Star and planet formation studies with the TMT

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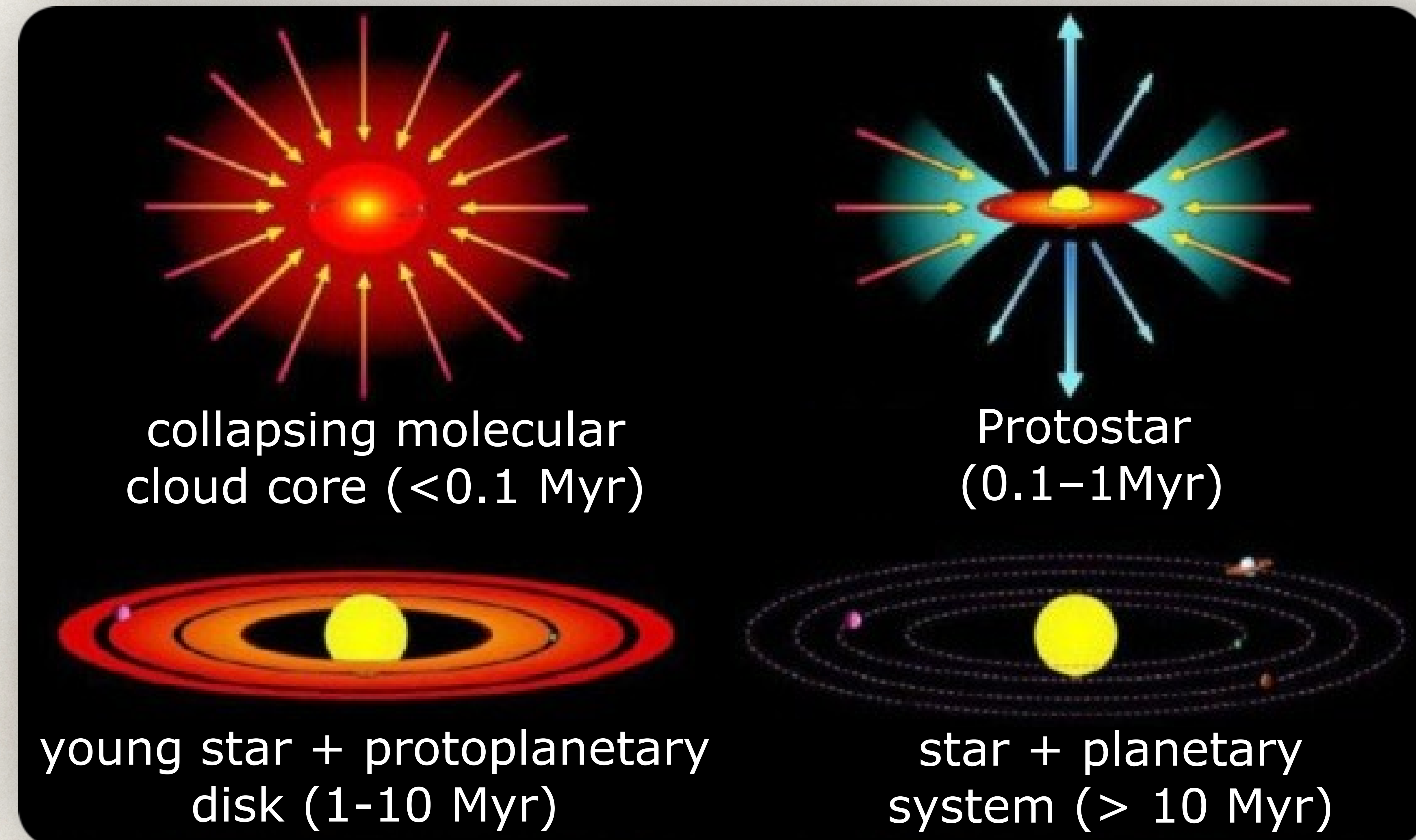
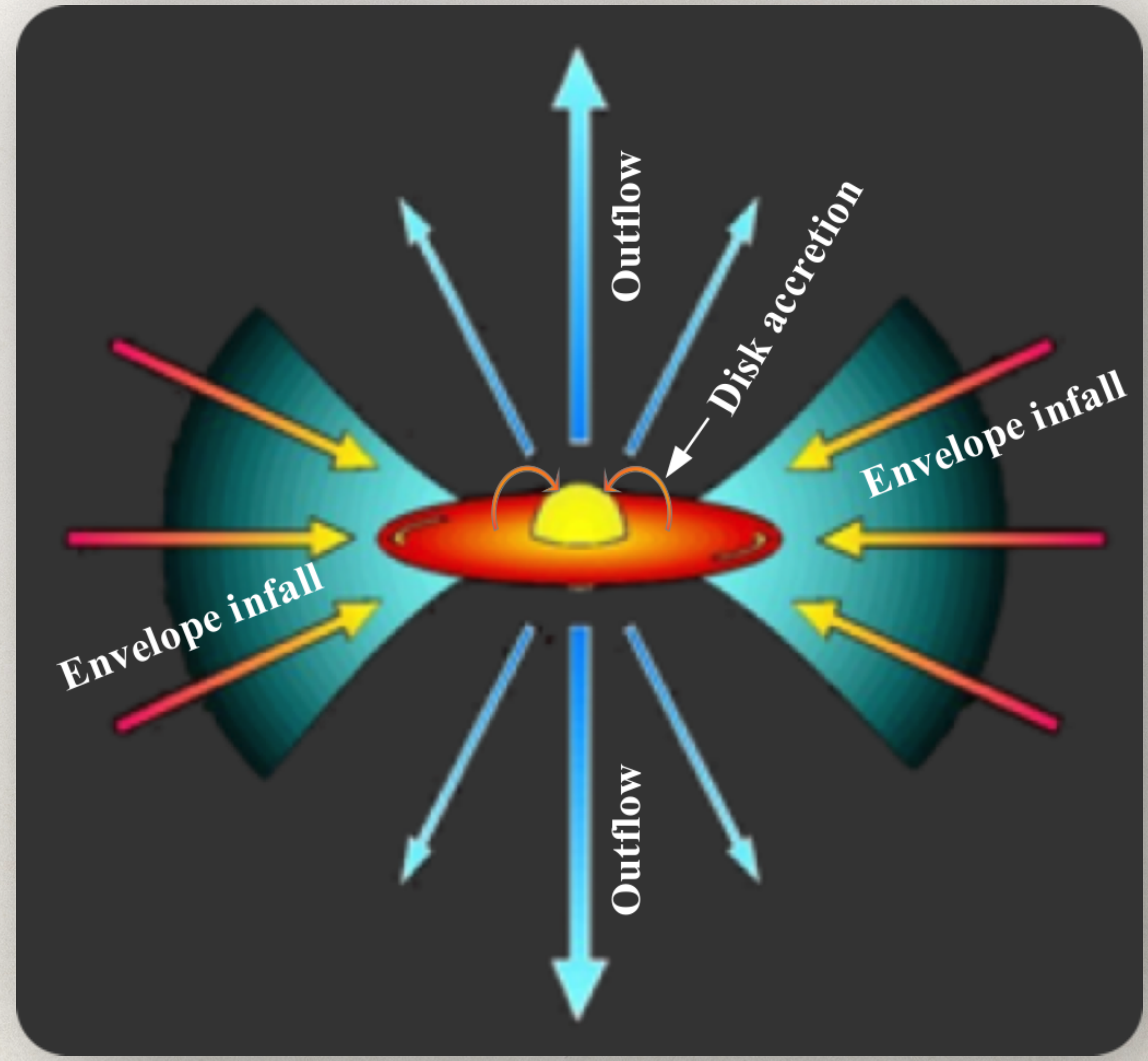
Overview of star & planet formation



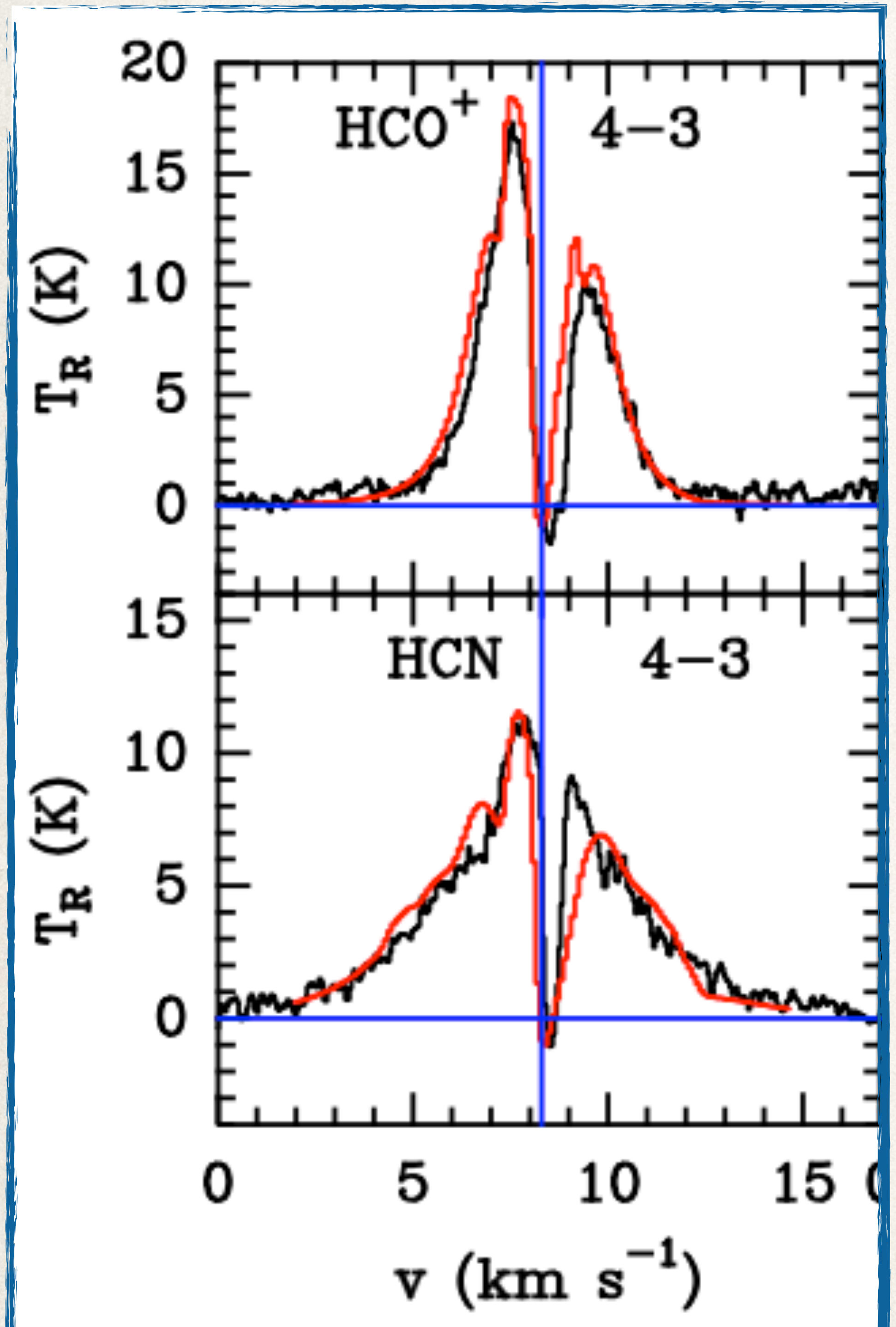
Protostellar evolution

Protostellar evolution is driven by three mass flows: envelope infall, disk accretion & outflows



Envelope infall rate

Traditionally observed in molecular lines at (sub-)mm wavelengths



(Evans et al. 2015)

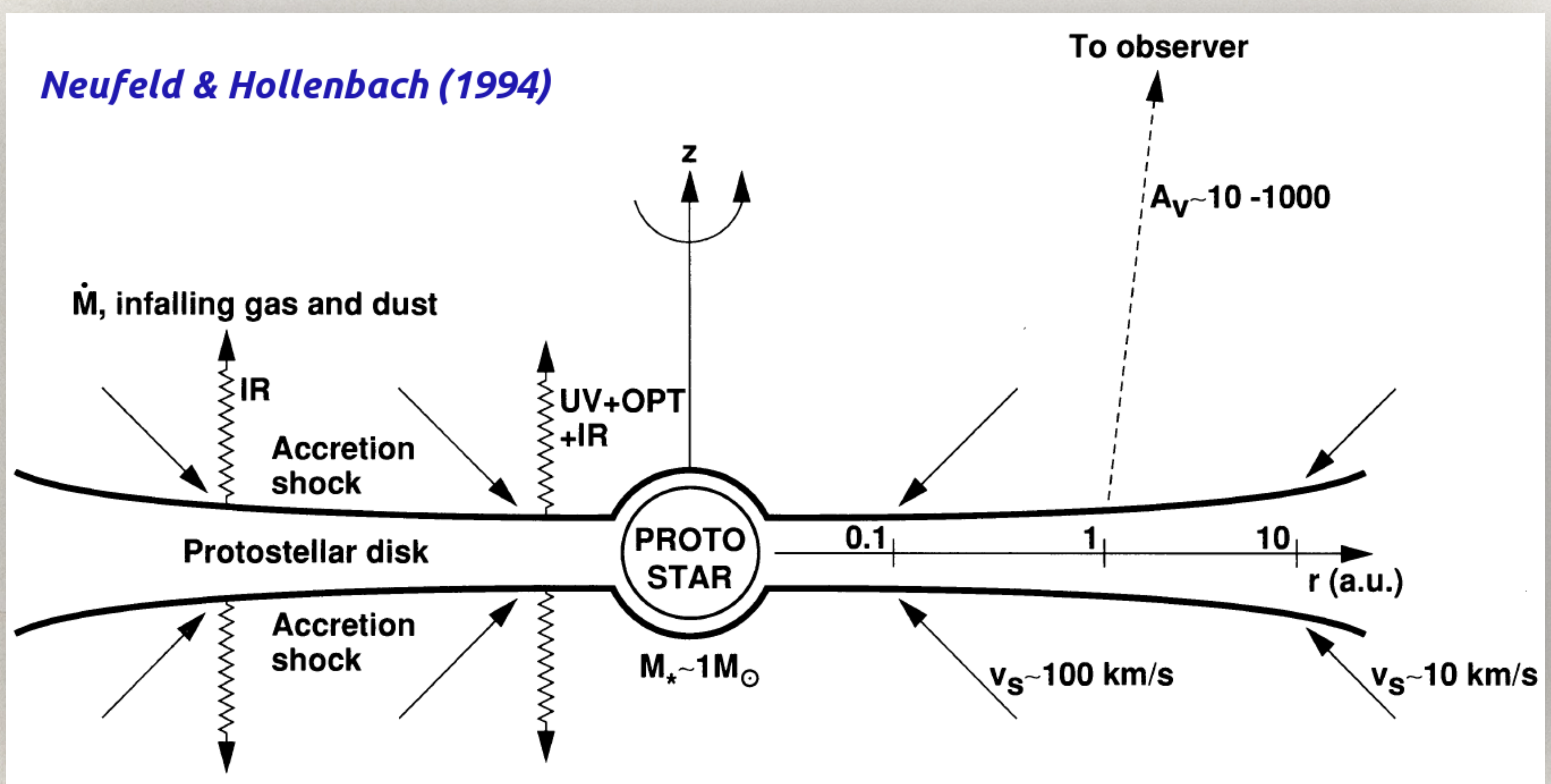
Measured infall rates:

