Low Mass Star Formation in the Diverse Environments of Orion: Results from the Herschel Orion Protostar Survey

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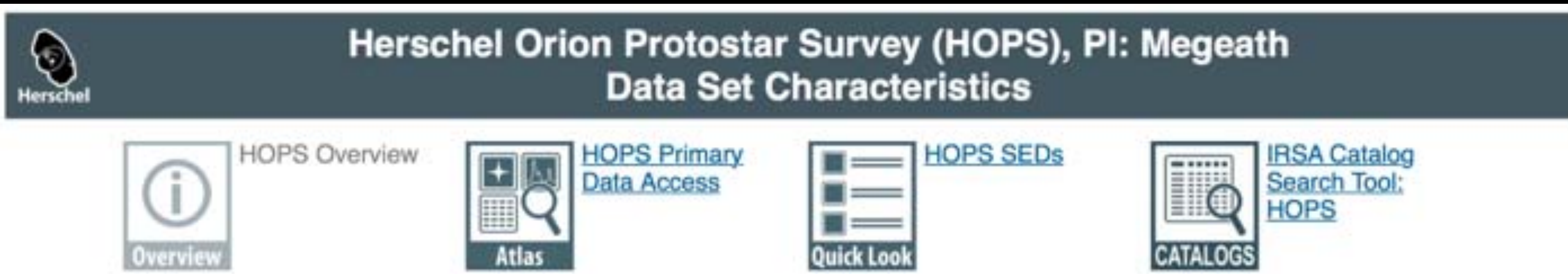
- PACS program to study Spitzer identified Orion Protostars (plus newly find Herschel Protostars)

- Imaging & SEDs
  - 110 square fields of 5′ to 8′ with PACS
  - 70 & 160 μm scans and cross-scans
  - 100 μm photometry from Gould Belt data
  - Spitzer 3.6-24 μm imaging
  - Spitzer 5- 40 μm spectra
  - HST WFC3/NICMOS imaging
  - APEX 870 and 350 μm imaging.

- Far-IR Line Spectroscopy
  - 33 targets; mix of pointed and mapping with PACS spectrometer
  - Coverage from 55 to 200 μm

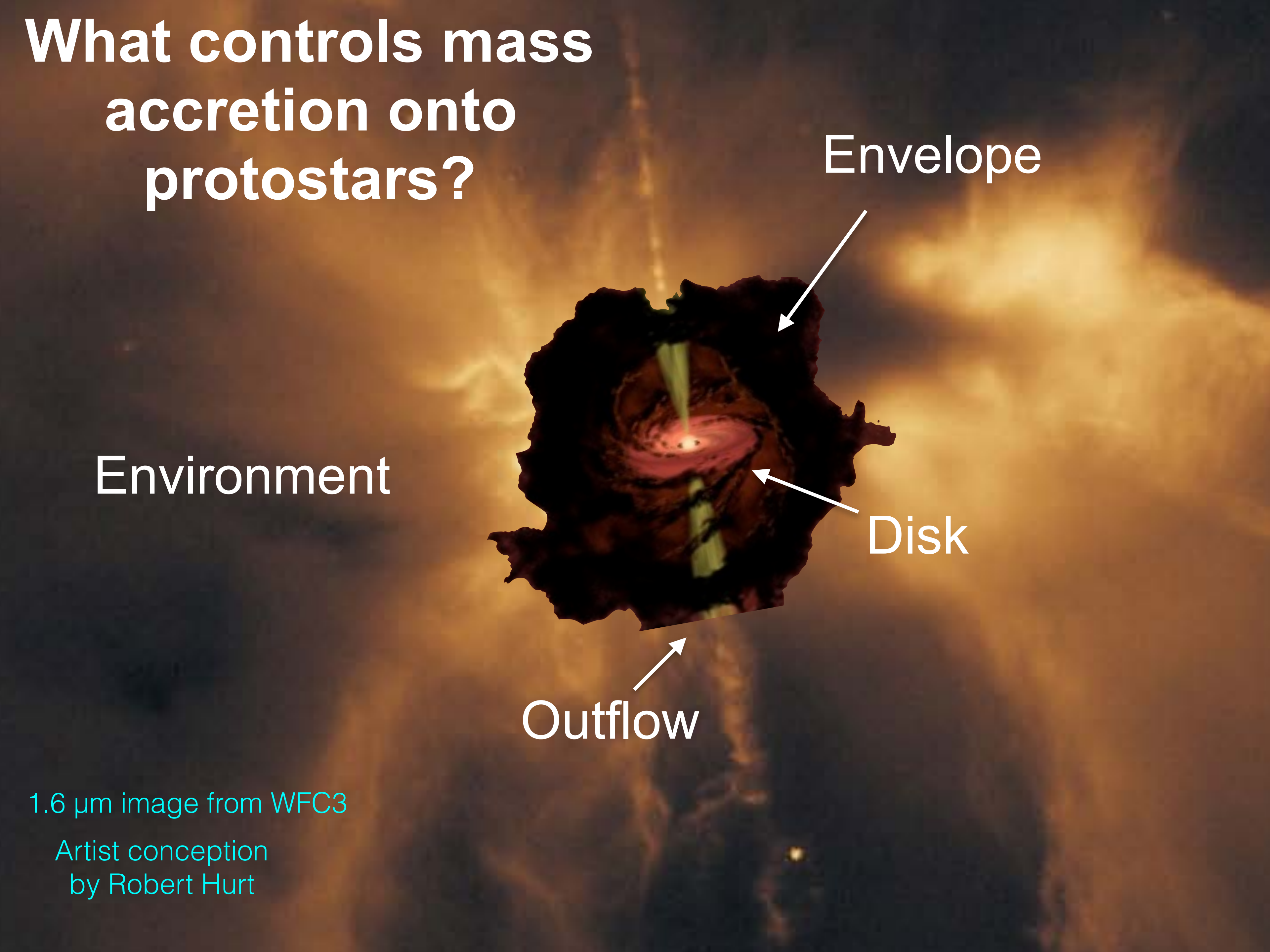
- Catalog of 330 YSOs (319 protostars)
  - 1.6 to 870 μm SEDs
  - luminosities and T_{bol}
  - fits to grid of 30400 models

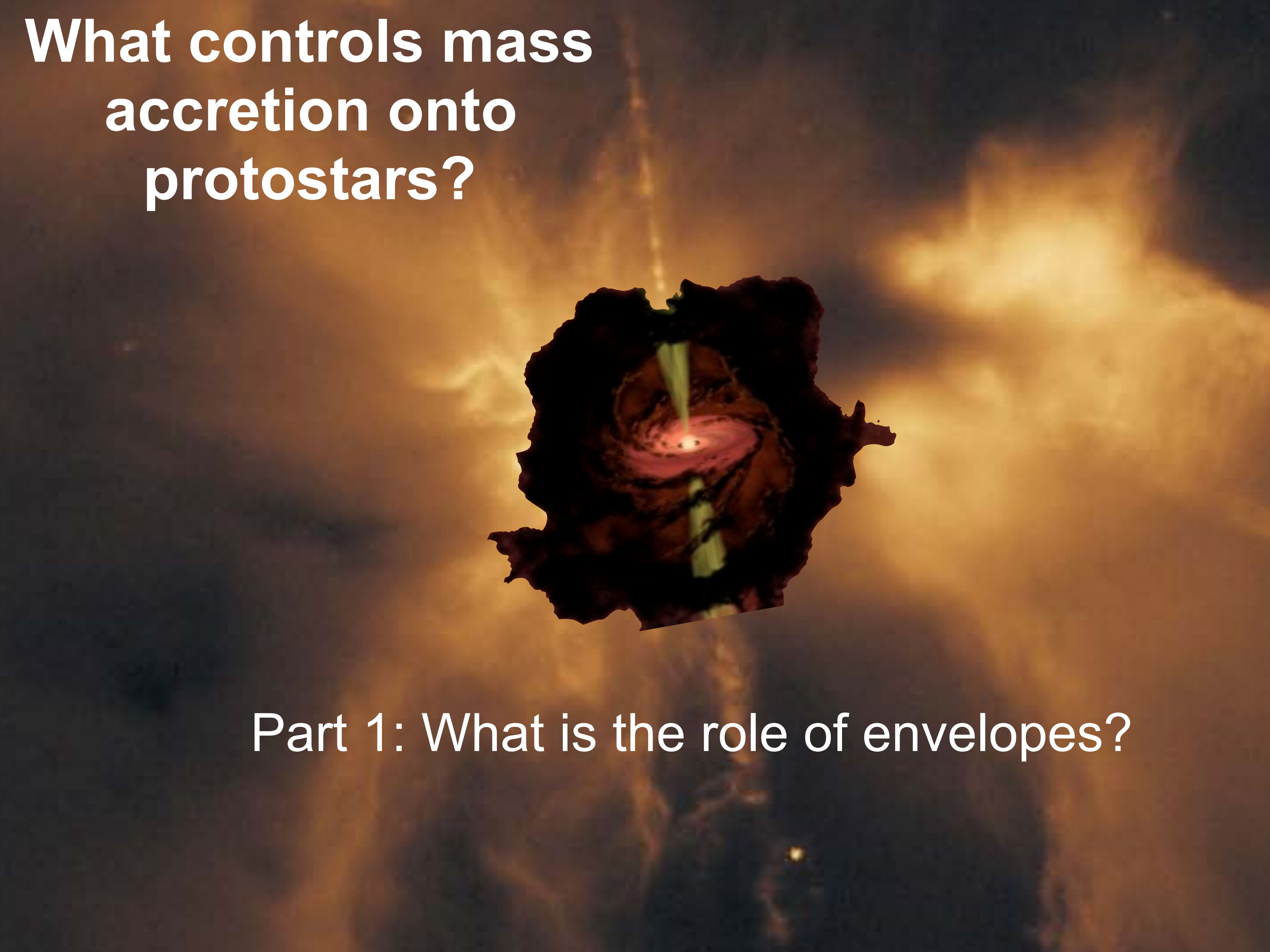
See Furlan et al. 2016
http://irsa.ipac.caltech.edu/data/Herschel/HOPS/overview.html



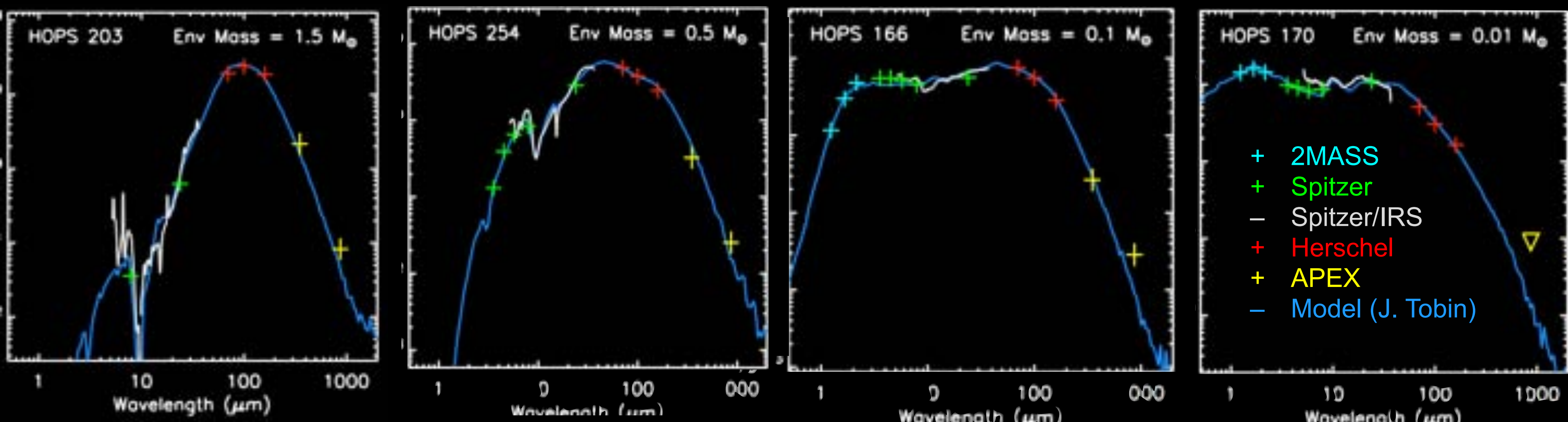
What controls mass accretion onto protostars?

1.6 μm image from WFC3


What controls mass accretion onto protostars?
Envelope
Environment
Disk
Outflow
1.6 μm image from WFC3
Artist conception by Robert Hurt


What controls mass accretion onto protostars?
Part 1: What is the role of envelopes?

