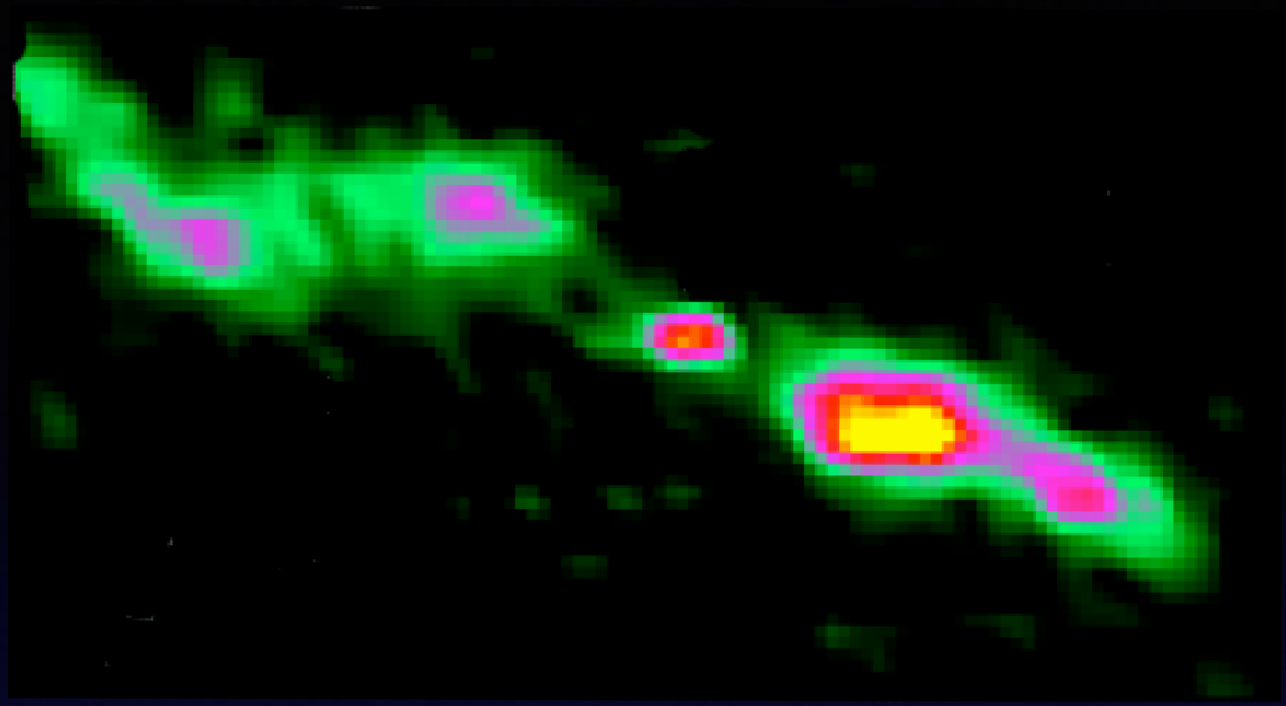


Water fountains from protostars - the signposts of FUV illuminated shocked gas

Agata Karska

Adam Mickiewicz University, Poznan, Poland

Collaboration

E. van Dishoeck
M. Kaufman
L. Kristensen
G. Herczeg
J. Mottram
J. Lindberg
J. Green
N. Evans
L. Tychoniec

+ WISH, WILL & DIGIT teams

“Water in star forming regions with Herschel”

PI: Ewine van Dishoeck

(van Dishoeck+2011)

“Dust, Ice, and Gas in Time”

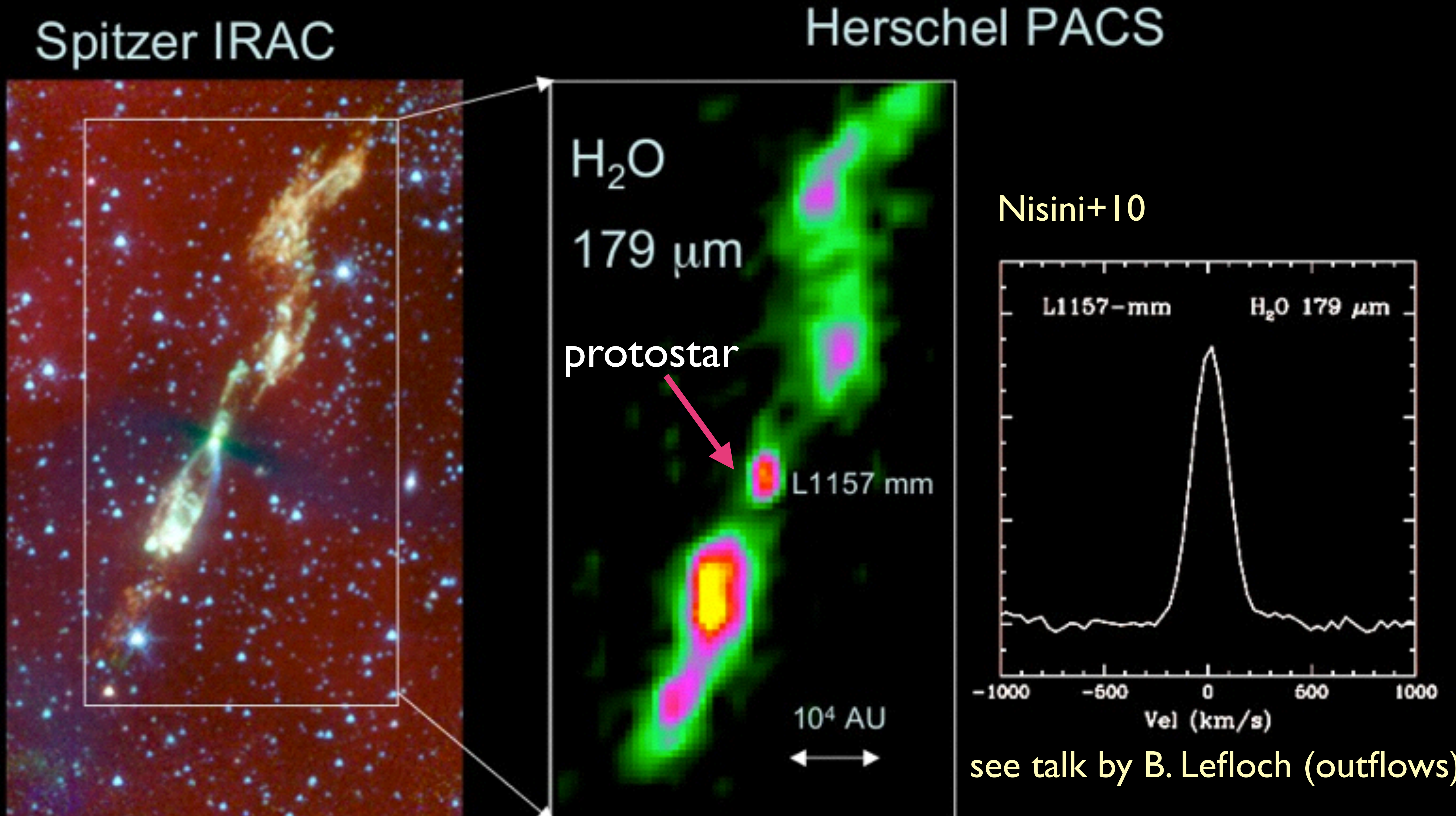
PI: Neal Evans II

(Green+2013)

“Water in low-mass protostars: the William Herschel Line Legacy”

PI: E. van Dishoeck (Mottram, subm)

