Investigating Accretion Variability Onto Deeply Embedded Protostars

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With:

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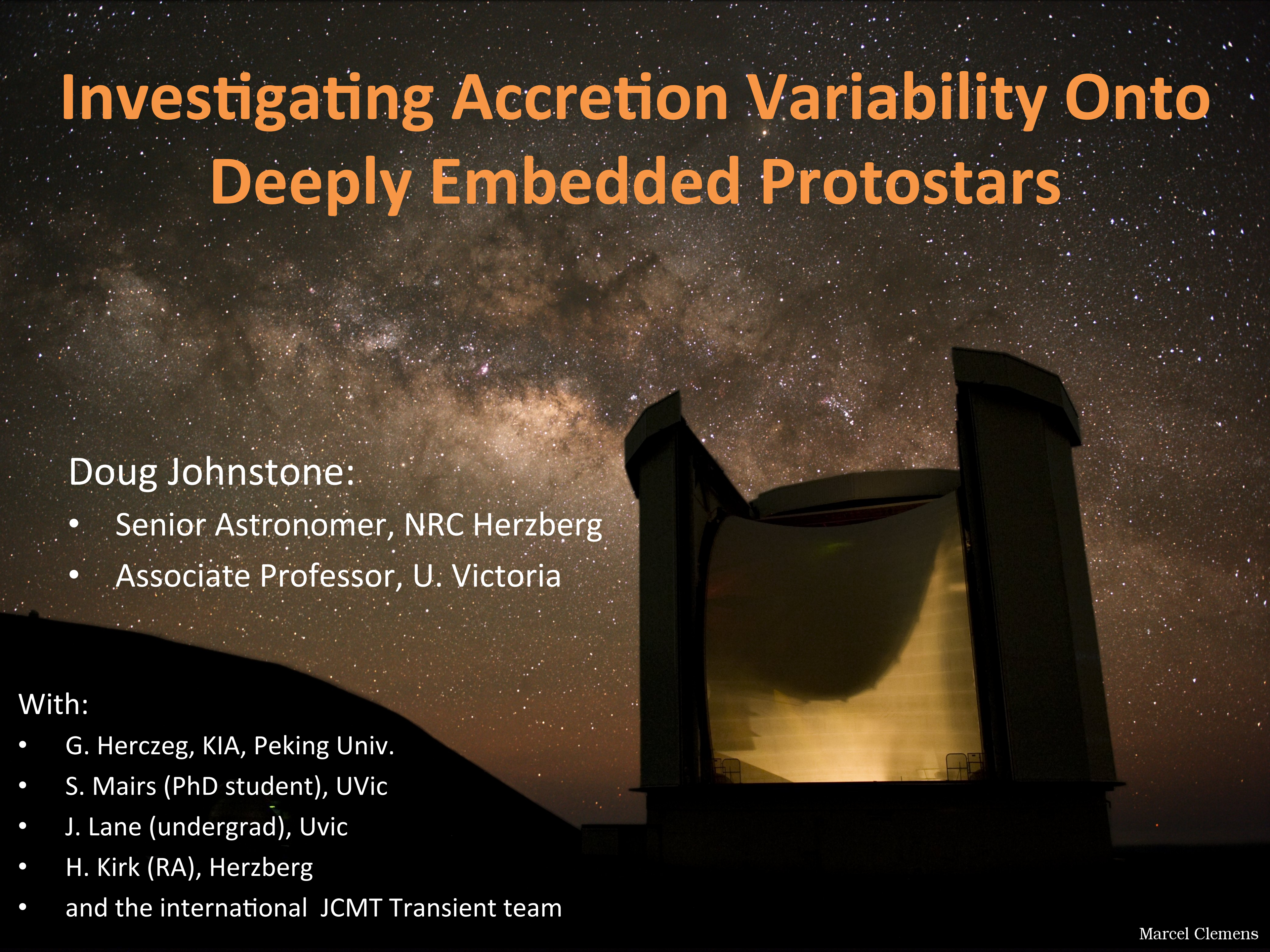
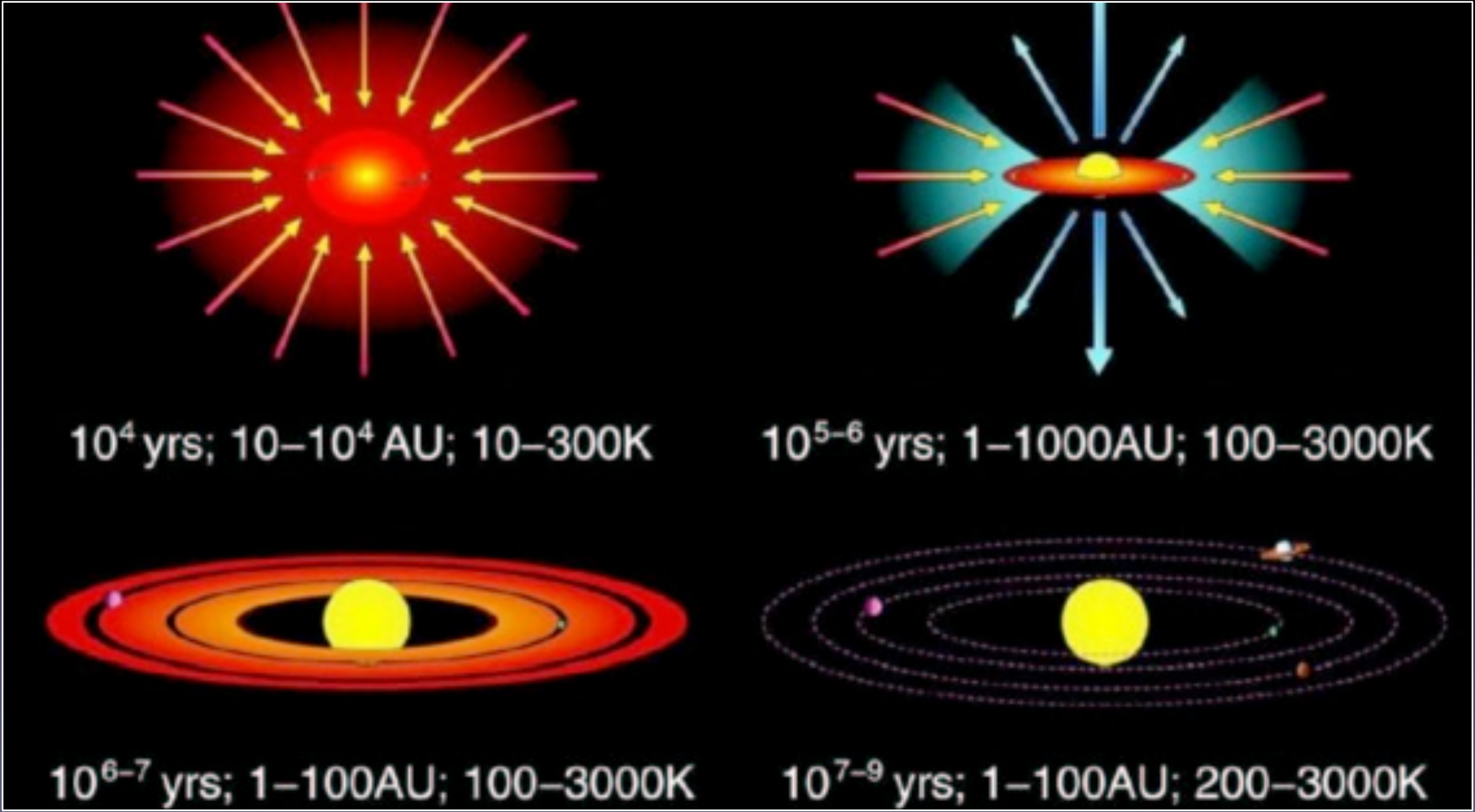
- S. Mairs (PhD student), UVic
- J. Lane (undergrad), Uvic
- H. Kirk (RA), Herzberg
- and the international JCMT Transient team



Marcel Clemens

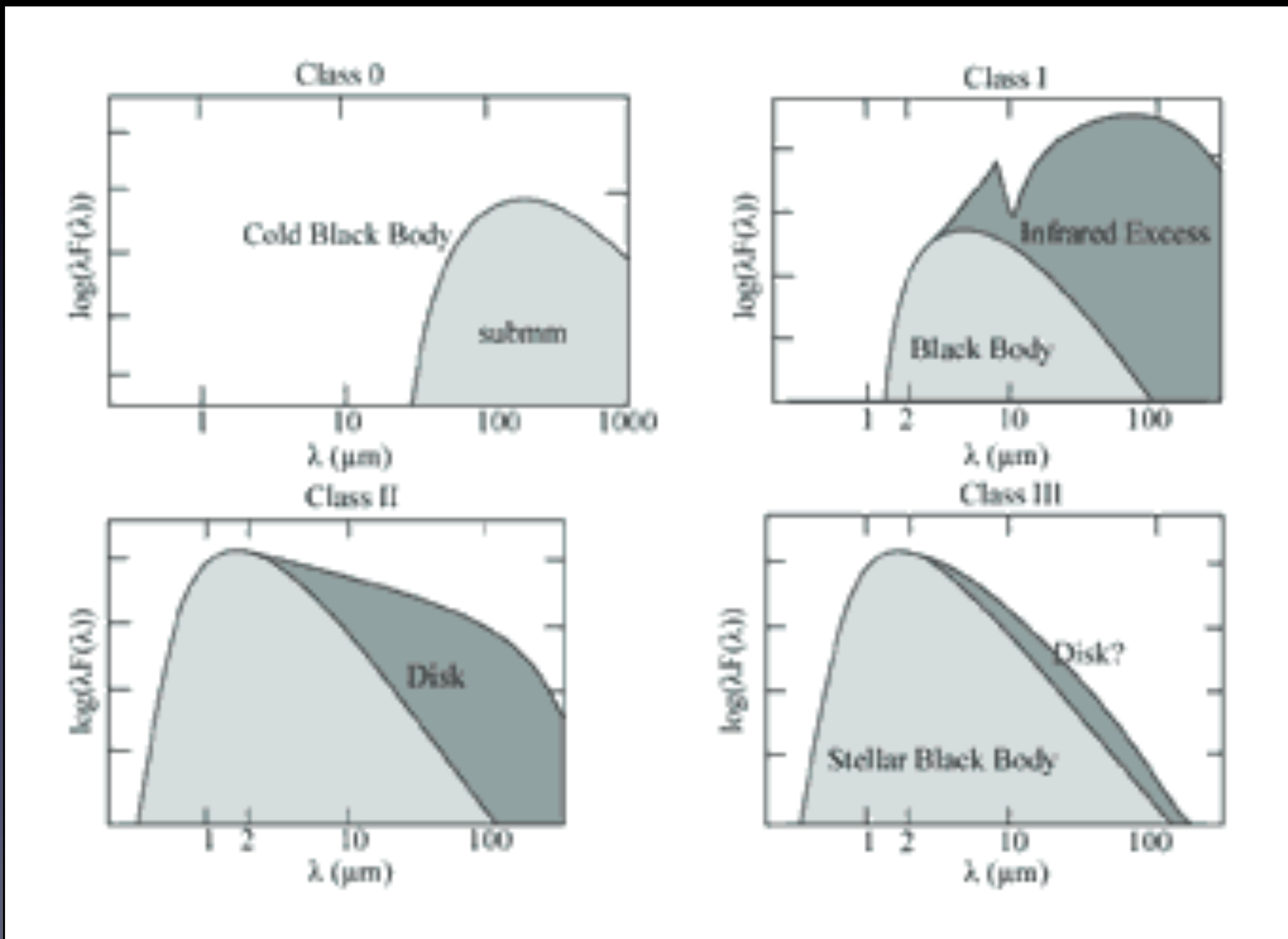
Formation of a (Proto)Star

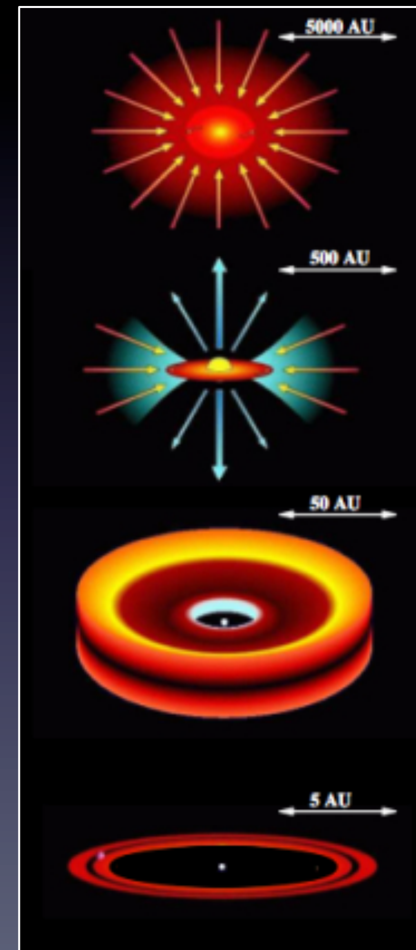
Stages of Star Formation



Formation of a (Proto)Star

Spectral Energy Distribution Evolution





Observational Constraints

Lifetimes:

$$t_f \sim t_* N_p/N_*$$

- Spitzer c2d programme finds that Class O/I lifetime is ~ 0.5 Myr, with 1/3 of these Class O
- Sets typical infall rate