Protostellar evolution in SEDs & images

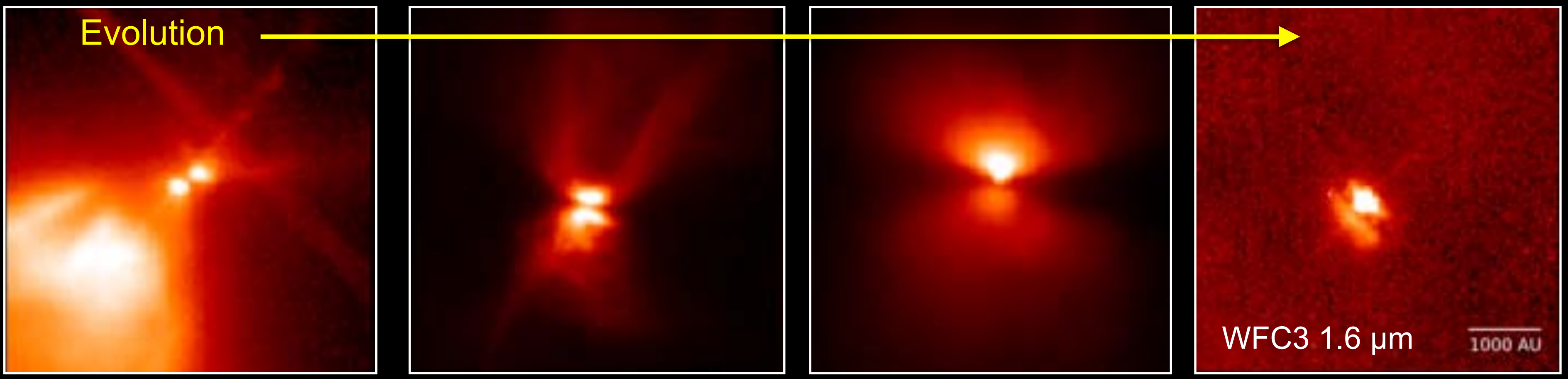


Class 0 Protostar

Class I Protostar

Flat Spectrum Protostar

Pre-ms star with disk



HERSCHEL ORION PROTOSTAR SURVEY

Manoj et al. 2013
Stutz et al. 2013

Fischer et al. 2014
Furlan et al 2016

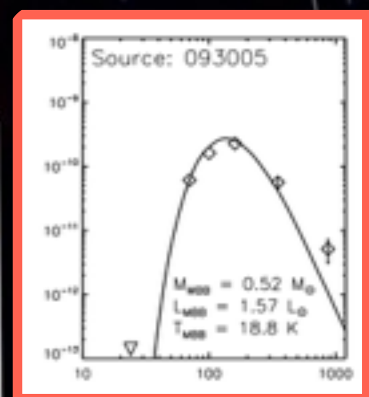
Kounkel et al. 2016
Booker et al. in prep.

How fast does evolution occur?

	Number	Fraction	Lifetime
PBRS	*18*	*0.06*	*0.03 Myr*
Class 0	*84*	*0.26*	*0.13 Myr*
Class I	*125*	*0.39*	*0.20 Myr*
Flat Spect.	*102*	*0.32*	*0.16 Myr*

Furlan et al. in 2016., Dunham et al. PPVI

Numbers assume a protostellar lifetime of 0.5 Myr



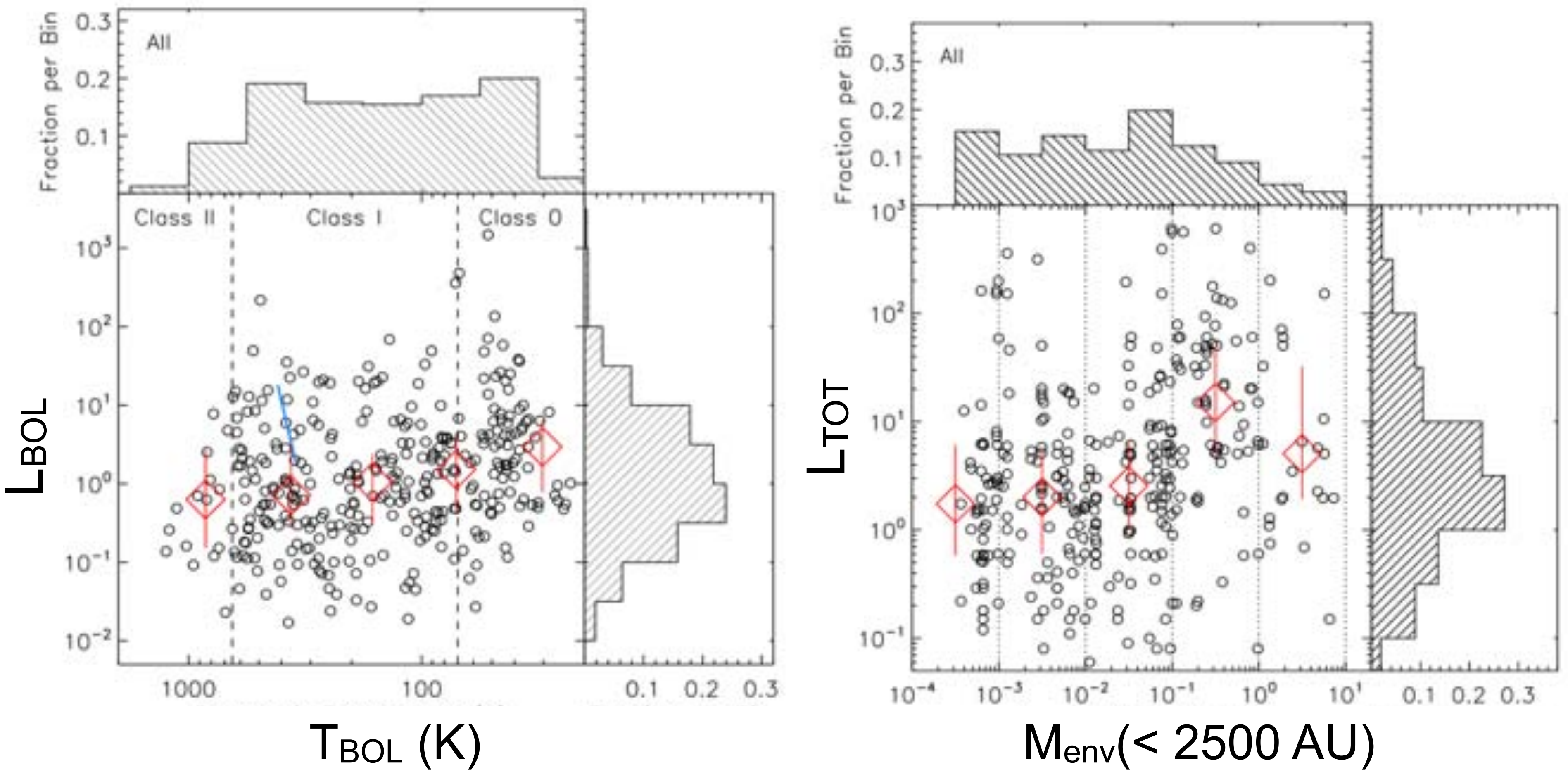
Stutz et al. 2013
Tobin et al. 2015
Tobin et al. 2016

24 µ
70 µm
870 µm

3.6 µm
8 µm
24 µm

Evidence for exponentially decreasing infall rates

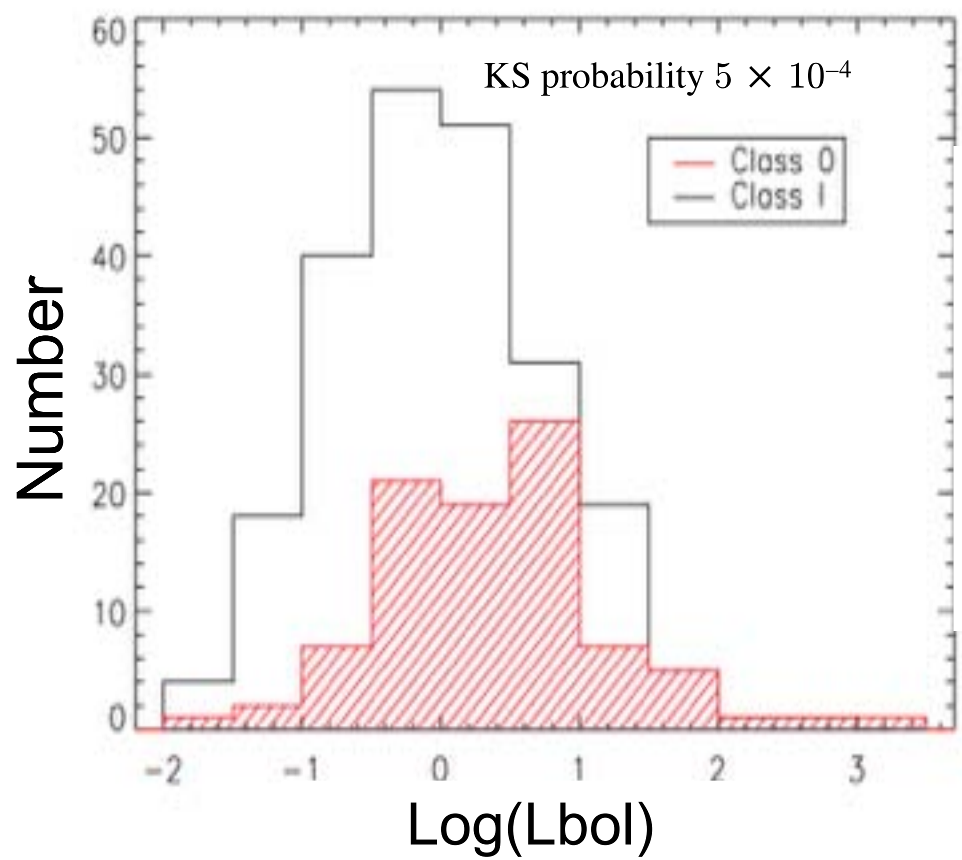
Fischer et al. in prep.

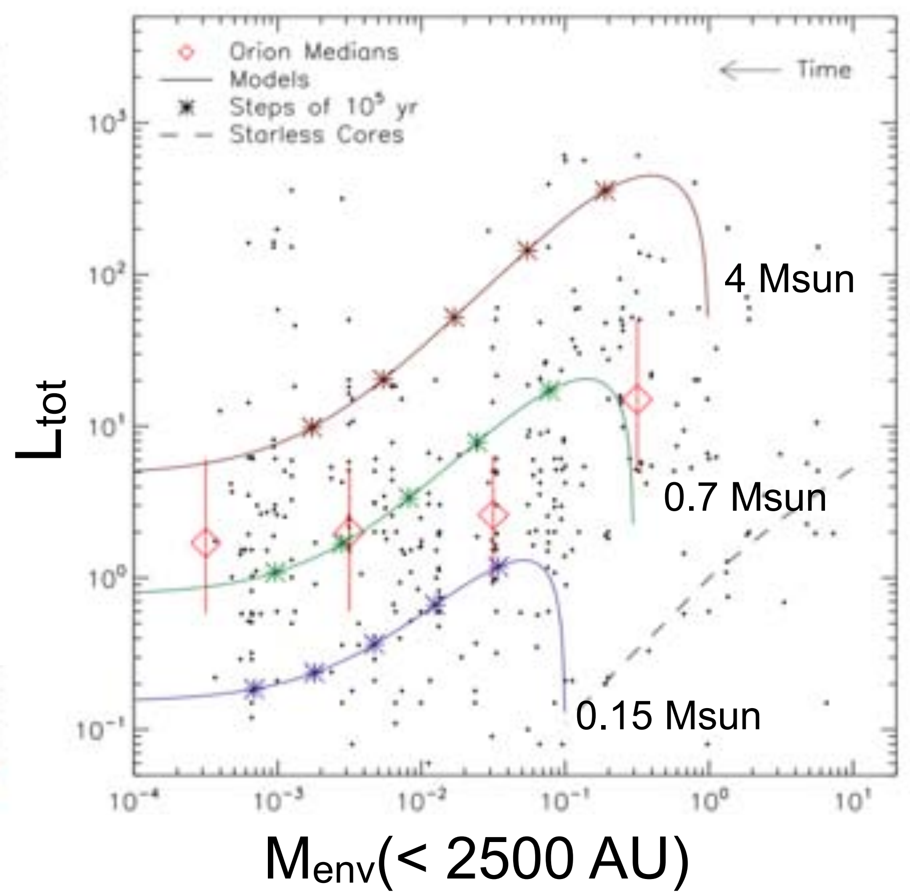


Flat distribution of T_{bol} and M_{env} + assumption of constant SFR =>
exponentially decreasing infall rate.

Decrease in bolometric luminosity: evidence for exponentially decreasing infall rates

Fischer et al. in prep.



