Accretion variability in young, low-mass stars

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Protoplanetary disks seen through the eyes of new-generation high-resolution instruments, Rome, June 26, 2018

Photometric variability: a long-asserted feature of young, low-mass stars

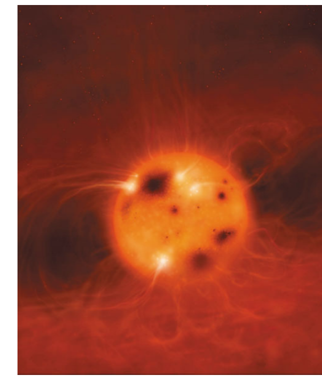
T TAURI VARIABLE STARS*

ALFRED H. JOY
Mount Wilson Observatory
Received June 9, 1945

ABSTRACT

Eleven irregular variable stars have been observed whose physical characteristics seem much alike and yet are sufficiently different from other known classes of variables to warrant the recognition of a new type of variable stars whose prototype is T Tauri. The distinctive characteristics are: (1) irregular light-variations of about 3 mag., (2) spectral type F5–G5 with emission lines resembling the solar chromosphere, (3) low luminosity, and (4) association with dark or bright nebulosity. The stars included are

Artist's view of a young, active star

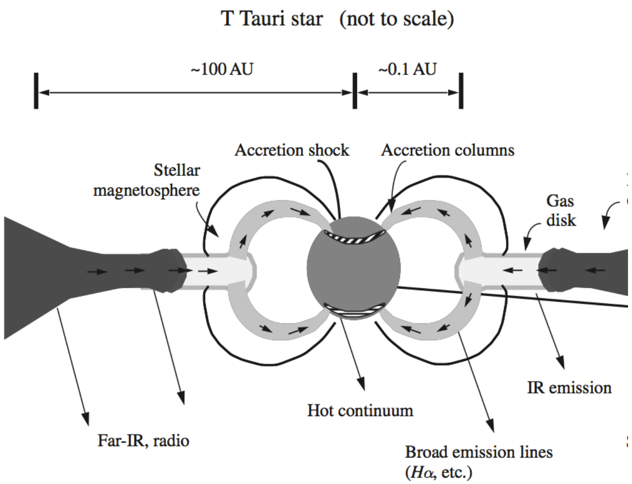


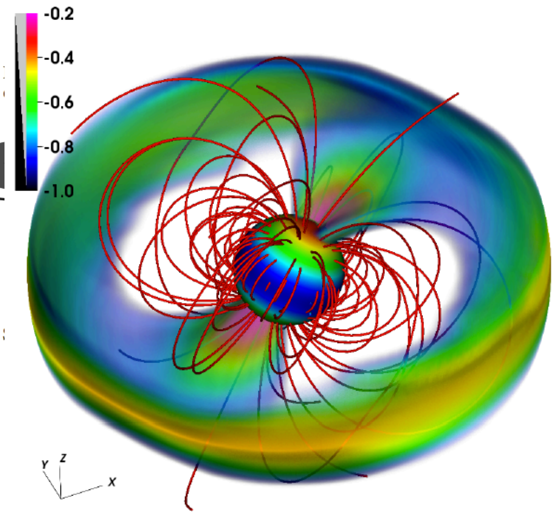
Short-to-mid-term variability surveys of young star clusters:

- NGC 1333 (1-2 Myr) -> *52%* of sources are variable (Rebull et al. 2015)
- Orion Nebula Cluster (2 Myr) -> *61%* of sources are variable (Morales-Calderon et al. 2011)
- NGC 2264 (3-5 Myr) -> *63-75%* of sources are variable (Venuti et al. 2015)
- σ Ori (6 Myr) -> *69%* of sources are variable (Cody & Hillenbrand 2010)

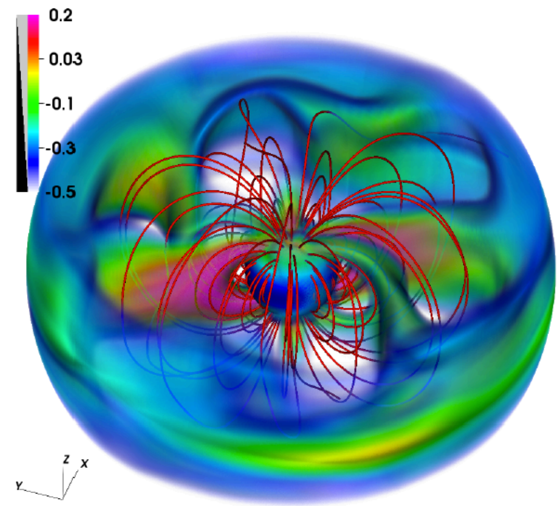
The variability rate increases to >70-80% among accreting/disk-bearing stars alone!

The star – inner disk region: magnetospheric accretion





Kurosawa & Romanova (2013)



Kurosawa & Romanova (2013)

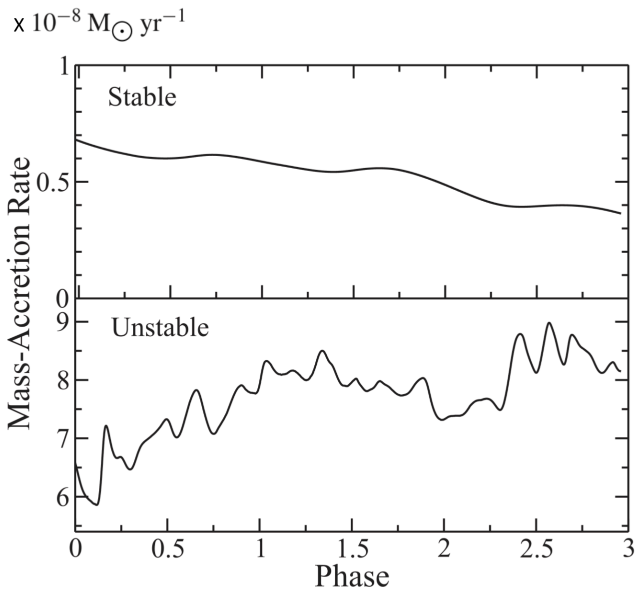
- Axisymmetric
- Steady regime

- Non-axisymmetric
- Steady regime

- Non-axisymmetric
- Unsteady regime

Different accretion regimes: theoretical predictions

Kurosawa & Romanova (2013)

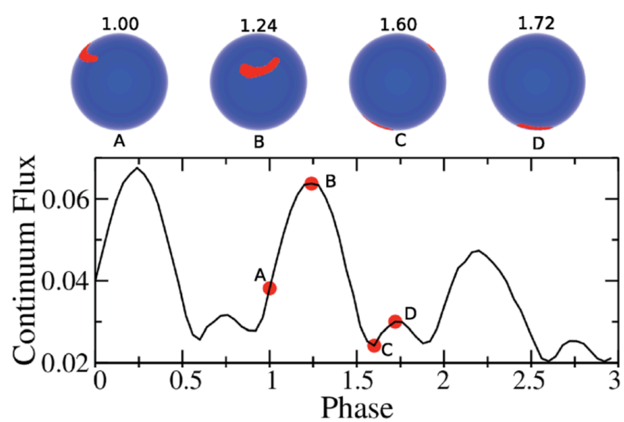


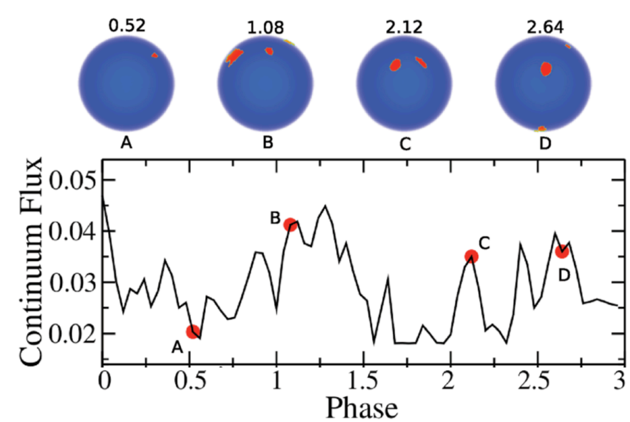
M_{acc} in stable vs. unstable accretion regimes:

- stronger accretion in unstable regime;
- similar amplitudes of variability on rotational timescales;
- stochastic changes in M_{acc} on timescales of hours in the unstable regime.

