What the Variability of Embedded Protostars Tells Us about Accretion

Past, Present, and Future

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With:

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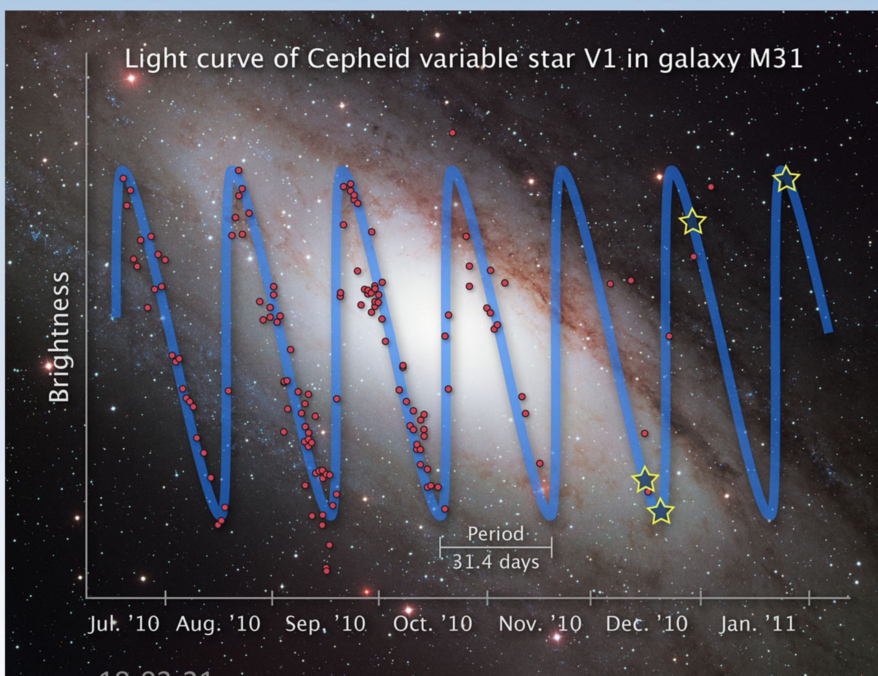
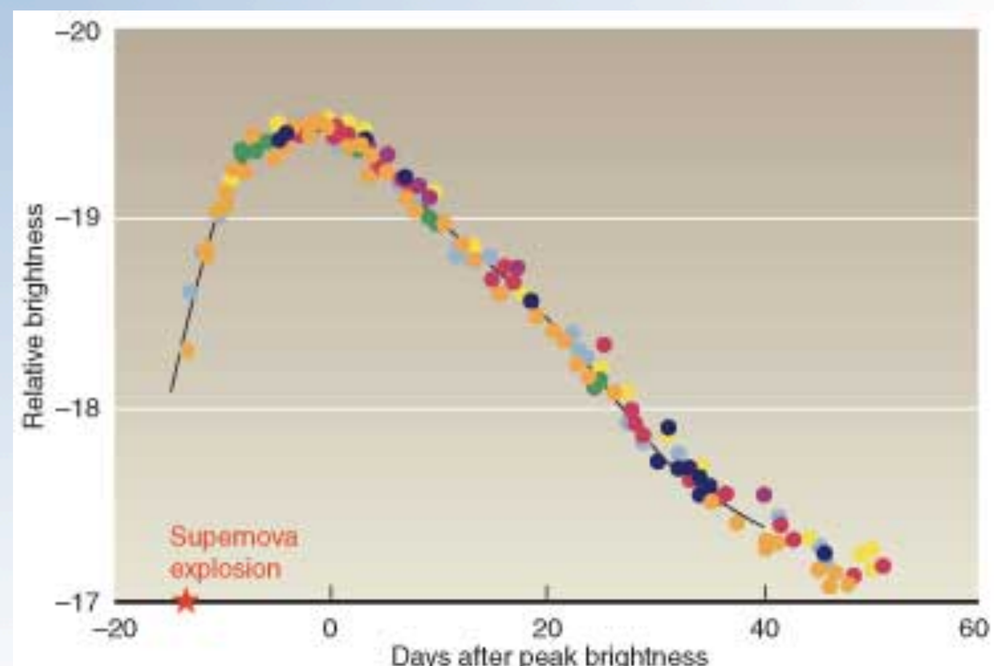
- J. Lane, H. Kirk - Canada
- S. Mairs, G. Bell, S. Graves - EAO
- H. Yoo, J-E Lee, S-J Kang, et al. - Korea
- The International JCMT Transient Survey Team

Variable Stars as Probes: Light Curve

1. Measurement of Amplitude, Period, Eigen-frequencies …
   - Deduce density and/or internal structure – **stellar seismology**
2. Determination of stellar properties
   - Standard Candles (Cepheids, Sne)
   - Probing Physics (mixing length theory)
   - Much, much more



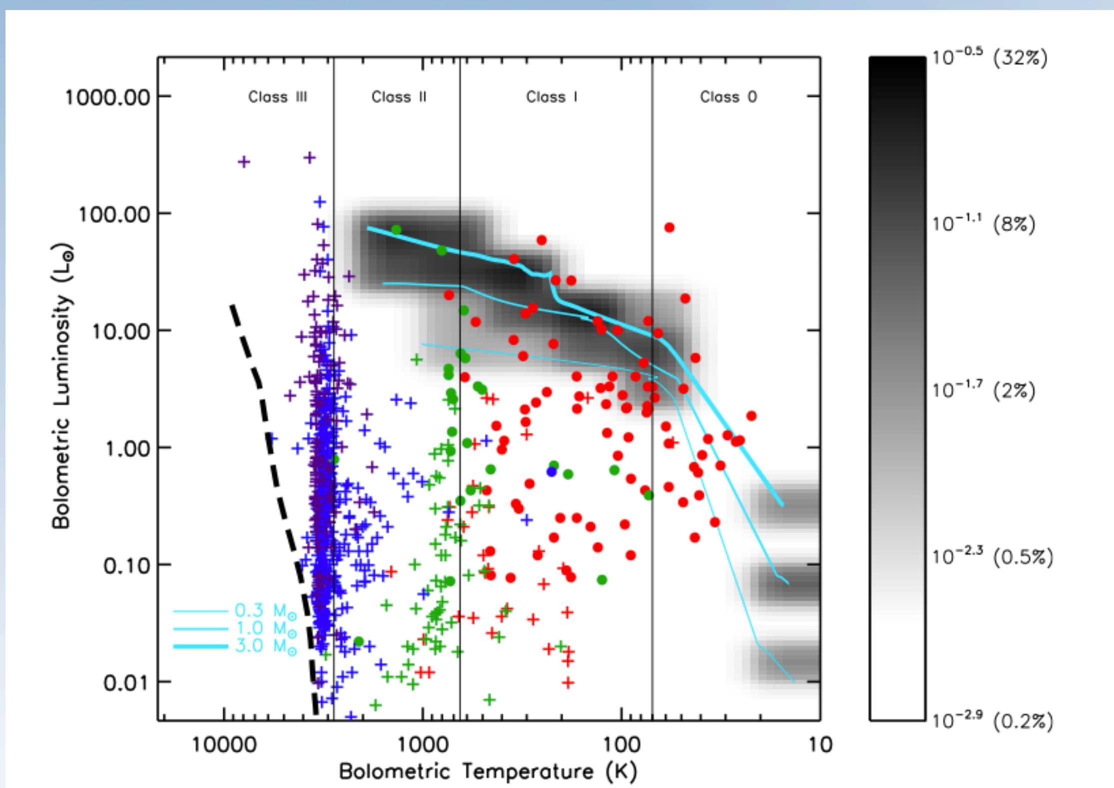


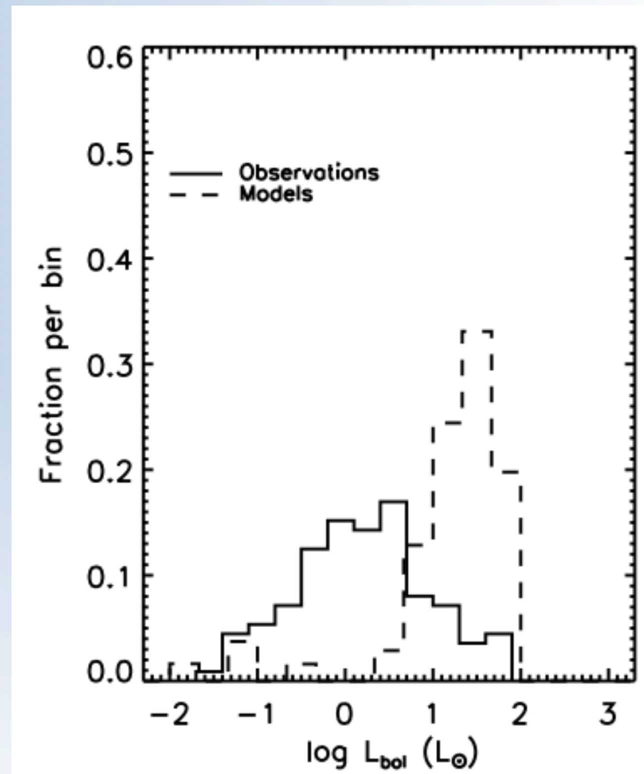
Spitzer: Protostars are Under Luminous

Protostar luminosity comes from accretion. Should only need only formation time to determine brightness.

Well known Kenyon et al. (1990) 'luminosity problem'.

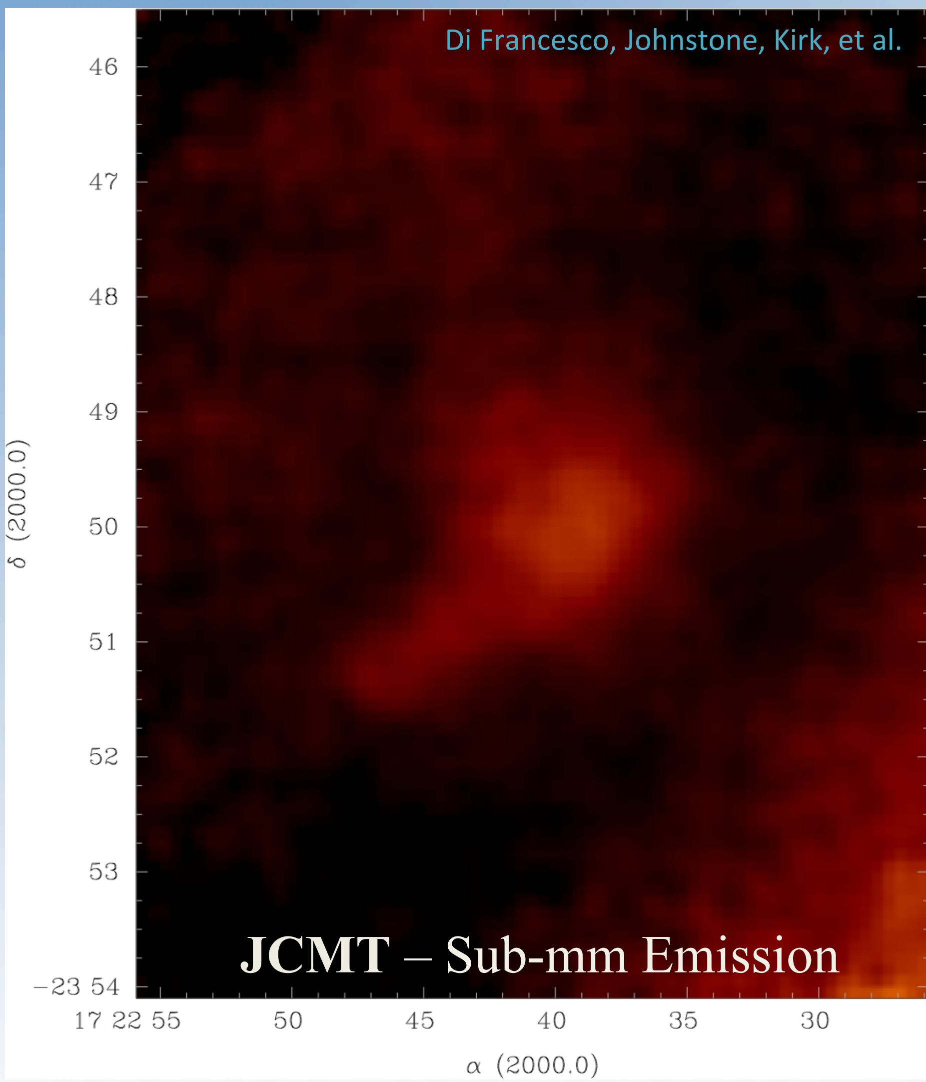
Motivation for the JCMT Transient Survey.



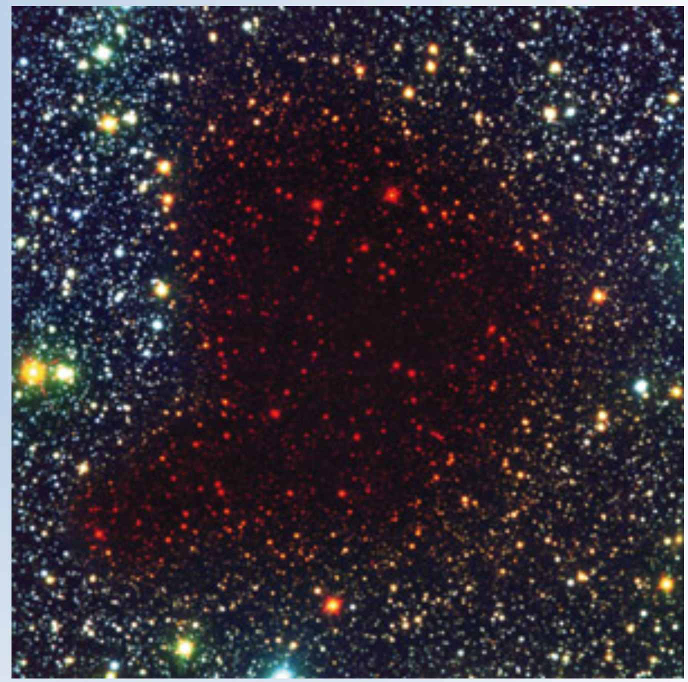


Dunham et al. 2010, ApJ

Why Do We Observe in the Sub-mm?



Optical and Infrared

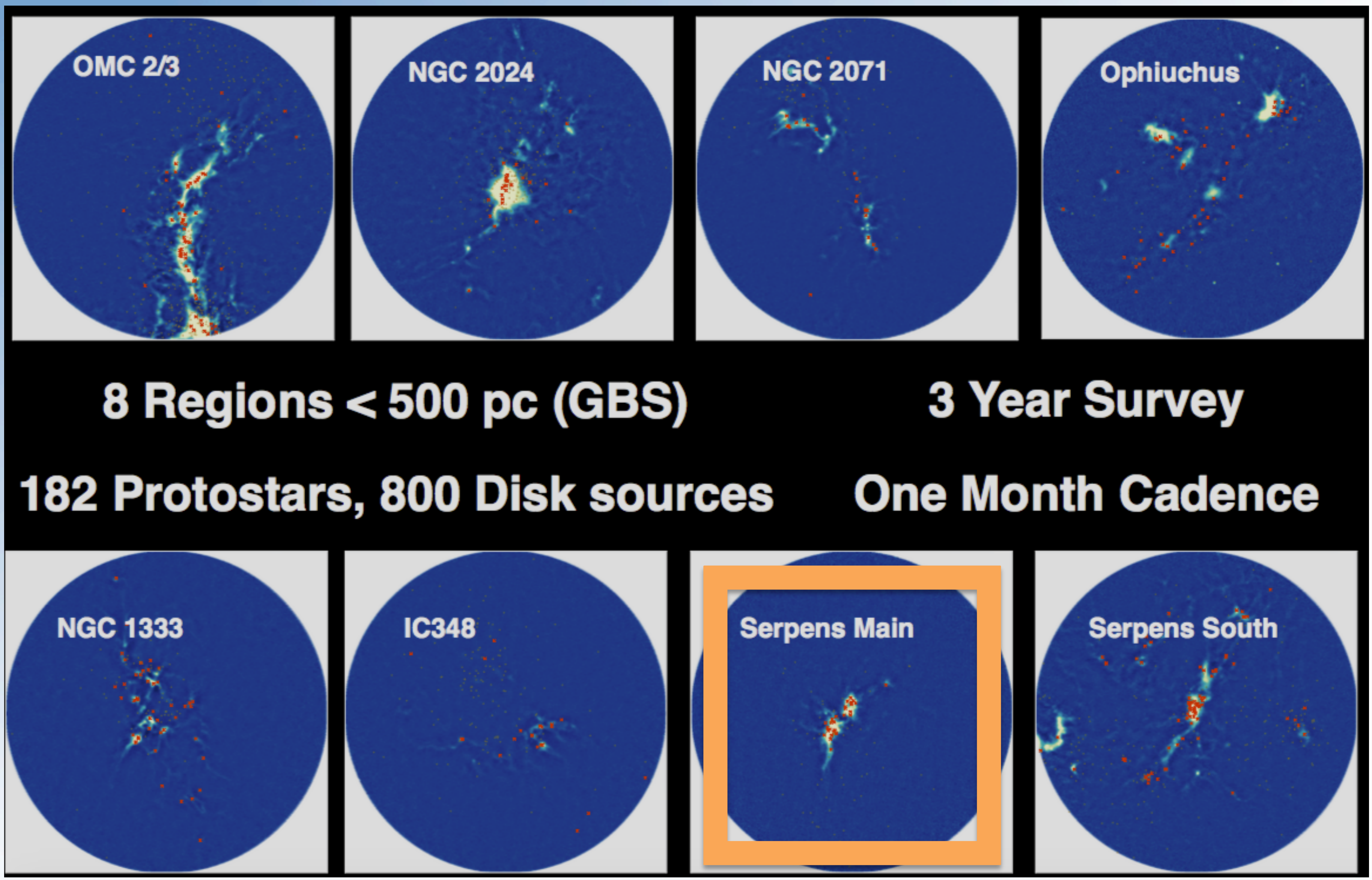


Cold Dusty Envelope:

Optical -> Obscures, Reddens

Sub-mm -> Glows Bright

The EAO/JCMT Transient Survey



(Herczeg et al. 2017, ApJ)

The First JCMT Protostellar Variable:

