Shocks in low-mass protostars:
From Herschel to ALMA via the SMA

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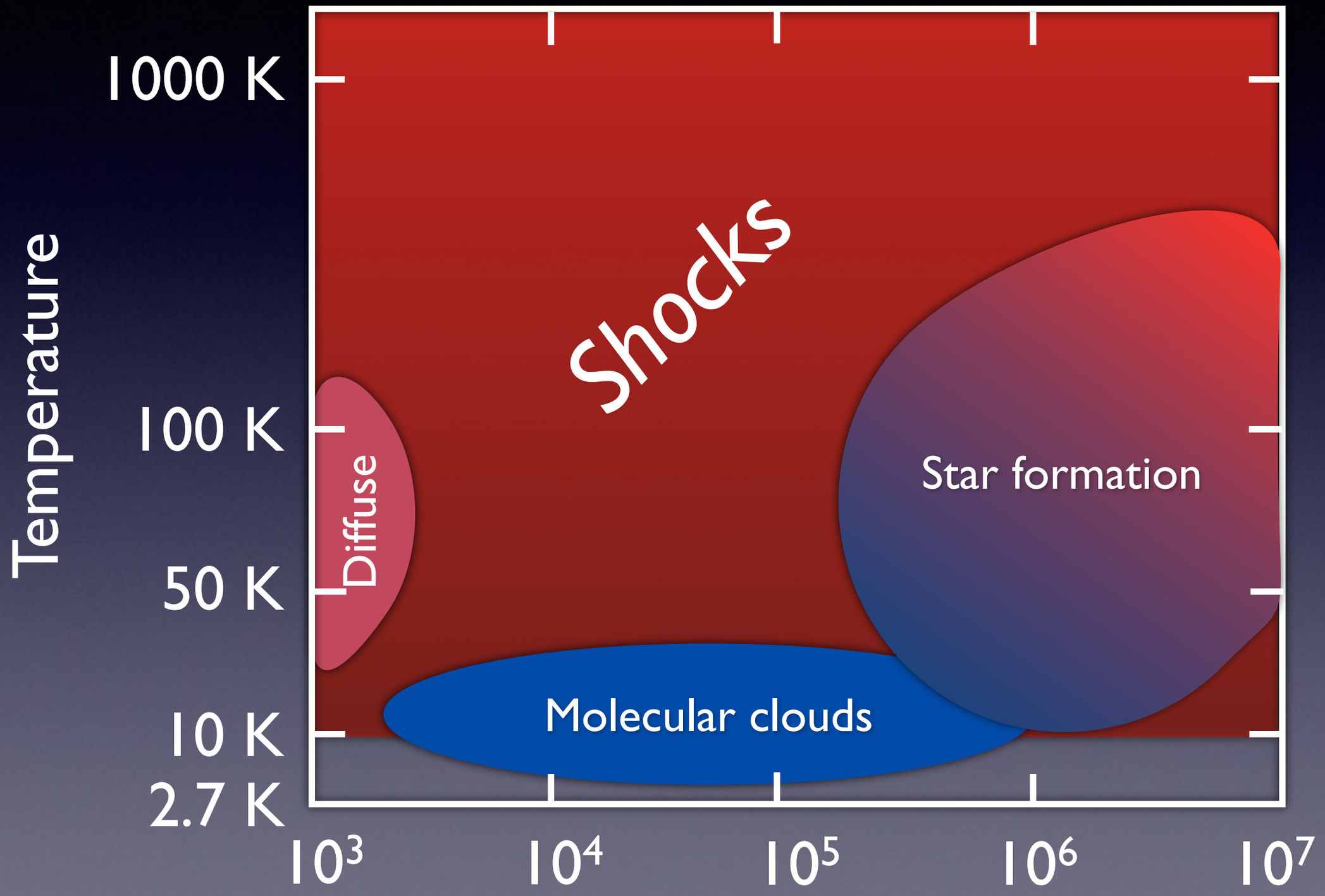
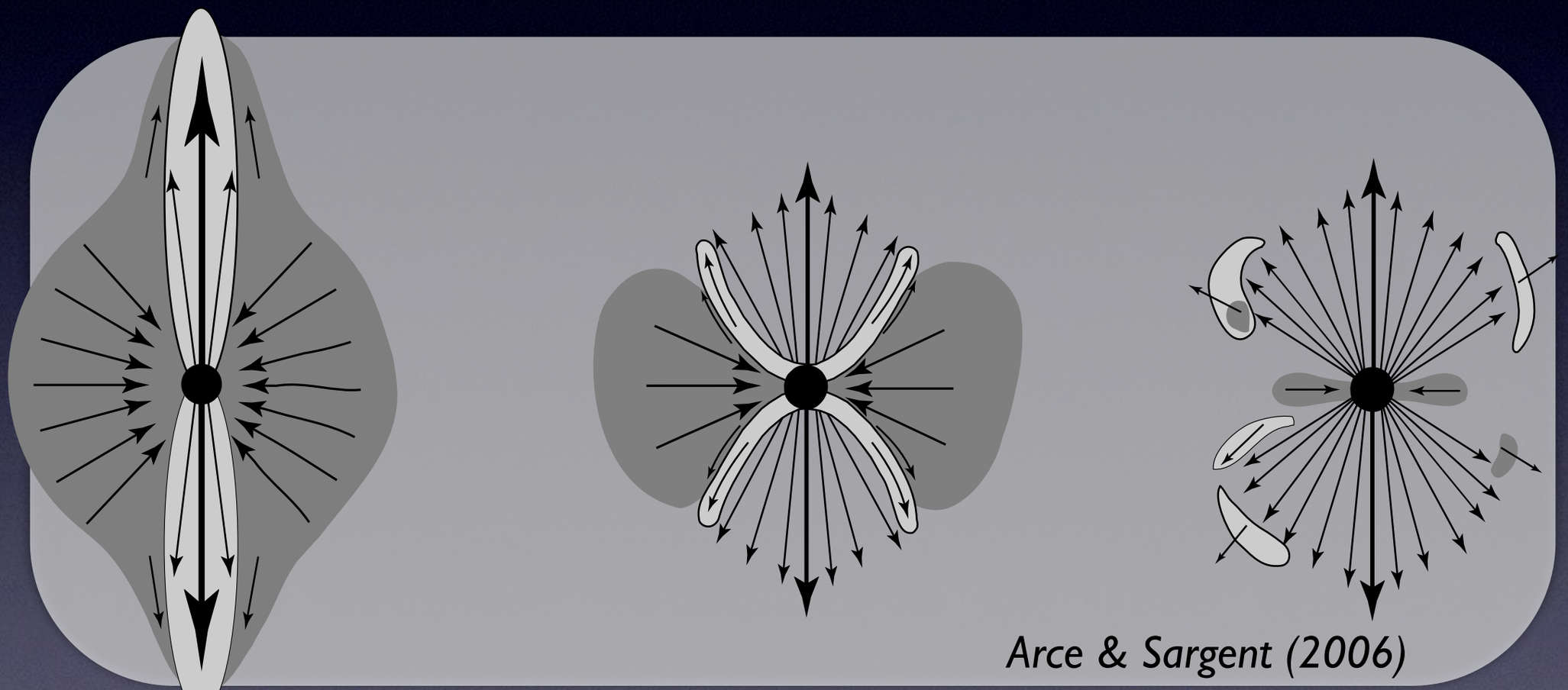
Why should you care?



Slide credit: E. Bergin

Low-mass YSO evolution

Class 0 Class I Class II



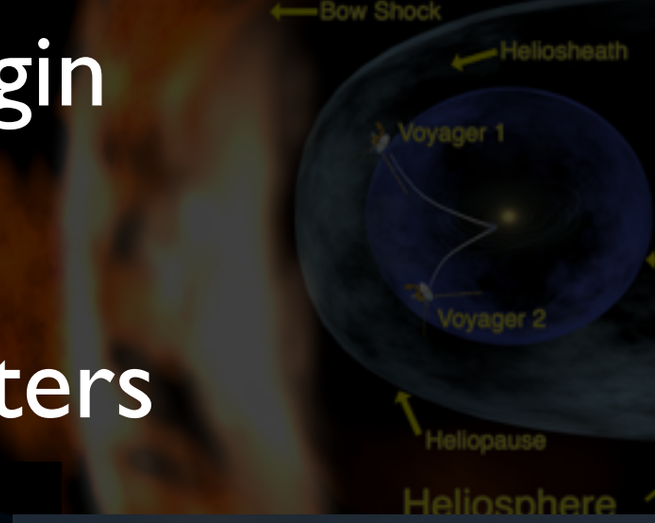
Arce & Sargent (2006)

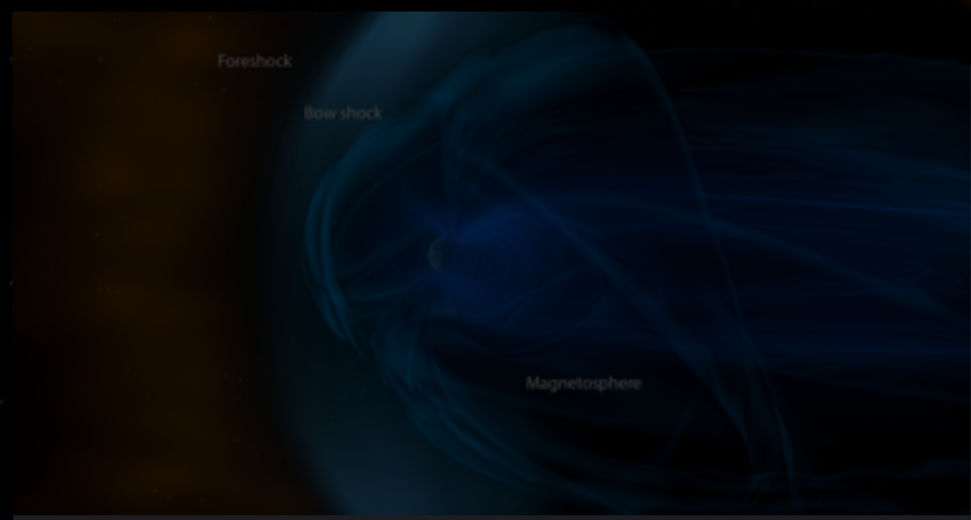
Jet / wind present at all evolutionary stages