Water in low-mass protostars

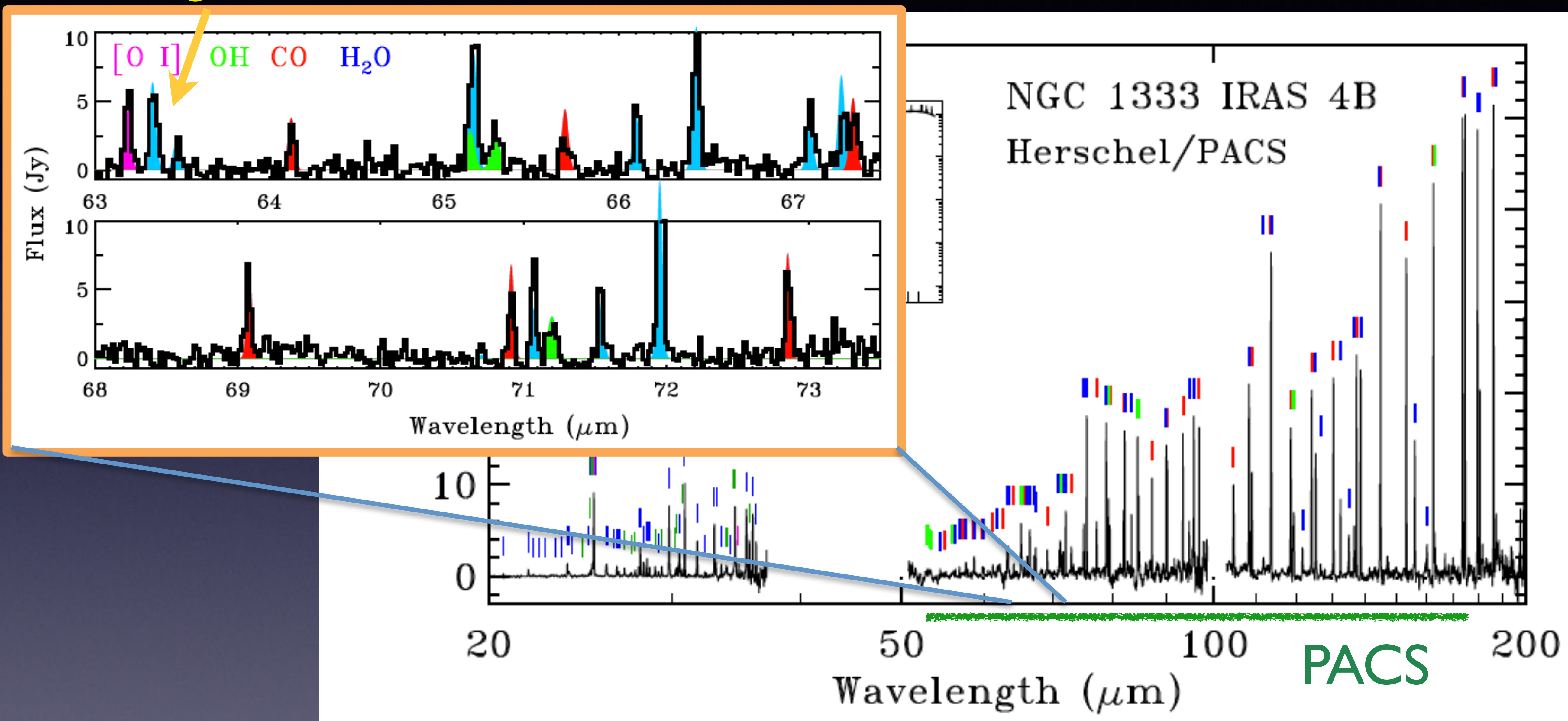


Water traces 'hot spots' in the outflows and central regions where jet and winds interact with the surrounding medium

Far-IR line emission

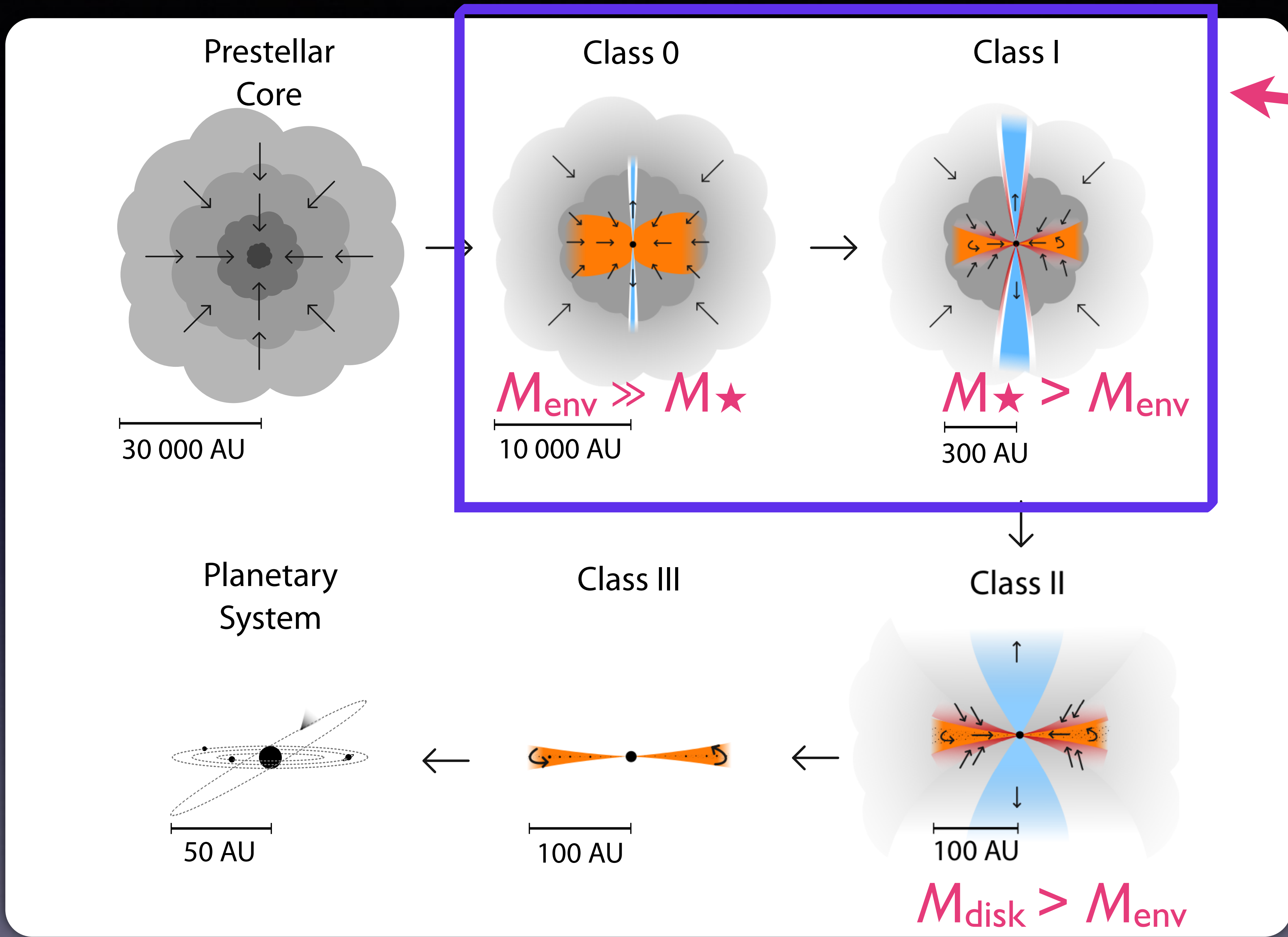
booming H_2O 8_{18}-7_{07} (E_{up}~1000 K)

Herczeg, Karska+12



Detections of CO J_{up}=14-49 and highly excited H_2O as well as [O I] and weak [CII]

Deeply-embedded protostars



deeply embedded stage

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

Fig. M. Persson

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

Motivation

1. What are the physical conditions of the gas where water is excited?

2. What is the role of water in the gas cooling budget? Evolution Class 0/I ?

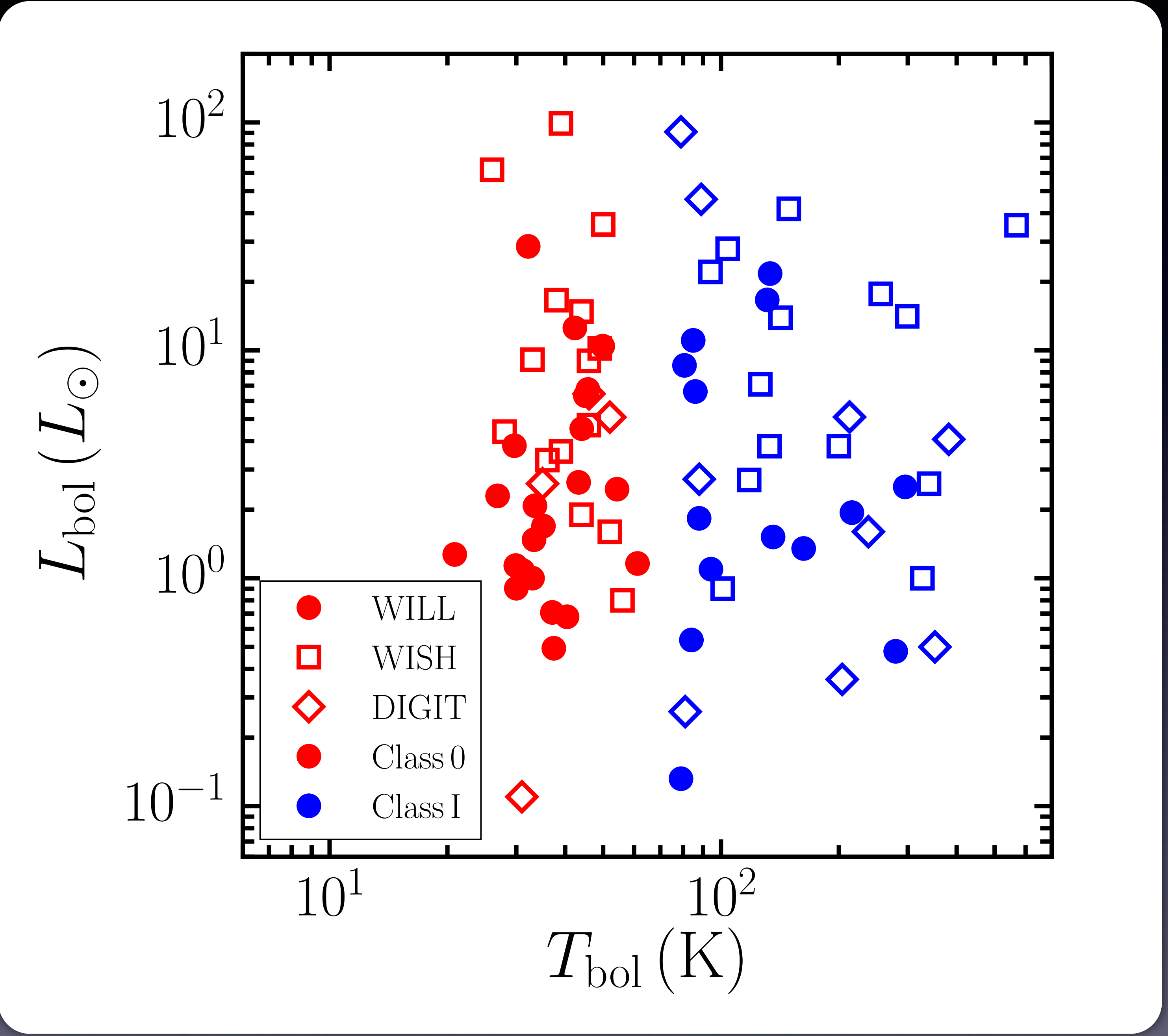
3. Which physical processes are responsible for the water emission?

