Time Domain Surveys and Young Stars

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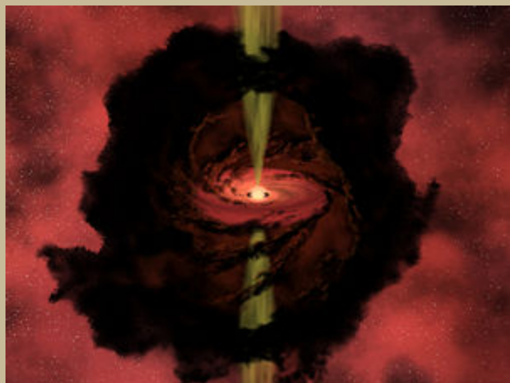
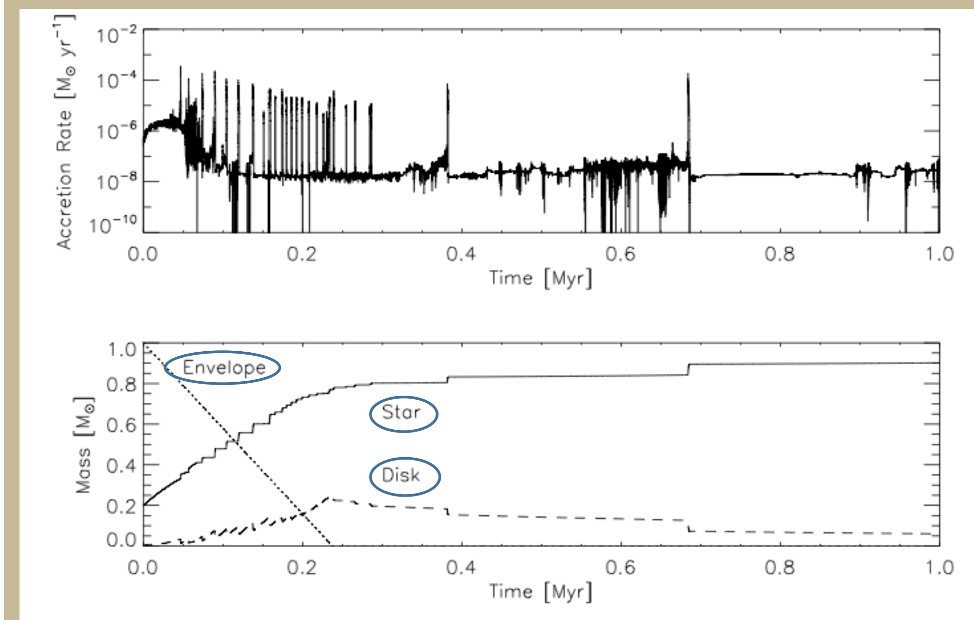
Caltech

Not Only Stars, but Planets being Born “Today”

Disk Formation, Accretion, Evolution

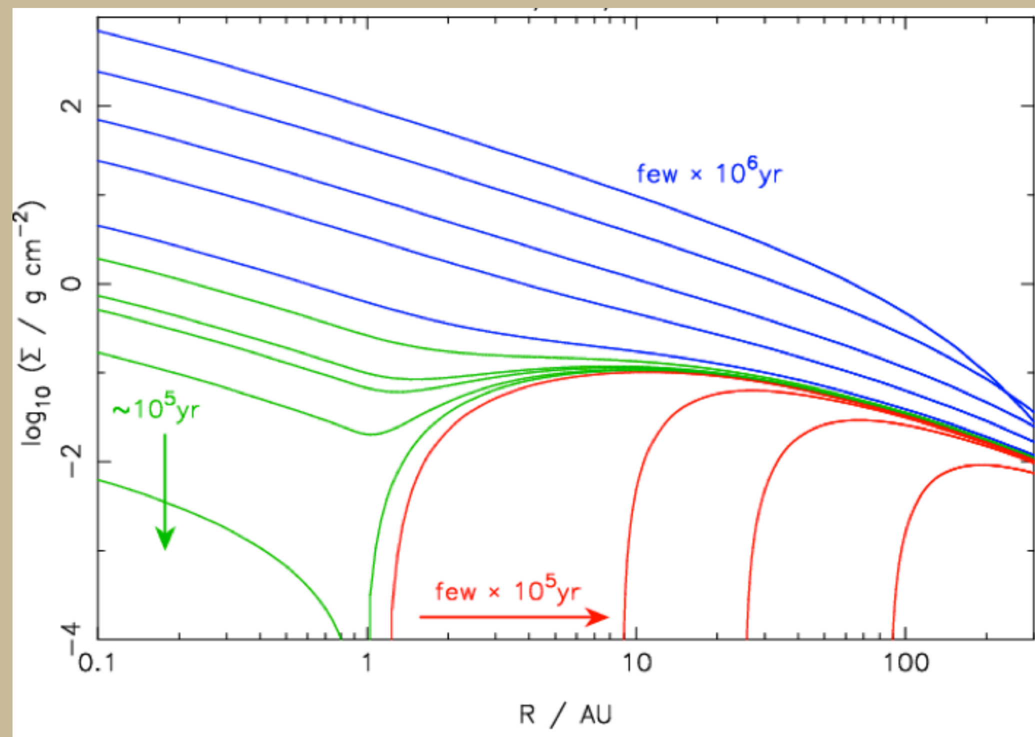


early accretion
(and outflow)



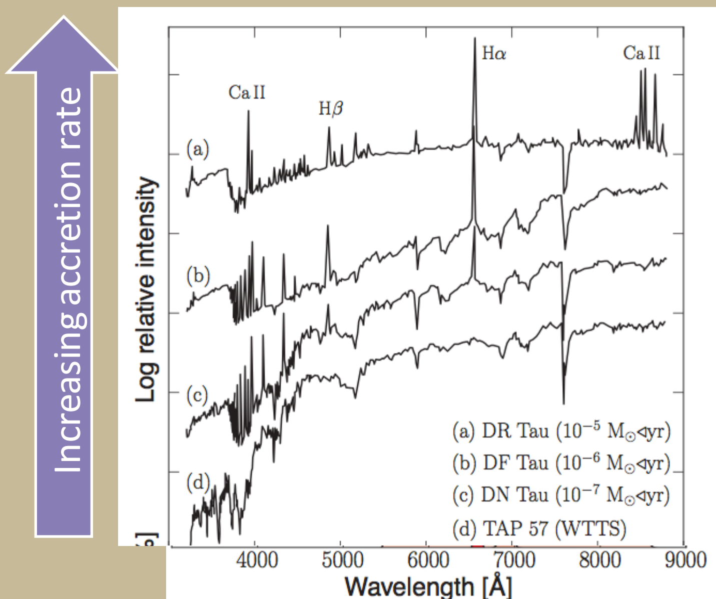
Bae et al. (2014)

later, viscous evolution and photo-evaporation

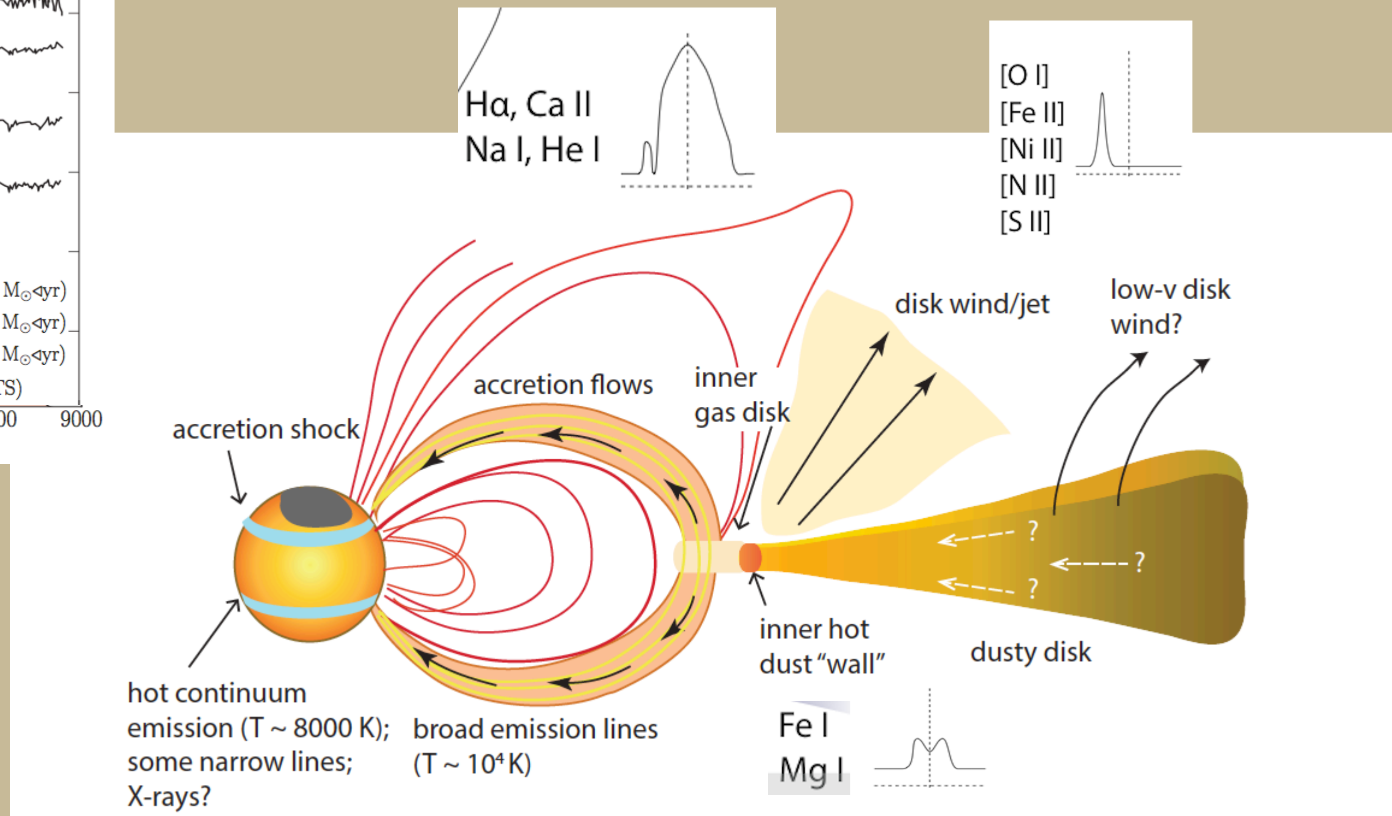


Alexander (2014)

Magnetospheric Accretion



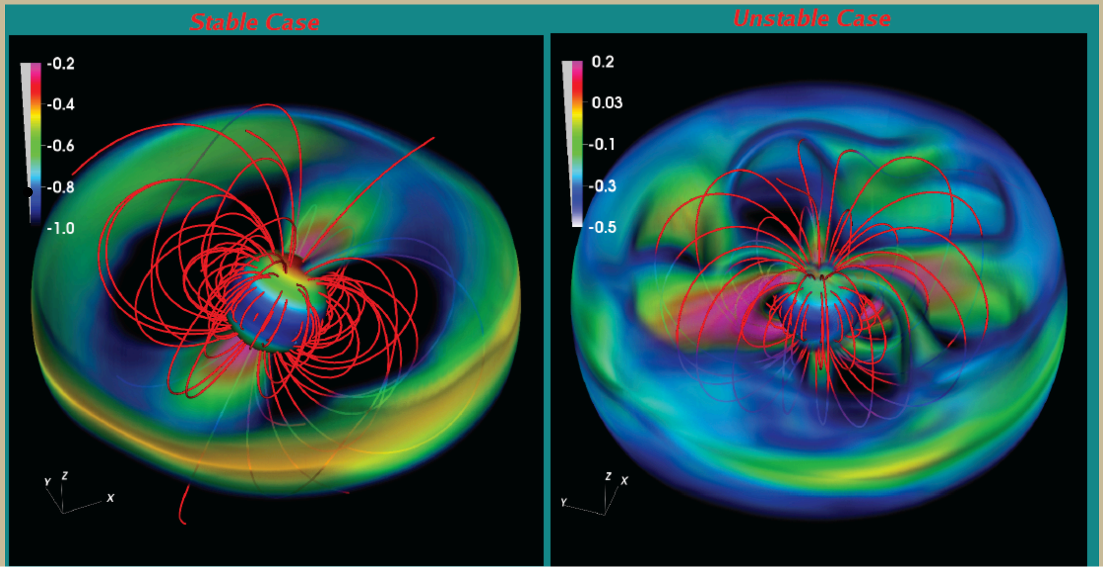
Barensten et al. 2013



Hartmann, Herczeg, Calvet 2016

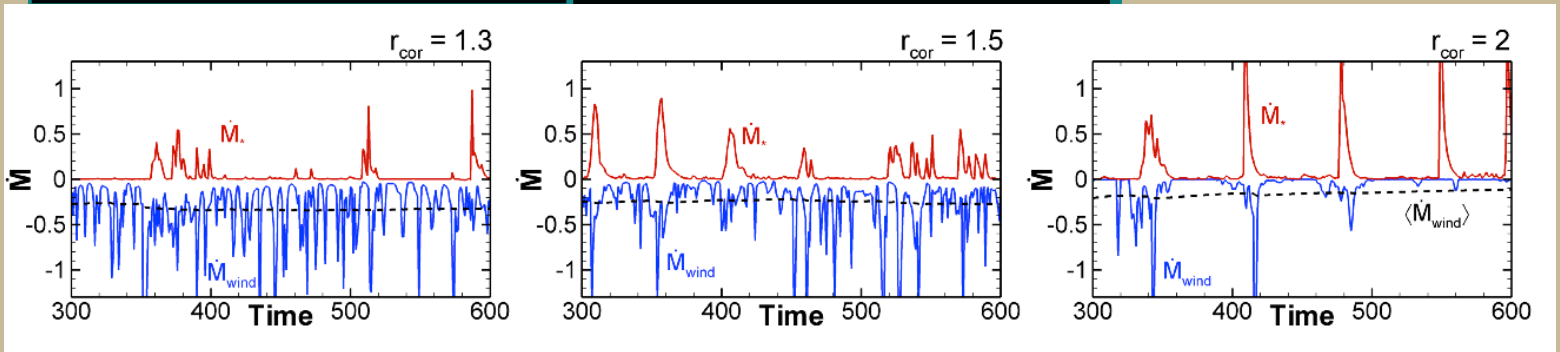
Innermost disk regions, r < 0.05 AU

- Dynamical time at the co-rotation radius ~1 week
- Infall time along magnetic field lines ~hours

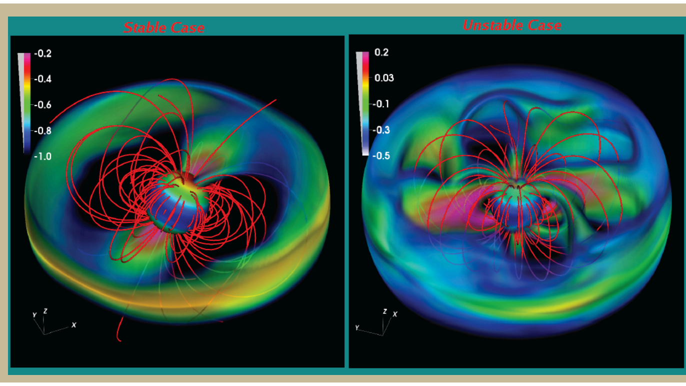


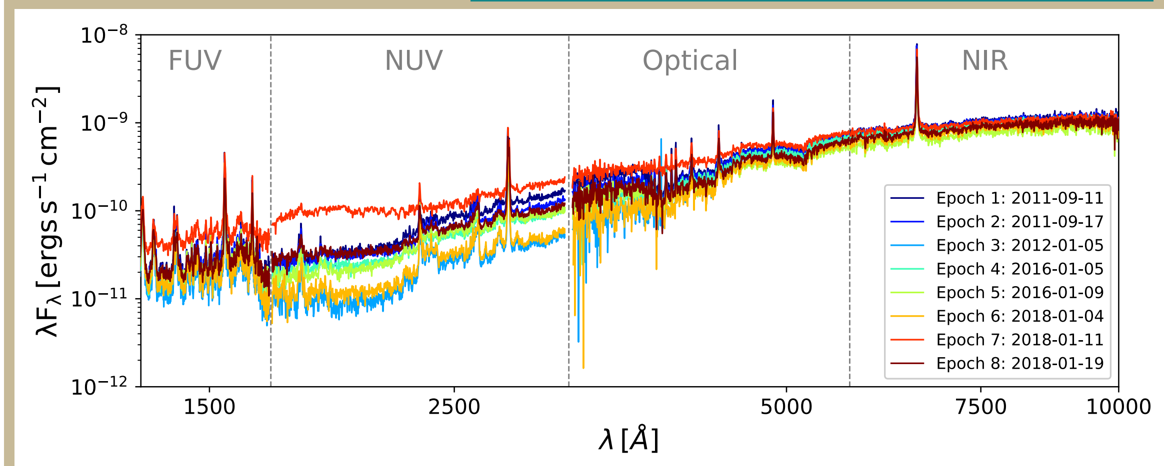
both accretion and ejection of material

Kurosawa, Romanova



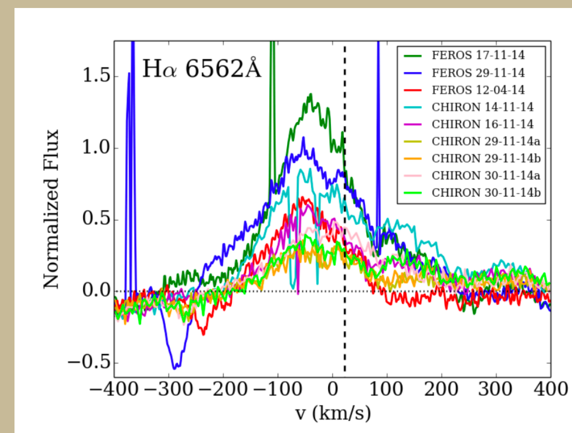
VARIABLE CONTINUUM

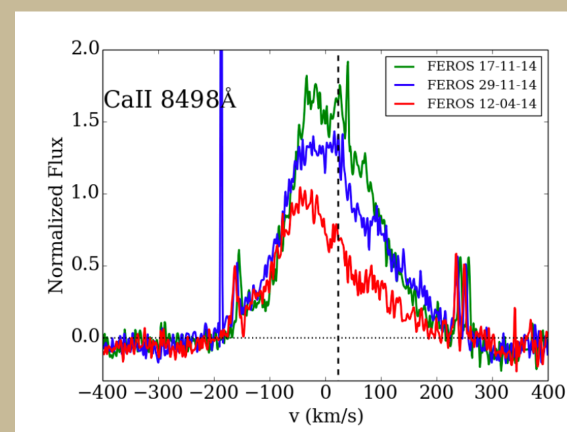




[Robinson et al. 2019]

