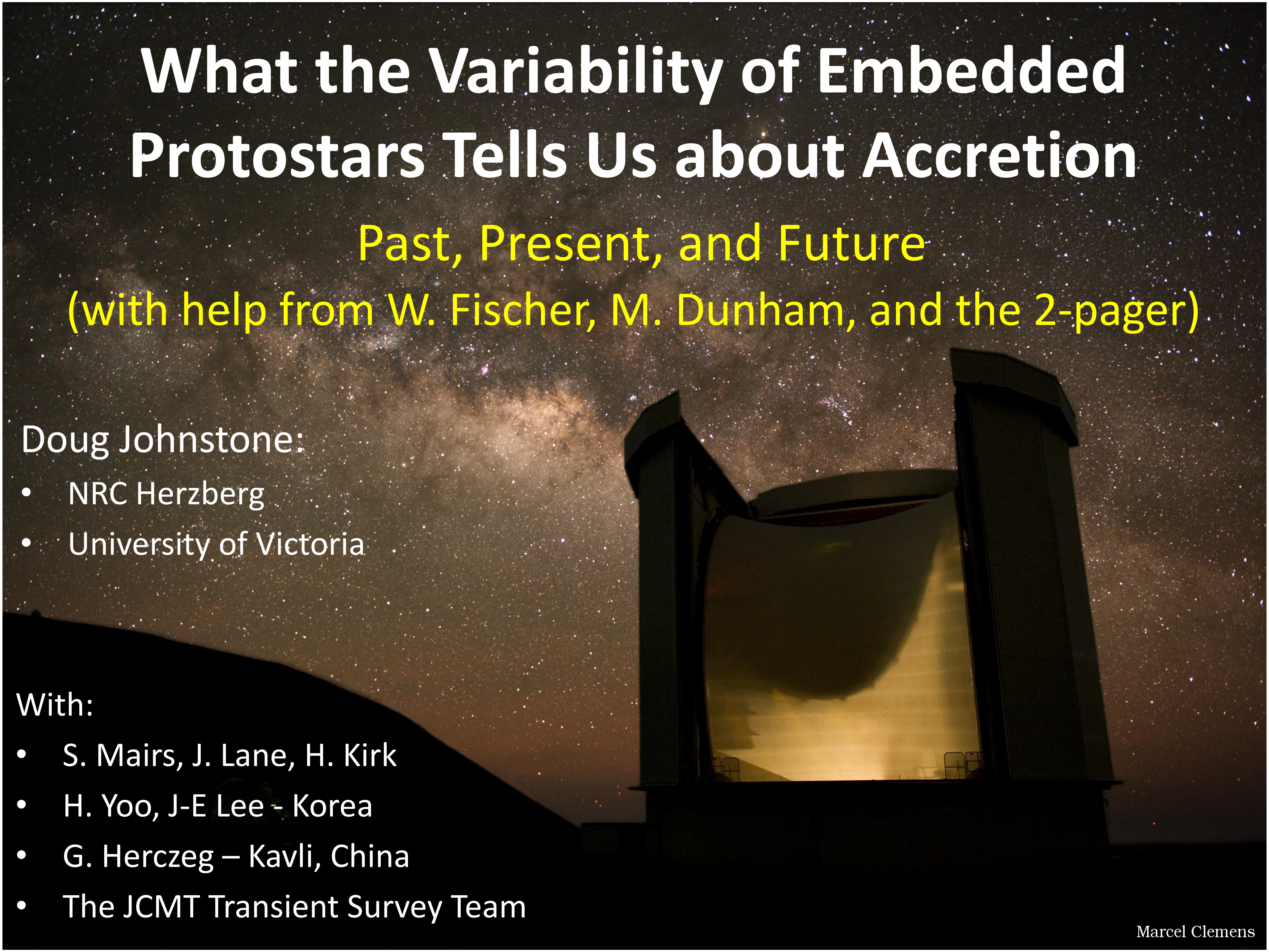


What the Variability of Embedded Protostars Tells Us about Accretion

Past, Present, and Future

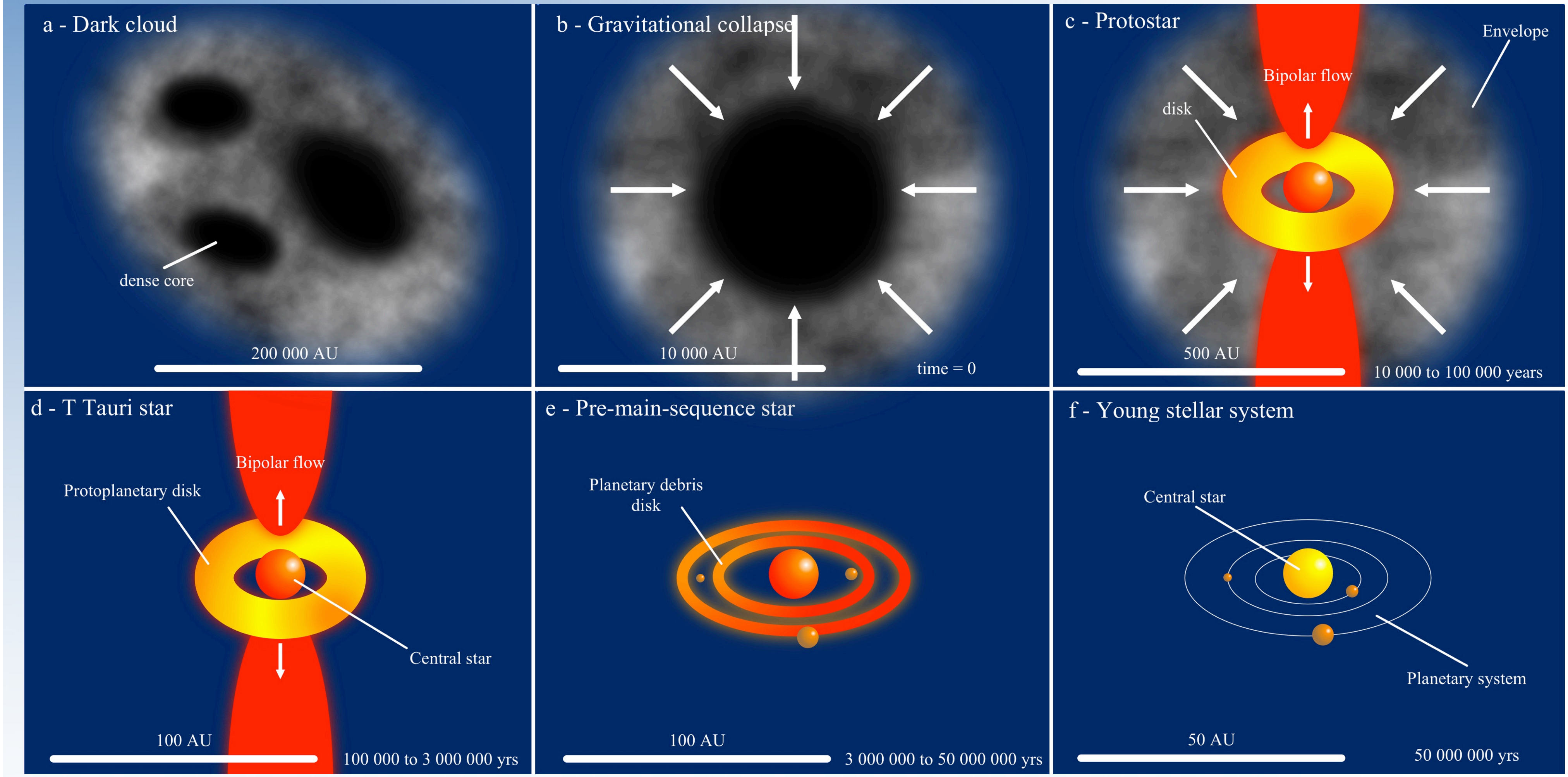
(with help from W. Fischer, M. Dunham, and the 2-pager)

Doug Johnstone:
- NRC Herzberg
- University of Victoria

With:
- S. Mairs, J. Lane, H. Kirk
- H. Yoo, J-E Lee - Korea
- G. Herczeg – Kavli, China
- The JCMT Transient Survey Team

Marcel Clemens

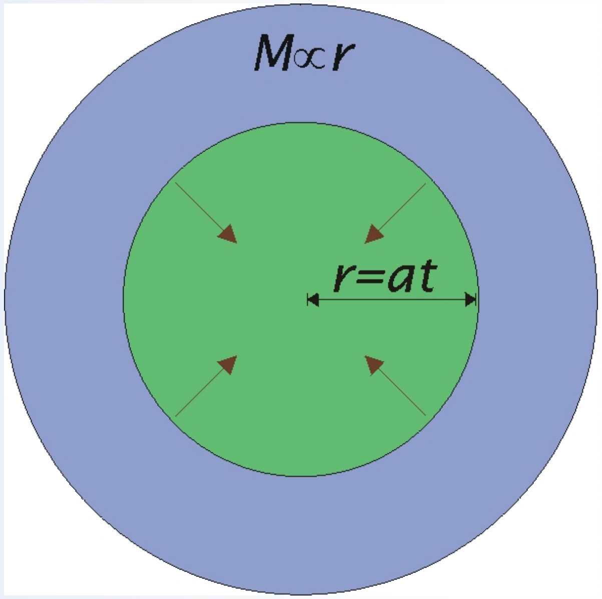
Formation of a star in one slide!



Key point for this talk: mass of star is assembled from cloud, through envelope and disk.

Accretion via Inside Out Collapse:

"Shu Model"



- Start with an isothermal sphere

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

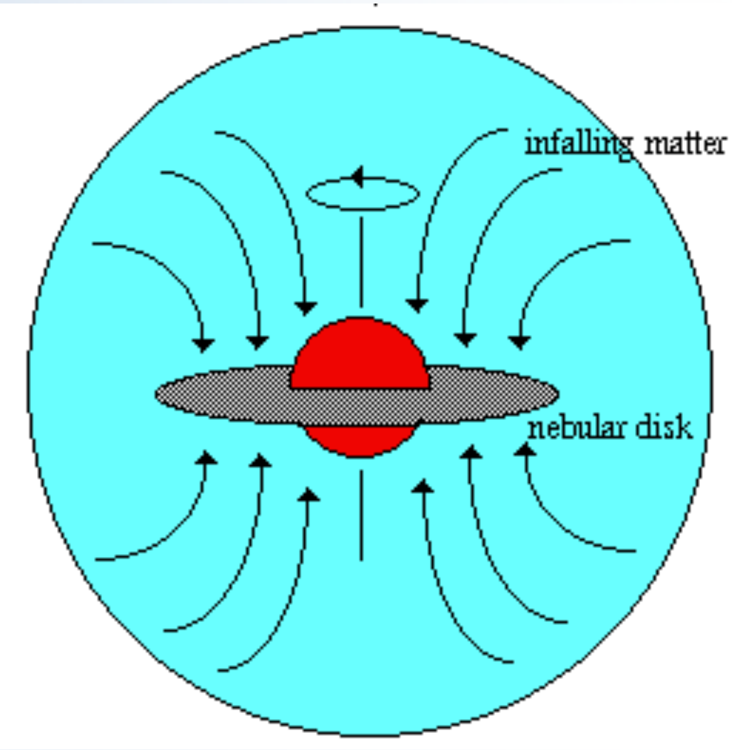
- Perturb the centre slightly
  - *Loss of pressure support yields collapse!*
- Rarefaction wave races out at sound speed

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

- 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):

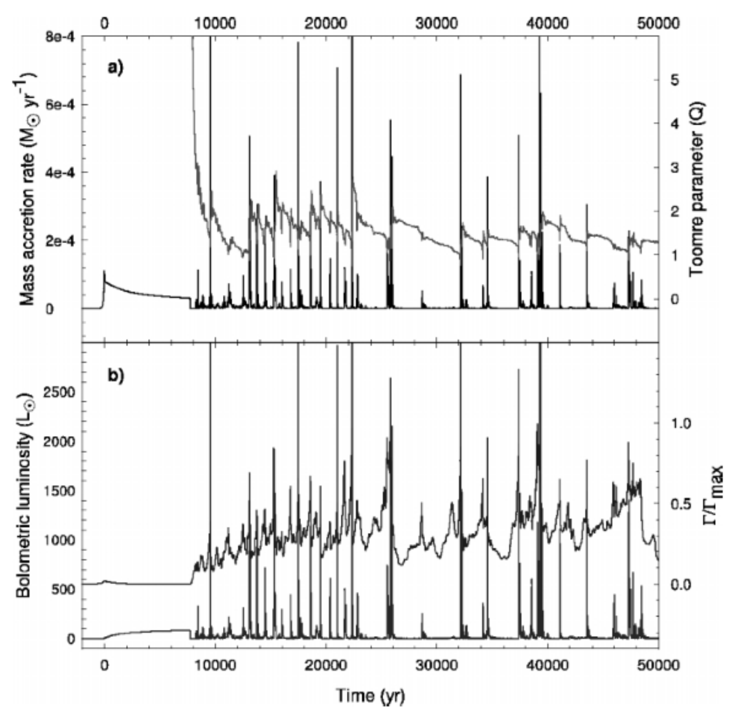
- Rotation (and B fields) break isotopic symmetry
  - Produces a flattened inner region (a disk)
- Mass flux that would have reached the protostar now *misses* and lands on disk
- No *a priori* reason why mass transport through disk = mass flux onto disk!
  - If disk transports *faster* – no disk build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

