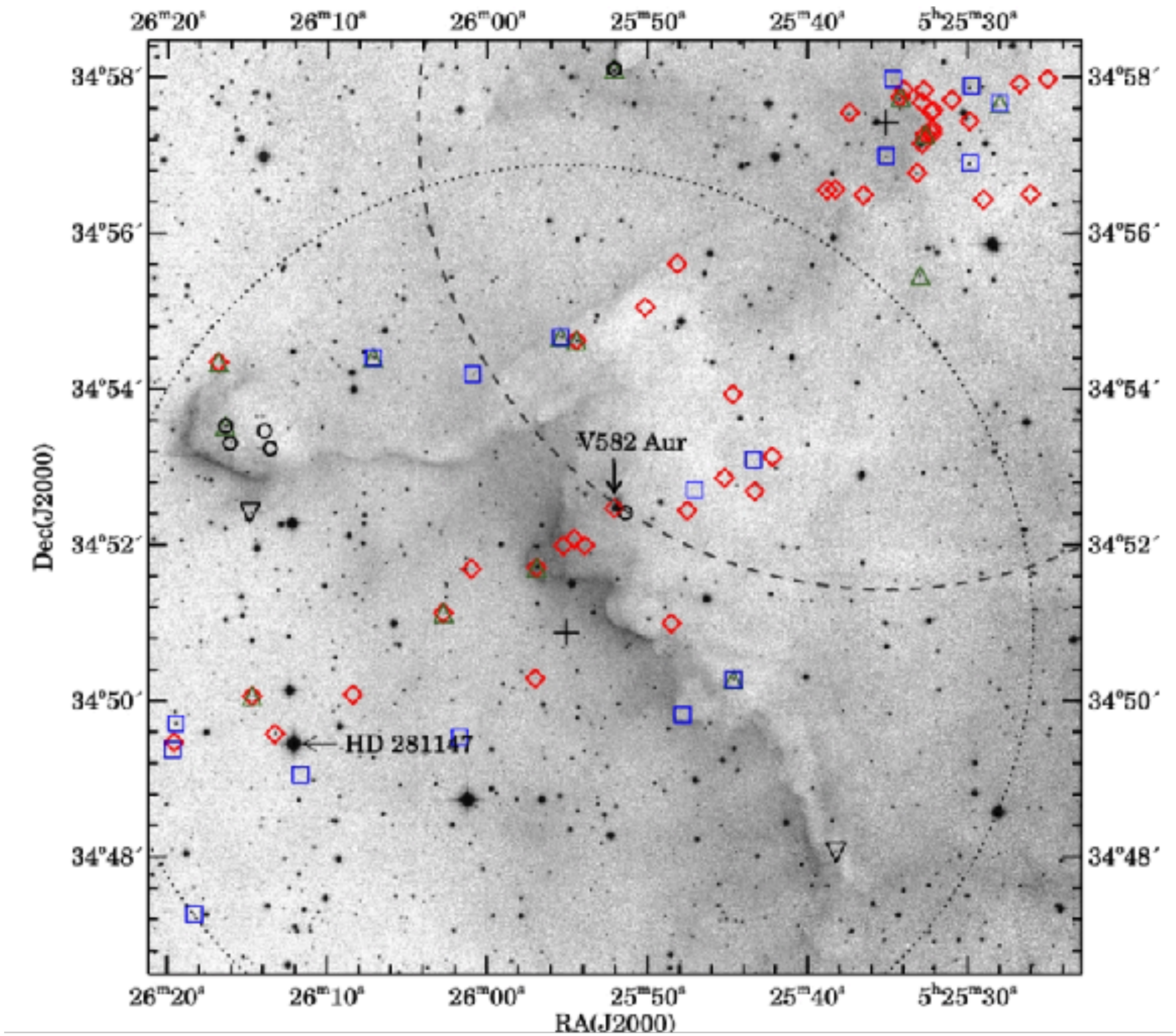
Outlook

- Question: what is the physical mechanism which could produce and maintain such huge dust concentrations?
- General significance: the existence of large density fluctuations in the inner part of the system, the planet-forming zone, may have consequences for grain growth and planetesimal formation



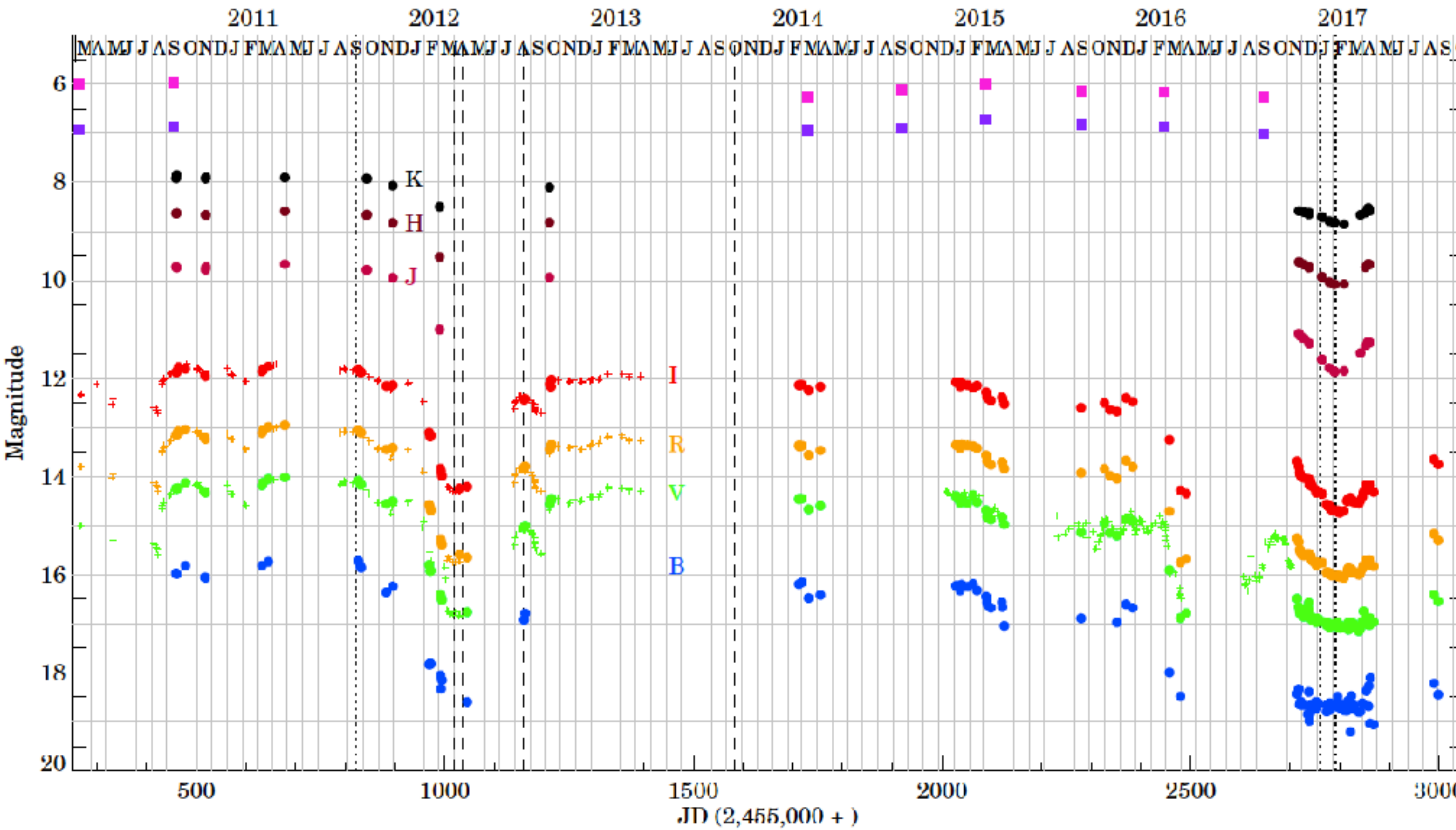
V582 Aur

- FU Ori-type outburst between 1980 and 1985 (Samus+ 2009)
- Aur OB1 association, 1.32 kpc in the Galactic plane
- Surrounded by a group of young stars (Kun+ 2017)
- Outburst luminosity: 150-230 L_{sun}



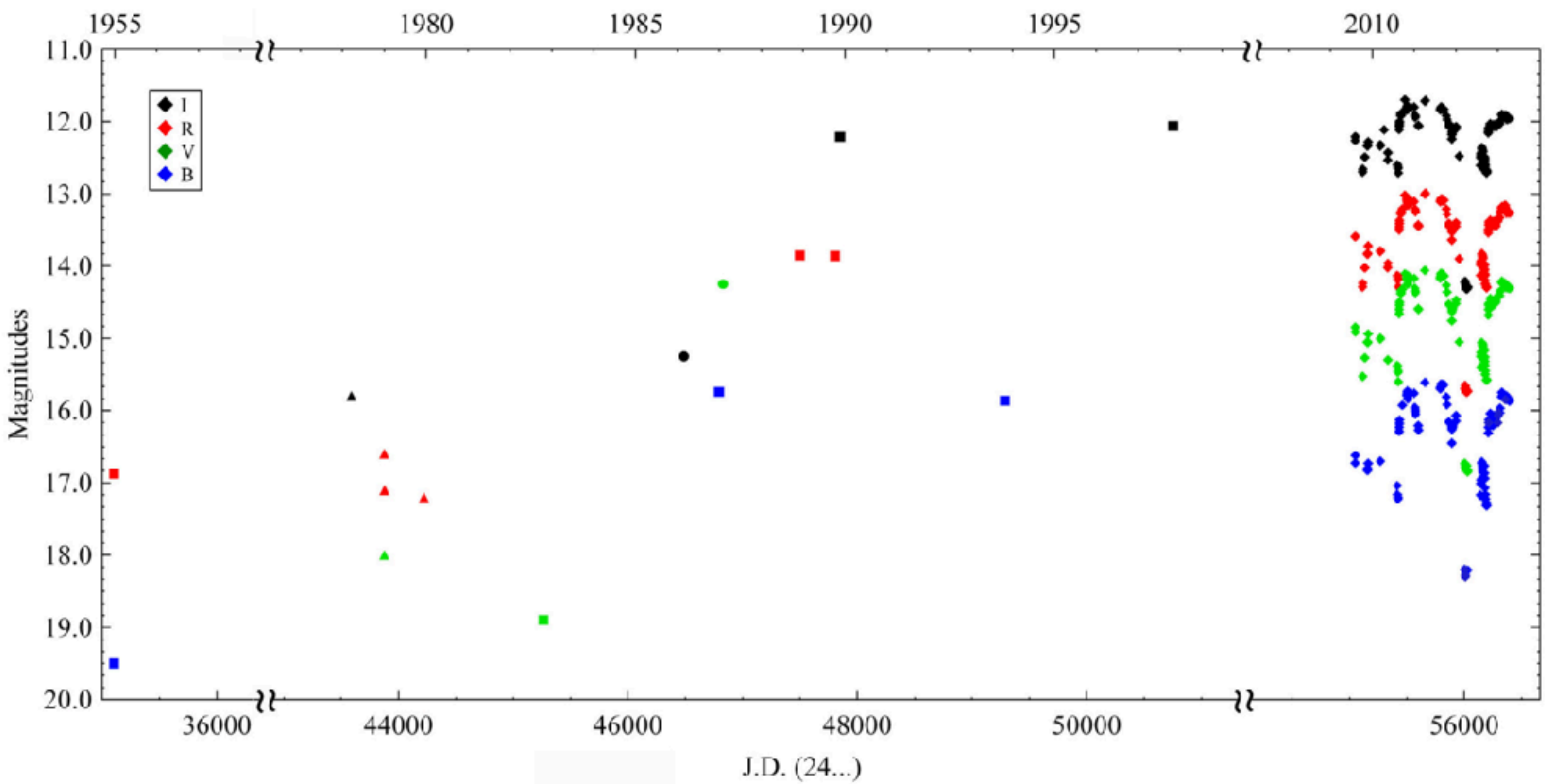
Semkov+ 2013, Kun+ 2017

Motivation++



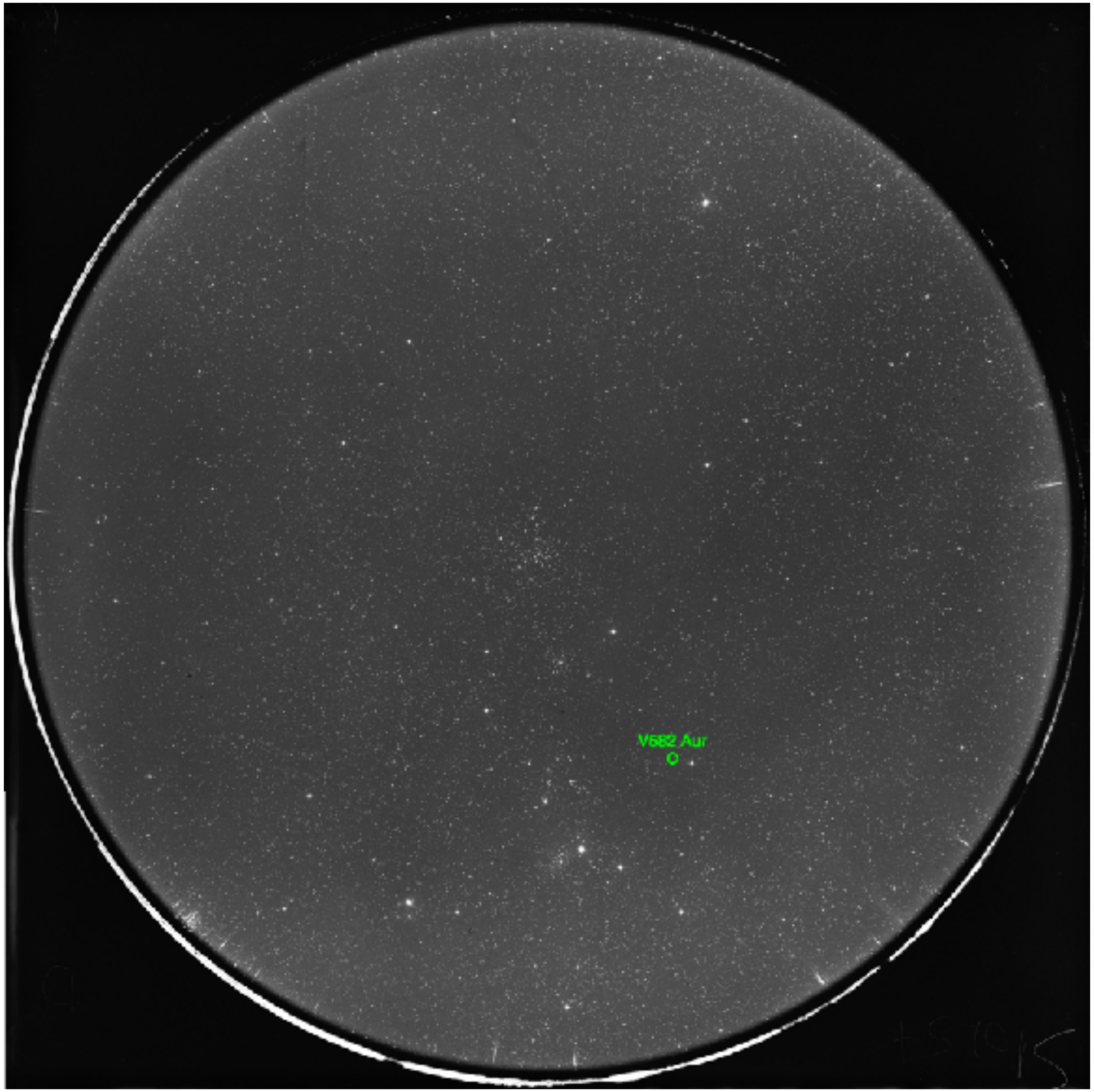
2011
2012
2013
2014
2015
2016
2017
K
H
J
I
R
V
B
Magnitude
JD (2,455,000 +)
500
1000
1500
2000
2500
3000
6
8
10
12
14
16
18
20

Pre-outburst history

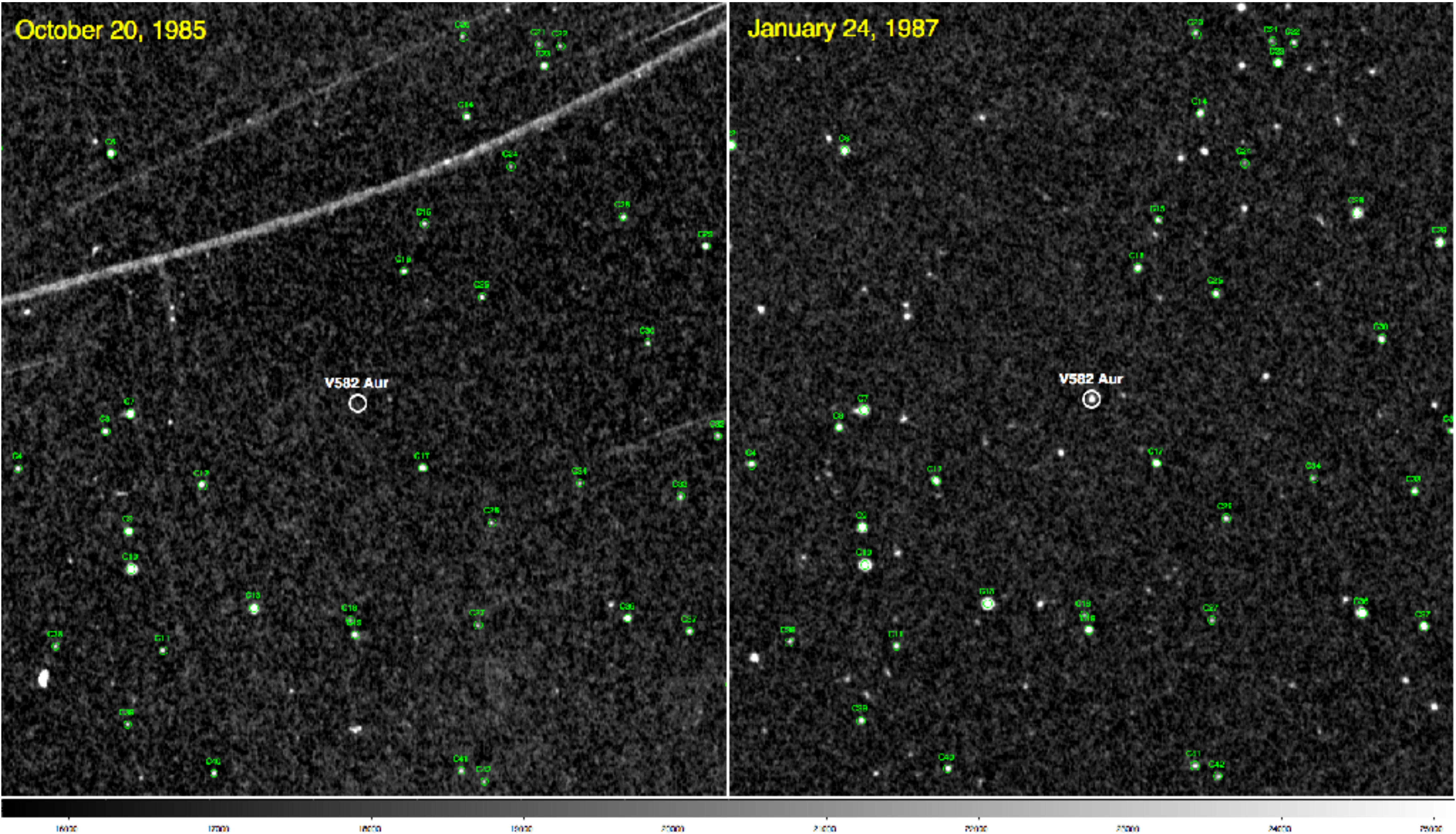


Semkov+ 2013

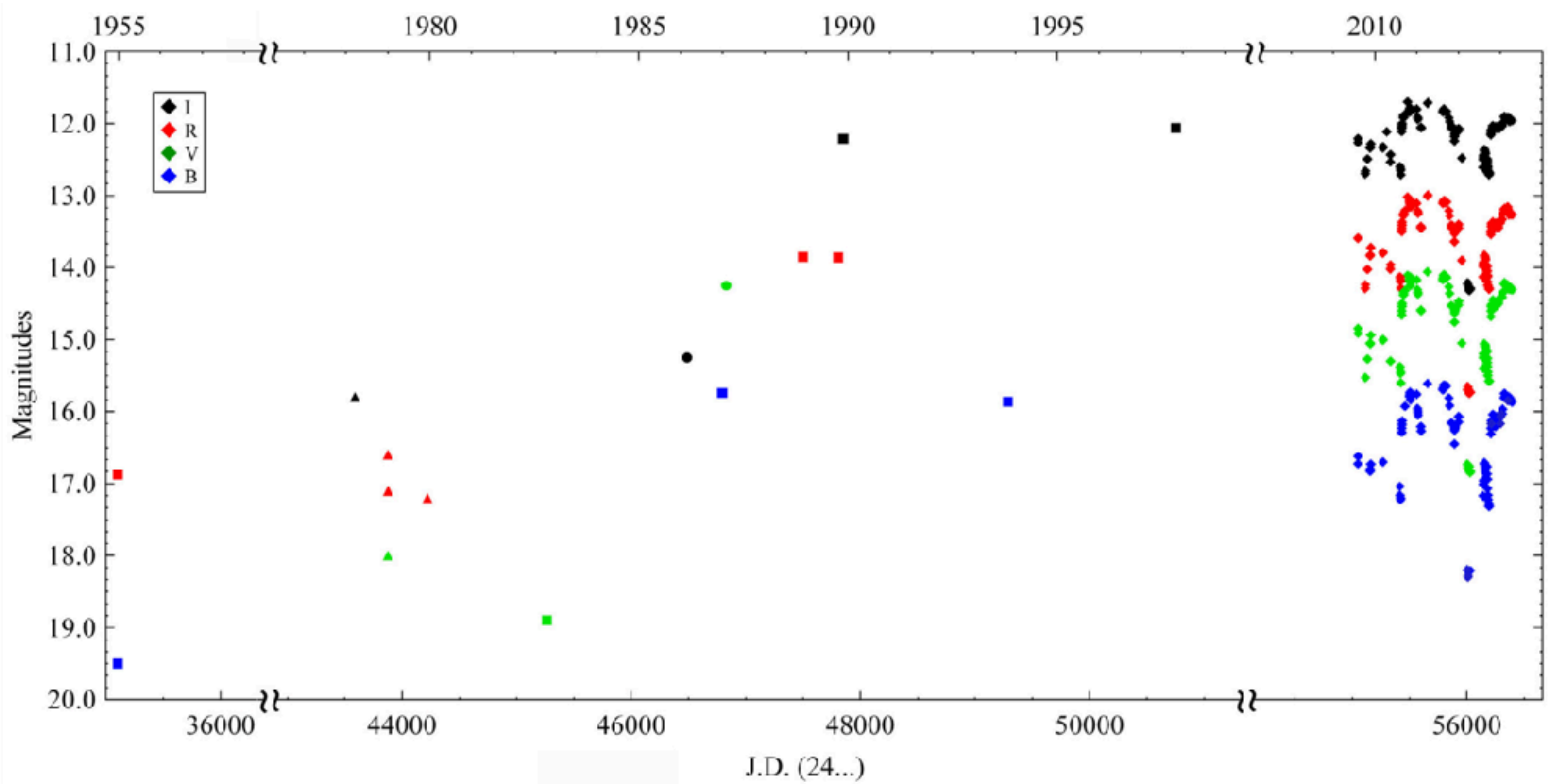
Photographic plates of Konkoly Observatory