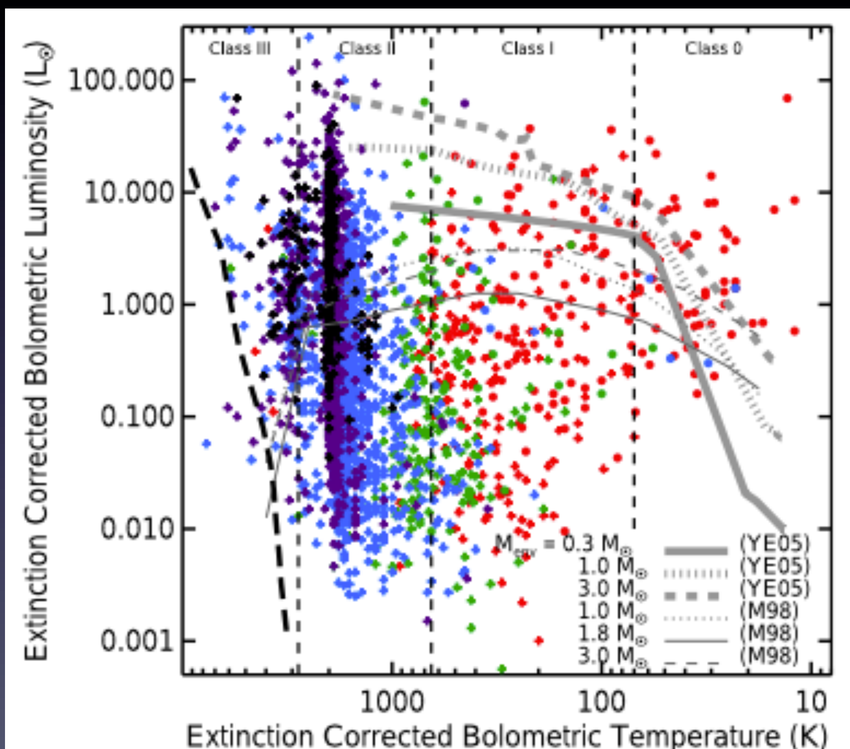
$$M_{dot} \sim 10^{-6}\, M_{sun}\, /\, yr$$

Red: Class O/I; Green: Flat; Blue: Class II; Purple: Class III - Dunham et al. 2015

Observational Constraints

Protostellar Luminosities:

$L_{acc} \sim G M_* M_{dot}/R_* > L_*$

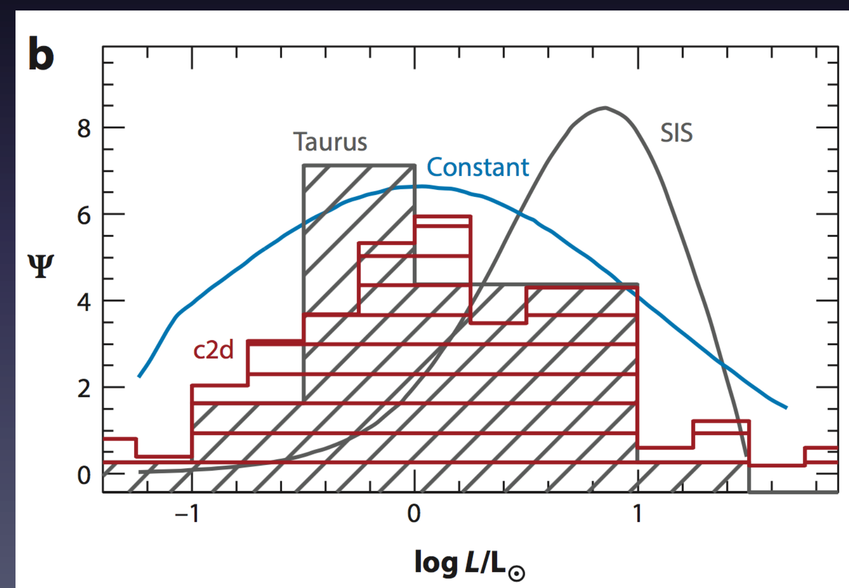


Dunham et al. 2015

Luminosity Distribution Functions:

Observed (Taurus, c2d) versus models.

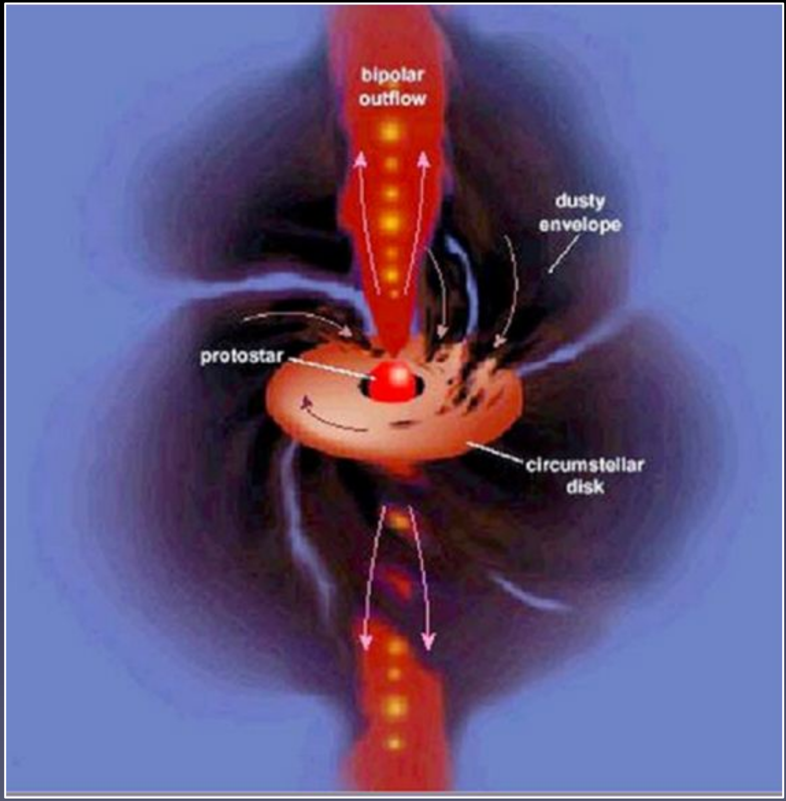
SIS: $M_{dot} \sim c_s^3/G$ (Shu 77), Constant: $M_{dot} \sim M_*$



Hartmann et al. 2016

Importance of the Disk

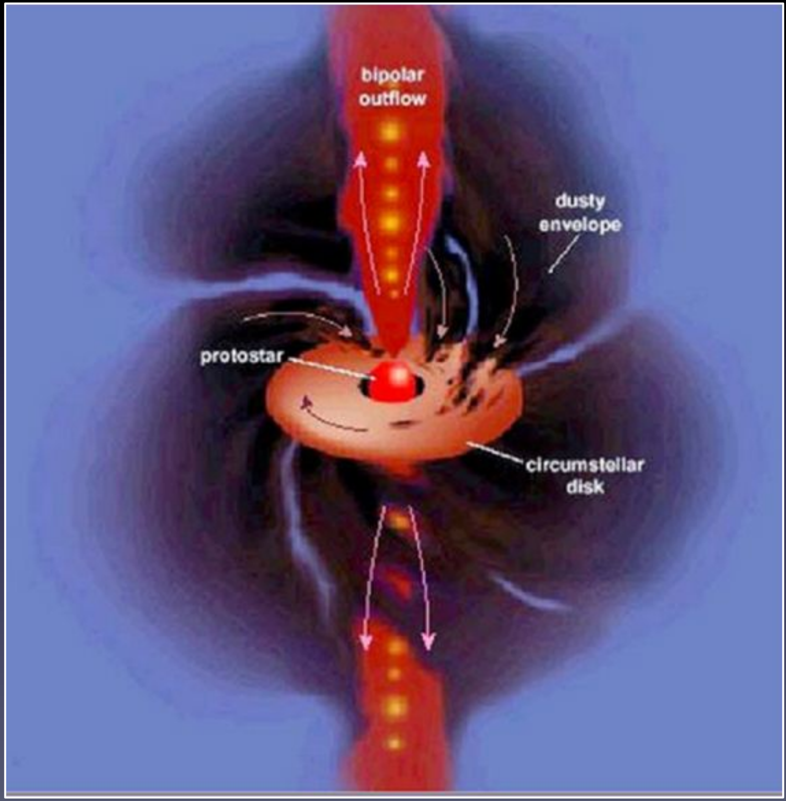
Cartoon of accretion/ejection



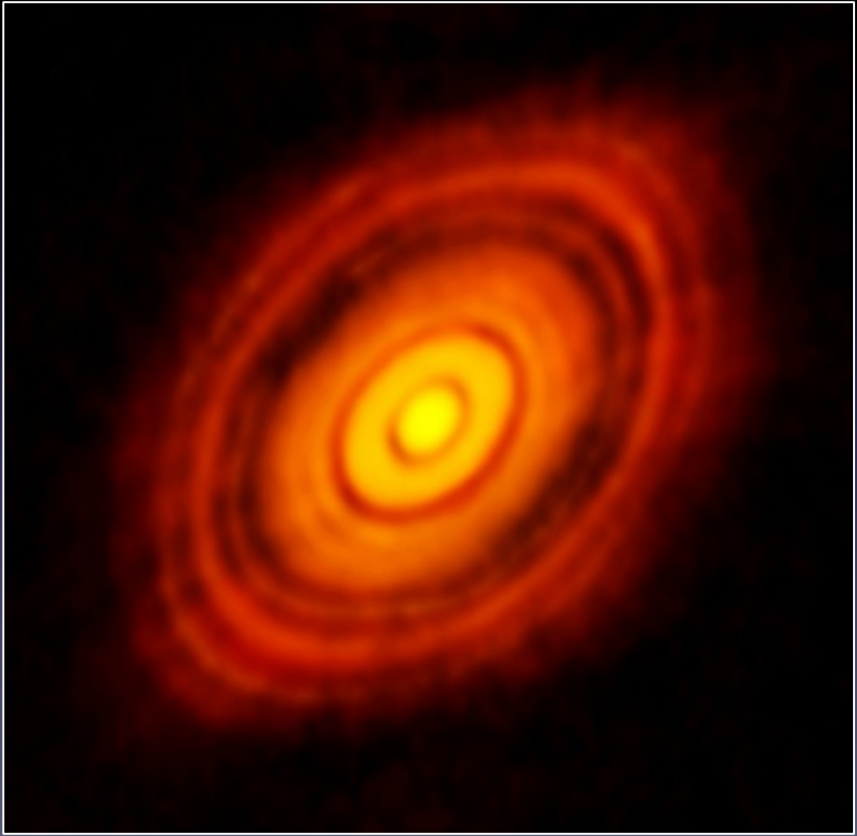
- Shu (77) SIS model considers free-fall accretion from envelope
- Accretion luminosity depends on accretion rate onto stellar surface
- Beetween envelope and star we expect to have a disk!
- No expectation for steady flow through the disk and onto star

