Time Domain Astronomy

Young Star TDA: The Future is Here

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(Caltech)

Traditional Radio Studies of Star Formation

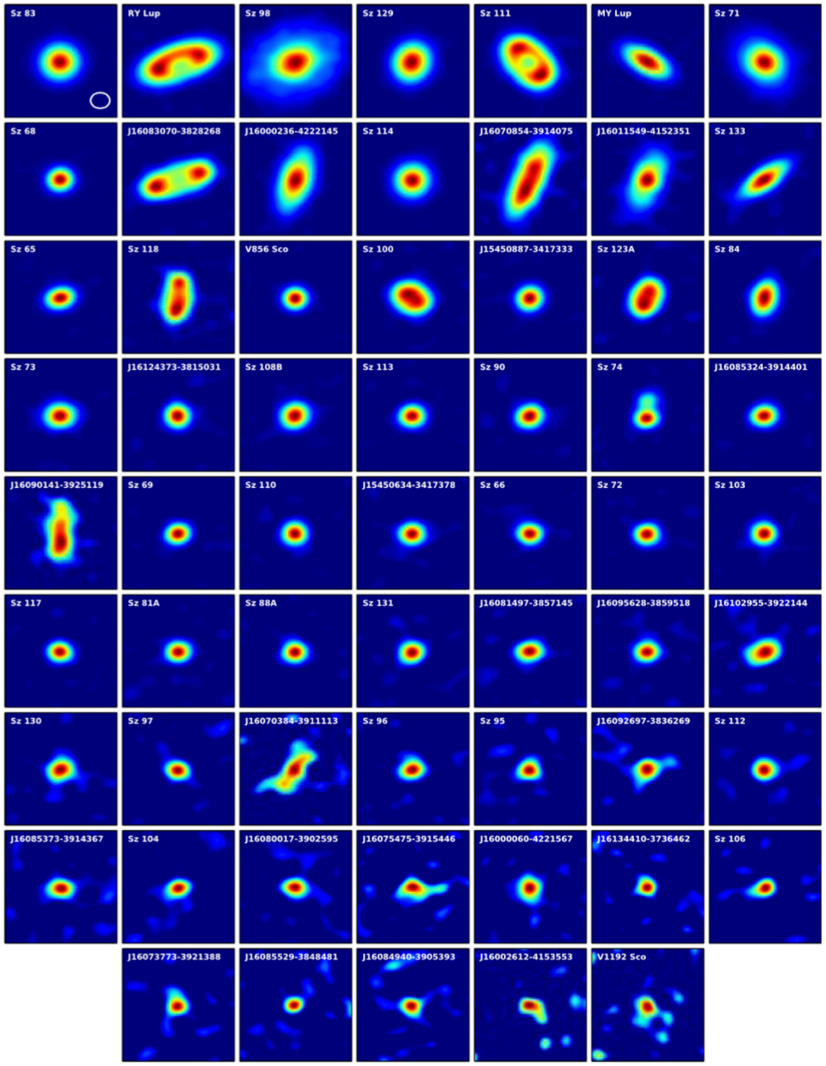
Star Forming Regions:

- Free-free emission from e.g. SN remnants, HII regions
- Gyrosynchrotron from large scale magnetic fields
- Thermal emission from embedded, clustered sources

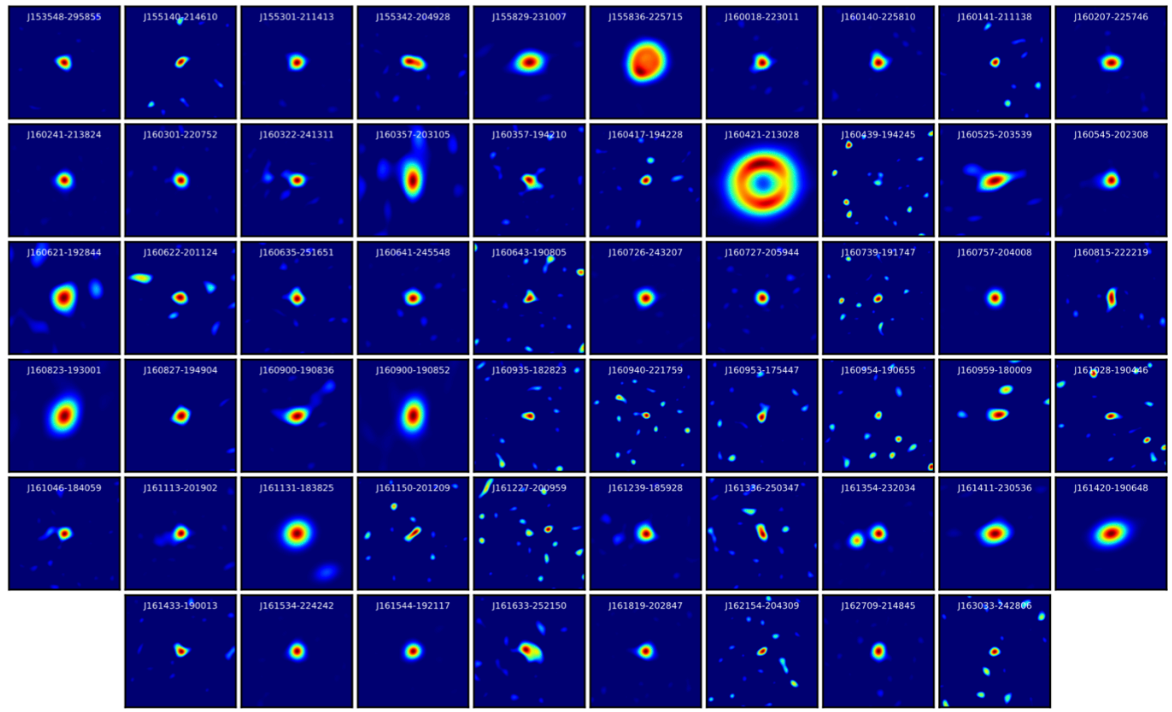
Individual Young Stars:

- Free-free emission from ionized outflows
- Gyrosynchrotron/Brehmstrahlung from magnetospheres
- Thermal emission from circumstellar disks

ALMA Continuum Data Spatially Resolves Circumstellar Disks

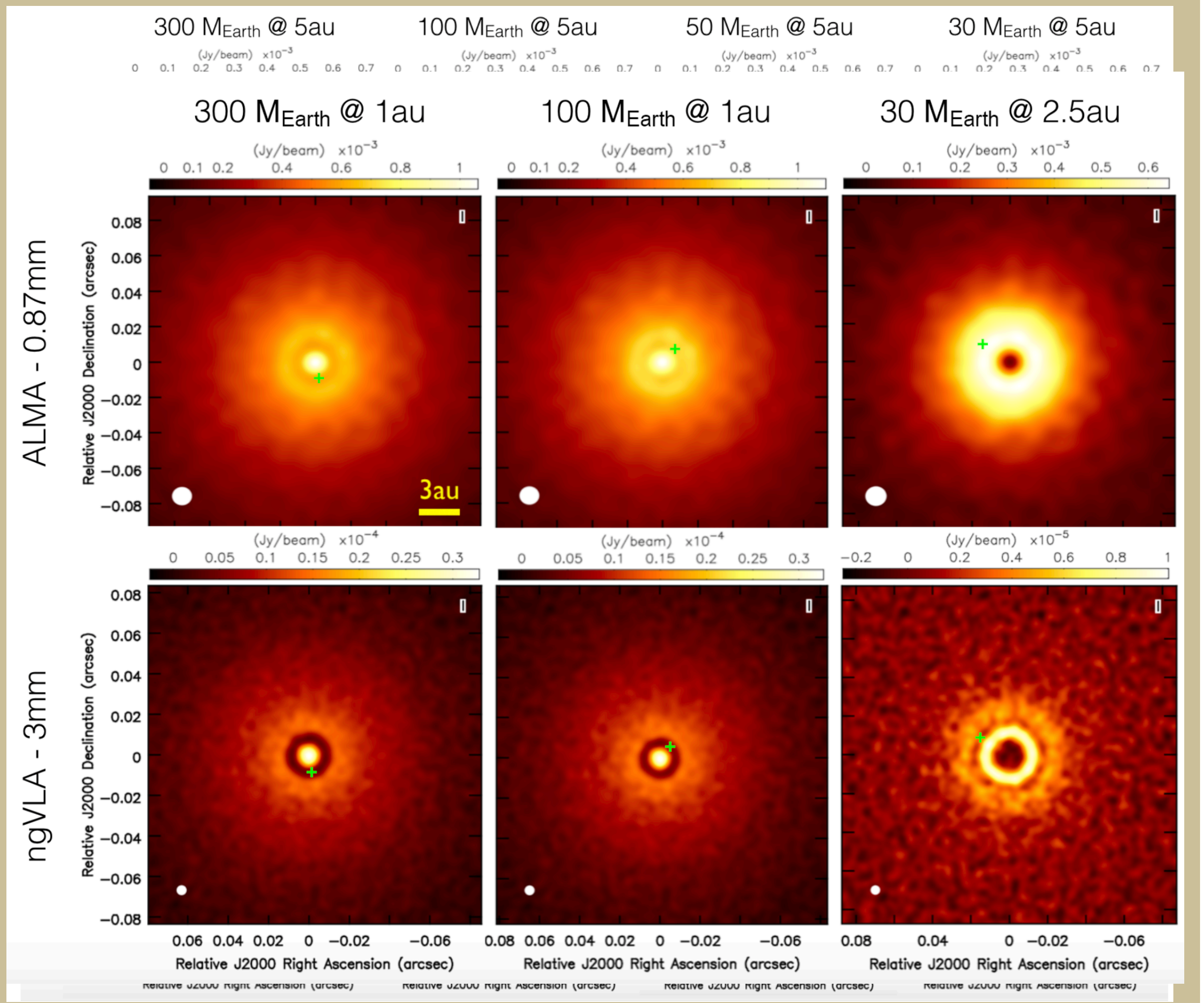


Ansdell et al. (2016)

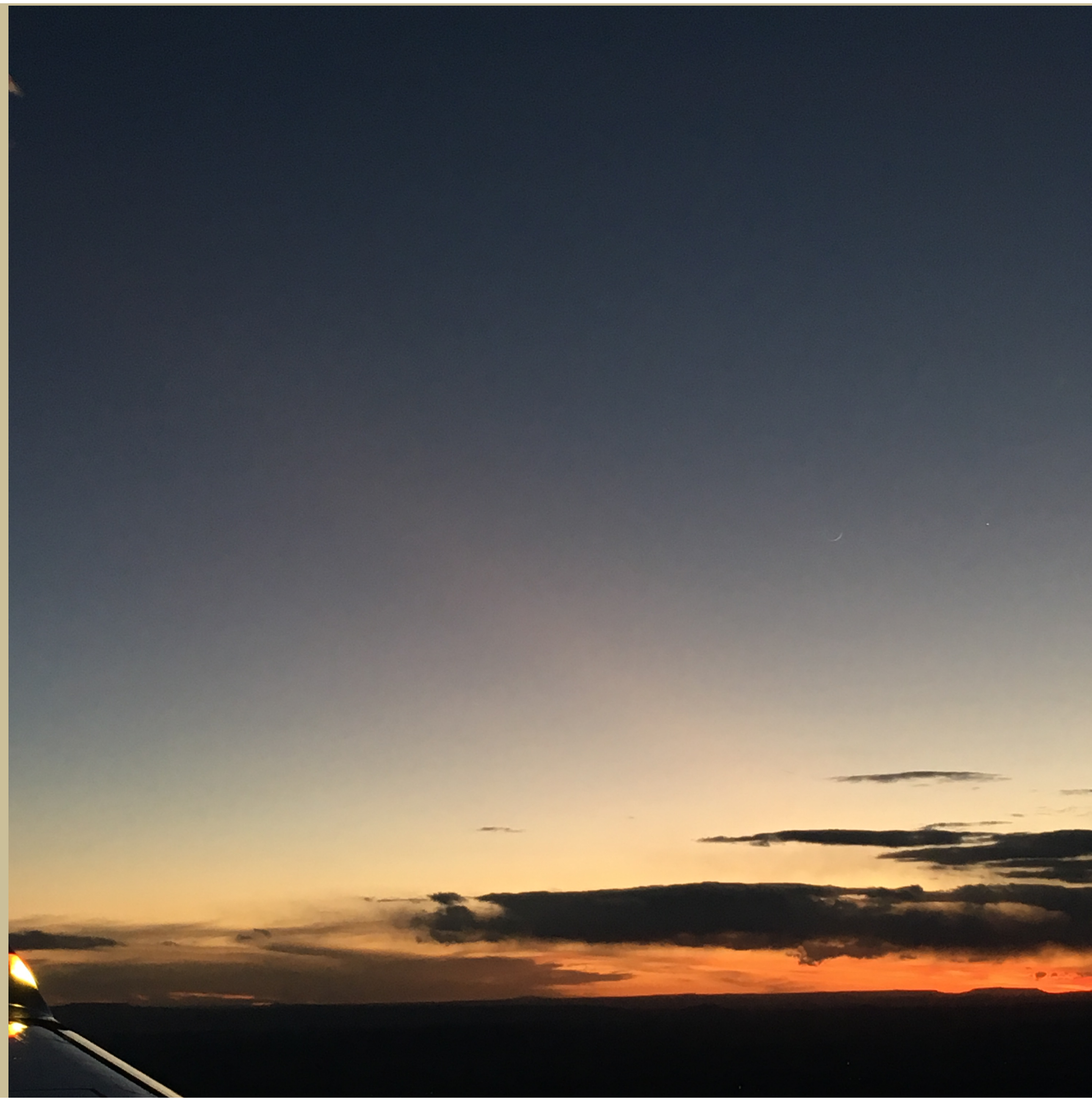


Barenfeld et al. (2017)

(Model)
Disks with Planets at Radio Wavelengths

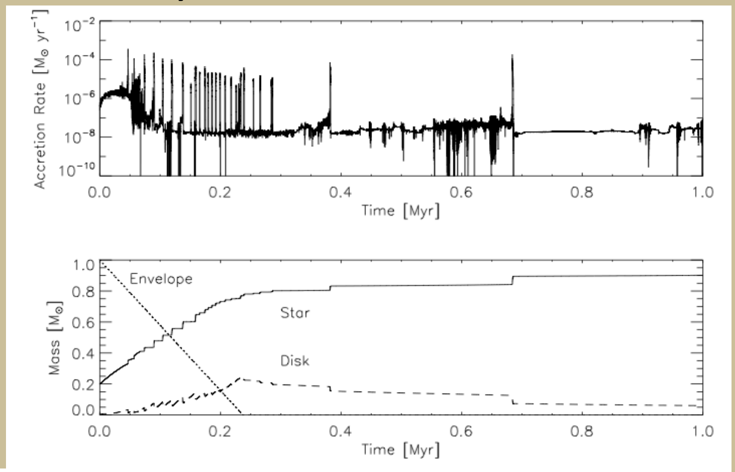


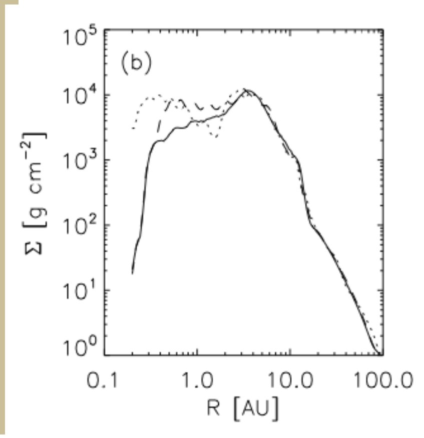
Ricci et al. (2018)



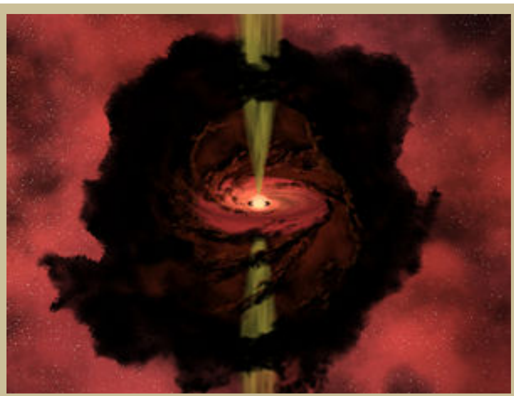
Star Formation and Disk Accretion / Evolution

early accretion and outflow

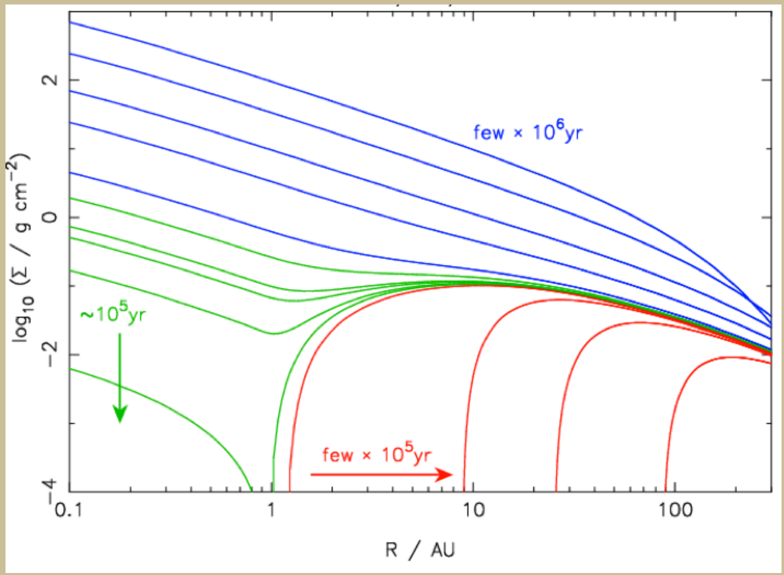




Bae et al. (2014)

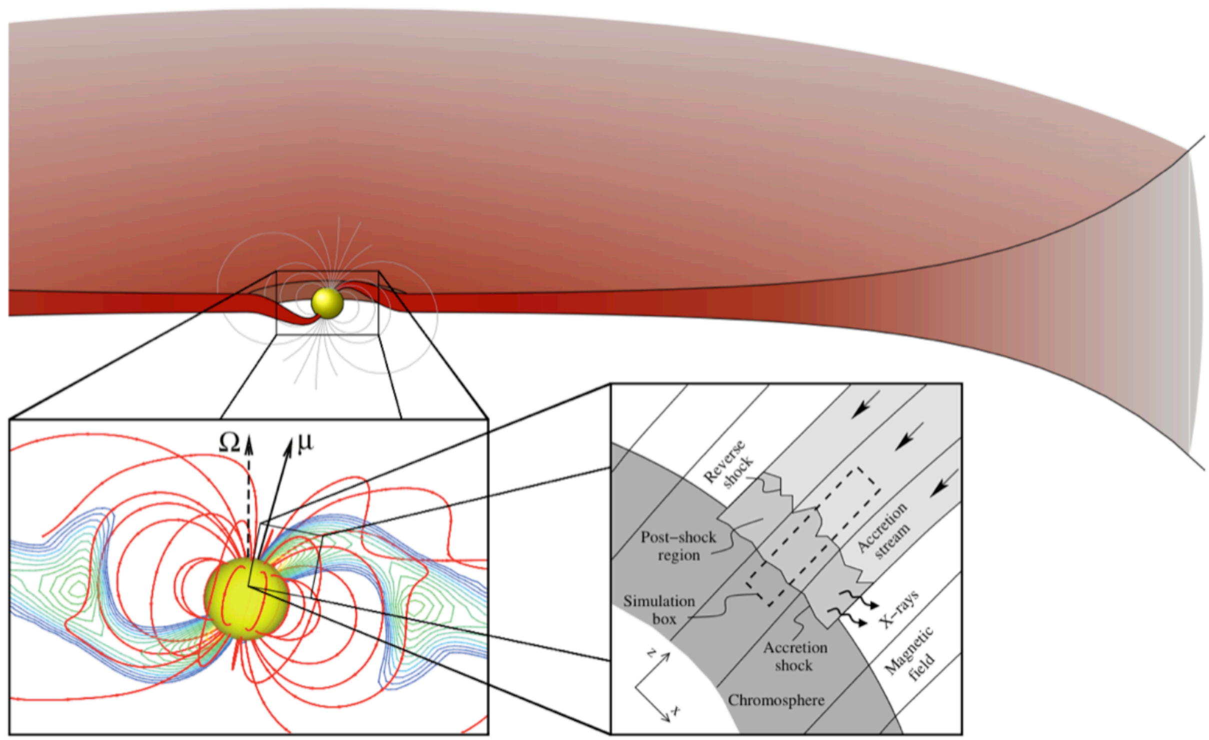


later, viscous evolution and photo-evaporative effects



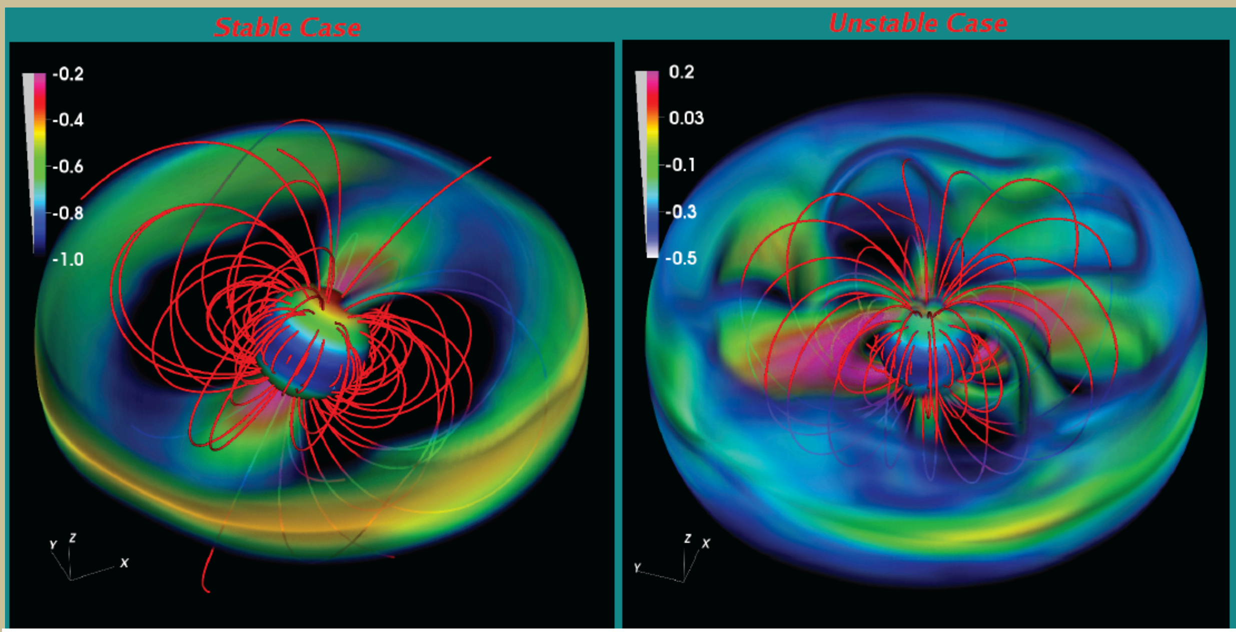
Alexander (2014)

Zooming in to the Disk-Magnetosphere-Star Zone



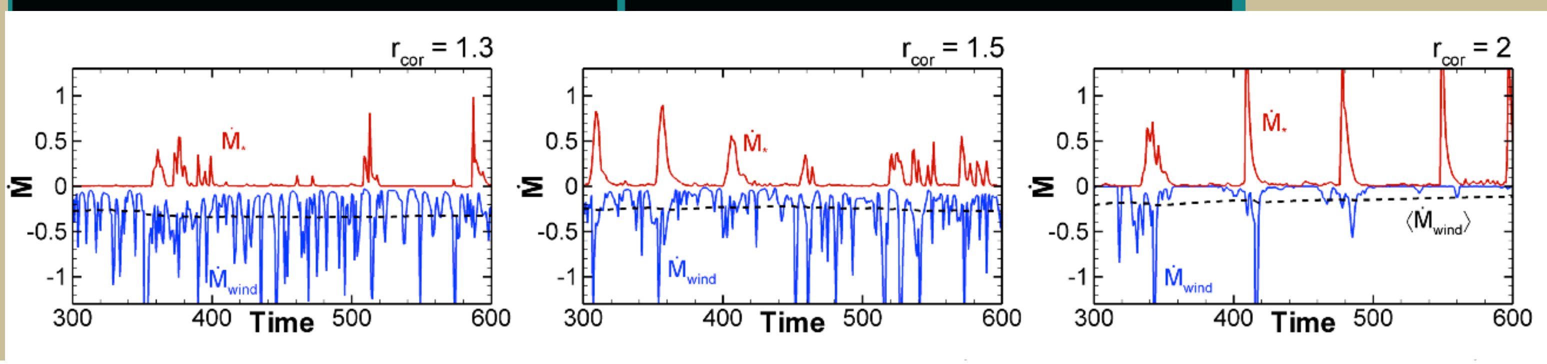
de Sá, Chièze, Stehlé+ 2014

How Does Gas get to the Star?



Kurosawa, Romanova

both accretion and ejection of material



How is Gas Ejected from the Star/Disk System?