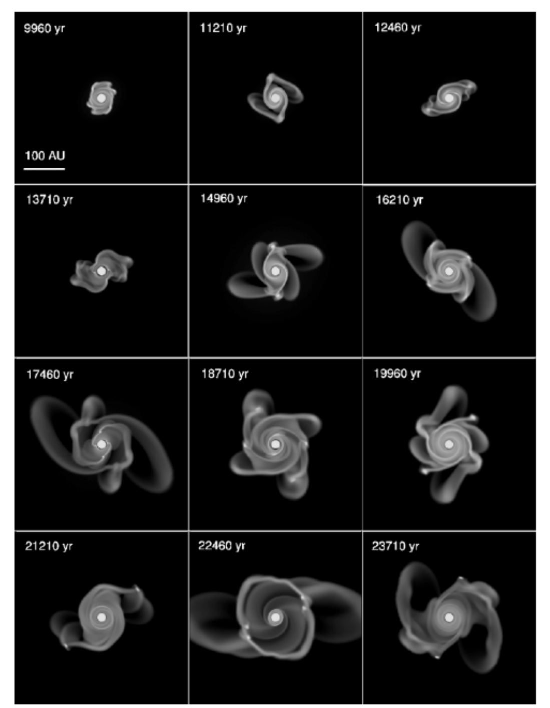


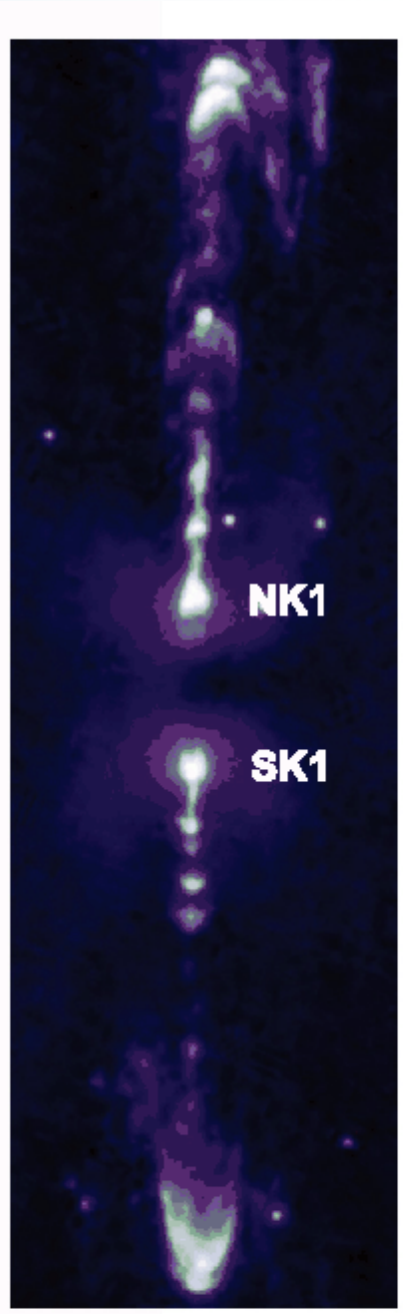
Note: mass transport through disk may even be radially dependent!

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 …





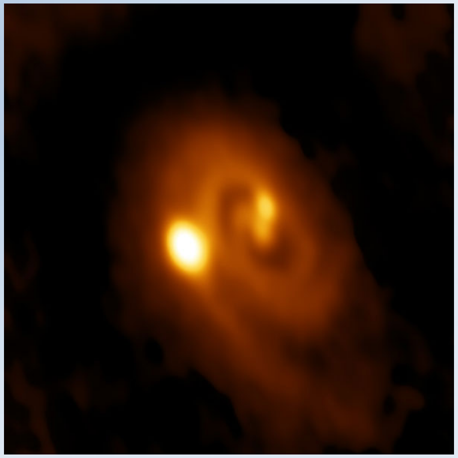


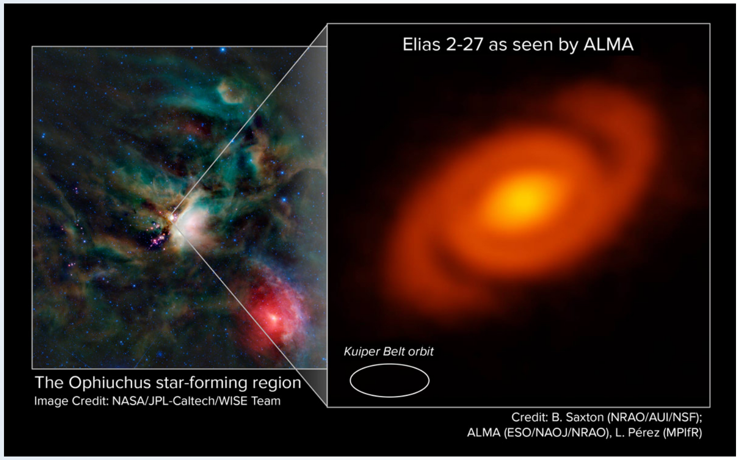
HH212

Vorobyov and Basu 2005, ApJ, 633, L137

Young Disk Observations (IR & mm):

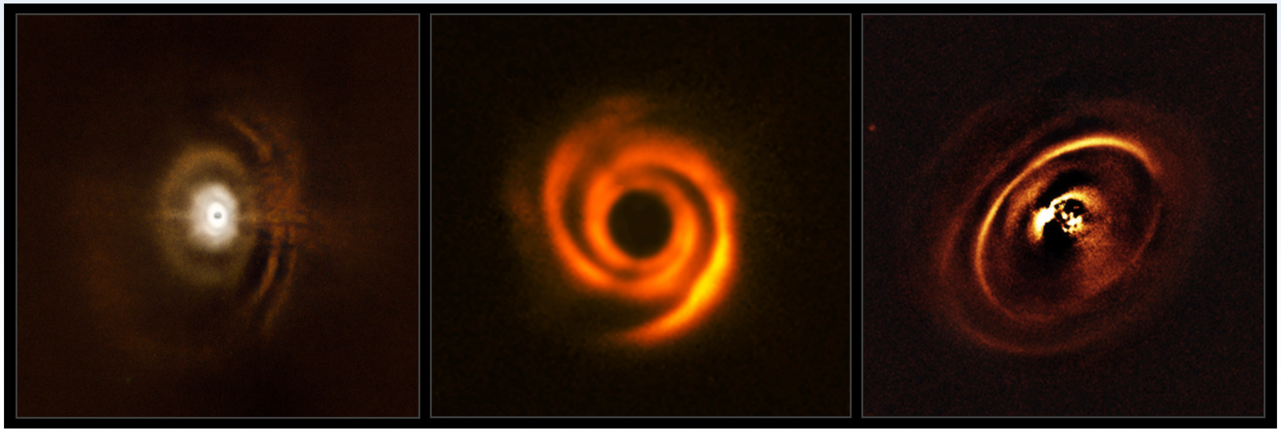
- Whether observed in *scattered light* (IR) or *dust emission* (mm) disks around young stars appear *structured*!
  (Spiral Driven Accretion: Bae et al. 2016, ApJ, Hennebelle et al. 2017 A&A)




Elias 2-27 as seen by ALMA

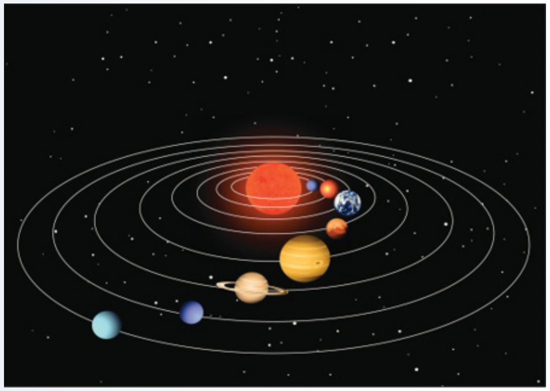
The Ophiuchus star-forming region
Image Credit: NASA/JPL-Caltech/WISE Team

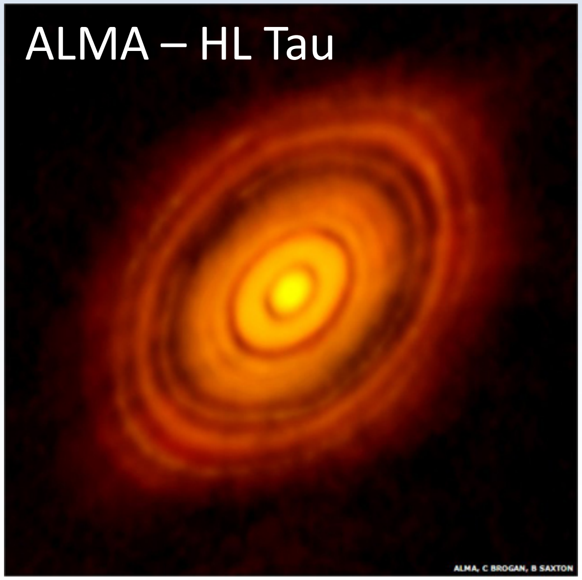
Credit: B. Saxton (NRAO/AUI/NSF);
ALMA (ESO/NAOJ/NRAO), L. Pérez (MPIfR)

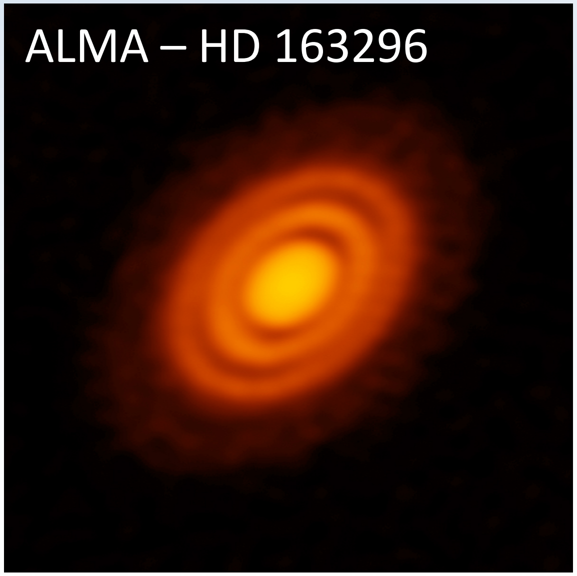


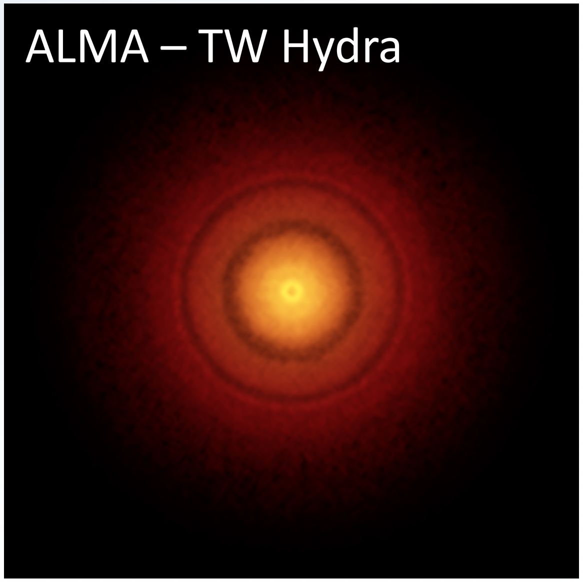
Young Disk Observations (IR & mm):

- 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?







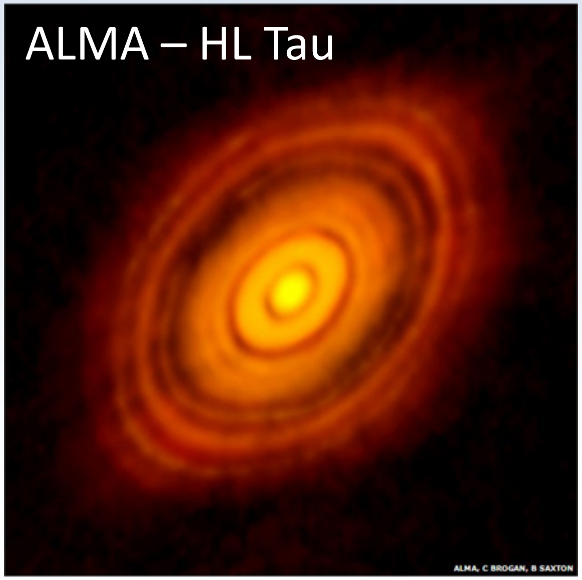


Young Disk Observations (IR & mm):

Gaps in disks may be due to sculpting by planets.

