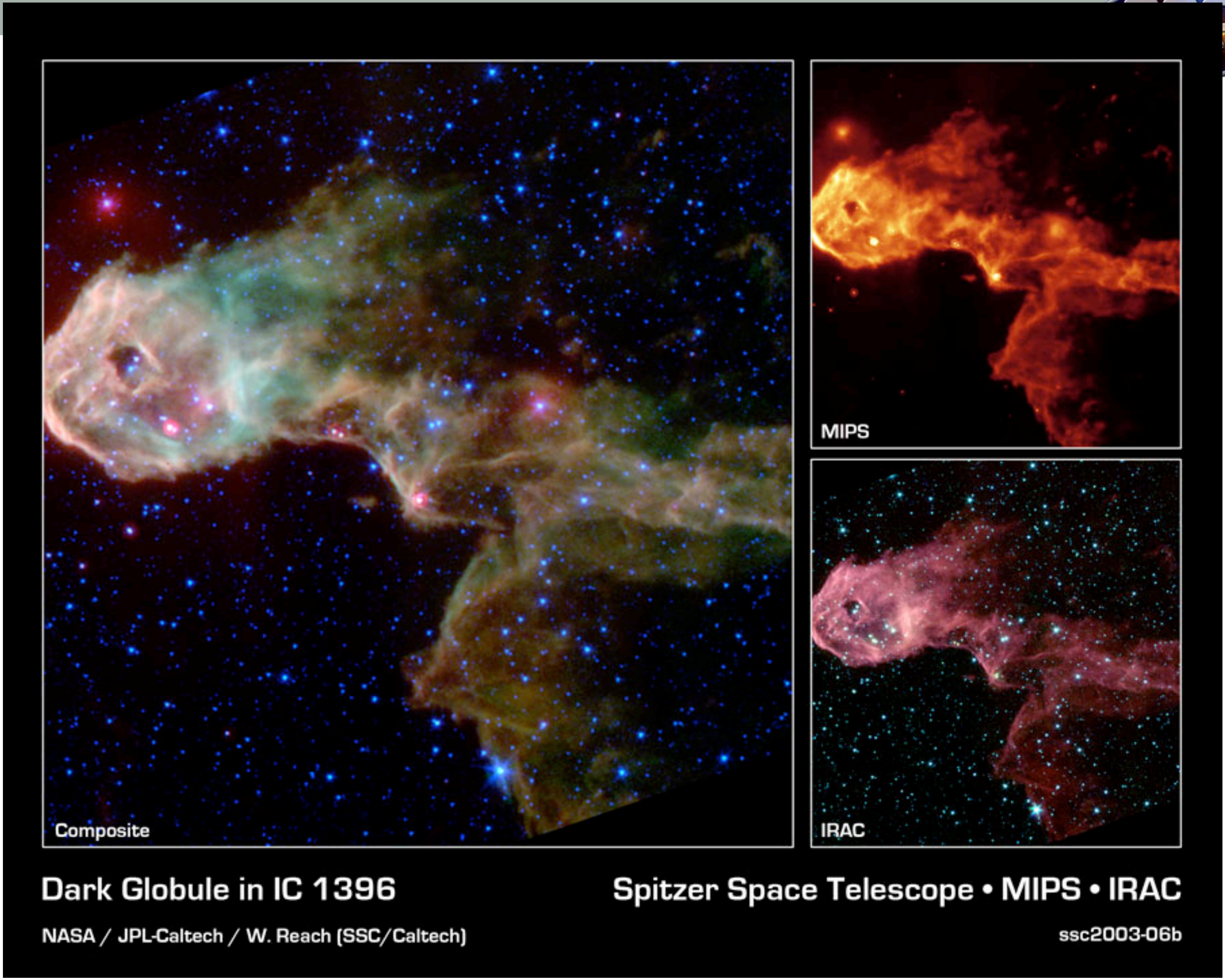
# Evidence of Variability from YSOVAR

Luisa Rebull
SSC/IPAC/Caltech
14 May 14


MIPS
IRAC
Composite
Dark Globule in IC 1396
Spitzer Space Telescope • MIPS • IRAC
NASA / JPL-Caltech / W. Reach (SSC/Caltech)
ssc2003-06b

# IC1396A (with Cold Spitzer)

- **Morales-Calderon et al. (2009)**: First *high-cadence* monitoring of young stars in IRAC bands (3.6, 4.5, 5.8, 8 um).
- More than half of the YSOs showed variations, from ~0.05 to ~0.2 mag, on variety of timescales → physical interpretations.
- Cool spots; hot spots illuminating inner wall of CS disk, plus large inclination angle; flares; Mdot flickering; disk shadowing, pulsation(!).
- Larger amplitude variables tend to be younger (more embedded).
- Accretion and simple models: $10^{-9}$ to $10^{-8}$ Msun/yr could match amplitudes, but some params have little effect in IRAC: “not dominant” source of variability.

# What is YSOVAR?

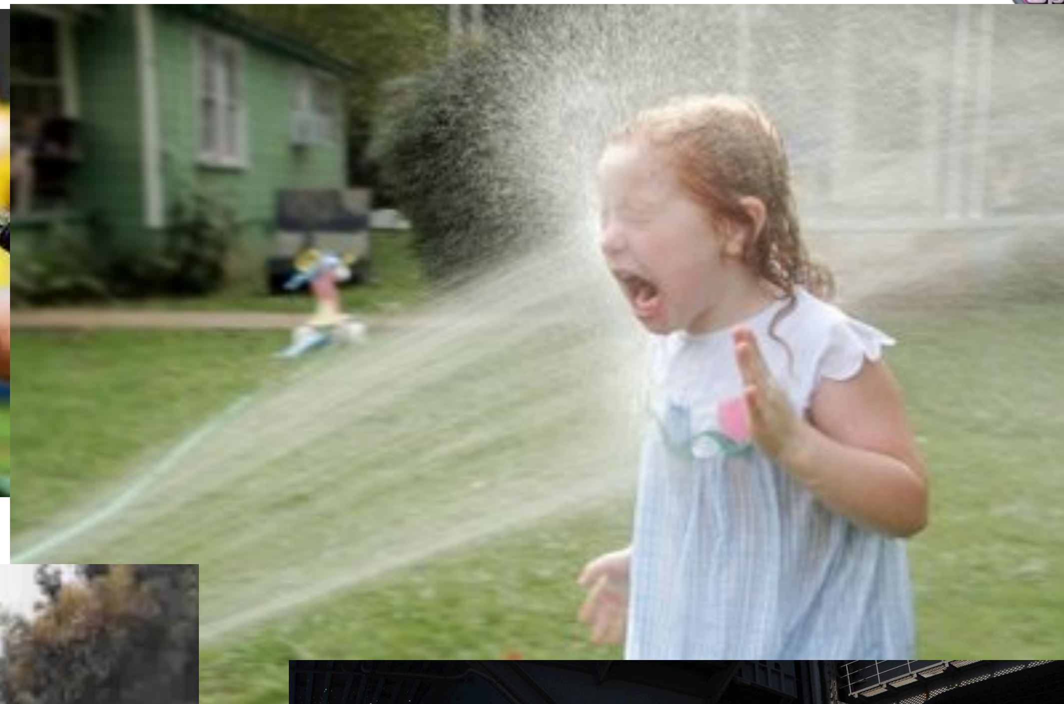
## Why-so-VARiable?

- Two big and several small Spitzer GO programs….
- First sensitive, wide-area, MIR (3.6 and 4.5 um) time series photometric monitoring of YSOs on t~hours (minutes) to years.
- Includes ~1 square degree of the ONC plus embedded regions of 11 other SFRs. (CSI2264=other big pgm.)
- → ~790 hours total of Spitzer time monitoring young stars
- Typically ~100 epochs/region (sampled ~2x/day for 40d, less frequently at longer timescales).
- ~32,000 objects with light curves → ~4000 YSOs with good light curves in 1 or both bands!
- Data taken over the period Sep 2009 – Jan 2014.

# Who is YSOVAR?

- PI: J. Stauffer (SSC)
- Deputy: L. Rebull (SSC)
- A. M. Cody (SSC)
- M. Morales-Calderon (INTA-CSIC)
- Plus *many* others… & more folks affiliated with specific sub-programs.
- http://ysovar.ipac.caltech.edu

SSC Spitzer Science Center



# Wet and bedraggled, we do seem to be gaining on it…

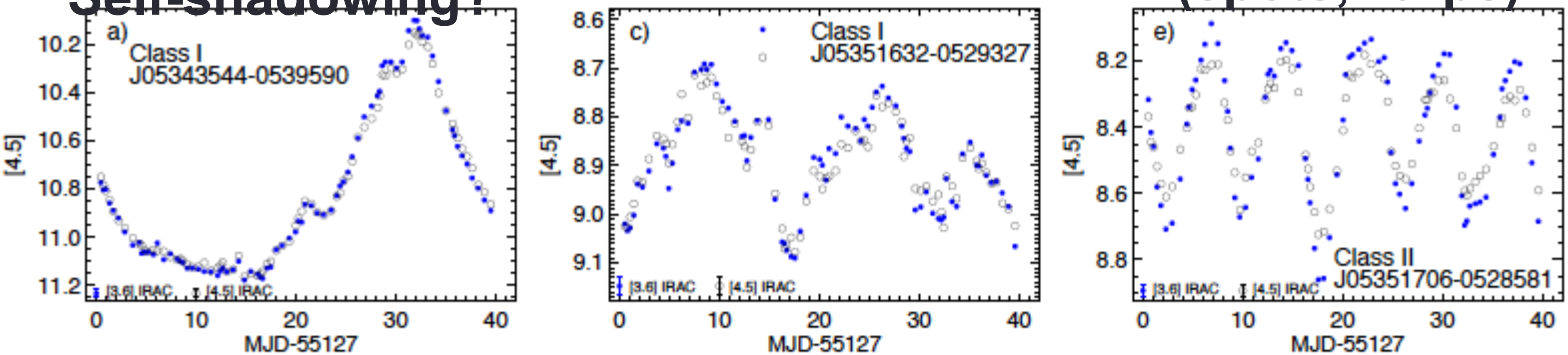
- **Orion, year one** : **Morales-Calderon et al. (2011)** identified "dipper stars" and others; Morales-Calderon et al. (2012) identified eclipsing binaries.
- **NGC 2264, year two** : HUGE amount of simultaneous data, makes huge difference in interpretation, classification.
  - **Cody et al. 2014, AJ** – the CSI project, classifications
  - **Stauffer et al. 2014, AJ** – **ACCRETION**!
- The **ensemble & smaller clusters**:
  - The ensemble, longest timescales (Rebull et al. 2014 *very nearly* submitted).
  - Papers on each cluster – e.g., L1688 (Guenther+ 2014 submitted); NGC 1333 (Rebull+ 2014 in prep).
- Approach: sort LCs, look for correlations.