Protostars with *Herschel*

WISH:
Kristensen+12,
Karska+13, prep.

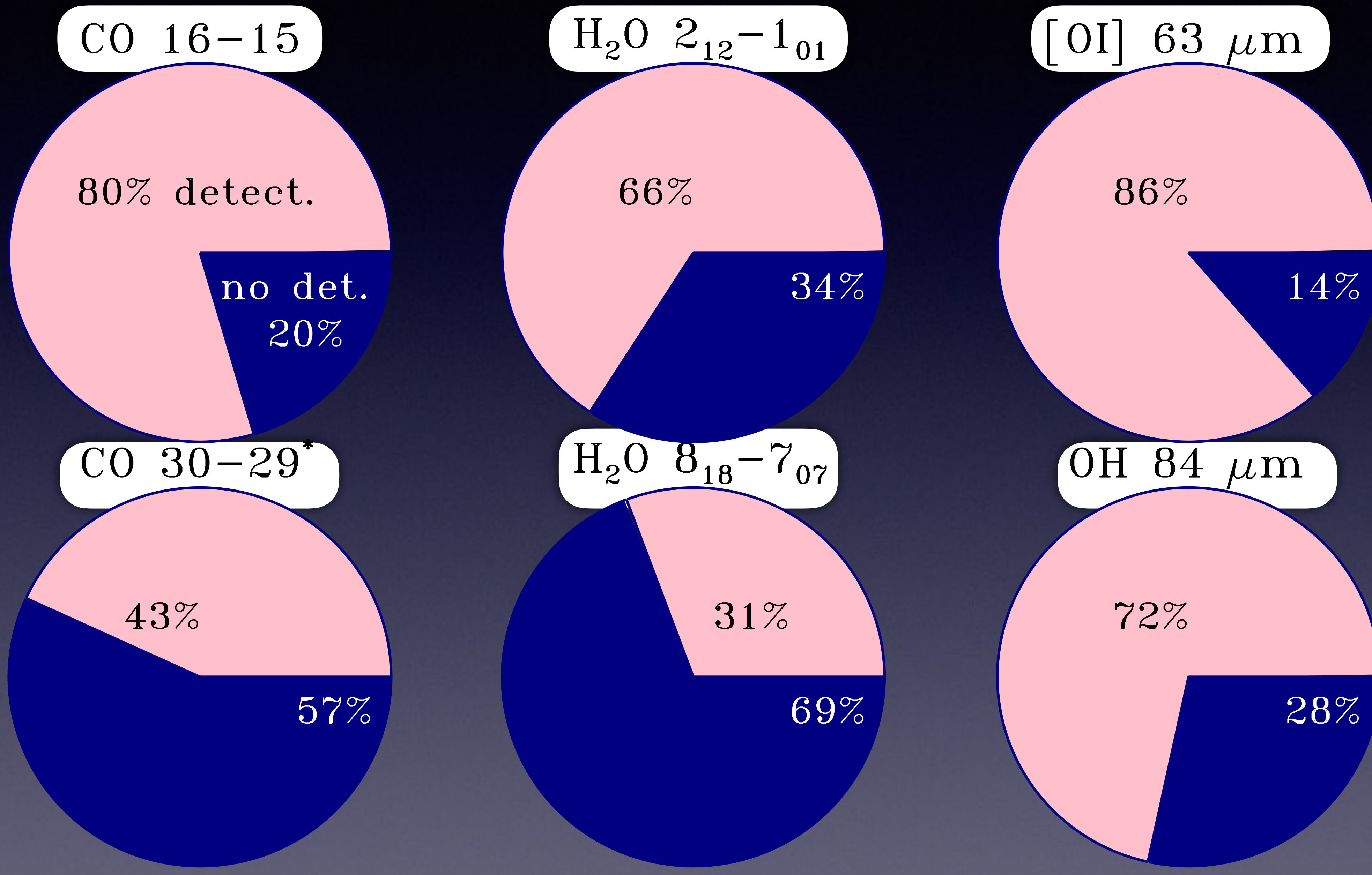
WILL:
Mottram, subm.

DIGIT:
Green+13



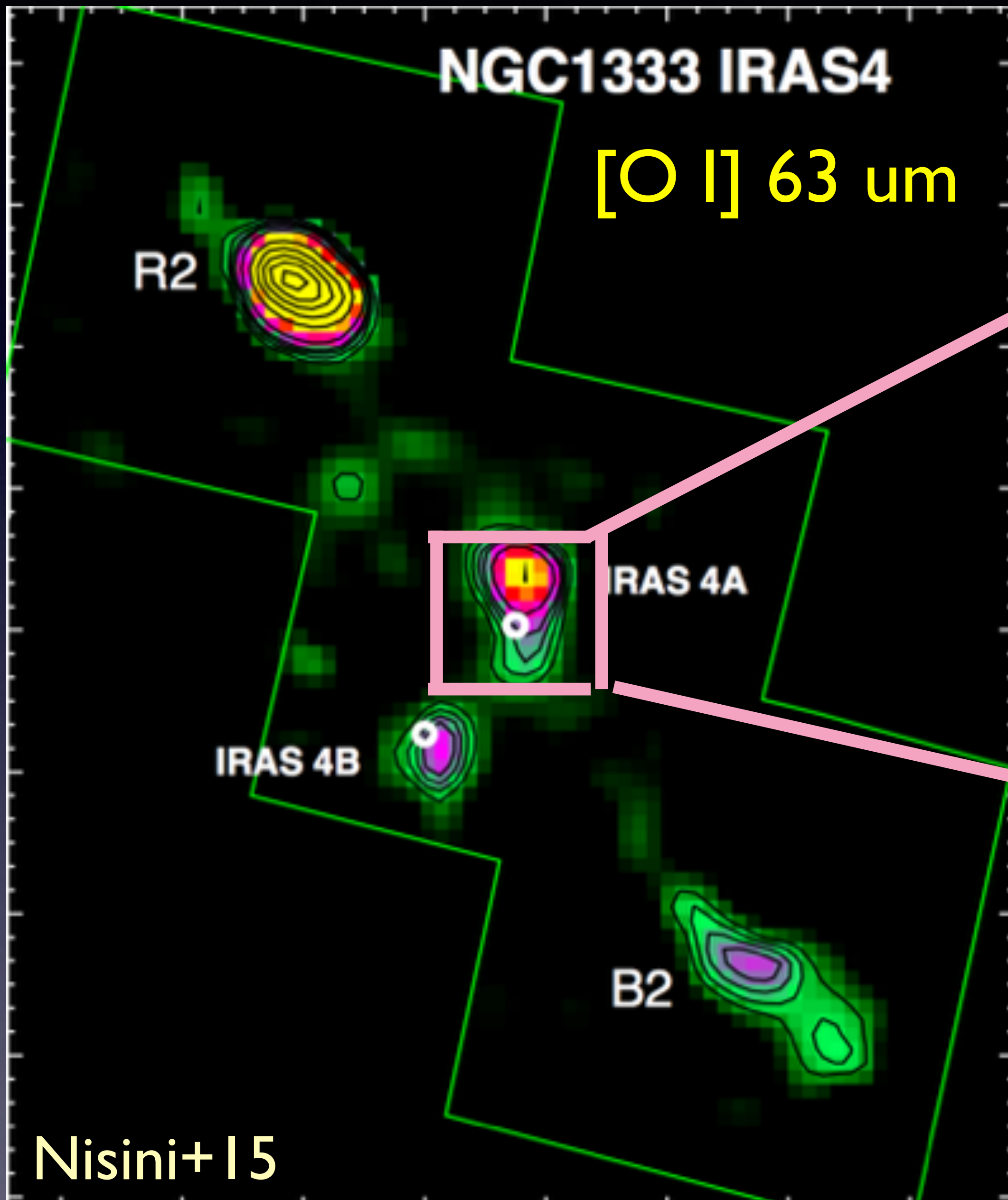
- flux-limited survey of 90 Class 0/I protostars, d < 500 pc
- good sampling of L_{bol} - T_{bol}