Part I
Tracing shocks in low-mass protostars

Part II
Hot water in disks: a shocked wind origin

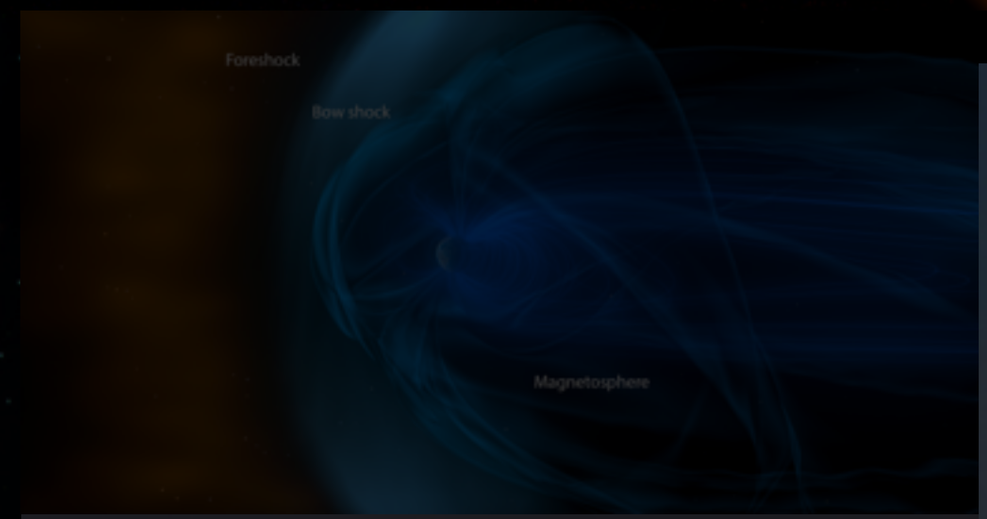
Part III
Low-mass protostars in high-mass clusters





Part I

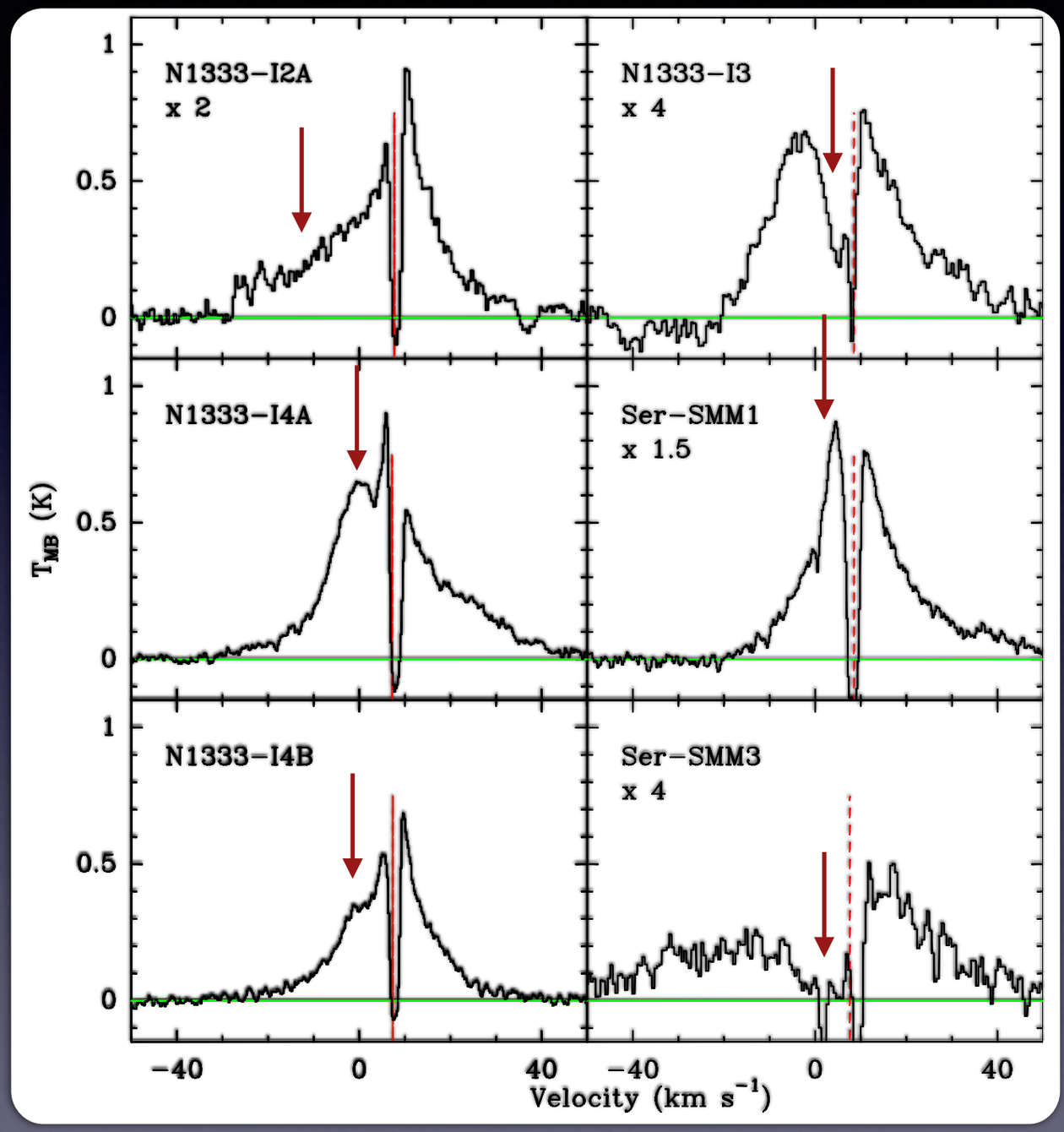
Tracing shocks in low-mass protostars



Spot shock components

- Typically offset to the blue by 5-10 km s^{-1}
- FWHM of 5-10 km s^{-1}
- New and unseen in, e.g., CO 3-2

(Kristensen et al. 2013)



H_2O 557 GHz $J = 1_{10}$-1_{01}
Observed with Herschel-HIFI

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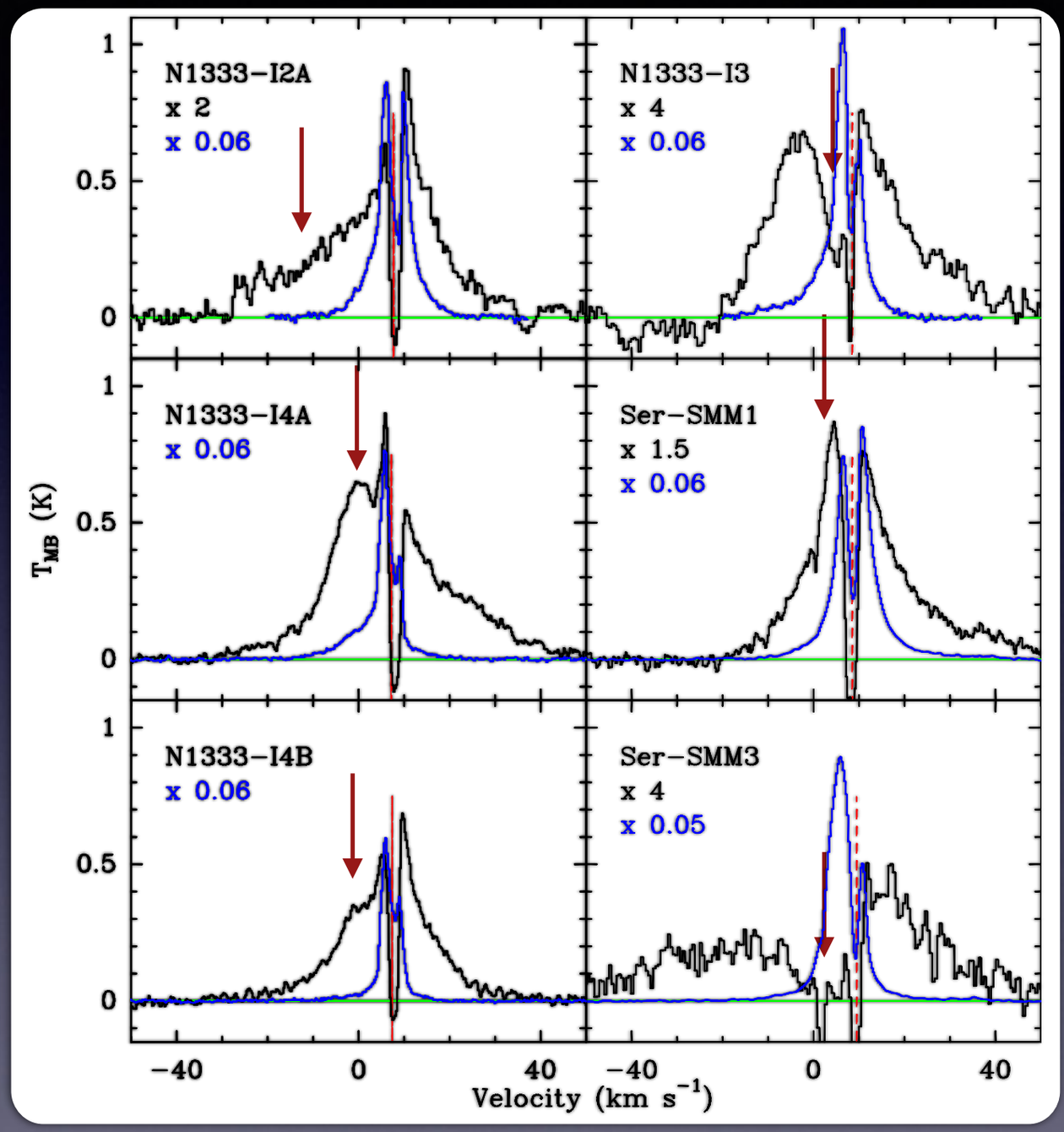
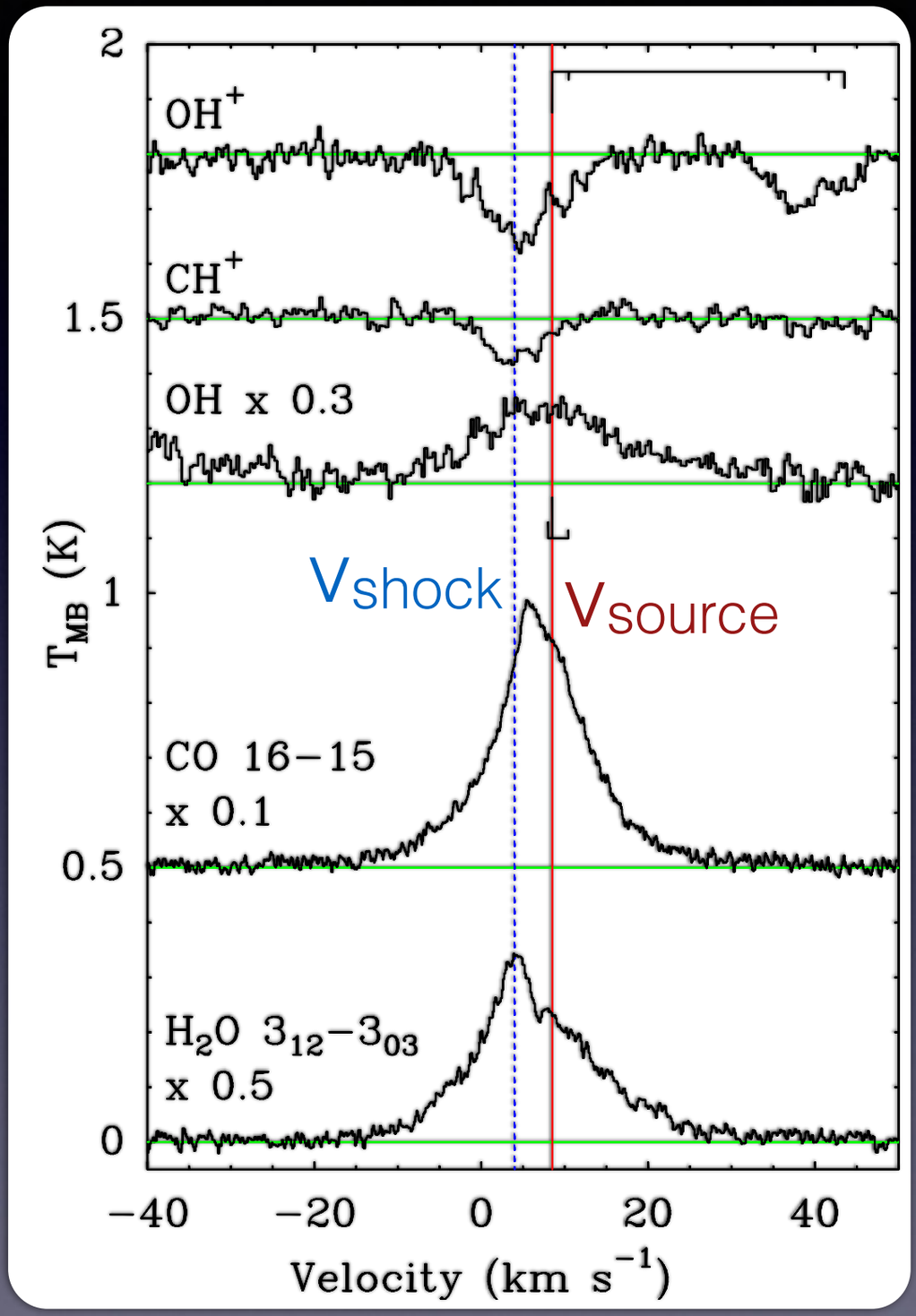