Serpens Main ~ 400pc

JCMT SCUBA-2 at 850 micron

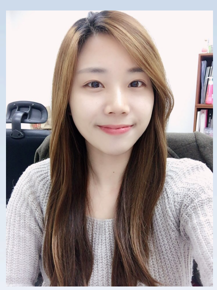
30' Pong – viewing central region

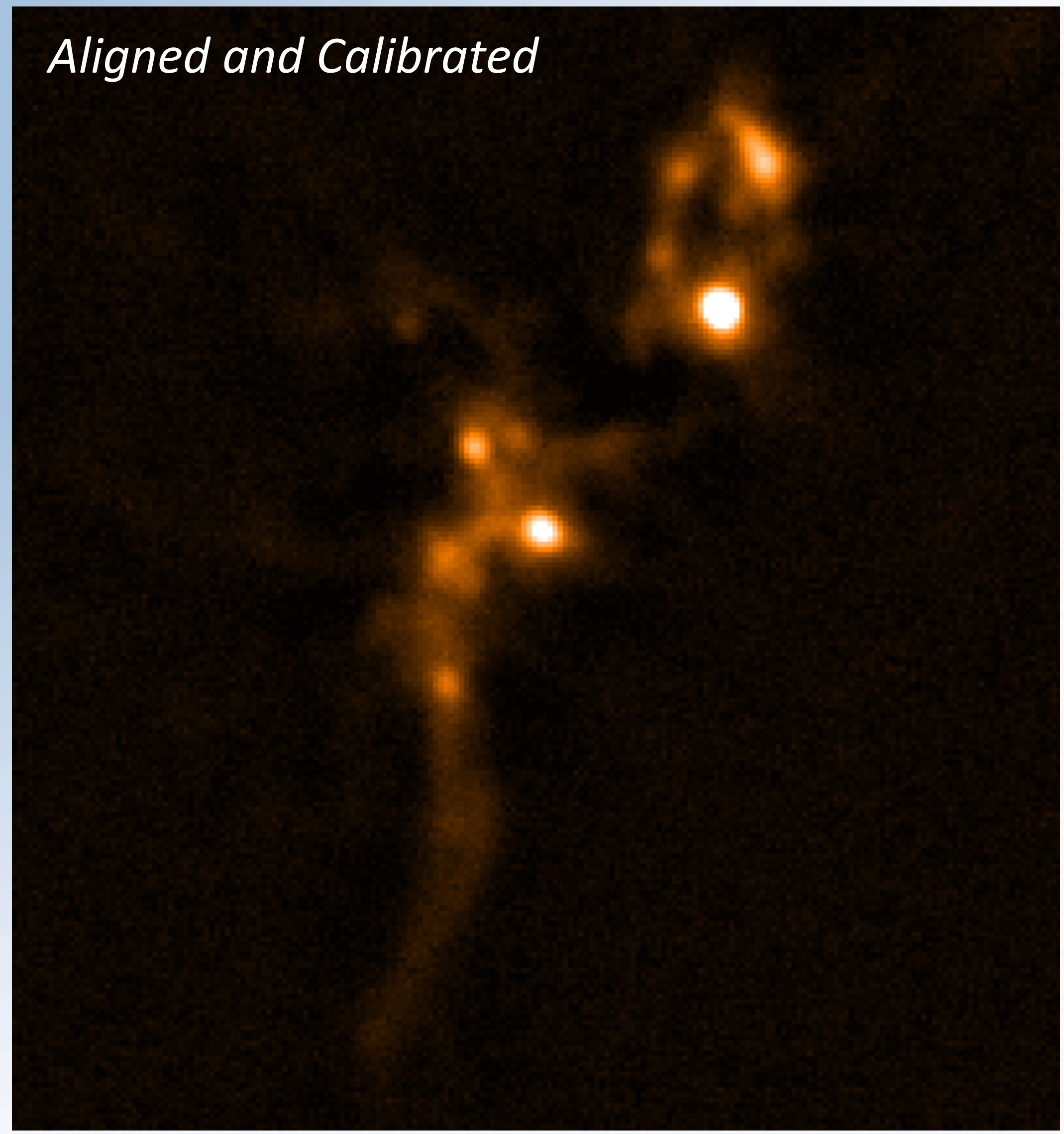
13 epochs ~ monthly cadence

2016-February – 2017-April

Careful Investigation by Korean graduate student Hyunju Yoo …

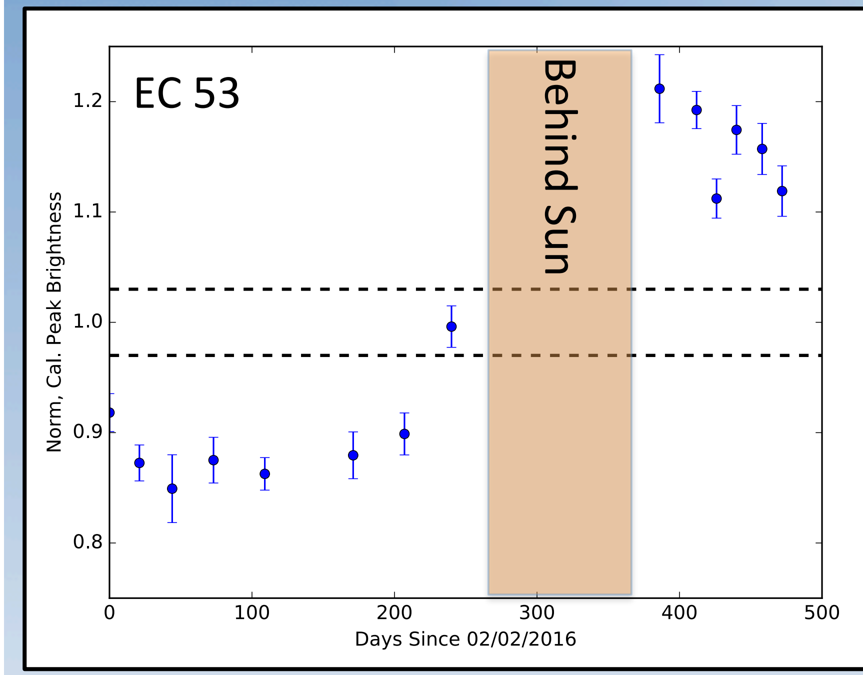
(Yoo et al. 2017, ApJ)

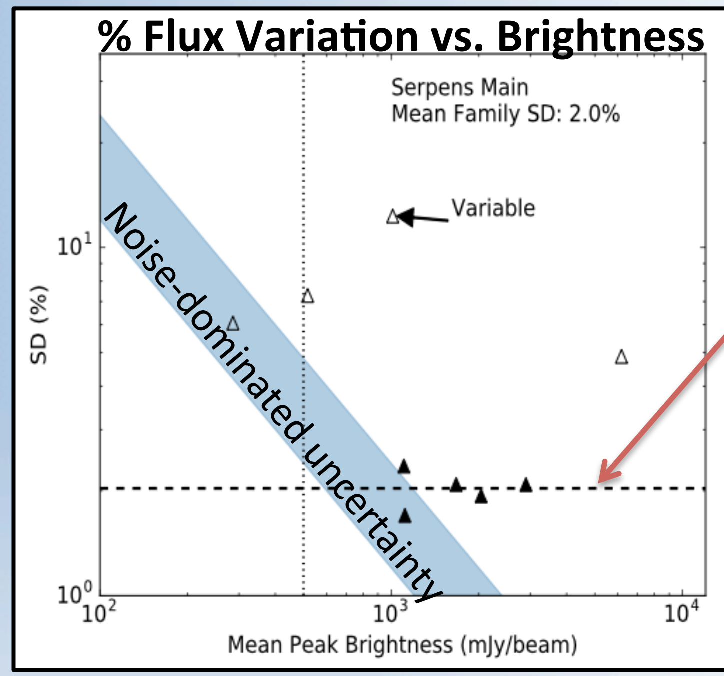




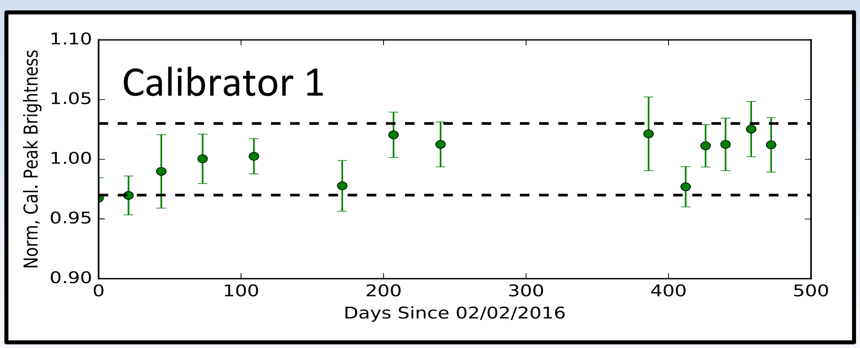
The First JCMT Protostellar Variable:

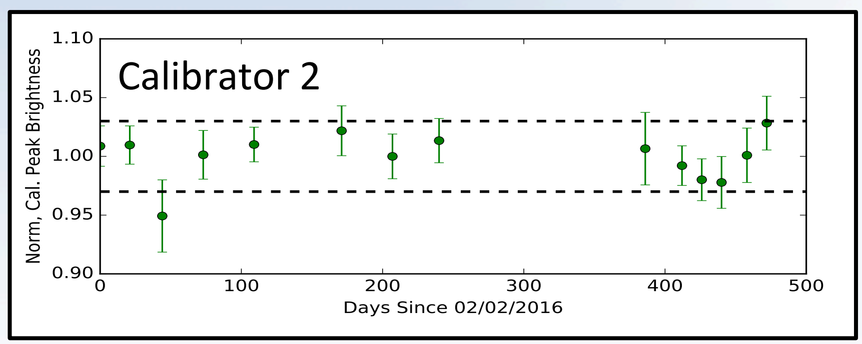
Light Curves at 850micron Yoo+17, ApJ, 849, 69 :Calibration Mairs+17, ApJ, 843,55



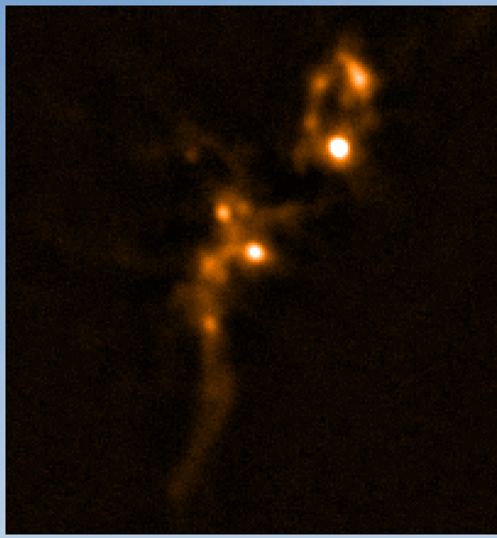


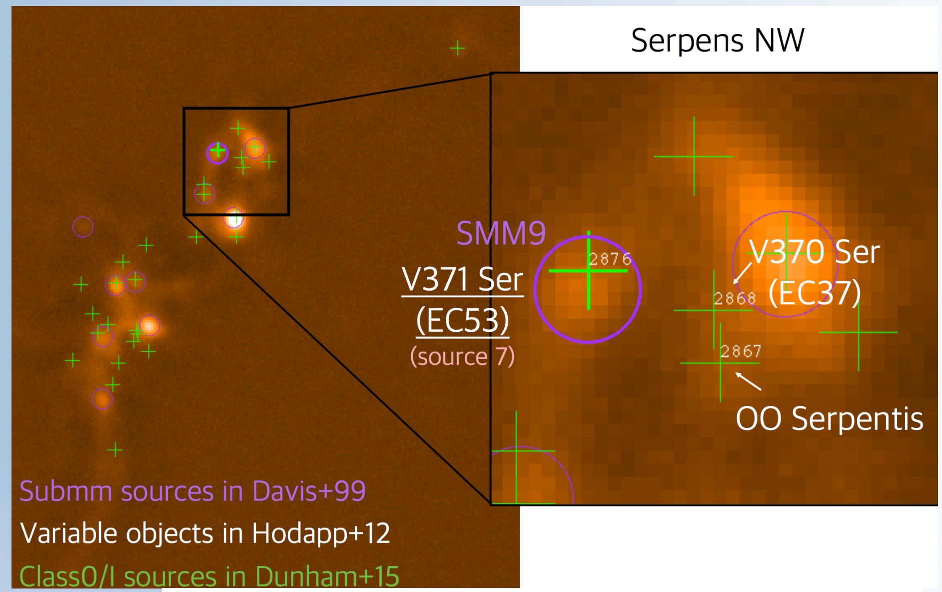
Relative Flux calibration ~ 2% limited to high S/N Sources.

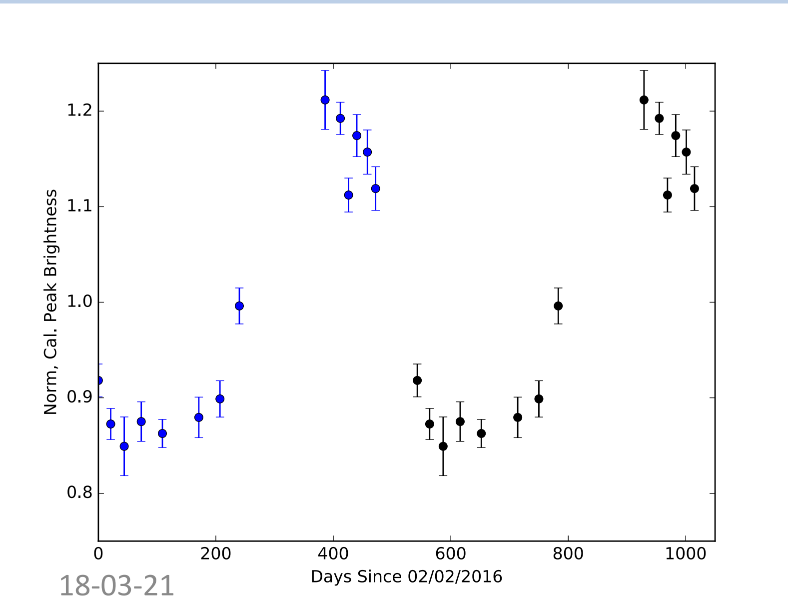




The First JCMT Protostellar Variable:







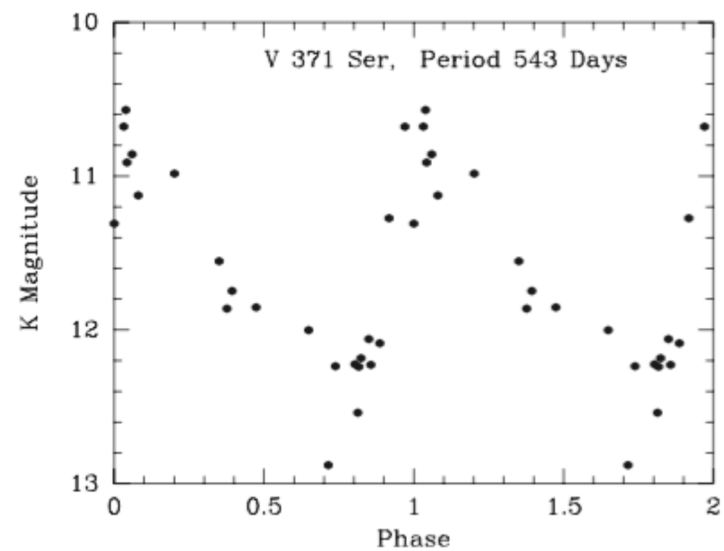


Figure 5. Phase diagram of the *K*-band variations of EC 53. The light curve shows a rapid rise and slower decline from the maximum.

The First JCMT Protostellar Variable:

- EC 53 (V371 Ser)
  - Class I source (Hodapp et al 1999)
    - [possibly Class 0 seen pole on]
  - Observed physical binary 296 mas (92 AU) away – possibly sub-stellar
  - Cometary nebula (One visible lobe of a bipolar structure)
  - Ongoing outflow activity (H_2 jet)
  - 18 month *periodic variable* at 2μm (Hodapp et al. 1999, 2012)

- Postulatation …
  - 18 month periodicity suggests disk irregularity at ~ 1 AU
  - Unseen inner companion star (Hodapp et al.) -> ejection of 92AU source?
    - *Or perhaps a planet in formation …*
  - We have observed for ~16 months with JCMT – awaiting full period
    - Planned monitoring at 2μm to determine lags and shape variations

Young Disk Observations (IR & mm):

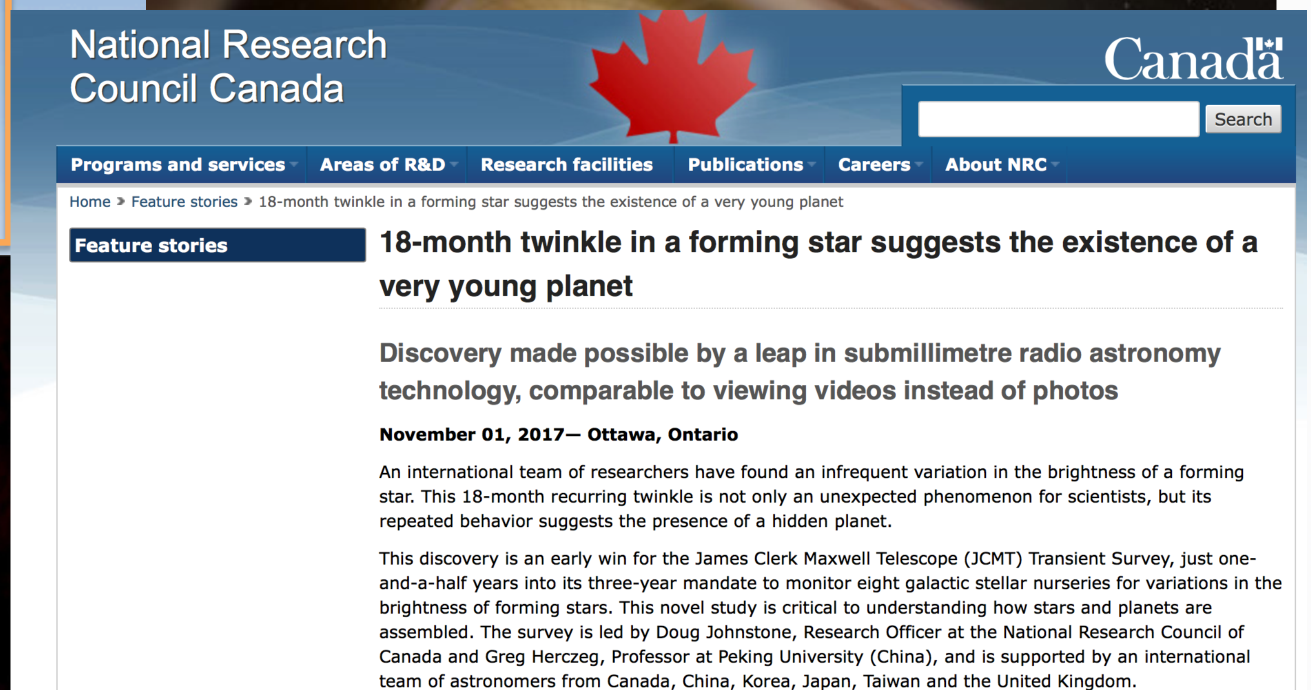
Gaps in disks may be due to sculpting by planets.

Accretion periodicity perhaps?

Very likely to be an unstable flow …

e.g. Munoz & Lai (2015)

Graduate University for Advanced Studies, Japan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Feature stories

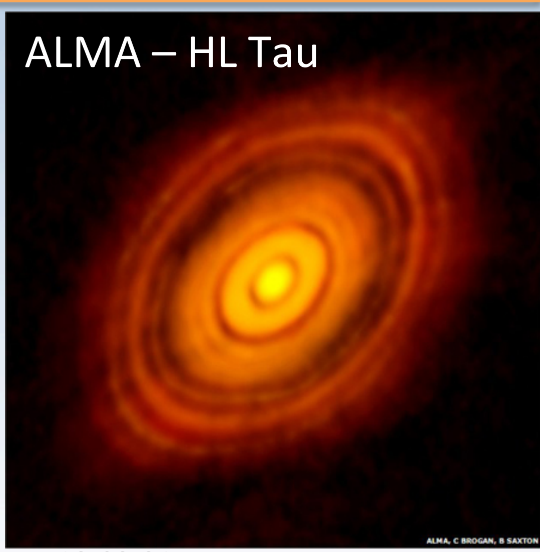
18-month twinkle in a forming star suggests the existence of a very young planet

Discovery made possible by a leap in submillimetre radio astronomy technology, comparable to viewing videos instead of photos

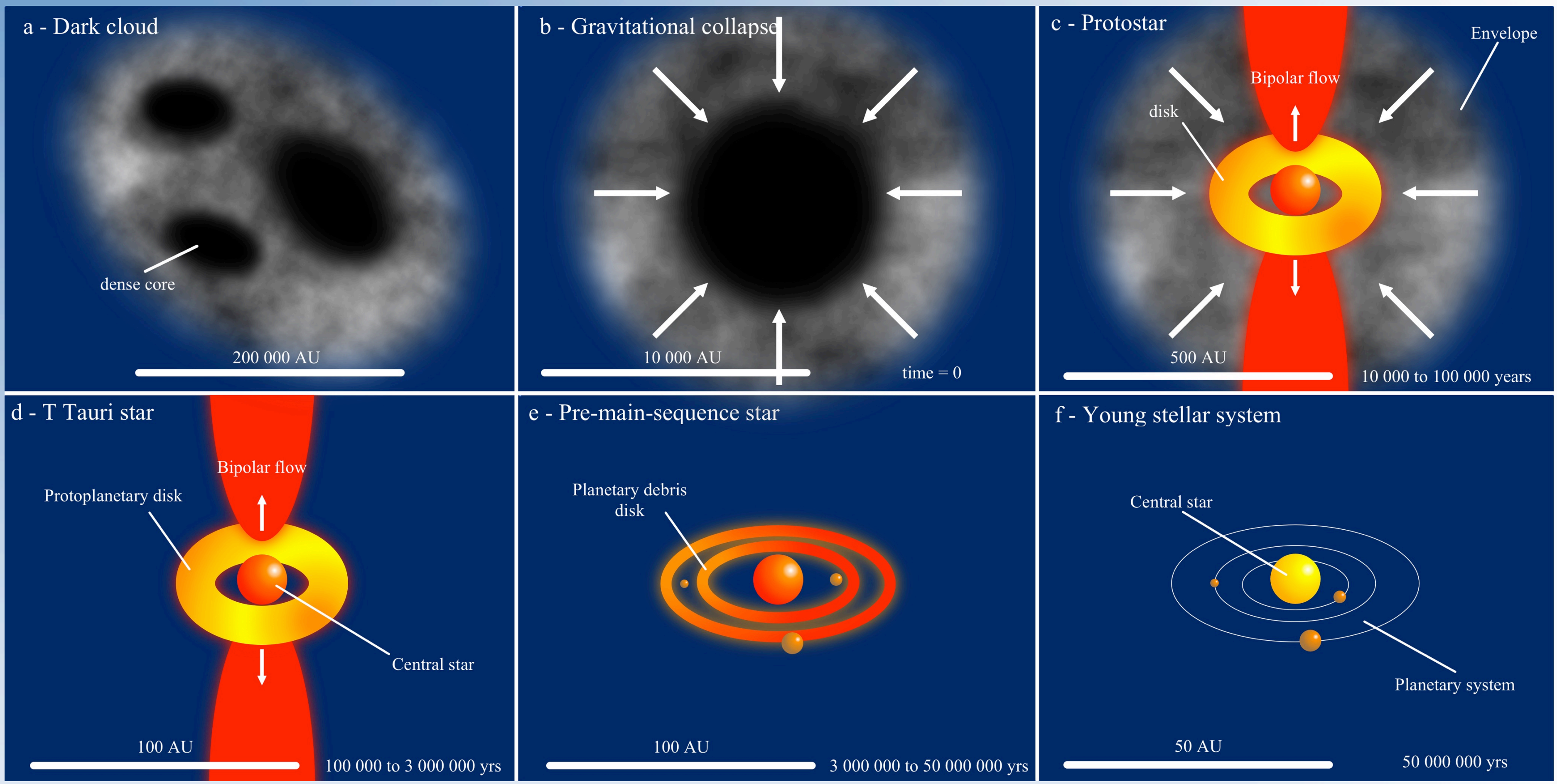
November 01, 2017— Ottawa, Ontario

An international team of researchers have found an infrequent variation in the brightness of a forming star. This 18-month recurring twinkle is not only an unexpected phenomenon for scientists, but its repeated behavior suggests the presence of a hidden planet.