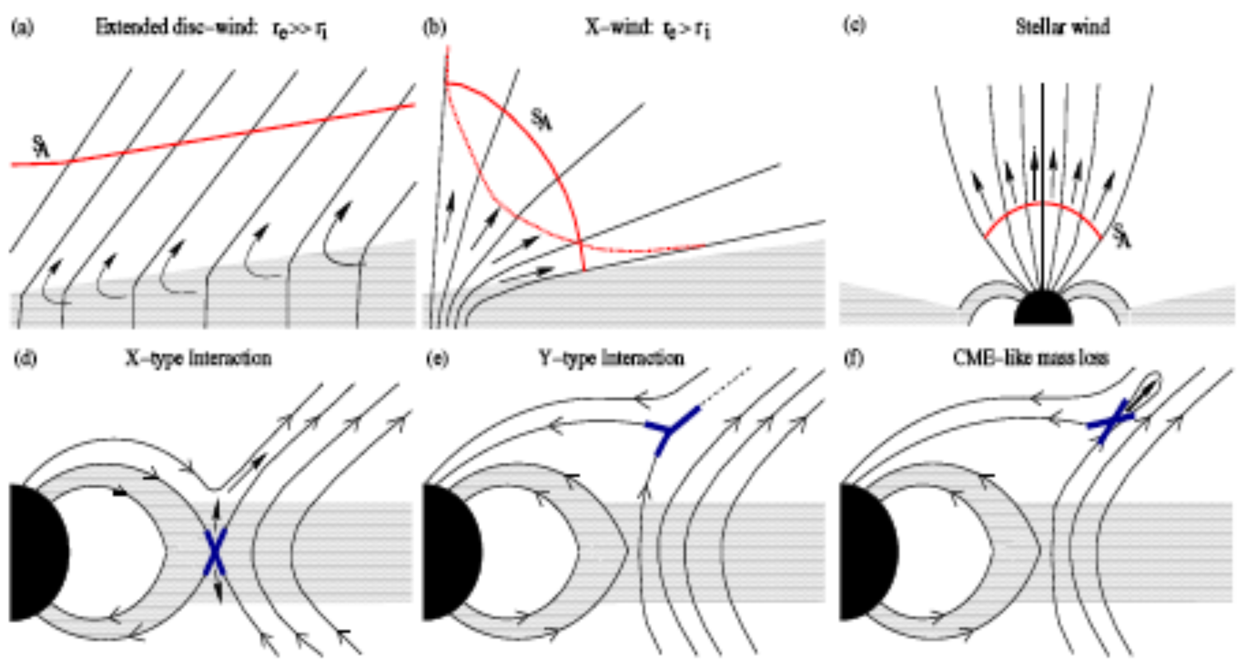
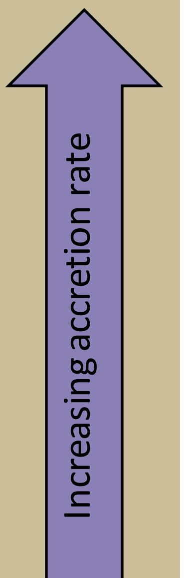
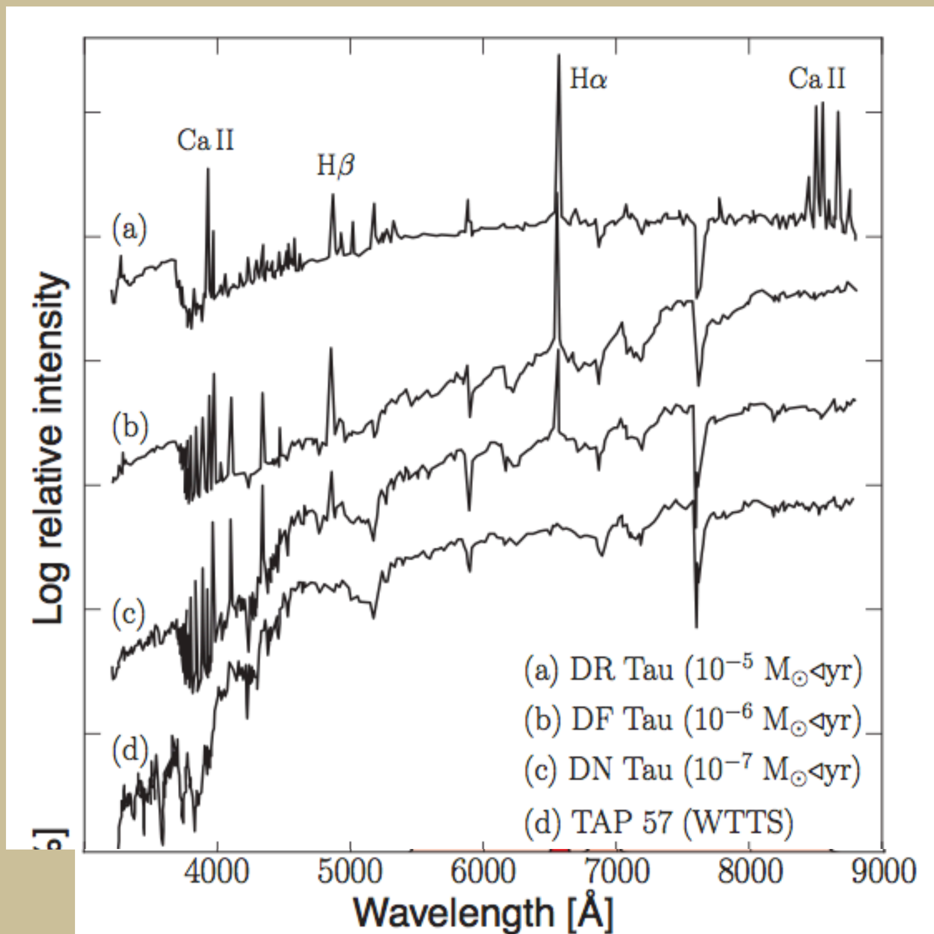


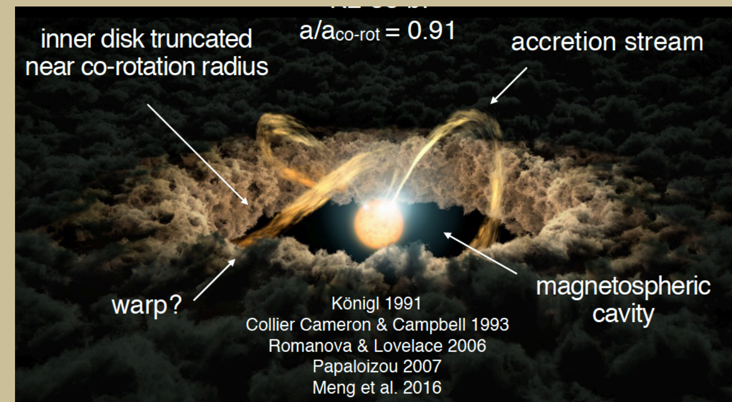
Fig. 1. Top: Classes of published stationary MHD jets for YSOs. When the magnetic field is threading the disc on a large radial extension (a: extended disc wind) or a small disc annulus (b: X-wind), jets are accretion-powered. They are mostly pressure-driven when the field lines are anchored onto a slowly rotating star (c: stellar wind). The corresponding Alfvén surfaces S_A have been schematically drawn (thick lines). In the X-wind case, two extreme shapes have been drawn: convex (solid line) and concave (dashed). **Bottom:** Sketch of the two possible axisymmetric magnetospheric configurations: (d) X-type neutral line driving unsteady Reconnection X-winds, when the stellar magnetic moment is parallel to the disc field; (e) Y-type neutral line (akin the terrestrial magnetospheric current sheet) when the stellar magnetic moment is anti-parallel (or when the disc field is negligible). (f) A CME-like ejection is produced whenever the magnetic shear becomes too strong in a magnetically dominated plasma. Such a violently relaxing event may occur with any kind of anti-parallel magnetospheric interaction (even with an inclined dipole). The thick lines mark the zones where reconnections occur.

Ferreira et al. 2006





Barensten et al. 2013



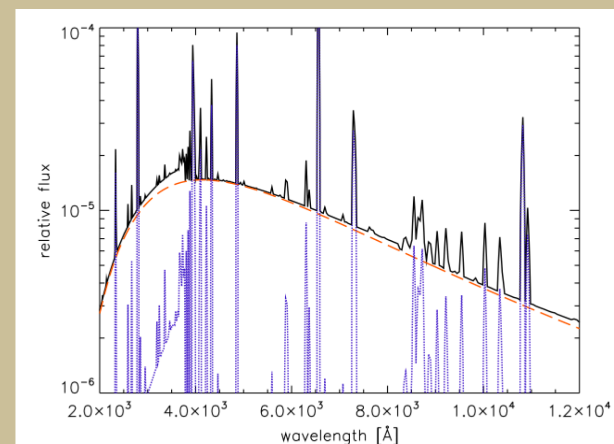
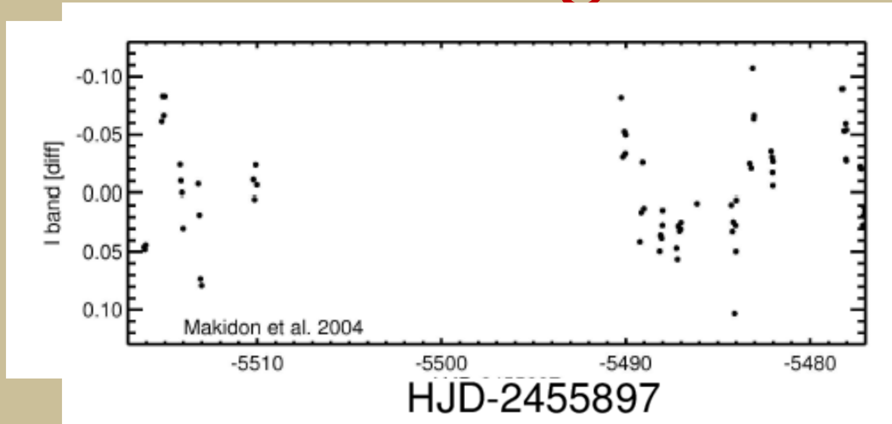
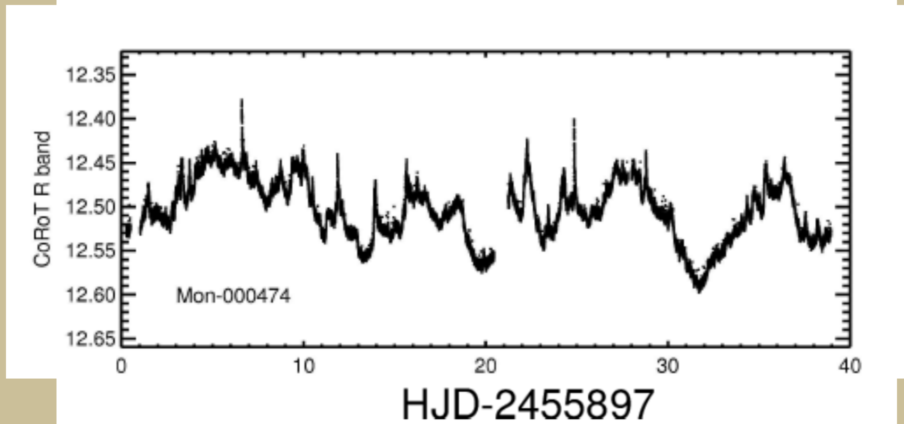


Figure 7. Accretion spectrum simulated with CLOUDY. The solid line is the total emission, which is the superposition of an optically thick emission, with $T_{\rm eff}$ = 7000 K, of the heated photosphere (dashed line) and the optically thin emission of ionized gas with density $n = 10^8$ cm^{-3} (dotted line).

Da Rio et al. 2010

The Quality of Modern Time-Series Optical-Wavelength 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

[McJunkin et al. 2013]

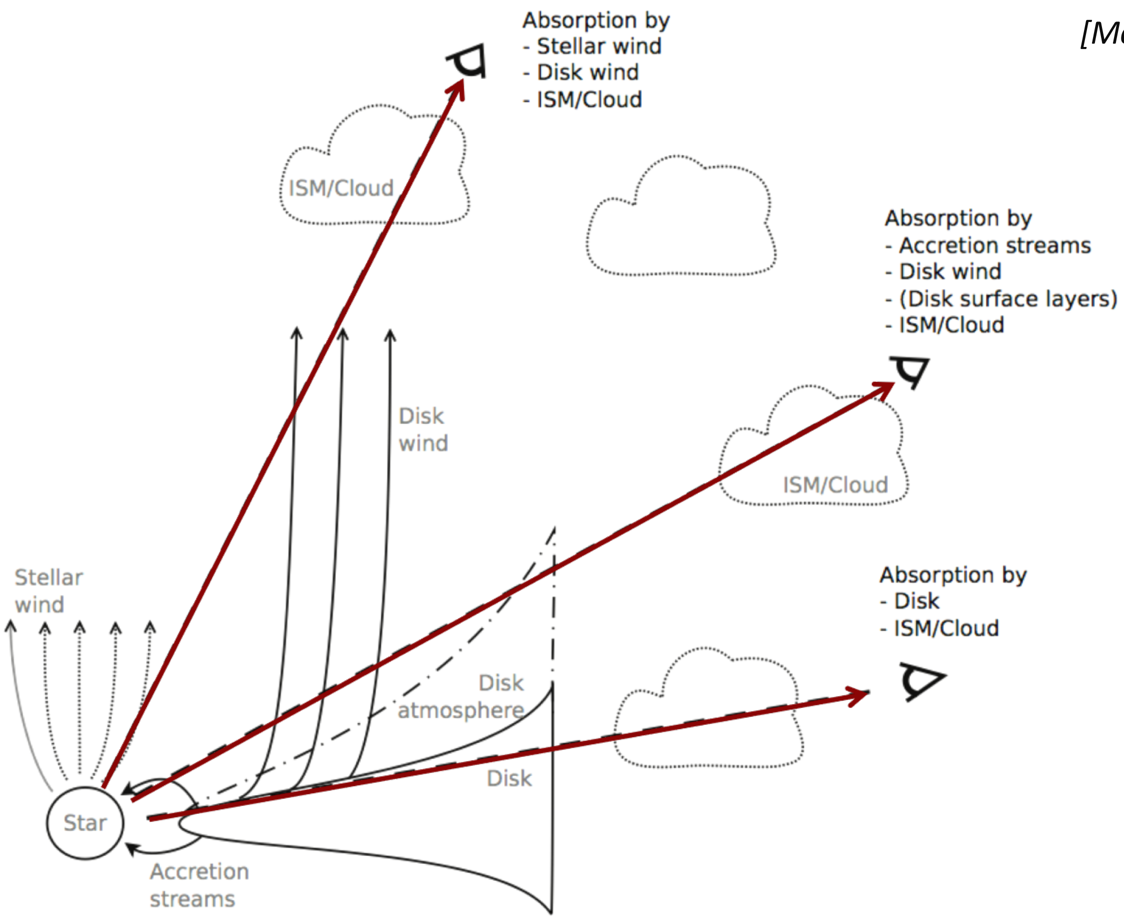
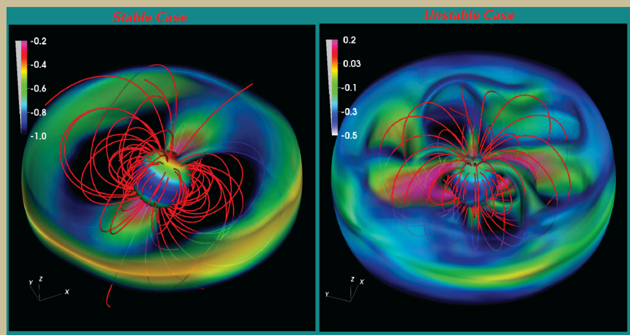
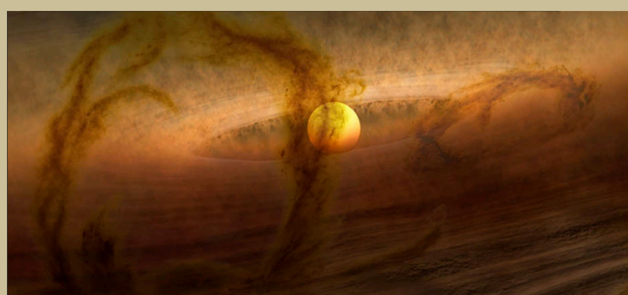


Fig. 9.— Sketch of the important components contributing to the absorption of the stellar emission. The absorption depends strongly on the viewing geometry. Lines with arrows indicate the plasma motion. Sightlines are dashed.

Young Star Variability

Kurosawa, Romanova





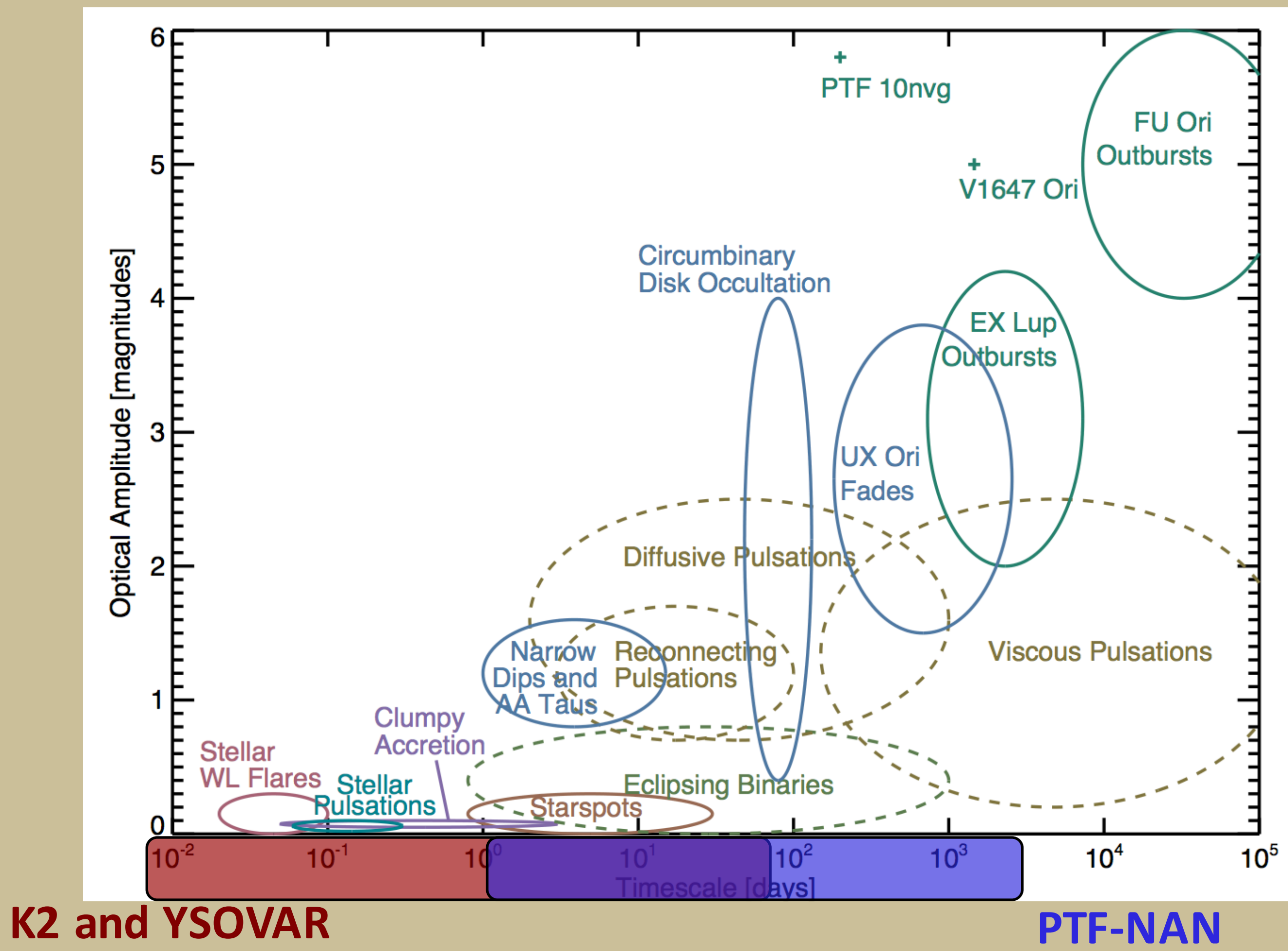
- Mechanisms include:
  - time variable magnetic activity on star
  - rotation of stellar surface inhomogeneities e.g. cool or hot spots
  - possible pulsation phenomena
  - time variable accretion from disk to star
  - disk inhomogeneities e.g. orbiting warps or vertical circulation
  - binary phenomena.
- Amplitudes range from <0.01 mag to >5 mag, typically 0.1-0.2 mag.
- Time scales range from hours to years, typically 0.5-2 days.

stellar

disk-related

- PTF dataset @ intermediate cadence = nightly during season, with gaps for weather, moon, etc.
  - Typically 150-200 epochs over 3 years; one region with 1300 epochs over 7 years.
  - About 20 star forming regions targeted.
- K2 dataset @ high cadence = every 30 min with no gaps.
  - Duration of 70-80 days.
  - Rho Oph / Upper Sco and Taurus are only young regions targeted.

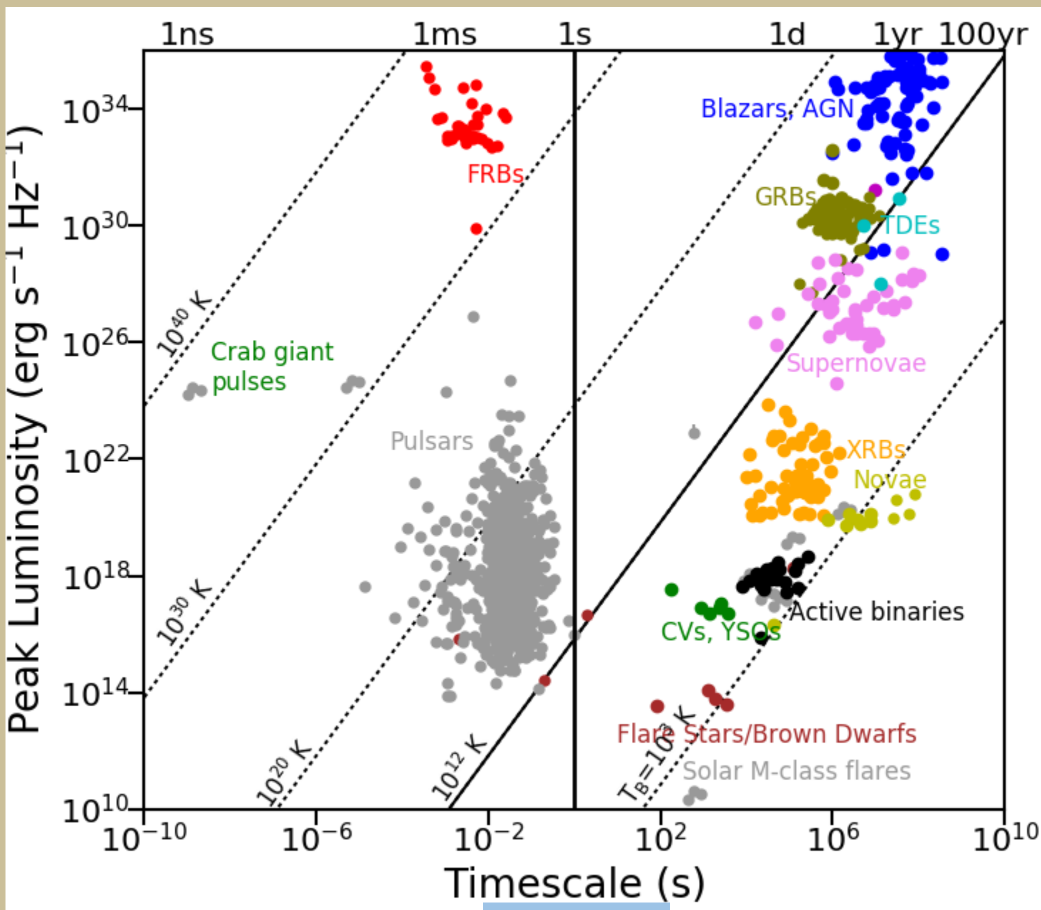
Expected Parameter Space for Young Star Variability



