Irregular variability during star formation: what can we learn about the circumstellar material?

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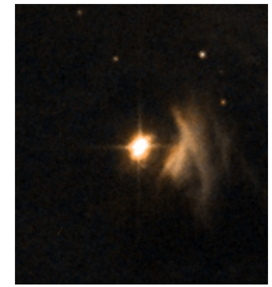
Great Barriers in Planet Formation – 2019 July 24

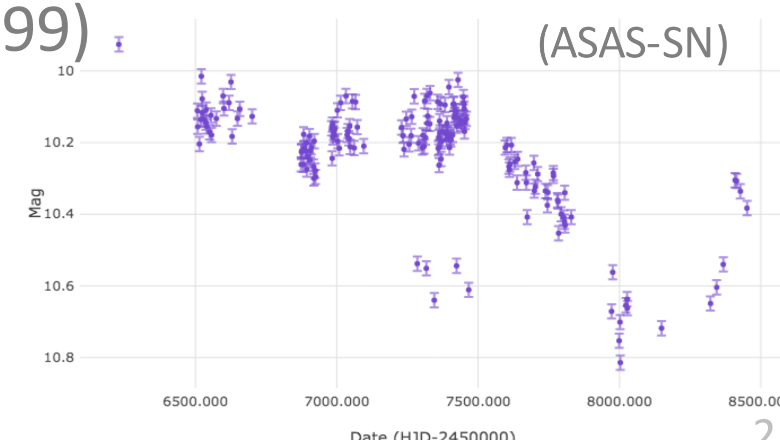
YSOs: traditional variable stars

- Many variable stars with traditional variable star designations (T Tauri, FU Orionis, V1057 Cyg, …) are YSOs
- Optical (*UBVR*) photometric monitoring of T Tauri and Herbig stars: virtually **all young stars are irregular variables** with amplitudes from barely detectable to > 4 mag (Herbst et al. 1994, Herbst & Shevchenko 1999)
- There are different reasons behind the variability, which cause different variability patterns

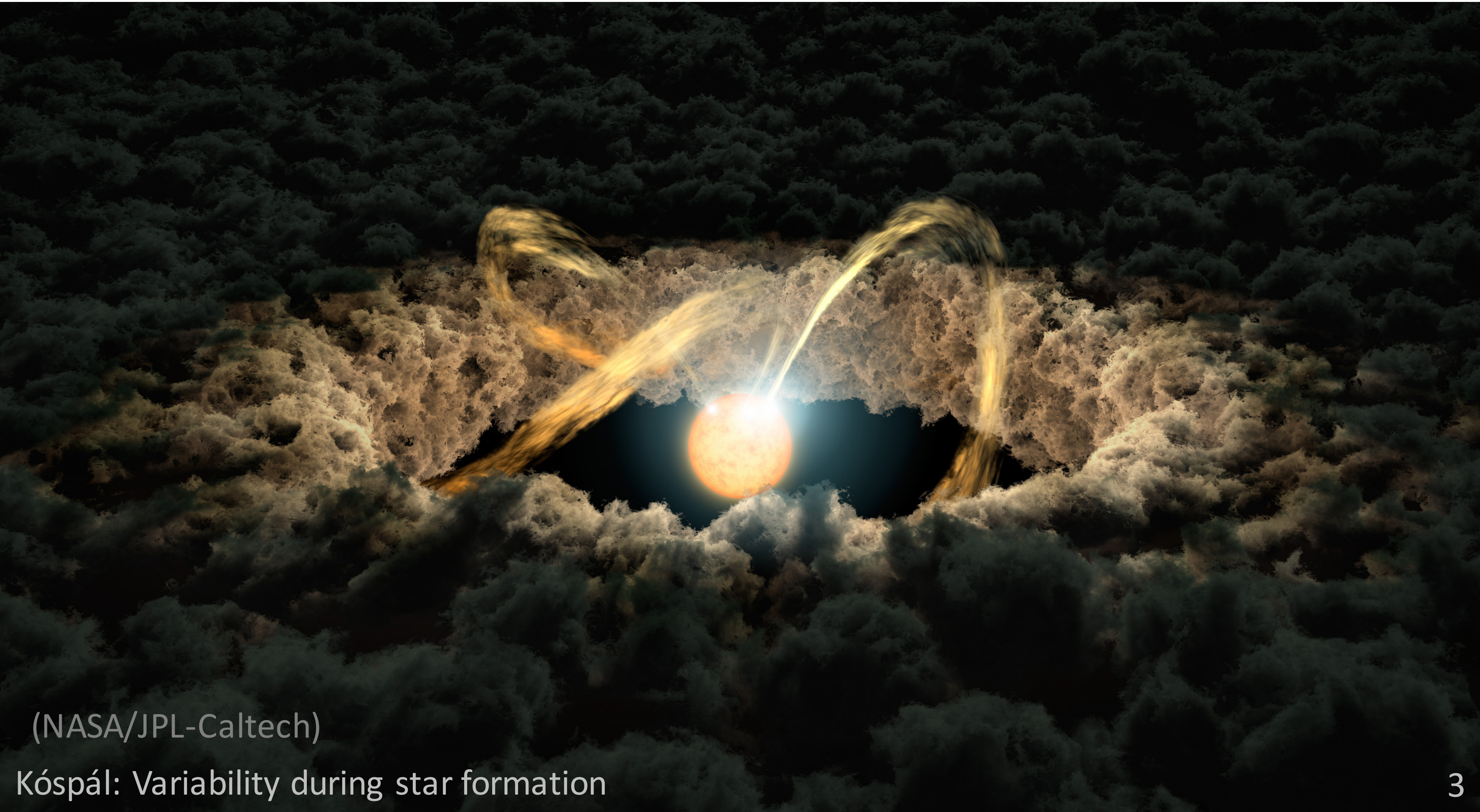


(Simbad)

(ASAS-SN)

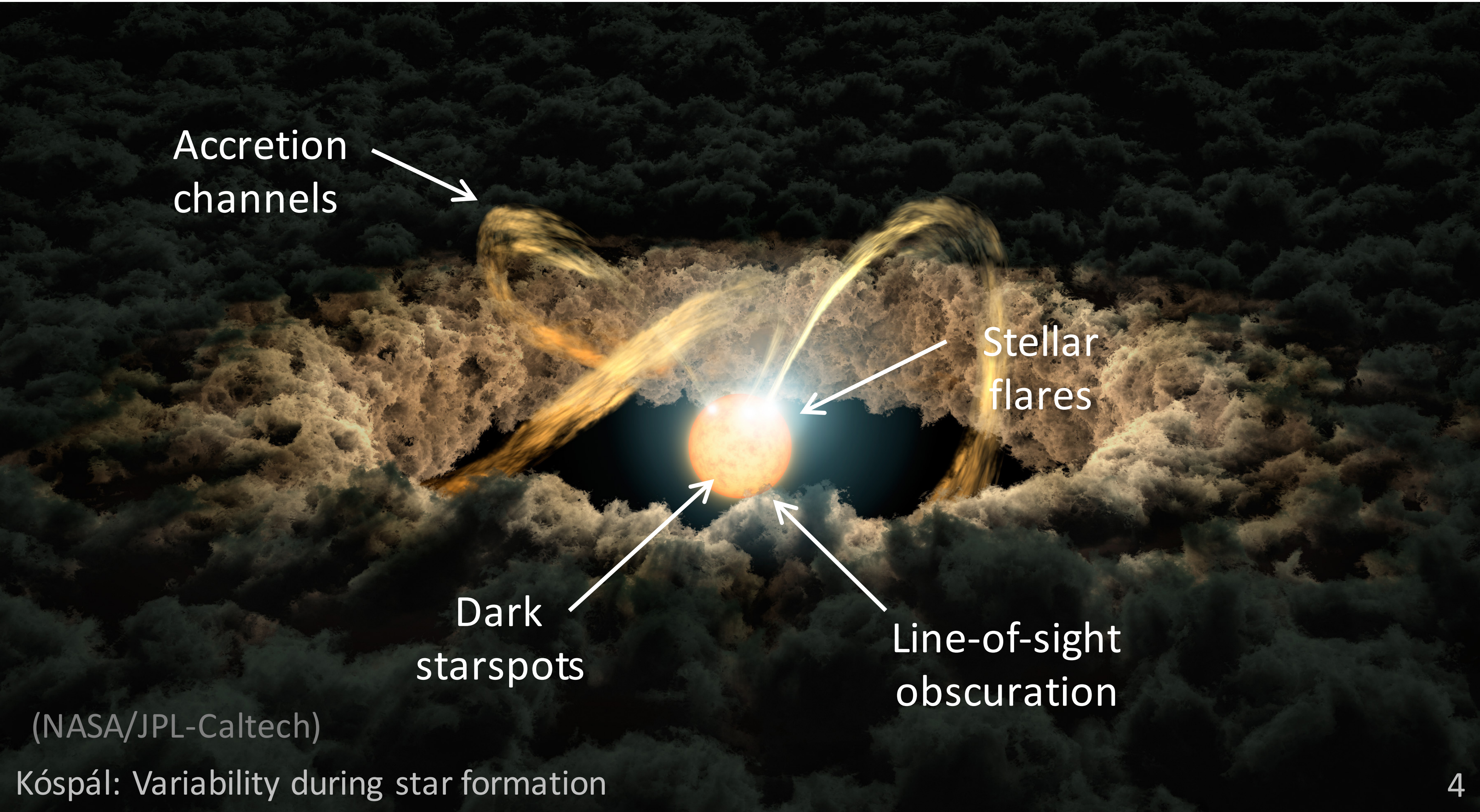


Circumstellar environment



(NASA/JPL-Caltech)

Circumstellar environment

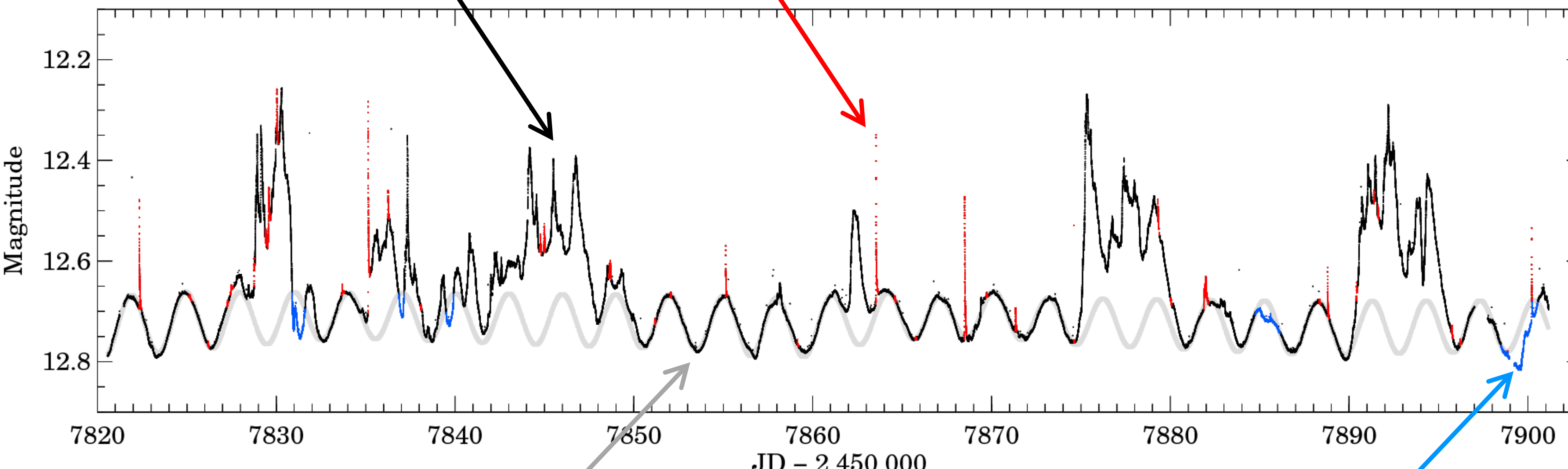


Discerning different effects in DQ Tau

Kepler/K2 light curve with 1 min cadence covering 80 days

Variable accretion

Stellar flares



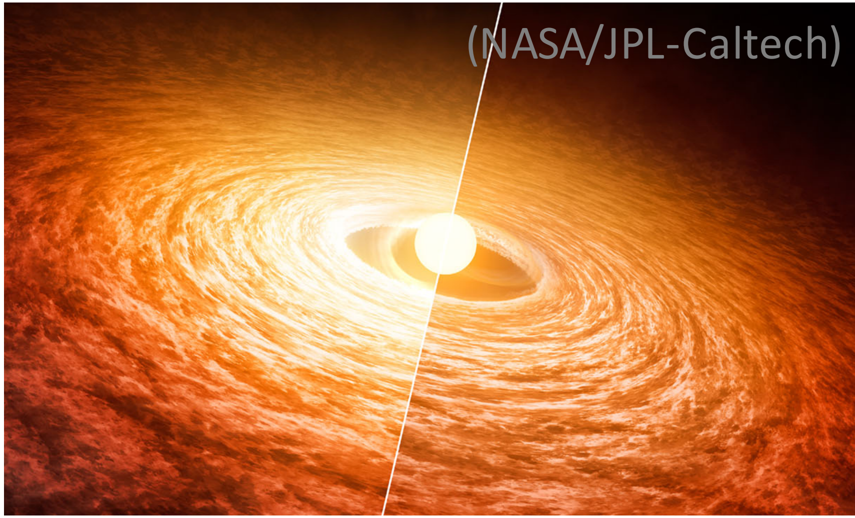
Rotational modulation due to cold starspots