This discovery is an early win for the James Clerk Maxwell Telescope (JCMT) Transient Survey, just one-and-a-half years into its three-year mandate to monitor eight galactic stellar nurseries for variations in the brightness of forming stars. This novel study is critical to understanding how stars and planets are assembled. The survey is led by Doug Johnstone, Research Officer at the National Research Council of Canada and Greg Herczeg, Professor at Peking University (China), and is supported by an international team of astronomers from Canada, China, Korea, Japan, Taiwan and the United Kingdom.



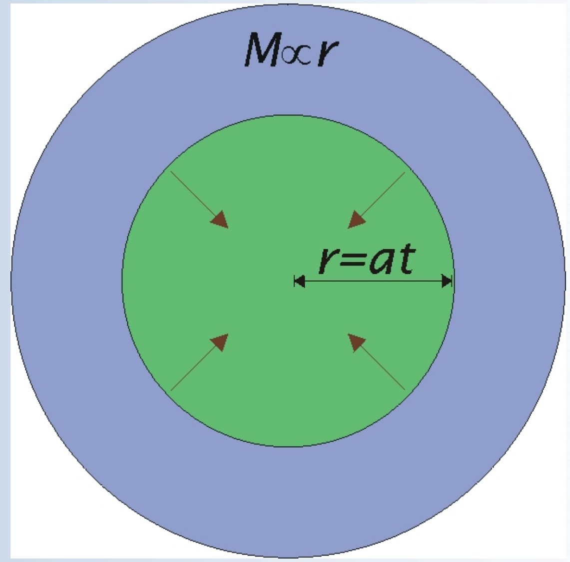
Formation of a star in one slide!



Key point for this talk: the material that forms a star is assembled from its prenatal cloud, through an envelope and disk.

Accretion via Inside Out Collapse:

“Shu Model”



- Start with an isothermal sphere

$$\rho(r) = \left(\frac{a^2}{2\pi G}\right) r^{-2}$$

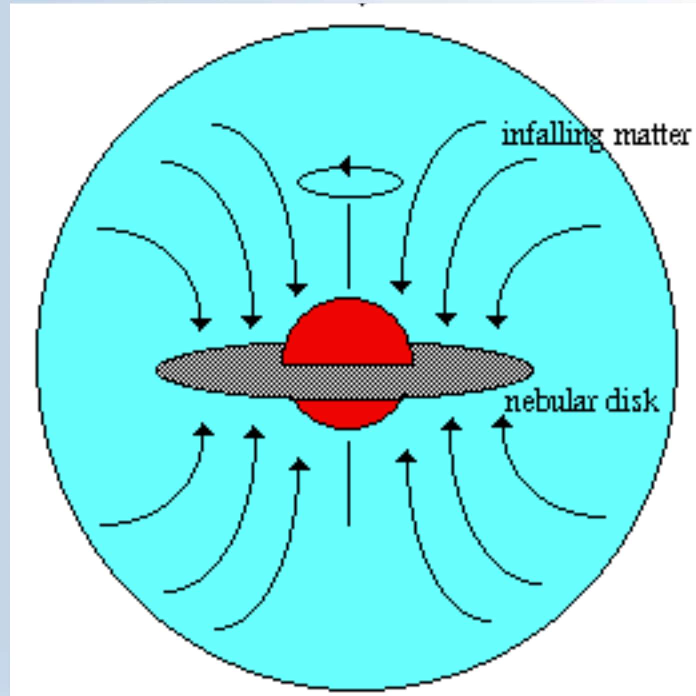
- Perturb the centre slightly
  - *Loss of pressure support yields collapse!*
- Rarefaction wave races out at sound speed

$$\frac{dM}{dt} = 4\pi a \rho r^2 = \frac{2a^3}{G}$$

- Half of this mass flux is accreted *onto* the central protostar while half is *added* to the in-falling envelope
  - *Steady-state protostellar accretion ~ a^3/G*

Importance of Rotation (or B fields):

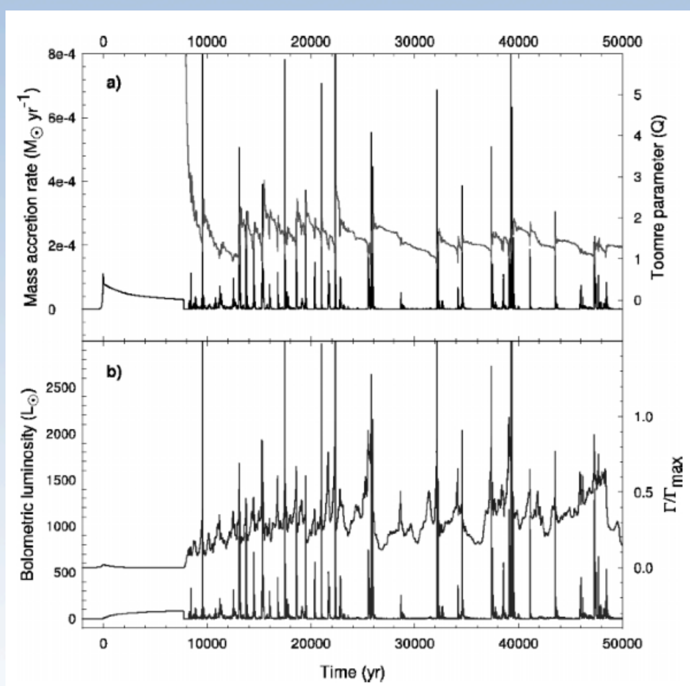
- Rotation breaks isotopic symmetry
  - Produce a flattened inner region (a disk)
- Mass flux that would have reached the protostar now *misses* and lands on disk
- No *a priori* reason why mass transport through disk = mass flux onto disk!
  - If disk transports *faster* – no disk build up
  - If disk transport *slower* – significant disk build up

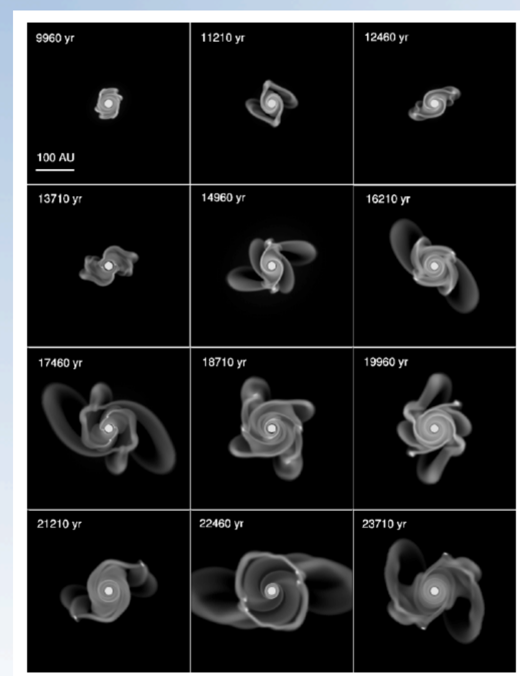


Note: mass transport through disk may even be radially dependent!

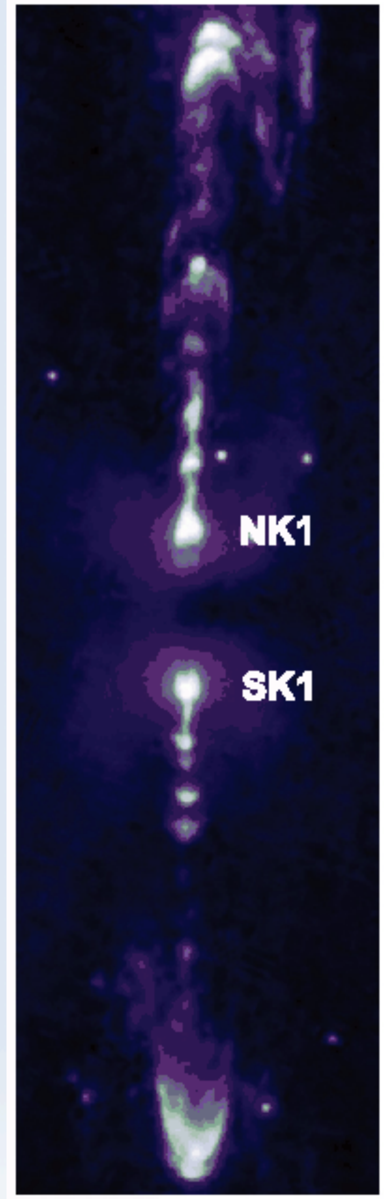
Mass Accretion – Non-Steady?

- Disk models suggest disk transport often ***inefficient***
  - Outer disk fills with mass until gravitationally unstable
  - Next, spiral forms in disk efficiently transporting mass inward
  - Accretion takes place in short energetic bursts and long quiescent intervening periods
- Observations of knots/bullets in jets also suggestive …





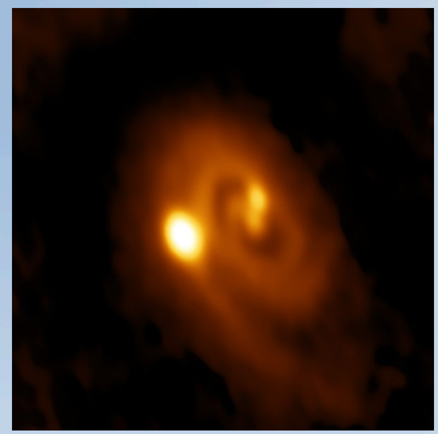
Vorobyov & Basu 2005, ApJ

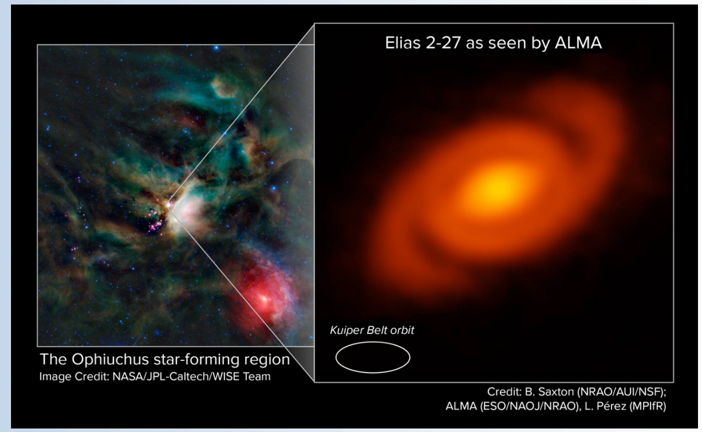


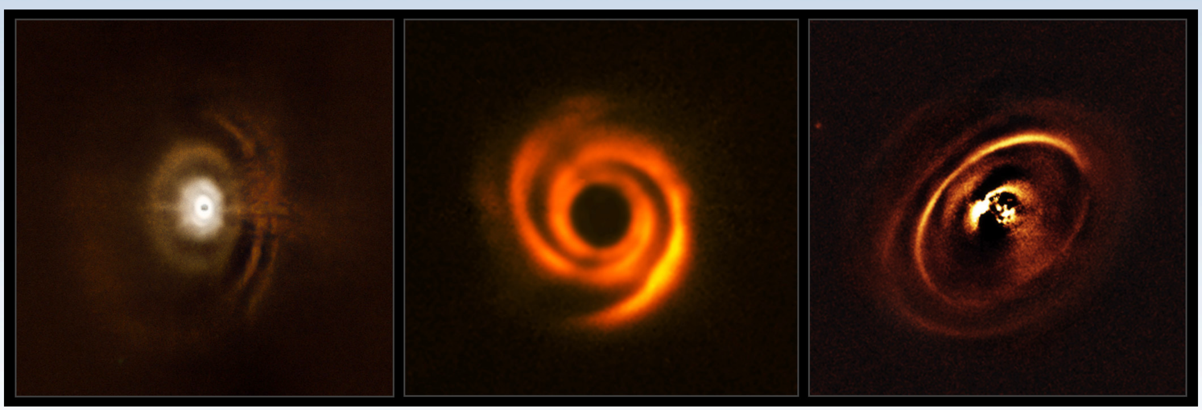
HH212

Young Disk Observations (IR & mm):

- Whether observed in *scattered light* (IR) or *dust emission* (mm) disks around young stars appear ***structured***!
  (Spiral Driven Accretion: Bae et al. 2016, ApJ, Hennebelle et al. 2017 A&A)

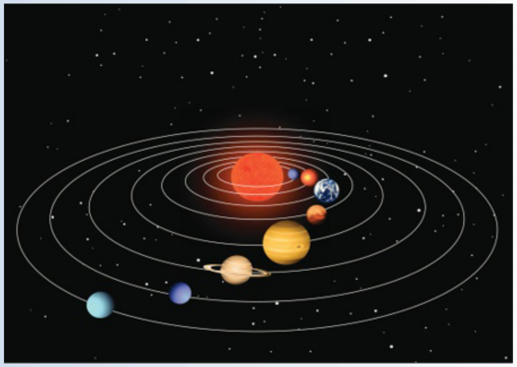


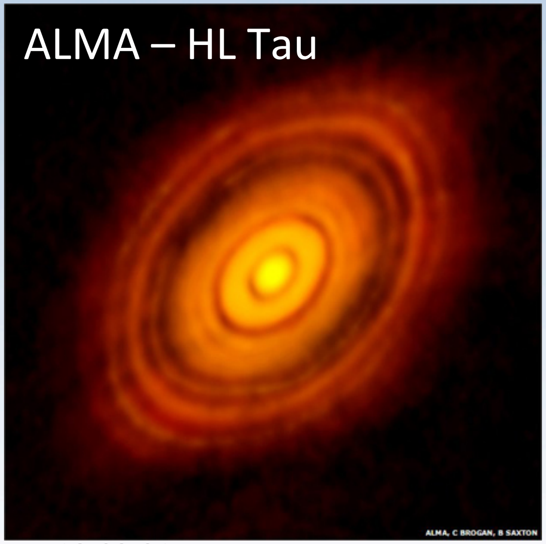


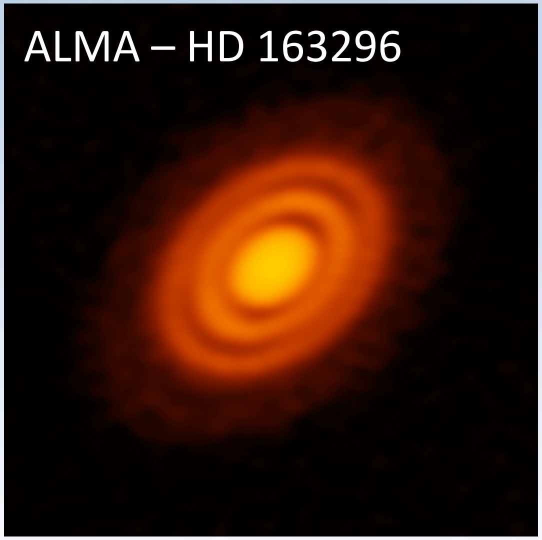


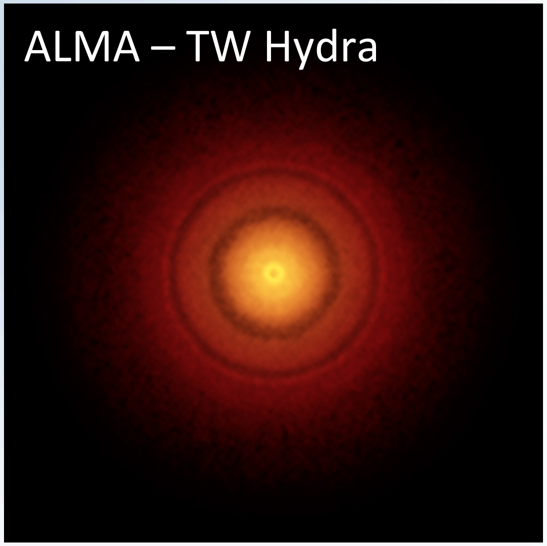
Young Disk Observations (IR & mm):

- Interestingly, many disks observed in mm show *rings and gaps* indicating a more quiescent environment, a non-smooth mass transport … and *suggesting* **planets in formation**!
- If significant mass from the envelope still falls onto the outer disk, how might this impact the time dependence of accretion?





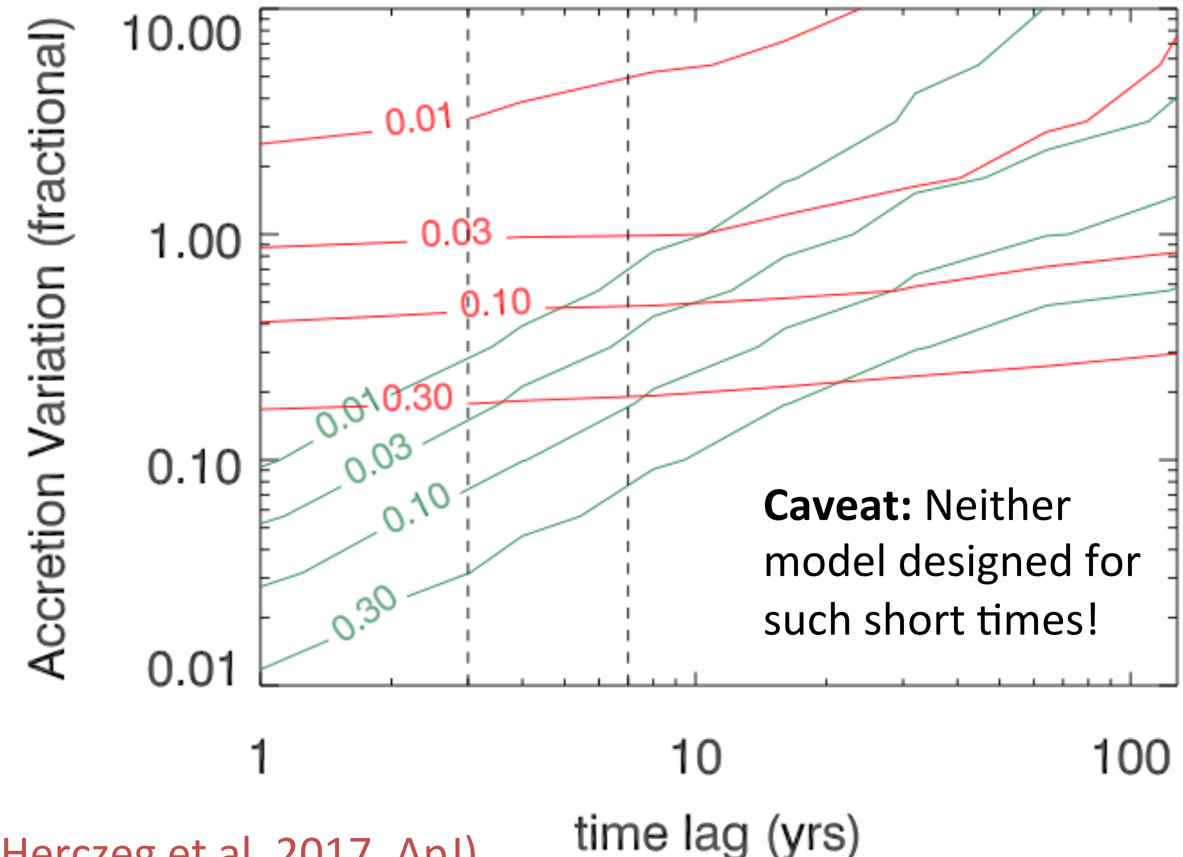




Accretion Through Disks – Non-Steady?