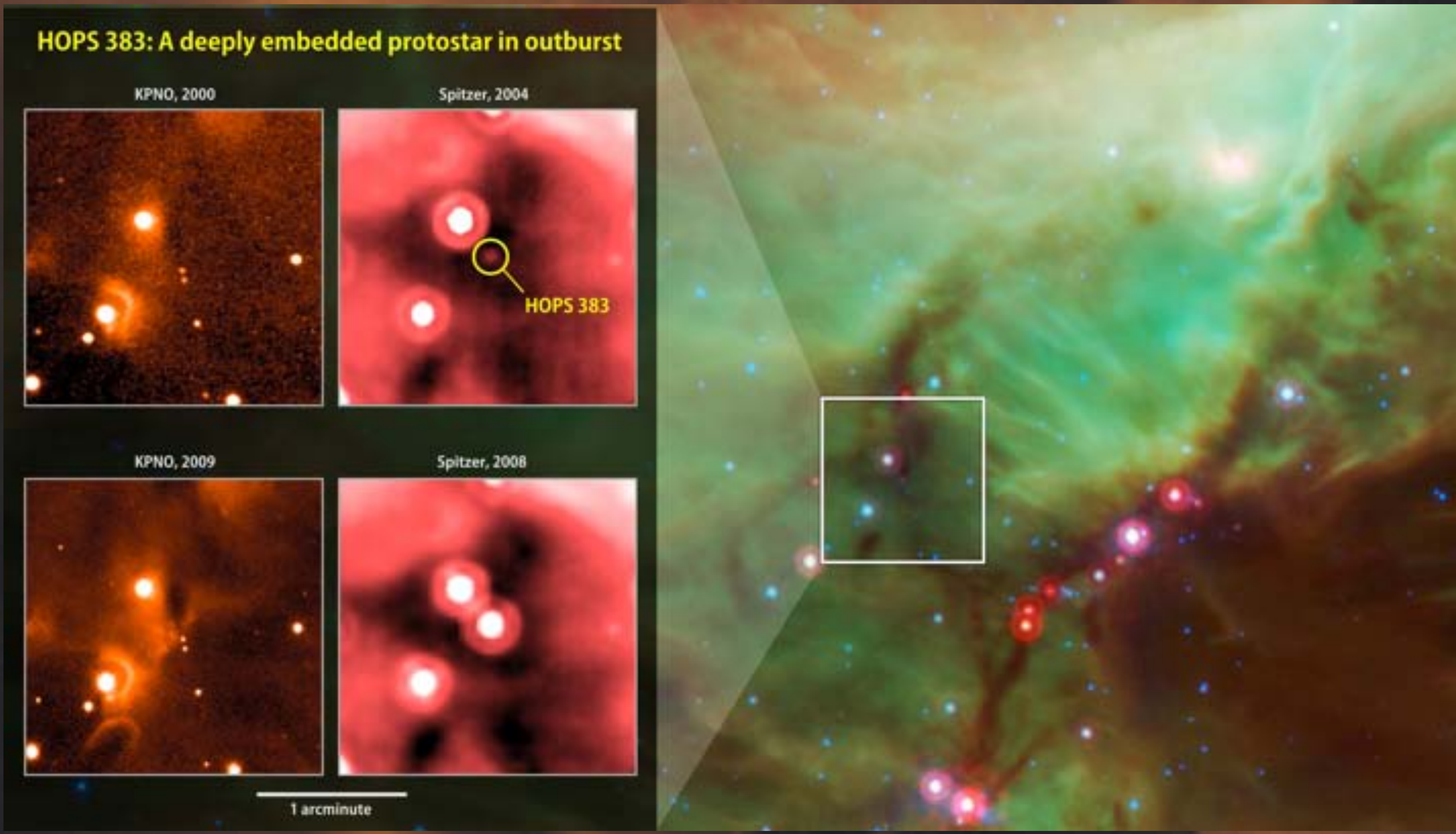


Decrease in luminosity can be explained by exponentially decreasing infall (and therefore accretion) rates.

But what factors are responsible?

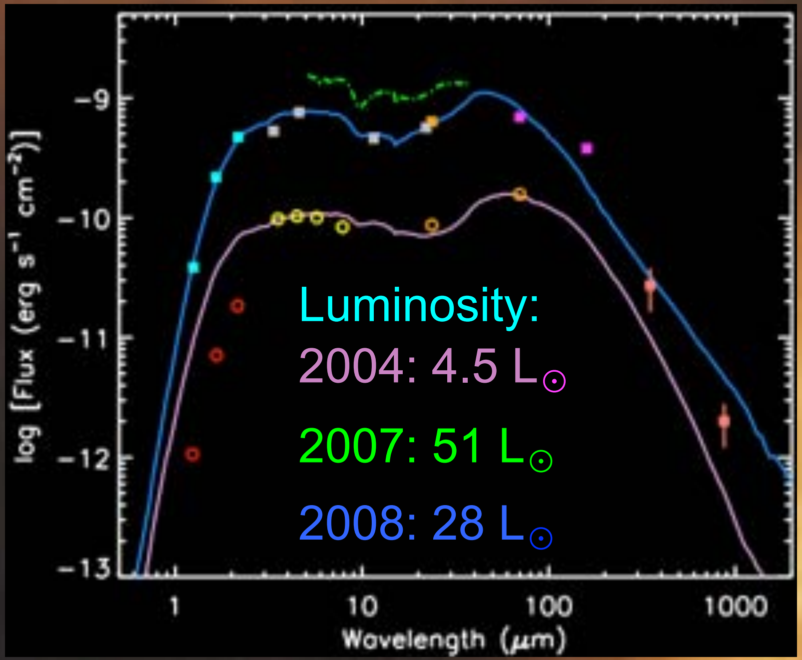

What controls mass accretion onto protostars?
Part 2: What is the role of disks?

HOPS 383
A class 0 protostar undergoing an outburst

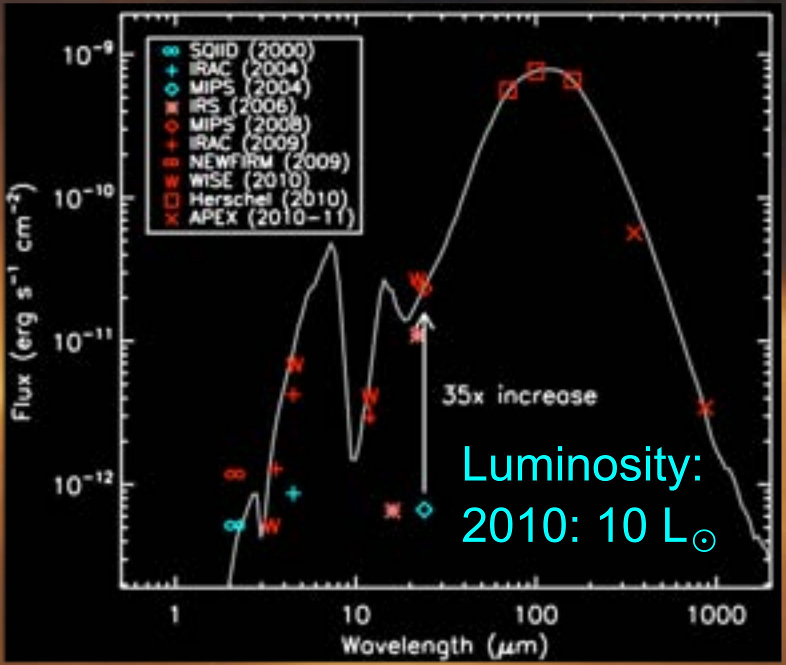


Safron, Fischer et al. 2015

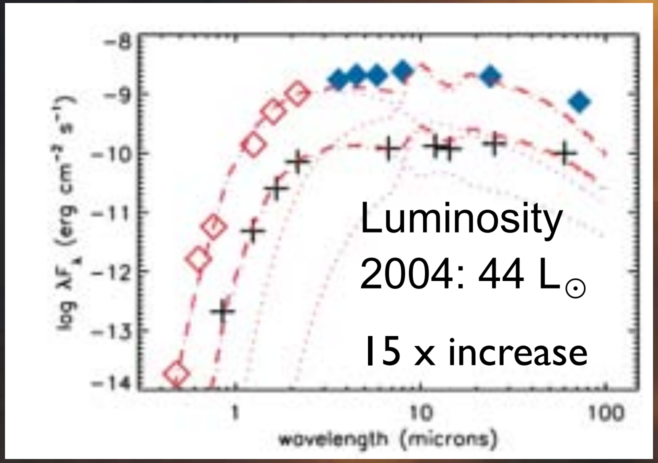
Known outbursts in Orion since 2004



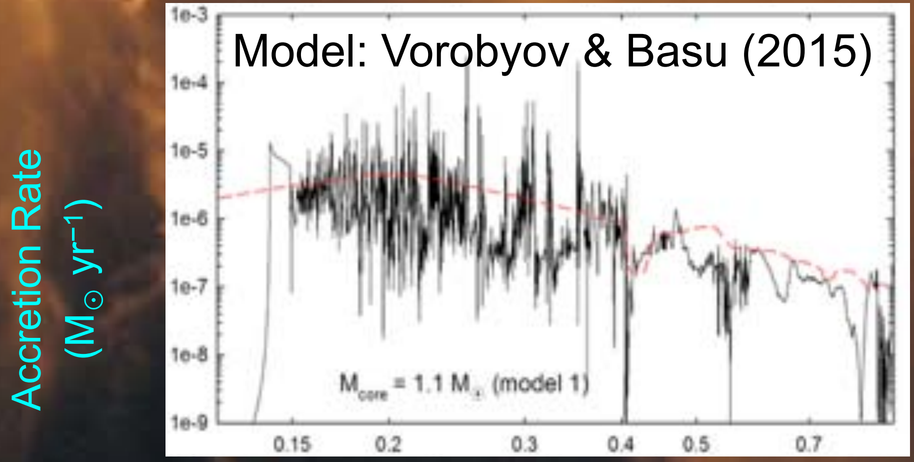
V2775 (HOPS 223): Carrati o Garrati 2011, Fischer et al 2012



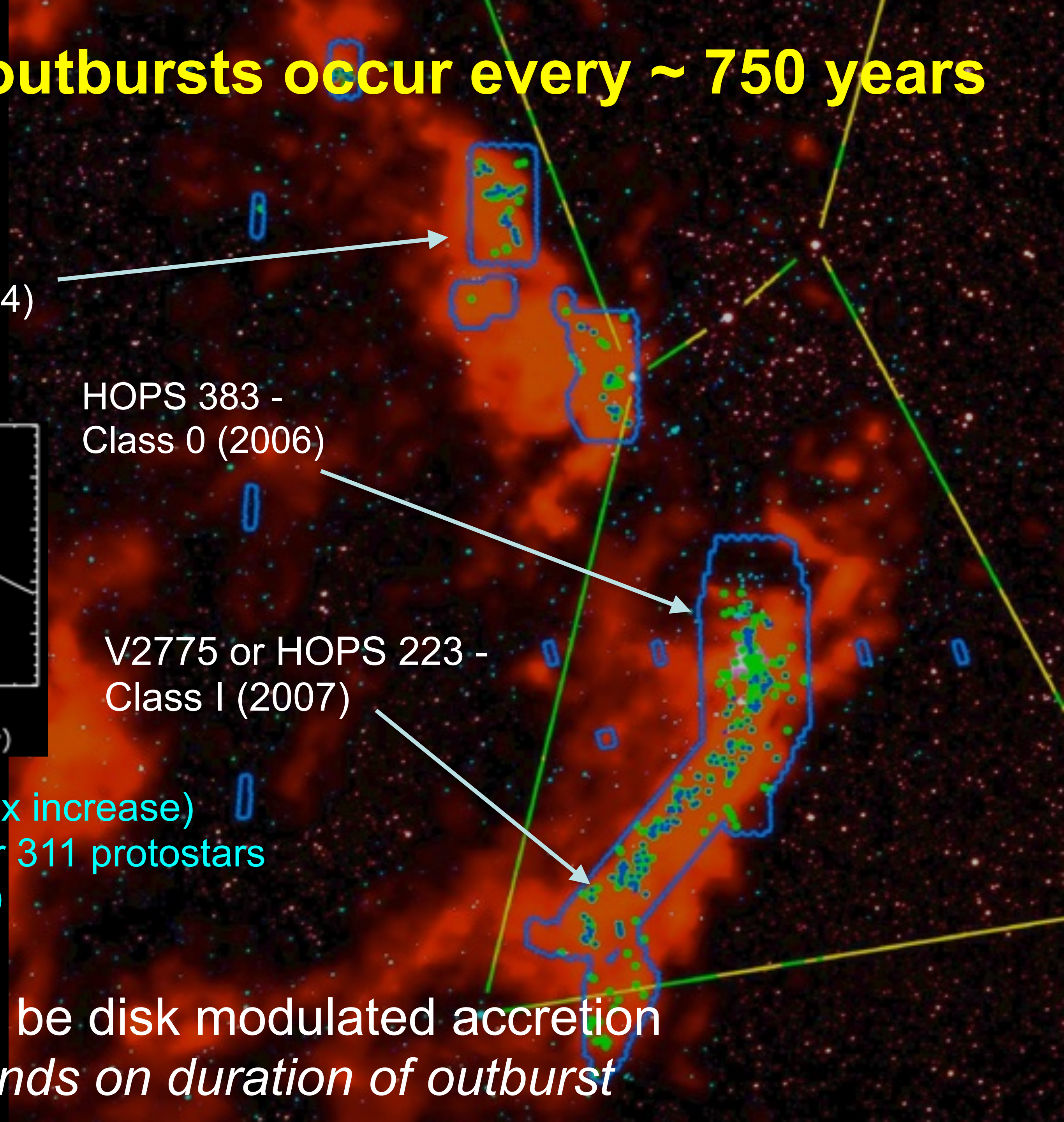
HOPS 383: Safron, Fischer et al. 2015



V1647: Muzerolle et al. 2005



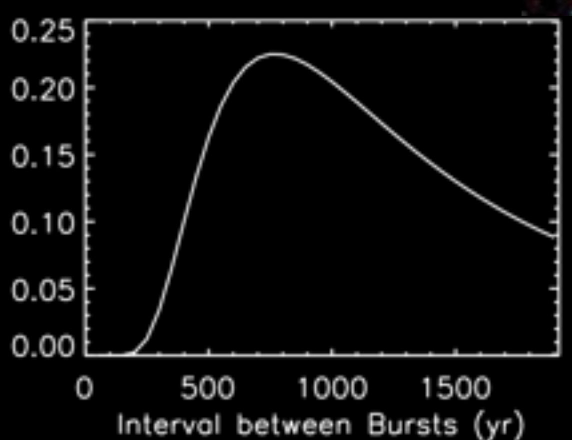
Protostellar outbursts occur every ~ 750 years