H_2O 557 GHz $J = 1_{10}$-1_{01}
Observed with Herschel-HIFI

Other species

- Seen in light ionized hydrides and CO 16-15
- *Points to origin close to protostar and hot, dense gas*

Ser SMM1
L ~ 30 $L_\odot$
D ~ 230 pc

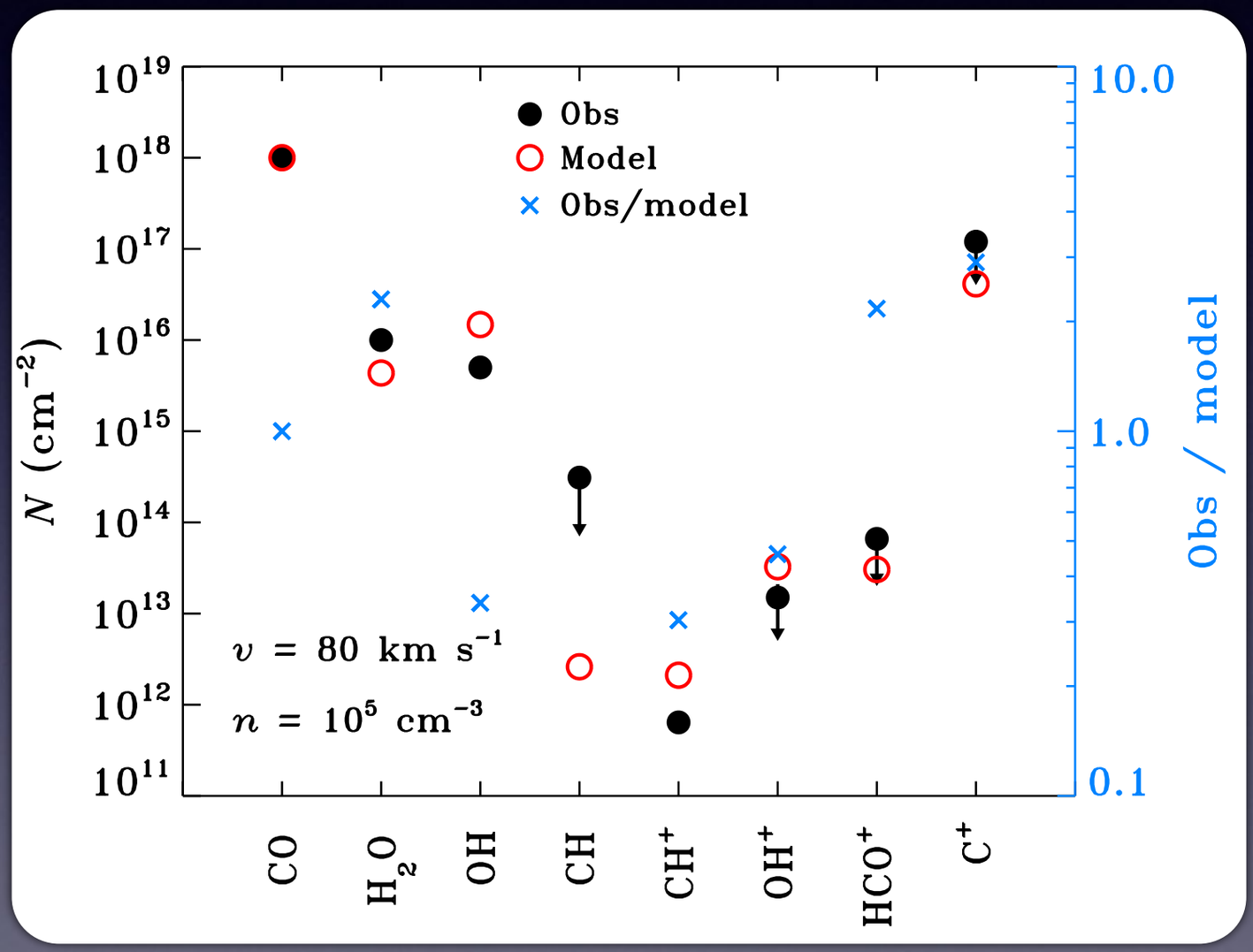


Kristensen et al. (2013)
Benz et al. (2015)

Model comparison

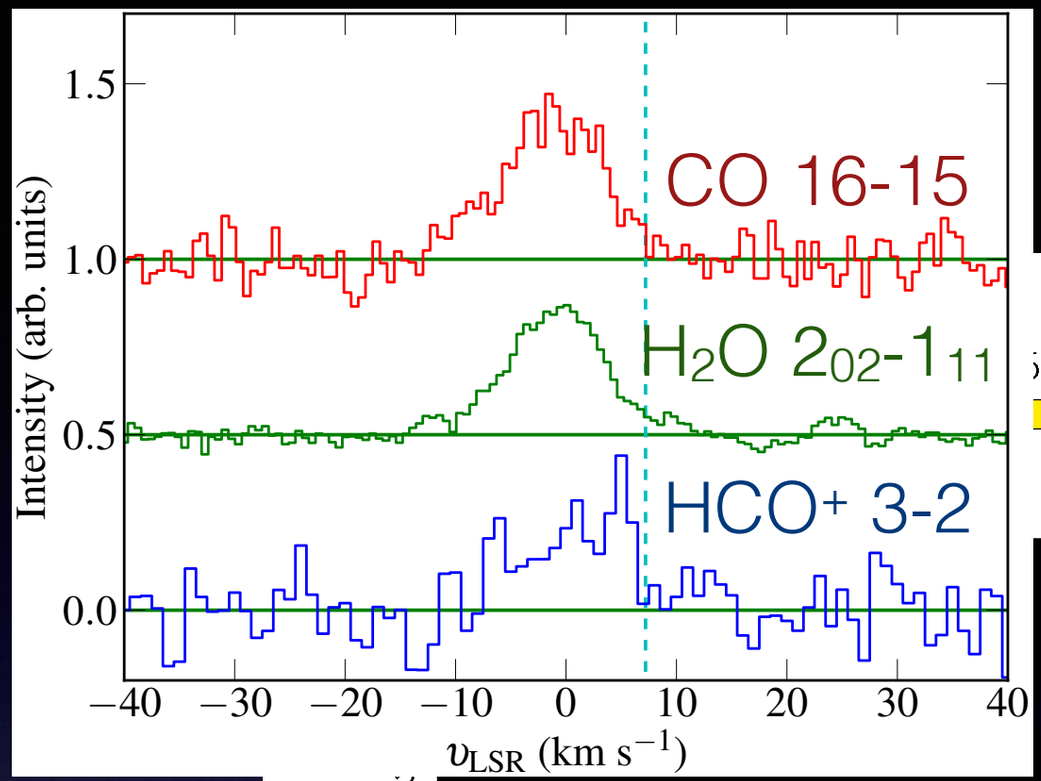
- Dissociative wind shocks
  (Neufeld & Dalgarno 1989)
- Column densities match within factor of 3