- B335
- NGC1333 IRAS4A

Traces large scale (~ 0.01 pc ~ 1000s of AU) infall motions in the envelope

Envelope infall rate

The envelope material falling in at supersonic velocities lands on the disk and decelerates, and is shocked.

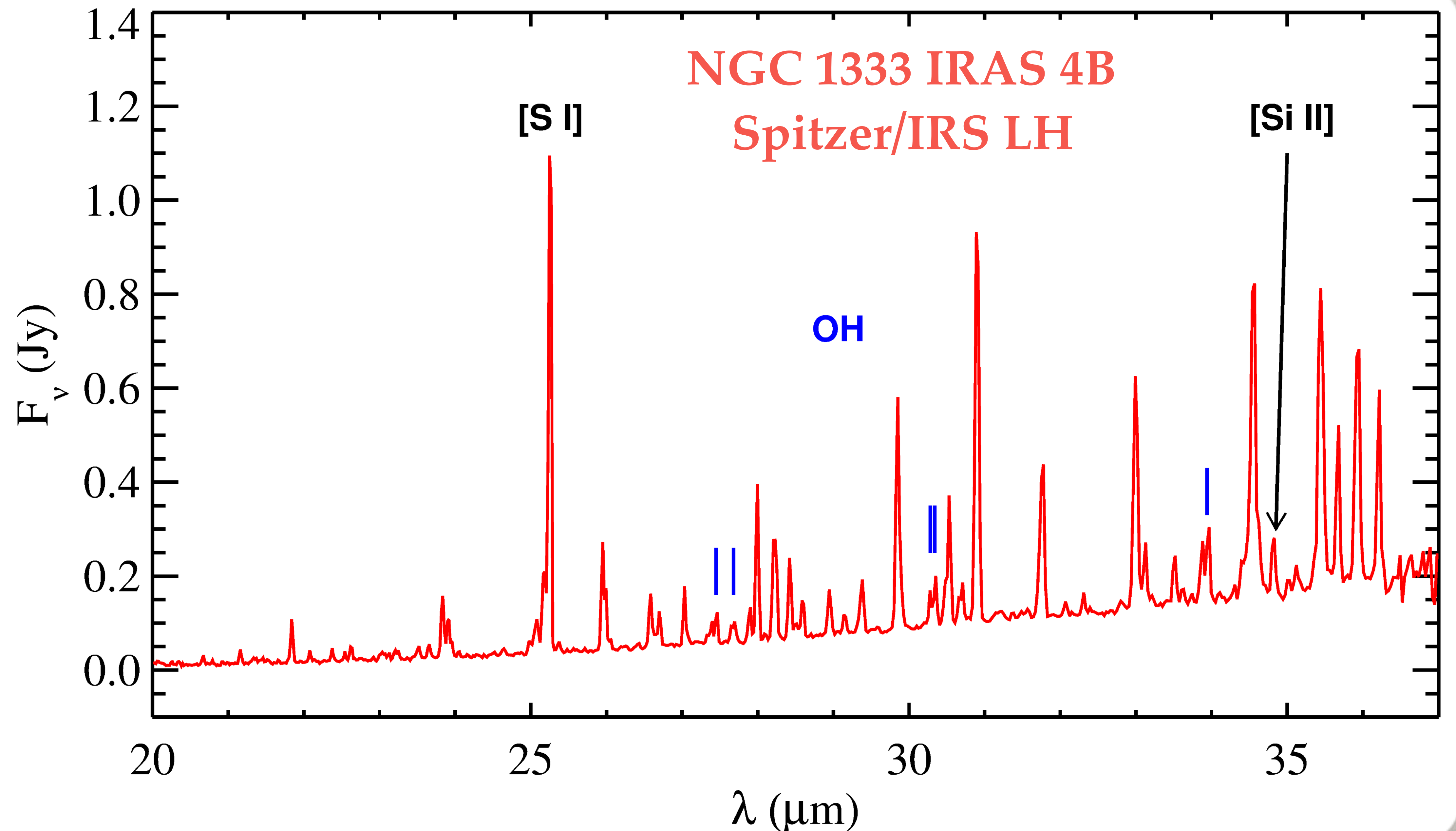


- Dense molecular J-shocks
  - — $v_s < 10$ km/s for $r > 10$ AU
  - — T ~ a few to several 100 K
  - — $n(H_2) > 10^8 – 10^9$ cm^{-3}

- Primary coolants of the post-shock gas: H_2O lines in the mid- & far-IR wavelengths

Envelope infall rate

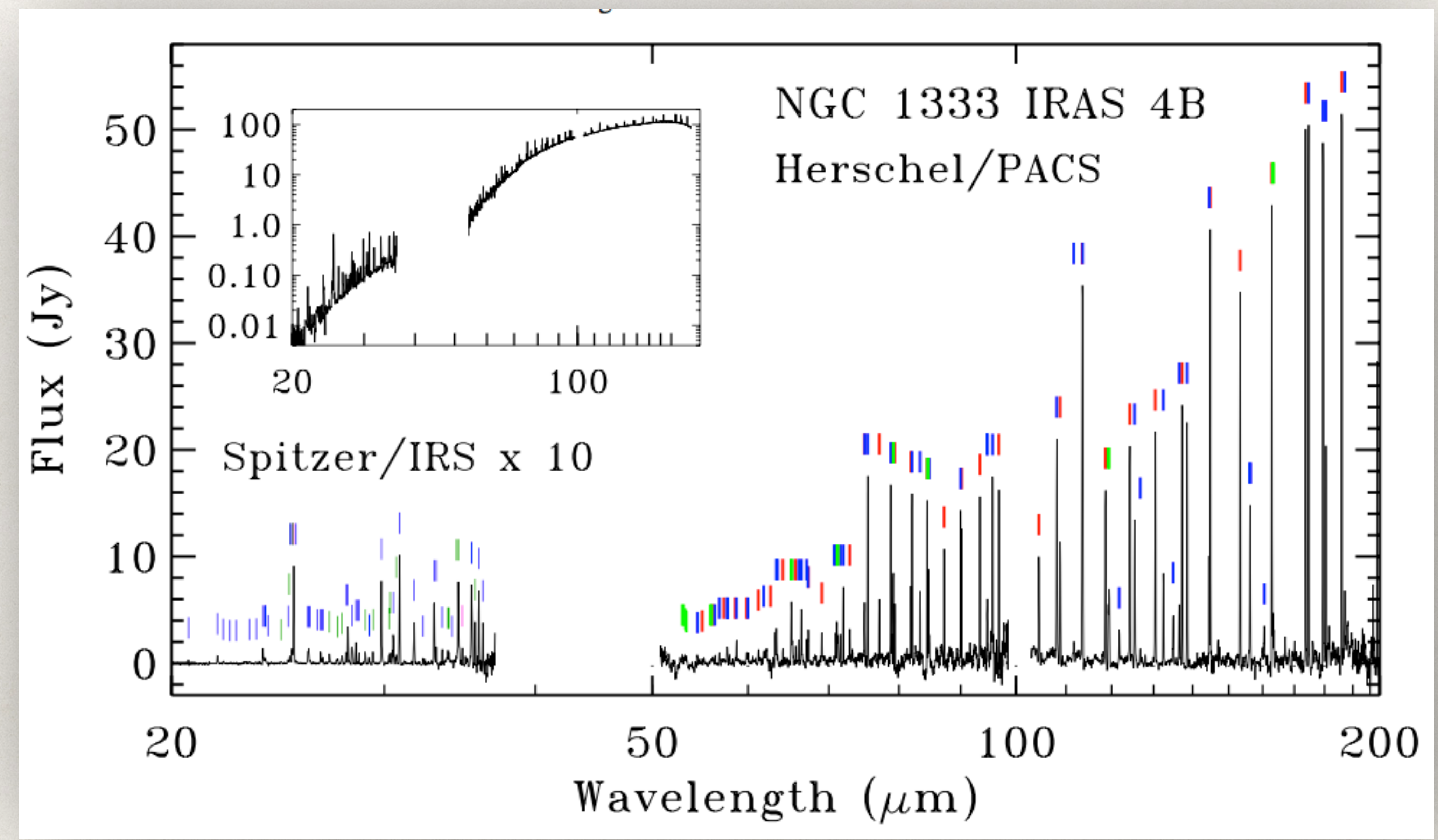
H_2O lines toward protostars in the mid-IR with Spitzer / IRS



(Watson et al. 2007)

Envelope infall rate

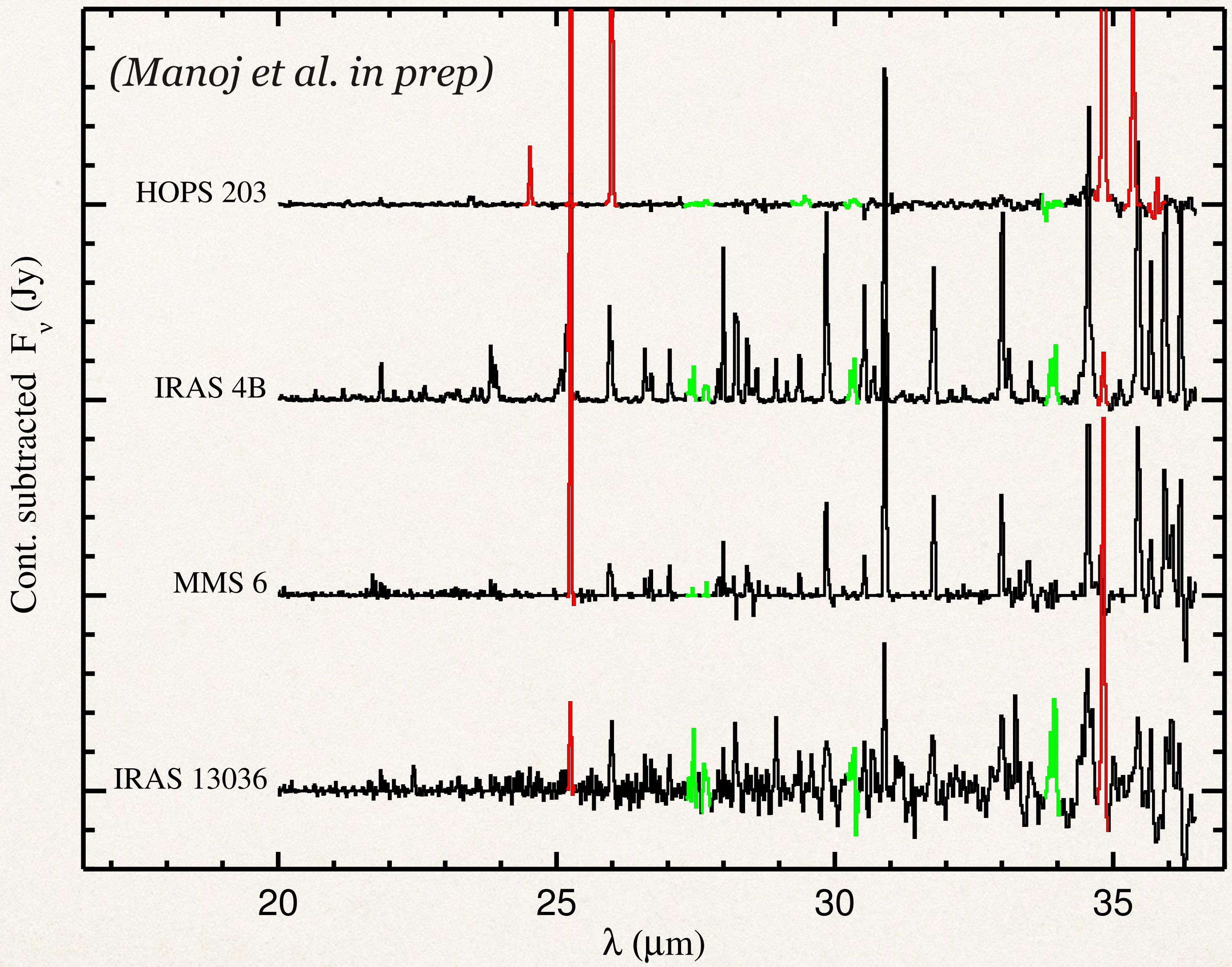
Outflow shocks also produce H
the emission from envelope-disk accretion



