What the Variability of Embedded Protostars Tells Us about Accretion

Past, Present, and Future

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Korea: J-E Lee, Y-H Lee, W. Park, S. Lee ++++ China: G Herczeg

Japan: Y. Aikawa, S.-I. Inutsoka, S. Takahashi Taiwan: S-Y Liu, H. Shang, Y-T Yang.

Canada: H Kirk, S Mairs, L Francis, C Broughton, S Plovie, K Douglas, J Lane

Marcel Clemens

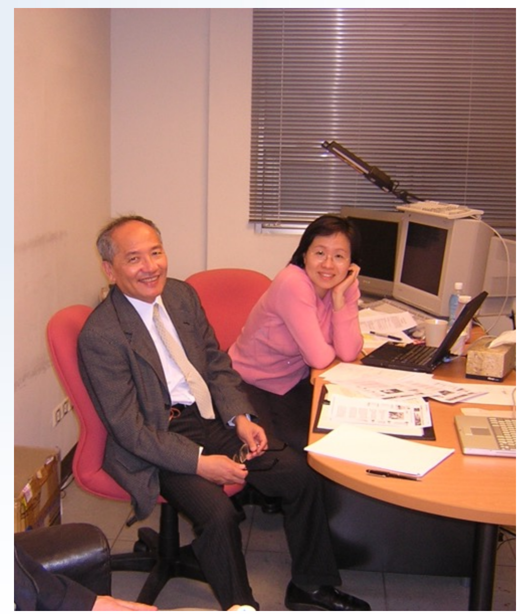
This Talk: In Memory of *Frank Shu*

1995 – My First Visit to Taiwan

1995 – I graduate from Berkeley

Things that remind me of my mentor

Many Taiwan visits since …



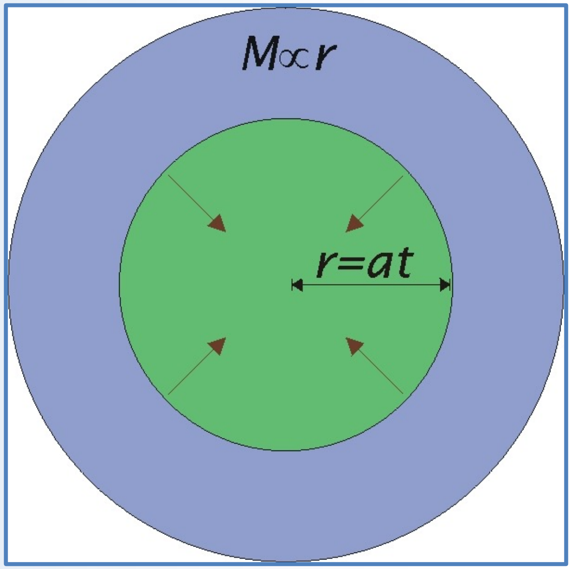
Accretion via Inside-Out Collapse

The Shu Model

- Start with an isothermal sphere

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

  – *Loss of pressure support yields collapse!*



- Rarefaction wave races out at sound speed

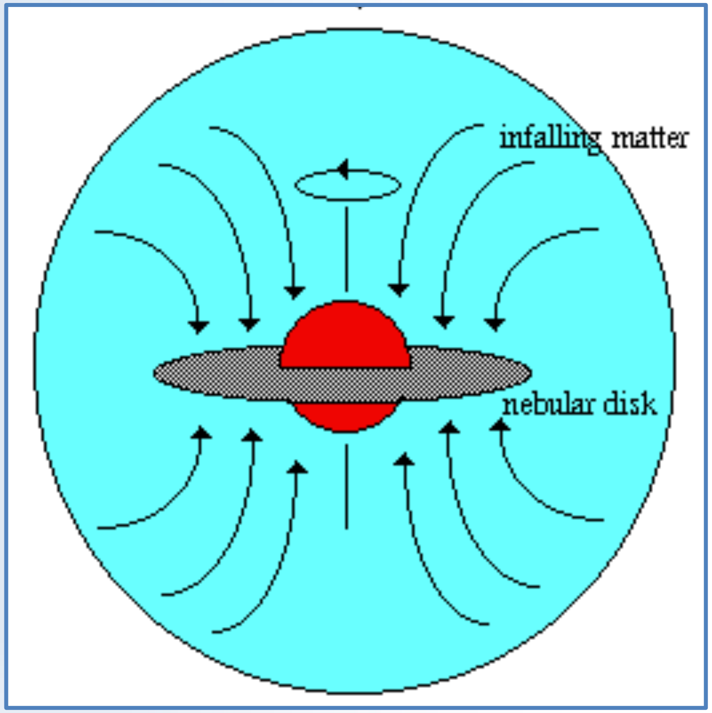
$$\frac{dM}{dt} = 4\pi a \rho r^2 = \frac{2a^3}{G}$$

  – *Half of this mass flux is accreted onto the central protostar while half is added to the in-falling envelope*

– *Steady-state gravity-fed protostellar accretion ~ a^3/G*

Importance of Rotation (or B fields)

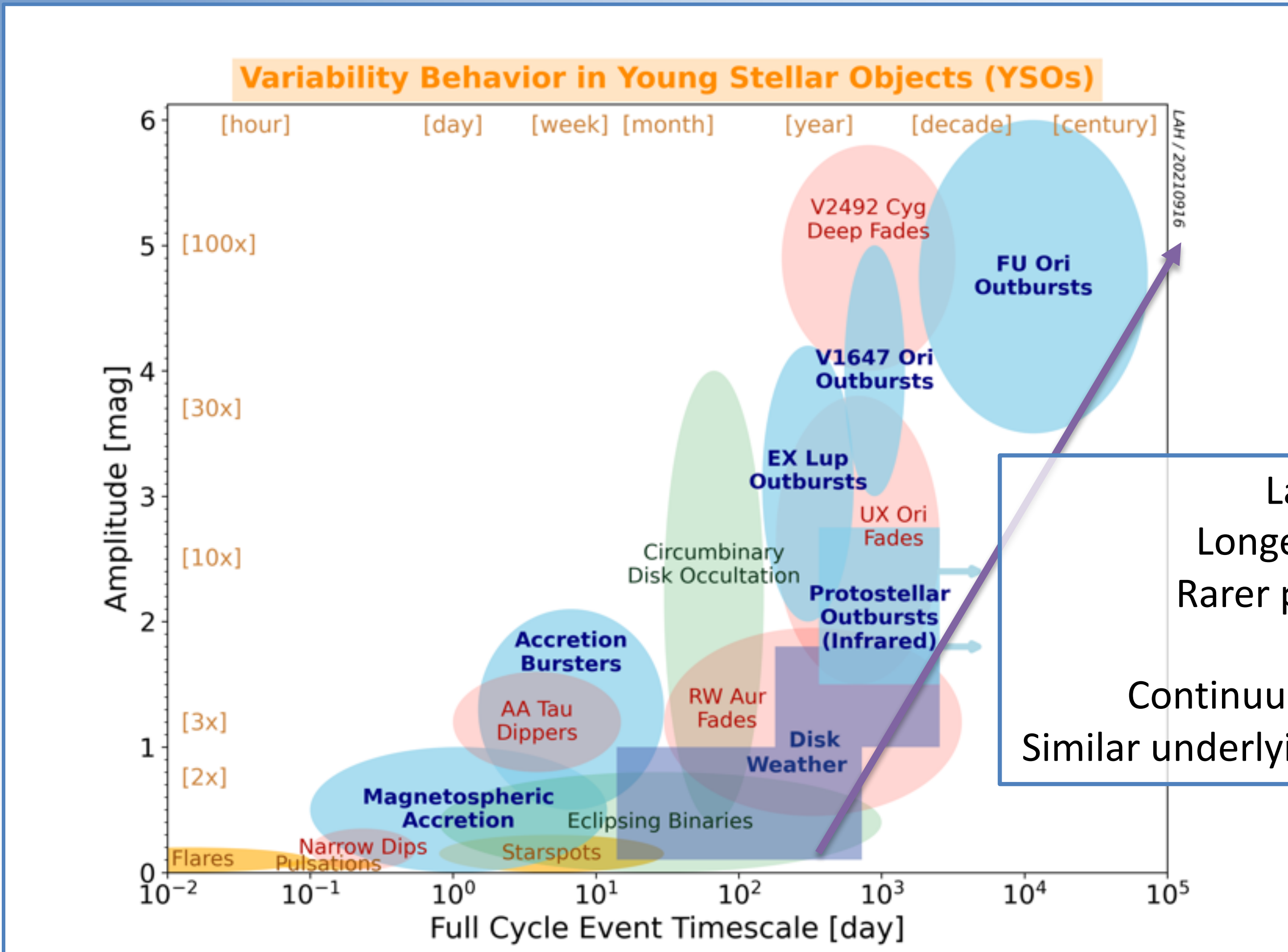
- Rotation breaks isotropic symmetry
  - Produces a flattened inner region (a disk)
- Mass flux that would have reached the protostar now *misses* and lands on disk
- No *a priori* reason why mass transport through disk = mass flux onto disk!
  - If disk transports *faster* – no disk build up
  - If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



[lots of theories for disk transport: few observational constraints]

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

Mass Accretion – Non-Steady?



Larger bursts
Longer durations
Rarer phenomena

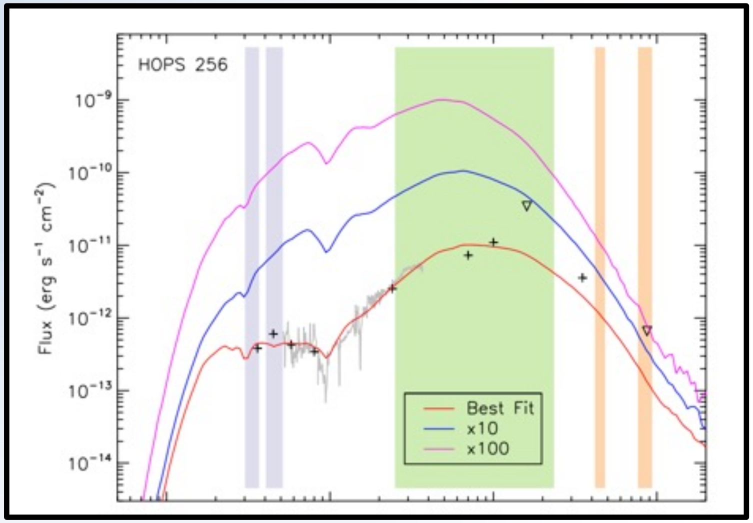
Continuum of types?
Similar underlying physics?

Fischer et al. 2023 PPVII: Accretion Variability Chapter.
[*Unexpectedly, Will passed away in April. He will be very much missed!!*]

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
- This energy is absorbed by the envelope and re-radiated in far-IR to mm. SED thus acts as a ***calorimeter/thermometer*** for accretion.