Vorobyov & Basu 2005, ApJ – driven by large-scale modes in gravitationally-unstable disk

Bae et al. 2014, ApJ – driven by activation of the magneto-rotational instability

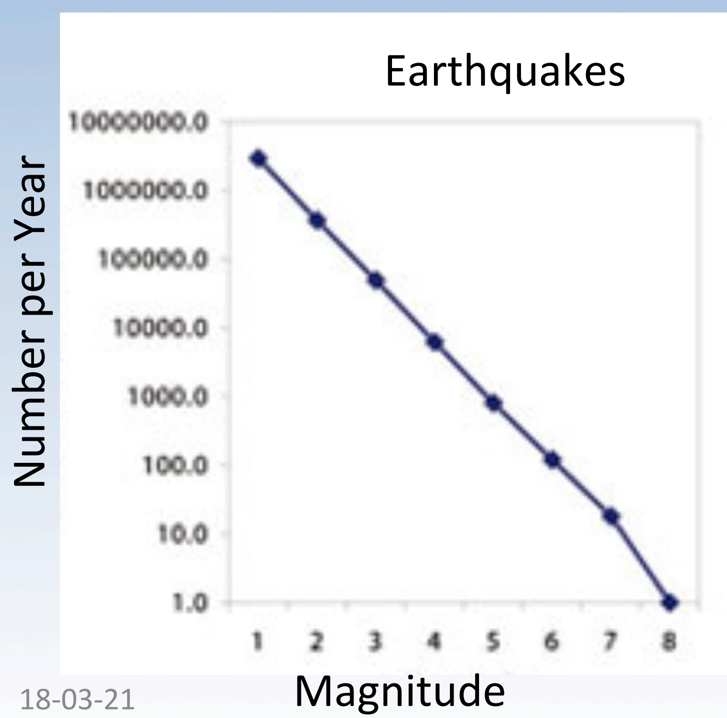


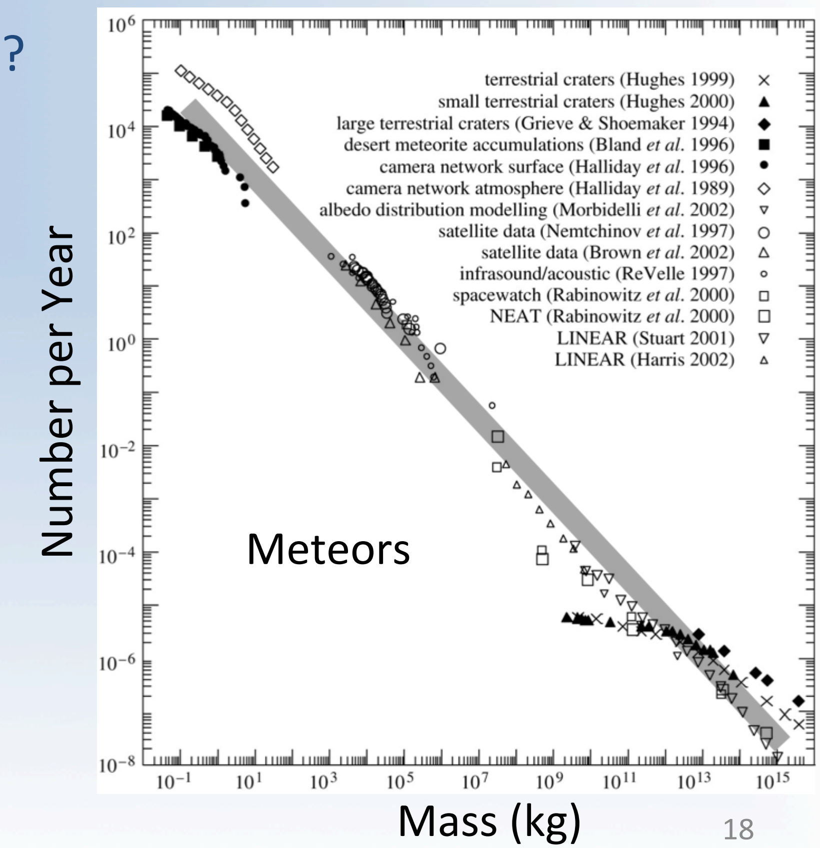
Caveat: Neither model designed for such short times!

(Herczeg et al. 2017, ApJ)

Aside: Variability and Accretion

- Much effort invested in determining how majority of mass accreted
  - Steady-state vs. powerful, rare outbursts
- But, accretion variability may be much more nuanced than this
  - c.f. earthquakes, meteor impacts
  - Timescale(s)/amplitude(s), process(es)?



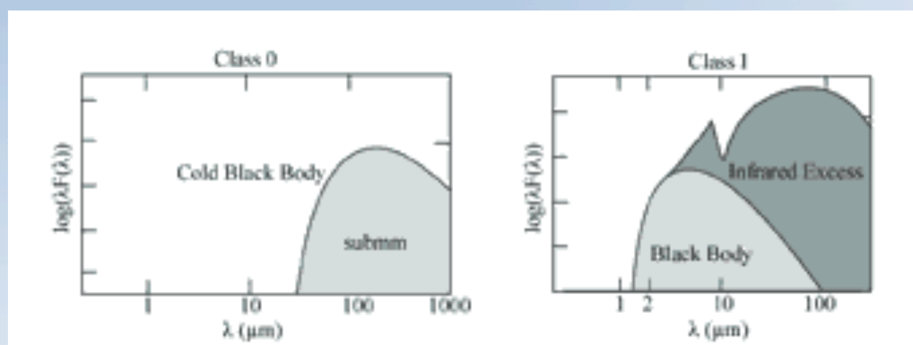


Spectral Energy Distribution (SED):

- For a low mass star, the mass accretion onto the protostar releases as much (or more) energy as the protostar itself produces

$$L_{\rm acc} \sim \frac{GM_*}{R_*}\dot{M}_{\rm acc}$$

- This energy is absorbed by the envelope and re-radiated in the far IR through mm. Thus, the SED acts as a ***calorimeter*** for accretion.



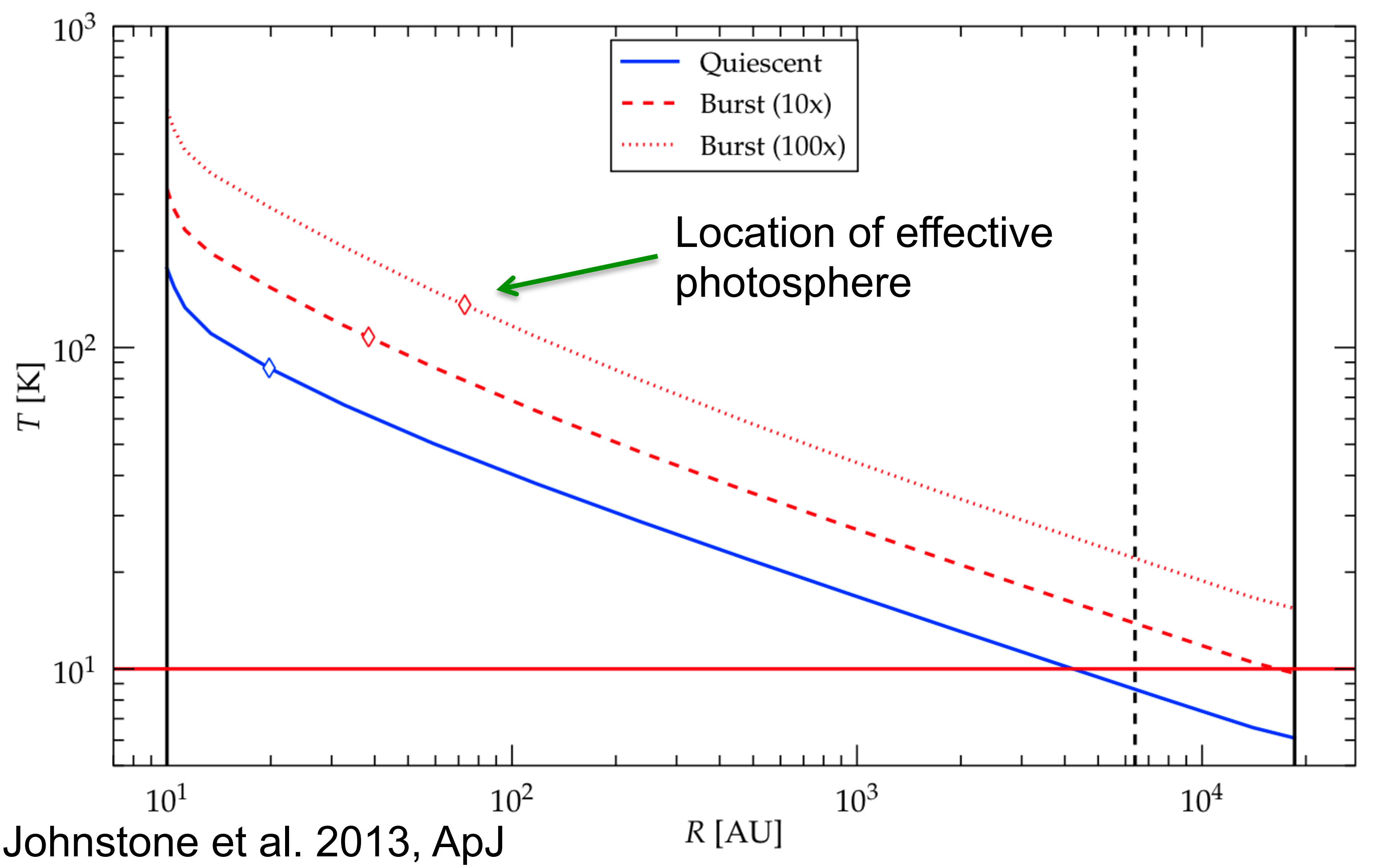
- Measurements near the SED peak provide a proxy for accretion. Thus, the *JCMT Transient Survey* or potential *SPICA/OST Variability Surveys* observe accretion variability through brightness variations.

Can We Observe Changes in the SED? Deeply Embedded Protostar Model

- **Density** structure follows inside-out collapse
  - M_{env} = 1.5 M_{sun}
  - R_{env} = 2×10^4 AU
  - R_x = 6×10^3 AU (transition from static to infall)
- Protostar **Mass** ~ 0.25 M_{sun}
- Possible **Luminosities**:
  - L_{PS} = 1.2 L_{sun}
  - L_{acc} = 5 L_{sun} (if steady-state: c^3/G)
  - L_{10} = 12 L_{sun}
  - L_{100} = 120 L_{Sun}

Implications of Variable Accretion - I

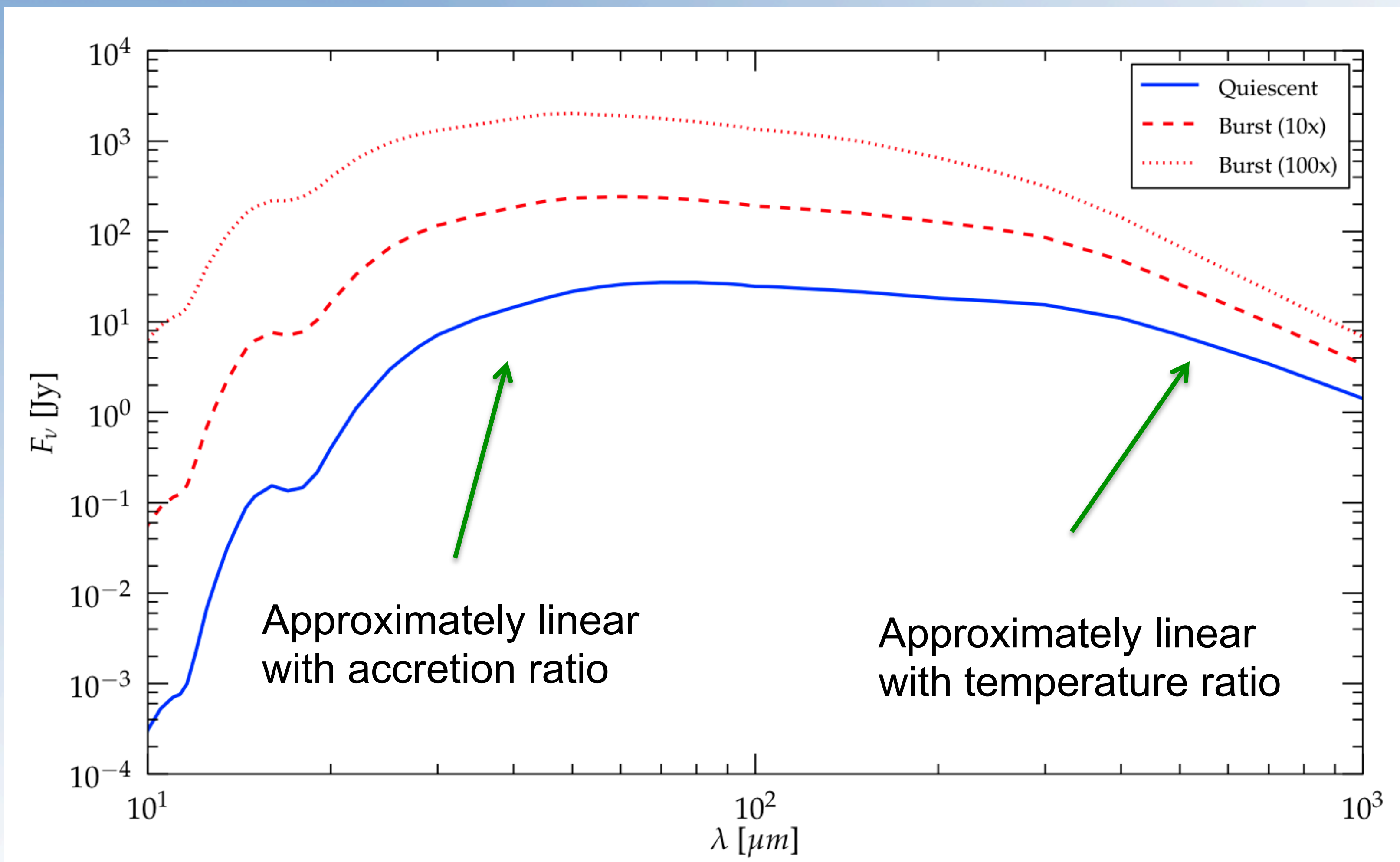
Temperature Profile of the Envelope responds to accretion luminosity



Johnstone et al. 2013, ApJ

Implications of Variable Accretion - II

Luminosity of Source gets higher and SED shifts to the blue (Warmer)



Implications of Variable Accretion - III

Dust must be heated (cooled) to these new temperatures …

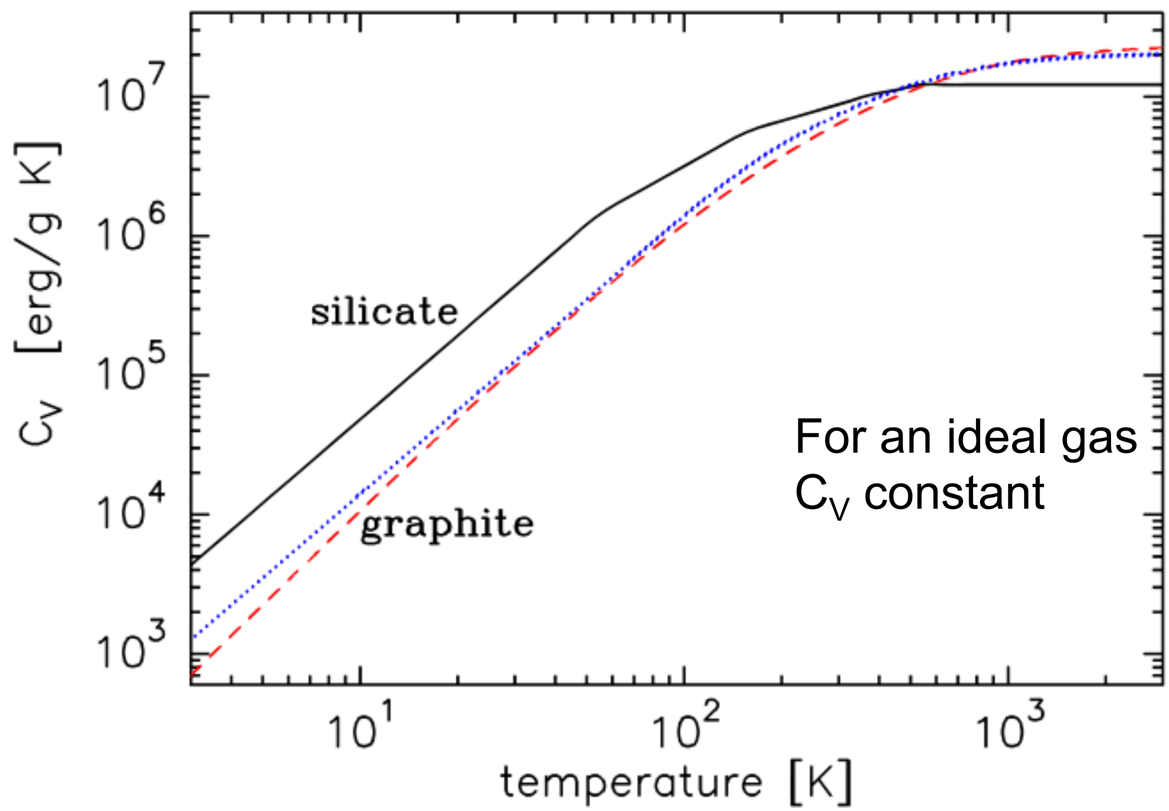
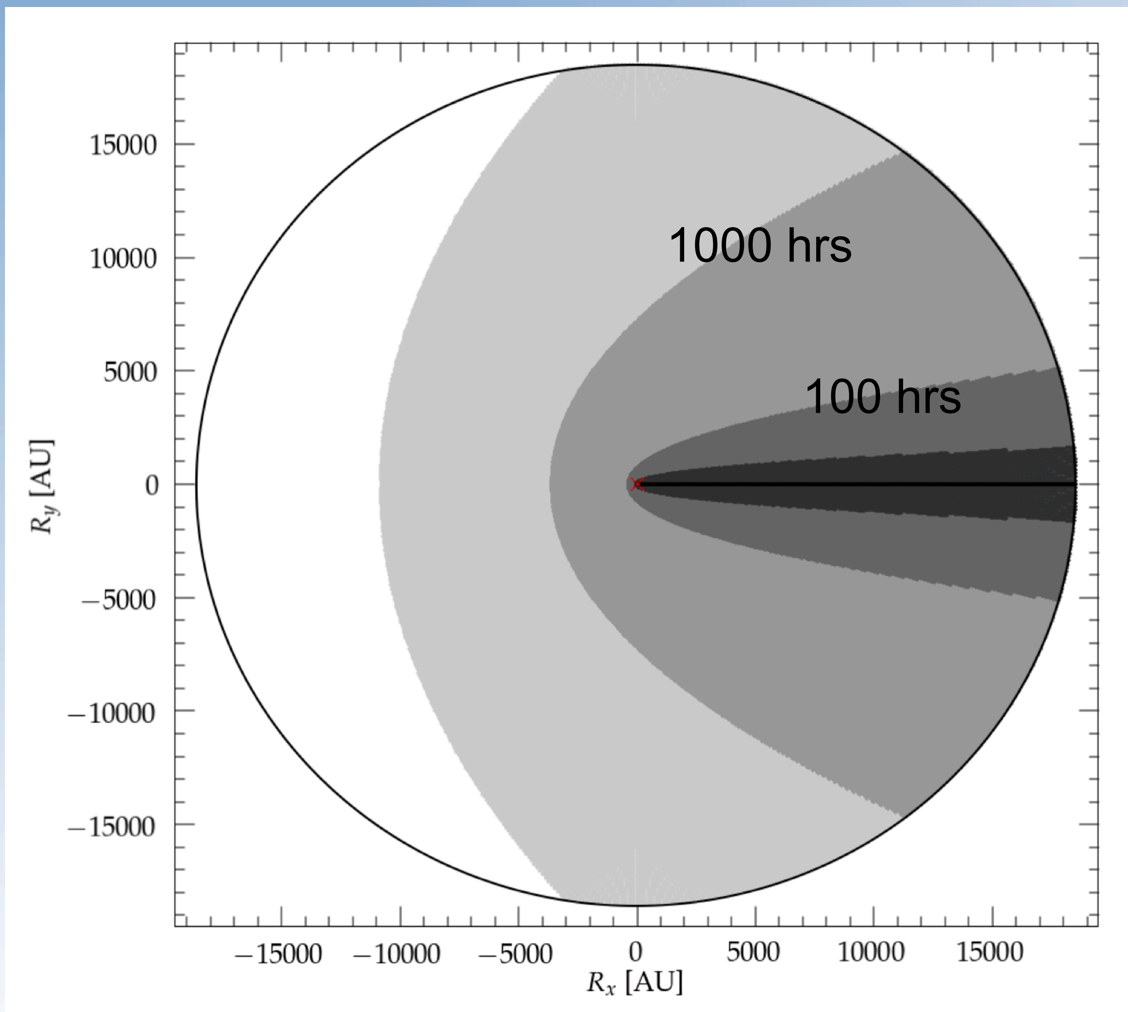
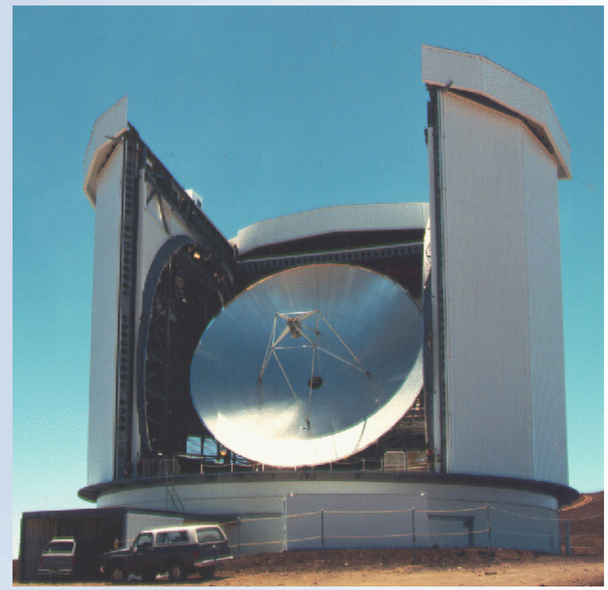