Far-IR line detections

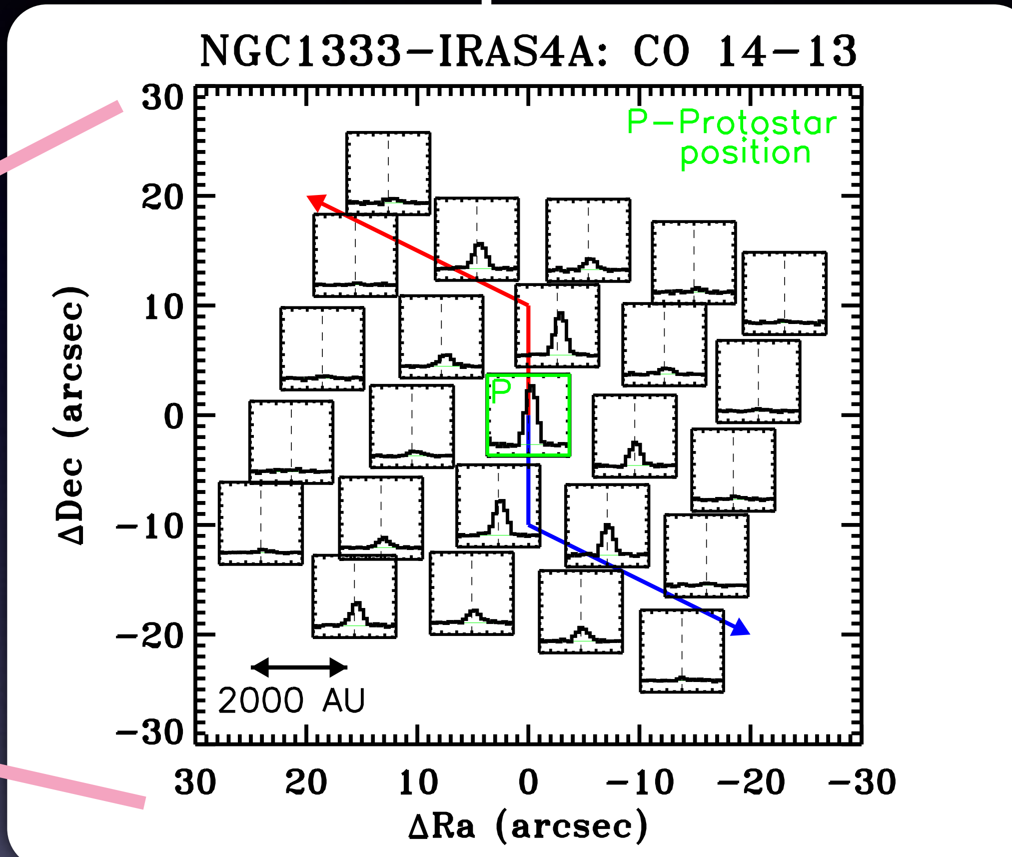


- CO, H_2O, OH, [O I] detected in > 70% of protostars
- very highly-excited lines of CO and H_2O in 30-40 %

Spatial extent of emission



PACS footprint

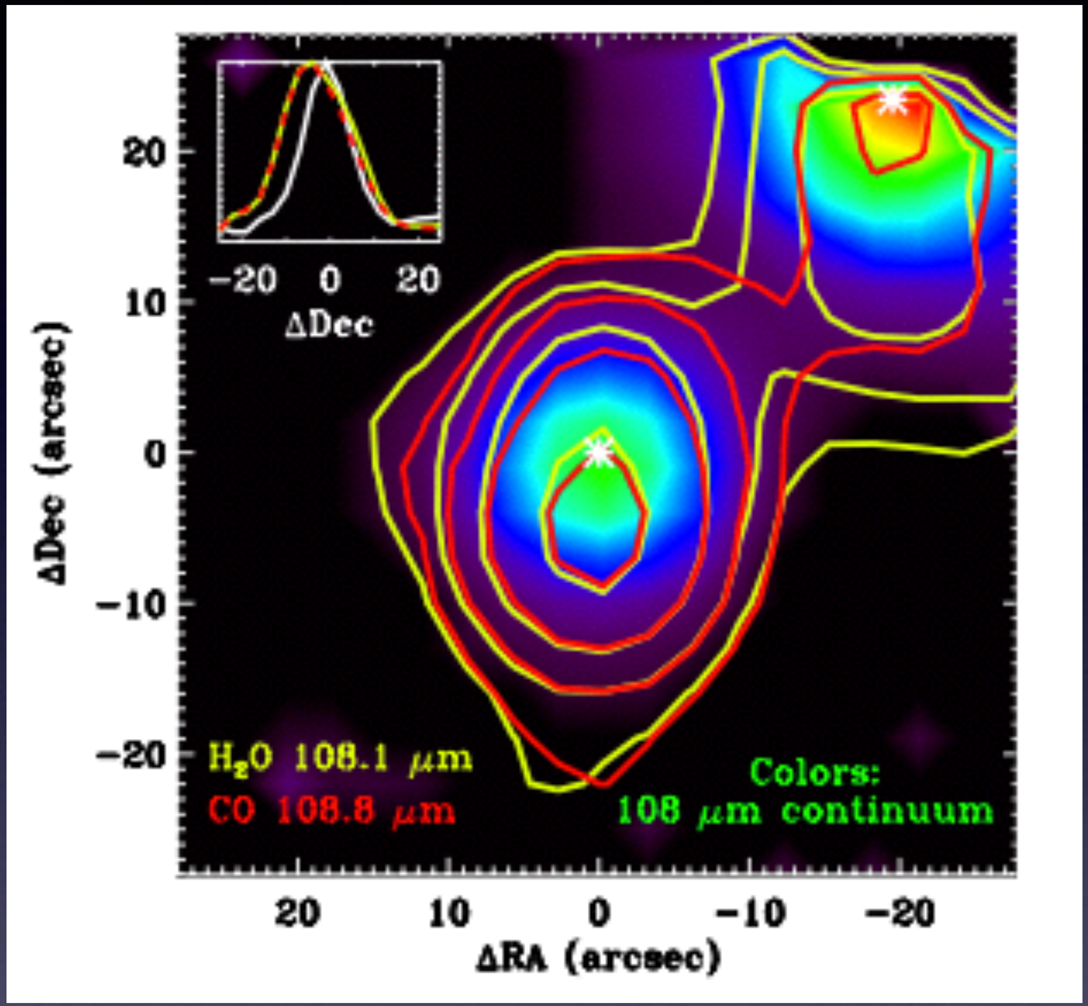


Karska+13

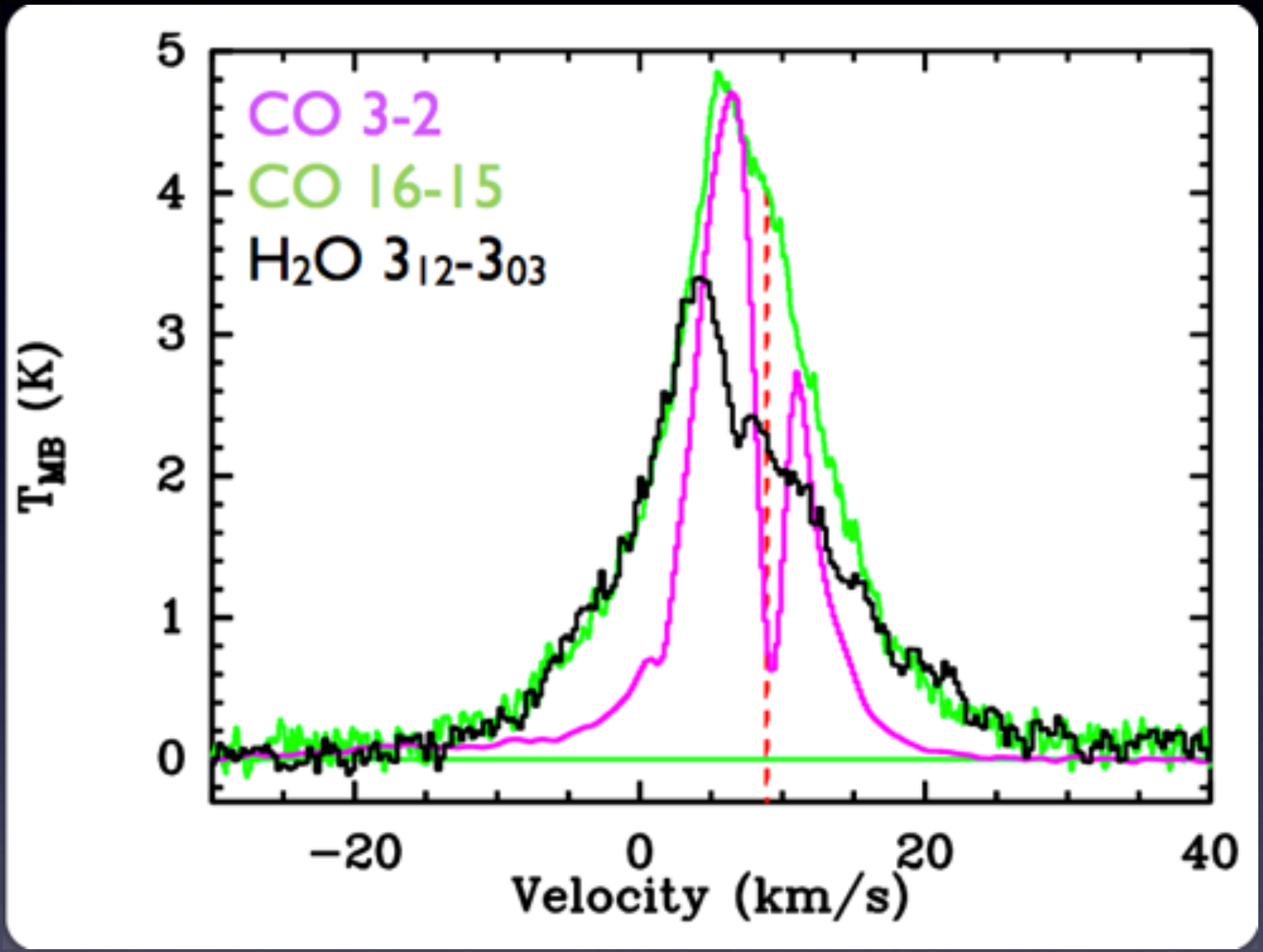
FOV ~ 50 x 50 arc sec
Spatial scales ~ 10^3 - 10^4 AU