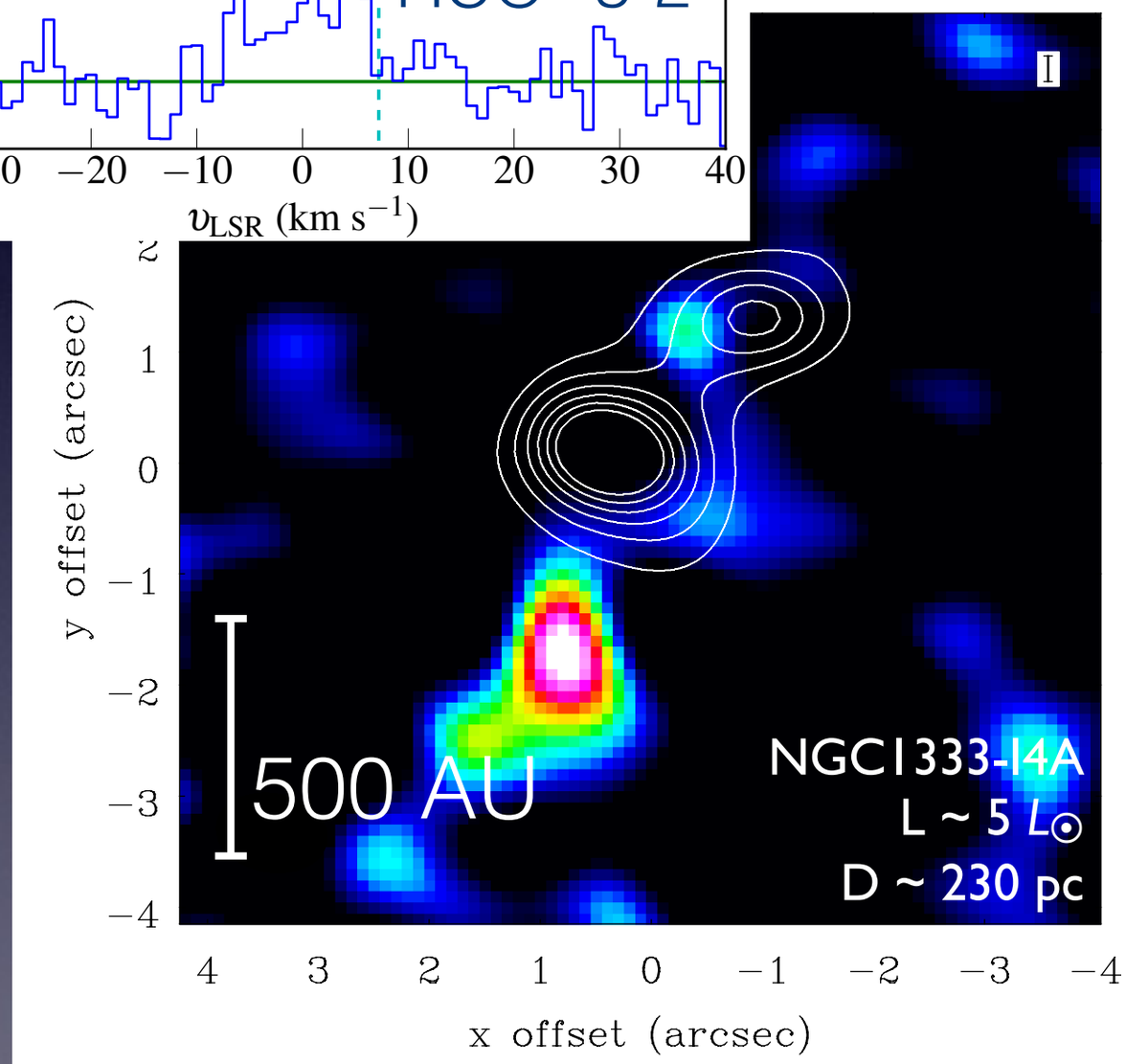
NGC1333-I4A
L ~ 5 $L_\odot$
D ~ 230 pc



Mapping spatial origin

- SMA observations of HCO^+ J=3-2, 4-3
- EXT: 1" resolution (200 AU) & filtering of envelope
- *Origin: wind impinging on inner cavity wall; imaging required for location*

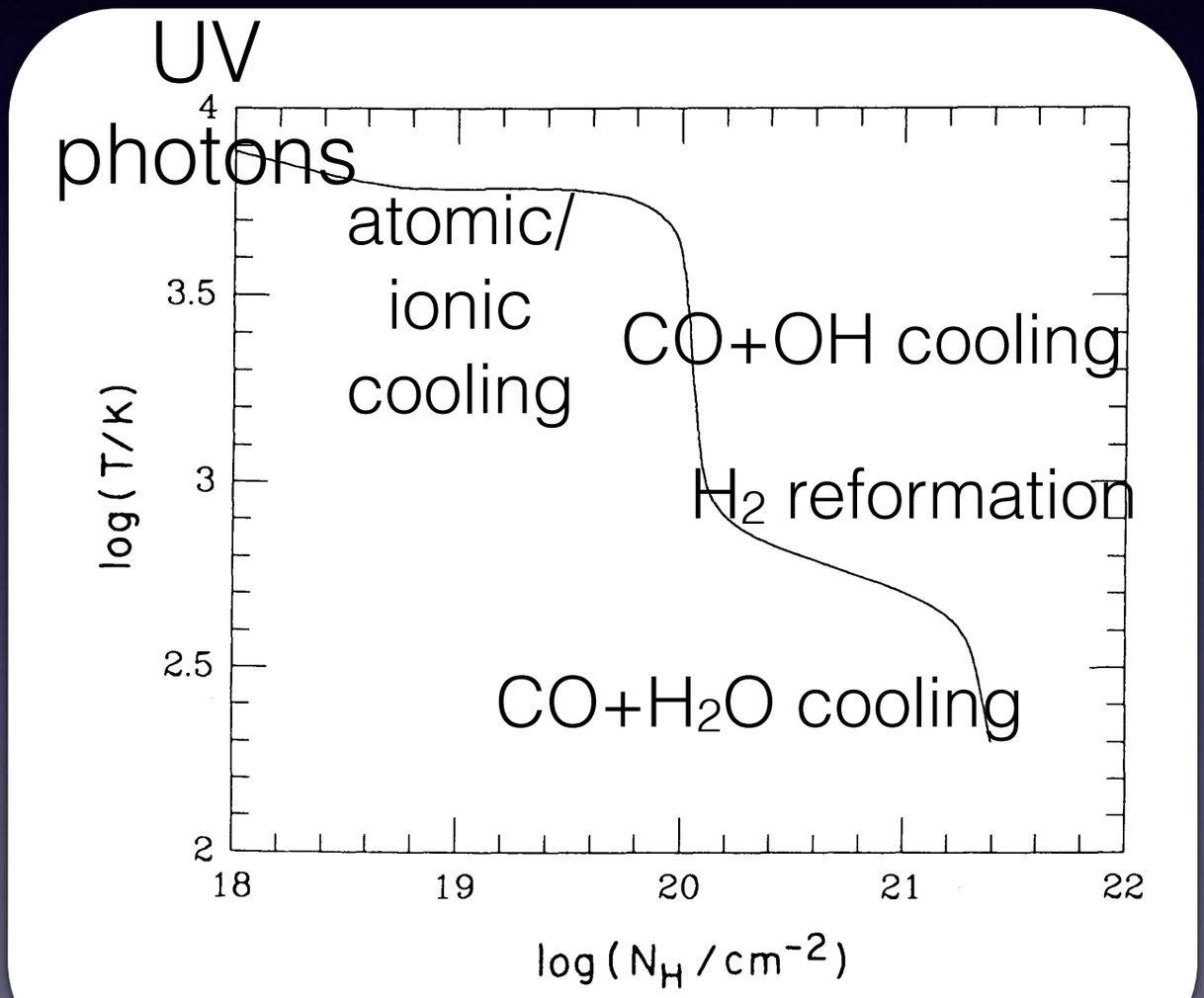




(Kristensen et al. 2015a in prep.)

Excitation & chemistry

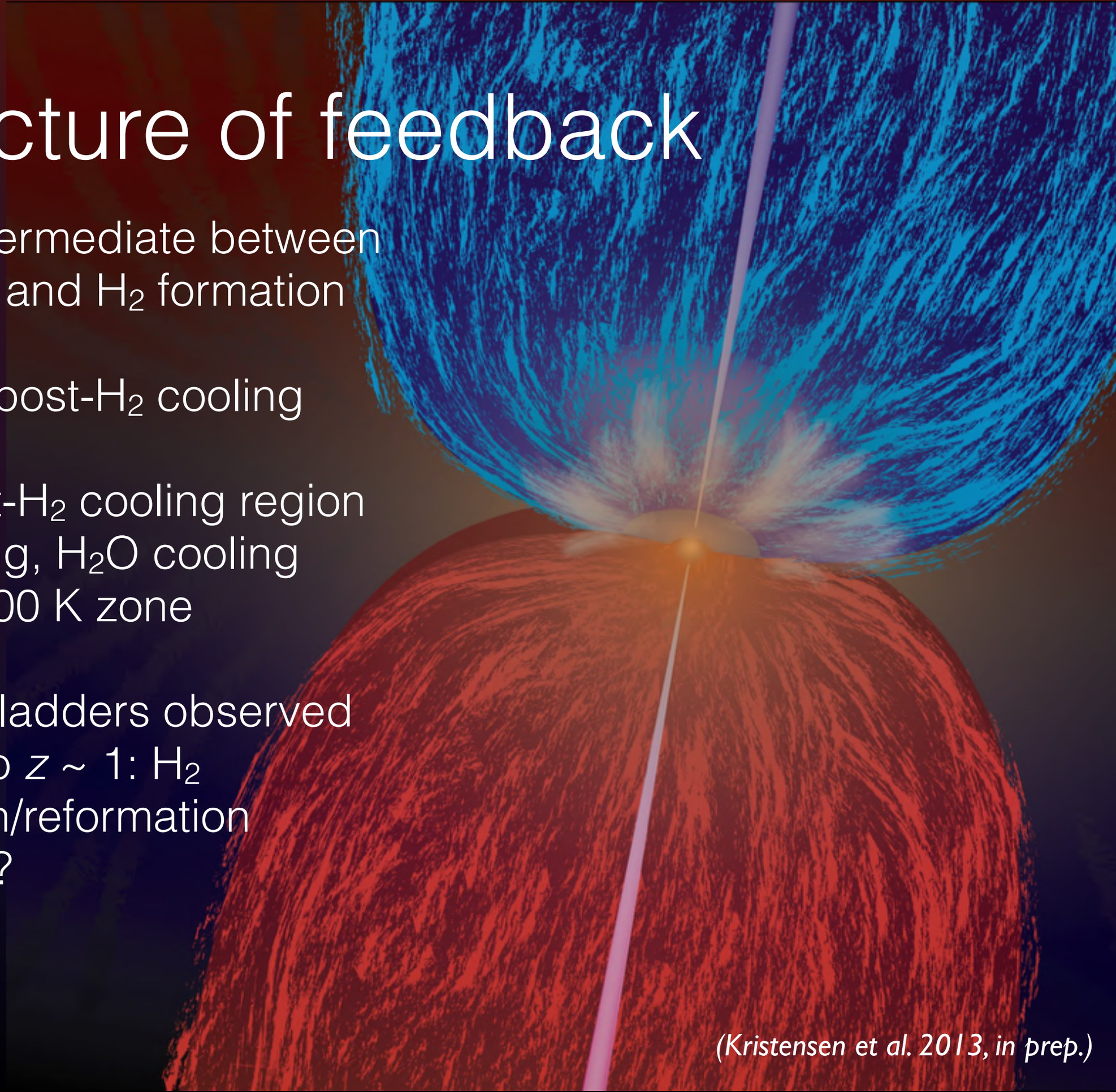
- Water/HCO^+ require dense medium, CO requires hot medium:
  $n(H_2) \sim 10^7$ cm^{-3}, T ~ 700 K
- Chemical key: H_2 dissociation + reformation
- UV radiation required for pre-dissociation



Neufeld & Dalgarno 1989
Kristensen et al. in prep.

New picture of feedback

- Hot CO: intermediate between atomic gas and H_2 formation
- Warm CO: post-H_2 cooling
- H_2O: if post-H_2 cooling region is expanding, H_2O cooling limited to 300 K zone
- Similar CO ladders observed from here to $z \sim 1$: H_2 dissociation/reformation always key?