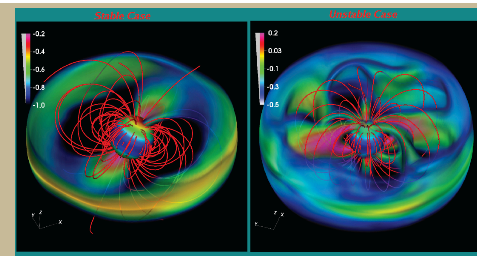
VARIABLE LINE PROFILES



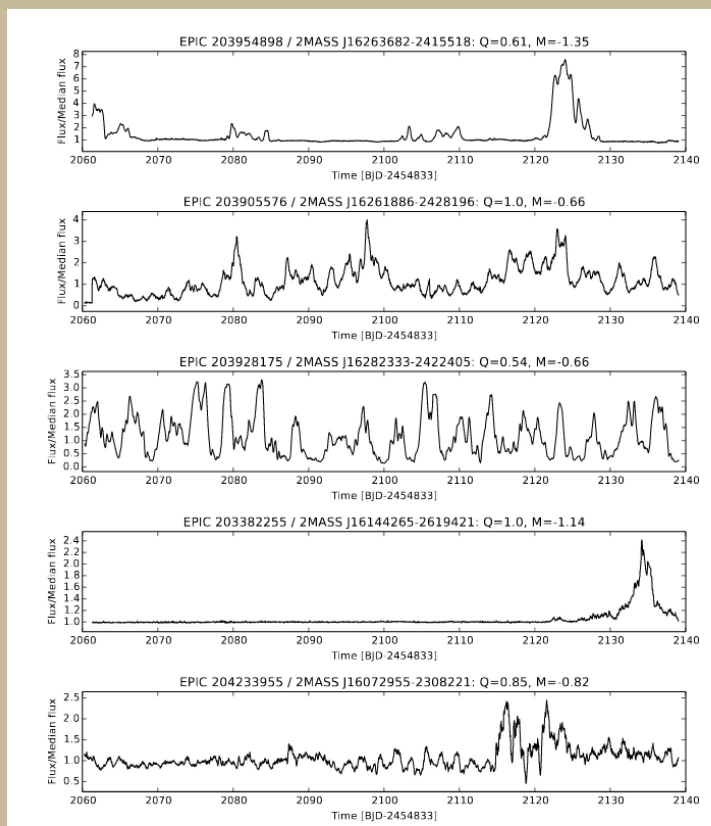


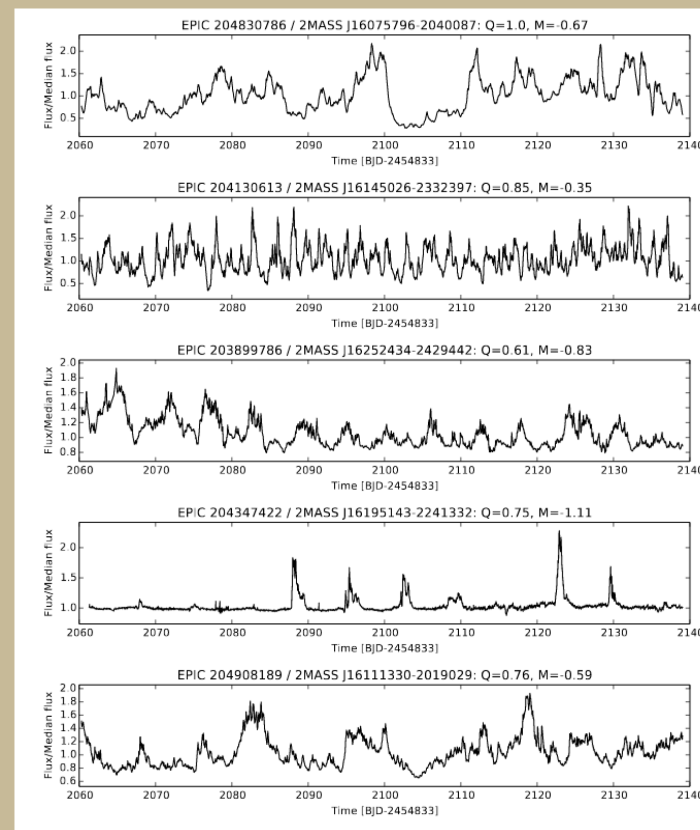
[Sicilia-Aguilar et al. 2017]

VARIABLE BROAD-BAND PHOTOMETRY: ACCRETION-DRIVEN BEHAVIOR



[Cody et al. 2017]





14% of the objects with disks exhibit with these types of lightcurves

A Range of Observing Strategies is Needed

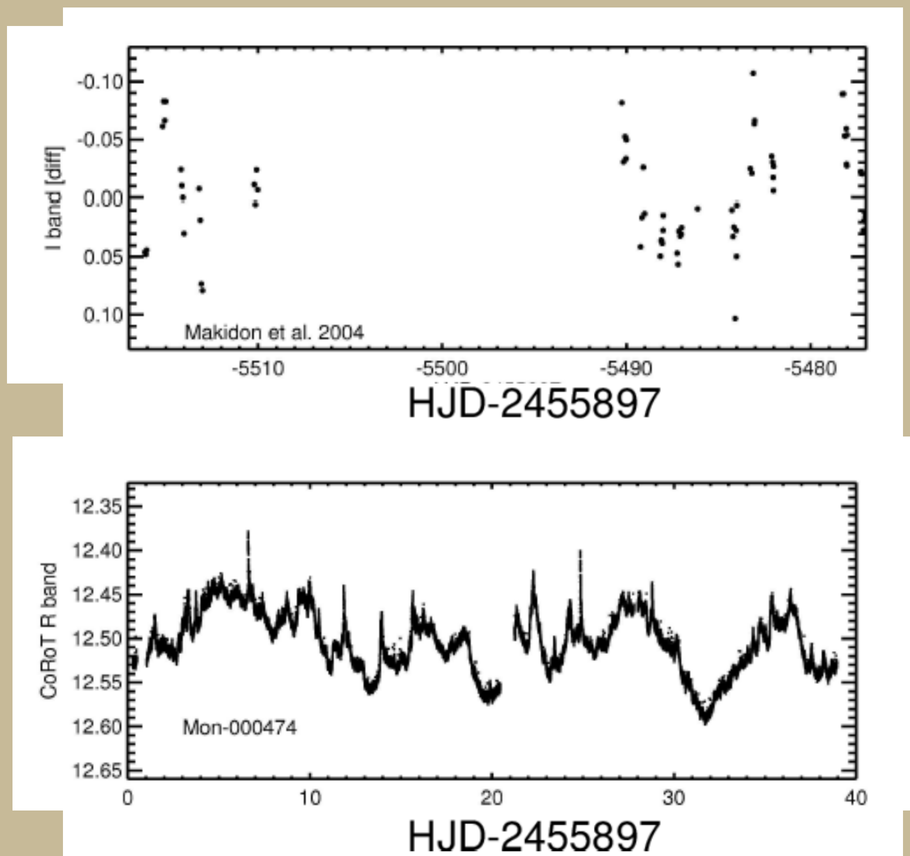
CoRoT + K2

PTF/ZTF + Gaia

Spitzer + NEOWISE

- High precision
  - Underlying stellar processes e.g. pulsations, spots, rotation
  - Details of accretion-driven and extinction-driven behavior
- High cadence
  - Resolve the time scales for accretion and/or inner disk geometry changes
- Long duration (can be lower precision)
  - Probe more dramatic accretion and disk morphology history
- Multiwavelength
  - Importance of dust extinction vs gas accretion processes
  - Importance of radiative vs dynamic processes

The Quality of Modern Data is Outstanding !



. Ground (top) vs. space time series (bottom)

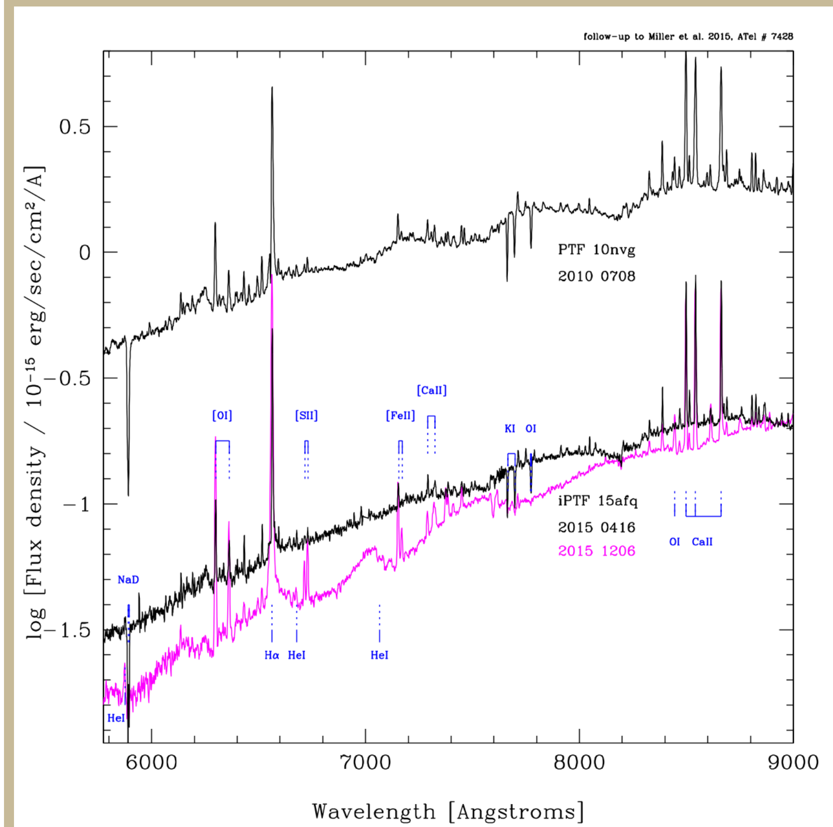
Ten to Fifteen years ago:

- ground-based
- precision-limited
- cadence-limited
- many gaps

Today:

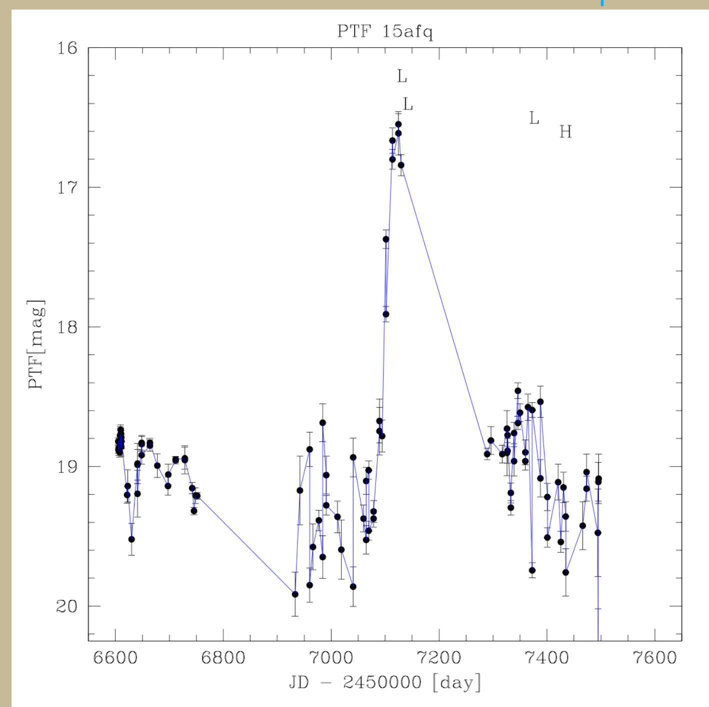
- space-based
- exquisite precision
- excellent cadence
- acceptable gaps

A LARGE SHORT-LIVED ACCRETION BURST



Increase in disk accretion rate caused ~3 mag brightening for several months accompanied by enhanced spectral veiling and TiO emission.

PTF 15afq



Miller et al. (2015)

A Somewhat Larger, Somewhat Longer-Lived, But Still Temporary Burst

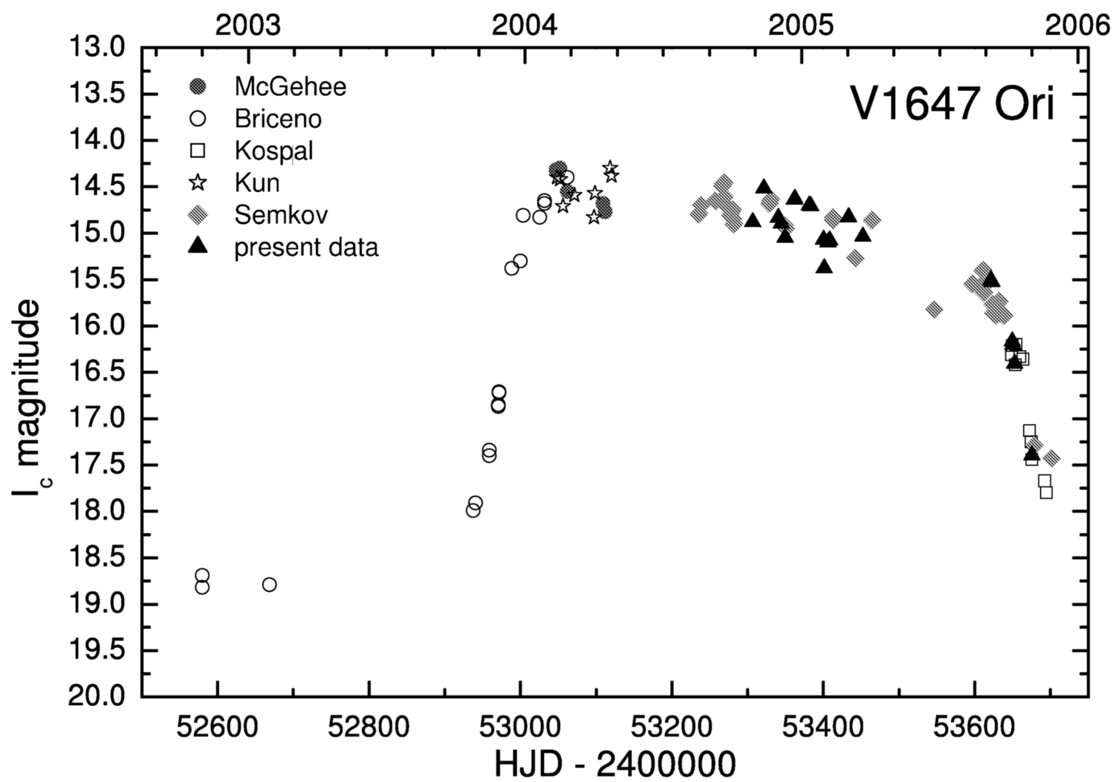


Figure 4. V1647 Ori light curve in the I_C passband. Our data and data from McGehee et al. (2004), Briceño et al. (2004), Kóspál et al. (2005), Kun et al. (2004) and Semkov (2004, 2006) were used.

Innermost Disk Instabilities

magnetospheric instability e.g. Goodson & Winglee (1999)

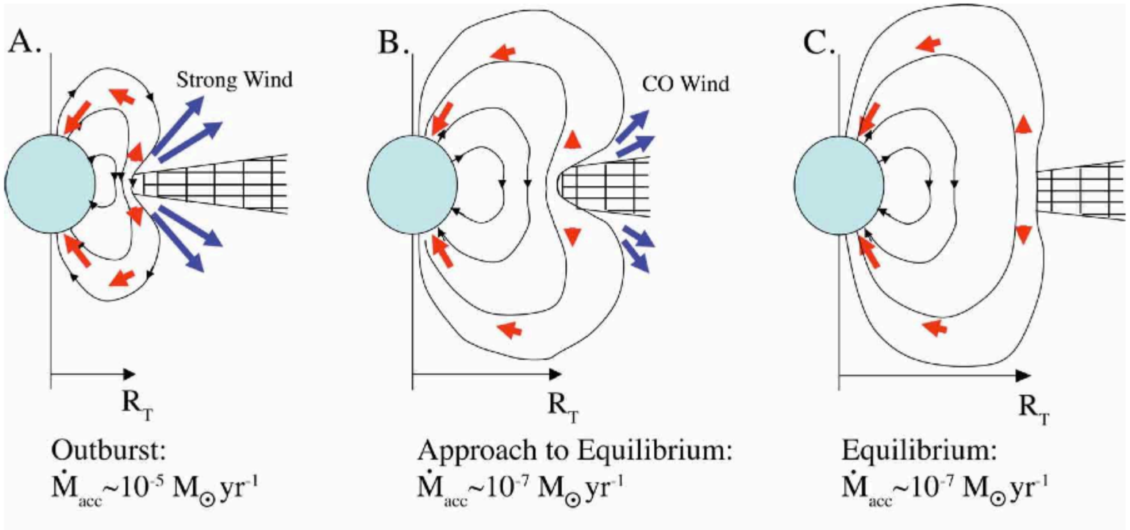
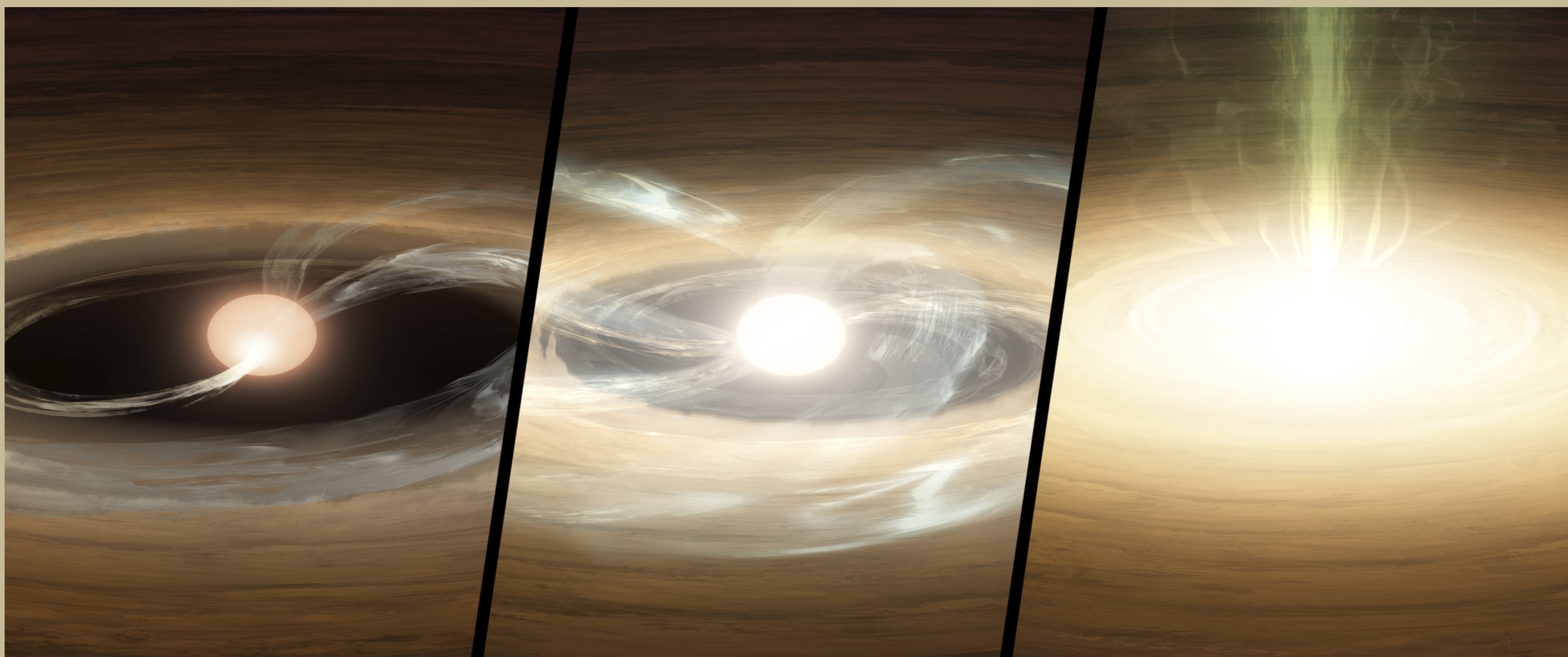