•=[3.6], o=[4.5]

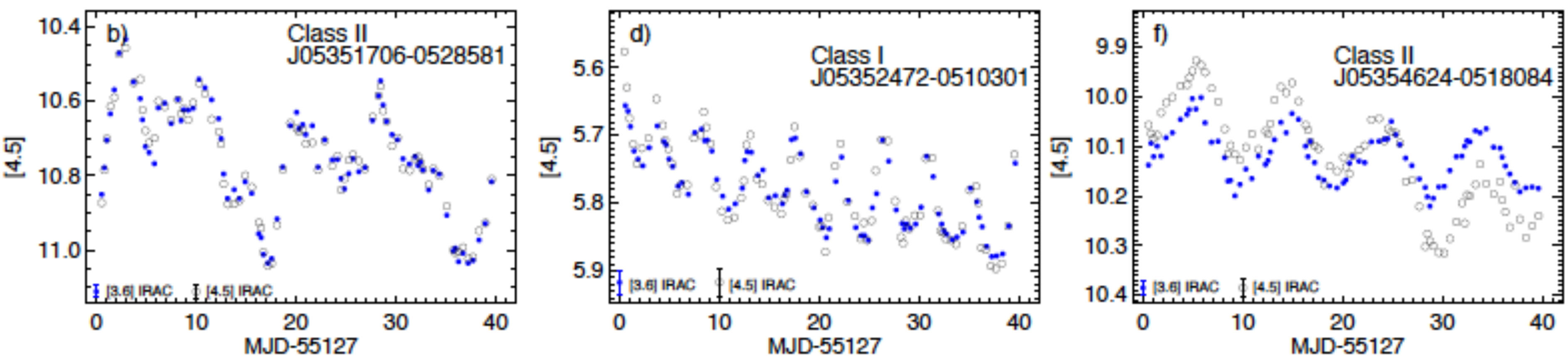
**Slow ΔMdot? Self-shadowing?**

**Flares**

**Periodic (spots,warps)**




~65% of Class I+II and ~30% of the Class III are variable.




**Δ Mdot geom?**

**High-mass… something**

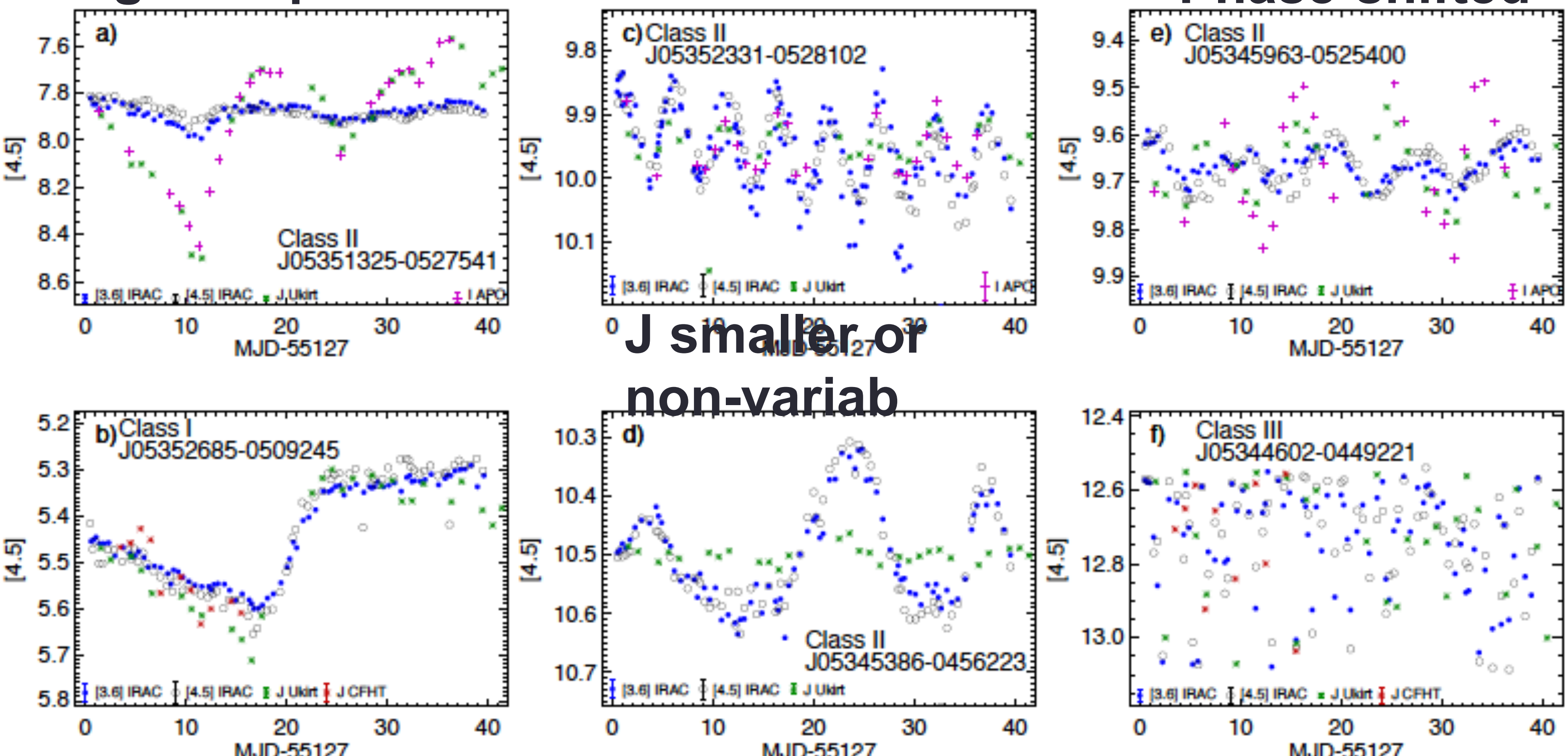
**??**

*Morales-Calderon et al. (2011)*

•=[3.6], o=[4.5], * or * =J, +=Ic

J similar shape,
larger ampl

Phase-shifted




J smaller or
non-variab

J similar shape,
similar ampl

Recovered
P~0.27d

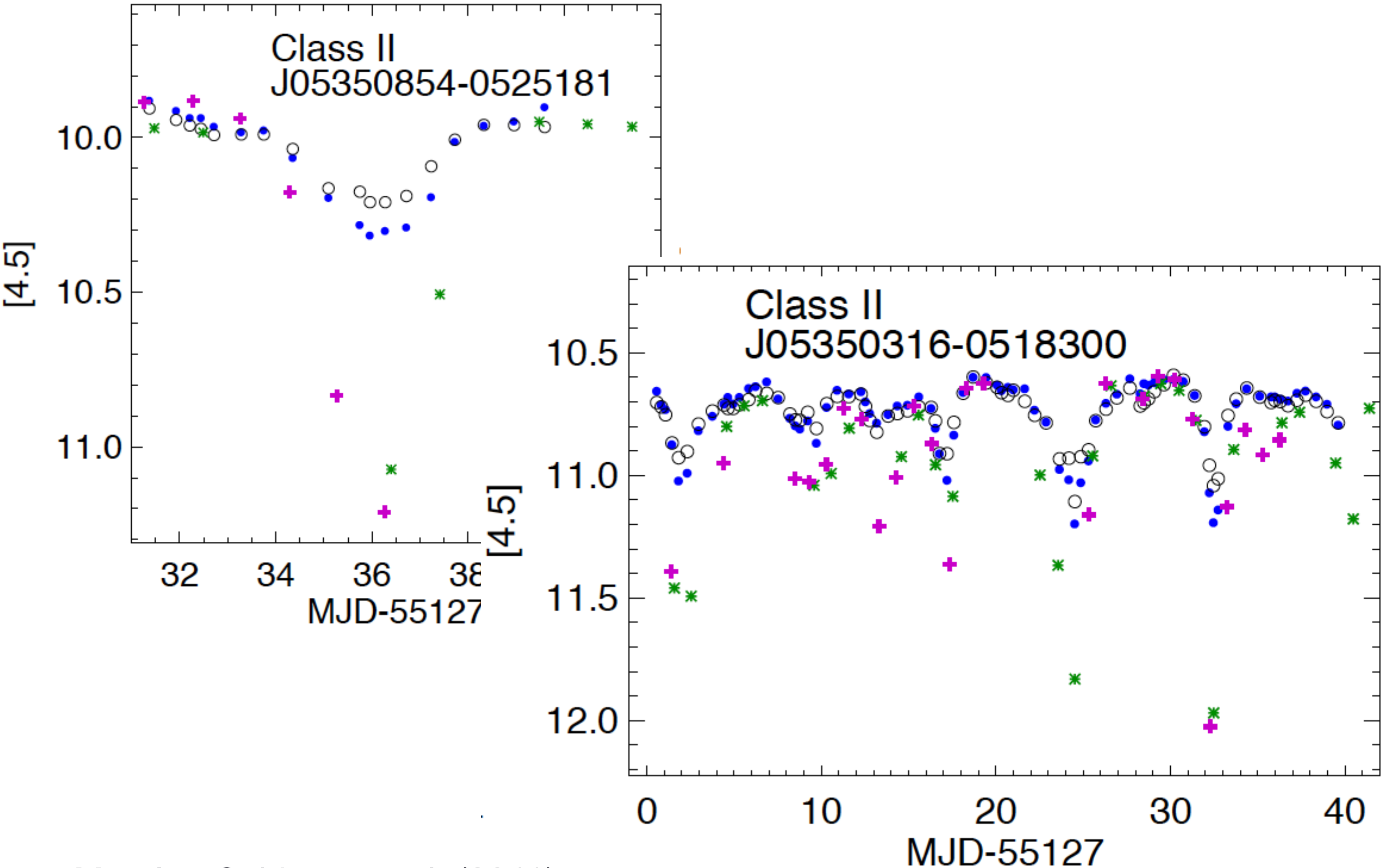
*Morales-Calderon et al. (2011)*

# “Dipper” objects

- Stars with narrow flux dips, t~days, typically >1 seen over our 40d window.
- Like AA Tau…
- Require >1 epoch unless corroborating data at another band.
- Optical or J band deeper by at least 50%.
- Continuum flat enough that dip “stands out.”
- 38 Class I or II objects (~3%) in our Orion Year 1 set are dippers.
- Interpret as structure in the disk (clouds, warps).