Photographic plates at Konkoly Observatory

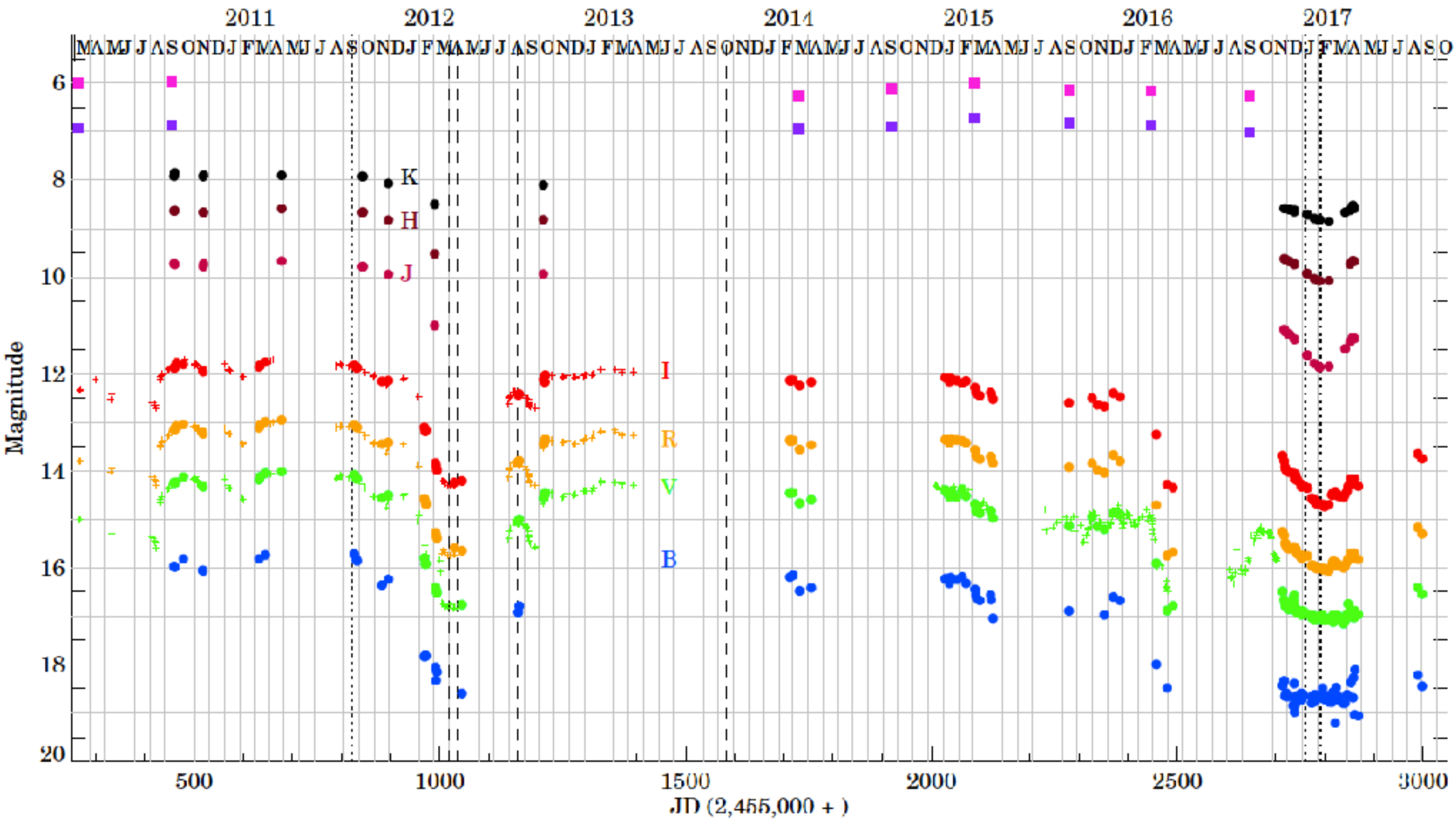


The initial brightening

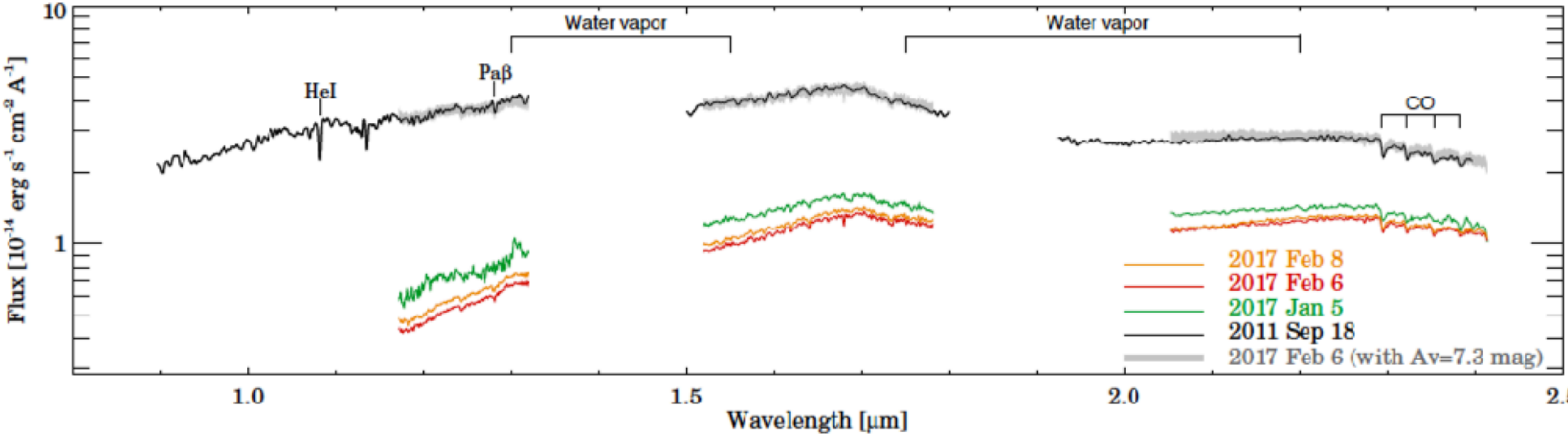


- V-band plates are analysed
- 1985 Oct 21: undetected (V>16.5 mag)
- 1987 Jan 24: detected (V=13.85)
- **The outburst occurred between 1986 Jan and Dec.**

Light curves and the evolution of the outburst



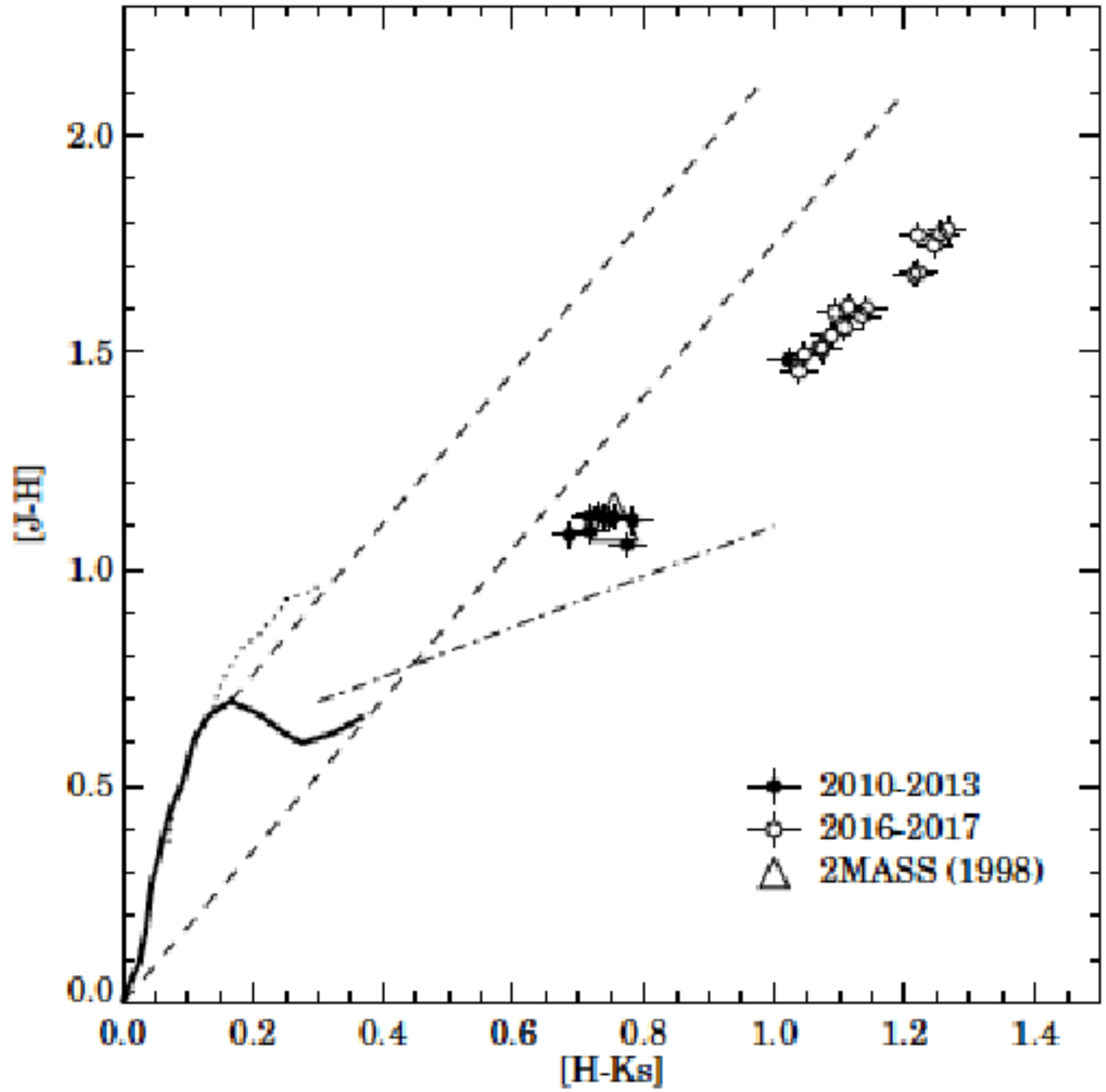
Infrared spectroscopy



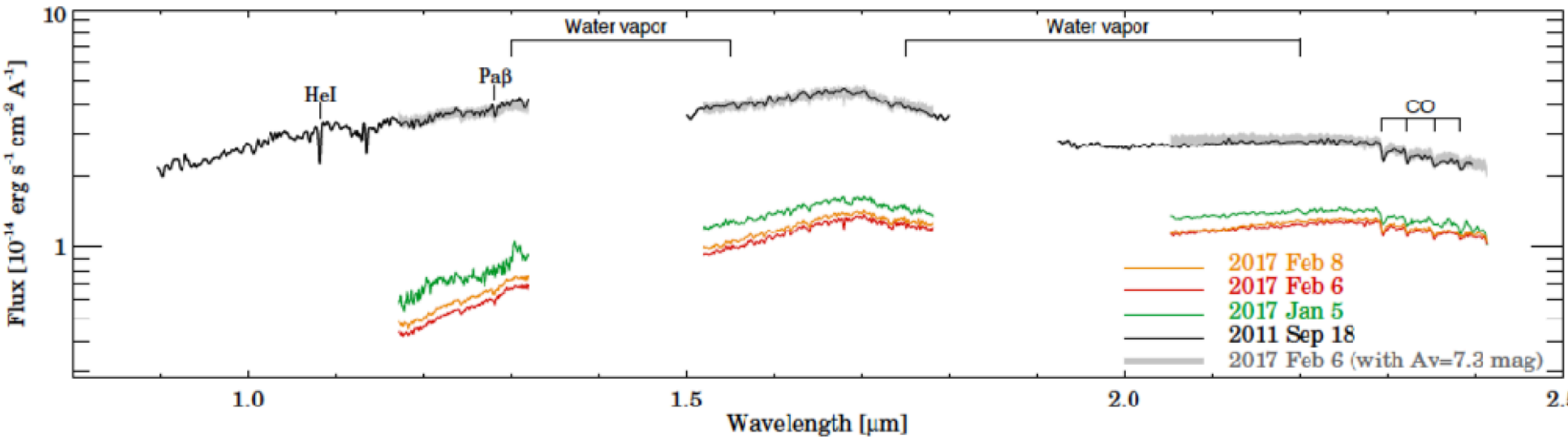
- The low-resolution spectrum from 2011 just prior to the 2012 minimum
- The other three spectra are in the present minimum
- Water vapor absorption
- Weak hydrogen Pa and Br series in absorption
- Neutral metallic lines
- CO bandhead in absorption (typical for FUors)

Discussion: color changes during the minima

- The data do not sample well the 2012 minimum, but one point indicates reddening changes
- In 2016-17 the variations point at reddening changes
- The main physical mechanism behind the flux changes in both minima seems to be changing extinction



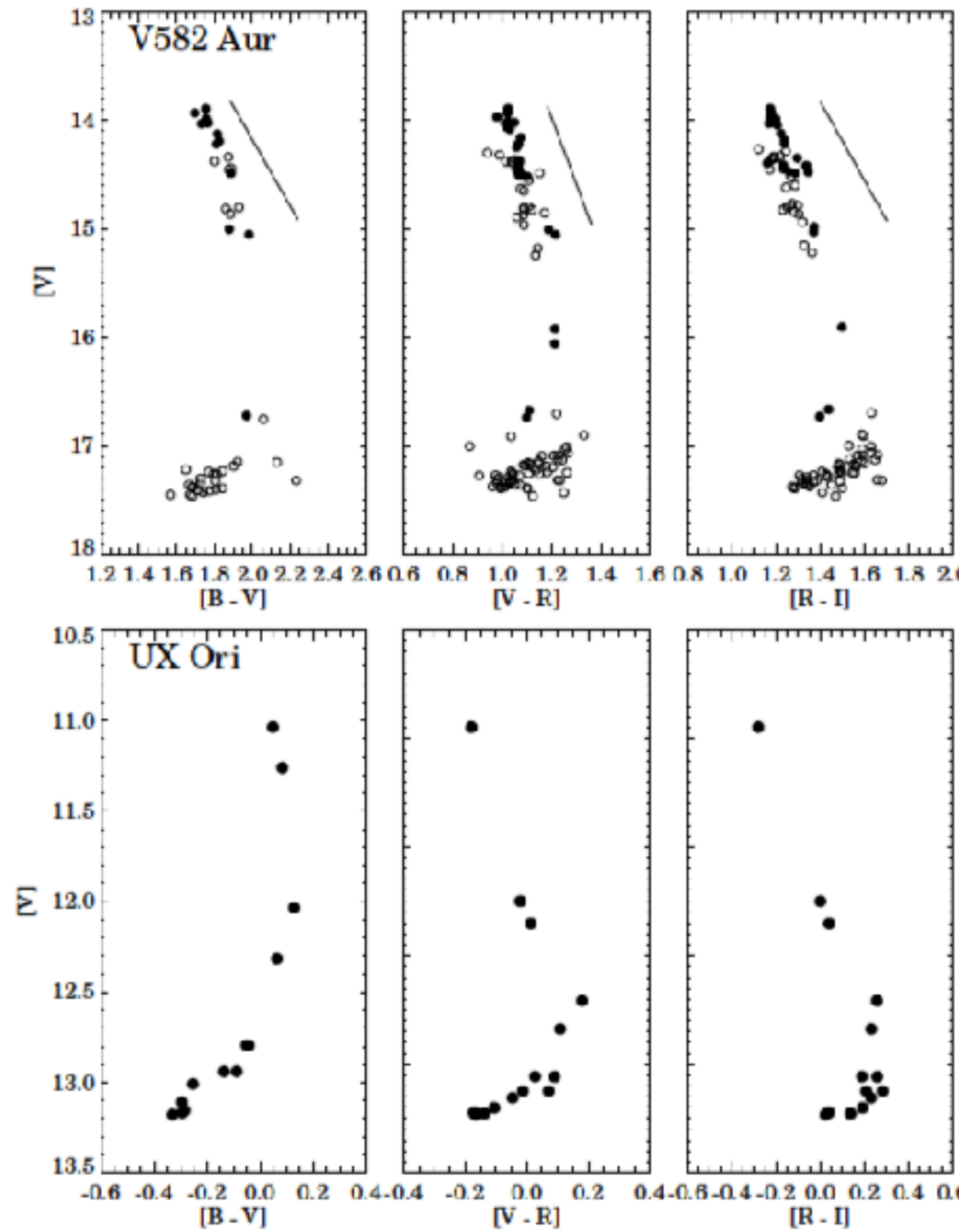
Discussion: color changes during the minima



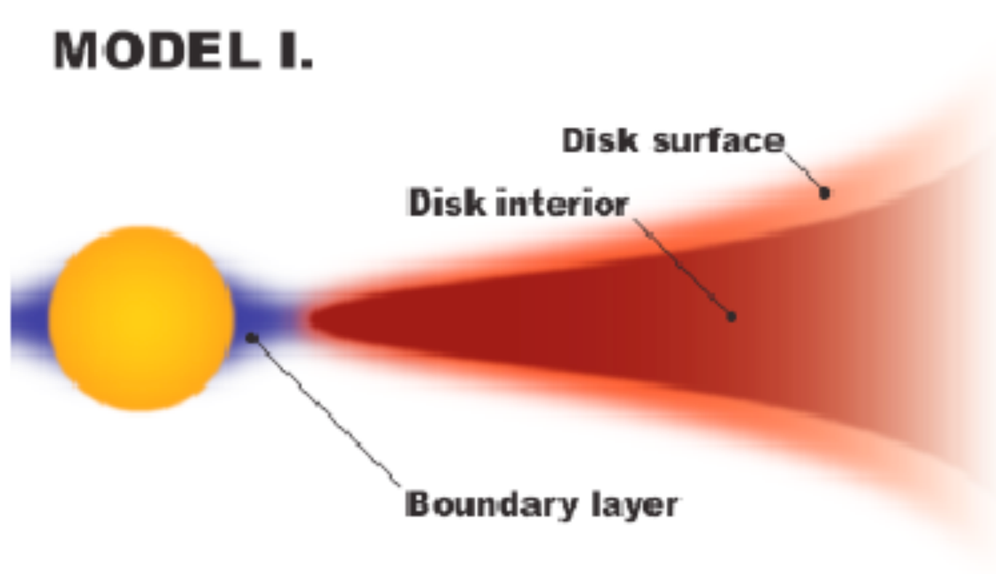
- Correcting the faintest spectrum for reddening by 0.3, 1.3, and 7.3 mag, the shape and absolute flux of the other spectra are perfectly reproduced!
- The match in the extended wavelength range of 1.17 - 2.41 micron gives a strong support to our hypothesis that the physical mechanism is time-dependent extinction

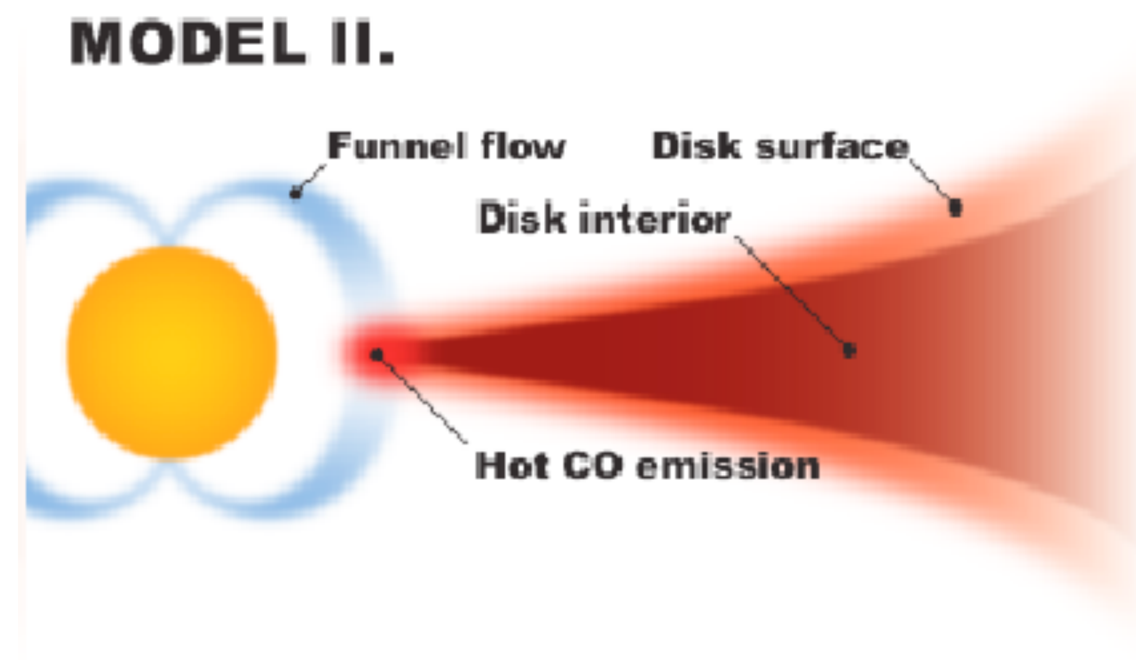
Discussion: color changes during the minima

- The points follow the extinction curve at high brightness, they deviate below a threshold
- Very similar to the “blueing” of UX Orionis stars
- Physical picture for UXor blueing: at deep eclipse the direct stellar light almost completely disappears, and light scattered from circumstellar dust dominates the observed flux
- Similar model for V582 Aur: dust clump which obscures the star but not the region where stellar light is scattered from