Simulated light curves:

- smooth and overall periodic (stable regime)
- irregular, short-term stochastic variations (unstable regime)



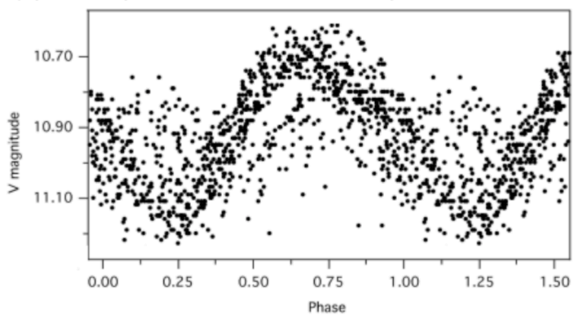


A comprehensive view of YSOs variability

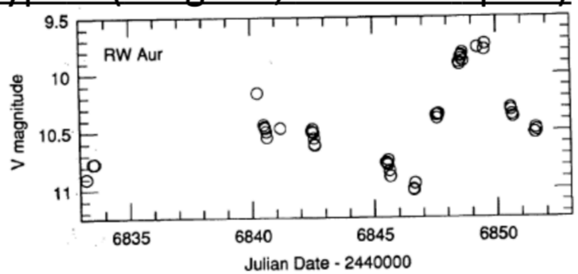
From the ground: *From the space (CoRoT surveys of NGC 2264):*

Herbst et al. 1994:

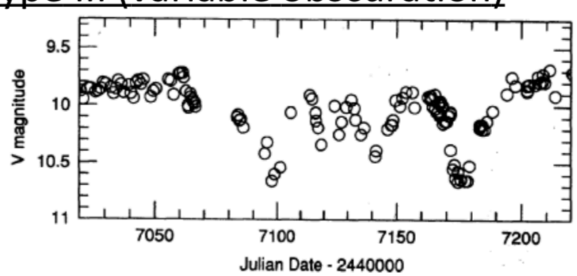
Type I (periodic, cold spots)



Type II (irregular, hot+cold spots)

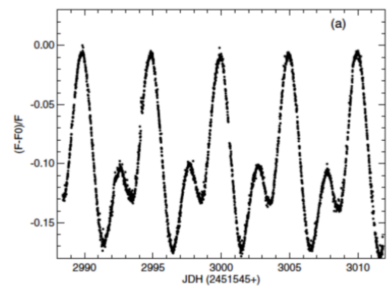


Type III (variable obscuration)

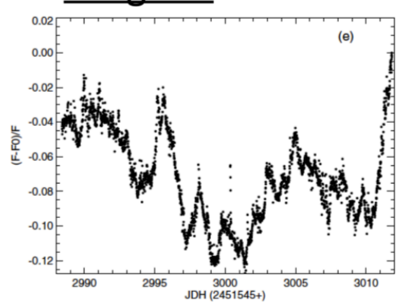


Alencar et al. 2010:

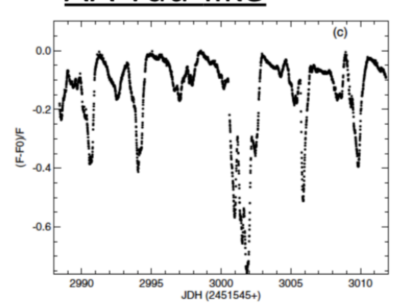
Spot-like



Irregular

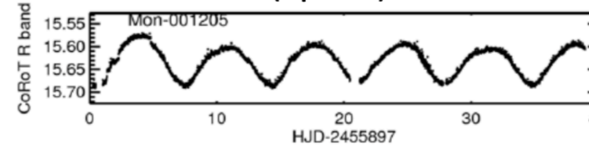


AA Tau-like

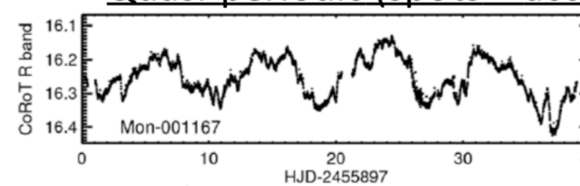


Cody et al. 2014: [from CSI 2264]

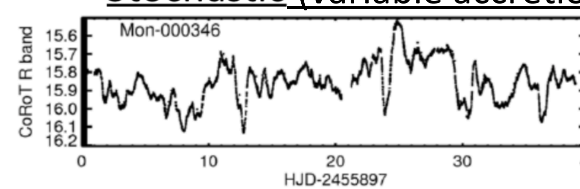
Periodic (spots)



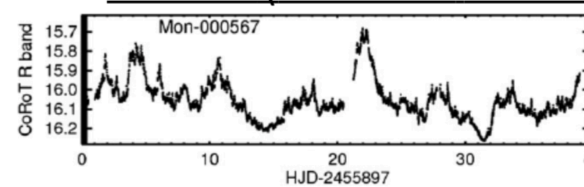
Quasi-periodic (spots + accretion)



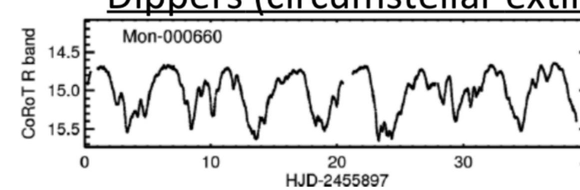
Stochastic (variable accretion)



Bursters (stochastic accretion)



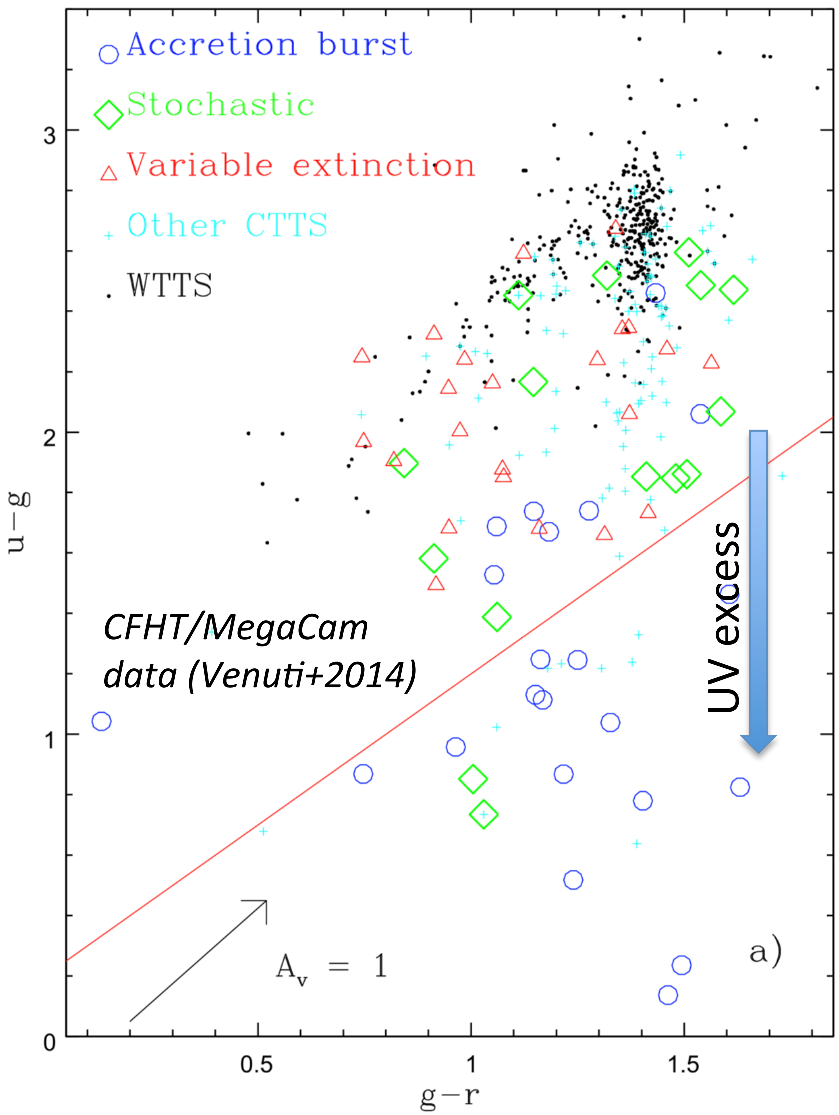
Dippers (circumstellar extinction)