V1647, HOPS 388,
McNeil's Nebula -
Flat Spectrum (2004)

HOPS 383 -
Class 0 (2006)

V2775 or HOPS 223 -
Class I (2007)

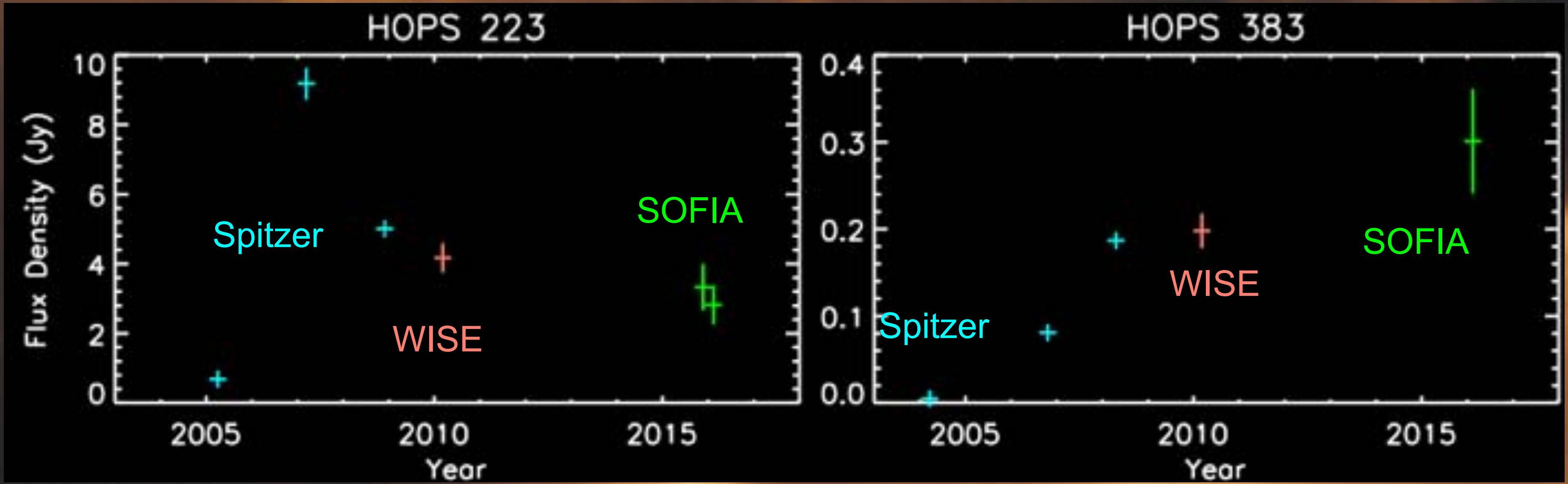


Three outbursts (10-40x increase)
between 2004-2010 for 311 protostars
(Safron, Fischer in prep)

This is thought to be disk modulated accretion
Importance depends on duration of outburst

How long do bursts last?

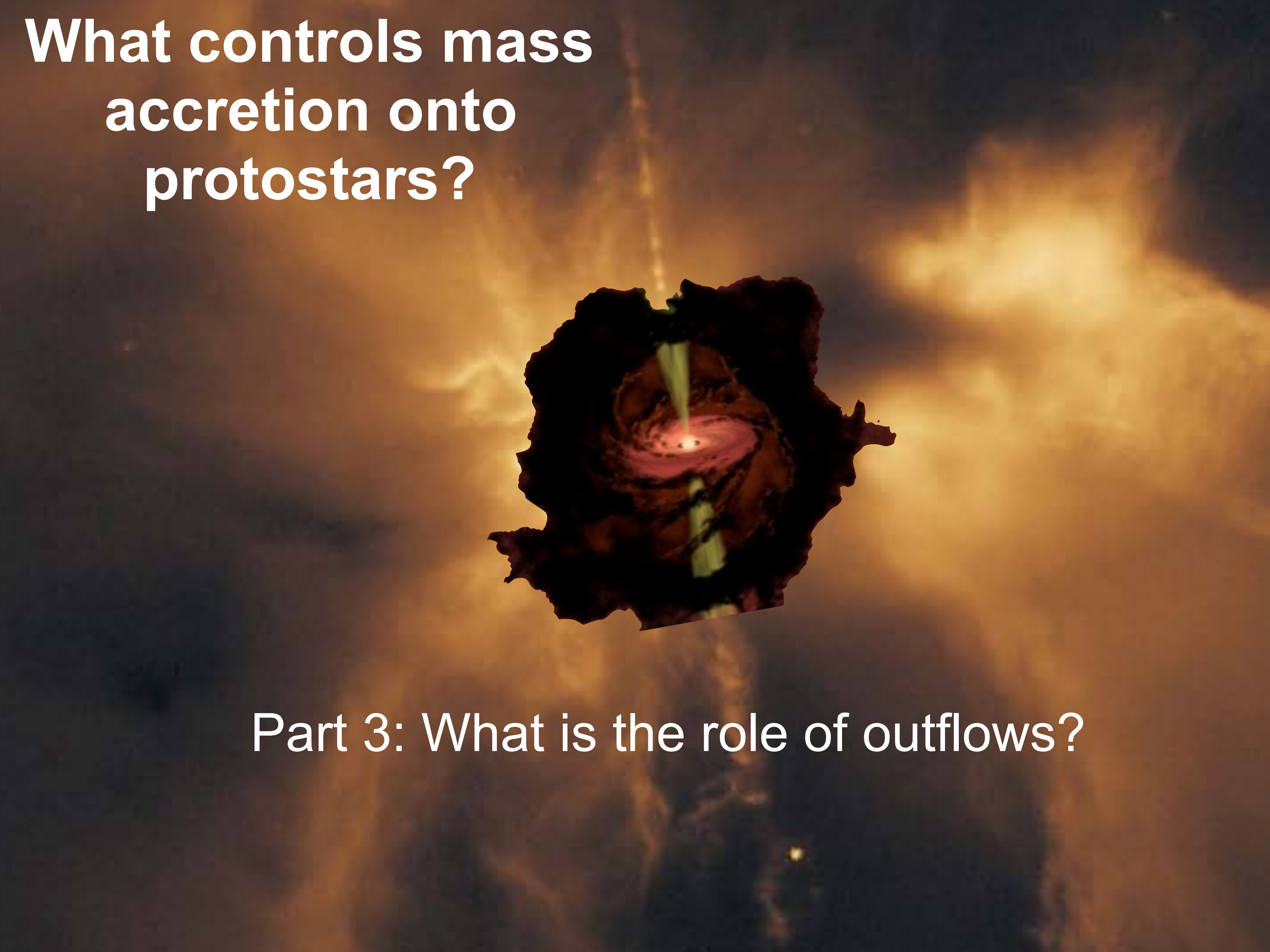
Spitzer/WISE/SOFIA 22-25 μm Light Curves of Outbursts (Fischer et al. in prep)



This is a constraint on the fraction of mass accreted:

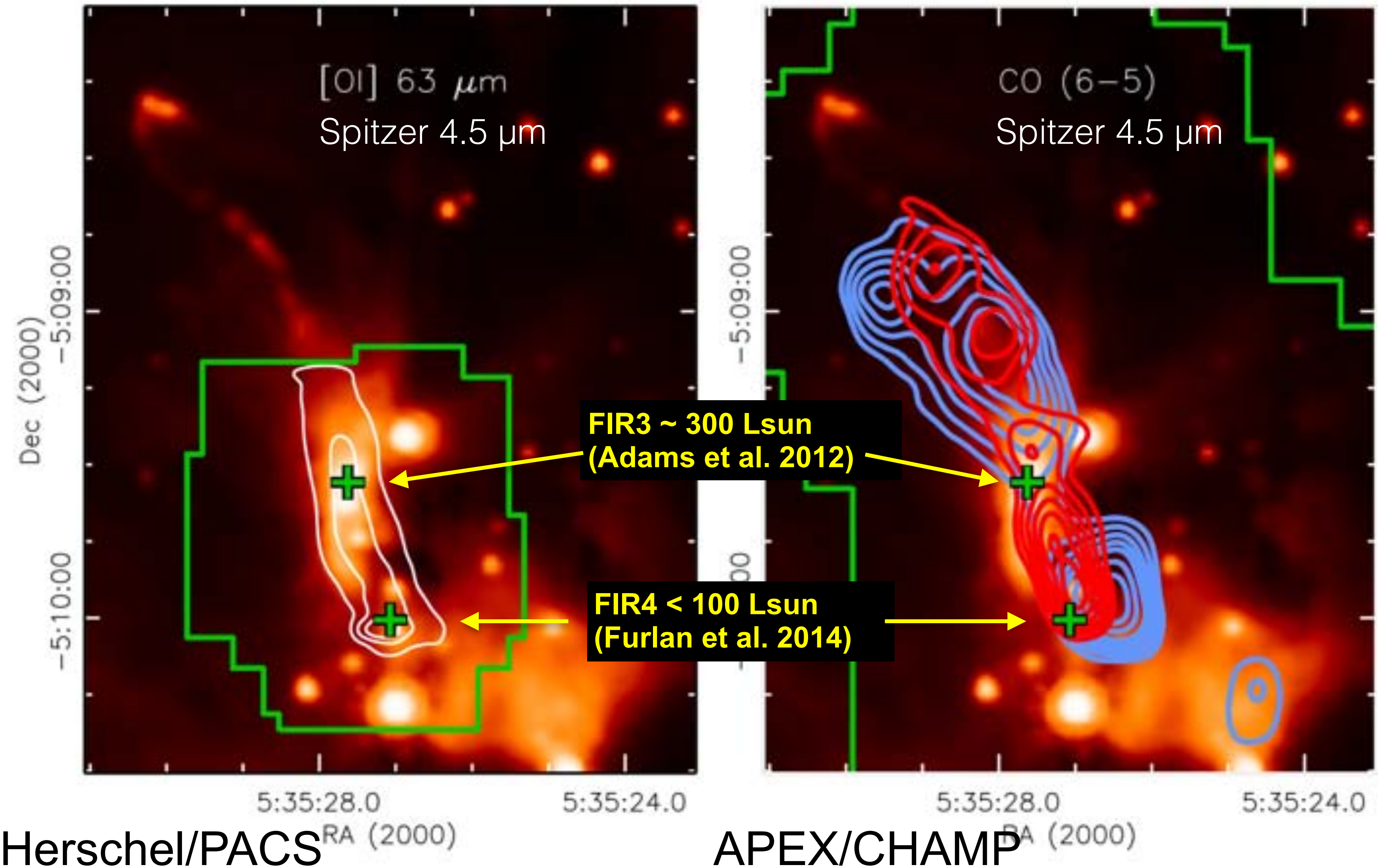
$$f_M(\mathrm{burst}) \sim \frac{r_{\mathrm{burst}} \times t_{\mathrm{burst}}}{(1 - r_{\mathrm{burst}} \times t_{\mathrm{burst}})} \times \frac{\dot{M}_{\mathrm{burst}}}{\dot{M}_{\mathrm{steady}}}$$

$> 5\%$


What controls mass accretion onto protostars?
Part 3: What is the role of outflows?