Figure 8.9. The specific heat per gram of dust for silicate (full curve, similar to [Guh89]), graphite (broken curve, after [Cha85]) and PAHs without hydrogen atoms (dotted curve, after [Kru53] using (8.44)). Guhathakurta & Draine 1989, ApJ

Implications of Variable Accretion - IV

The light propagation time must be taken into account …

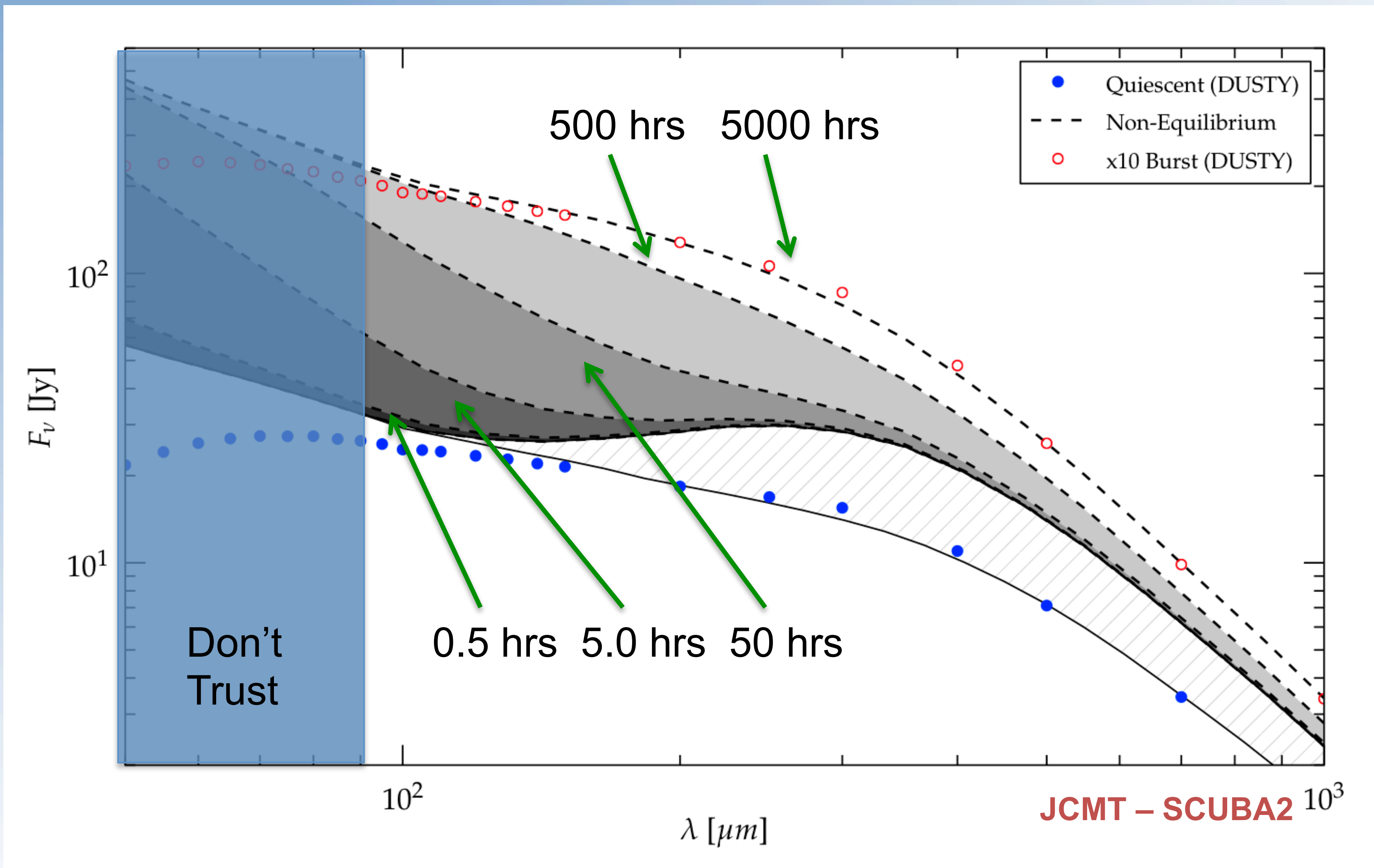




Crossing time of the effective photosphere, R_{ph} ~ 50 AU, is about 5 hrs.

Implications of Variable Accretion - V

The observable timescale for variability can be assessed:



Spitzer/Wise Variability …

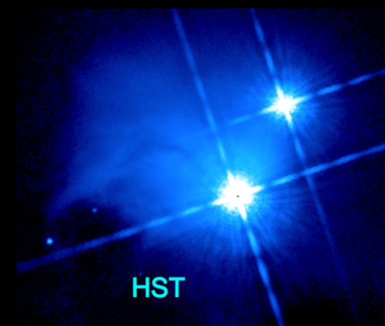
Slide from W. Fischer

Outbursts seem to be common

McNeil's Nebula / V1647 Ori (2003)

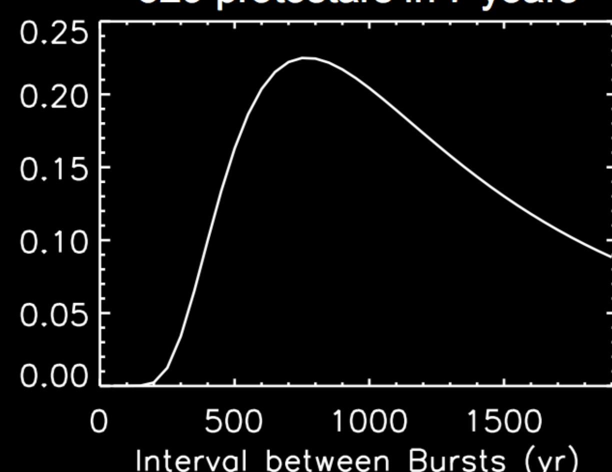
HOPS 383 (~2005)

HOPS 223 (~2006)



- Over 7 years, 3 of 329 protostars began outbursts
- Suggests ~ 800 yrs between outbursts; each protostar has many over its formation period
- But these three luminosity increases are of order ~ 10x (canonical FU Oris are > 100x)

Probability of 3 outbursts among 329 protostars in 7 years



Herschel Variability …

70 and 160 microns

Orion observed six times over six weeks.

8/17 found to have >10% flux variability (LHS of figure)!

Argue likely due to inner disk variability in mass accretion.

THE ASTROPHYSICAL JOURNAL LETTERS, 753:L35 (8pp), 2012 July 10 BILLOT ET AL.

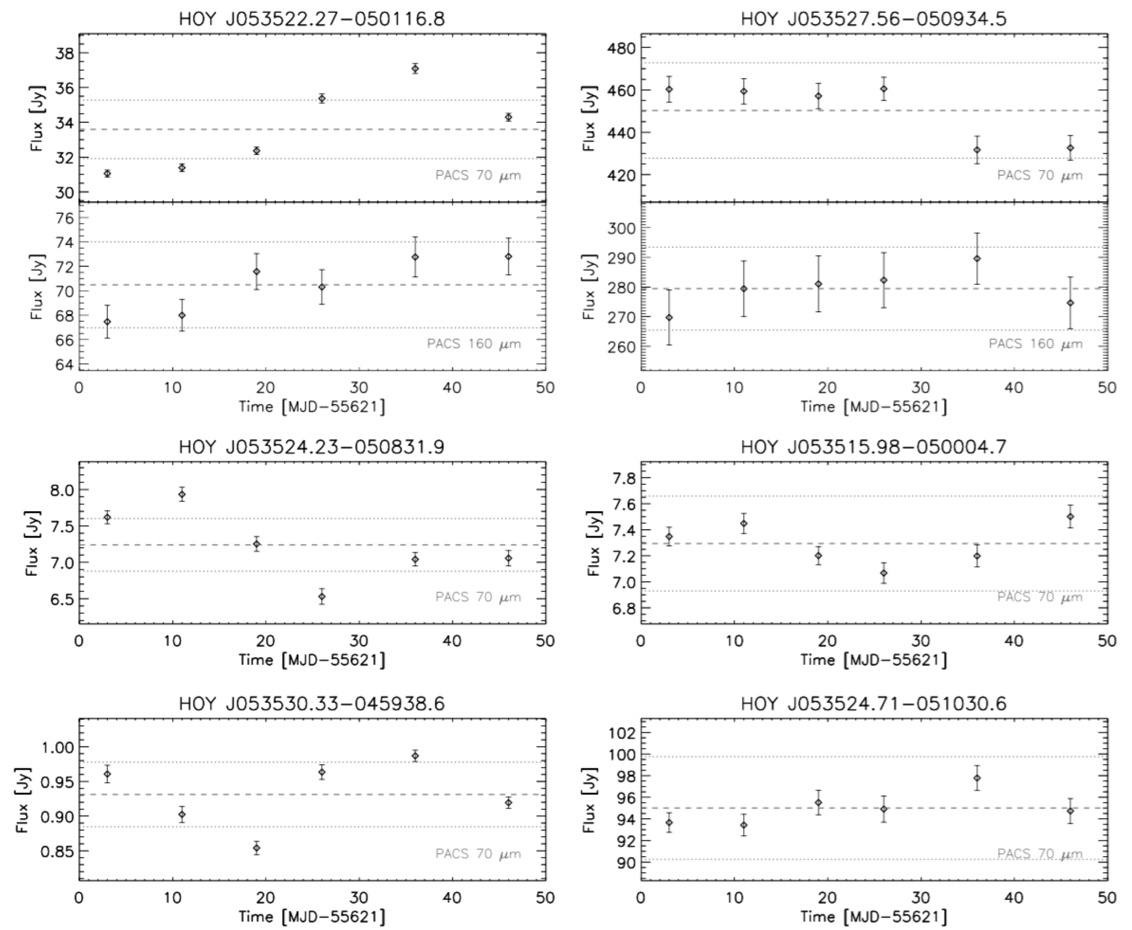
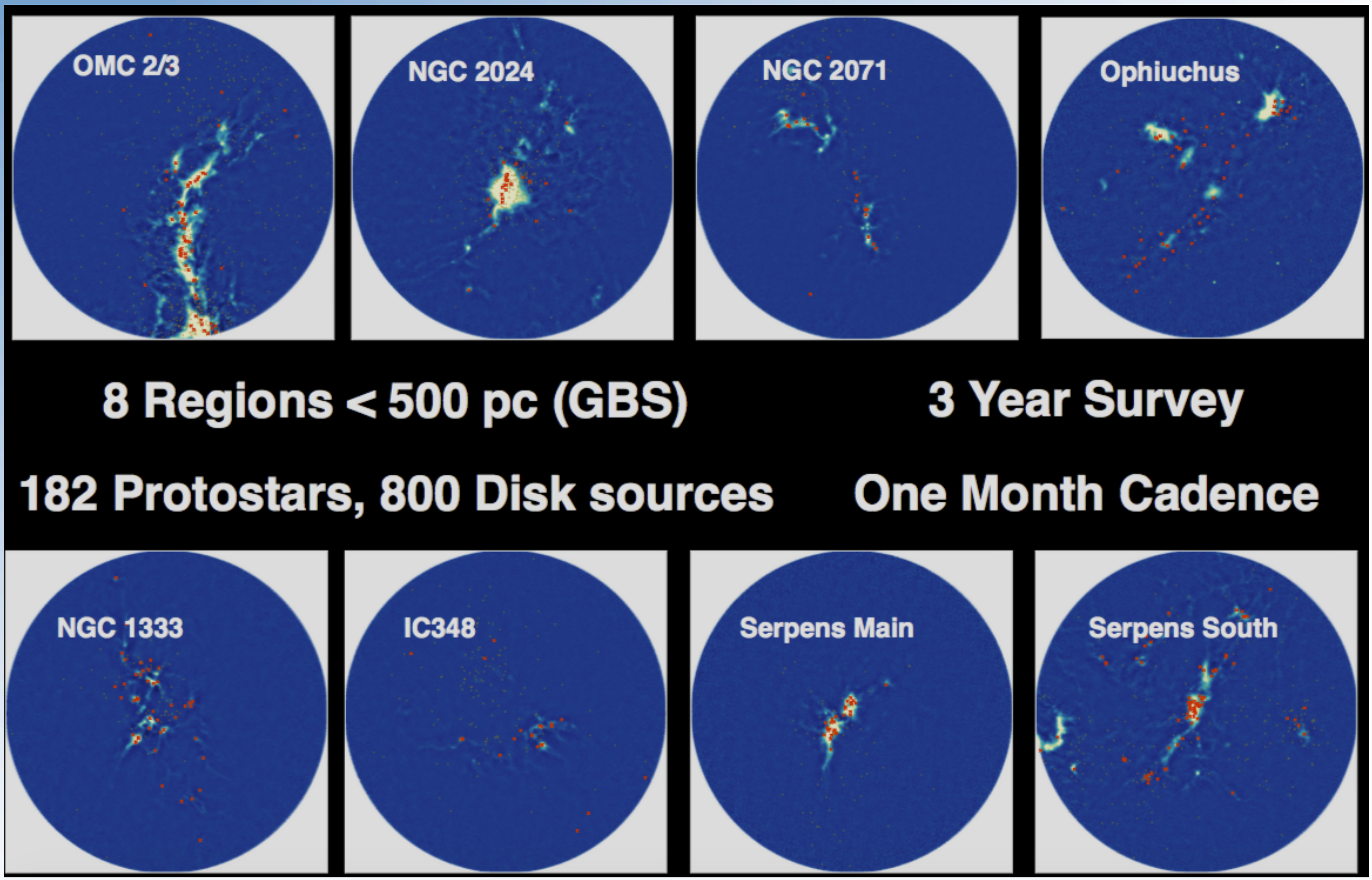


Figure 2. Sample of reliable PACS light curves drawn from Table 2. The left column presents the light curves of variable protostars, and the right column contains those that show flux variations within the estimated photometric uncertainties (see Section 2.3 for details). The set of graphs in the top row show the light curves at 70 μm and 160 μm when both are deemed reliable, while the other plots give 70 μm fluxes only. The horizontal dashed and dotted lines give the average flux of the sources and the ±5% variations around the mean, respectively, indicating our level of confidence for variability detections. The first epoch was obtained on 2011 February 26, corresponding to the *Herschel* Operational Day 653 or MJD 55618.

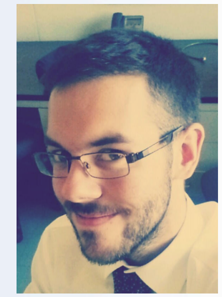
(Billot et al 2012)

The EAO/JCMT Transient Survey



(Herczeg et al. 2017, ApJ)

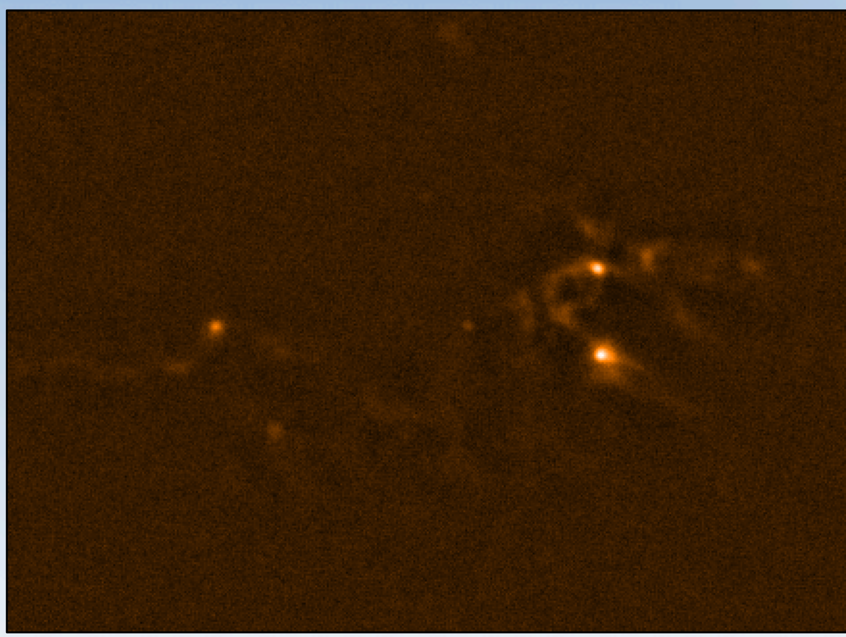
Calibration Methodology

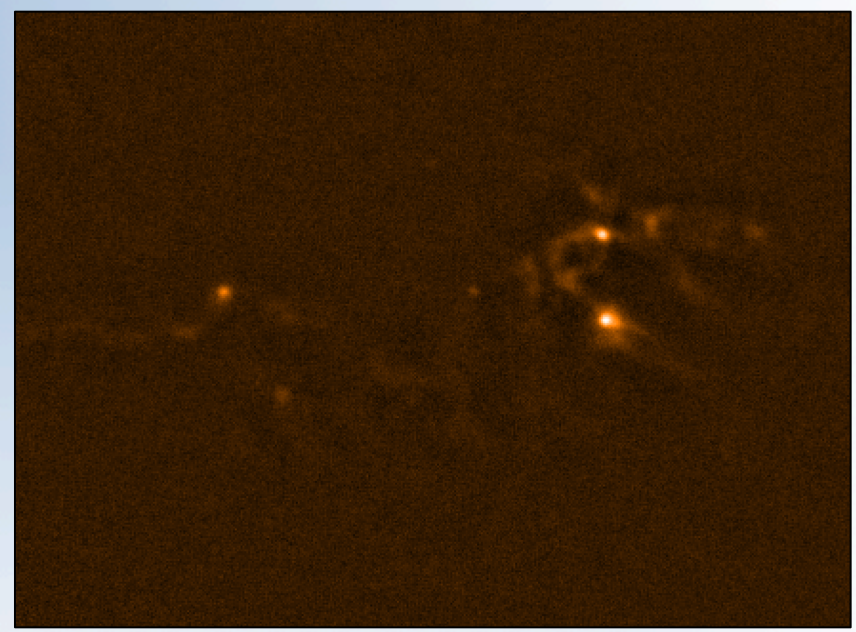


Run Source-Finder on all epochs of the field (PhD student- Steve Mairs).

Determine which sources are in common between observations.