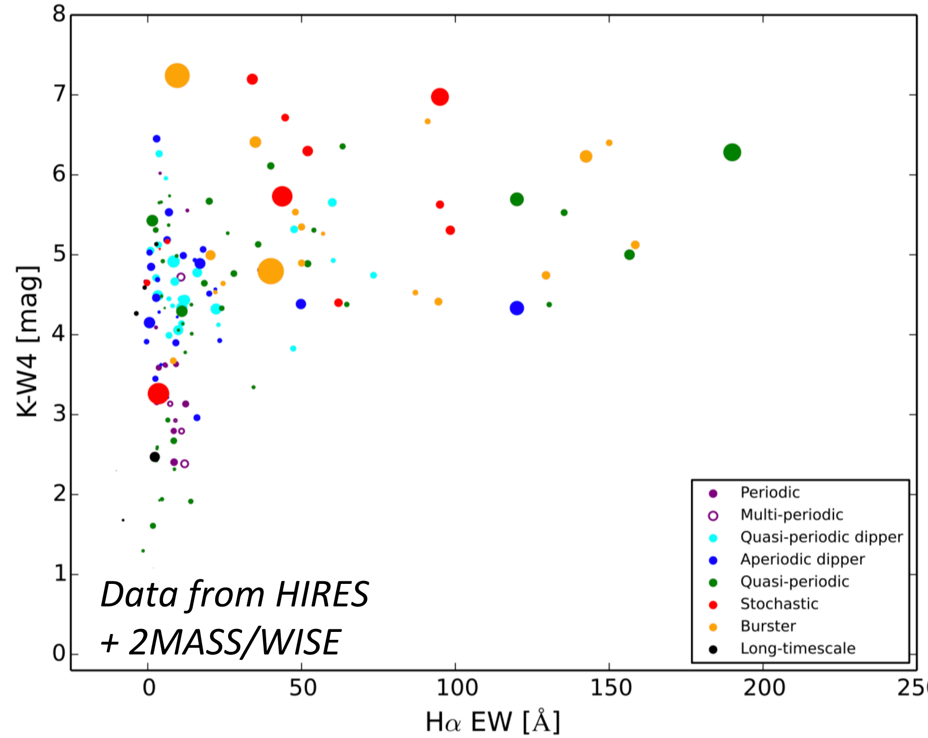
All of the profiles are observed among accreting/disk bearing stars in a single region

YSO variability vs. disk/accretion properties

NGC 2264 (Stauffer et al. 2016)



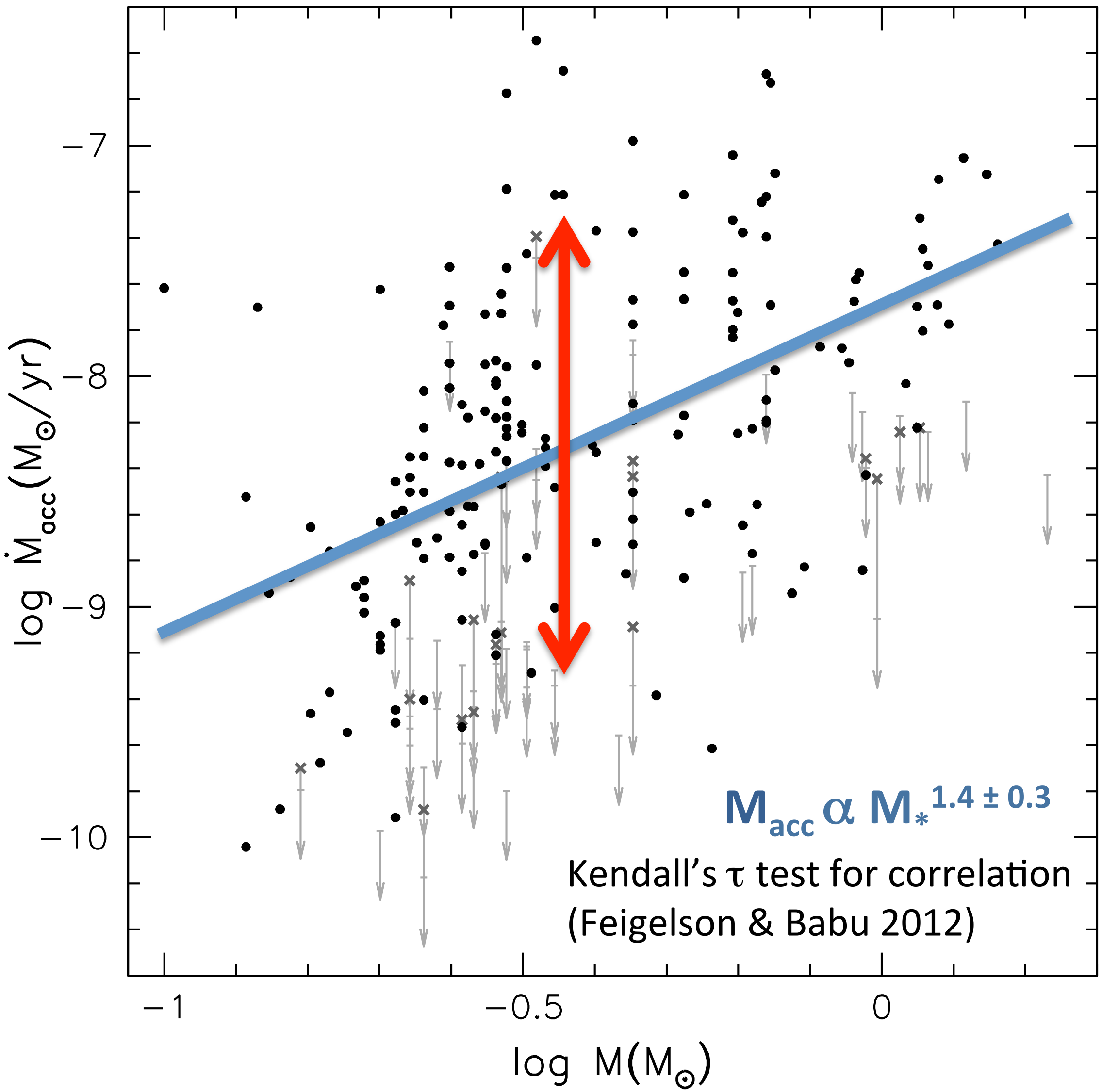
Upper Sco + ρ Oph (Cody & Hillenbrand 2018)



Irregular variability is typically found among sources with the strongest accretion and disk signatures

M_{acc} and variability: the case of NGC 2264

Venuti et al. 2014, A&A 570, A82



M_{acc} measurements:

- *u*-band excess measured relative to WTTS
- UV excess -> L_{acc} -> M_{acc}
- detection limits estimated from the scatter of WTTS colors around ref. sequence
- *M_{acc} measured for 240 CTTS*

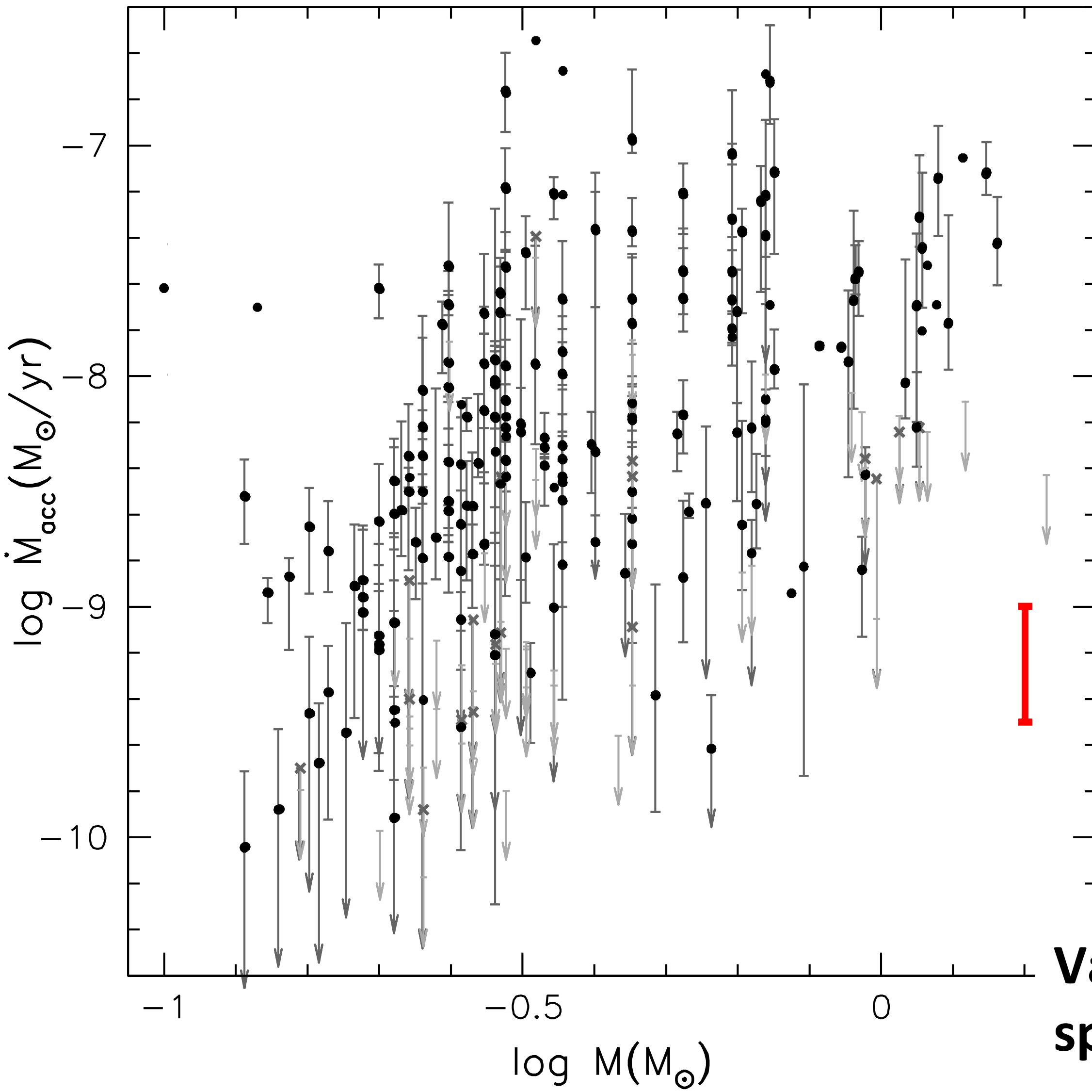
M_{acc} – M relationship:

- statistical correlation to >5σ (Kendall's τ test)
- significant spread (up to 2 dex) in M_{acc} at any given stellar mass

Can the scatter be due to accretion variability?