(Kóspál et al. 2018,
see also
Tofflemire et al. 2017,
Czekala et al. 2016)

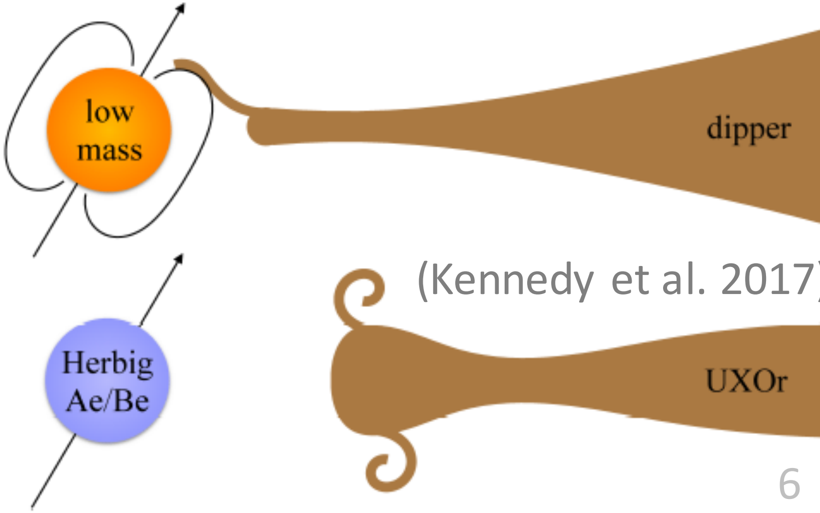
Obscuration

Examples for extreme variables

- FU Orionis-type variables (FUors)
- EX Lupi-type variables (EXors)



- UX Orionis-type variables (UXors) / dippers



How can we understand variability?

- Multi-filter photometry; multi-wavelength photometry (X-ray, UV, optical, infrared, millimeter, radio)

- Precision photometry (e.g., at the μmag-mmag level): MOST, CoRoT, Kepler/K2, Gaia, TESS, PTF, ZTF, VVV(X), LSST

  talk by Carlos Contreras Peña

- Spectroscopic monitoring (UV, optical, infrared, millimeter)

  talk by Connor Robinson

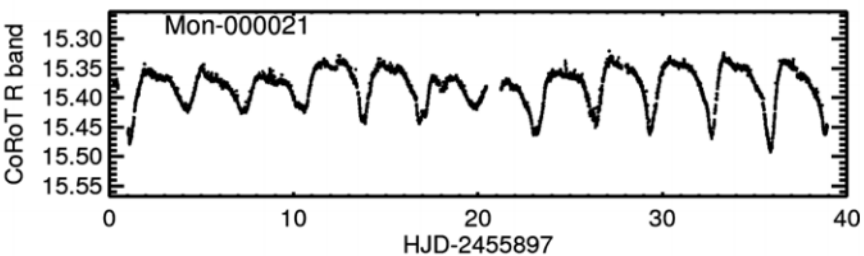
- Spatially resolved imaging or interferometric monitoring (e.g., VLT, Gemini, Subaru, VLT Interferometer)

- Dynamical models to predict time-dependent observables

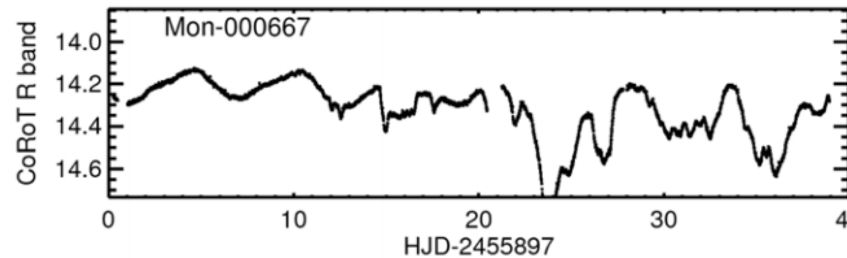
Variability types of disk-bearing stars

Simultaneous CoRoT (optical) and Spitzer (3.6 and 4.5 μm) photometric monitoring of disk-bearing stars in NGC 2264

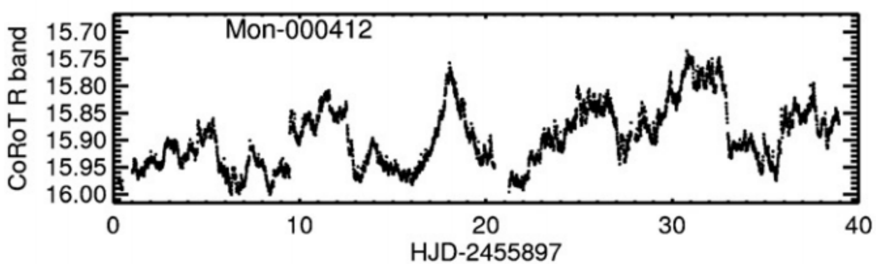
Quasi-periodic dipper



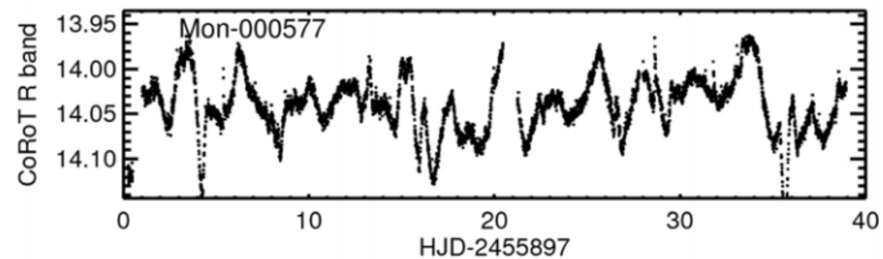
Aperiodic dipper



Burster

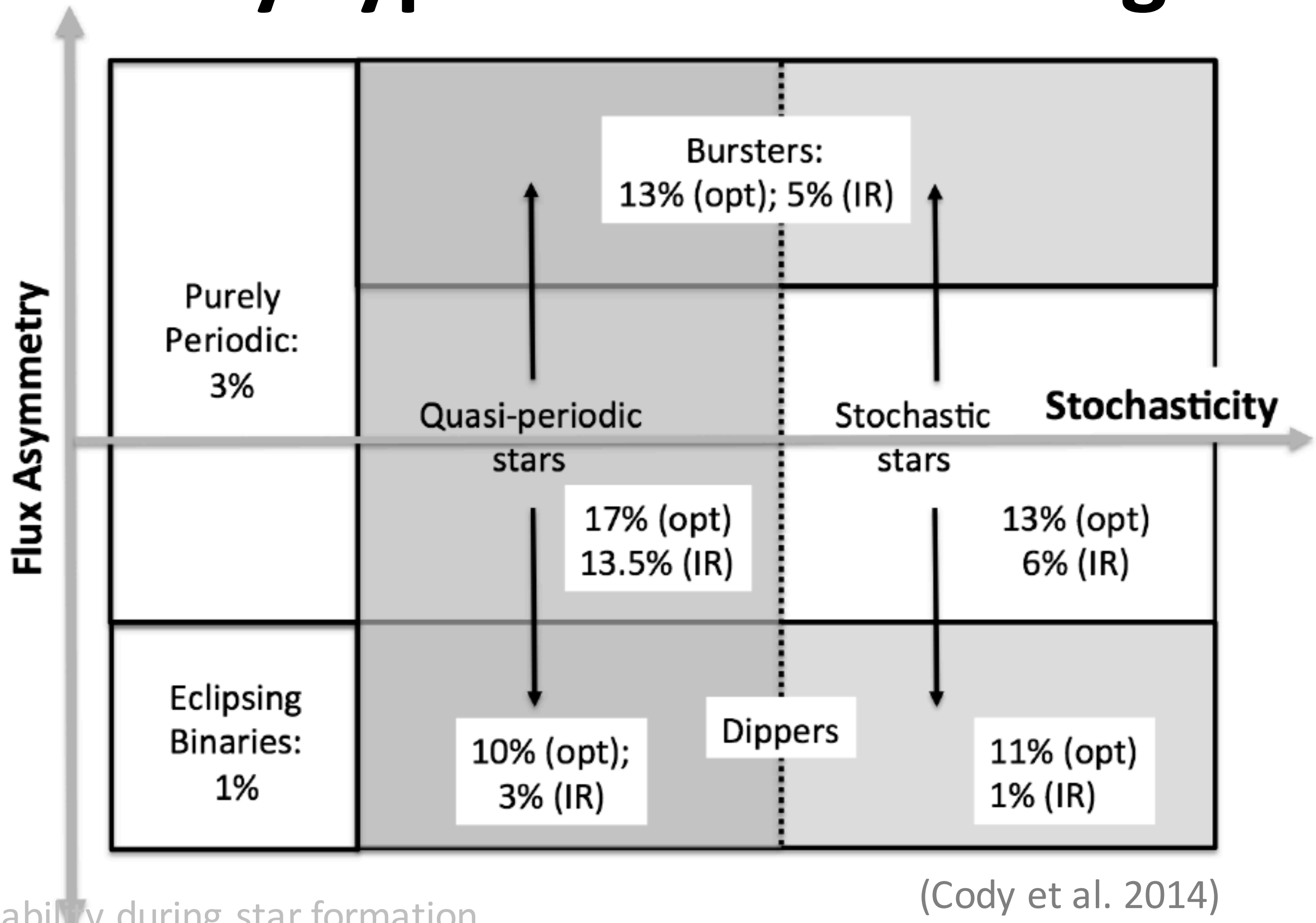


Stochastic variable



(Cody et al. 2014)