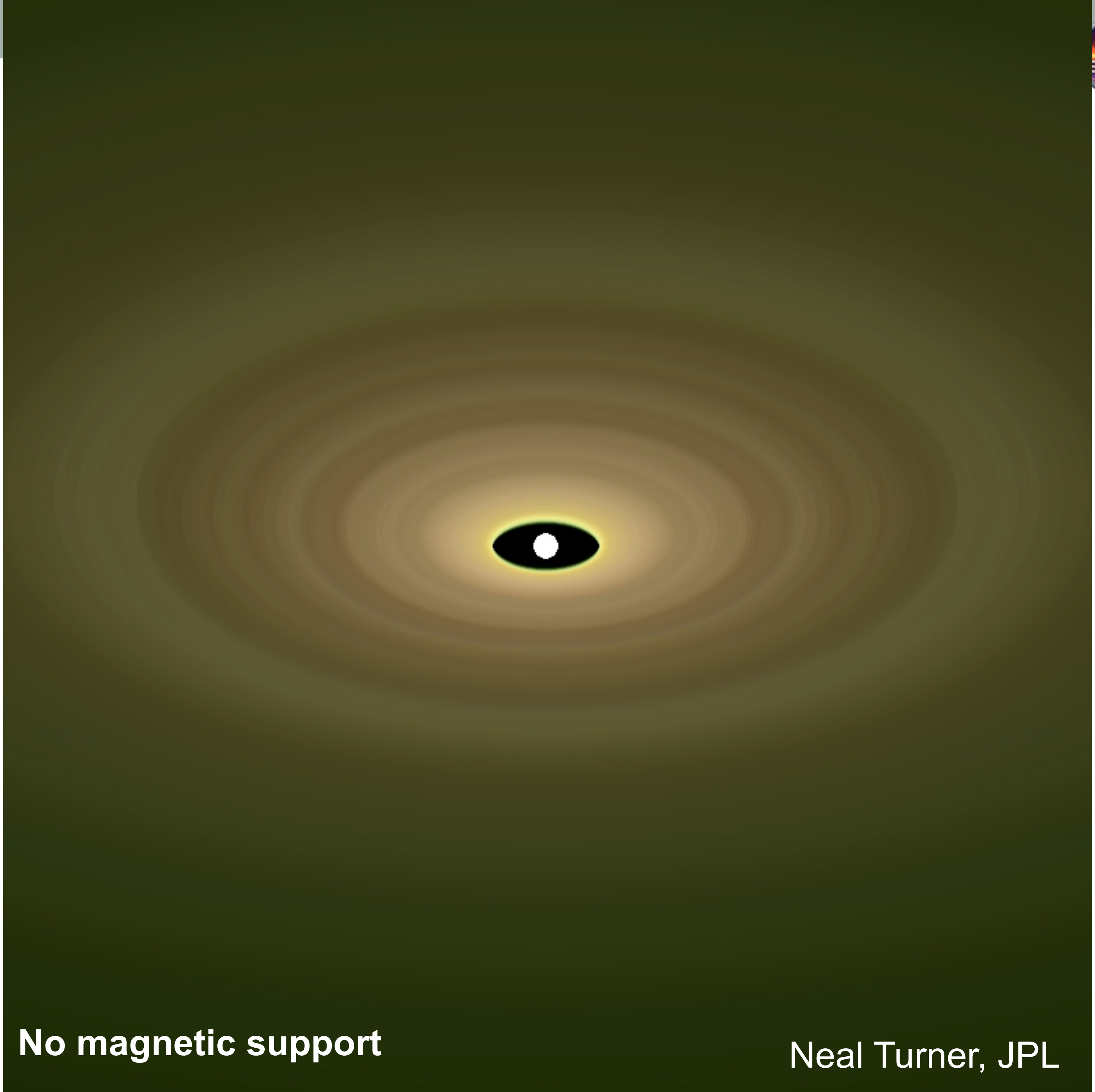
*Morales-Calderon et al. (2011)*

•=[3.6], o=[4.5], * or * =J, +=Ic



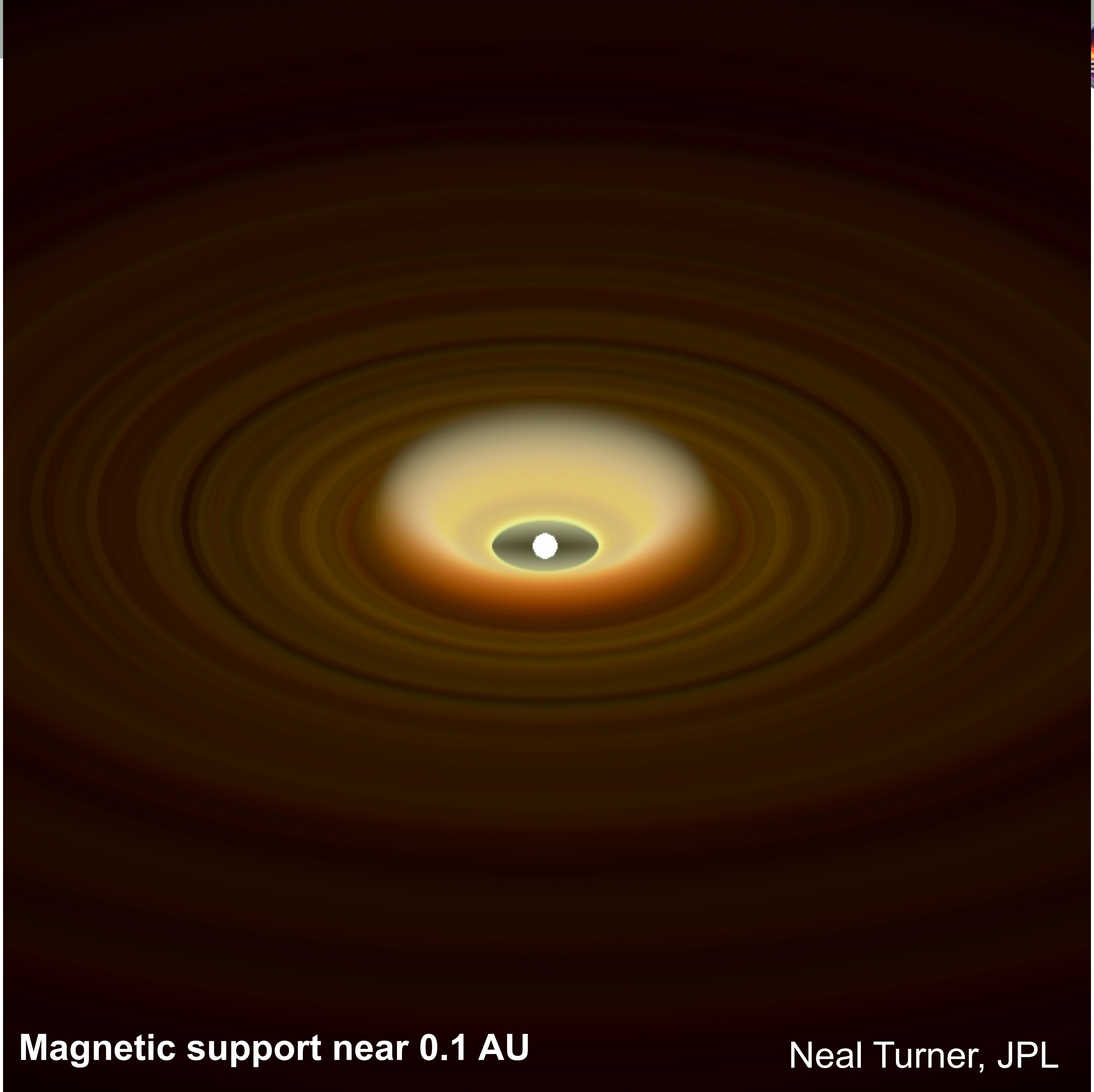

Morales-Calderon et al. (2011)

60°
0.8 AU

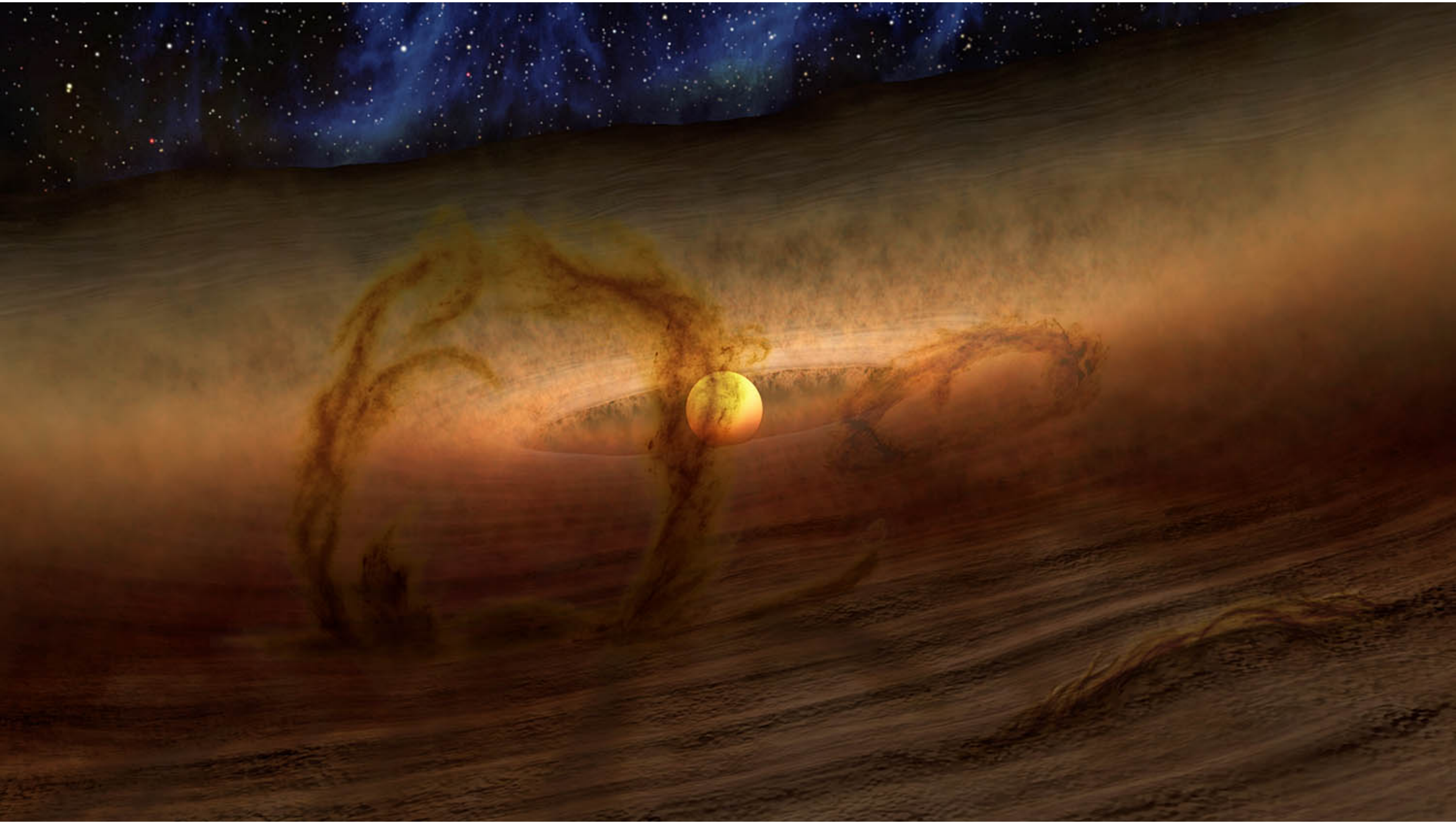



V
J
3.6

60°
0.8 AU




V
J
3.6



NASA/JPL-Caltech/R. Hurt (IPAC)