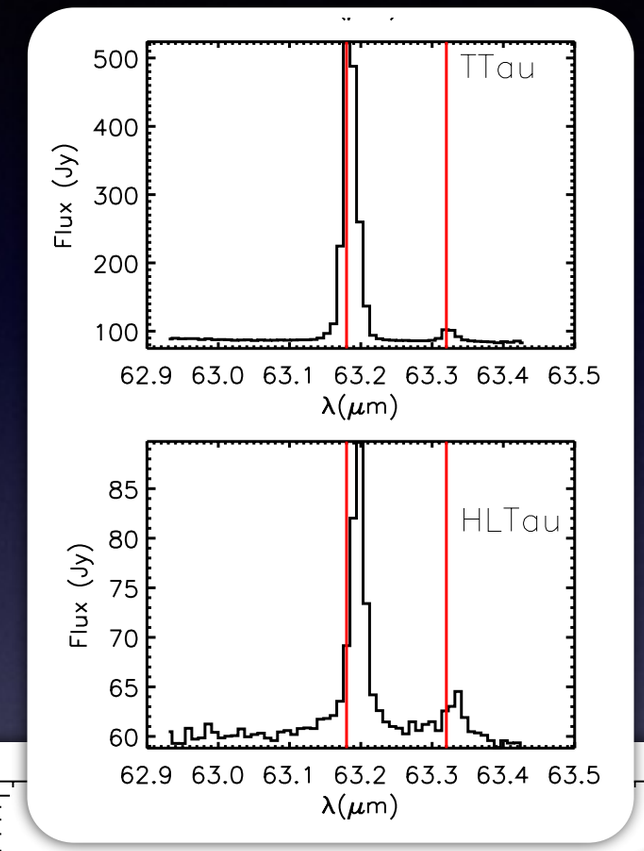
(Kristensen et al. 2013, in prep.)

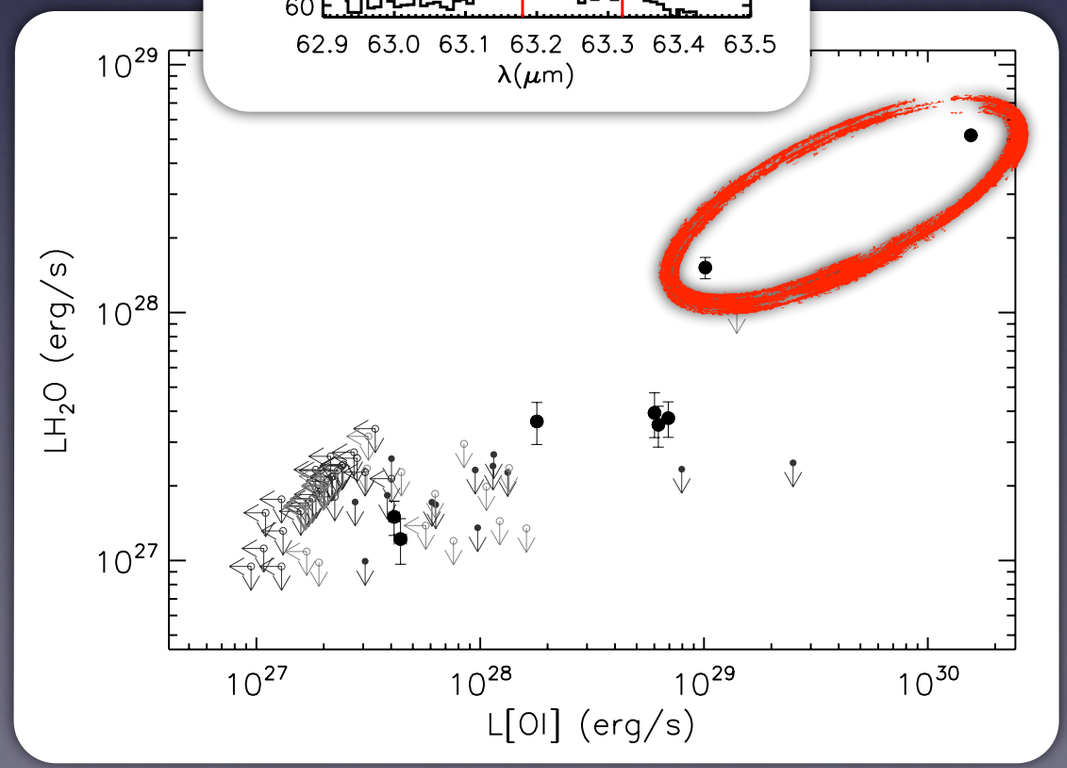
Part II

Hot water in disks: a shocked wind origin

PACS hot water in disks

- Observed the 63 mu line, spectral resolution ~ 100 km/s
- Detected in 24% of gas-rich disks
- Emission, when detected, correlates with [OI] also at 63 mu
- No spatial extent seen: disk origin?
- Test with SMA: detect and image 321 GHz line (E_{up}/k_B ~ 1800 K)





Riviere-Marichalar et al. 2012

HL Tau: recent headliner

The ALMA Partnership, Brogan et al. (2015)

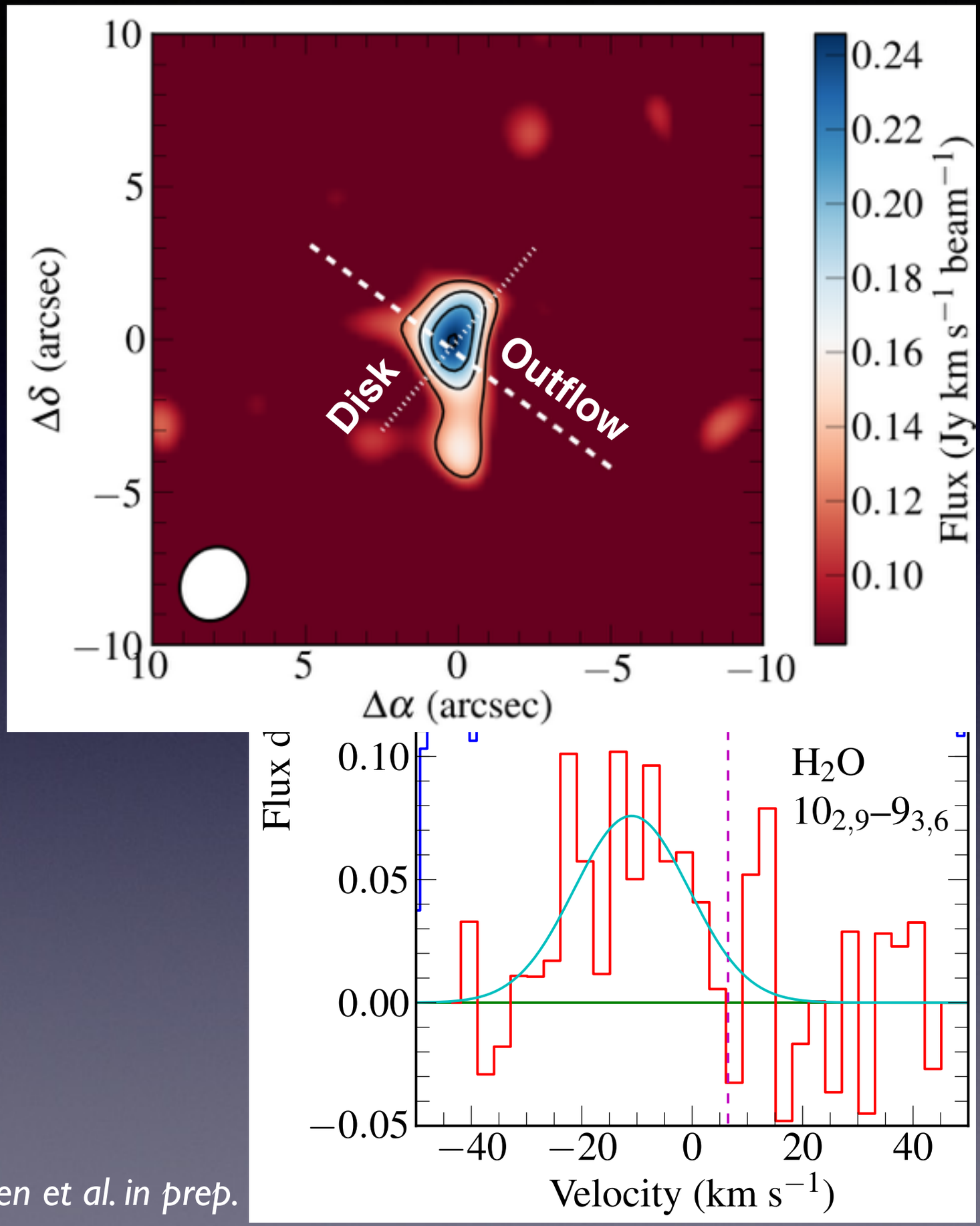
- Pictures don't always reveal the whole truth

SMA data

- H_2O detected at 5σ (single beam), 8σ integrated, toward HL Tau

- Matches disk position, tentative (3-4σ) extended emission

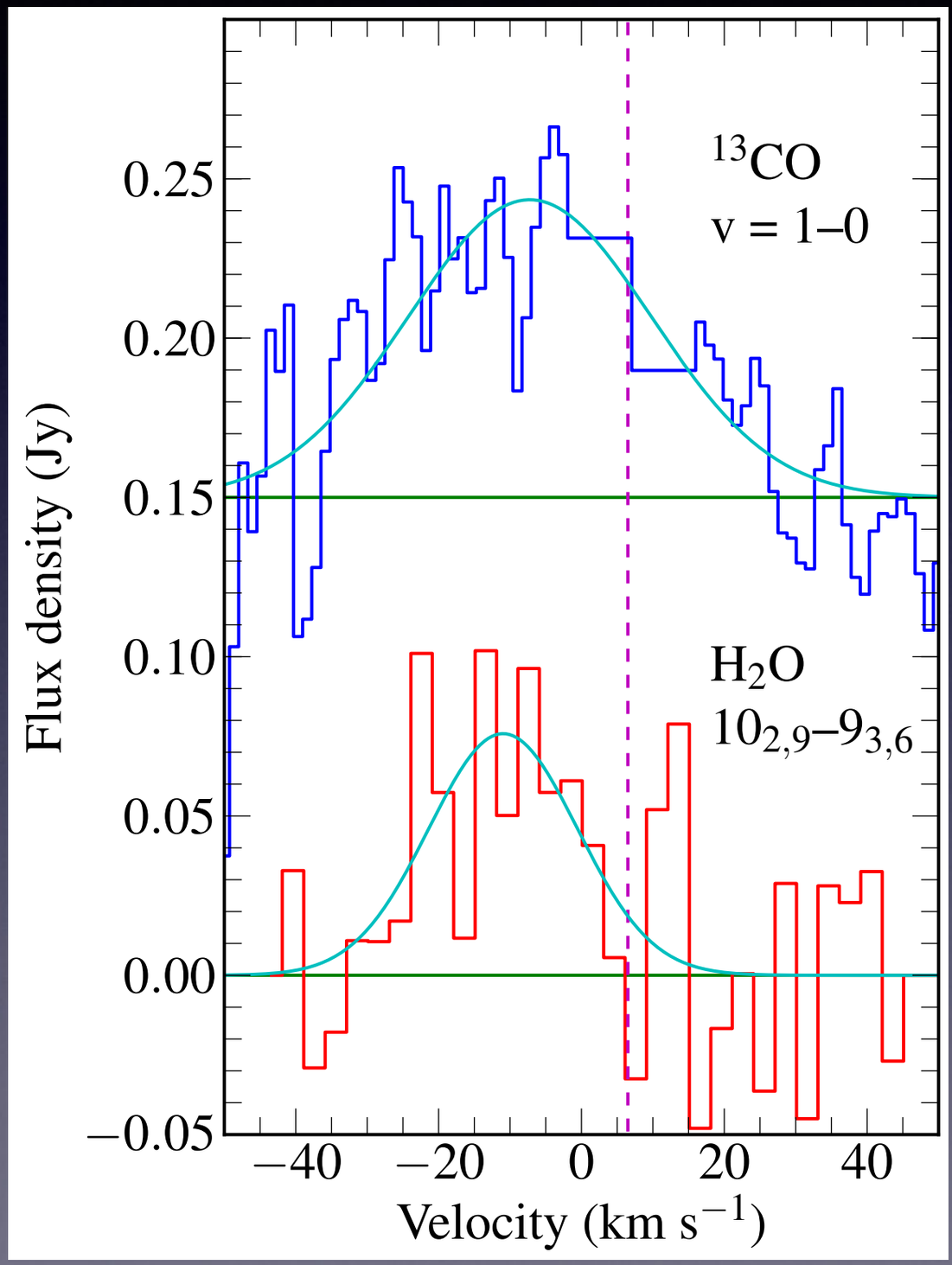
- Profile: blue-shifted (-15 km/s) and broad (20 km/s)!