Importance of the Disk

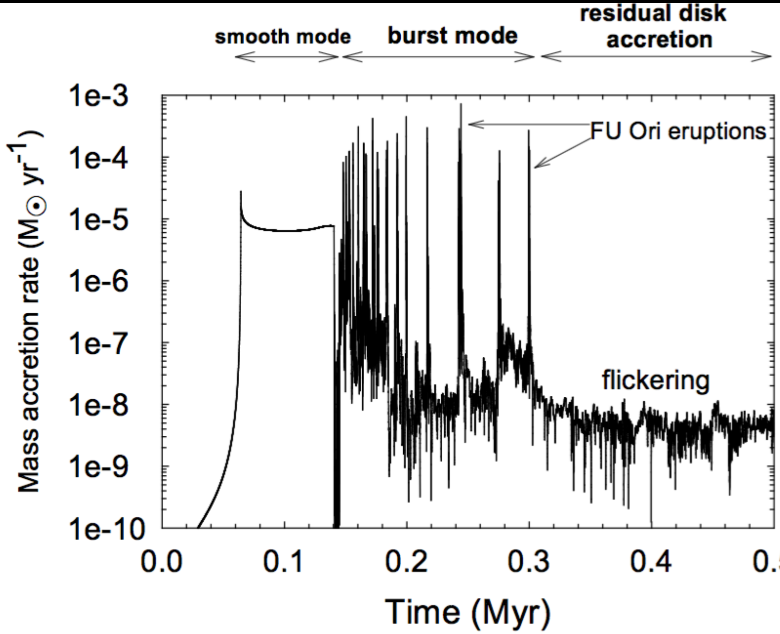
Cartoon of accretion/ejection

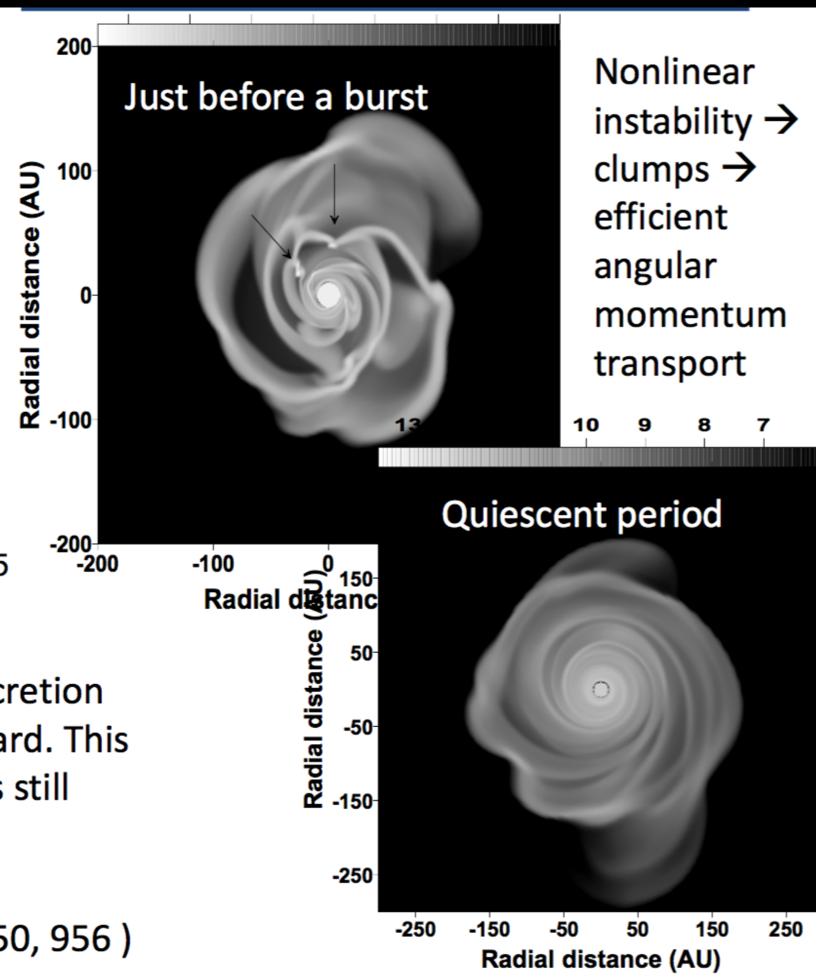


HL Tau disk observed with ALMA (rings)



Numerical Simulation of the Disk





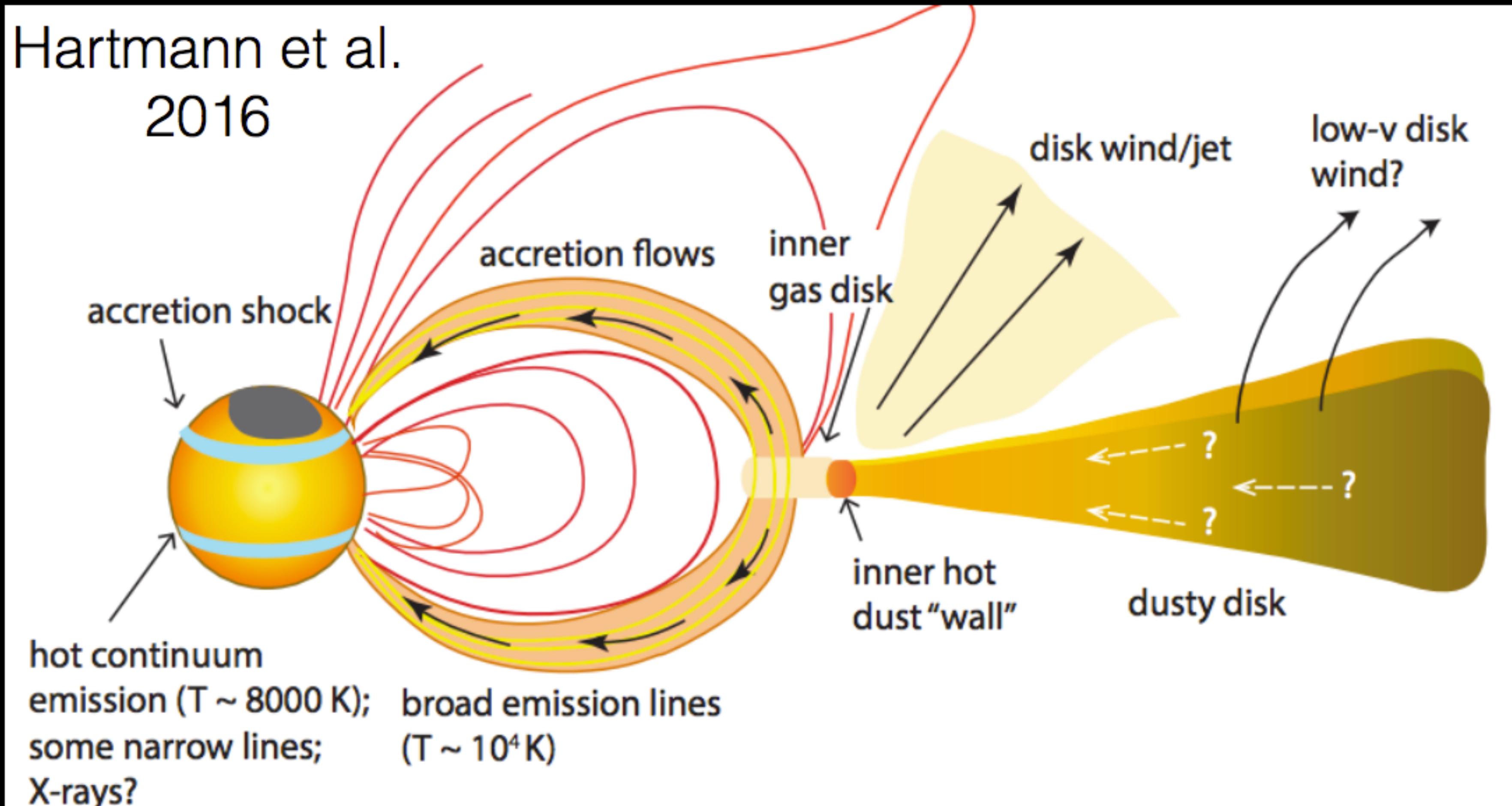
Nonlinear instability → clumps → efficient angular momentum transport

Bursts of accretion occur during the early accretion phase, as clumps are formed and driven inward. This is followed by a more quiescent phase that is still characterized by flickering accretion.

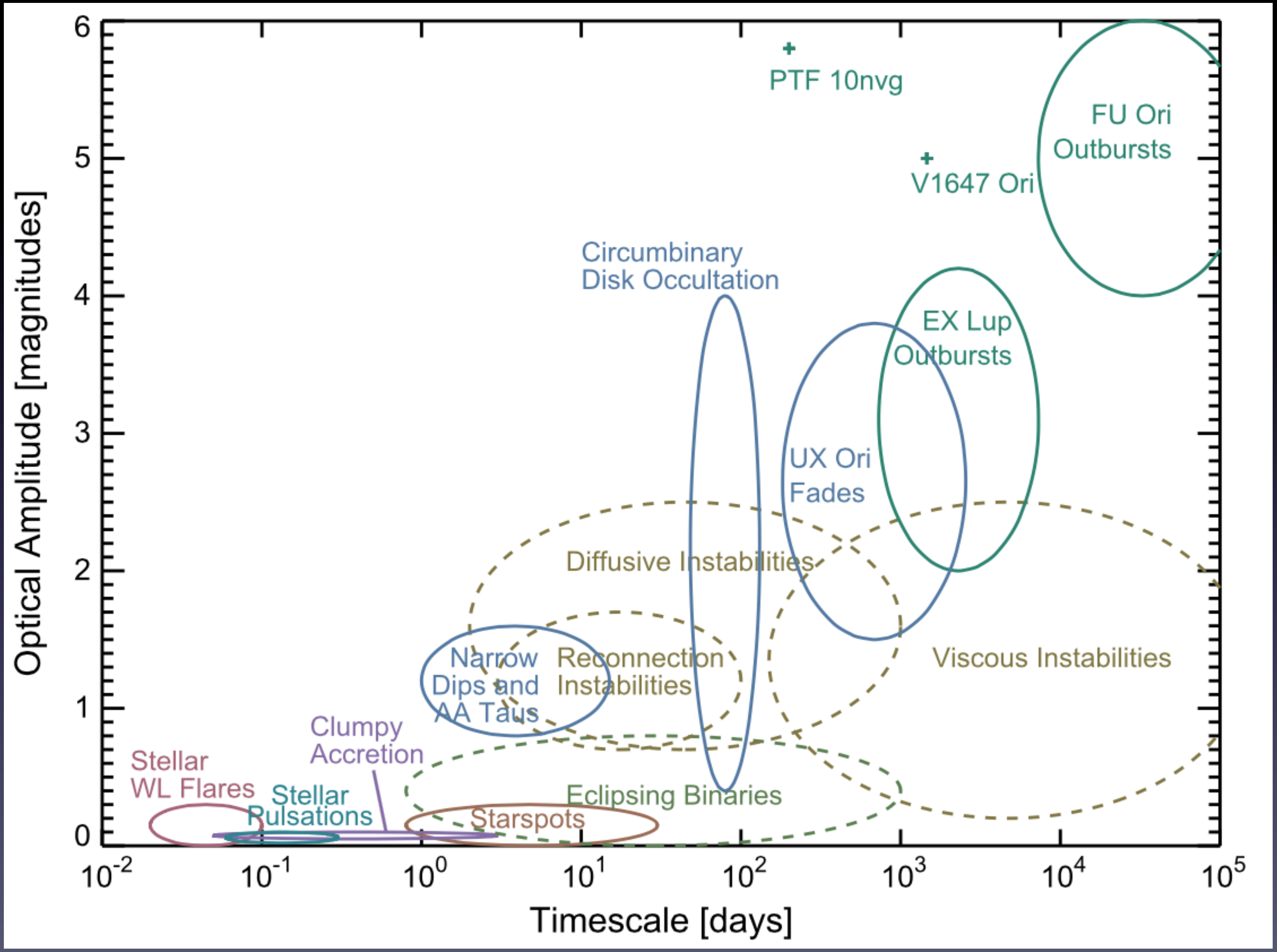
Vorobyov & Basu (2006, ApJ, 650, 956)

Gravitational instability shown but also MRI instabilities, etc …

Importance of the Inner Disk



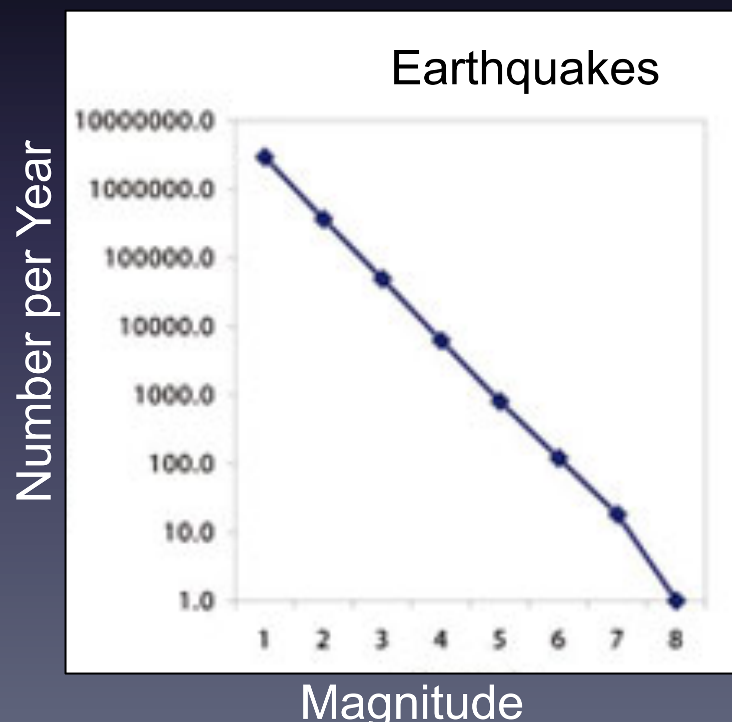
A Range of Possible Timescales
Probing both location and physics