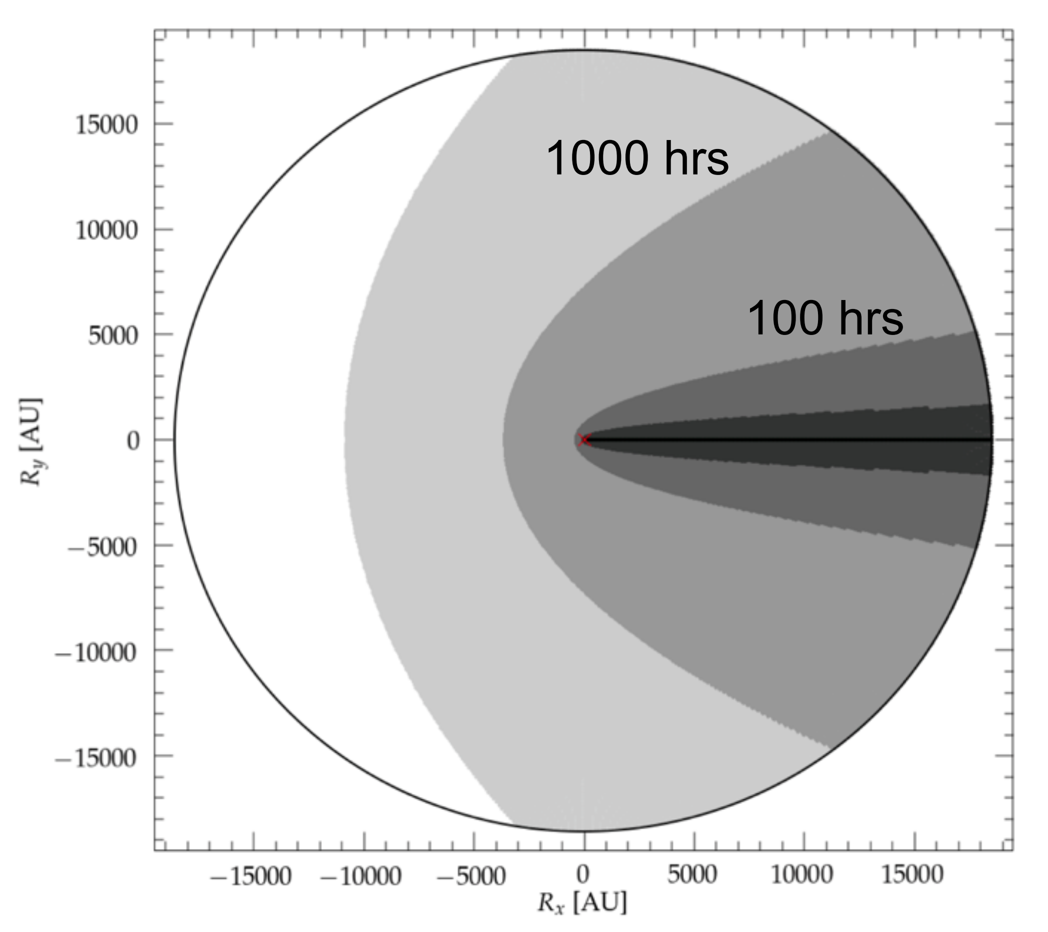
$$L_{\rm acc} \sim \frac{GM_*}{R_*}\dot{M}_{\rm acc}$$



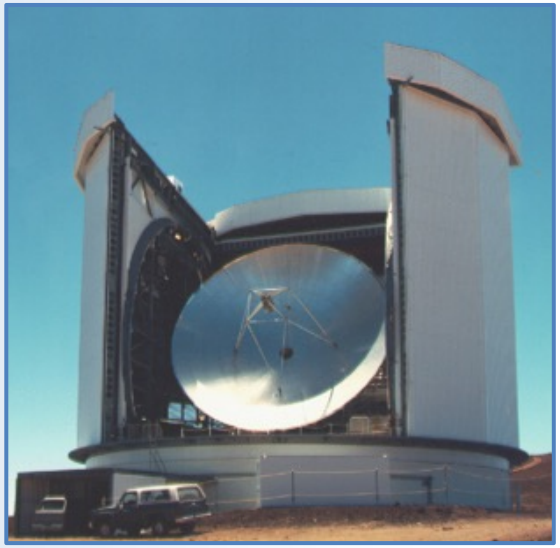
Johnstone+ 2013: ***Far-IR*** and ***sub-mm*** provide a proxy for accretion. Hence, the power of the ***JCMT Transient Survey*** and future ***Sub-mm Survey Telescope*** and ***FIR Space Probe*** *Variability Surveys.*

Timescale for Variable Accretion

The light propagation time must be taken into account …



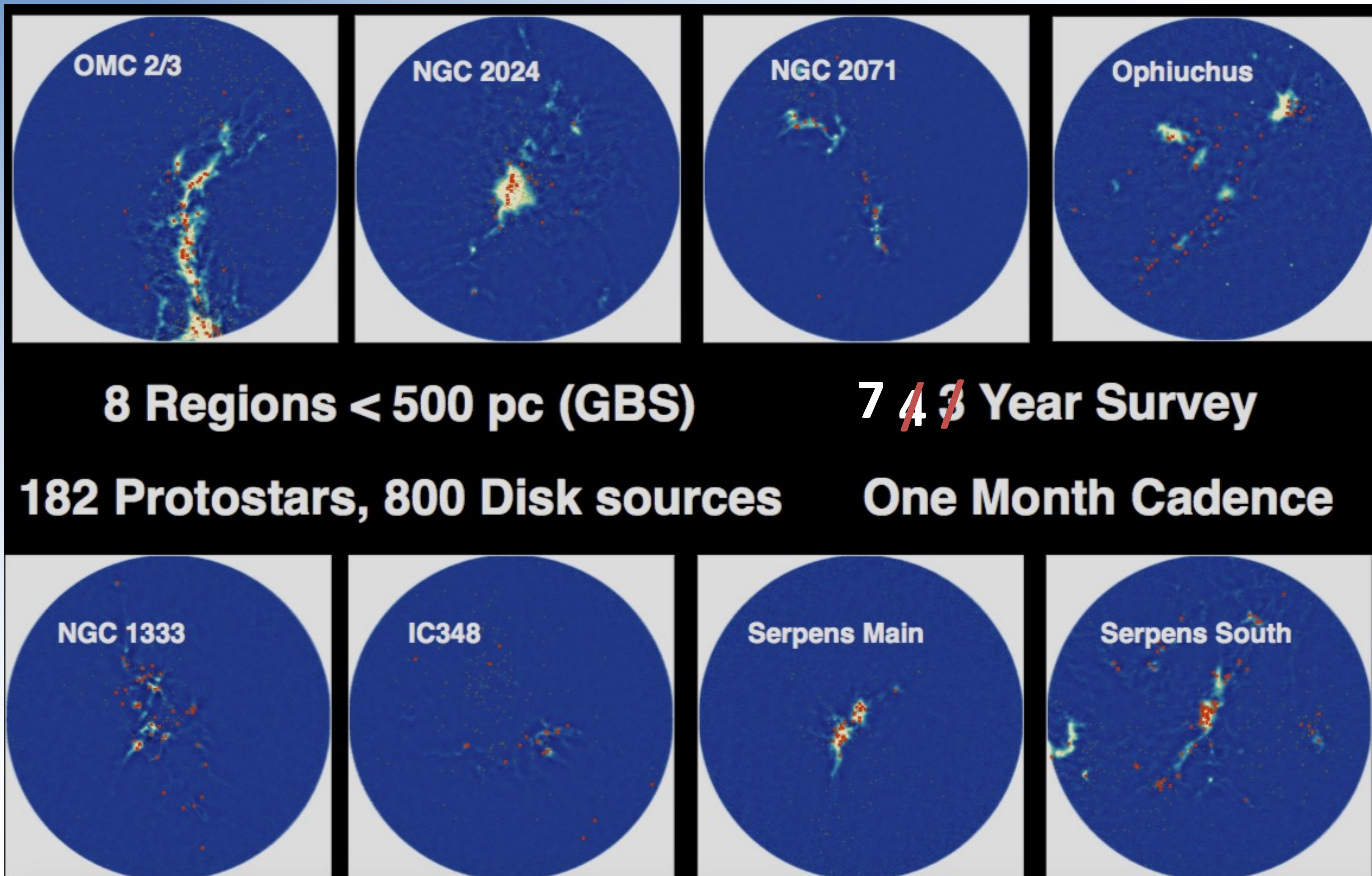
[Johnstone+ 2013, ApJ]



Crossing time of the effective photosphere, R_{ph} ~ 50 AU, requires about **6 hrs**.

Crossing time of envelope, R_{env} ~ 5000 AU, **~ 1 month.**

The EAO/JCMT Transient Survey



[Herczeg+ 2017, ApJ]

The Astrophysical Journal, 920:119 (23pp), 2021 October 20
https://doi.org/10.3847/1538-4357/ac1679

The JCMT Transient Survey: Four-year Summary of Monitoring the Submillimeter Variability of Protostars

Yong-Hee Lee[1], Doug Johnstone[2,3], Jeong-Eun Lee[1], Gregory Herczeg[4], Steve Mairs[5], Carlos Contreras-Peña[6],