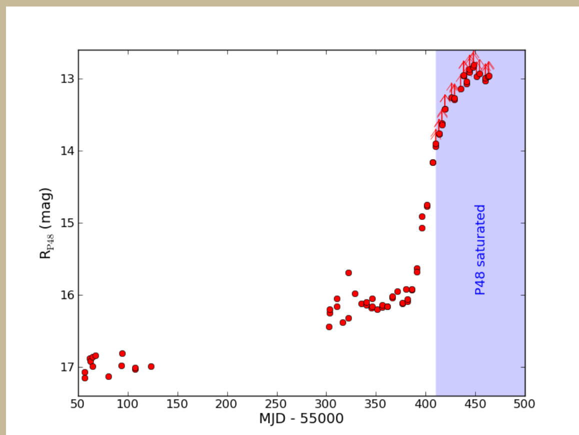
Fig. 6 Schematic model of an Exor V1647 Ori. During the outburst the accretion rate is enhanced so that the magnetospheric radius R_m decreases and the magnetic field lines were bunched (A). This results in a fast, hot outflow. As the accretion rate decreases, the disk moves outward and this results in a slower, cooler CO outflow (B). Further decrease in the accretion rate leads to a quiescence state where the production of warm outflows stops (C). From Brittain et al. (2007).

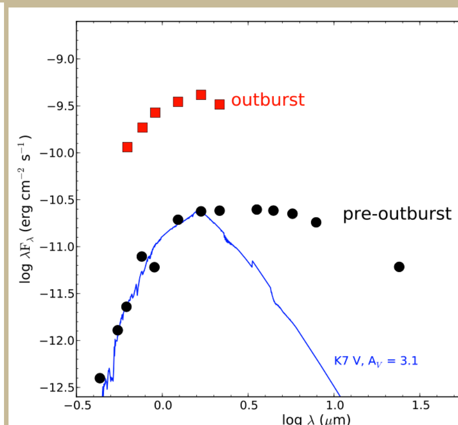
Extreme Outbursts = FU Ori Stars



Witnessing an FU Ori Outburst (PTF)

Miller et al. (2011)





PTF10qpf

=

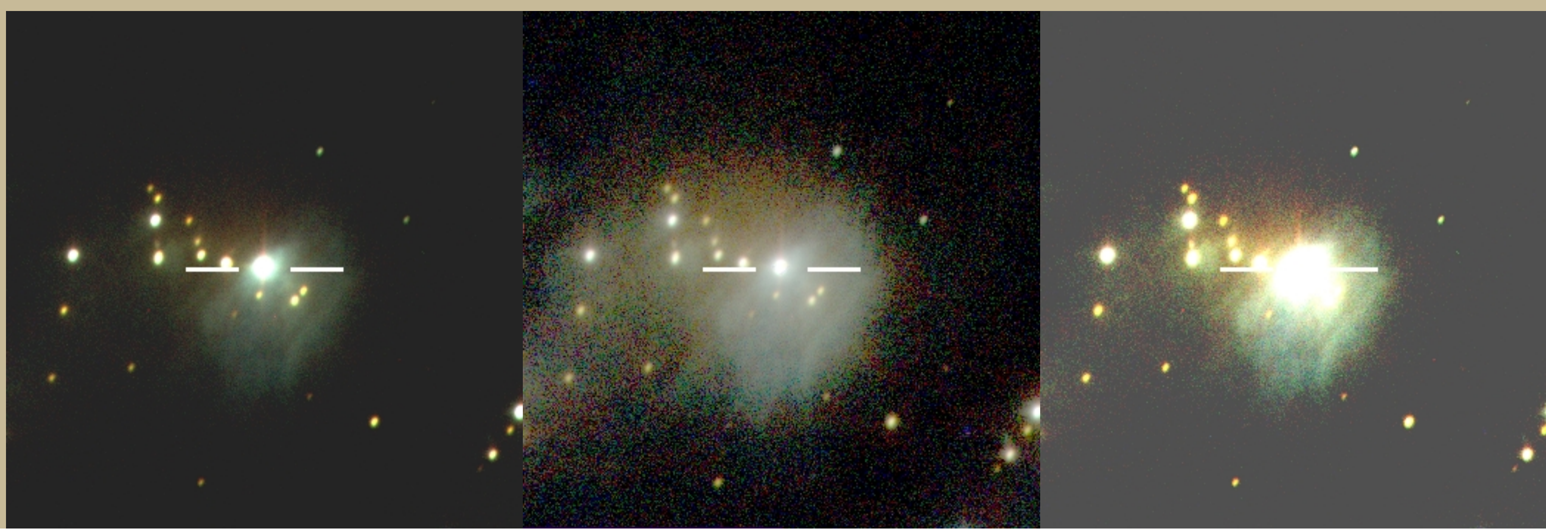
LkHa 188/G4

=

HBC 722

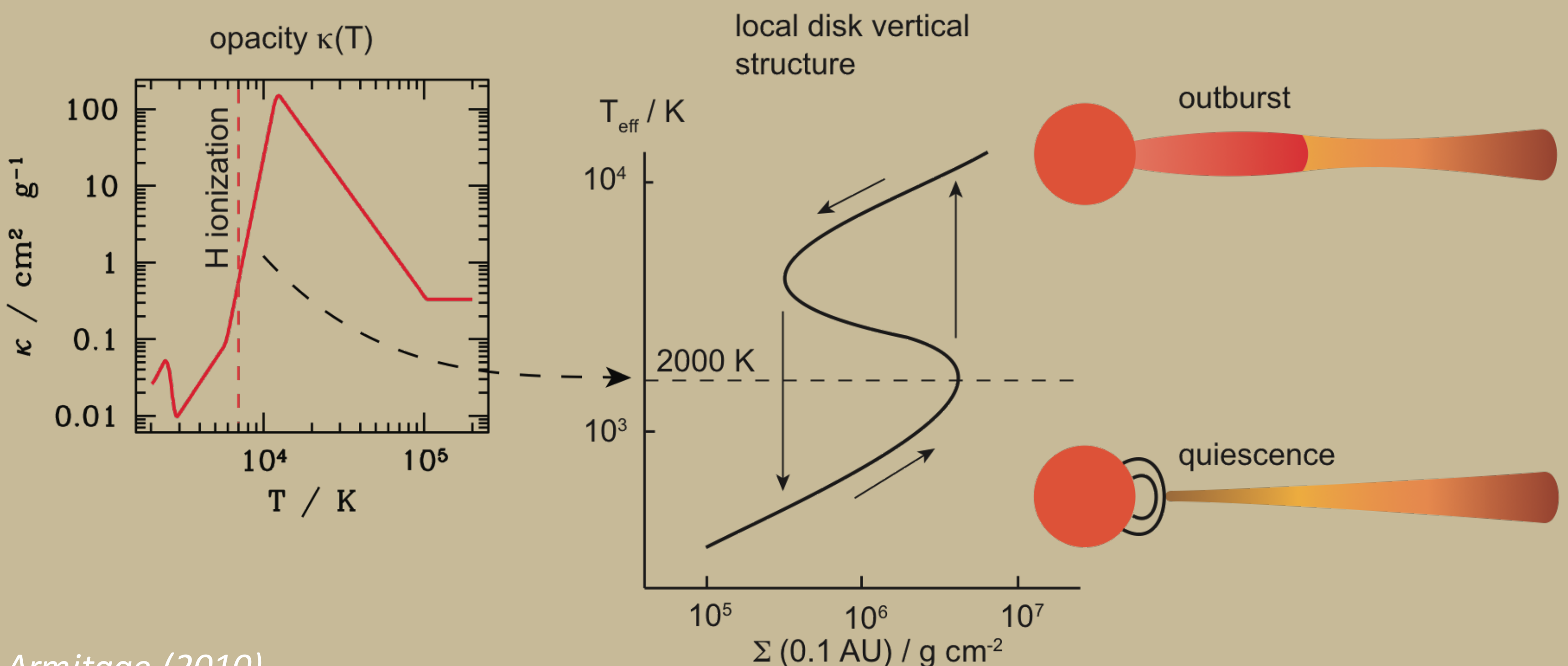
=

V 2493 Cyg



Broader Disk Instabilities

classical thermal instability driven by change in kappa e.g. Bell & Lin (1994)

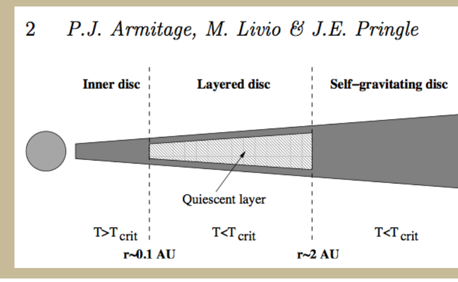


Armitage (2010)

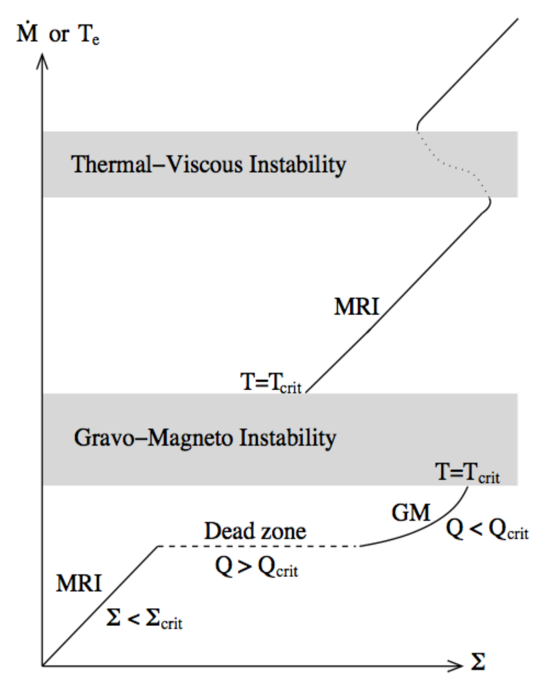
Broader Disk Instabilities

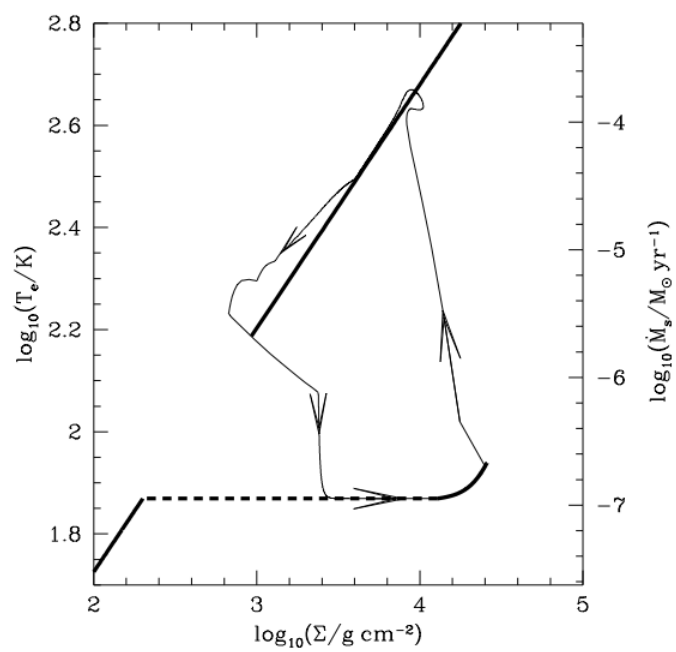
- Magneto-rotational instability, driven by
    - change in ionization e.g. Balbus & Hawley (1991)
    - change in alpha e.g. Zhu et al
- Gravitational instability driven by accumulation of mass

➔ Gravo-magneto instability studied by Martin & Lubow (2011)



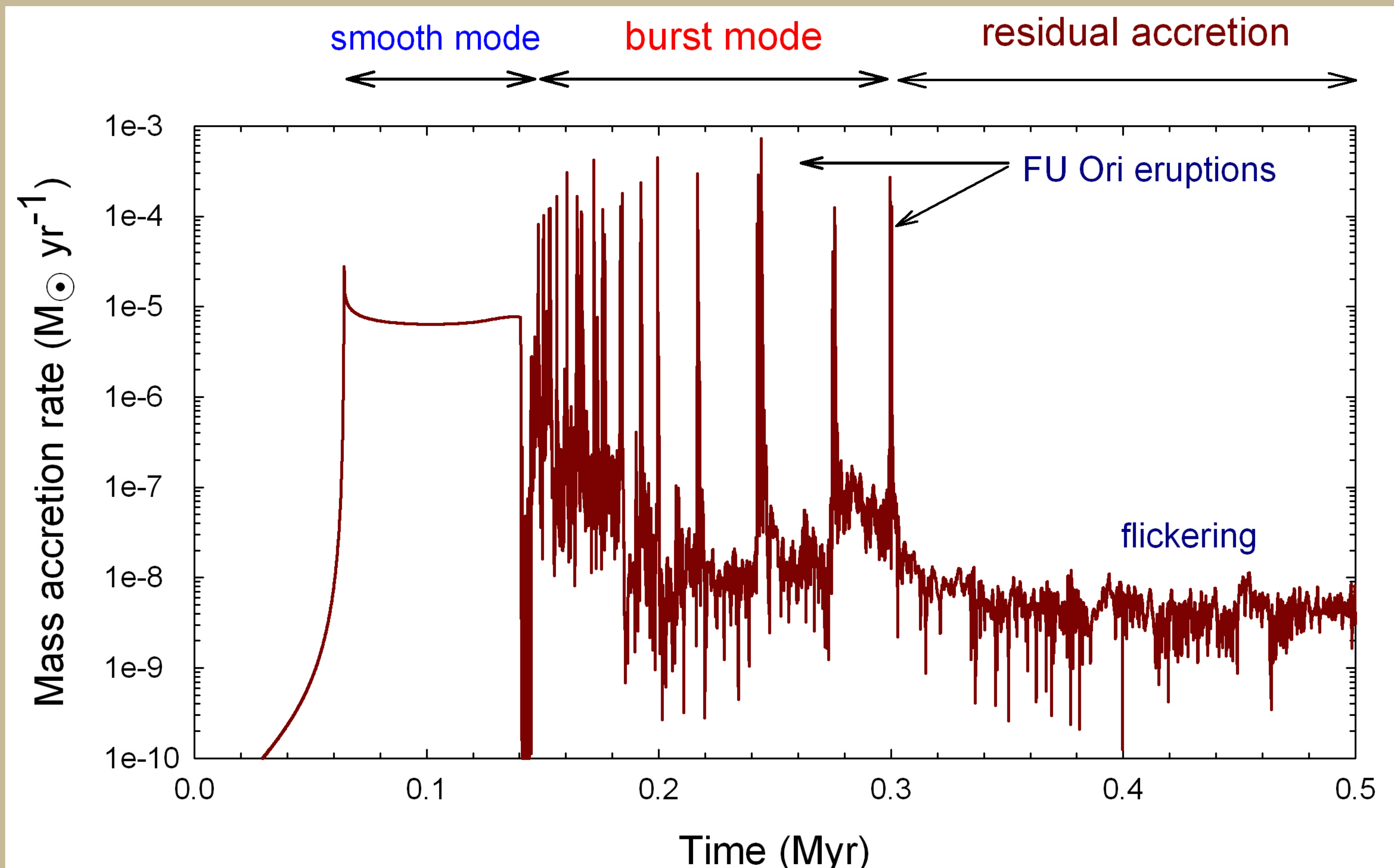
Armitage (2010)





tic diagram of steady disk solutions in the Σ–$\dot{M}$ plane at some radius in

HOW FREQUENT ARE THE EXTREME OUTBURSTS?