# Questions about dippers

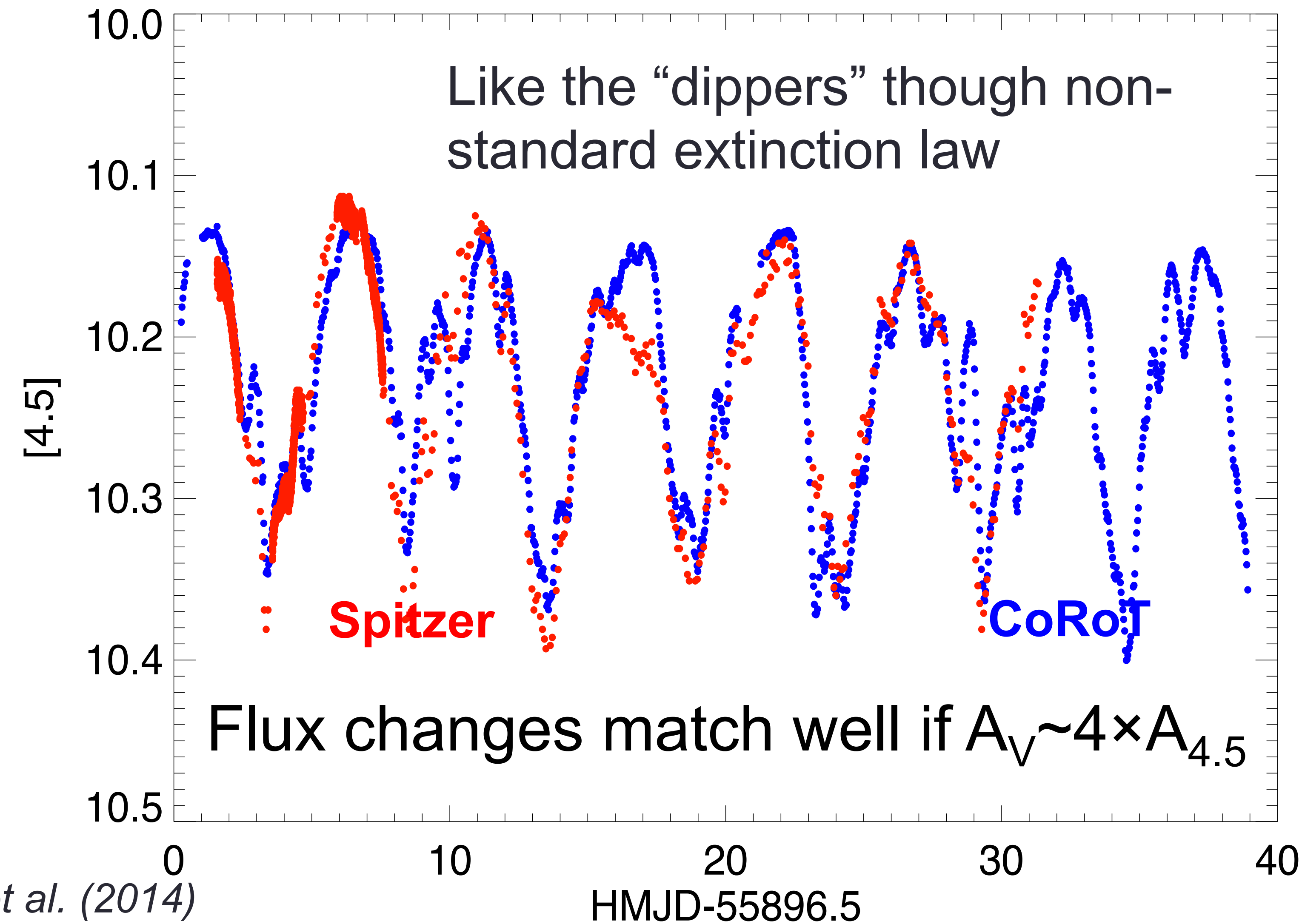
- Disk must be seen at relatively high (and relatively narrow range of) inclinations to do this, so expect that they are ~rare.
- YSOVAR Orion (year 1): Morales-Calderon et al. (2011) finds overall fraction likely ~5% (2011).
- First CoRoT short run (2008) on NGC2264: Alencar et al. (2010) finds overall fraction likely ~30%.
- What's going on? Different ages of stars (Orion vs. NGC 2264)? Different wavelengths (optical vs. IR)? Different cadences? (Different definitions of the category?)

# Coordinated Synoptic Investigation of NGC 2264 (CSI:2264)

- (mostly) December 2011
- Spitzer,
- CoRoT,
- Chandr
- MOST,
- VLT/Fla
- Ground-
- High precision photometry, high resolution spectra; timescales from <1 min to >1 month.

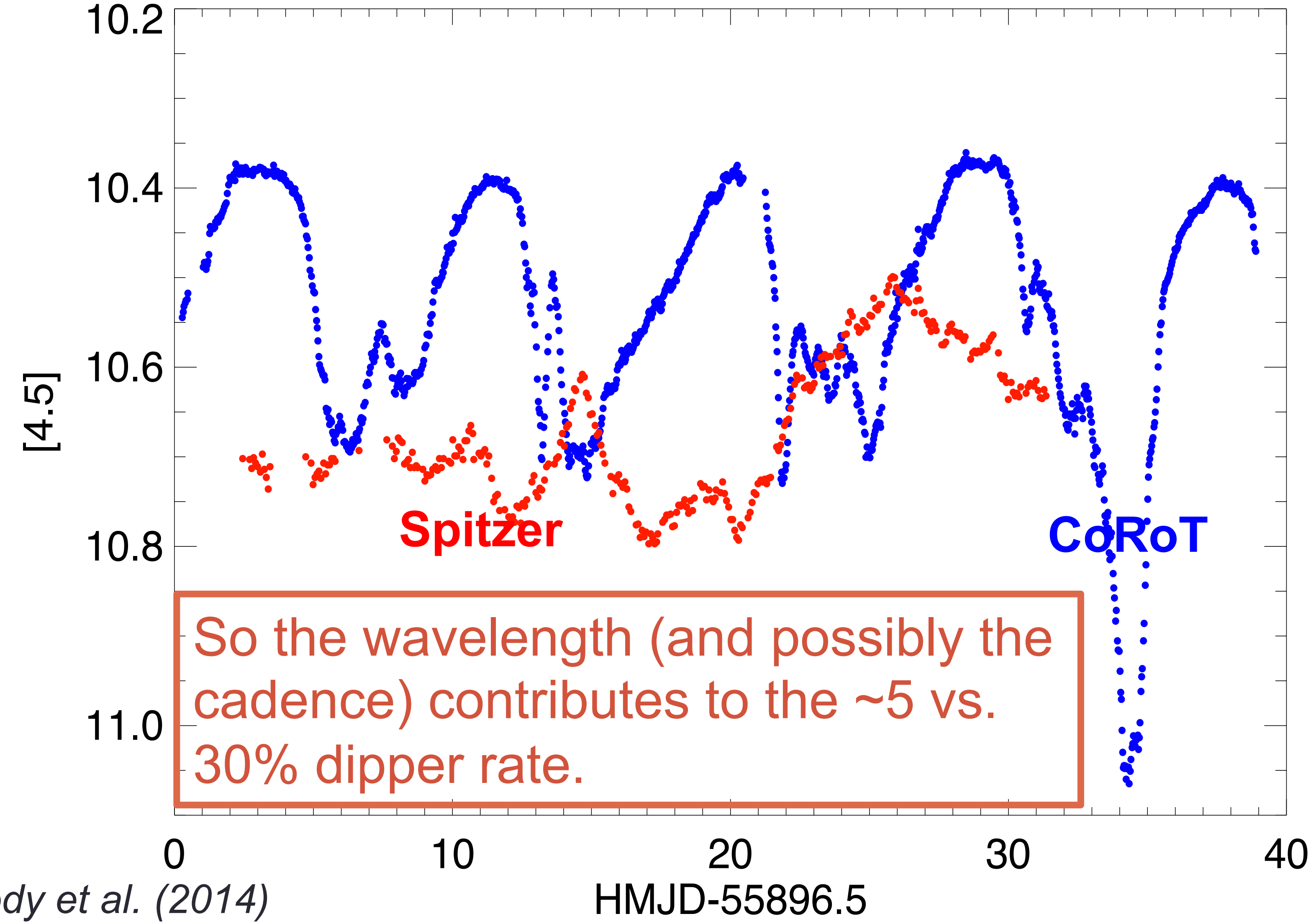
NB: NGC 2264 is the only star-forming region observed by CoRoT. CSI:2264 had both Spitzer and CoRoT working. **There is not, nor is there likely to be any time soon, another data set like this one.** Nothing else even on the horizon can do this to this precision.

# Some patterns: dust obscuration




*Cody et al. (2014)*

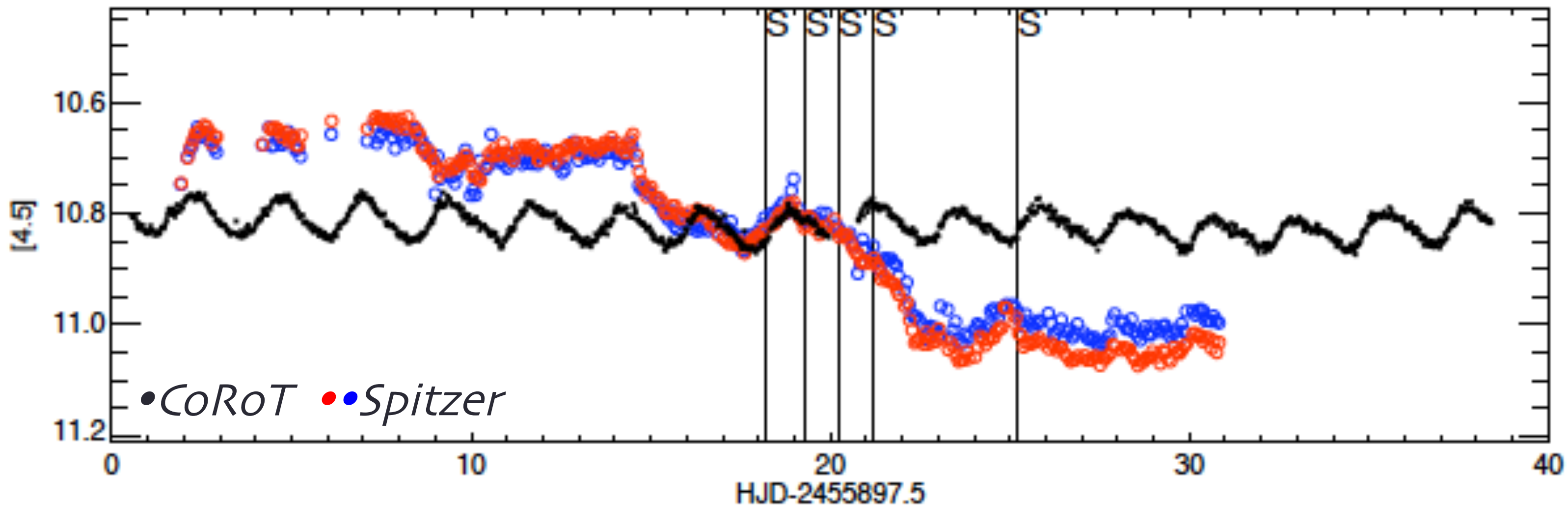
# Some patterns: NOT dust…

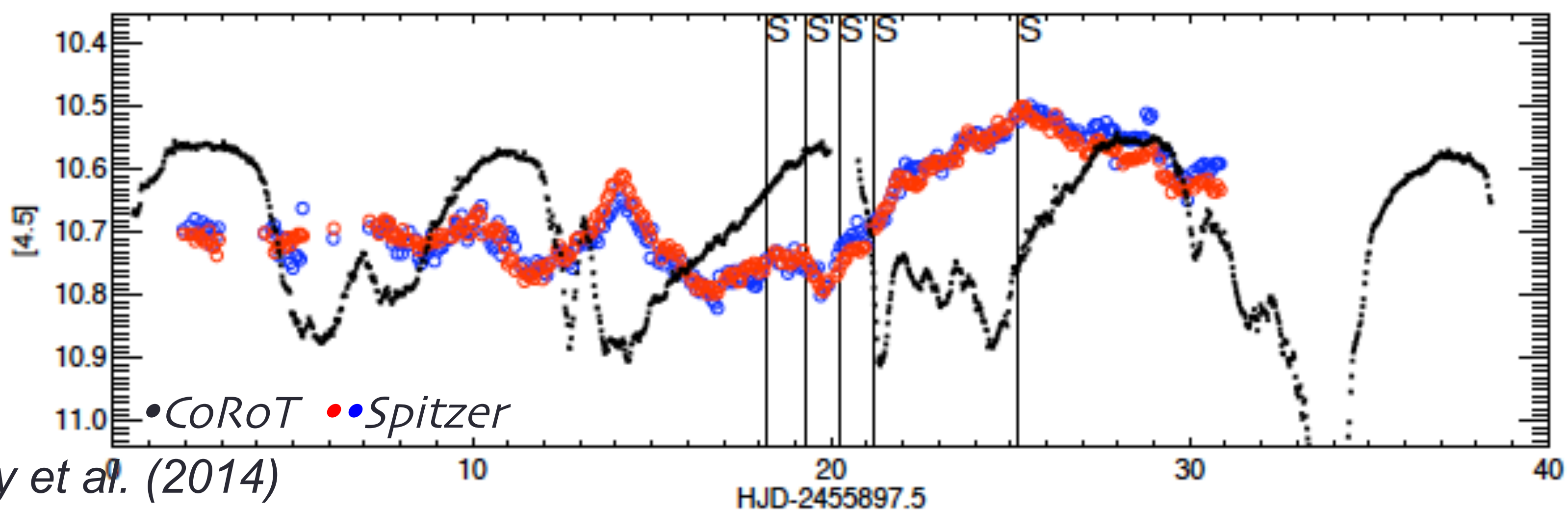



So the wavelength (and possibly the cadence) contributes to the ~5 vs. 30% dipper rate.