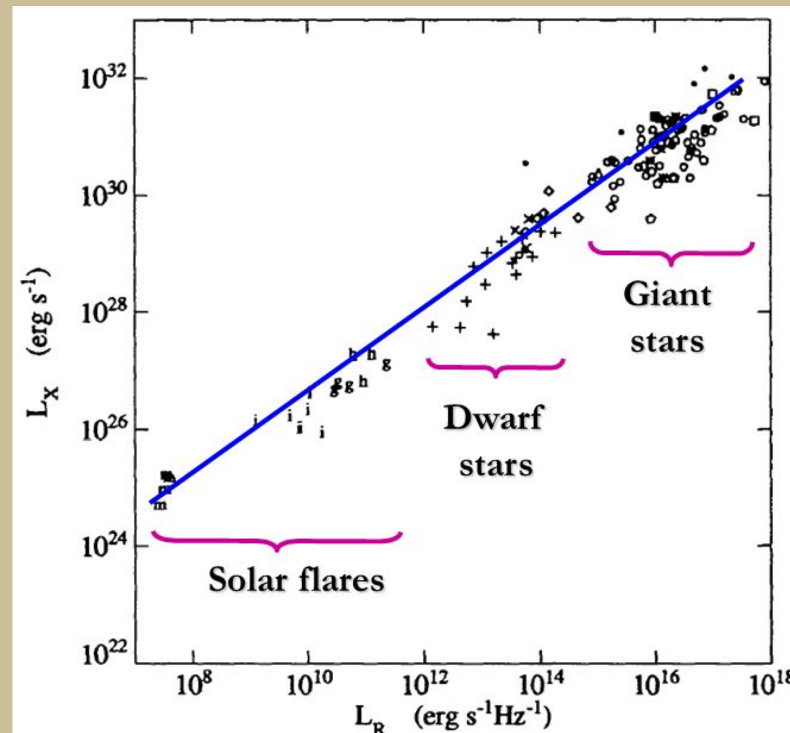
Hillenbrand & Findeisen, 2015

Young Stars In the Context of Known Radio Transient Classes

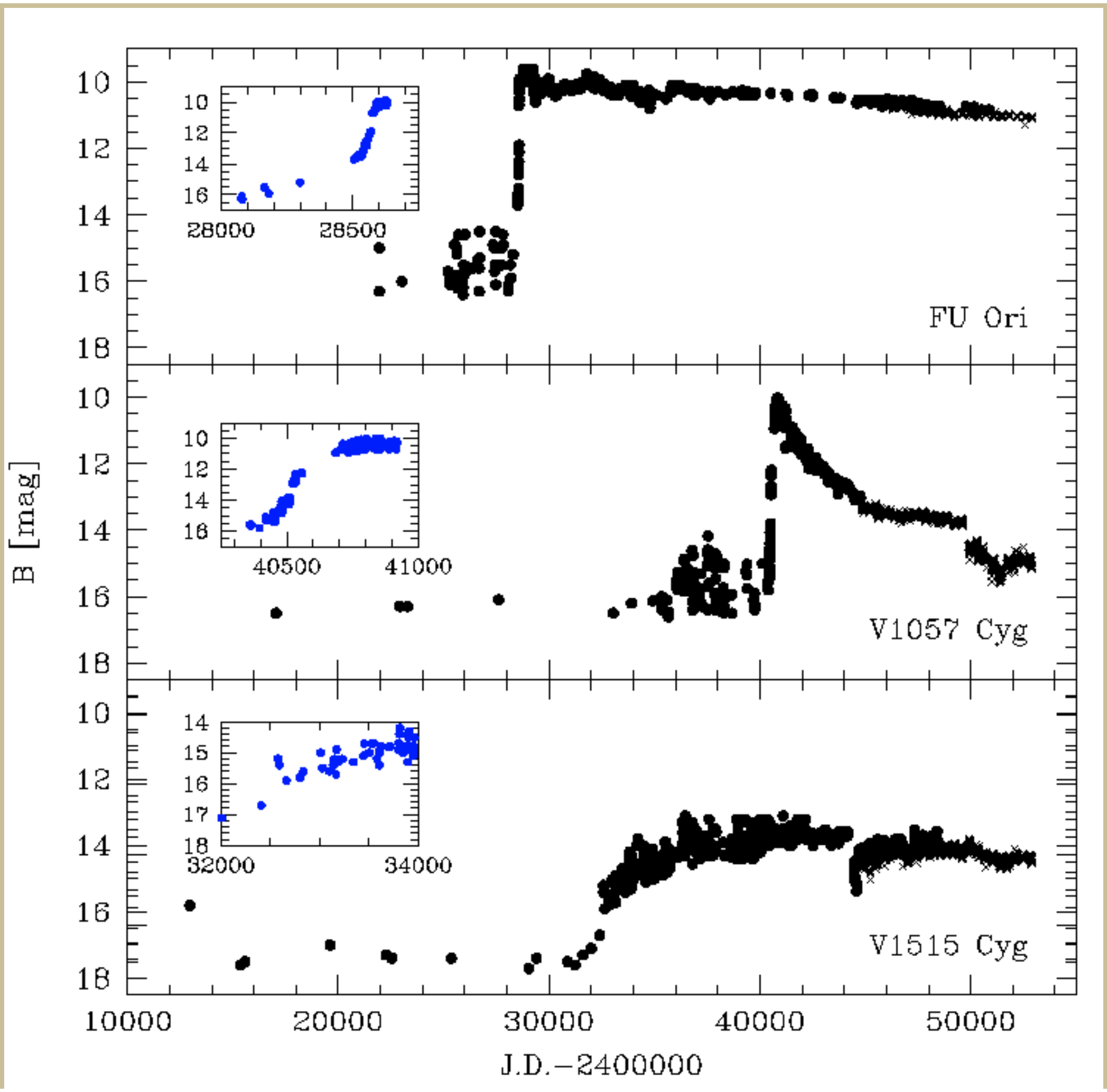
Radio Luminosity at Peak



Rise Time



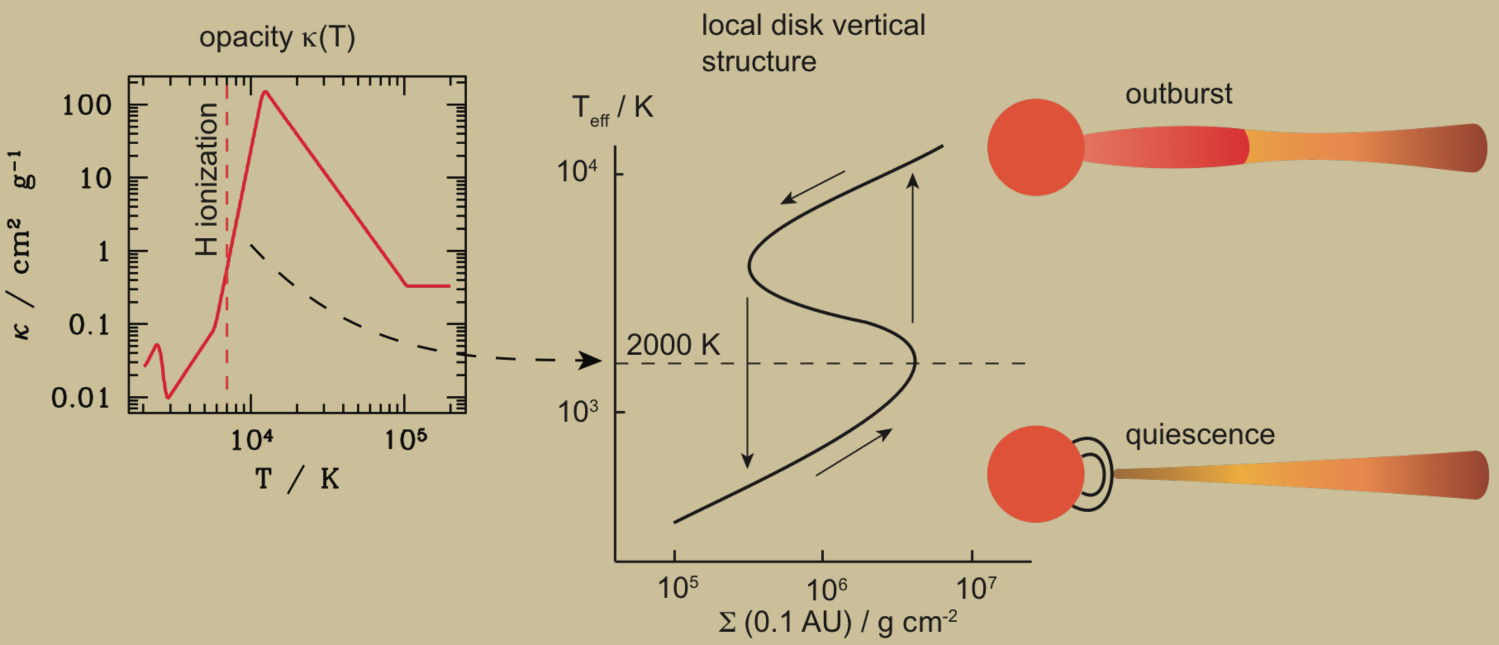
[image credit: K. Mooley]



The First Three FU Ori Stars

Inner Disk Instabilities

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

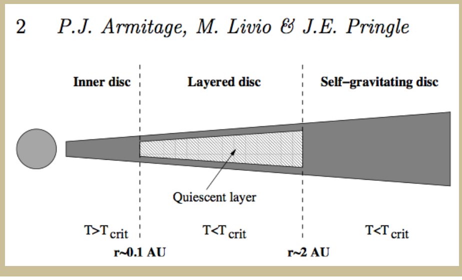


Armitage (2010)

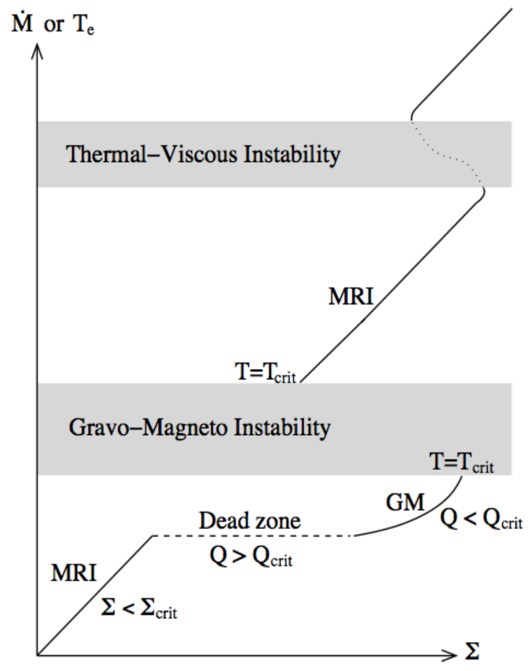
Inner Disk Instabilities

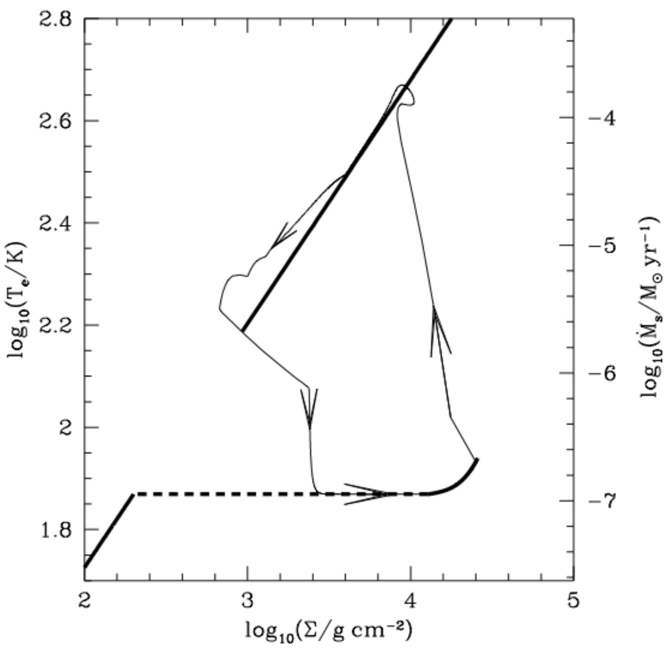
- *Magneto-rotational instability, driven by*
  - *change in ionization e.g. Balbus & Hawley (1991)*
  - *change in alpha e.g. Zhu et al*
- *Gravitational instability driven by accumulation of mass*

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



Armitage (2010)

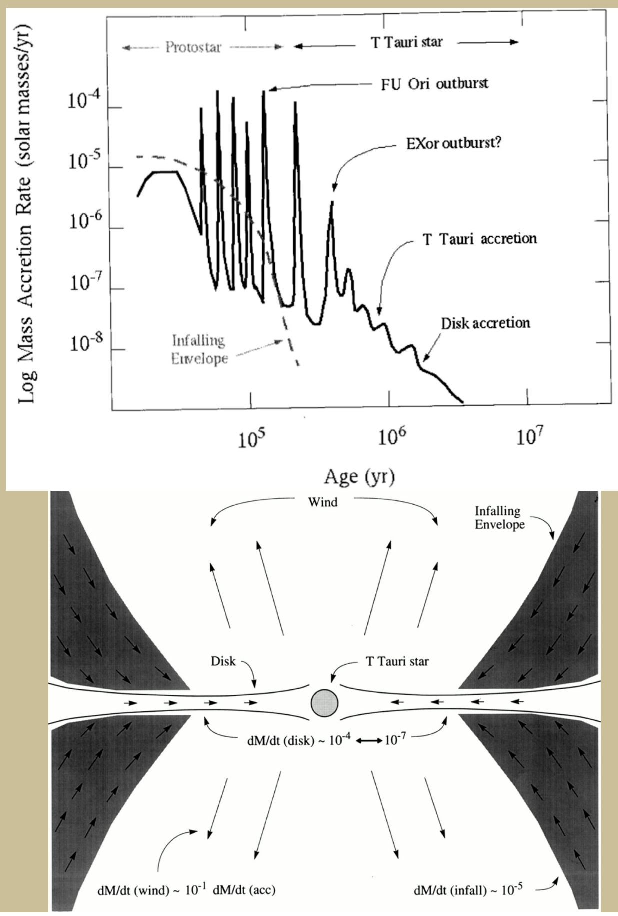




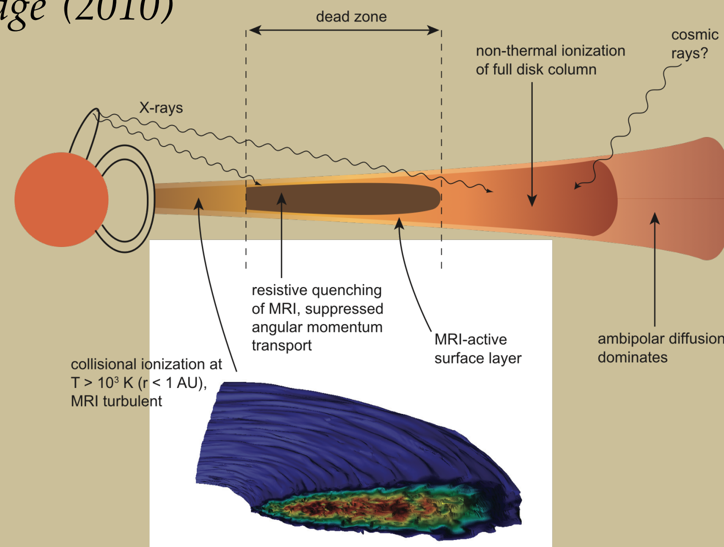
tic diagram of steady disk solutions in the Σ–$\dot{M}$ plane at some radius in

The FU Ori paradigm: episodic disk instability

Hartmann & Kenyon (1996)



Armitage (2010)



- Steady state can't be the full story as it is not enough to deplete disk "in time" via M / (dM/dt).
- But catching an FU Ori outburst is rare.

Extreme Outbursts – How Frequent?

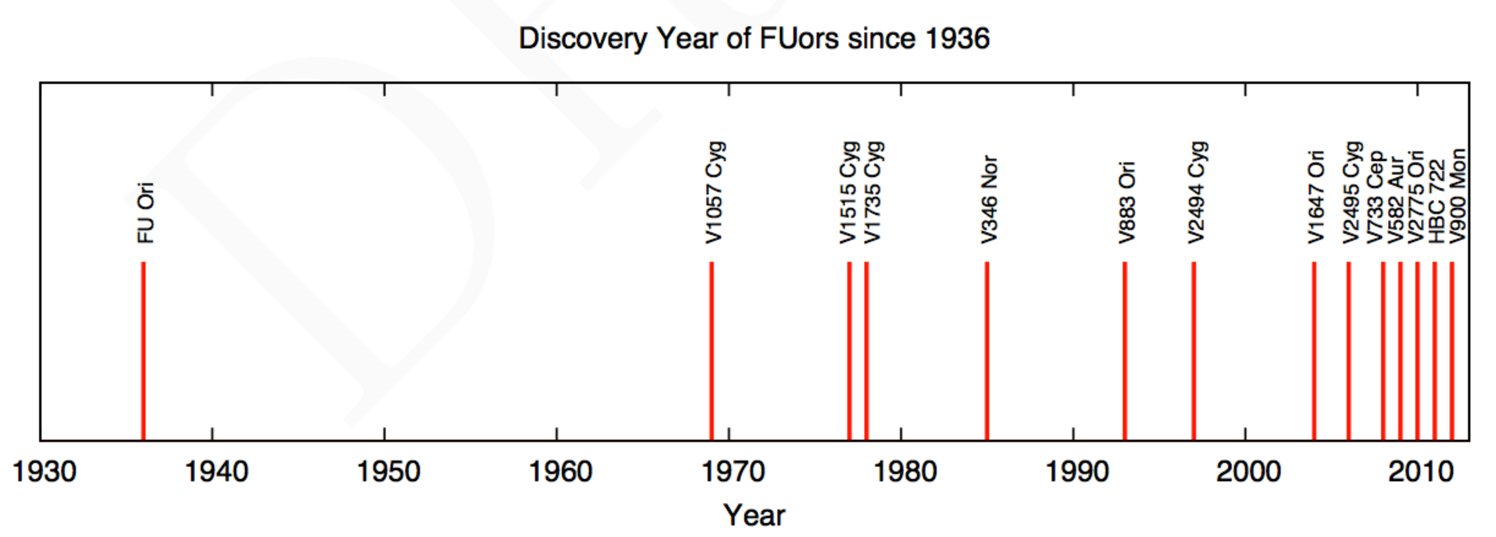
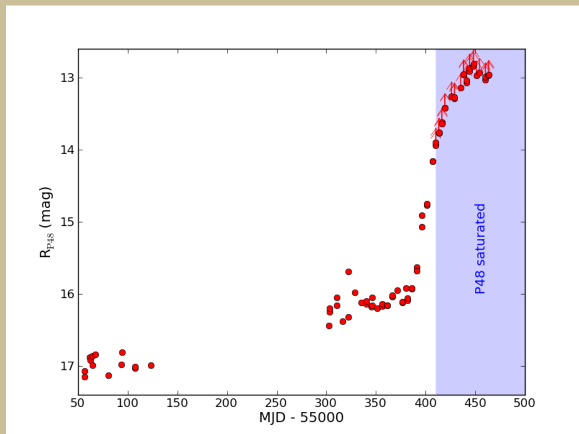


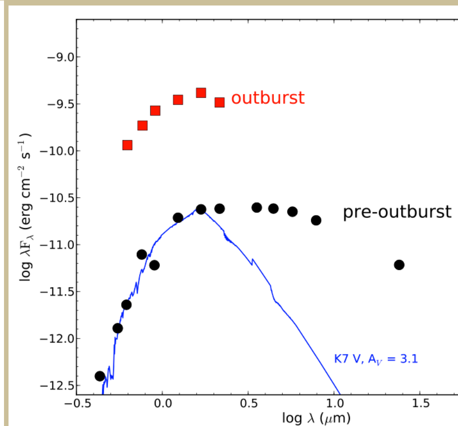
Figure 72: *The number of FUor discoveries has been increasing since the FU Ori outburst was observed in 1936.*

figure credit: B. Reipurth

Witnessing an FU Ori Outburst

Miller et al. (2011)