H_2O lines in the far-IR with Herschel/PACS *(Herczeg et al. 2012)*

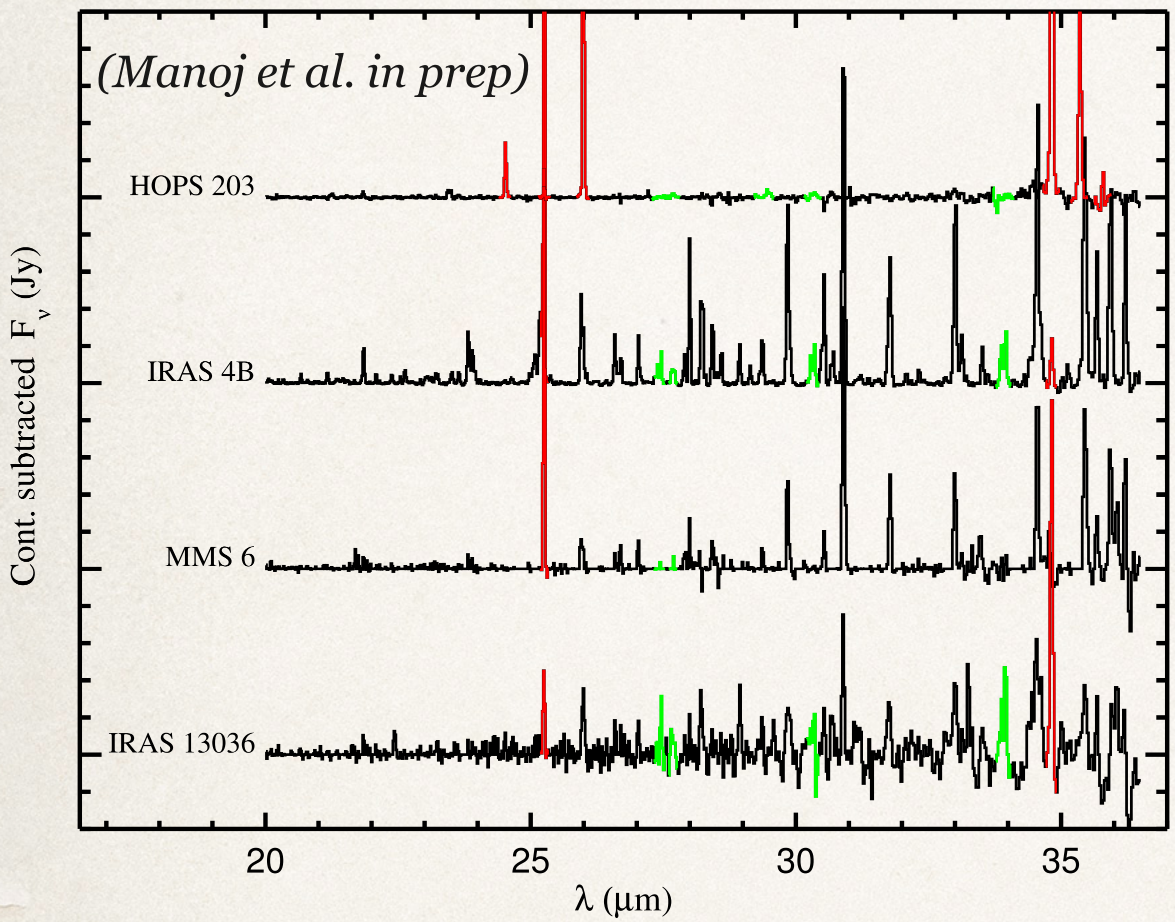
Envelope infall rate

High spatial (~ tens of AU) & spectral resolution (R ~ 60000) in the mid-IR required



- Spitzer IRS survey of ~ 100 protostars in nearby star forming regions.
- half of them show water emission

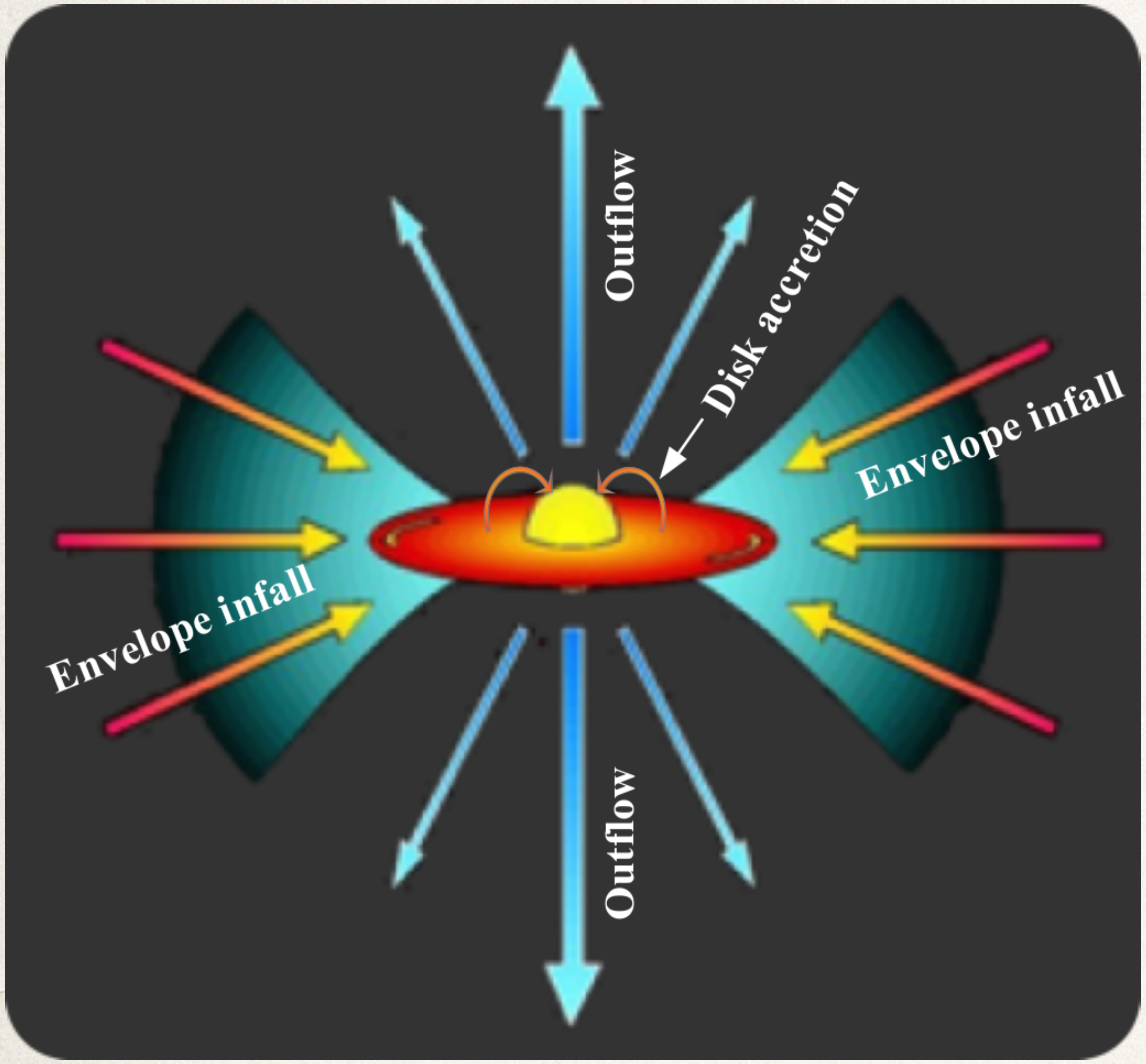
Envelope infall rate



- 8-10 m class telescopes do not have the sensitivity
- JWST does not have the spectral resolution (MIRI; R ~ 3000)
- no Q-band (16-25 μm) spectroscopic capability on METIS/ELT
- high resolution mid-IR spectroscopy with TMT

Total cooling luminosity (observations provide

Measuring disk accretion rate



instantaneous infall & accretion: how well are they coupled ?

how efficient are disks in transporting mass ?

L_{bol}

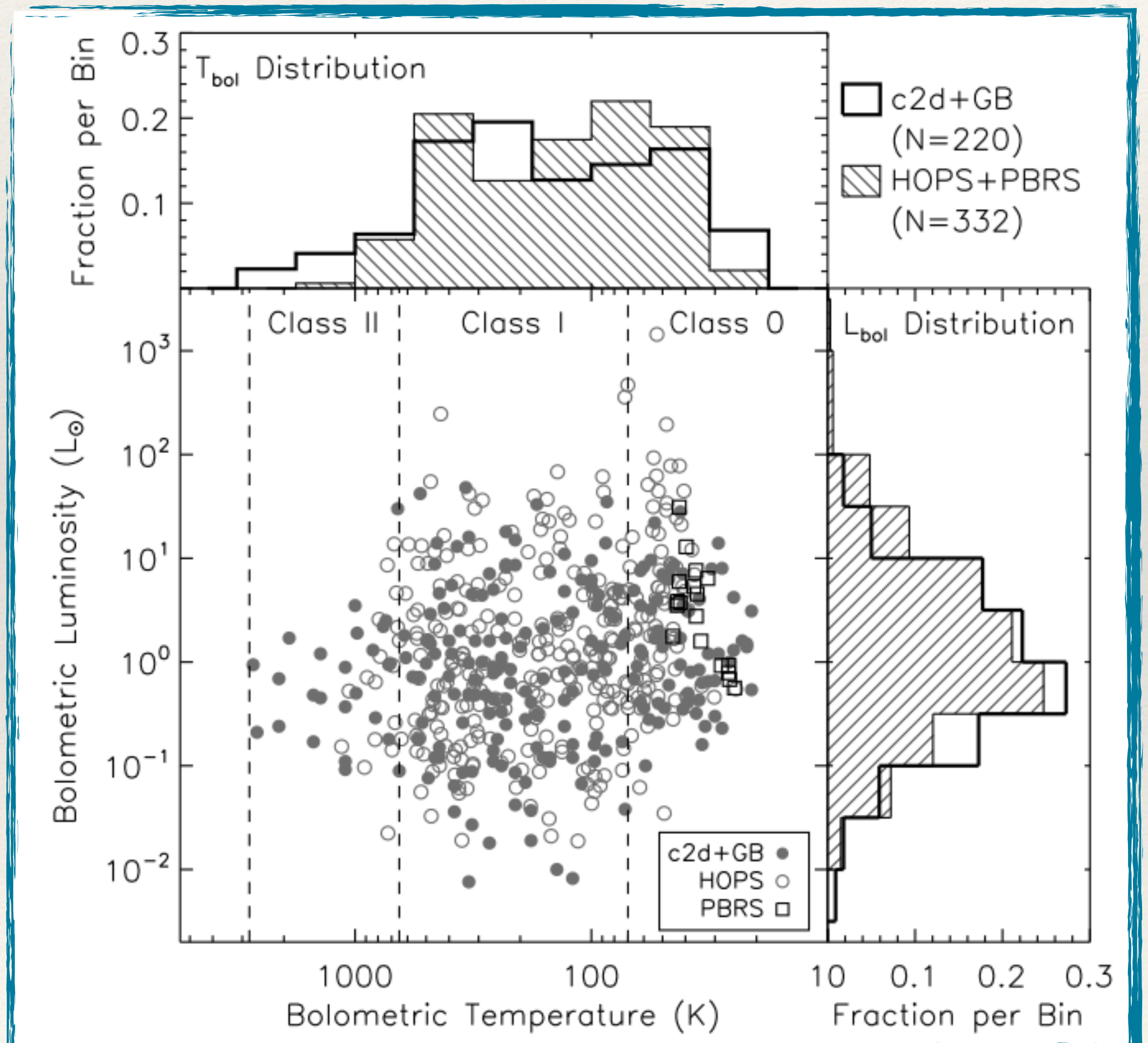
$$L_{bol} = L_{phot} + L_{acc}$$

$$L_{acc} = f_{acc}\,\frac{GM_\star(t)\dot{M}}{r}$$

Protostellar luminosity problem

$\Rightarrow$ 0.25 $M_\odot$ @ 5×10^{-6} $M_\odot$ $yr^{-1} \Rightarrow$ $L_{acc} \sim 10$ $L_\odot$