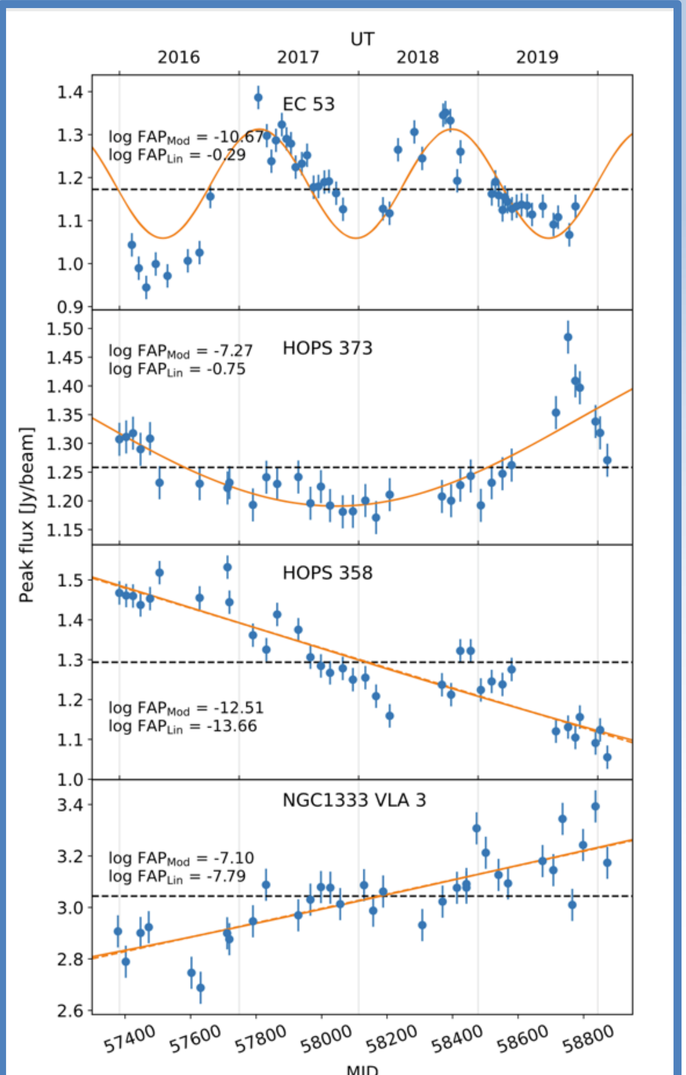


Table 5
Variability Detection by Source Brightness

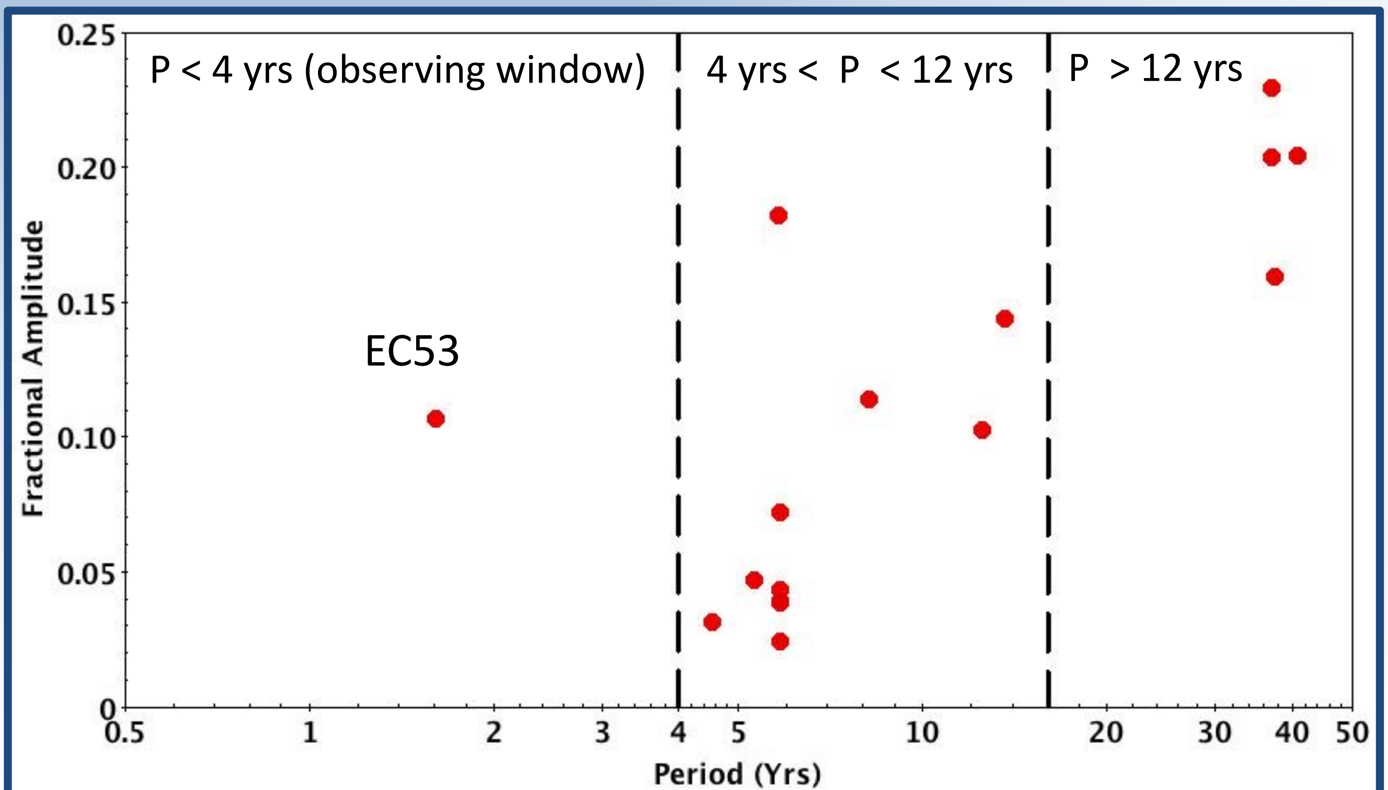
Condition (Jy bm^{-1})	S/N	N_{submm}	$N_{protostar}$	$N_{secular}$	P_{sec}[a]
⩾0.14	10	295	83	18	0.22
⩾0.35	22	141	51	17	0.33
⩾0.5	29	95	43	16	0.37
⩾1.0	41	48	31	11	0.35
⩾2.0	47	45	15	6	0.40

Note.
[a] Fraction of secular variables ($N_{secular}/N_{protostar}$).

This analysis suggests that at least 1 in 4 protostars is varying on years timescales with amplitudes that are at least of order unity.

Bright Source Secular Variability: 50 months

- Determine best periodic light curve (***secular variables ~ 20 sources***)
  - In total we are following ~ 60 bright protostars > 0.25 Jy/bm **(> 30% vary!!**)
- Plot fractional amplitude against derived period (yrs)



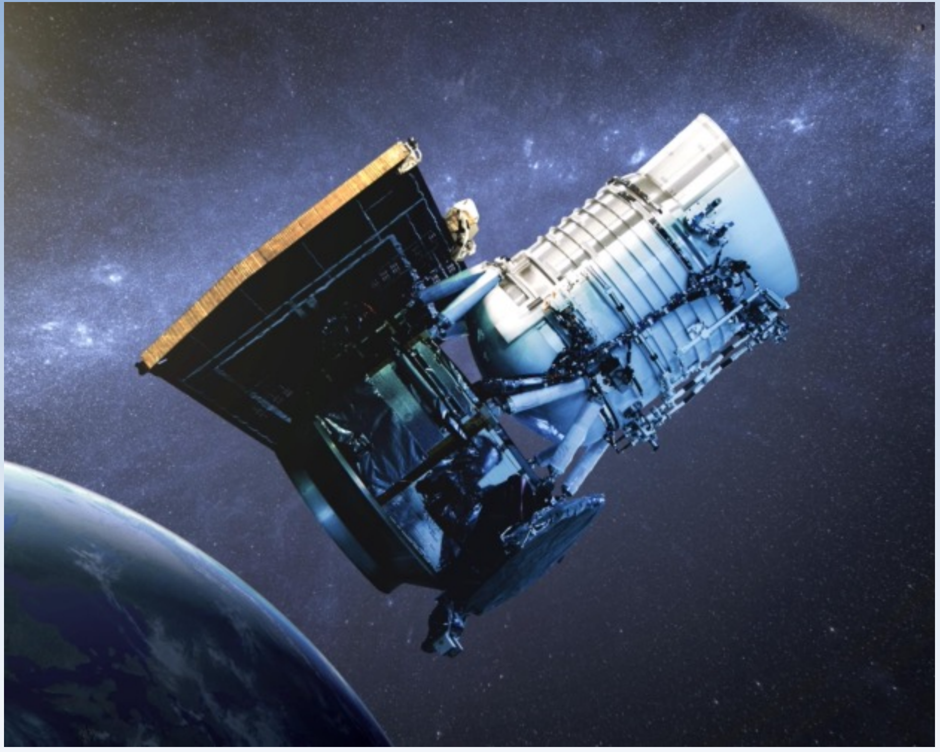
Bottom Line:
Roughly 30% of our known protostars appear to be varying.

One has a short, < 2yr, period (***EC53***).

Roughly 65% (20%) have timescales 4 to 12 yrs.

Roughly 35% (10%) have longer/unknown timescales.

Monitoring the Mid-IR - (NEO)WISE



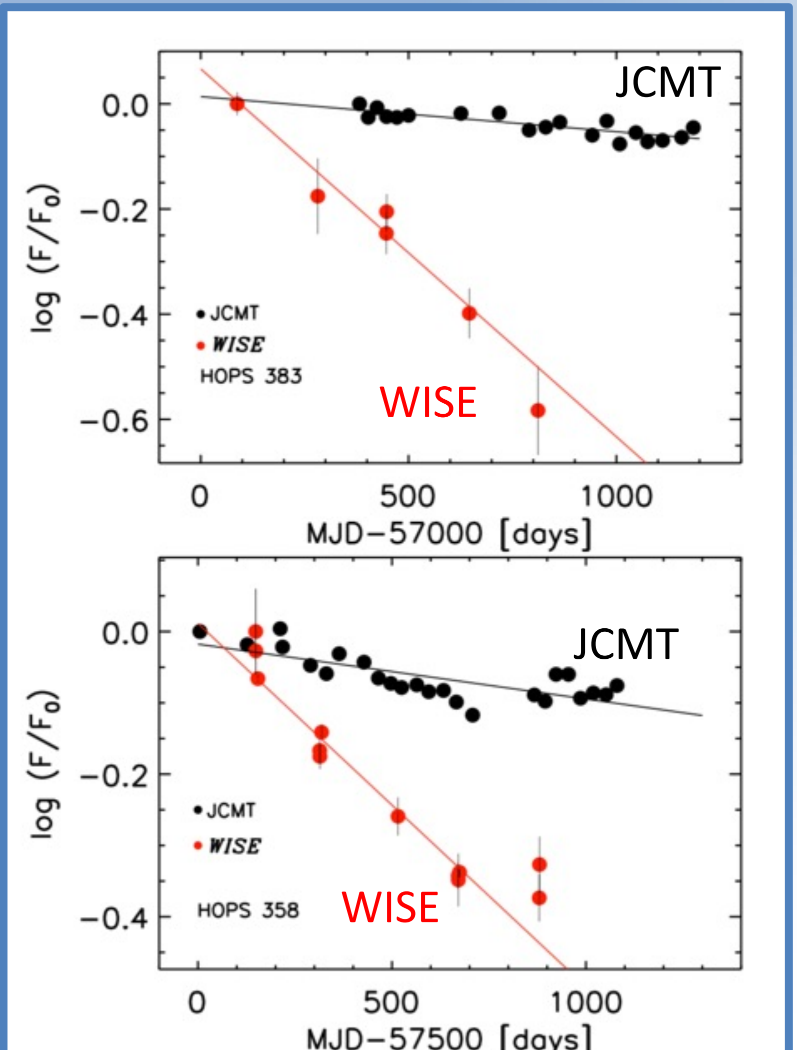
Launched as WISE in 2009
- 10 month mission to observe mid-IR sky

Mirror
- 40cm diameter
- Original filters 3.4, 4.6, 12, & 22 microns

Reactivated in 2013 as NEOWISE
- Search for near earth objects
- Observes entire sky twice a year at
  3.4 & 4.6 microns
- All data made public
  plenty of citizen science

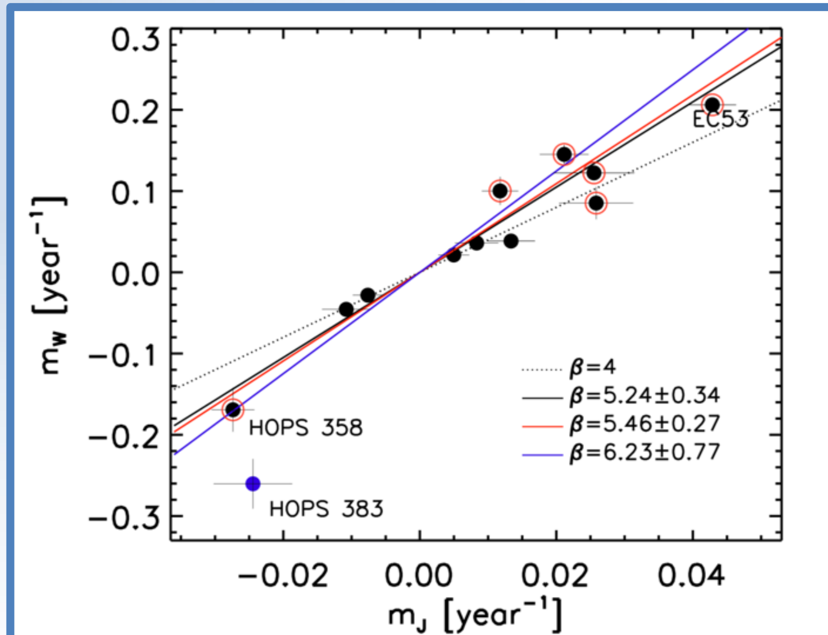
Spectral Energy Distribution Redux

Careful comparison between WISE/NeoWISE 4.6 micron light curves and JCMT 850 micron light curves for 50 sources ***(12 clear variables!!)***



$F(\text{submm}) \propto T_{dust}$

$F(\text{MIR}) \propto L^{1.5}$



UK Post-Doc Carlos Contreras Pena:
[Contreras Pena+ 2020, MNRAS]
See also Park+ 2021, ApJ

The Astrophysical Journal, 920:132 (33pp), 2021 October 20 https://doi.org/10.3847/1538-4357/ac1745

Quantifying Variability of Young Stellar Objects in the Mid-infrared Over 6 Years with the Near-Earth Object Wide-field Infrared Survey Explorer

Wooseok Park[1], Jeong-Eun Lee[1], Carlos Contreras Peña[2,3], Doug Johnstone[4,5], Gregory Herczeg[6,7], Sieun Lee[1], Seonjae Lee[8], Anupam Bhardwaj[9], and Gerald H. Moriarty-Schieven[4]