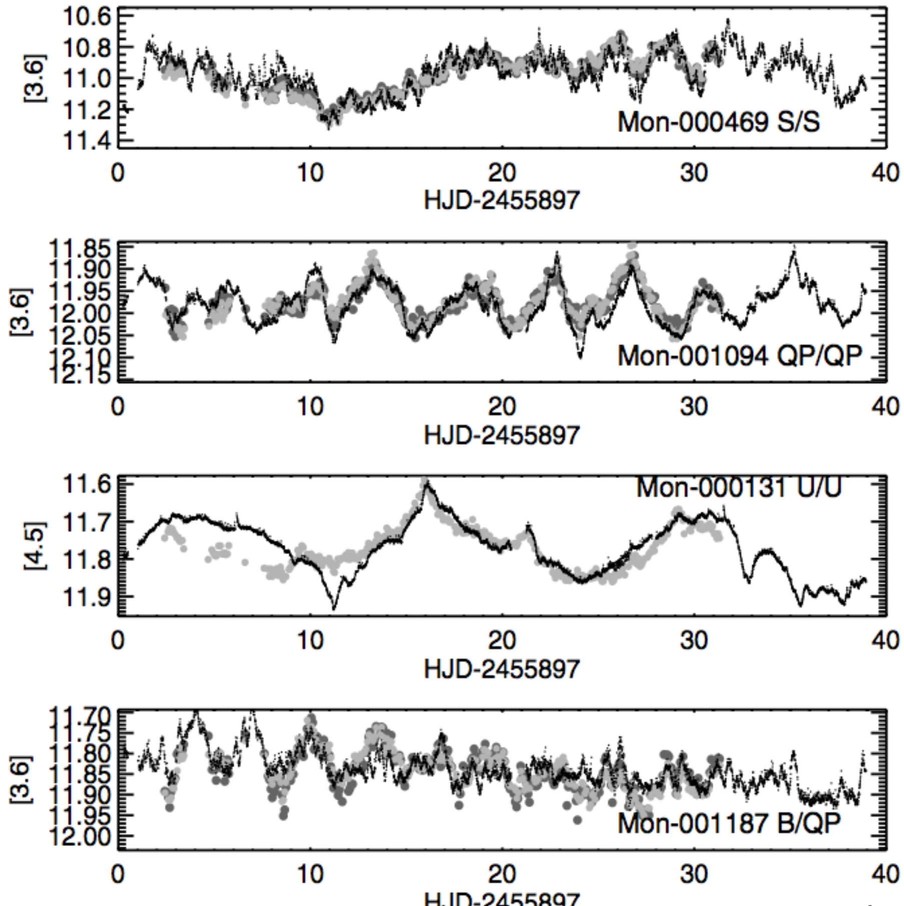
Variability types of disk-bearing stars



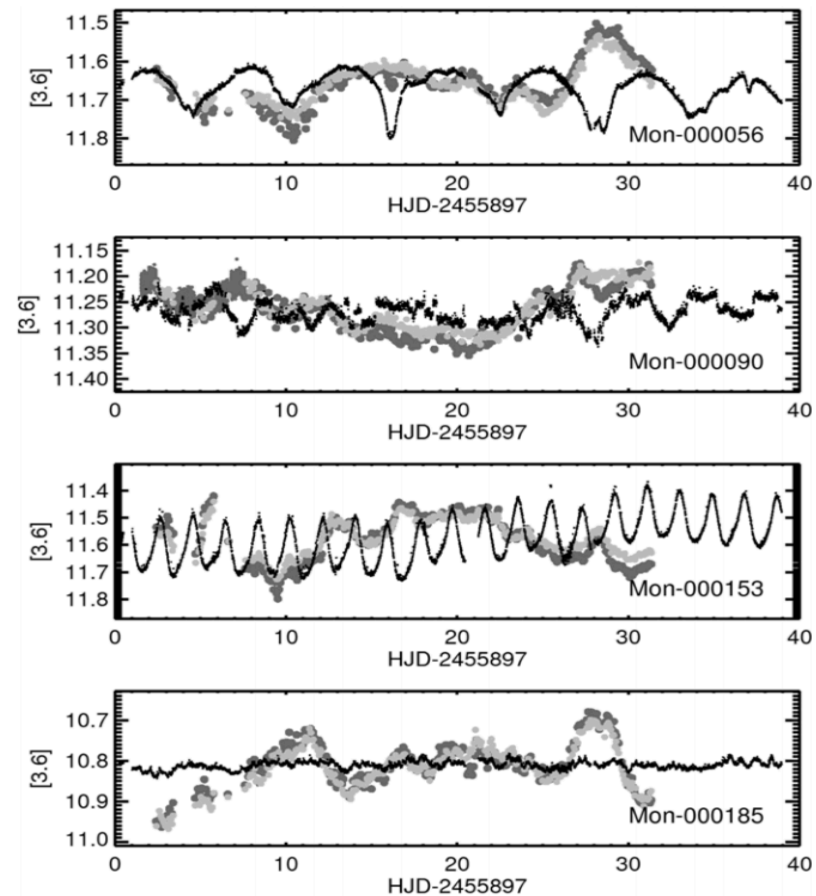
(Cody et al. 2014)

Variability types of disk-bearing stars

Correlated optical-IR behavior

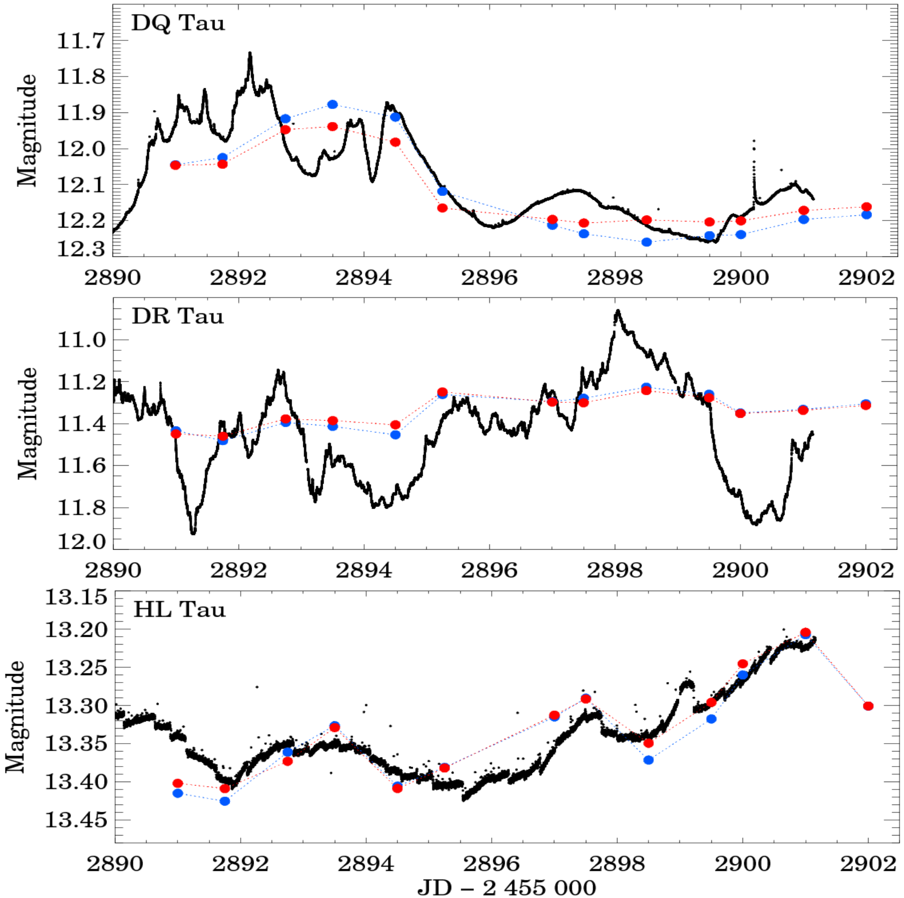


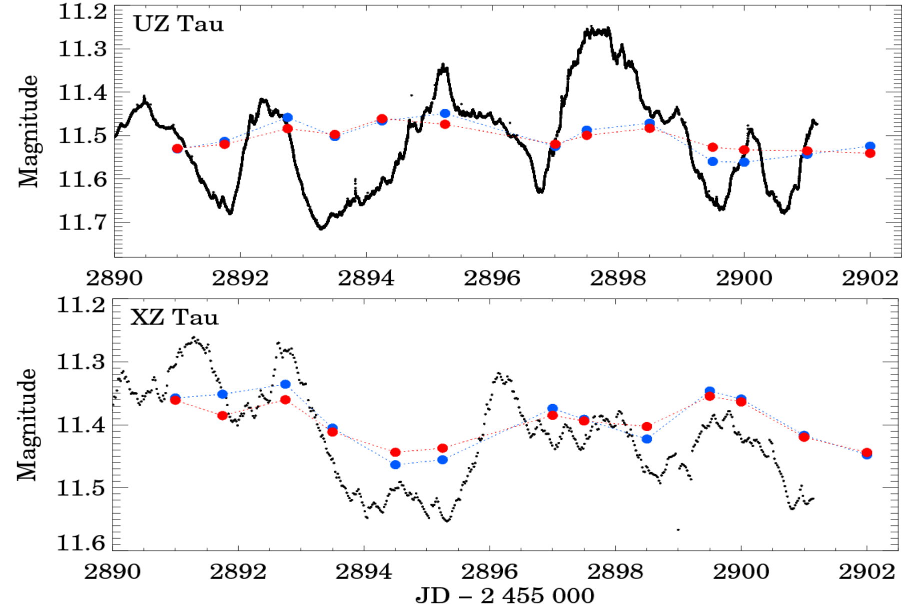
Unorrelated optical-IR behavior



(Cody et al. 2014)

K2 + Spitzer monitoring in Taurus

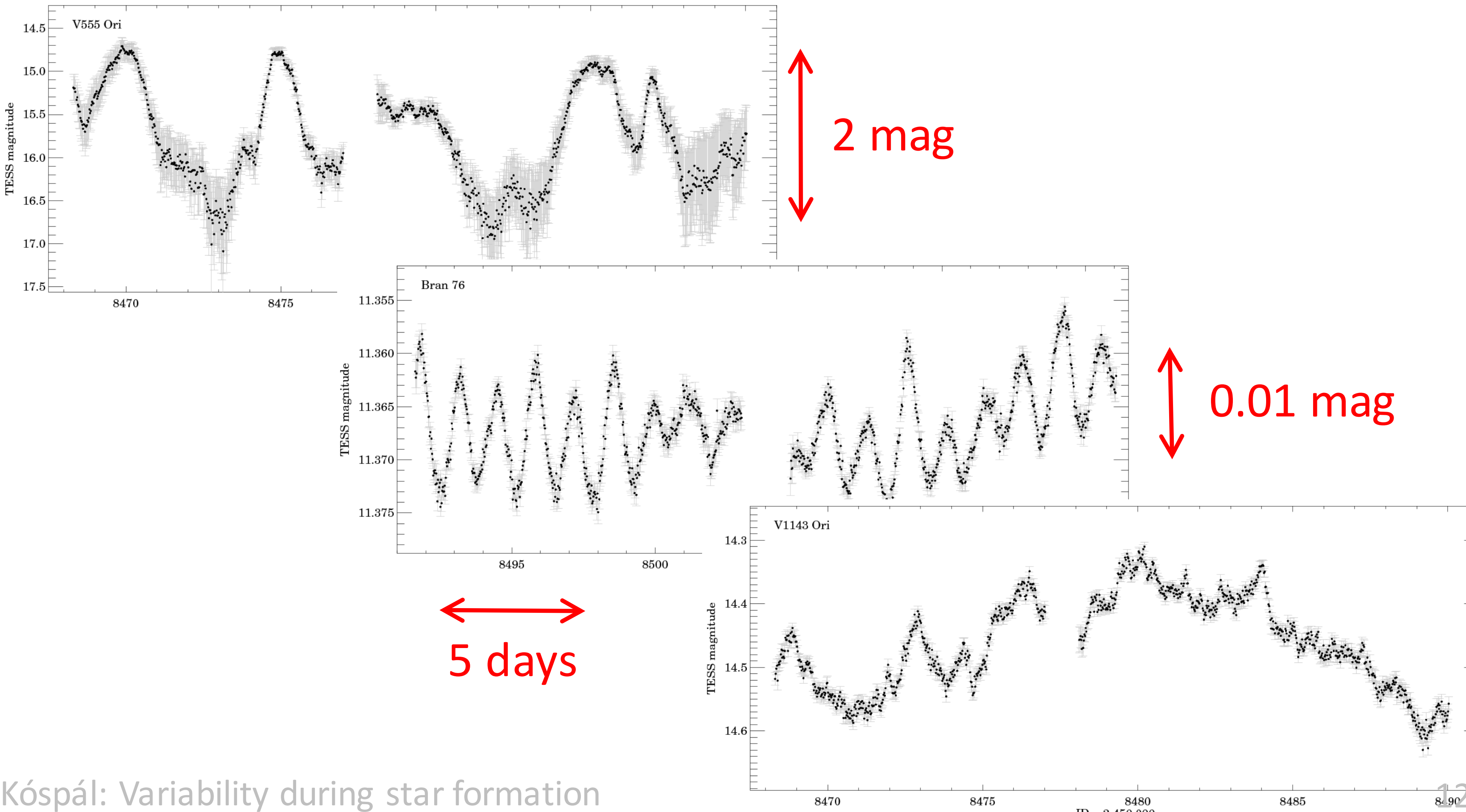




(Kóspál et al. 2018, Zsidi et al. in prep.)

- Correlated optical-IR behavior
- Variability amplitude: similar or smaller in the IR
- Different proportion of optically thick/thin emission?