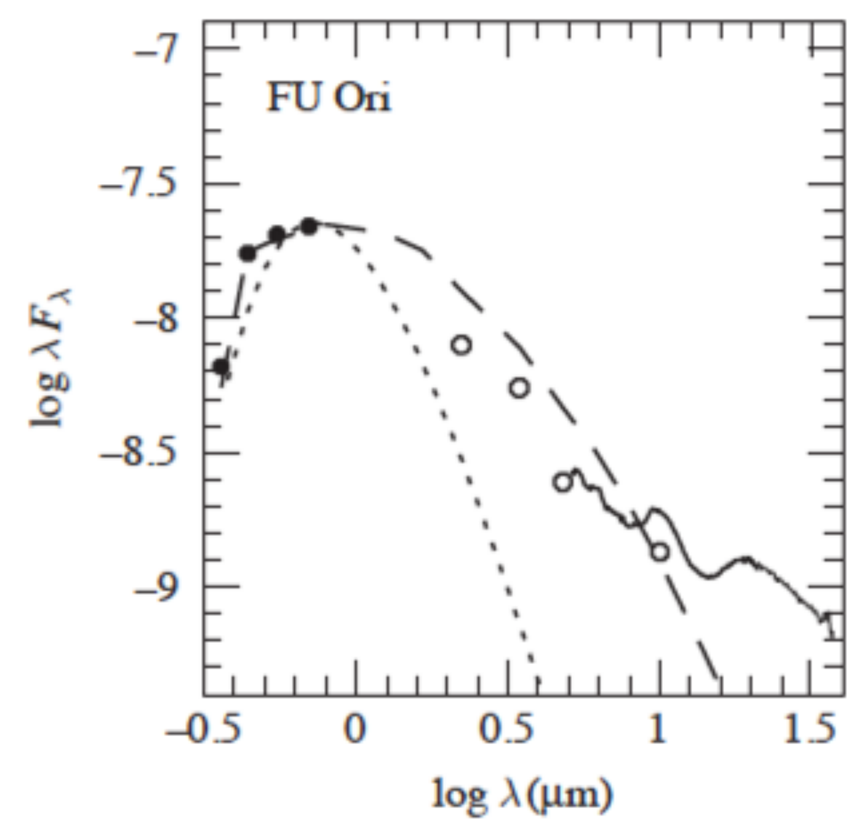
Accretion disk modeling



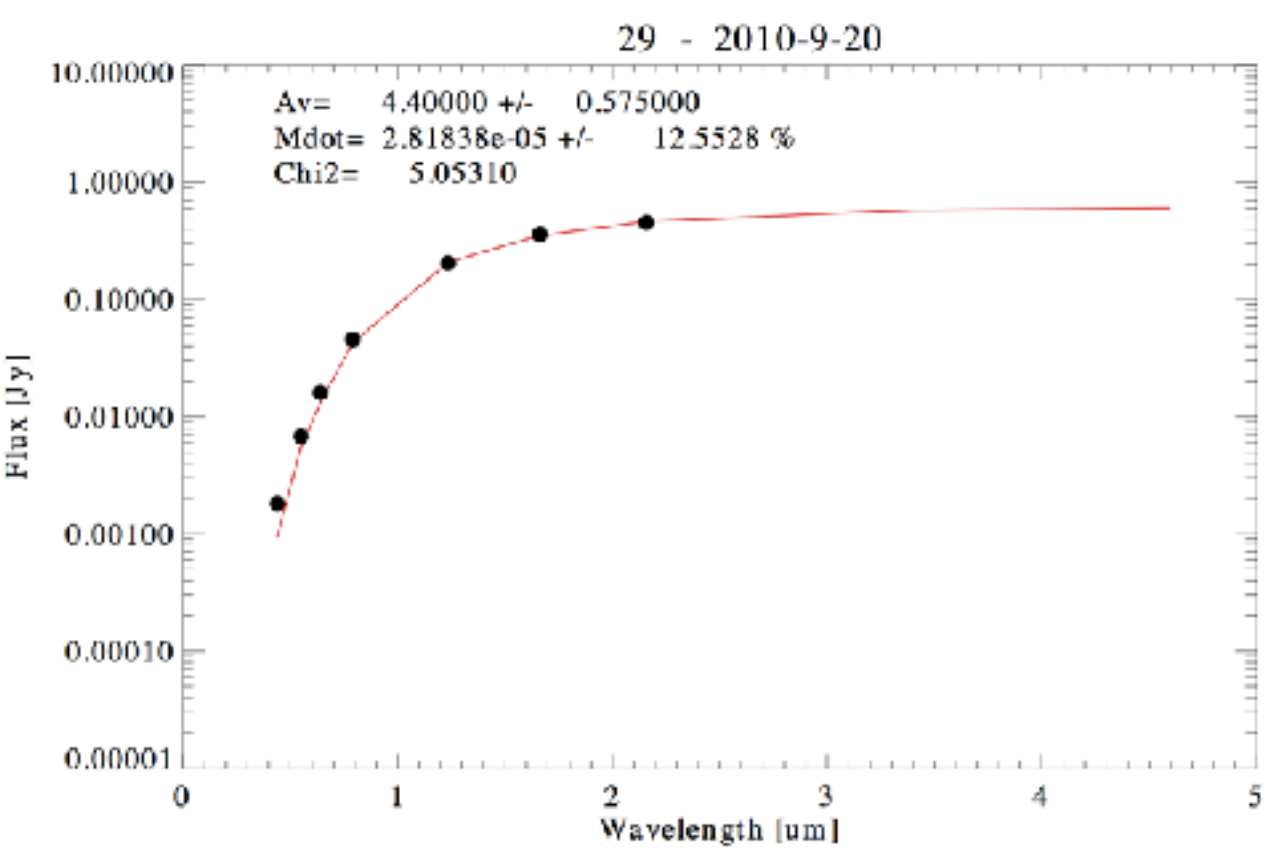


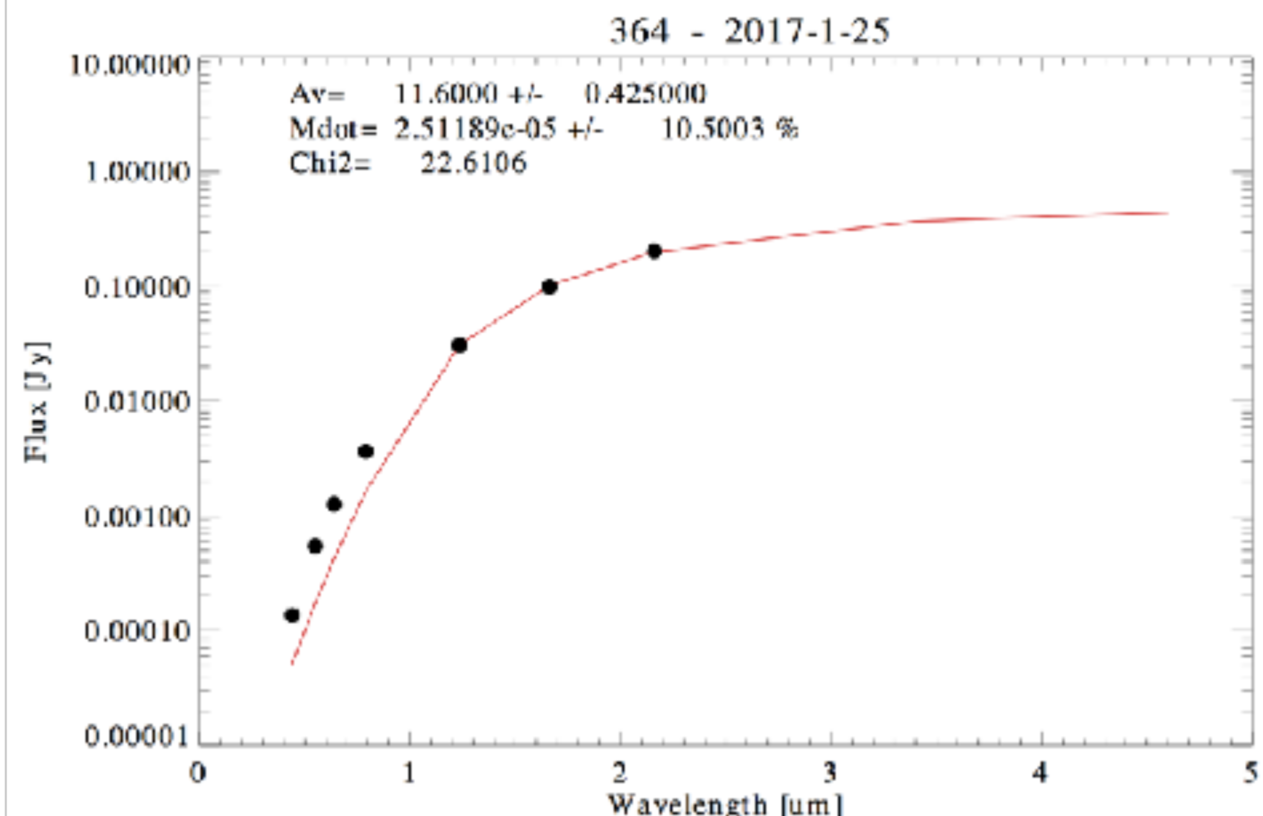
- Shakura-Sunyaev acretion disk
- steady optically thick and geometrically thin viscous accretion disk, with a radially constant mass-accretion rate

$$T_d^4 = \frac{3GM_* \dot{M}}{8\pi\sigma R^3}\left[1-\left(\frac{R_i}{R}\right)^{1/2}\right]$$



Accretion disk modeling



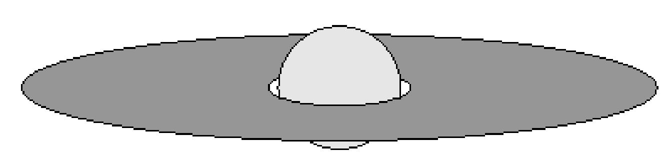


- R_{star} = 3 R_{sun}
- R_{out} = 2 au
- *i* = 45 deg
- M_{star} = 1 M_{sun}

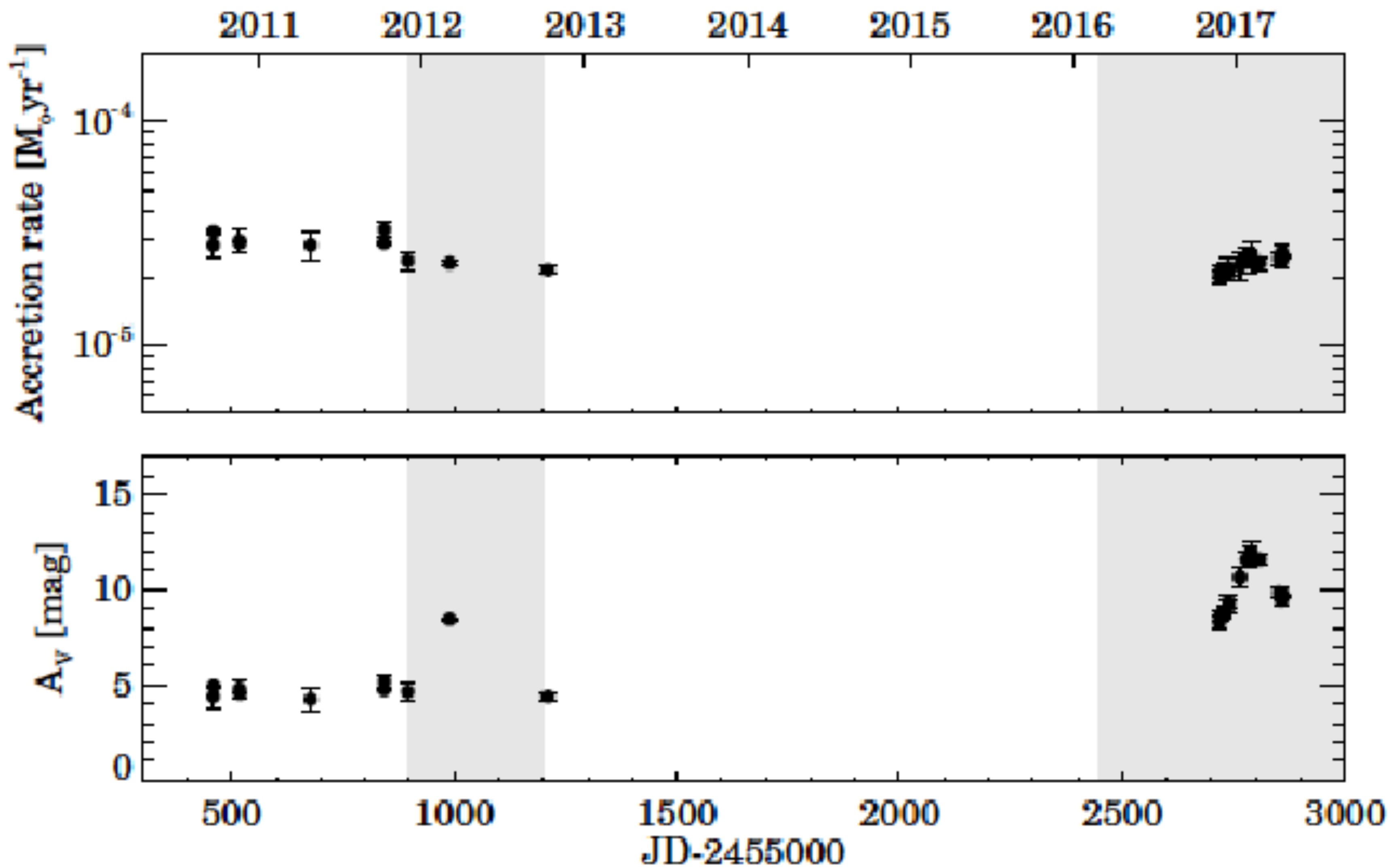
accretion disk + progenitor (Taurus median)

only the near-infrared points are fitted

scattered component in the optical light

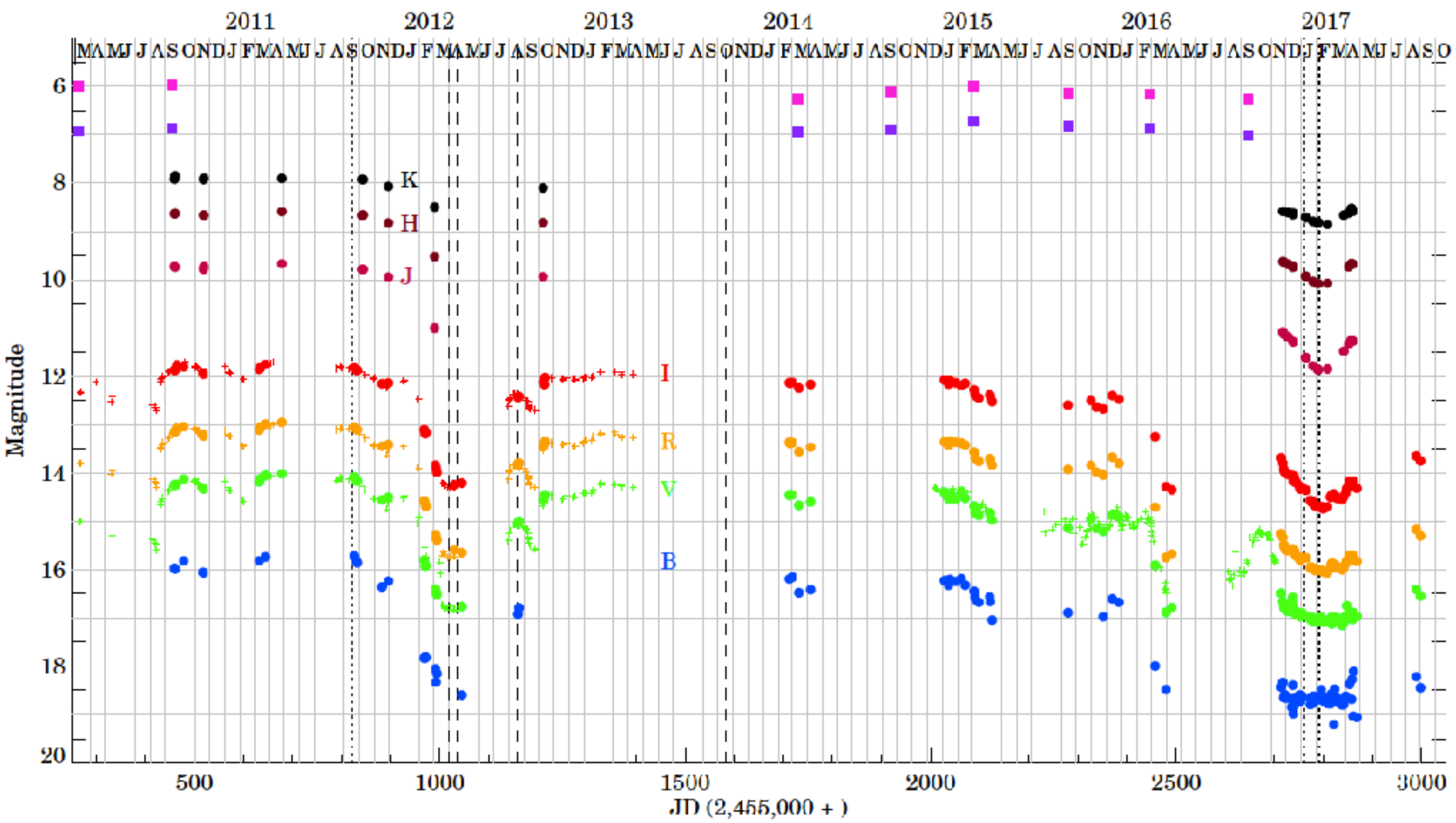


Accretion disk modeling



- Accretion rate is constant within15% over the whole period
- Extinction increased during the two minima, from 4.5 mag to 12.5 mag
- ΔA_V ~8 mag, consistent with the 7.3 mag obtained from the LIRIS spectra

Structural changes related to the outburst?



If the eclipses are periodic:

- Period ~ 4.75 year
- Keplerian radius from a 1 M_{sun} star: 2.84 au
- large enough to cover the whole accretion disk, and fade mid-infrared emission
- small enough not to cover the scattering regions

Structural changes related to the outburst?

Sublimation radius? Can we have a dust cloud at this distance?

- In quiescence let's assume L ~ 1 L_{sun} -> R_{sub} = 0.068 au
- In outburst L = 150 - 320 L_{sun} (Kun + 2017) -> R_{sub} = 0.84-1.23 au
- The sublimation radius is smaller than the orbital radius of the dust clump

Length of the dust clump?

- Perimeter of a circular orbit with R=2.84 au = 17.8 au.
- The typical length of an eclipse is ~1 yr (1/5 of the orbit)
- Length of the clump is 3.5 au (can obscure the accretion disk)

Mass of the clump

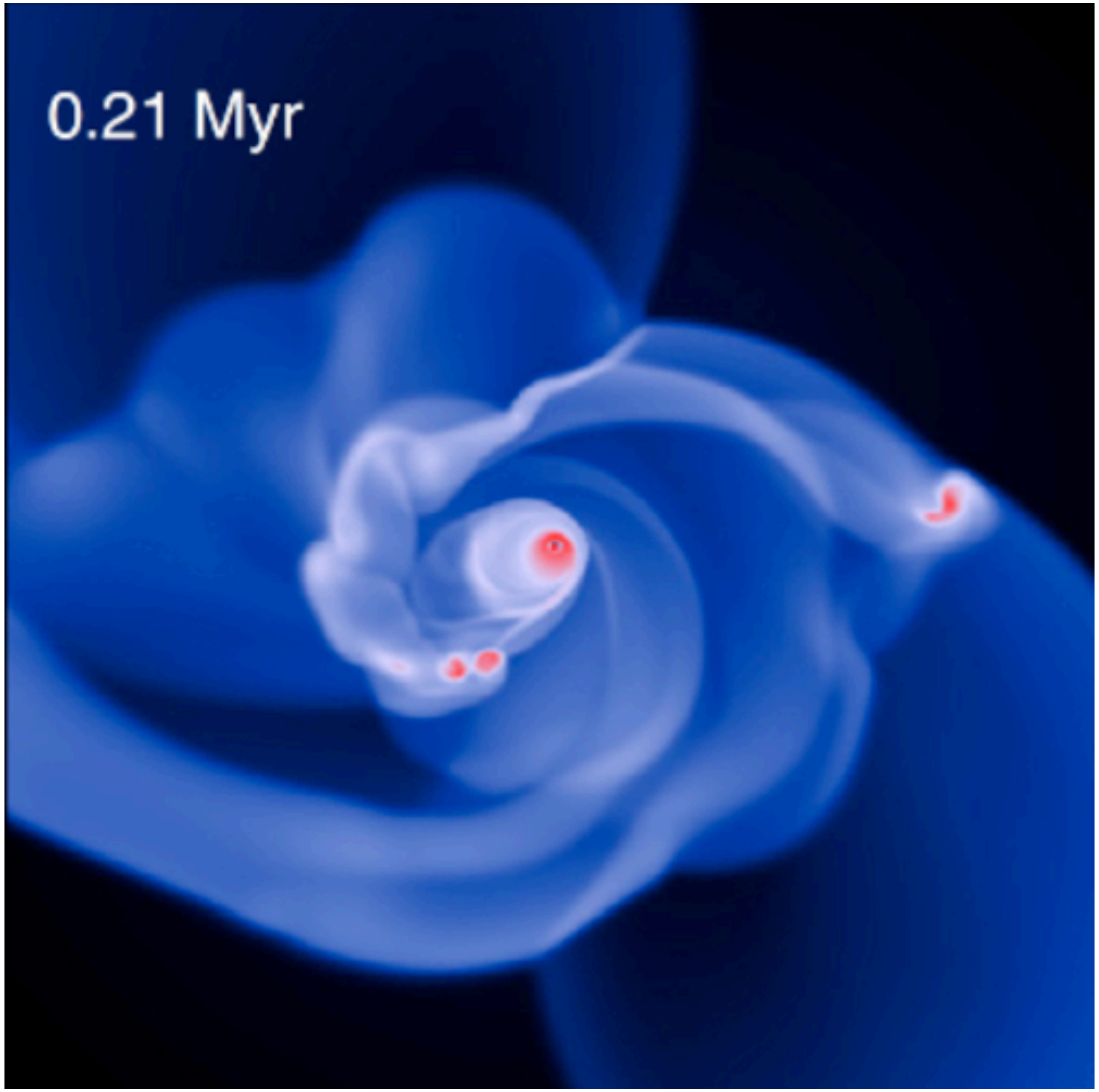
- Assume a height of 1 au -> M_{clump} = 1.16x10^{-8} M_{sun} = 0.004 M_{earth}
- So-far accreted matter: 8x10^{-4} M_{sun}
- The clump is a small perturbation…

If the clump is aperiodic…

szupercomet approaching the central star

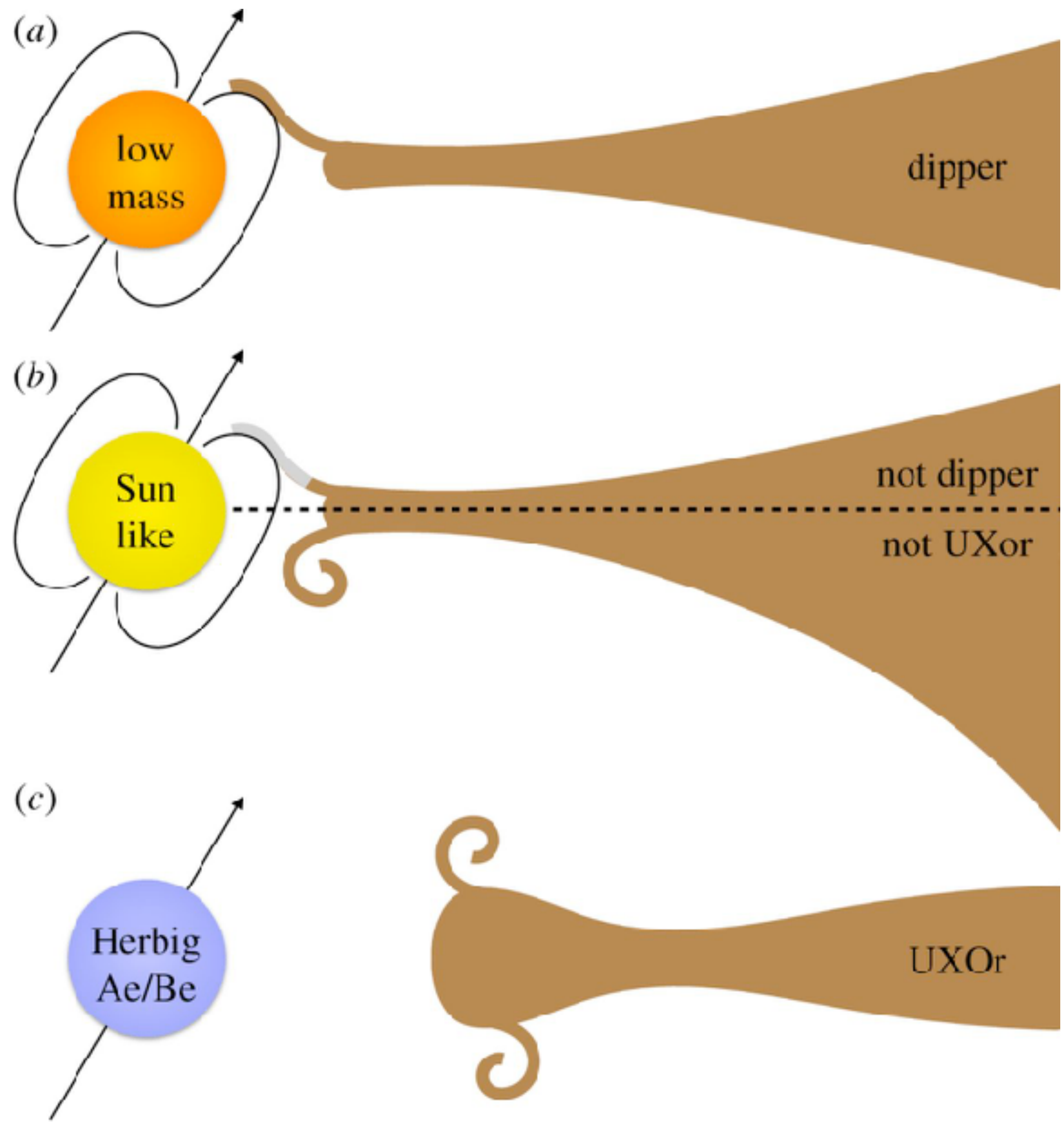
Possible origin of the dust clump: GI?