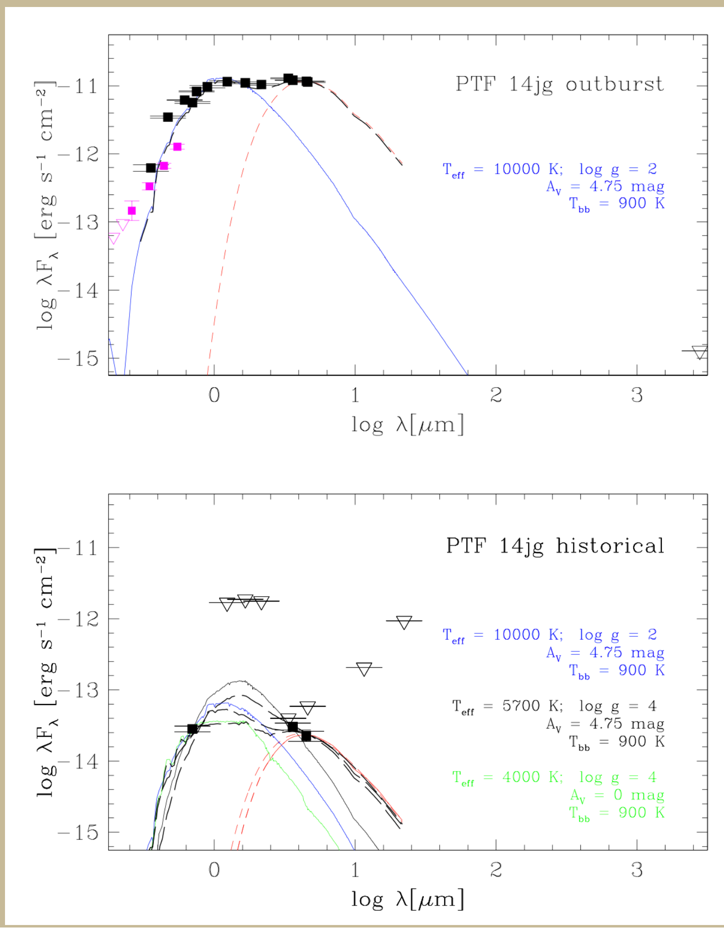


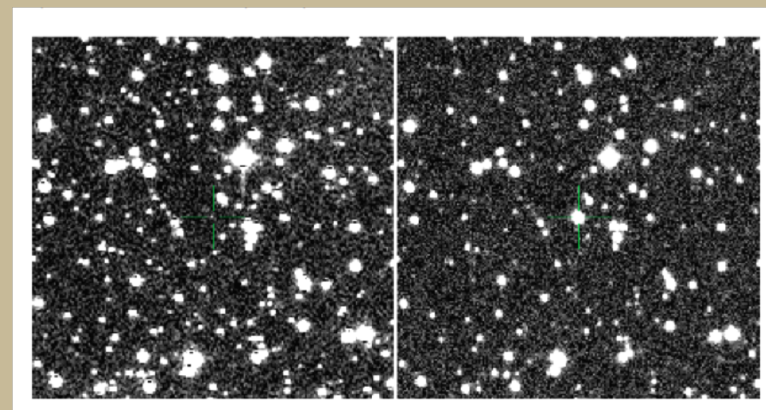
Vorobyov 2006

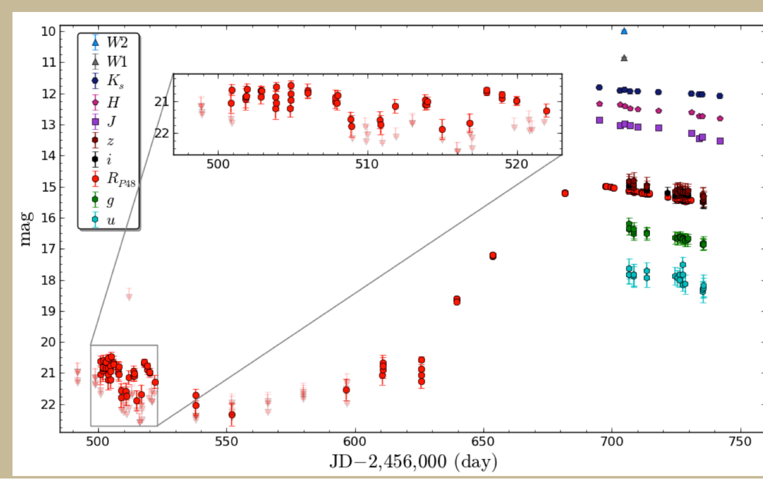
Another PTF-Discovered Likely FU Ori Event

Hillenbrand et al. (2019)

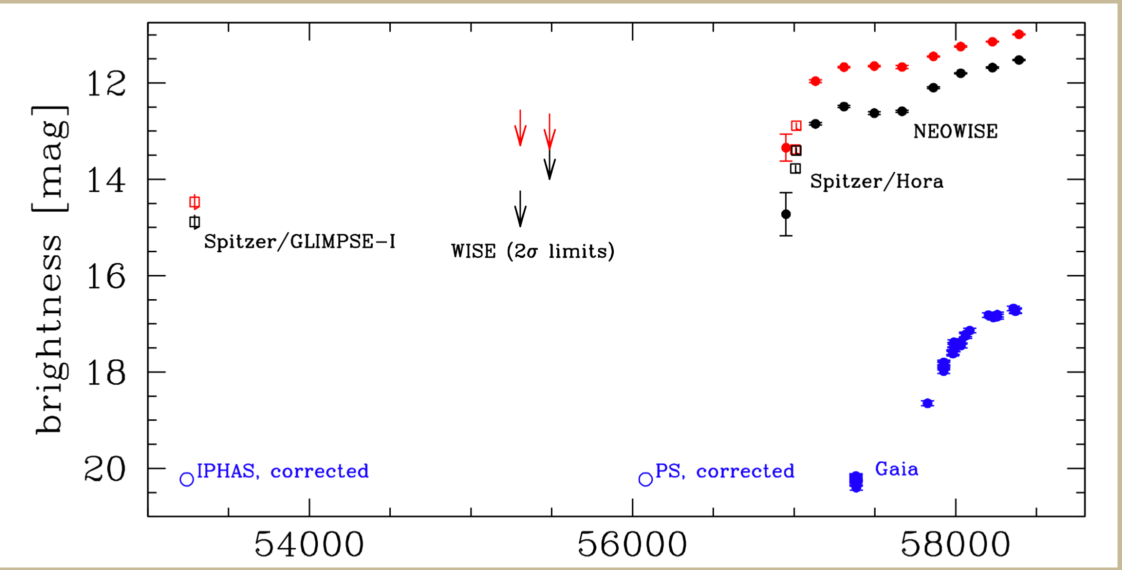
PTF14jg
(near W4 HII region)



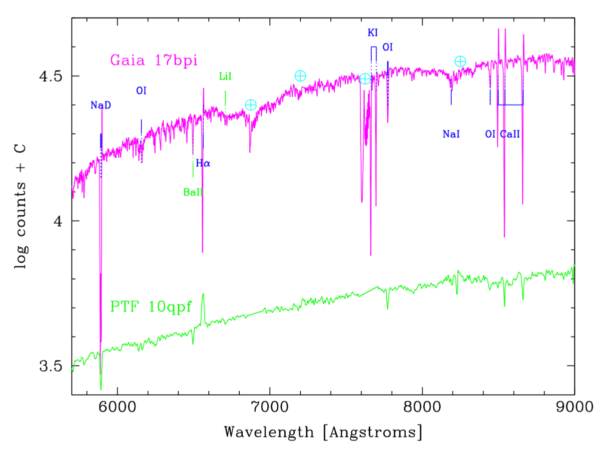


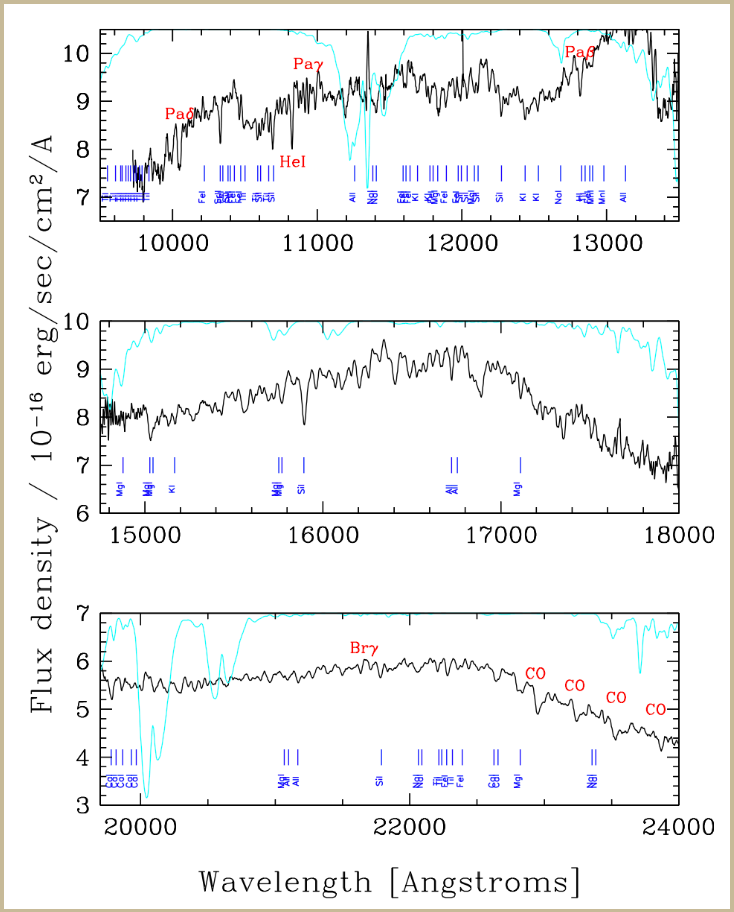


A Gaia-Discovered FU Ori Star



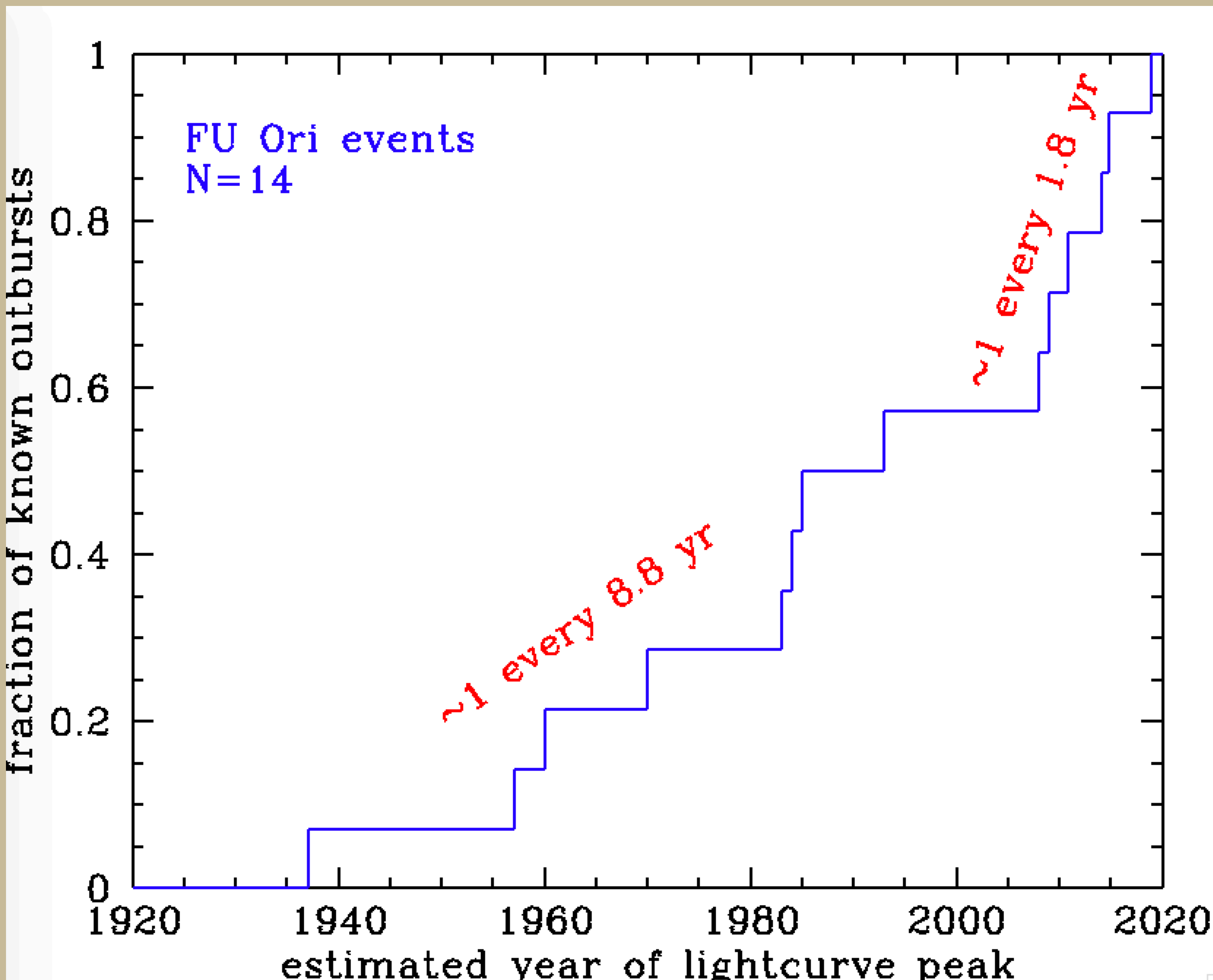
Gaia 17bpi
(in a relatively unstudied dark cloud)





Hillenbrand et al. (2018)

Extreme Outbursts – How Frequent?



Only 14 outbursts actually observed in the act (out of a total sample of only ~25 !)

- Though we appear to be getting better at noticing outbursting young stars, undoubtedly, we are not finding them all.
- In order to estimate the outburst rate – as distinct from the detection rate -- we need to understand our efficiency (or better stated, inefficiency).
- Rate estimation is difficult without more complete young star census information.

Compare to the Even More Intrinsically Rare Tidal Disruption Events

Theory:

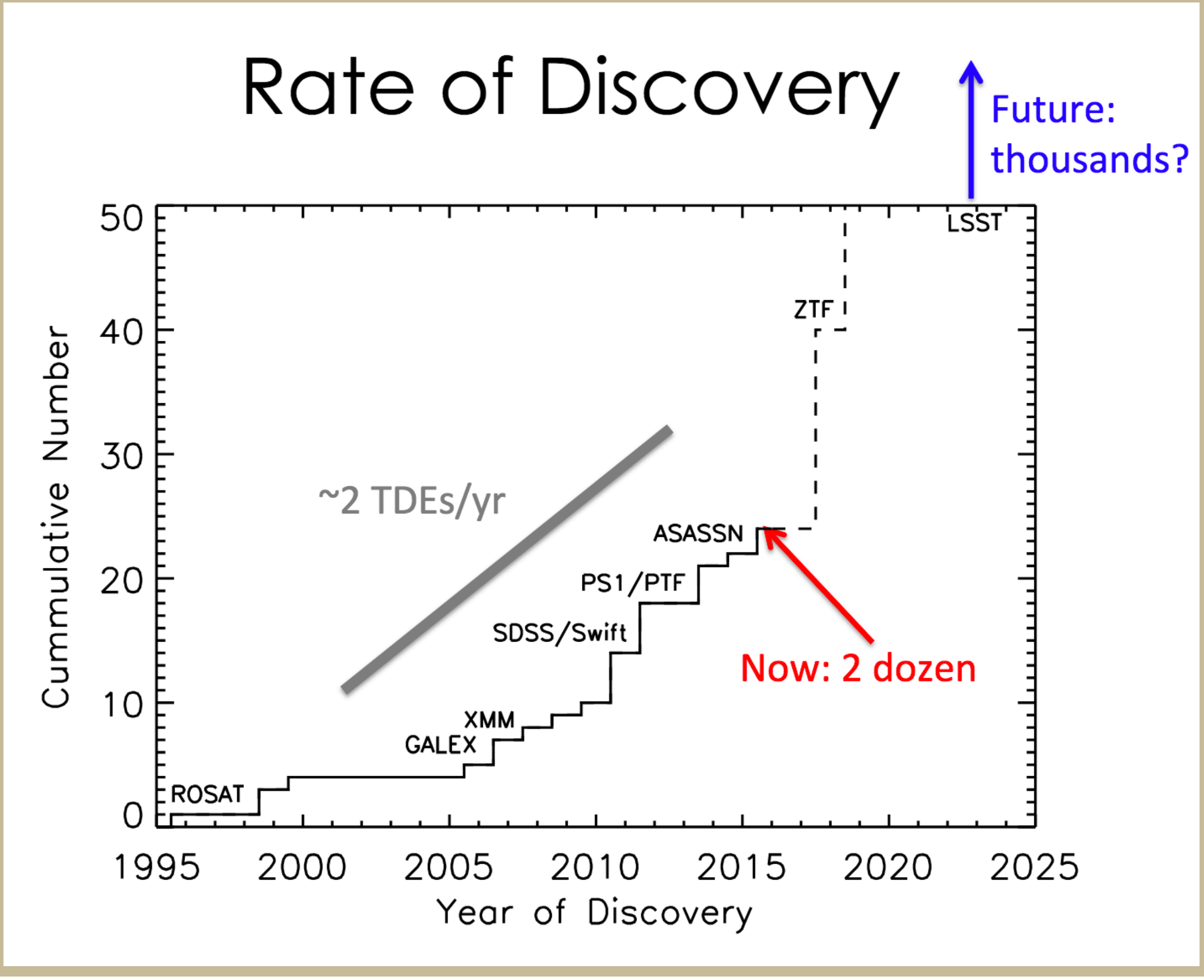
$\sim 10^{-5}$ to 10^{-4} / year / galaxy

Current Census:

~45

Young star researchers should be embarrassed!

plot from S. Gezari



Constraining the Rate of FU Orionis Outburst Events

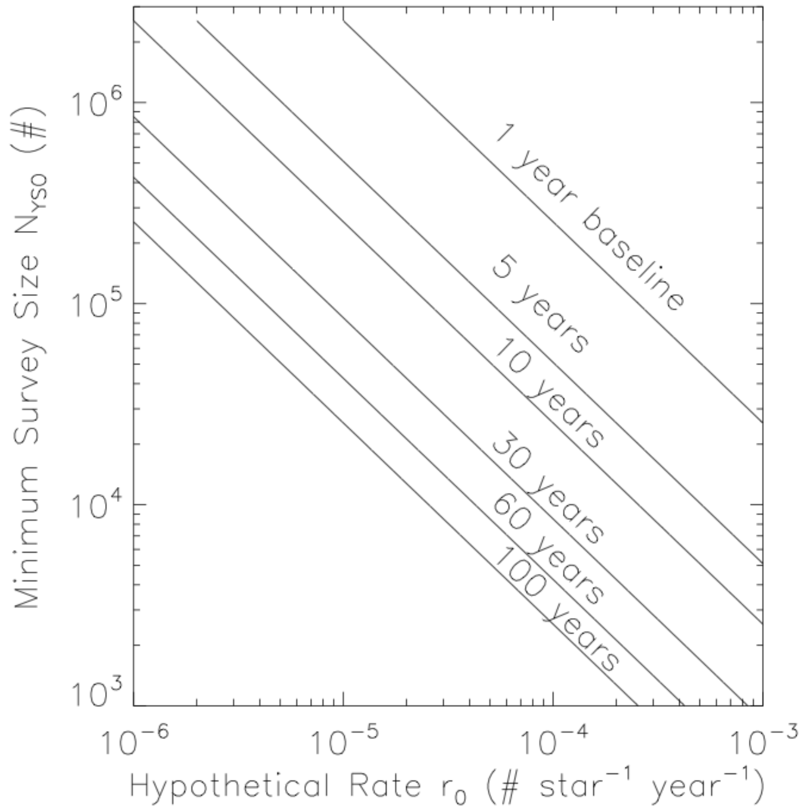


FIG. 2.— The survey size needed to have a 90% chance of constraining the outburst rate to a factor of 2 at 90% confidence, as a function of the true outburst rate r_0 (abscissa) and the time baseline (labels). One may reduce the needed survey size by choosing a longer time baseline, by admitting higher uncertainty than a factor of 2, or by requiring a lower confidence than 90%.