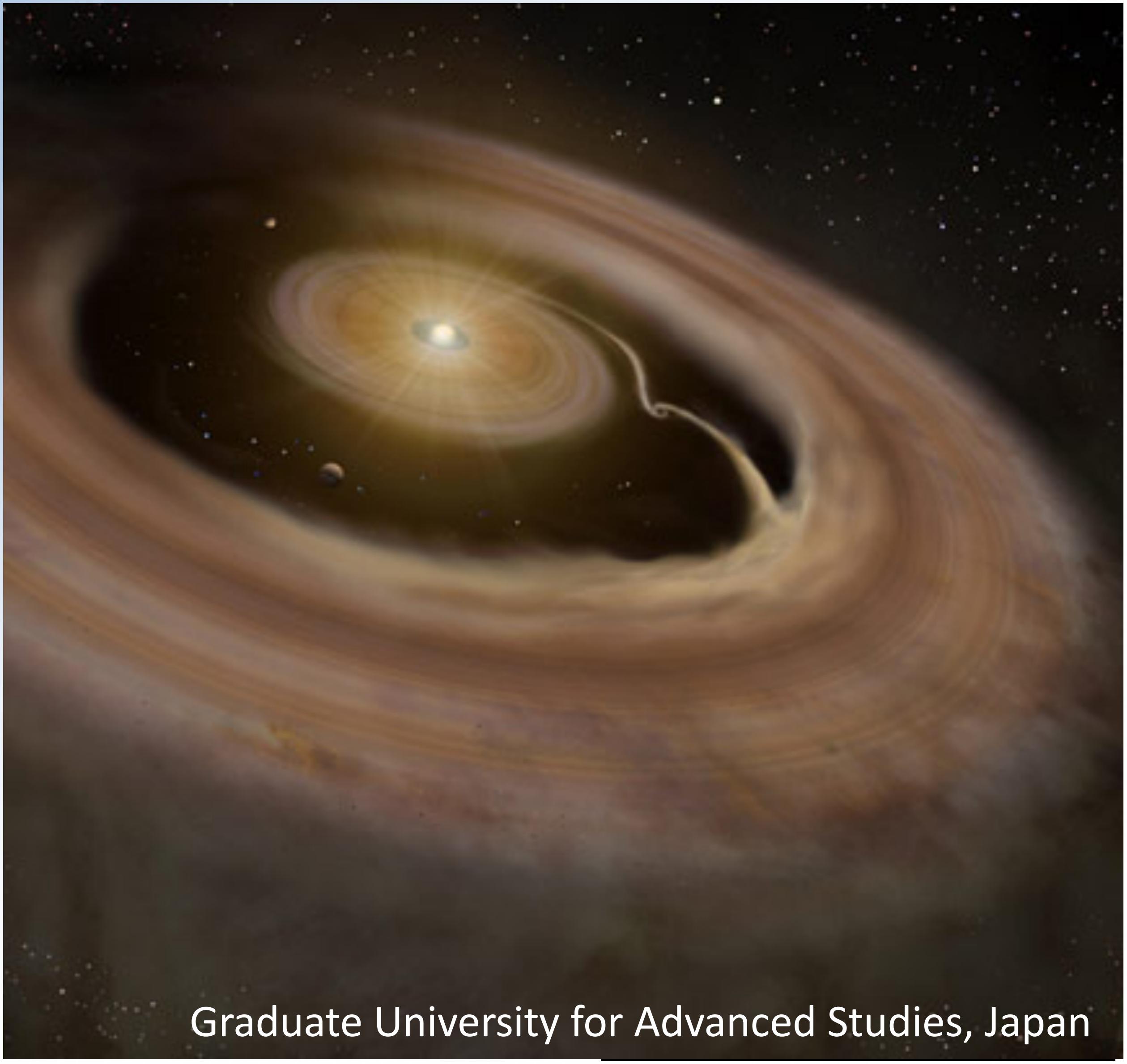
Accretion periodicity perhaps?

Very likely to be an unstable flow …



ALMA – HL Tau

ALMA, C BROGAN, B SAXTON



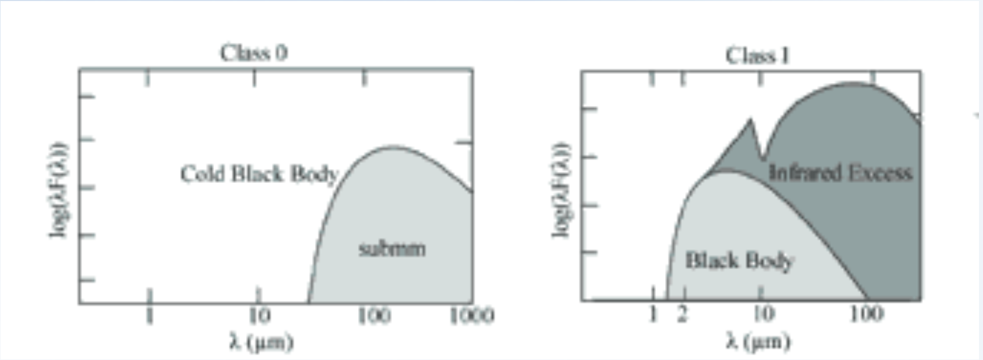
Graduate University for Advanced Studies, Japan

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

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

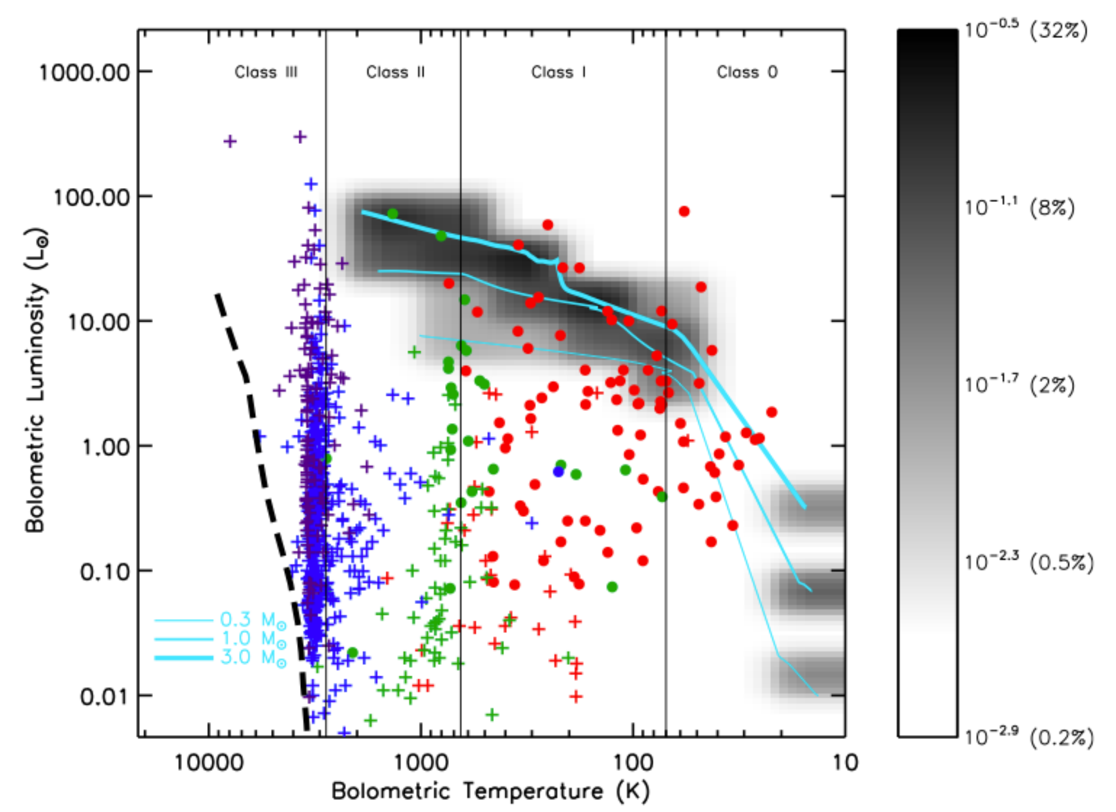
- This energy is absorbed by the envelope and re-radiated in the far IR through mm. Thus, the SED acts as a calorimeter for accretion.

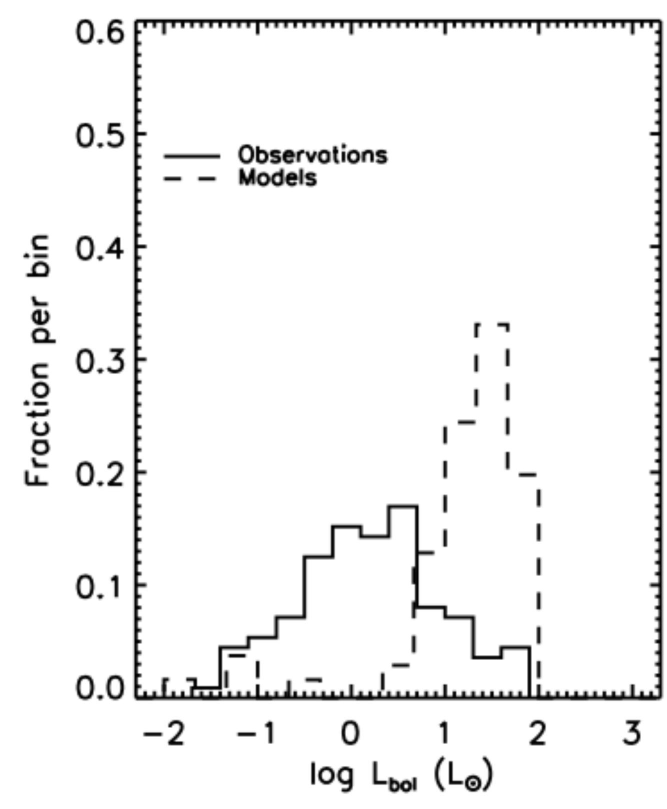


- Observations near the SED peak provide a proxy, allowing surveys such as a potential *OST Variability Survey* to search for accretion variability through brightness variations.

Spitzer: Mass Accretion Result

Confirms the well known Kenyon et al. (1990) 'luminosity problem'





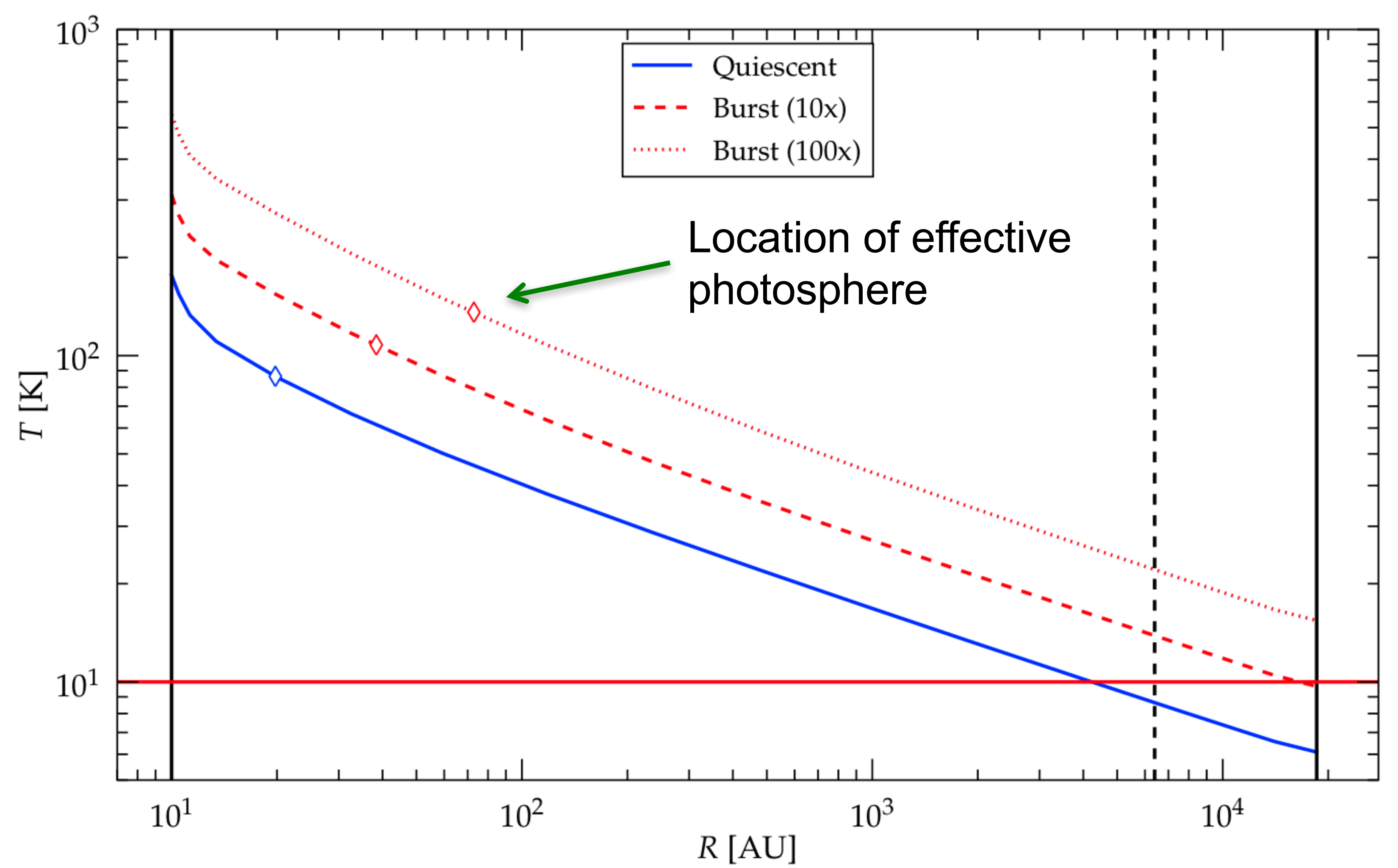
Dunham et al. 2010, ApJ, 710, 470

Protostellar Envelope Model: Deeply Embedded Phase

- Density structure follows inside-out collapse
  - M_{env} = 1.5 M_{sun}
  - R_{env} = $2x10^4$ AU
  - R_x = $6x10^3$ AU (transition from static to infall)
- Protostar mass ~ 0.25 M_{sun}
- 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

