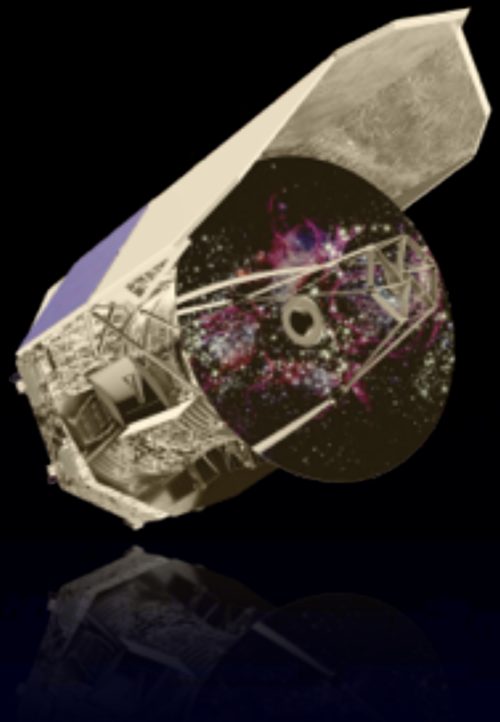
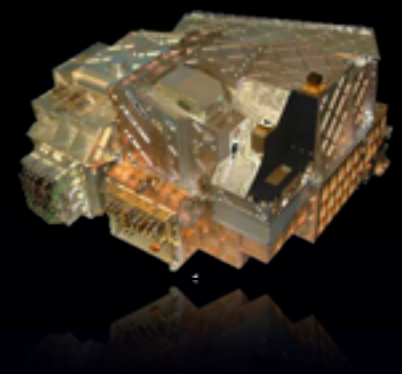
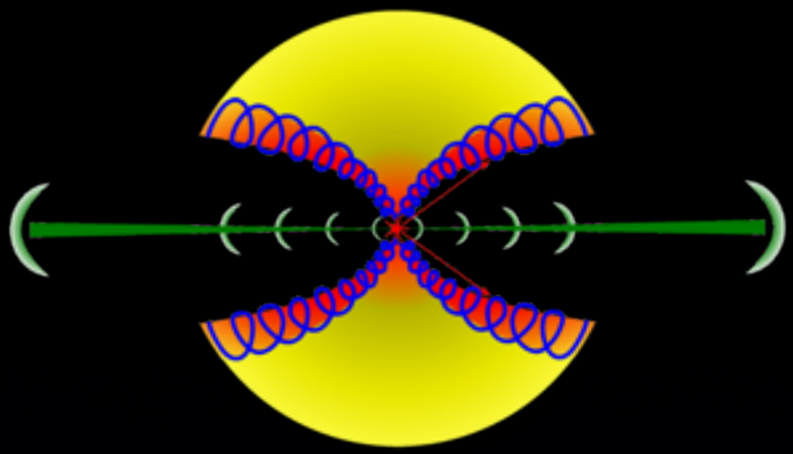


Herschel-PACS





Herschel / PACS view of feedback from deeply-embedded low-mass protostars

Agata Karska

Adam Mickiewicz University in Poznań, Poland

Collaborators

Leiden, June 2012

"Water in star forming regions with Herschel"
PI: Ewine van Dishoeck; 70+ scientists from 30 institutes

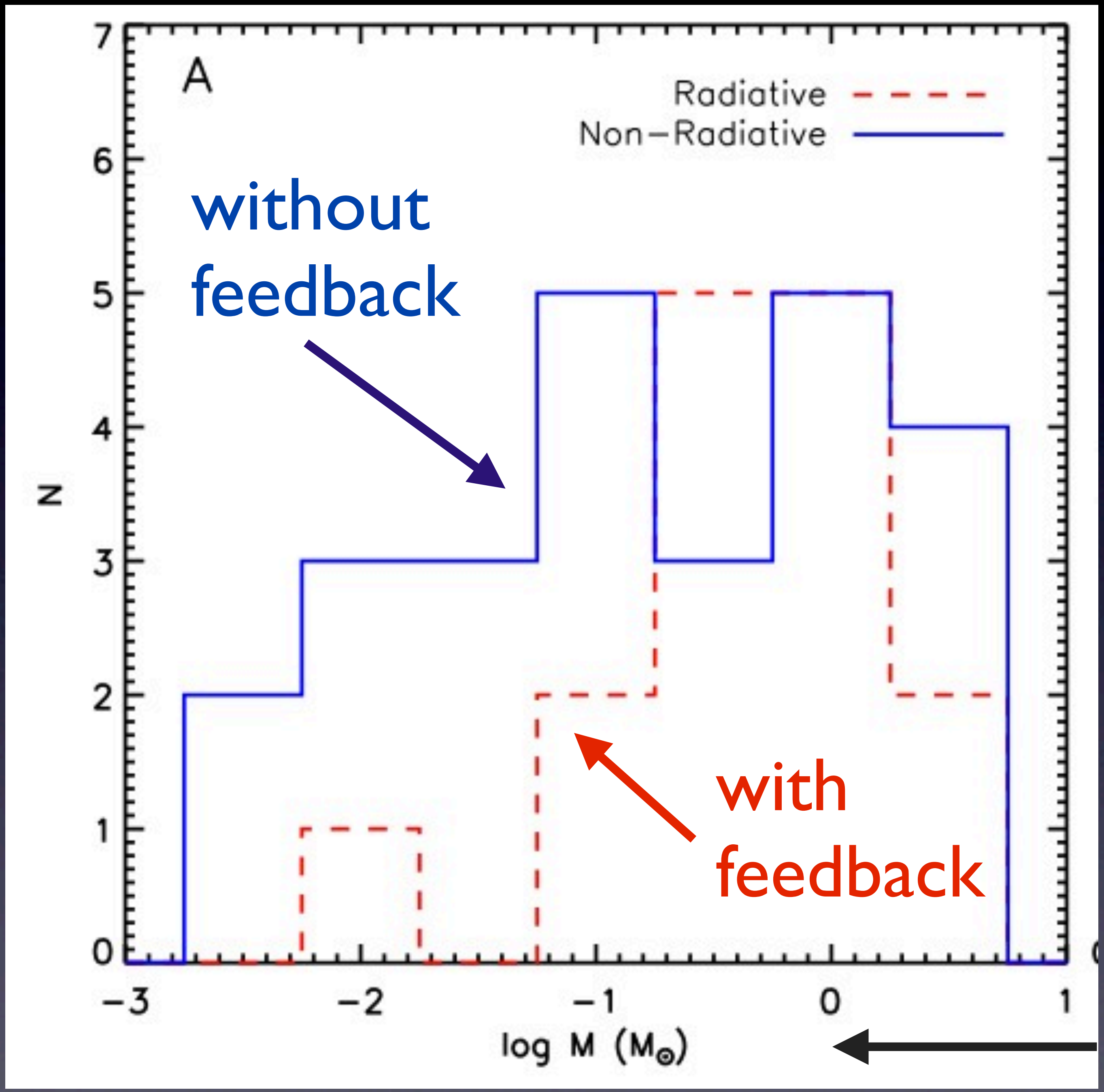
"Dust, Ice, and Gas in Time"
PI: Neal Evans

"Water in low-mass protostars: the William Herschel Line Legacy"
PI: Ewine van Dishoeck

Importance of feedback

Offner10

number of stars

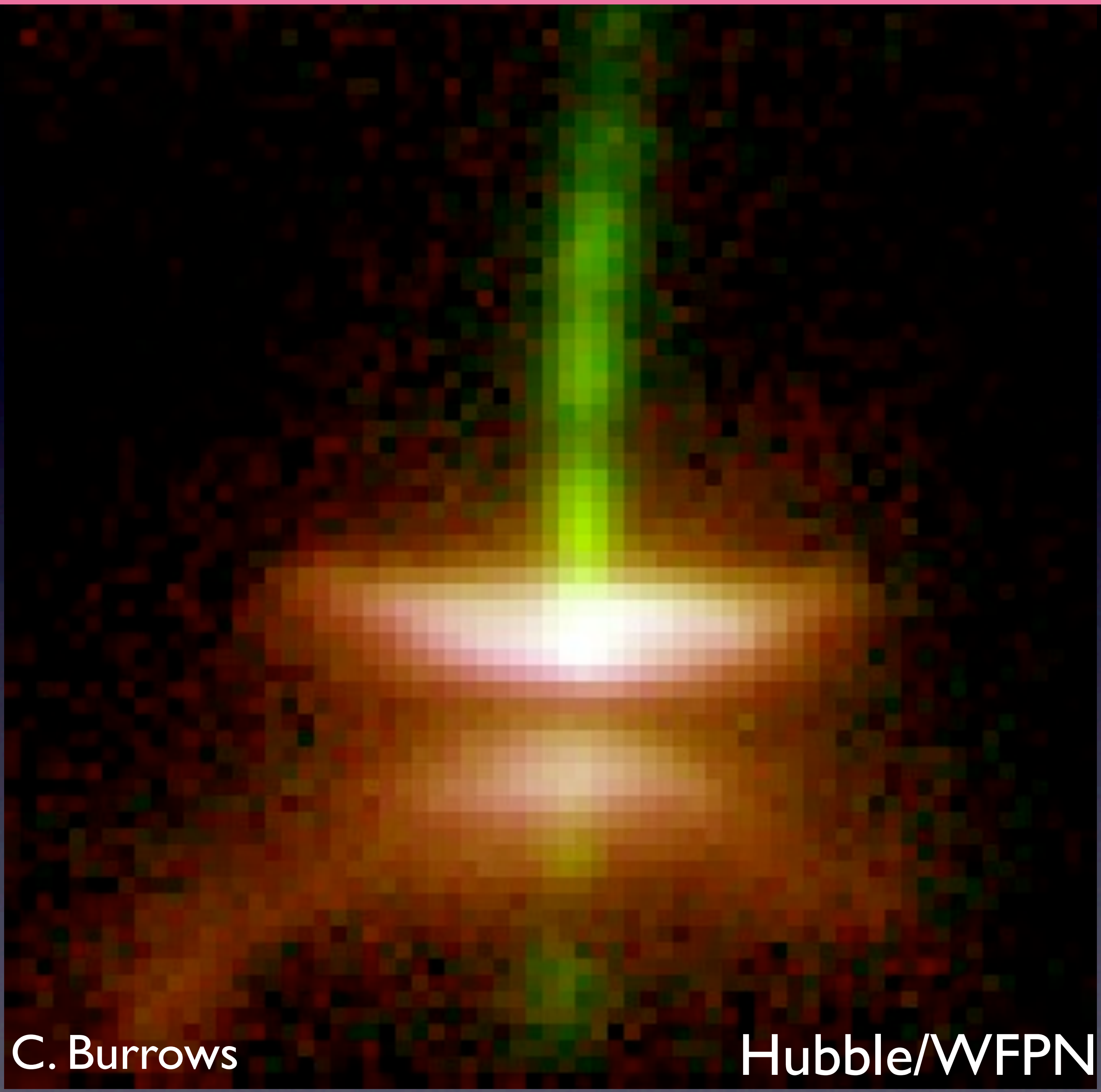


stellar mass

- Efficiency of observed star formation?
- Shape of stellar mass function?
- Binary fraction?

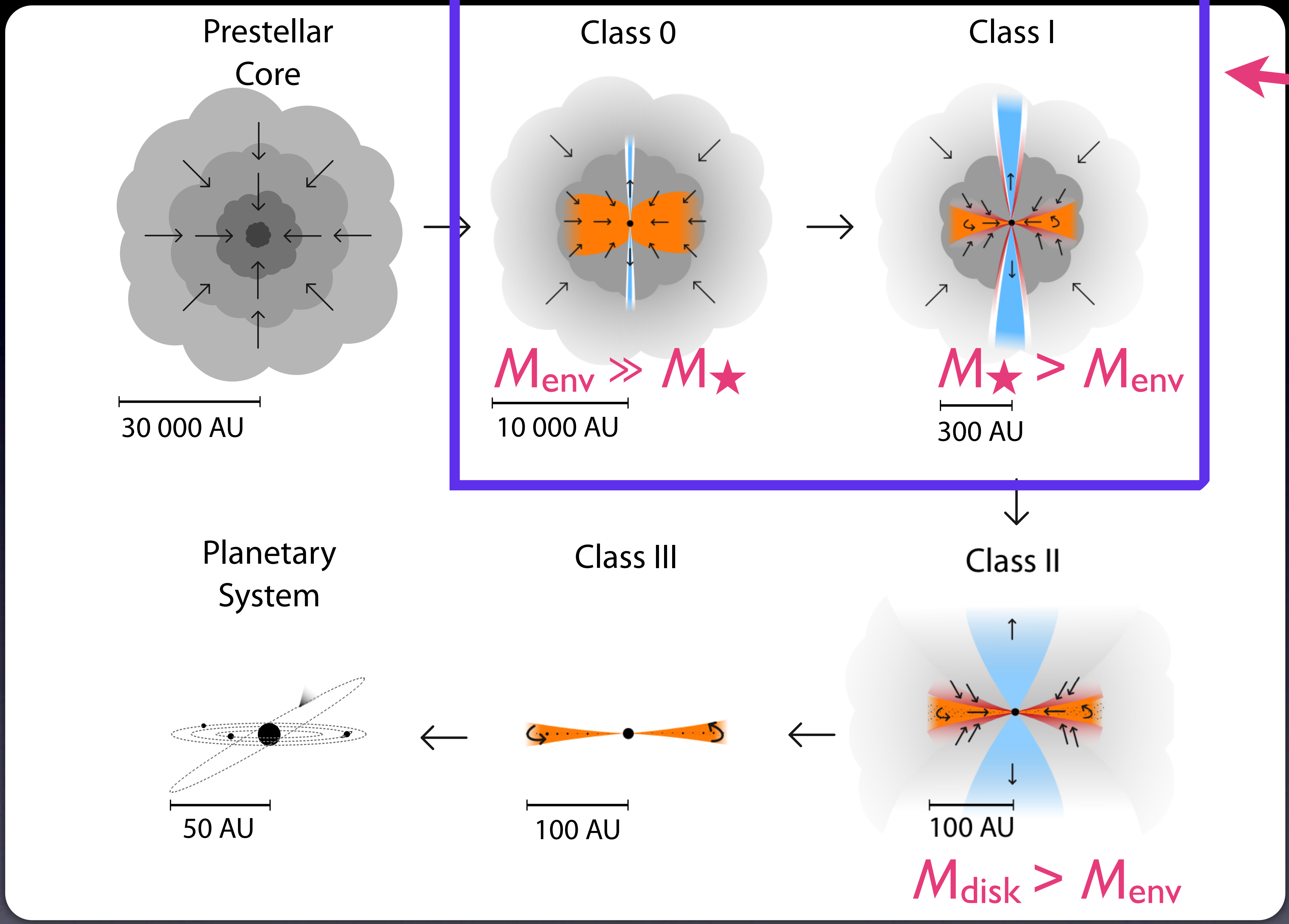
Better understanding of feedback in *individual protostars* key to connect the theory with observations

Disk and jets in HH30



In deeply-embedded sources extinction due to envelope / cloud too high to see the jets

Deeply-embedded protostars

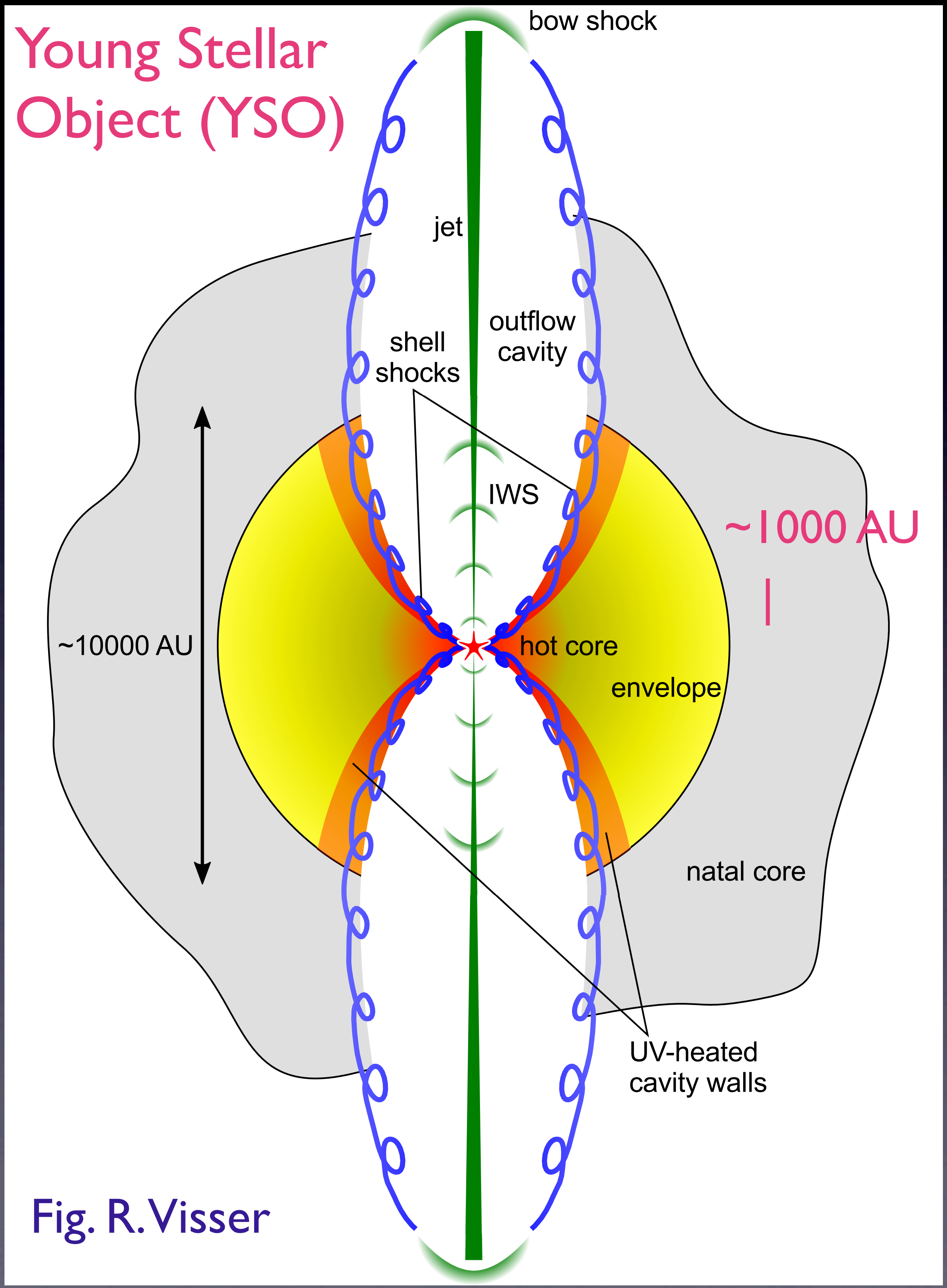


Andre+93,00
Robitaille+06
Young & Evans+05

Fig. M. Persson

Feedback most important during deeply embedded stage, when accretion rate is the largest

Physical structure of Class 0/I

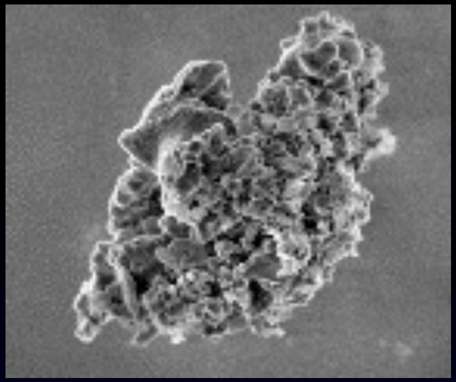


- Natal core
- Envelope
- Protostar
- Bipolar outflow
- (Hidden) jet

Processes leading to gas heating?