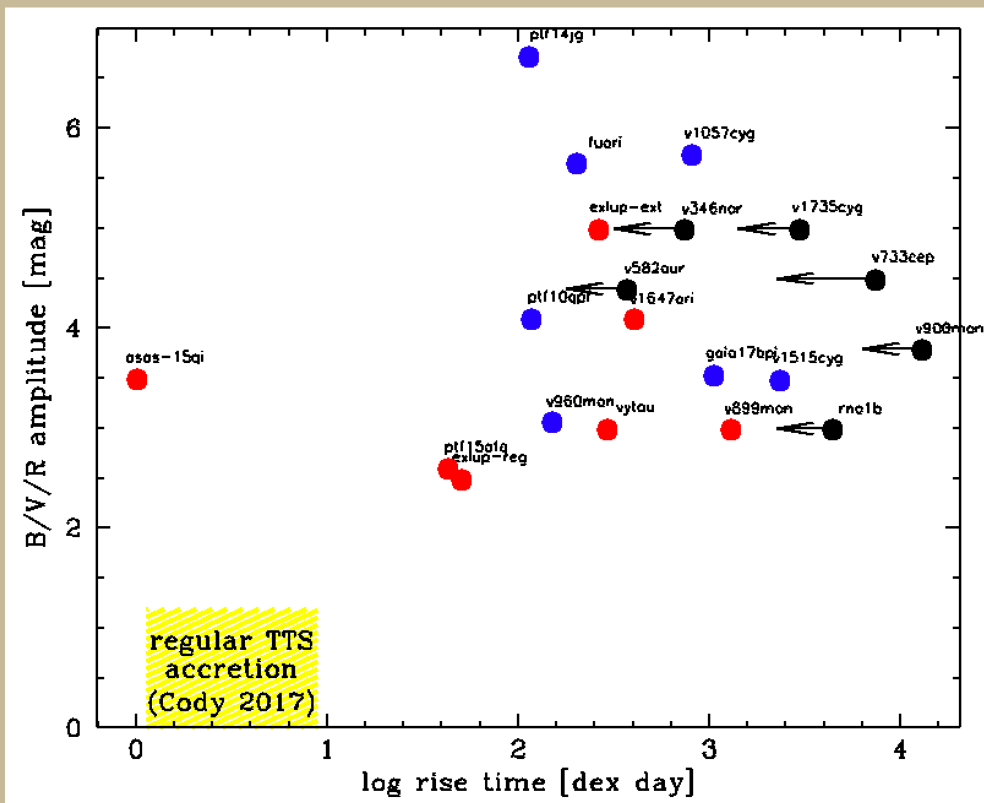
Need to know the numerator.

Need to know the denominator.

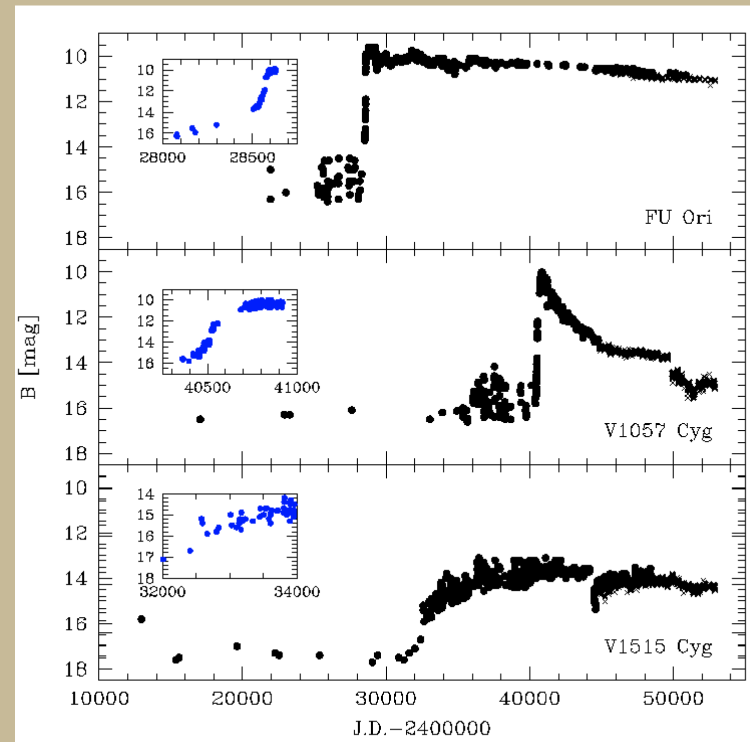
Need to have enough stars for meaningful statistics!

Hillenbrand and Findeisen (2015)

How Can we Recognize True FU Ori Events
vs
other Types of Young Star Outbursts ?



Hillenbrand (2019)

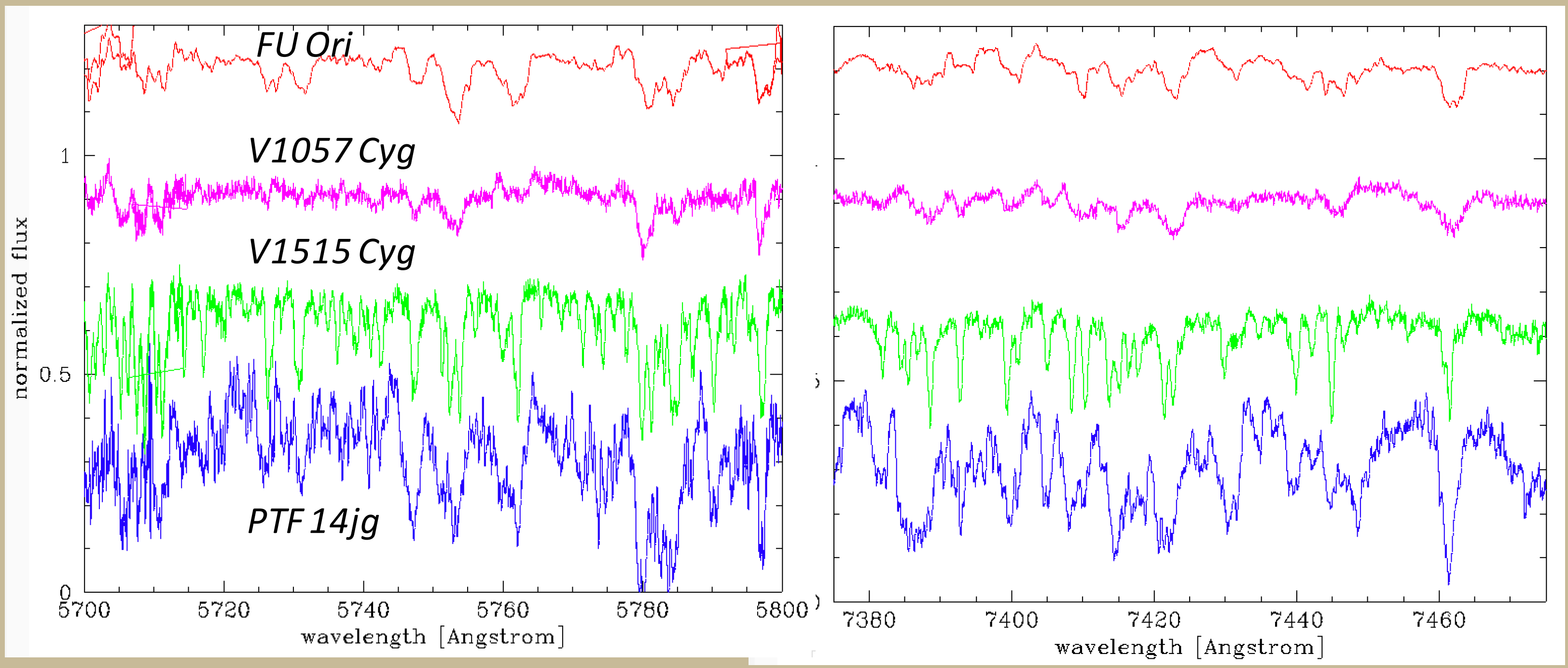


Measuring the duration of an outburst usually requires impatient people to wait….

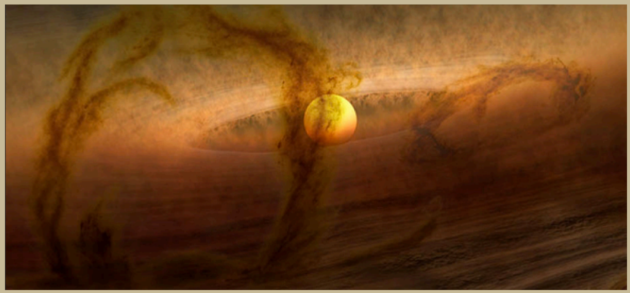
- G. Herczeg

How Can we Recognize True FU Ori Events
vs
other Types of Young Star Outbursts ?

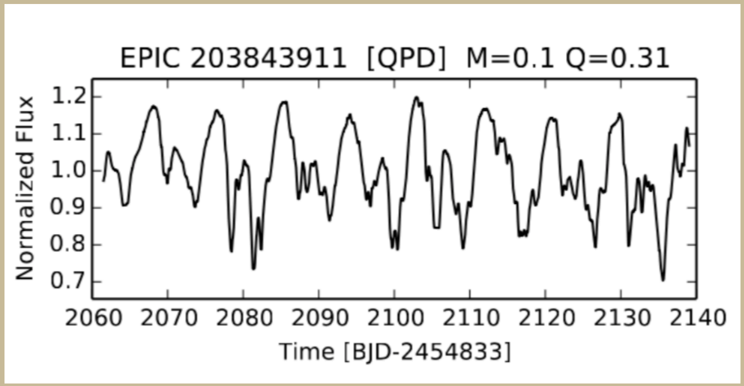
High Dispersion SPECTRA ➔ disk photosphere (composite, not single-temperature)

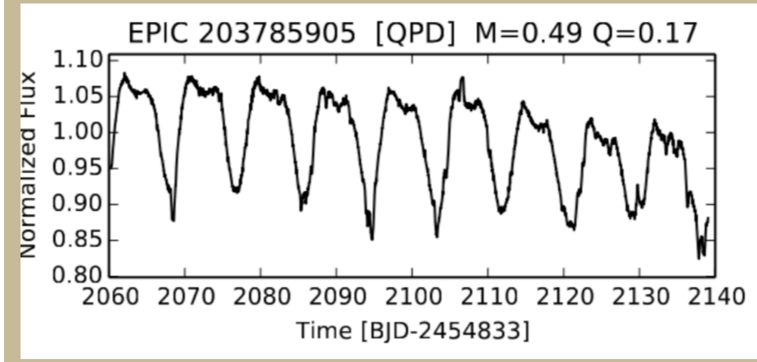


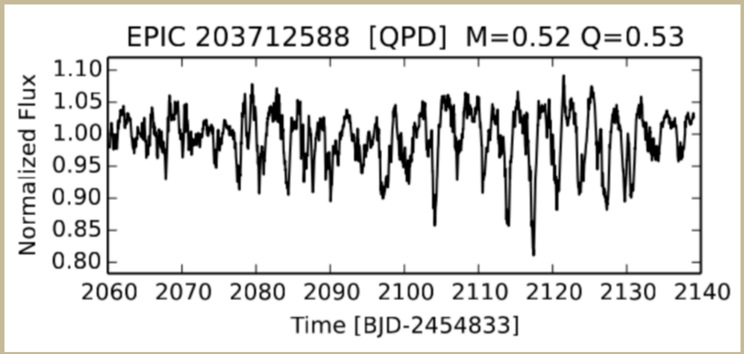
VARIABLE PHOTOMETRY: EXTINCTION-DRIVEN BEHAVIOR

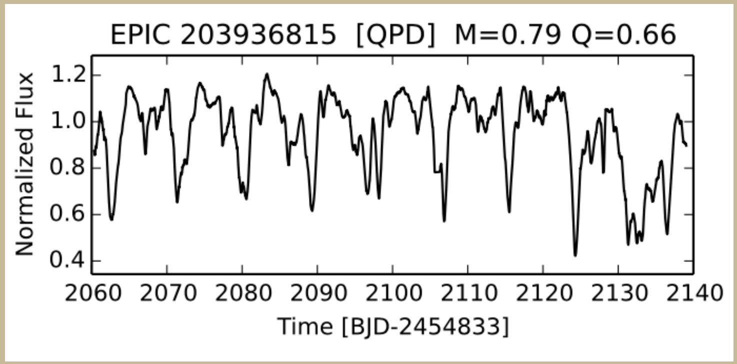


[Cody et al. 2018]