- molecular emission generally compact at 10^3-10^4 AU scales
- atomic emission extending along the outflow direction

Link between high-*J* CO and H_2O



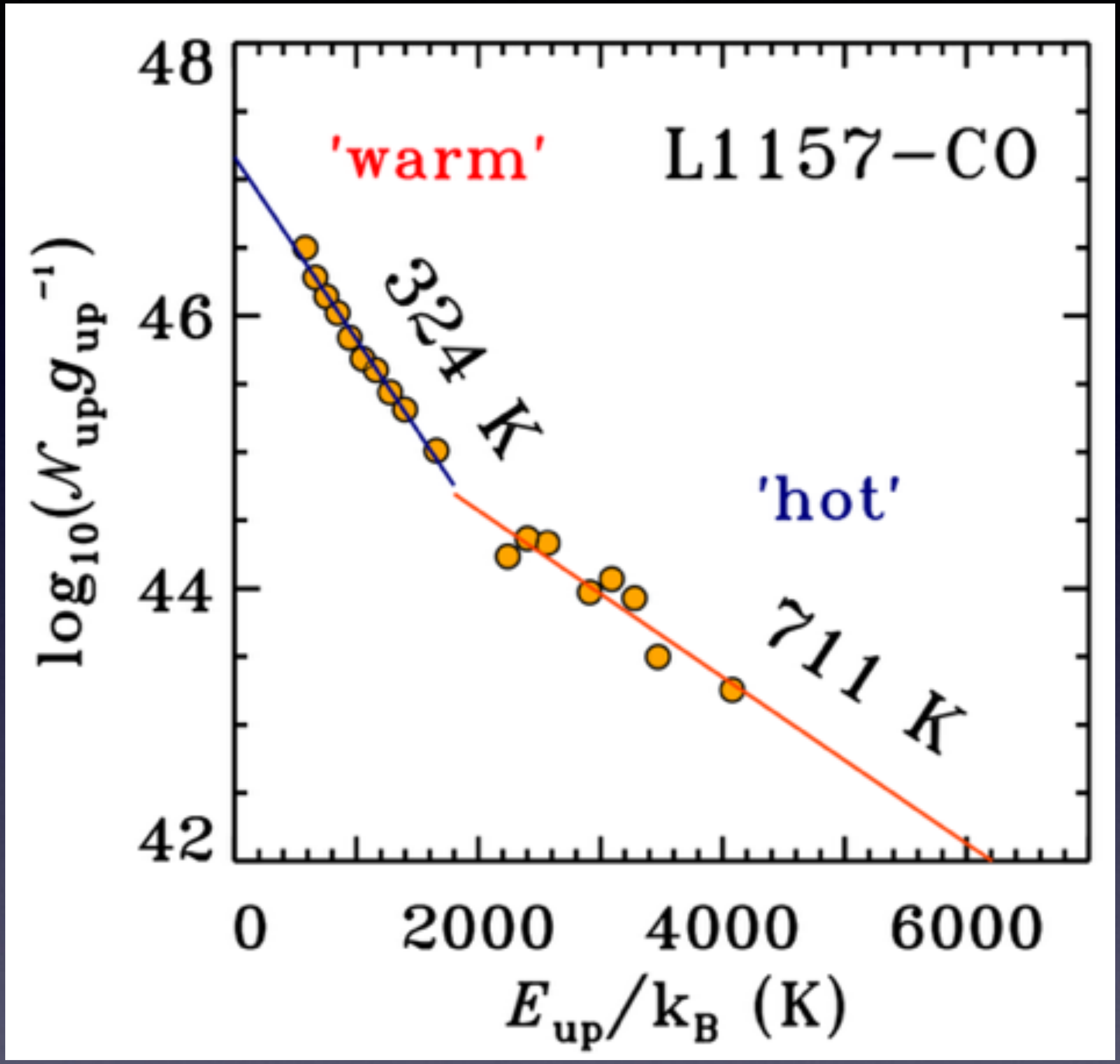
Herczeg+12, Karska+13, Lindberg+14



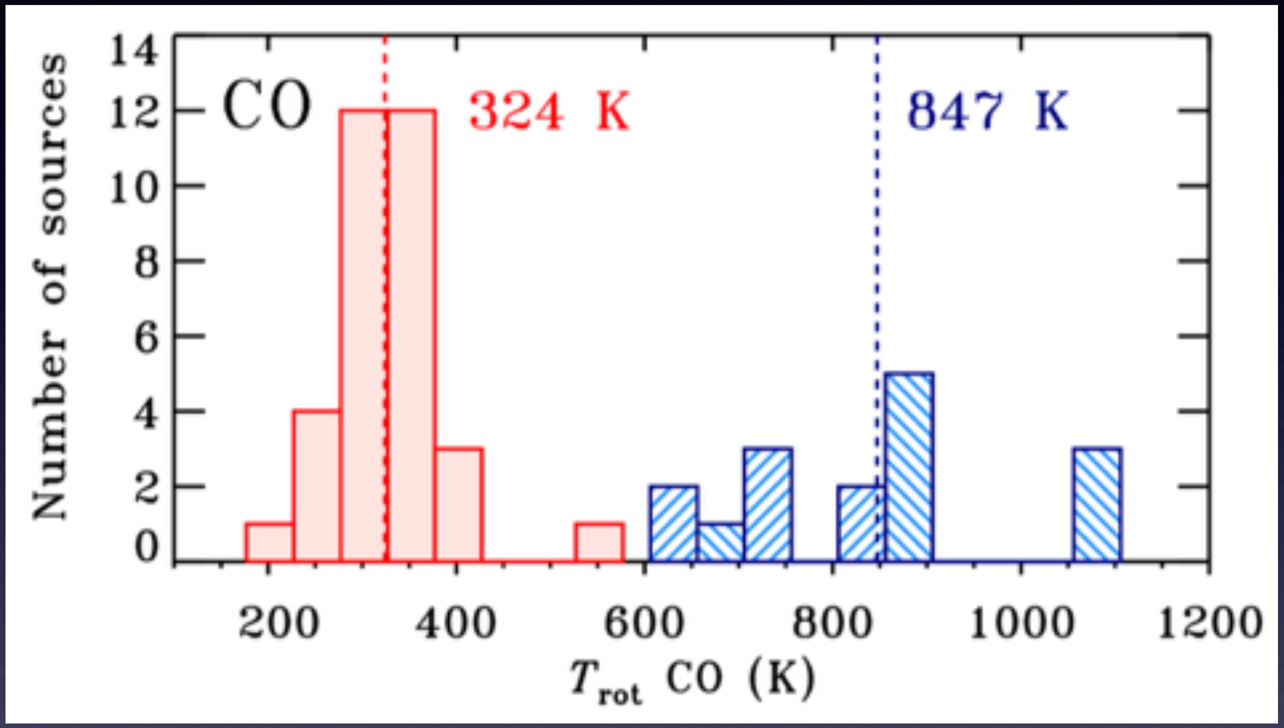
Kristensen+ in prep., 12, Mottram+14
see talk by L. Kristensen

- H_2O and high-*J* CO co-spatial but different from [O I] and low-*J* CO
- similarity of the velocity-resolved profiles (HIFI)

Molecular excitation: CO



Goicoechea+12, Herczeg+12, Manoj+13, Karska +13, Green+13, Dionatos+13, Je+15, Lee+15 …