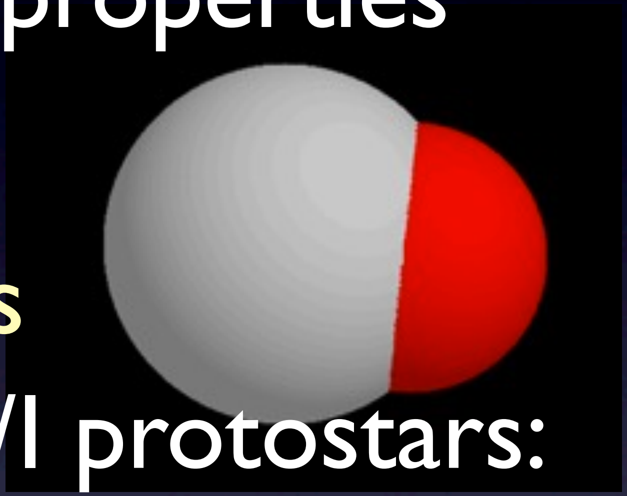
Main cooling channels?

Main cooling channels



Dust

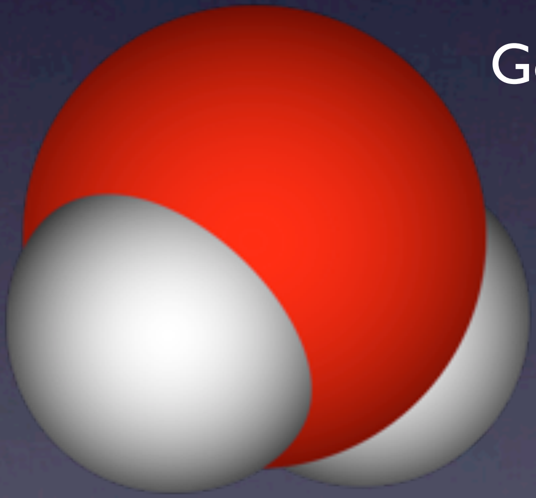
- absorbs UV, re-emits far-IR radiation
- excellent tracer of envelope properties



Molecules and atoms

- in physical regimes of Class 0/I protostars:

Goldsmith & Langer+78, Neufeld & Kaufman+93, Giannini+01, Nisini+02



H_2O

CO

OH

Gas cooling via far-infrared lines of H_2O, CO, OH

- unique tracers of heating processes (=feedback), key for simulations and star formation efficiency

Cooling by H_2O

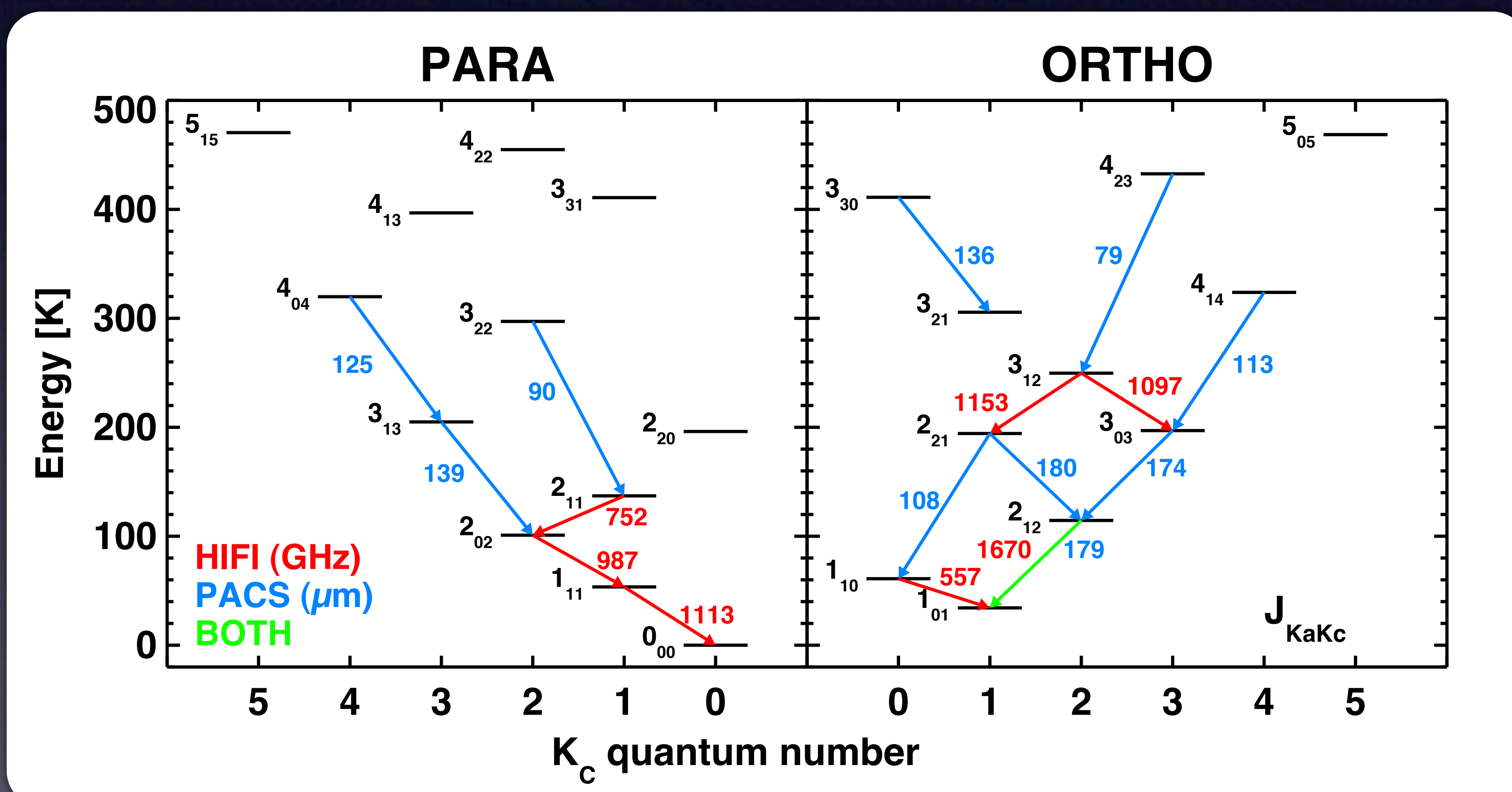
- Forms efficiently in high-*T* reactions and on the grains

T> 300 K: $O + H_2 \longrightarrow OH + H$

$OH + H_2 \longrightarrow H_2O + H$

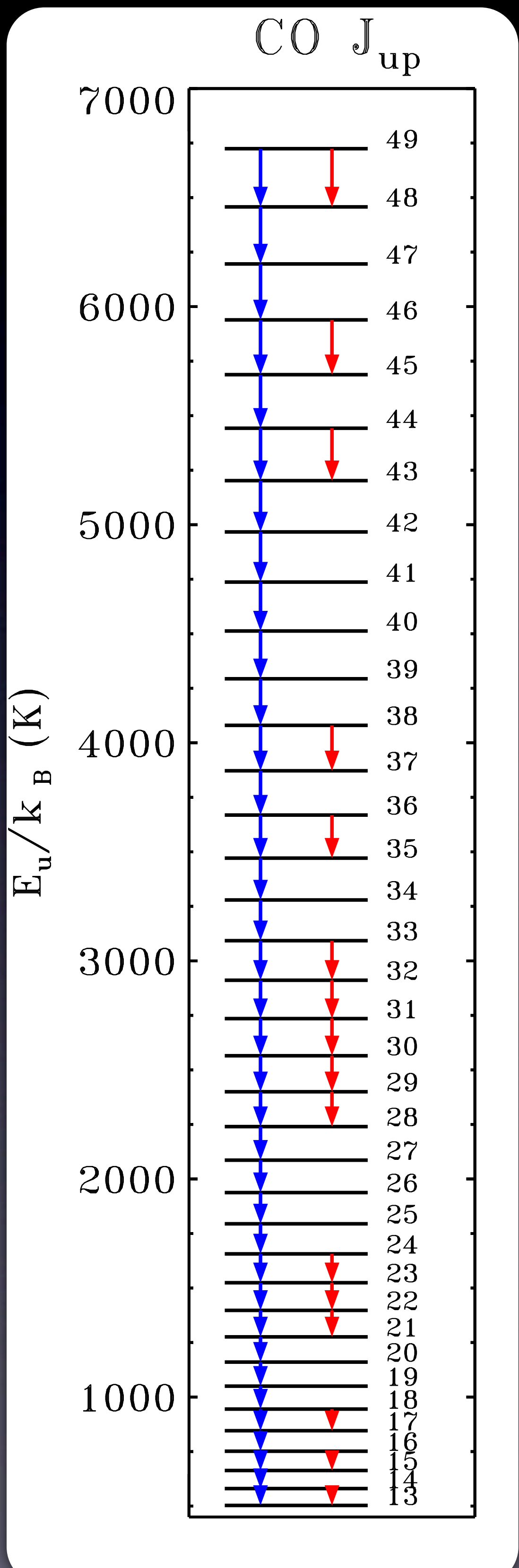
v_{shock} > 15 km/s:
molecules released from grains

- Asymmetric rotor with many energy levels + large radiative rates

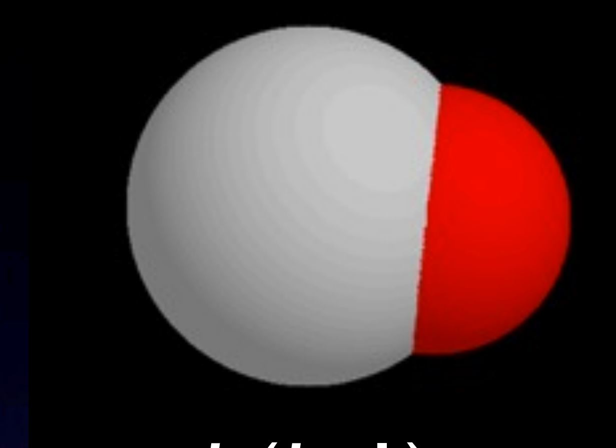


Possible key gas coolant, "switches on" when feedback at play

Cooling by CO



- Second most abundant molecule in the interstellar medium after H_2



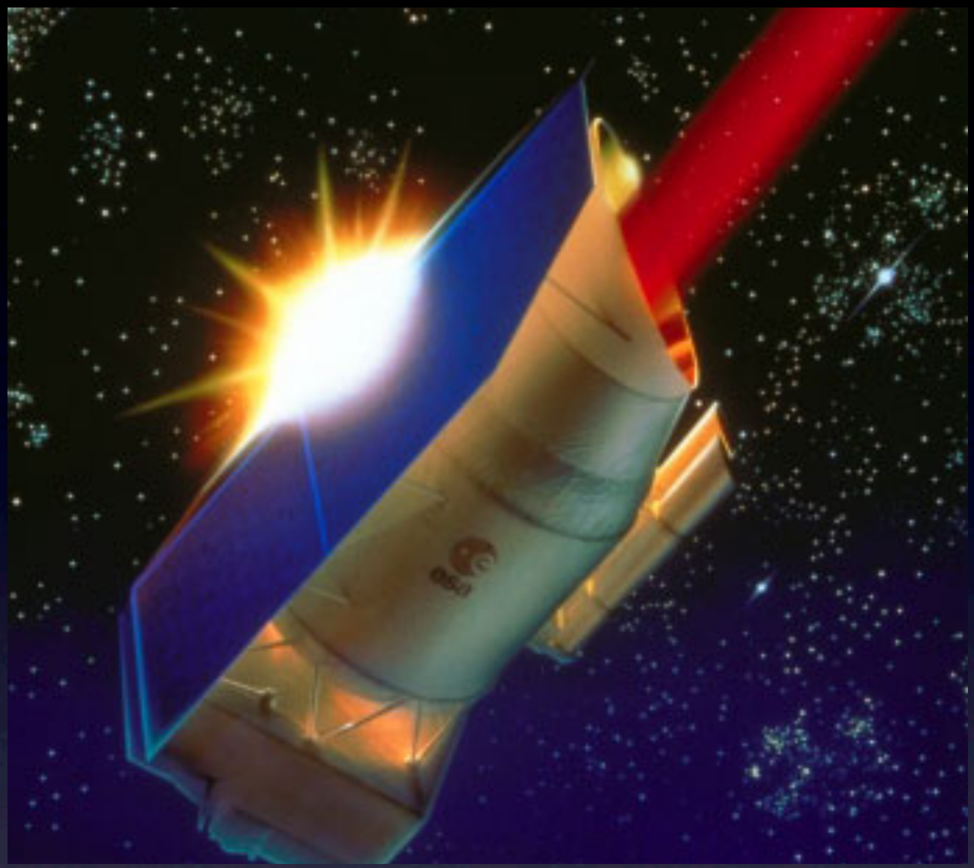
- Level energies closely spaced, scale as $\propto J\,(J+1)$

- Collisionally excited even at low T, good diagnostic of gas kinetic temperature

- Up to recently, CO 1-0, 2-1 and 3-2 accessible

Important coolant and tracer of physical conditions

Far-IR observatories



- ISO / LWS: ~45-200 μm
- R~200 (R~10,000 for bright lines)
- large beam of 80"

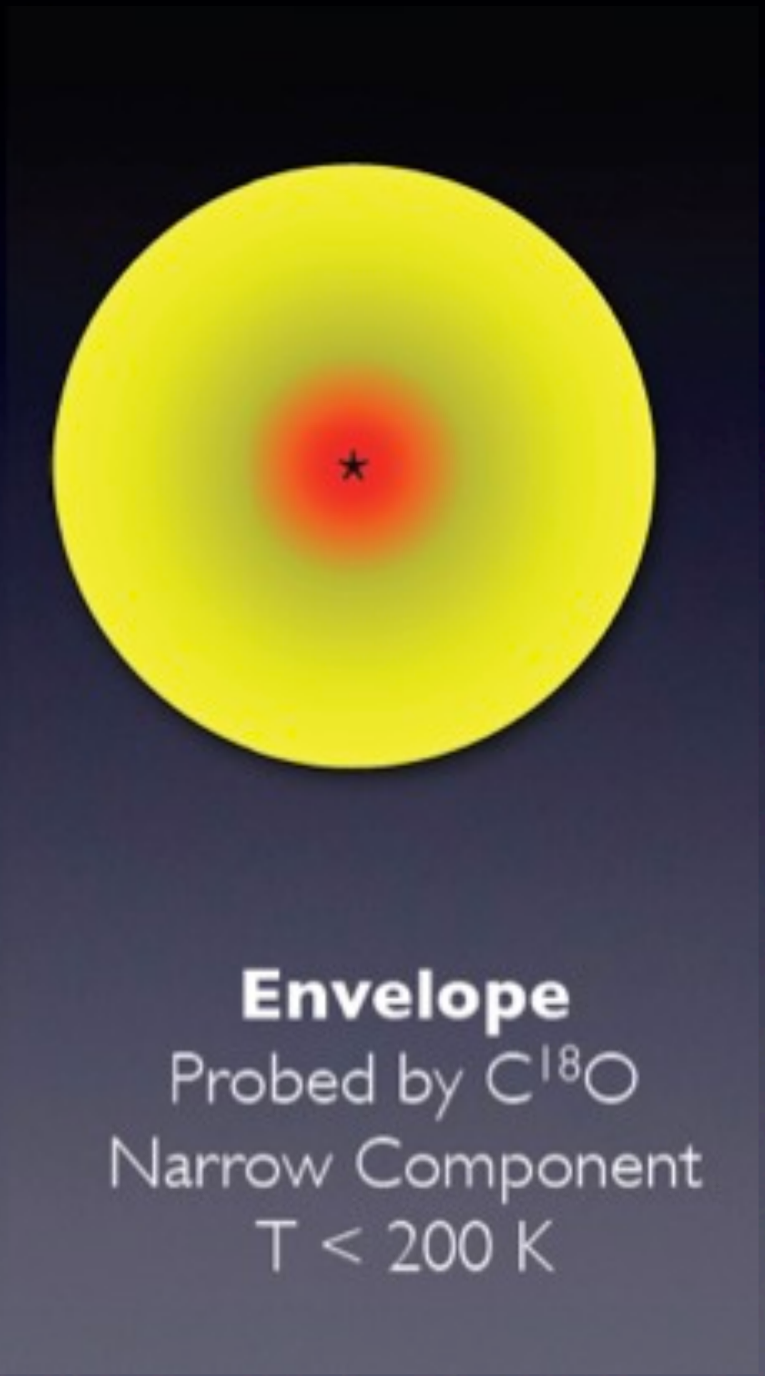
ISO (60cm)
1995-1998

Herschel (3.5 m)
2009-2013

- *Herschel* / PACS: ~55-200 μm
- R~1000-5500
- FOV ~50"x50" resolved into ~10" px