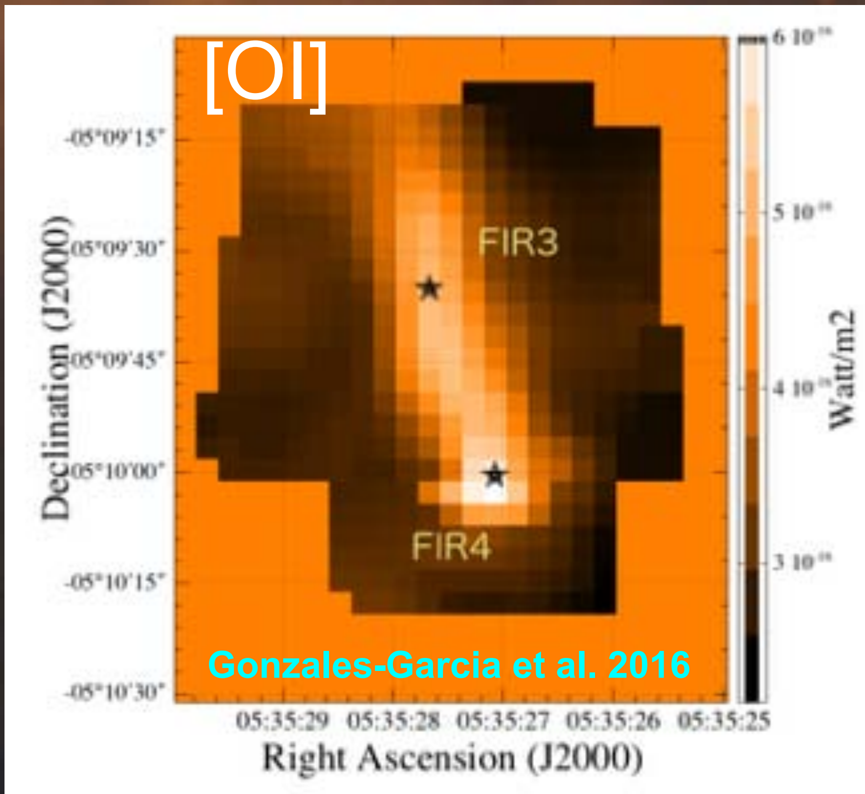
GREAT observations of the Orion OMC-2 region

Megeath, Wiesemeyer et al.