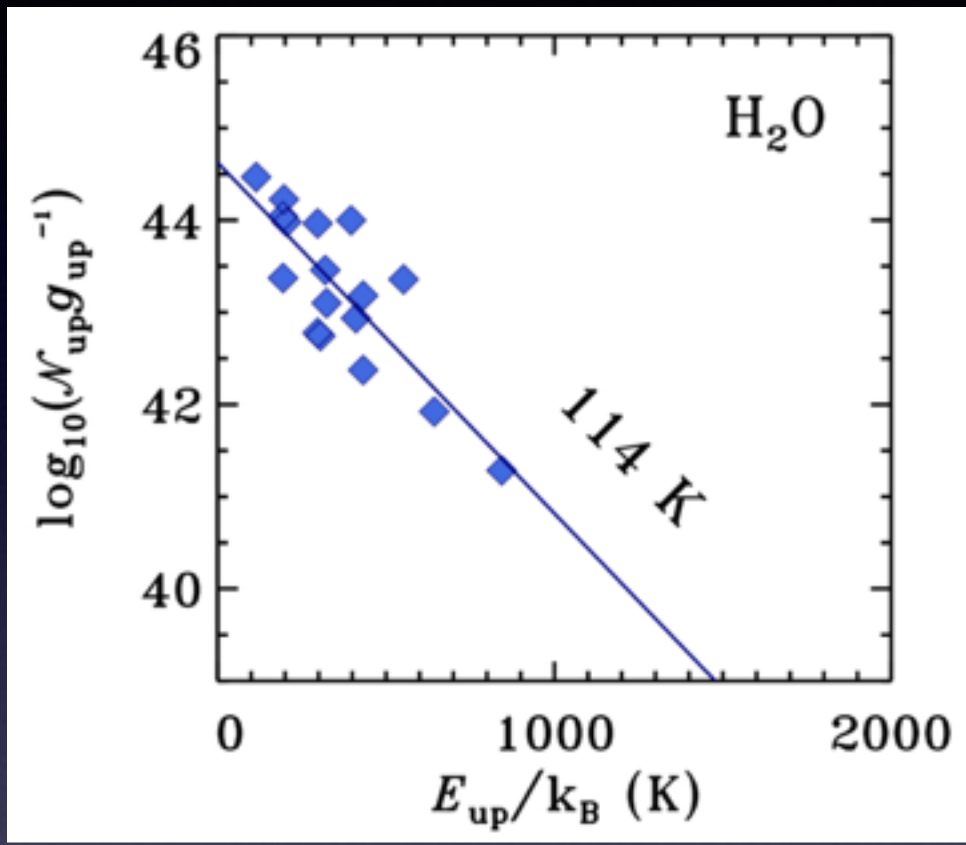


Karska+ in prep., see also Manoj+13 for Orion

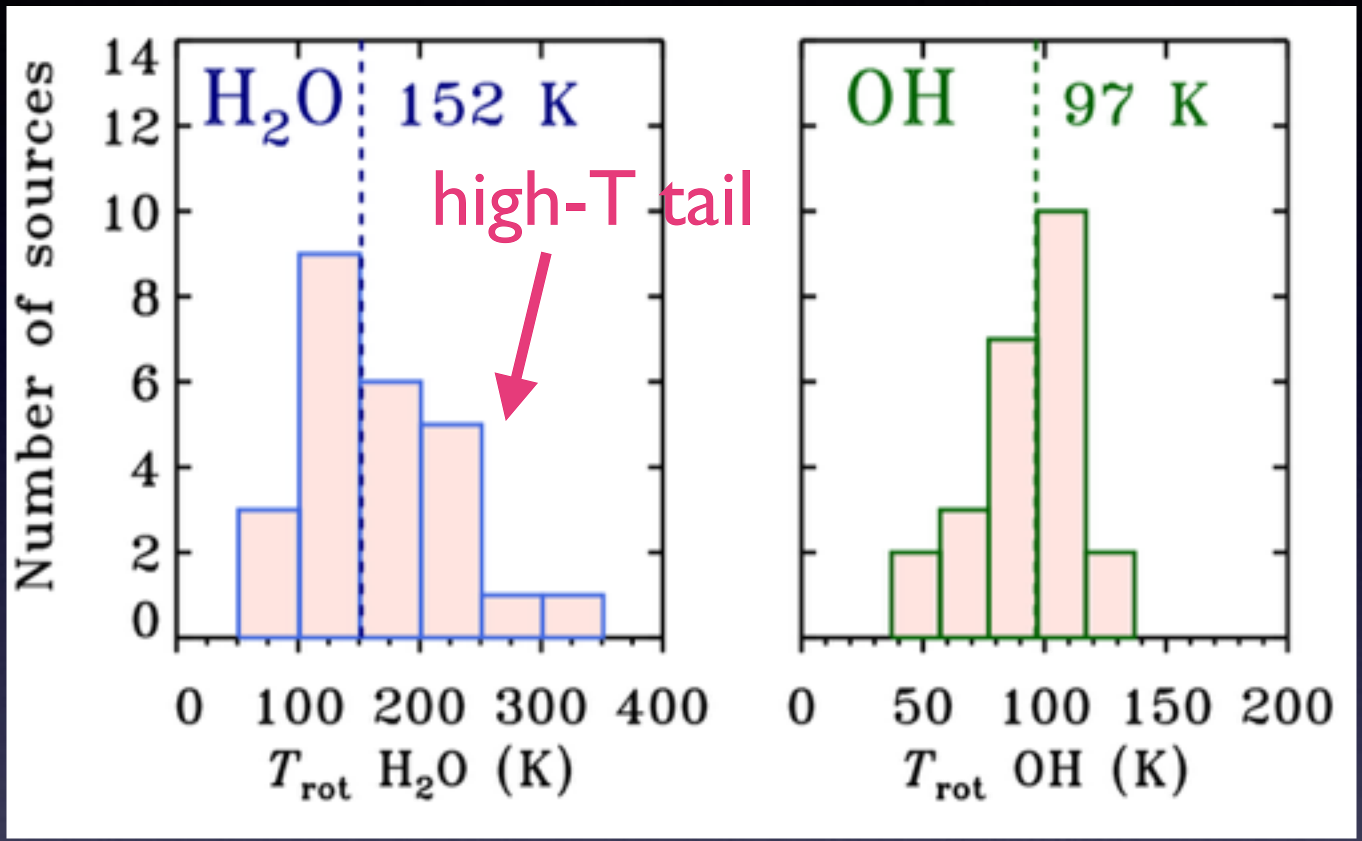
- Universal CO T_{rot}~ 300 K ('warm component')
- Less frequent 'hot component' with median T_{rot}~ 900 K

Molecular excitation: H_2O & OH

L1157



Karska in prep., Green+13



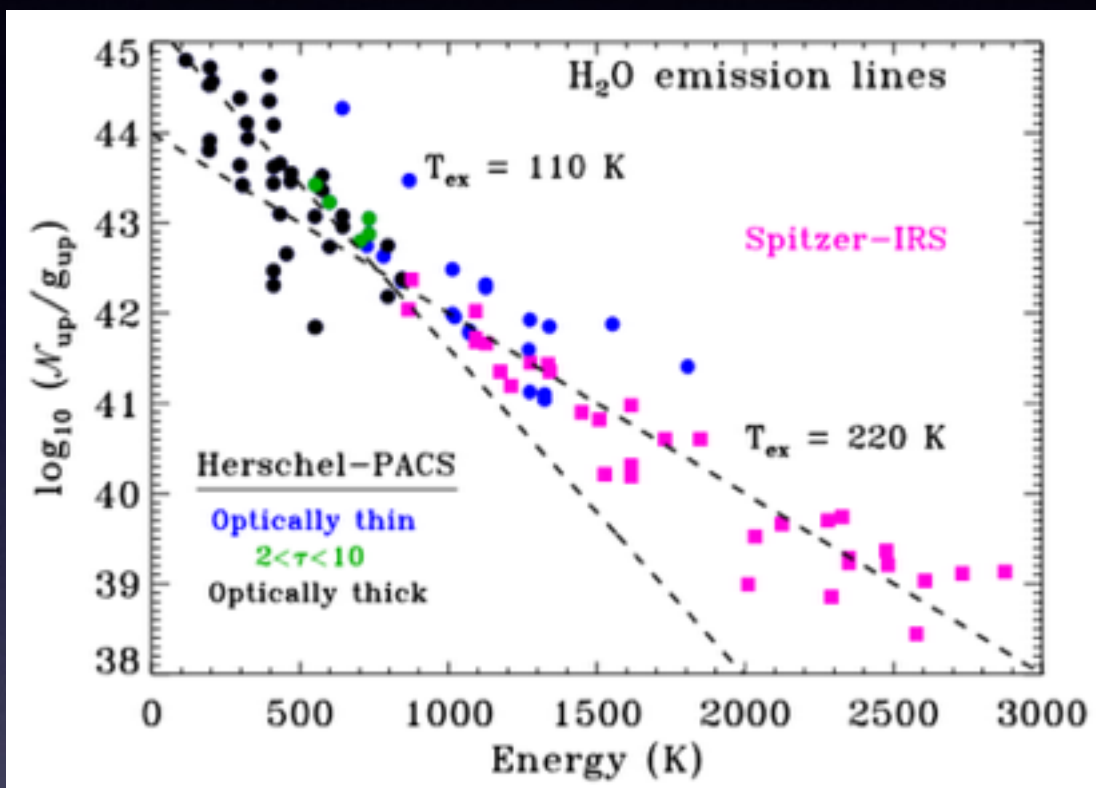
OH: Wampfler+13, Lee+14

- Typically 1 components at H_2O and OH diagrams at ~150 K and ~ 100 K, but large scatter