Envelope heating by protostar

Fig. R. Visser



- Accretion luminosity dominates the protostellar luminosity

- Only inner envelope is hot, the rest quickly cooled by dust (far-IR continuum)

- Gas heated by gas-dust collisions

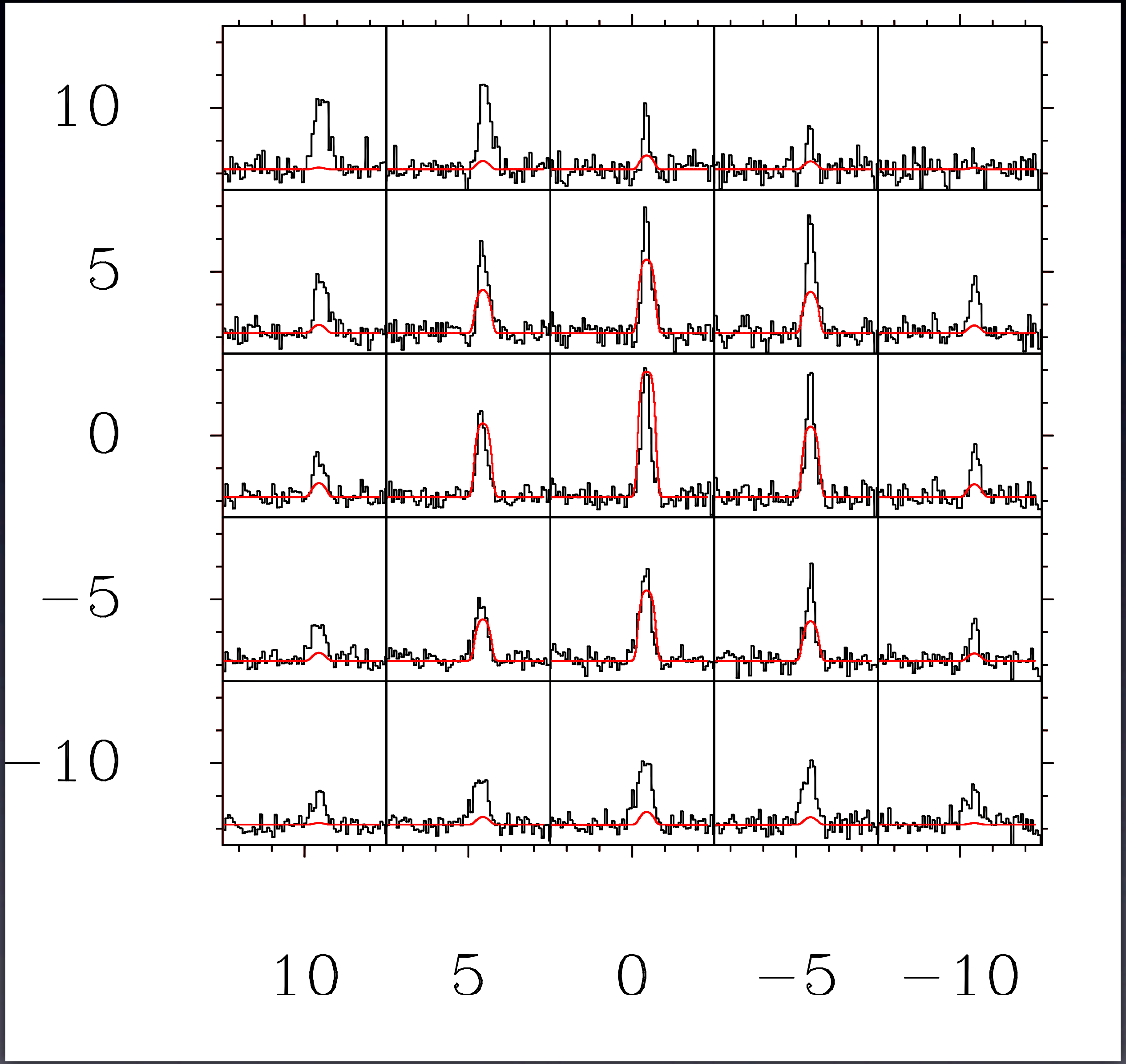
Recent models: hot cores only few % of observed line cooling

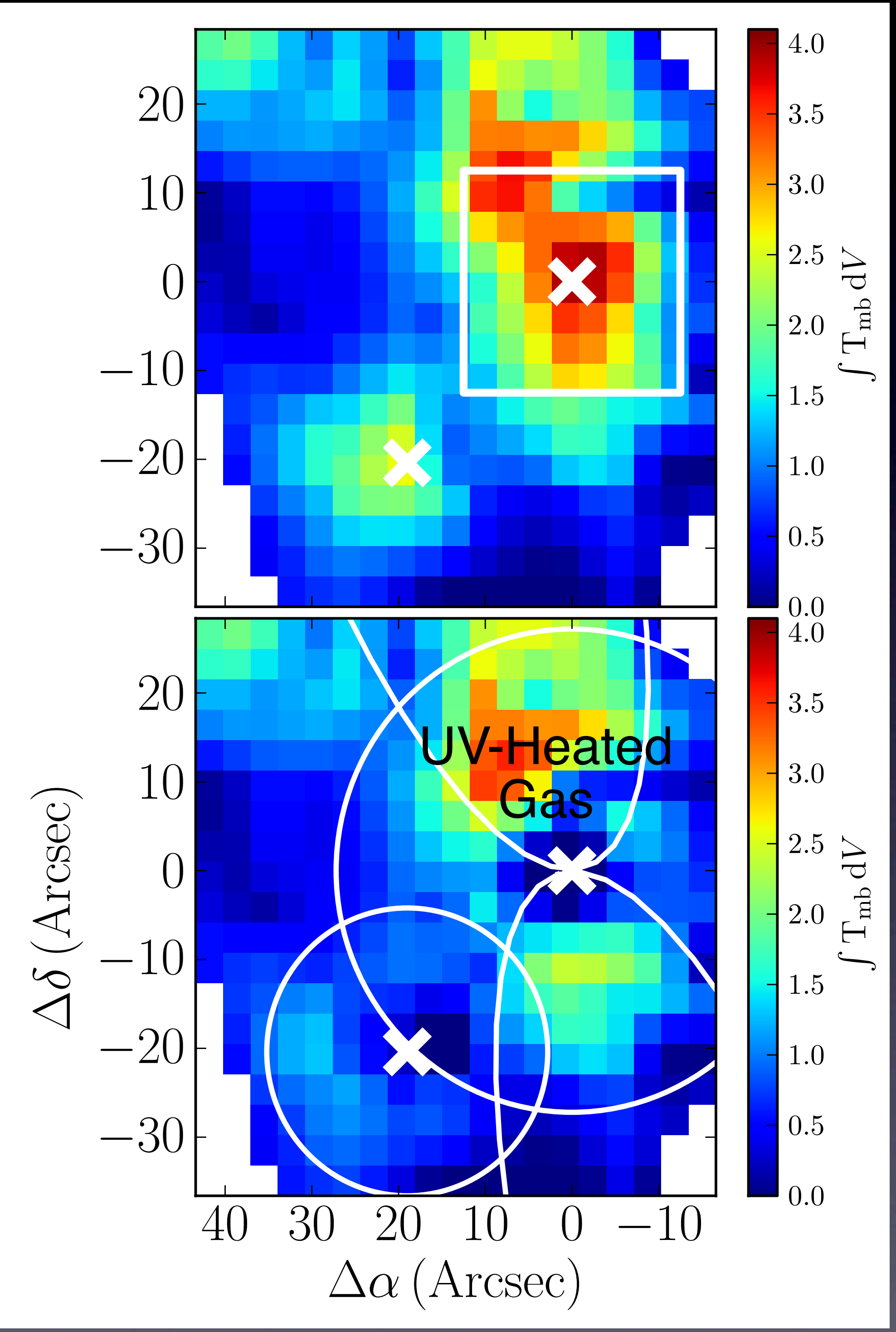
Visser+12

Envelope is a minor contributor of hot gas

Ultraviolet heating

- UV from the vicinity of a protostar and dissociative shocks in the jet



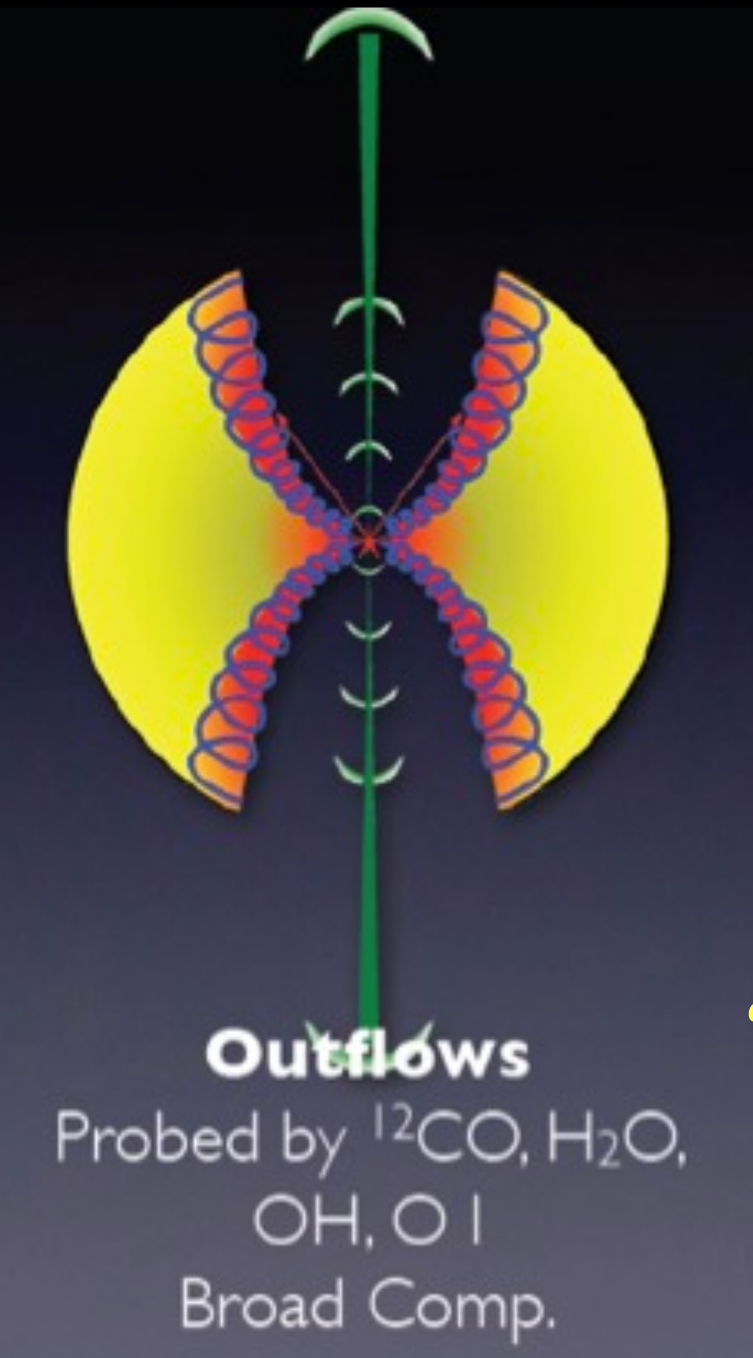


Yildiz+2012, 2015

UV heated cavity walls a likely source of *T*~50 K gas

Shocks in outflow cavities / jets

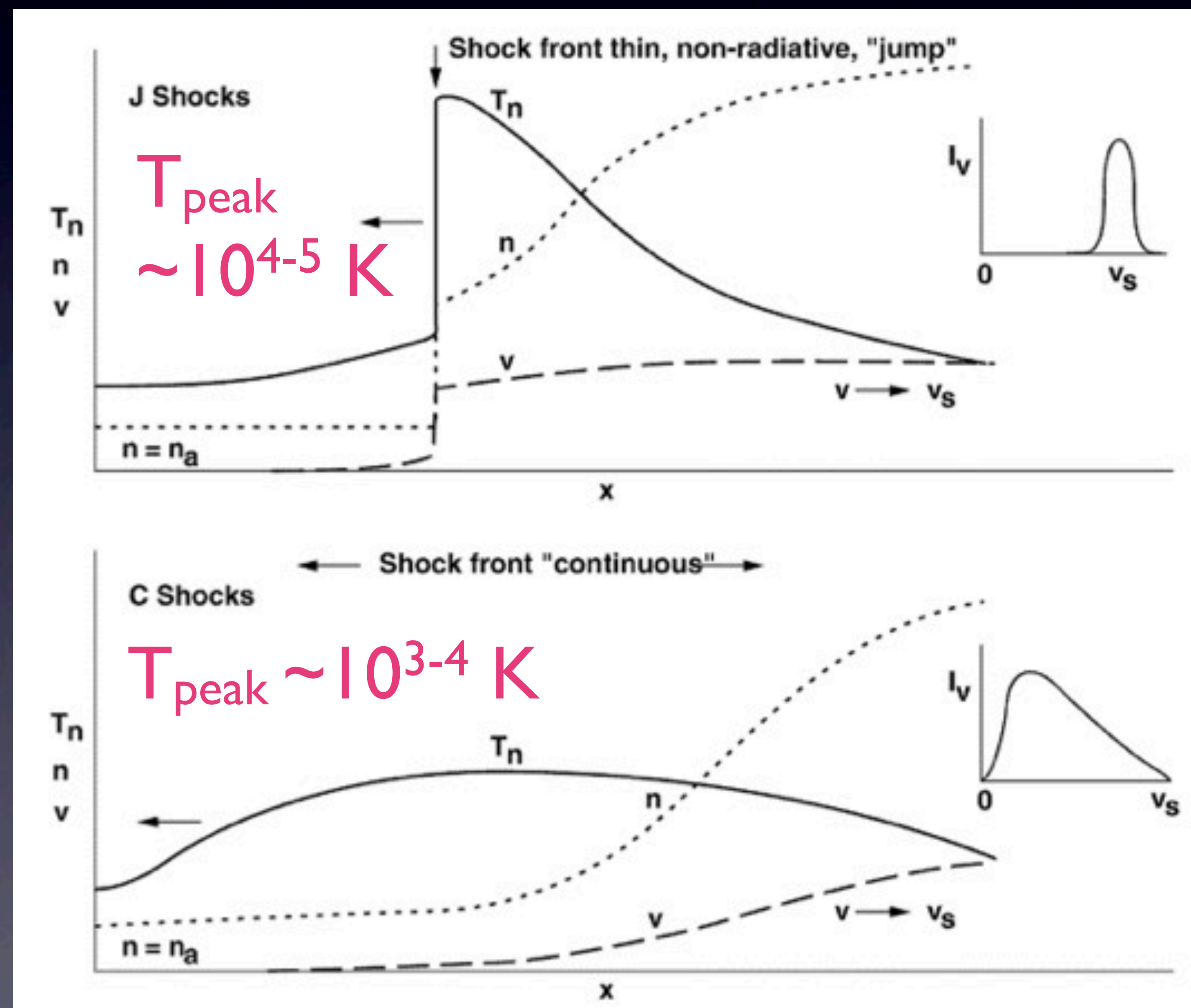
Fig. R. Visser



- Large-scale shocks produced by jets / winds impacting the envelope of two types: Draine 80 Hollenbach 97

'Jump' (*J*-type)

'Continuous' (*C*-type)