M_{acc} and variability: the case of NGC 2264

Venuti et al. 2014, A&A 570, A82



Variability bars:

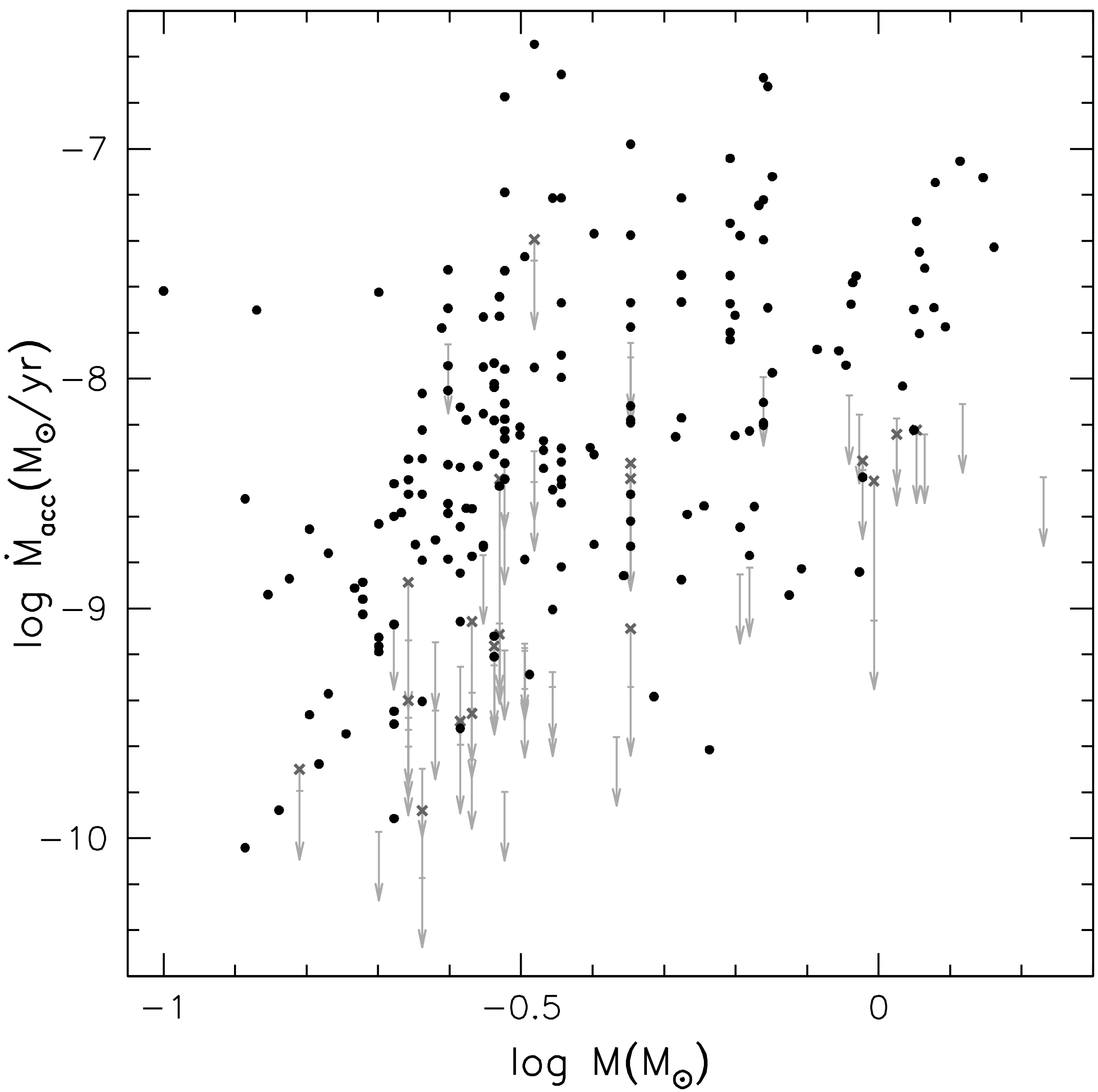
- encompass 17 epochs over 2 weeks
- connect maximum-minimum M_{acc} detected during monitoring

Average variability on week timescales: 0.5 dex

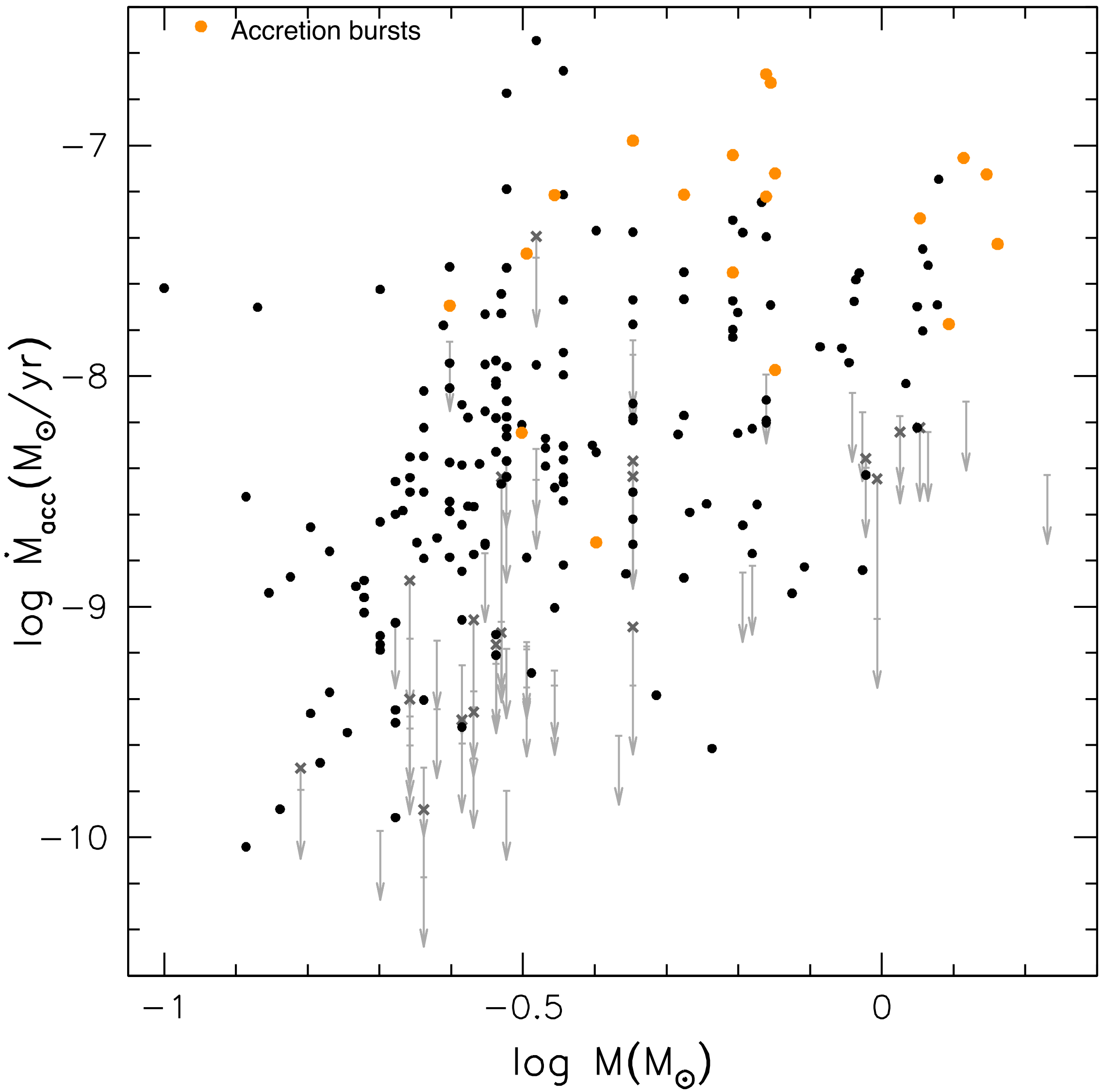
<< spread in M_{acc} at a given stellar mass