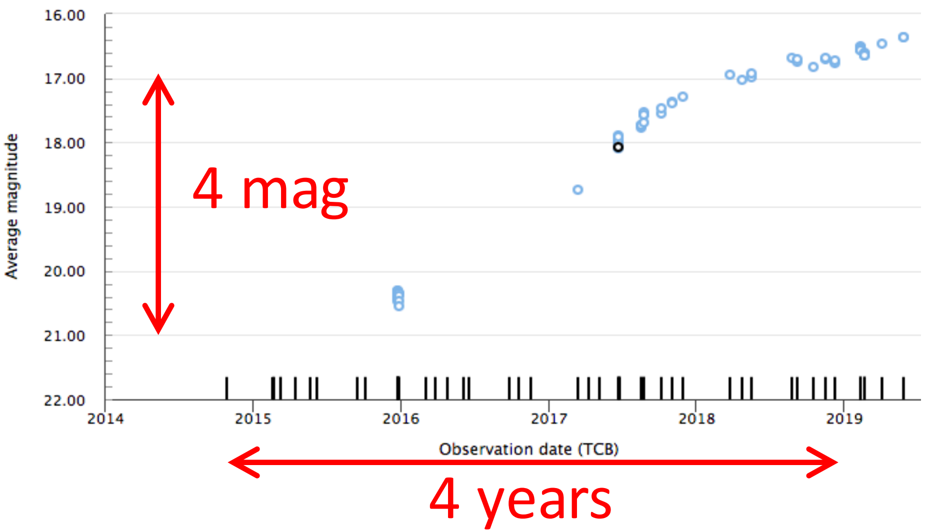
TESS light curves of YSOs



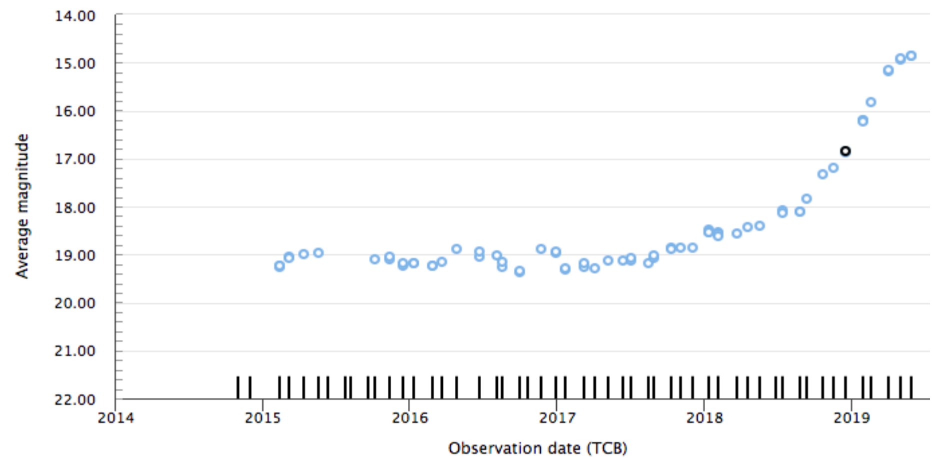
Gaia alerts

- Gaia alert webpage: http://gsaweb.ast.cam.ac.uk/alerts/
- Young outbursting stars among the Gaia alerts:

(Hillenbrand et al. 2018)

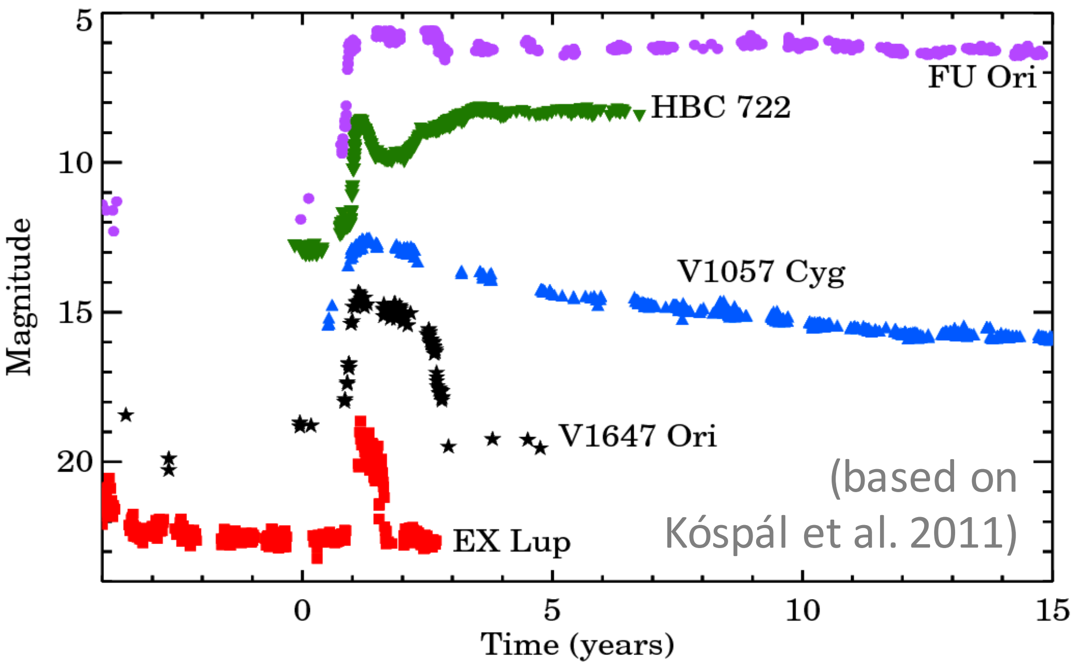


(Szegedi-Elek et al. in prep.)



- Final Gaia data release will contain billions of light curves + colors + spectra!

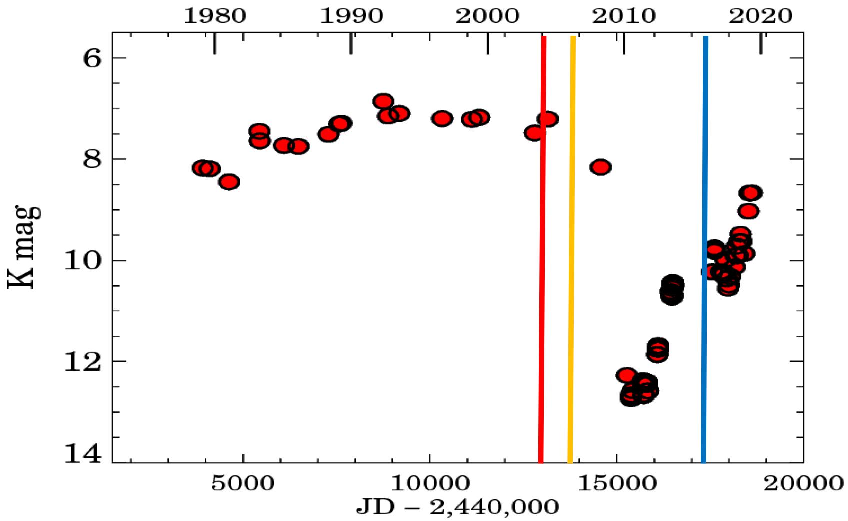
Young eruptive stars



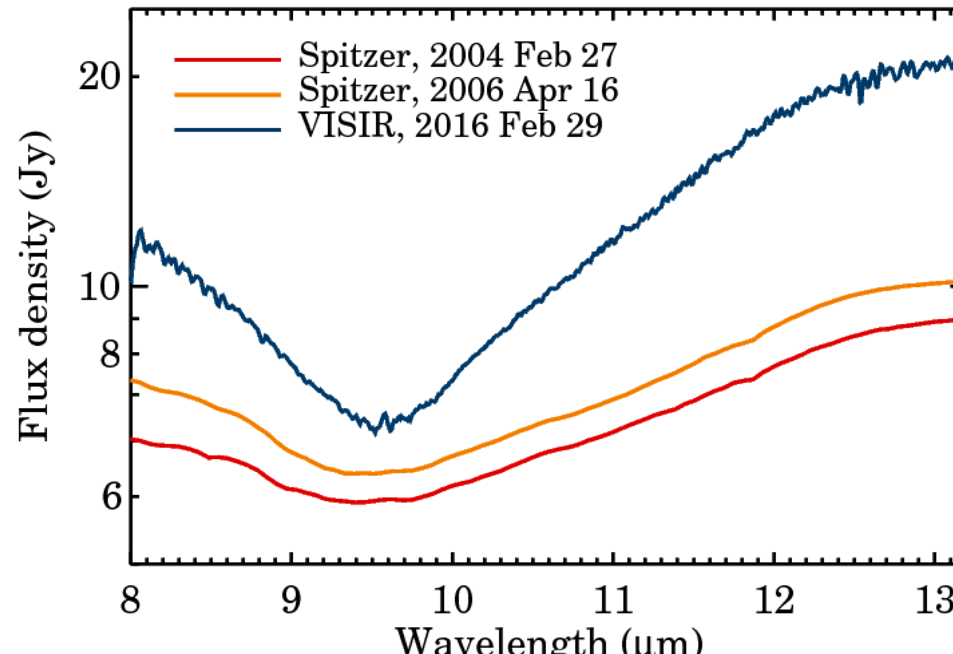
- Structural changes: V346 Nor
- Mineralogical changes: EX Lup
- Physical/chemical changes: EX Lup

- Powerful accretion outbursts
- Peak bolometric luminosity up to several 100 $L_\odot$
- Outbursts induce important changes in the disk, especially in the terrestrial planet-forming zone

Structural changes in V346 Nor



- Two Spitzer/IRS spectra during outburst
- One VLT/VISIR spectrum post-outburst

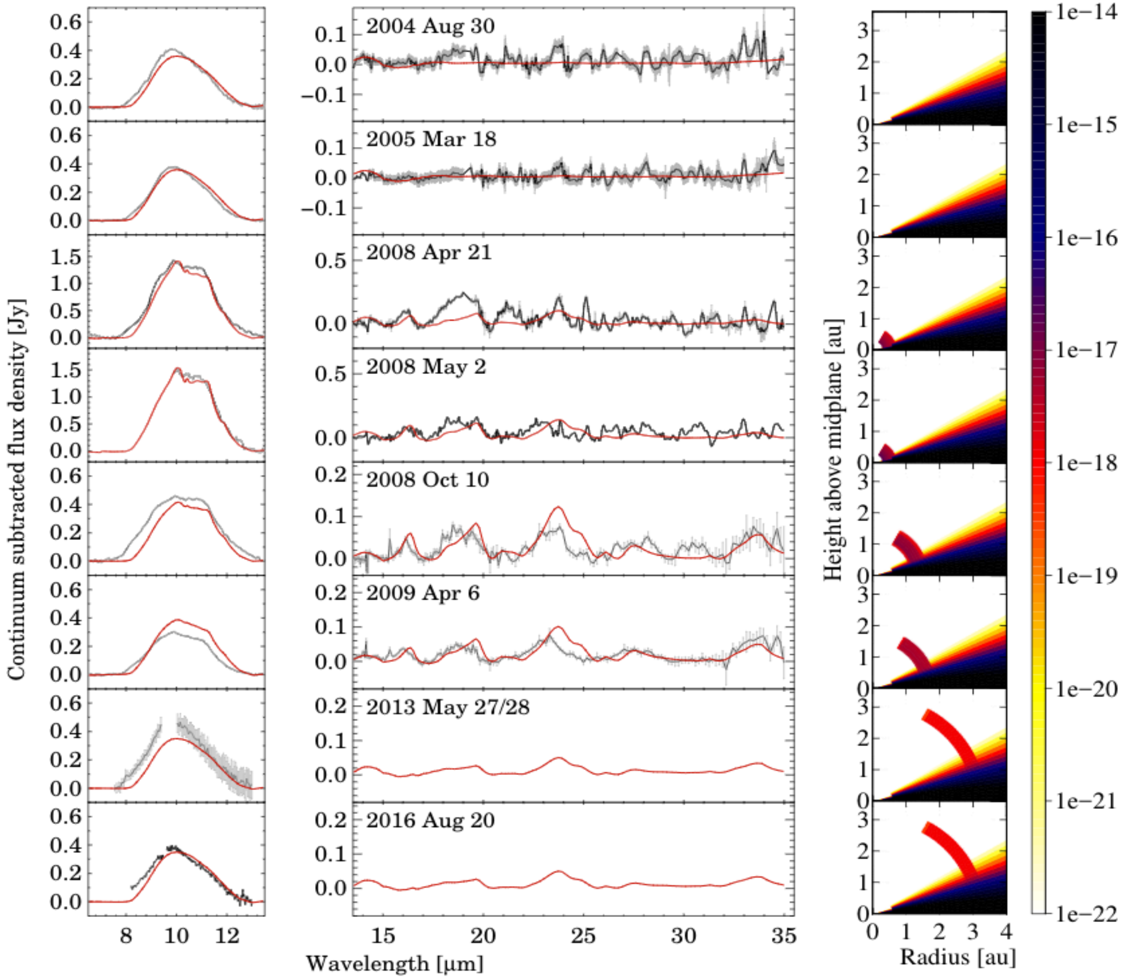


- Changes in the optical depth of the 10 µm silicate feature
- Changes in the line-of-sight extinction
- Density rearrangements between outburst and post-outburst