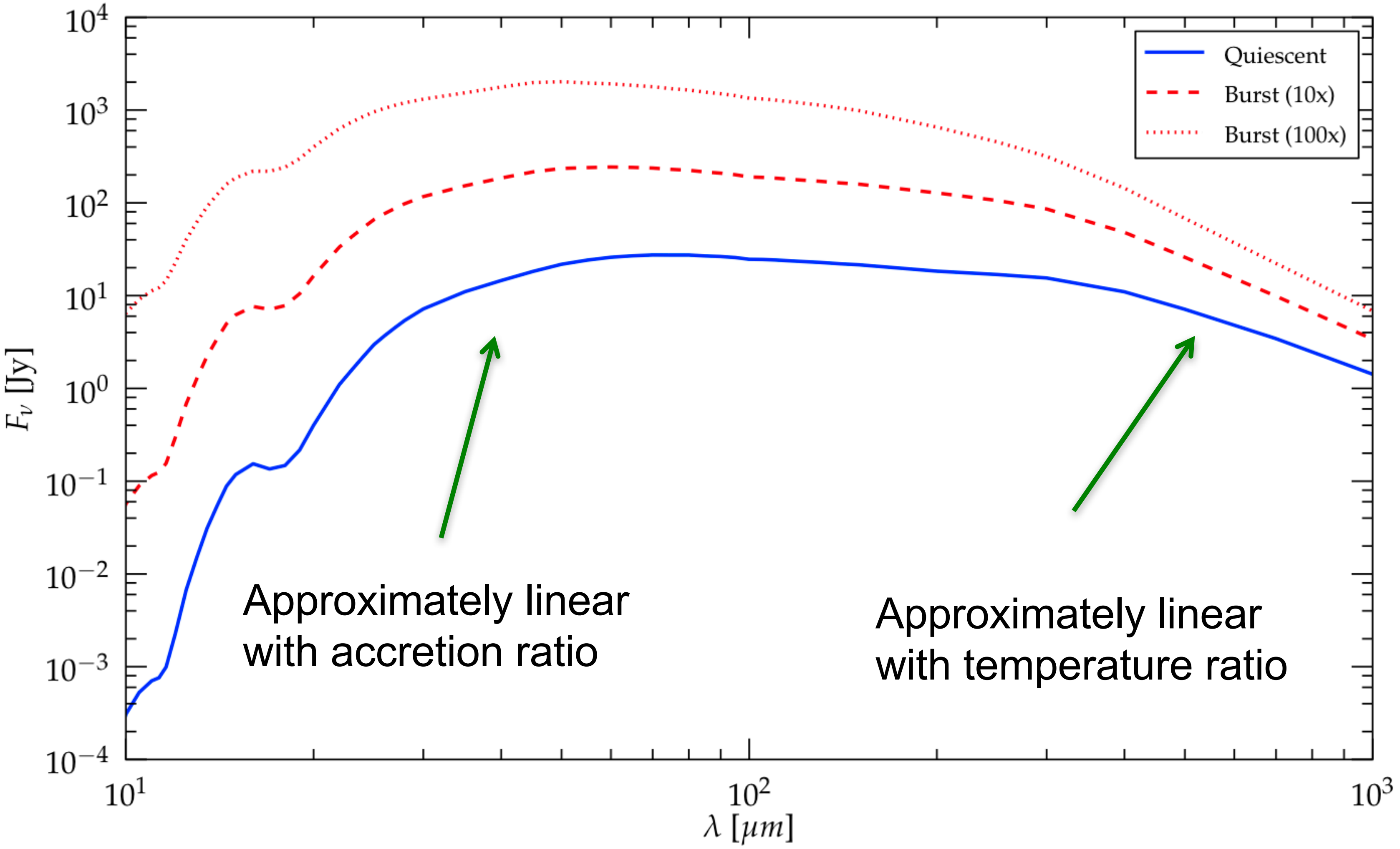


Location of effective photosphere

Johnstone et al. 2013, ApJ, 765, 133

Implications of Variable Accretion - II

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



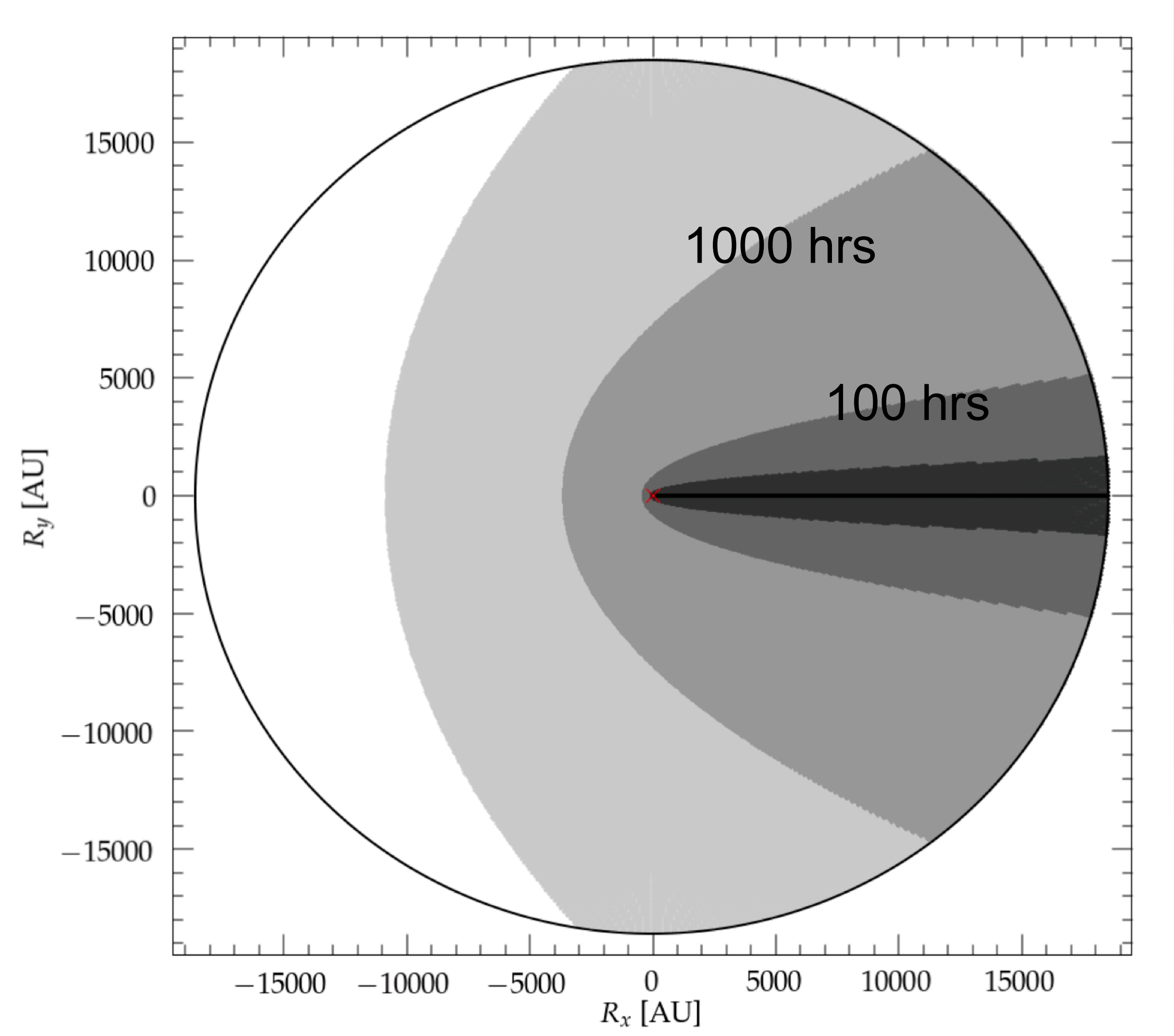
Approximately linear with accretion ratio

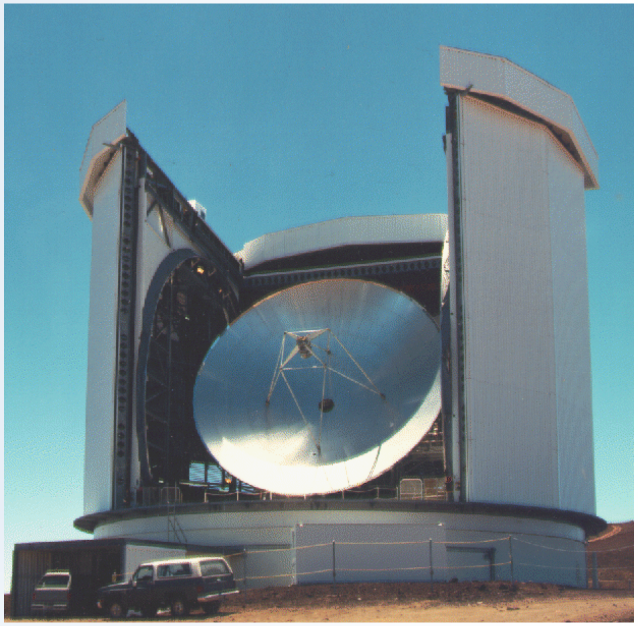
Approximately linear with temperature ratio