Variability does not explain the spread in M_{acc} at a given M_*

Distinct accretion regimes in NGC 2264

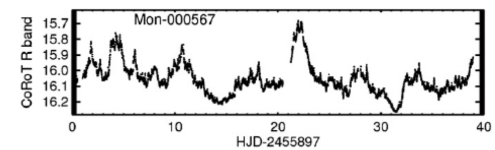


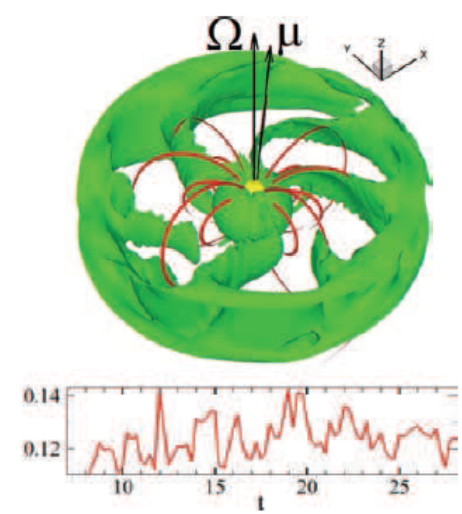
Distinct accretion regimes in NGC 2264



1. **Bursters** **(Stauffer+2014)**:
   - stochastic accretion
   - $M_{acc} \approx 7x10^{-8} M_\odot$/yr
   - match predictions for unstable regimes

   (Kulkarni & Romanova 2008)





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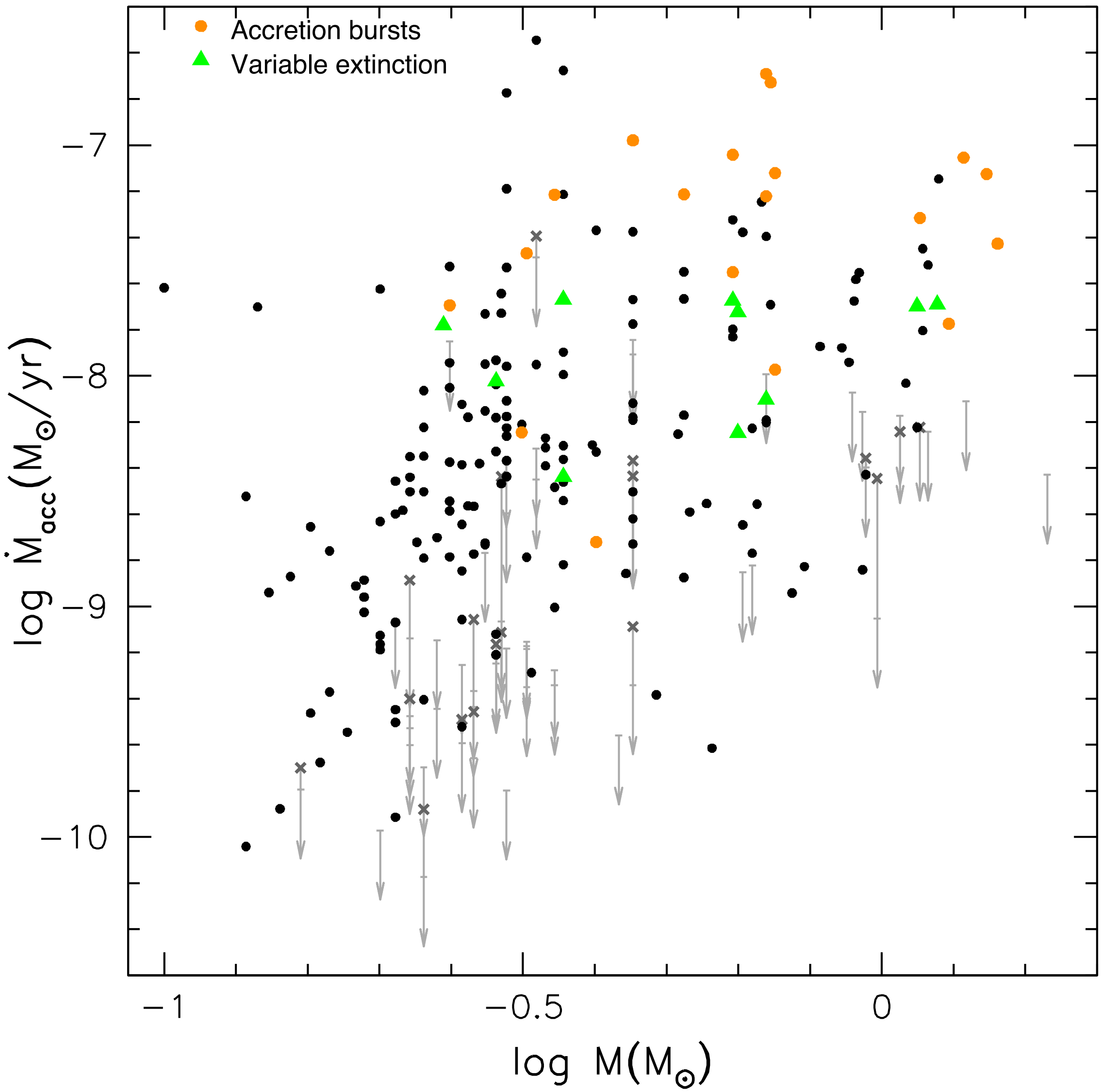

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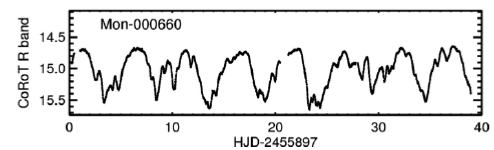
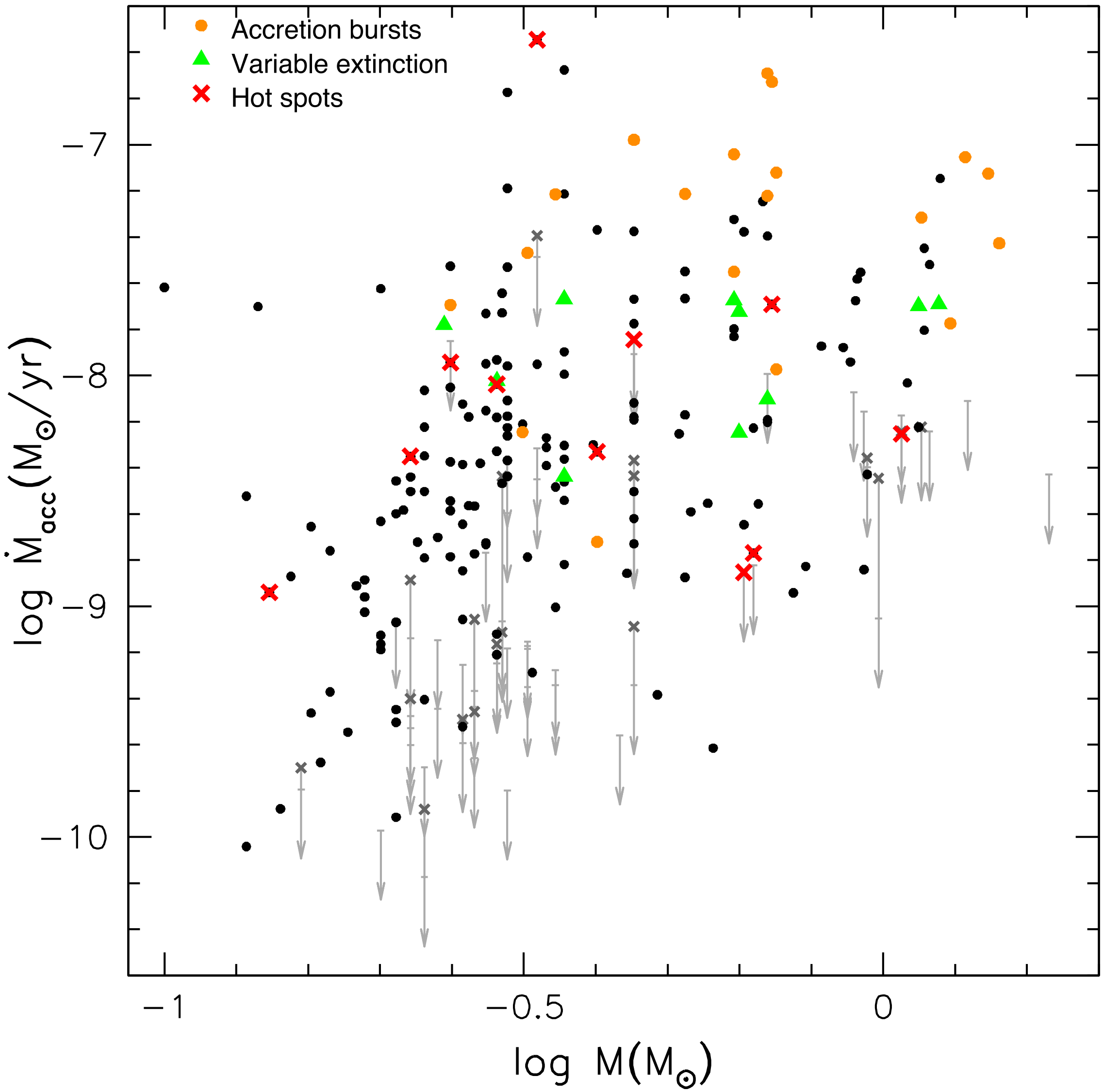
2. **Variable extinction (McGinnis+2015)**:
   - circumstellar occultation
   - $M_{acc} \approx 2 \times 10^{-8}\ M_\odot/yr$
   - periodic -> AA Tau's