observed L_{bol} of most protostars $\lesssim$ 10 $L_\odot$



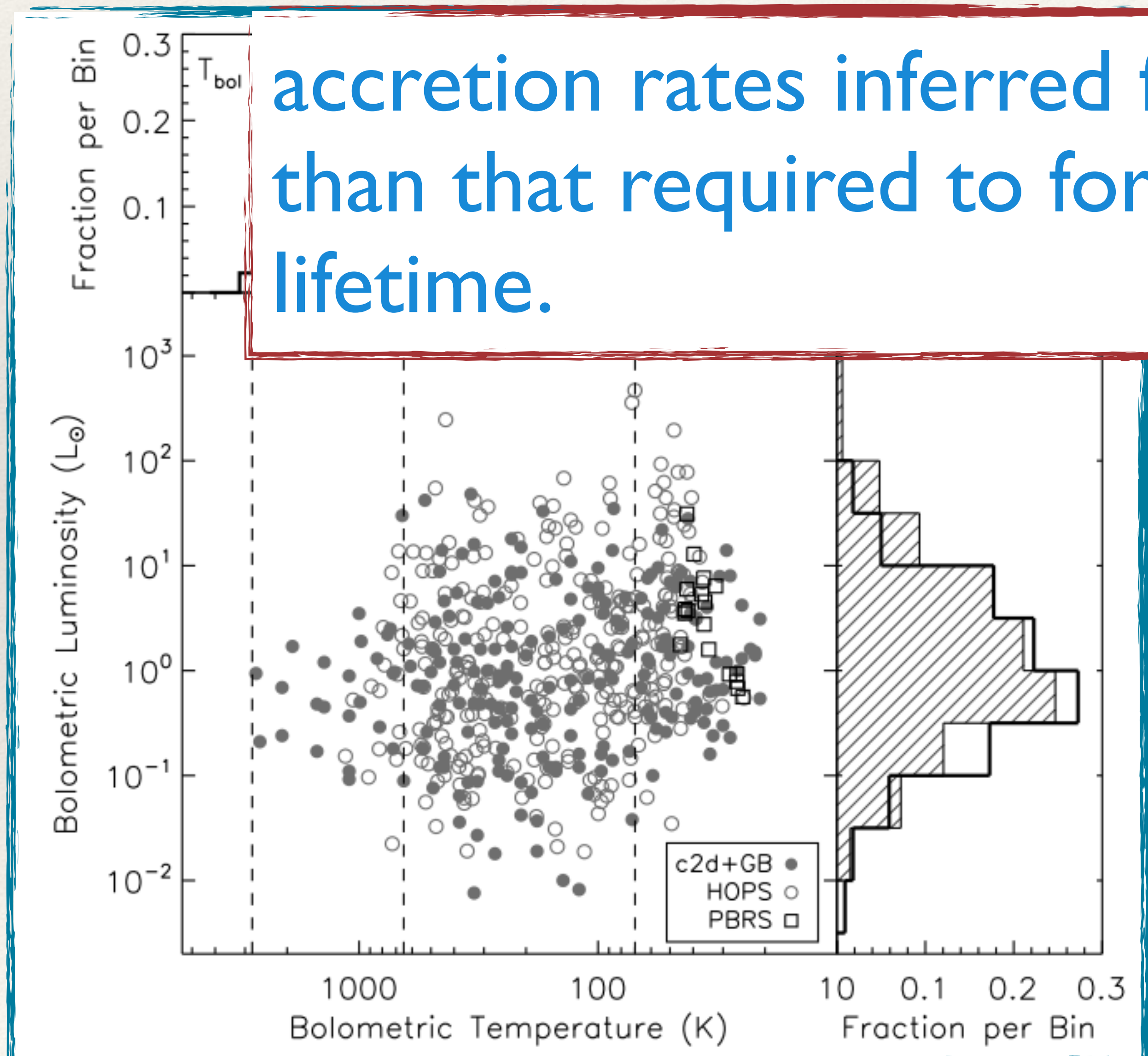
(Dunham+ 2014)

Protostellar luminosity problem

$\Rightarrow$ 0.25 $M_\odot$ @ 5×10^{-6} $M_\odot$ yr^{-1} $\Rightarrow$ $L_{acc} \sim 10$ $L_\odot$

observed L_{bol} of most protostars $\leq$ 10 $L_\odot$

accretion rates inferred from L_{bol} are significantly lower than that required to form a star within the protostellar lifetime.



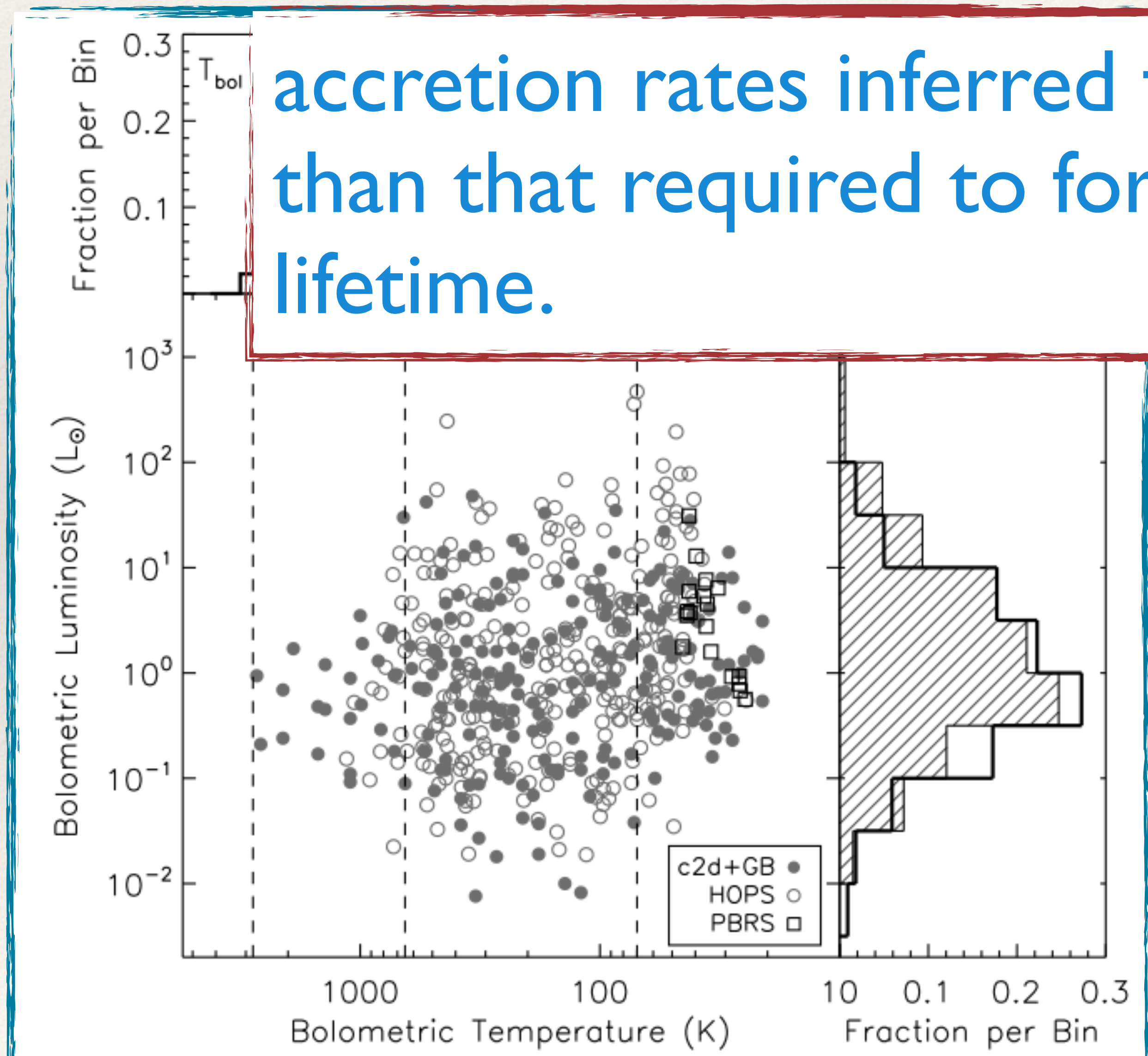
(Dunham+ 2014)

Protostellar luminosity problem

$\Rightarrow$ 0.25 $M_\odot$ @ 5×10^{-6} $M_\odot$ yr^{-1} $\Rightarrow$ $L_{acc} \sim 10$ $L_\odot$

observed L_{bol} of most protostars ≤ 10 $L_\odot$

accretion rates inferred from L_{bol} are significantly lower than that required to form a star within the protostellar lifetime.

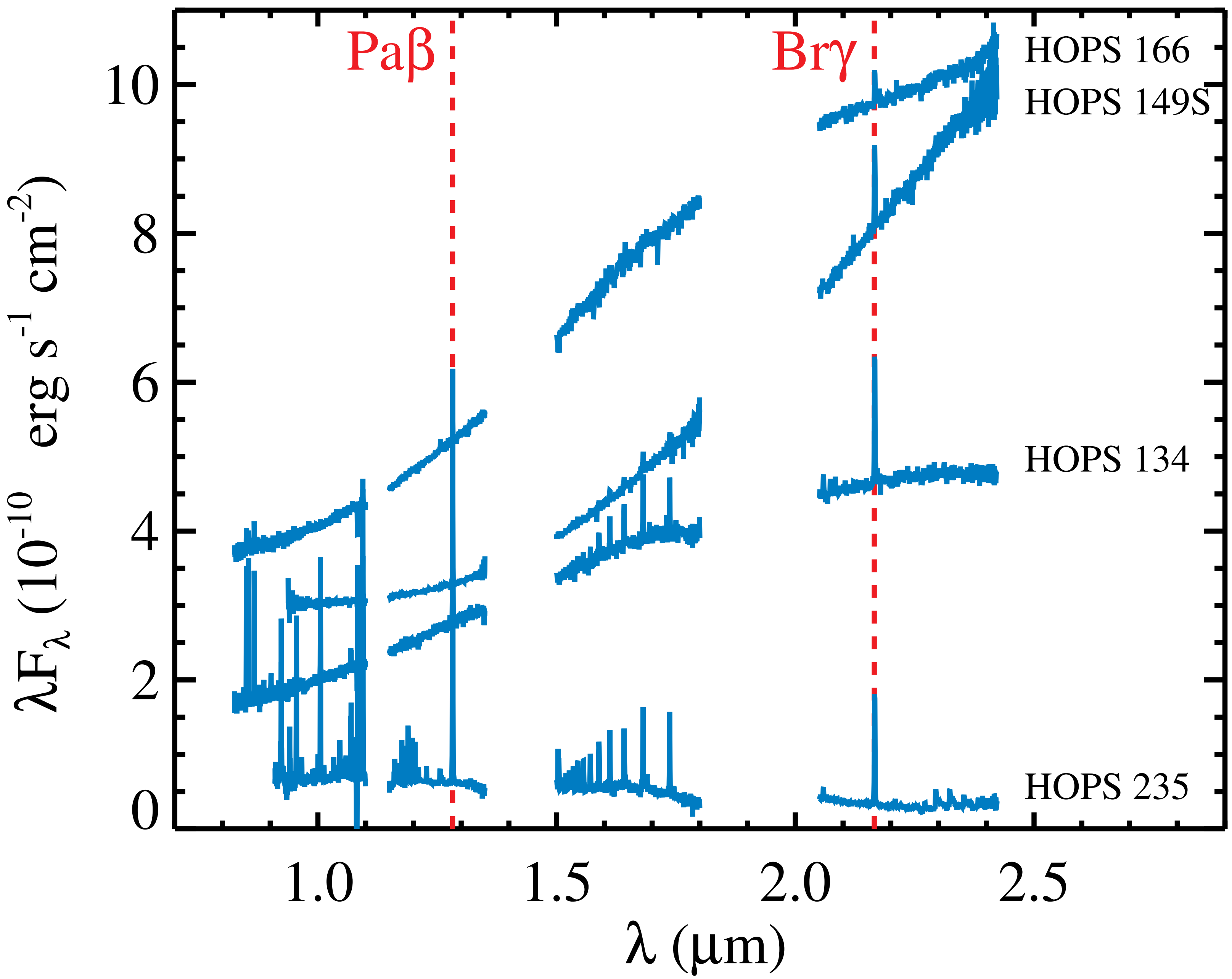


disk accretion is episodic!

(Dunham+ 2014)

Disk accretion rates

Direct tracers of accretion such as Hα, Pβ, Brγ, (λ < 2.5
observe in deeply embedded protostars



(Fischer et al. in prep)

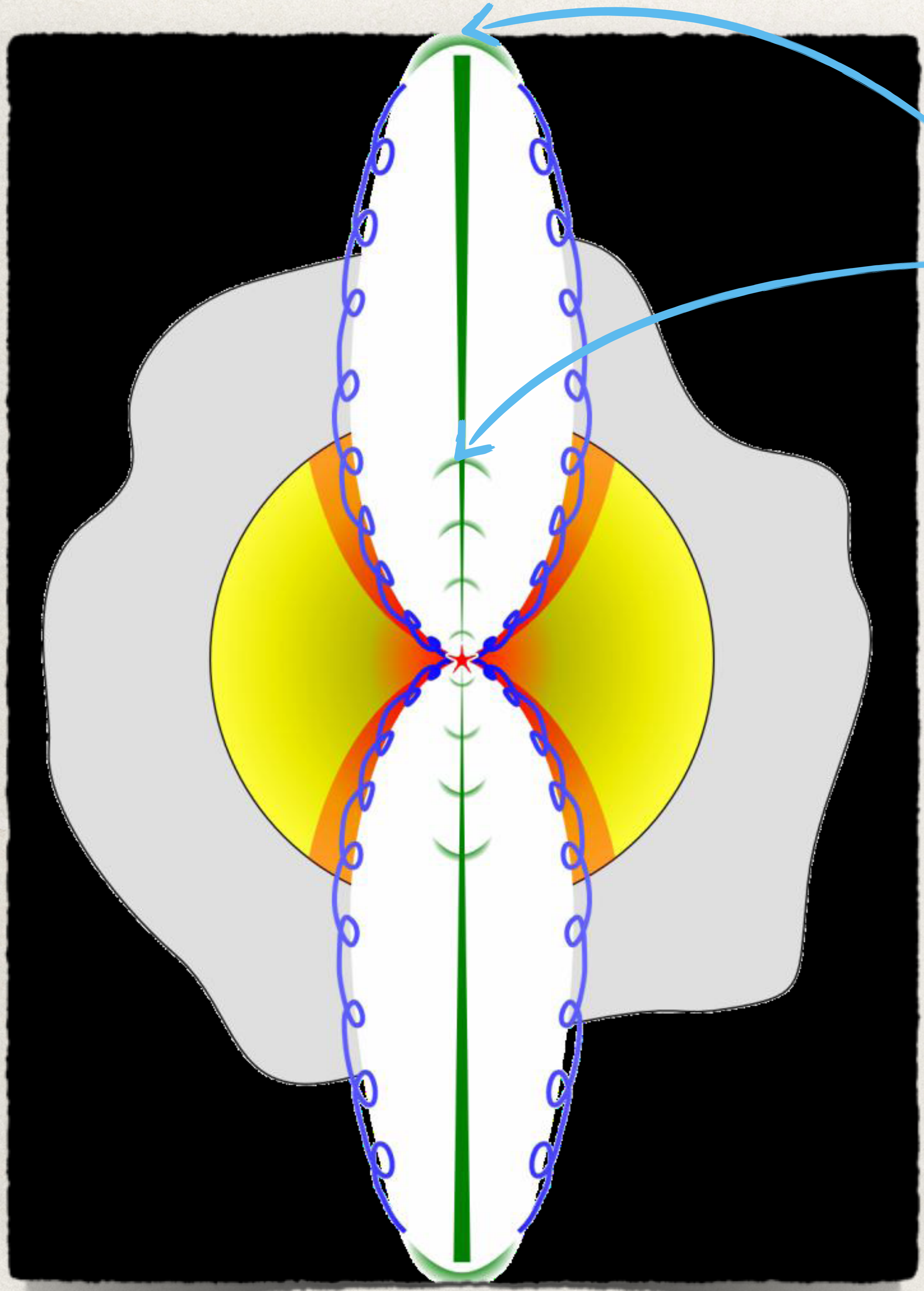
Disk accretion rate

Higher excitation hydrogen lines H (9-7) @11.3 μm & H (7-6) @ 12.4 μm as direct tracers of accretion in the early protostellar phase
al. 2012)