- Some show a hot component at H_2O diagrams

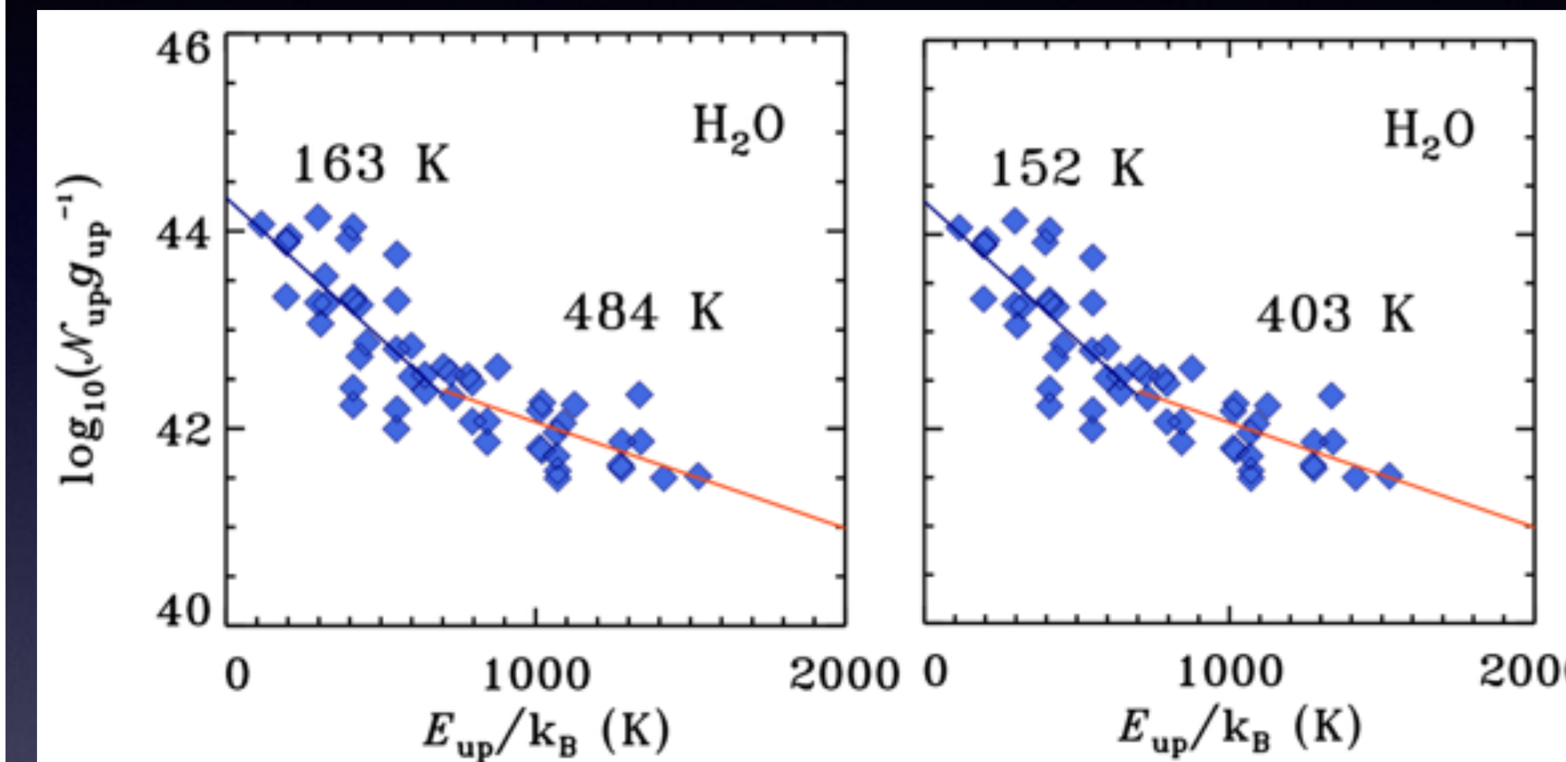
Hot water component

NGC1333 IRAS4B (Perseus)



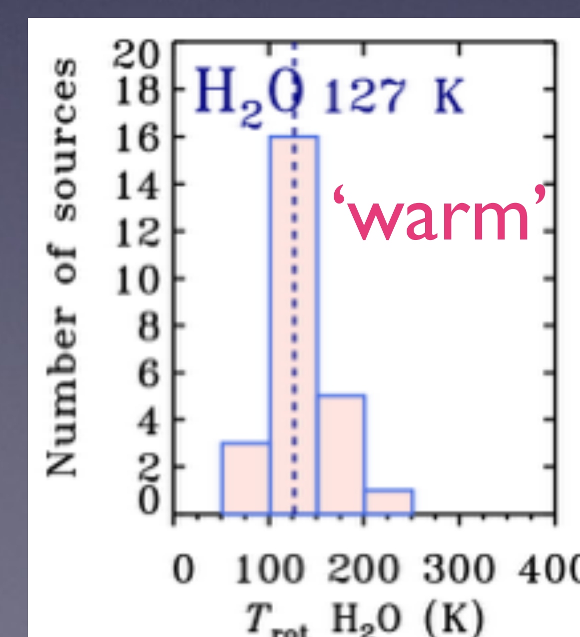
Herczeg+12

Elias 29 (Oph) GSS30 IRS1 (Oph)