Johnstone et al. 2013, ApJ, 765, 133

Implications of Variable Accretion - IV

The light propagation time must be taken into account …



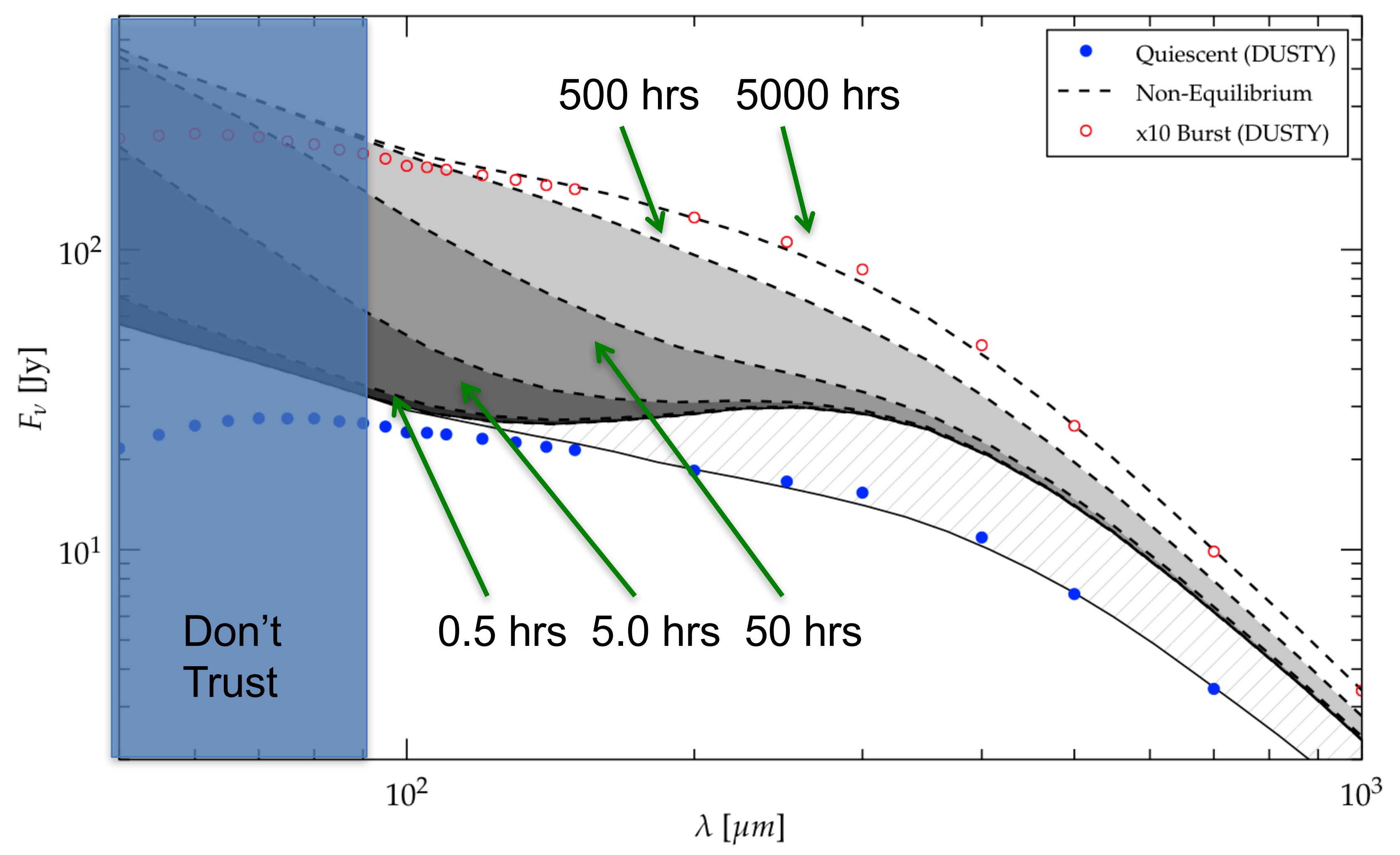


Crossing time of the effective photosphere (R_{ph} ~ 50 AU) is ~ 5 hrs

Johnstone et al. 2013, ApJ, 765, 133

Implications of Variable Accretion - V

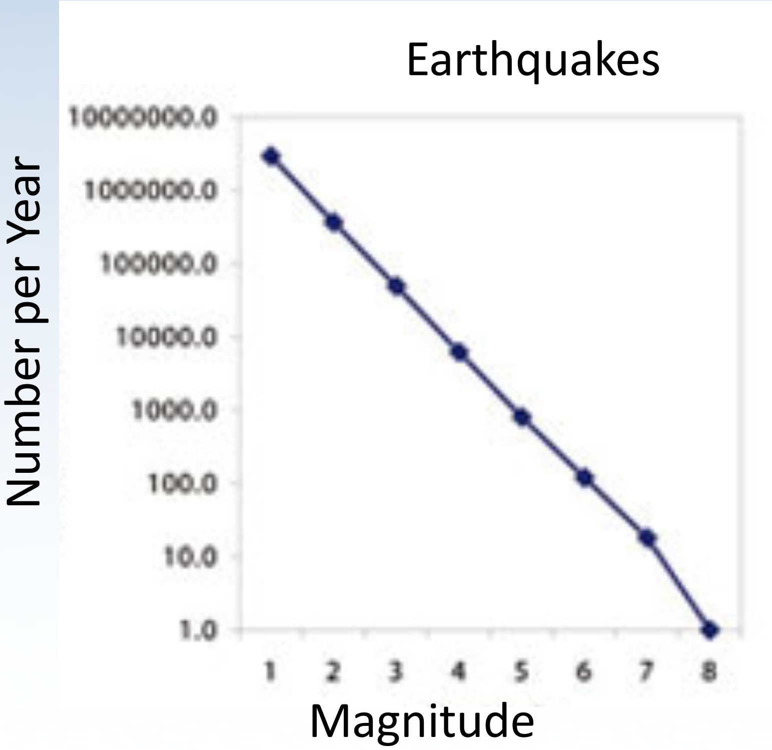
The observable timescale for variability can be assessed:

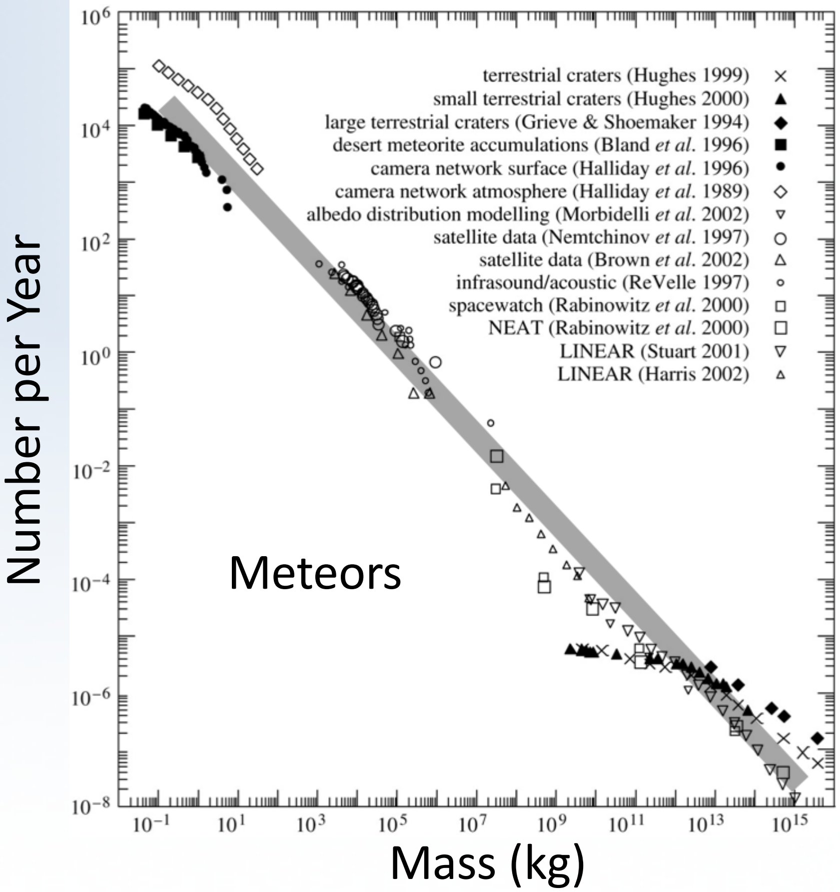


Johnstone et al. 2013, ApJ, 765, 133

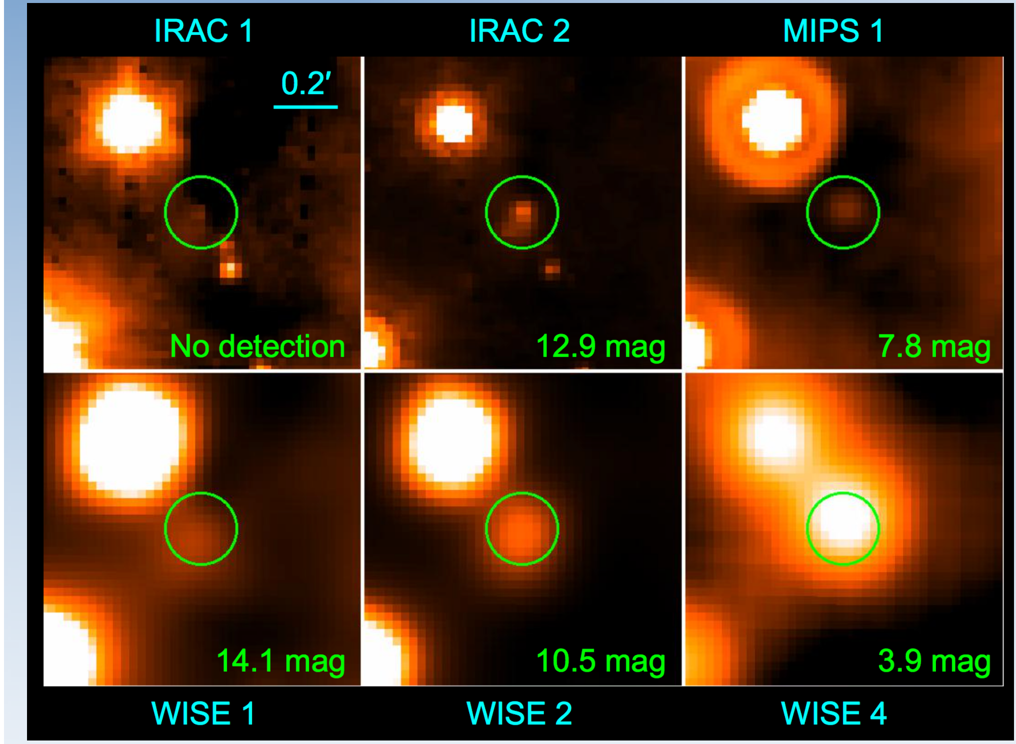
Aside: Variability and Accretion

- 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)?





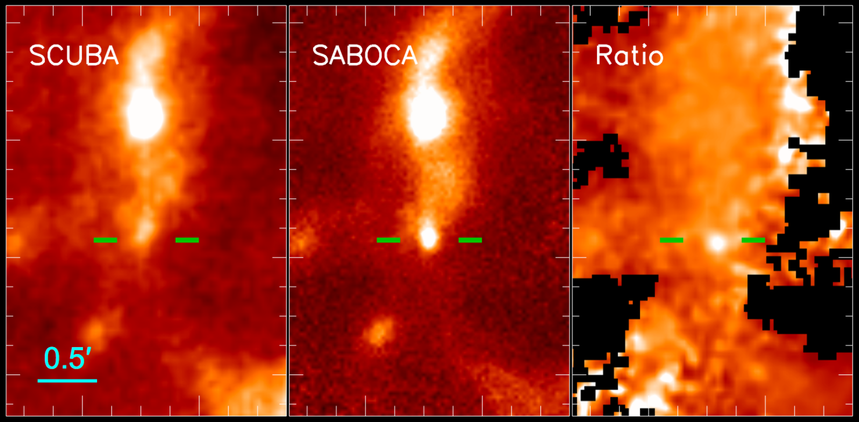
Spitzer/Wise Variability … (W. Fischer)



Spitzer vs *Wise* ~ 5-10 year delta

HOPS 383, for example

Submillimeter comparison rules out a change in extinction

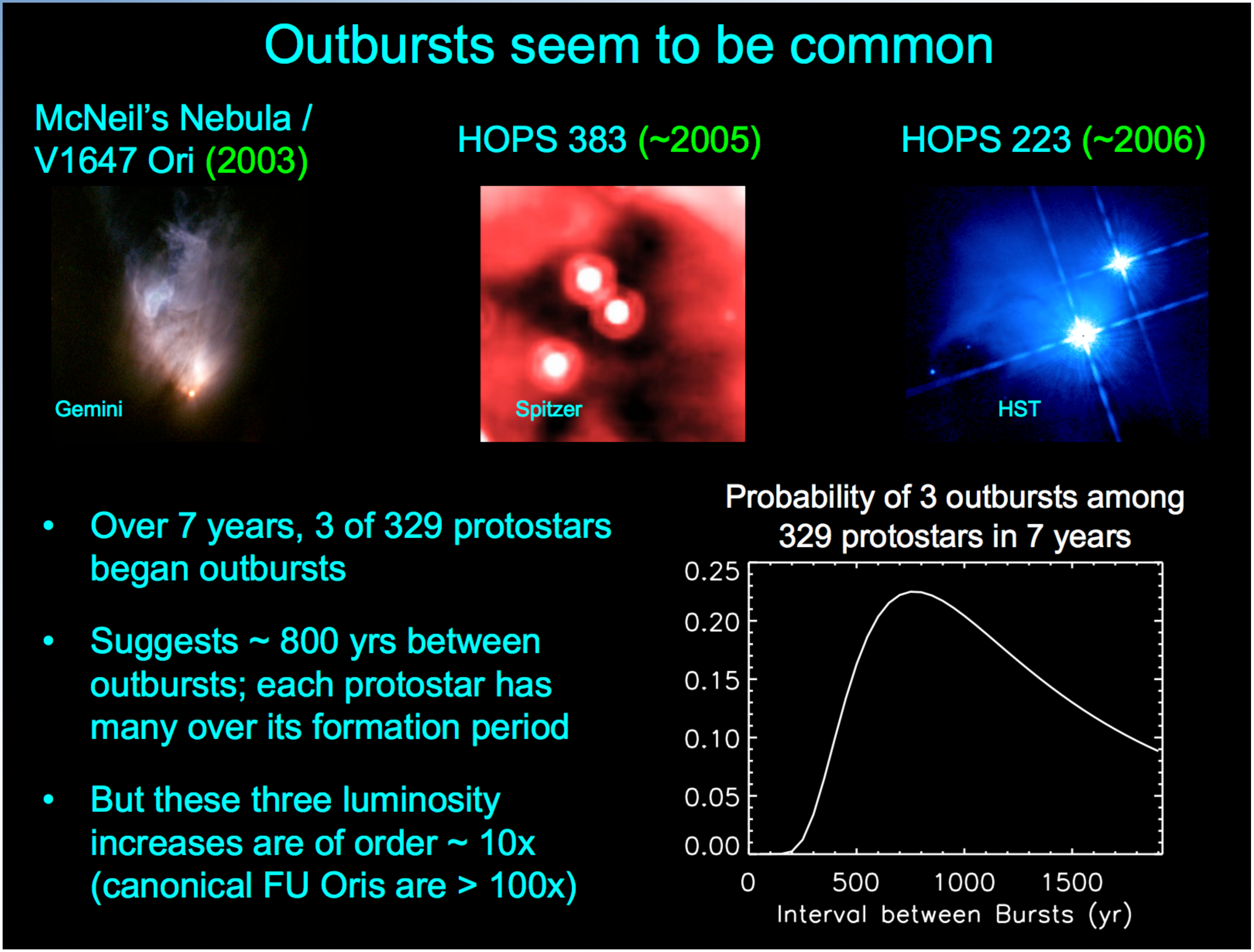


1998
(450 µm)