PTF10qpf

=

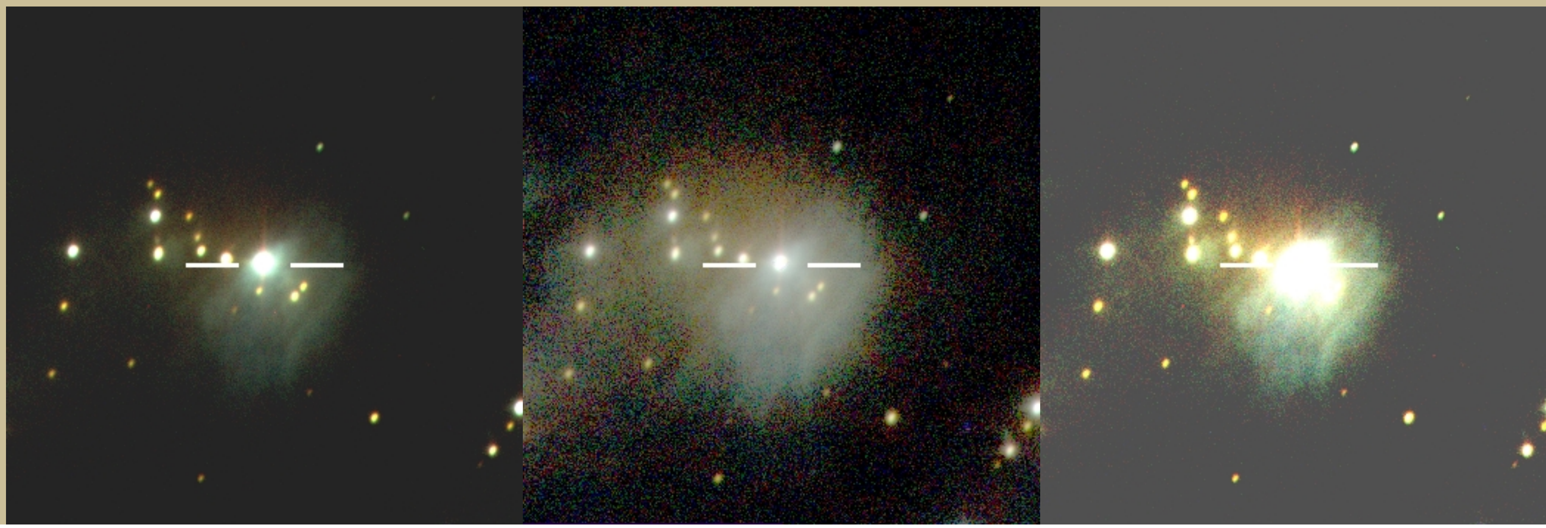
LkHa 188/G4

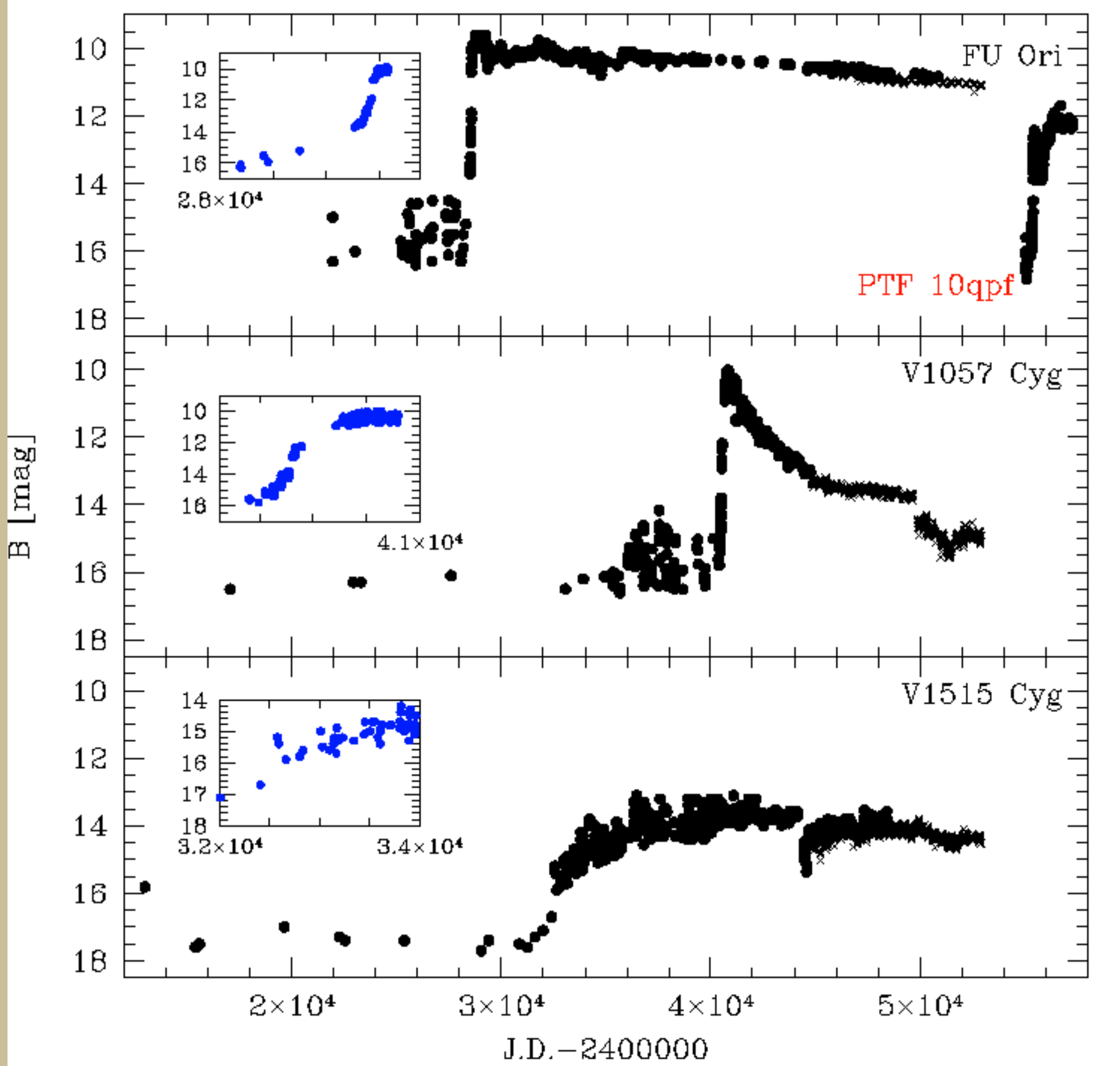
=

HBC 722

=

V 2493 Cyg



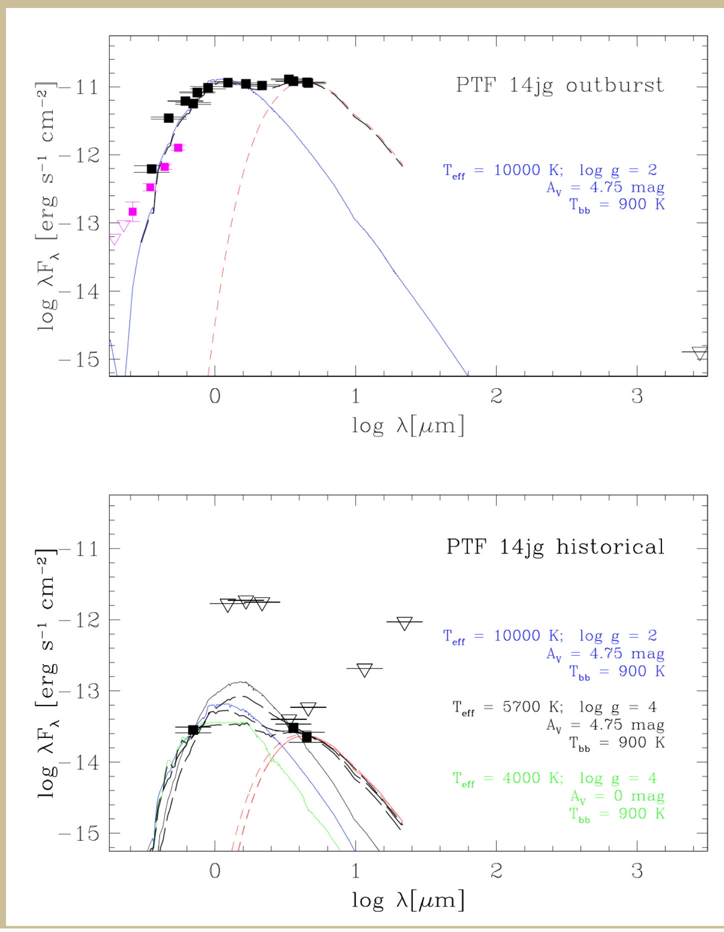


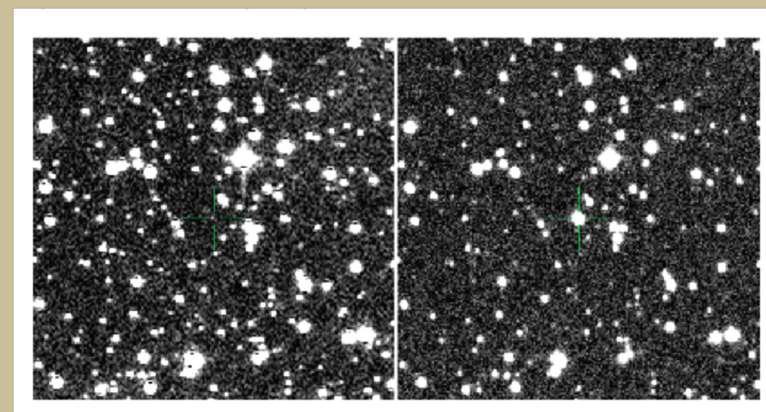
A New Addition to the FU Ori Class

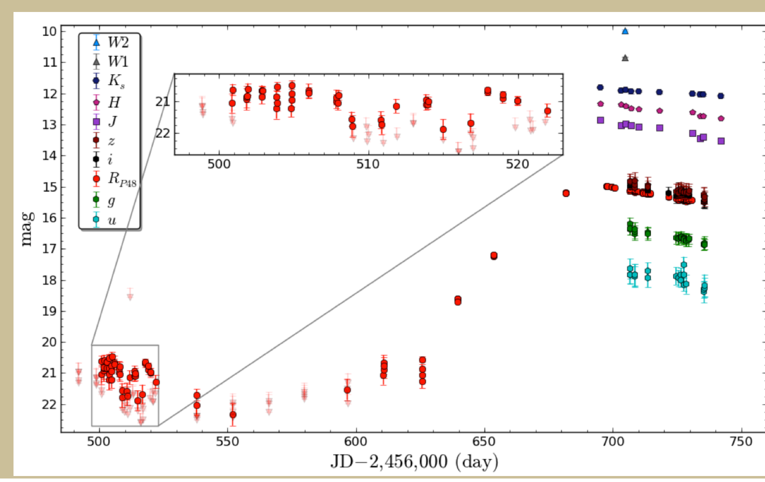
Another Likely FU Ori

Hillenbrand et al. (2018)

PTF14jg
(near W4 HII region)







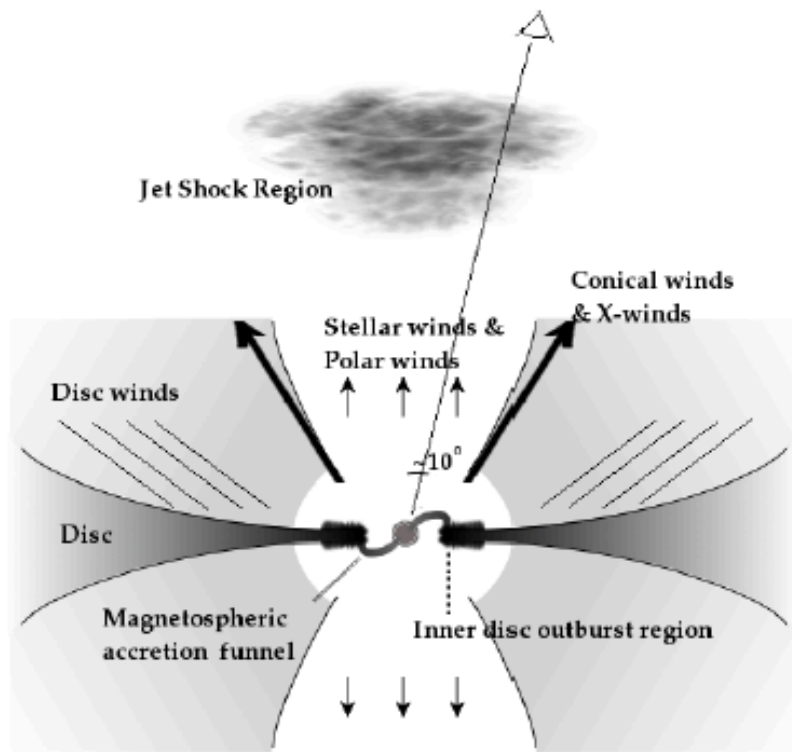
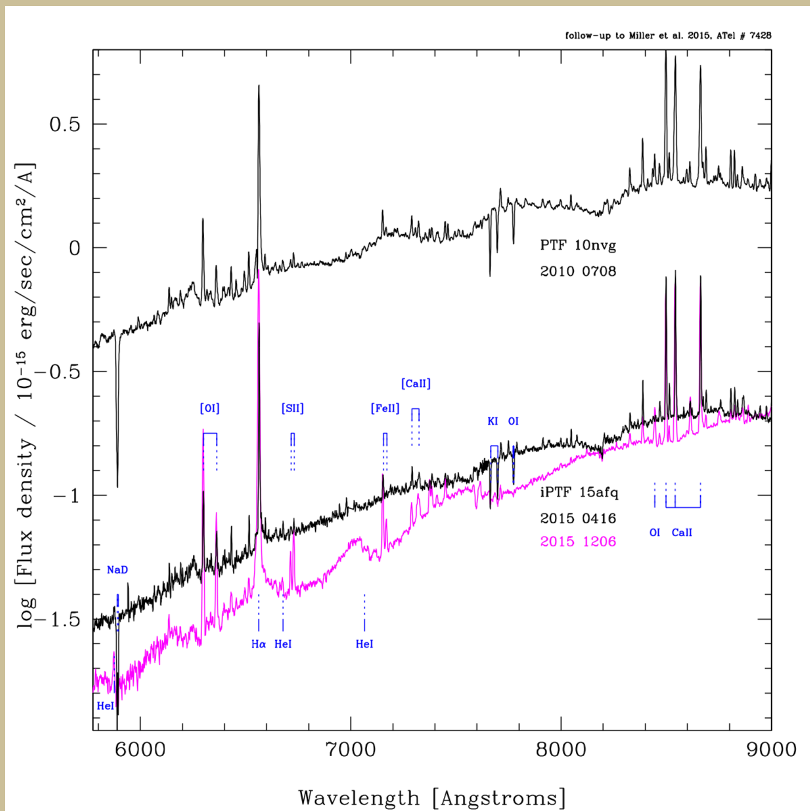


FIGURE 2: Schematic diagram of various outflow mechanisms which could be present in V899 Mon.

Ninan et al. (2016)

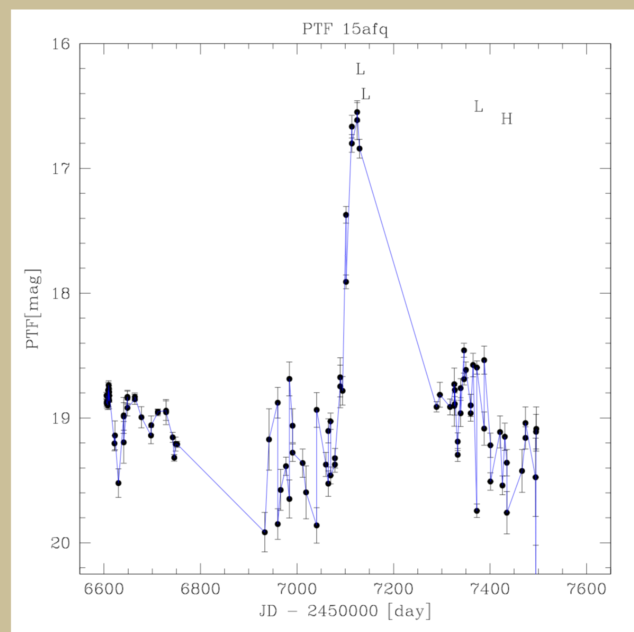
A Large, Short-lived Burst



Miller et al. (2015)

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

PTF15afq



Inner Disk Instabilities

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

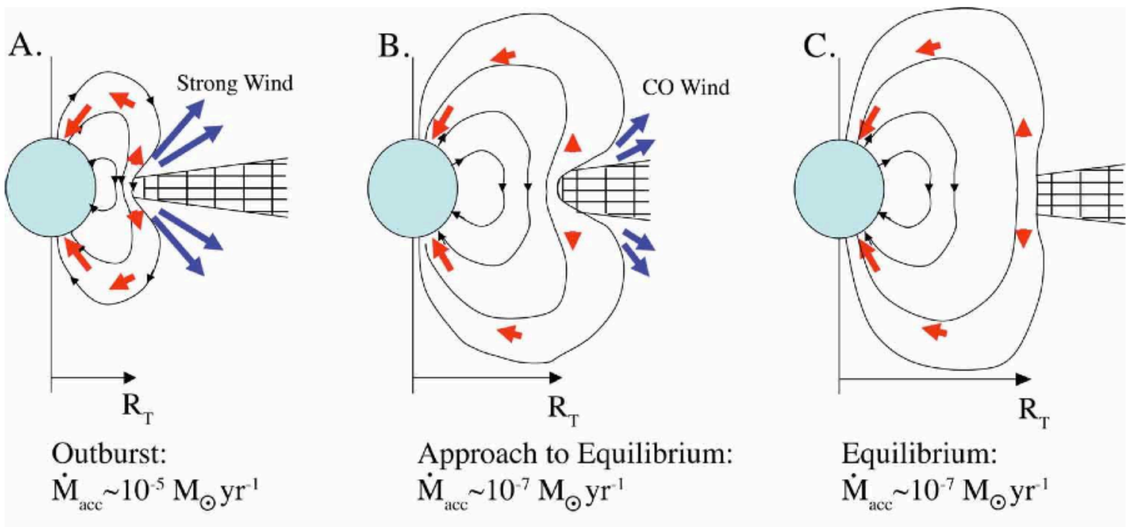
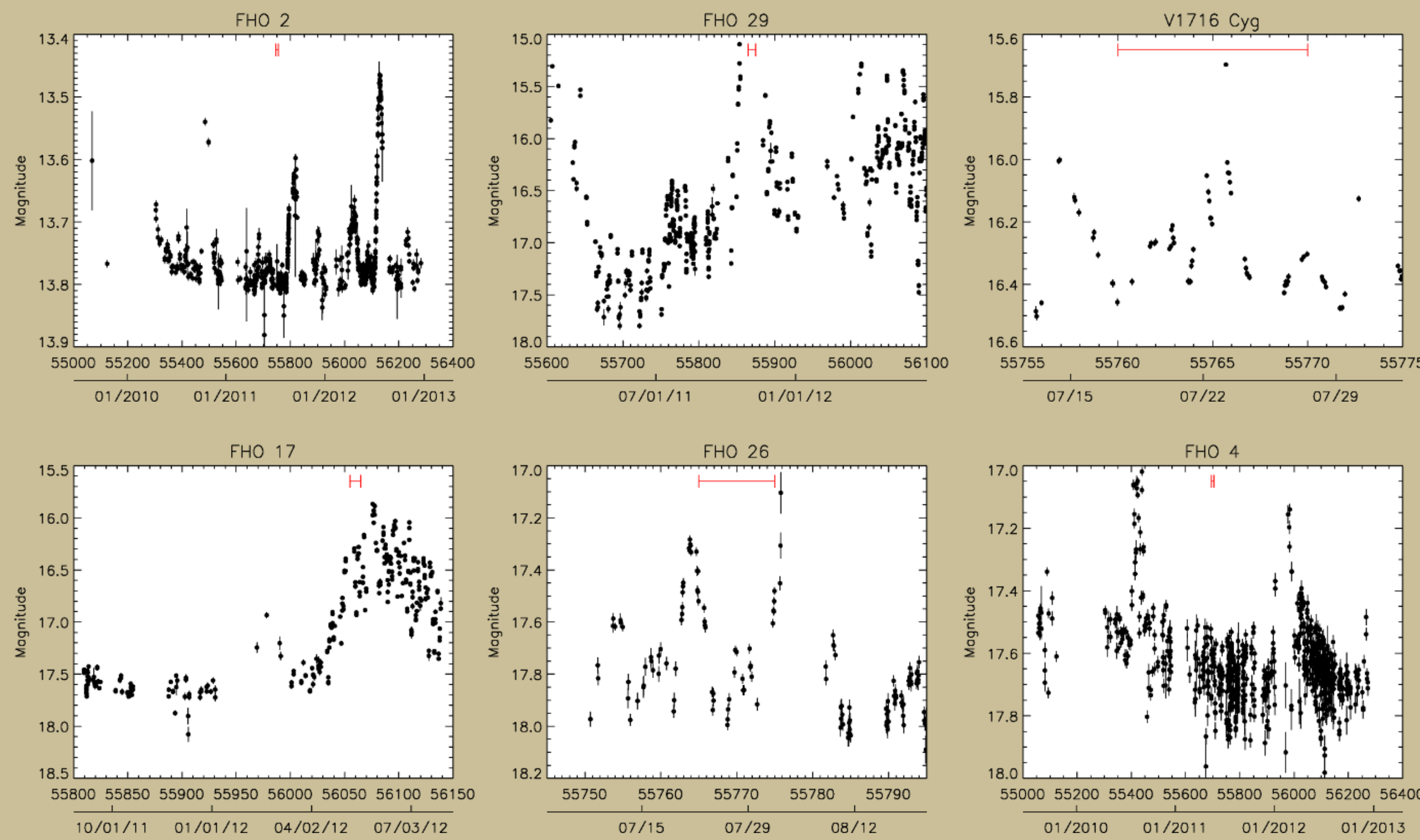


Fig. 6 Schematic model of an Exor V1647 Ori. During the outburst the accretion rate is enhanced so that the magnetospheric radius R_m decreases and the magnetic field lines were bunched (A). This results in a fast, hot outflow. As the accretion rate decreases, the disk moves outward and this results 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).

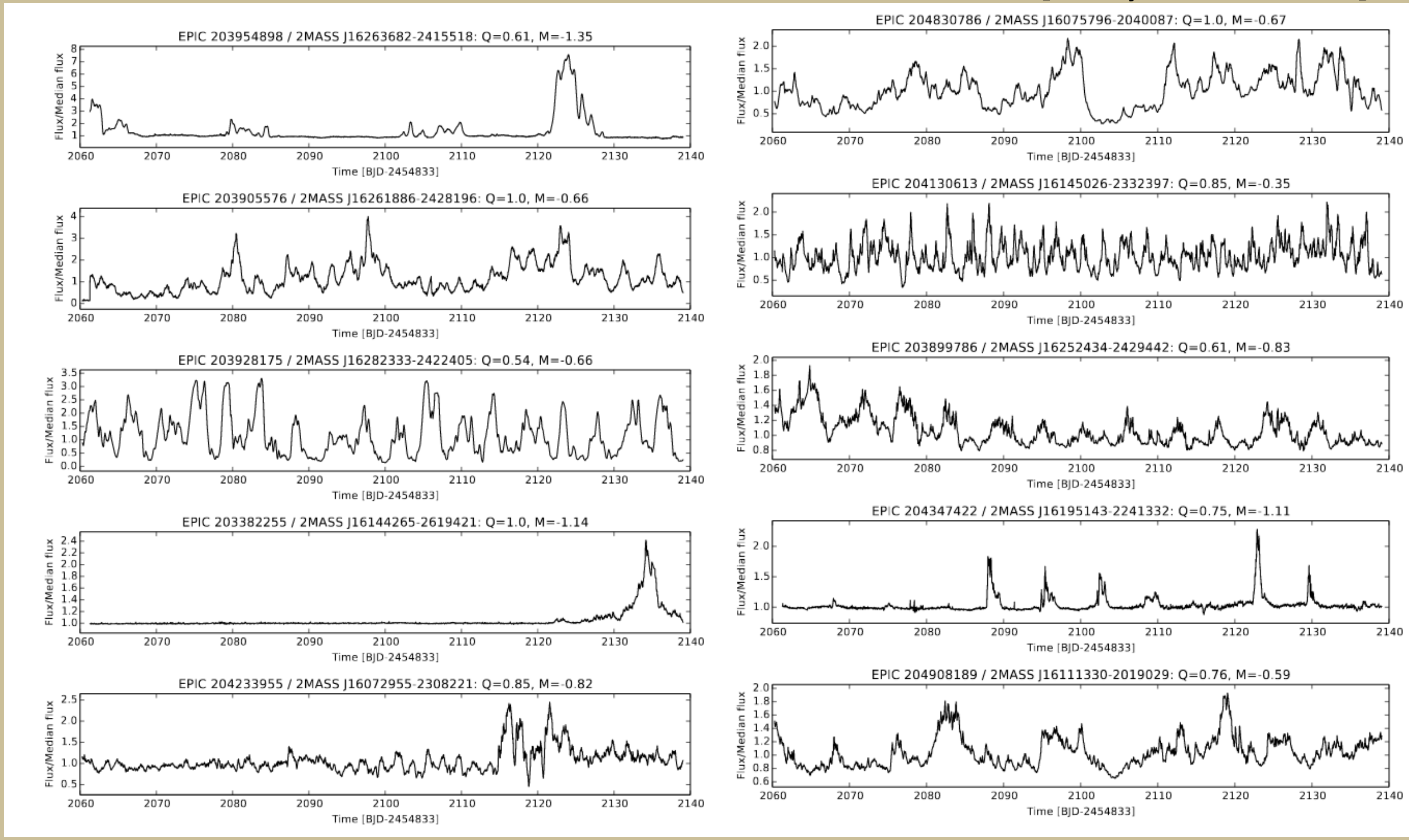
Small and Moderate-Amplitude Bursters in PTF



[Findeisen et al. 2013]

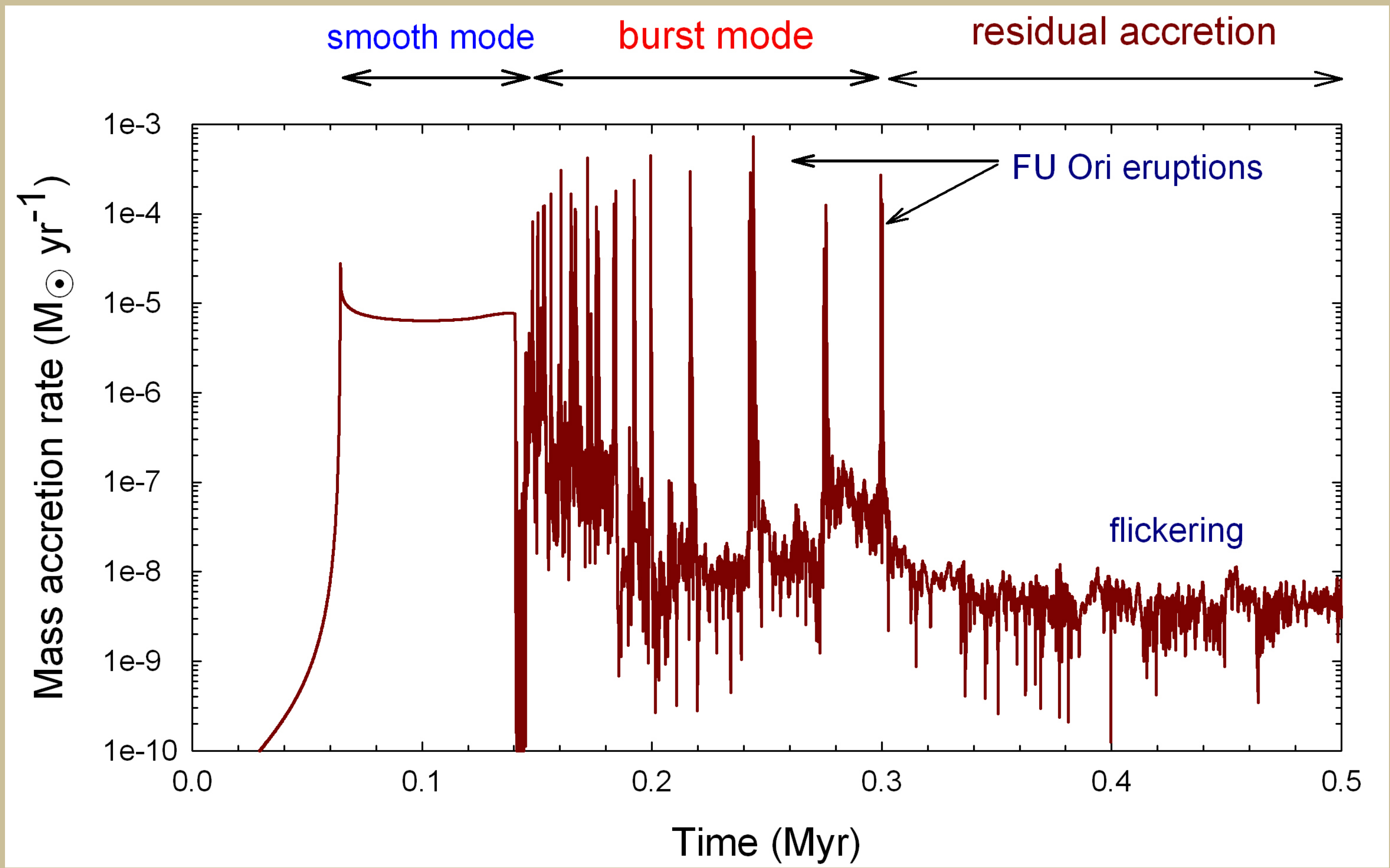
A Continuum of Accretion Burst Behavior

[Cody et al. 2017]

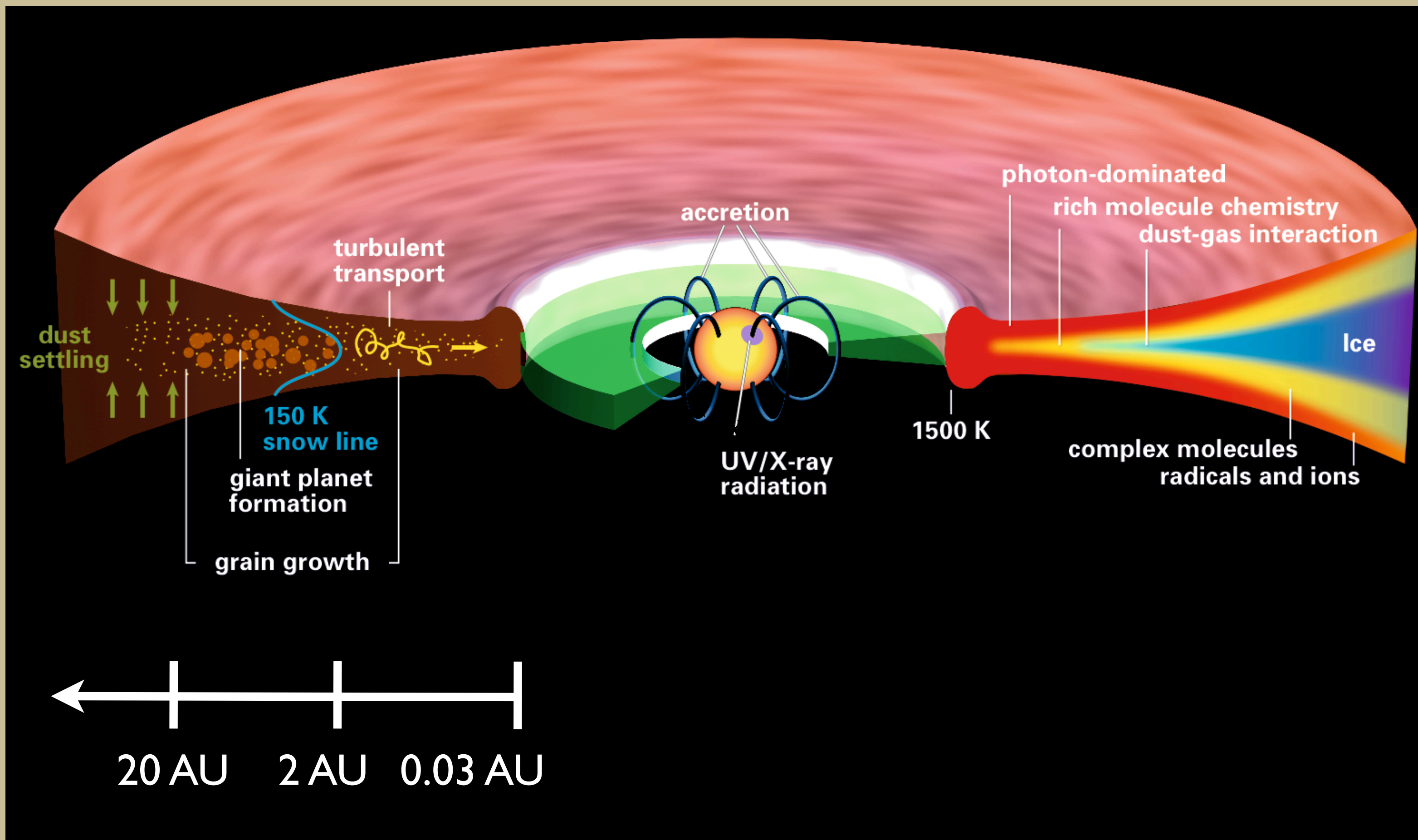


14% of the objects with disks exhibit with these types of lightcurves

Extreme Outbursts – How Frequent?