Shocks are efficient factories of hot molecular gas

Entrained outflow gas

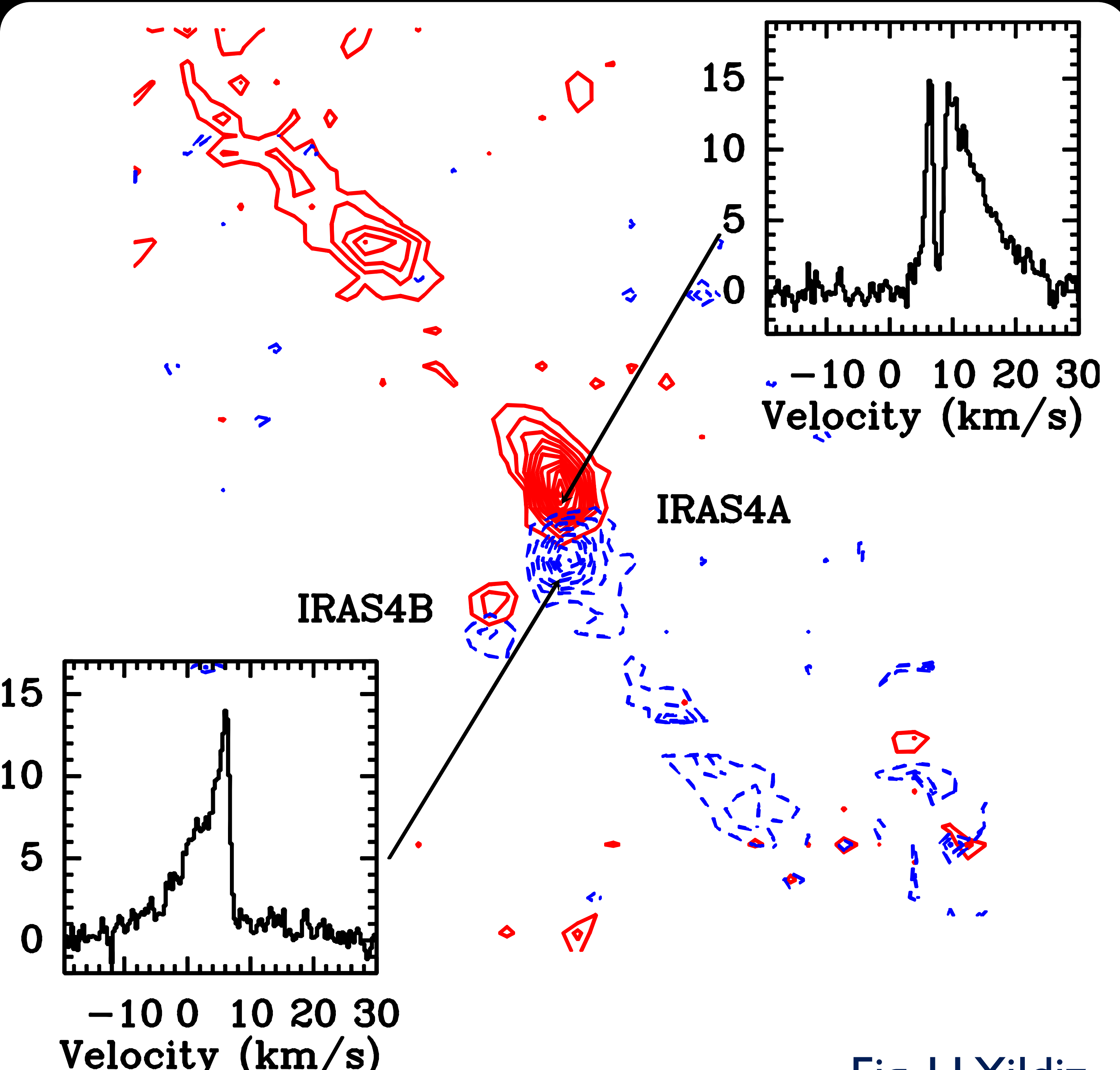


Fig. U.Yildiz

Envelope material incorporated and swept along the outflow

Best traced by high velocity resolution CO lines

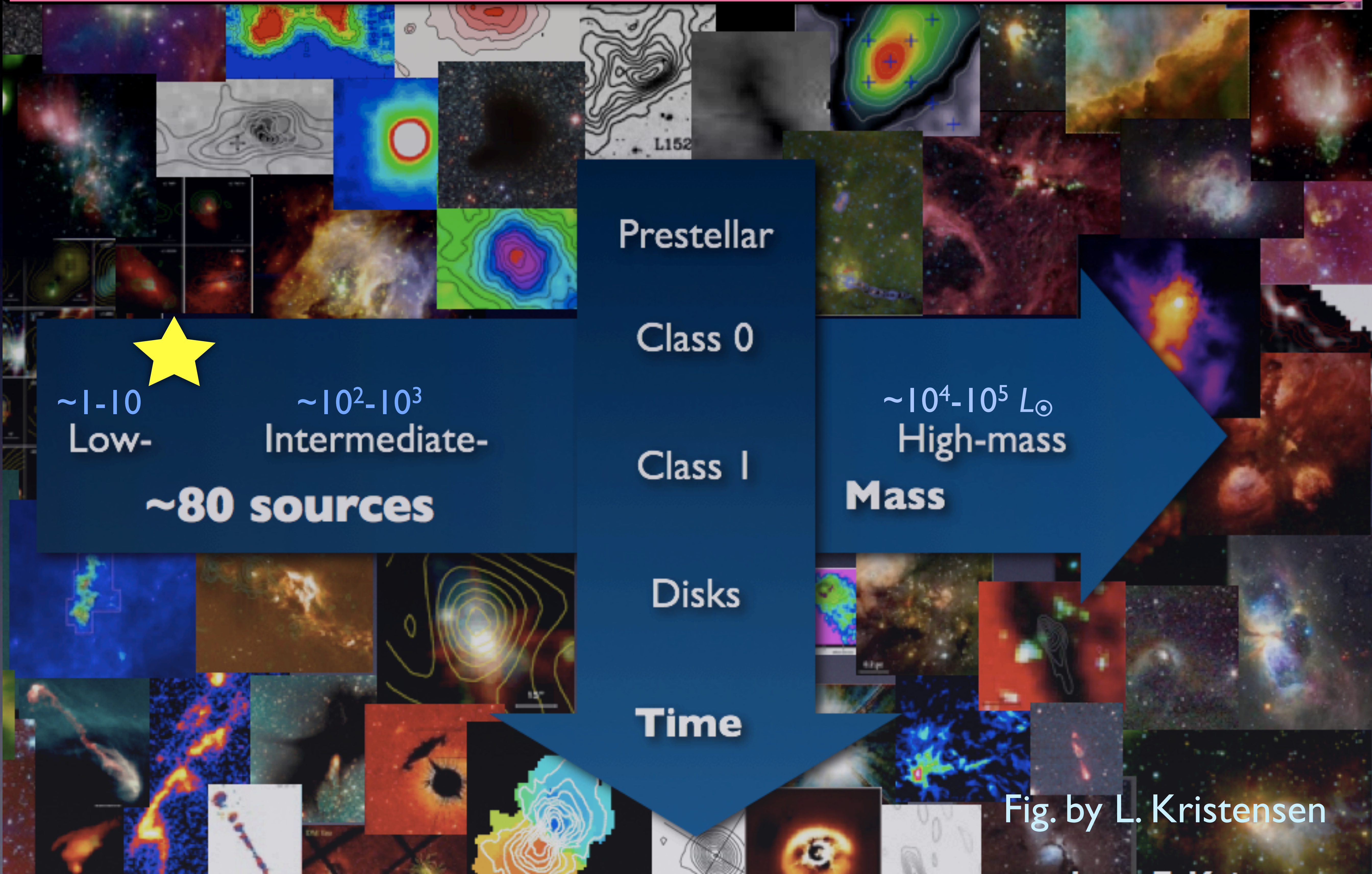
Temperatures of < 100 K

Equally important as UV heating for less energetic transitions

Yildiz+12

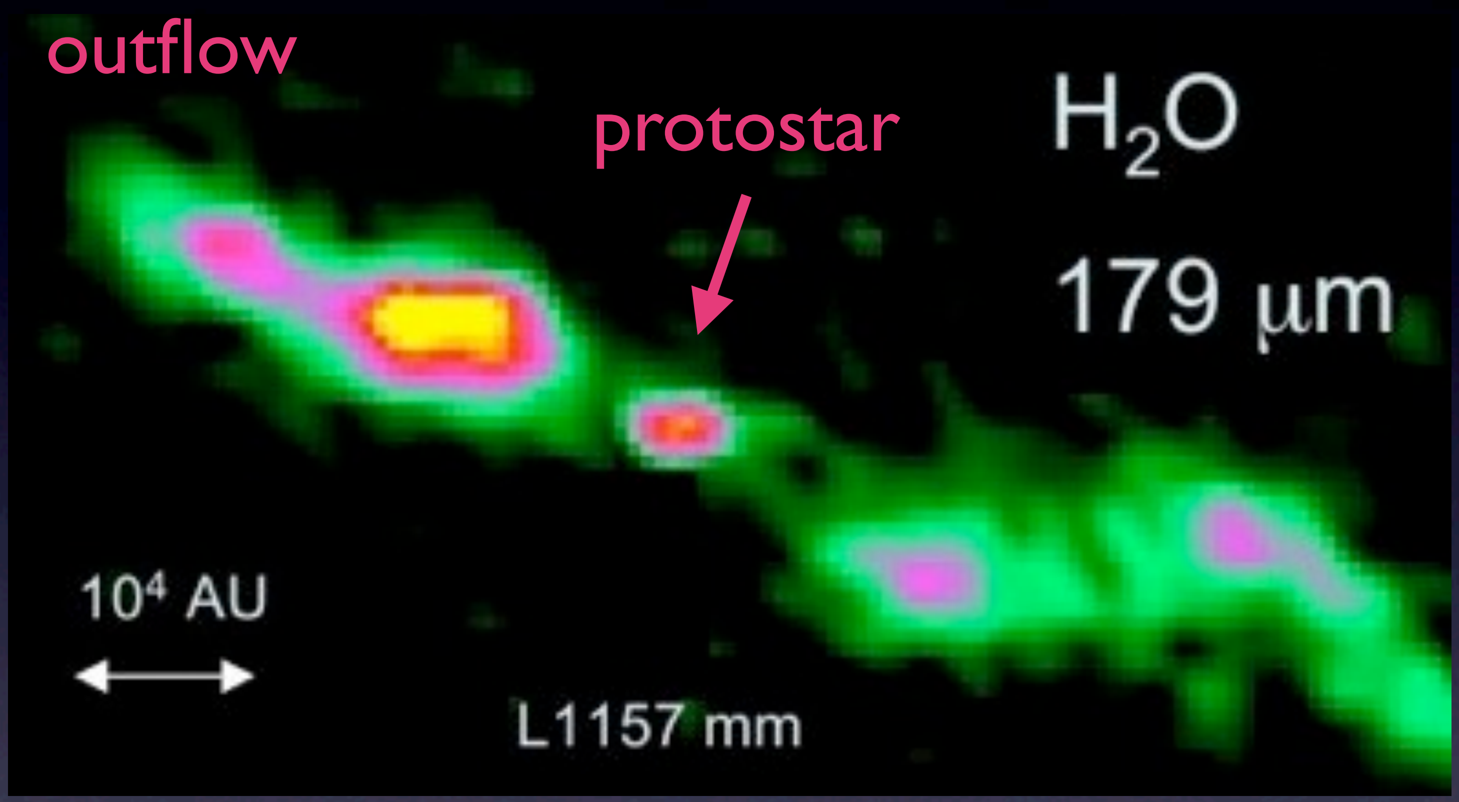
Emits in cold molecular gas - small contribution to far-IR lines

WISH, DIGIT, and WILL programs



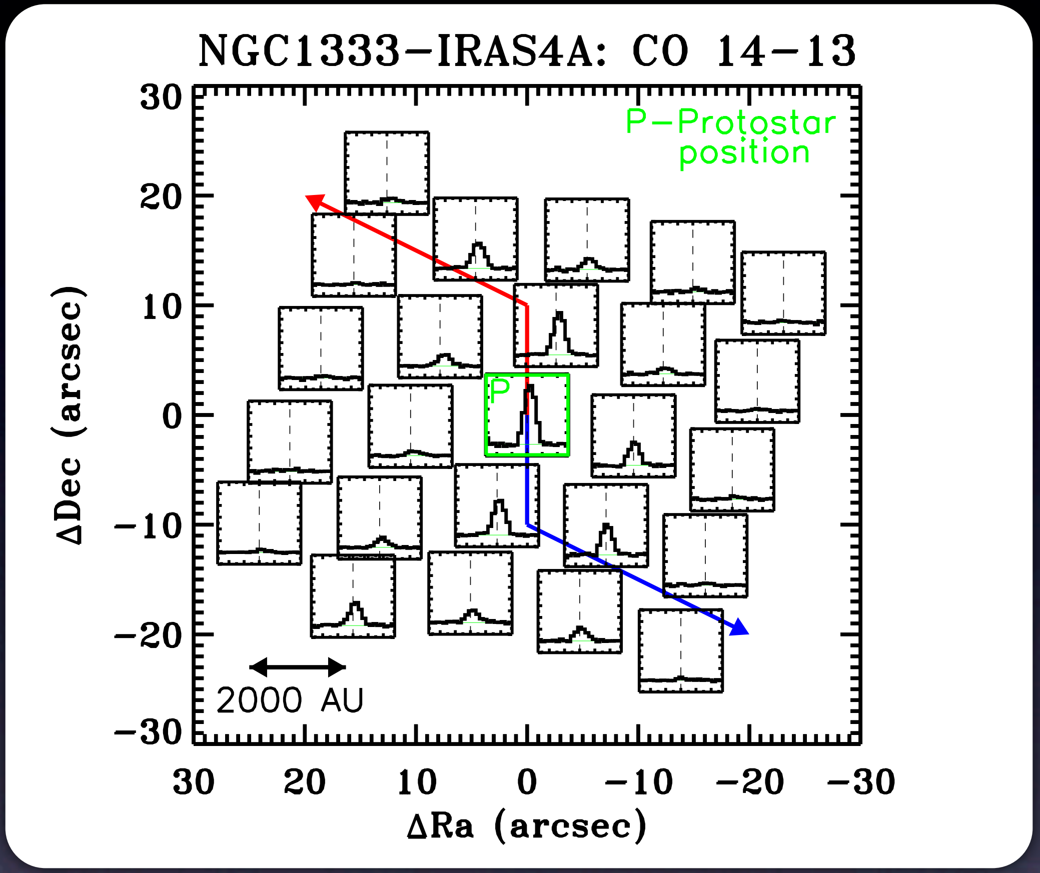
Maps of far-IR emission

Finely sampled map:



Nisini+2010

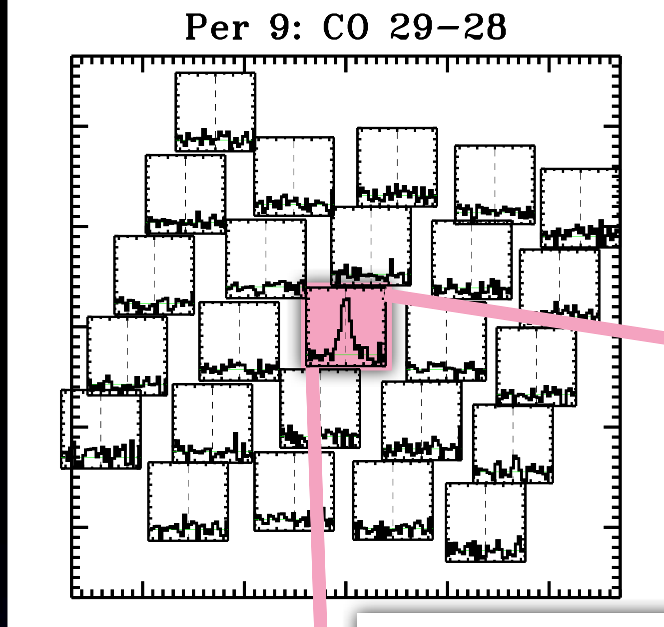
Typical map:



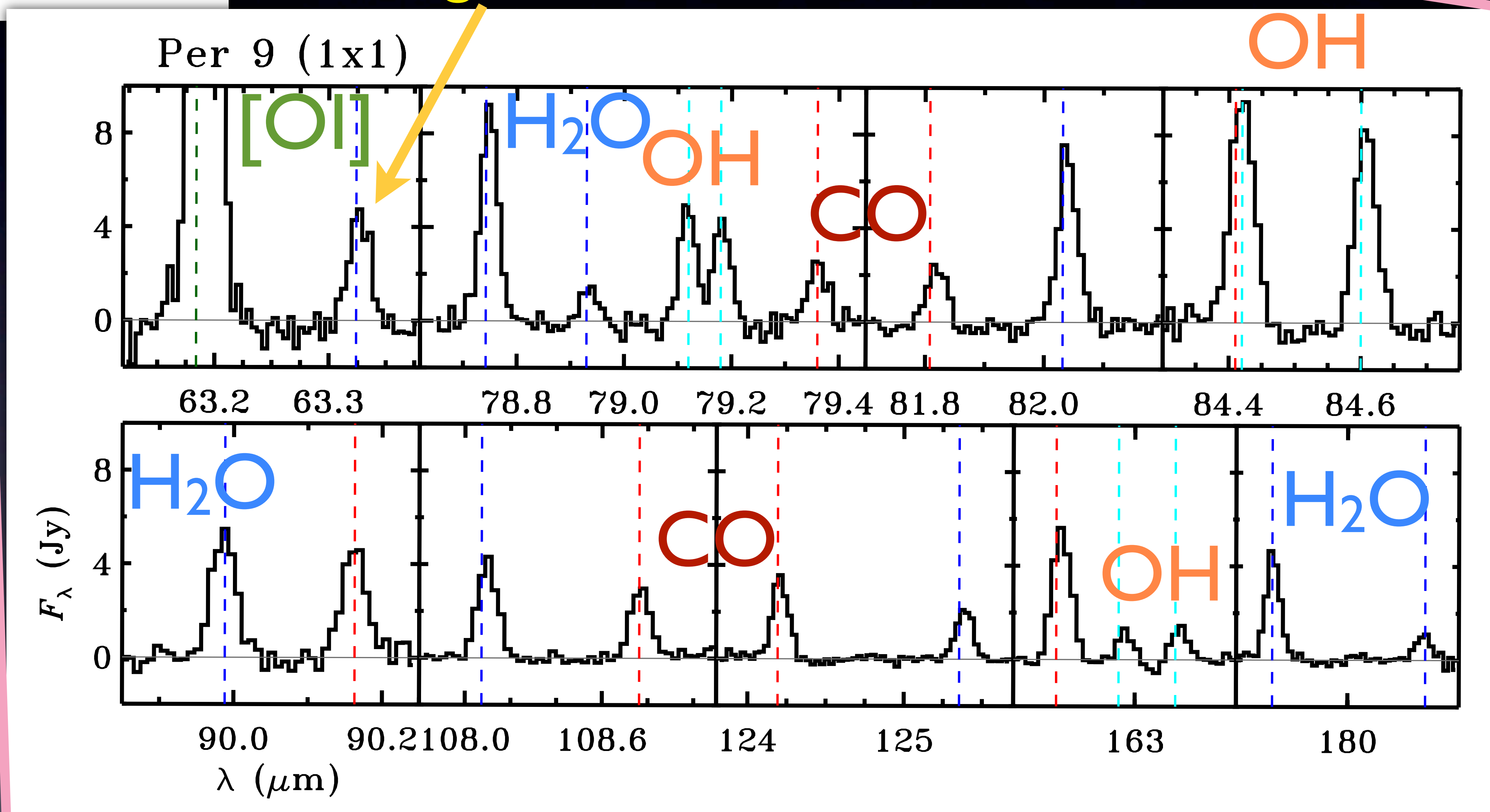
Karska+2013

- Well-resolved extended molecular emission along the outflow direction
- Detected in ~10% of sources, esp. Class 0