Distinct accretion regimes in NGC 2264



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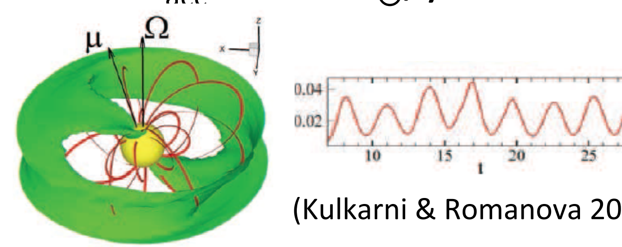
   - $M_{acc} \approx 2\times10^{-8}\,M_\odot$/yr
   - periodic -> AA Tau's

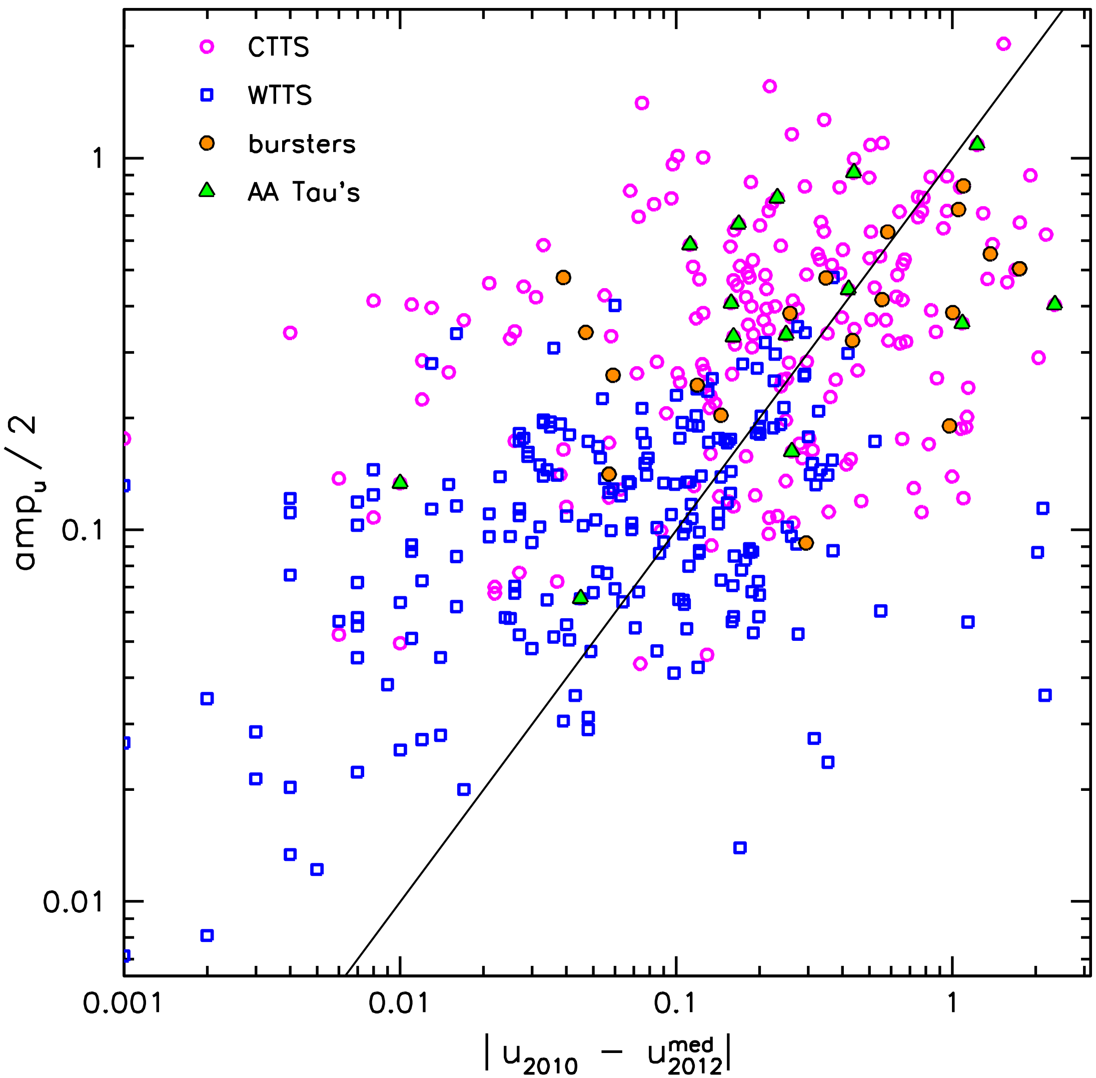
3. **Hot-spotted objects**:
   - dominated by spots
   - $M_{acc} \approx 10^{-8}\,M_\odot$/yr



(Kulkarni & Romanova 2008)

Timescales of accretion variability

Venuti et al. 2015, A&A 581, A66



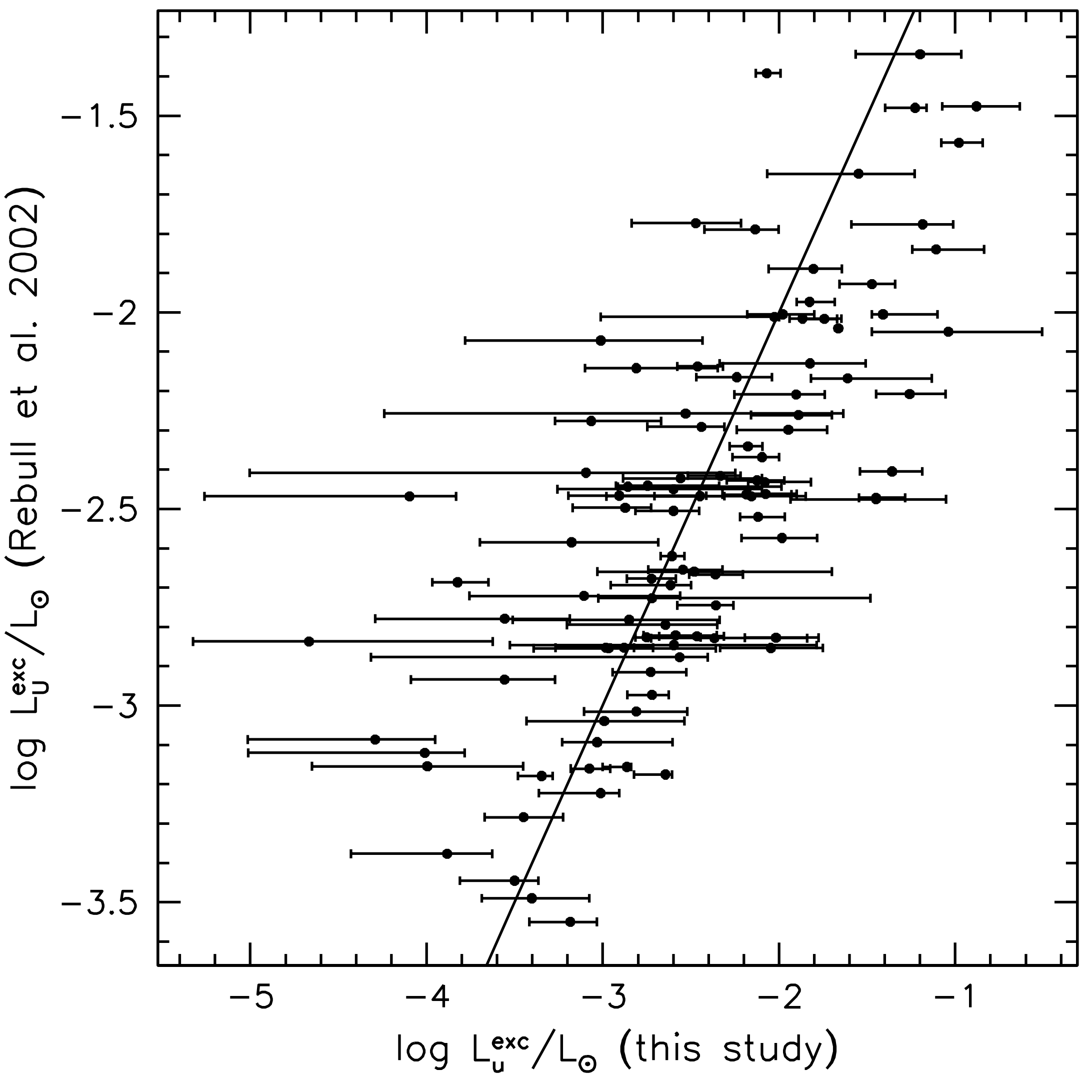
~1 year-long variability in NGC 2264:

- *Dec. 2010*: u-band mapping
- *Feb. 2012*: 2-week u-band monitoring
- comparison between the week-long photometry range and single-epoch data one year apart

> - Accreting stars more variable than non-accreting stars
> - Similar behaviors for the two groups around the equality line on the diagram
> - The year-long variability is statistically consistent with the week-long variability

Timescales of accretion variability

Venuti et al. 2014, A&A 570, A82



~10 years-long variability in NGC 2264

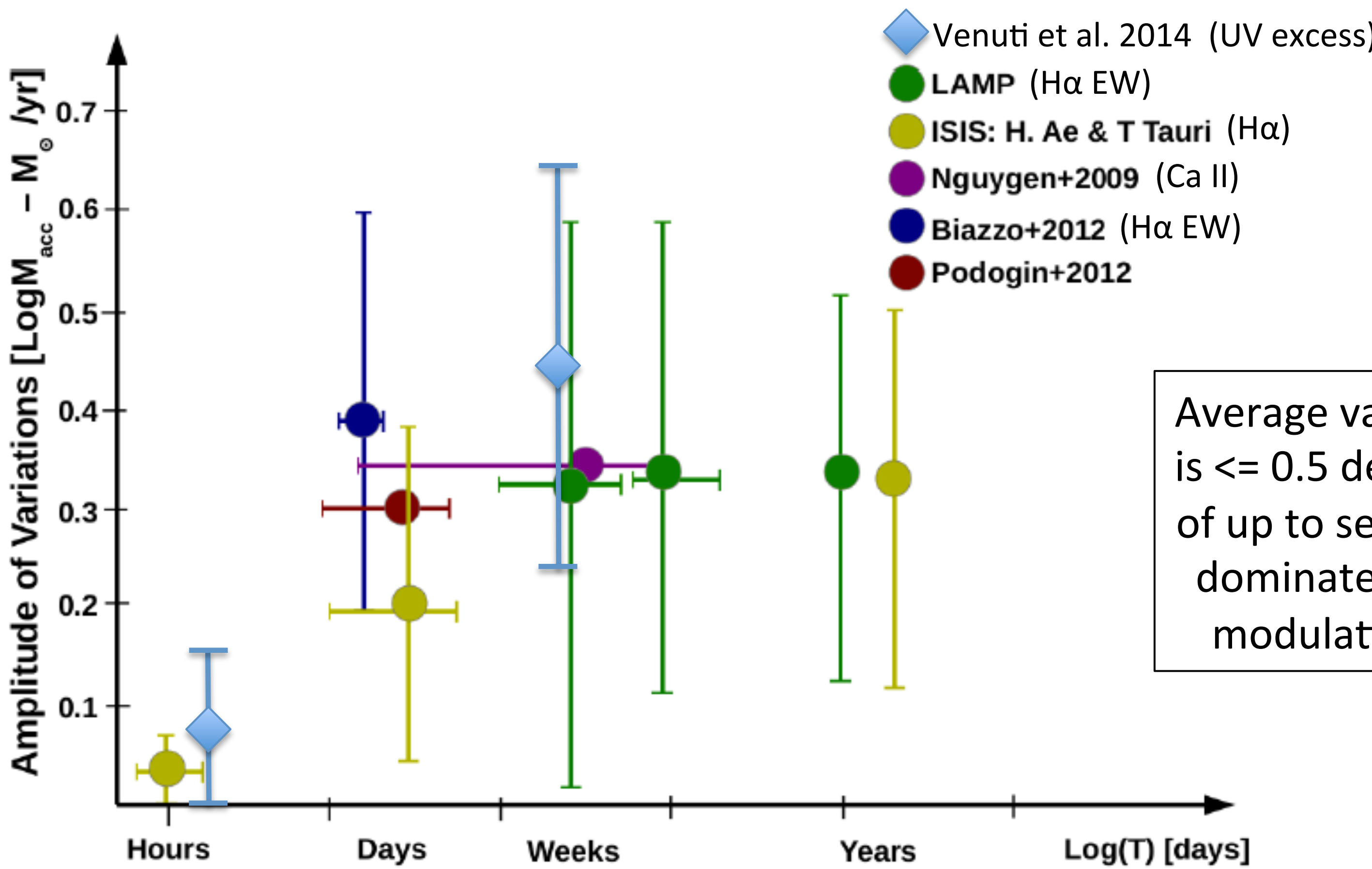
- *Rebull et al. (2002)*: single-epoch survey of accretion from U-excess
- *Venuti et al. (2014)*: mean L_{UV} and L_{UV} variability on week timescales

L_{UV} measured at distance of years are typically consistent within the mid-term (days) variability bars

Timescales of weeks dominate the picture of variability up to baselines of several years

Timescales of accretion variability

Adapted from Costigan et al. 2014, MNRAS 440

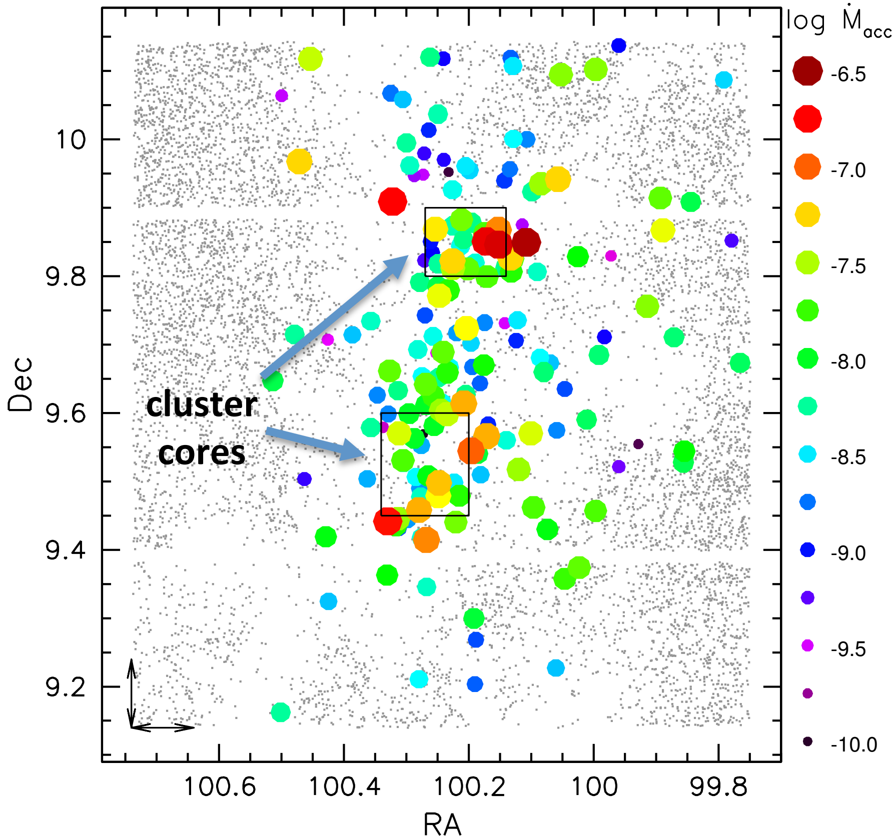


Average variability on M_{acc} is <= 0.5 dex on timescales of up to several years, and dominated by rotational modulation timescales