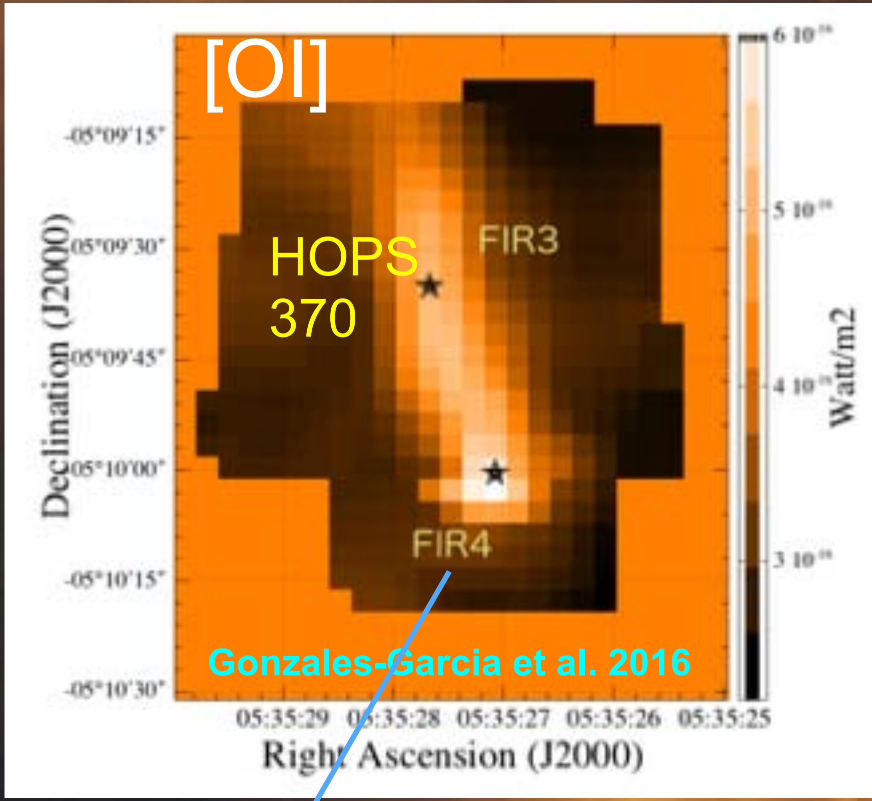
The OMC2 outflow with PACS/GREAT

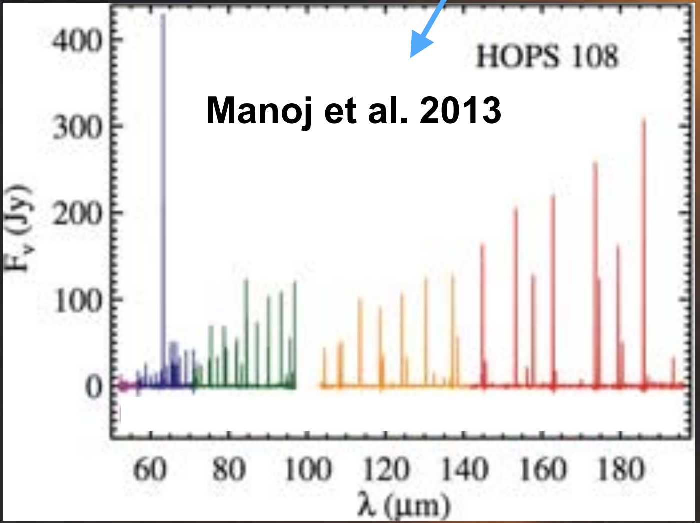
Herschel PACS



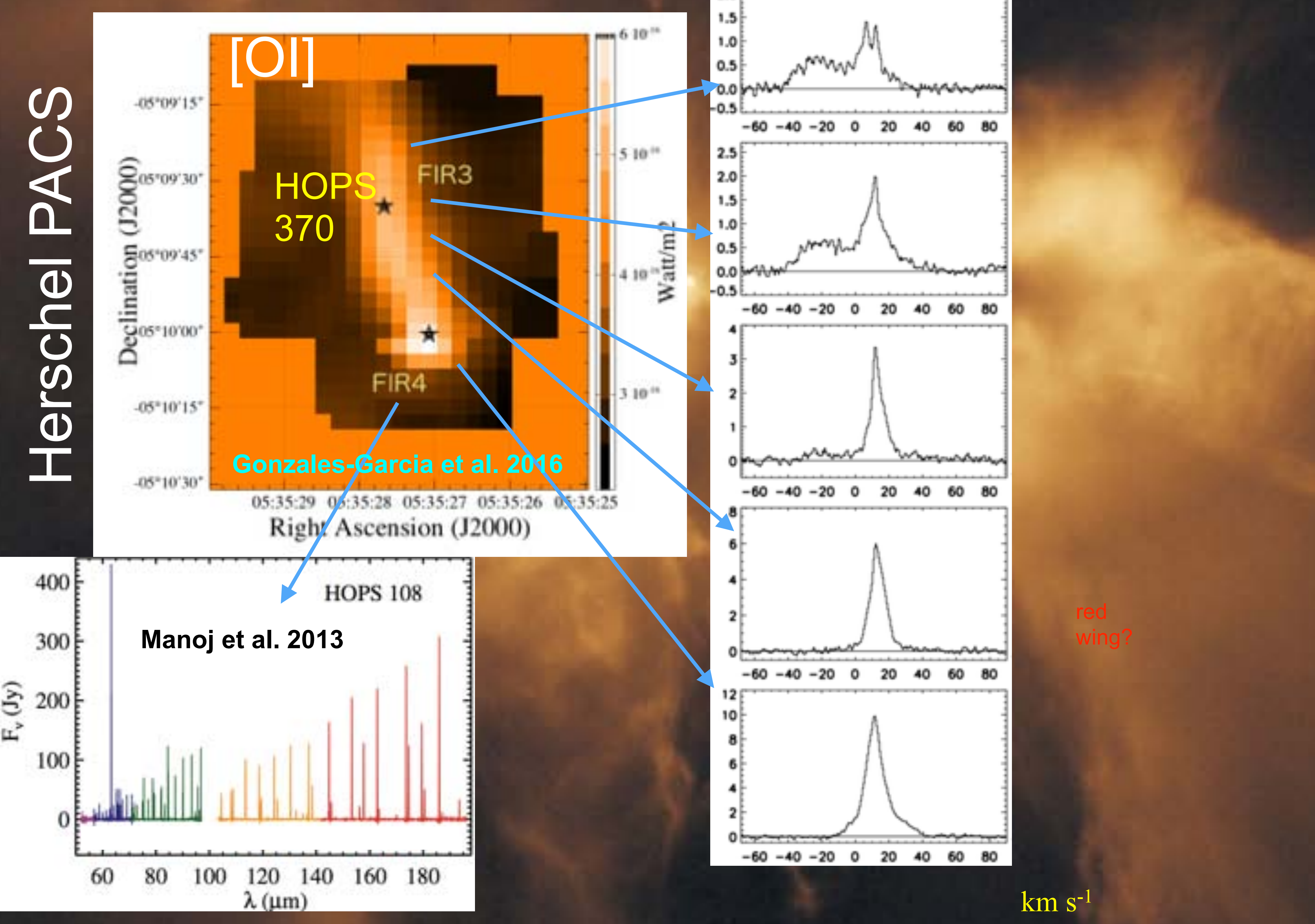
The OMC2 outflow with PACS/GREAT

Herschel PACS

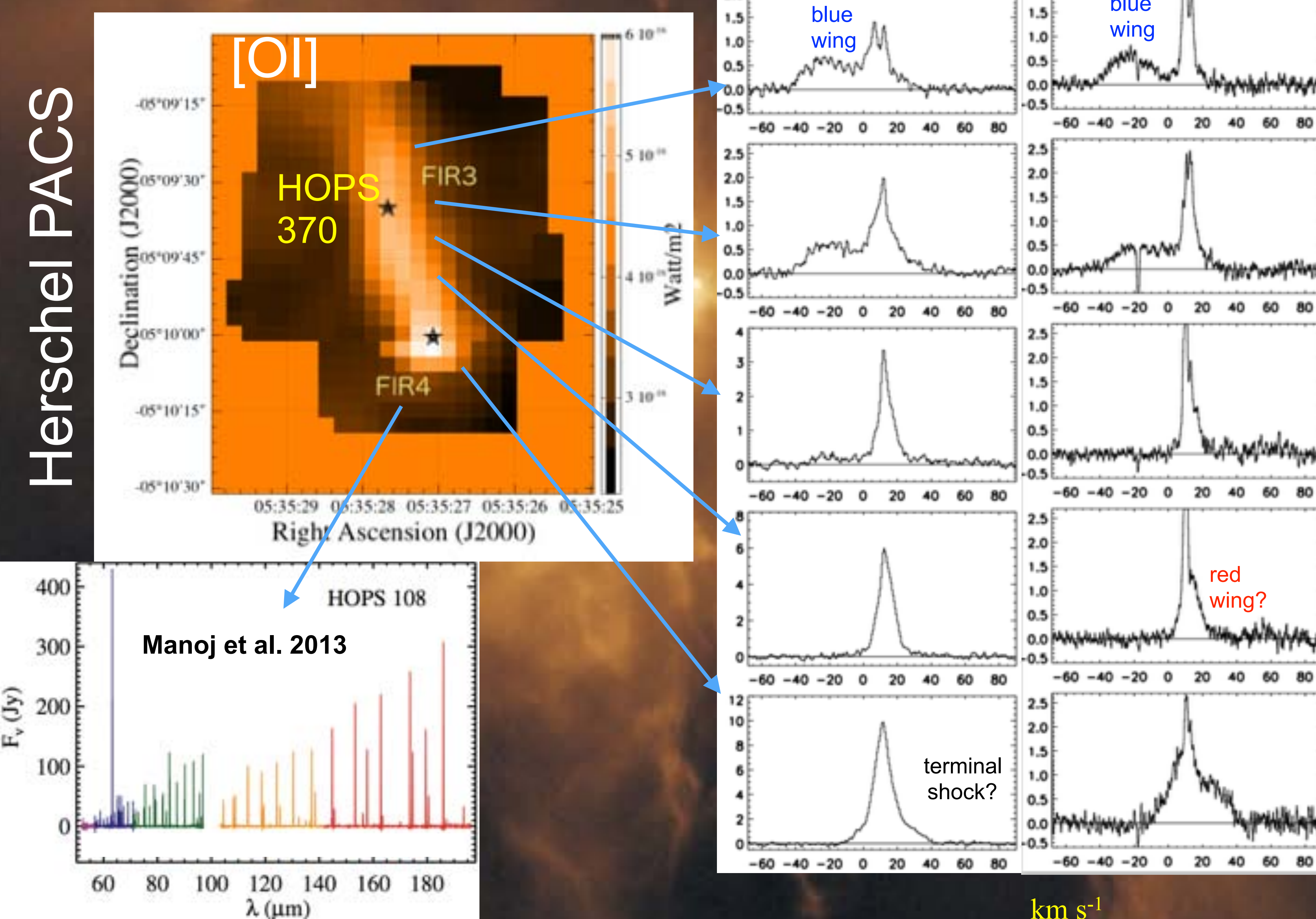




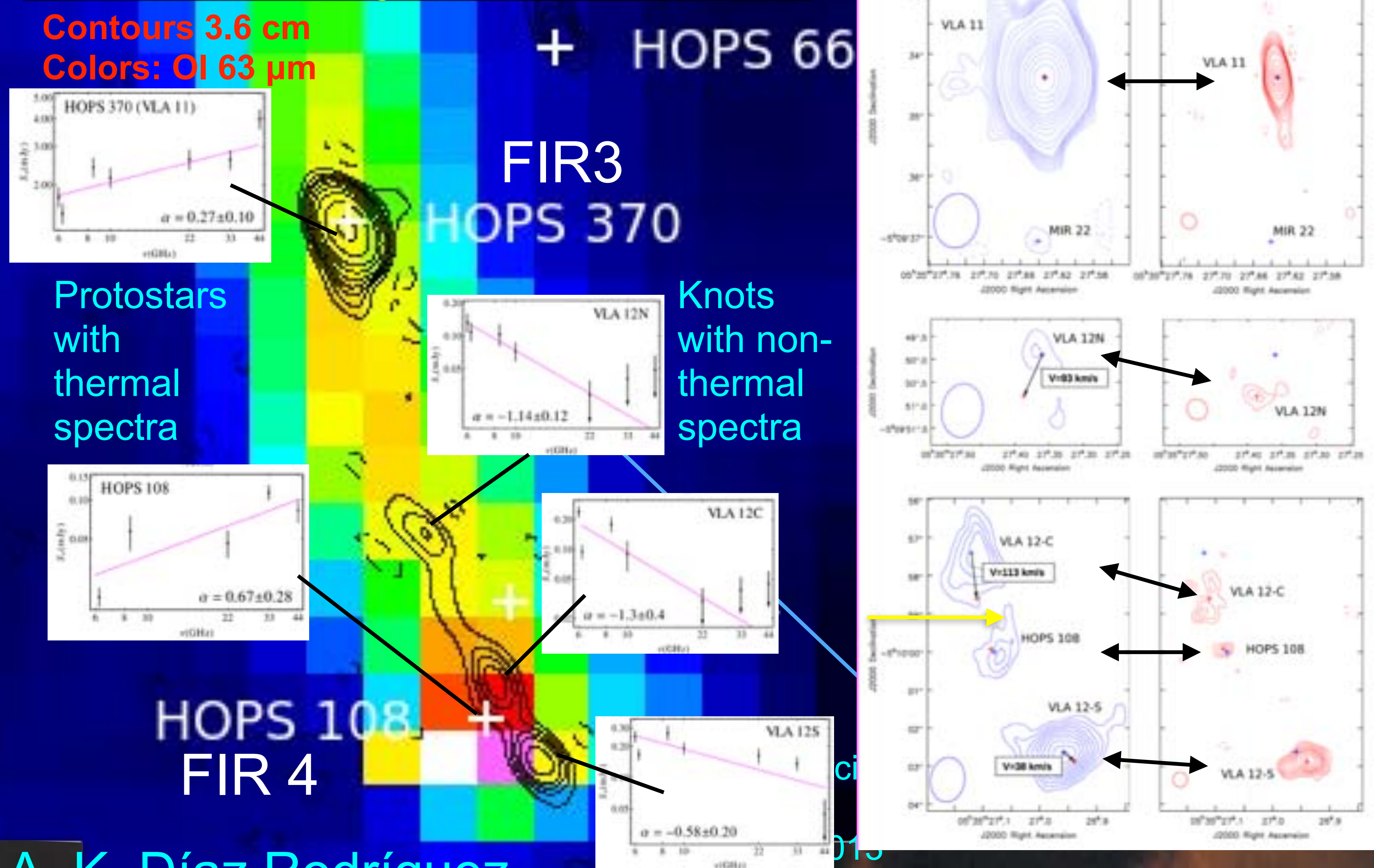
The OMC2 outflow with PACS/GREAT



The OMC2 Outflow with PACS/GREAT



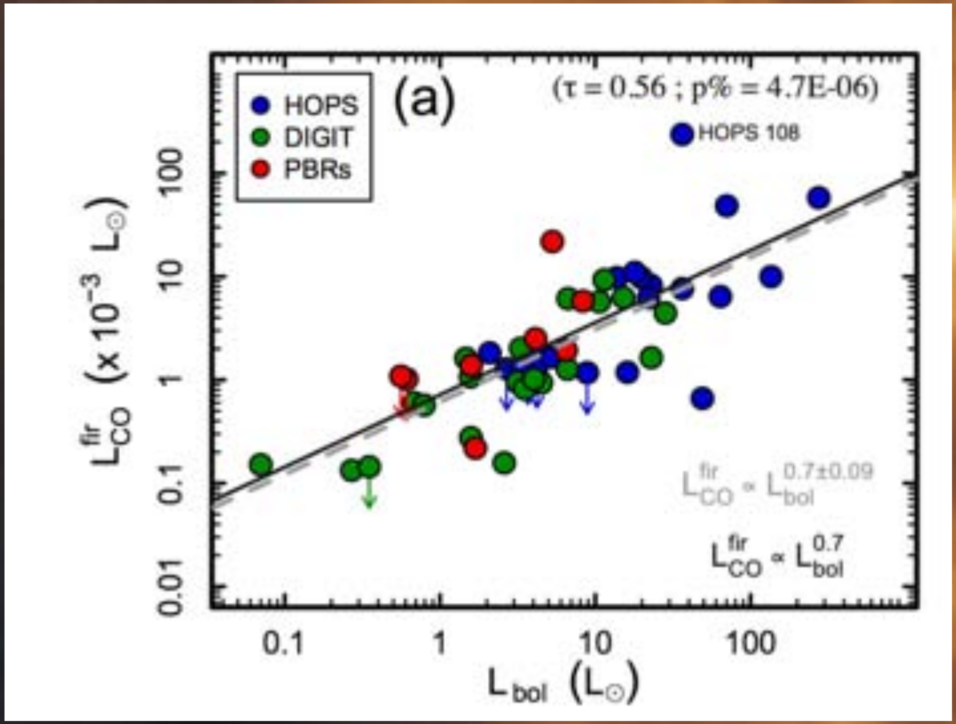
Multi-Epoch VLA observations of the OMC-2 jet

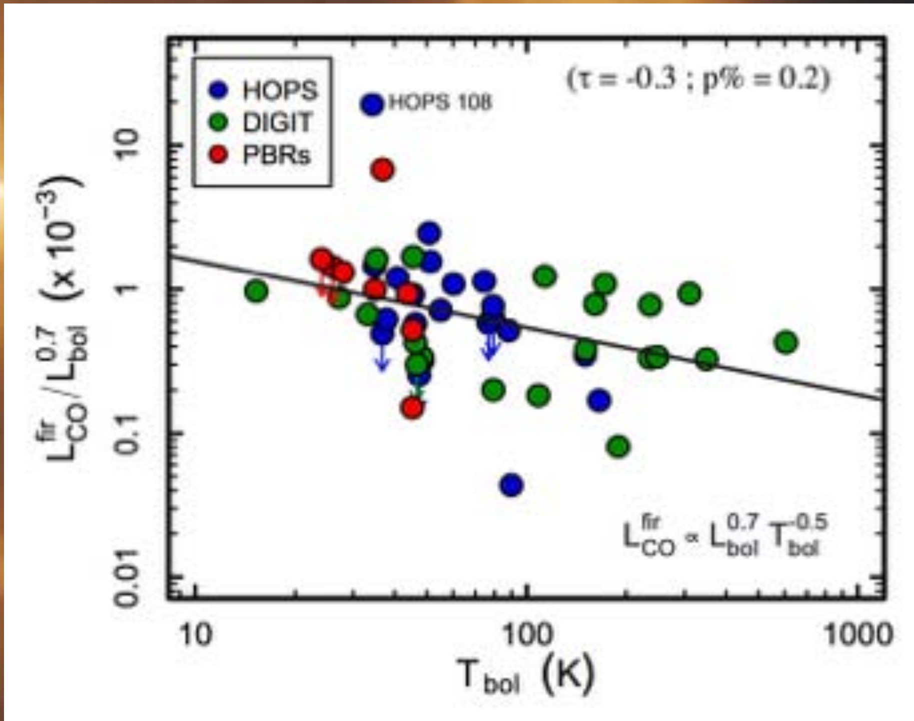


A. K. Díaz Rodríguez

L_{CO} correlated with L_{bol}, but weak (or no) correlation with T_{bol}

Manoj et al. 2016 (also see Karska et al. 2013)

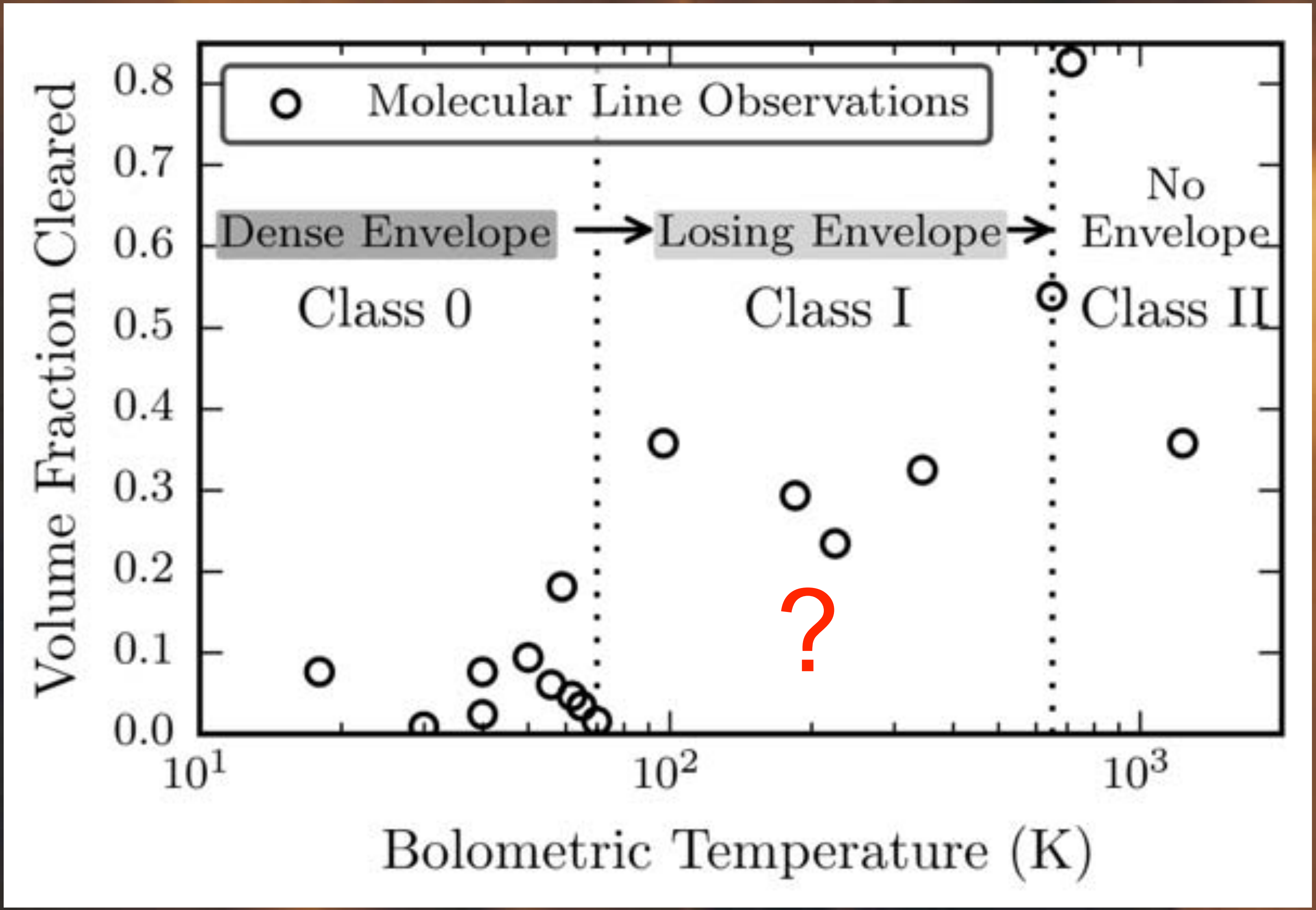




Reinforces connection between "instantaneous" outflow & accretion rate

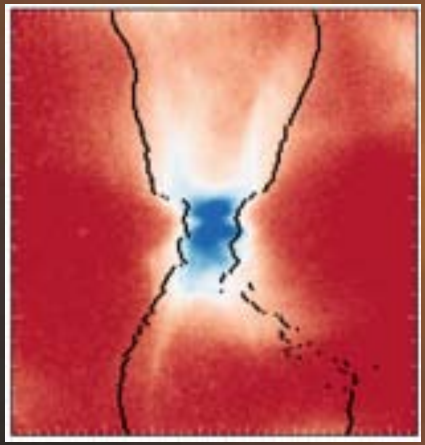
Ratio of launched/accreted gas ~ 0.1 (Watson et al. 2015)

Do outflows clear envelopes?