Vorobyov & Basu (2010): Snapshot of the surface density distribution of a gravitationally unstable disk model

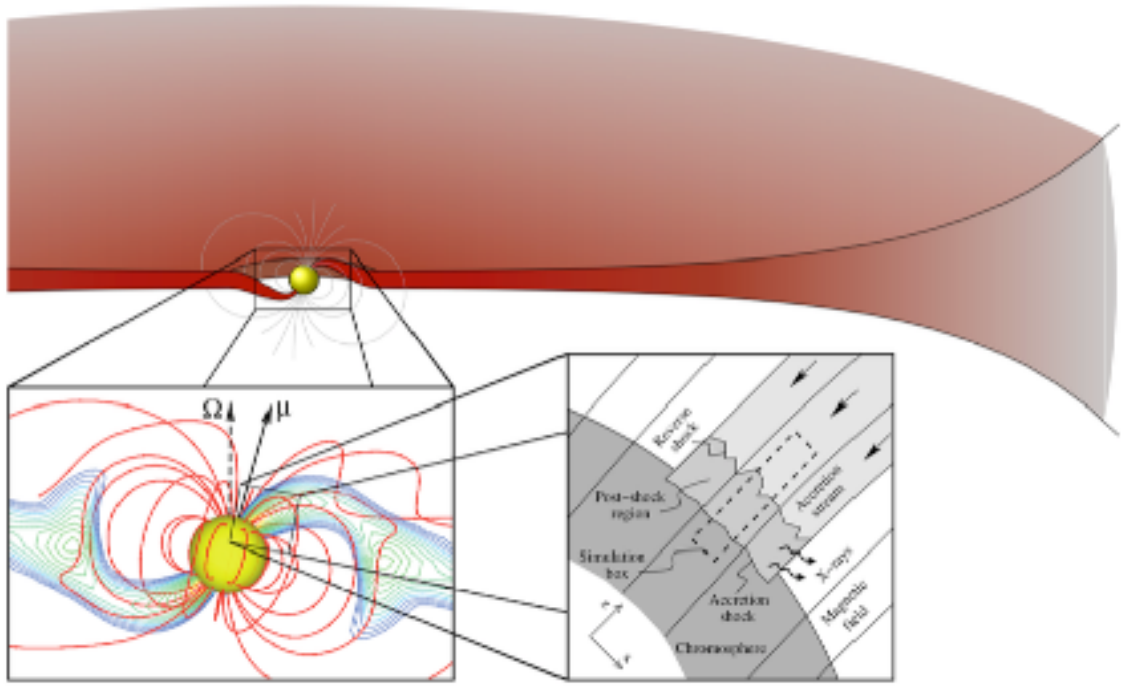


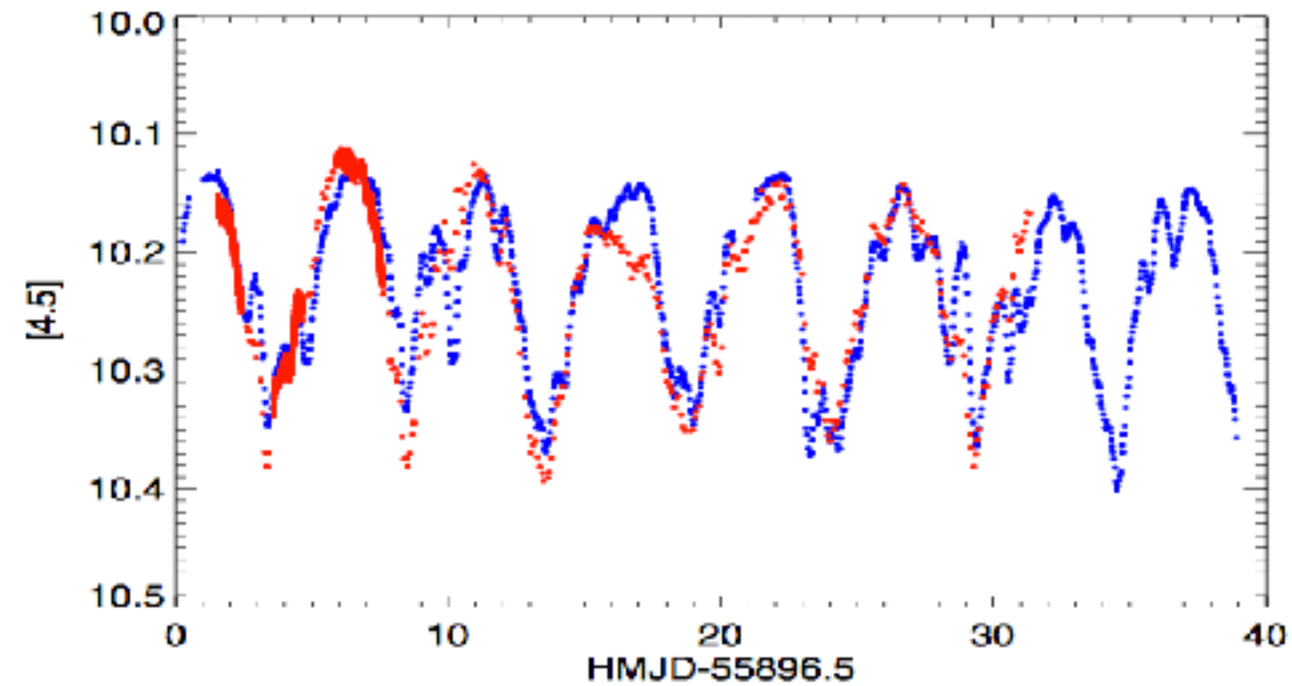
Possible origin of the dust clump: disk structure

Kennedy+ 2017



Possible origin of the dust clump: a dipper?





AA Tau-type variability

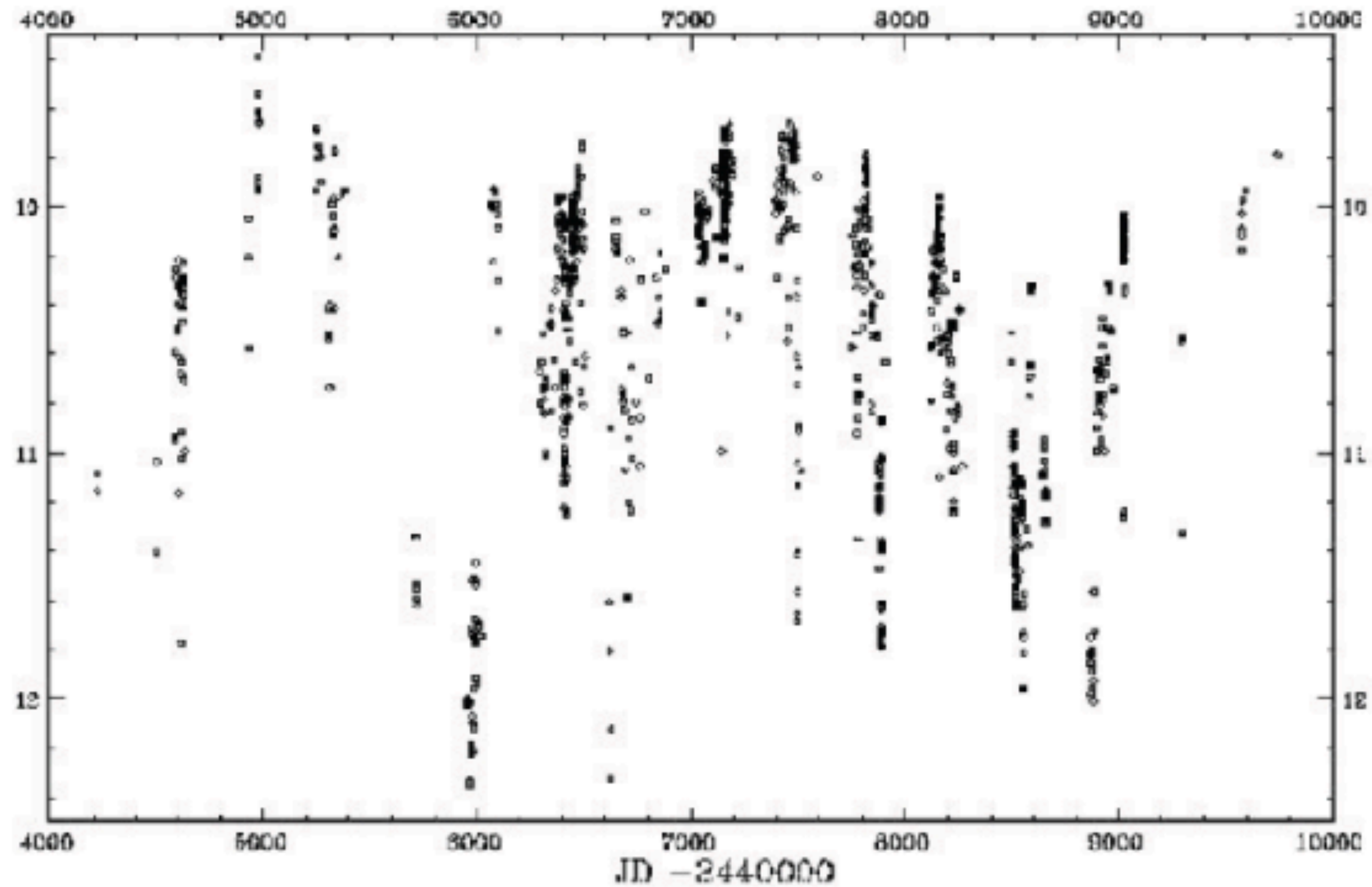
stable accretion funnel flow

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: an UXor?

Dullemond+2013



UX Ori-type variability

deep eclipses, blueing: OK

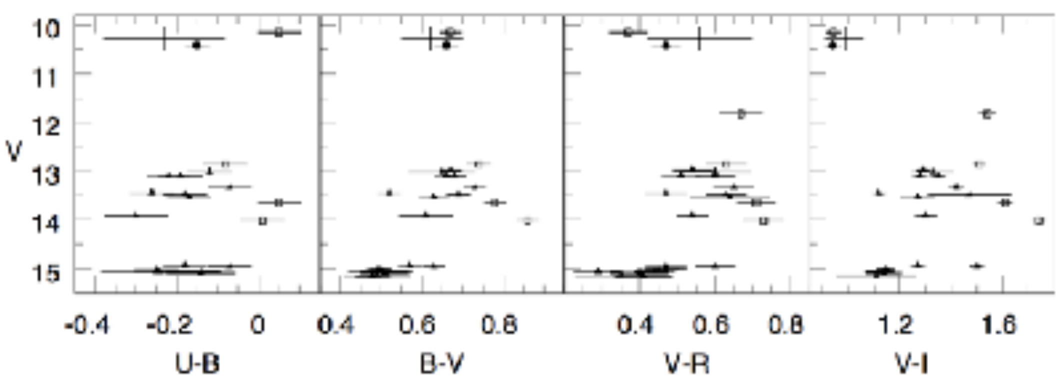
the timescale is a typically a few weeks, too short for V582 Aur.

Super-UXor? Proto-UXor in the embedded phase?

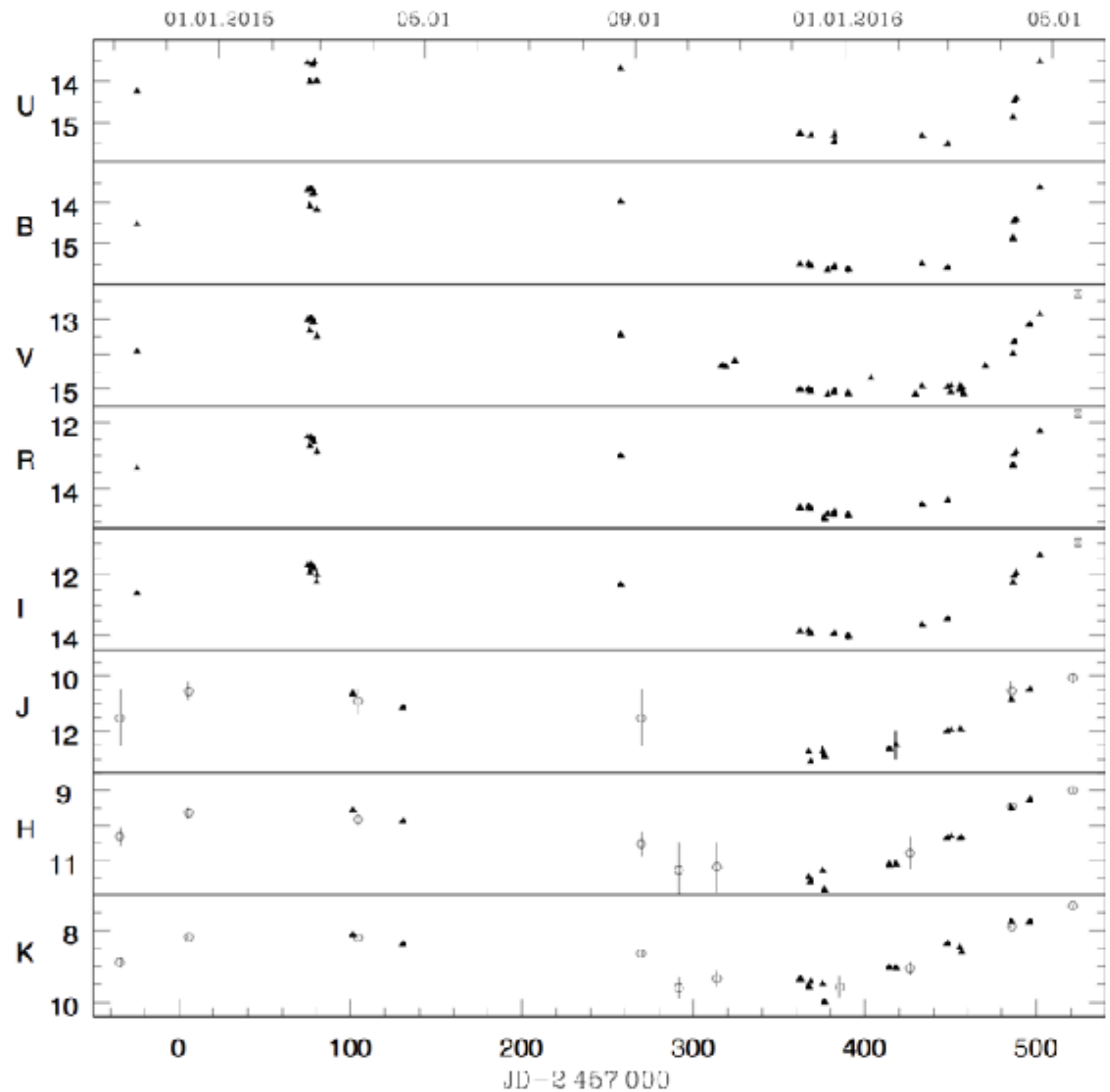
In outburst the star temporarily becomes a Herbig star. It could evaporate the inner disk, and convert from dipper to UXor (or super-UXor). If true, we wittness a direct effect of the outburst on the inner disk density structure. **What will happen with the forming planets?!**

Similar cases: RW Aur A

Lanzin+2017: 2014-16 dimming

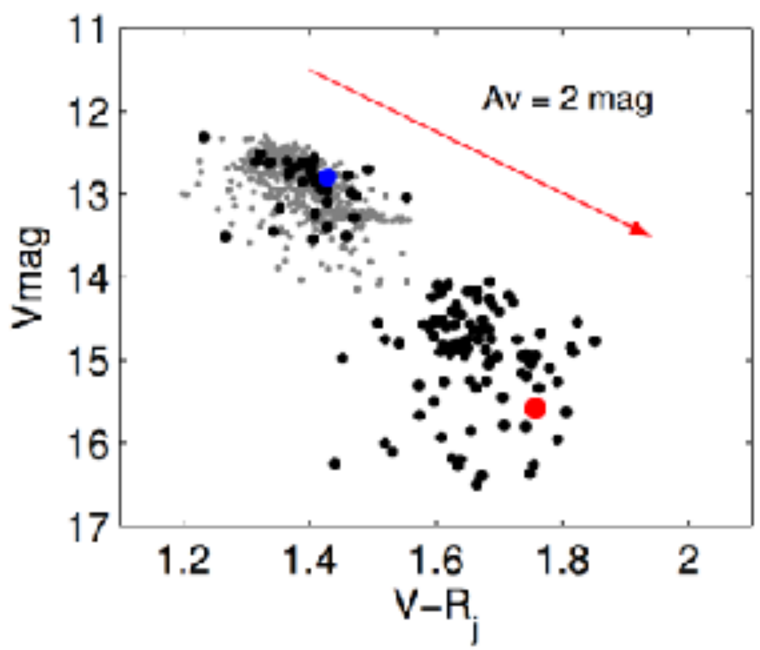


"Our results confirm that *both dimming events were due to eclipse of RW Aur A by dust cloud,* grains of which produce selective absorption. In some respects the behavior of the star reminds that of UXORs, but duration and amplitude of 2014-16 eclipse are much larger, linear polarization of light is much stronger and has another orientation. In our case dust screen eclipses not only the star, but also significant part of scattering disc and a region where iron emission lines are originated. We don't know the nature of the dust screen (a tidal arm, dusty disk wind etc.), but its origin undoubtly connected with tidal disturbance of RW Aur A disk by recent fly-by of the companion. "