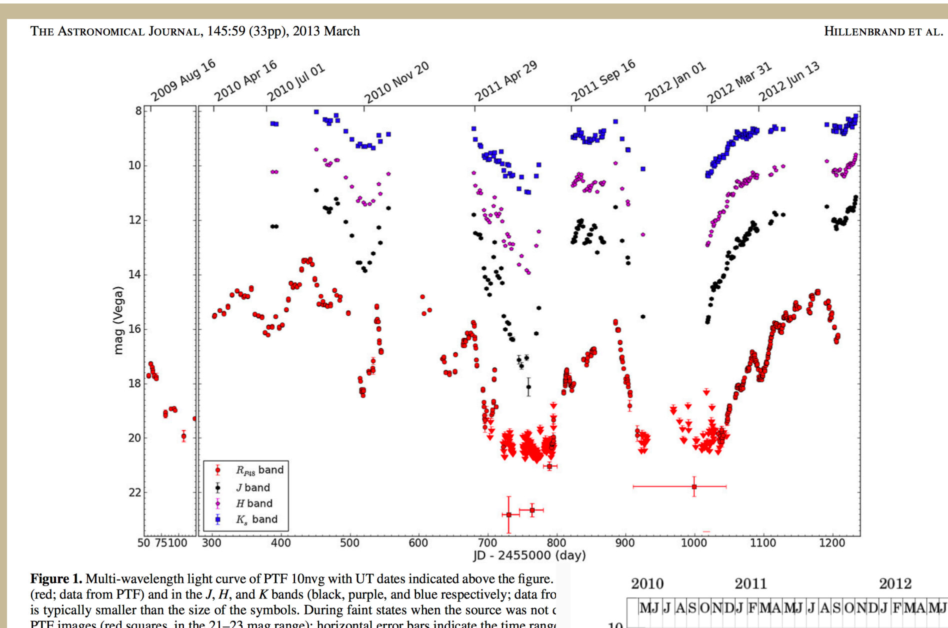






33% of the objects with disks exhibit with these types of lightcurves

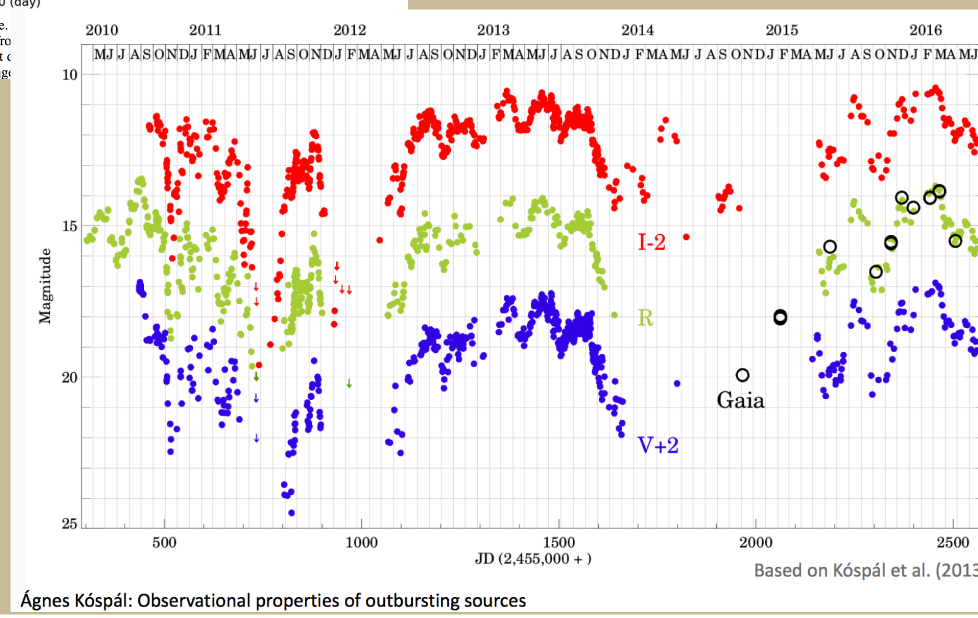
EXTREME EXTINCTION



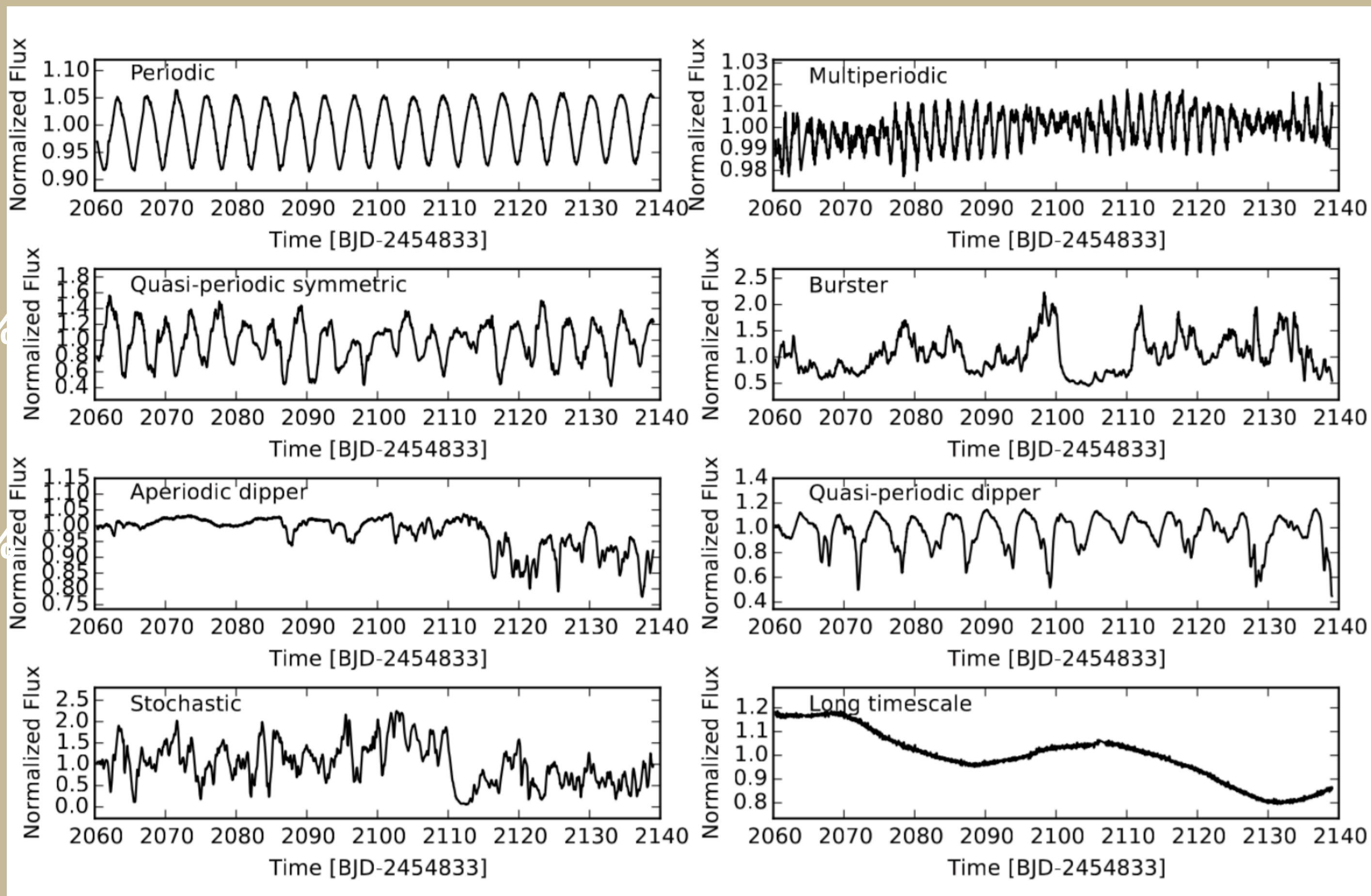
Long-duration fades of 5-7 mag!

Catching this repeating cycle in a rising part of the phase might cause incorrect interpretation as an outburst event.

(see Gaia data points)



LIGHTCURVE MORPHOLOGY CLASSIFICATION



7% 26% 16% 8%

5% 14% 17% 3%

Cody and Hillenbrand

LIGHTCURVE MORPHOLOGY CLASSIFICATION

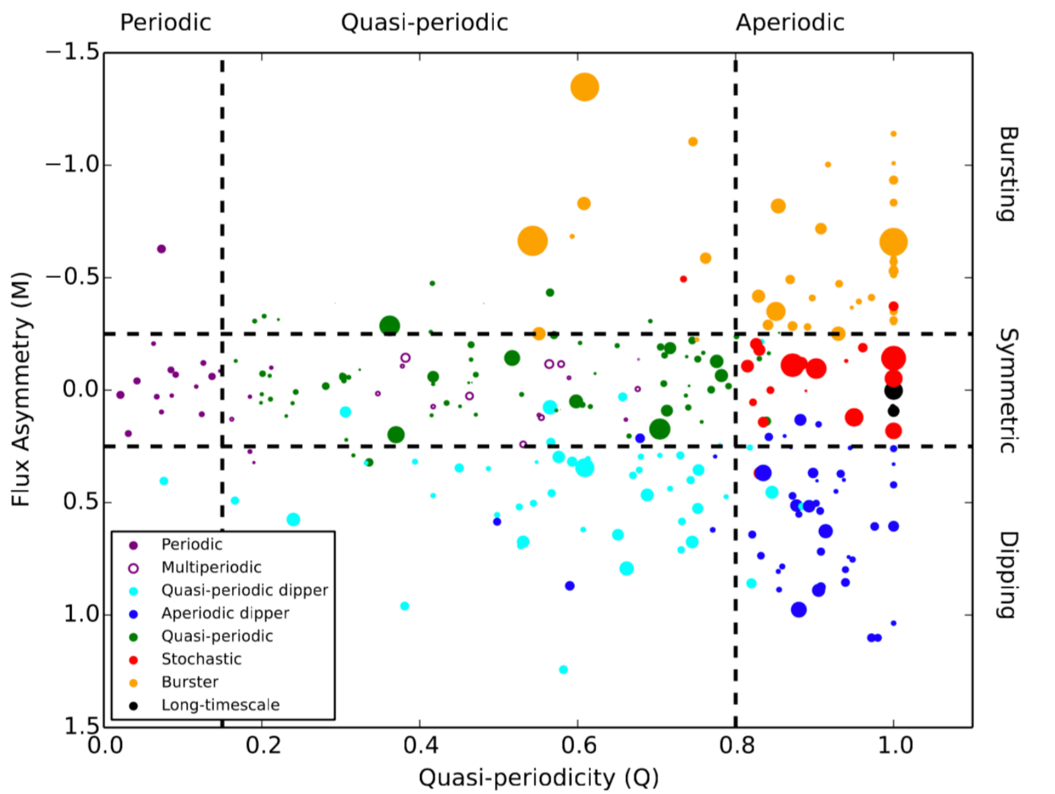
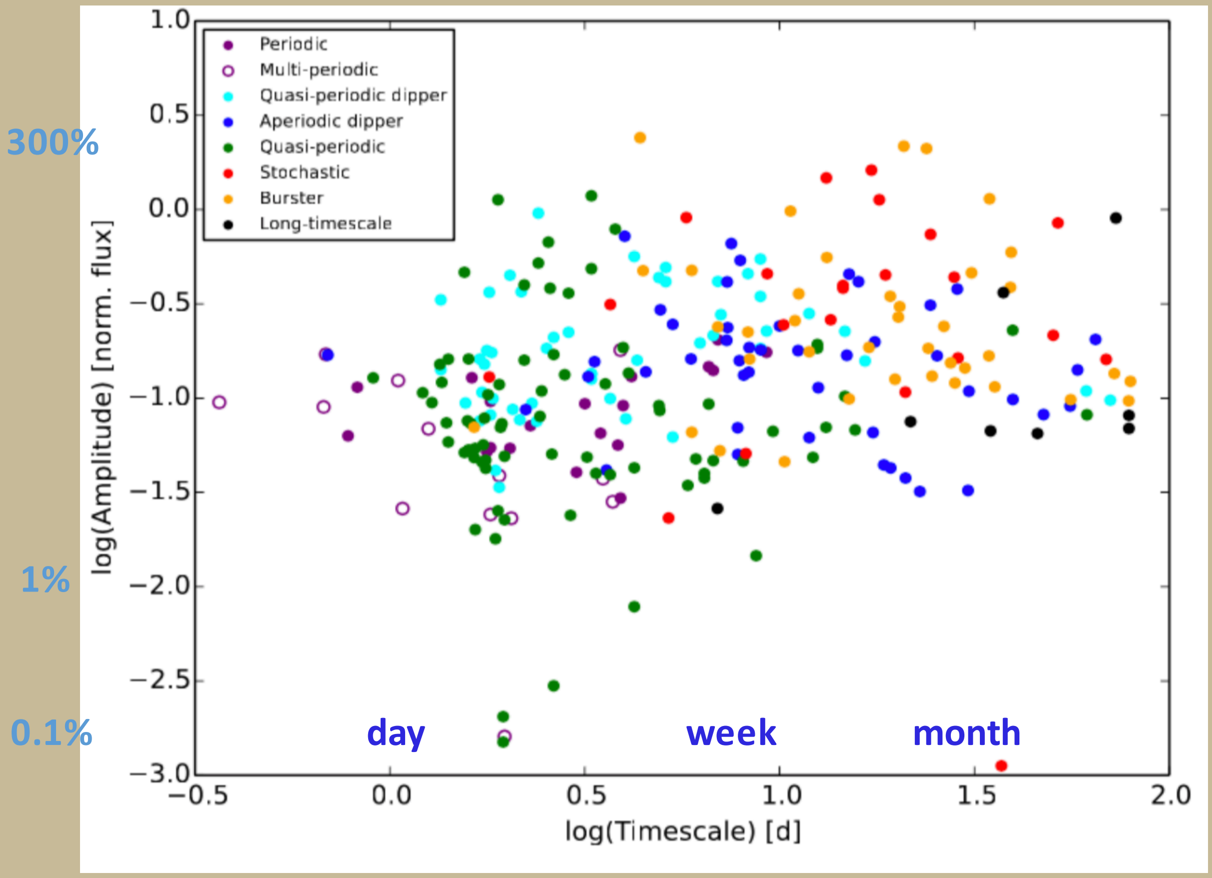


FIG. 6.— Q and M statistics for our sample of disk-bearing stars in Upper Scorpius and ρ Ophiuchus. Colors denote different types of variables, as identified by eye. Non-variable objects are excluded. Point sizes in this and subsequent plots are scaled according to variability amplitude.

Cody and Hillenbrand (2018)

TIMESCALES AND AMPLITUDES



Cody and Hillenbrand (2018)

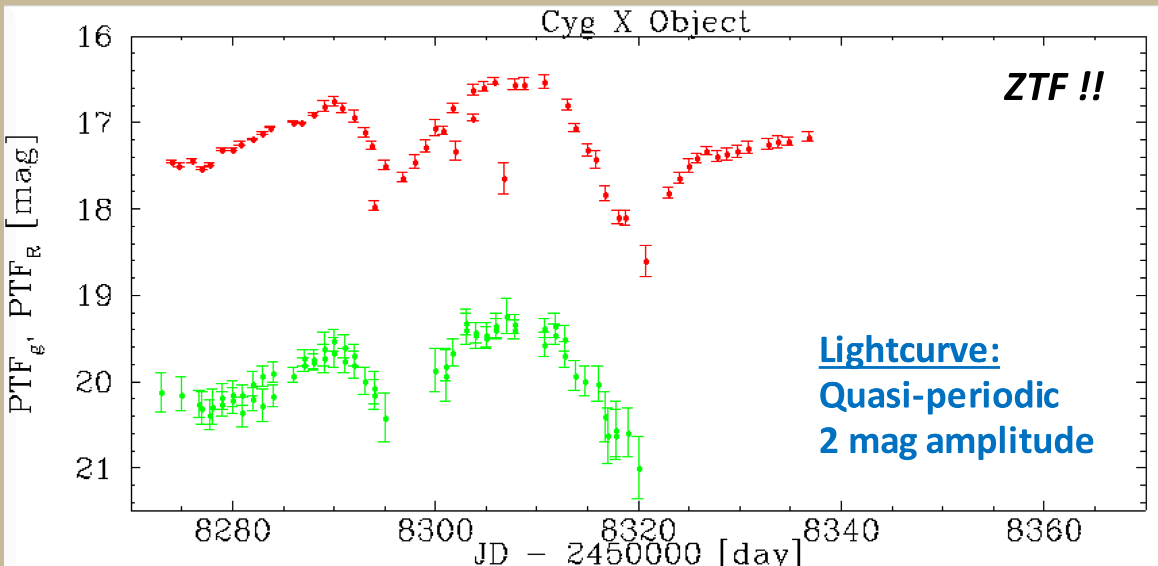
Amplitude ranges of most disk categories are similar.

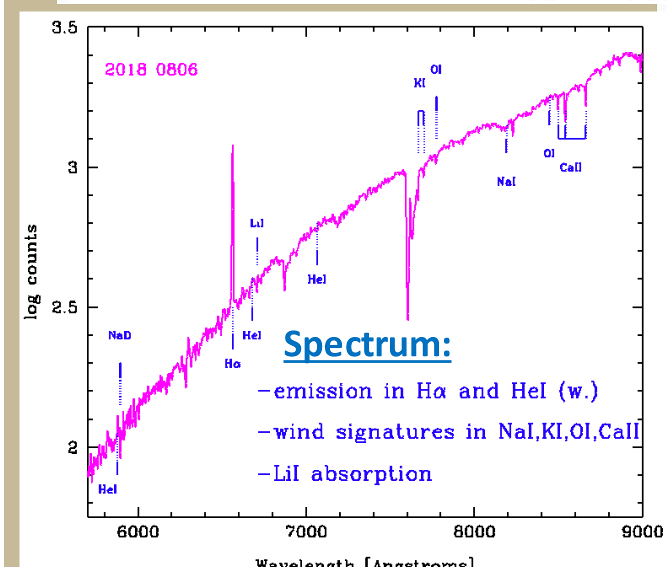
Timescales vary, however:

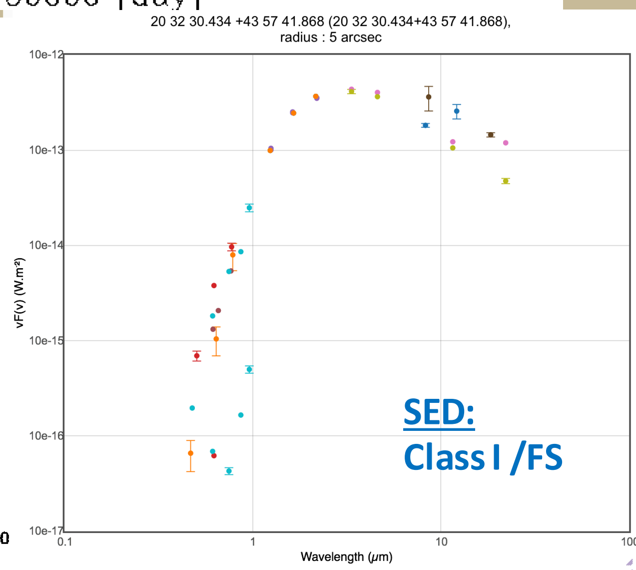
Long = Bursters, Stochastics
Aperiodic Dippers

Int = Quasi-periodic Dippers
Quasi-periodic Symm.

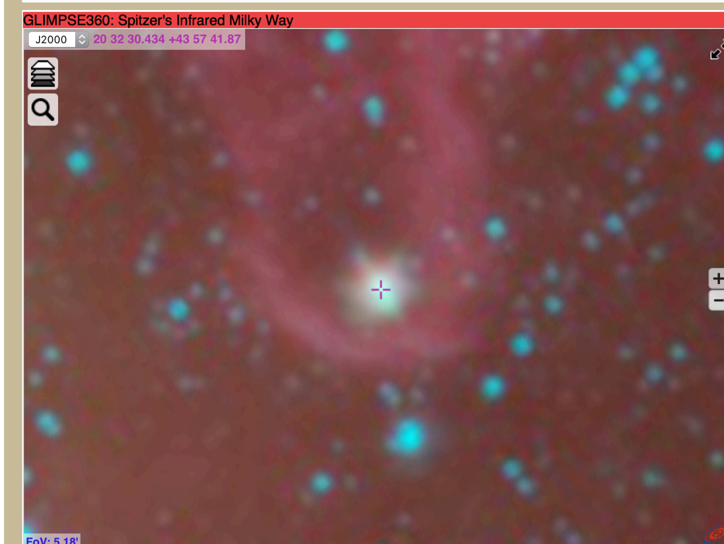
Short = Periodic
Multi-Periodic


Cyg X Object
ZTF !!
Lightcurve:
Quasi-periodic
2 mag amplitude
PTF_g' PTF_R [mag]
16
17
18
19
20
21
8280
8300
8320
8340
8360
JD − 2450000 [day]

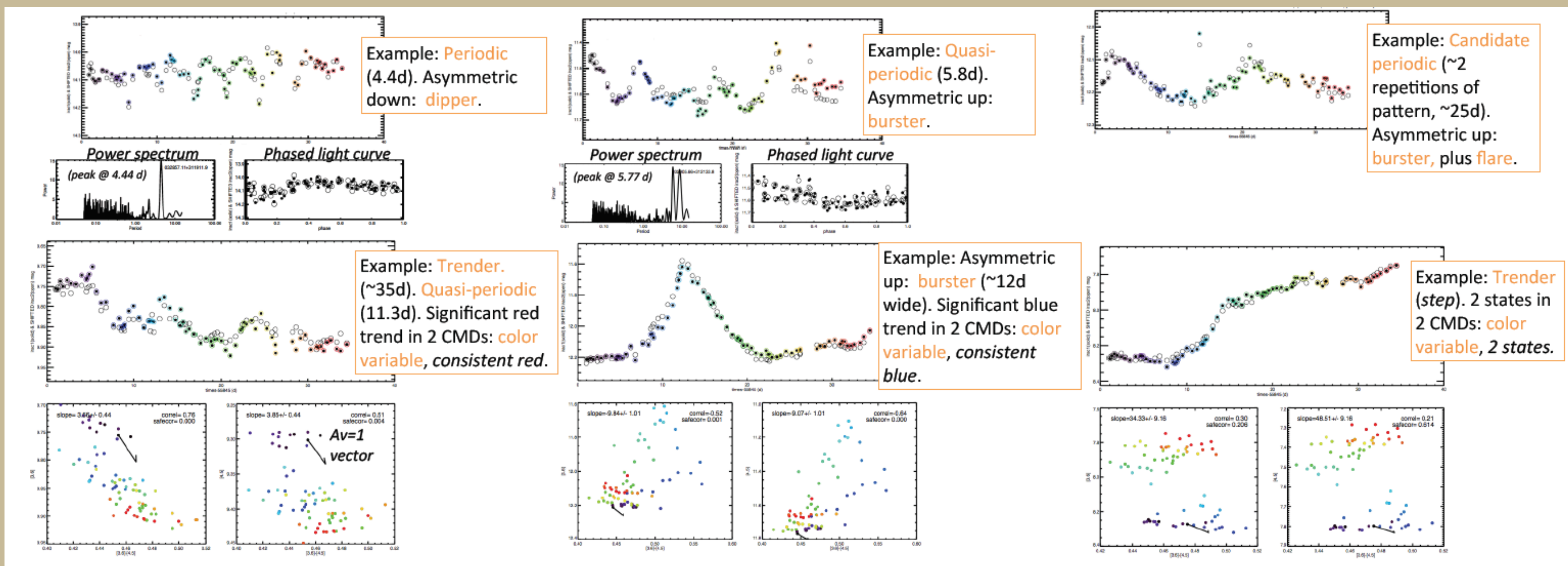

2018 0806
Spectrum:
−emission in Hα and HeI (w.)
−wind signatures in NaI,KI,OI,CaII
−LiI absorption
NaD
HeI
Hα
HeI
LiI
HeI
KI
OI
NaI
OI
CaII
log counts
3.5
3
2.5
2
6000
7000
8000
9000
Wavelength [Angstroms]