Arce & Sargent 2006

Outflows Clear < 40% of Mass

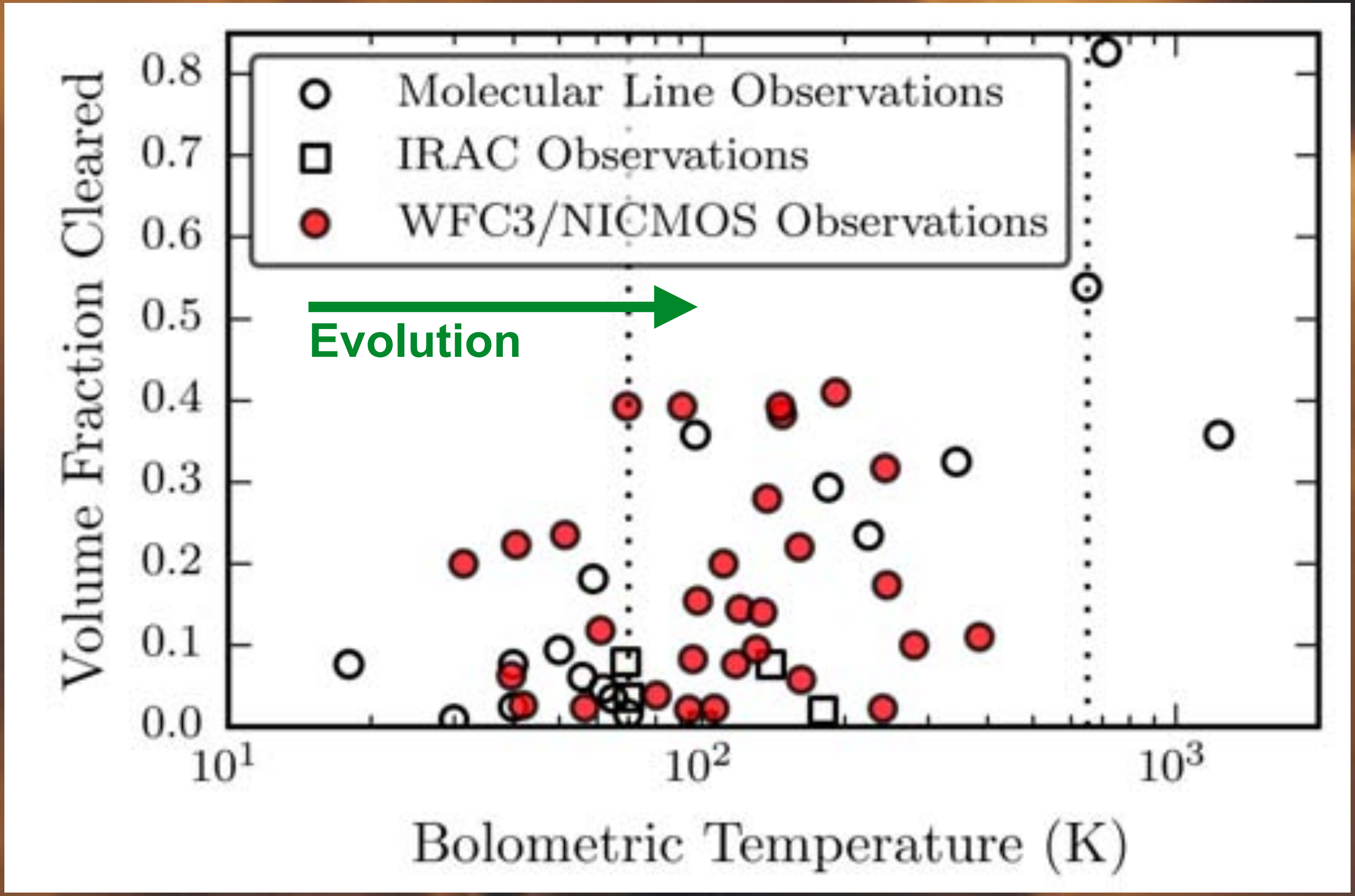


Use HST mapping of outflow cavities

No evidence for progressive clearing

Protostars with evolved envelopes can have narrow cavities.

Booker et al. in submitted.



Dense Envelope

Dispersing Envelope

No Envelope

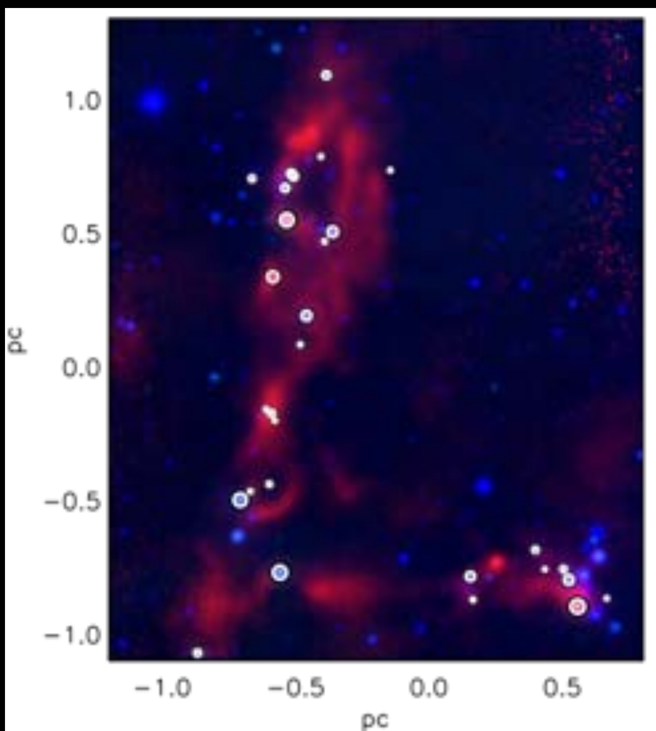
What controls mass accretion onto protostars?

Part 4: What is the role of environment?

Also Kryukova et al 2012, 2014

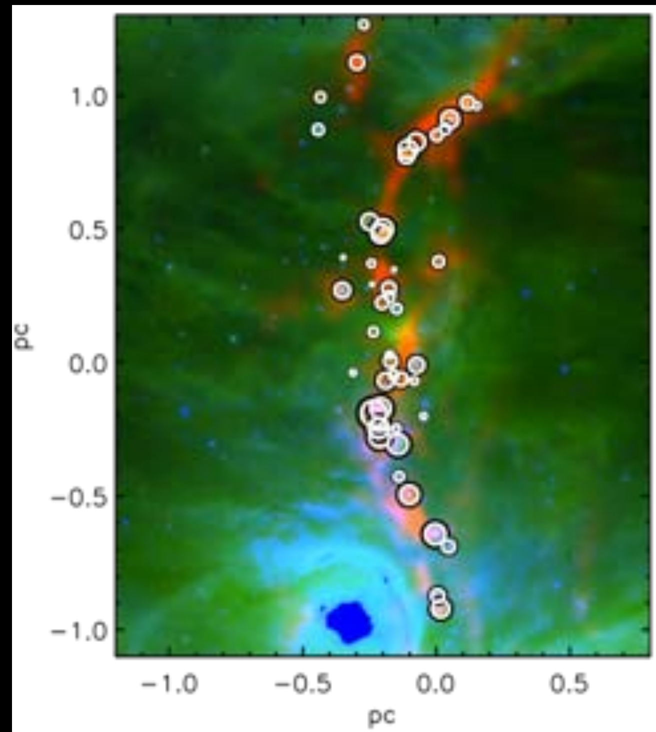
Environment controls spacing and luminosity

<L> = 0.7 Lsun
<spacing> = 13000 AU

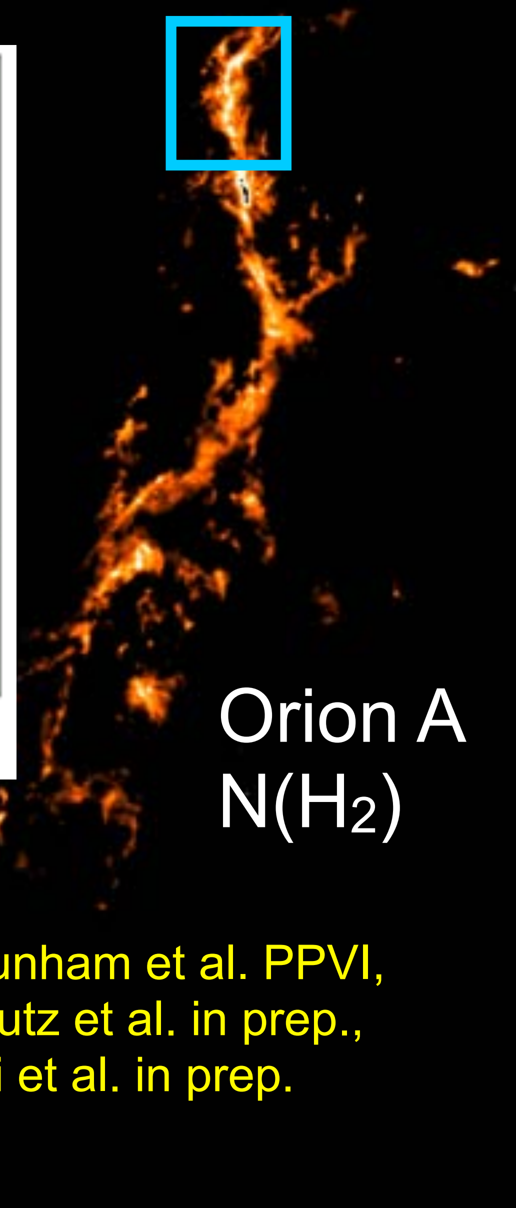


3.6 μm / 24 μm / 870 μm

<L> = 7.6 Lsun
<spacing> = 8000 AU



3.6 μm / 24 μm / 870 μm

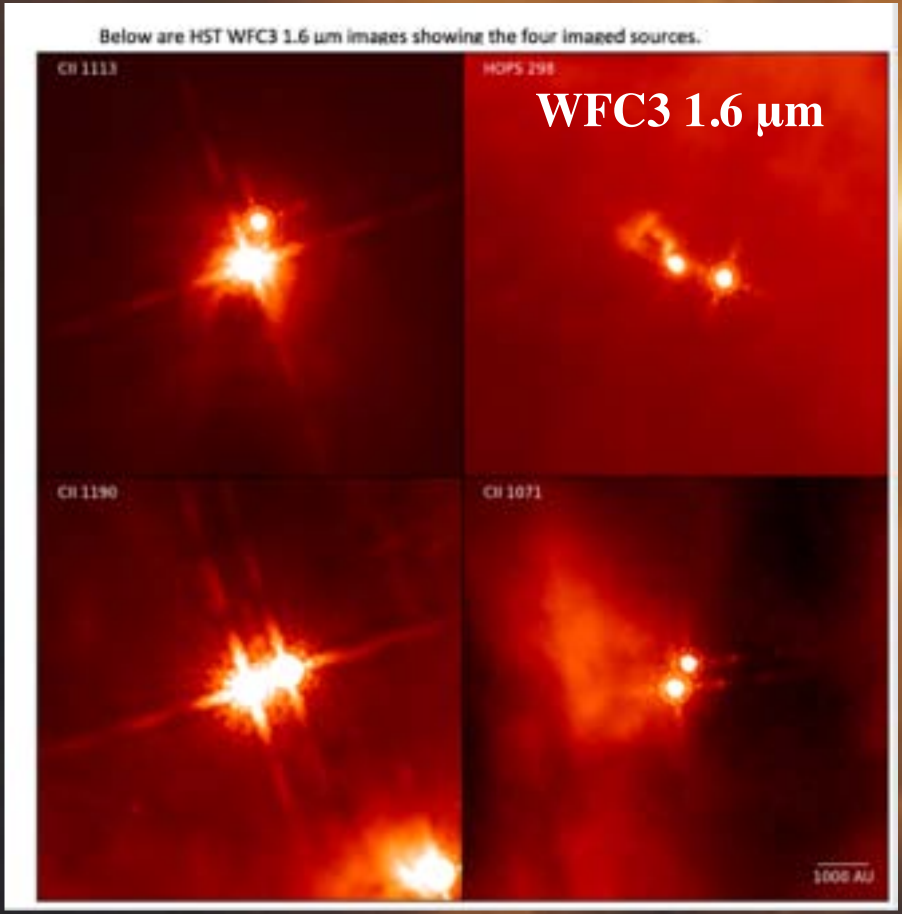


Dunham et al. PPVI,
Stutz et al. in prep.,
Ali et al. in prep.