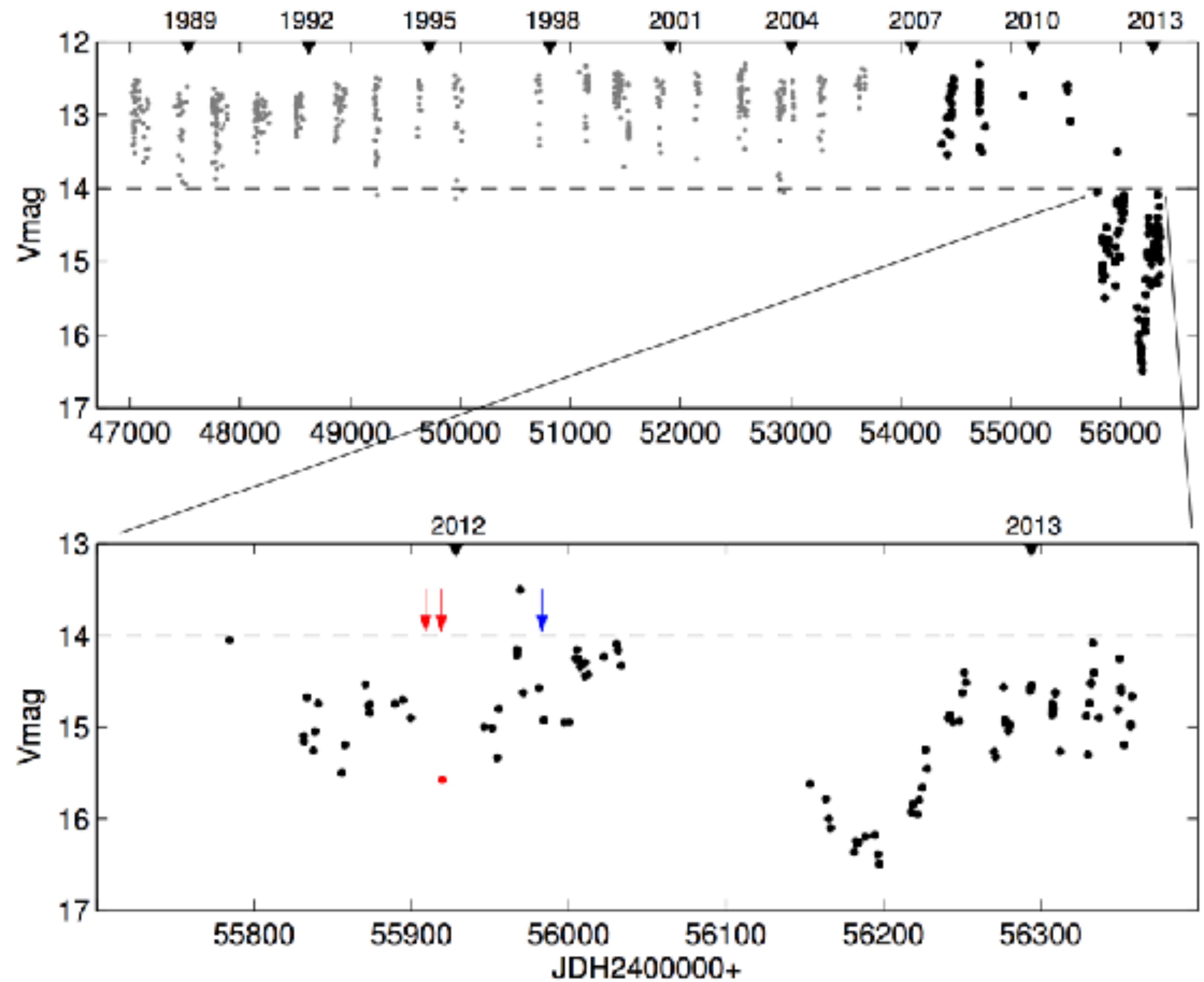


Similar cases: AA Tau

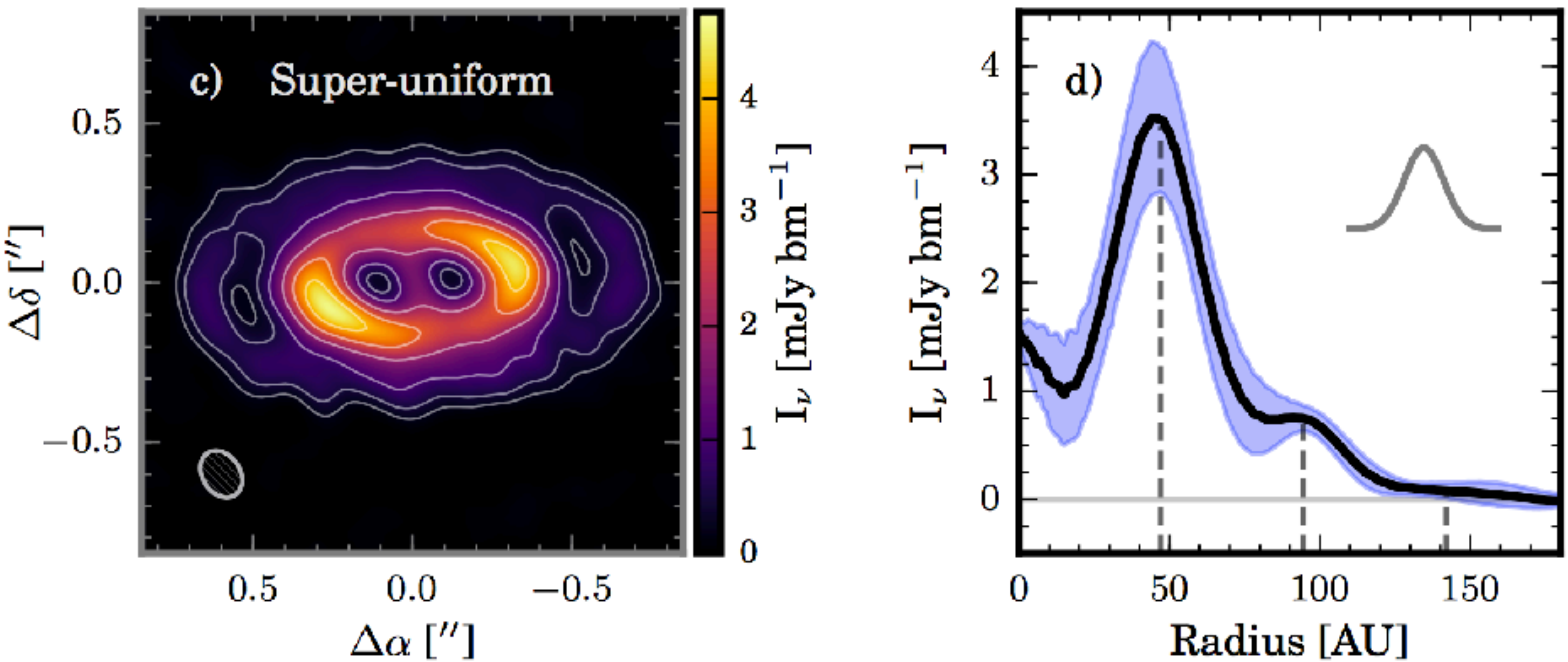
Bouvier+ 2013: 2011- dimming



“We conclude that the deepening of the AA Tau system is due to a sudden increase of circumstellar dust extinction on the line of sight without concomitant change in the accretion rate. We suggest that the enhanced obscuration may be produced by a nonaxisymmetric overdense region in the disk, located at a distance of 7.7 AU or more, that was recently brought into the line of sight by its Keplerian motion around the central star. “



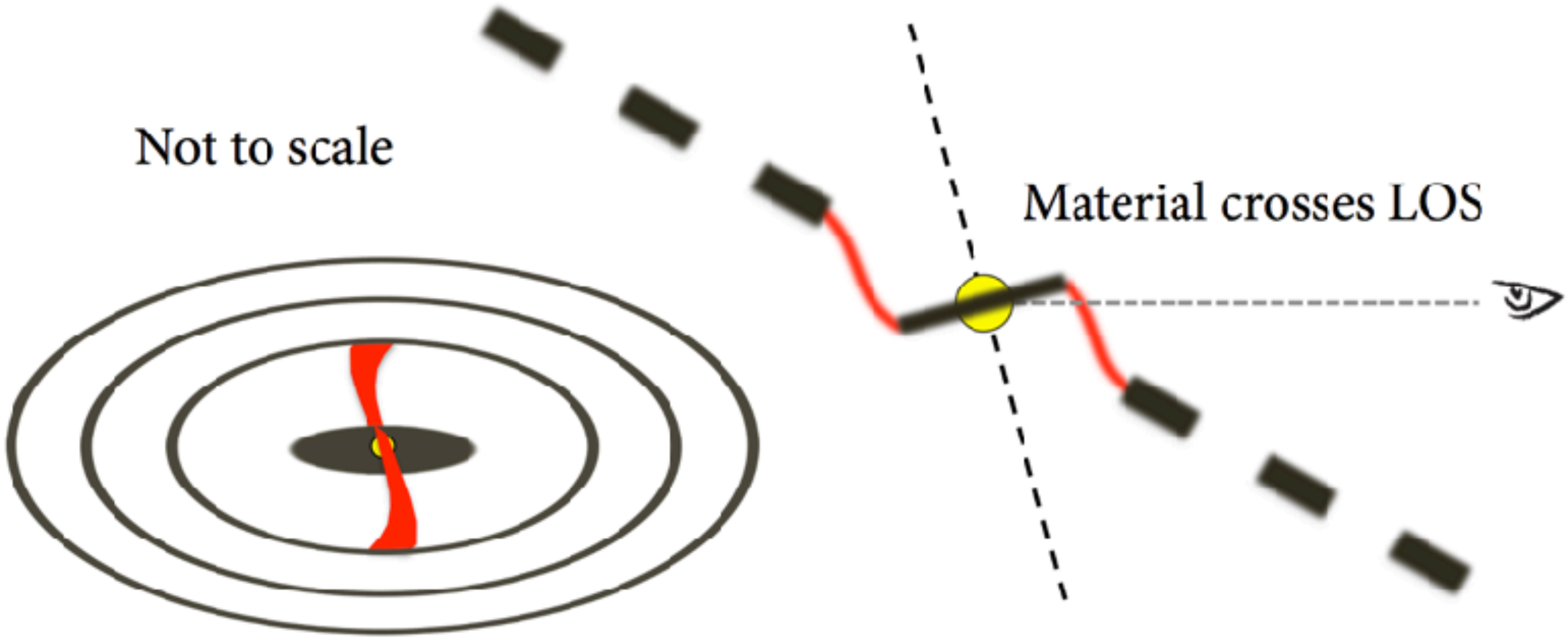
Similar cases: AA Tau

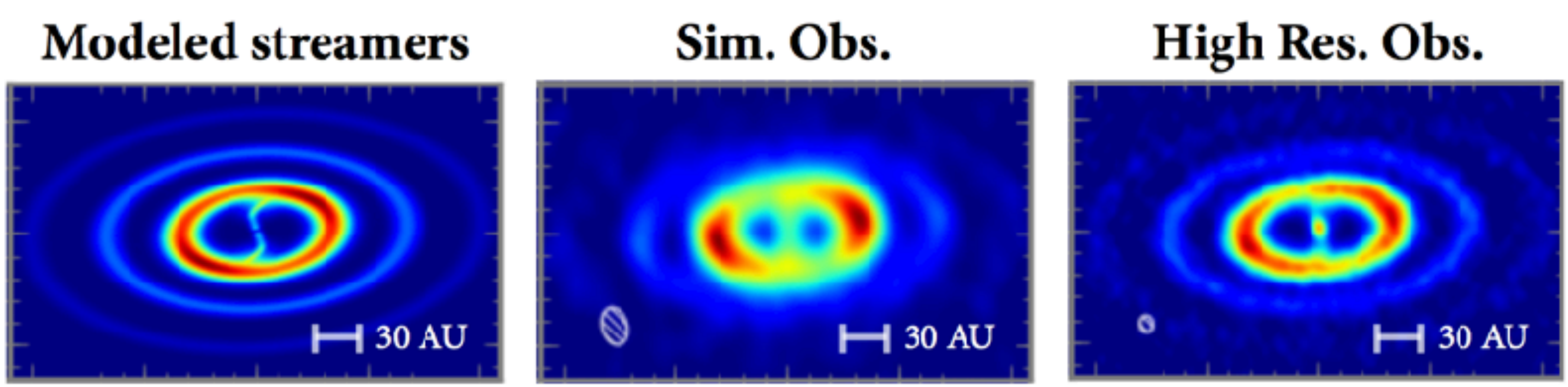


ALMA continuum observations

Loomis+ 2017

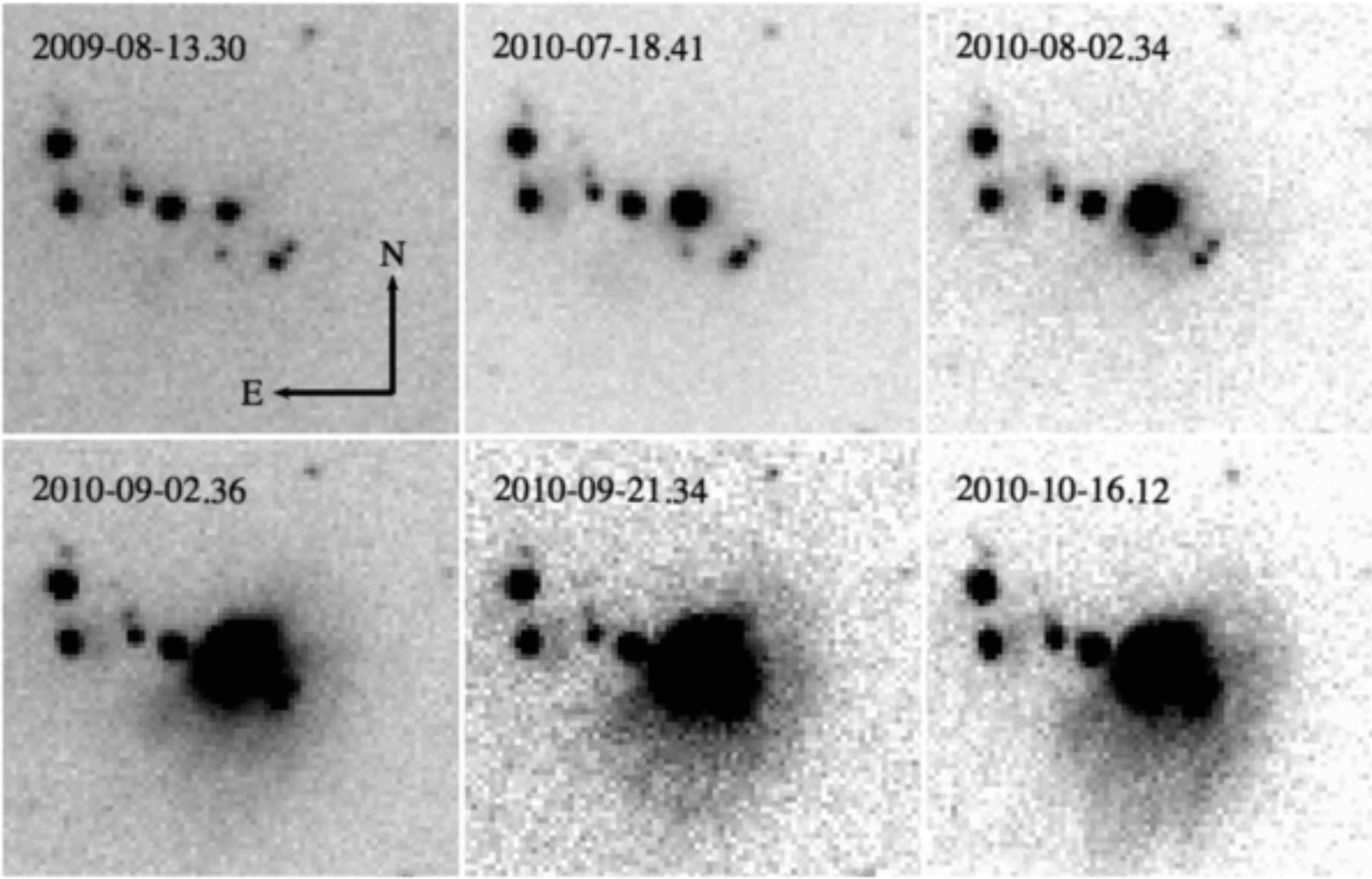
Similar cases: AA Tau





Loomis+ 2017

The outburst of HBC 722

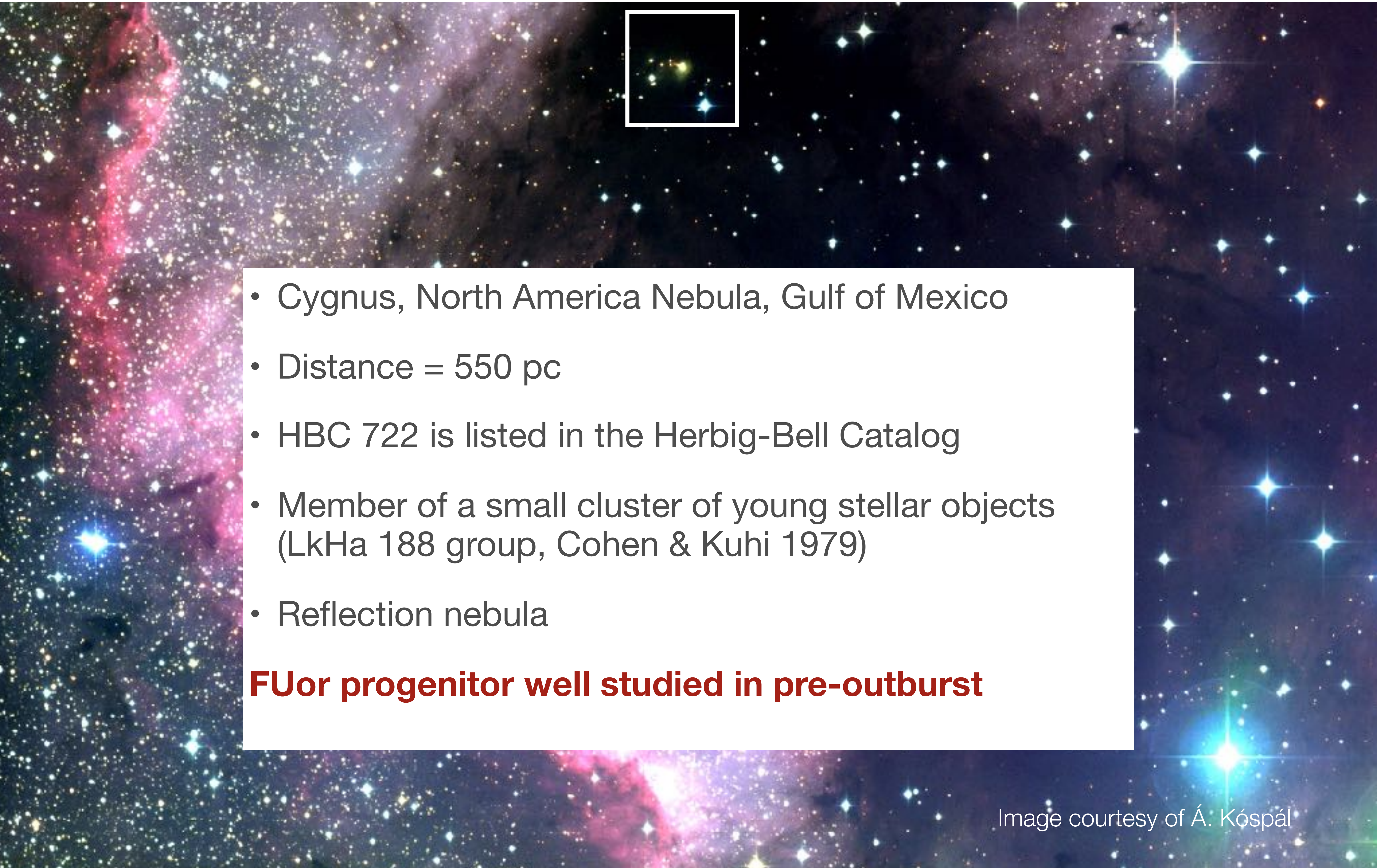


Miller et al. (2011)

The outburst of HBC 722

The outburst of HBC 722

The outburst of HBC 722

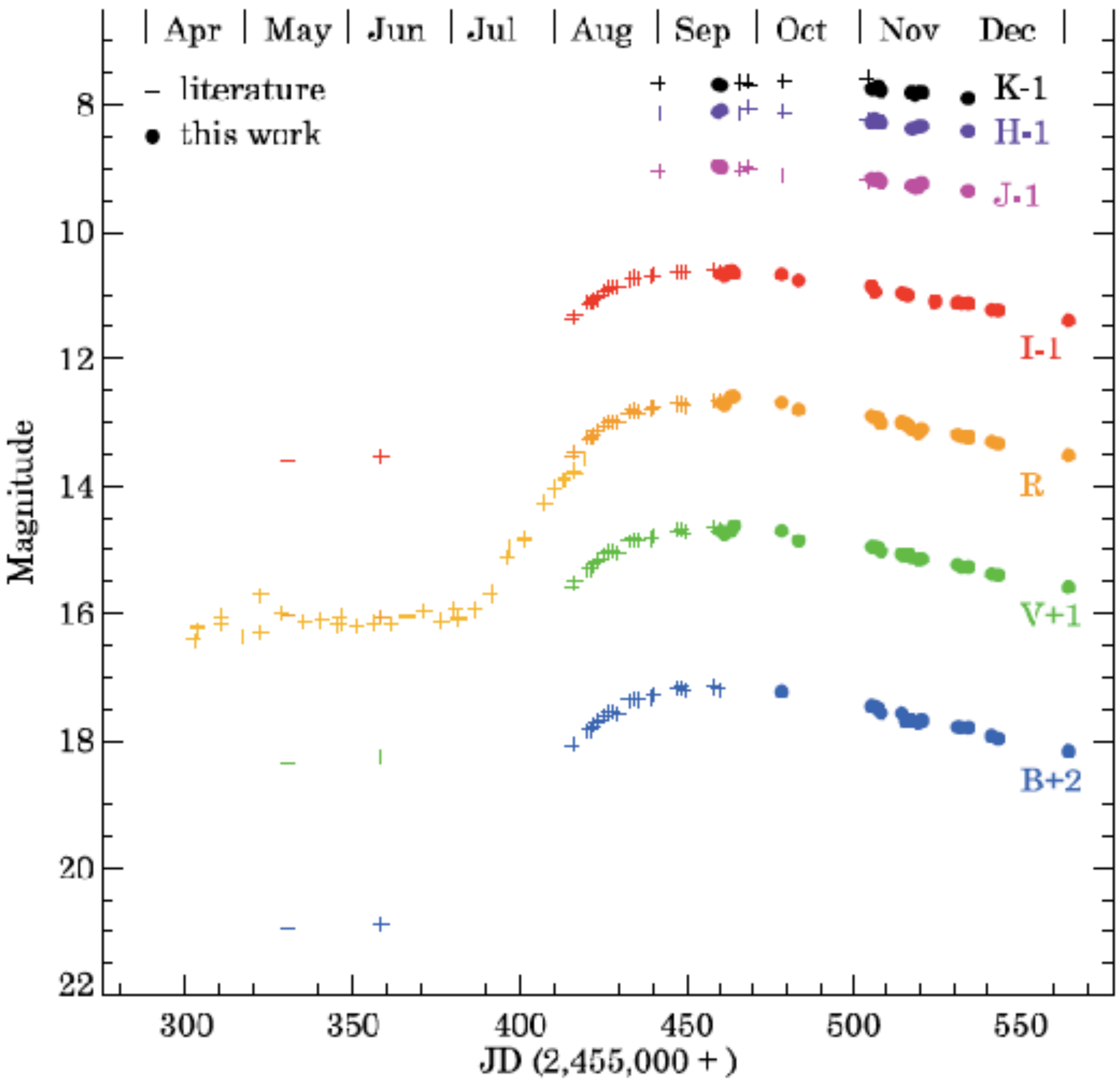


- Cygnus, North America Nebula, Gulf of Mexico
- Distance = 550 pc
- HBC 722 is listed in the Herbig-Bell Catalog
- Member of a small cluster of young stellar objects (LkHa 188 group, Cohen & Kuhi 1979)
- Reflection nebula