Typical spectra

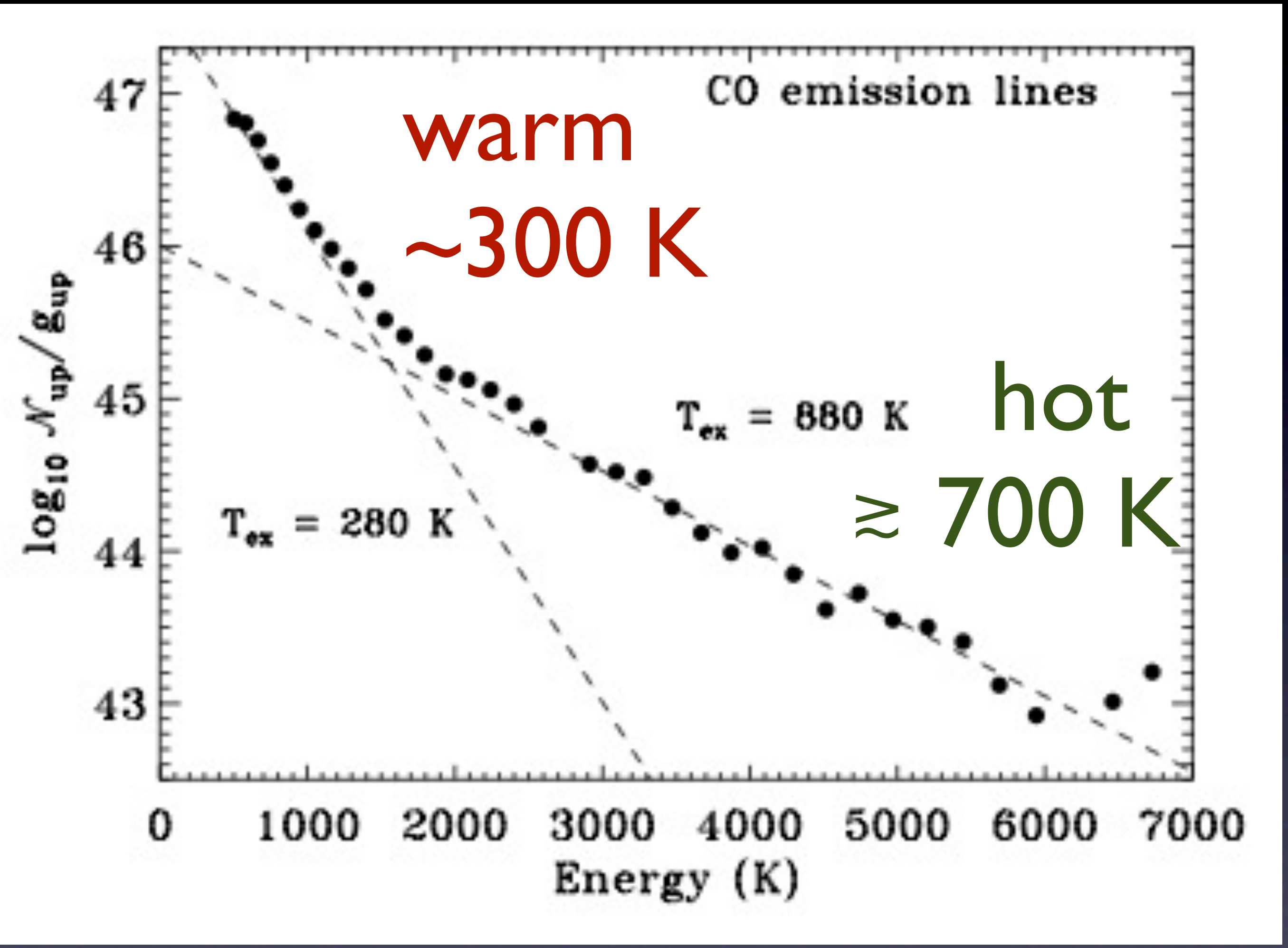


booming H_2O 8_{18}-7_{07} (E_{up}~1000 K)



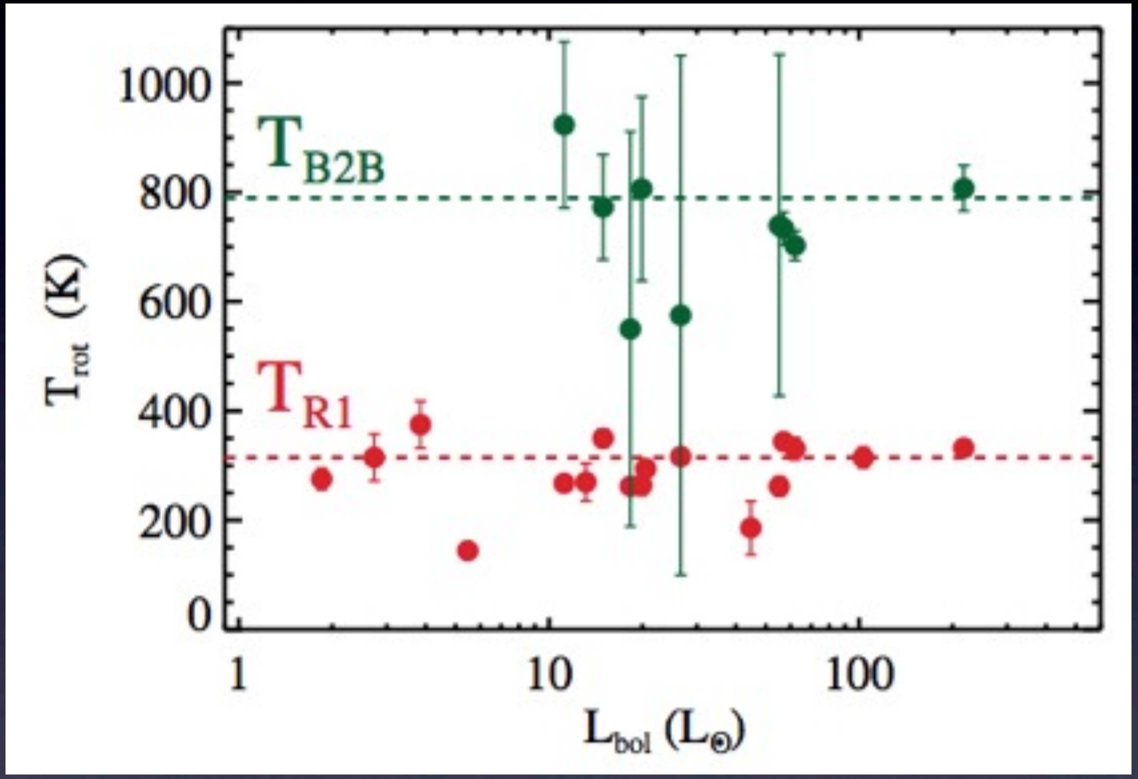
Compact and rich line emission in CO, H_2O, OH, very highly-excited lines detected

CO rotational diagrams



Herczeg+2012, Green+13, Karska+13, Goicoechea+2012

Manoj+2013:



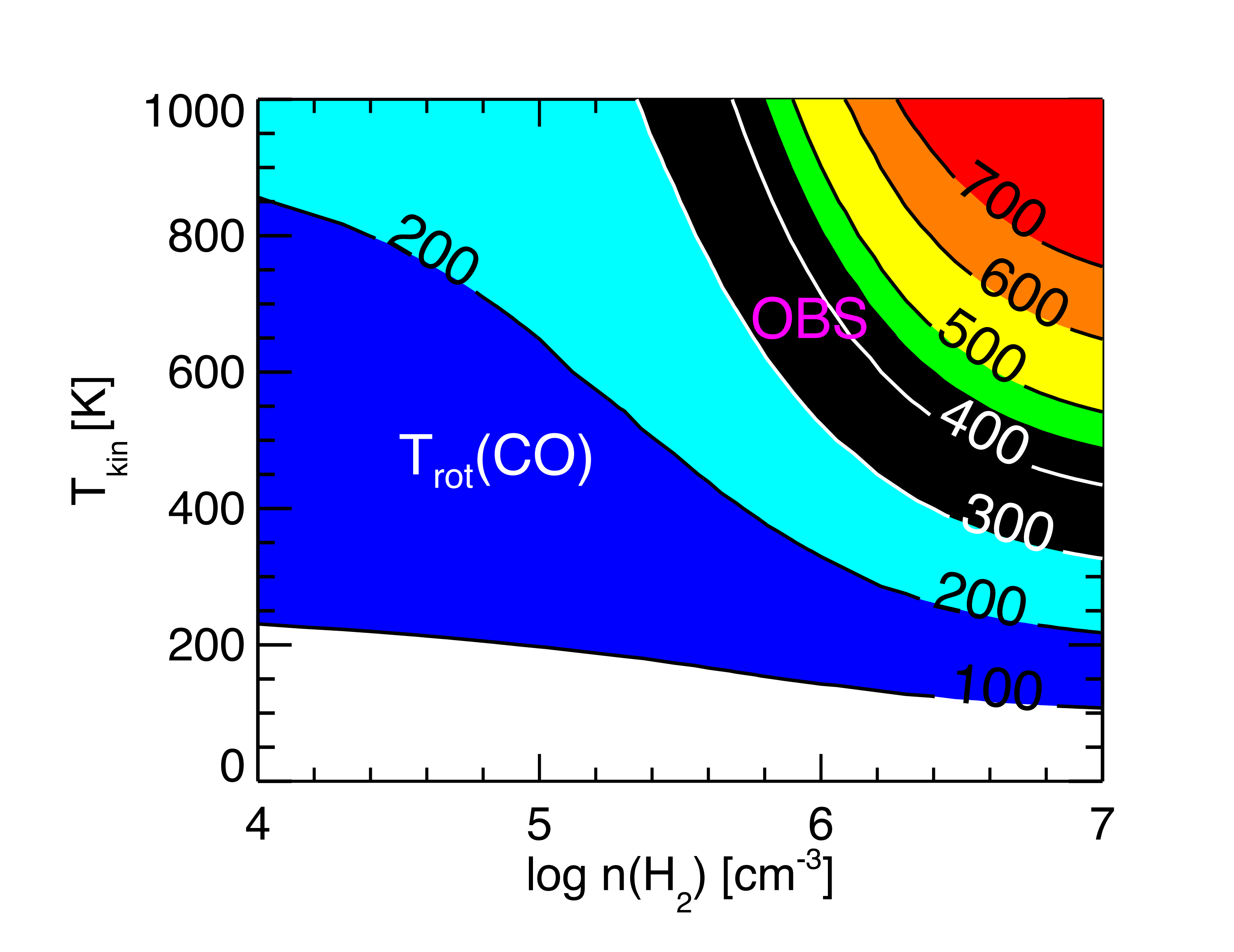
see Matuszak+2015

- Universal warm CO component *T*~ 300 K
- Differences in hot CO *T* - need for larger source sample

Gas physical conditions

Karska+2013

Radiative transfer model predictions give a range of temperatures and densities:



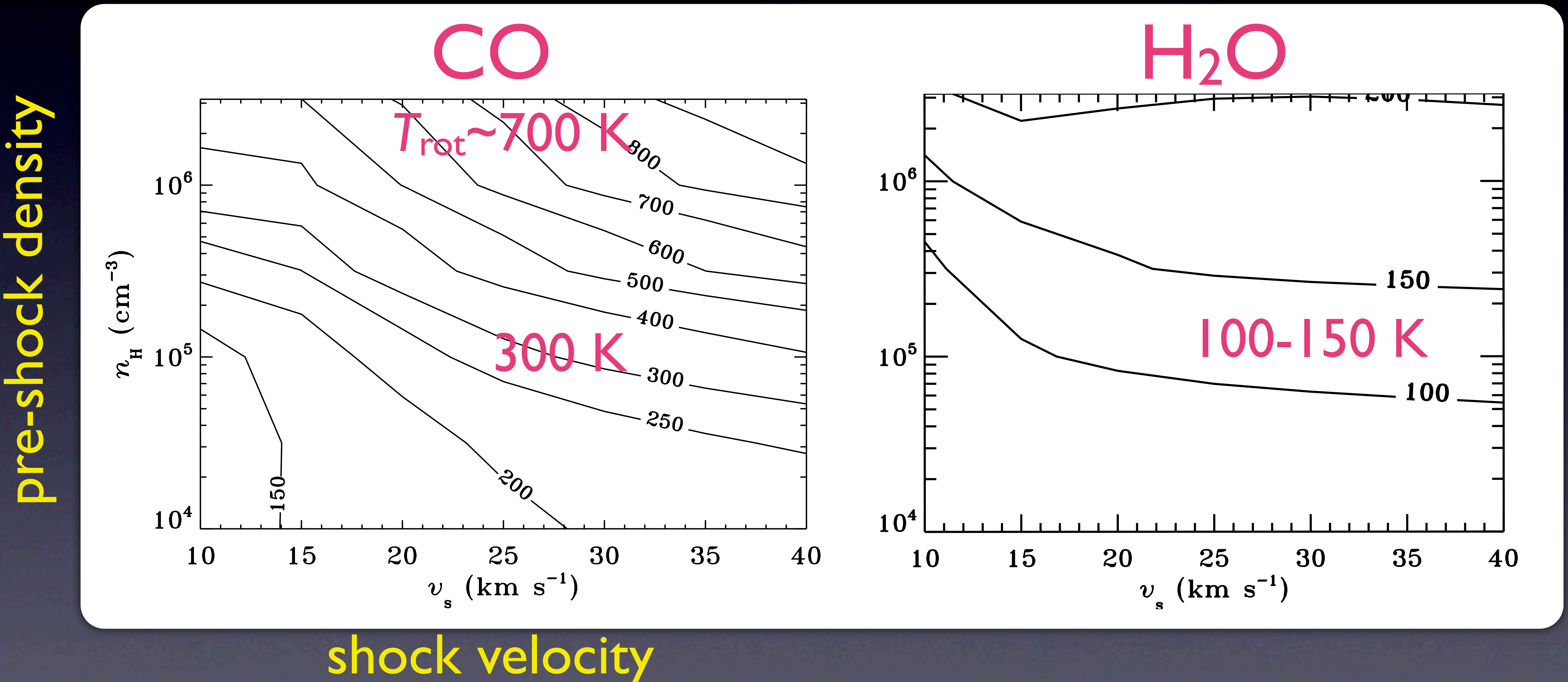
see also Neufeld 12

Observations reproduced with densities $n > 10^5$ cm^{-3} and T > 300 K, or: lower densities (n~10^{3-4} cm^{-3}) and much higher T (> 1000 K)