*Cody et al. (2014)*

# LOTS are uncorrelated…

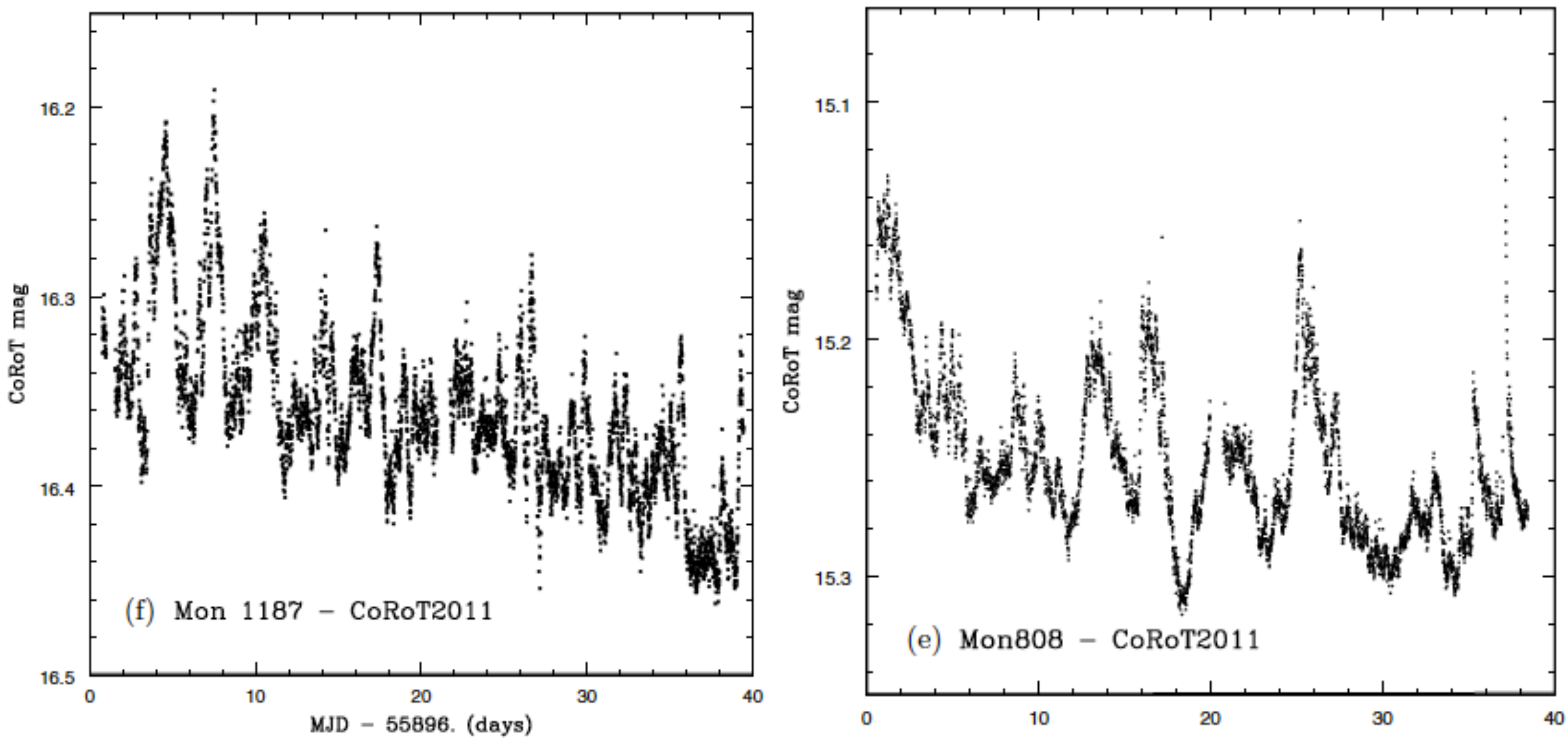



Cody et al. (2014)

# Stochastic Accretors

Need CoRoT data to identify…




*Stauffer et al. (2014)*

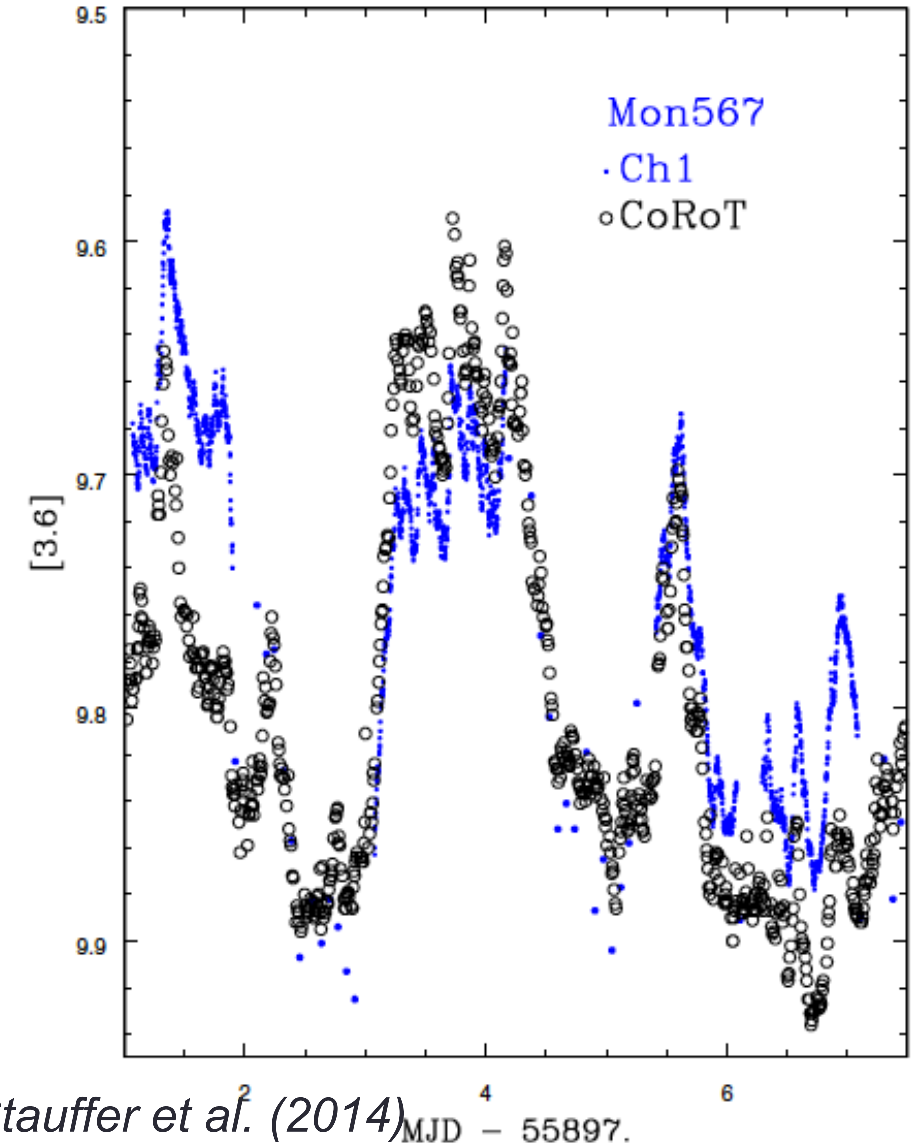
# Stochastic Accretors

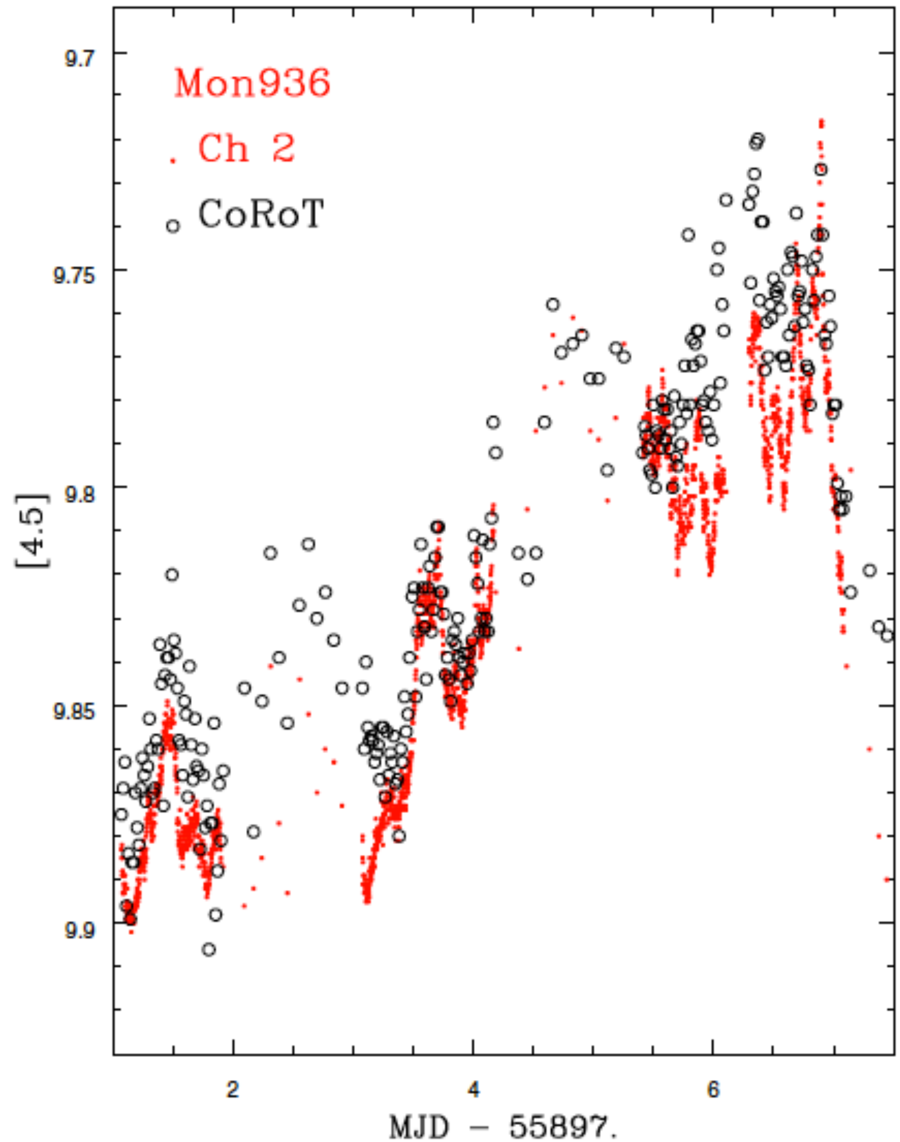
- 25 YSOs with CoRoT (from 2008 and/or 2011) light curves that look like stochastic accretion.
- Criteria:
  - a flat or only slowly varying “continuum”
  - an intrinsic noise level in the light curve less than 1%
  - presence of ≥6 narrow (~1hr-day), sharply peaked flux “bursts”, with ≥1 w/ amplitude >5% of the continuum level.