Table 1
YSO Catalogs and Classifications

Region	Class 0/I [P][a]	Class II [D]	Class III+Evolv
Orion A/B	319 (478)[b]	2160 (2991)	…
Aquila	105 (148)	275 (330)	742 (8
Auriga/CMC	35 (43)	67 (73)	17 (1
Cepheus	16 (29)	50 (61)	12 (1
Chamaeleon	5 (12)	57 (81)	17 (2
Corona Australis	5 (15)	17 (22)	13 (1
IC5146	25 (38)	66 (79)	14 (1
Lupus	12 (13)	53 (58)	84 (1
Musca	1 (1)	1 (1)	5 (1
Ophiuchus	57 (74)	167 (177)	42 (5
Perseus	79 (111)	225 (235)	35 (3
Serpens	42 (52)	118 (131)	37 (4
Taurus	34 (45)	203 (238)	186 (2
	735 (1059)	3459 (4477)	1204 (1

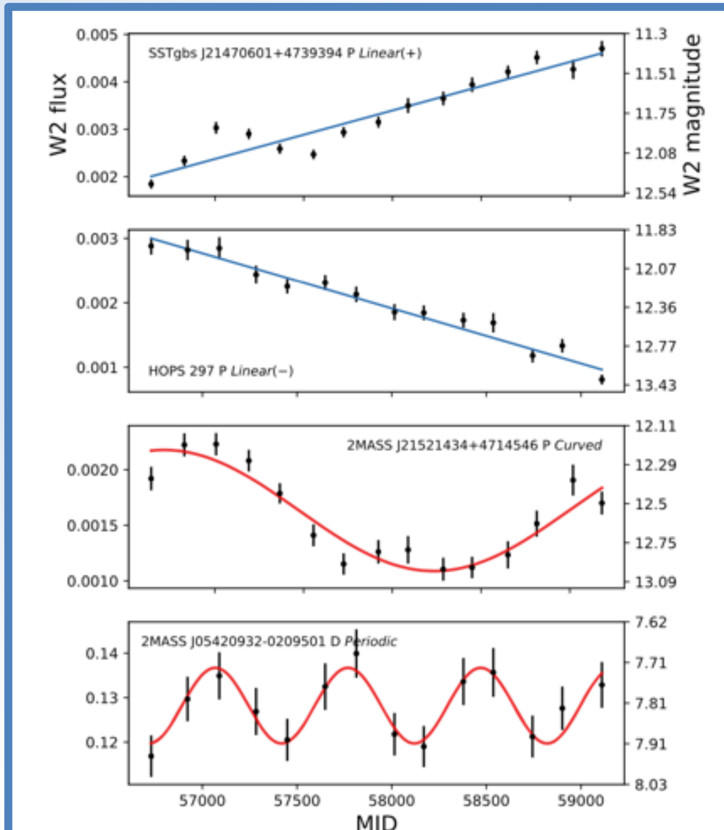


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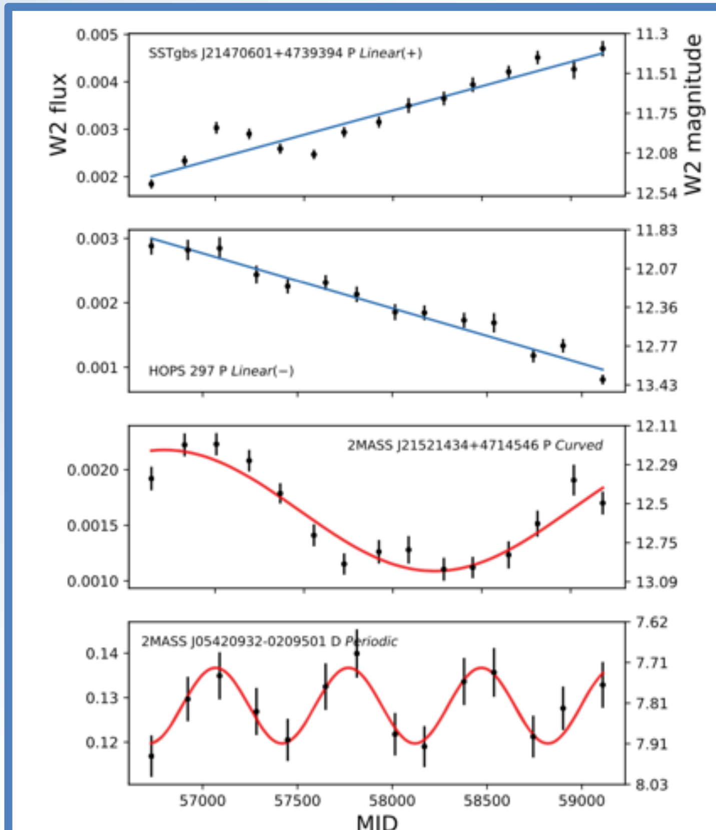
Table 2
Variable Type by YSO Classification

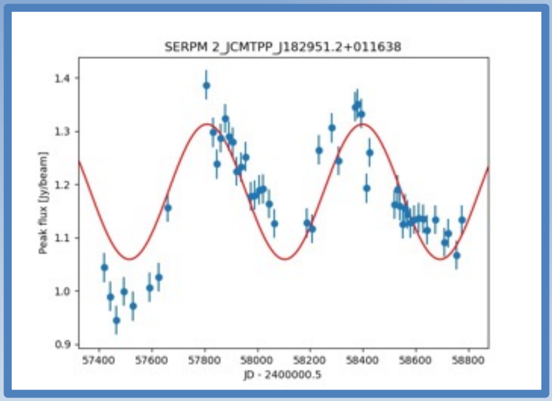
	Class 0/ I [P]	Class II [D]	Class III+Evolved [PMS+E]	Total
Linear	37 (5.0)[a]	31 (0.9)	9 (0.7)	77
Curved	103 (14.0)	183 (5.3)	27 (2.2)	313
Periodic	6 (0.8)	31 (0.9)	81 (6.7)	118
Burst	13 (1.8)	117 (3.4)	7 (0.6)	137
Drop	0 (0)	27 (0.8)	7 (0.6)	34
Irregular[b]	244 (33.2)	757 (21.9)	54 (4.5)	1055
Total	403 (54.8)	1146 (33.1)	185 (15.4)	1734

() indicate percentage of sample

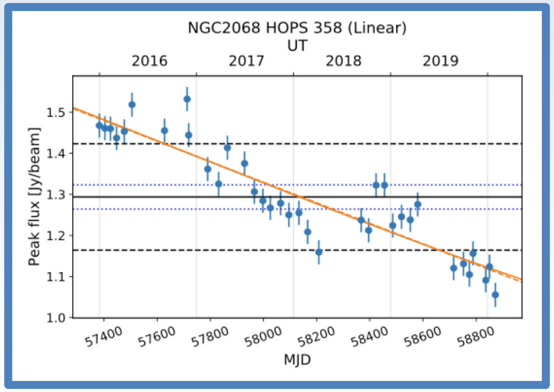


Similar to sub-mm analysis, here we suggest that at least 1 in 5 protostars is varying on years timescales with amplitudes that are at least of order unity.
Plus many more with short term stochastic variability.

Two Case Studies



EC53 – Class I quasi-periodic sub-mm variable
- Multi-wavelength light curve analysis
- Signal time delay through envelope (tomography)

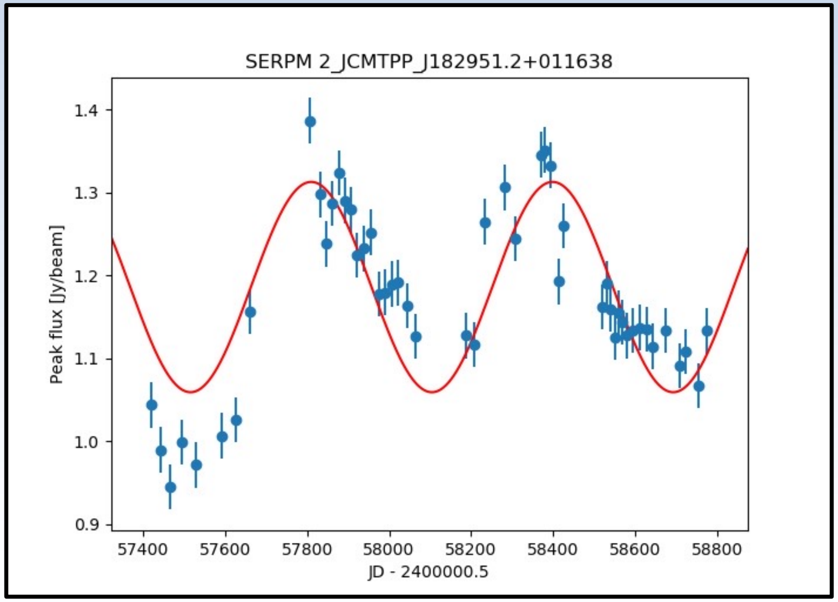


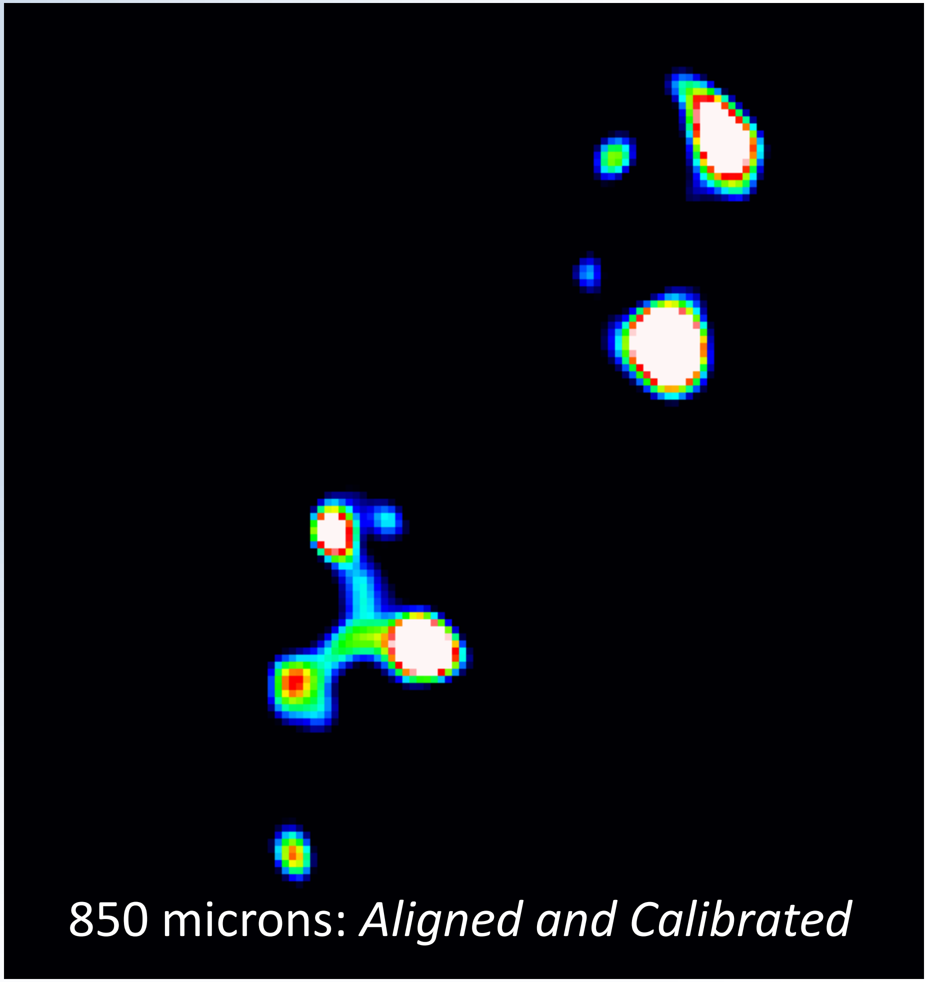
HOPS358 – PBRS decaying sub-mm variable
- Warped disk
- Multiple ALMA epochs