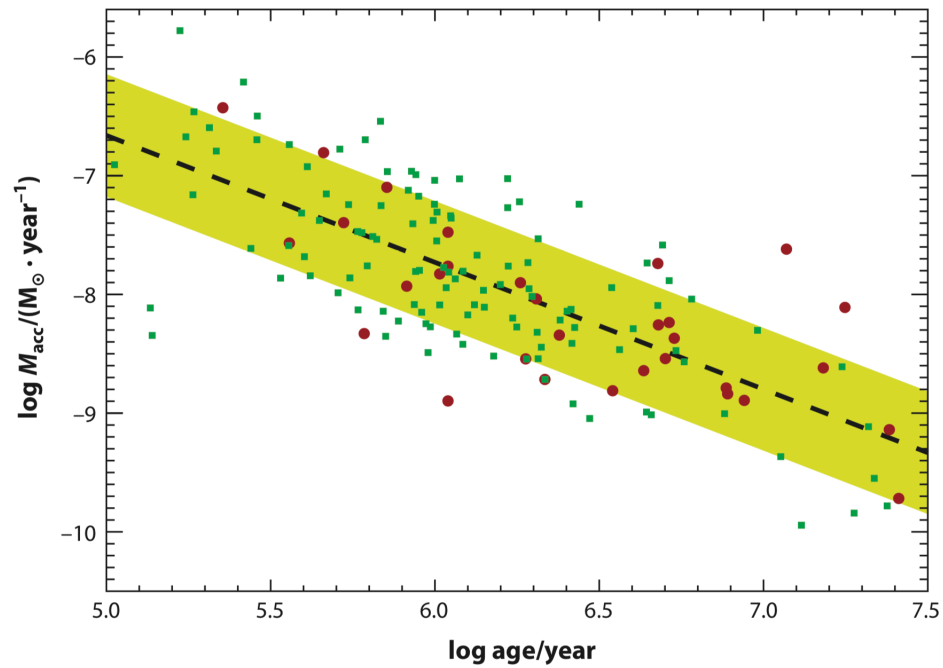
➢ **Accretion process globally stable on a timescale of years, although with more erratic behavior on the short term (discrete accretion events)** [Grankin et al. 2007, Venuti et al. 2015]

Distinct M_{acc} regimes: link to M_{acc} evolution?

Venuti et al. 2014, A&A 570, A82: *Spatial map of accreting stars in NGC 2264 as a function of M_{acc}*



Hartmann, Herczeg, & Calvet 2016, ARA&A 54, 135: *M_{acc} for 0.3-1.0 $M_\odot$ stars, scaled to M_{acc} at 0.7 $M_\odot$, as a function of their estimated ages*



- Strongest M_{acc} associated with earlier evolutionary stages
- (Steady?) decrease in M_{acc} with age

↳ implications for the dynamics and timescales of disk evolution and planet formation/migration

What about the time evolution of M_{acc} variability?

K2 survey of young clusters: YSOs variability between 1 and 10 Myr

- 80 day-long monitoring of:
  - YSOs in Taurus
  - ρ Ophiuchi (1-3 Myr)
  - Lagoon Nebula (2 Myr)
  - Upper Scorpius (5-10 Myr)
- Statistical mapping of hour-to-month YSOs variability across disk lifetimes
- Ancillary observations to assess accretion/disk properties, binarity etc.

Cody & Hillenbrand 2018

Variability types among young disk-bearing stars

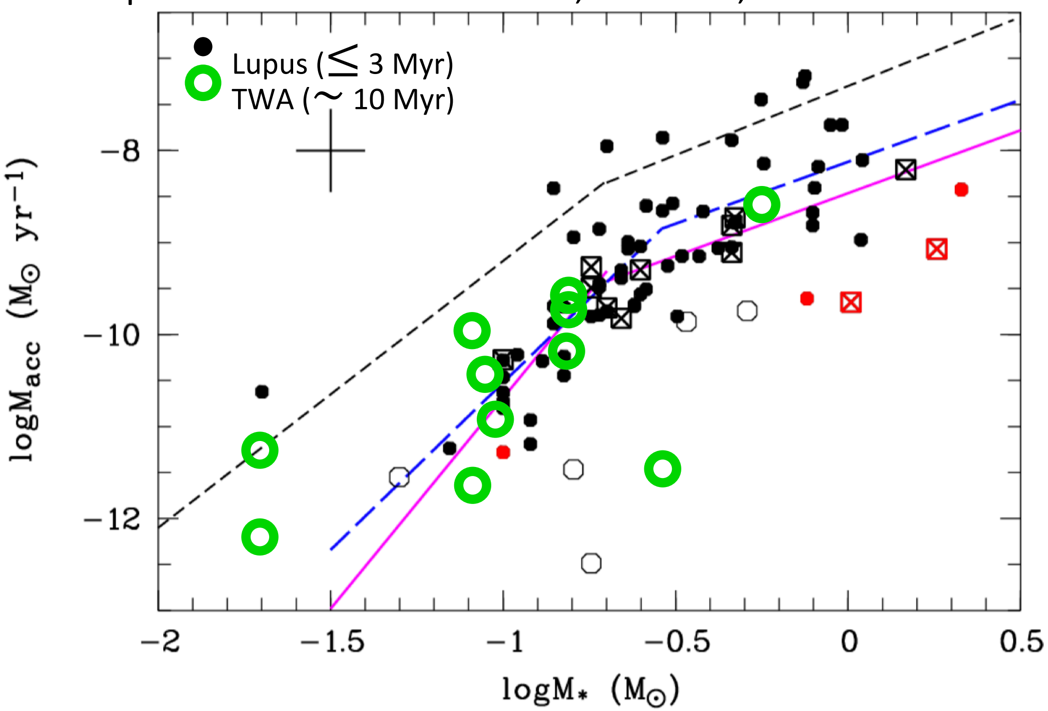
Morphology class	Oph %	Sco %	Sco/Oph composite %	NGC 2264 (3-5 Myr) %
Categories based on periodicity and stochasticity				
All Bursters	14^{+5}_{-2}	13^{+3}_{-2}	14^{+2}_{-2}	13^{+3}_{-2}
Aperiodic symmetric (Stochastic)	12^{+4}_{-3}	6^{+2}_{-1}	8^{+2}_{-2}	13^{+3}_{-2}
Quasi-periodic symmetric	20^{+5}_{-4}	29^{+3}_{-2}	26^{+3}_{-2}	17 ± 3
Aperiodic dippers	9^{+5}_{-2}	18^{+3}_{-2}	16^{+2}_{-2}	11^{+3}_{-2}
Quasi-periodic dippers	14^{+5}_{-3}	18^{+3}_{-2}	17^{+2}_{-2}	10.5^{+3}_{-2}
Periodic symmetric	6^{+4}_{-2}	7^{+2}_{-2}	7^{+1}_{-2}	3^{+2}_{-1}
Other Categories				
Multiperiodic	7^{+4}_{-2}	4^{+2}_{-1}	5^{+2}_{-1}	1^{+2}_{-1}
Long timescale	8^{+4}_{-2}	0^{+2}_{-0}	3^{+1}_{-1}	1^{+2}_{-1}
Unclassifiable	2^{+3}_{-0}	0^{+2}_{-0}	1^{+1}_{-1}	11^{+3}_{-2}
Non-variable	6^{+4}_{-2}	3^{+2}_{-1}	4^{+1}_{-1}	19 ± 3

Preliminary indications:

- (blue) % of stochastic light curves decreases with age, while % of quasi-periodic increases;
- (green) % of dipper light curves increases with age;
- (red) no apparent changes in the percentage of burster light curves with age.

TWA: accretion in very low-mass stars and at the upper end of disk lifetimes

Adapted from Alcalá et al. 2017, A&A 600, A20



- X-shooter survey of accreting stars in TW Hydrae association
- 14 sources with disk observed
- survey complete down to $\sim$0.02 $M_\odot$
- multi-epoch observations already acquired for 5/14 sources
- Analysis ongoing: Venuti, Stelzer, Alcalá, Manara, Frasca
- Age-dependent variability: TWA vs. Lupus (multi-epoch data available for $\sim$10% of accreting stars)

Preliminary indications:

- in the lower mass regime, same range in M_{acc} as found, *with the same method*, in younger regions (Lupus, Chamaeleon I; see also talk by C. Manara)
- distinct accretion timescales in different mass regimes?
- different $M_\star - M_{acc}$ behavior at the lowest masses?

Conclusions/perspectives

- Variability monitoring of accreting stars crucial to probe the structure of the inner disk region and the dynamics of the star-disk interaction
- Two distinct scenarios of disk accretion: *stable* vs. *unstable*, reflecting in "regular"/quasi-periodic vs. burster/stochastic light curves
- Unstable regimes translate to erratic short-term behavior, but in both scenarios the accretion process appears globally stable on the longer term (month-to-year M_{acc} variability dominated by week-long timescales)
- The ratio of stochastic to quasi-periodic variables tends to decrease with age, but "bursters" are similarly represented in clusters of different ages
- Different timescales for M_{acc} evolution may pertain to distinct stellar mass regimes, with lower-mass stars (< 0.3 $M_{\odot}$) exhibiting comparable levels of accretion between < 3 and 10 Myr
- Assessing the time evolution of M_{acc} variability is key to test the evolving dynamics of star-disk interaction across protoplanetary disk lifetimes