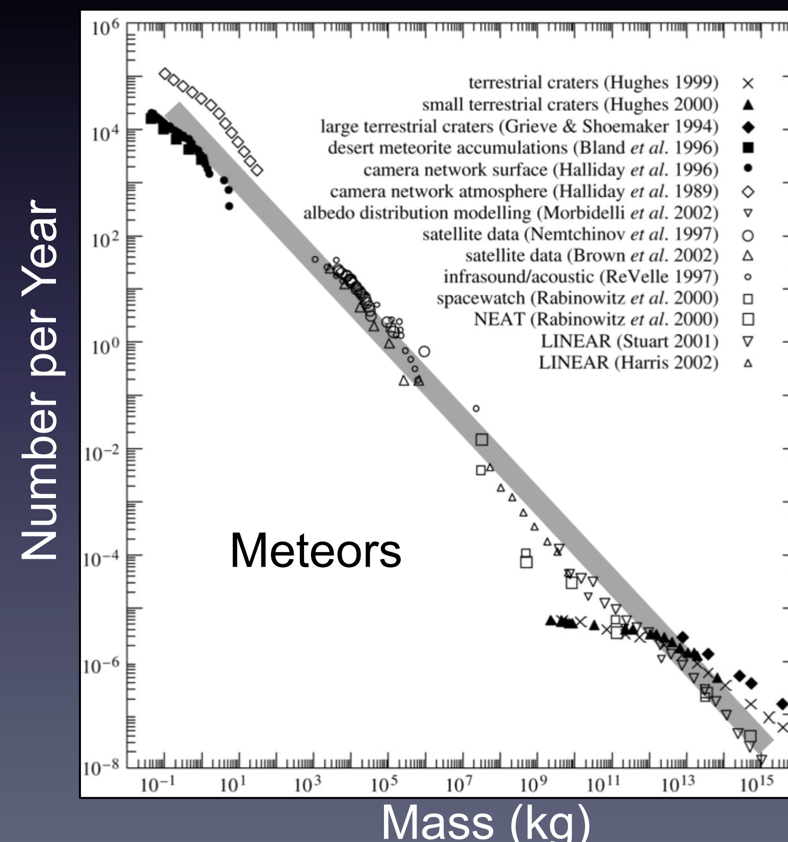


Hillenbrand & Findeisen 2015

Aside: Variability and Accretion

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





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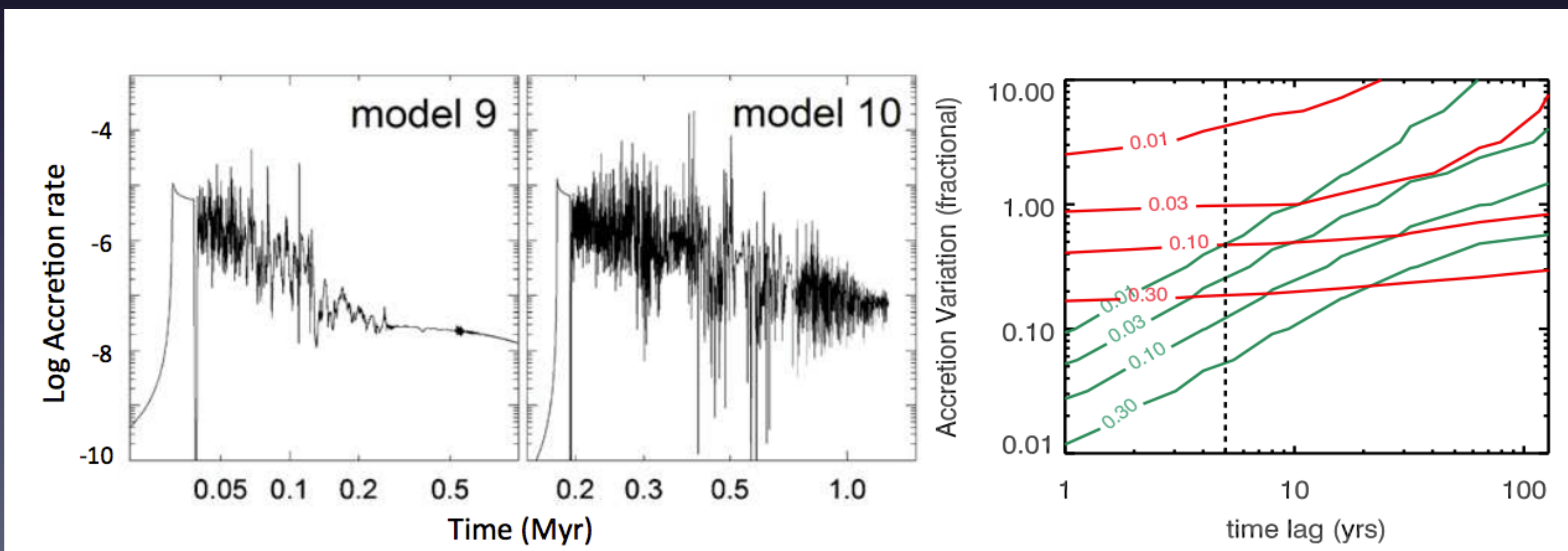
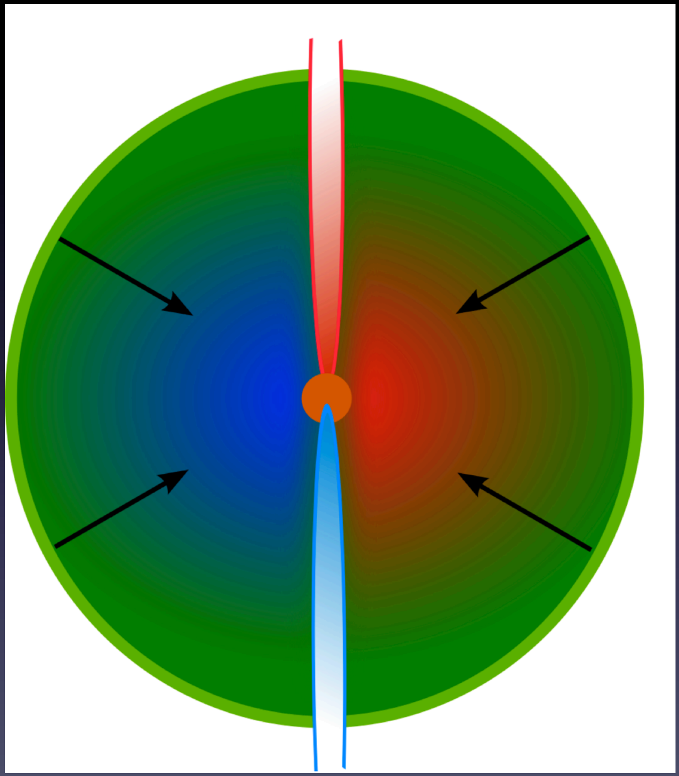


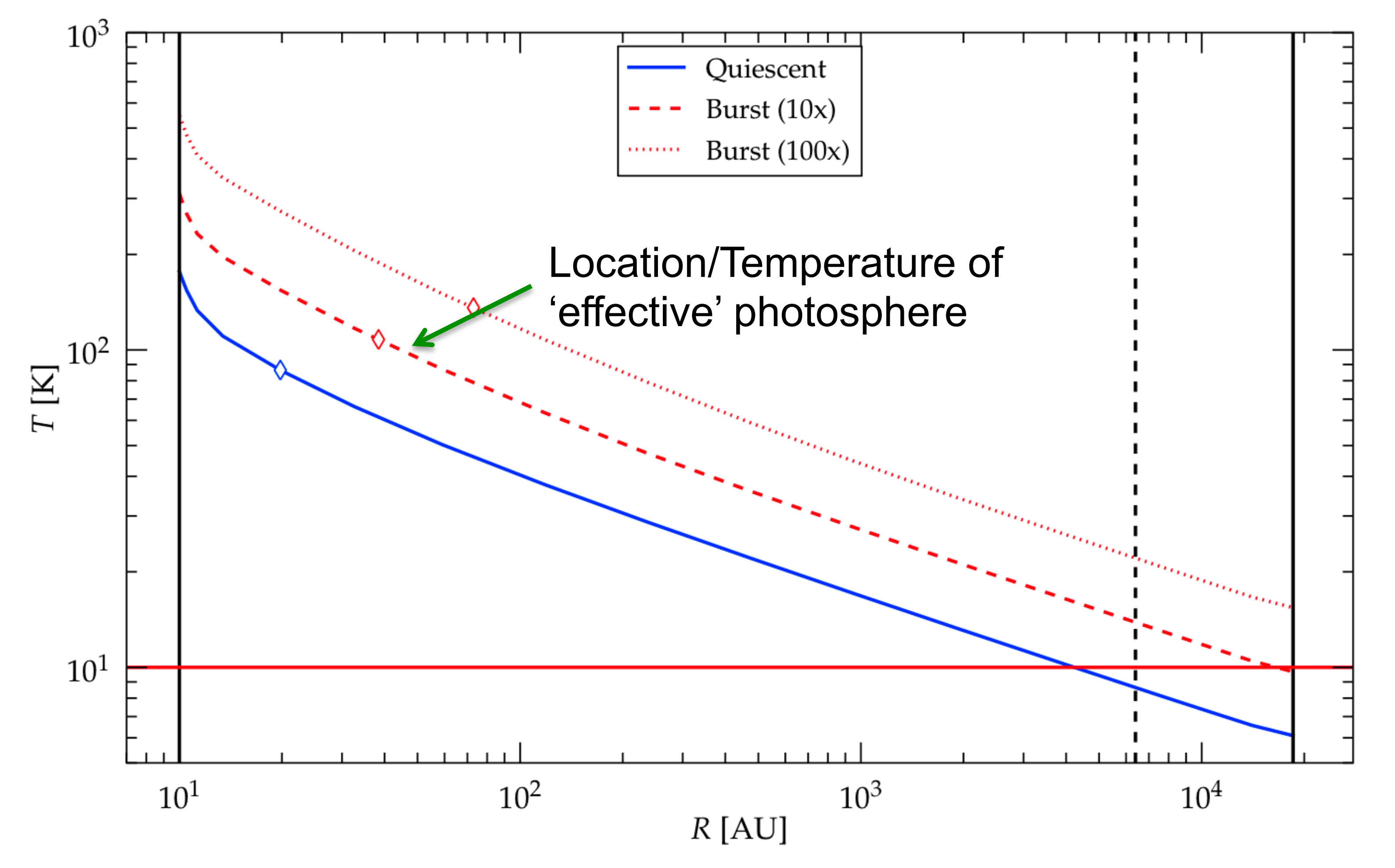
Protostellar Envelope Toy Model

- Density structure follows SIS inside-out collapse
  - M_{env} = 1.5 M_{sun}
  - R_{env} = $2x10^4$ AU
  - R_x = $6x10^3$ AU
    - transition from static to infall
- Protostellar mass ~ 0.25 M_{sun}
- Luminosities:
  - L_{PS} = 1.2 L_{sun}
  - L_{acc} = 5 L_{sun} (if steady-state: c_s^3/G)
  - L_{10} = 12 L_{sun}
  - L_{100} = 120 L_{Sun}