EC53: Quasi-Periodic Sub-mm Variable

Serpens Main ~ 400pc

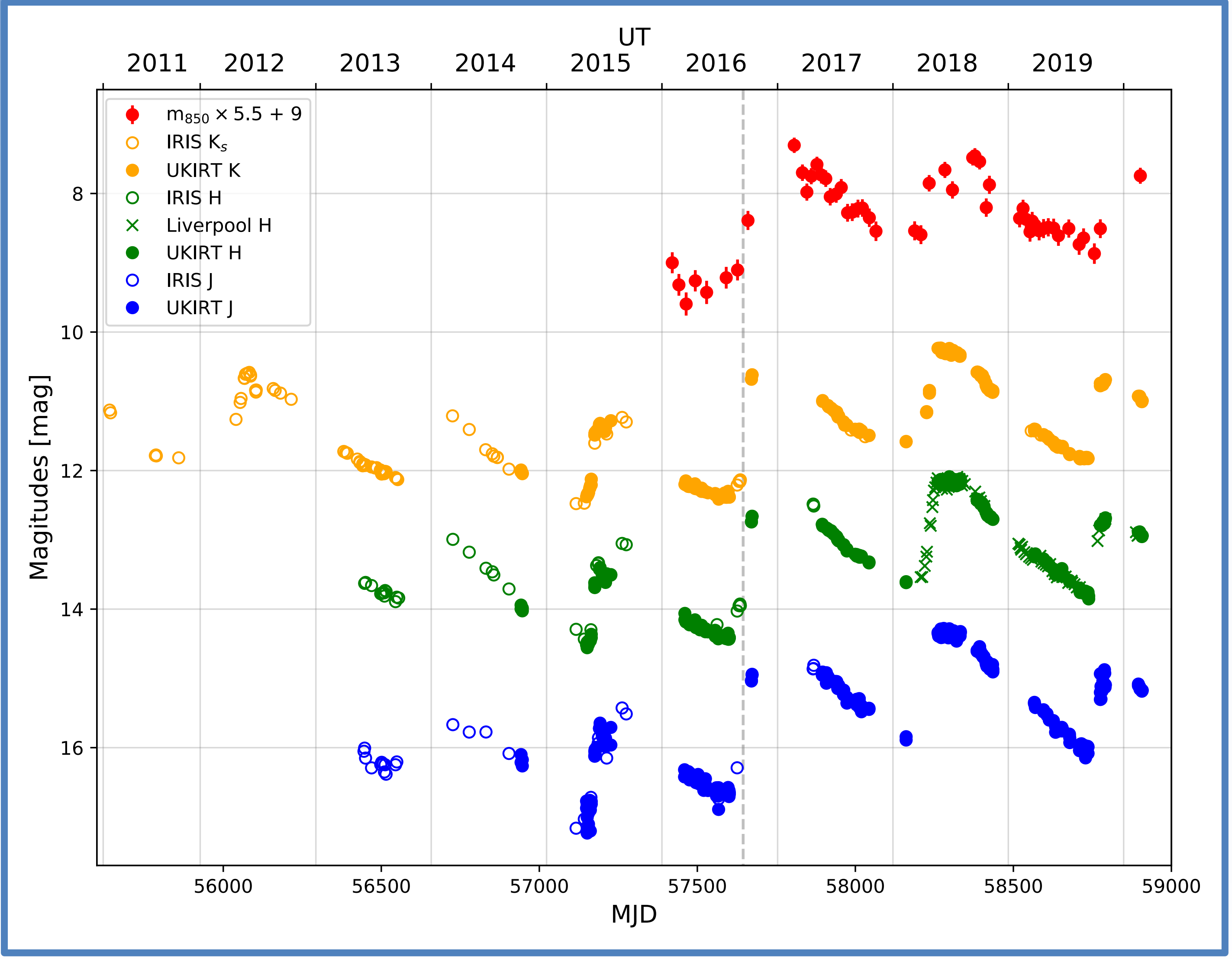
- Class I source (Hodapp + 1999, 2012)
- Physical binary 296 mas (92 AU)
- One visible lobe of a bipolar structure
- Ongoing outflow activity (H_2 jet)
- 18 month ***periodic variable*** at 2µm





Korean PhD student: Yong-Hee Lee
[Lee+ 2020, ApJ]

EC 53 – Analysis over multiple cycles



Submm

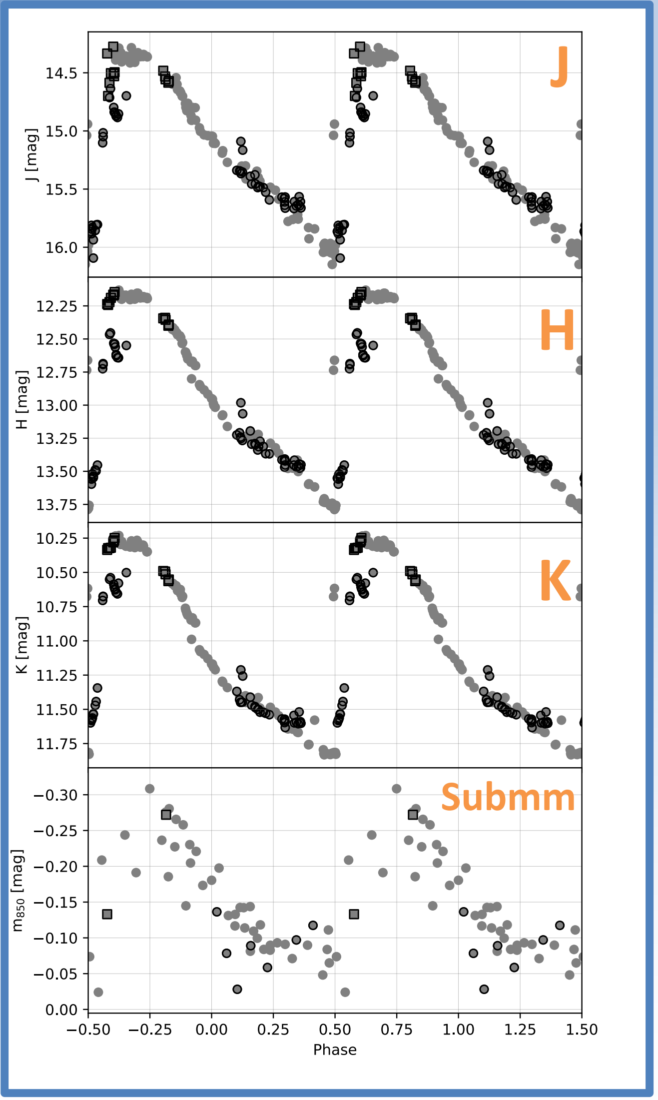
K-band

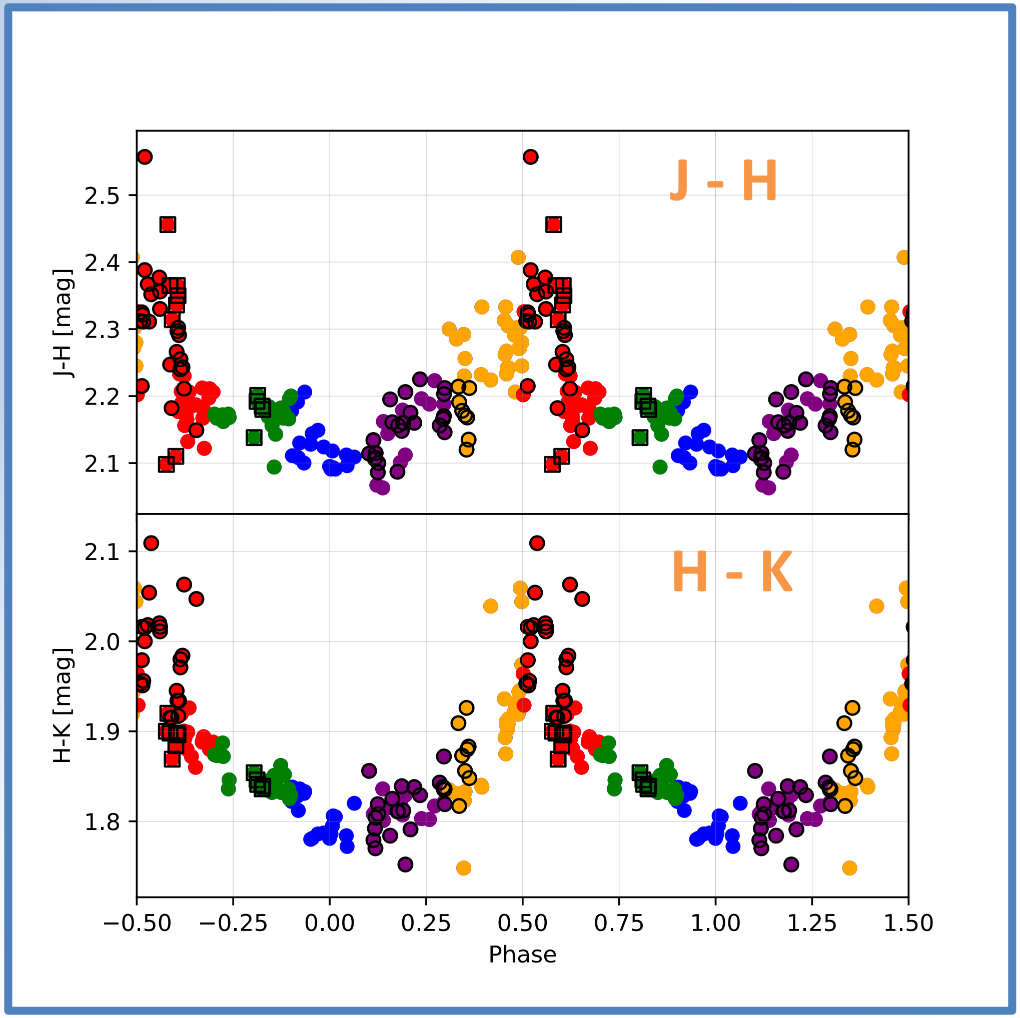
H-band

J-band

[Lee+ 2020, ApJ]

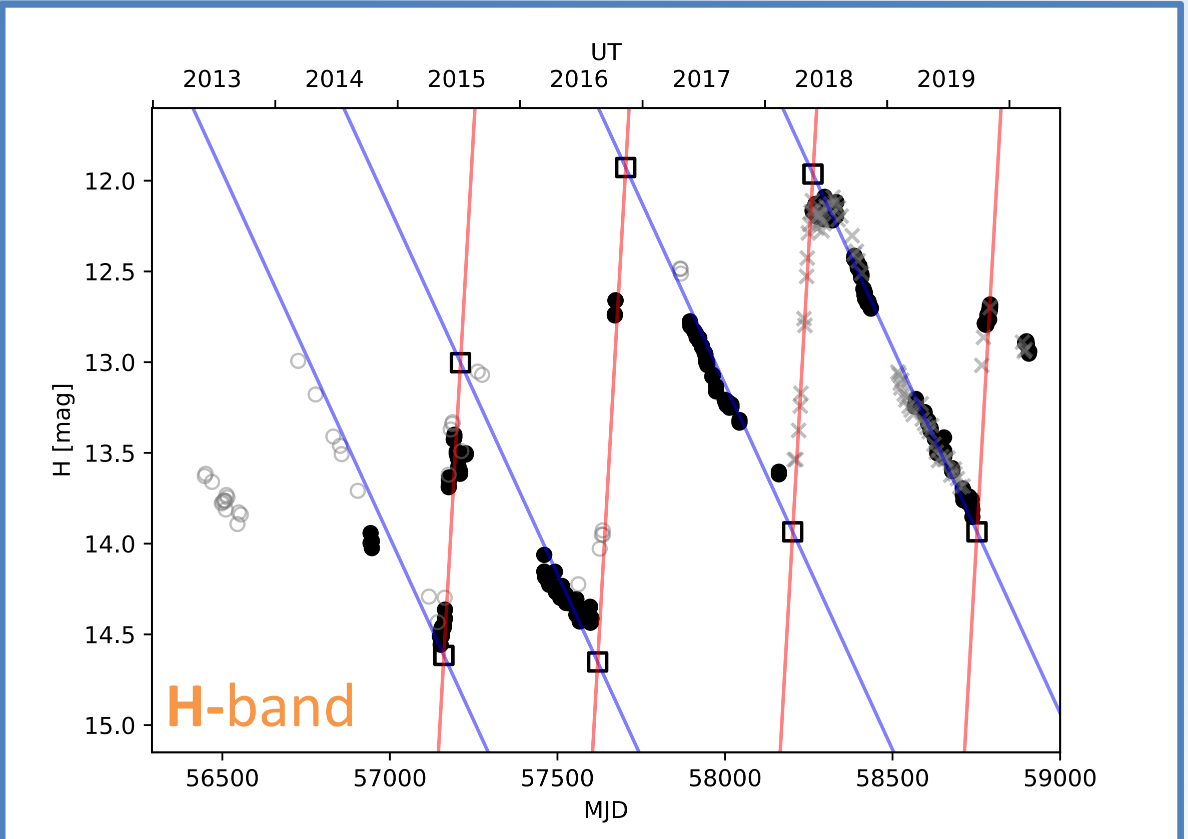
EC 53 – Analysis over multiple cycles





[Lee+ 2020, ApJ]