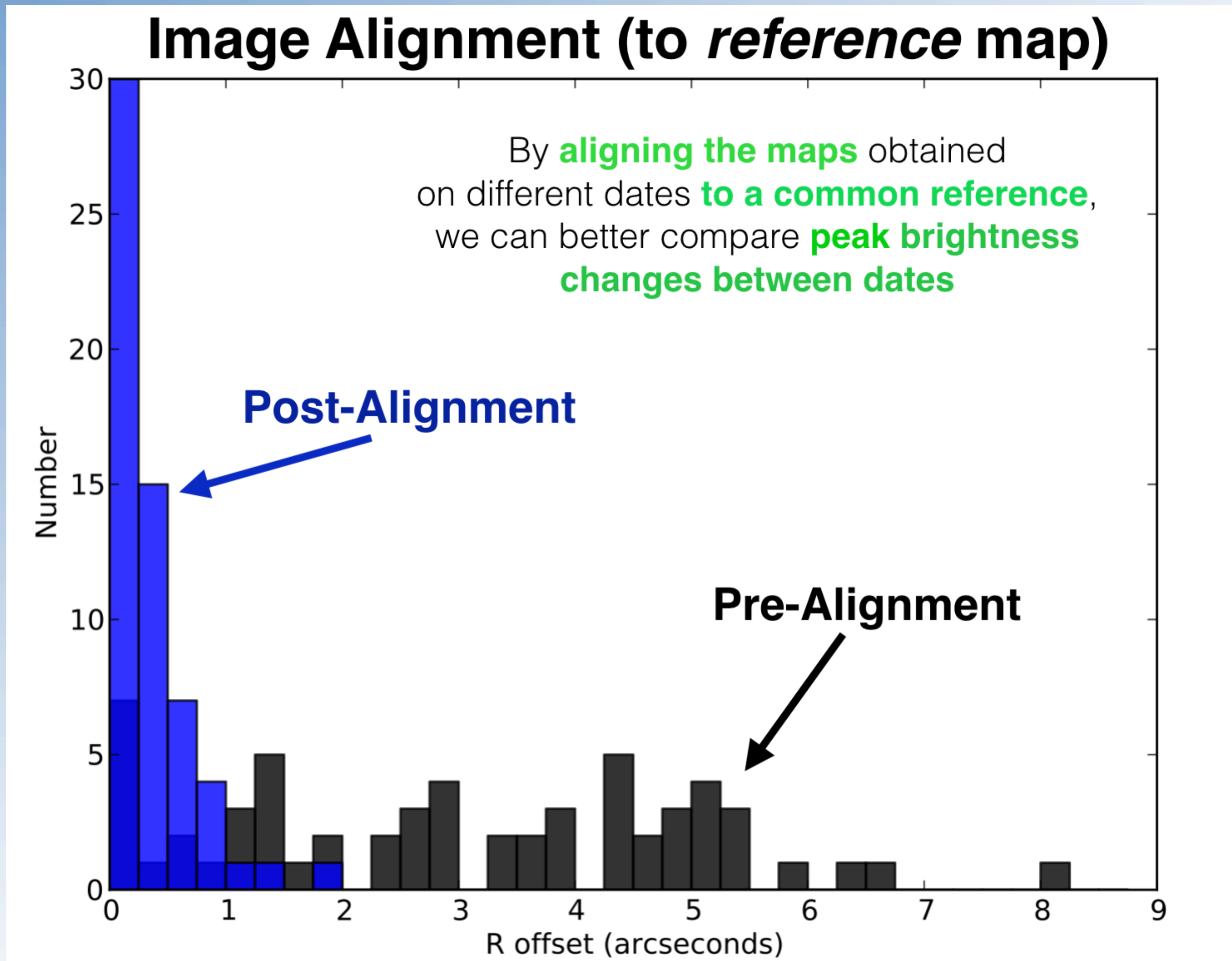
Compare clump centroids and relative brightness between observations.





Six epochs of IC348 observed over half a year.
Left: Before residual offset calibration; Right: after applying offset.

Calibration Methodology

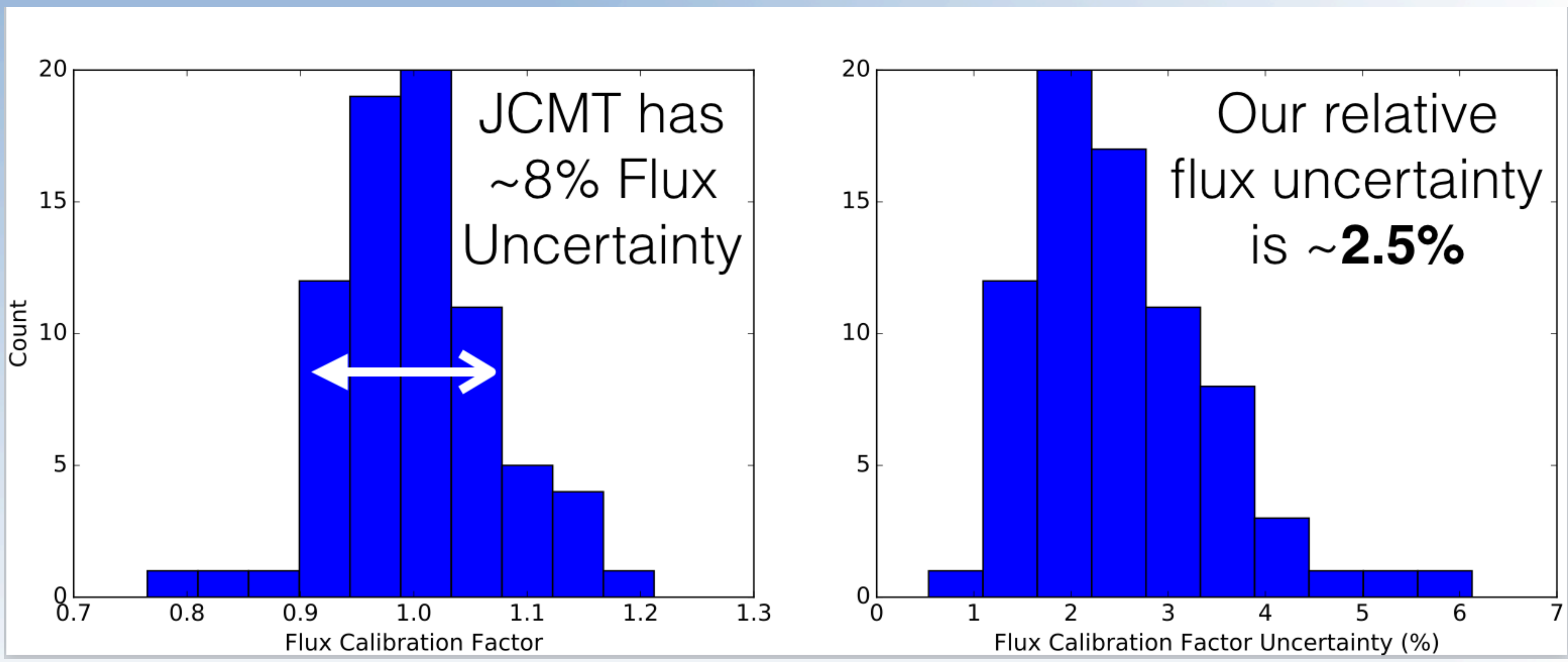


Calibration Methodology

Achieve relative alignment calibration of better than one arcsecond.

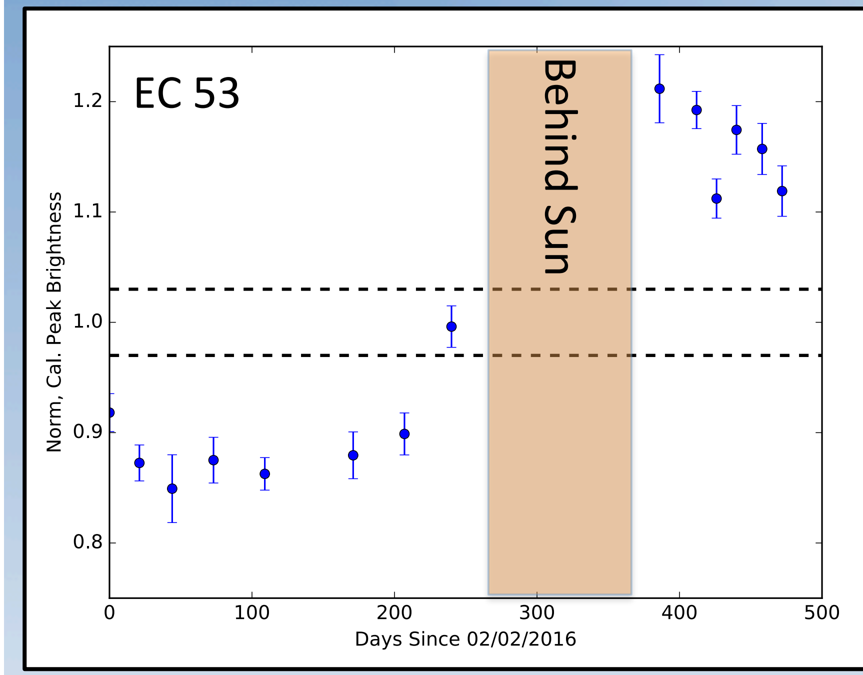
Achieve relative flux calibration of better than 3%.

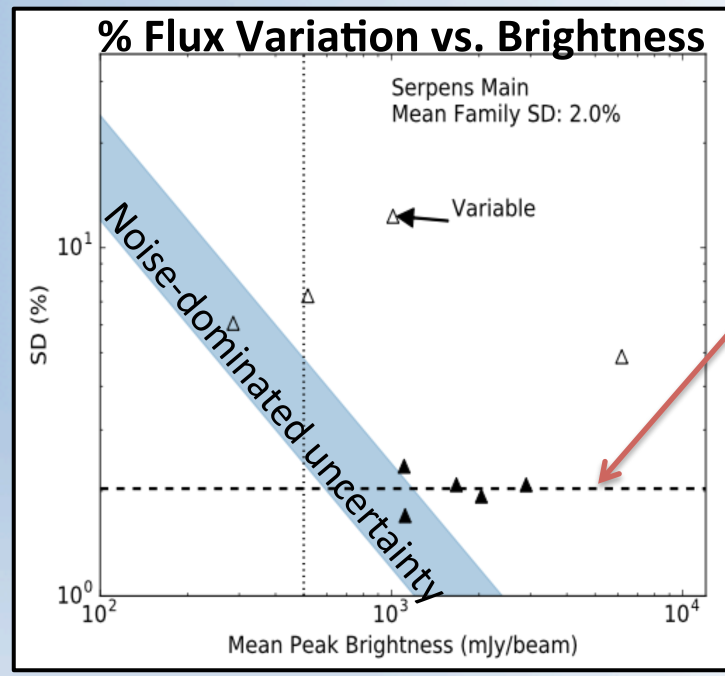
(Mairs et al. 2017a, ApJ)



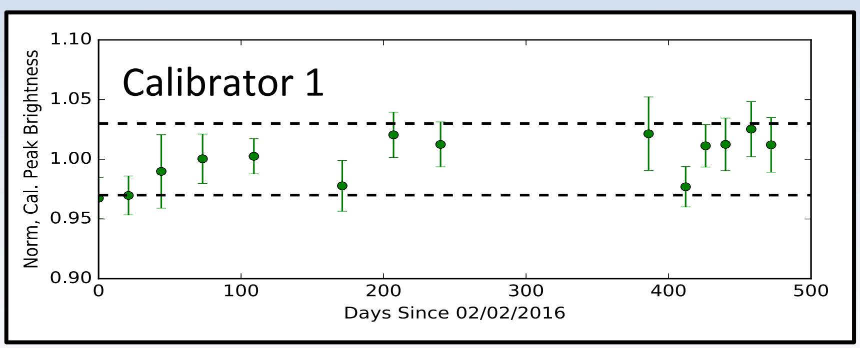
Calibrated Light Curves and Variance:

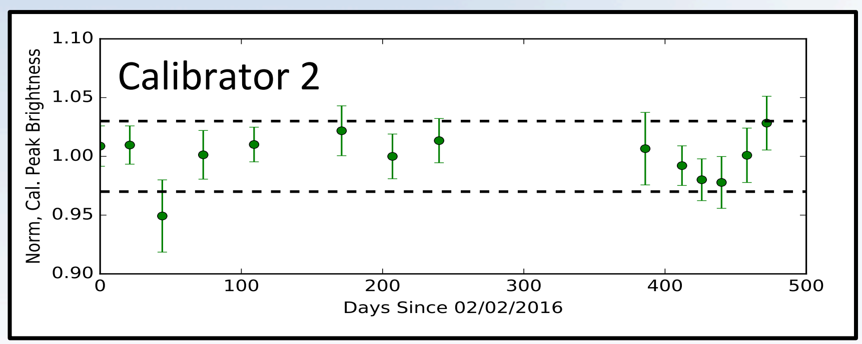
Light Curves at 850 microns – Calibrated Images (Mairs et al. 2017a, ApJ)





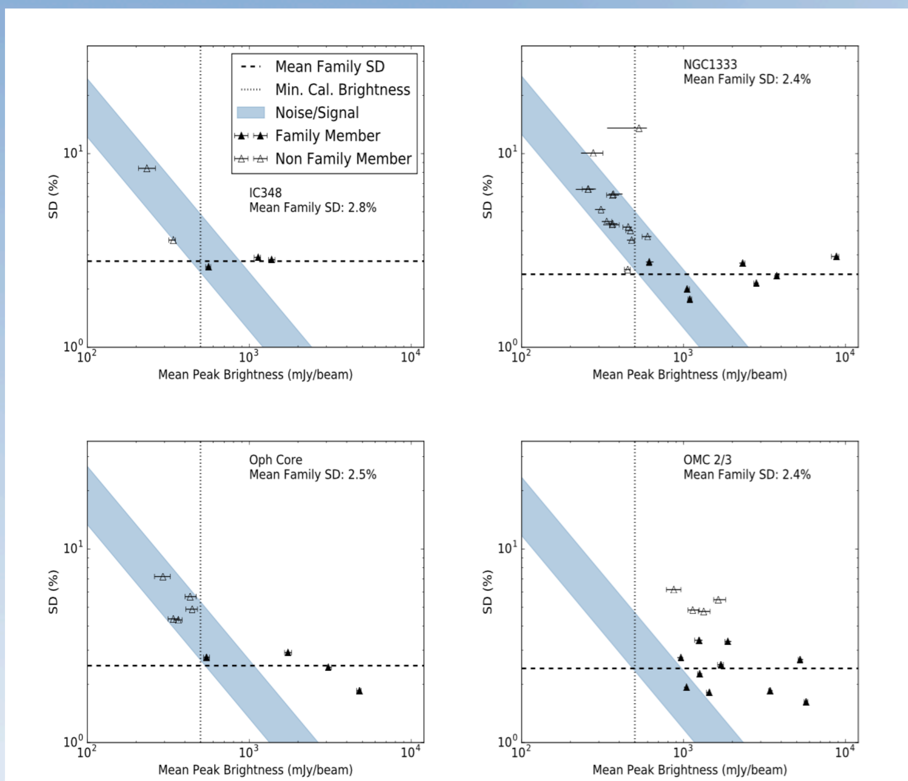
Relative Flux calibration ~ 2% limited to high S/N Sources.

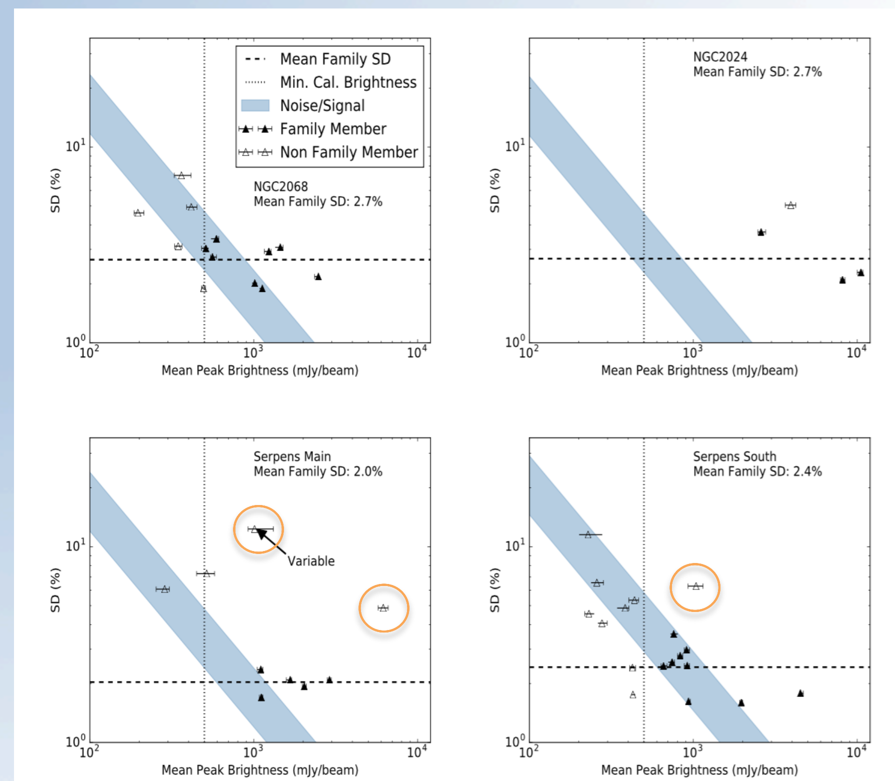




Calibrated Light Curves and Variance:

Light Curves at 850 microns – Calibrated Images (Mairs et al. 2017a, ApJ)





JCMT Variation Over A Few Years …

Align and apply relative calibration to, 2-4yr prior, GBS Survey images.

Look for robust signs of brightness changes. (Mairs et al. 2017b, ApJ)

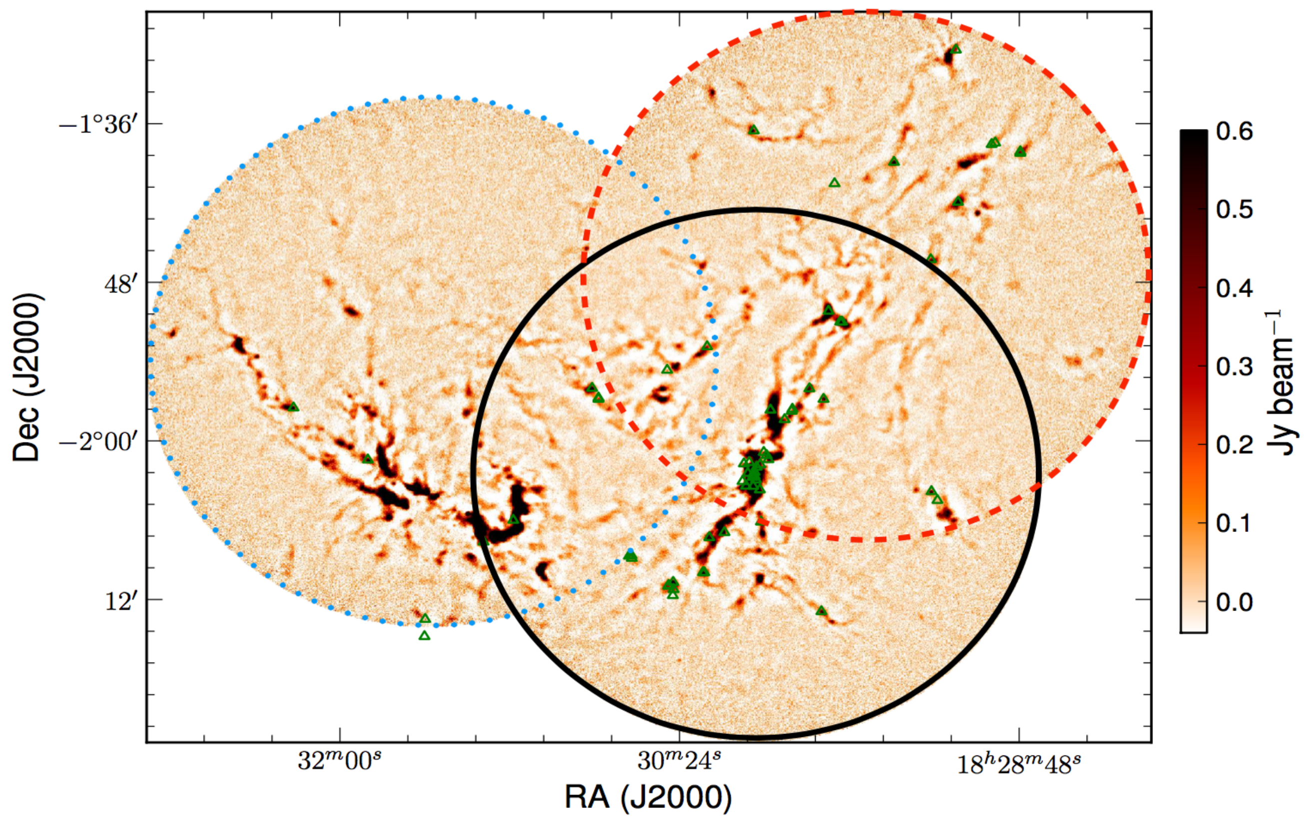
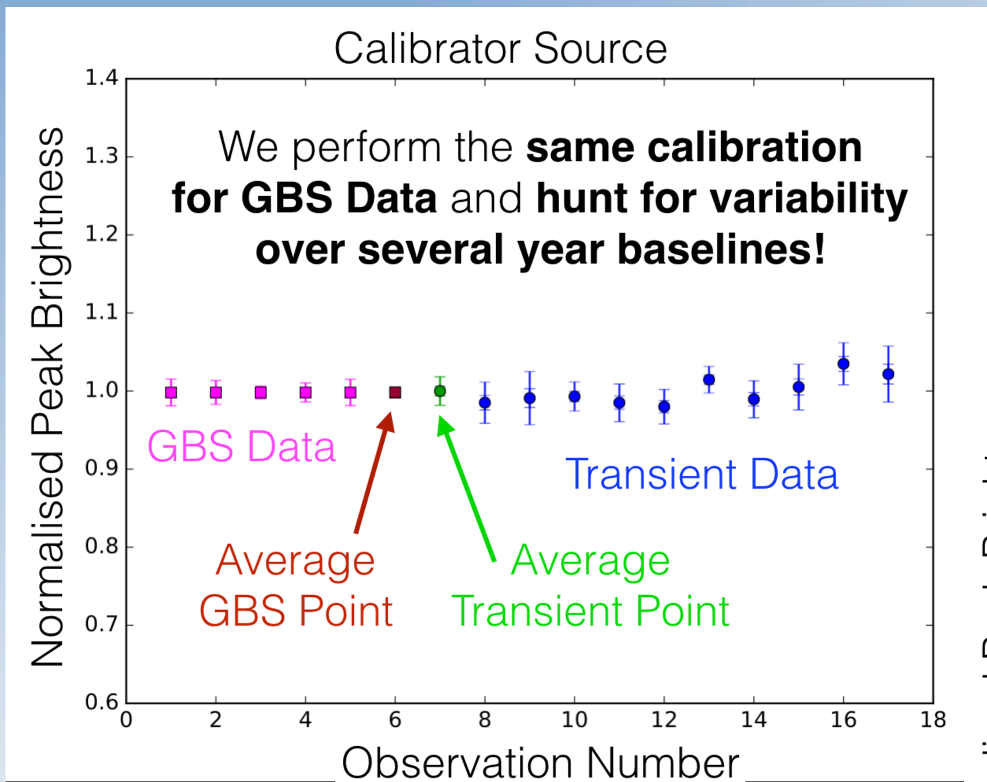
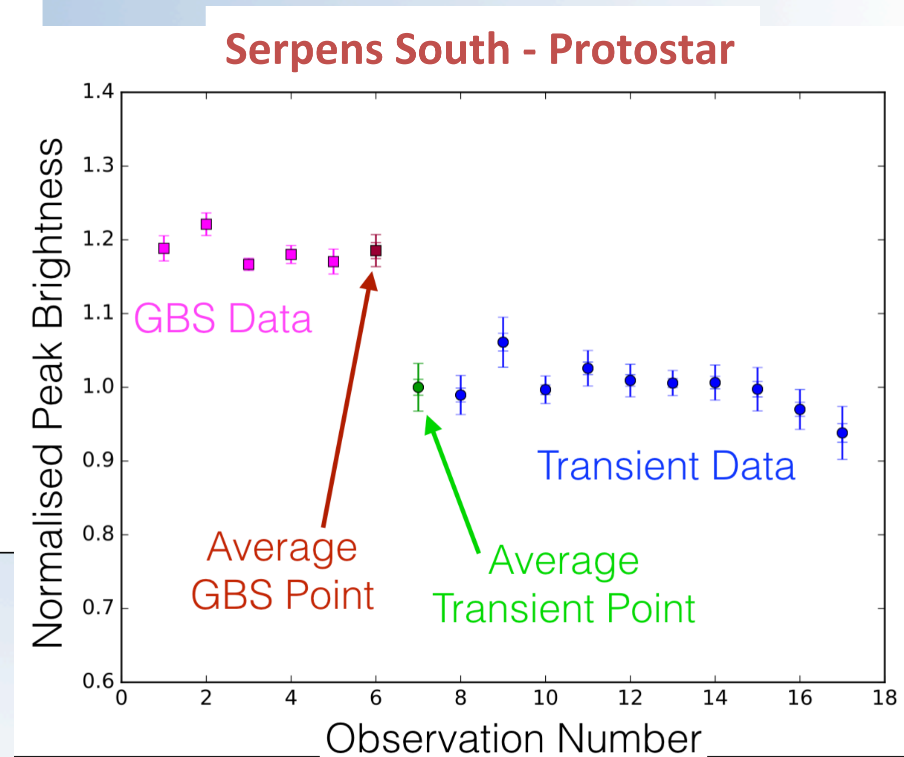