2011
(350 µm)

Brightness increase of ~ 2x

Spitzer/Wise Variability … (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

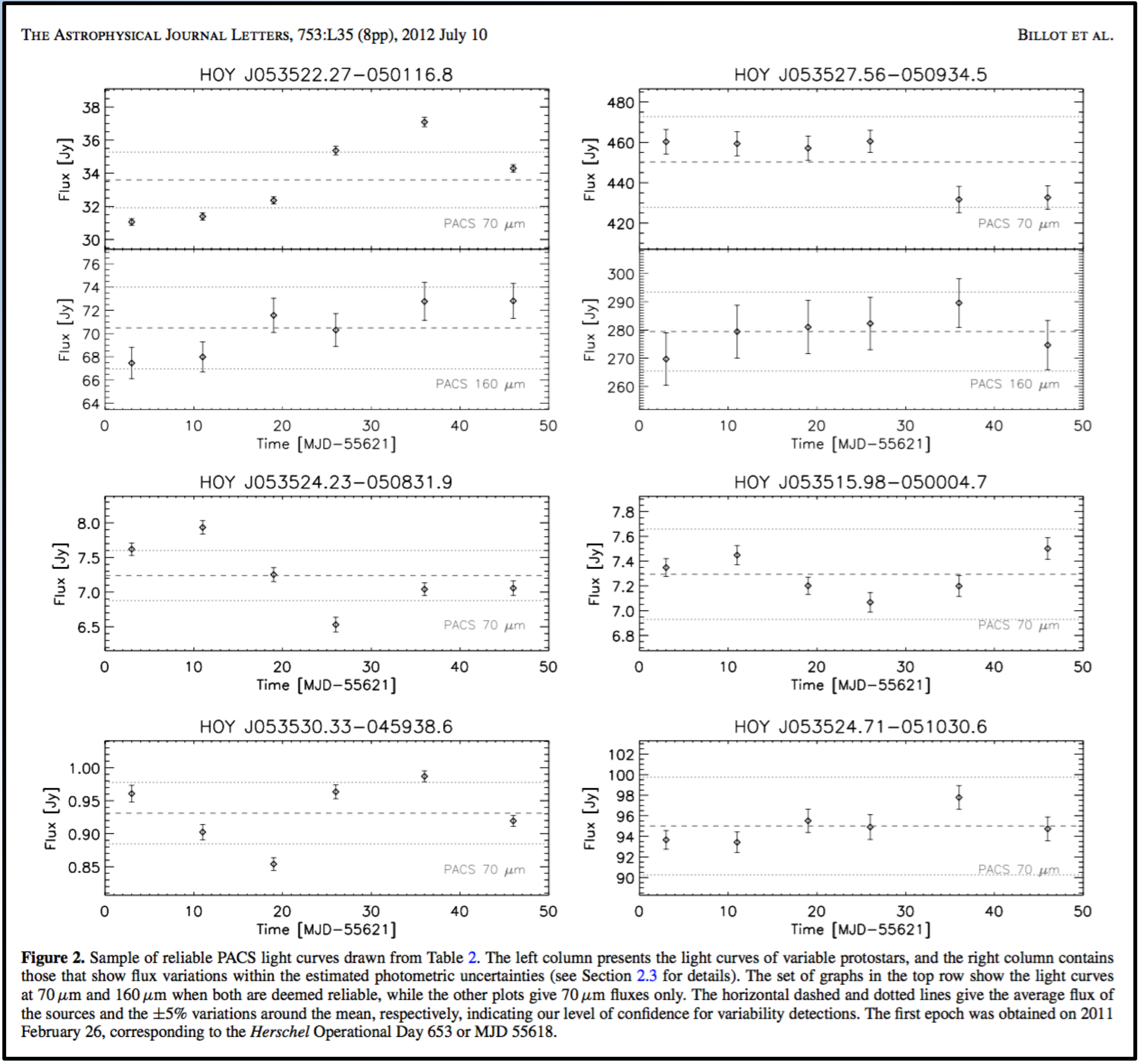
Herschel Variability … (Billot et al 2012)

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.

The First JCMT Protostellar Variable:

Serpens Main ~ 400pc

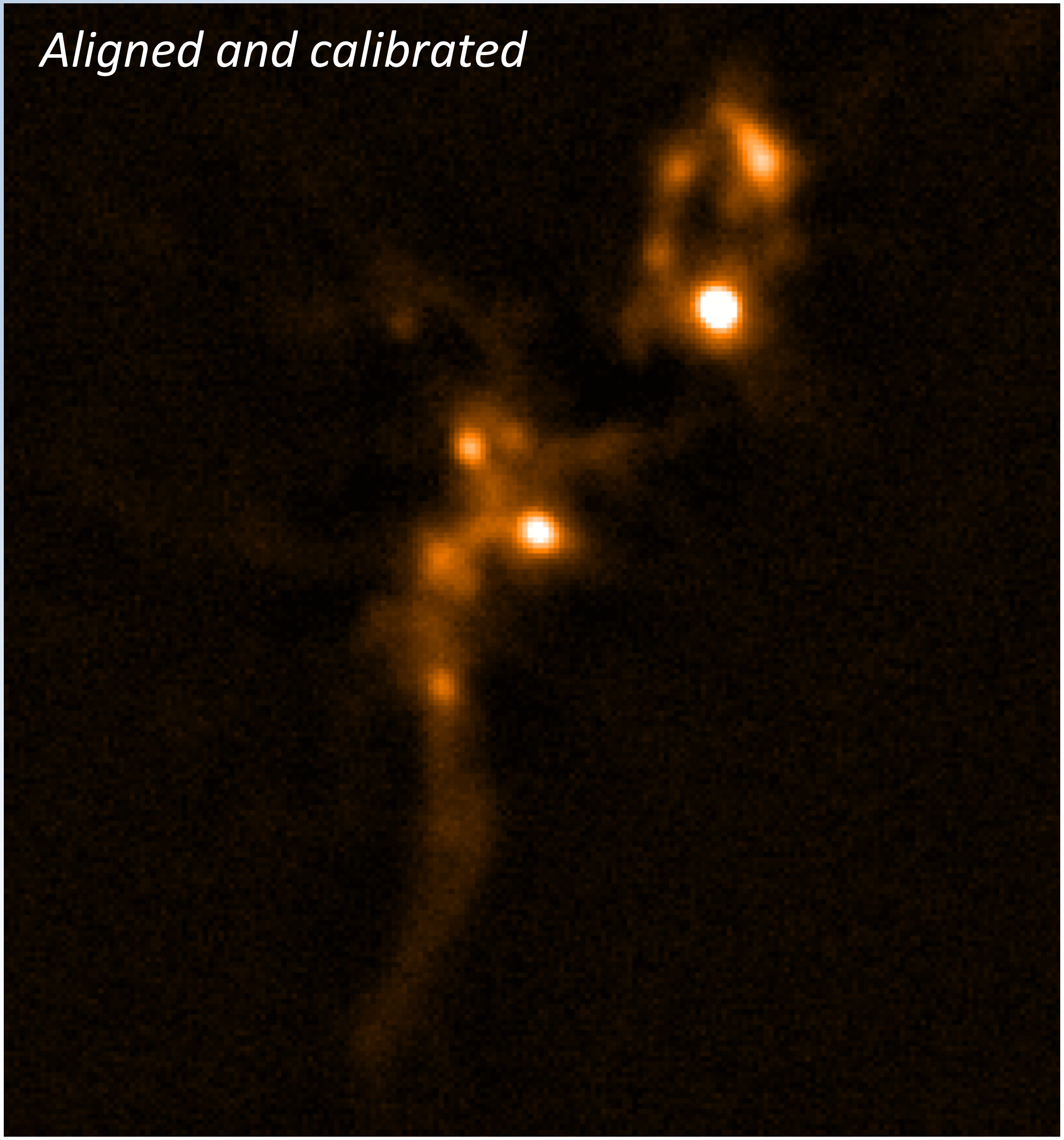
JCMT SCUBA-2 850 micron

30’ Pong (viewing central region)

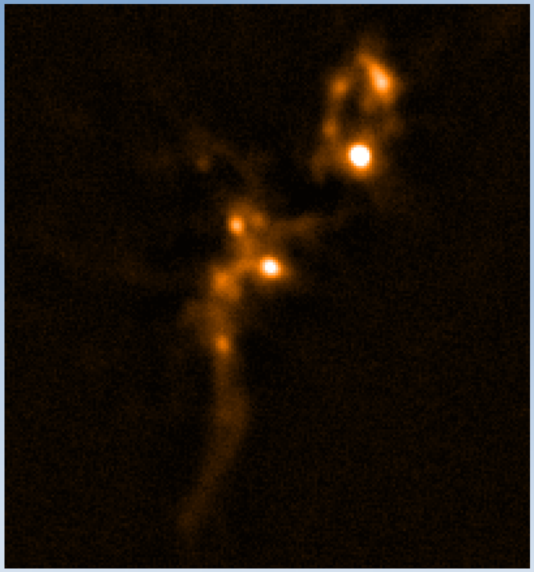
13 epochs ~ monthly cadence

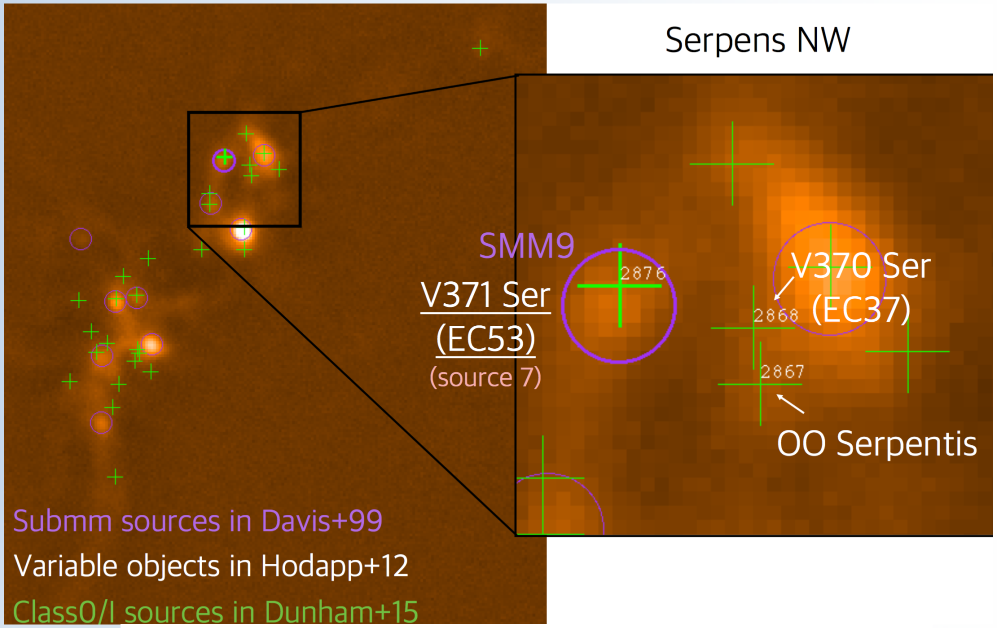
2016-February – 2017-April

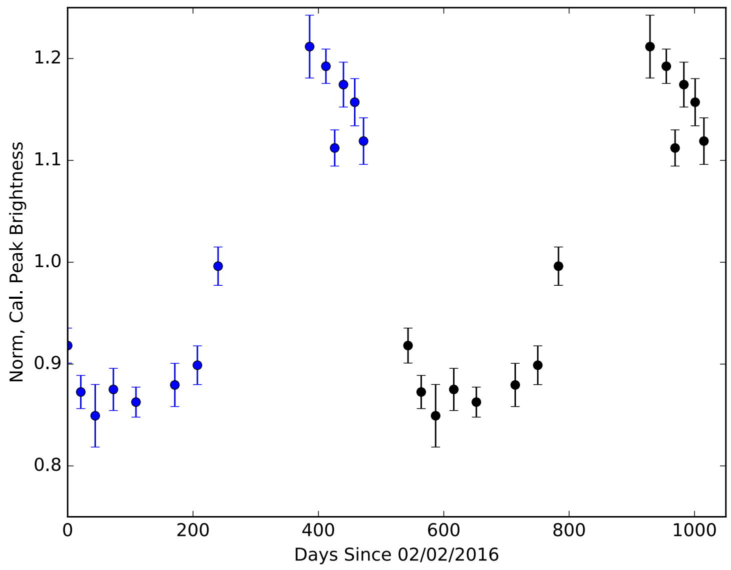
Careful Investigation by Korean graduate student Hyunju Yoo …



The First JCMT Protostellar Variable:







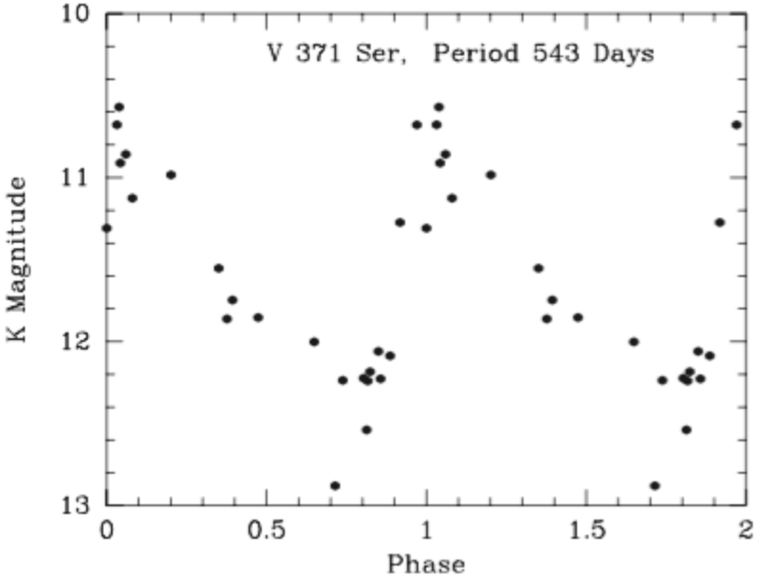


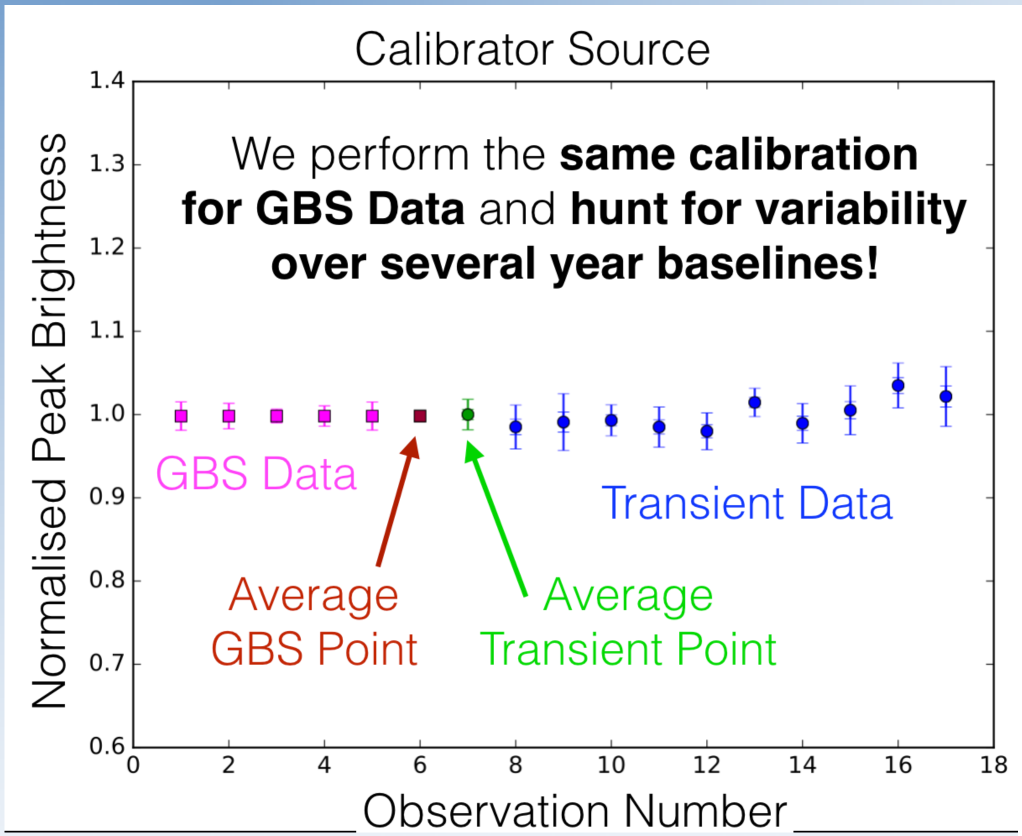
Figure 5. Phase diagram of the *K*-band variations of EC 53. The light curve shows a rapid rise and slower decline from the maximum.

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)

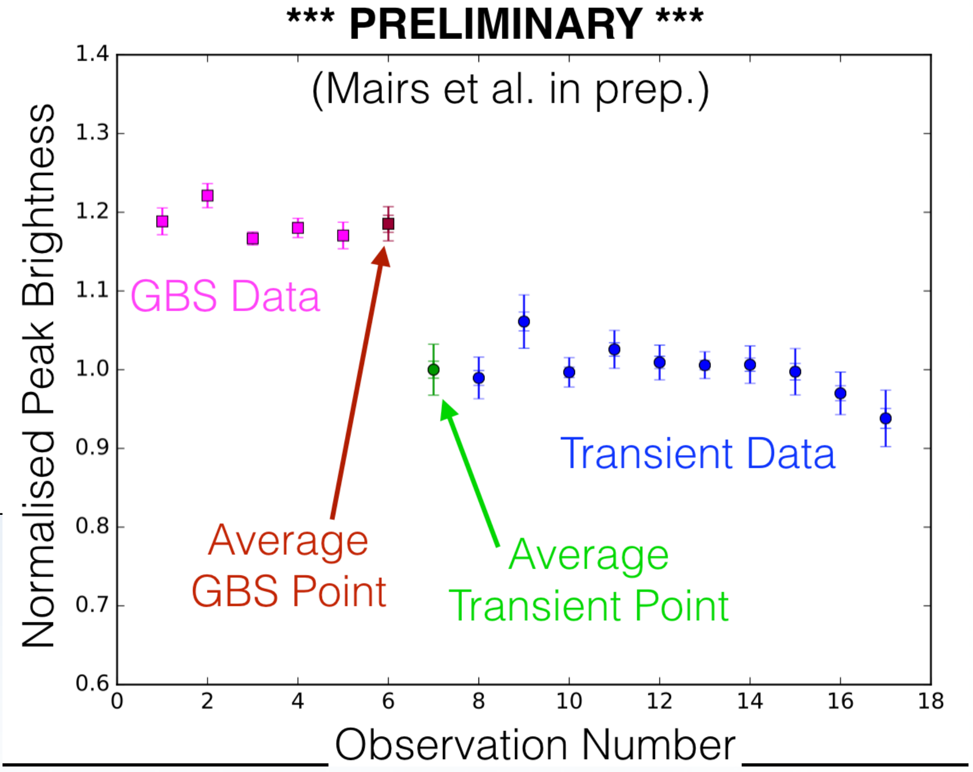
- Postulatation …
  - 18 month periodicity suggests disk irregularity at ~ 1 AU
  - Unseen inner companion star (Hodapp et al.) -> ejection of 92AU source?
    - *Or perhaps a planet in formation …*
  - We have observed for ~14 months with JCMT – awaiting full period
    - Planned monitoring at 2µm to determine lags and shape variations

JCMT Variation Over A Few Years …



We perform the **same calibration for GBS Data** and **hunt for variability over several year baselines!**

GBS Survey ~4yrs before Transient Survey



Bottom Line:

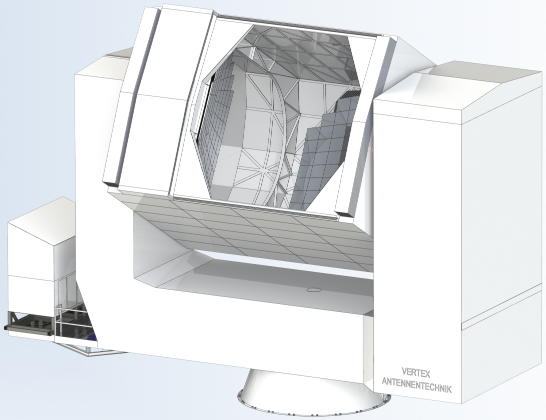
With the JCMT we are, so far, sensitive to less than 100 sources. So even these two detections, plus a few others that ‘look’ good, provides *a few percent return* at 850 microns.

What Requirements with OST …

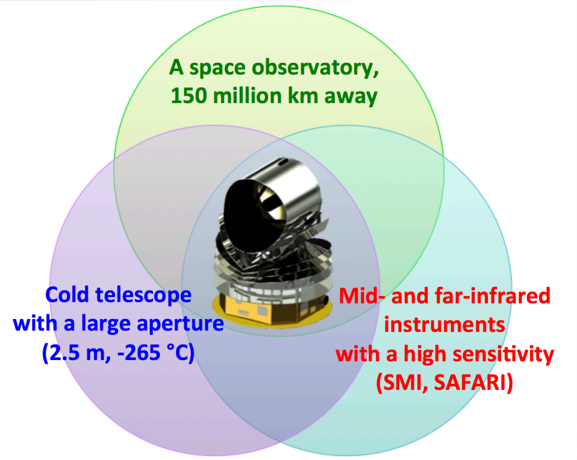
- Protostar Peak Brightness ranges from ~200 Jy to 0.02 Jy
  - 2 pager suggest 10% calibration – I'd argue for ~1% (e.g. 200 μJy noise)
  - To capture bright and faint sources requires a dynamic range ~ 10^6
  - Prefer to capture as broad a wavelength range as possible
    - 50 – 300 micron would be ideal (MRSS perhaps)
- Statistics for FU Ori's suggest ~1000 to 10^4 protostars (out to 1 kpc)
  - 2 pager suggest need to observer about 60 sq. degree
  - Scaling from Matt's MRSS Galaxy survey case suggests ~60 hrs (per epoch)
  - With 1% calibration, I anticipate we will see variations in ~10% of sources
- Cadence of once a year (nominal) or perhaps every few months
  - Yearly will provide enough epochs to spot variations and calculate calibration statistics but bi-monthly will provide evidence of short term periodicity
  - For 5 year mission 5 epochs (300 hrs) to 30 epochs (1800 hrs)
    - Could do smaller, rich fields bi-monthly and larger sample yearly
- Mid- to Far-IR spectra (MRSS) could be helpful diagnostic too

Other Opportunities In Next Decades?

- JCMT Transient – Steve Mairs (PhD) James Lane (u.grad)
  - Continues for another 2 yrs (at least)
- ALMA Monitoring/Serendipity – Logan Francis (Masters)
  - ALMA Cycle 5 proposal to resolve inner part of EC 53 during quiescence and burst
  - Archival comparison of sources over time
- CCAT-P
  - Higher sensitivity, larger field of view, higher frequency observations possible



- Far IR Space Telescopes (SPICA/ORIGINS)
  - The future of well calibrated temporal studies of protostars

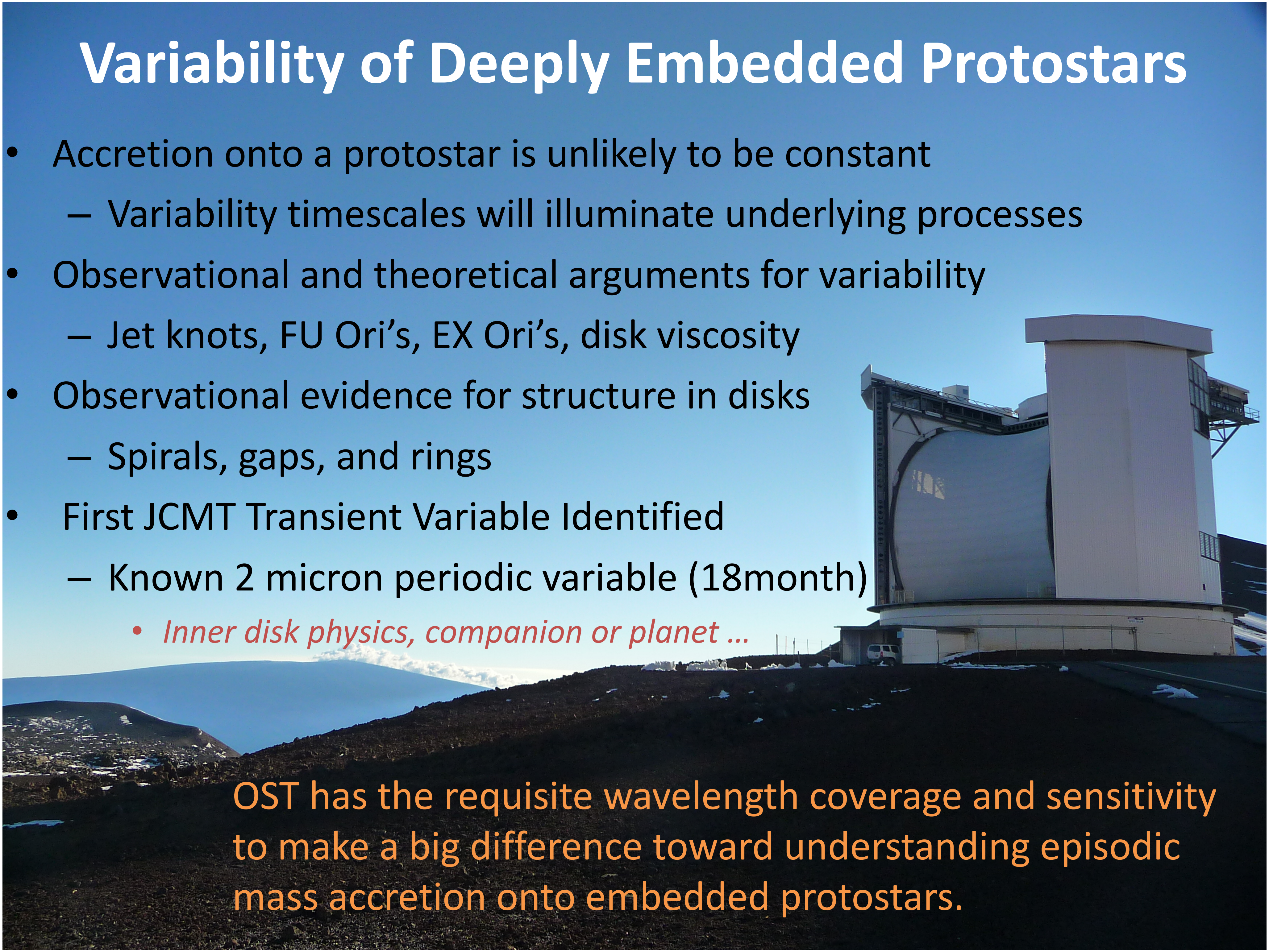


A space observatory,
150 million km away

Cold telescope
with a large aperture
(2.5 m, -265 °C)