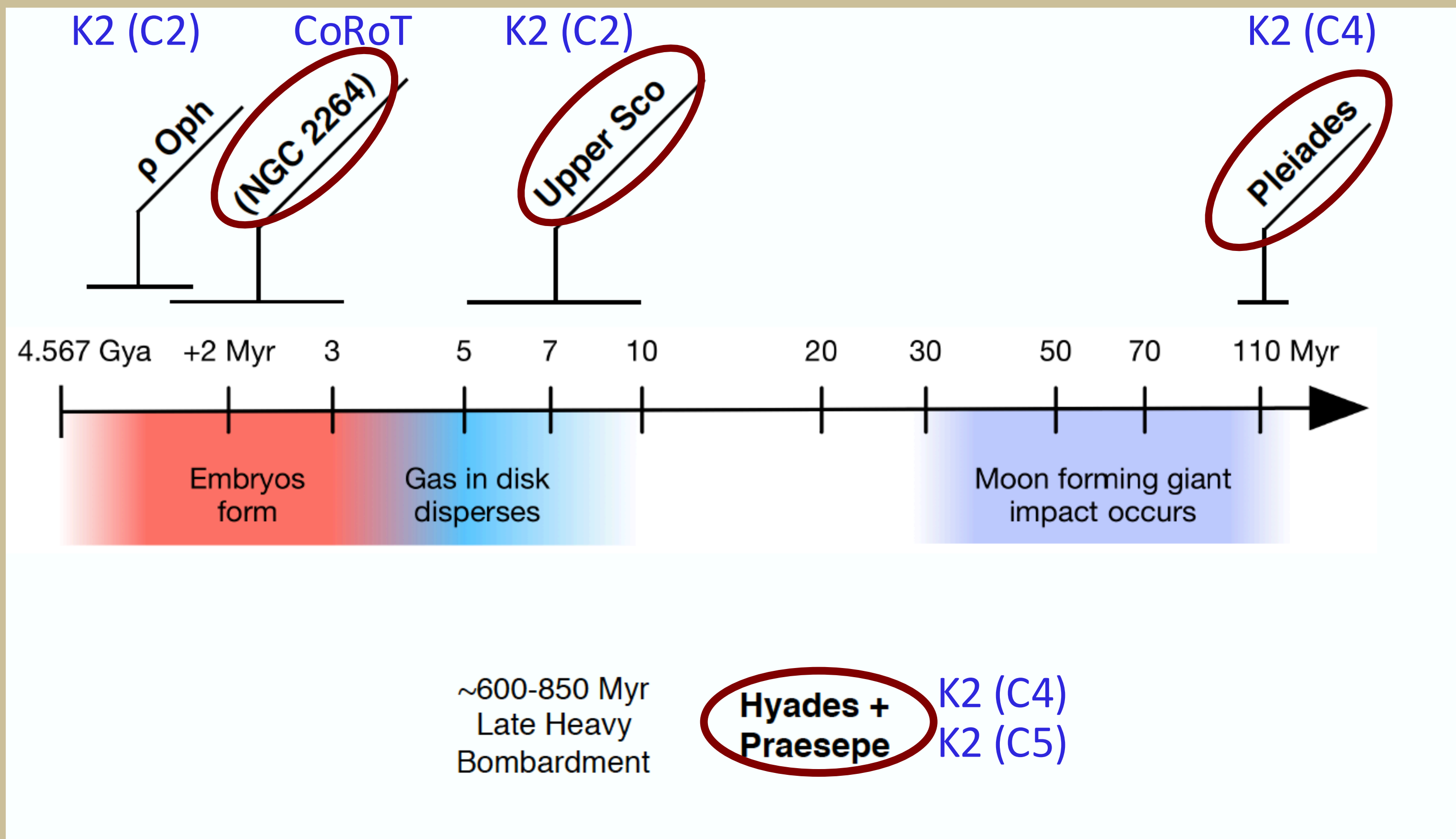


Vorobyov 2006



Semenov & Henning

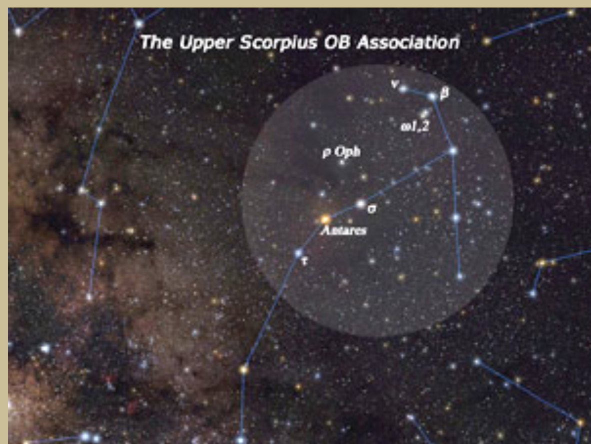
Availability of High Precision Photometry in the Context of Star/Disk Evolution



[modified from Quintana et al. 2015]

Upper Scorpius in K2/C2

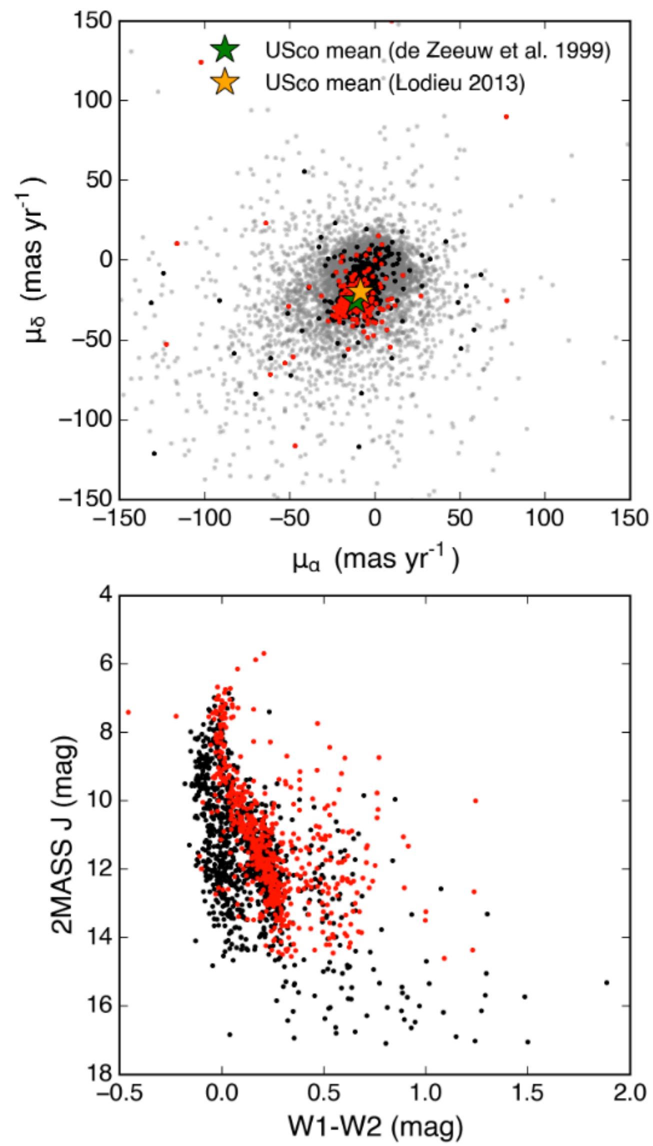
slide credit:
T. David



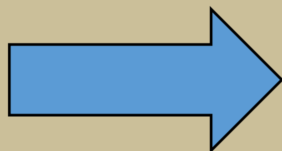
• Young association, spanning nearly complete IMF including brown dwarfs.

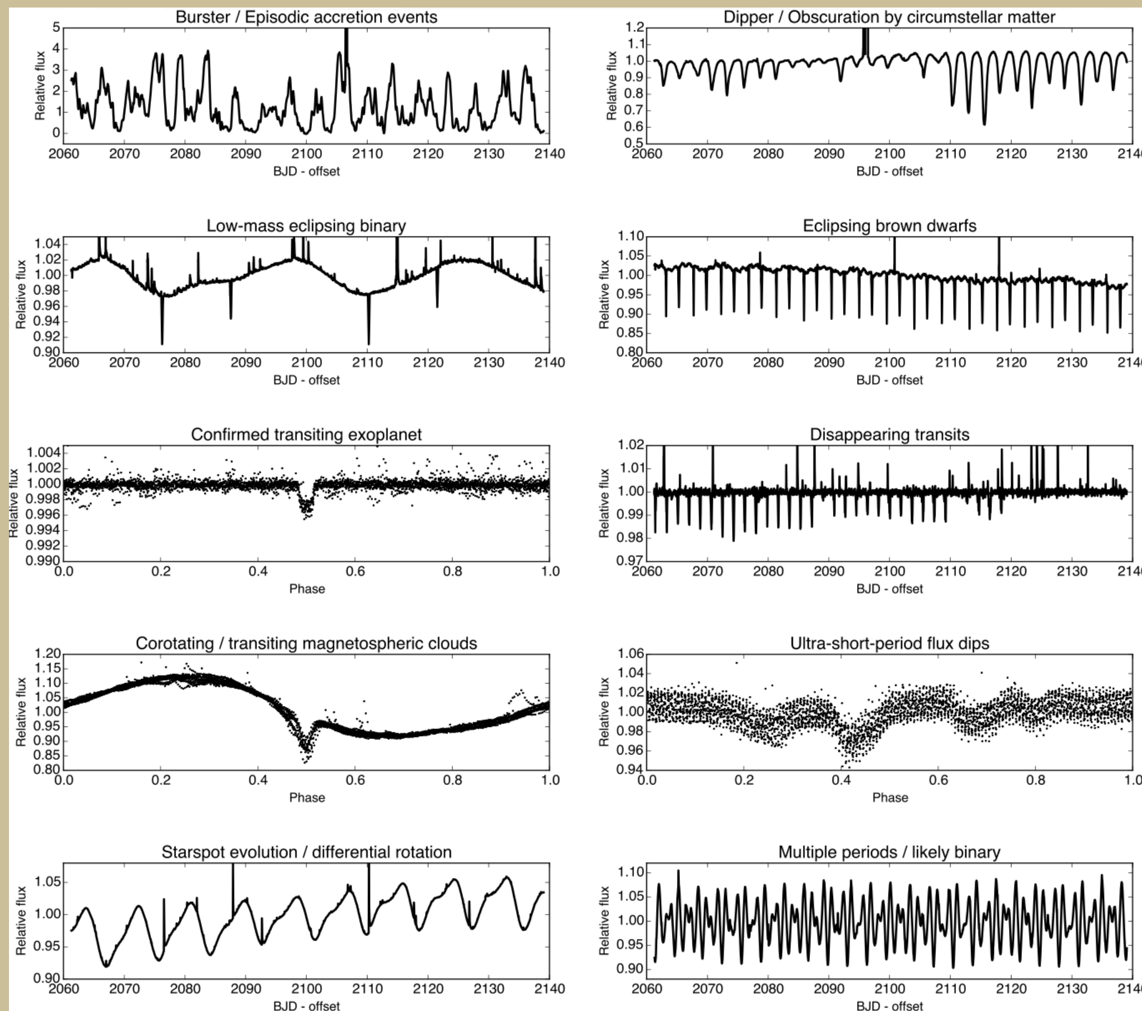
• Large area on the sky.

• Membership estimated via proper motion, color-magnitude diagram, activity indicators, etc.

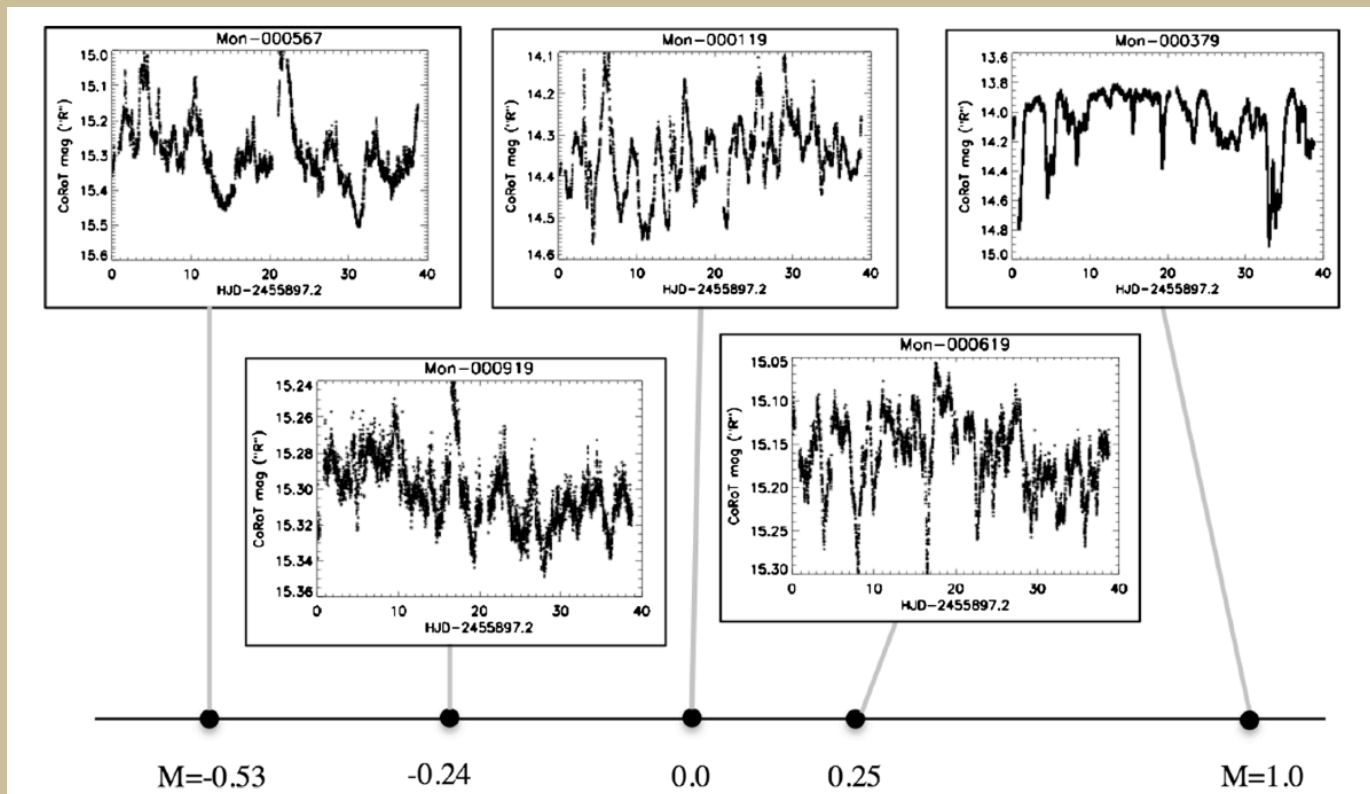


Lightcurve Gallery at 5-10 Myr Including Non-Disk Stars





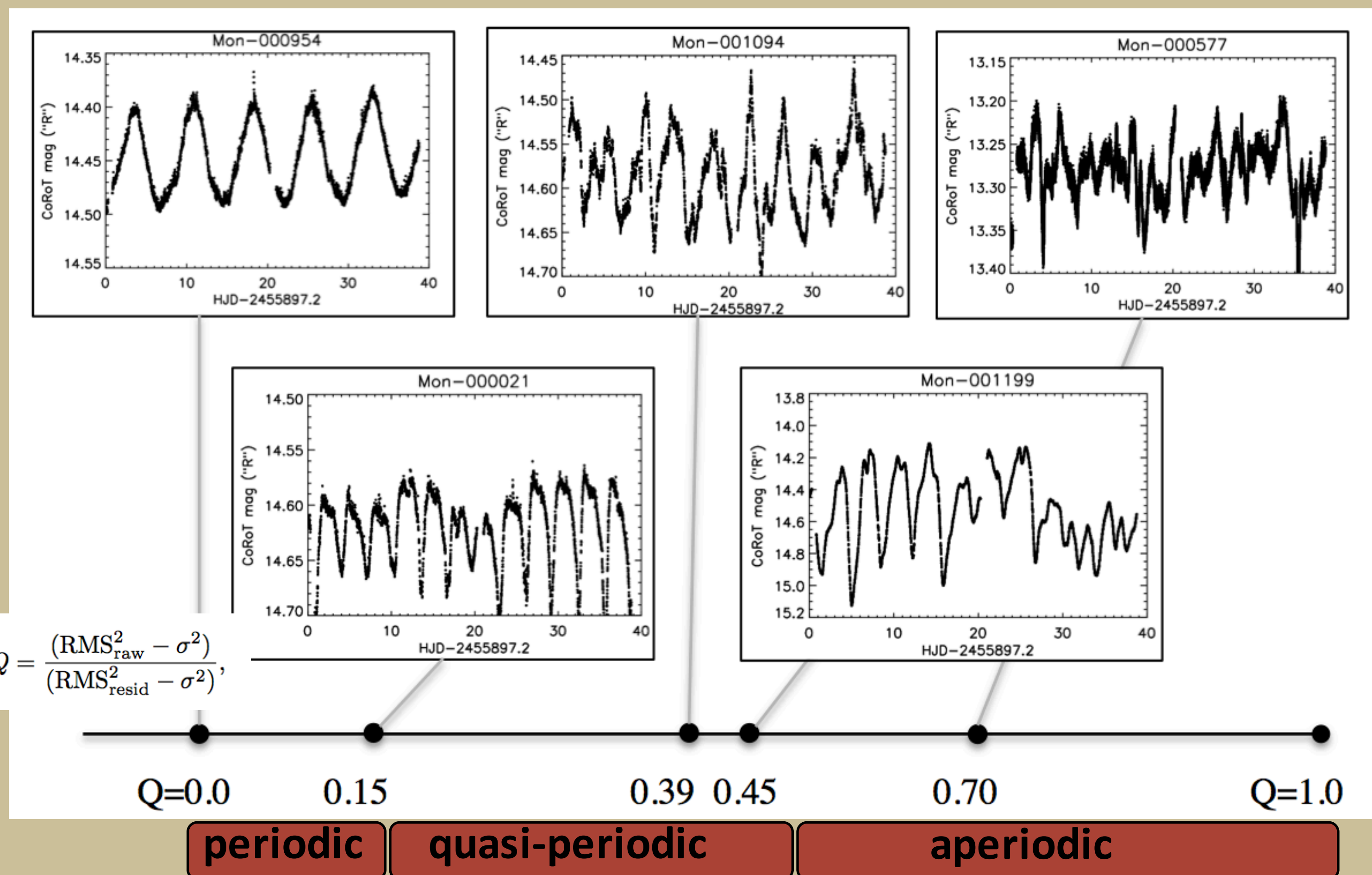
Quantifying Lightcurve Symmetry



bursting **symmetric** **dipping**

Cody et al. (2014)

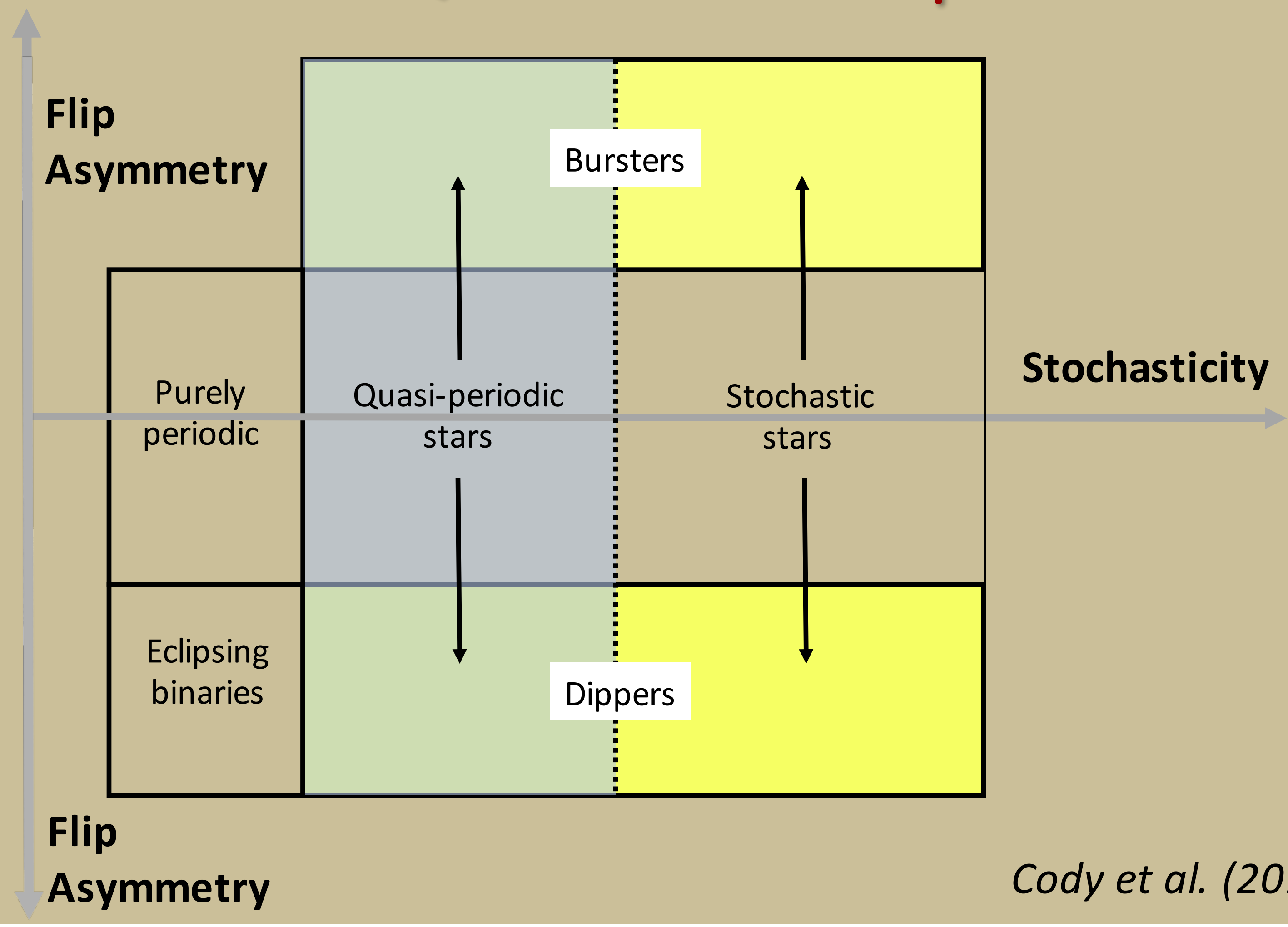
Quantifying Degree of Periodicity



$$Q = \frac{(\mathrm{RMS}^2_{\mathrm{raw}} - \sigma^2)}{(\mathrm{RMS}^2_{\mathrm{resid}} - \sigma^2)},$$