*Stauffer et al. (2014)*

# High-cadence IRAC

**Where we have high-cadence IRAC data, bursts seen in both, break up into sub-bursts.**




*Stauffer et al. (2014)*

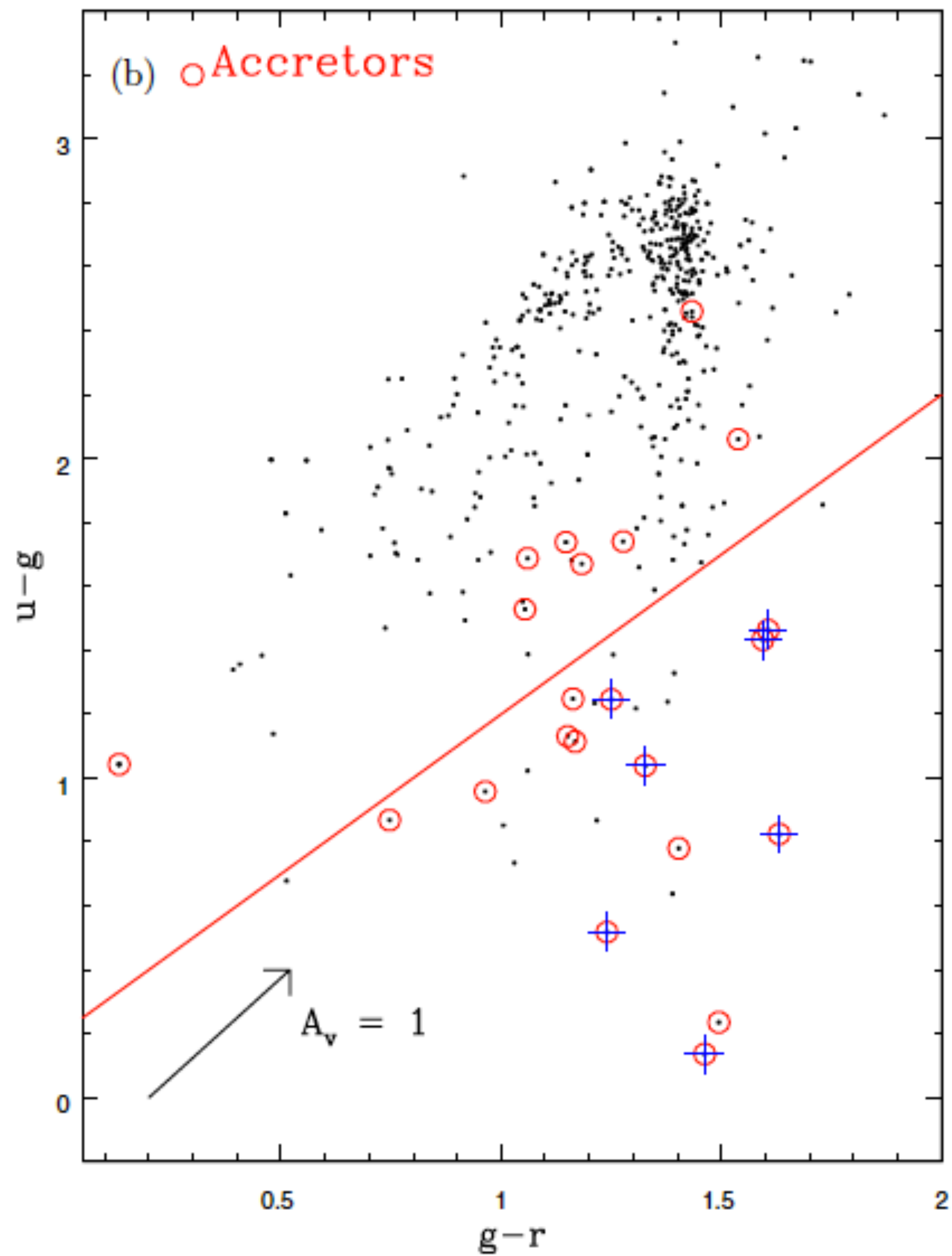
# Stochastic Accretors

- Well-matched to Romanova+ (2008,2012) theoretical LCs – **instability-driven accretion** onto YSOs.
- Among most heavily accreting, there are more bursty LCs than stable hot-spot LCs → **instability driven accretion dominates over funnel flow accretion** (at least at high Mdot).
- We found these from LC shapes; turn out to also have UV excess and Halpha suggesting high accretion.

*Stauffer et al. (2014)*

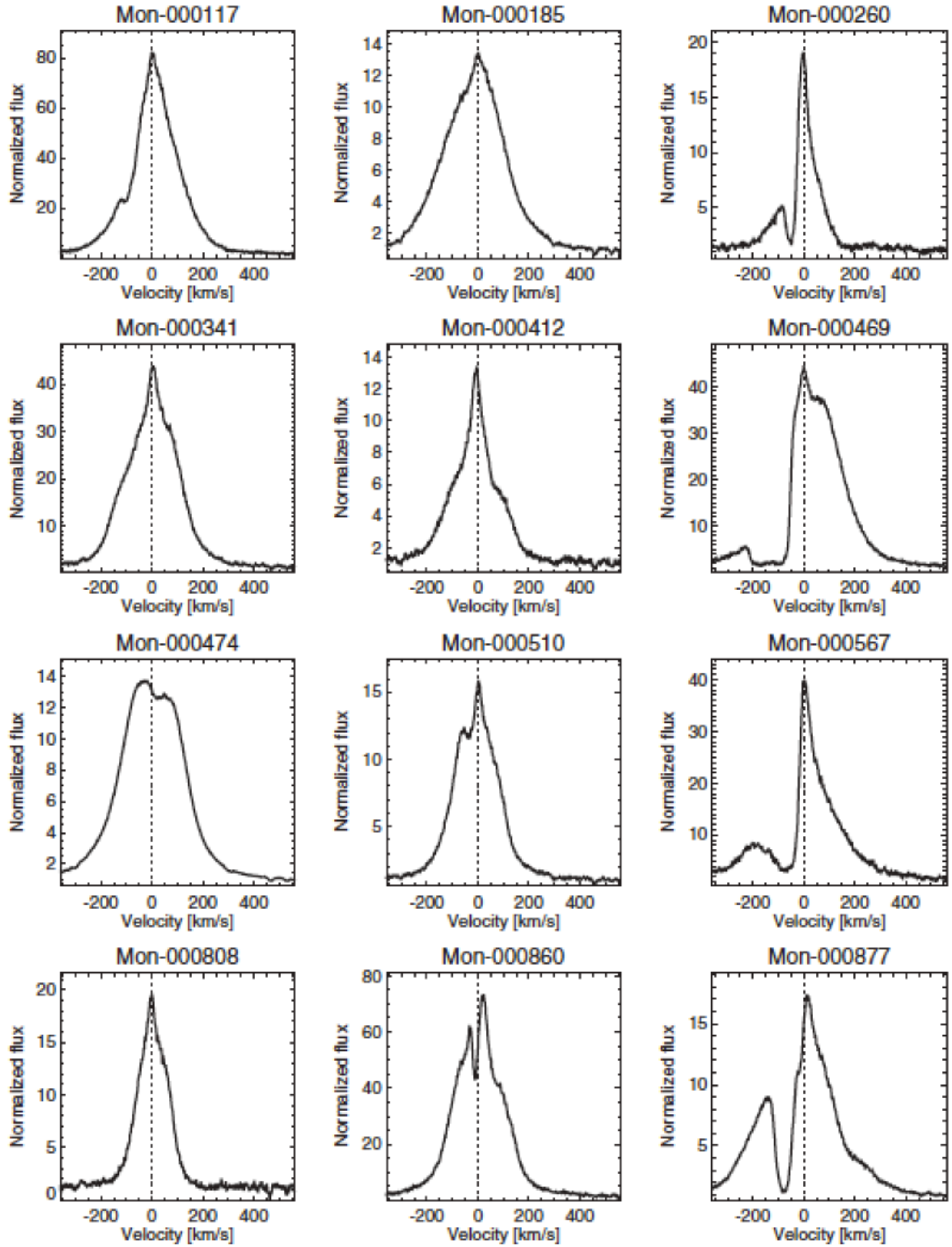
•= Objects with "stochastic accretor" LCs, also have large UV excesses.
+ also have Halpha profiles suggesting high Mdot.