Implications of Variable Accretion - I

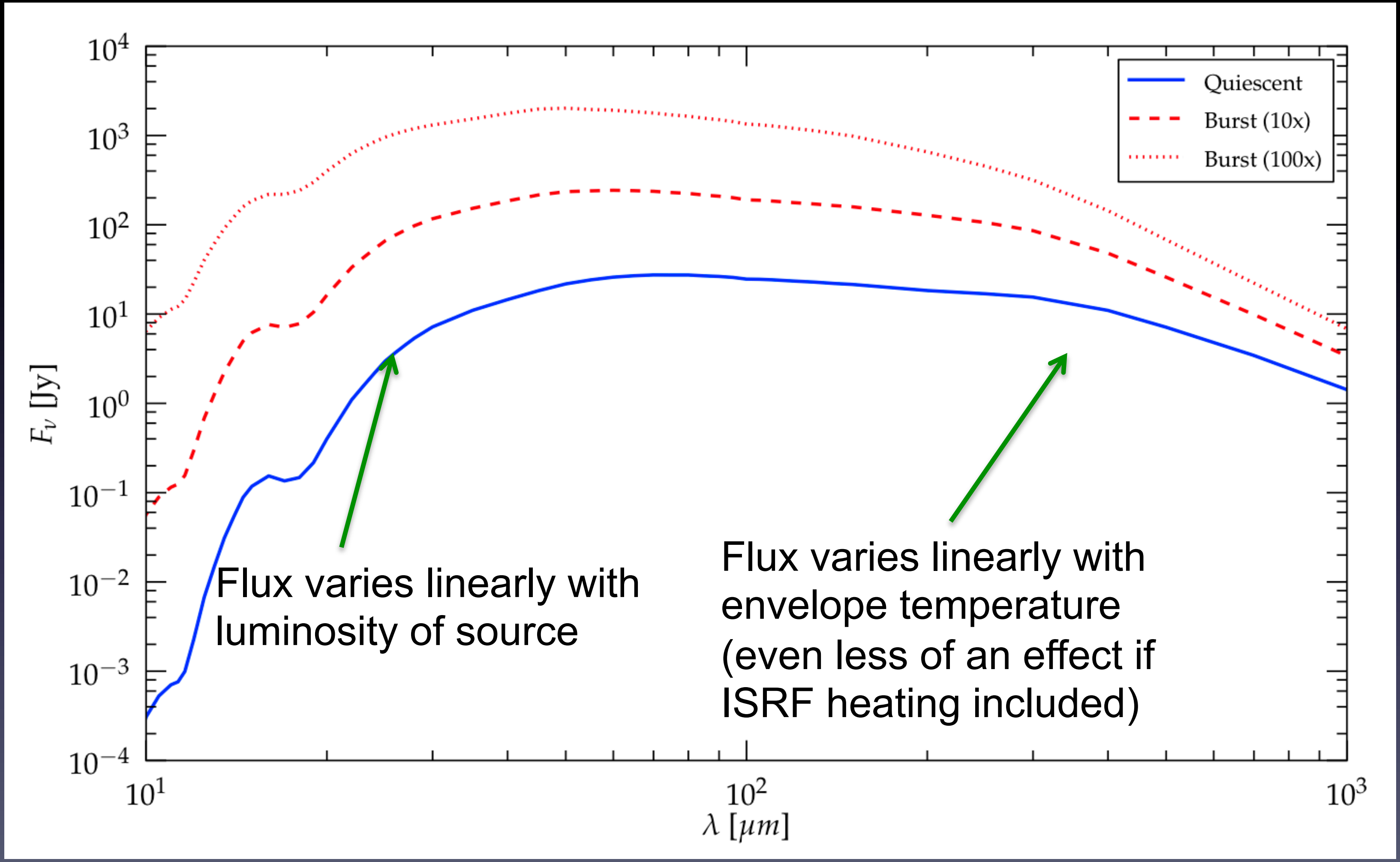
Temperature profile of the envelope responds to accretion luminosity.



Dusty Model: Ivezic & Elitzur 1997

Implications of Variable Accretion - II

Luminosity of Source higher -> SED shifts to the blue (Warmer)



Dusty Model: Ivezic & Elitzur 1997

Implications of Variable Accretion - III

Dust must be heated to these new temperatures …

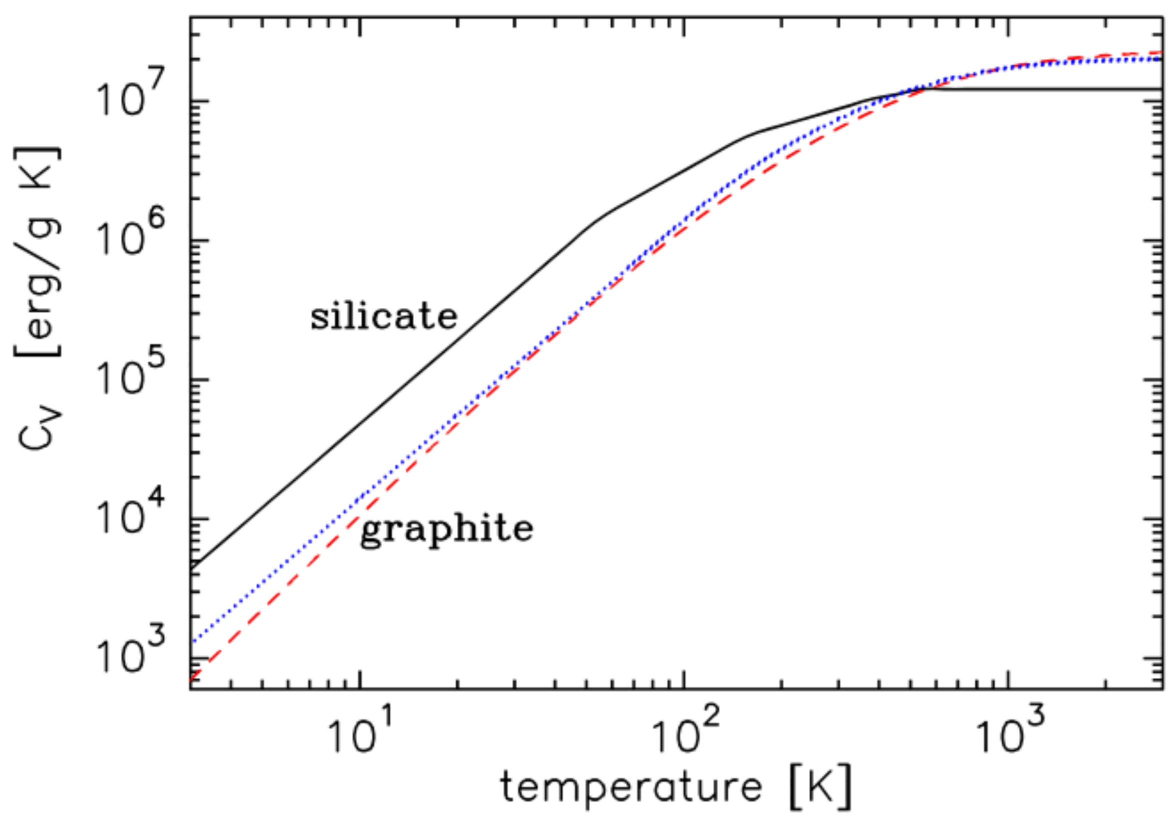
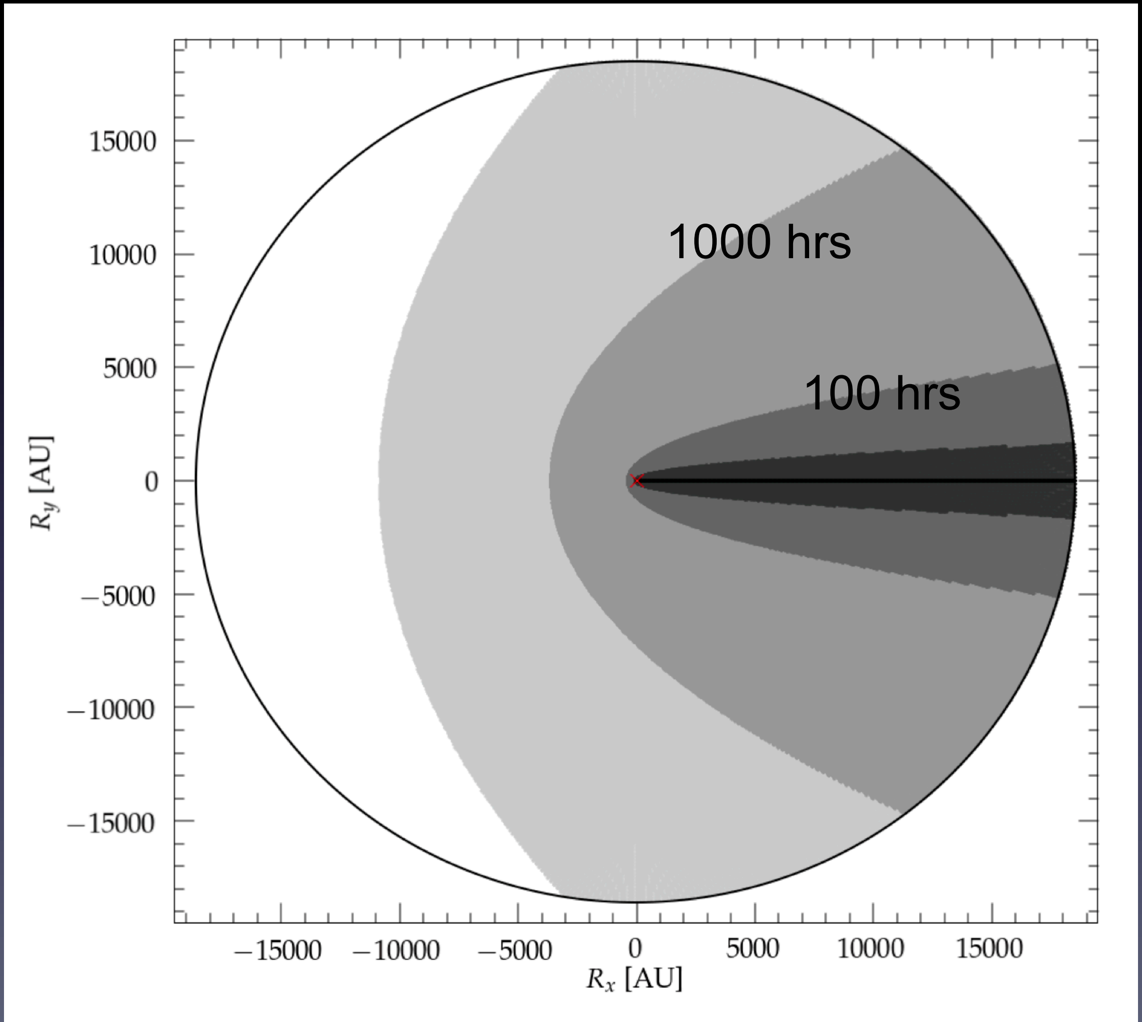


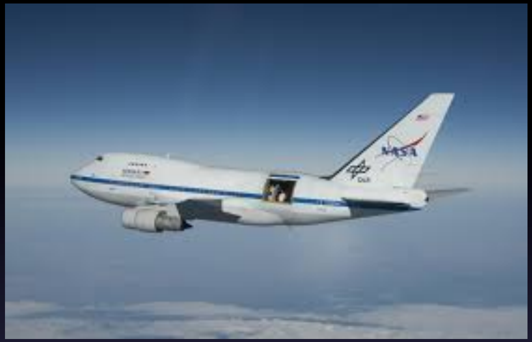
Figure 8.9. The specific heat per gram of dust for silicate (full curve, similar to [Guh89]), graphite (broken curve, after [Cha85]) and PAHs without hydrogen atoms (dotted curve, after [Kru53] using (8.44)).