FUor progenitor well studied in pre-outburst

Image courtesy of Á. Kóspál

The outburst of HBC 722

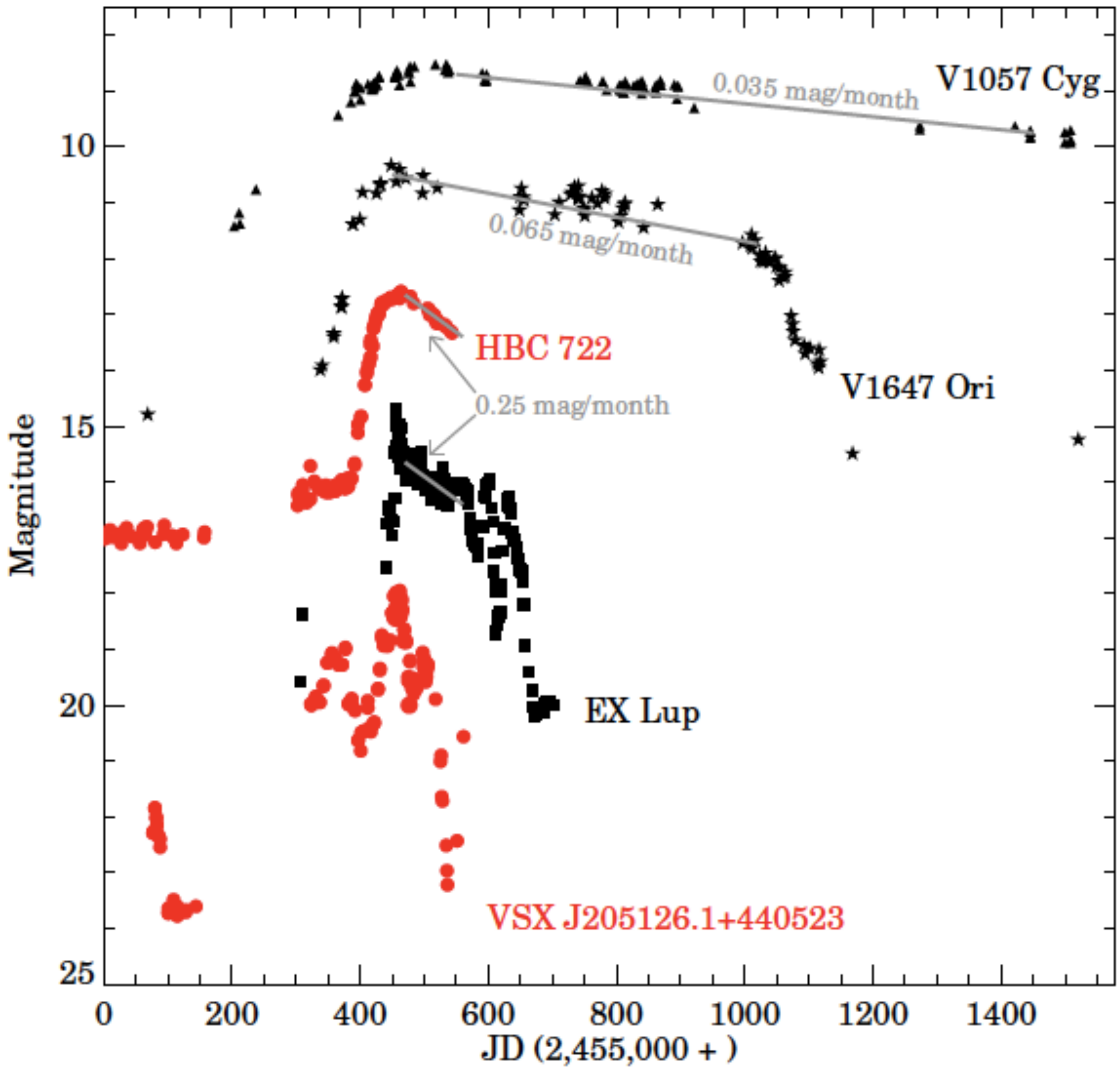


Kóspál et al. (2011)

- Optical photometry from Hungary: 1m RCC, 0.9m Schmidt

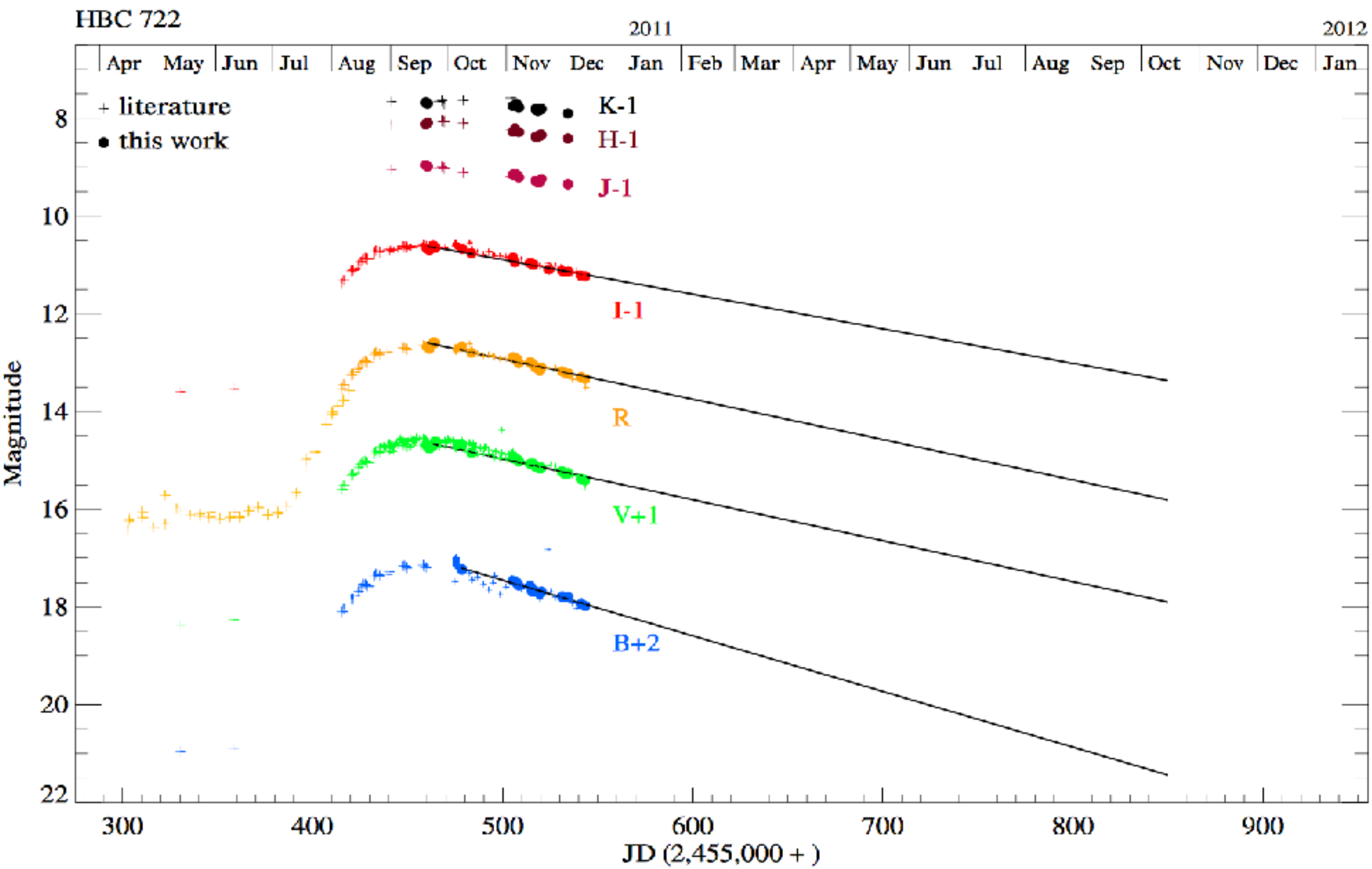
- Near-infrared photometry with 1.52m TCS at Teide Observatory, Spain

Light curve comparison with eruptive stars



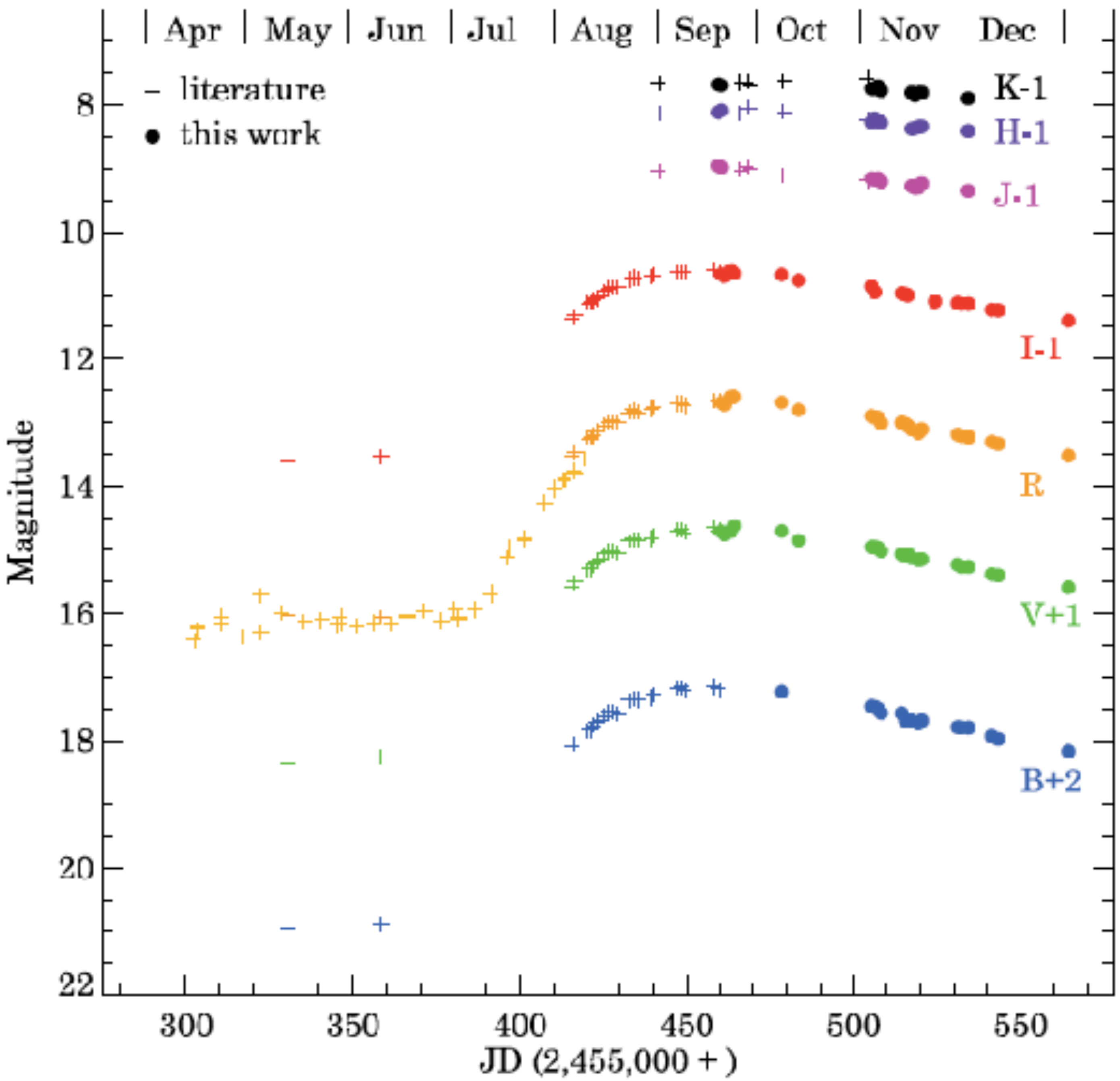
Kóspál et al. (2011)

Fading rate



HBC 722
2011
2012
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
+ literature
● this work
K-1
H-1
J-1
I-1
R
V+1
B+2
Magnitude
8
10
12
14
16
18
20
22
300
400
500
600
700
800
900
JD (2,455,000 +)

Eruptive star classification of HBC 722



Kóspál et al. (2011)

- From spectroscopic point-of-view, it looks as a *bona fide* FUor!
- (Miller et al. 2011):

(i) an increase in brightness by > 4 mag, (ii) a bright optical/near-infrared reflection nebula appeared, (iii) optical spectra are consistent with a G supergiant and dominated by absorption lines, the only exception being Halpha which is characterized by a P Cygni profile, (iv) near-infrared spectra resemble those of late K--M giants/supergiants with enhanced absorption seen in the molecular bands of CO and H_2O, and (v) outflow signatures in H and He are seen in the form of blueshifted absorption profiles

- But L = 10 - 20 L_{sun}, and M_{acc} = 10^{-6} M_{sun}/yr!

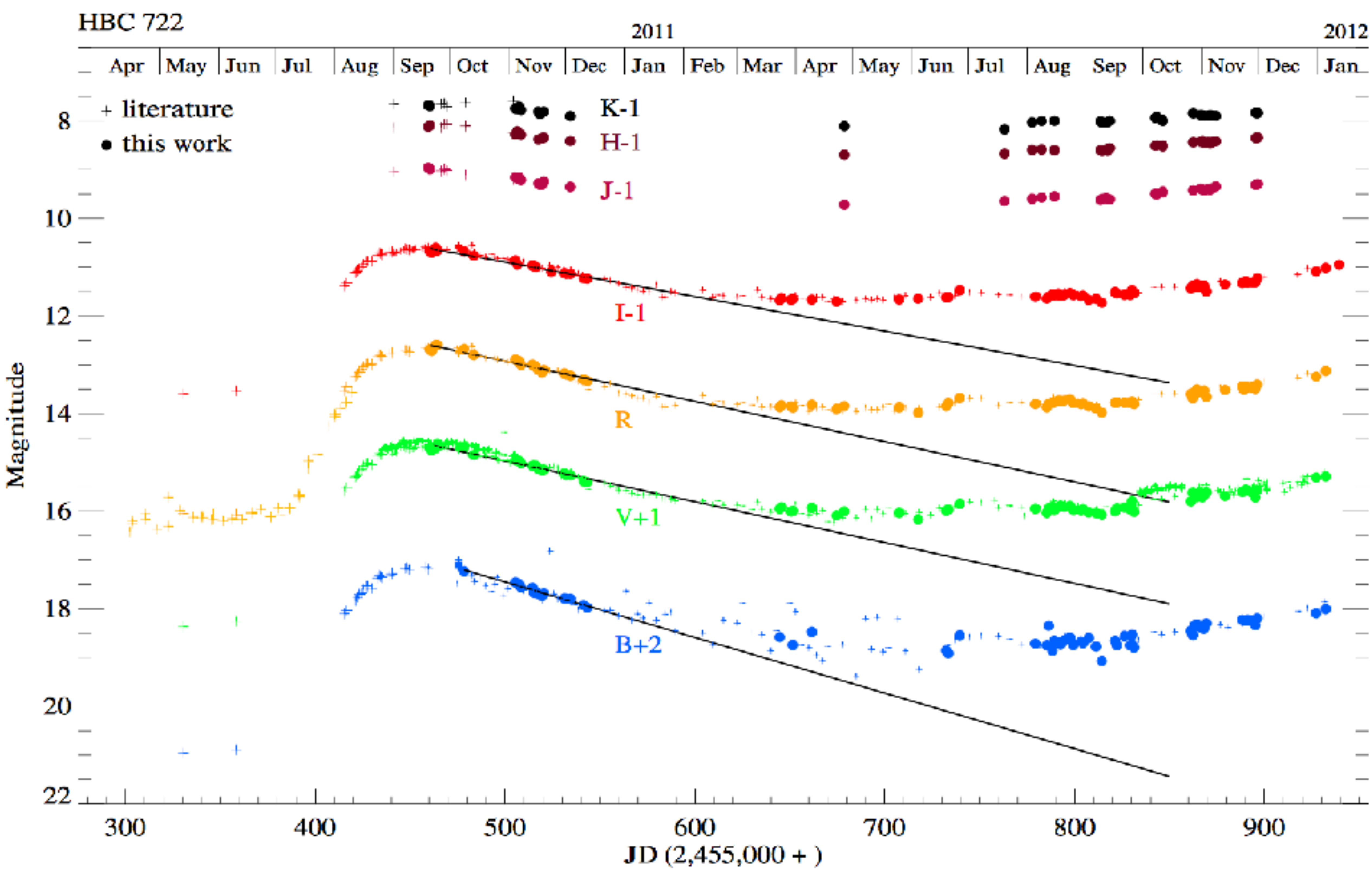
NOT typical FUor values!

FU Orionis-type stars (FUors)

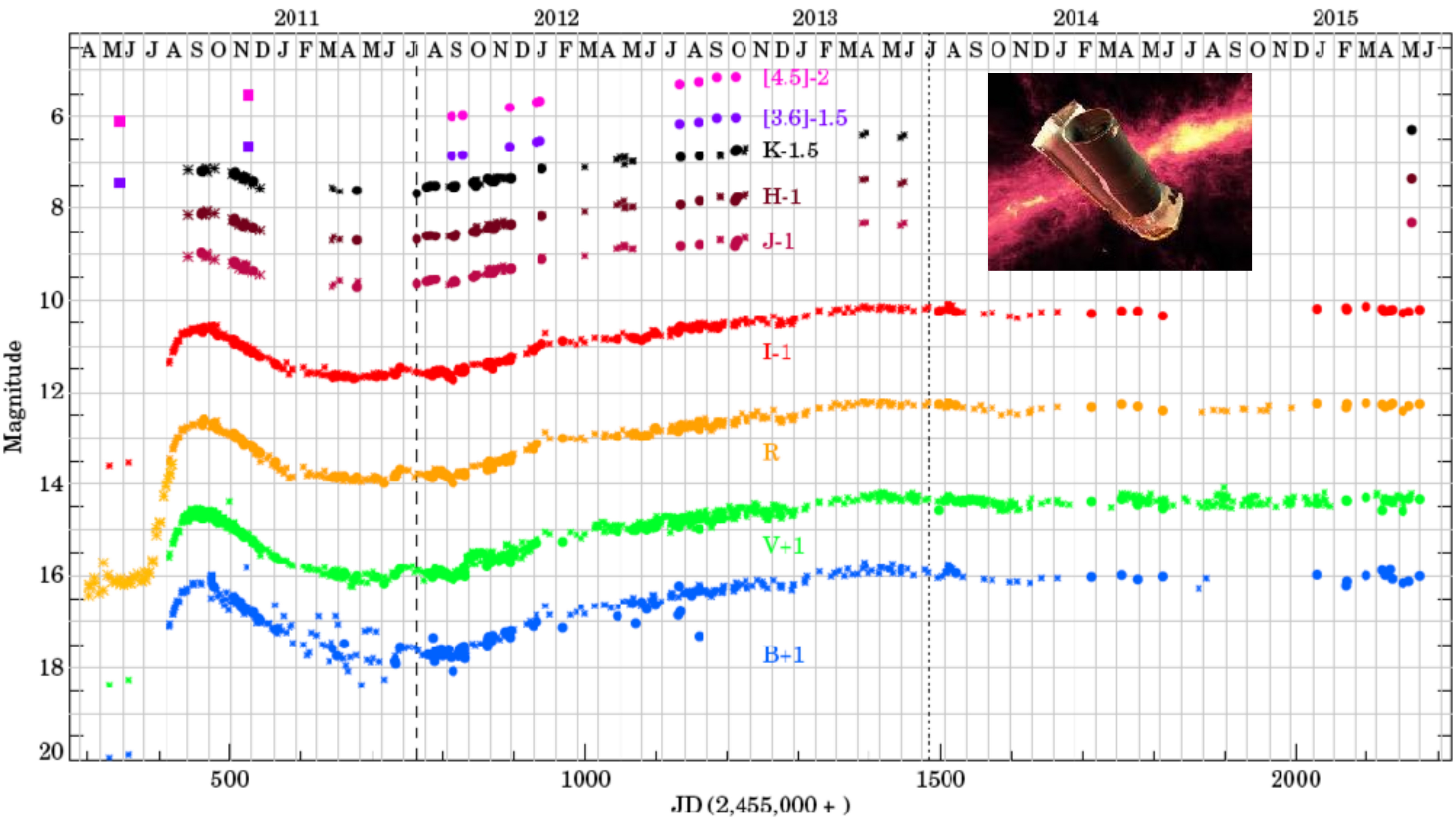
Object	Outburst	t(Rise)	t(Decay)	d(kpc)	$L/L_{\odot}$	CO flow	Jet/HH
FU Ori	1937	~ 1 yr	~ 100 yr	0.5	500	no	no
V1057 Cyg	1970	~ 1 yr	~ 10 yr	0.6	800–250	yes	no
V1515 Cyg	1950s	~ 20 yr	~ 30 yr	1.0	200	no	no
V1735 Cyg	$\sim$ 1957–65	< 8 yr	> 20 yr	0.9	>75	yes	no
V346 Nor	$\gtrsim 1984$	< 5 yr	> 5 yr	0.7	?	yes	yes
BBW 76	< 1930	?	~ 40 yr	1.7?	?	?	no
Z CMa	?	?	> 100 yr	1.1	600	yes	yes
L1551 IRS5	?	?	?	0.15	≥ 20	yes	yes
RNO 1B,C	?	?	?	0.8	?	yes?	no

Hartmann & Kenyon (1996)