Kristensen et al. in prep.

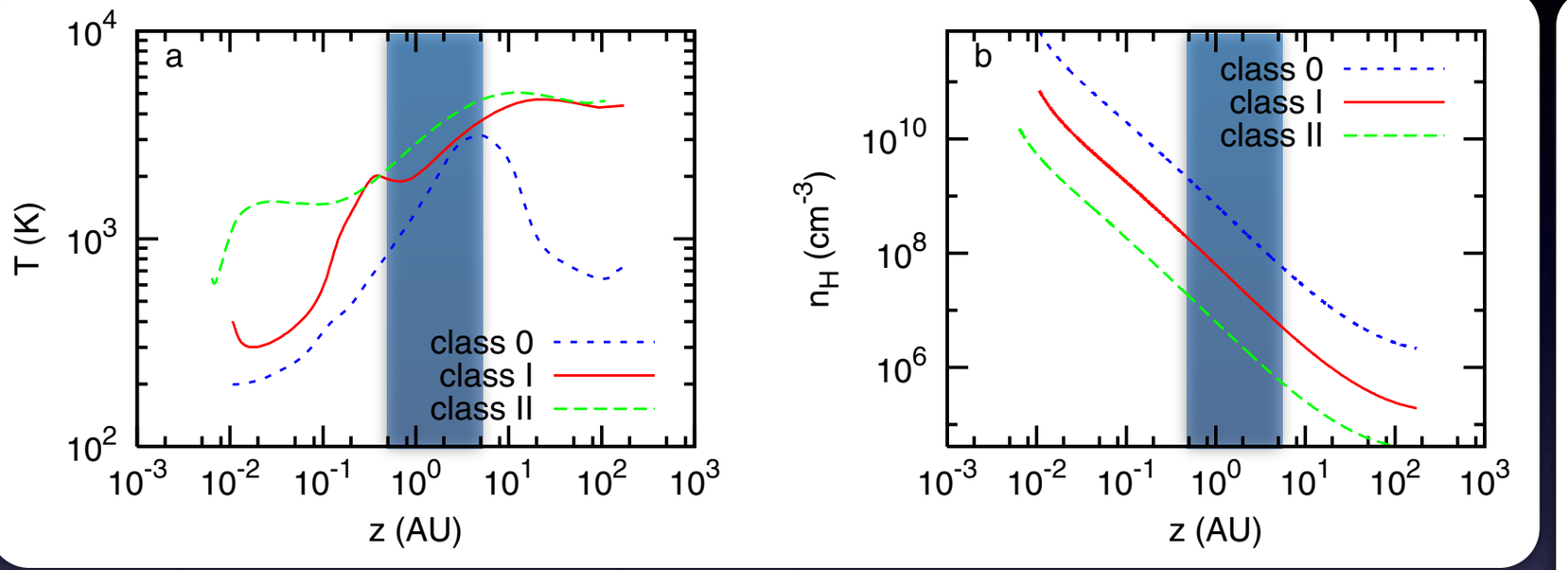
Vibrational CO: wind

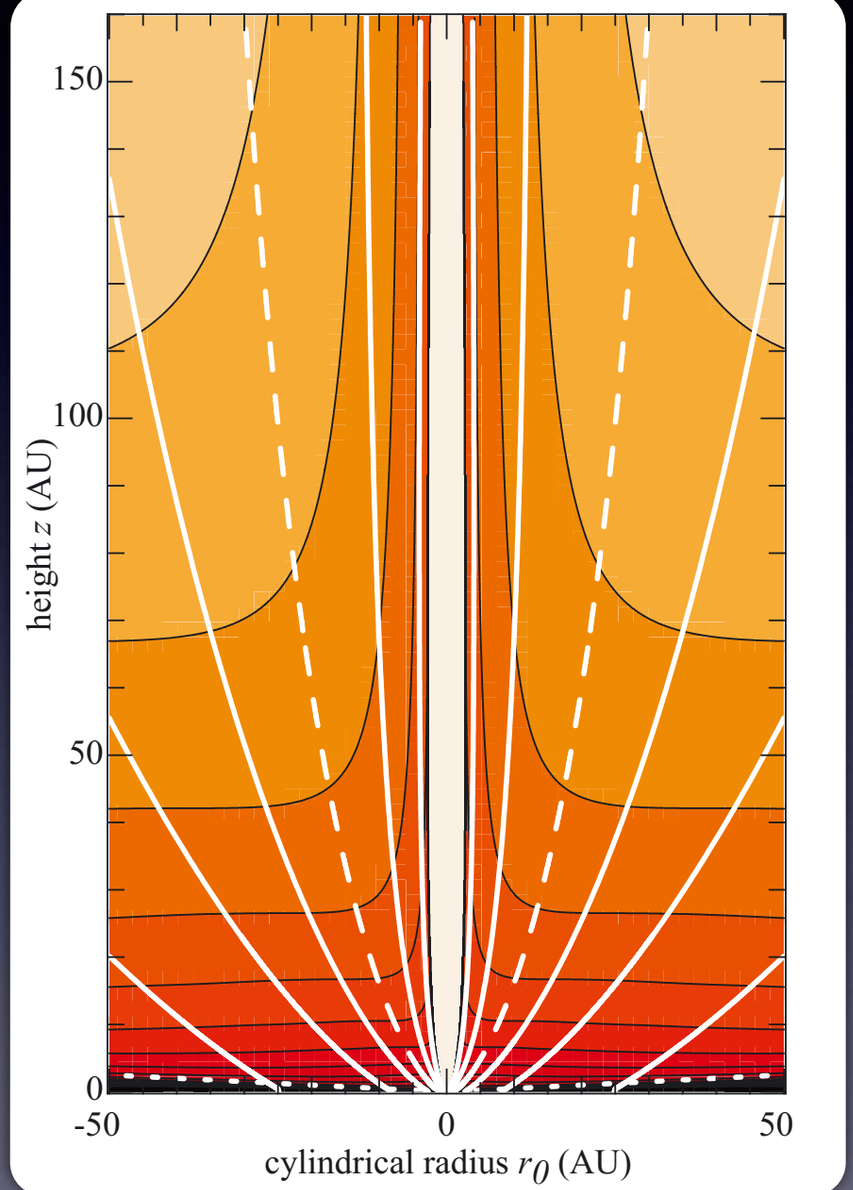
- 4.7 mu rovibrational emission from CO supports wind hypothesis
- Identical line profiles, within uncertainty
- CO emission unresolved at 0.2" resolution (30 AU)



Herczeg et al. 2011

Molecular protostellar winds

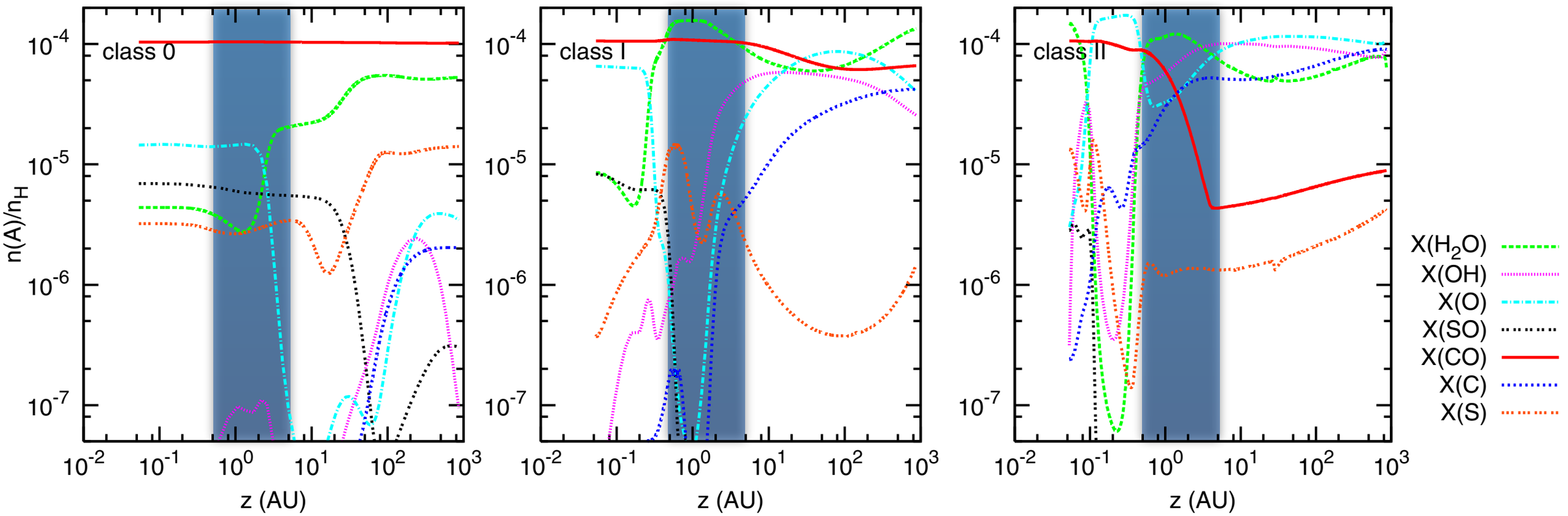




- Model calculations show molecules survive launching in MHD winds
- Physical conditions in wind close to what is inferred from radiative transfer