(Kóspál et al. in prep.)

talk by Péter Ábrahám

Episodic crystallization and transport



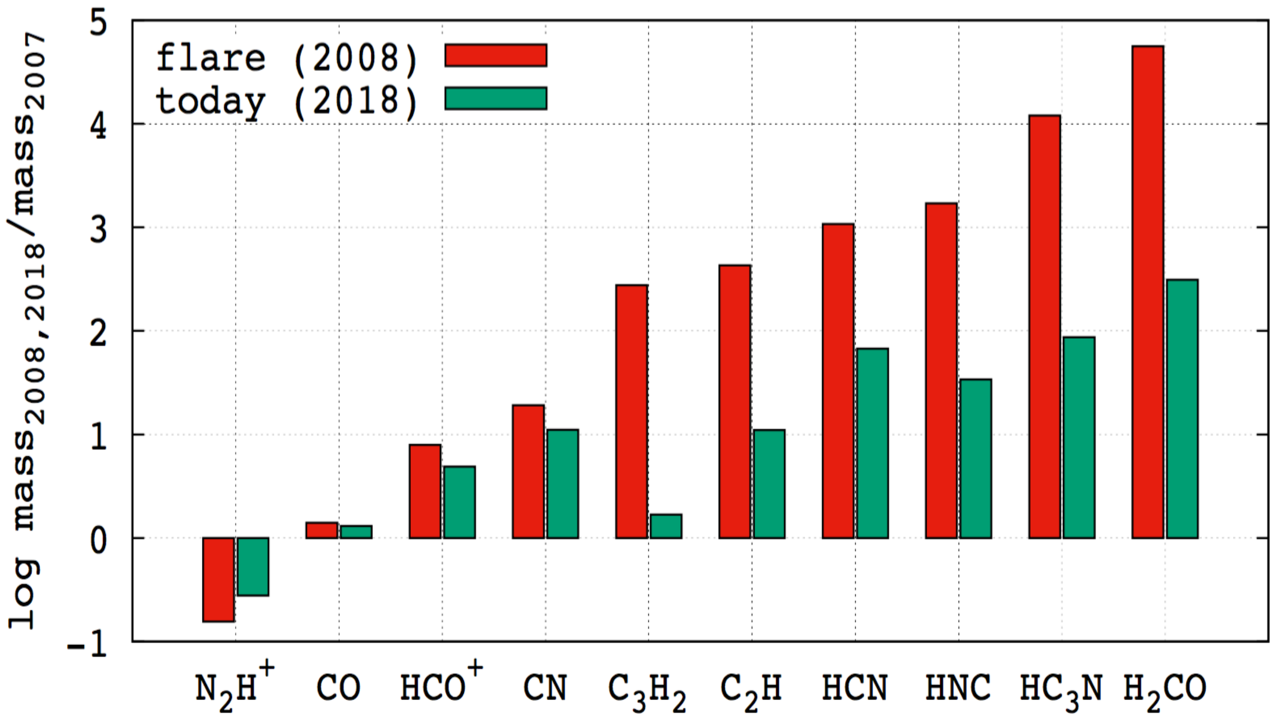
- **EX Lup**
- The previously amorphous 10 μm silicate feature became crystalline in early 2008
- Colder crystals appeared in late 2008
- Crystalline features disappeared by 2013

(Ábrahám et al. in prep.)

For gas lines ↔ accretion variability: talks by Marc Audard and Connor Robinson

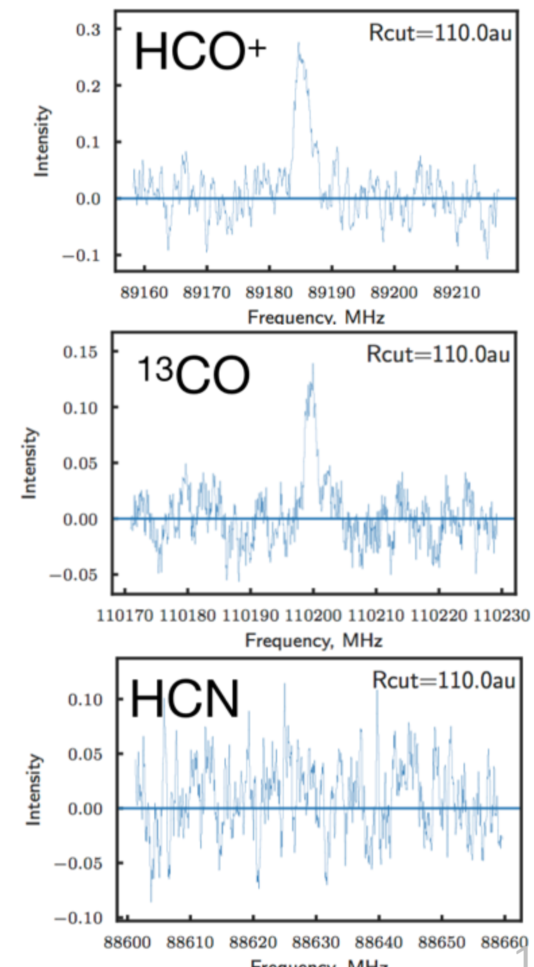
Chemical modeling for EX Lup

Expectation: many species may still have non-equilibrium abundances

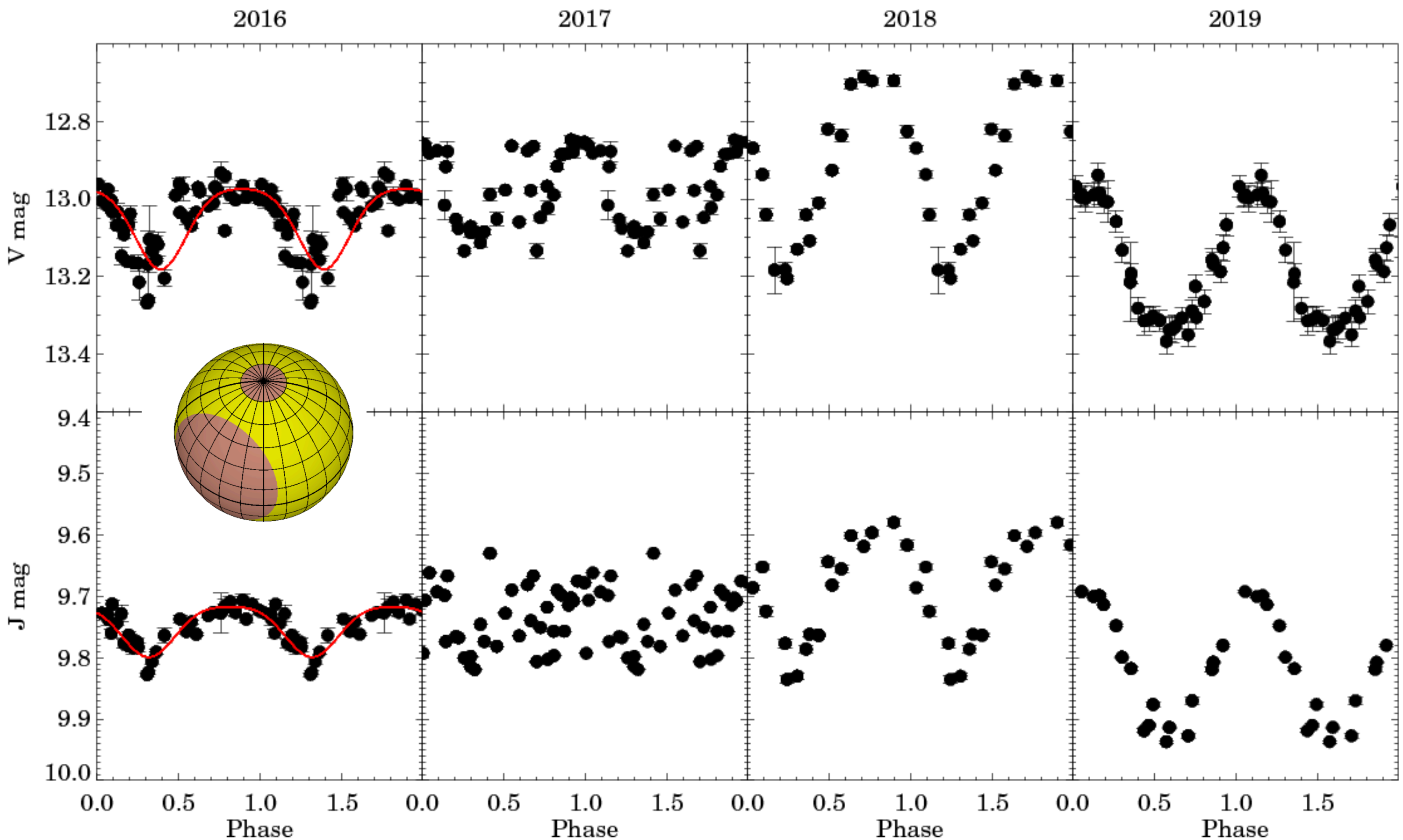


(Kóspál, Semenov, et al. in prep.)

ALMA



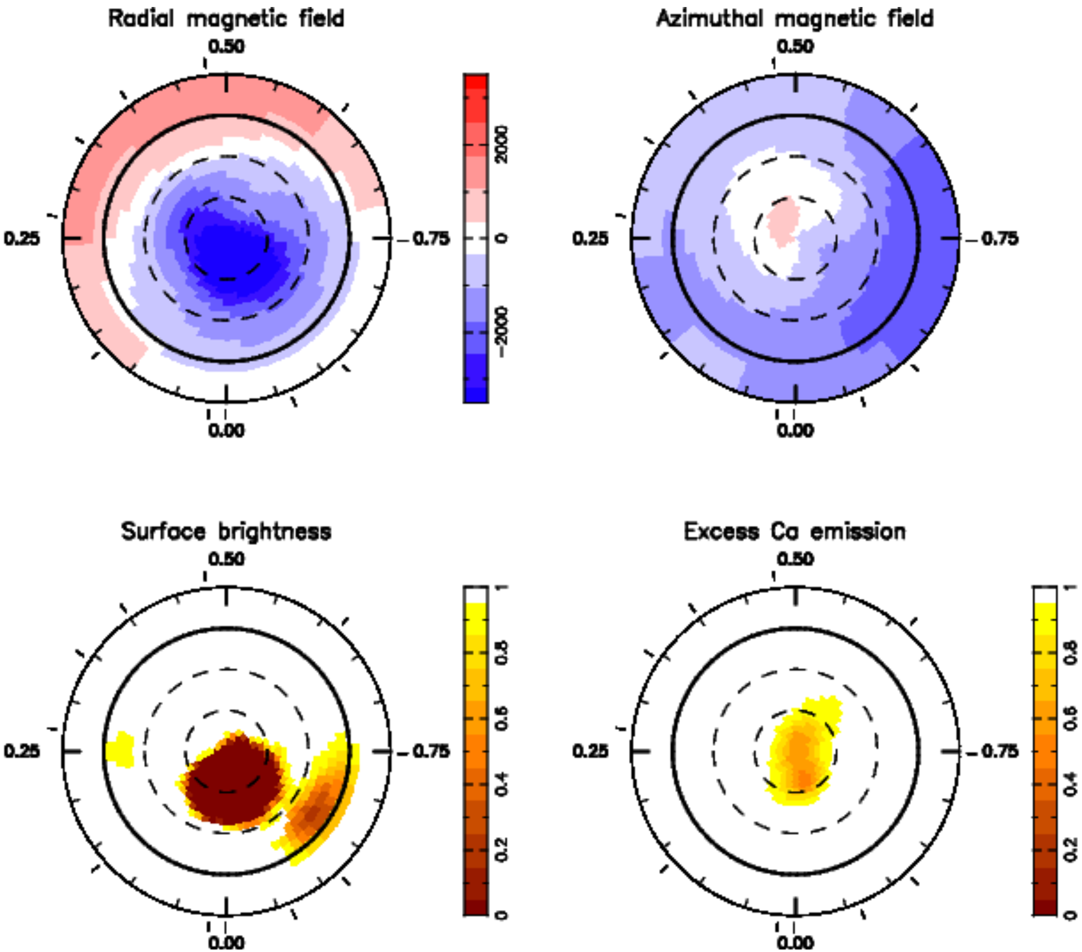
Magnetic topology in EX Lup



When accretion is low, EX Lup is a regular spotted star, but spot coverage changes from year to year

(Kóspál, Donati, et al. in prep.)