*Stauffer et al. (2014)*



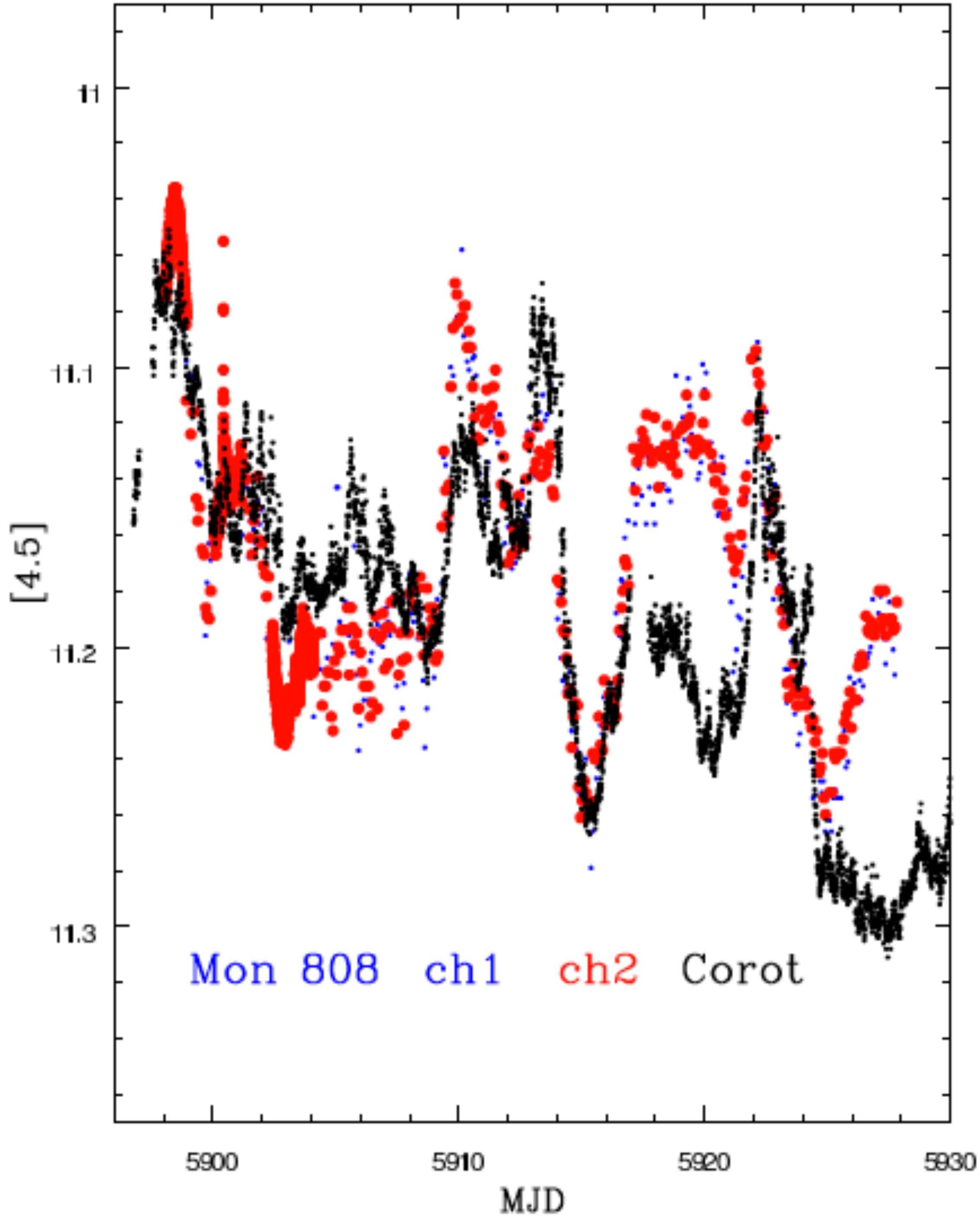
# Hα

VLT data: evidence of outflows and infall




*Stauffer et al. (2014)*

Some of the stochastic accretors have well-correlated CoRoT and Spitzer…



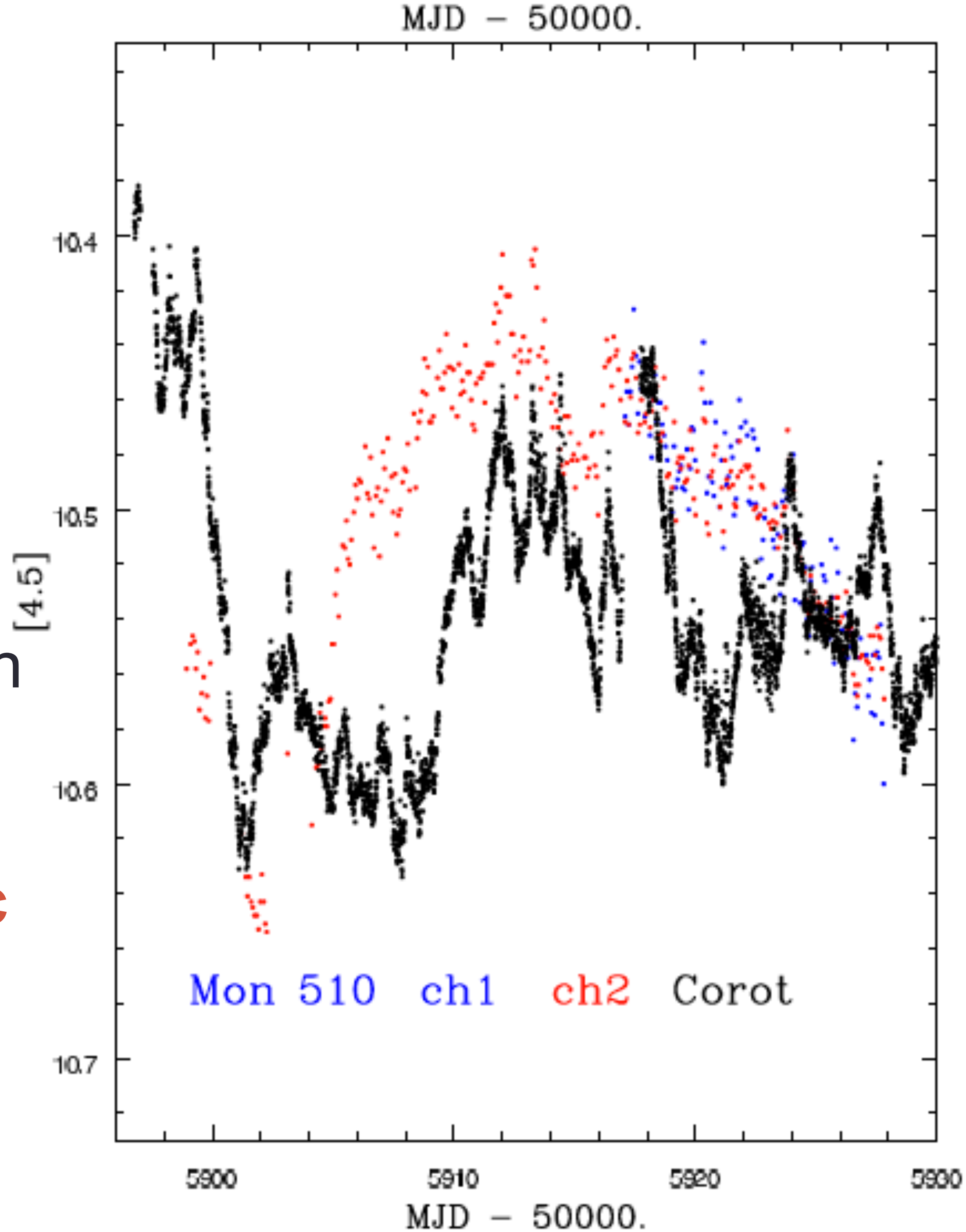

*Stauffer et al. (2014)*

… and some do not.

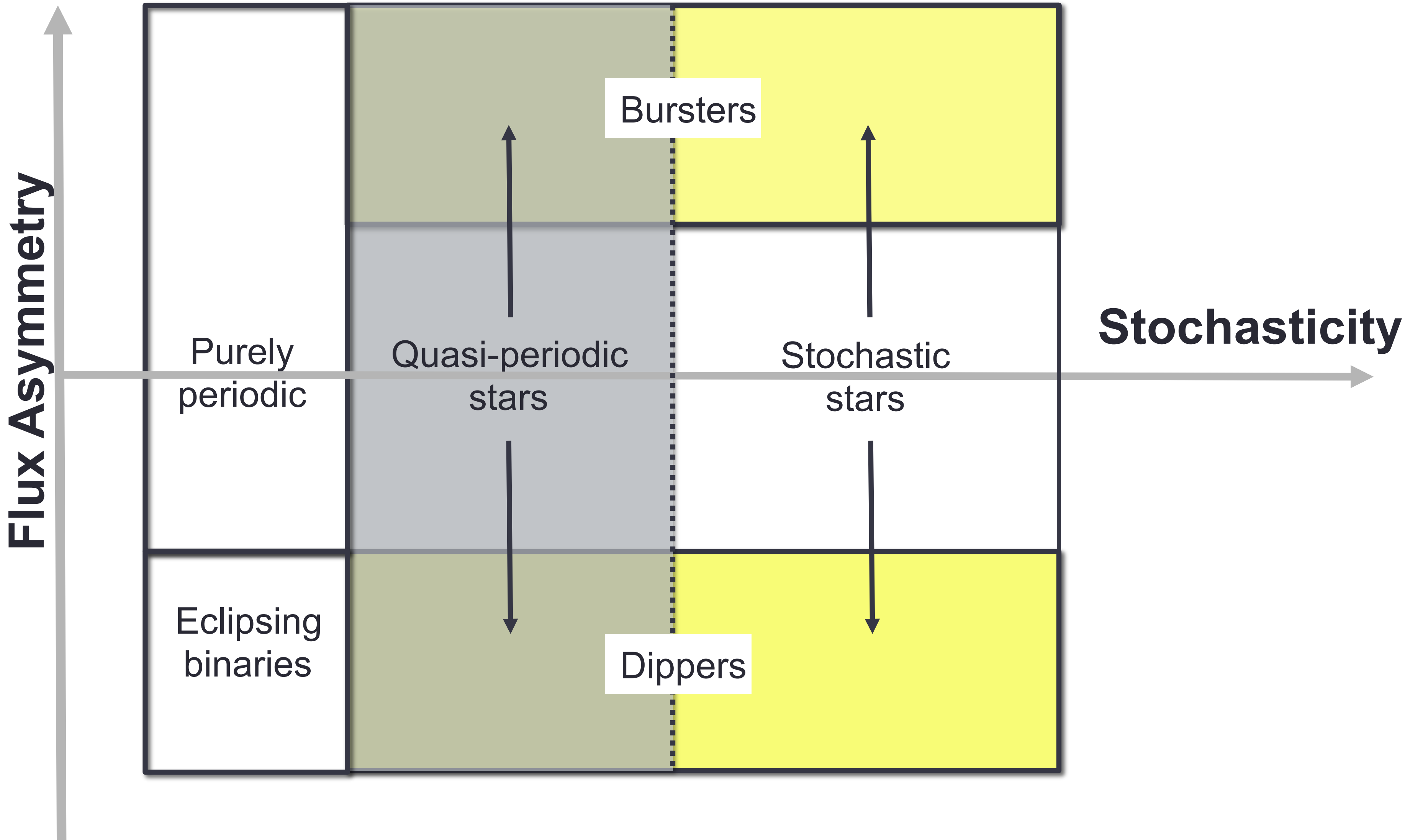
This must be telling us something about the system inclination.

Others have bursts in QP clusters – **mixture of funnel flow and stochastic bursts**?