Panoglou et al. 2012

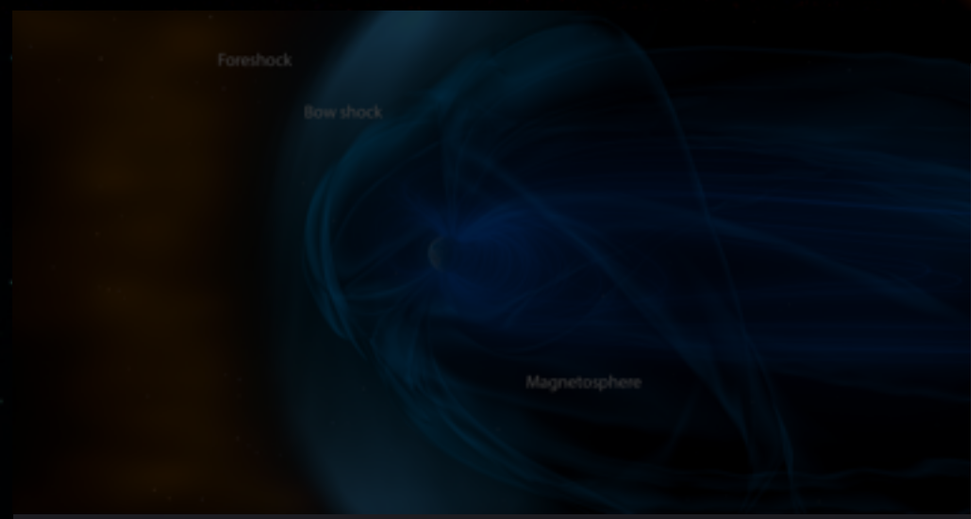
Wind solution: a match

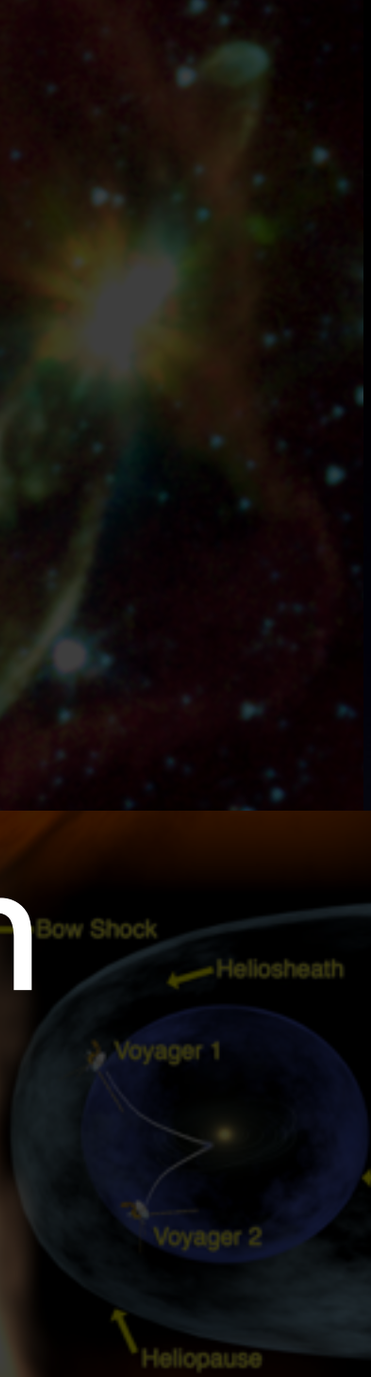


- $N(H_2O) / N(CO) \sim 1$
- Model predictions reproduce observations: wind origin

Part III

Low-mass protostars in high-mass clusters



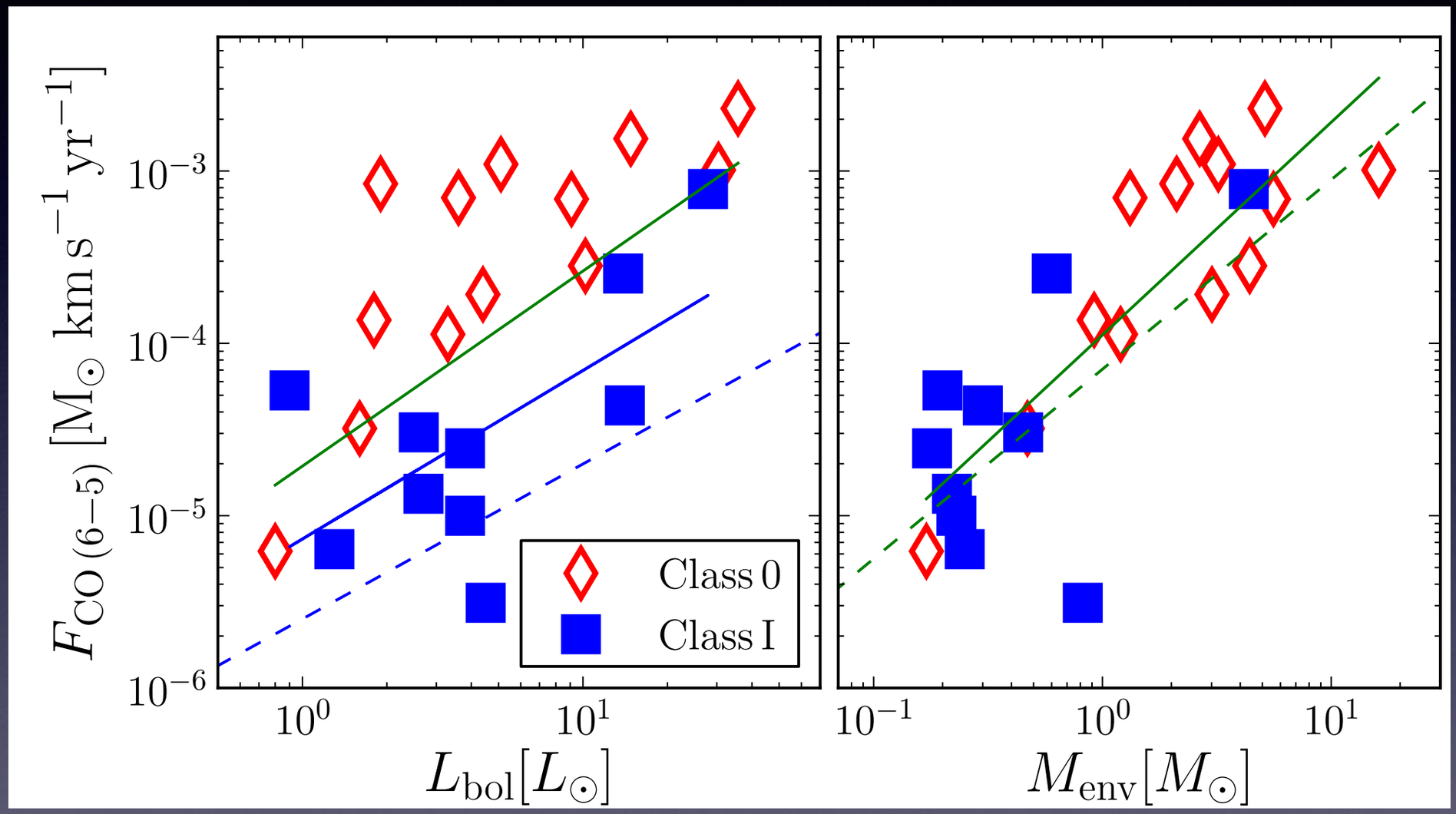


Stars form in clusters

But how do low-mass stars form in the presence of high-mass stars?

Cygnus X, Herschel
Hennemann & Motte

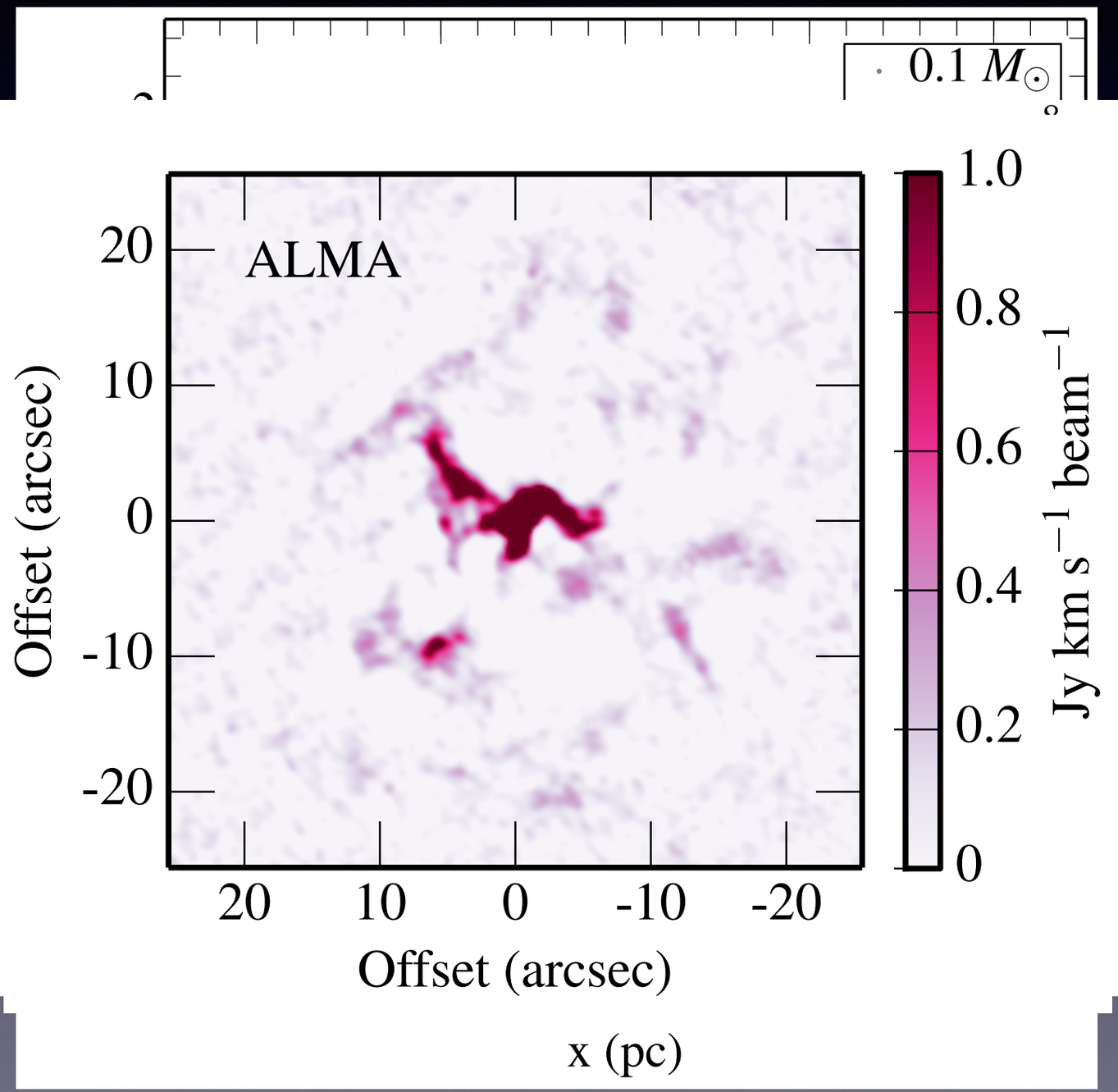
Low-mass outflows scale with M_{env}



- Idea: Outflows provide a low-contrast tracer of low-mass population in clusters