EC 53 – Analysis over multiple cycles



Timescale (e-folding):

- Decay ~ 0.75 yr
- Rise ~ 0.10 yr

If inner disk viscous time:

- R_{inner} ~ 10 R_{sun}
- $\alpha_{inner} \sim 0.3$

Peak accretion rate:

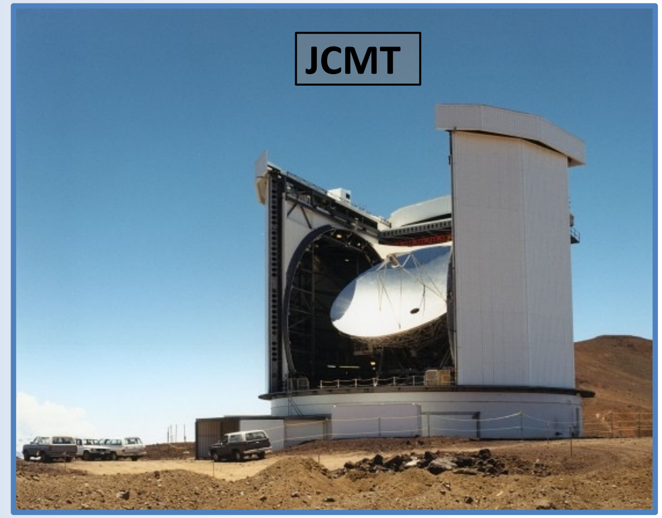
- $\dot{M} \sim 8 \times 10^{-6}$ M_{sun}/yr
- High for a Class I source

Outer disk conditions:

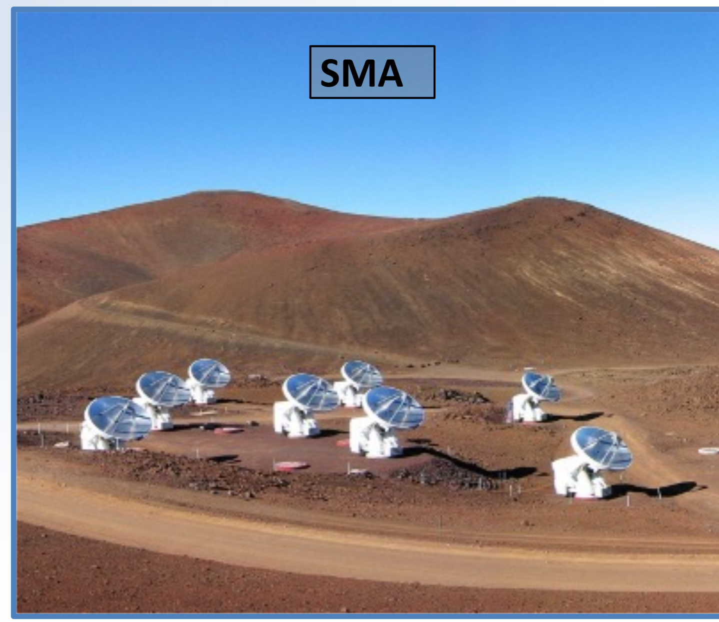
- $M \sim 0.07$ M_{sun} (ALMA)
- R_d(outer) ~ 100 AU (ALMA)
- $\dot{M} \sim 3.6 \times 10^{-6}$ M_{sun}/yr
- $\alpha_{outer} \sim 0.002$

[Lee+ 2020, ApJ]

Monitoring Variable protostars - ACA/SMA



- Our 850 µm ALMA/ACA observations monitored targets with a low cadence over 3 years (thanks to COVID)
- Our 1.3 mm SMA observations targeted specifically EC 53 during its (predicted) 2021 outburst
- ACA/SMA Beam size: ~3.5''/1500 au (compare against 15" JCMT beam)



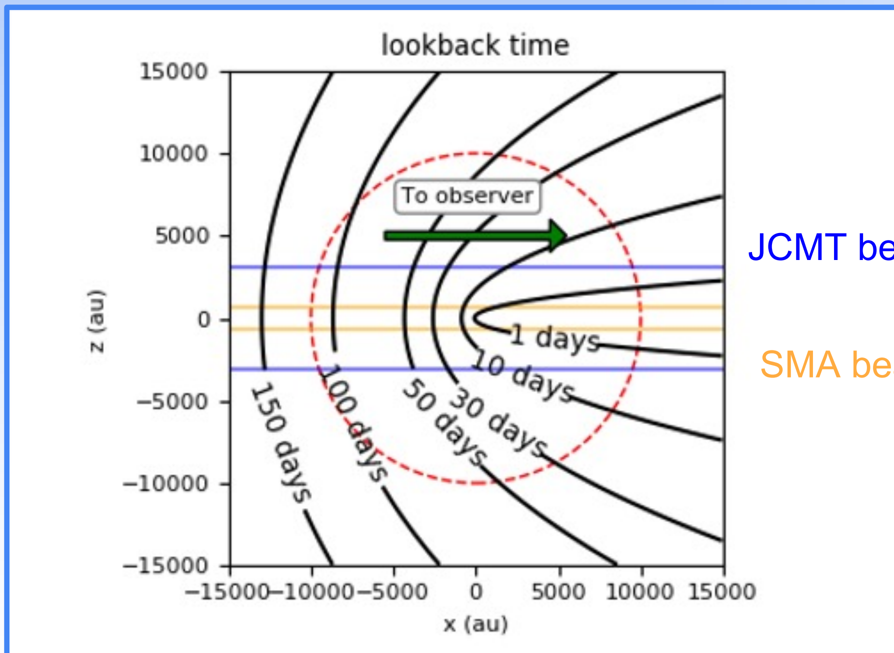
[Francis+ 2022, ApJ]

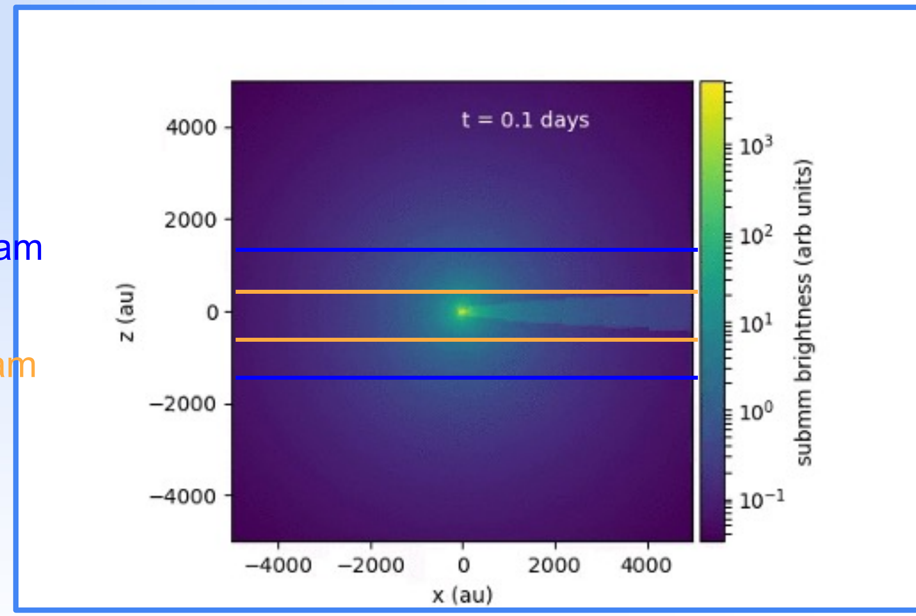
Model lookback time

UVic PhD student:
Logan Francis

Light travel time across envelope =>
telescope dependent modulation of observed dust heating

$$t_{\rm lb} = (r - x)/c,$$





[Francis+ 2022, ApJ]

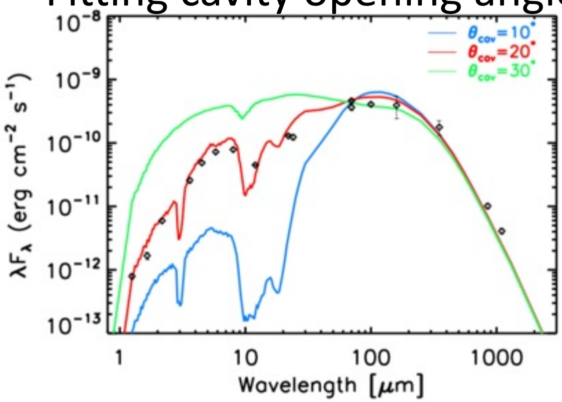
Spectral Energy Distribution (SED)

Accretion energy is absorbed by the envelope and re-radiated in the Far-IR through mm. The SED acts as a ***calorimeter*** for accretion.

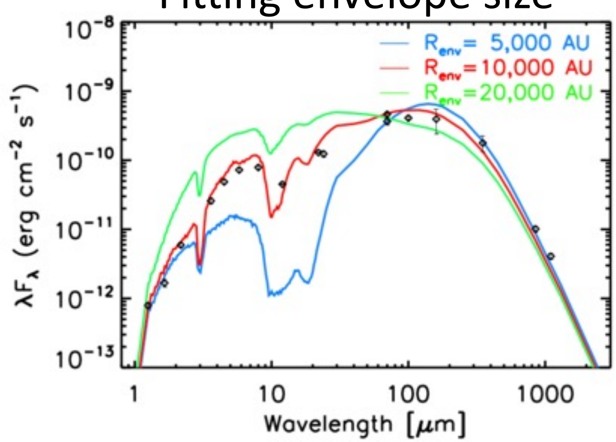
$$L_{\rm acc} \sim \frac{GM_*}{R_*}\dot{M}_{\rm acc}$$

Submm Variable EC 53

Fitting cavity opening angle



Fitting envelope size



Fitting brightness variation

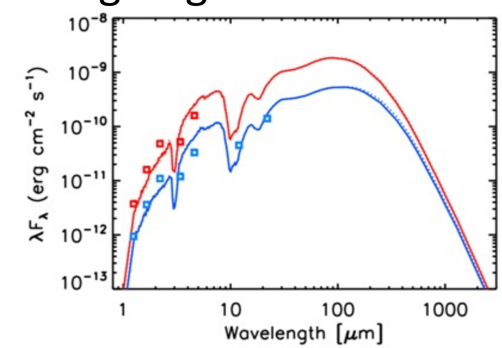
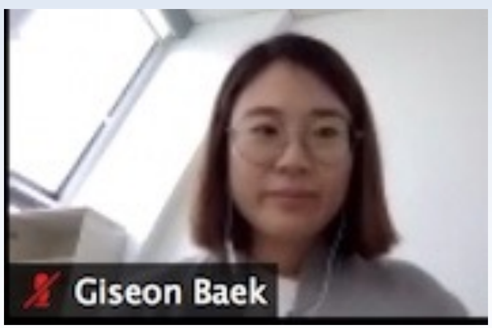