Comparison to shock models

Karska+2013

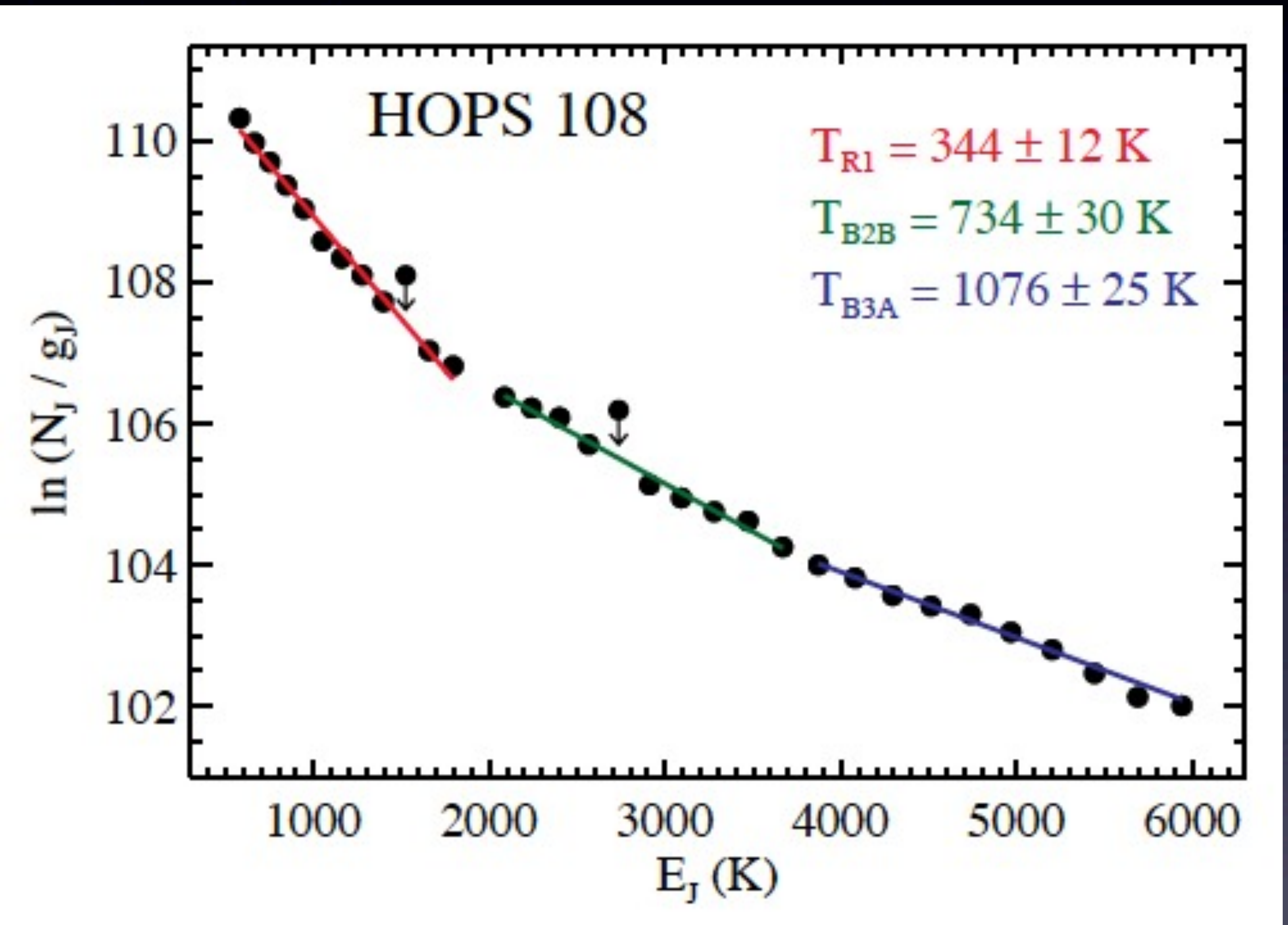
Kaufman & Neufeld 96 models

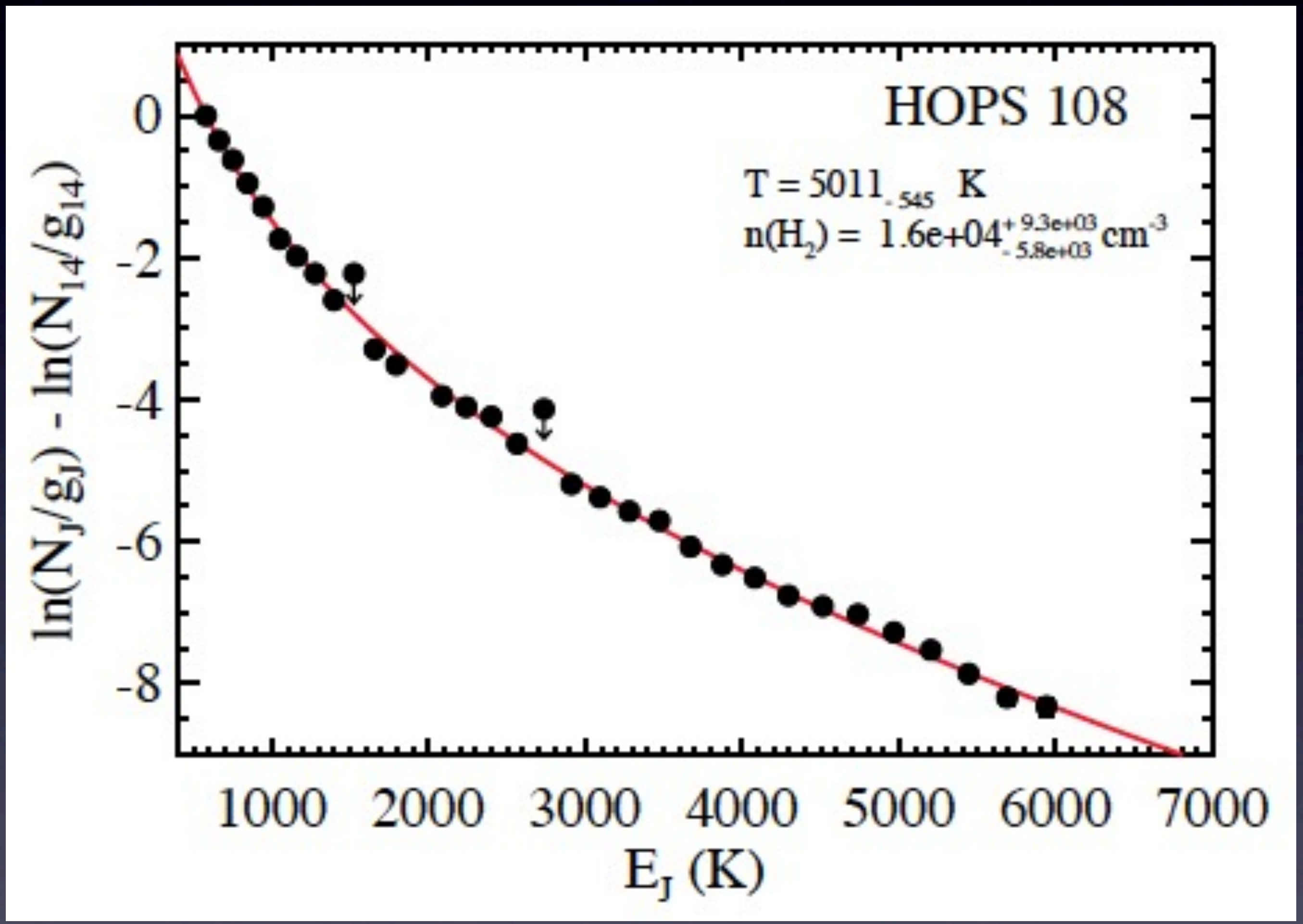


Comparison to *C*-type shock models favors high pre-shock densities (10^4-10^5 cm^{-3}) and thus $n > 10^5$ cm^{-3} & T ~ few 100 K

Alternative approach

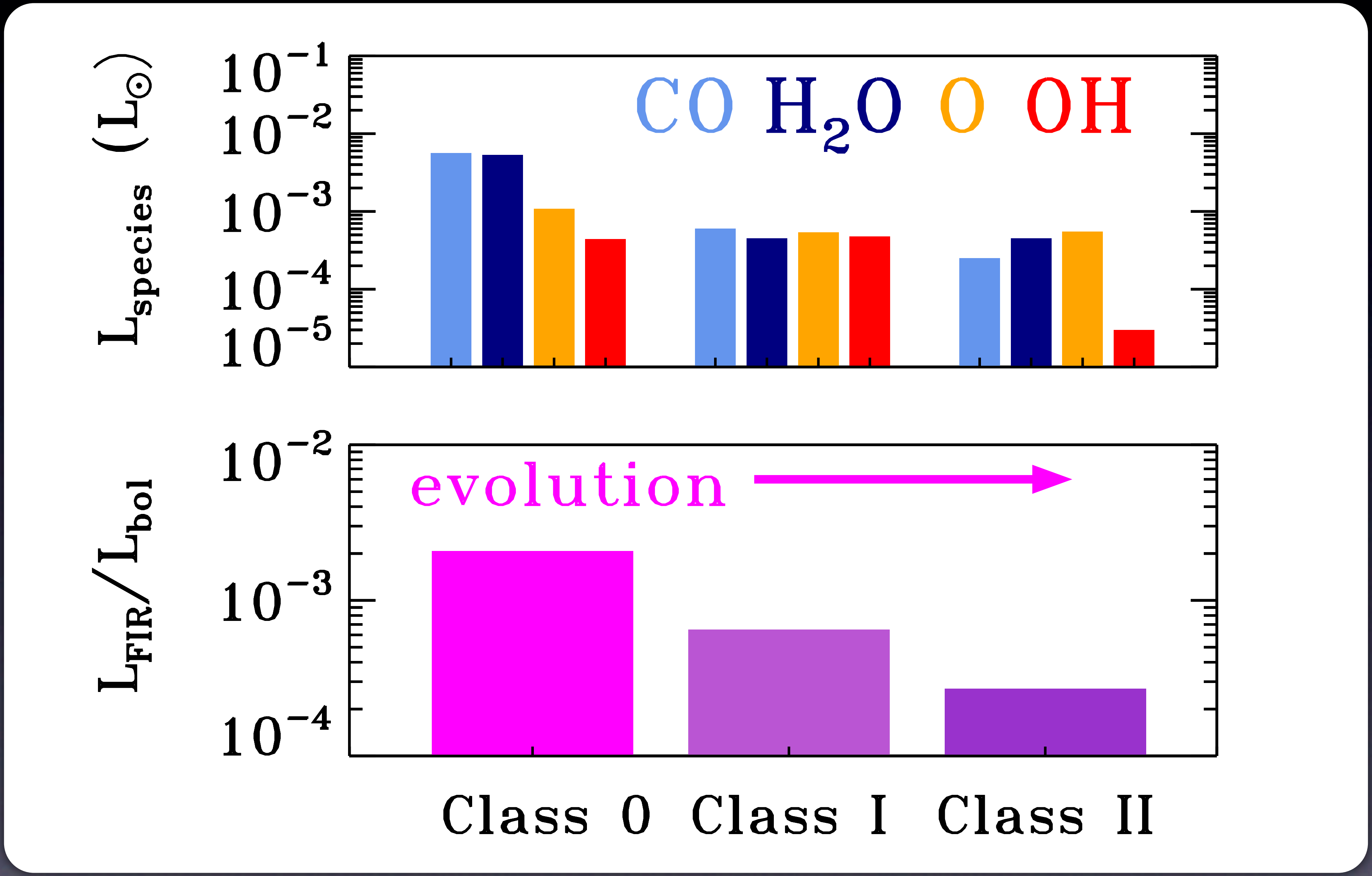
Neufeld+12, Manoj+13, Green+13





Single component fits require low-densities (≲10^4 cm^{-3}) and very high temperatures T ≳ few 1000 K

Gas cooling budget



Class 0/I
Karska+2013

Class II
Podio+2012

Total far-IR cooling dominated by CO and H_2O - shocks
O increasing for more evolved sources - more UV heating

Shock models vs. observations

	H_2O	CO	OH	method
Ser SMM3 (Dionatos+13)	C shock, v~30 km/s, n~10^4 cm^{-3}	J shock, v~20 km/s, n~10^4 cm^{-3}	C shock, v~30 km/s, n~10^4 cm^{-3}	best fit to rotational diagrams
L1448-MM (Lee+13)	C shock, v~40 km/s, n~10^5 cm^{-3}		-	
L1448-R4 (Santangelo+12)	J shock, v~20 km/s, n~10^5 cm^{-3}	-		HIFI line ratios
L1448-R4 (Santangelo+13)	C shock, v>20 km/s, n~10^5 cm^{-3}			PACS line ratios
L1157 B1 (Benedettini+12)	-	dissoc. J shock, v>30 km/s n~10^4 cm^{-3} v>20 km/s n~10^5 cm^{-3}		OI fluxes, O/CO & OH/CO
L1157 B1 (Busquet+14)	non-dissoc. J shock	-		cooling in H_2O lines

Lack of agreement between various authors: different approaches and / or real differences between objects

More robust comparisons

Test case:
22 low-mass protostars

Karska+2014b

Shock models:

- non-dissociative *C*-type shock models from Kaufman & Neufeld 96

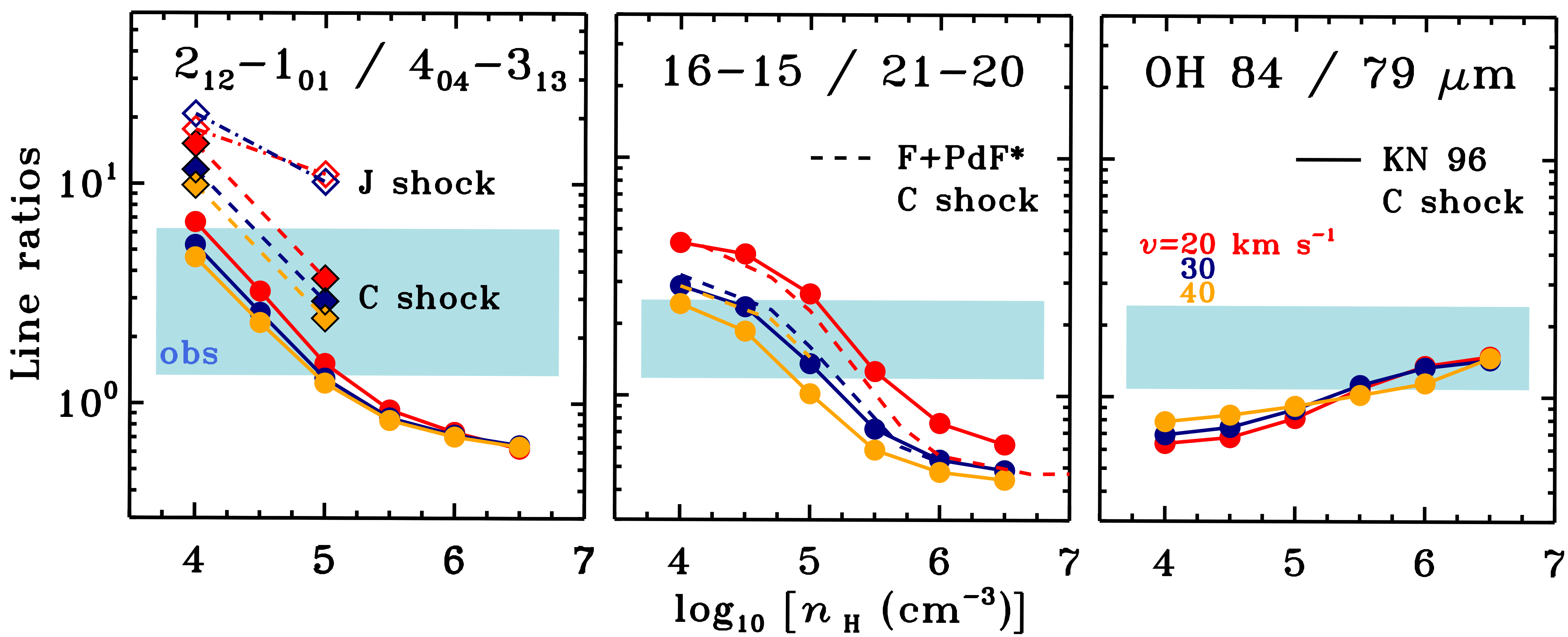
- non-dissociative *C*- and *J*-type shock models: Pineau des Forets & Flower 10

- extension of PdF&F to higher-*J* CO

Aim: test the observations of significant sample of sources against the shock models in a uniform way

Line ratios vs. shock models
- excitation

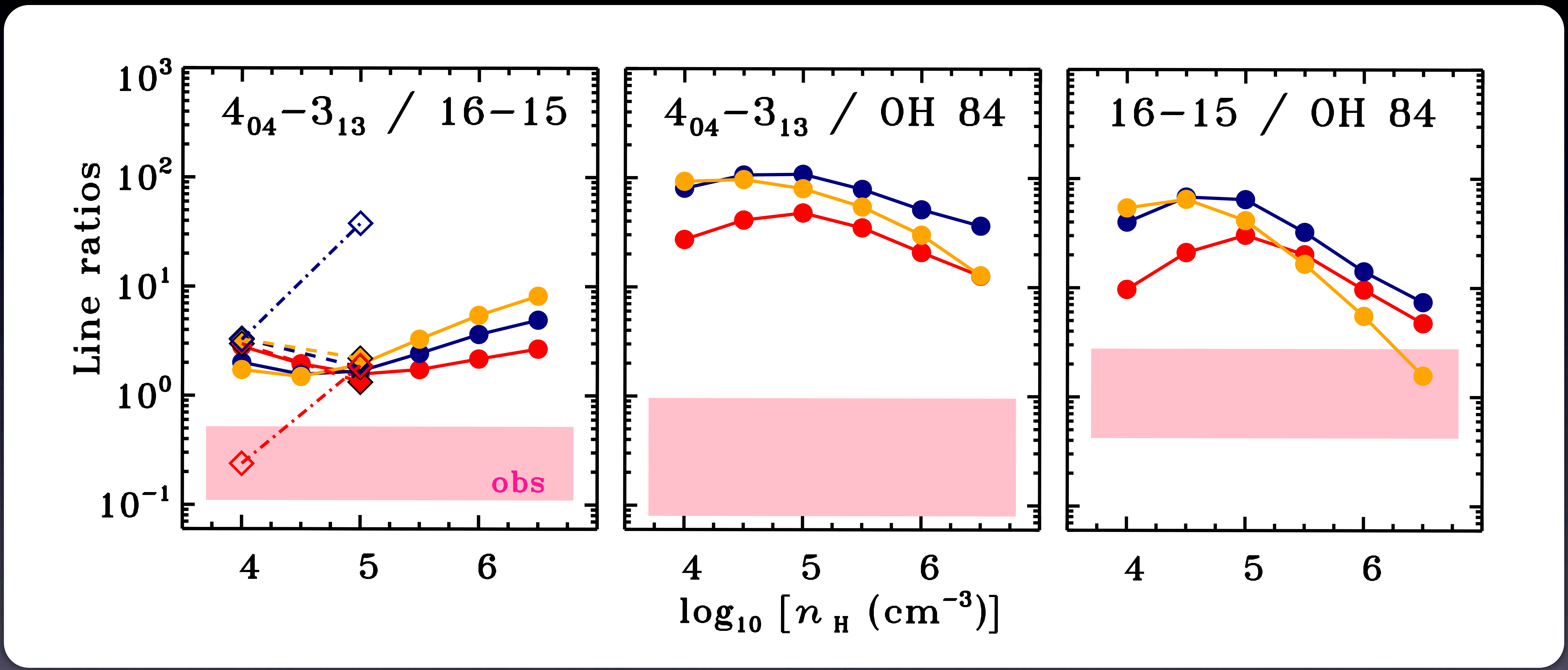
Karska+14b



- Line ratios remarkably similar across the sample
- Velocities > 20 km s^{-1}, pre-shock densities of ~10^5 cm^{-3}

Line ratios vs. shock models
- abundances

Karska+14b



- Observed ratios with H_2O much lower than models
- Irradiated shock models - decrease in H_2O abundances

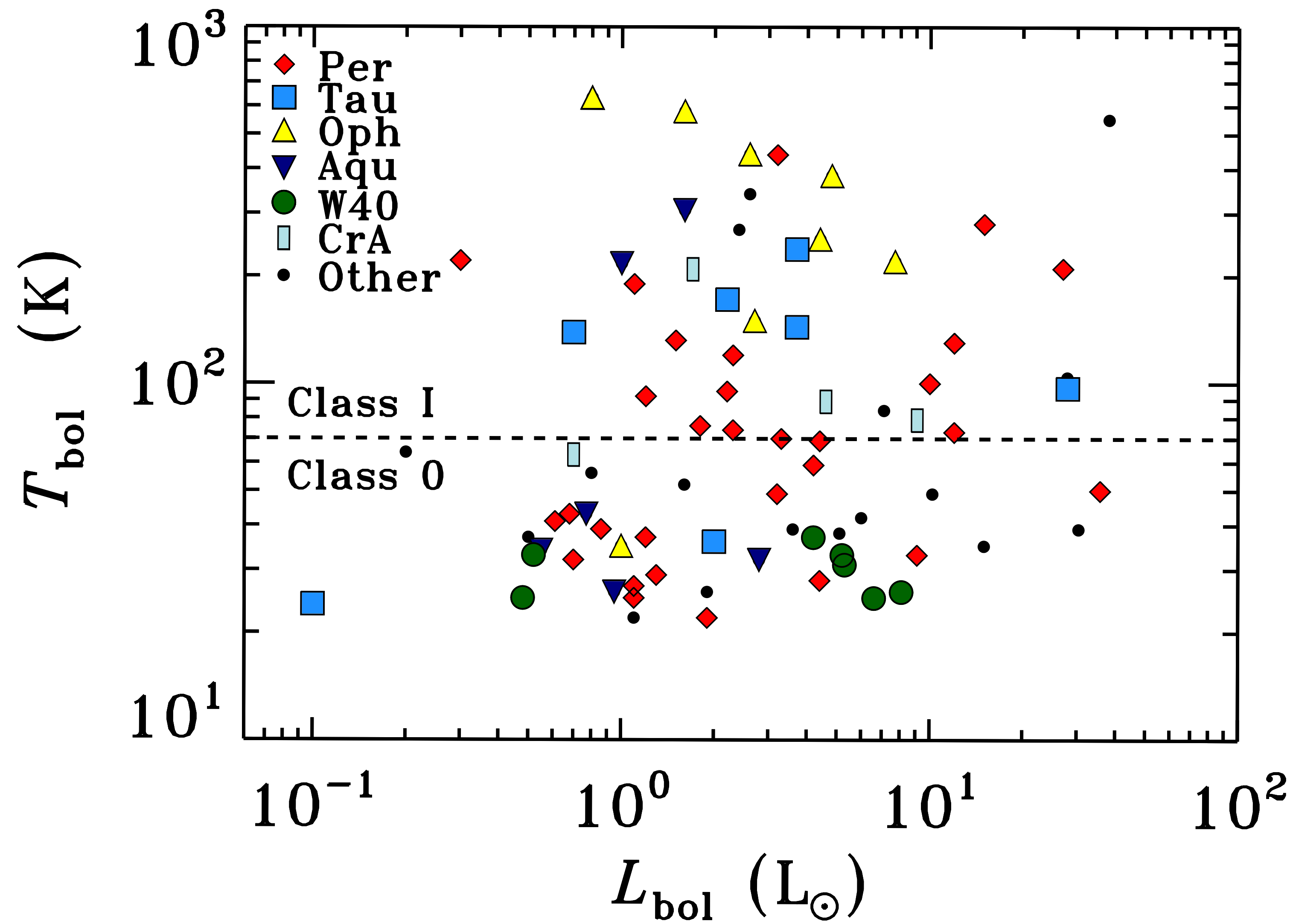
Survey: WISH+DIGIT+WILL

WILL survey:

- additional 50 protostars

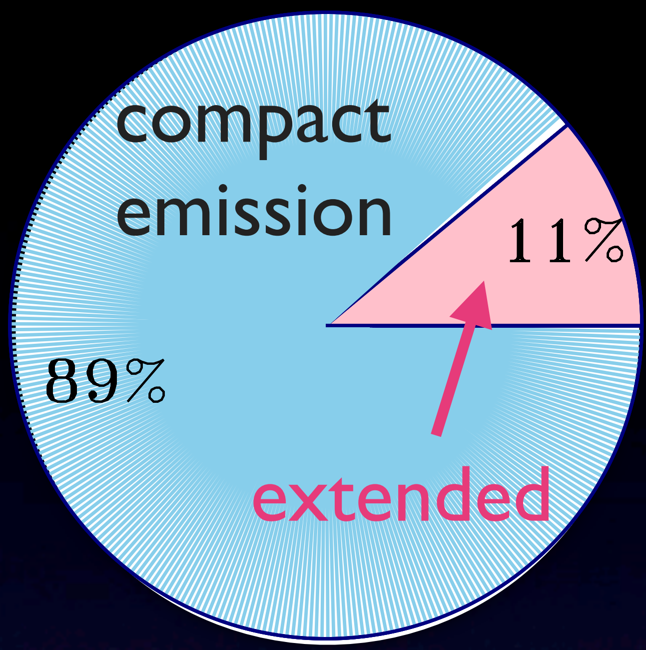
total of ~ 90 sources

full spectra for ~ 30 src (DIGIT/WISH)



- unbiased flux-limited survey of low-mass protostars
- good sampling of $L_{\rm bol}$ - $T_{\rm bol}$ but cloud differences

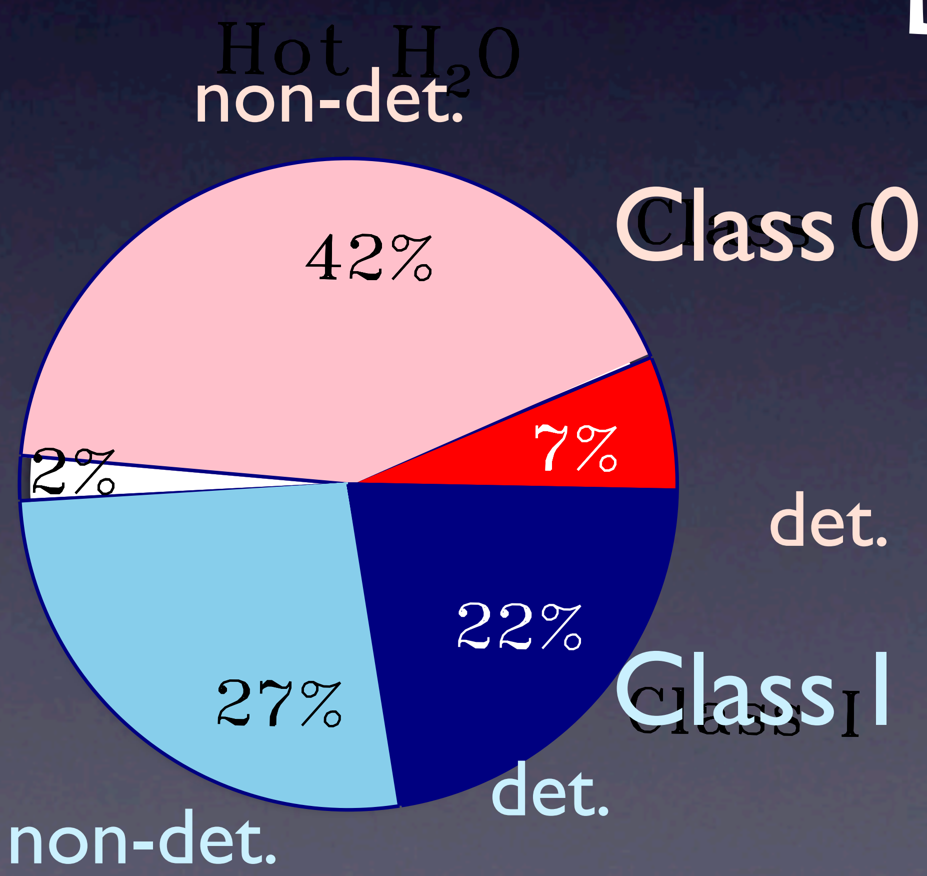
Extent of emission



- much less common than in the WISH survey; mostly seen in Class 0

Detection of hot water

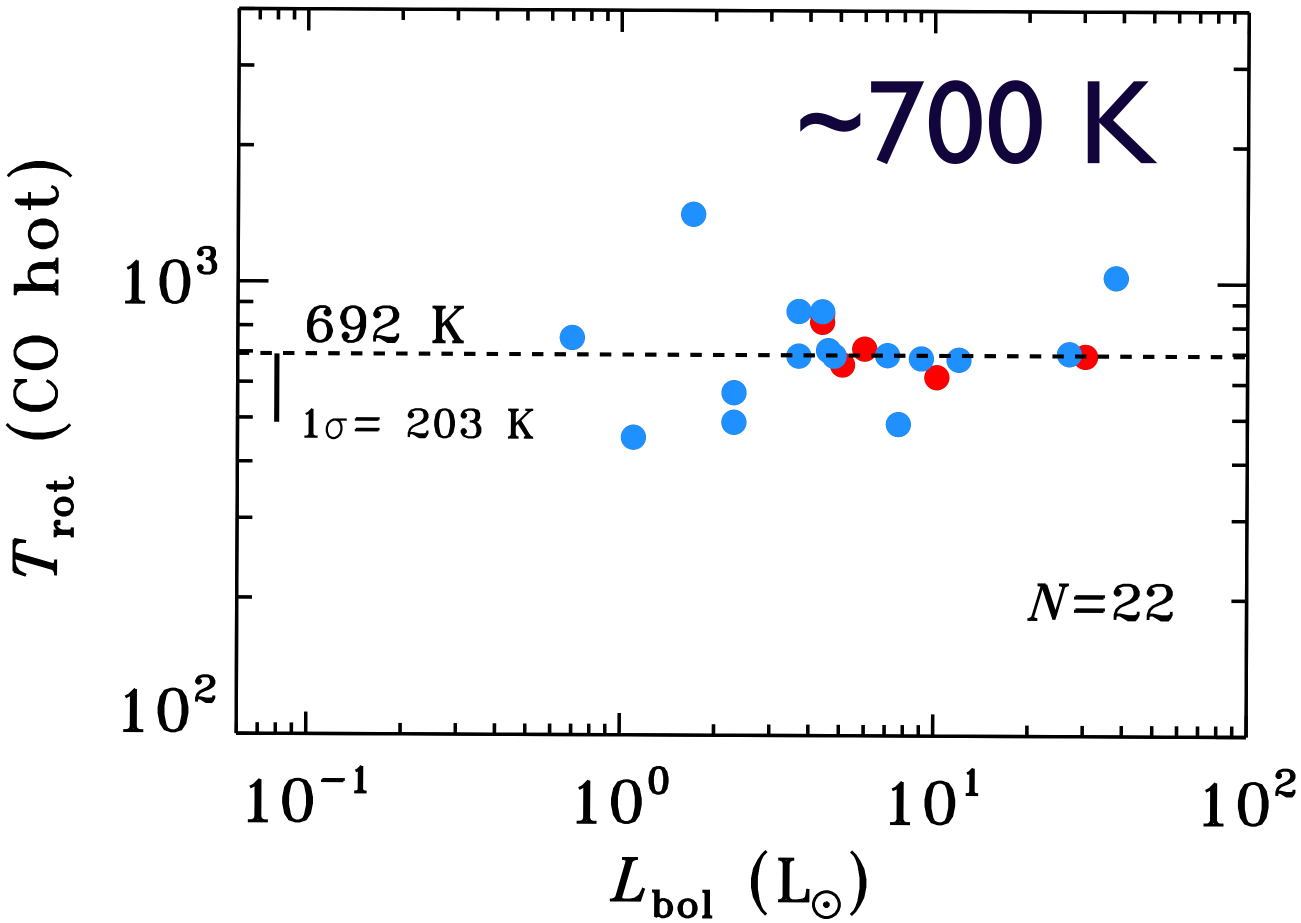
H_2O 8_{18}-7_{07} (E_{up}~1000 K)



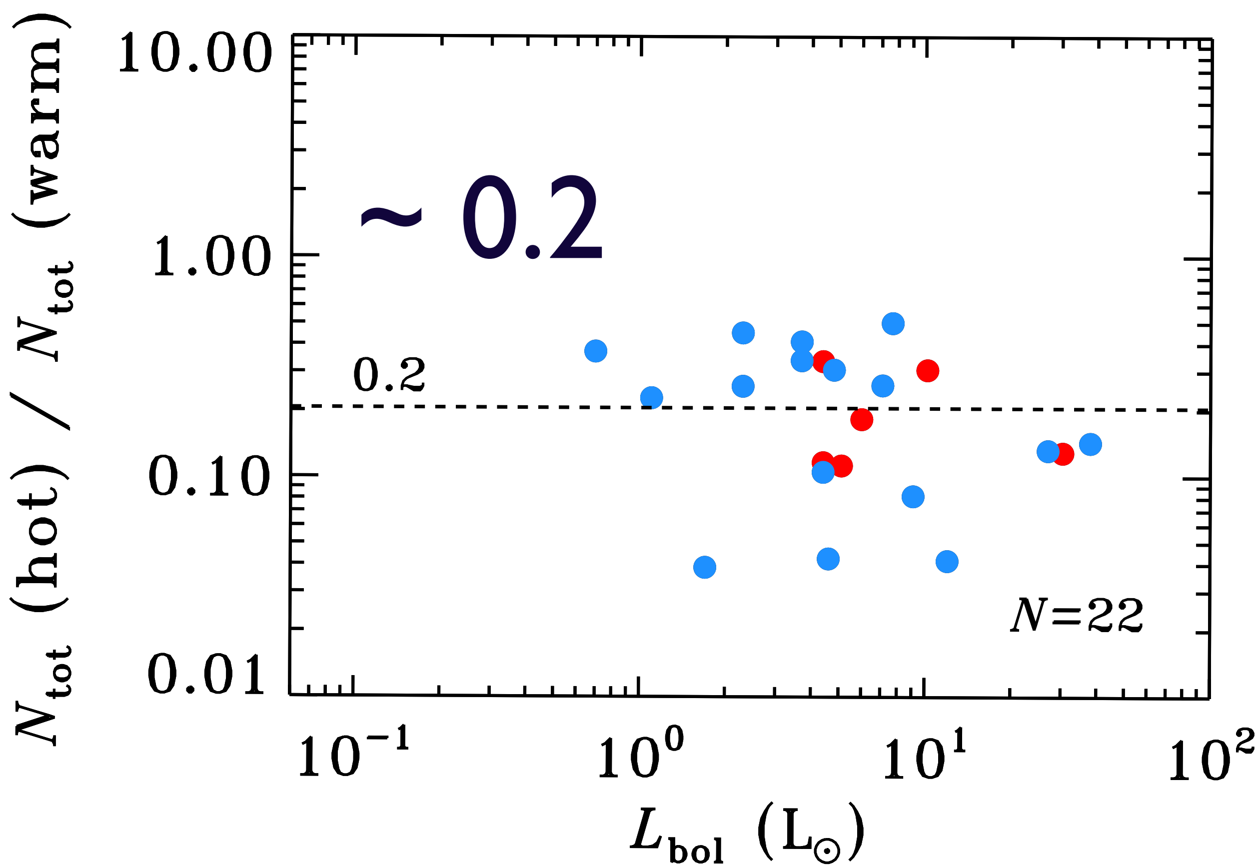
- mostly Class I sources
- seen together with hot CO
- origin in outflow vs. disk

CO diagrams - update

T_{rot} vs. L_{bol}



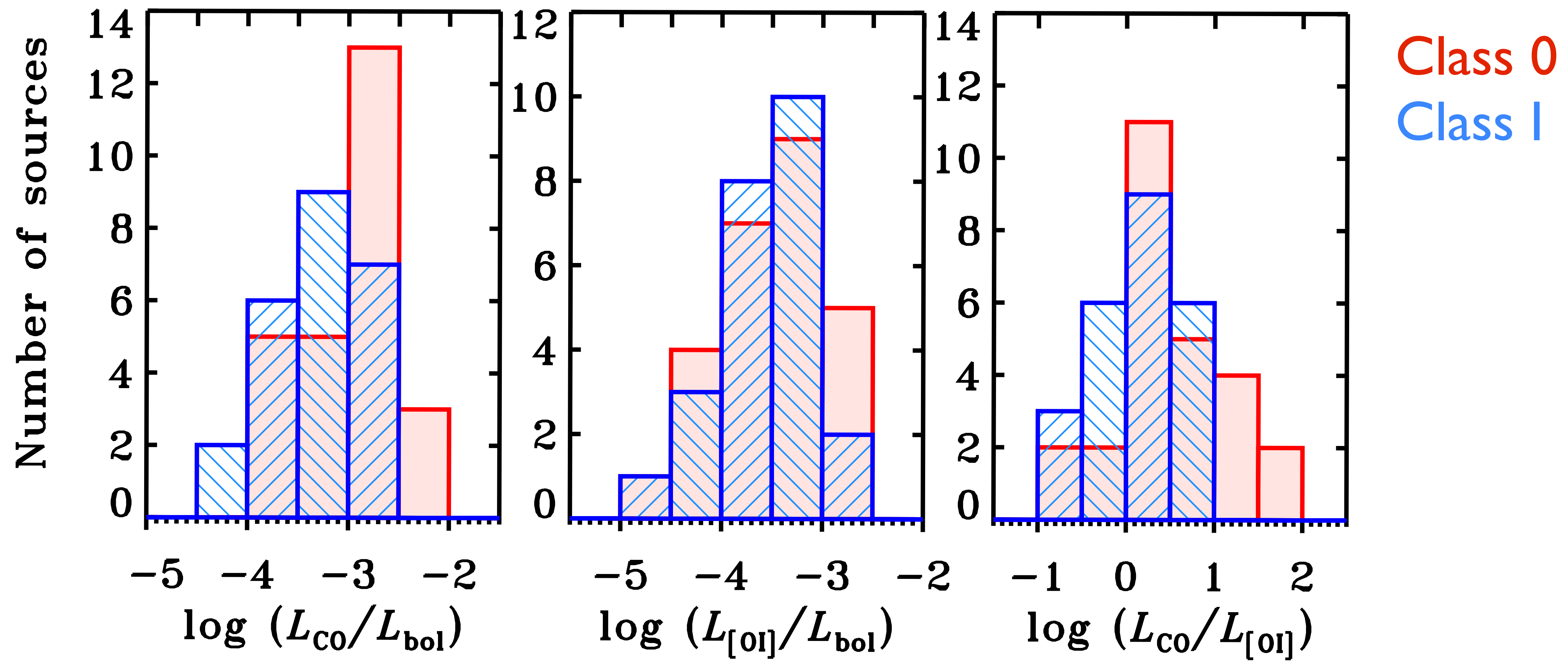
N_{tot} ratios



- CO rotational temperatures of ~ 700 ± 200 K (TBC)
- 20% of emitting molecules are hot

Origin of [OI] emission?

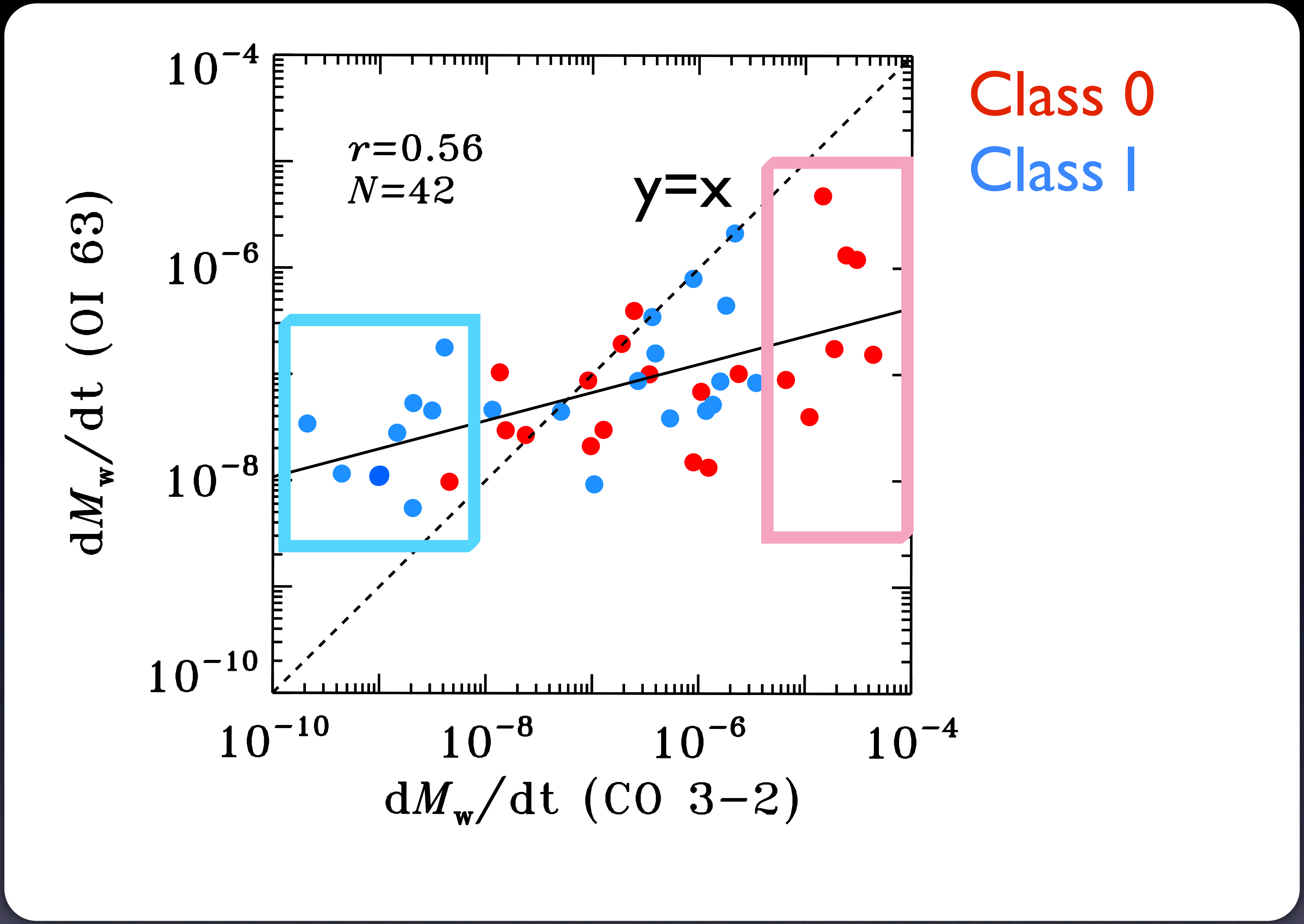
Karska,+ in prep.