Cody et al. (2014)

The Q-M Parameter Space



Cody et al. (2013)

Lightcurve Mophology Classification of Rho Oph and Upper Sco Disk-Bearing Stars

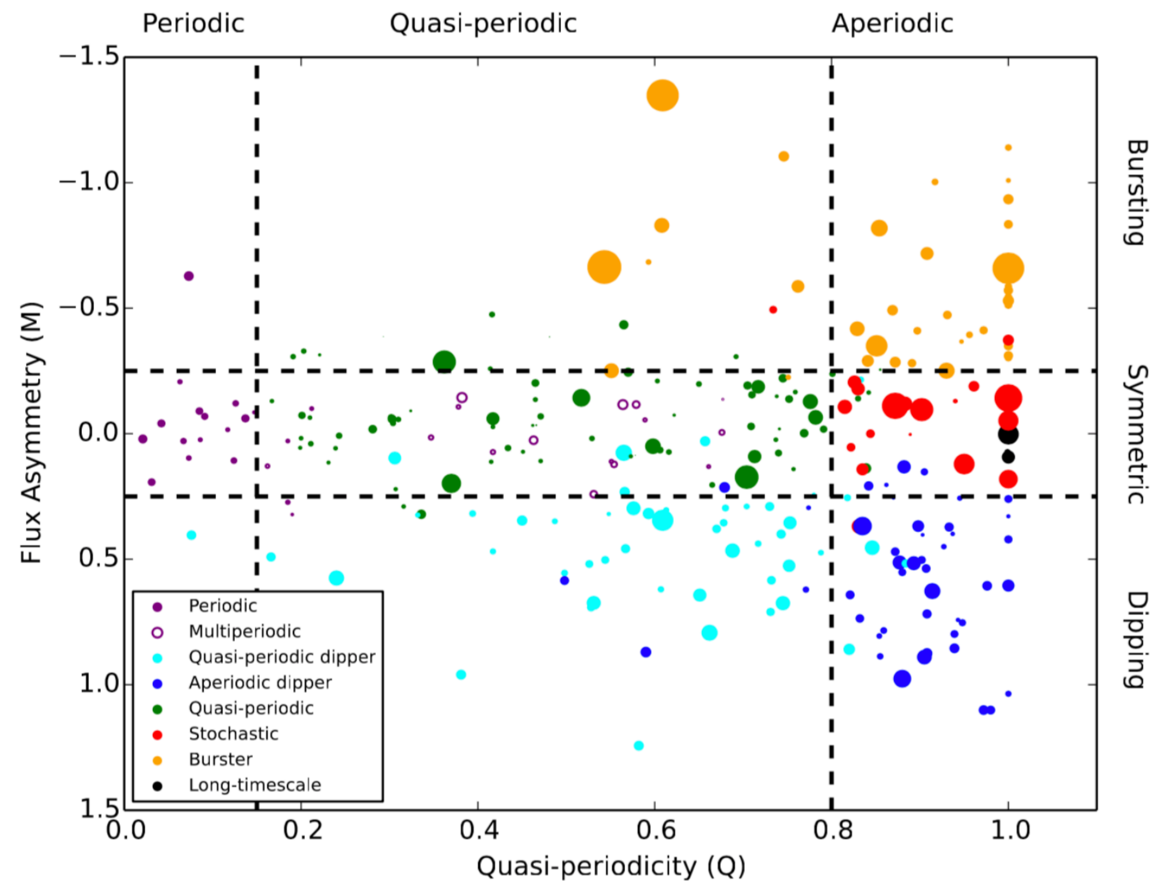
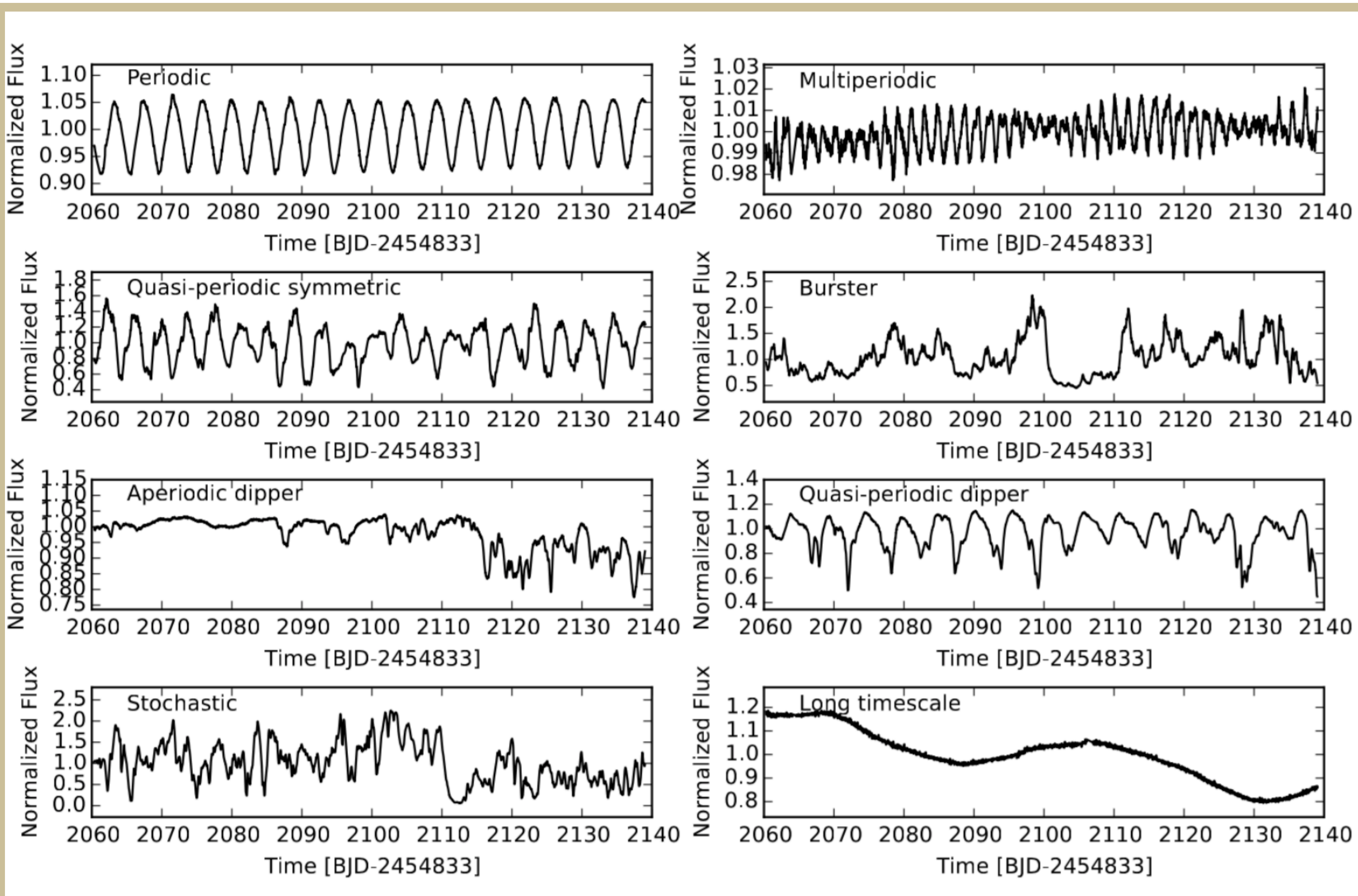


FIG. 6.— Q and M statistics for our sample of disk-bearing stars in Upper Scorpius and ρ Ophiuchus. Colors denote different types of variables, as identified by eye. Non-variable objects are excluded. Point sizes in this and subsequent plots are scaled according to variability amplitude.

Cody and Hillenbrand (2018)



7% 5%

26% 14%

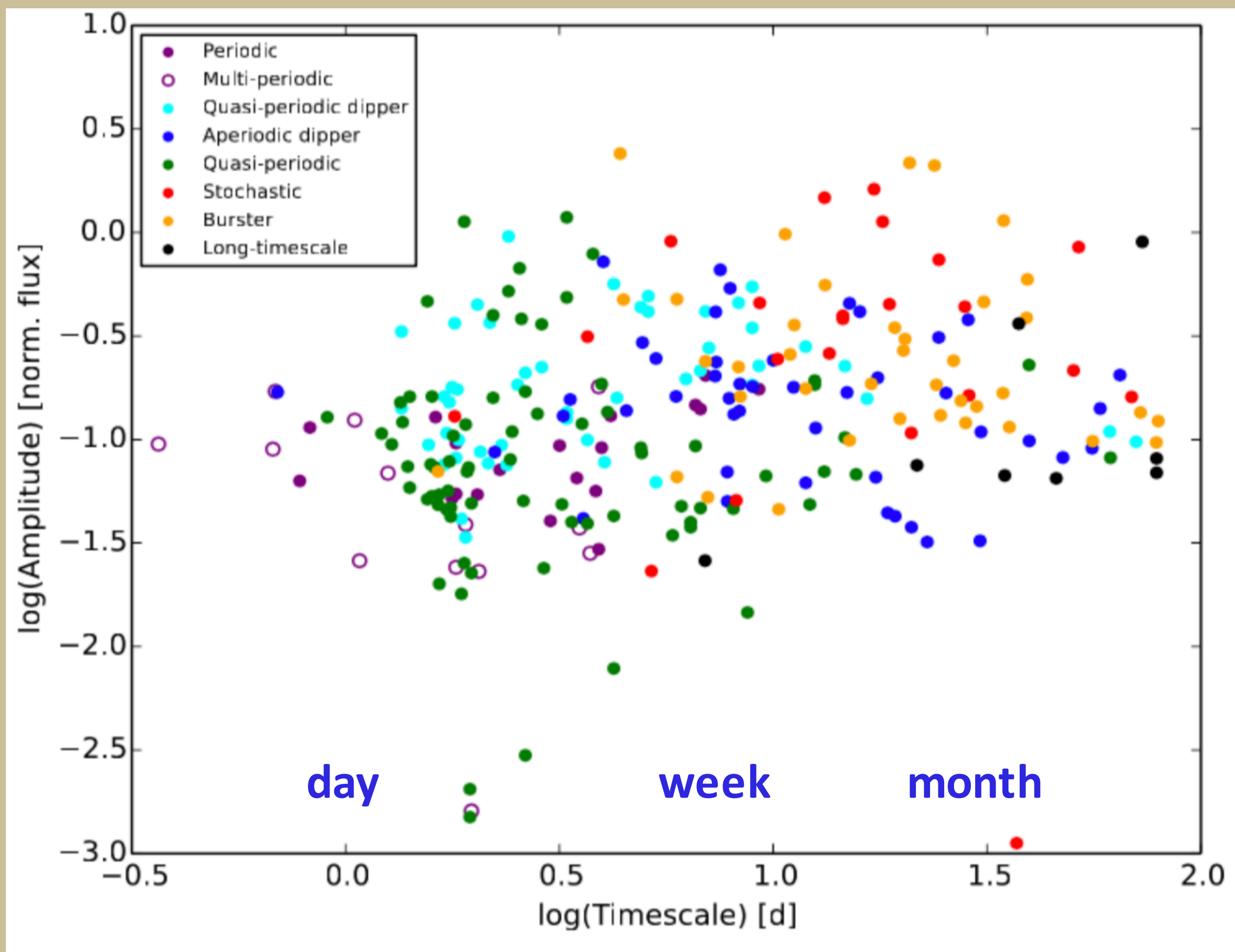
16% 17%

8% 3%

Cody and Hillenbrand (2018)

Time Scales and Amplitudes

3x



0.1%

Long = Bursters, Stochastics
Aperiodic Dippers

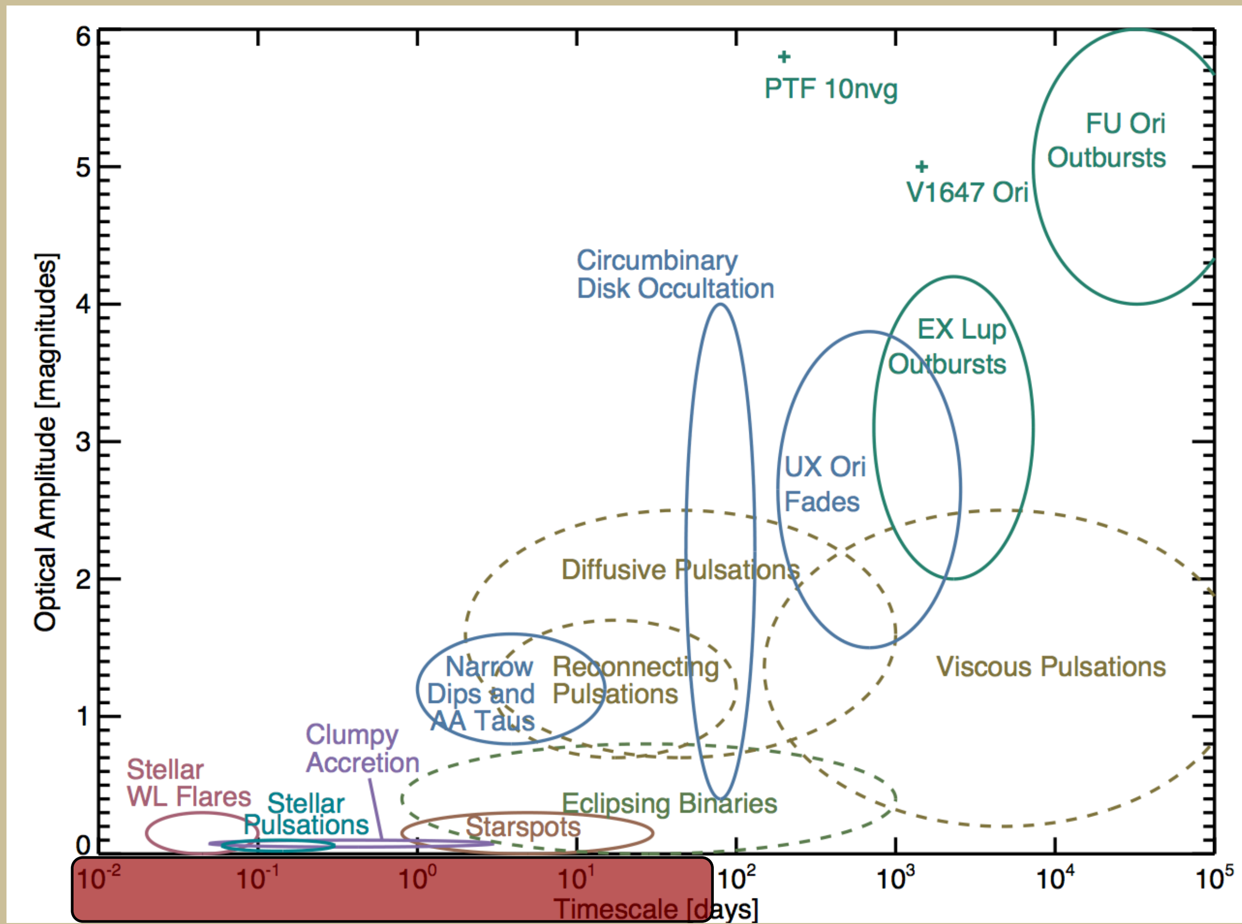
Int = Quasi-periodic Dippers
Quasi-periodic Symm.

Short = Periodic
Multi-Periodic

Amplitude ranges of most disk categories are similar.

Cody and Hillenbrand (2018)

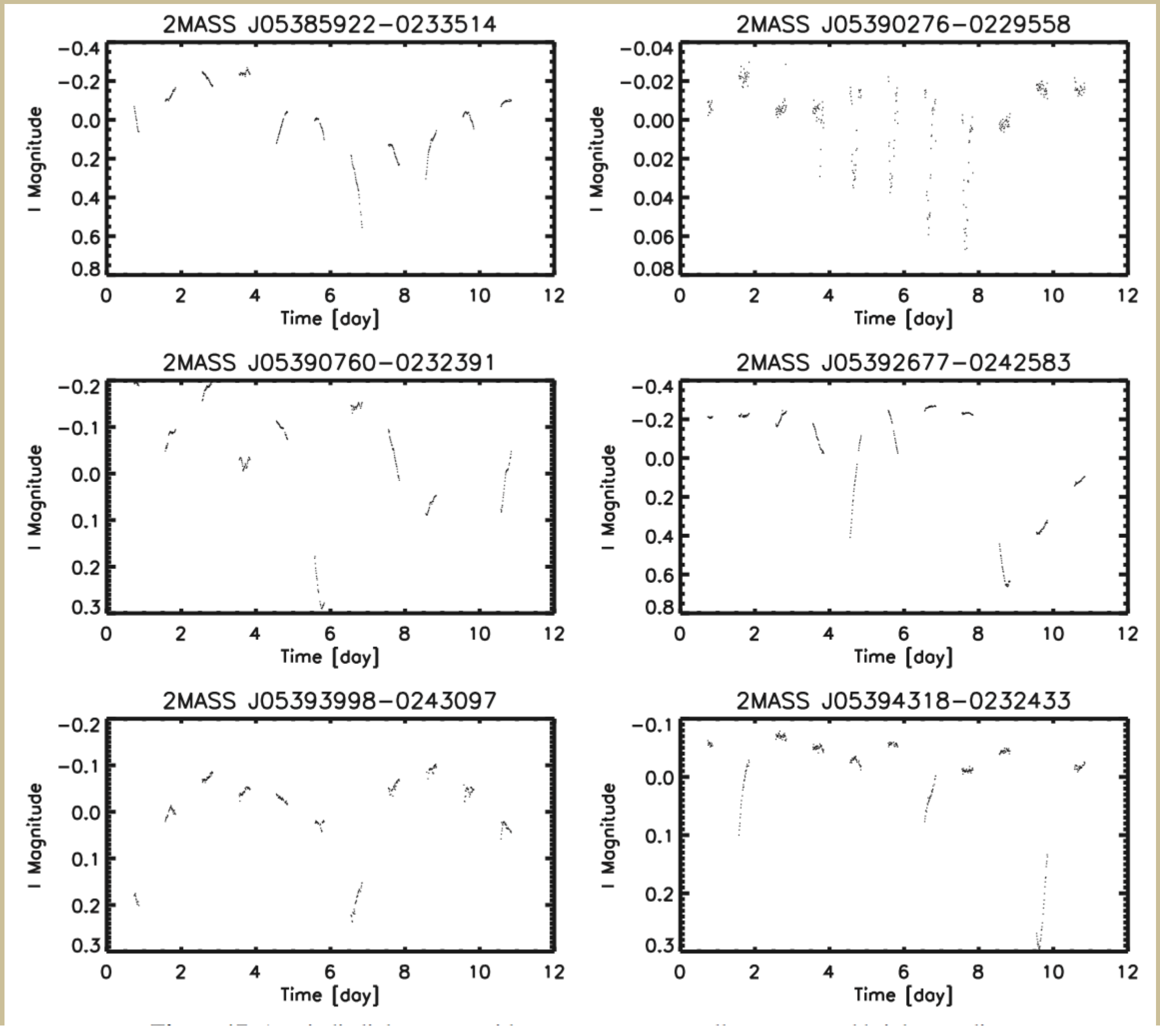
Expected Parameter Space for Young Star Variability



Hillenbrand & Findeisen, 2015

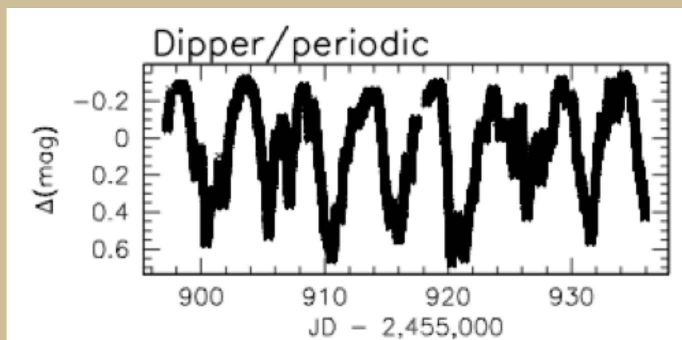
K2 and YSOVAR

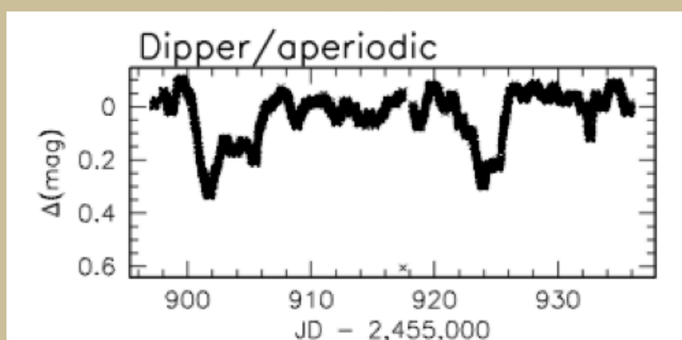
``Dippers" from Ground-Based Data (CTIO)



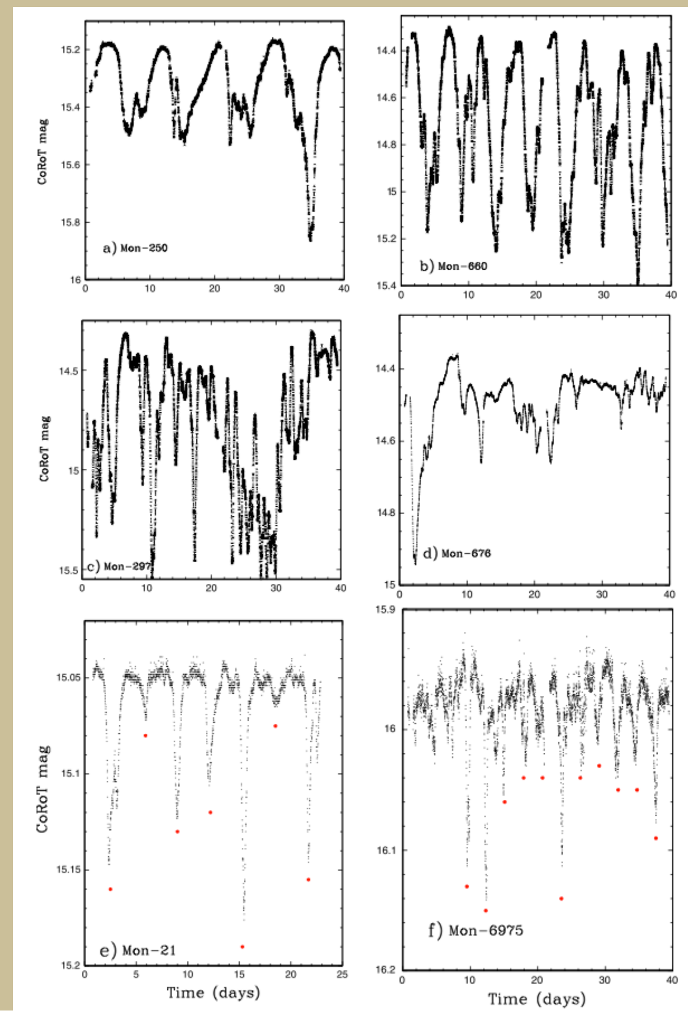
[Cody and Hillenbrand 2011]

Narrow Fades, a.k.a. ``Dippers”