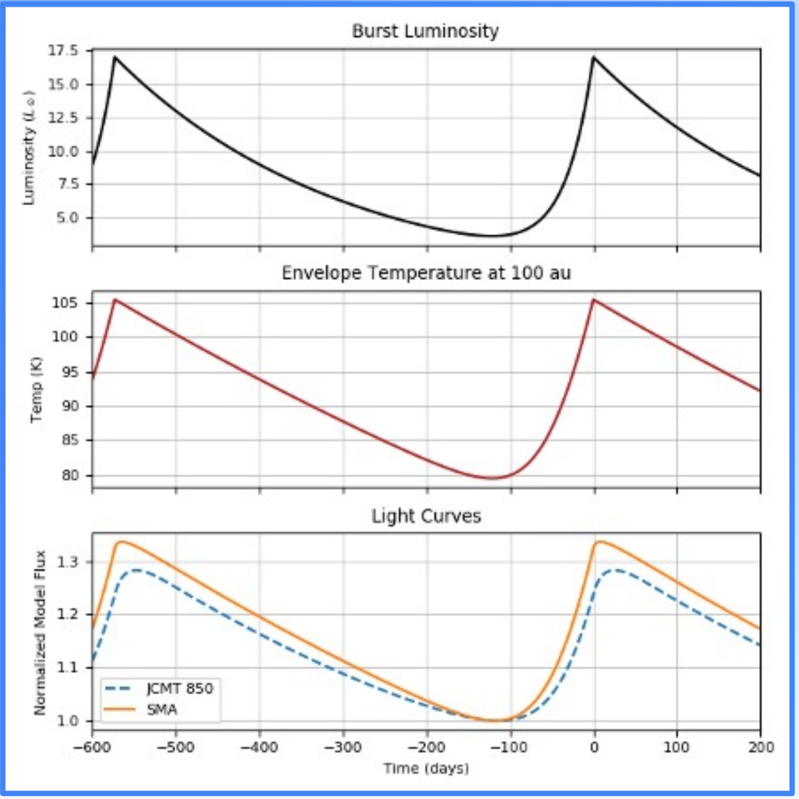
Figure 11. The 2D modeling SEDs for both in the quiescent (blue lines) and outburst (red lines) phases. The solid and dotted lines represent the SEDs without and with the ISRF heating, respectively. UKIRT J, H and K bands and WISE 3.4 and 4.6 μm photometric data are presented both in the quiescent and outburst phases. WISE 12 and 22 μm data are presented only in quiescent phase.

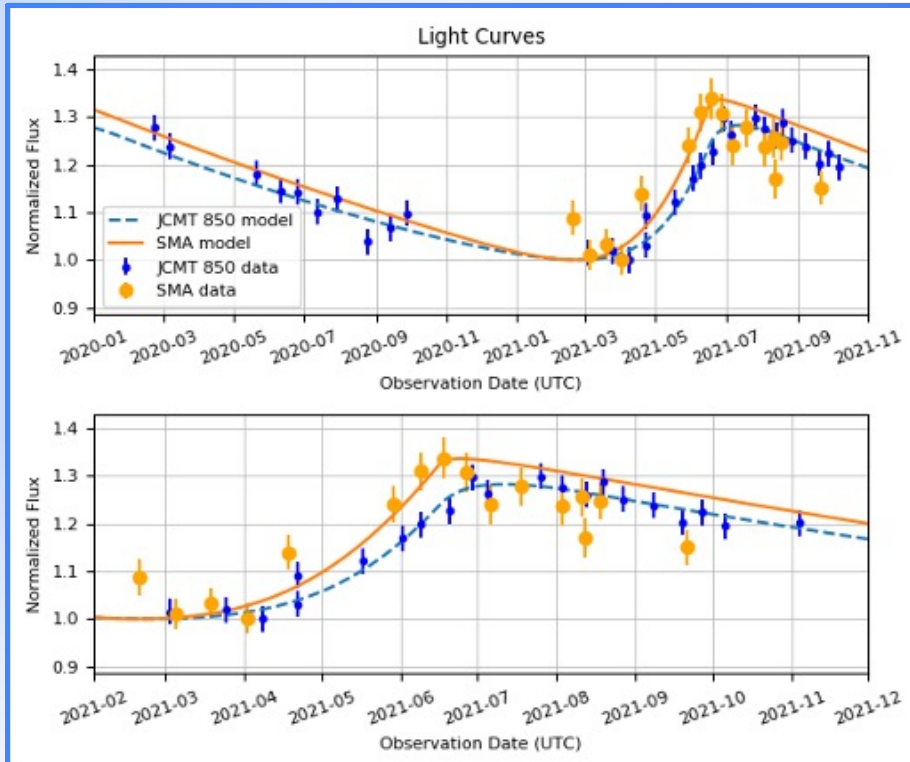


Korean PhD student Giseon Baek: [Baek et al. 2020, ApJ]

SED varying with time breaks degeneracy with respect to disk/outflow cavity/envelope structure.

Fiducial Model for EC 53 Outburst





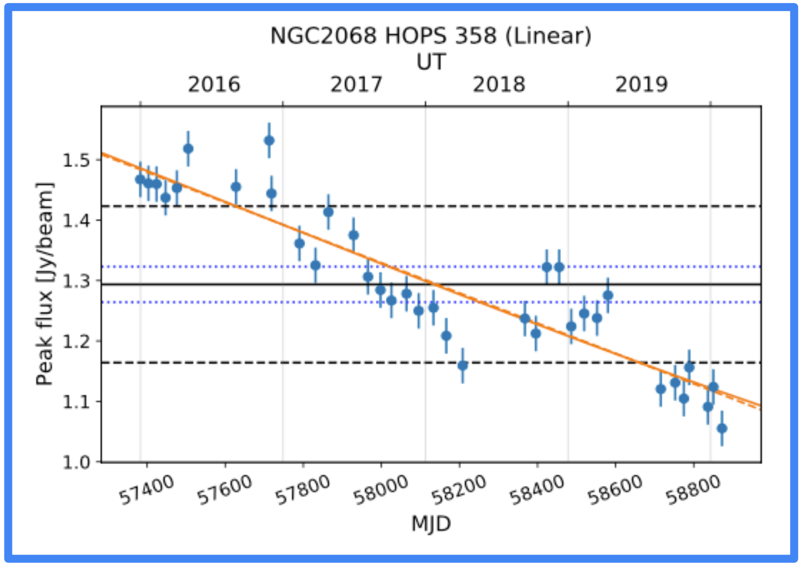
Observed time delay of ~2 weeks matches the expectations based on the previously modeled EC53 envelope properties and burst profile!

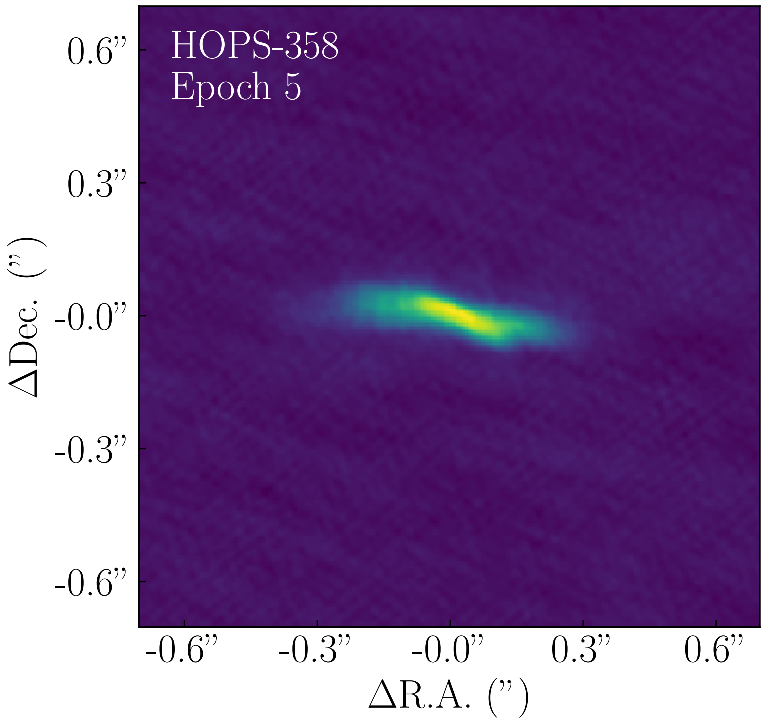
[Francis+ 2022, ApJ]

UVic PhD student: Logan Francis

HOPS 358 – Variability and a Warped Disk

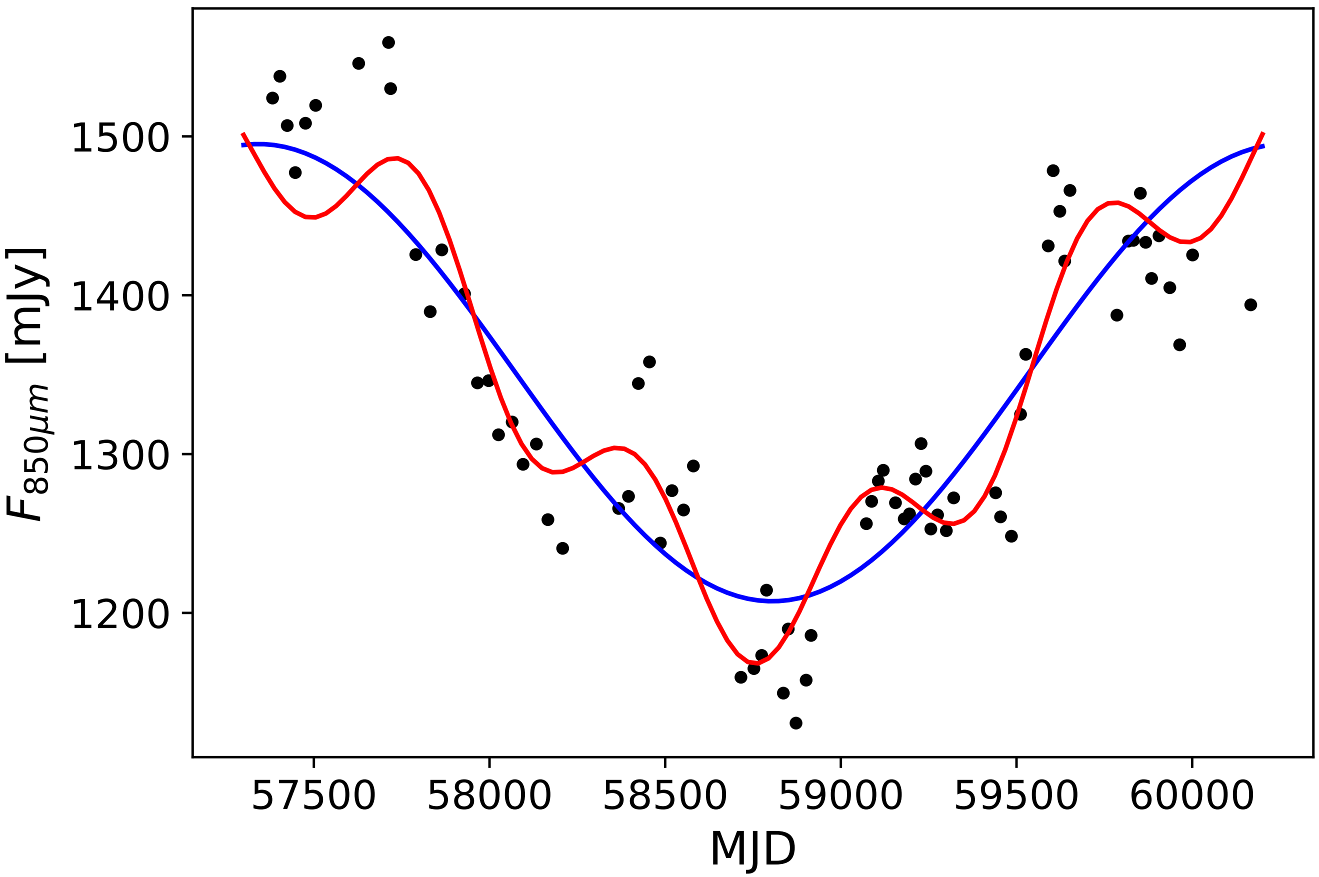
HOPS 358 is a PACS Bright Red Source (hypothesized very young Class 0)