- less likely to be contaminated by contribution from protostellar jets
- MIRI/JWST & METIS/ELT will have access to these lines (N-band)

With TMT/MICHI near-simultaneous observations of envelope infall & accretion rates

Measuring mass loss rates



J-shocks (v_S ~ 100 km/s)

T ~ 500 - 5000 K & n(H) ~ 10^3– 10^7 cm^{-3}

[OI]@63 µm

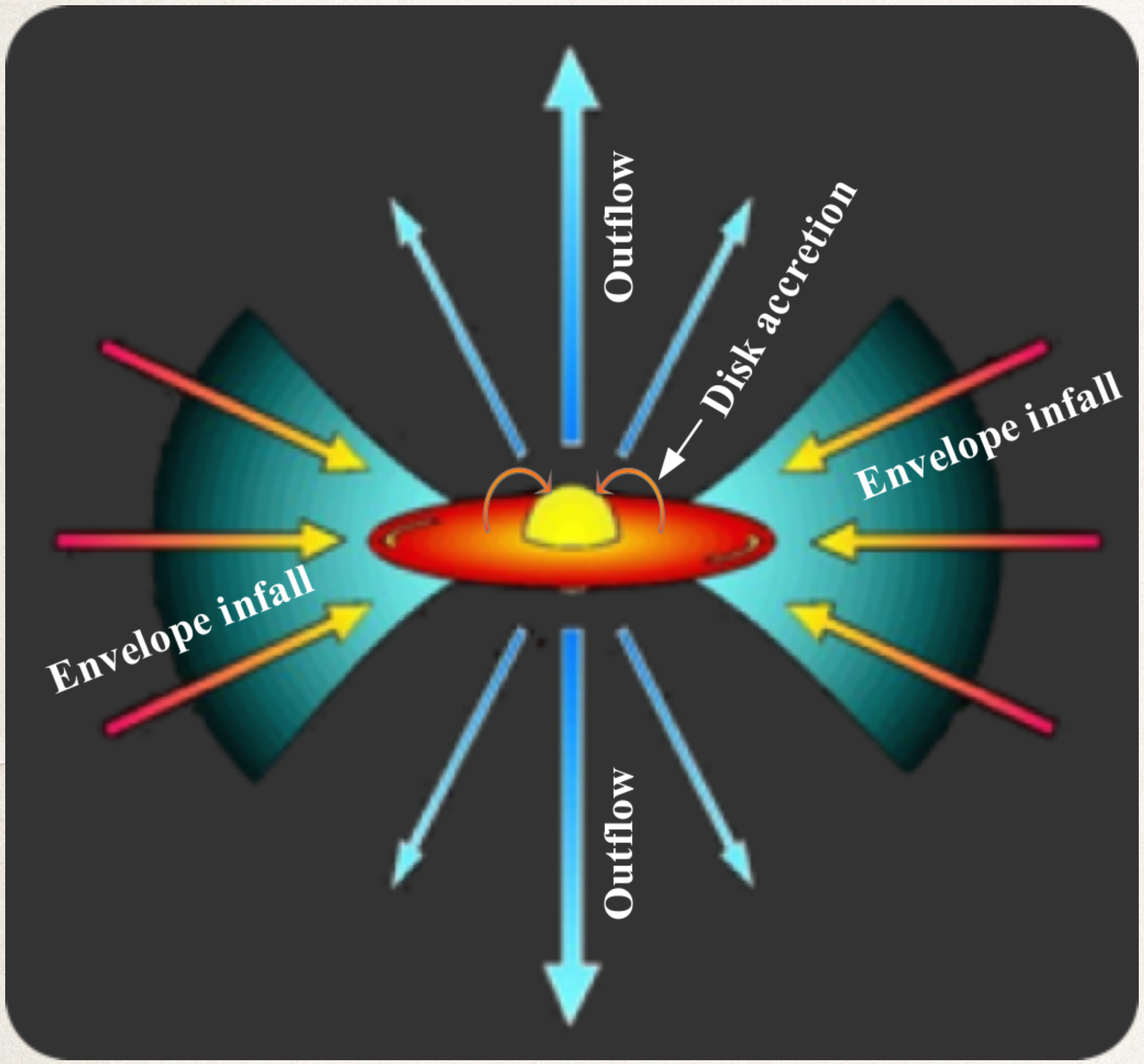
(Hollenbach 1985; Hollenbach et al. 1989)

$$L([OI]) \sim \dot{M}_{\rm outflow}\ m_{\rm H}^{-1}\ k\ T(5000K)$$

MIR & FIR FS lines: the most direct & accurate method of deriving protostellar mass loss rates

Mass accretion-ejection connection

Theoretical models for jet launching mechanisms predict direct proportionality between accretion and ejection rates

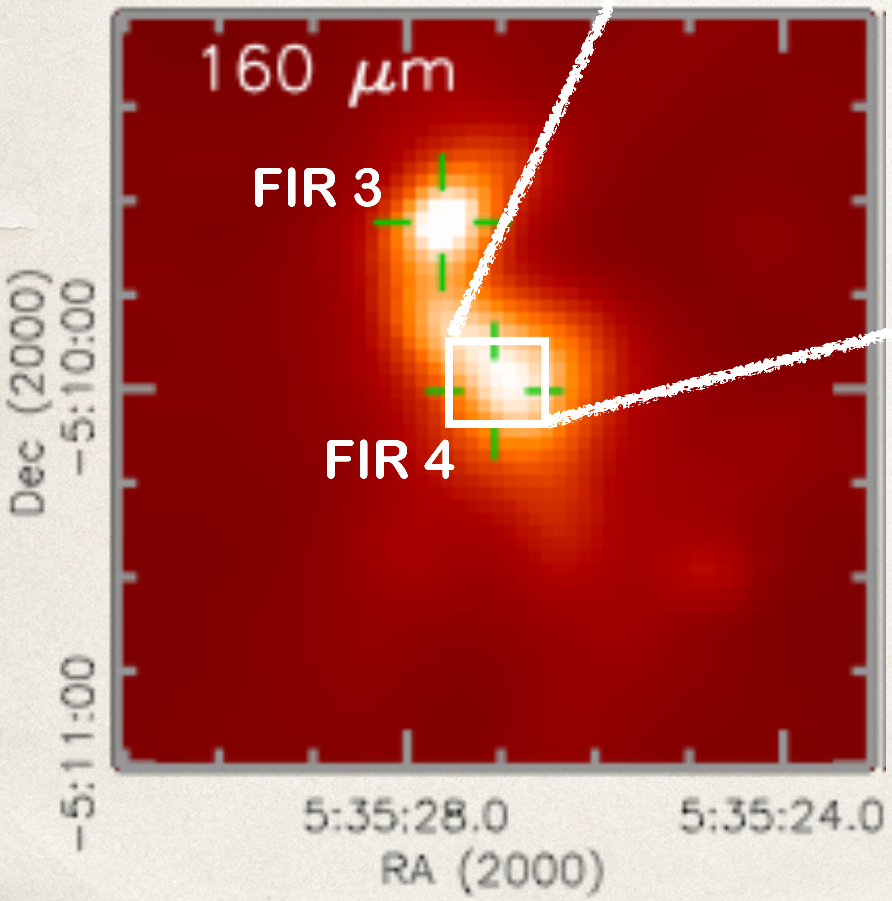


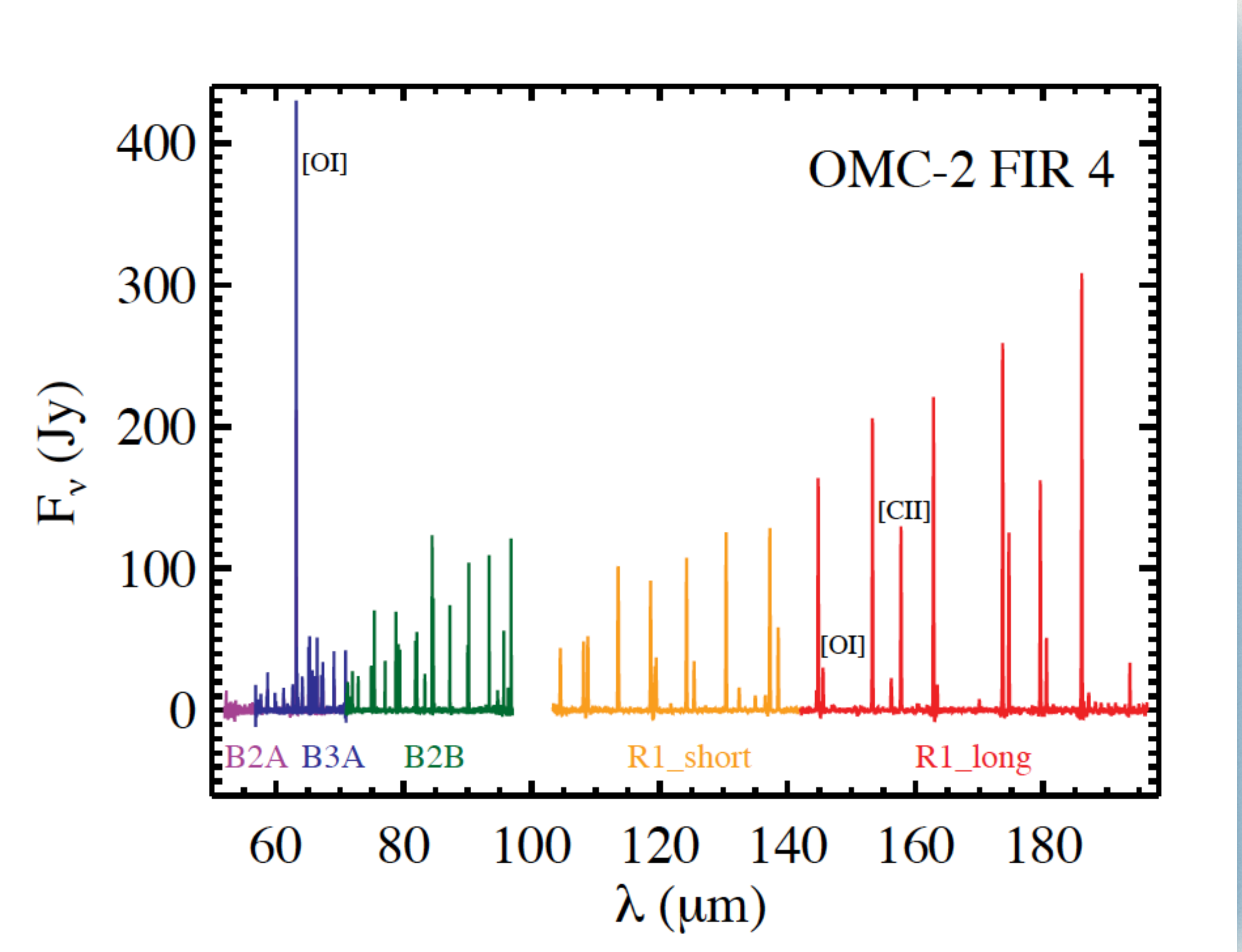
1. X winds
   (Shu+ 1994, 2000, Najita & Shu 1994)
2. Disk winds
   (Pelletier & Pudritz 1992, Konigl & Pudritz 2000)
3. Accretion Powered Stellar Winds (APSW)
   (Matt & Pudritz 2005, 2008)

$$\boxed{\dot{M}_{\mathrm{outflow}} = b\,\dot{M}_{\mathrm{acc}}}$$

b = branching ratio (0.1 - 0.3)