- Decrease of molecular emission with evolution
- BUT: integrated [OI] emission very similar for Class 0/I

Mass flux rates

[OI] assumed to trace dissociative shocks



CO 3-2 (Mottram+ prep)

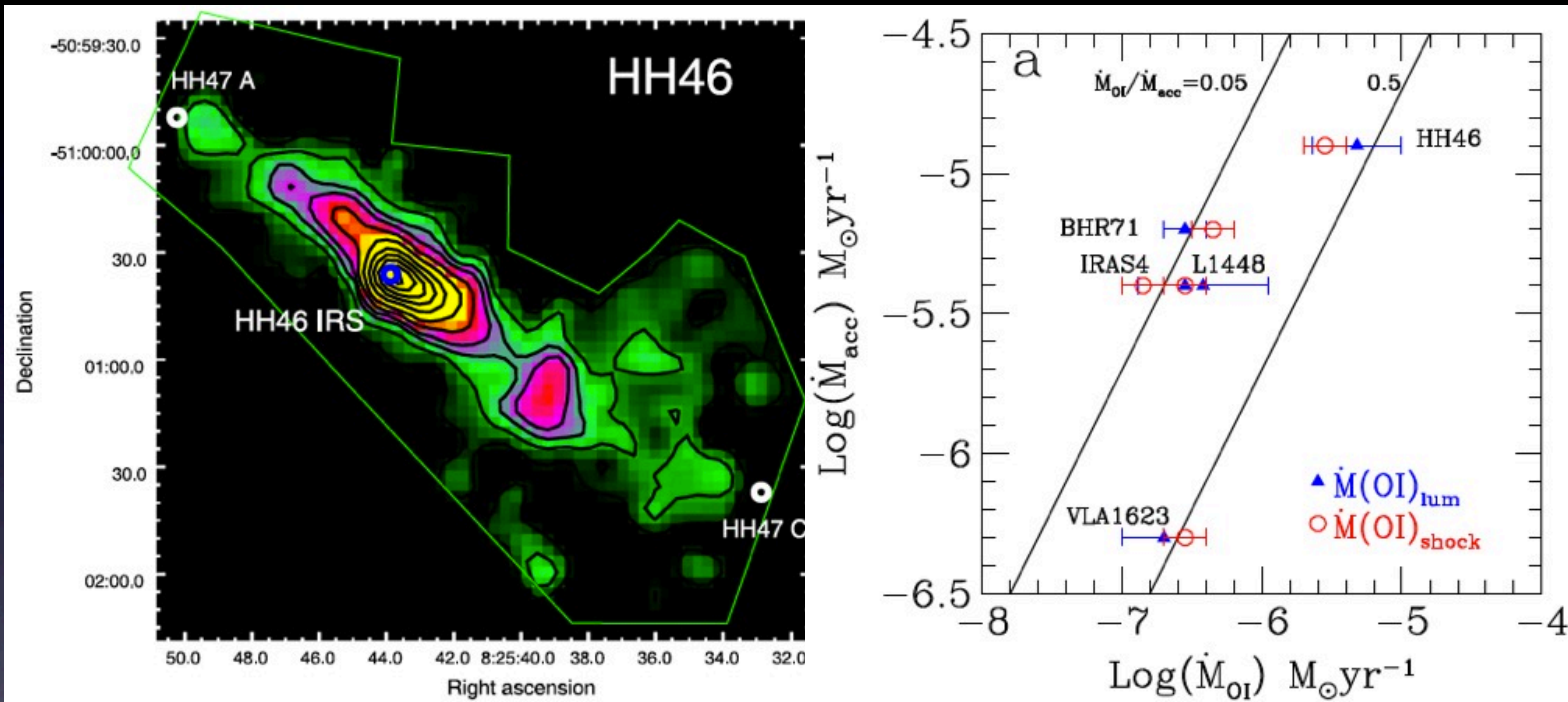
Class 0:

$dM_{CO}/dt > dM_{[OI]}/dt$

- [OI] mass flux rates are of order 10^{-8}-10^{-6} M_{sun}/yr
- possible evolution from molecular to atomic jet
- [OI] not a good tracer of maximum flux rate (cf. Hollenbach 85)

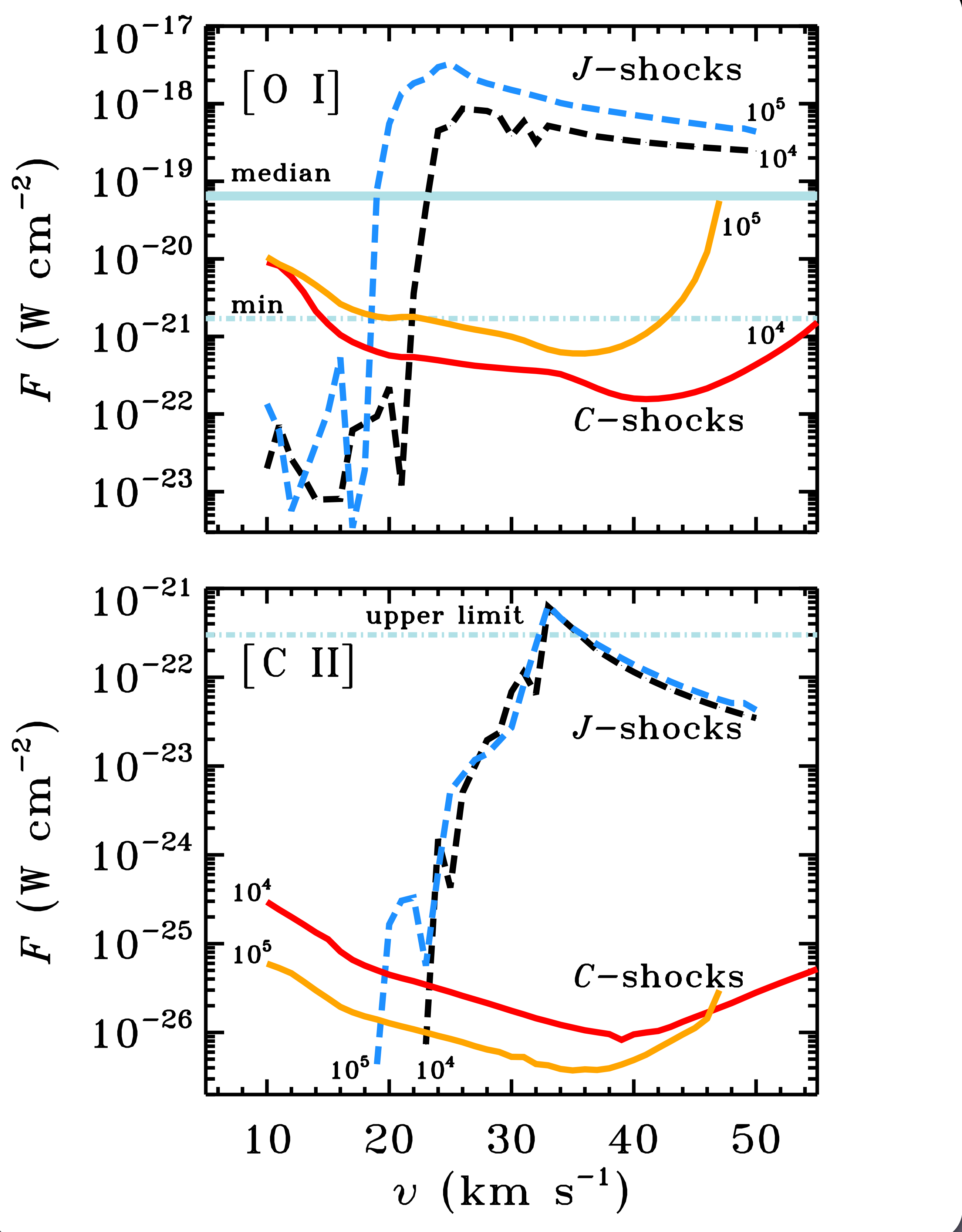
Oxygen maps / PACS

Nisini+15



- mass flux rate from shock models is reliable
- ejection-to-accretion rate of the order of 0.05-0.5

Shocks / absolute intensities



Karska,+ in prep.

- intensities of CO & H_2O governed by *C*-type shocks (not shown)

- *J*-type shocks needed to reproduce [OI]

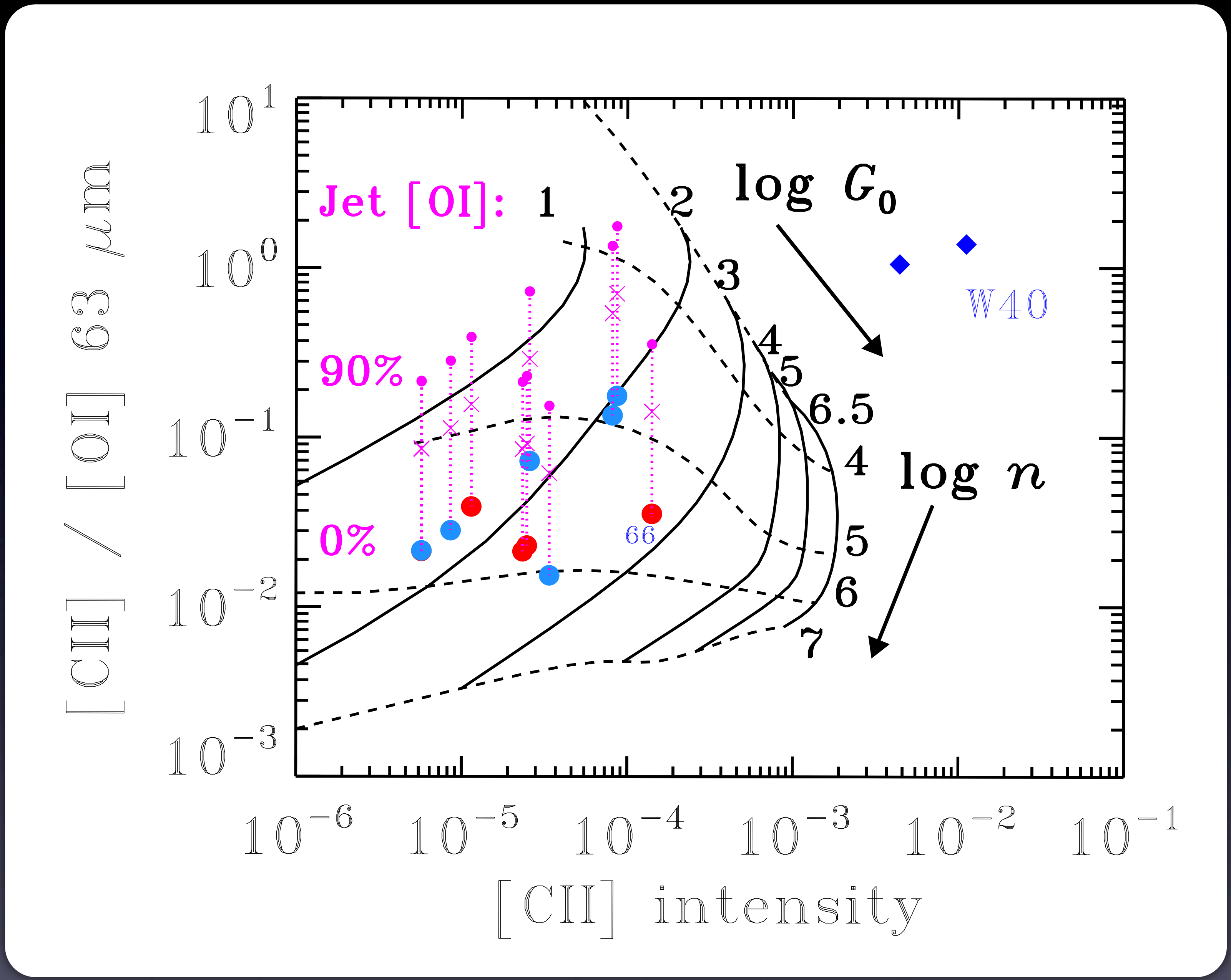
- *J*-type shocks are not sufficient to reproduce [CII]

Need for additional UV!

Comparisons to PDR models

Karska,+ in prep.

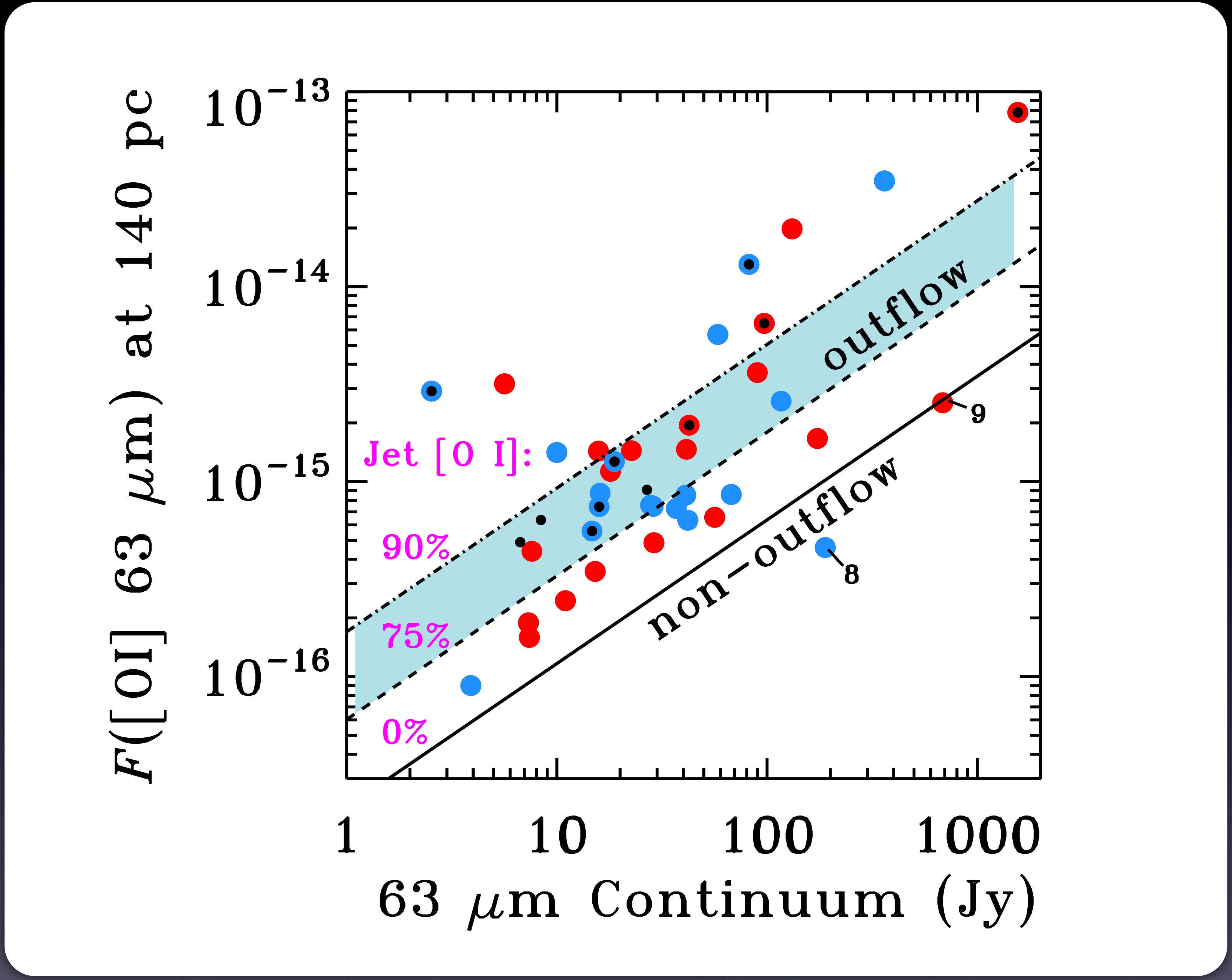
G_o=1.6 10^{-3} erg cm^{-2} s^{-1}



- UV fields of ~10-100 G_o and densities n~10^4-10^5 cm^{-3}
- low densities suggest the origin in outflow cavities

[OI]: disk vs. jet

Karska,+ in prep.



relations from Howard+2013

- Minor contribution of the disk to [OI] emission

Conclusions

- good statistics on hot CO, H_2O, extended emission but does not answer all questions

- first use of C+, comparisons to PDR models require understudying of the oxygen story

- part of O clearly traces hidden atomic jet but not all, evolution from molecular to atomic jet

- molecular cooling decreases with time, but not the O cooling

- we really need to treat UV+shocks together and not as separate phenomena