*Stauffer et al. (2014)*

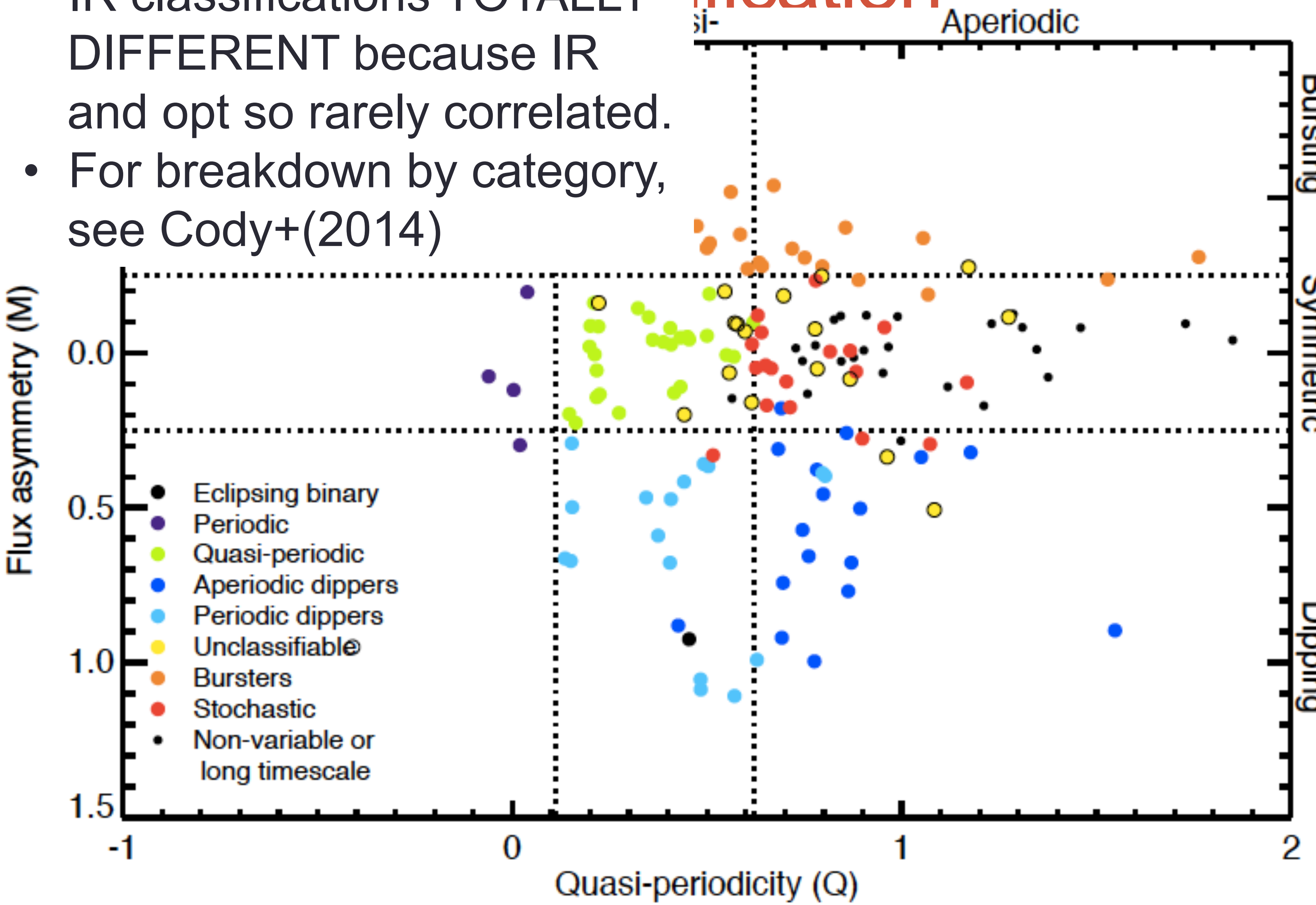


# Cody+(2014) Classification



ification

- Class IIs only!
- IR classifications TOTALLY DIFFERENT because IR and opt so rarely correlated.
- For breakdown by category, see Cody+(2014)



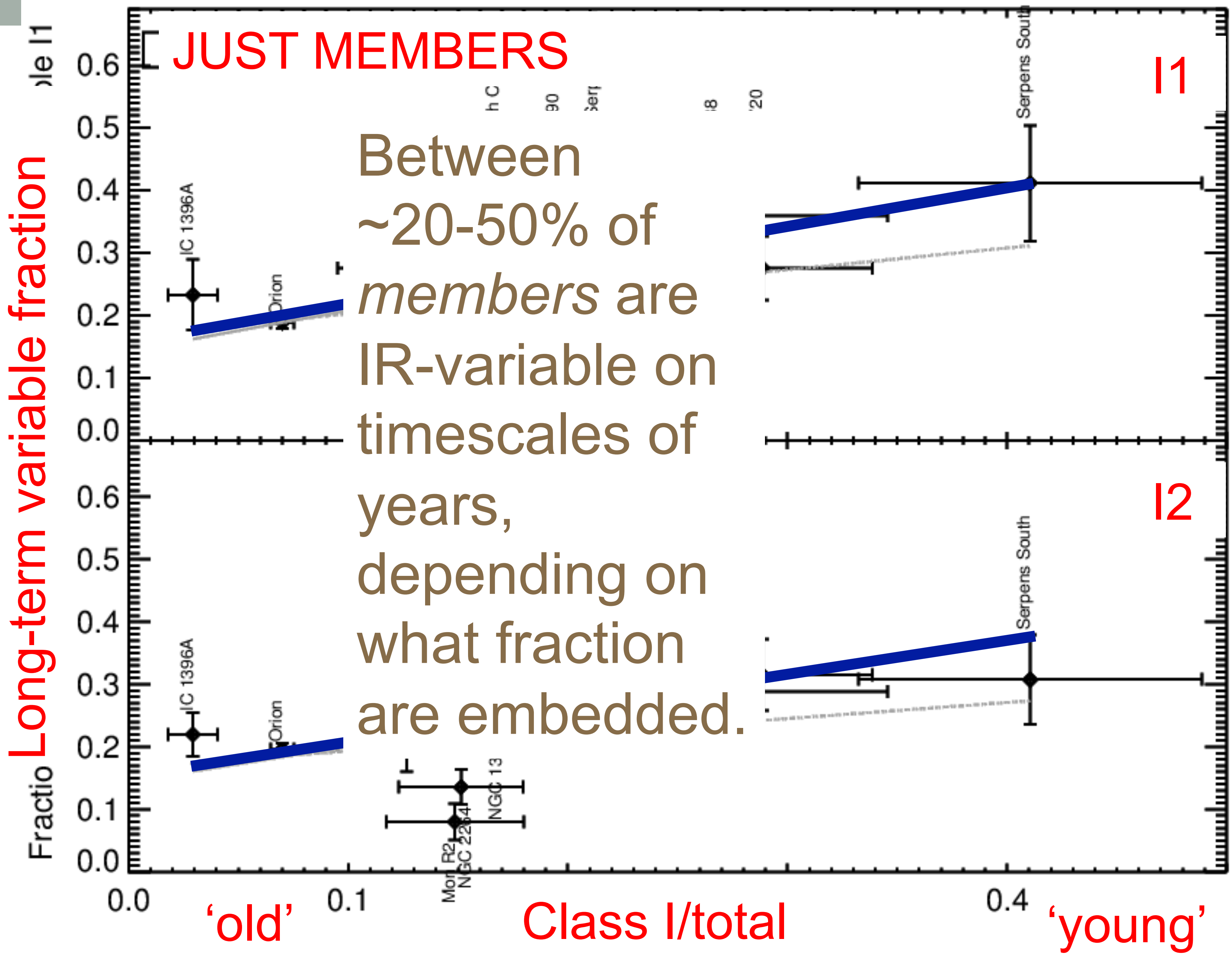
# What about “smaller-field clusters”?

- Large map of Orion, NGC 2264.
- Smaller maps of 10 (11 including N2264) smaller clusters, mostly very embedded, all very young.
- Generally not as much ancillary data.
  - Not as much simultaneous monitoring (certainly no CoRoT!)
  - Not as much member/non-member weeding in literature
- Generally far smaller field (and thus far lower field contamination).
- *Not yet done scrutinizing every source & LC.*
- Can we use everything all at once to constrain things?

# Long-term variability

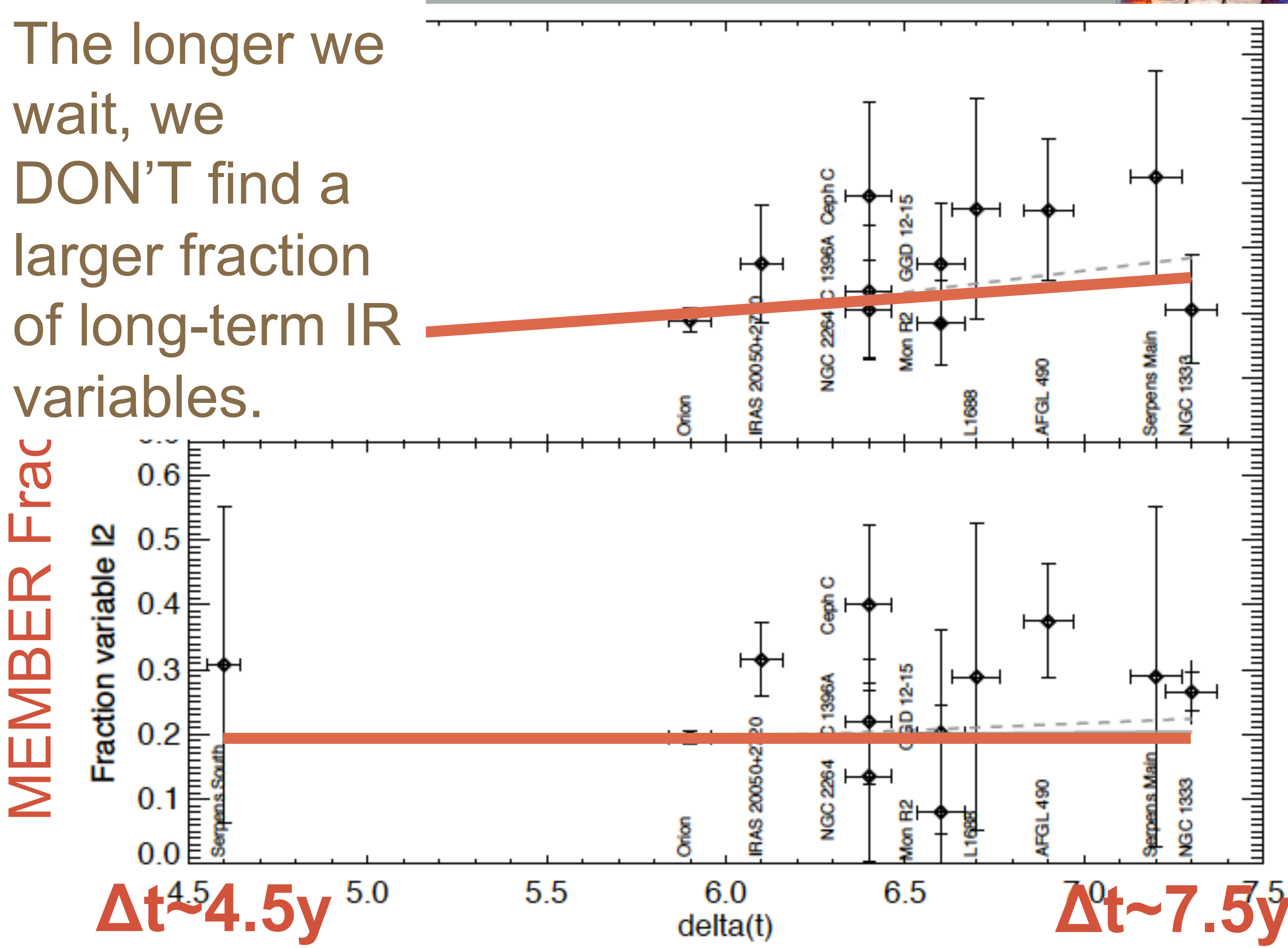
- Each of the clusters has a cryo observation (usually early in mission).
- Can compare cryo to average YSOVAR brightness and look for differences to try to characterize changes on t~6-7years.
- On average, see as many brightenings as fadings.
  - (crit: 3σ different than rest of sources in field, so >0.1-0.15 mag)
- Disks don't go away or appear (<0.02% rate).
  - (crit: biggest color changes)

*Rebull+ 2014 in prep*




Between ~20-50% of *members* are IR-variable on timescales of years, depending on what fraction are embedded.

The longer we wait, we DON'T find a larger fraction of long-term IR variables.



# Papers

- IC1396A: the original : Morales-Calderon+ (2009)
- Orion, year one : Morales-Calderon+ (2011) identified "dipper stars" and others; Morales-Calderon+ (2012) identified eclipsing binaries.
- CSI:2264 : HUGE amount of data. CoRoT makes huge difference in how we can interpret the light curves; have been able to classify objects. (Cody+ 2014 and Stauffer+ 2014)
- Papers on each of the smaller clusters (in prep)– e.g., L1688: Guenther+2014 (submitted); NGC 1333: Rebull +2014; etc…
- Statistics on the long-term variables in the ensemble (Rebull et al. 2014, *nearly submitted*)