Figure 17. Same as Figure 10, but showing the Serpens South field with its corresponding archival GBS fields. The red (dashed) circle shows the SerpensS-NW GBS field while the blue (dotted) circle shows the SerpensSouthS-NE GBS field.

JCMT Variation Over A Few Years …



GBS Survey ~4yrs before Transient Survey



JCMT Variation Over A Few Years …

Uncover 4 strong protostellar variable candidates and one likely variable protostar.

Find 1 variable with no known protostar (Perseus Bolo-40) . (Mairs et al. 2017b, ApJ)

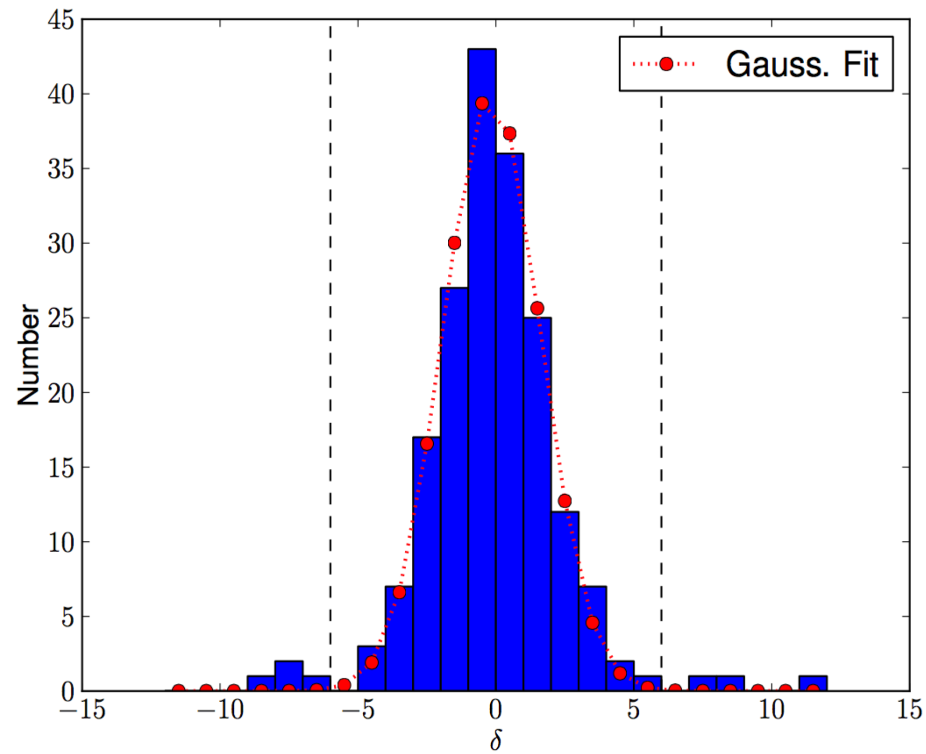
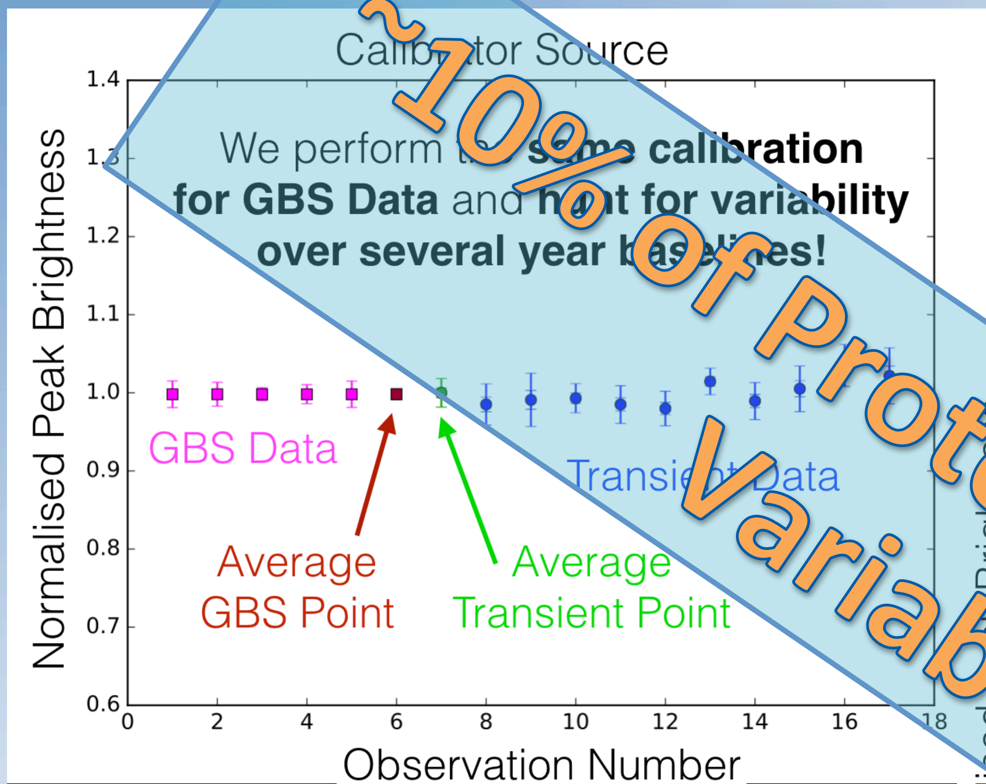
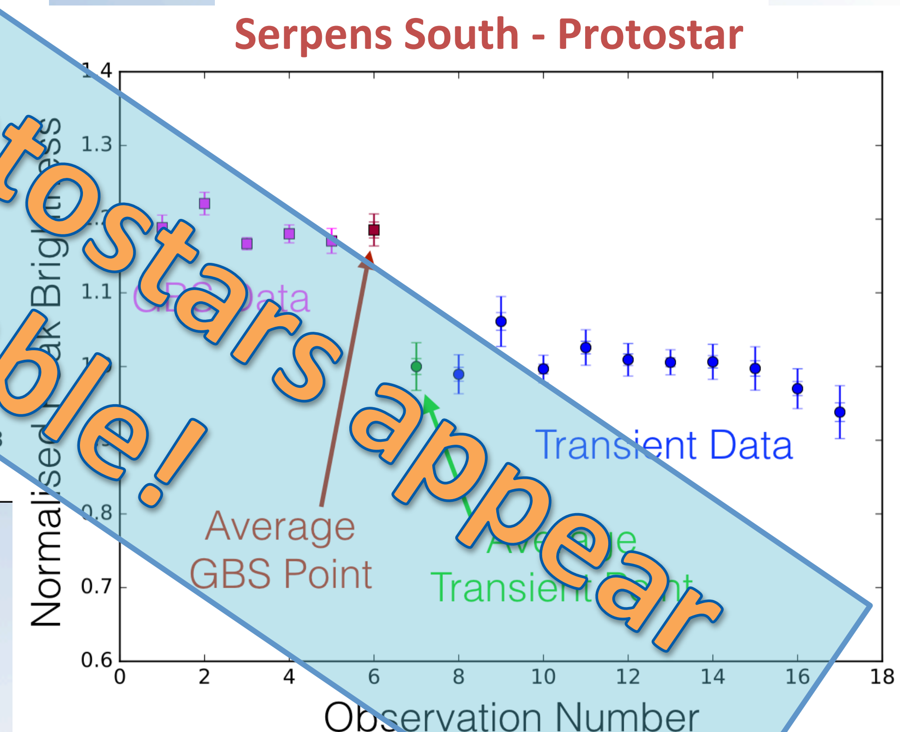


Figure 7. The distribution of δ values for all sources. The red points represent a Gaussian fit to the histogram. The vertical dashed lines indicate the threshold for a significant detection of a variable candidate.

JCMT Variation Over A Few Years …



GBS Survey ~4yrs before Transient Survey



~10% of Protostars appear Variable!

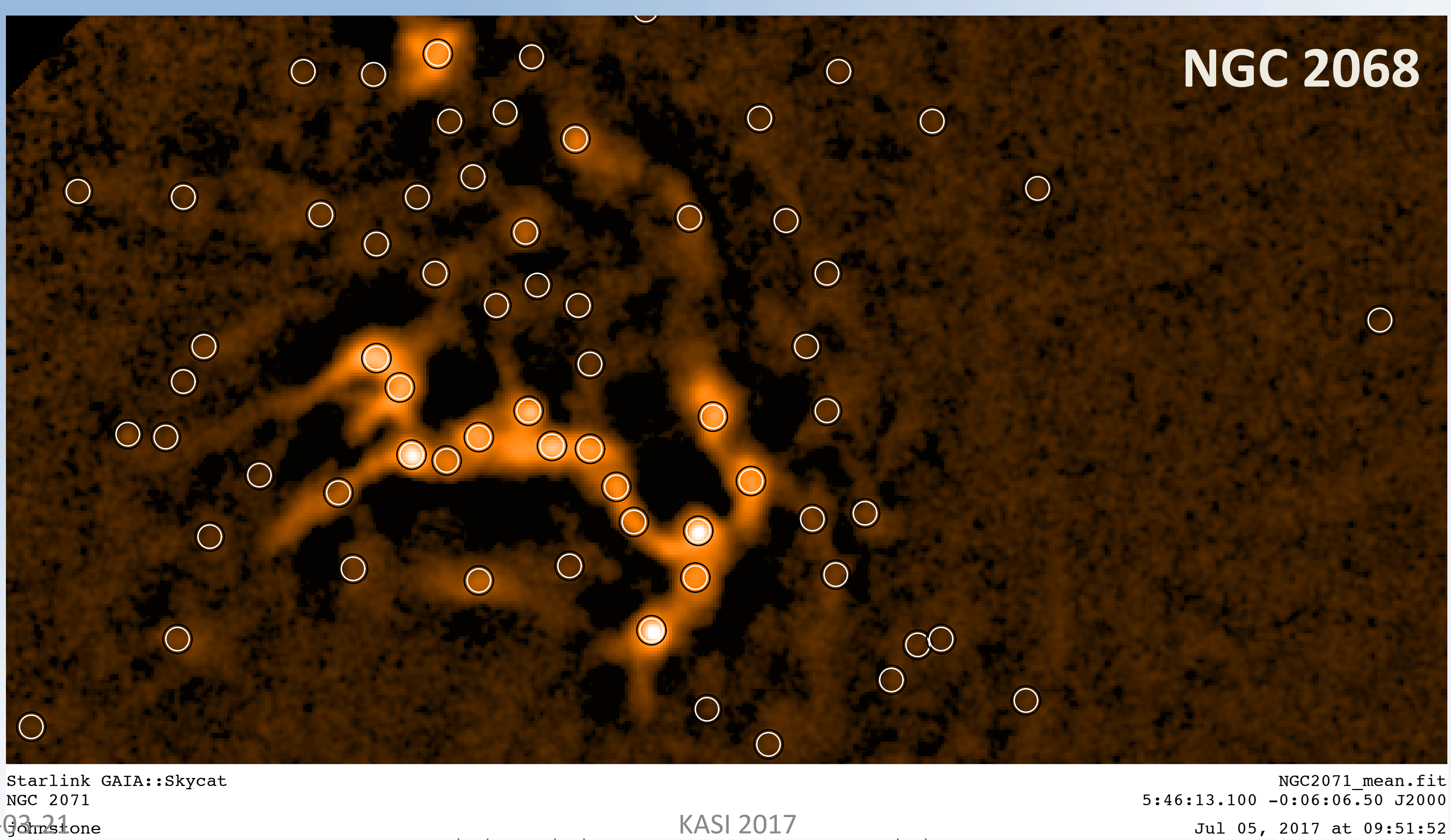
Bottom Line: There are approximately a half dozen sources with a robust detection of flux variation between GBS and Transient epochs.

$|\Delta f/f| < 0.20$ ---> $|\Delta f/f| < 0.05$ per year.

(Mairs et al. 2017b, ApJ)

JCMT Ensemble Variability: ~Δ1.5 Yrs

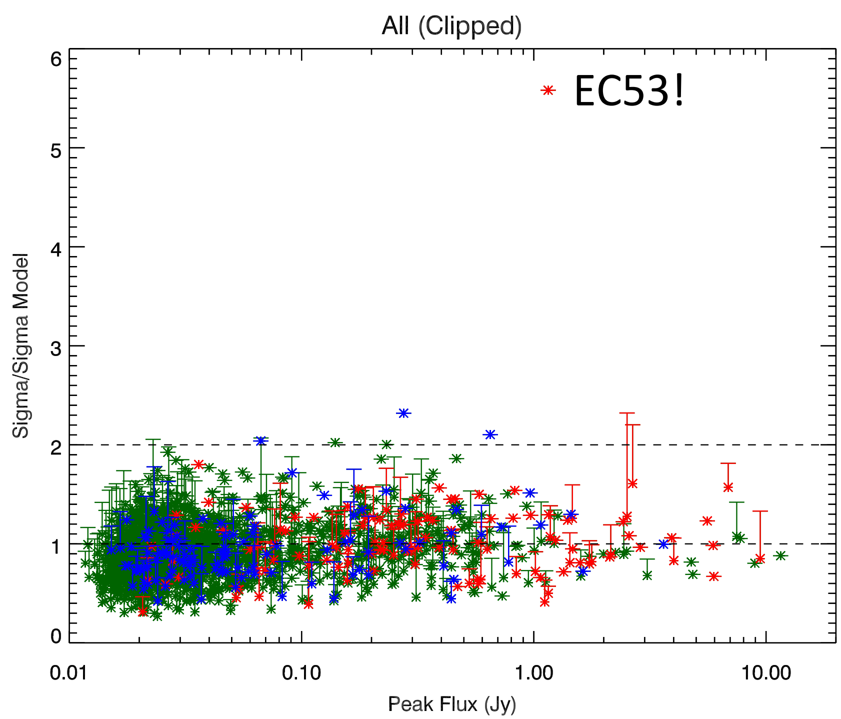
1) Create a mean map from all epochs: deepest images
2) Find all the peaks in the map: we use Fellwalker (JSACatalogue)
3) Collate peaks with known protostars and disks: *Herschel & Spitzer*



JCMT Ensemble Variability: ~Δ1.5 Yrs

4) Determine standard deviation (**sigma**) for all peaks/all regions
   - With and without sigma-clipping for outliers (small # of epochs)

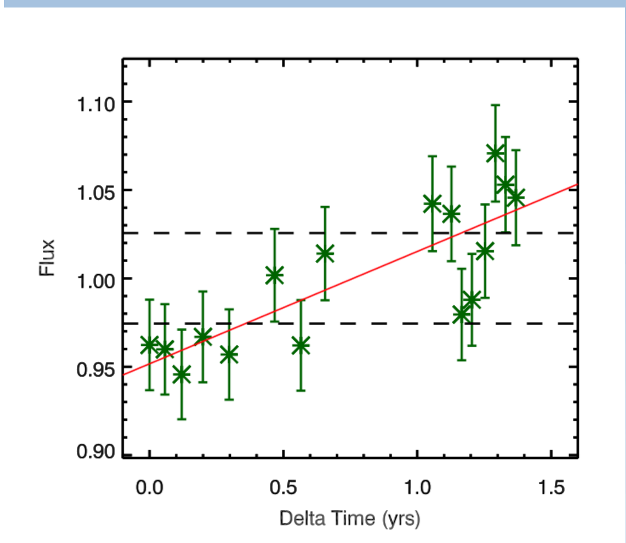
5) Compare against fiducial model for measurement uncertainty
   - Low flux: *Noise dominates*; High flux: *Calibration dominates*

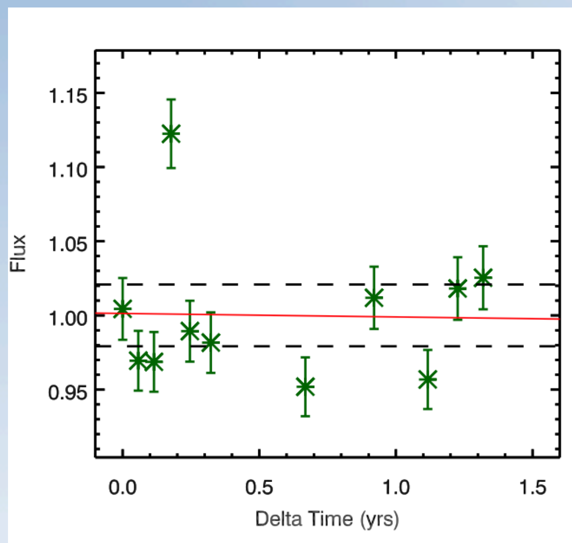


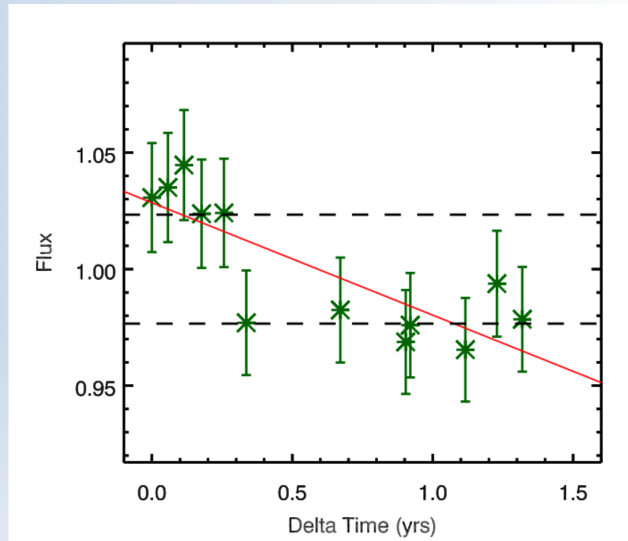
Bottom Line:
So far only EC53 stands out as a clear outlier in measurement uncertainty.