Magnetic topology in EX Lup



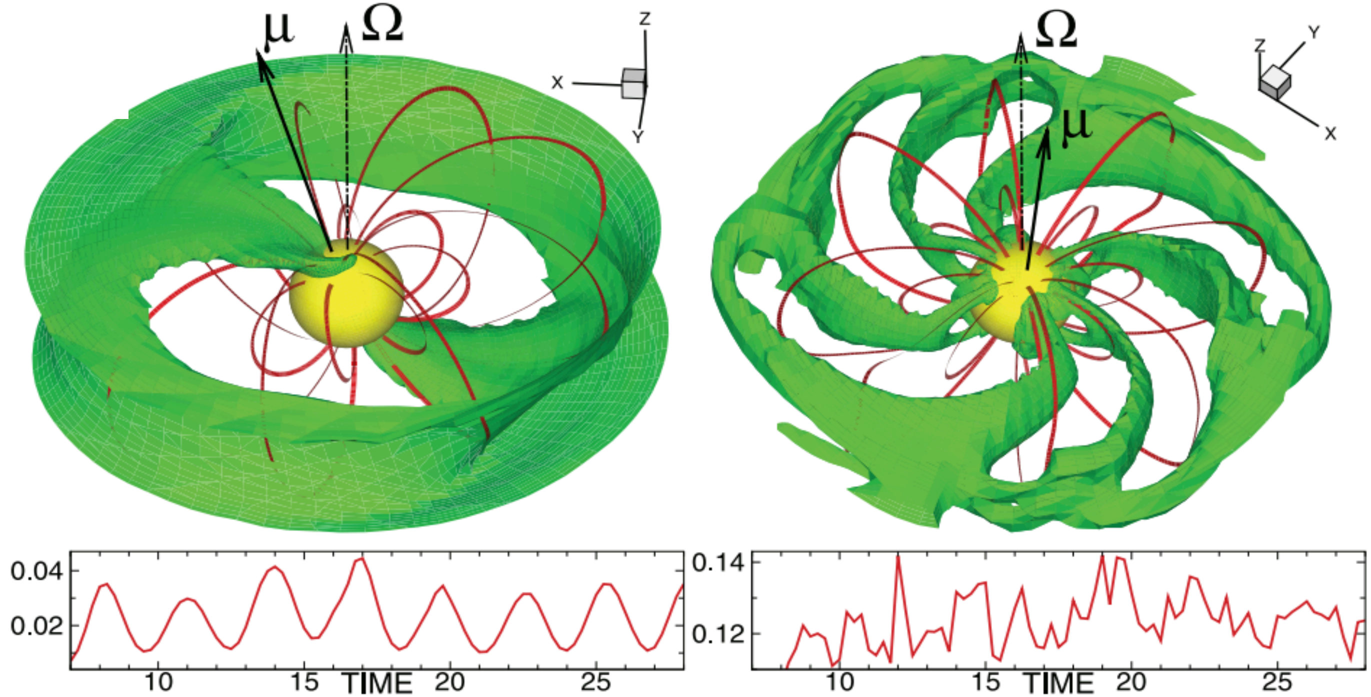
CFHT/ESPaDOnS spectropolarimetric observations revealed strong (3 kG) dipole magnetic field

(Kóspál, Donati, et al. in prep.)

Models of magnetospheric accretion

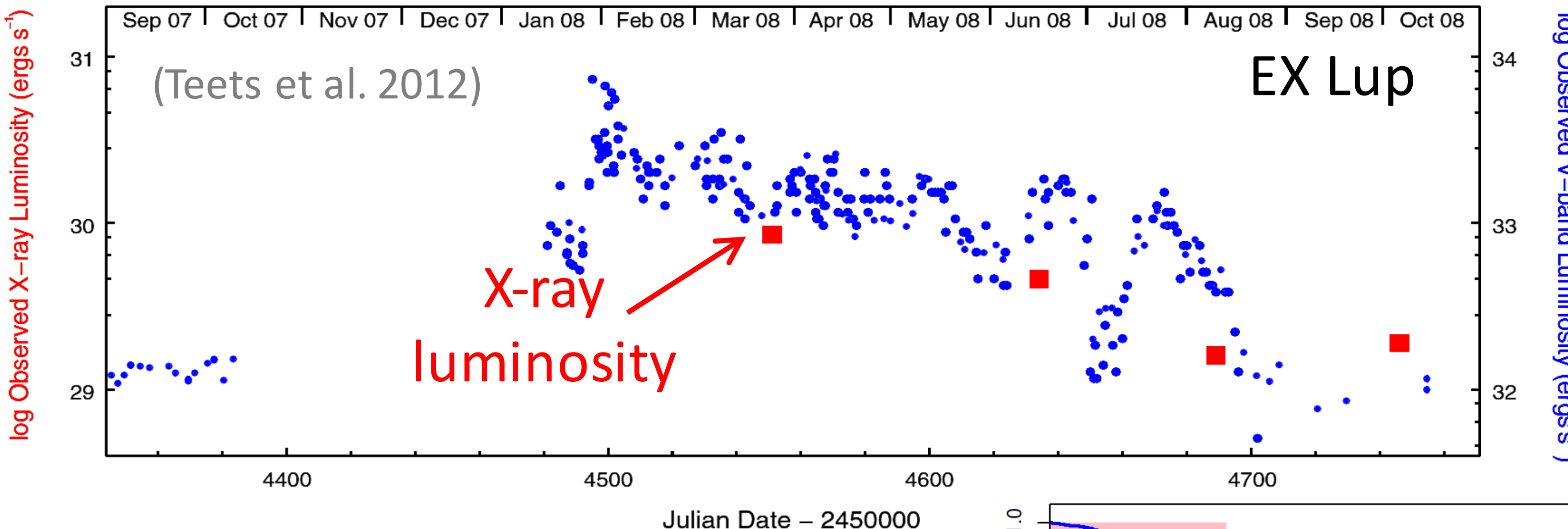
3D MHD models from Romanova, Kulkarni & Lovelace (2008)

Stable accretion | Unstable accretion

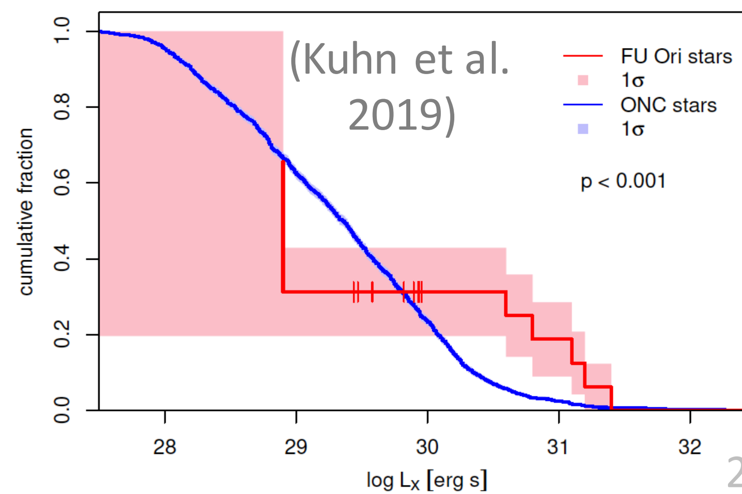


Periodic light curve | Stochastic light curve

X-ray variability of young eruptive stars



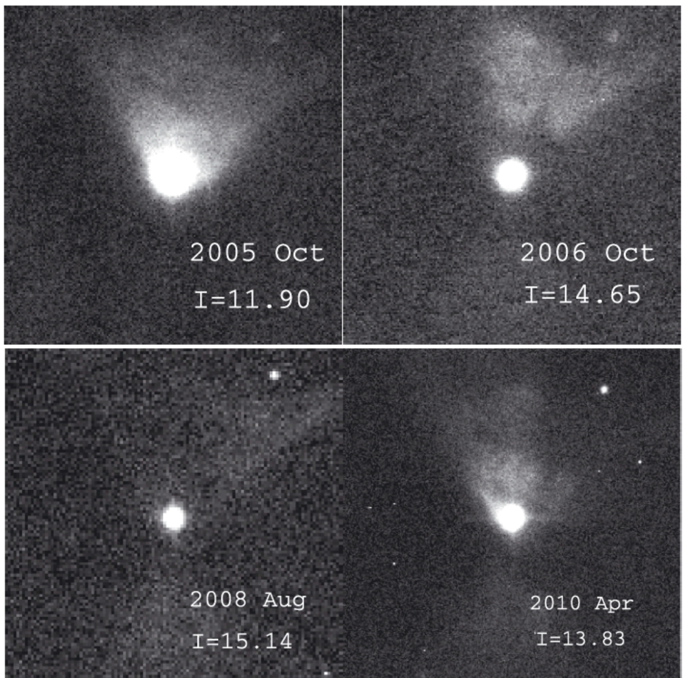
- Appearance of accretion-generated X-ray plasma during the outburst of EX Lup
- Statistically speaking, FUors are typically brighter in X-ray than quiescent YSOs



Morphological changes

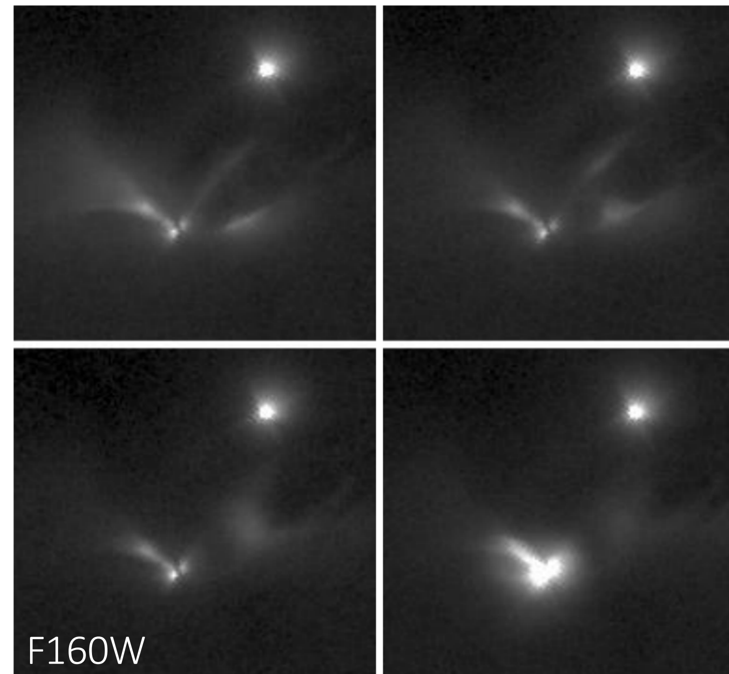
PV Cep: inner disk rearrangements revealed by dramatic brightness and morphological changes

(Kun et al. 2011)