The OMC-2 region in Orion A



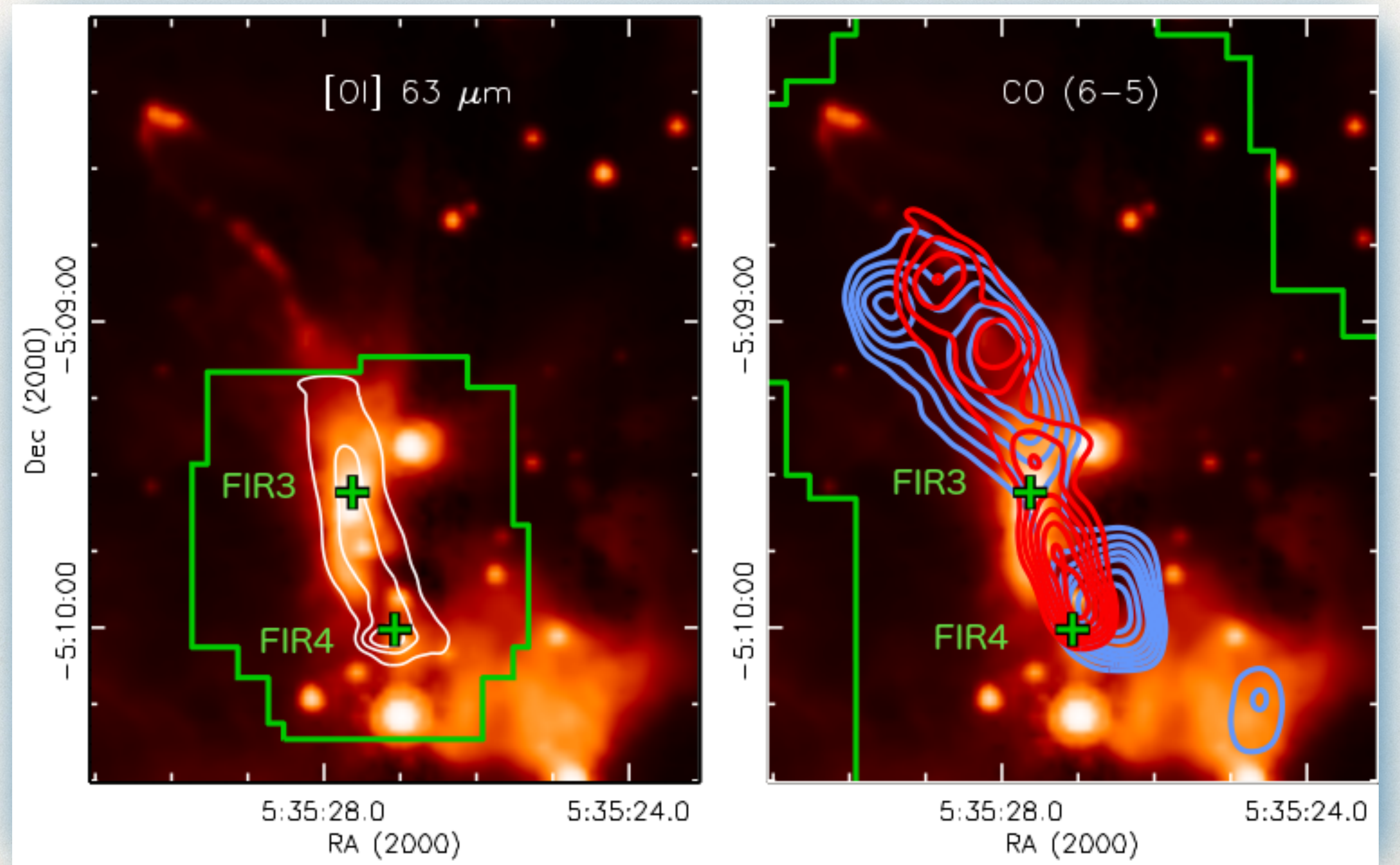


Richest & brightest FIR spectra observed towards a low mass protostar

(Manoj et al. 2013, Furlan et al. 2014)

[O I] jet in OMC-2

[O I] jet aligned with jet/outflow seen in IRAC 4.5 μm band and CO (6-5), both centered on FIR 3

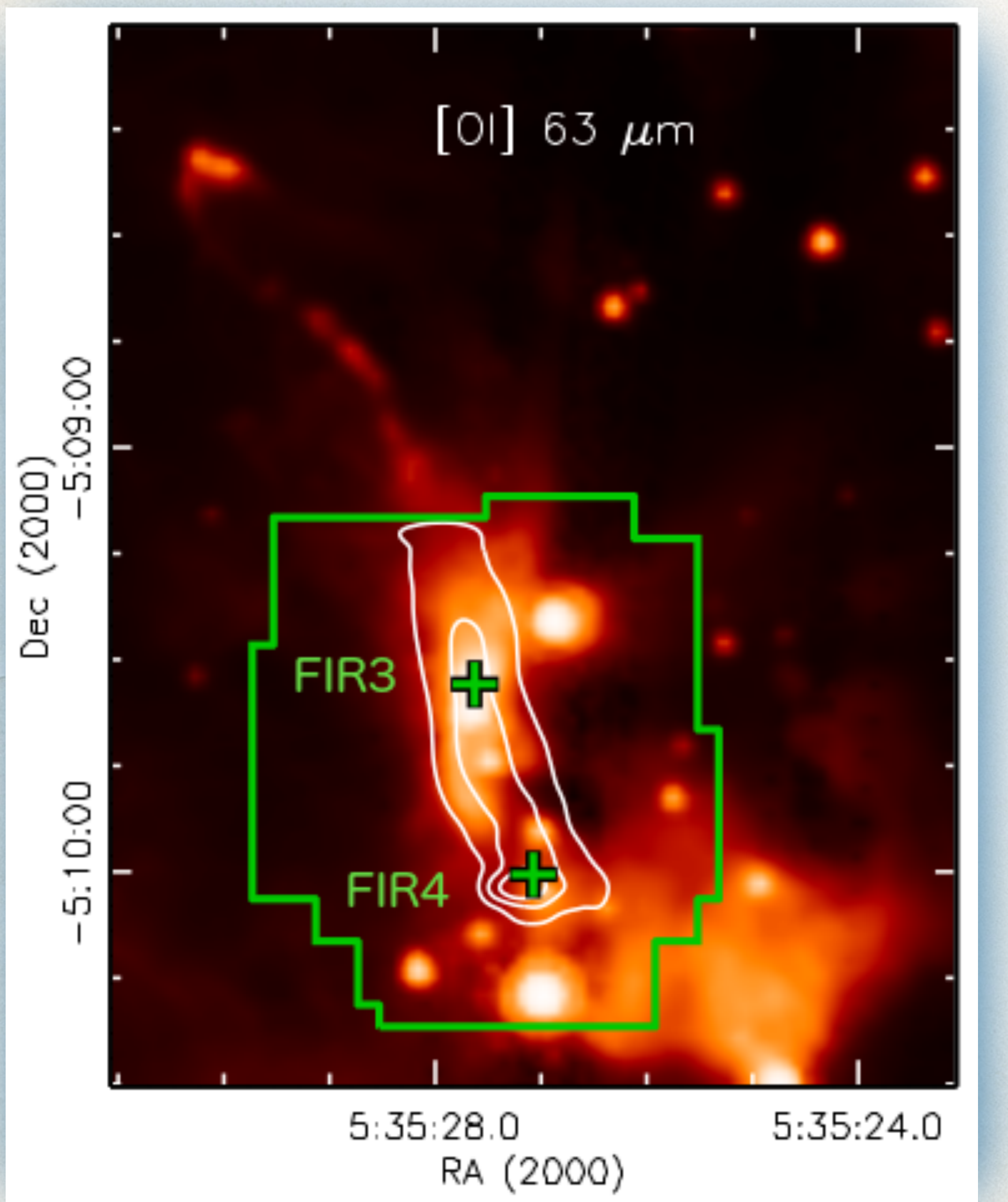


(Beatriz, Manoj et al., A&A, under review)

Mass loss rates in the jet

Total [O I] 63 μm line luminosity = $6.7 \times 10^{-2}\ L_\odot$

$$\Longrightarrow \text{ mass loss rate, } \dot{M}_{\rm out} = 5.4 \times 10^{-6} M_\odot\ yr^{-1}$$



for a branching ratio $b = 0.1$

$$\Longrightarrow \dot{M}_{\rm acc} = 5.4 \times 10^{-5} M_\odot\ yr^{-1}$$

$$\Longrightarrow L_{\rm acc} \sim 300 L_\odot$$

But, FIR 4 has an $L_{\rm bol} = 38\ L_\odot$, so it cannot be driving this jet

the observed [OI] jet driven by FIR 3

(Beatriz, Manoj et al., A&A, under review)