JCMT Ensemble Variability: ~Δ1.5 Yrs

6) Fit simple linear brightness profiles to bright sources (> 350 mJy)
   - determine slope and the uncertainty in the slope
7) Randomize order of epochs and repeat fitting process
   - Compare random distribution against ordered distribution





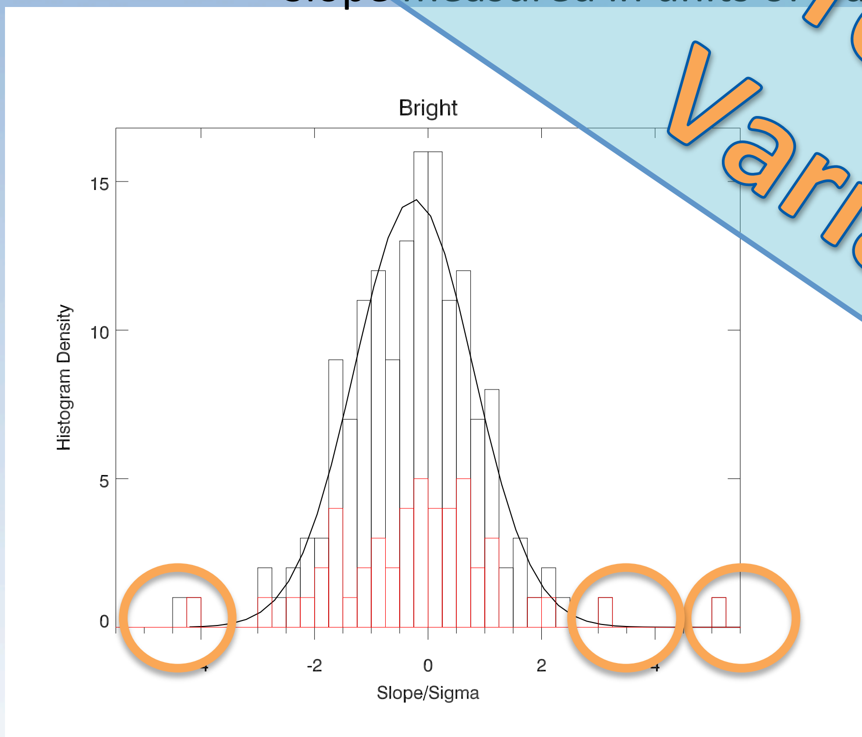


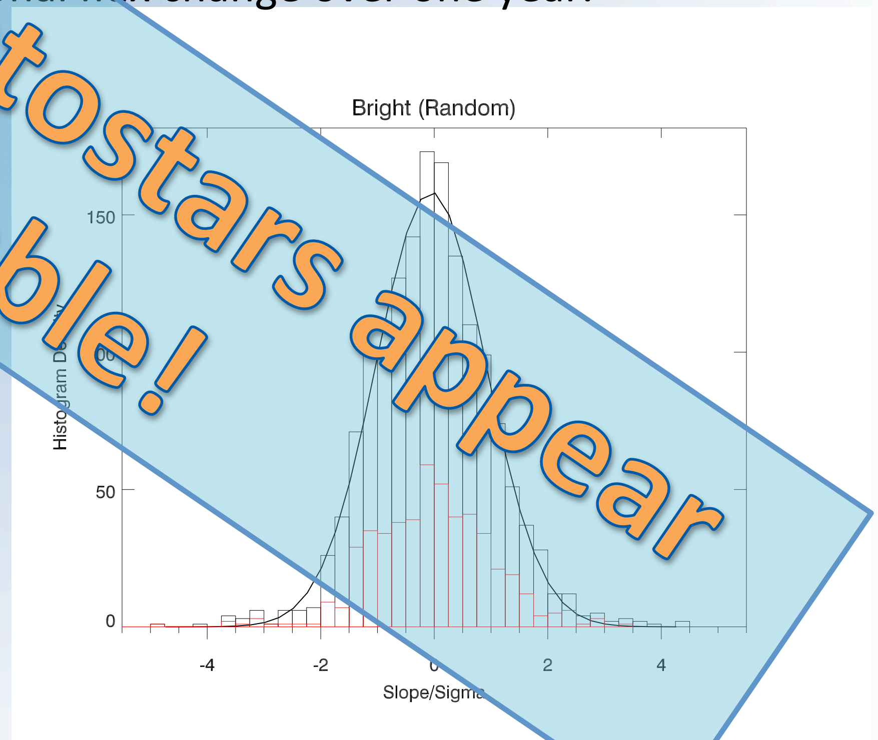
(Johnstone et al. 2018, ApJ, in press)

JCMT Ensemble Variability: ~Δ1.5 Yrs

6) Fit simple linear brightness profiles to bright sources (> 350 mJy)
   - determine slope and the uncertainty in the slope
7) Randomize order of epochs and repeat fitting process
   - Compare random distribution against ordered distribution

Slope measured in units of fractional flux change over one year.





~10% of Protostars appear Variable!

JCMT Variation Over A Few Years …

Table 7. Comparison of Identified Variable Sources

Region	Name	Transient Analysis $S/\Delta S$[a]	Transient Analysis S (yr^{-1})	Transient-GBS Analysis δ[b]	Transient-GBS Analysis S (yr^{-1})	Comment
Serpens M	EC 53	7.9	0.28	NA	NA	See Section 5.1.
Serpens S	IRAS 18270-0153	4.1	-0.05	11.81	-0.04	Strong detection by both analyses.
NGC 2068	HOPS 373	4.3	-0.05	5.34	-0.04	Strong detection by both analyses.
Serpens M	SMM-1	3.2	0.05	6.85	0.02	Strong detection by both analyses.
OMC 2/3	HOPS 383	3.0	-0.04	4.17	-0.03	Moderate detection by both analyses.
NGC 1333	Bolo 40	1.5	-0.04	7.99	-0.03	Only source not identified with protostar.
NGC 1333	IRAS 4A	-	-	7.66	0.02	Not detected by present analysis.
NGC 1333	[LAL96] 213	-	-	8.31	-0.09	Not detected by present analysis.
Serpens M	SMM 10	5.1	0.07	NA	NA	Source too faint for Transient-GBS detection.

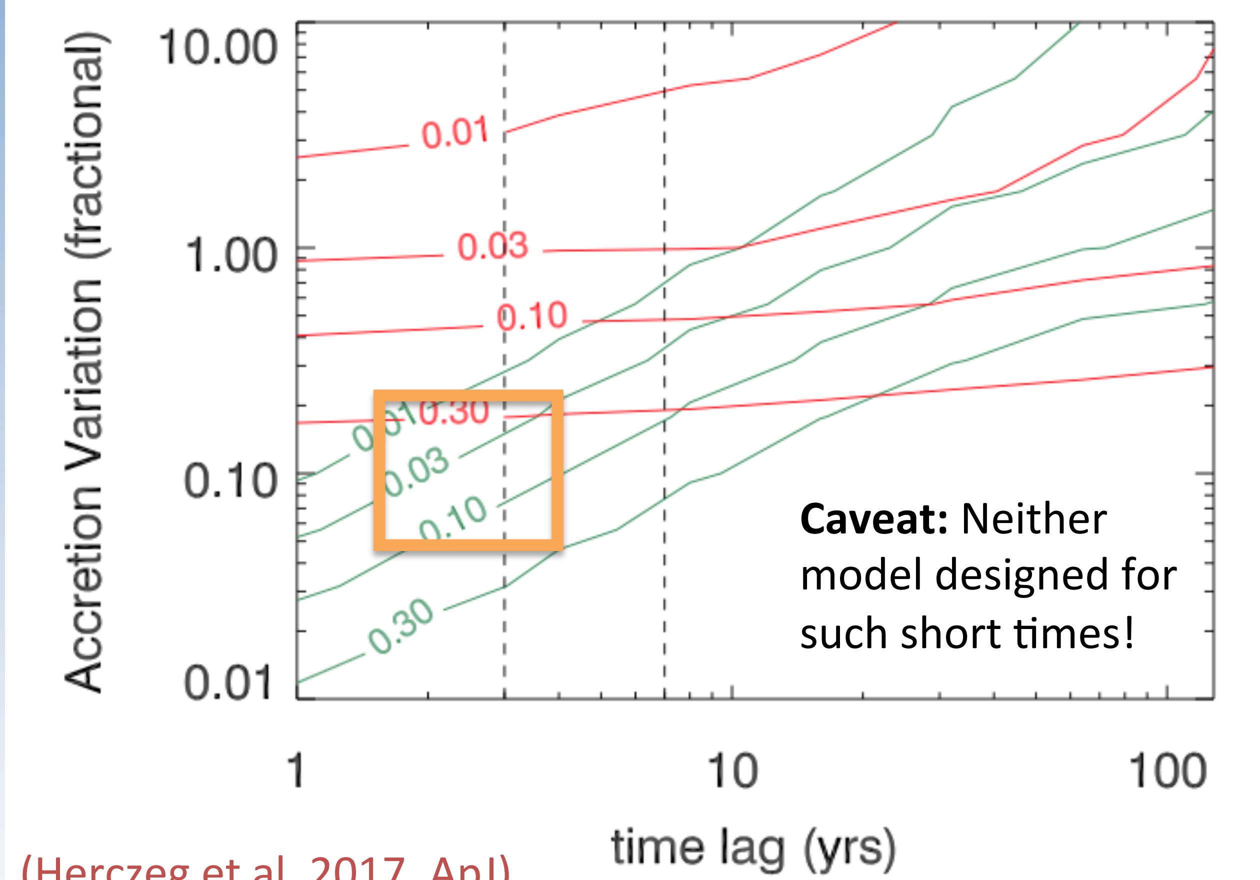
[a] Sources with $S/\Delta S > 4$ are robust against false-positives within the entire ensemble (see §4). Those sources with $S/\Delta S \geq 3$ are strong candidates when treated as a special case.

[b] Sources with $\delta > 5$ are robust against false-positives within the entire ensemble (see Mairs et al. 2017a). Those sources with $\delta > 4$ are strong candidates when treated as a special case.

Mass Accretion – Non-Steady?

Vorobyov & Basu 2005, ApJ – driven by large-scale modes in gravitationally-unstable disk

Bae et al. 2014, ApJ – driven by activation of the magneto-rotational instability

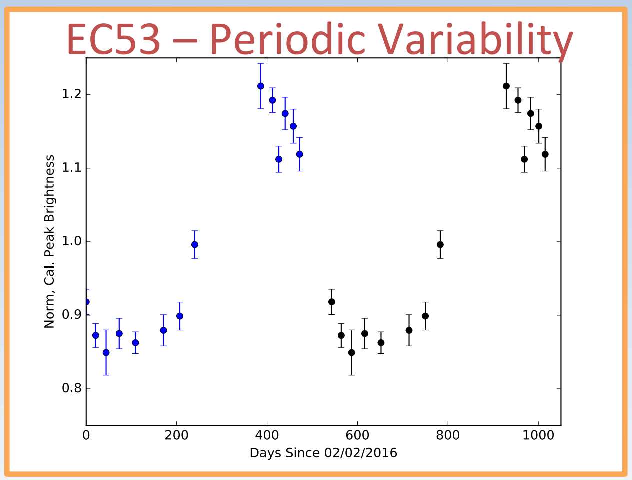


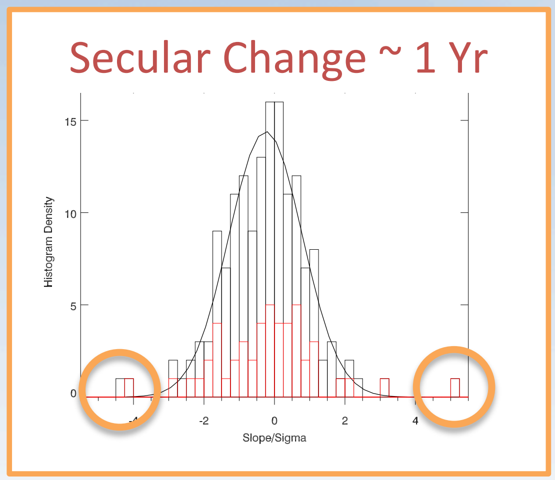
(Herczeg et al. 2017, ApJ)

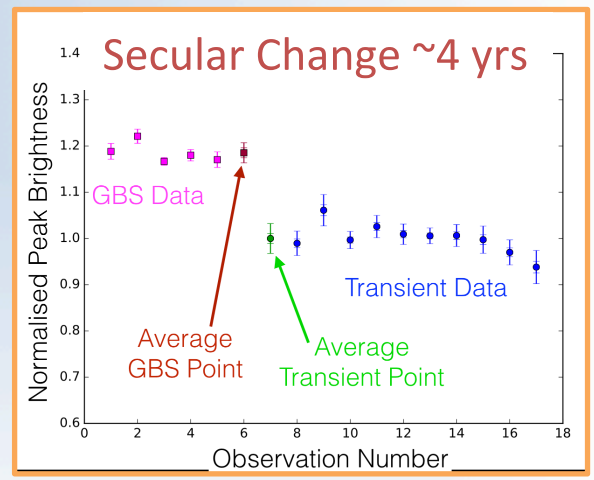
Putting It All Together …

- JCMT Transient Survey finds ~10% of protostars vary ~10% percent per yr
- *Herschel/Wise* suggests ~1% of protostars vary ~500 percent per 10 yrs
- Episodic Accretion implies 100% of protostars vary orders of mag per 1000 yrs

At end of JCMT Transient Survey we should have much better statistics on the observed secular variability and a cleaner handle on transient phenomena.

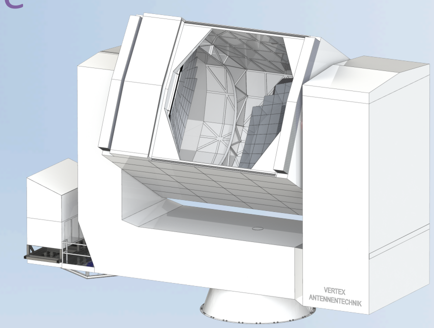




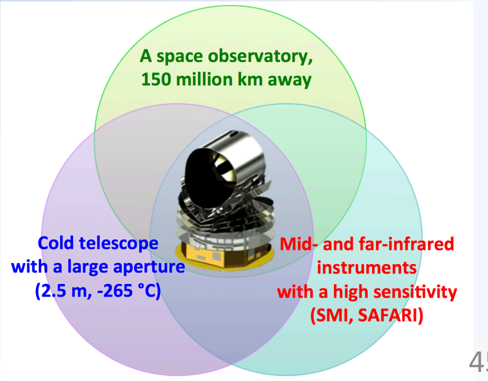


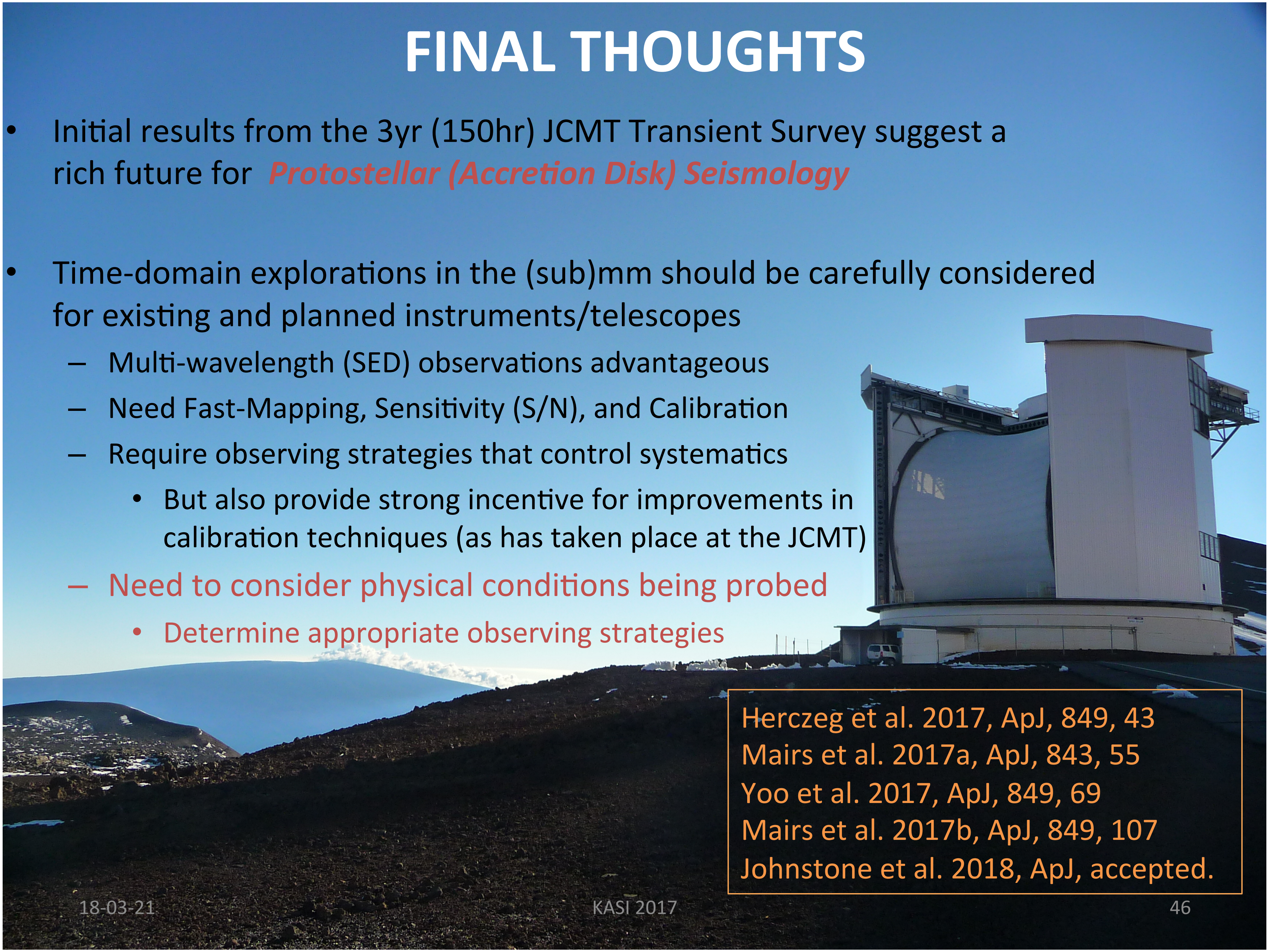
Other Opportunities For Time-Domain

- JCMT Transient – Steve Mairs (PhD), James Lane (Undergrad)
  - Continues for another 1.5 yrs (at least)
- ALMA Follow-up/Monitoring/Serendipity – Logan Francis (MSc)
  - ALMA Cycle 5 proposal to resolve inner part of EC 53 during quiescence and burst
  - Archival comparison of sources over time
- CCAT-P (and other single-dish)
  - Higher sensitivity, larger field of view, higher frequency observations possible
  - For CCAT-P can monitor almost all Orion protostars at 350 microns (S/N > 100) with ~hr per epoch



- Far IR Space Telescopes (SPICA/ORIGINS)
  - Excellent calibration opportunity, limited lifetime




FINAL THOUGHTS
• Initial results from the 3yr (150hr) JCMT Transient Survey suggest a rich future for *Protostellar (Accretion Disk) Seismology*
• Time-domain explorations in the (sub)mm should be carefully considered for existing and planned instruments/telescopes
– Multi-wavelength (SED) observations advantageous
– Need Fast-Mapping, Sensitivity (S/N), and Calibration
– Require observing strategies that control systematics
• But also provide strong incentive for improvements in calibration techniques (as has taken place at the JCMT)
– Need to consider physical conditions being probed
• Determine appropriate observing strategies
Herczeg et al. 2017, ApJ, 849, 43
Mairs et al. 2017a, ApJ, 843, 55
Yoo et al. 2017, ApJ, 849, 69
Mairs et al. 2017b, ApJ, 849, 107
Johnstone et al. 2018, ApJ, accepted.
18-03-21
KASI 2017
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