Column Density Map of Orion A: Stutz and Kainulainen et al. 2015

Multiplicity increases in dense environments

Companion fraction between 100 and 1000 AU



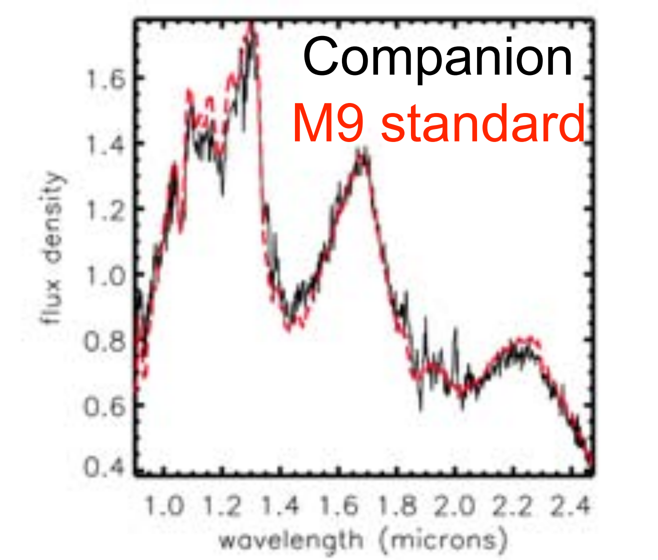
Envir. Density	>45 pc^{-2} (high)	< 45 pc^{-2} (low)
Proto stars	19.2%	10.8%
Pre-ms stars	13.9%	10.2%
Merged YSOs	15.6%	10.5%

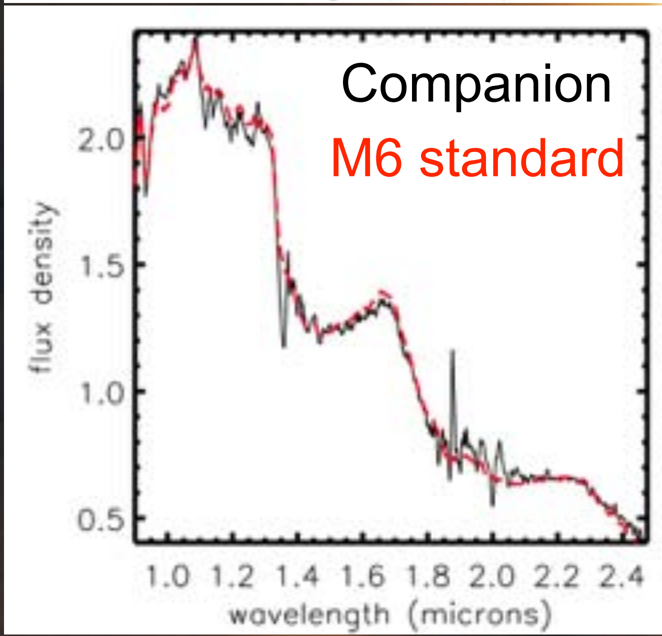
Kounkel et al. 2016

+/- 1-2% uncertainty due to LOS correction

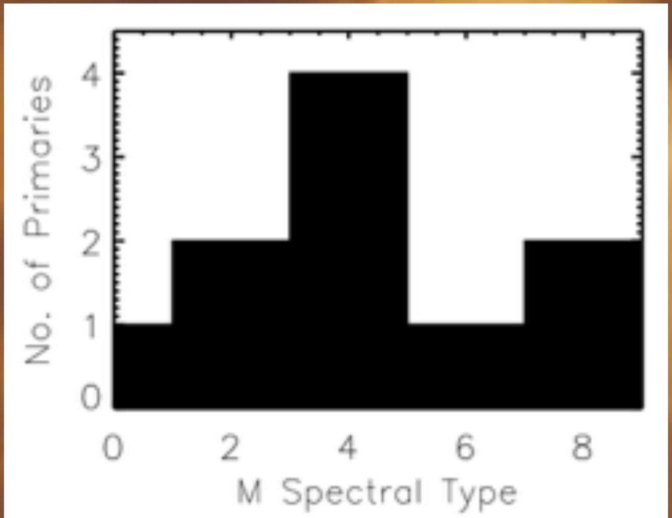
Evidence of enhanced formation of companions in dense environments.

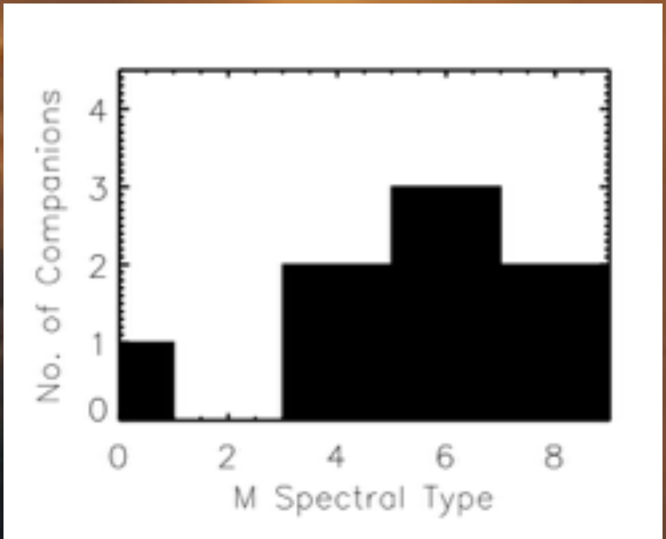
Do companions form prompt/turbulent fragmentation or disks fragmentation? Mazur et al. in prep.



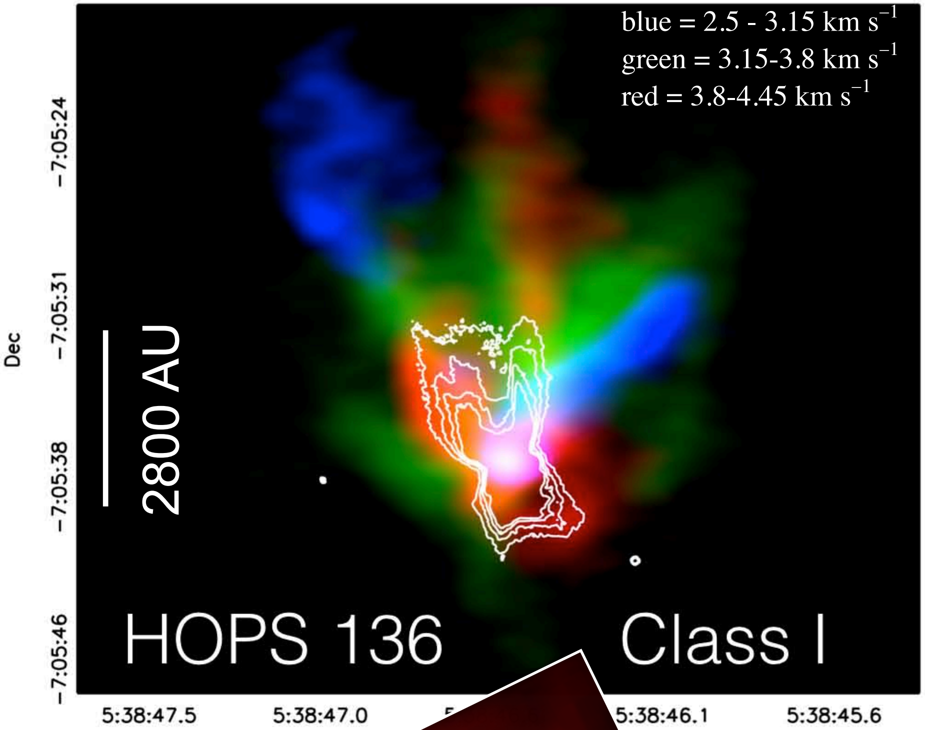


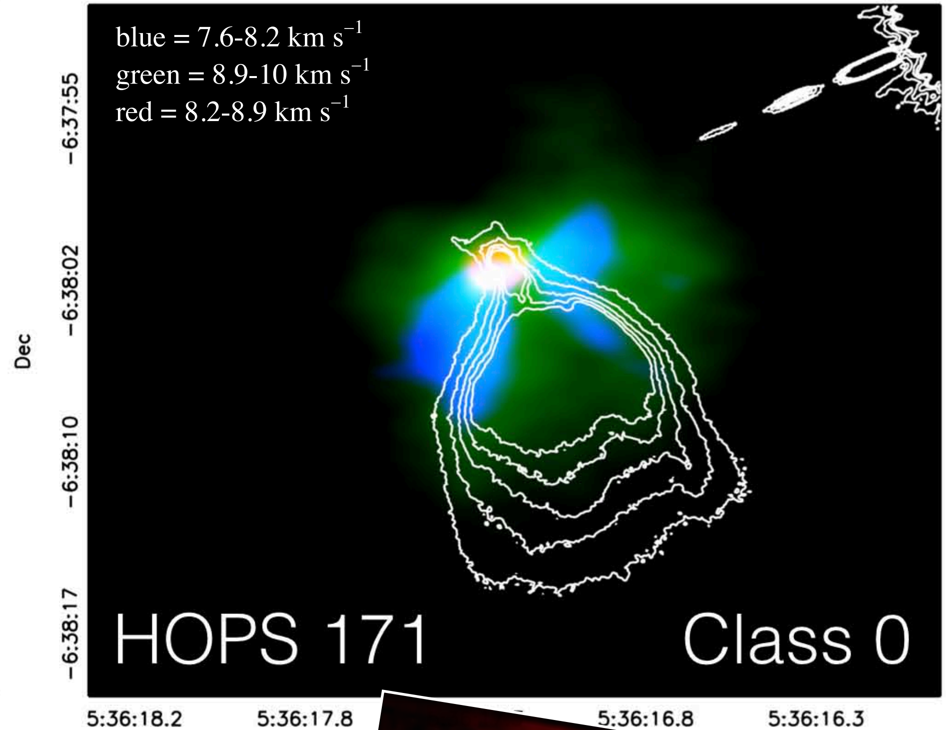
Current result

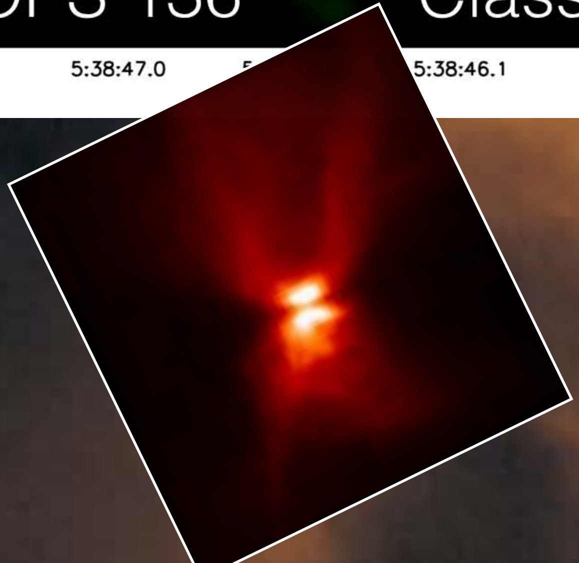


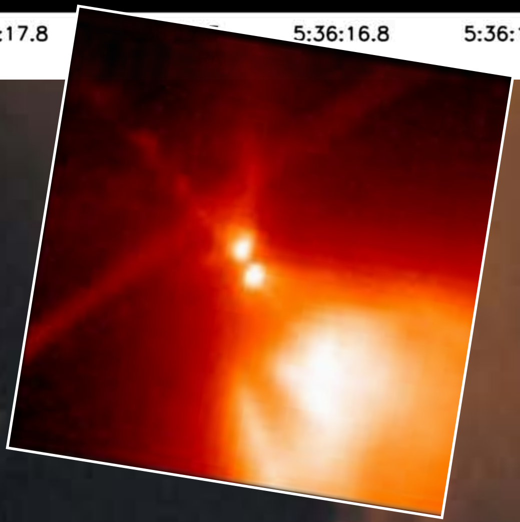


ALMA ^{13}CO and $C^{18}O$ Mapping of Orion Edge-on Protostars (12 m + ACA + TP) Zsofia Nagy









HST
1.6 μm

What controls mass accretion onto protostars?

1. Exponential depletion of envelope reduces/stops mass accretion. But what depletes envelope?

2. burst rate of 1000 years for 10x increase in accretion rate: disk modulate accretion

3. Outflow may have <40% reduction of mass accretion, but not dominant. Can trace mass accretion through far-IR lines

4. Environments with higher densities of gas show evidence for closer spacing of protostars, higher accretion rates, and a higher incidence of 100-1000 AU binaries.