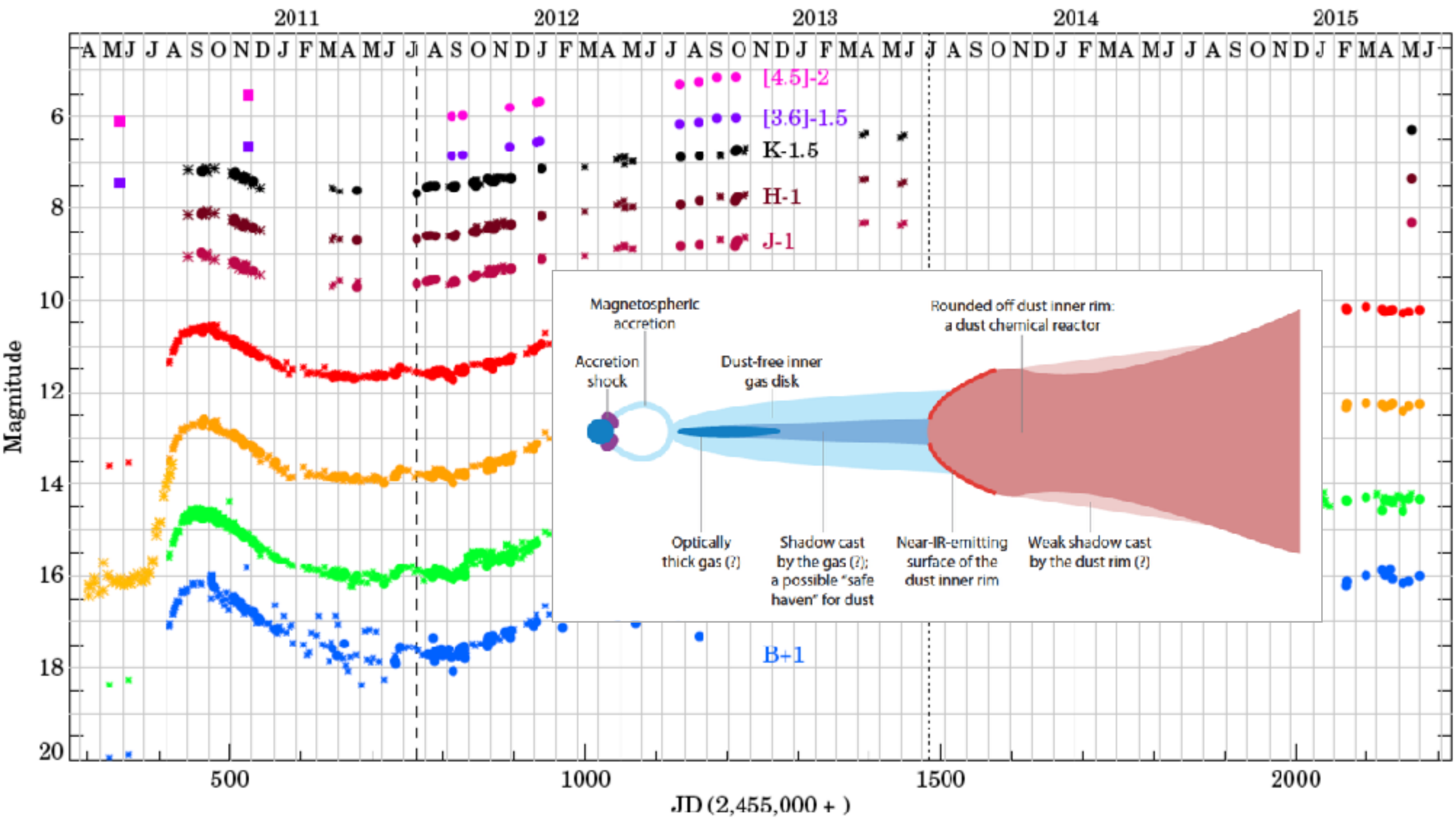
Long-term evolution



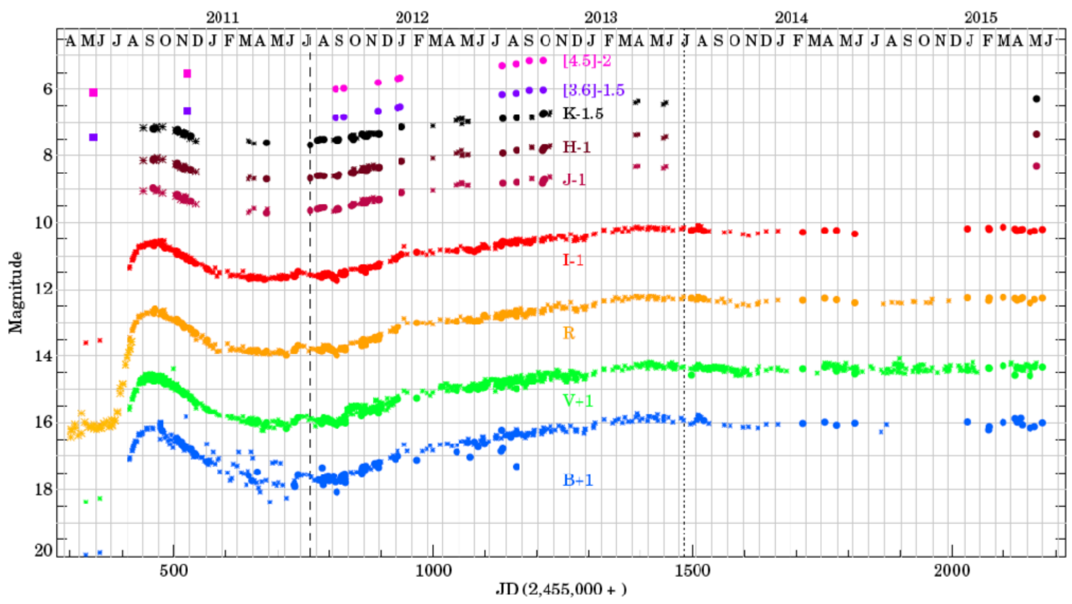
Long-term temporal evolution

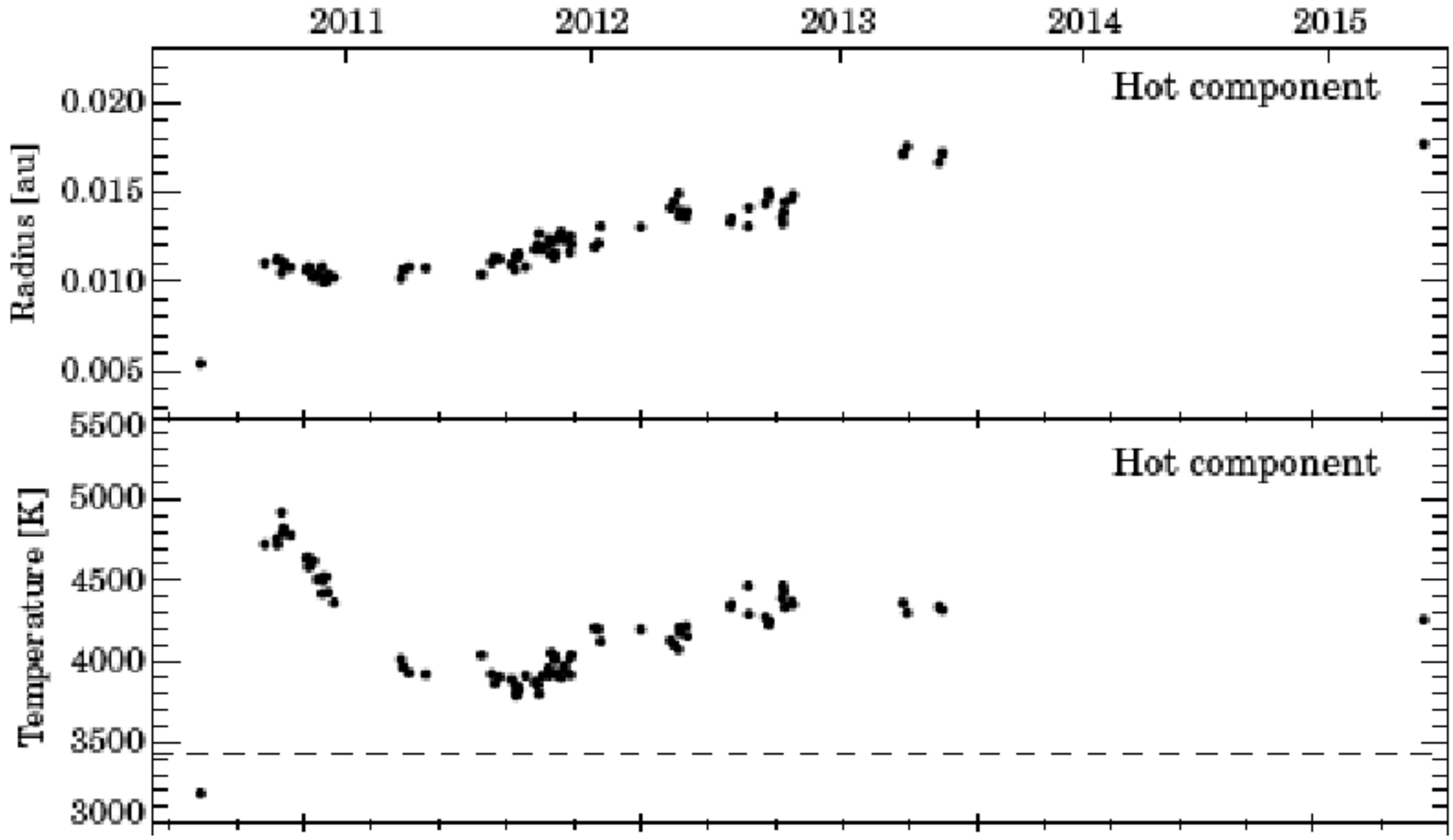


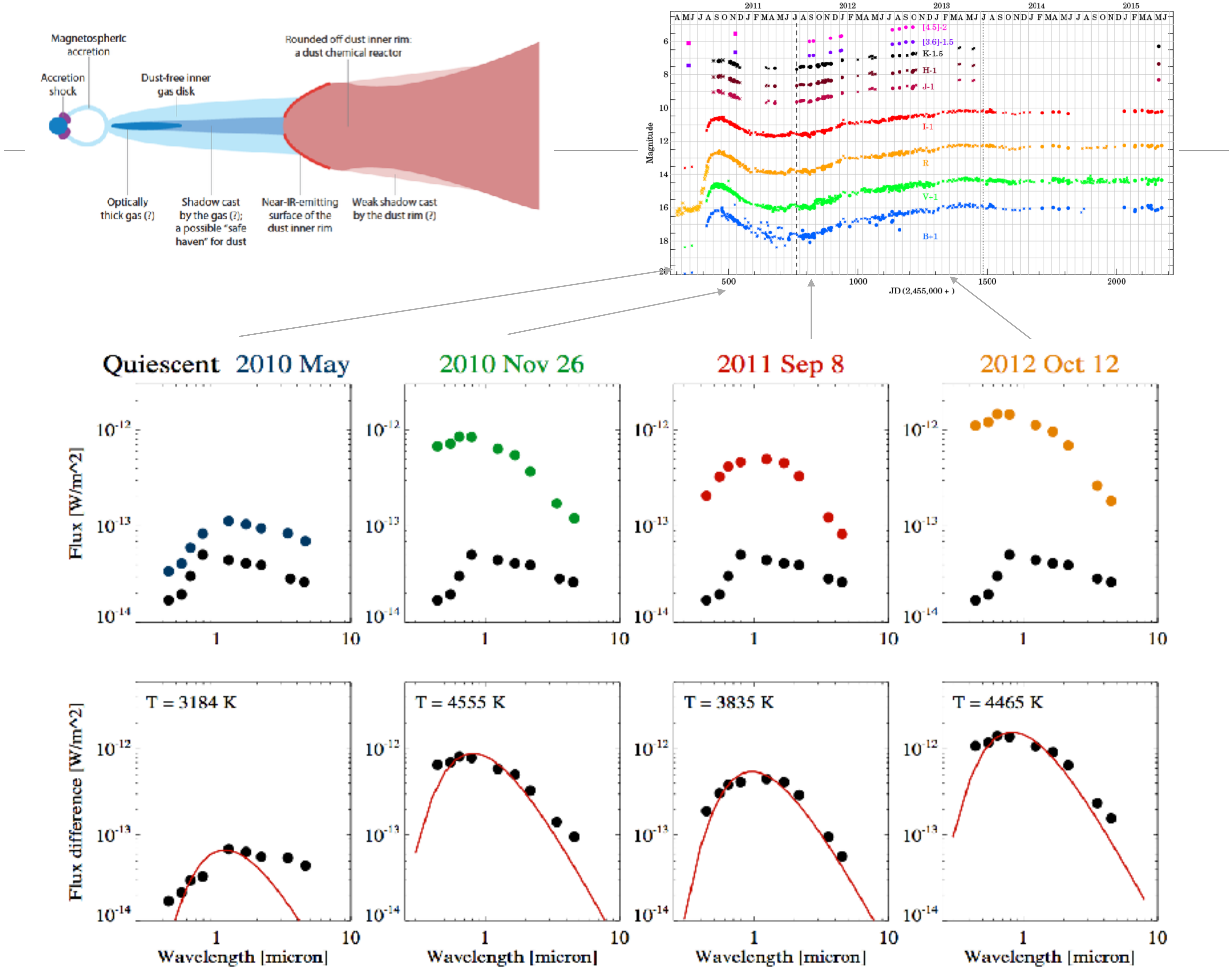
Long-term temporal evolution



Evolution of the inner disk

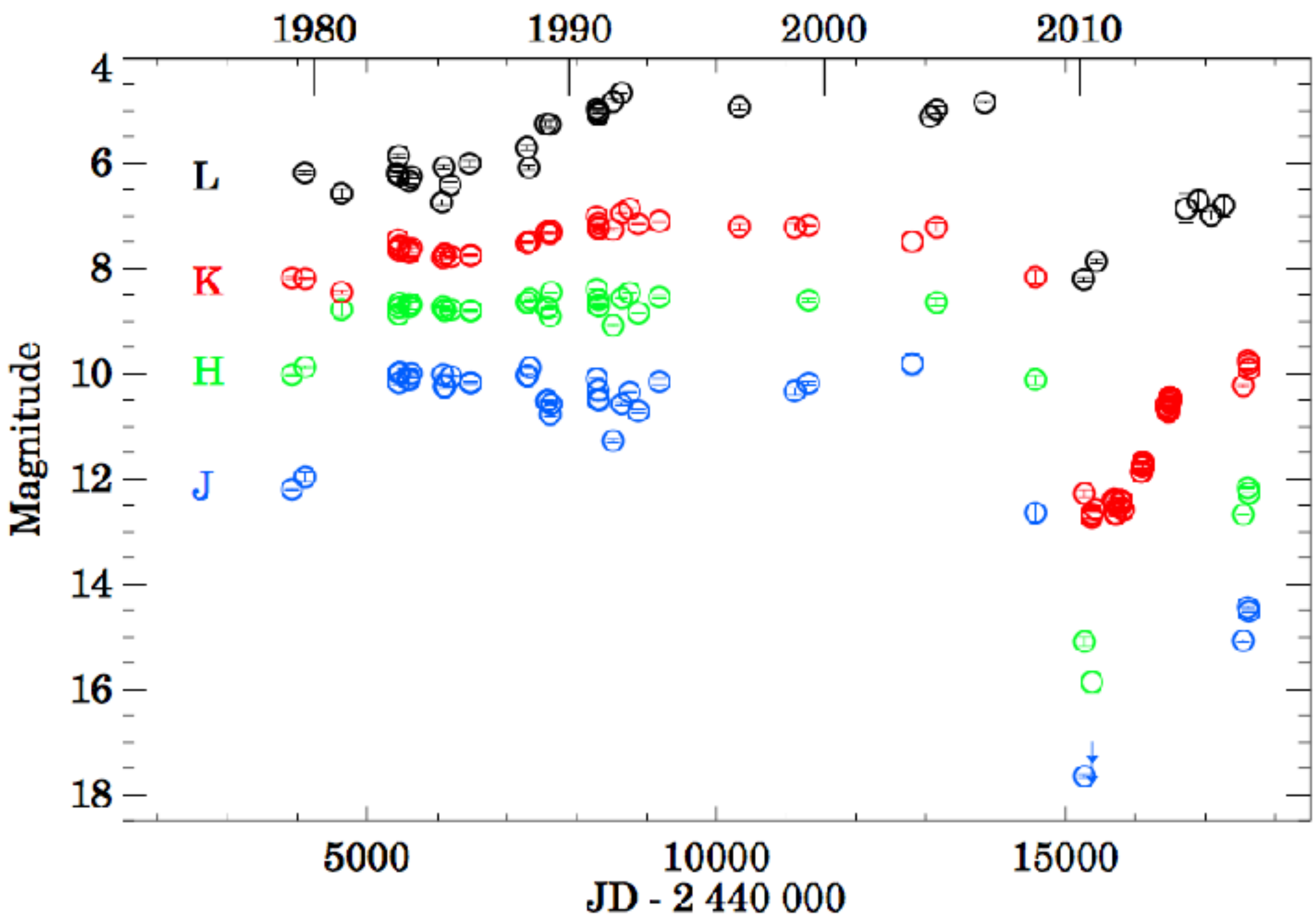






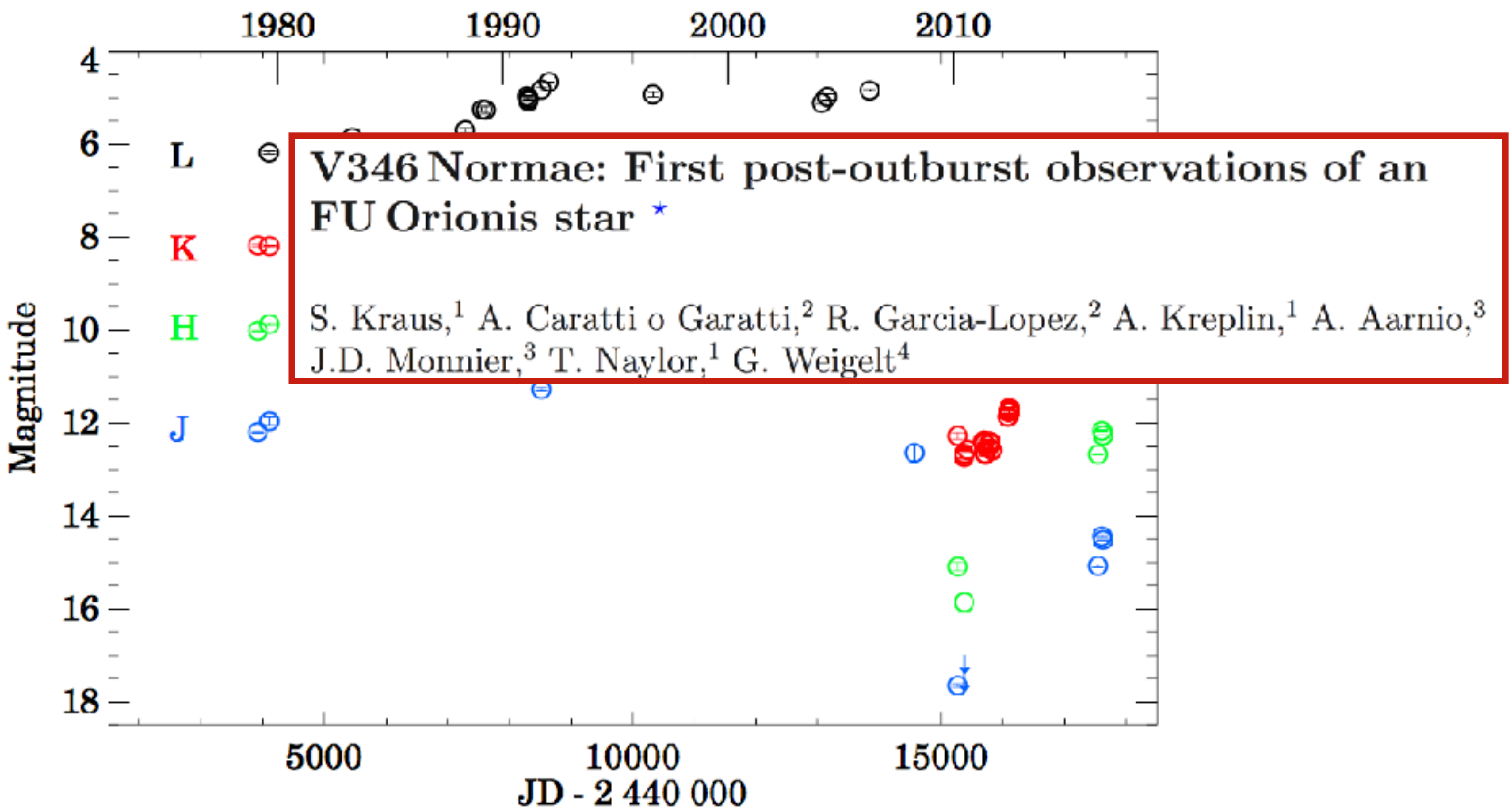
Magnetospheric accretion
Accretion shock
Dust-free inner gas disk
Rounded off dust inner rim: a dust chemical reactor
Optically thick gas (?)
Shadow cast by the gas (?); a possible "safe haven" for dust
Near-IR-emitting surface of the dust inner rim
Weak shadow cast by the dust rim (?)
2011
2012
2013
2014
2015
Magnitude
[4.5]-2
[3.6]-1.5
K-1.5
H-1
J-1
I-1
R
V-1
B+1
JD (2,455,000 +)
Quiescent 2010 May
2010 Nov 26
2011 Sep 8
2012 Oct 12
Flux [W/m^2]
Flux difference [W/m^2]
T = 3184 K
T = 4555 K
T = 3835 K
T = 4465 K
Wavelength [micron]
Wavelength [micron]
Wavelength [micron]
Wavelength [micron]

V346 Nor



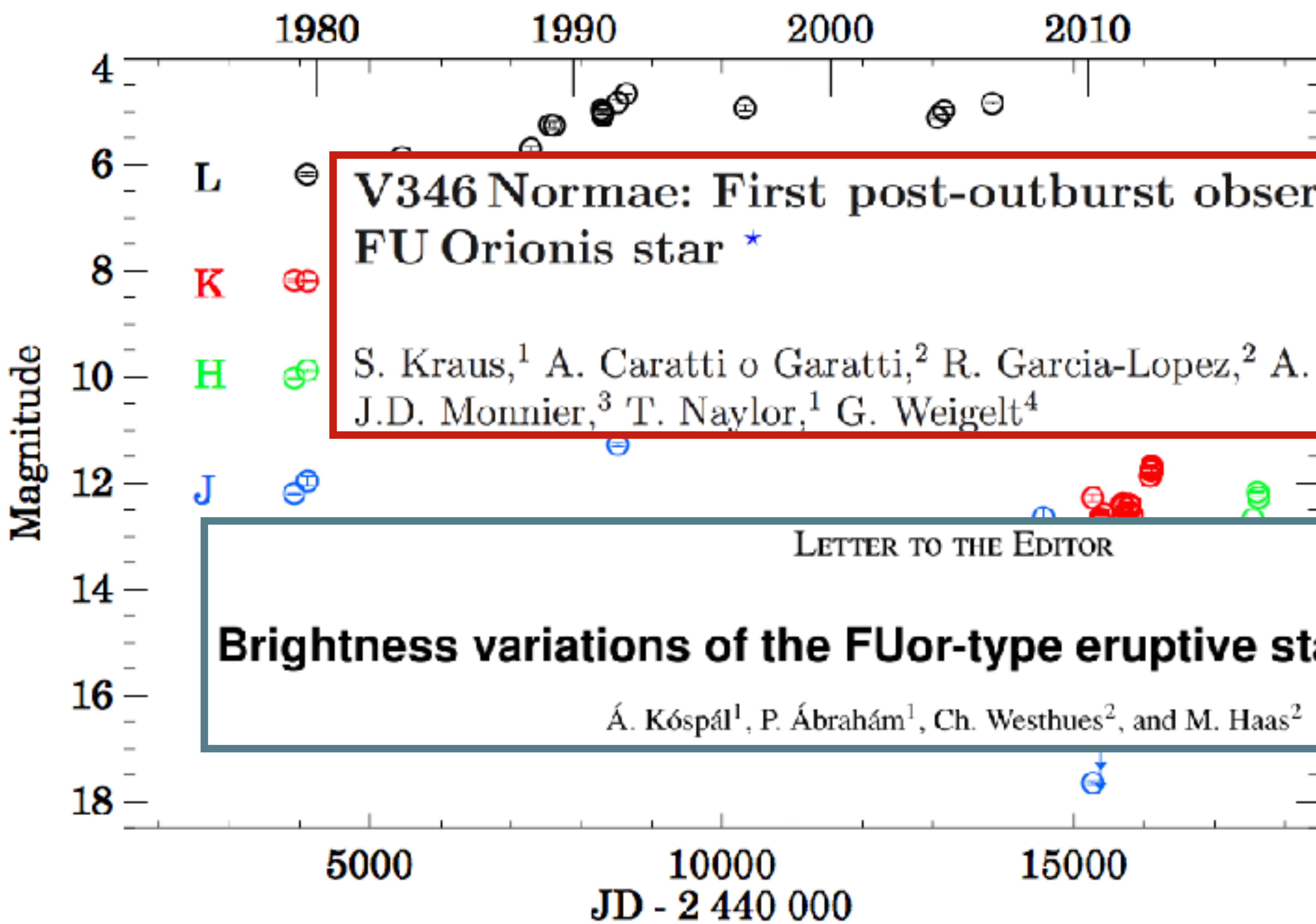
Kóspál+ 2017: the dimming in 2010 is due to a halt in the accretion rate.

V346 Nor



Kóspál+ 2017: the dimming in 2010 is due to a halt in the accretion rate.