[Sheehan++ in prep]

HOPS 358 – Variability and a Warped Disk



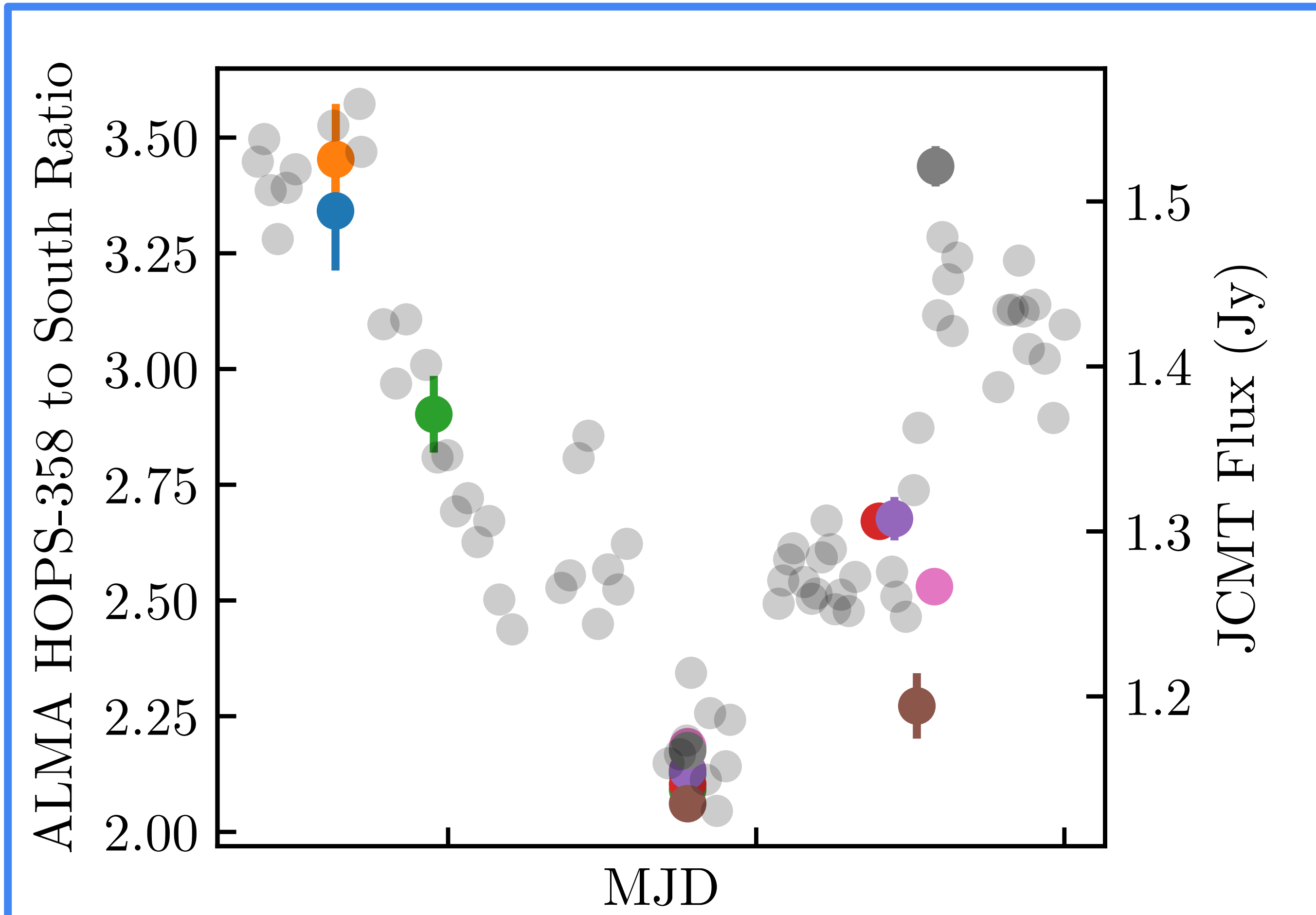
Two timescales:
~8 yrs
~2 yrs

Note that the shorter period is similar to that of EC53 (hmm …)

[Sheehan++ in prep]

HOPS 358 – Variability and a Warped Disk

Many ALMA epochs,
with the same correlator set-up but different array configurations.



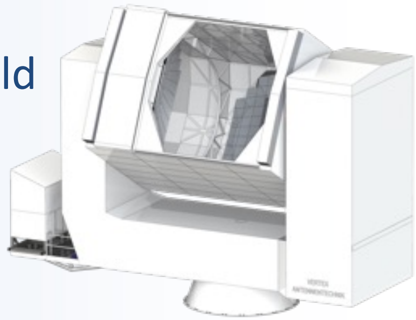
[Sheehan++ in prep]

What's Next for Protostar Variability?

JCMT Transient

- Continues at least until end of year (*recently added 6 intermediate mass regions* **Sheng-Yuan**)
- Calibration and analysis of 450 micron data complete and submitted (**UVic & Korean UGs**)

CCAT (FYST) Survey Telescope



- Higher sensitivity, higher frequency (optimal at 350 microns), larger field
- 2019 *NRC New Beginnings Grant* to design basic 350 micron camera
  (HAA now part of Canadian full camera project; UVic UG supported)

ALMA/ACA Monitoring/Follow-up

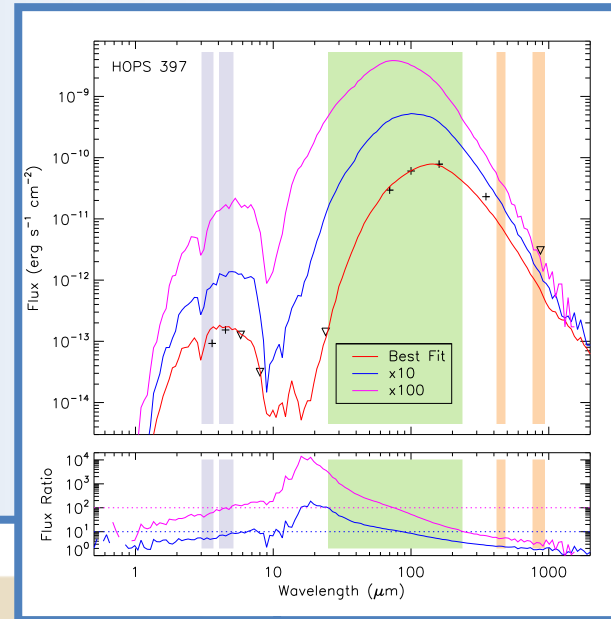
- Many proposals to monitor and investigate interesting protostellar variables
- Important test of default ALMA calibration and improvement methods
  (**see e.g. Francis+ 2020**)

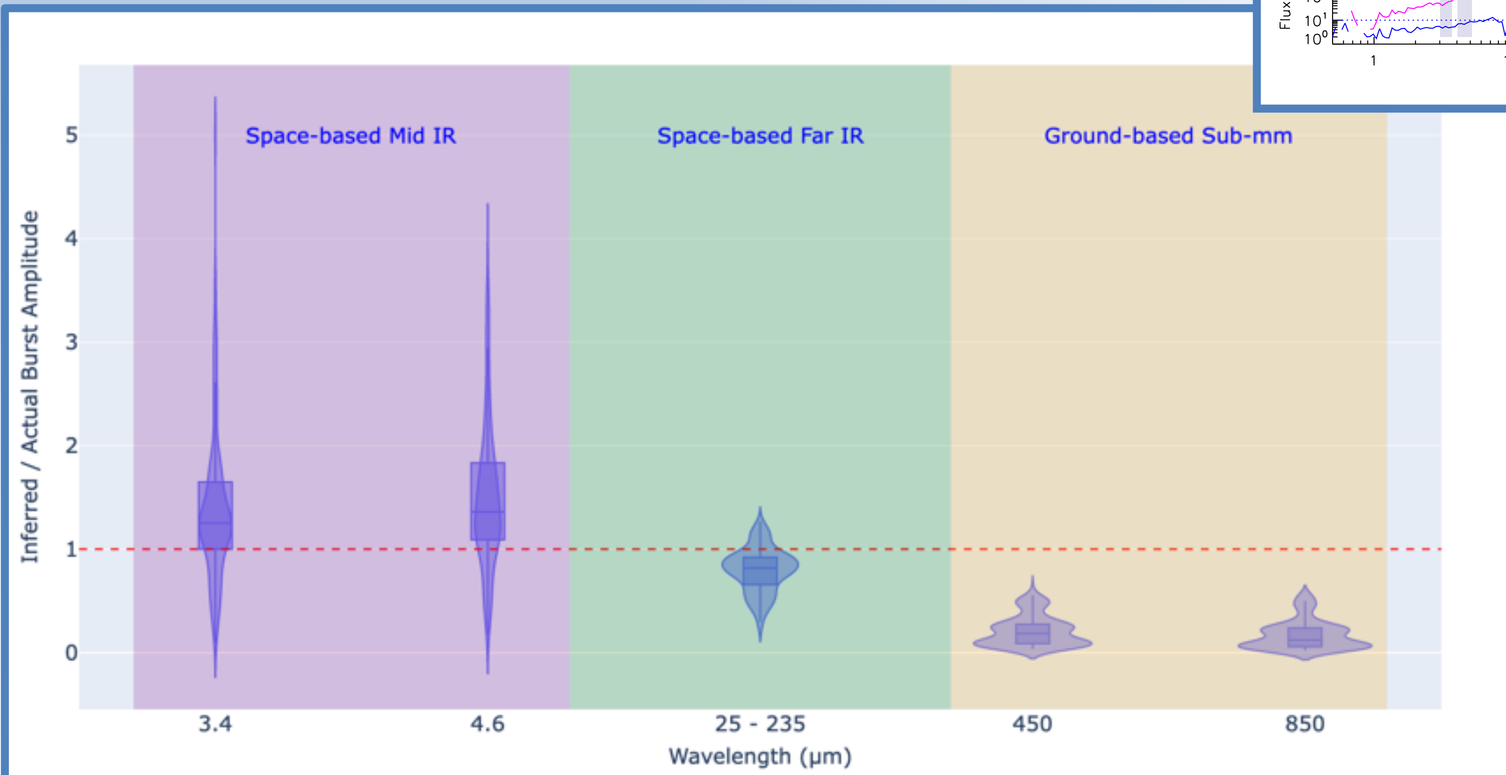
Preparing for Future Far IR Space Telescopes (PRIMA/ORIGINS)

- Wonderful wavelength coverage across peak of SED
- Excellent calibration opportunity but limited lifetime
- Better suited for follow-up of ground-based monitoring?

PRIMA FIR Probe Concept

The importance of monitoring at the peak of the SED.





[Fischer+ 2024, ApJ]

Summary/Lessons Learned/Best Practice

- Results from the 7yr (400 hr) JCMT Transient Survey demonstrate a rich future for *Protostellar (Accretion Disk) Seismology.*
- *Protostars are variable* >25% have order unity variations over years.
- *Can observe in mid-IR (caution) and sub-mm* but wish for Far-IR!
- Many sub-mm variables with multi-wavelength analysis of physical properties.
- Interesting short (few years) `resonant' feature.
- Time-domain explorations in the (sub)mm important for existing and planned instruments/telescopes.