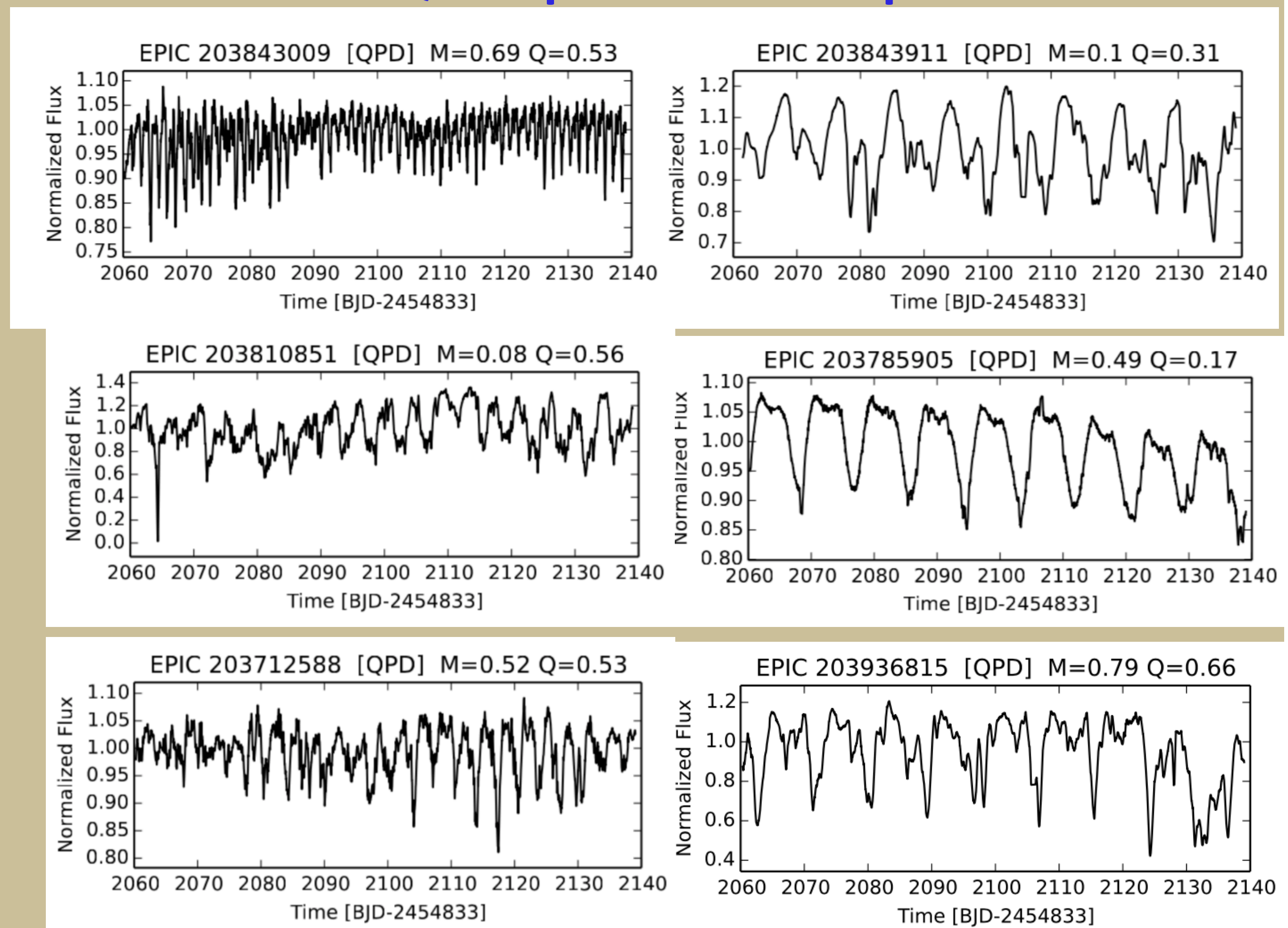
[Venuti et al. 2017]



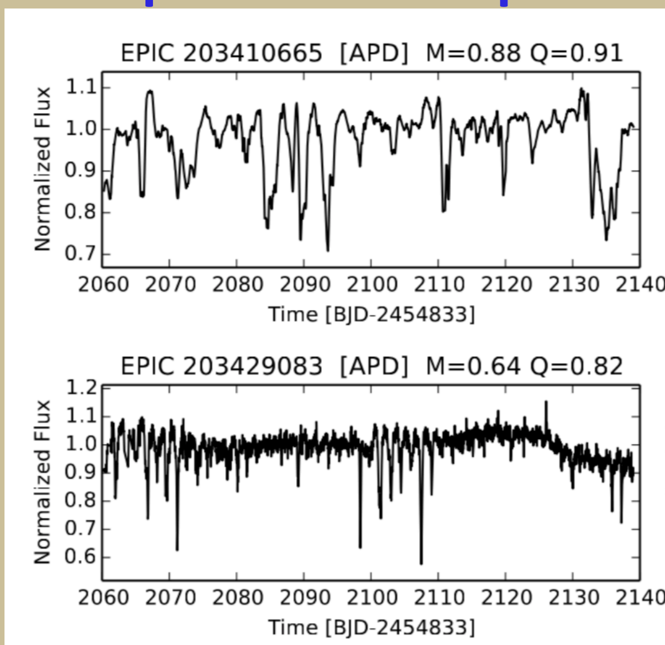
[Stauffer et al. 2015]

``Dippers" from K2 in Upper Sco

Quasi-periodic Examples



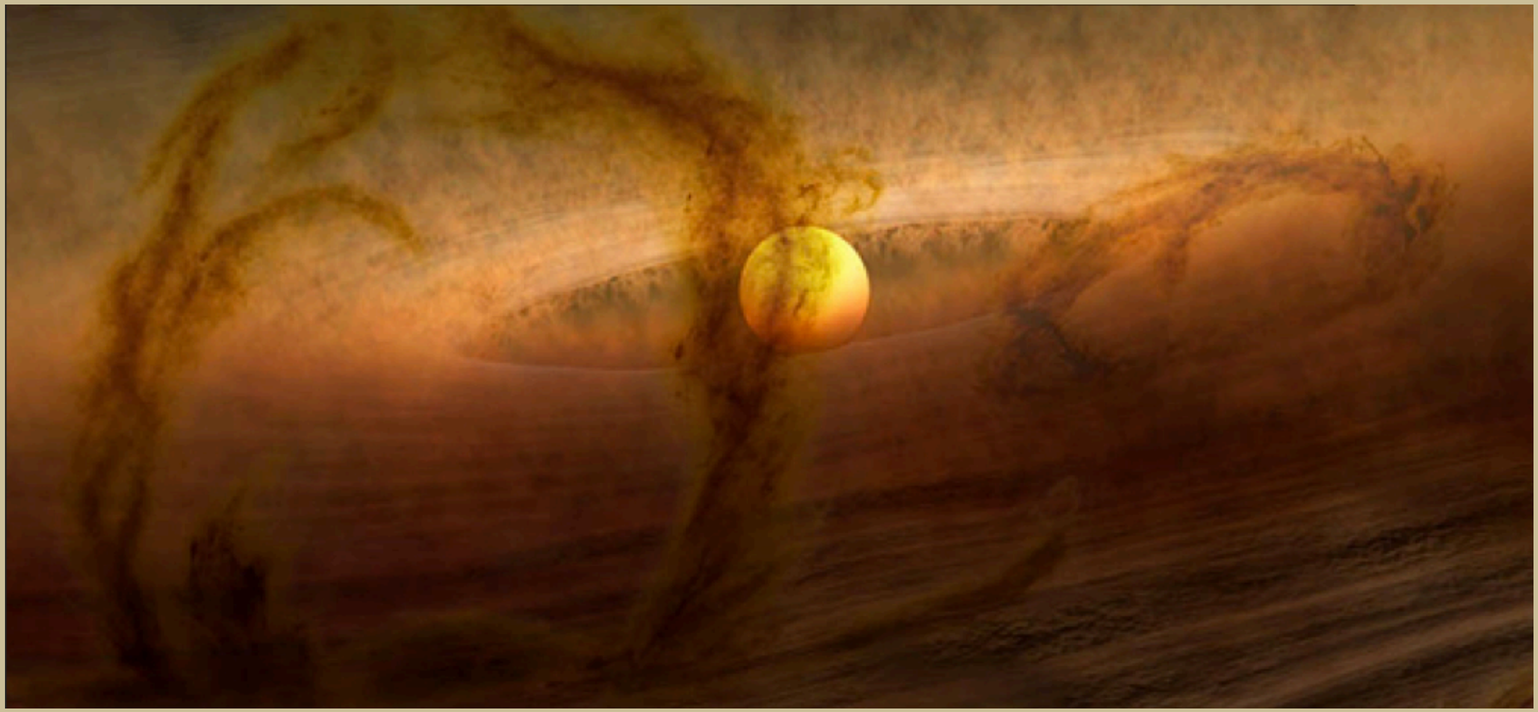
Aperiodic Examples



Cody and Hillenbrand (2018)

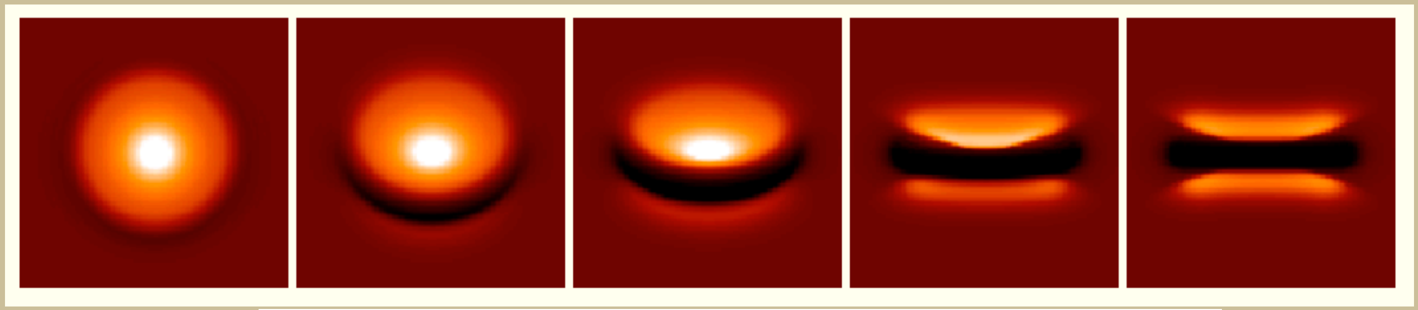
[see also Ansdell 2016 and Hedges 2018]

Geometry of Circumstellar Dust?



Viewing Angle Sets Line-of-Sight Opacity

- Dust blocks light from star / inner disk when viewed at high inclination
- Consider inhomogenous (i.e. clumpy) disk or radially structured disk



[Dullemond]

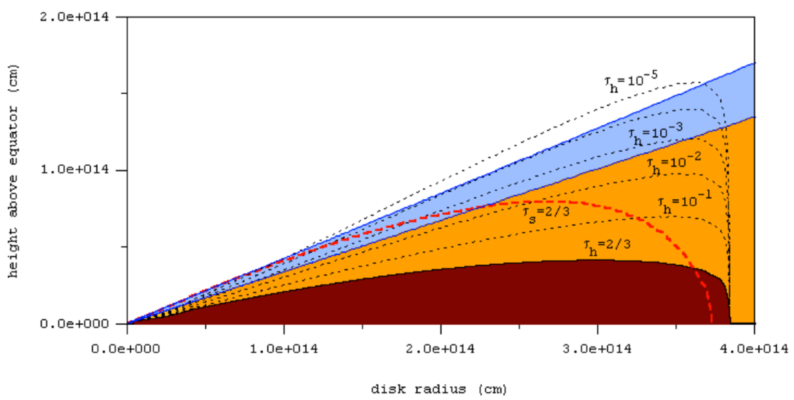


Fig. 1. CTTS disk profile. The dark-shaded (dark red) area shows the vertical disk photosphere ($\tau_h = 2/3$) while the thin dotted lines show contours of equal vertical optical depth τ_h with values ranging from 10^{-1} down to 10^{-5}. The medium-shaded (yellow) area indicated the range of view angles over which the central star is totally obscured by the disk. The light-shaded (light blue) area indicates the range of view angles where partial occultation of the star can be expected. The thick dotted (red) line, corresponding to $\tau_s = 2/3$, shows how deep into the disk an outside observer sees at each view angle s.

[Bertout 2000]

Inclination Effects in Upper Sco

Low Inclination = Bursters, Stochastics

High Inclination = Aperiodic Dippers (2 exceptions)
Quasi-periodic Dippers
Quasi-periodic Symmetric

Disk sizes similar among the lightcurve categories

Cody and Hillenbrand (2018)

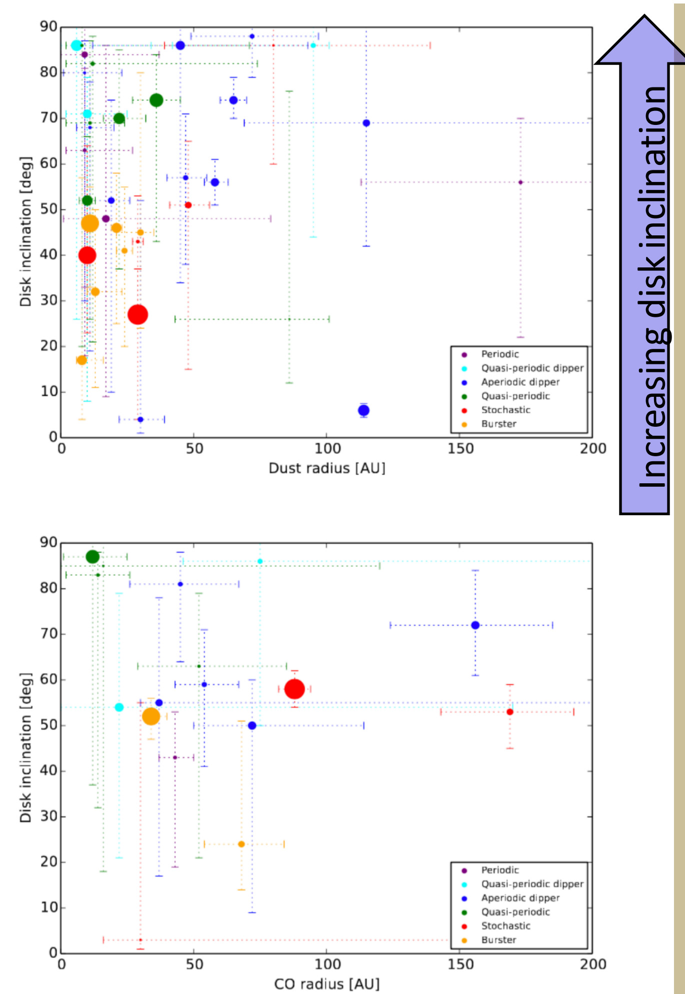
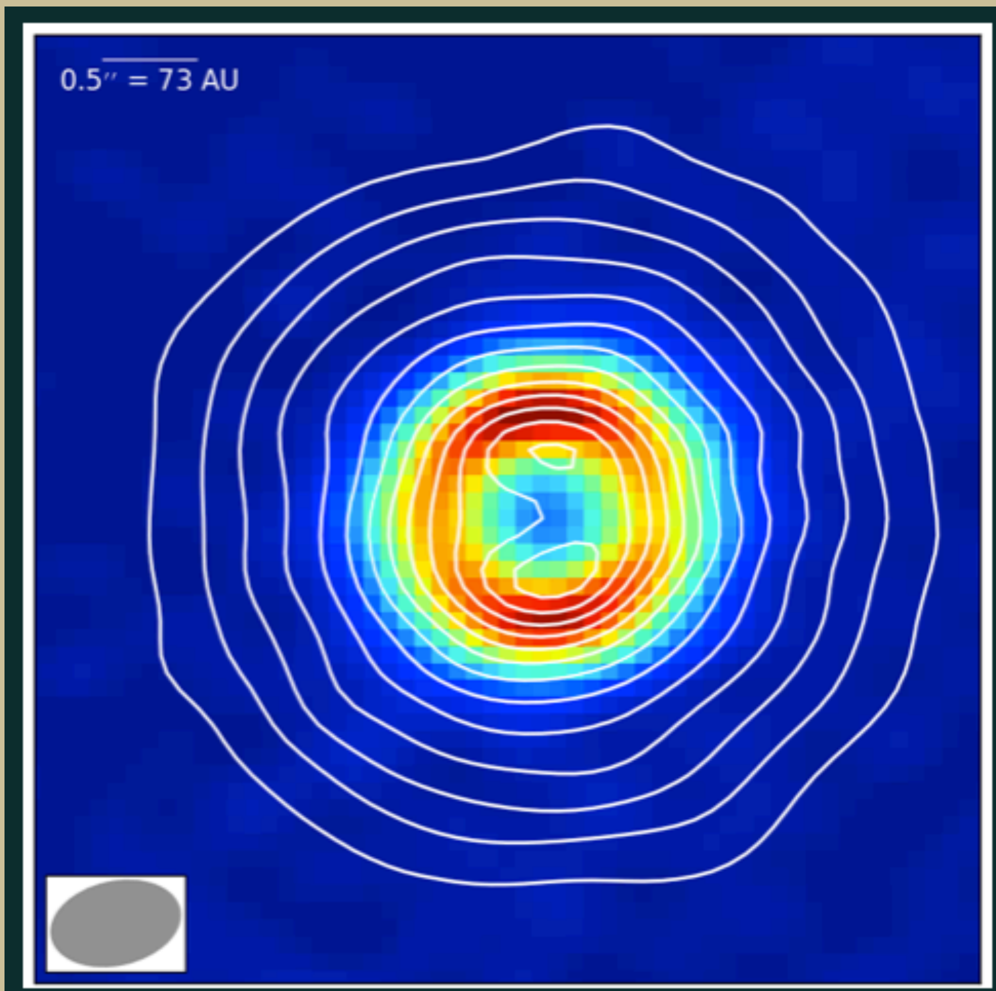
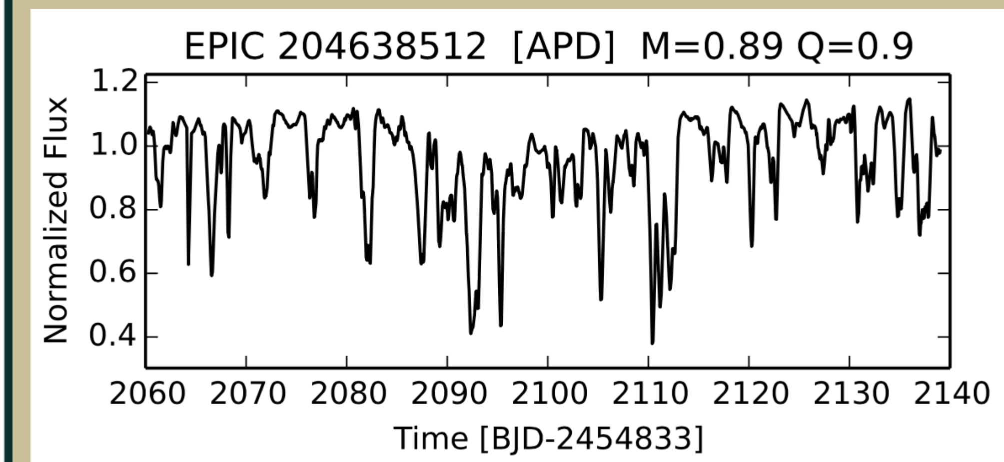


FIG. 12.— Dust continuum (top panel) and CO gas (bottom panel) disk radius, versus disk inclination, based on *ALMA* observations where they are available for our sample. Point sizes are scaled proportional to light curve amplitude. Although the measurements are noisy, there is clear segregation of some variability types in inclination.

One Misbehaving Source

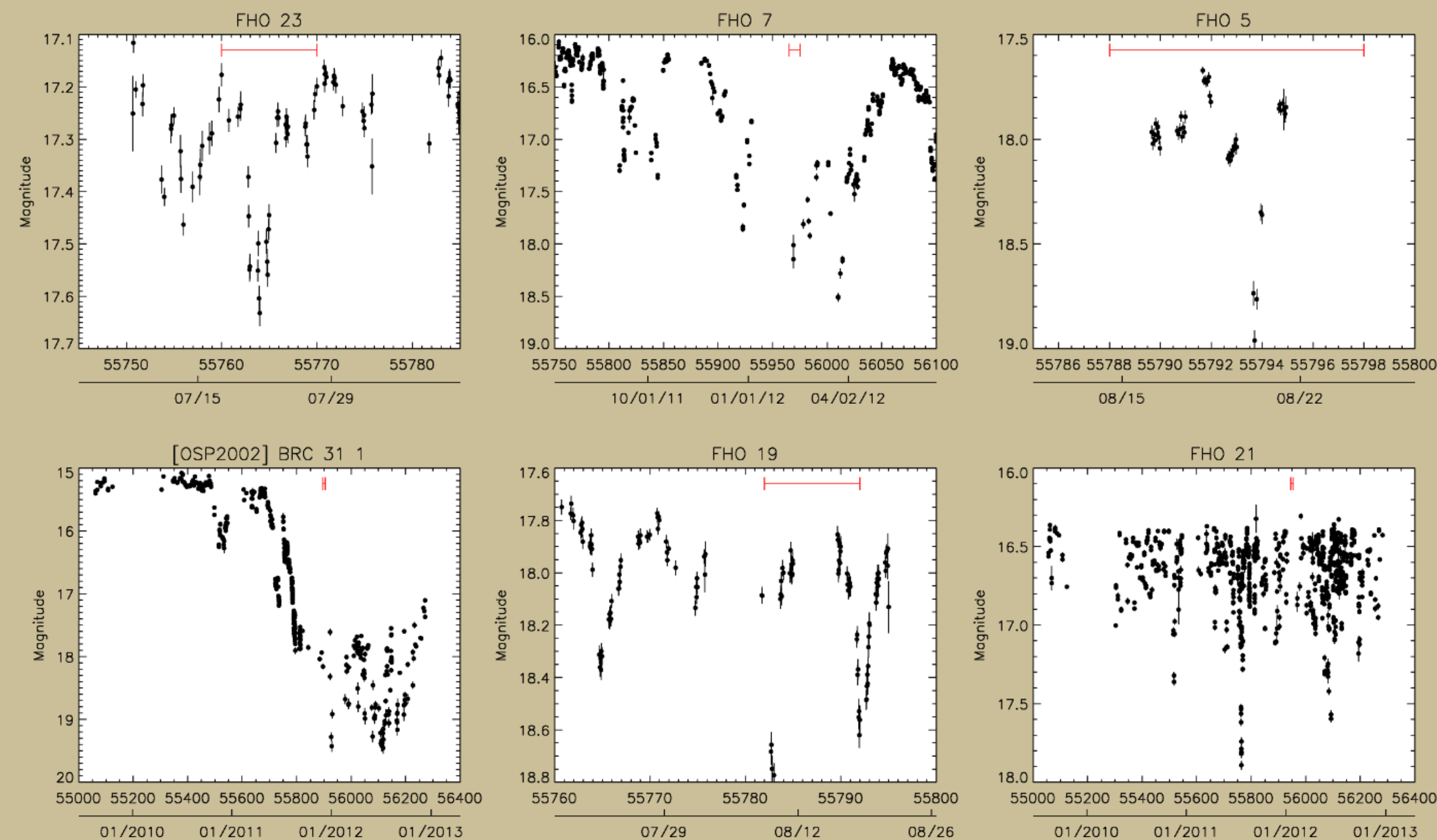


Carpenter et al. (2014)



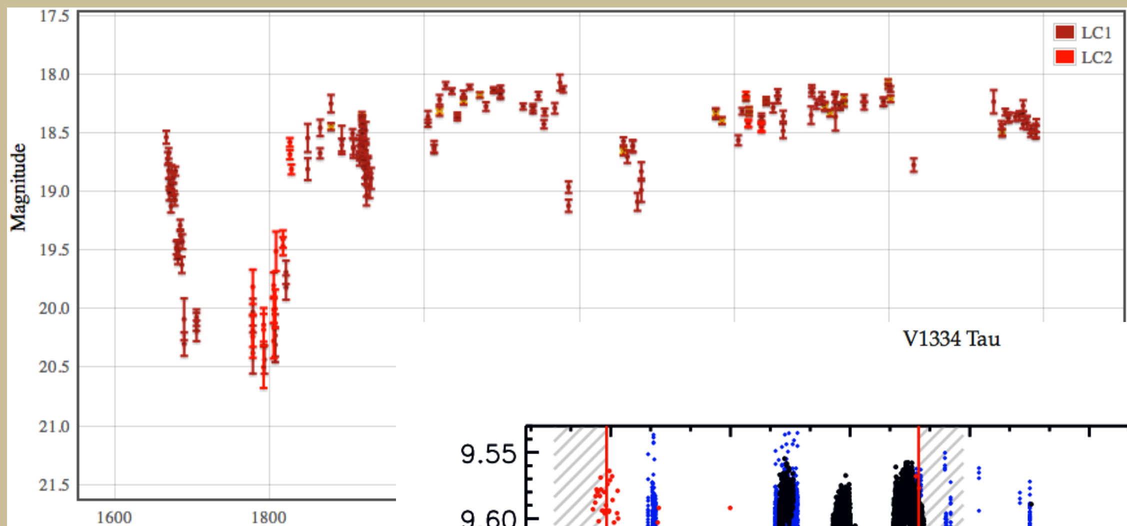
Cody and Hillenbrand (2018)

Moderate Amplitude Faders in PTF



[Findeisen et al. 2013]

Likely A Continuum of Faders Too



deep depressions lasting months

shallow fades lasting years

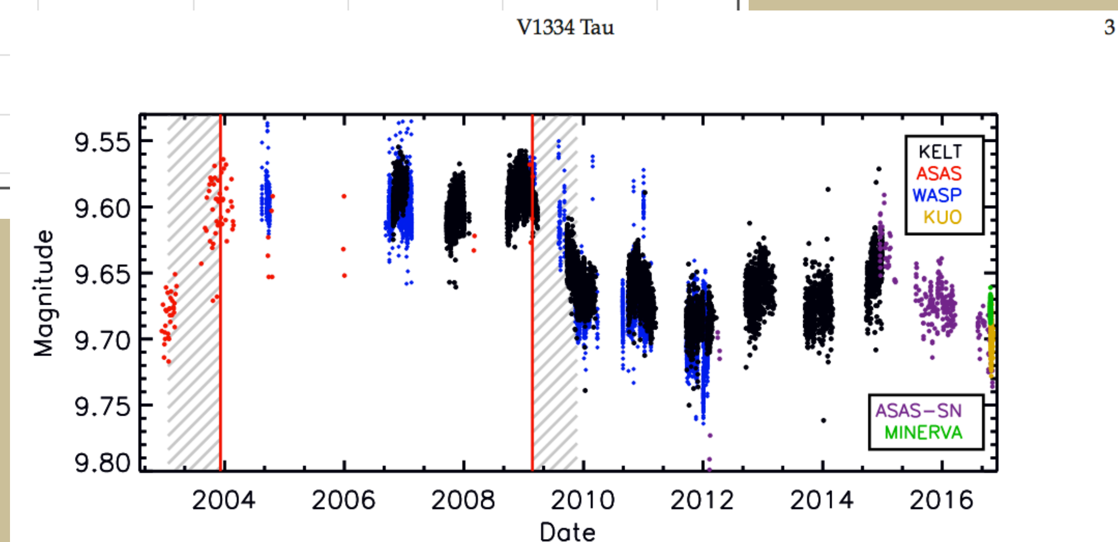


FIG. 1.— The KELT (black), ASAS (red), WASP (blue), ASAS-SN (purple), KUO (yellow), and MINERVA (green) photometric observations of V1334 Tau from 2002 until late 2016. Only the *V*-band observations from KUO and MINERVA are shown. The red vertical lines represent the estimated end of the pre-2004 events and the start of the 2009 event. The grey shaded region represents the estimated egress/ingress for each event described in §5. The intercalibration of the data sources is described in §5.