V346 Nor



V346 Normae: First post-outburst observations of an FU Orionis star *

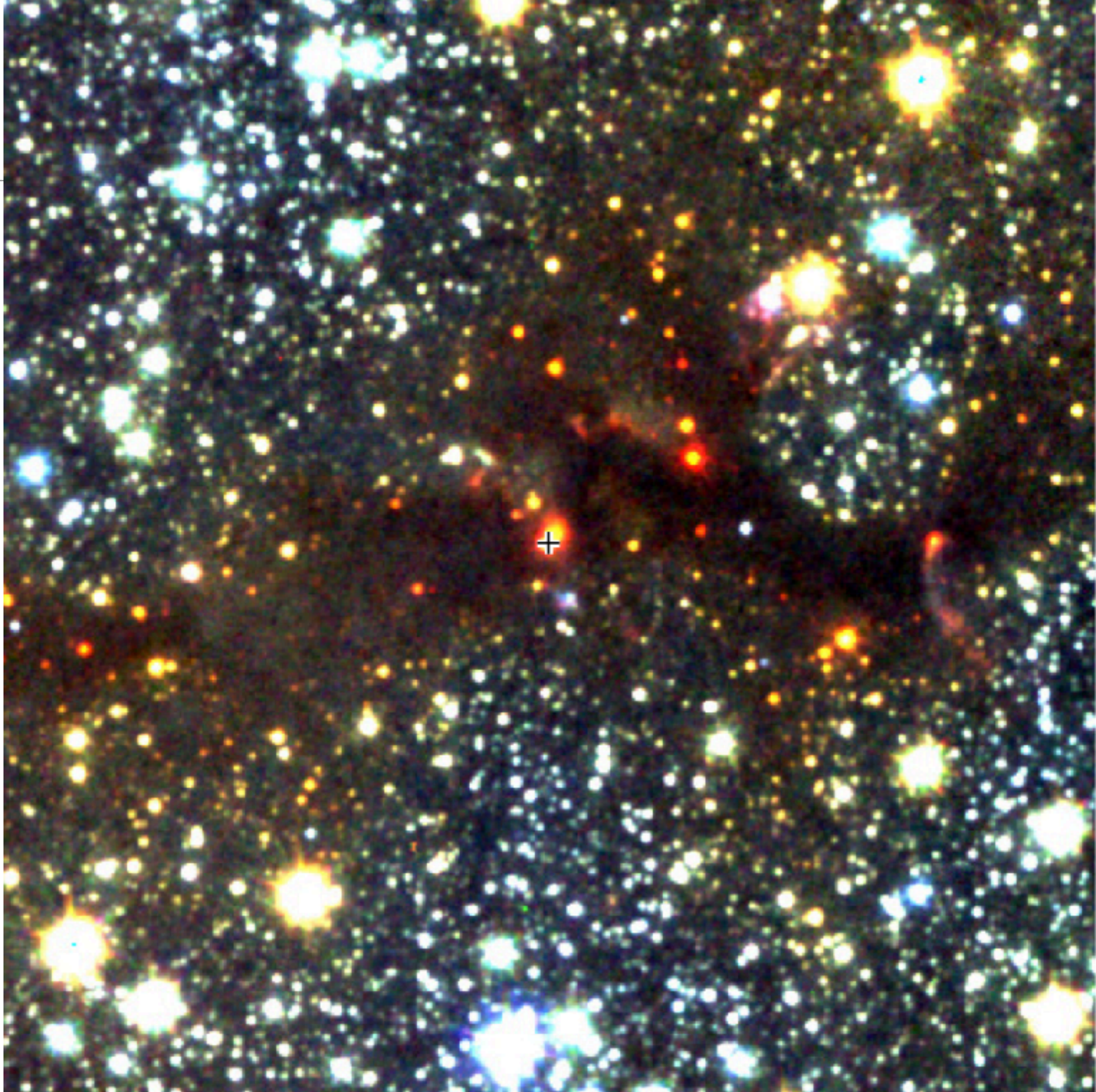
S. Kraus,[1] A. Caratti o Garatti,[2] R. Garcia-Lopez,[2] A. Kreplin,[1] A. Aarnio,[3] J.D. Monnier,[3] T. Naylor,[1] G. Weigelt[4]

LETTER TO THE EDITOR

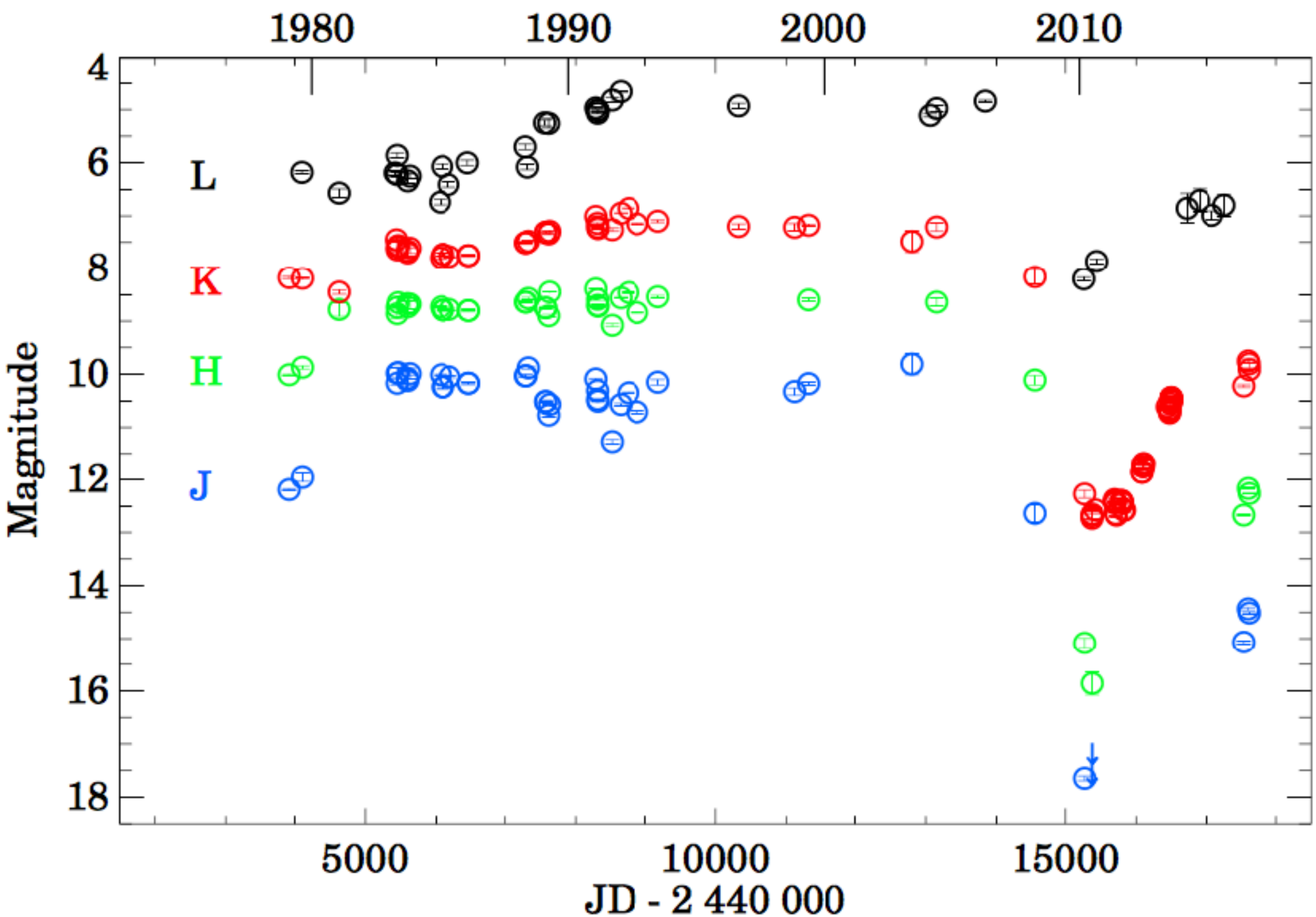
Brightness variations of the FUor-type eruptive star V346 Normae

Á. Kóspál[1], P. Ábrahám[1], Ch. Westhues[2], and M. Haas[2]

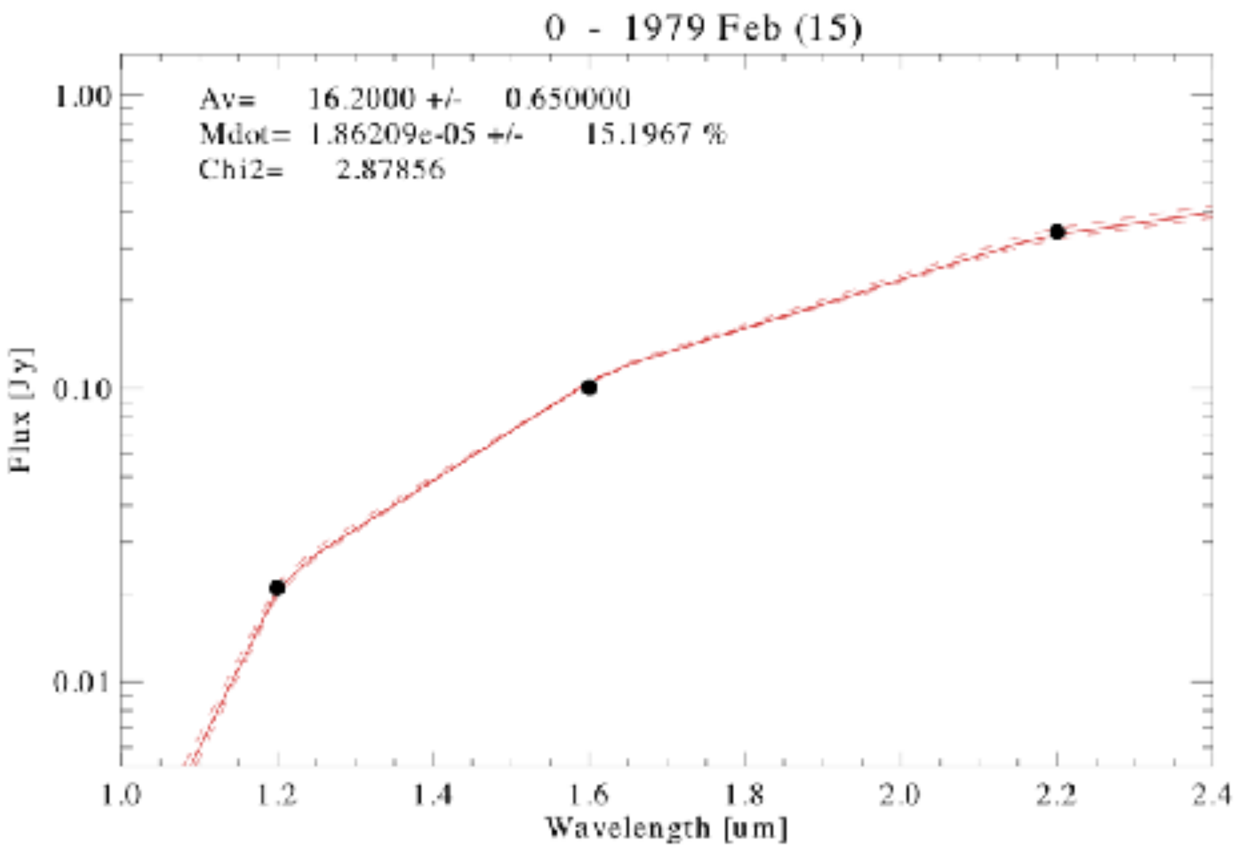
V346 Nor



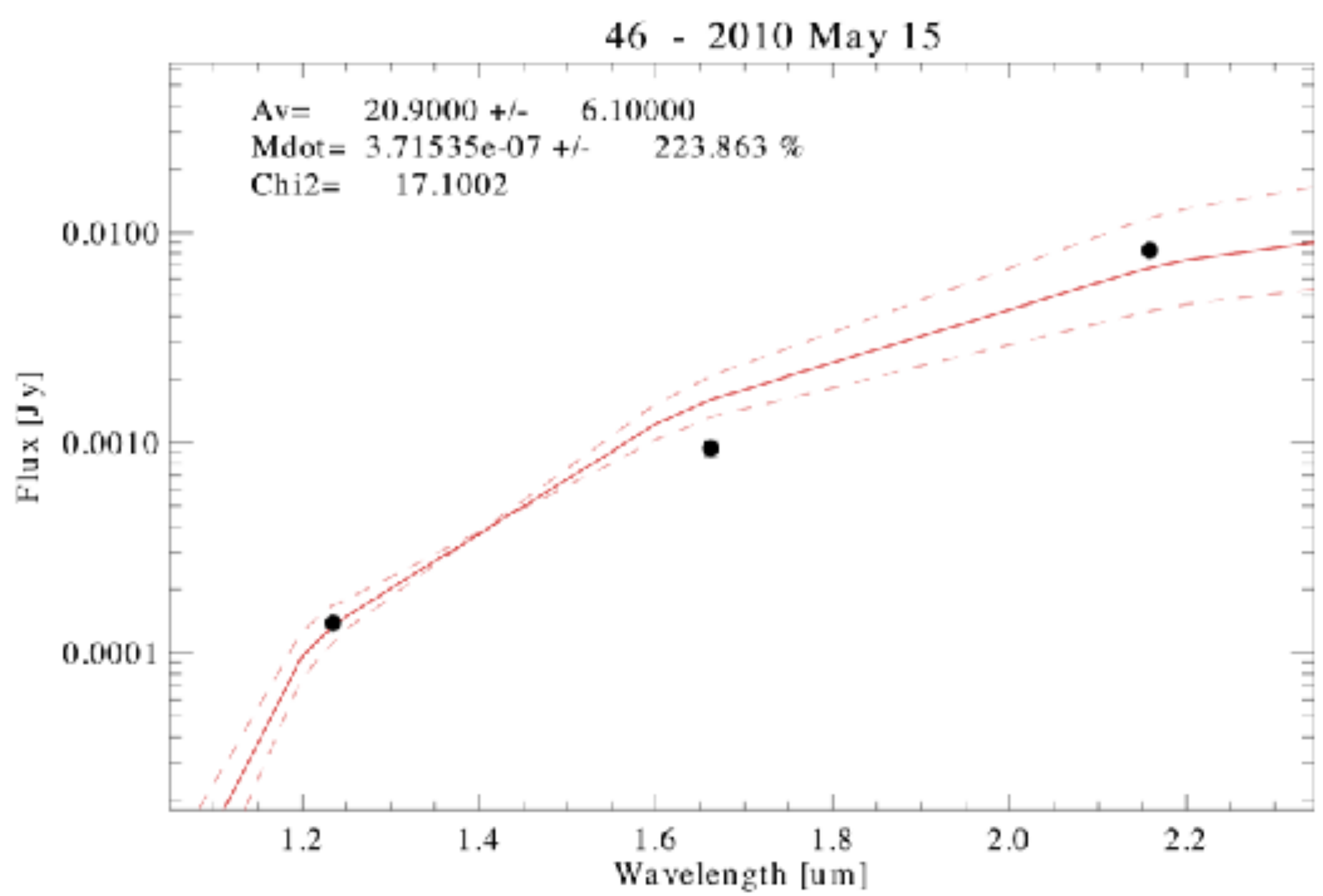
V346 Nor


1980
1990
2000
2010
4
6
8
10
12
14
16
18
L
K
H
J
Magnitude
5000
10000
15000
JD - 2 440 000

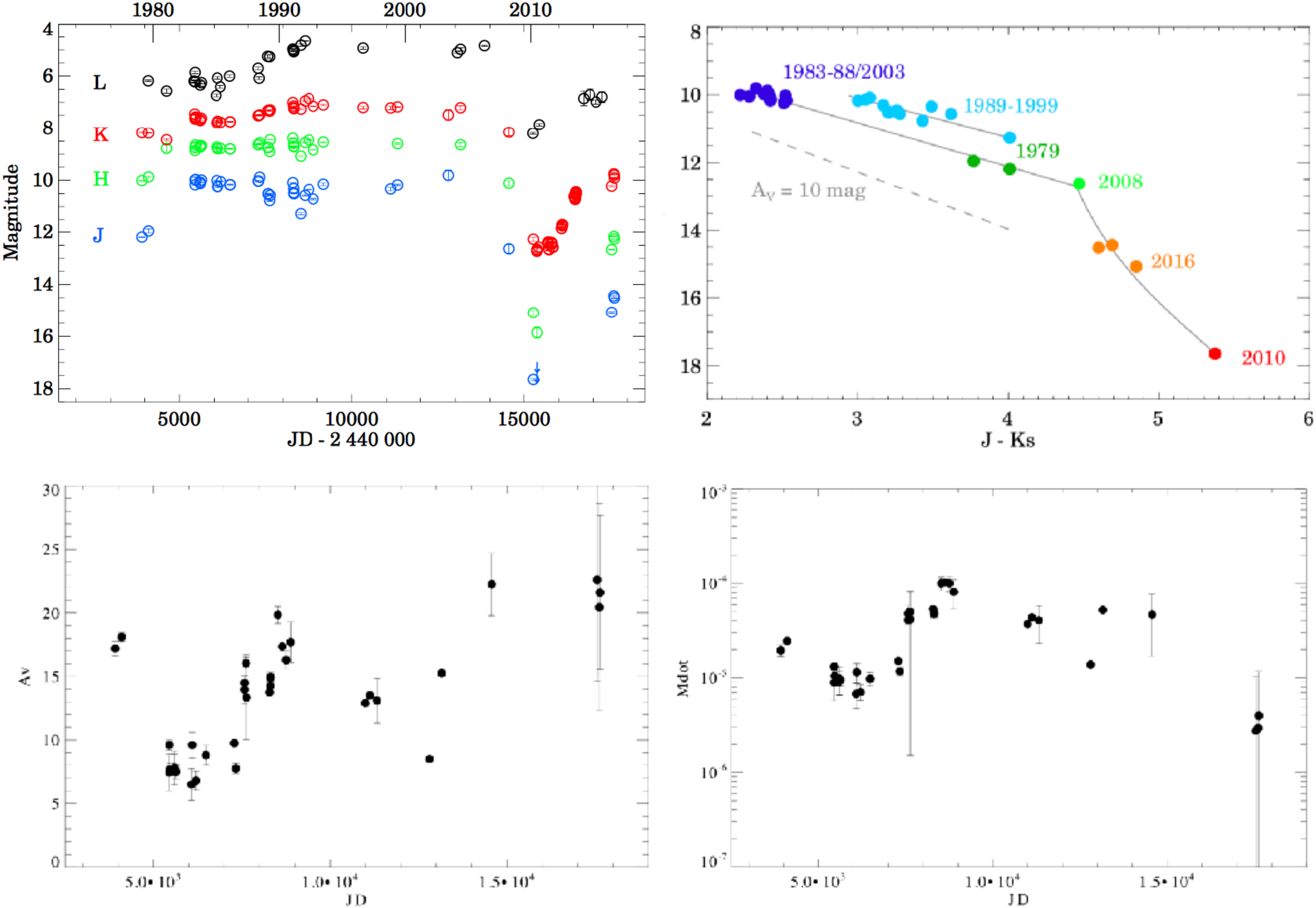
V346 Nor



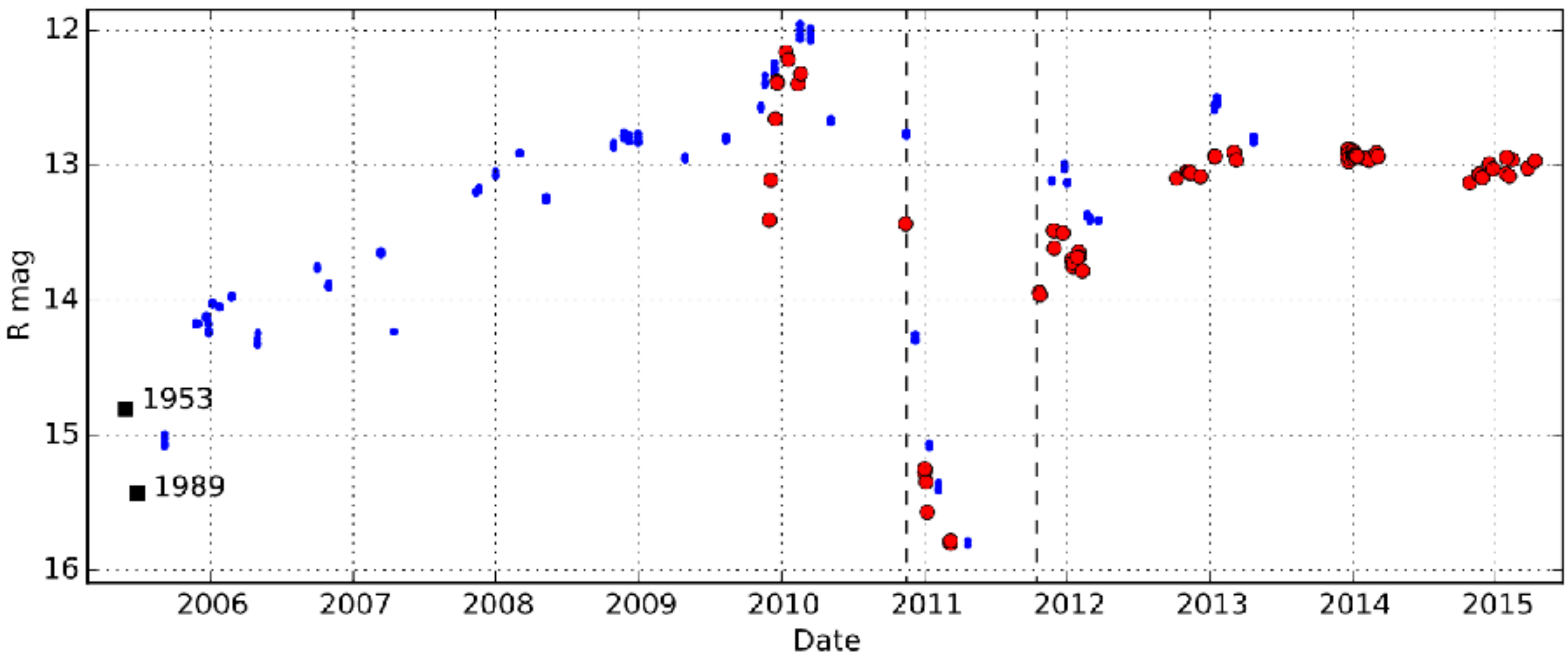
0 - 1979 Feb (15)
Av= 16.2000 +/- 0.650000
Mdot= 1.86209e-05 +/- 15.1967 %
Chi2= 2.87856
1.00
0.10
0.01
Flux [Jy]
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Wavelength [um]



46 - 2010 May 15
Av= 20.9000 +/- 6.10000
Mdot= 3.71535e-07 +/- 223.863 %
Chi2= 17.1002
0.0100
0.0010
0.0001
Flux [Jy]
1.2
1.4
1.6
1.8
2.0
2.2
Wavelength [um]


1980
1990
2000
2010
L
K
H
J
Magnitude
JD - 2 440 000
1983-88/2003
1989-1999
1979
2008
2016
2010
A_V = 10 mag
J - Ks
Av
JD
Mdot
JD

V899 Mon



Ninan+ 2015: the dimming in 2011 is due to a halt of the accretion process. An instability associated with magnetospheric accretion being the physical cause of the sudden short-duration pause of the outburst in 2011.

Halt of accretion

Ninan+ 2015: accretion can stop if

- the inner truncation radius of the disk moves outside the corotation radius (D’Angelo and Spruit 2010)
- the differential rotation between the inner accretion disk and the star can lead to inflation of the funnel, resulting in field lines opening and reconnecting, reducing accretion flow while enhancing outflow (Bouvier et al. 2003).