Recipe

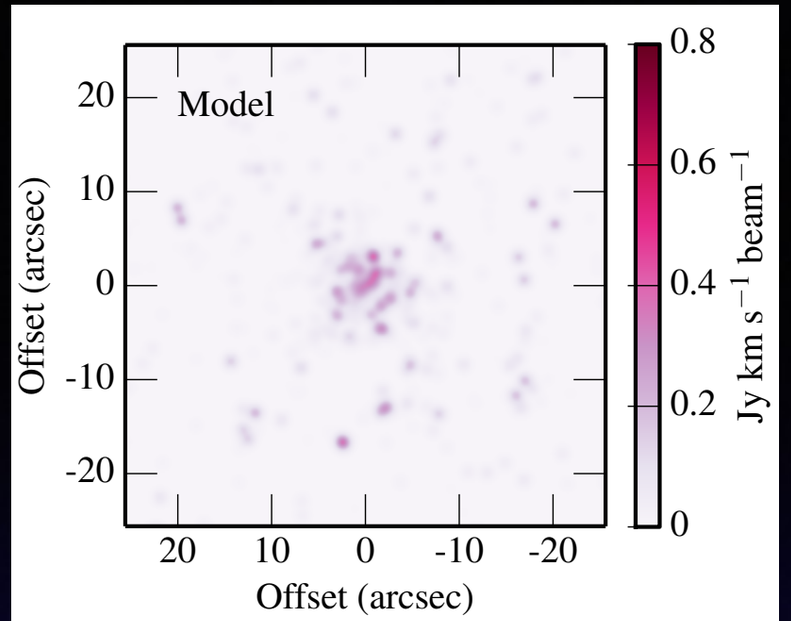
- Step I: Build a cluster-in-a-box
- Step II: Measure outflow emission from nearby low-mass clouds
- Step III: Assign emission to cluster members
- Step IV: Observe

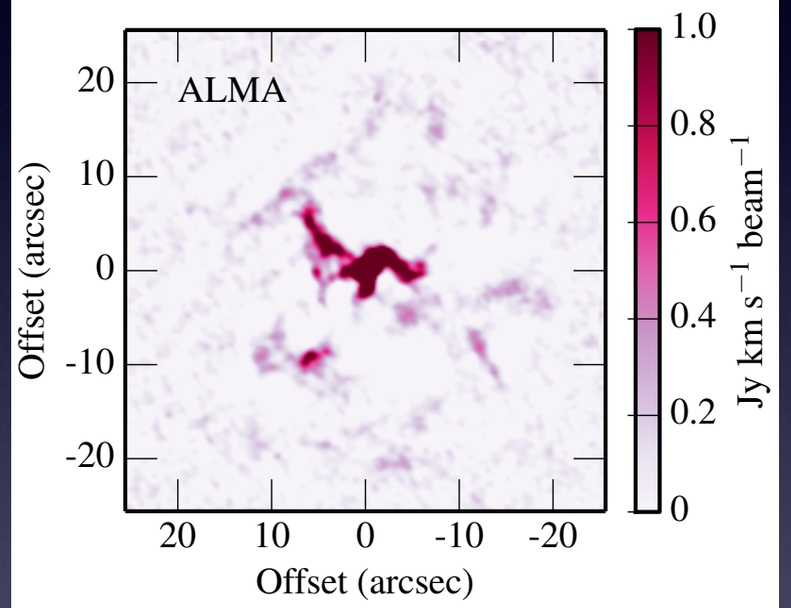


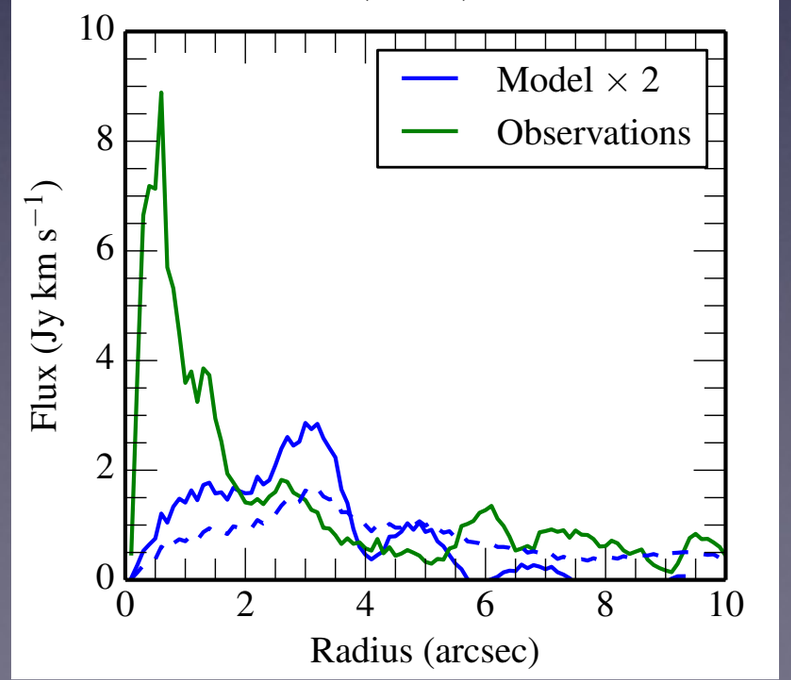
Kristensen & Bergin (subm.)
ALMA observations: Higuchi et al. 2015, IRAS16547

Benchmarking model

- Observations contain hot core, high-mass outflow, low-mass outflows
- Radial average matches at 50%
- Toy model reproduces observations: fine-tuning required

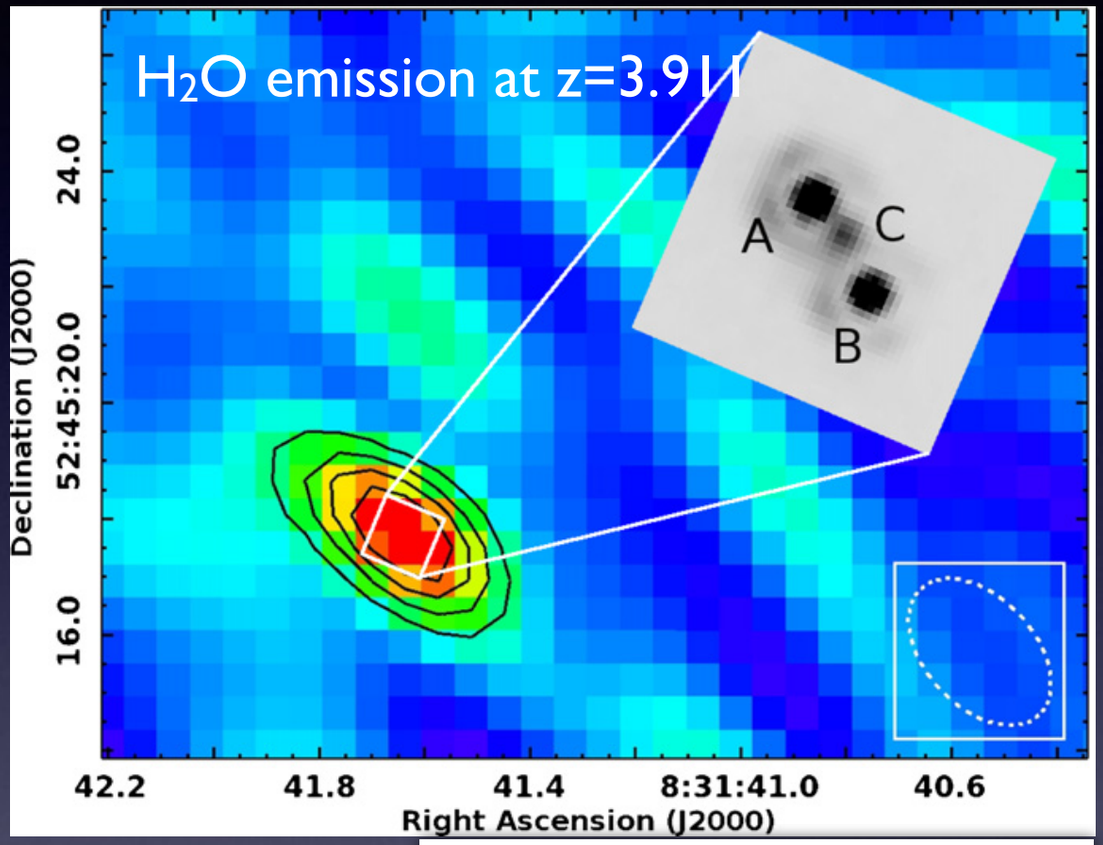


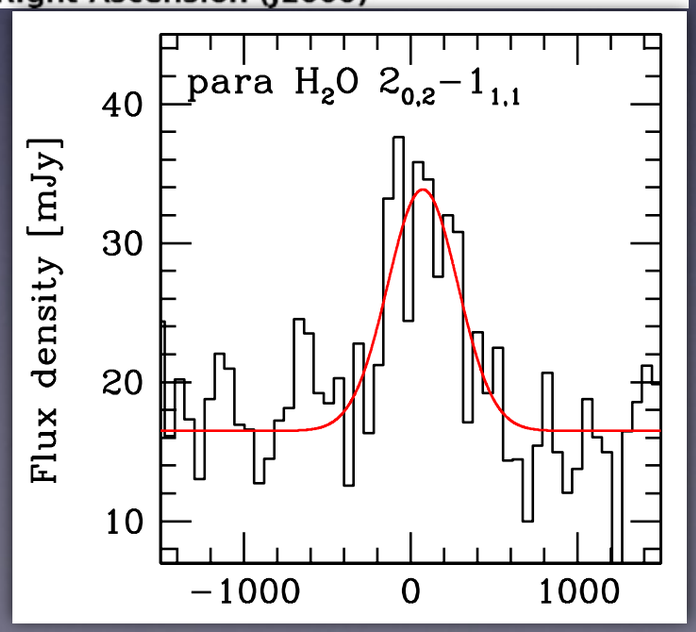




Next steps

- Include contribution from high-mass outflows
- Explore parameter space: cluster age, IMF, cluster mass, …
- Other species: H_2O, high-J CO as unique shock tracers
- Extrapolate to high-z starburst galaxies





van der Werf et al. 2011

Conclusions

- Shocks in protostars traced by water, high-J CO and hydrides: H_2 dissociation/reformation key for CO ladder

- Hot water toward HL Tau originates in wind, not inner disk: implications for hot water in disks?

- Cluster-in-a-box models provide access to low-mass populations in embedded high-mass clusters