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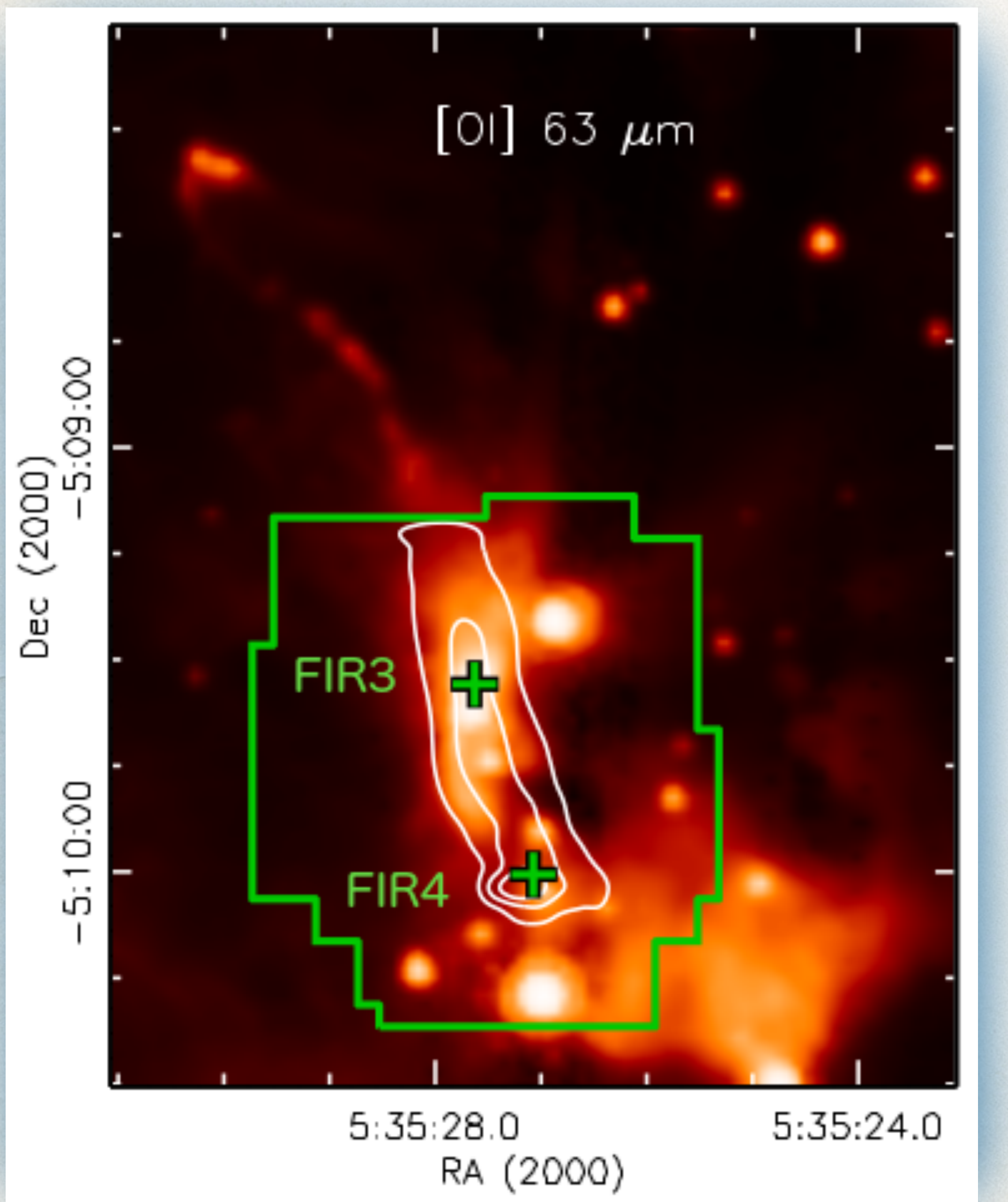
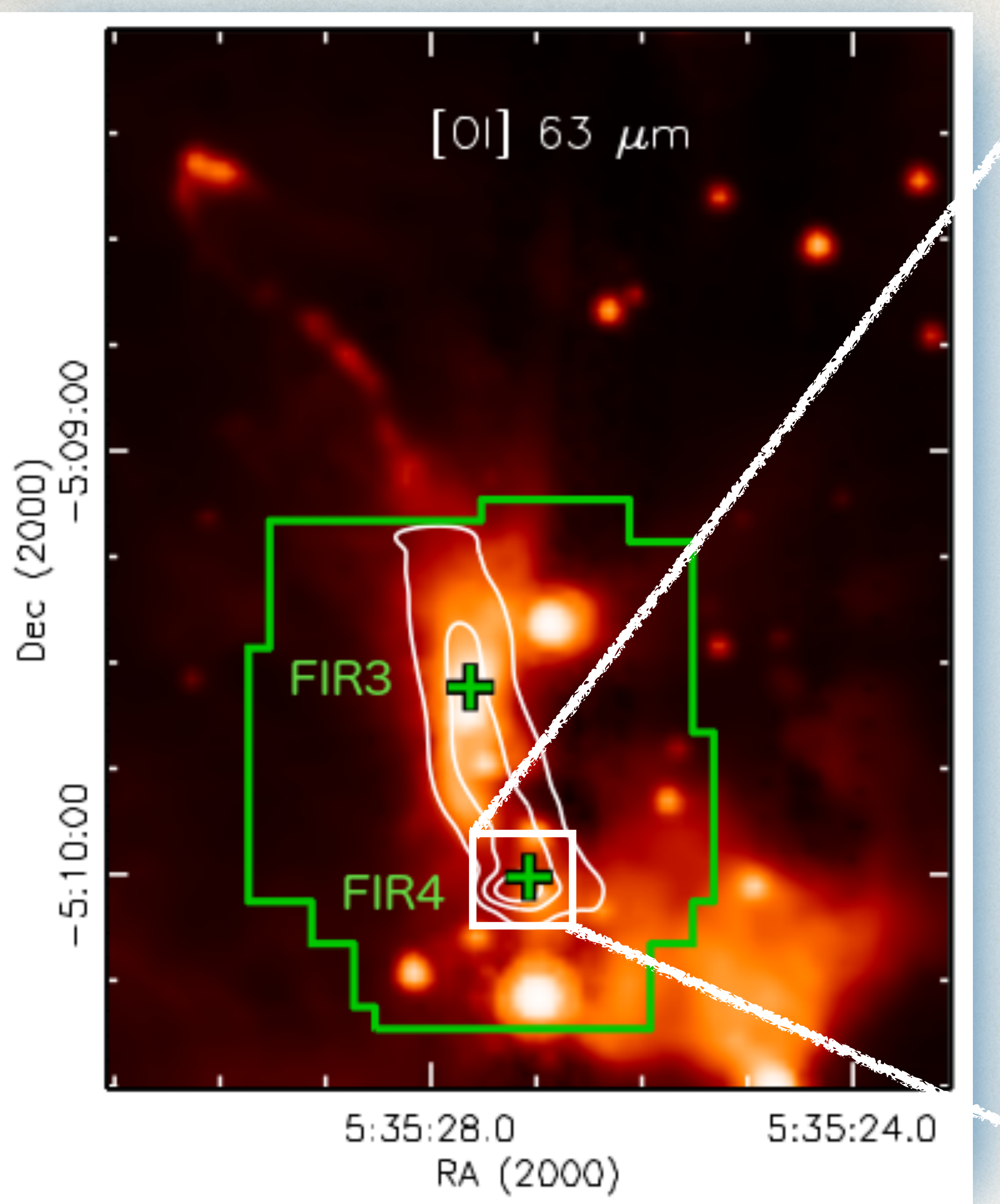
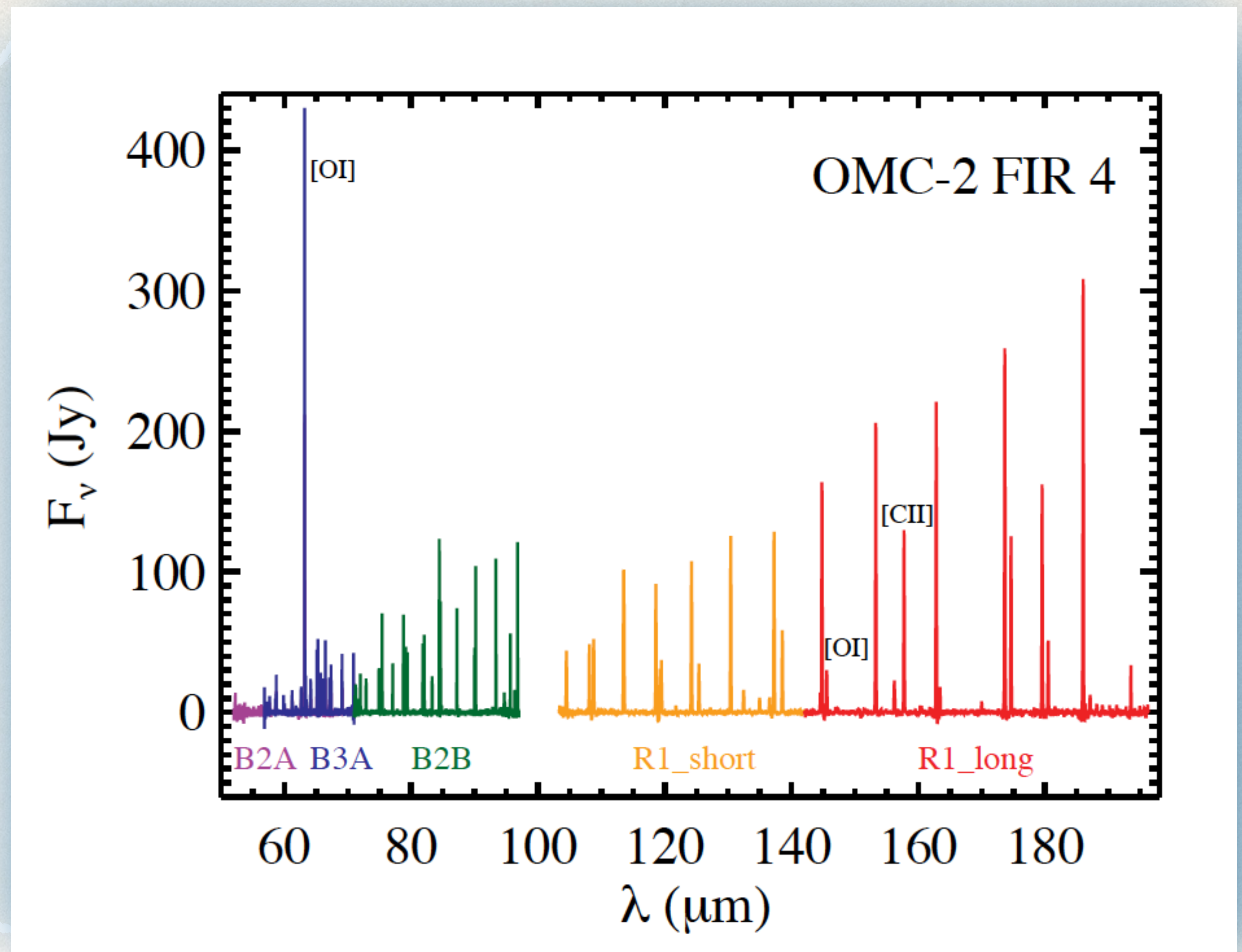


the observed [OI] jet driven by FIR 3

the first [O I] jet to be imaged from an intermediate mass protostar…

(Beatriz, Manoj et al., A&A, under review)





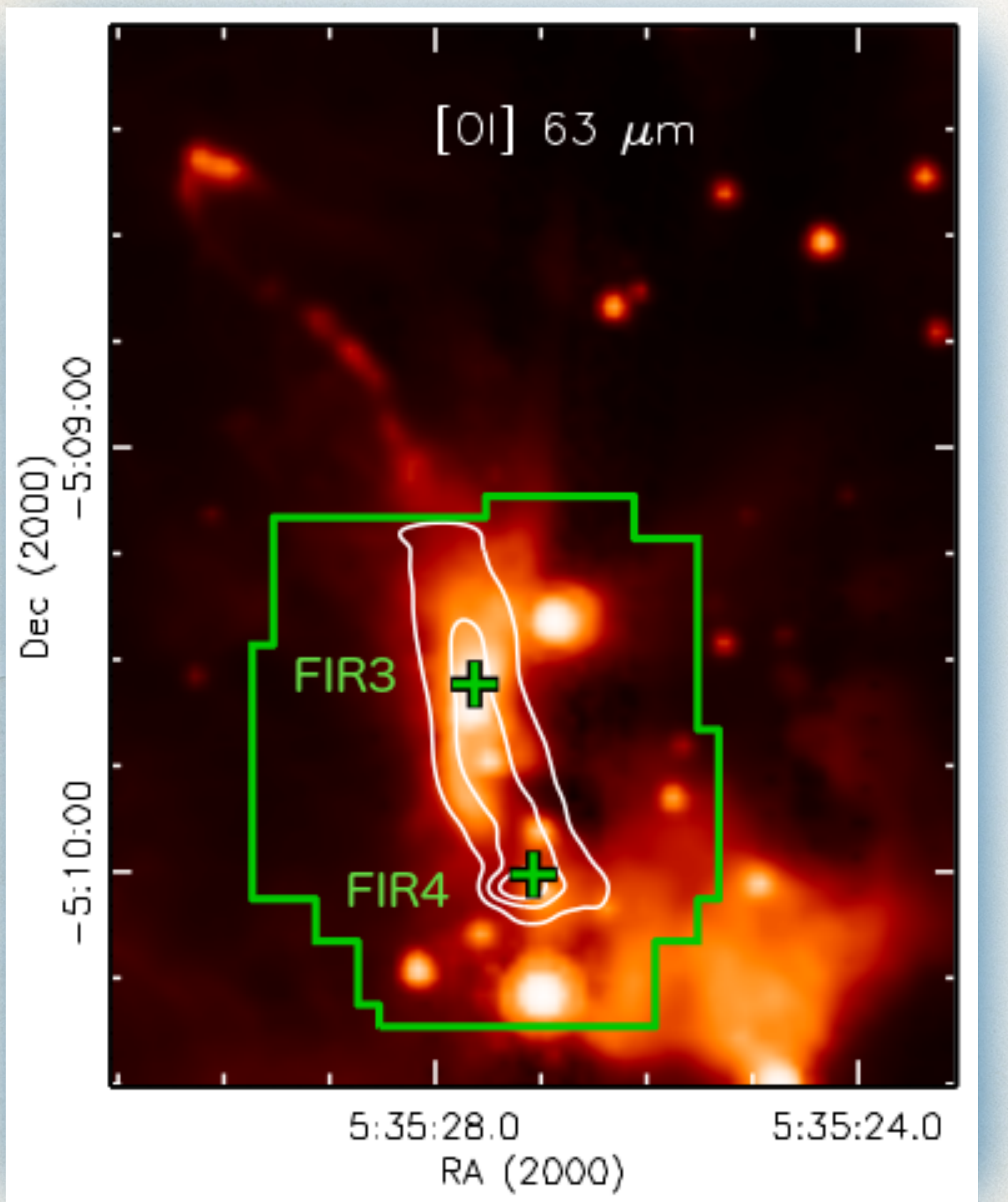
the intense line emission seen toward FIR 4 produced by the terminal shock (Mach disk) of the FIR 3 jet.

(Beatriz, Manoj et al., A&A, under review)

Mass loss rates in the jet

Total [O I] 63 μm line luminosity = 6.7 ×10^{-2} L$_\odot$

$$\Longrightarrow \text{ mass loss rate, } \dot{M}_{\rm out} = 5.4 \times 10^{-6} M_\odot \; yr^{-1}$$



[O I] jets in low mass stars *(Nisini et al. 2015)*

$$\Longrightarrow \dot{M}_{\rm out} = 1 - 4 \times 10^{-7} M_\odot \; yr^{-1}$$

intermediate mass protostars appear to drive more powerful jets than their low mass counterparts.

⟹ they also accrete at a higher rate

(Beatriz, Manoj et al., A&A, under review)

Mass loss rates with TMT

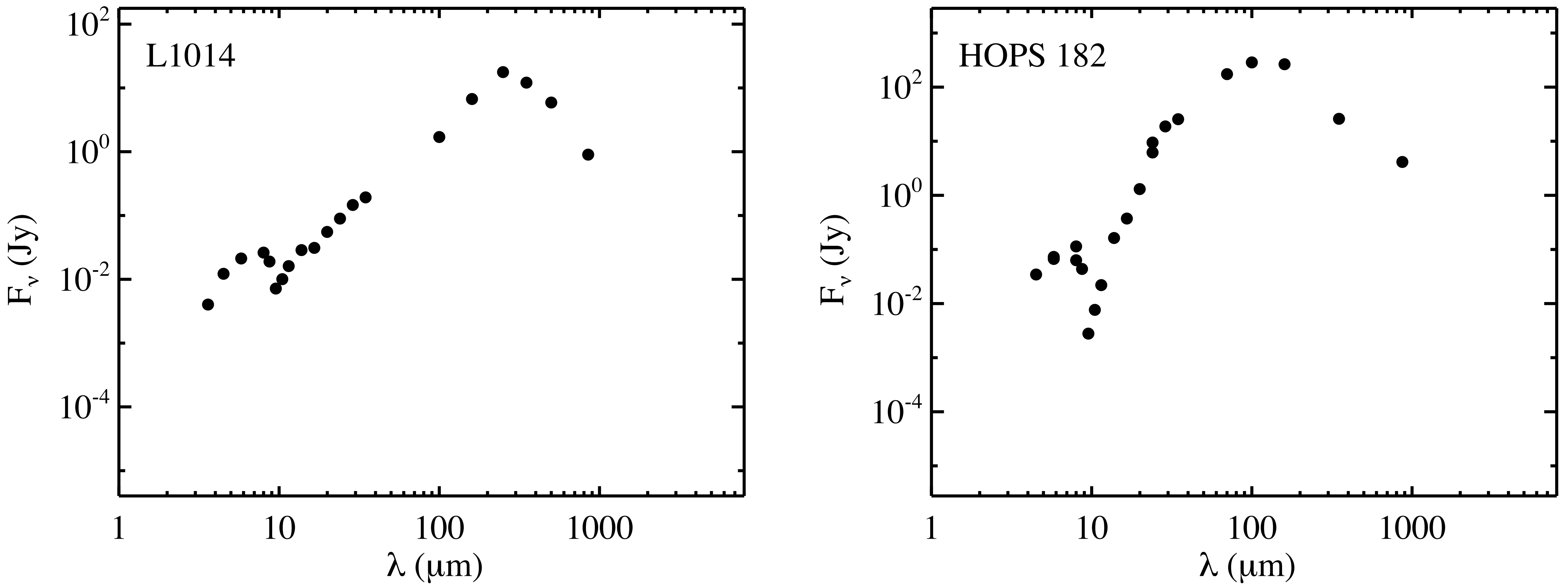
[Fe II] lines in the mid-IR follow [O I] 63 μm line, and can be used as proxies to measure mass loss rates
Watson et al. 2016)

Several
probes of jet/outflow shocks

TMT/MICHI spatially and spectrally resolve jet/outflow morphology and energetics even at the base of the flow, close to the driving source.