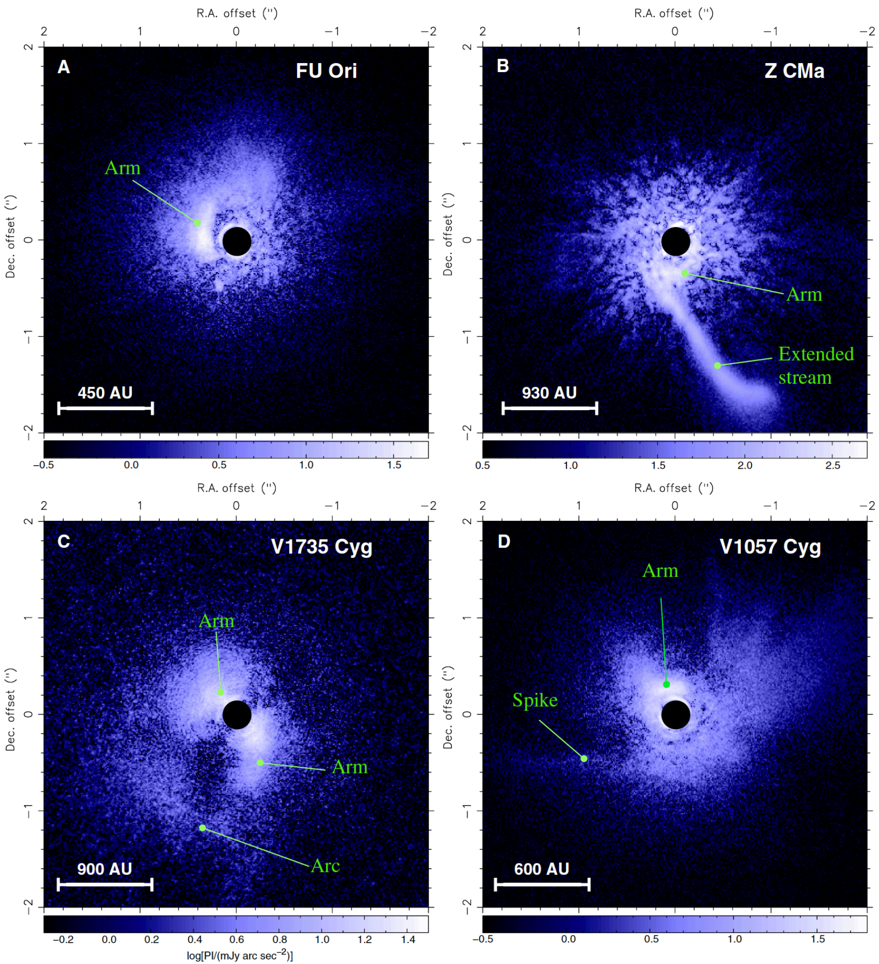


LRLL 54361: pulsed accretion in a variable protostar in IC 348, light echo seen in the scattered light

(Muzerolle et al. 2013)



Complicated morphologies

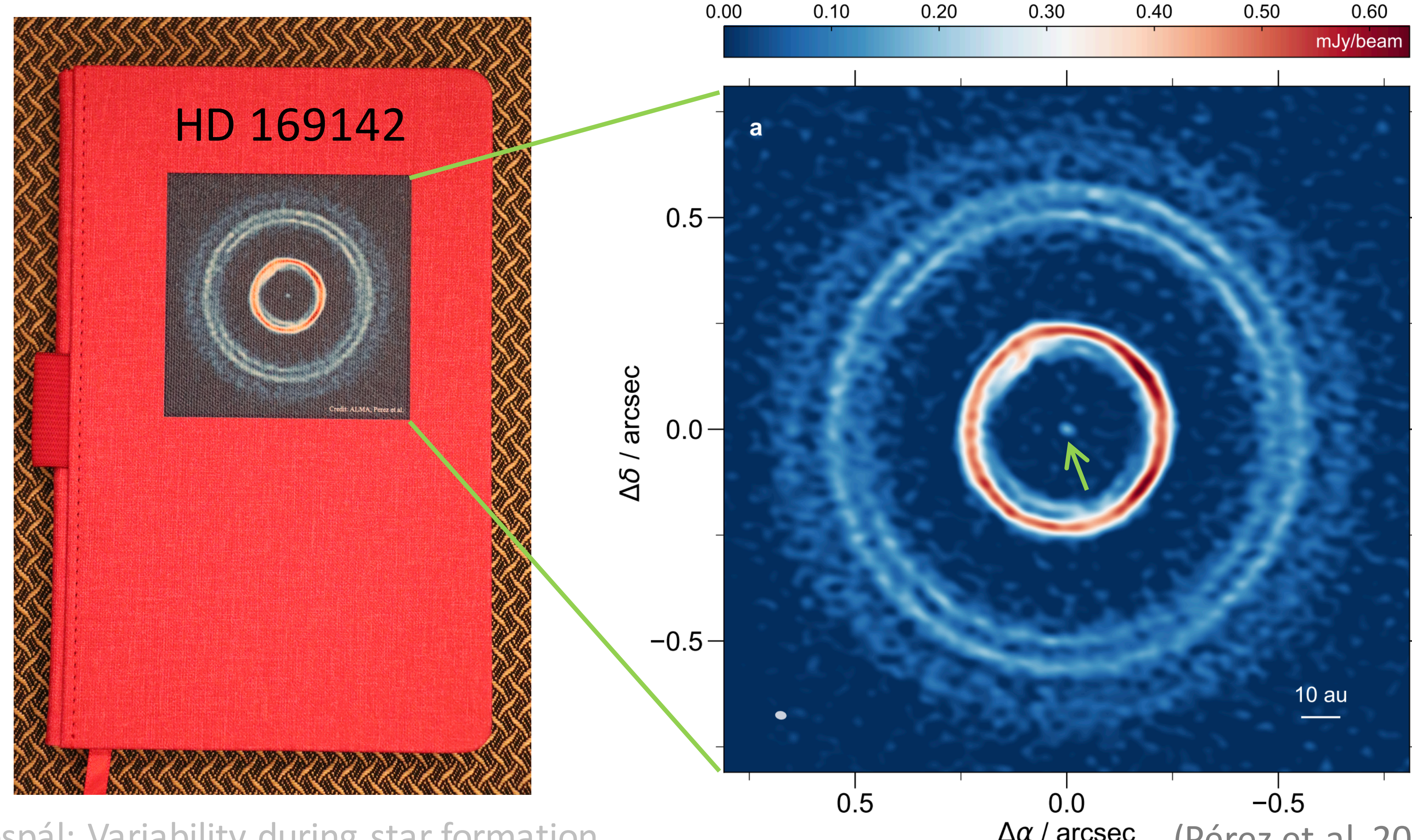


- Subaru/HiCIAO H-band observations of the scattered light around FUors
- Possible causes:
  - gravitational instability?
  - past stellar fly-bys?

talk by Nicolás Cuello

(Liu et al. 2016, Takami et al. 2018)

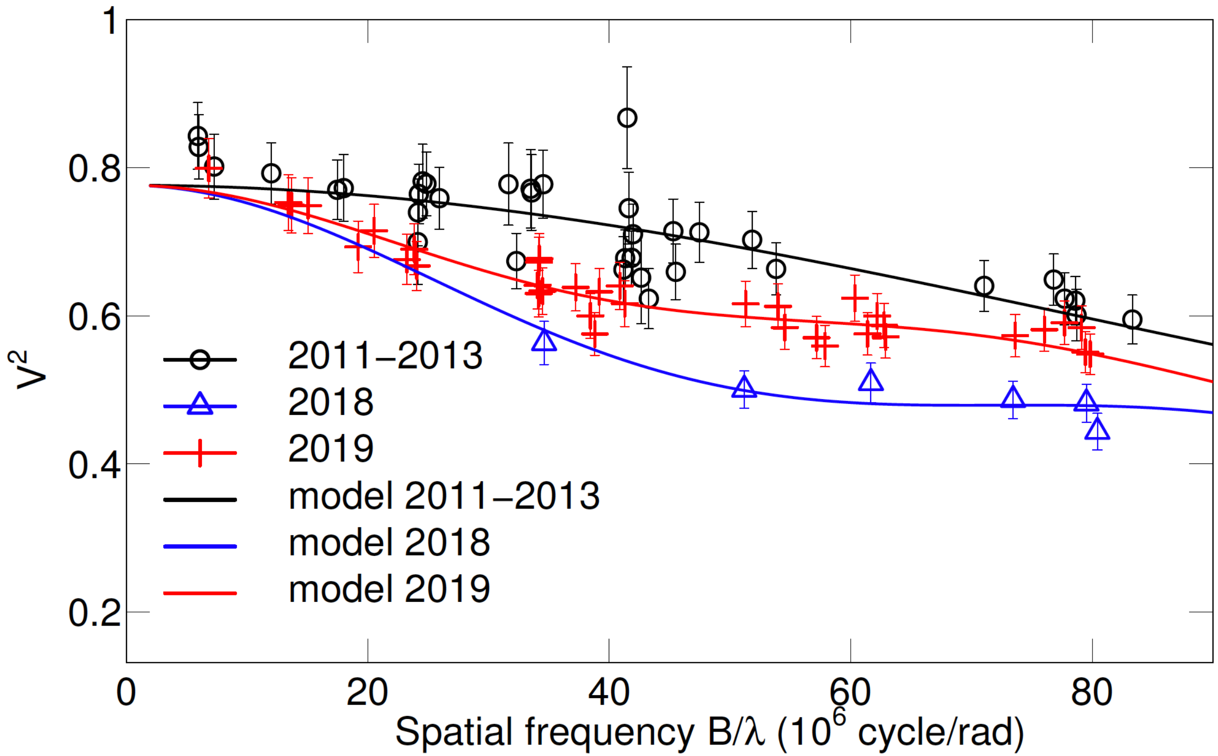
Changing dust distribution

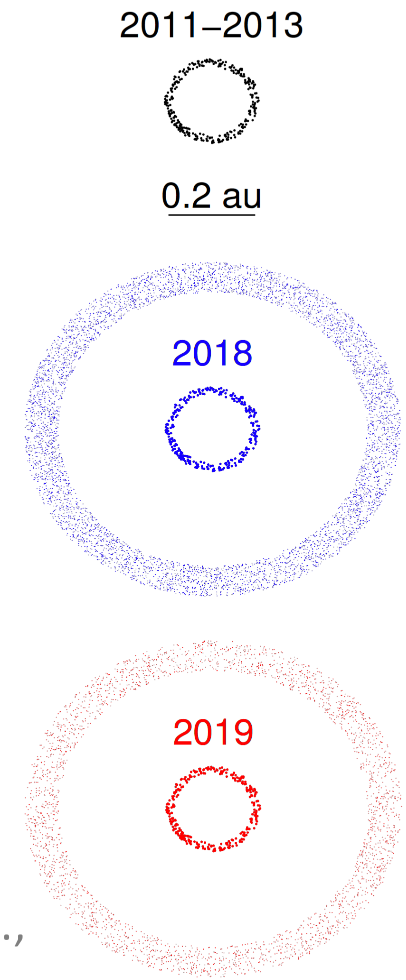


(Pérez et al. 2019)

Changing dust distribution

VLTI/PIONIER observations of the disk of the Herbig star HD 169142 (*H* band, 1.65 μm)



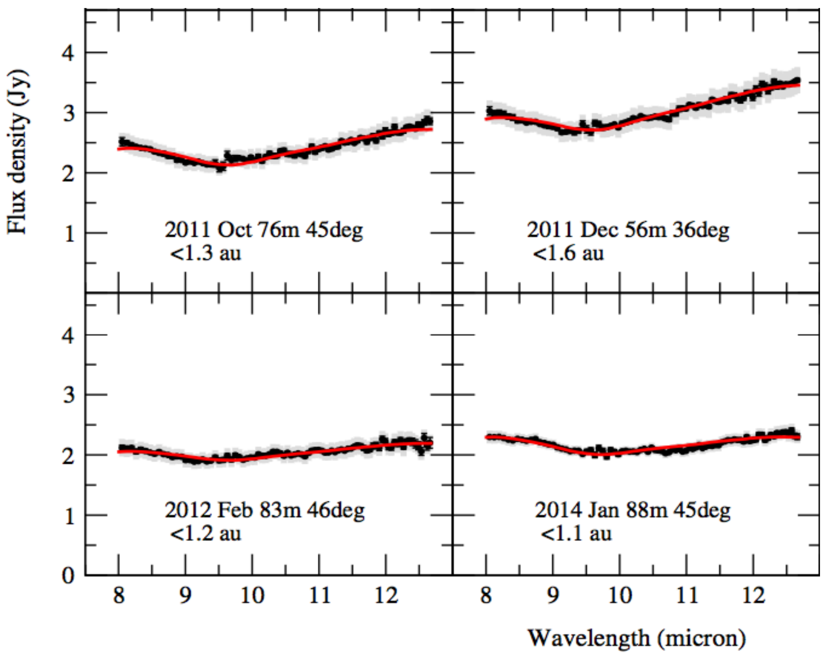


(Chen et al. 2018, in prep., Wagner et al. 2015)