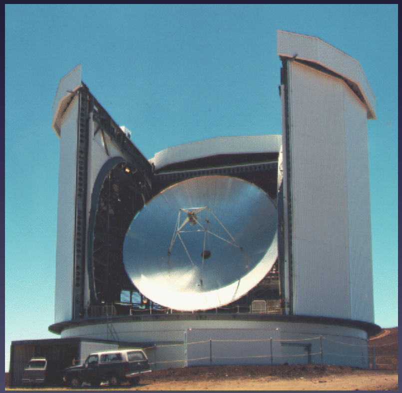
Guhathakurta & Draine 1989, ApJ, 345, 230

Implications of Variable Accretion - IV

Light propagation time must be taken into account …



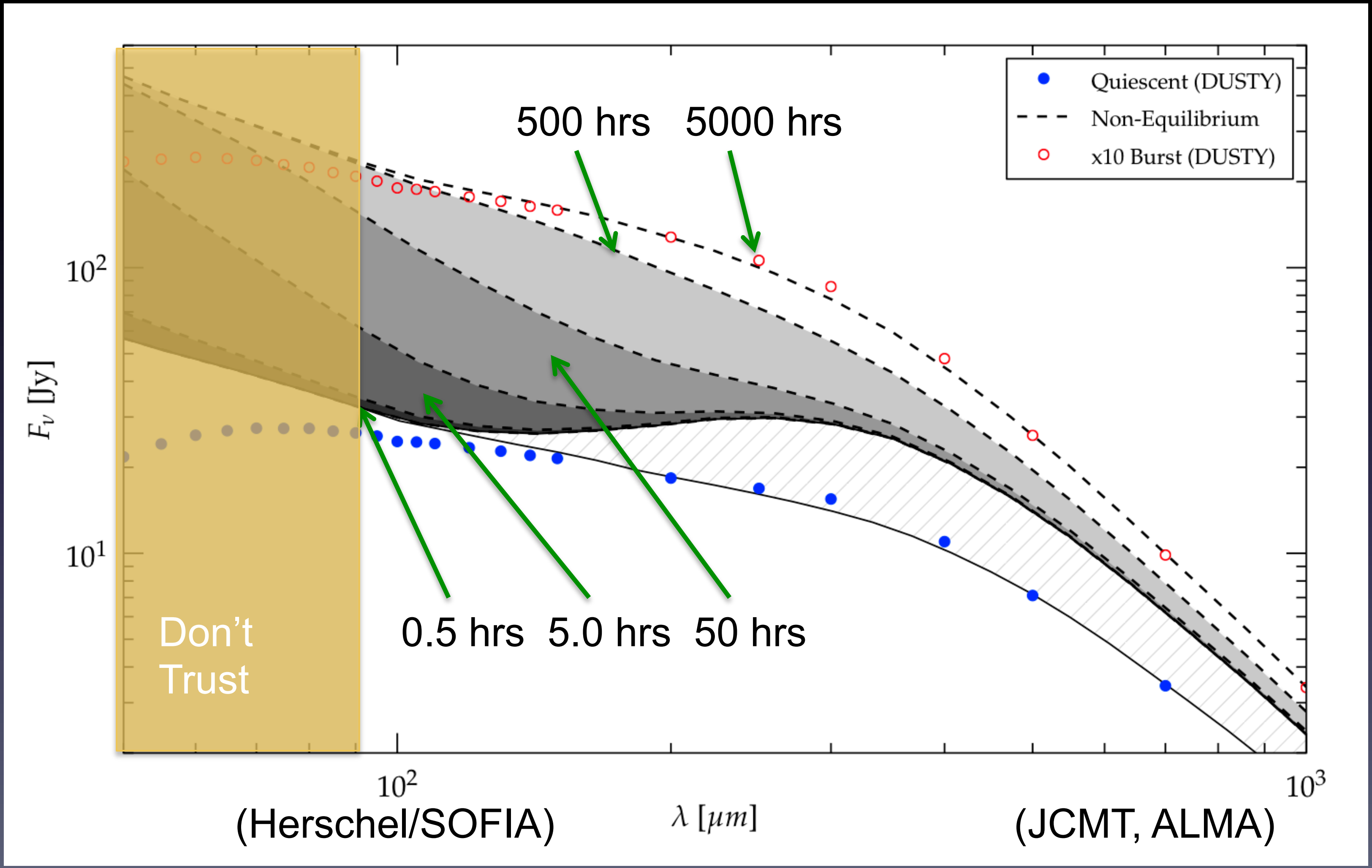




Crossing time at the effective photosphere is ~ day (R_{ph} ~ 100 AU)

Implications of Variable Accretion - V

The observable timescale for variability can be assessed:



Implications of Variable Accretion - VI

What about the gas?

- Gas heat capacity is $C_g \sim k/m_p \gg C_d$ and 100 x more mass in gas
- Therefore, time to heat gas >> than time to heat dust

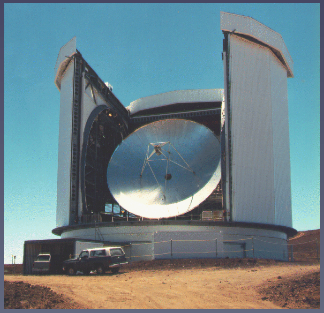
- Assuming effective coupling between gas and dust
  - inner regions ($R \sim 10^2$ AU) take $\sim 10^5$ s to heat (day)
    - On par with light crossing time
  - intermediate regions ($R \sim 10^3$ AU) take $\sim 10^8$ s to heat (years)
    - Longer than light crossing time

Mismatch suggests gas may trace history of accretion while dust follows the instantaneous accretion state.

- Visser et al 2015, Jorgensen et al 2015, Frimann et al 2015

Possible Observing Strategies:

1. Monitor at short wavelengths (near peak of SED) for variations
   - Maximal change in brightness, shortest delay times
   - Herschel (archive) ~70 microns, SOFIA-HAWC+, CCAT ?
   - Lack of truly appropriate instruments available for this purpose (cadence)
2. Monitor at longer wavelengths
   - Large aperture mapping: dominated by outer envelope (JCMT-SCUBA-2)
   - Small aperture pointings: probe photosphere (ALMA)
3. Follow (and follow-up) interesting sources with interferometry (ALMA)
   - Both time-dependent and wavelength dependent observations
   - In principle can use reverberation mapping to uncover structure of envelope



EAO/JCMT Transient Survey
[150 hrs, 8 fields, 3 yrs, monthly cadence]

Coordinators

Doug Johnstone (co-PI; Canada)

Greg Herczeg (co-PI; China)

Vivien Chen (Taiwan)

Yuri Aikawa (Japan)

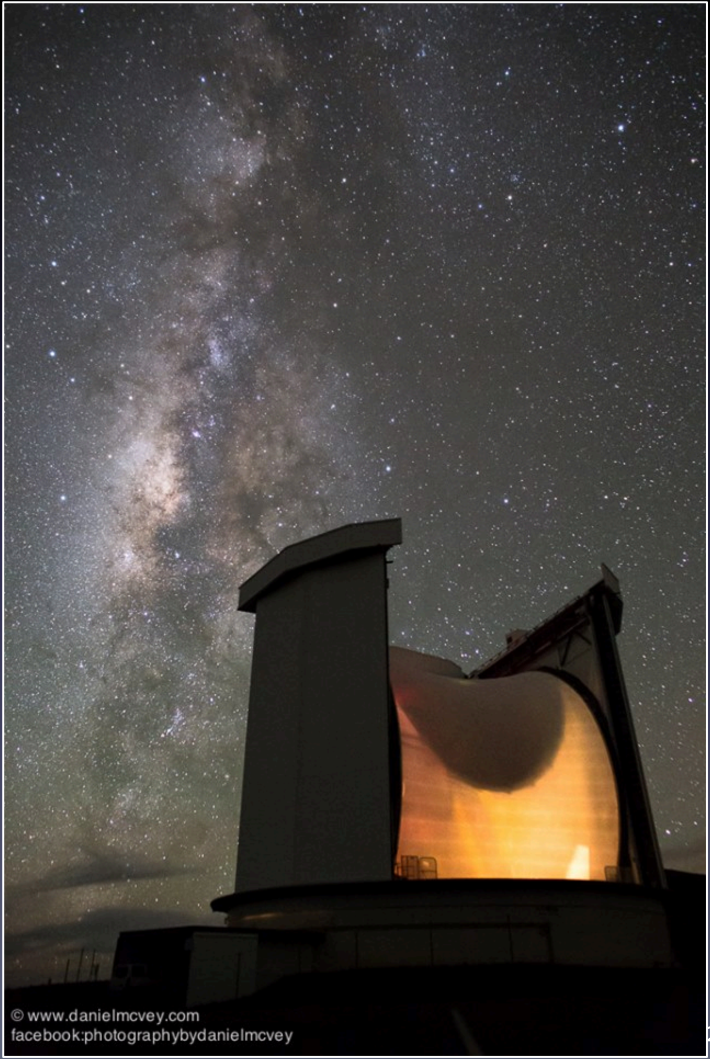
Geoff Bower (Taiwan)

Jennifer Hatchell (UK)

Jeong-Eun Lee (Korea)

65 international team members

(9 CA, 13 CN, 4 EAO, 3 JPN, 14 KR, 17 TW, 10 UK)

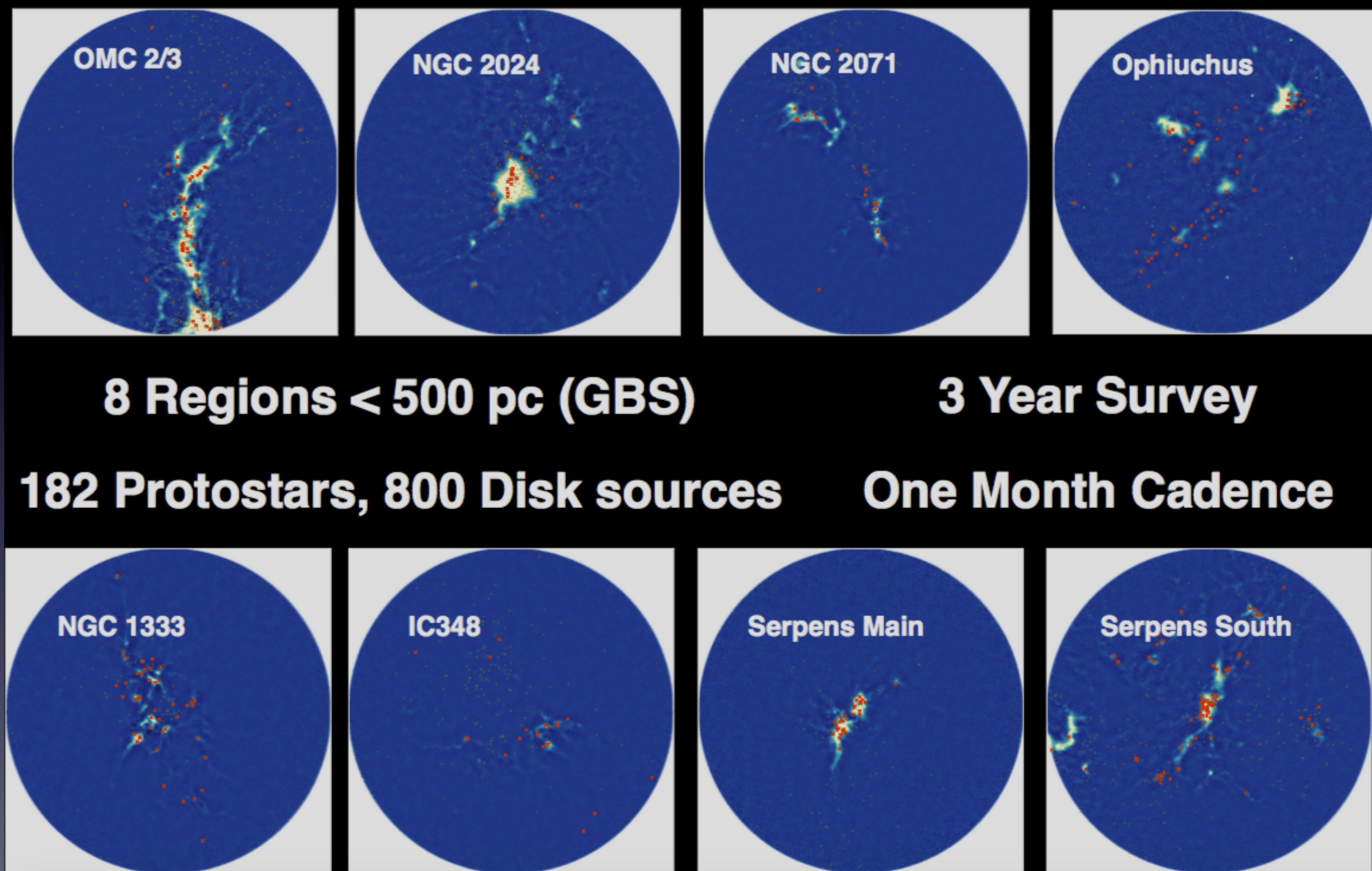


Observation Strategy

- Eight regions observed as 30' diameter fields
- Each region observed once per month for three years
  - Just under 25% complete so far
- Monitor for signs of variability across epochs
  - Compare against previous GBS observations (> 5 yr baseline!)
- Co-add epochs to produce deepest sub-mm images of each region
  - Reach extragalactic confusion limit!