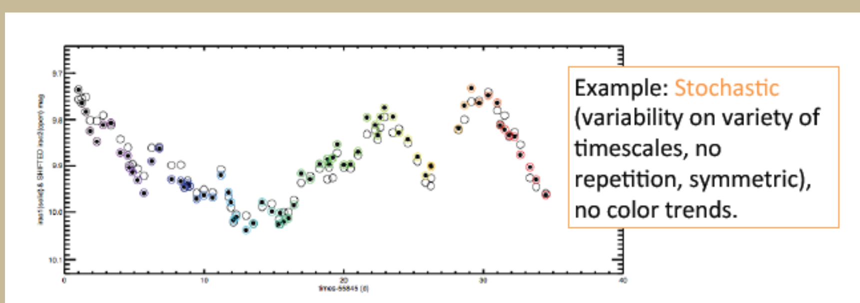

20 32 30.434 +43 57 41.868 (20 32 30.434+43 57 41.868),
radius : 5 arcsec
SED:
Class I /FS
νF(ν) (W.m²)
10e-12
10e-13
10e-14
10e-15
10e-16
10e-17
0.1
1
10
100
Wavelength (µm)


GLIMPSE360: Spitzer's Infrared Milky Way
J2000
20 32 30.434 +43 57 41.87
FoV: 55.75'


GLIMPSE360: Spitzer's Infrared Milky Way
J2000
20 32 30.434 +43 57 41.87
FoV: 5.18'

Infrared Variability Too (Spitzer)





[Rebull et al 2014, 2015]

~50% of identified variables also vary in color

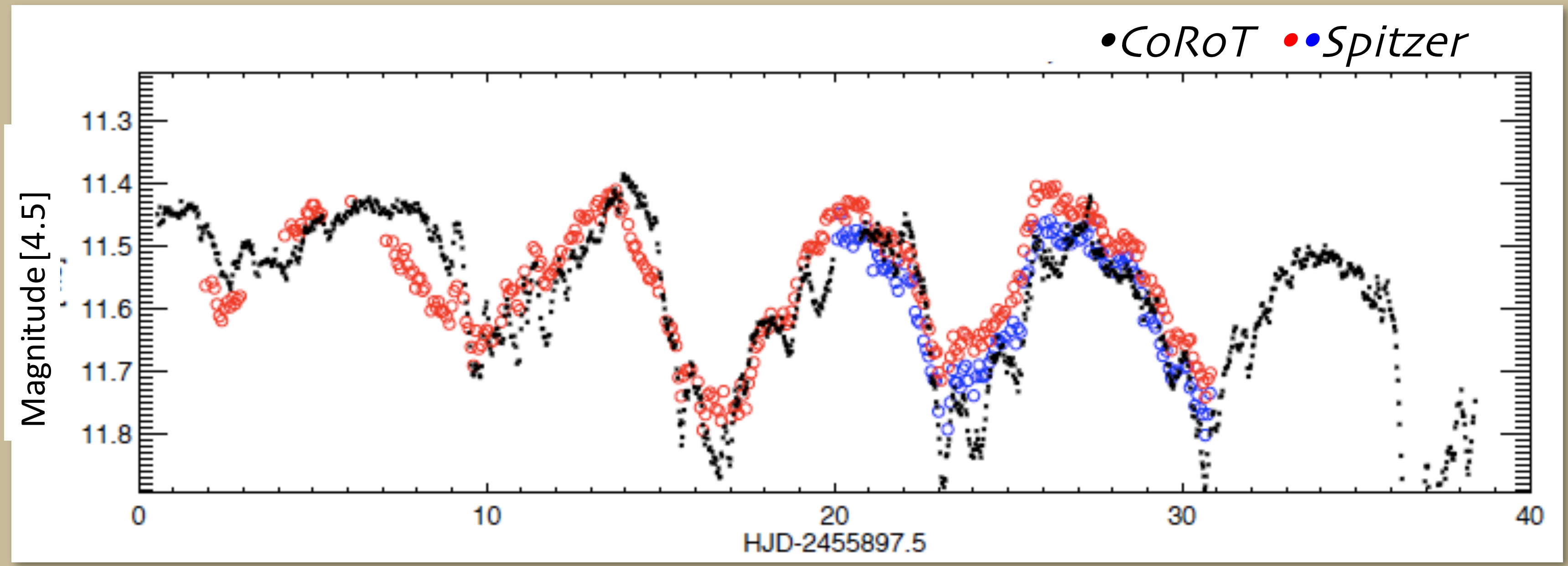
~33% are periodic

~25% “dip” and ~25% “burst”

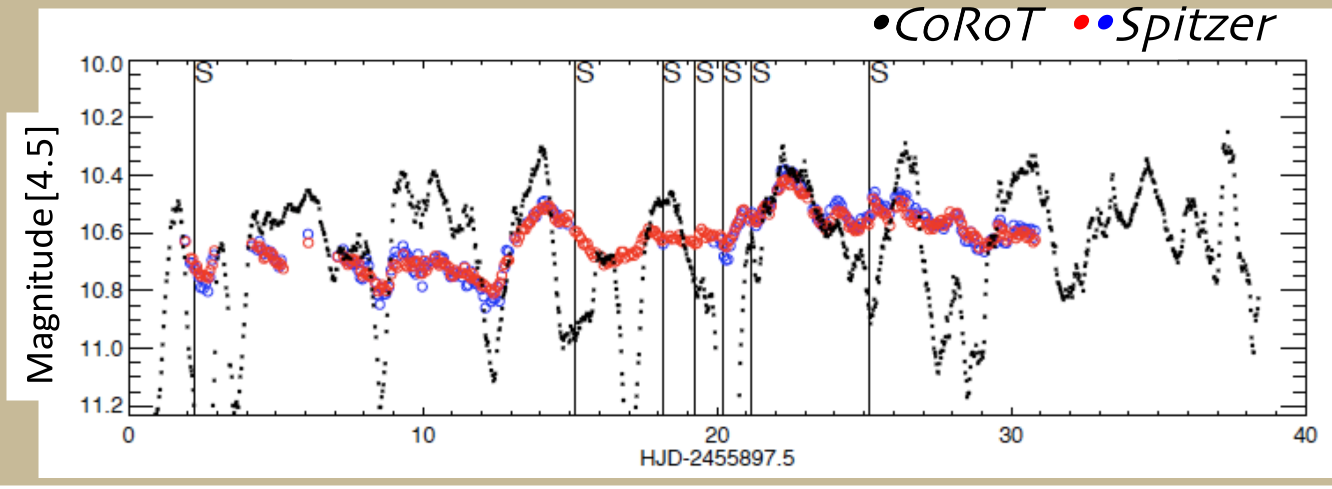
~50% “trend” over a month

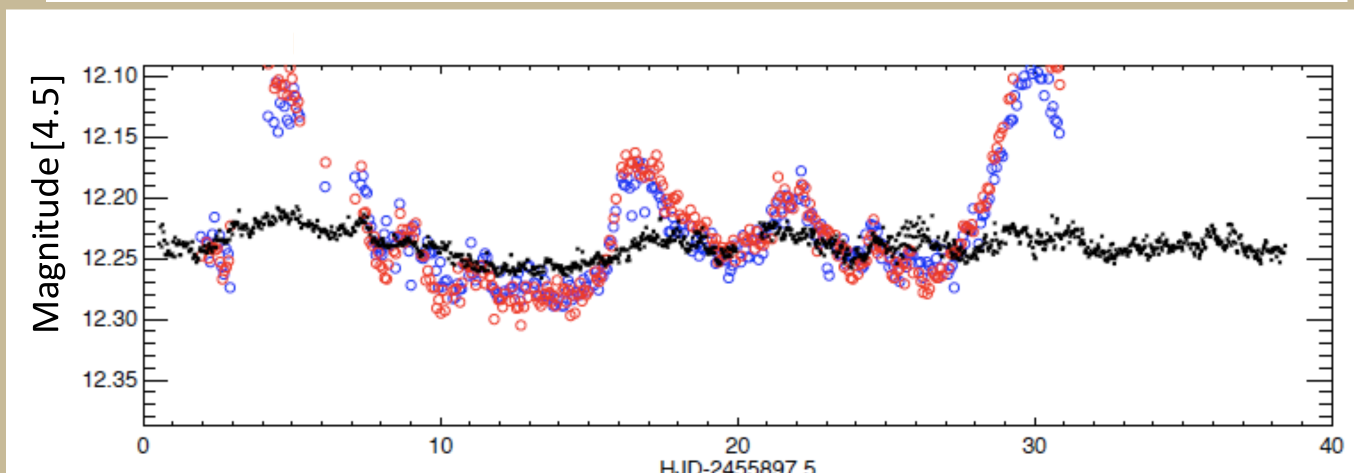
~20% “stochastic”

Optical and Infrared Sometimes Quite Similar

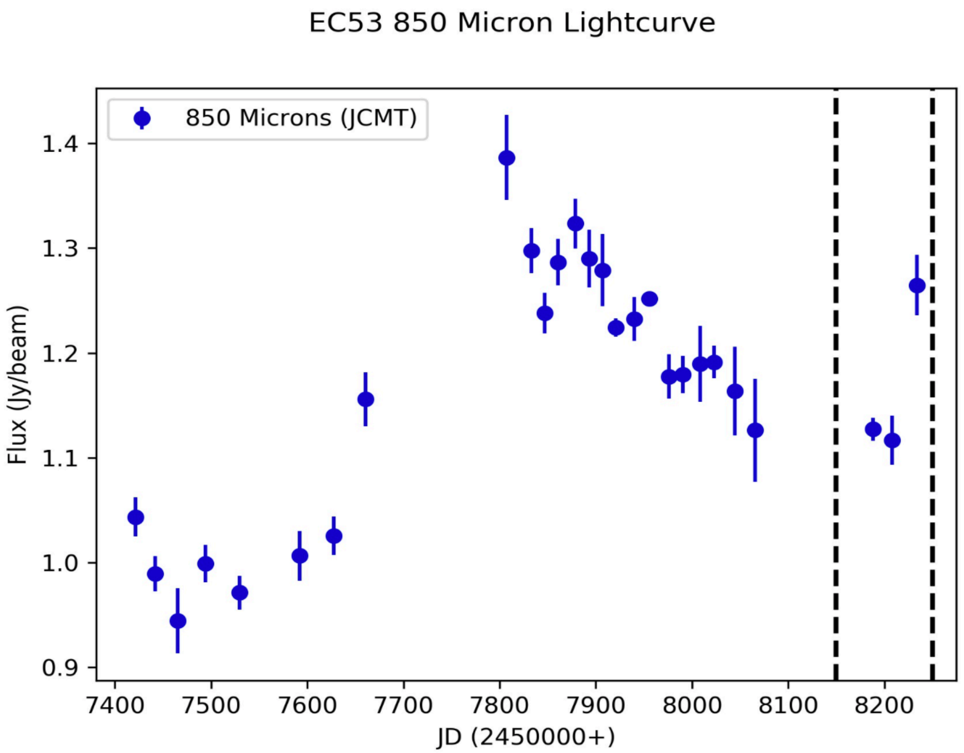


Sometimes Very Different





Even Sub-millimeter Variability is Observed!



The 850 micron light curve of EC 53 obtained by the Submillimetre COmmon User Bolometer Array 2 (SCUBA-2) at the JCMT. The dashed lines show the x-axis boundaries for the infrared data presented below. For more information about the variability of EC 53, see **Hodapp et al. 1996, ApJ: 468:861**, **Hodapp et al. 2012, ApJ: 744:56**, **Yoo et al. 2017, ApJ: 849:69**, and **Mairs et al. 2017, ApJ: 849:107**. For more information about the Transient Survey and how this light curve was generated, see **Herczeg et al. 2017, ApJ: 849:43**, **Mairs et al. 2017, ApJ: 843:55**, and **Johnstone et al. 2018, ApJ: 854:31**.

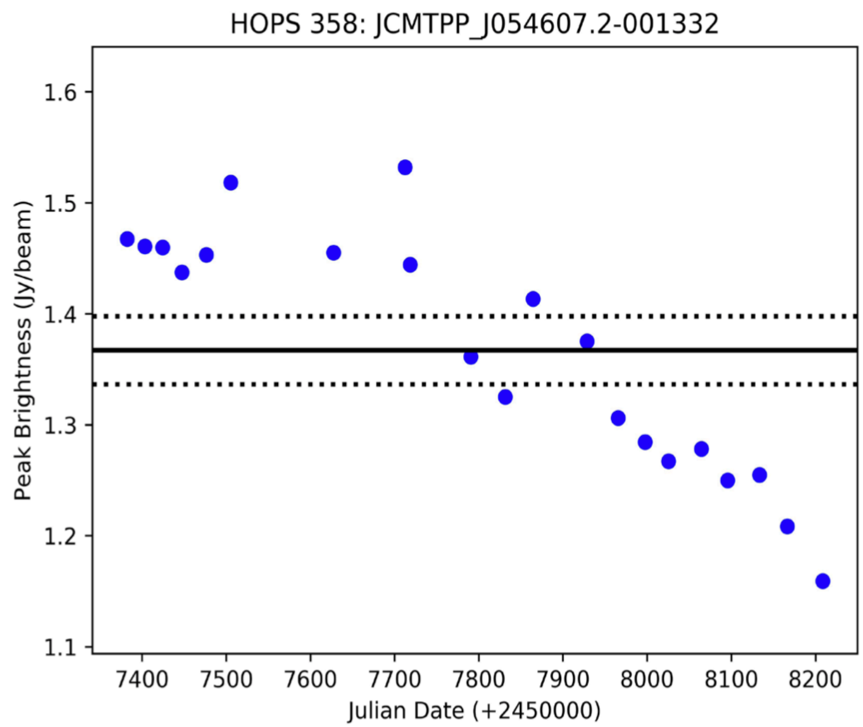
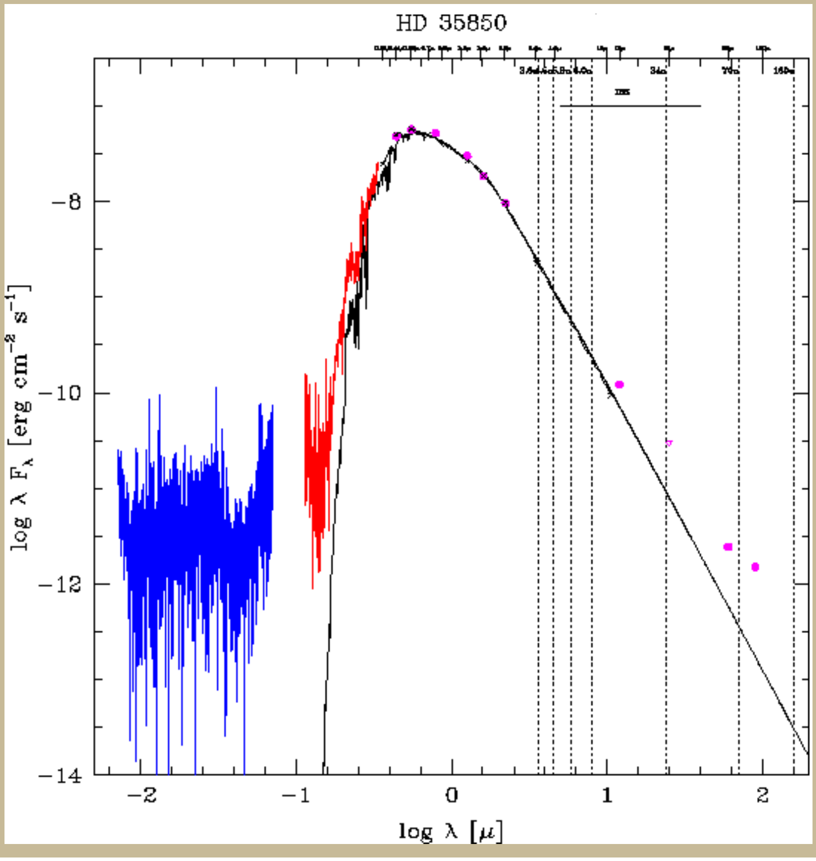
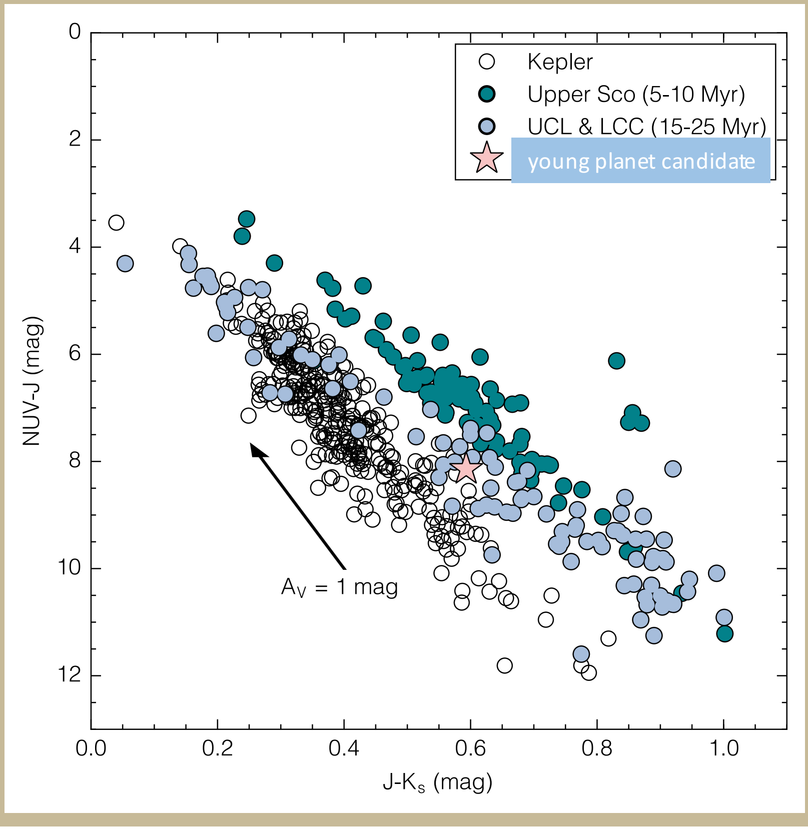


Figure 17. Secular Variables. Linear fits are performed for light curves and the significance of their slopes are tested by team members. HOPS 358 was the subject of a recent ATel released by the Transient Team (see text).