Mid- and far-infrared
instruments
with a high sensitivity
(SMI, SAFARI)

Variability of Deeply Embedded Protostars



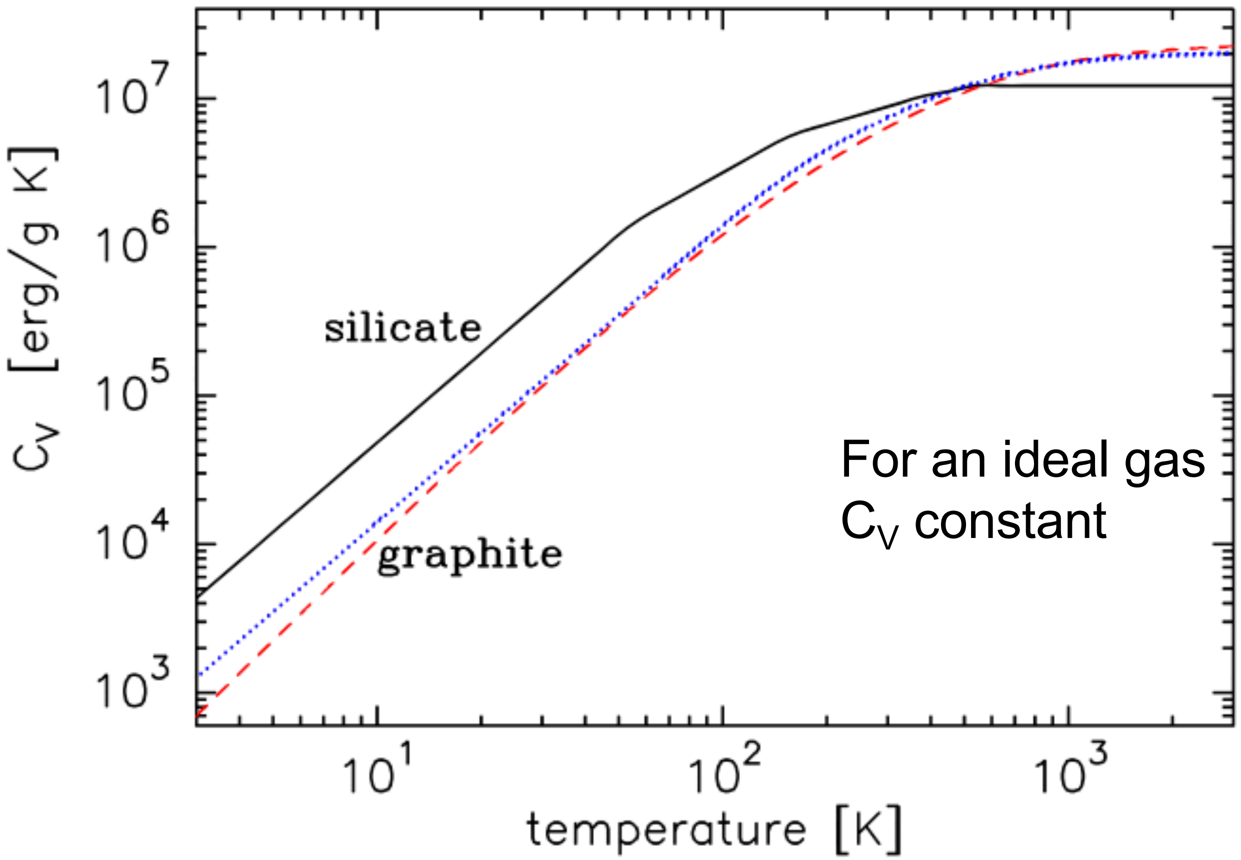
- Accretion onto a protostar is unlikely to be constant
  - Variability timescales will illuminate underlying processes
- Observational and theoretical arguments for variability
  - Jet knots, FU Ori’s, EX Ori’s, disk viscosity
- Observational evidence for structure in disks
  - Spirals, gaps, and rings
- First JCMT Transient Variable Identified
  - Known 2 micron periodic variable (18month)
    - *Inner disk physics, companion or planet …*

OST has the requisite wavelength coverage and sensitivity to make a big difference toward understanding episodic mass accretion onto embedded protostars.

Fin

Implications of Variable Accretion - III

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



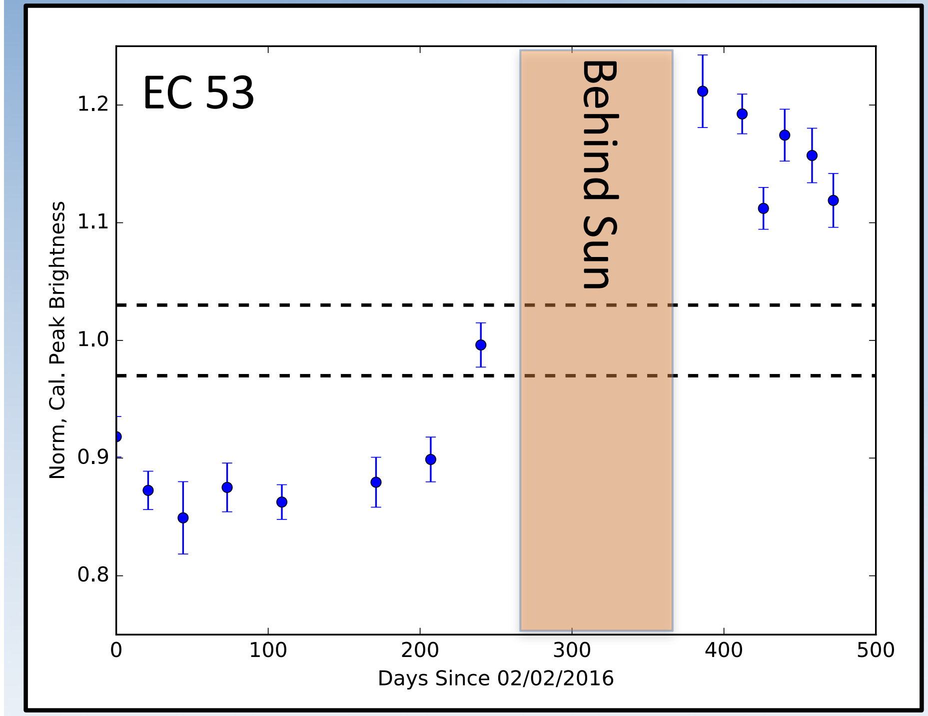
For an ideal gas
C_V constant

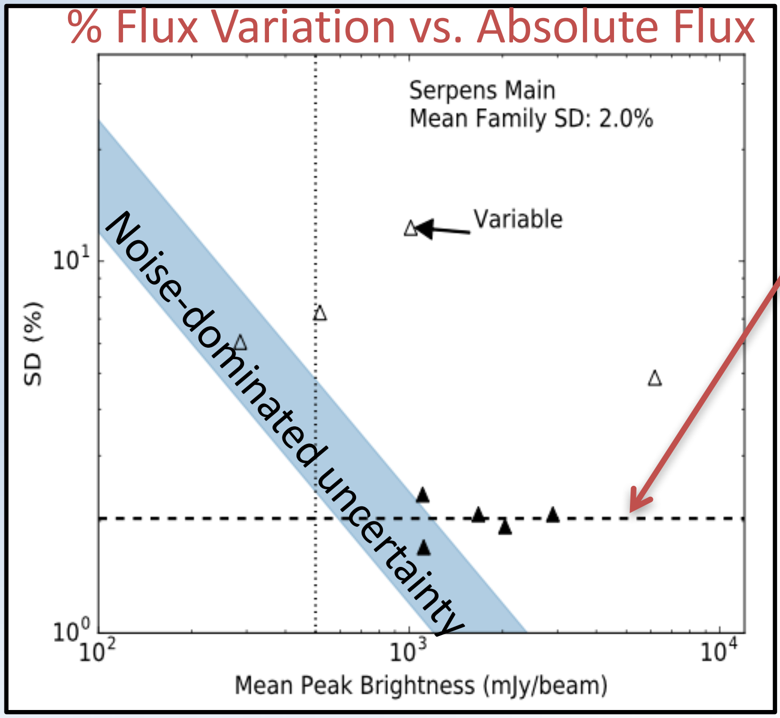
Figure 8.9. The specific heat per gram of dust for silicate (full curve, similar to [Guh89]), graphite (broken curve, after [Cha85]) and PAHs without hydrogen atoms (dotted curve, after [Kru53] using (8.44)).

Guhathakurta & Draine 1989, ApJ, 345, 230

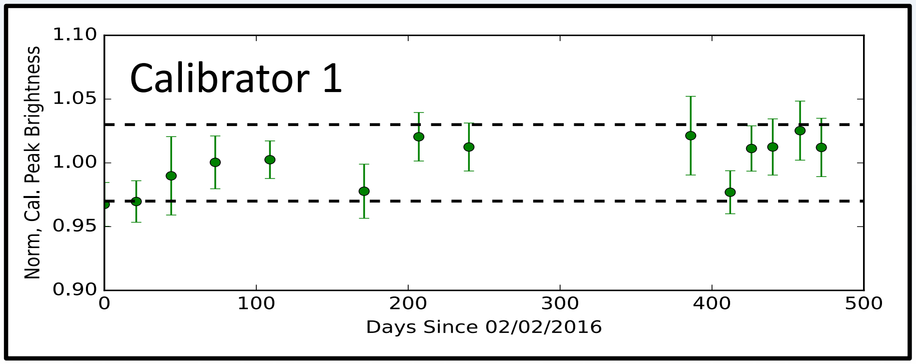
The first JCMT Protostellar Variable:

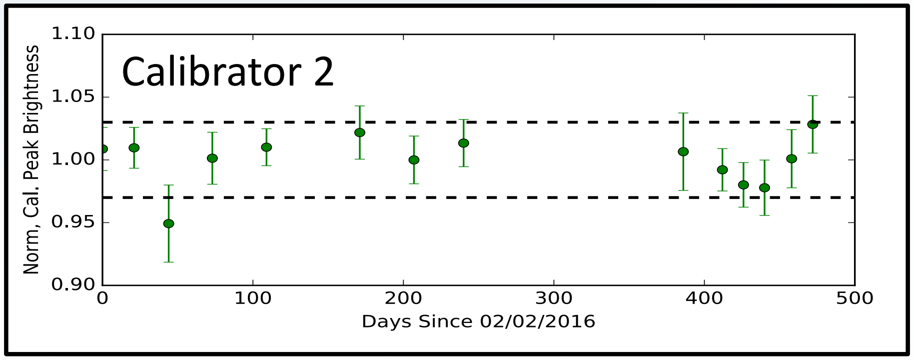
Light curves – 850 microns – Calibrated Images (see Steve's Talk)




% Flux Variation vs. Absolute Flux

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





Implications of Variable Accretion - V

1. A stepwise change in accretion luminosity will be smeared out
    - Within envelope's effective photosphere – hard to detect variation
        - Photons don't freely escape – high optical depth
        - Sets minimum timescale for process R_{ph} ~ 50 AU -> t_{ph} ~ 5hrs
        - Sets peak wavelength for source SED -> T_{ph} ~ 100 K
    - Emission at longer wavelengths dominated by larger, colder envelope
        - Takes ever longer to heat the enormous envelope
        - Sets maximum timescale R_{env} ~ 10^4 AU -> t_{env} ~ 10,000 hrs
2. Observations of variability should be able to constrain theory
    - Identify the underlying timescales for accretion changes
        - Periodic?, Episodic?, Stochastic?, Structured chaos?
    - Probe variations in amplitude of mass accretion with timescales?
3. Possibility to open up a new branch of star formation studies