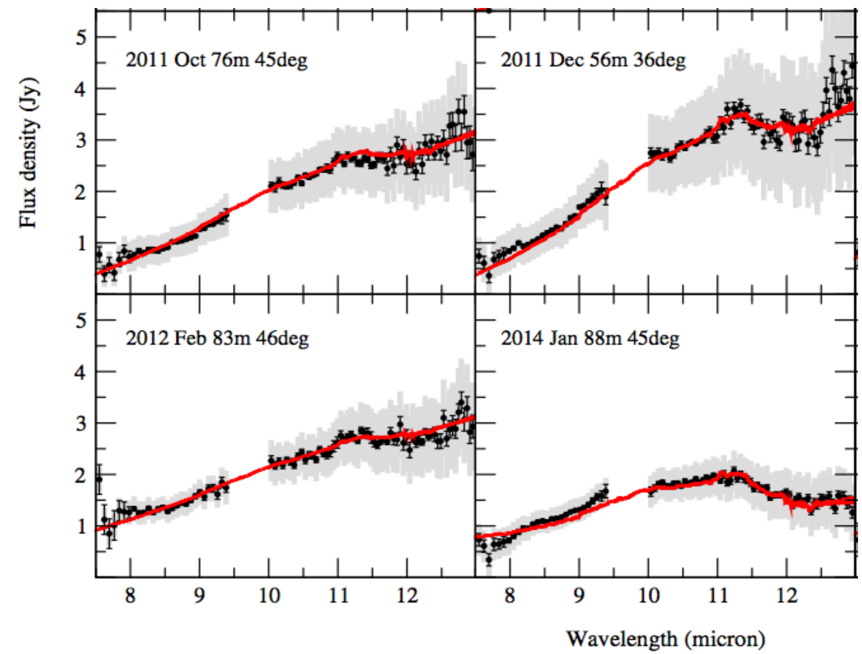
The curious case of DG Tau

VLTI/MIDI observations in the *N* band, 8 – 13 µm

Absorption in the inner disk (within few au)



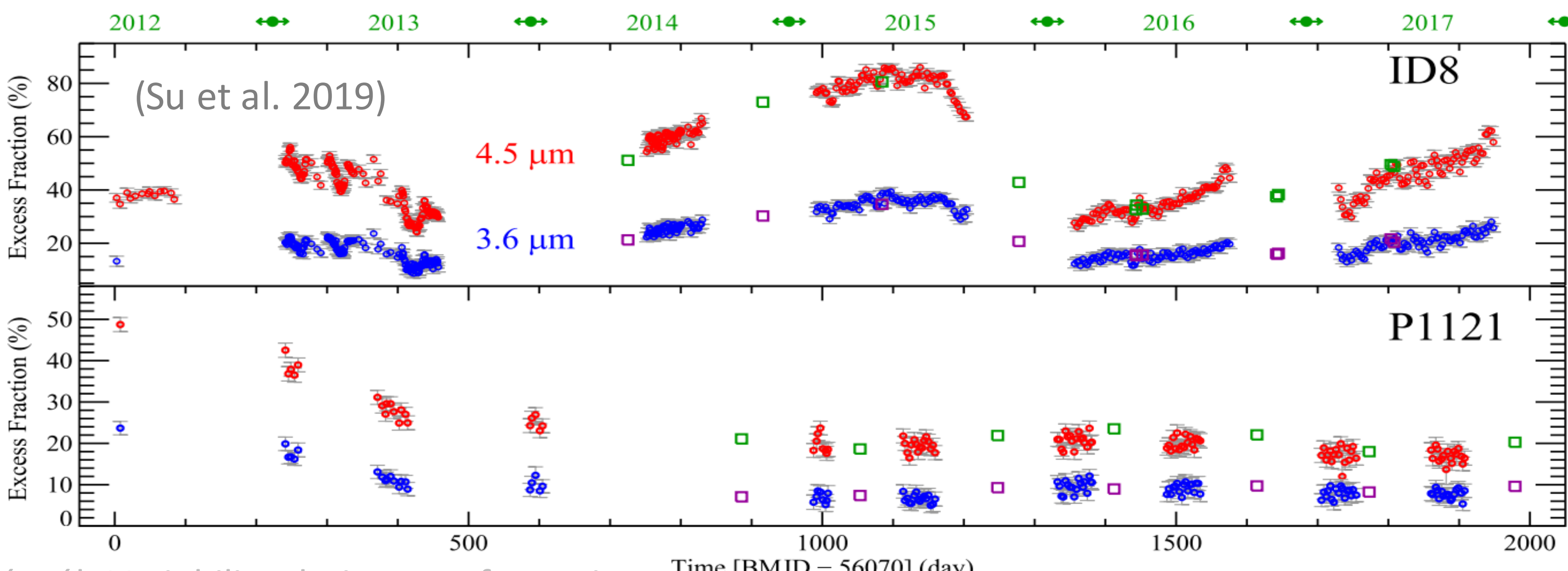
Variable crystalline silicate emission outside of a few au



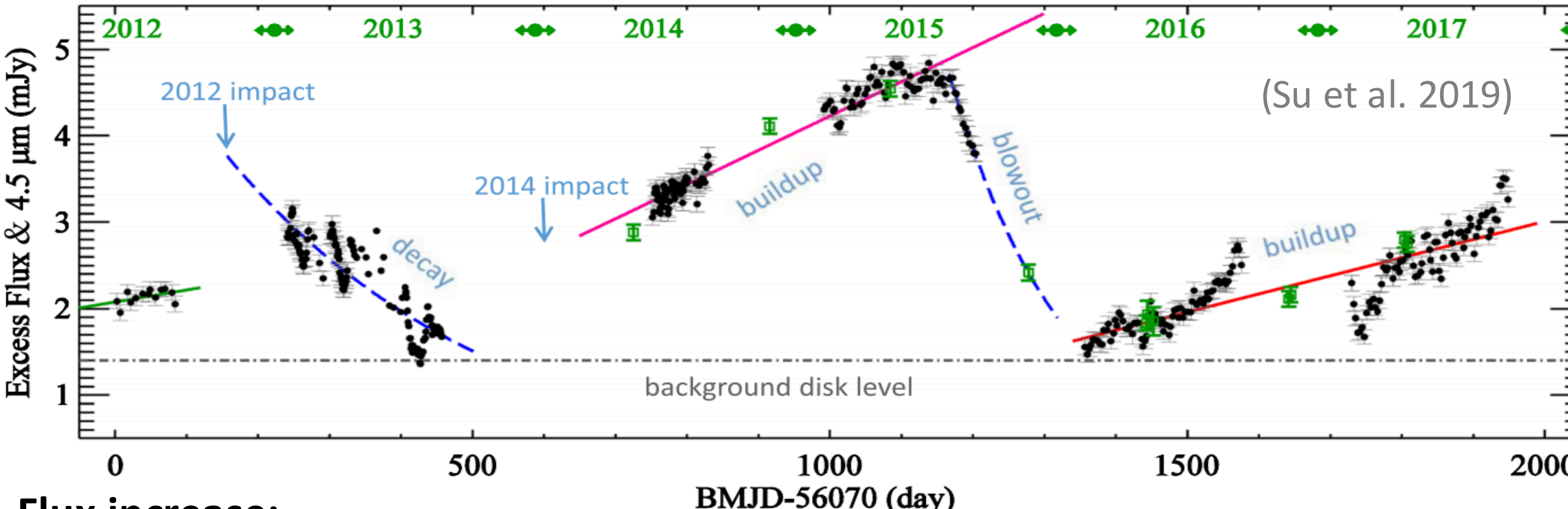
(Varga et al. 2017)

Extreme debris disks (EDDs)

- **Debris dust**: dust grains around main sequence stars have short lifetime, need to be continuously replenished by collisions between planetesimals
- Replenishment may not be continuous, we may be able to discern **individual collisions** through infrared variability



Interpretation of EDD variability



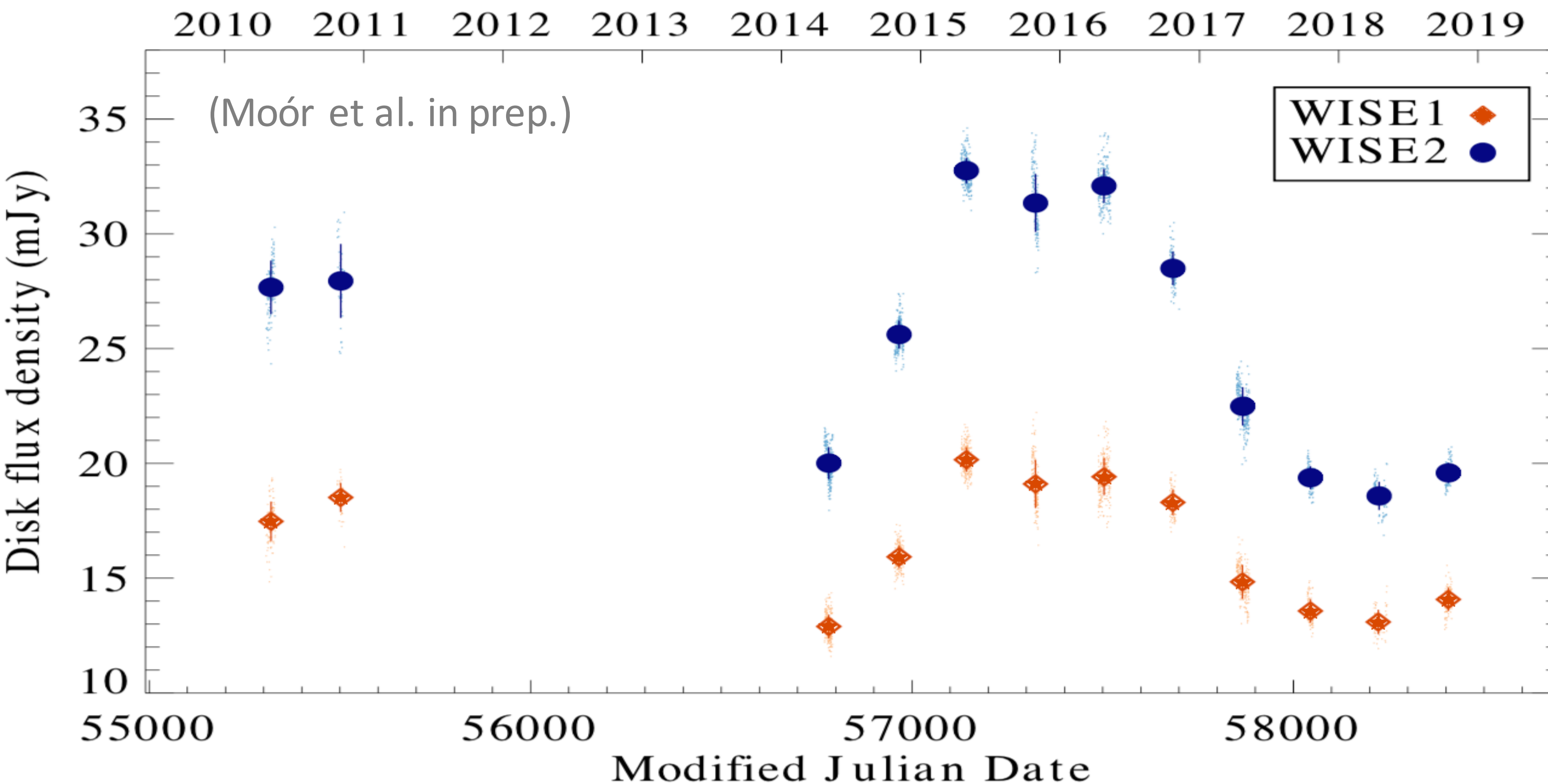
Flux increase:

- sudden production of fragments and vapor condensates due to a hyper-velocity impact between planetesimal-size bodies
- gradual build-up of debris due to collisional evolution

Flux decrease:

- rapid evolution of vapor condensates (collisional destruction of grains)
- rapid loss of grains due to radiation pressure (blowout)

More discoveries to be published



- The NEOWISE Reactivation is a treasure trove for finding these events

Take-away messages

- **Variability is a powerful tool, a 4th dimension to study disks around young stars**
- **It reveals otherwise unattainable information about the circumstellar matter**
- **If you ignore it, you are probably making a mistake**