Long Wavelength Variability?

[Herczeg et al. 2017; Johnstone et al.. 2018; Mairs et al.. 2018]

JCMT 850um survey of <200 protostellar sources; only 1 significant variable.

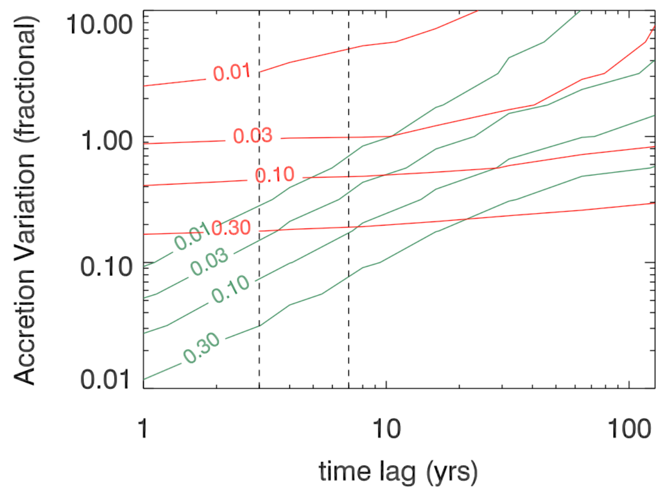
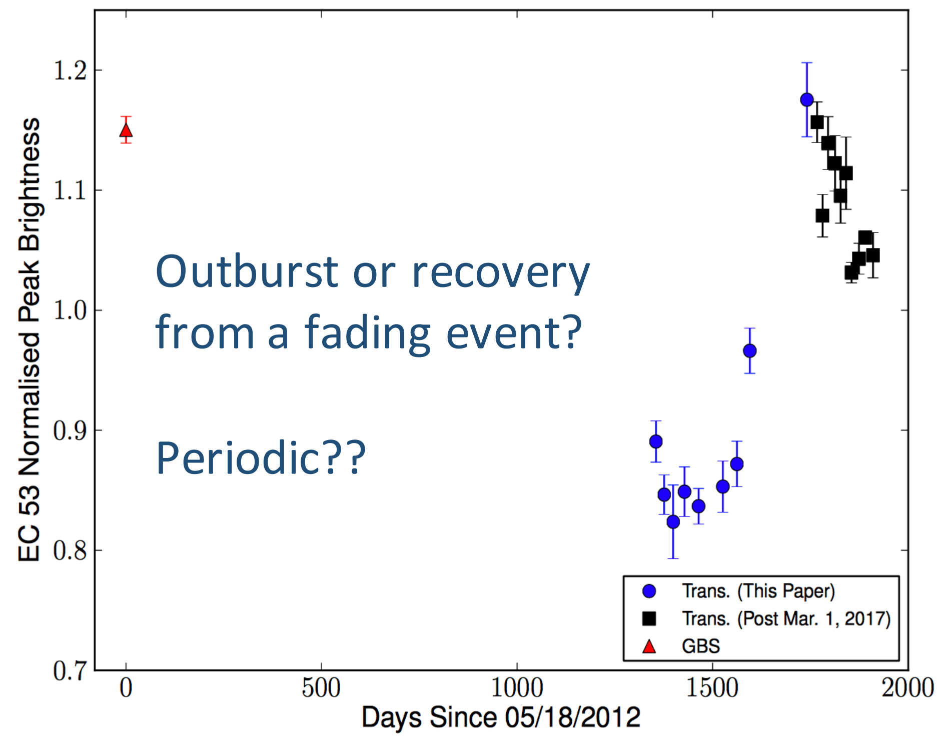
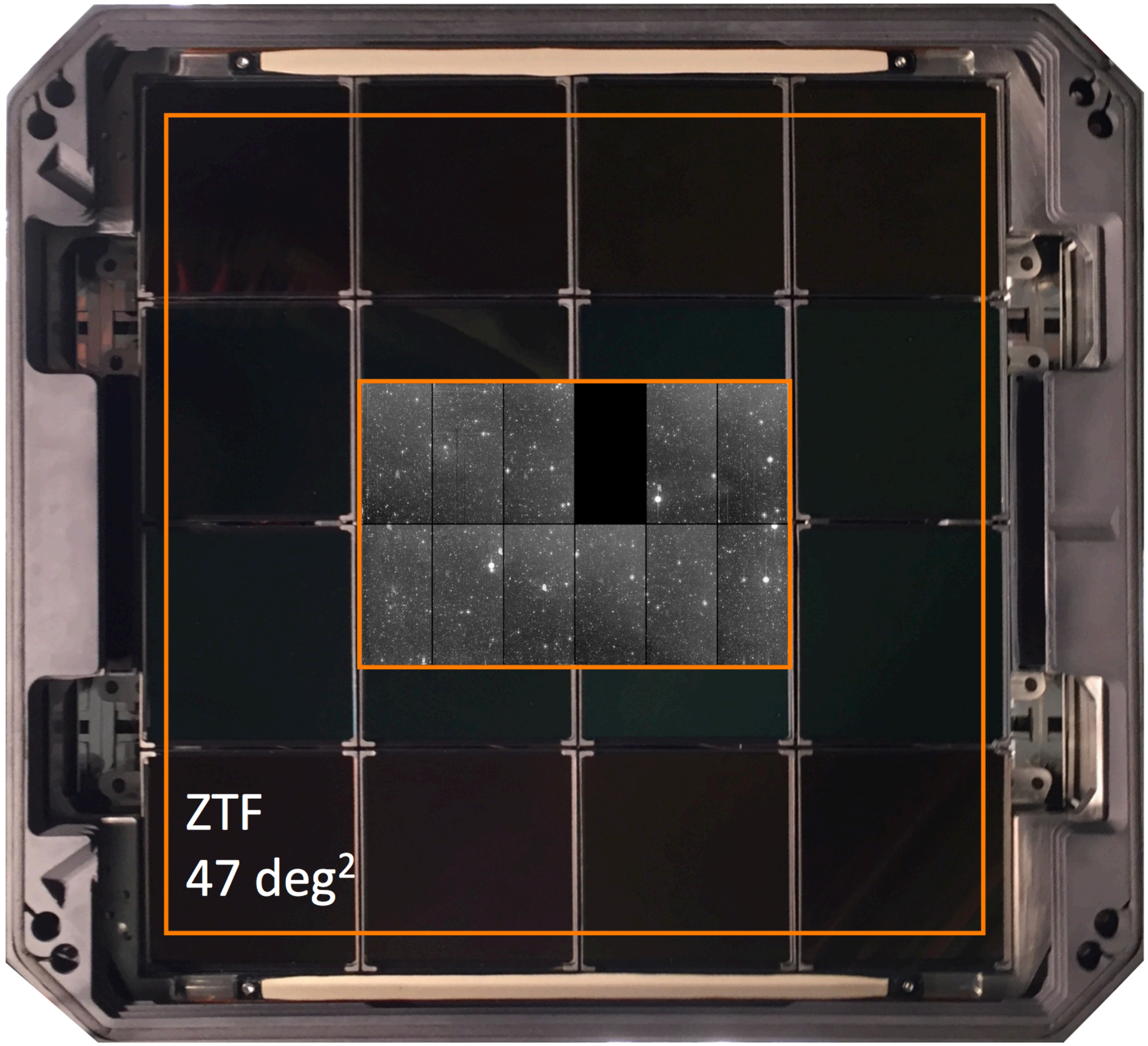


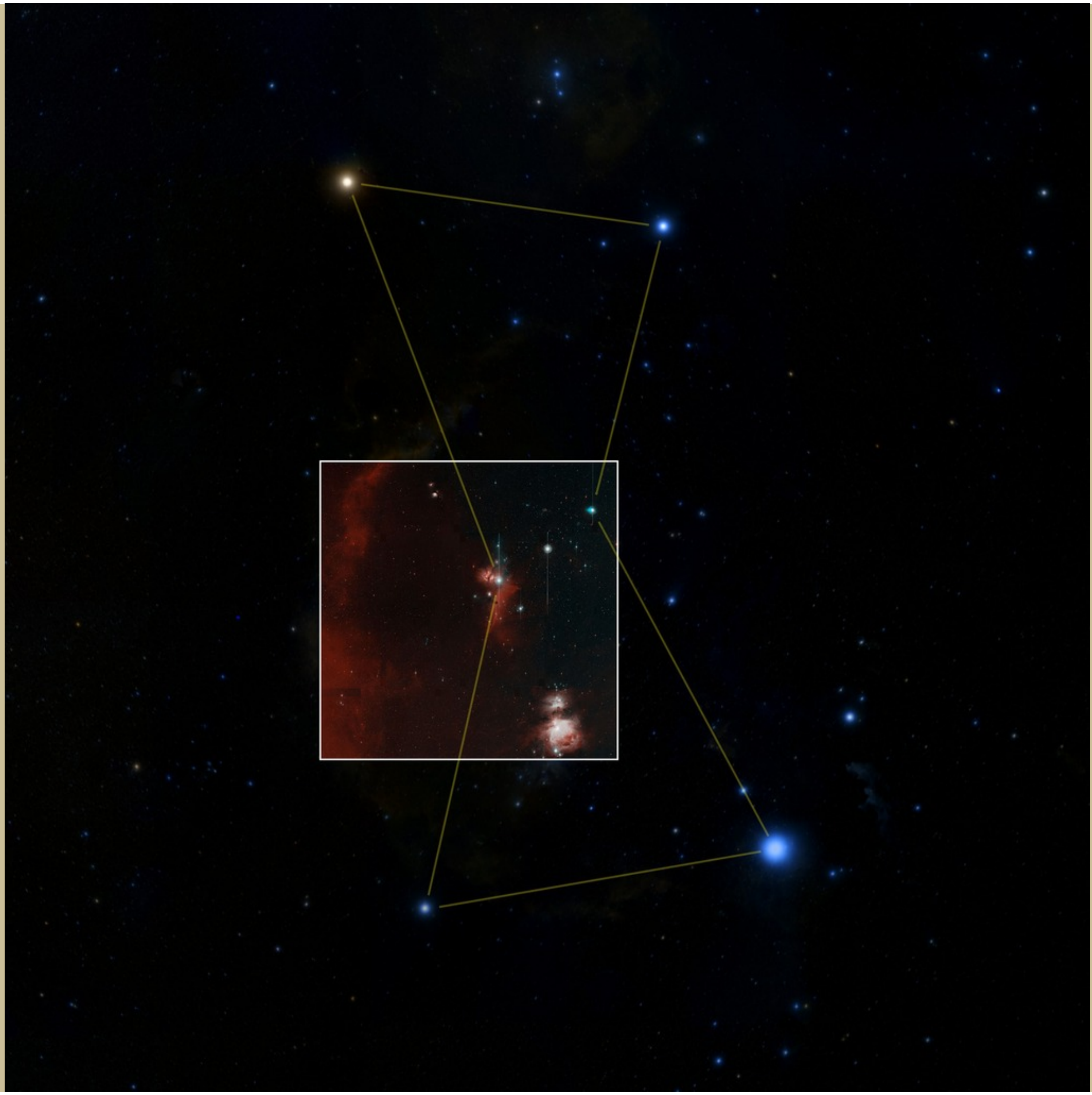
FIG. 3.— The expected fraction of time that a given theoretical model returns an amplitude variation greater than a specific amount as a function of the time lag between observations. The green contours show results for a Vorobyov & Basu (2010) model in which accretion variability is driven by large-scale modes within the gravitationally-unstable disk. The red contours show result for a Bae et al. (2014) model in which accretion variability is driven by the activation of the magneto-rotational instability in the otherwise magnetically inert inner disk, via heating from gravitational instability-driven spiral waves. The contours are labeled with the fraction of stars that would show the level of variability. In both models, larger amplitudes correlate with longer times. The dashed lines denotes a three-year separation in time for our survey and a seven-year separation in time between earlier epochs from the JCMT Gould Belt Survey and the end of our survey.



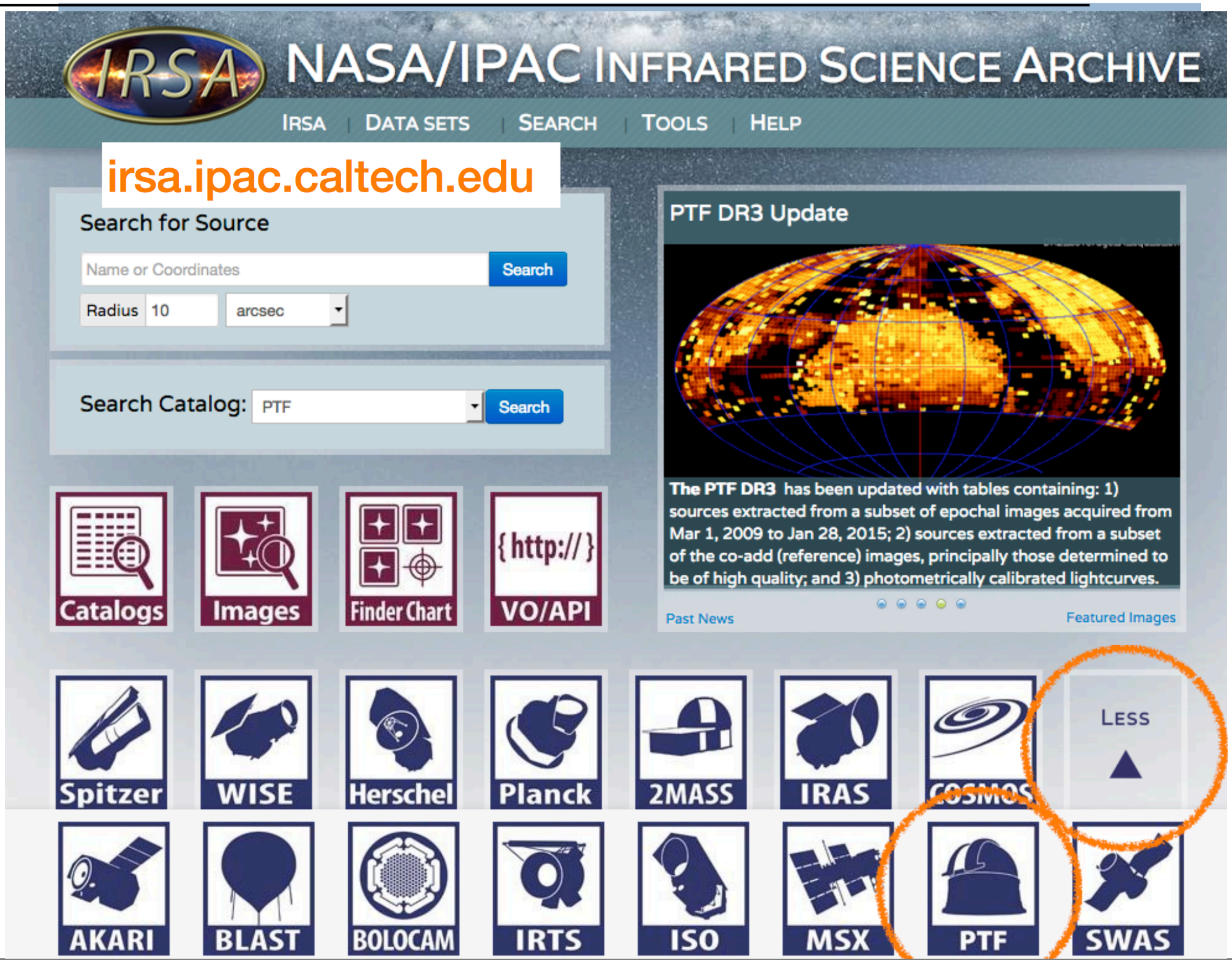
ZTF's new camera will fill the P48 focal plane.

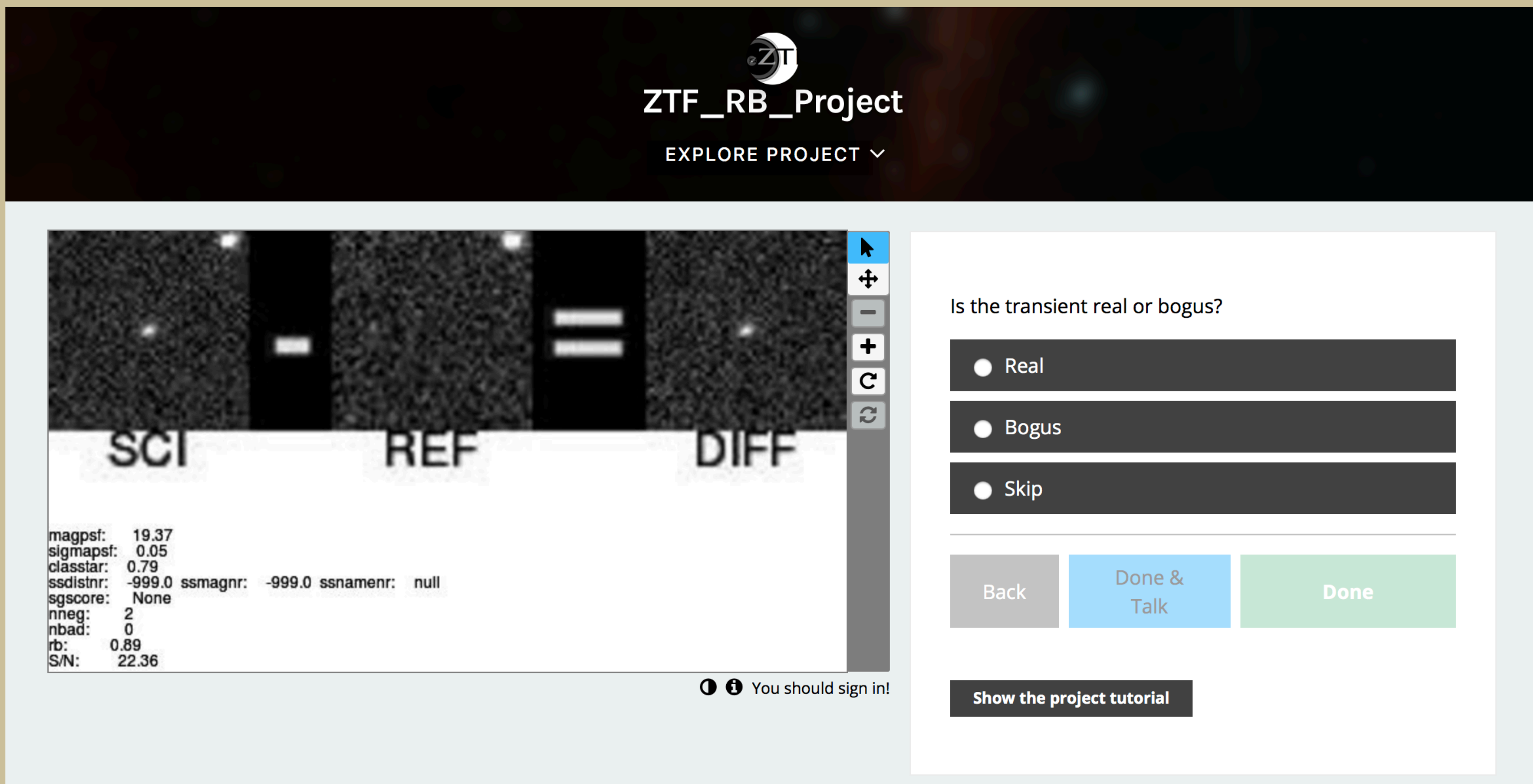
Coming Soon: ZTF



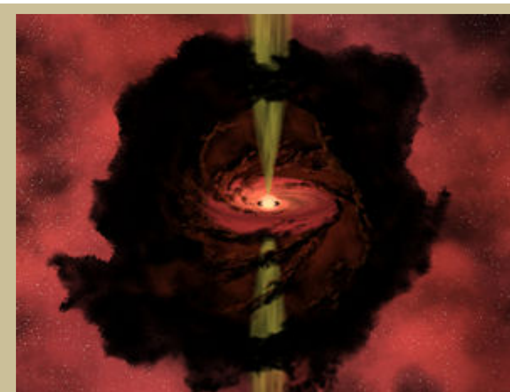


IRSA provides access to PTF, iPTF, and ZTF data.

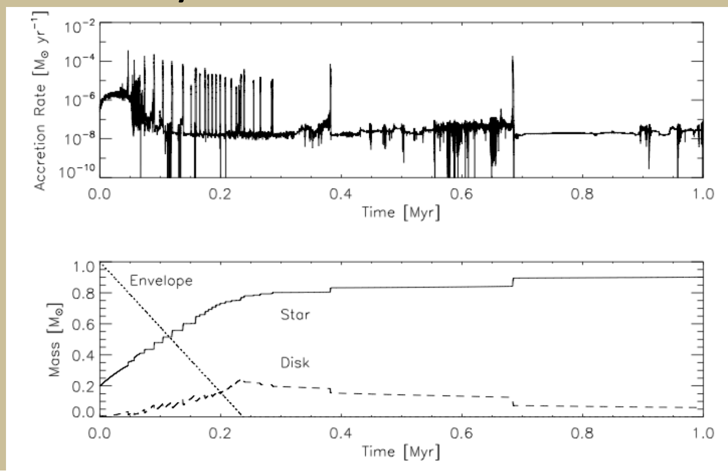


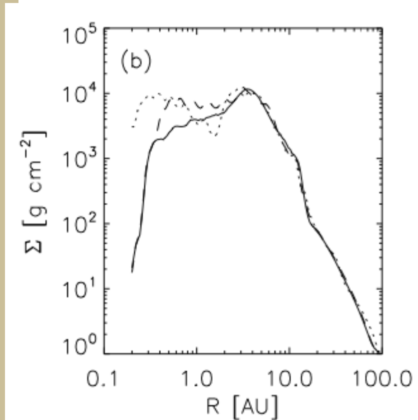

ZTF_RB_Project
EXPLORE PROJECT
SCI
REF
DIFF
magpsf: 19.37
sigmapsf: 0.05
classtar: 0.79
ssdistnr: -999.0 ssmagnr: -999.0 ssnamenr: null
sgscore: None
nneg: 2
nbad: 0
rb: 0.89
S/N: 22.36
You should sign in!
Is the transient real or bogus?
Real
Bogus
Skip
Back
Done & Talk
Done
Show the project tutorial

Star Formation and Disk Accretion / Evolution



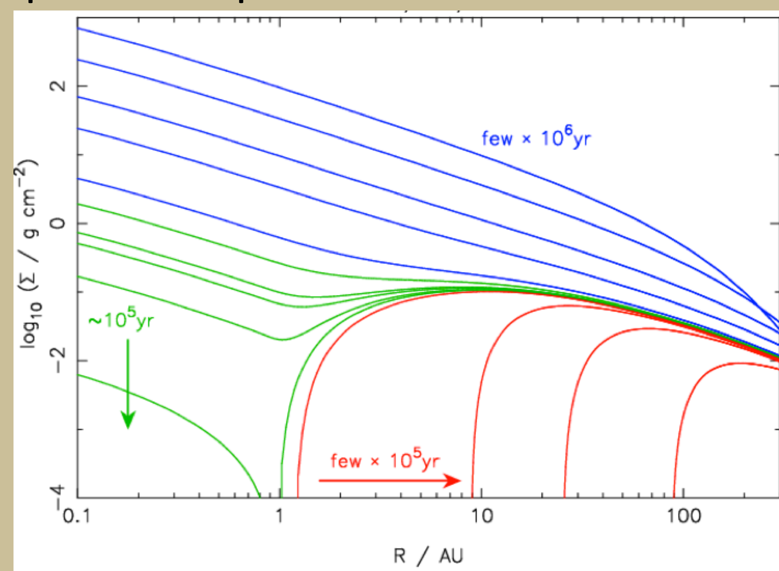
early accretion and outflow





Bae et al. (2014)

later, viscous evolution and photo-evaporative effects



Alexander (2014)

Characteristics of Youth

- Active and variable / moody
- (Believe that) everything orbits them
- Still gaining mass
- Can oscillate between steady low state and more punctuated episodes of rapid accretion.
- Prone to instabilities, outbursts and outflows
- Sometimes long term depressive states
- Can be obscured (or at least obscure)
- Hard to figure out!

LHillenbrand inspired by GHerczeg