The Sample

- several hundred protostars within 400 pc, observed with Spitzer & Herschel
- uniformly sampled SEDs, with the well sampled peaks
- protostellar properties (L

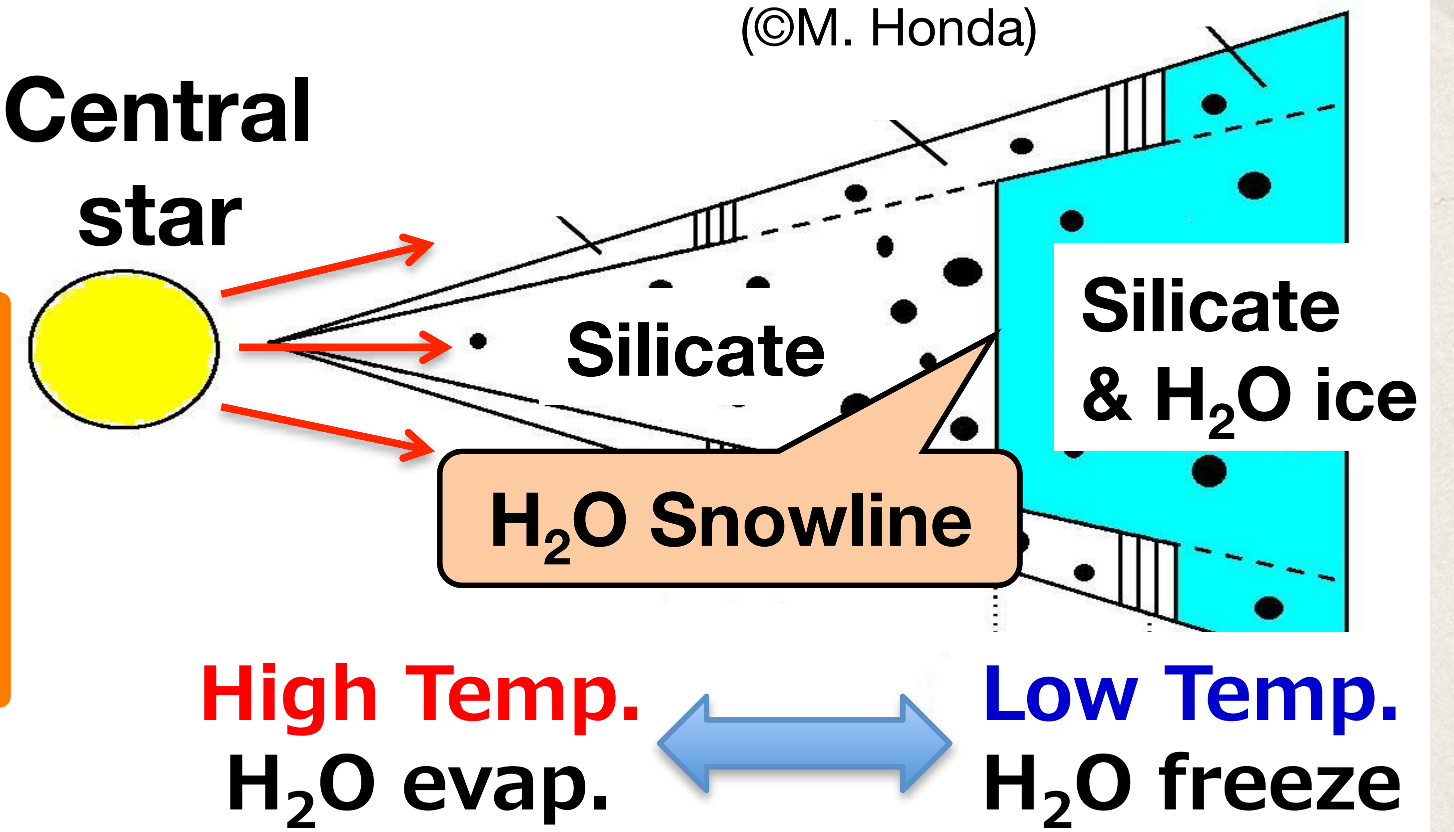


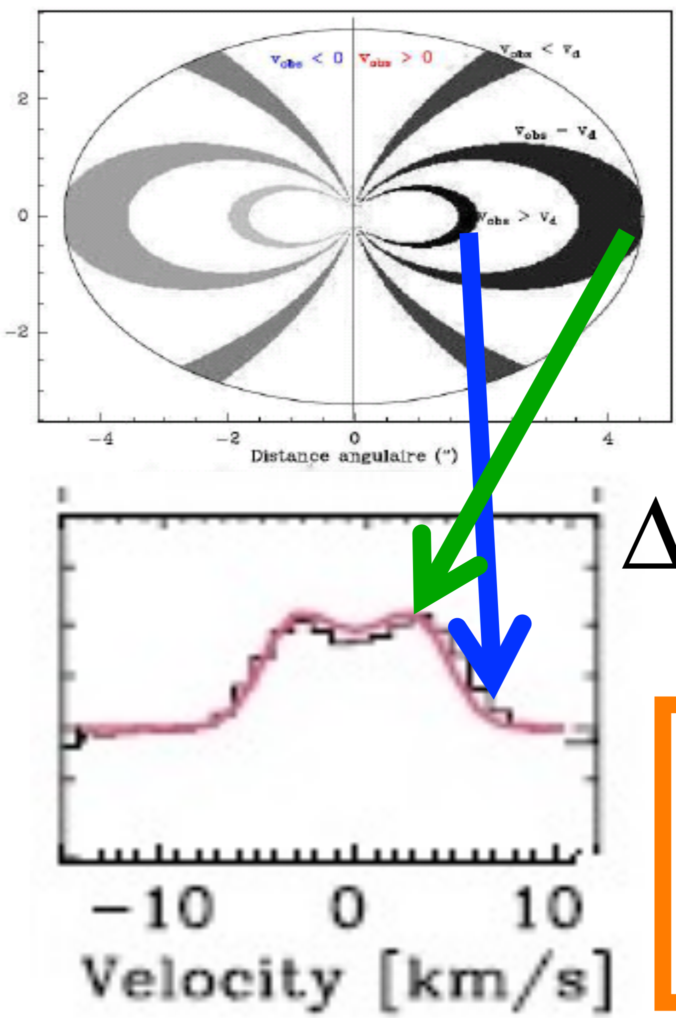
(Manoj et al. submitted to ApJ)

H_2O Snowline

Dividing regions of **rocky planet** & **gas giant planet formation**

(e.g., Hayashi et al. 1981,1985)





Kepler rotation

$$\Delta v = \sqrt{\frac{GM_s}{r}} \sin i$$

i: inclination angle

Spectroastrometry of water lines to locate the snowline

$R \sim \lambda/\Delta\lambda$

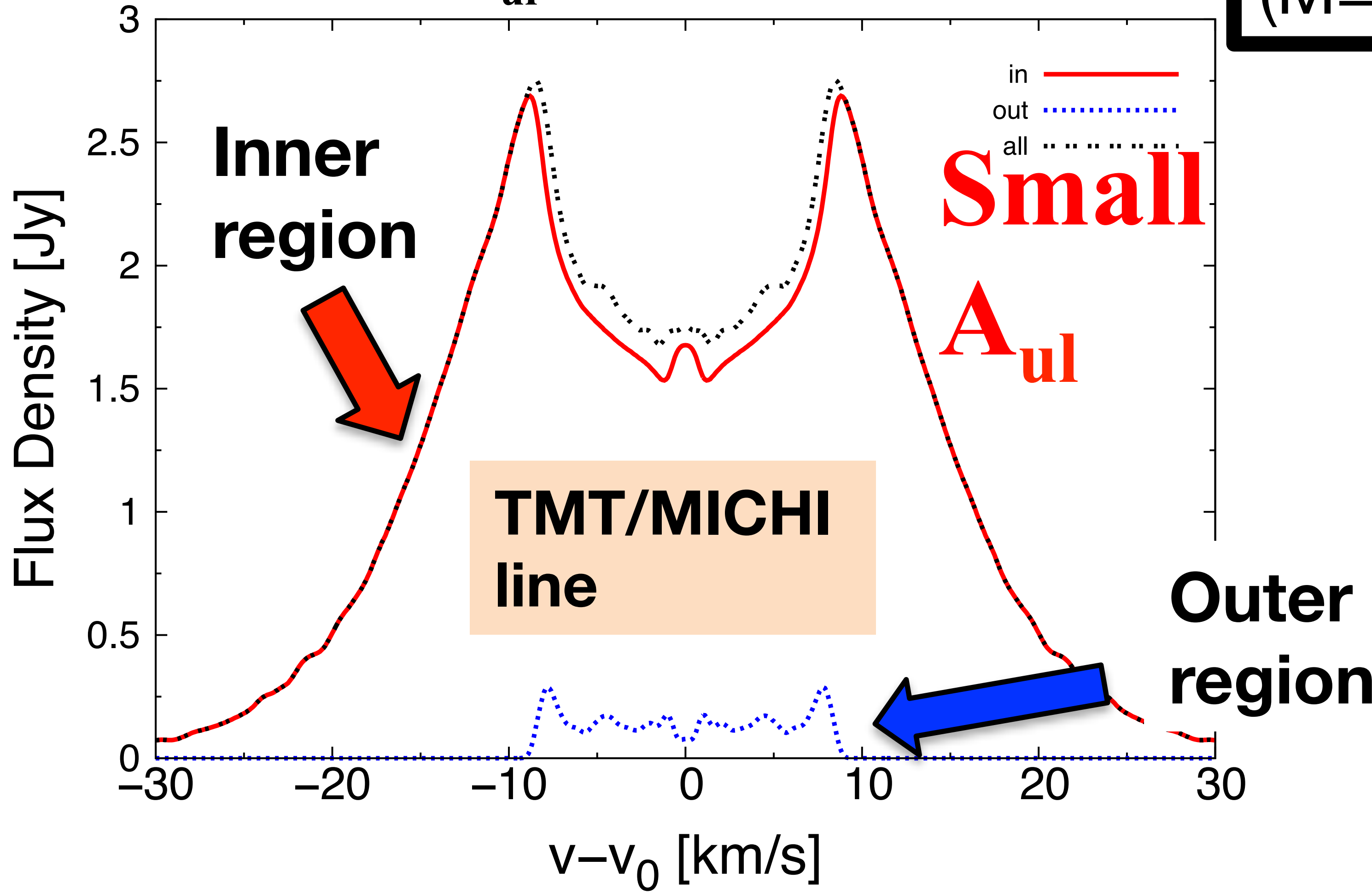
Typical width of IR lines from PPDs : **Δv~10-20km/s**
→ need high-R spectroscopy (R~15,000) for detections.
need very high-R (R~100,000) for analyzing profiles.

Physical disk models + Chemical reactions + Water line calculations

cf. 26th, Notsu's talk at Session 10-A

o-H_2O **17.77**μm

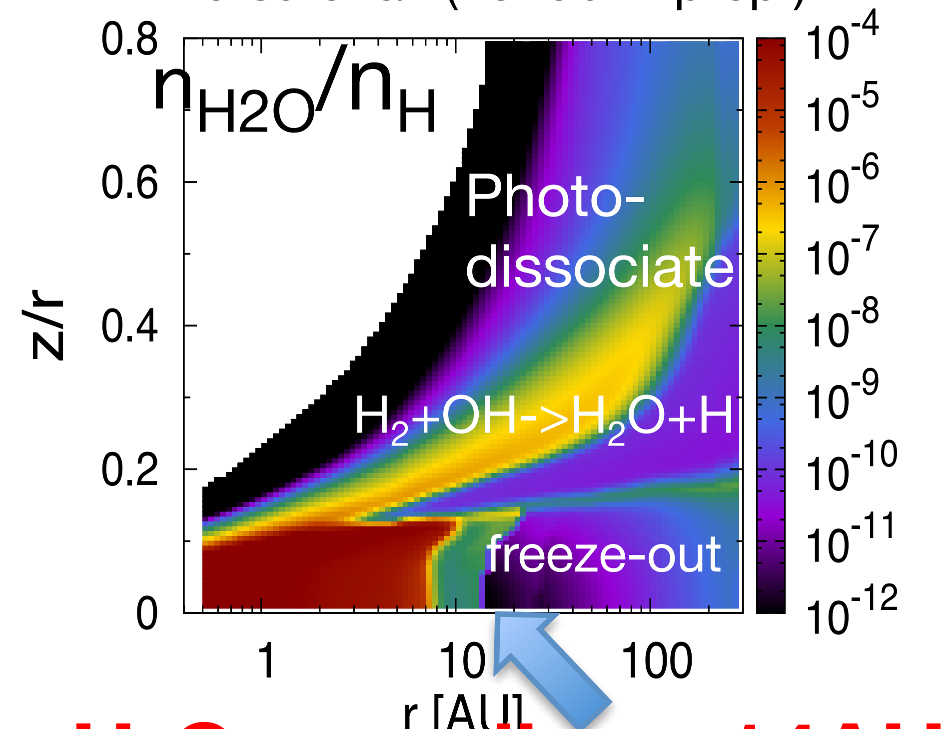
A_{ul} ~ **0.0029** (s^{-1})



Herbig Ae star

(M=2.5M_{sun} T_{eff}=10,000K R=2R_{sun})

Notsu et al. (2016a, ApJ, submitted)
Notsu et al. (2016b in prep.)



H_2O snowline ~14AU

We can locate the H_2O snowline through investigating the profiles of emission lines that have small A_{ul} (10^{-6}~10^{-3} s^{-1}) and relatively large E_{up}(~10^3 K).