		SCUBA-2 peak flux/beam			Spitzer Sources		
Name	Location	> 0.2 Jy	> 0.5 Jy	> 1.0 Jy	Class 0/I	Flat	Class II
Perseus - NGC1333	032854+311652	27	9	5	31	13	57
Perseus - IC348	034418+320459	5	3	2	11	6	94
Orion A - OMC2/3	053531-050038	60	30	17	32	29	158
Orion B - NGC2024	054141-015351	21	9	5	11	12	87
Orion B - NGC2071	054613-000605	25	11	4	14	5	54
Ophiuchus	162705-243237	26	5	2	18	27	60
Serpens Main	182949+011520	14	10	7	18	10	47
Serpens South	183002-020248	20	5	2	47	30	113

EAO/JCMT Transient Survey

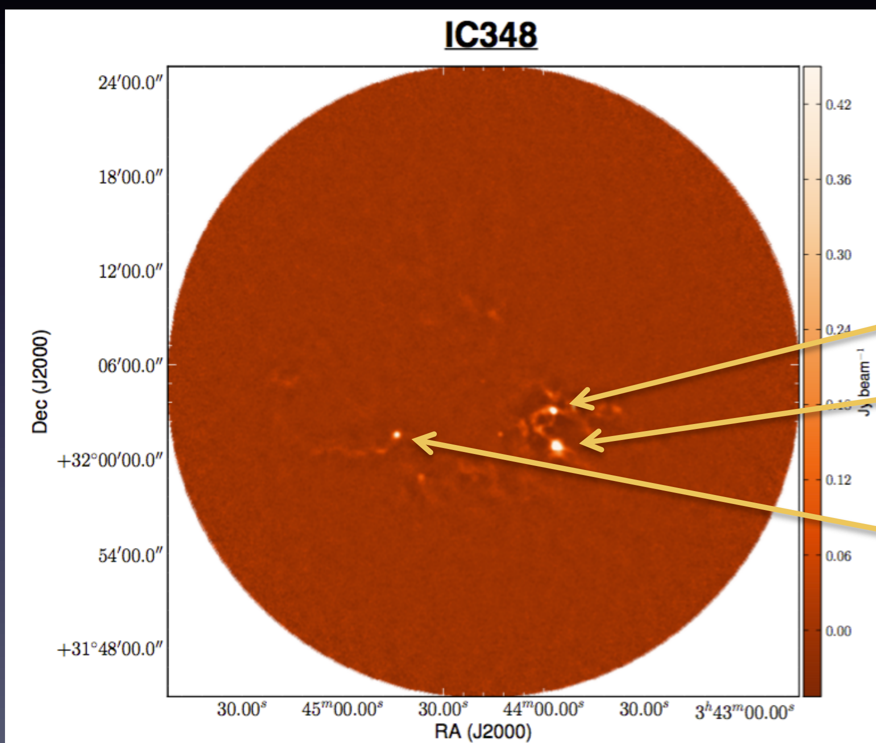


Analysis Methodology

Run Source-Finder on all observations of the same field.

Determine which sources are in common between observations.

Compare clump centroids and relative brightness between observations.



Source-Finder Output

Peak flux, Centroid_x,y

Peak flux, Centroid_x,y

Peak flux, Centroid_x,y

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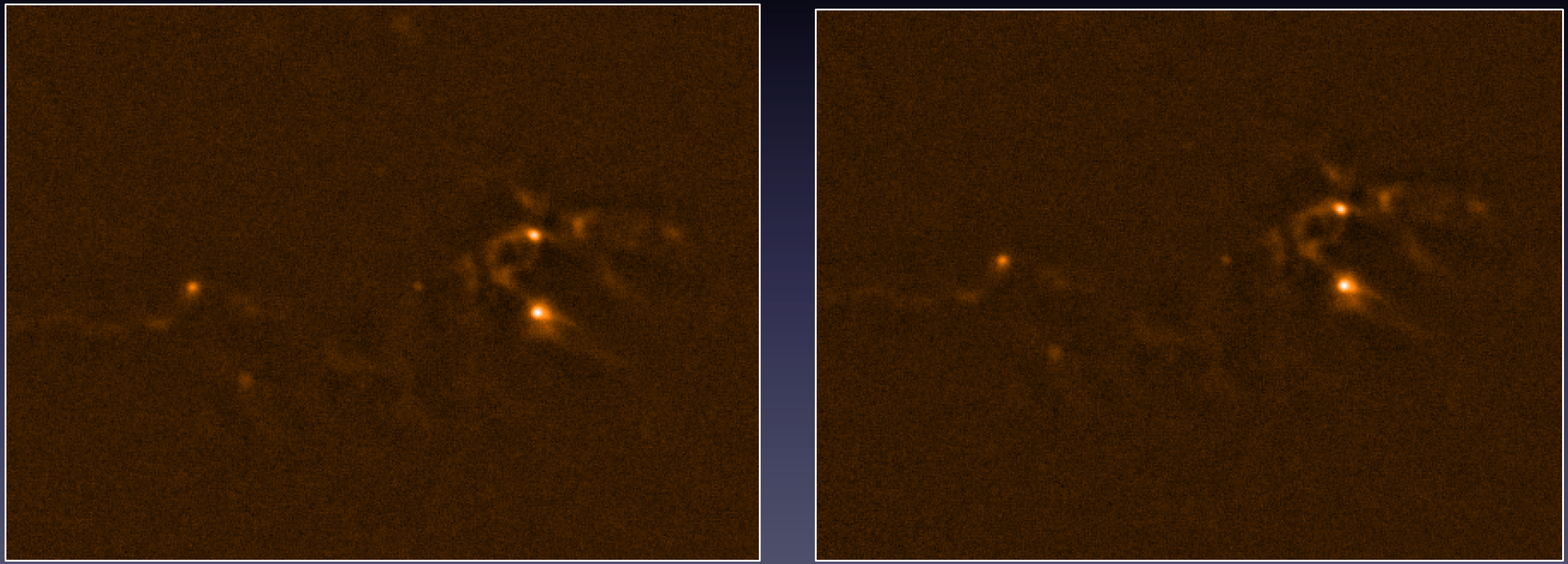
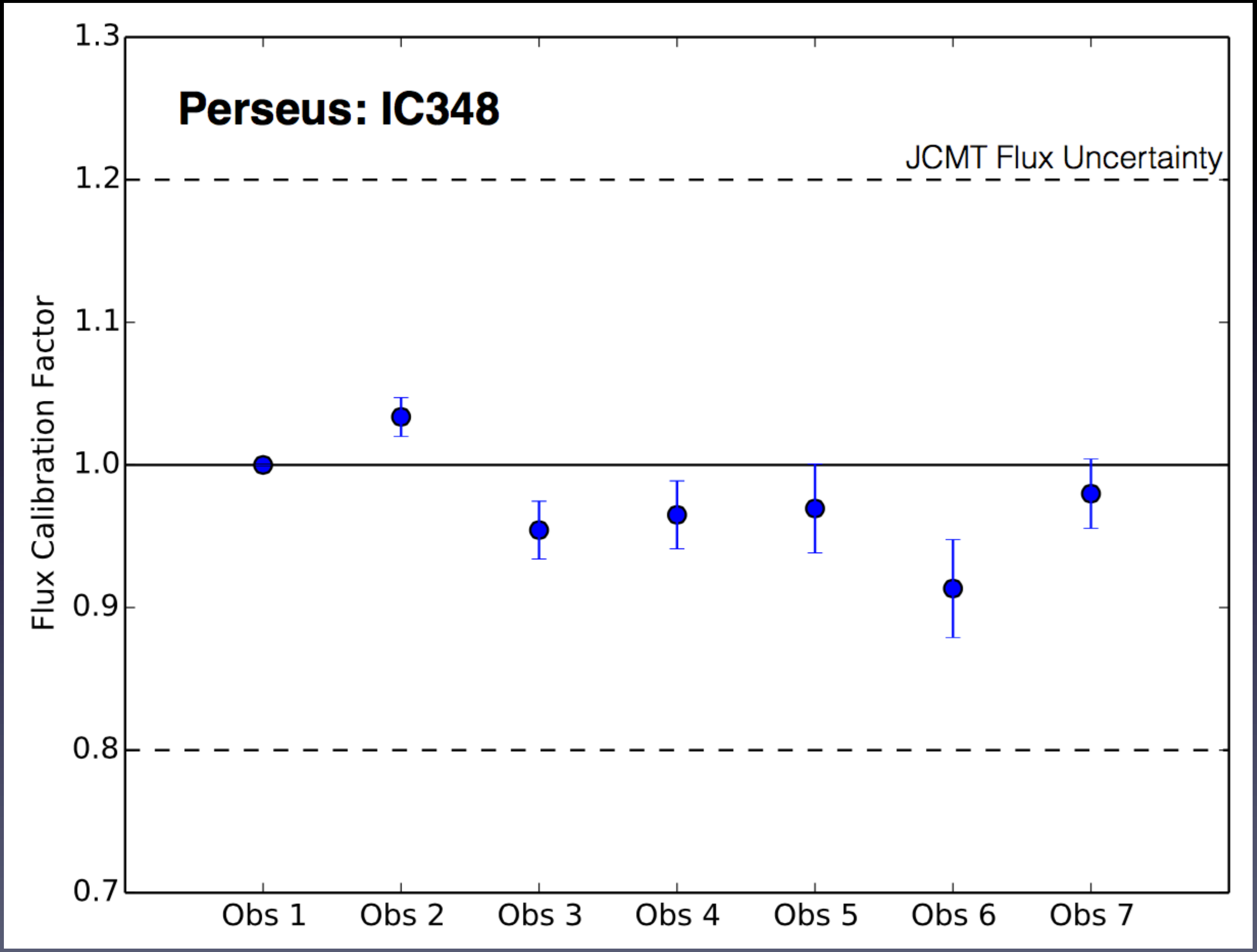


Six epochs of IC348 observed over half a year.
Left: Before residual offset calibration; Right: after applying offset.

Analysis Methodology

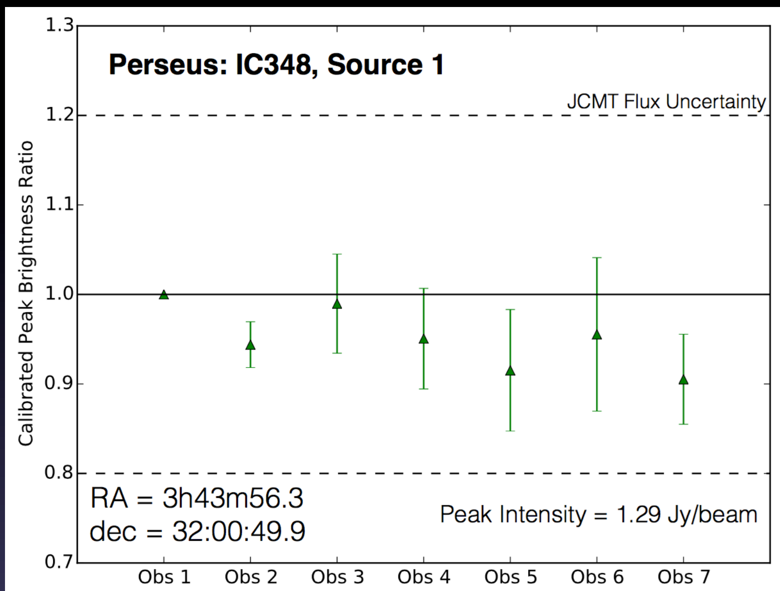
Compare Brightness of Clumps Over Time: First Calibrate

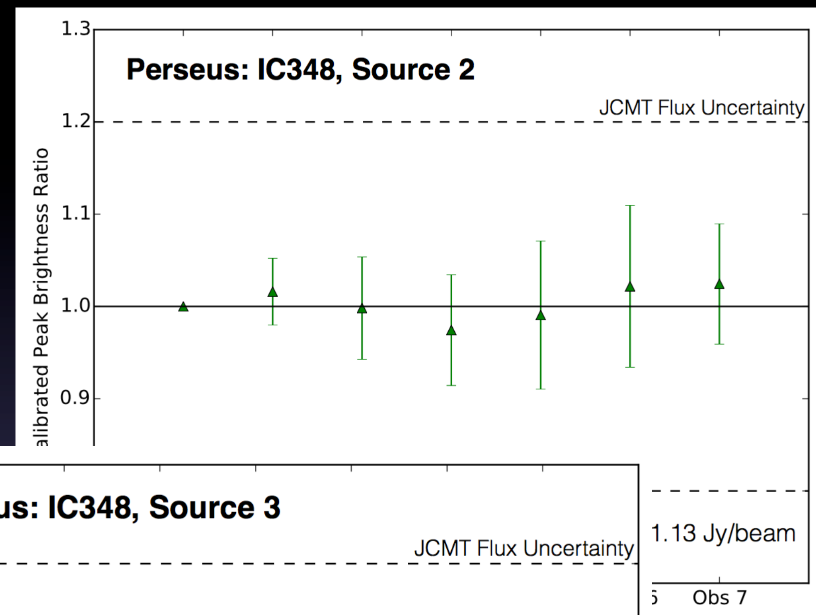


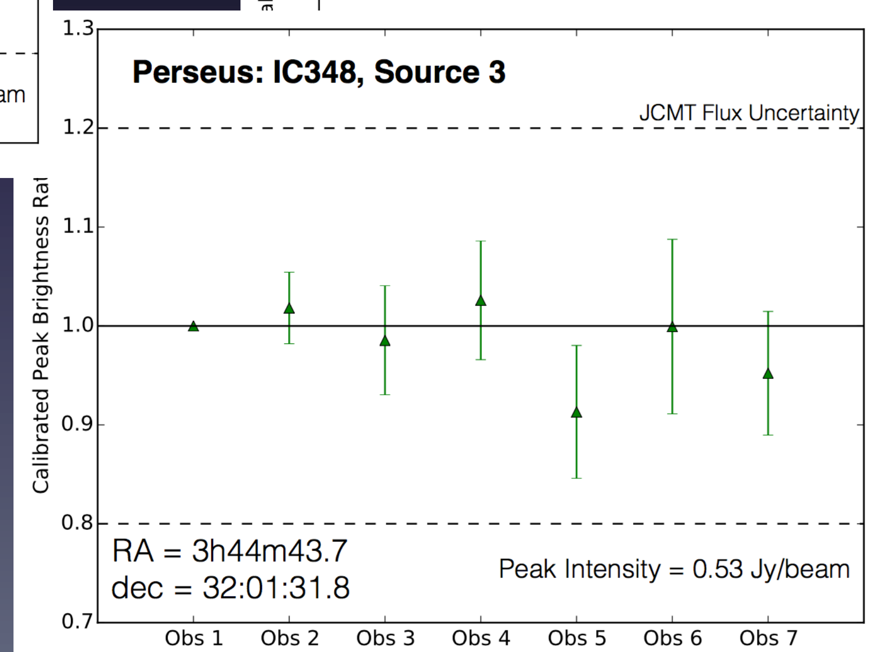
Seven epochs of IC348:

Analysis Methodology

Compare Brightness of Clumps Over Time: Sources







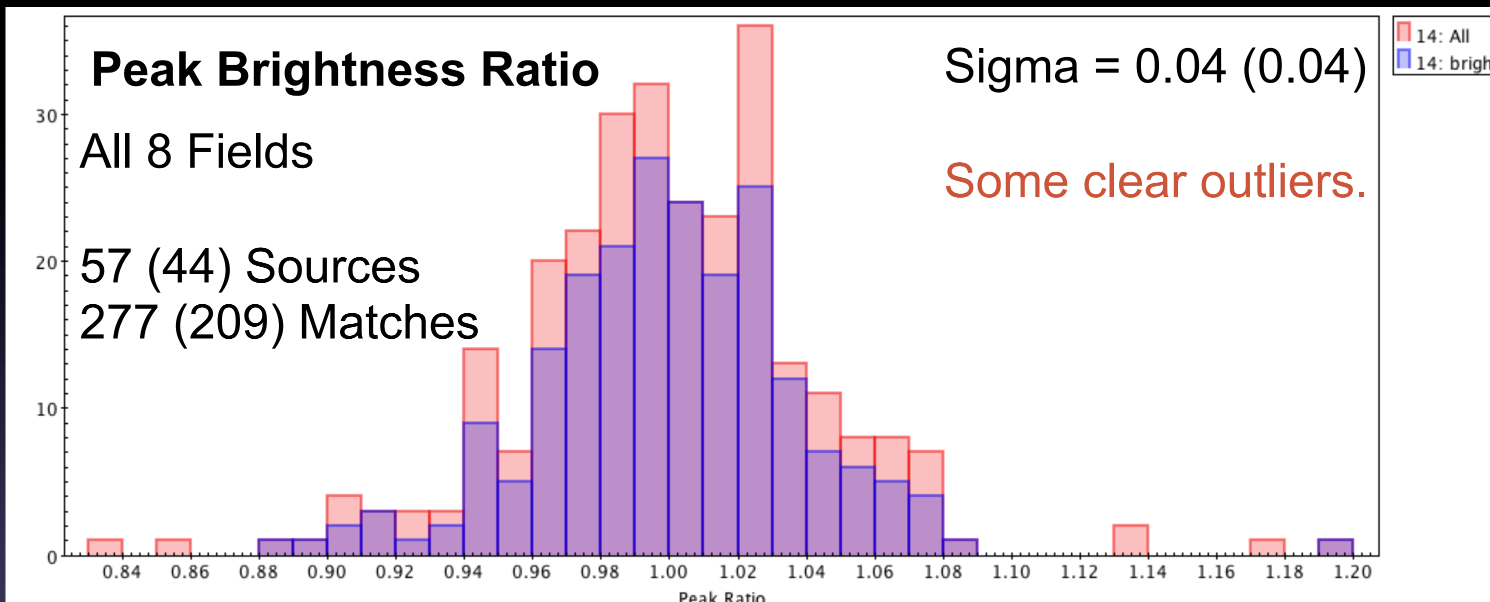
Seven epochs of IC348:

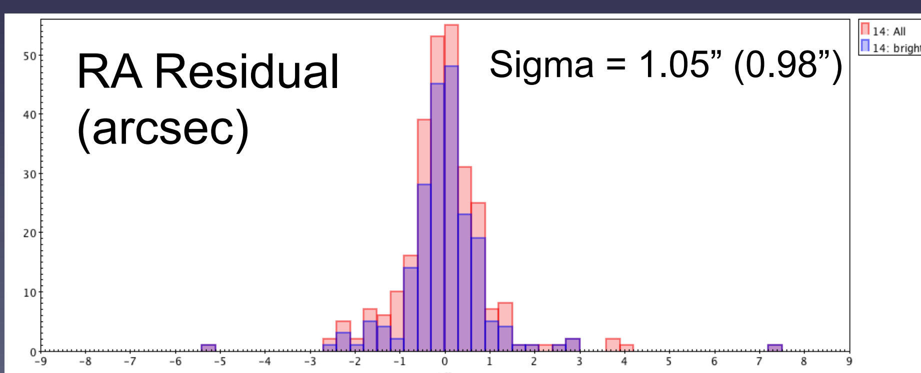
No evidence of variability yet and obtaining an uncertainty of ~ 3% (1 sigma)

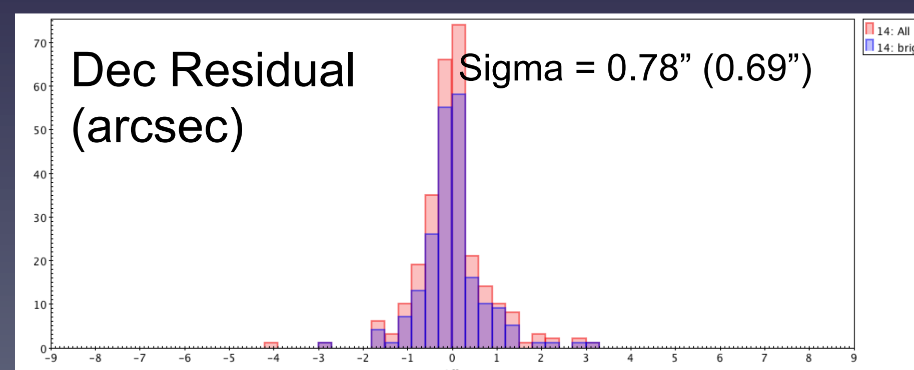
Still need to compare against GBS observations

Analysis Methodology

A variety of ensemble metrics suggest we'll reach 3 sigma ~ 10%







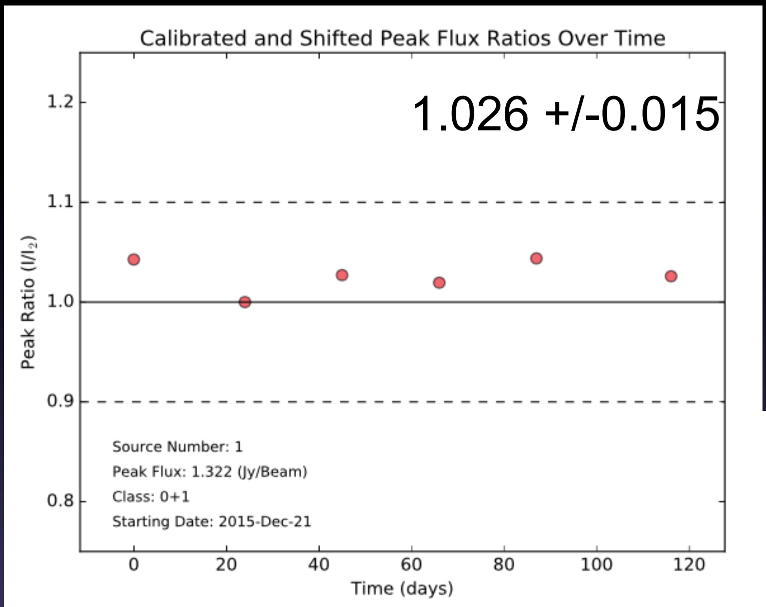
Variability of Deeply Embedded Protostars

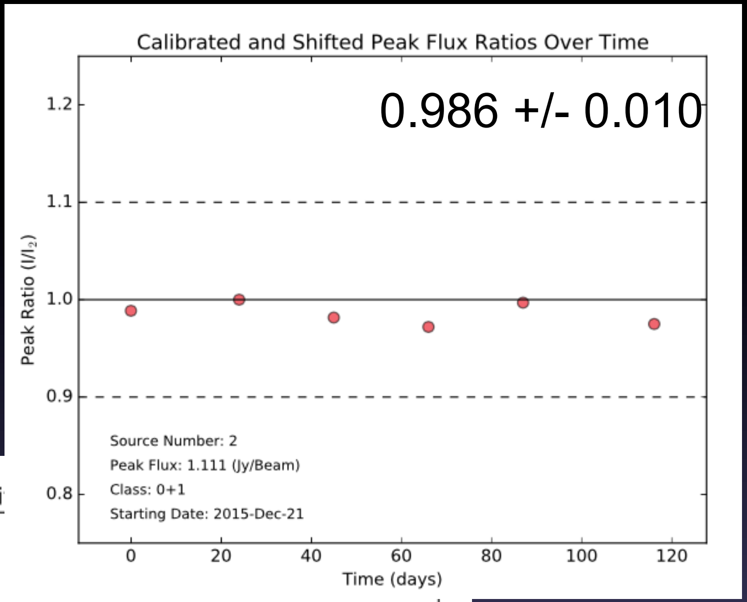
- The mass of a protostar grows through (variable) accretion of the natal envelope
  - Mediated, probably, by a complex circumstellar disk
- The luminosity of the protostar will react predictably to this varying accretion
  - hours to years, set by light crossing time
- This variability should be monitored
  - A direct probe of the underlying (disk) physics
- **SOFIA can play important role here!**

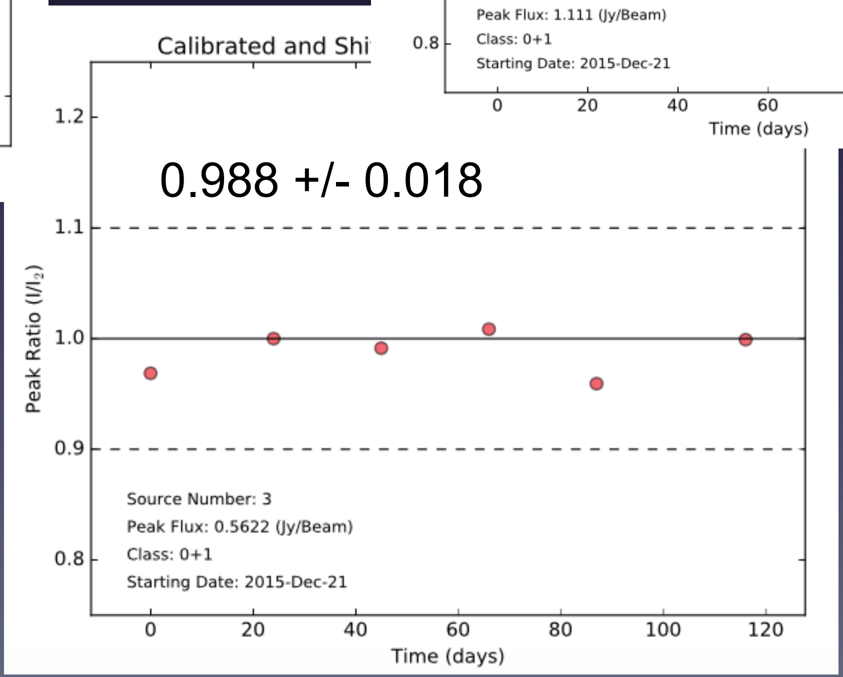
For further information read: Johnstone et al. 2013, 765, 133

Analysis Methodology

Compare Brightness of Clumps Over Time







Six epochs of IC348:
Note that the 2nd epoch is treated as the default.
Also note that we still need to add robust error bars to these data points!