Post-Accretion Pre-Main Sequence Star SED



NUV excess ==> stellar youth up to ~100 Myr



Much larger ultraviolet variabiliy amplitudes compared to regular active late-type stars in the field (2-800x).

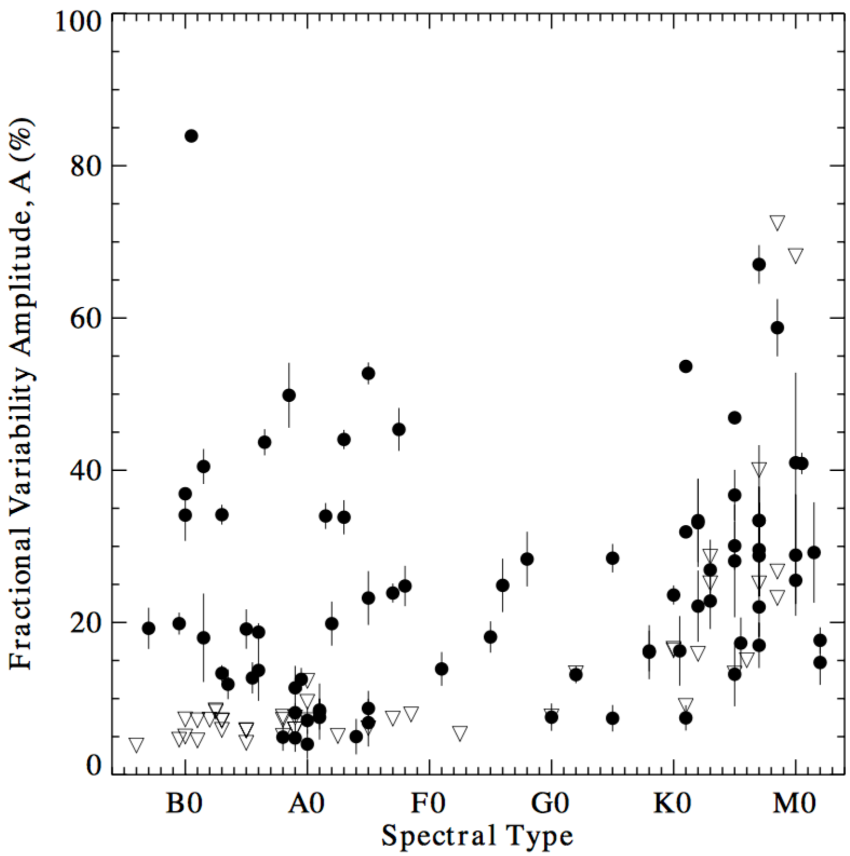
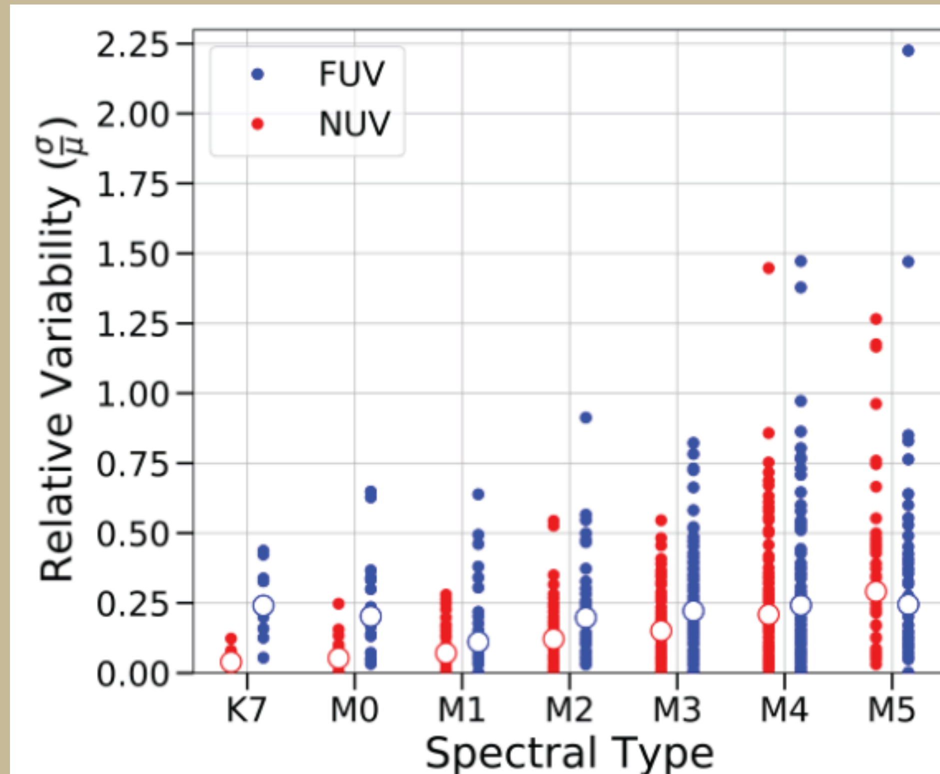


FIG. 9.—Mean deviation in 1900–3200 Å flux, relative to the global mean for all spectra of a given PMS star. Triangles indicate 2 σ upper limits. Only stars observed more than once by *IUE* are shown. Few PMS stars of spectral class F were observed by *IUE*, but LW data are adequate to show that they can vary significantly.

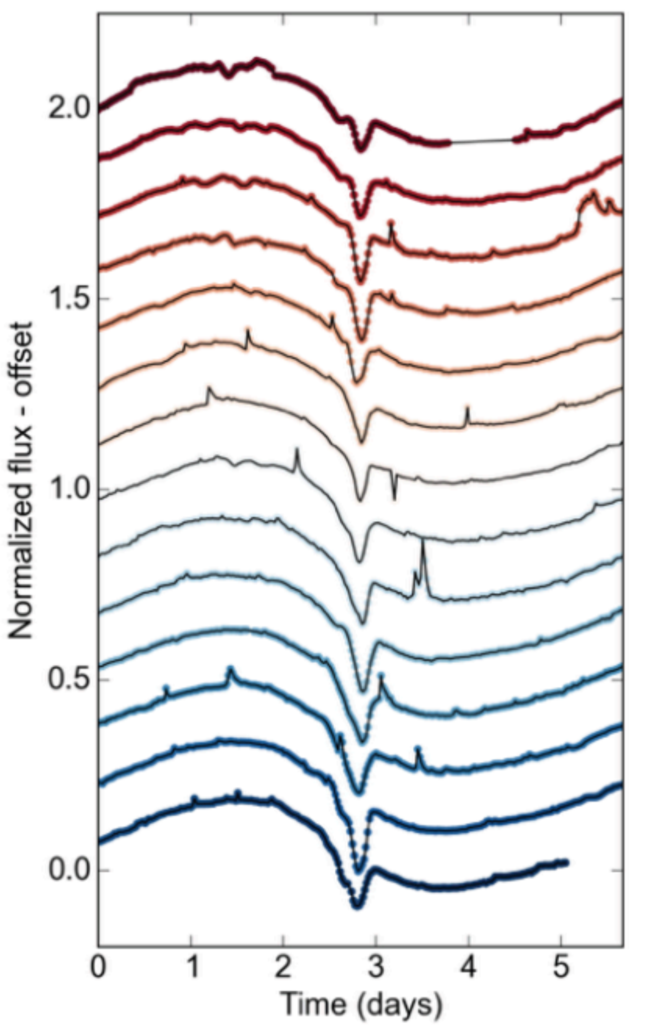


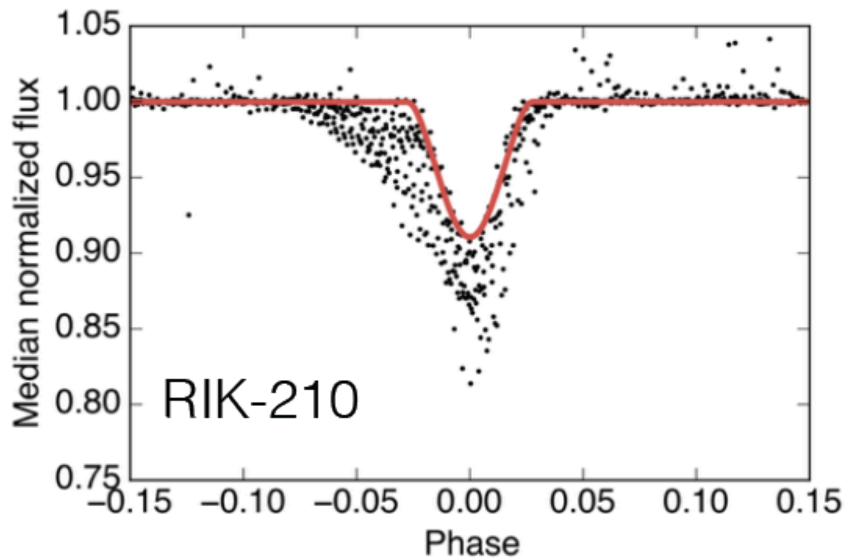
Shkolnik 2018

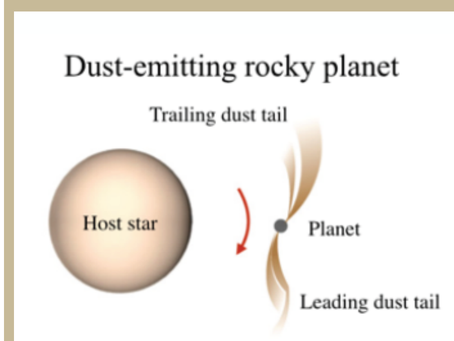
Transient dimming of a young star lacking a protoplanetary disk

David et al. 2017, ApJ (arXiv:1612.03907)

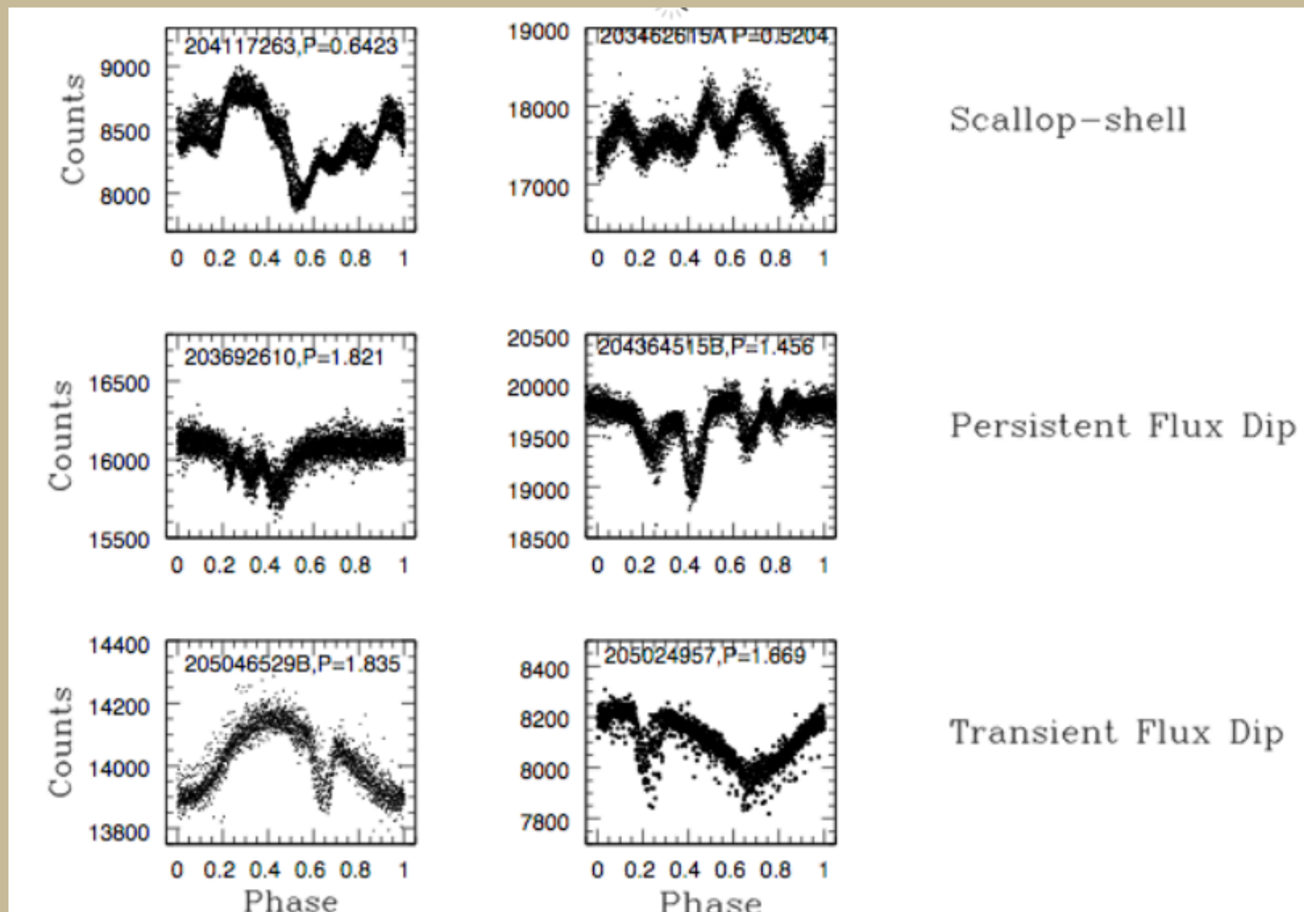
magnetospheric clouds?
dusty accretion column?
corotating planetary debris?







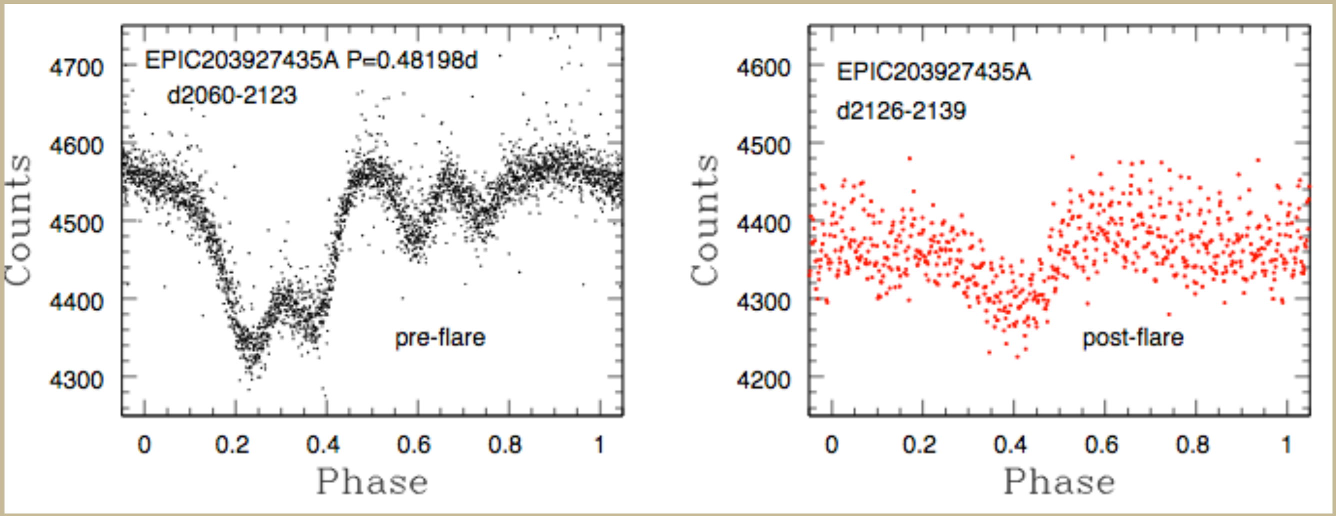
More Interesting Co-Rotating Structure



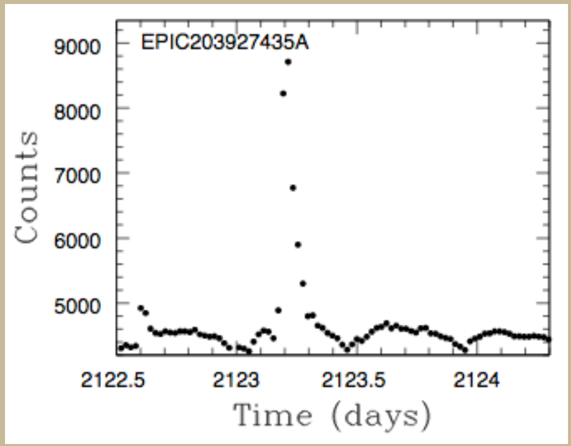
~9% of the objects *<u>without</u>* *evidence for infrared excess (disks) exhibit these types of lightcurves*

[Stauffer et al. 2017, 2018]

Waveform Can Change During the ~80 Day K2 Campaign



changes seen at restricted phases, sometimes closely following detected flares.



Orbiting Clouds of Material at or near the Keplerian Co-Rotation Radius in Late M Dwarfs WTTs of Upper Sco

[Stauffer et al. 2017]