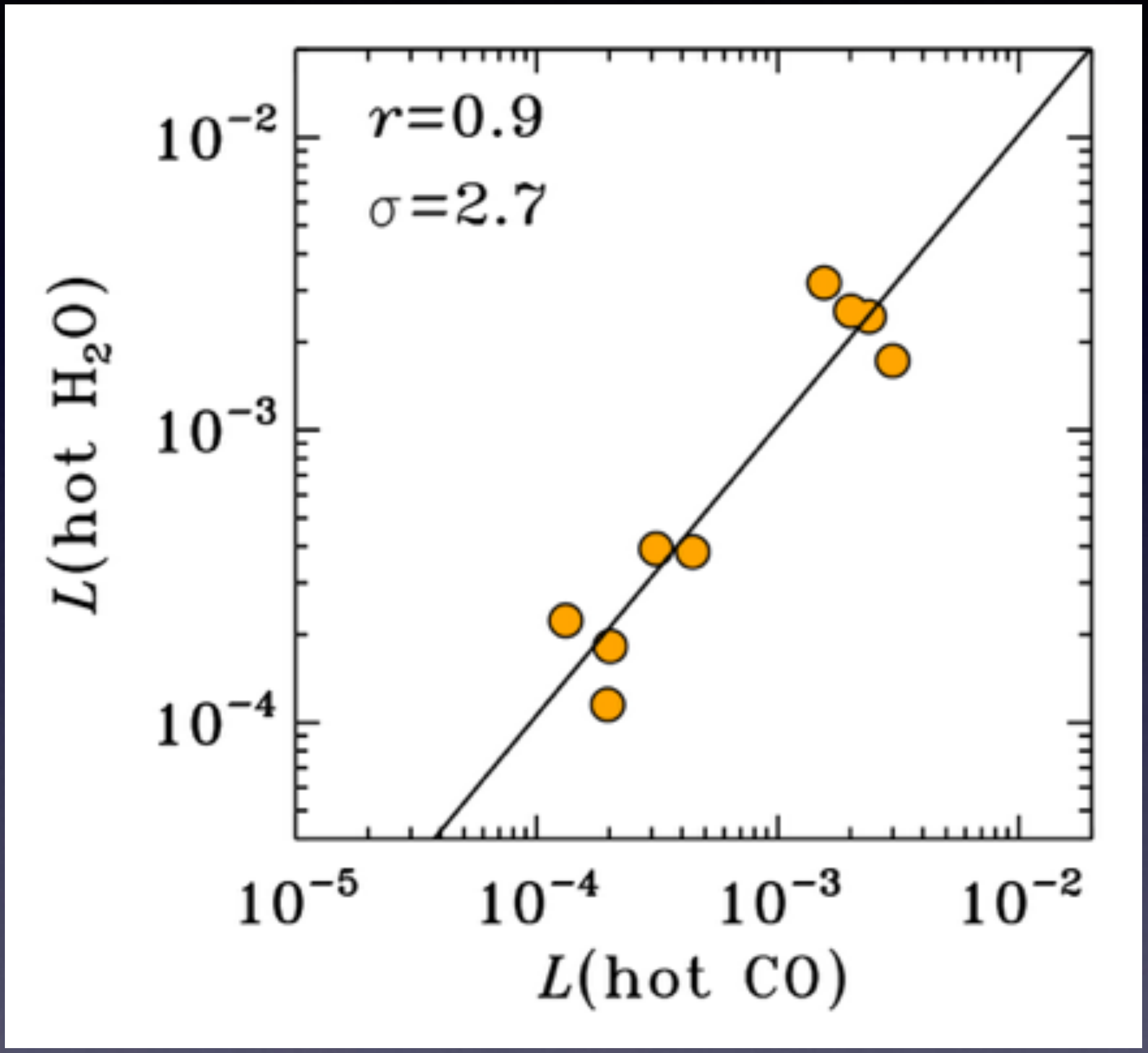
Green +13 H. Je, J-E. Lee, S. Lee+15

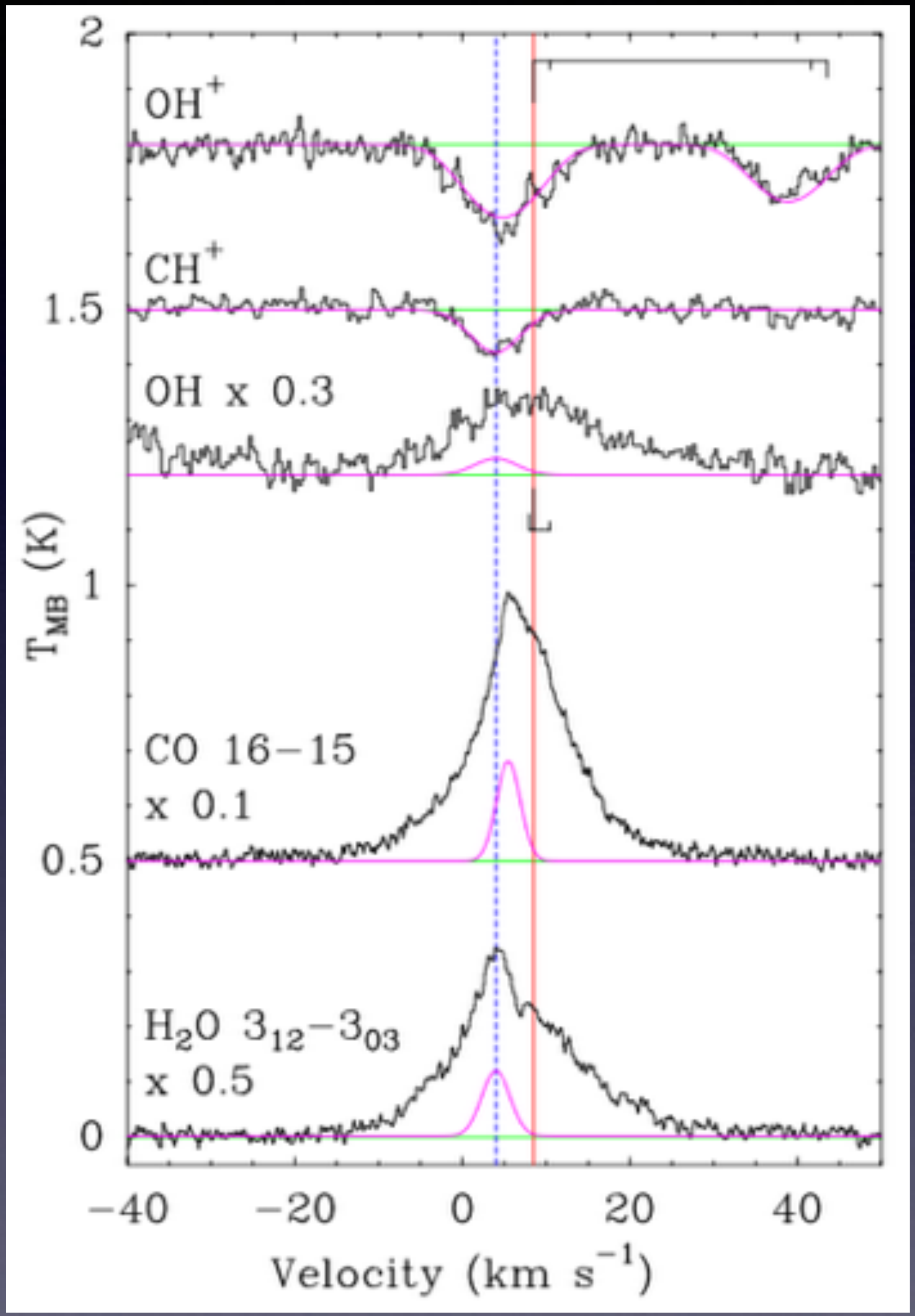
- Clear detection in 10 sources: T_{rot2} ~ 200-500 K
- Corrected histogram for the warm component shows a median at ~130 K



Hot CO vs. hot H_2O

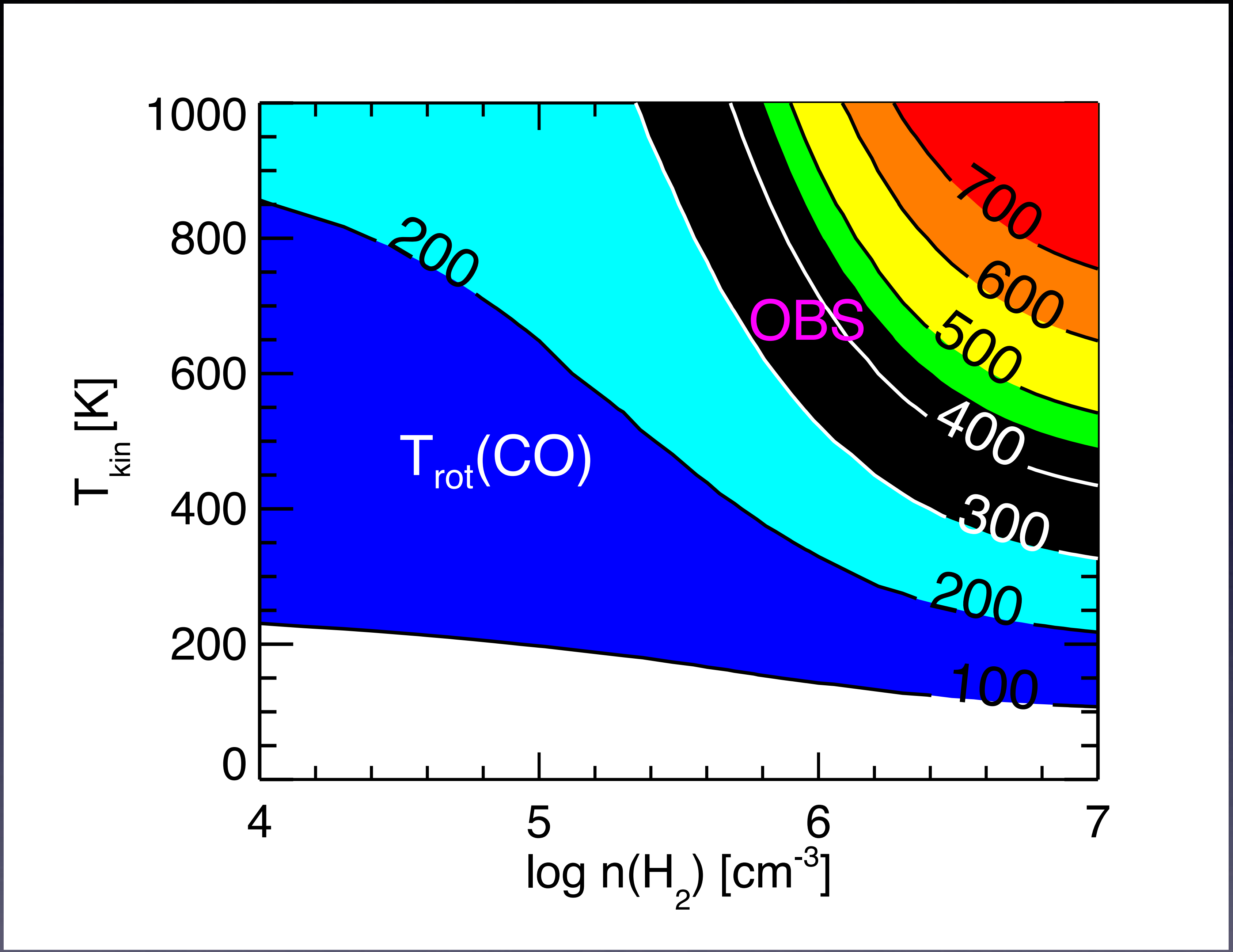
Kristensen+13





- Strong link between the hot H_2O and hot CO
- Respective kinematic component seen in the line profiles at same velocities as hydrides - impact of UV irradiation

Gas physical conditions

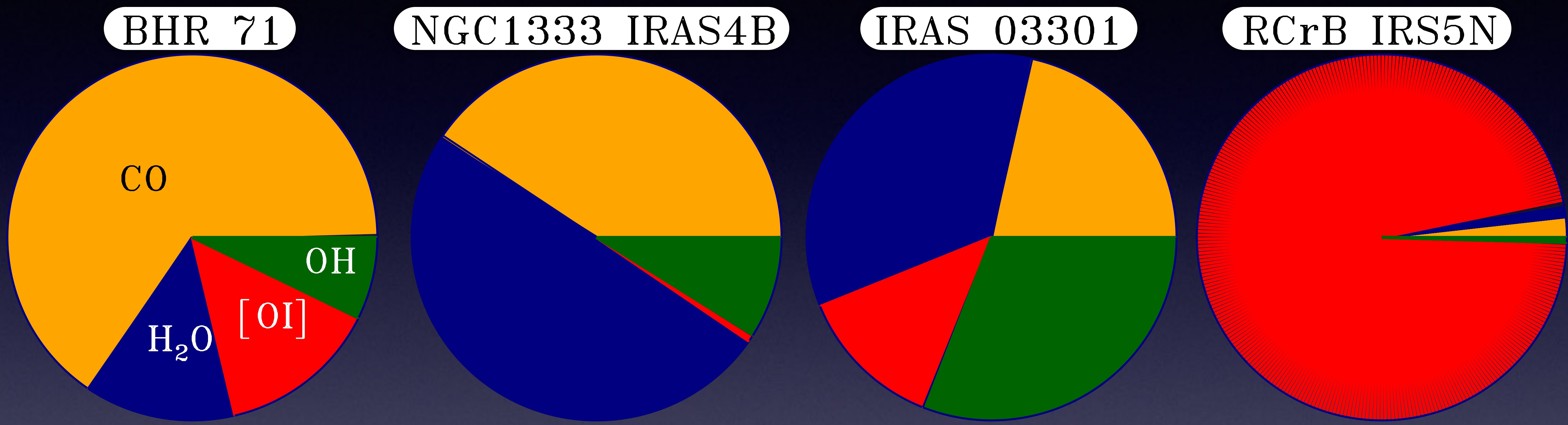


CO J_{up}=14-24

Karska+13, 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)
- Excitation of water lines require the higher-density solution

Far-IR line cooling

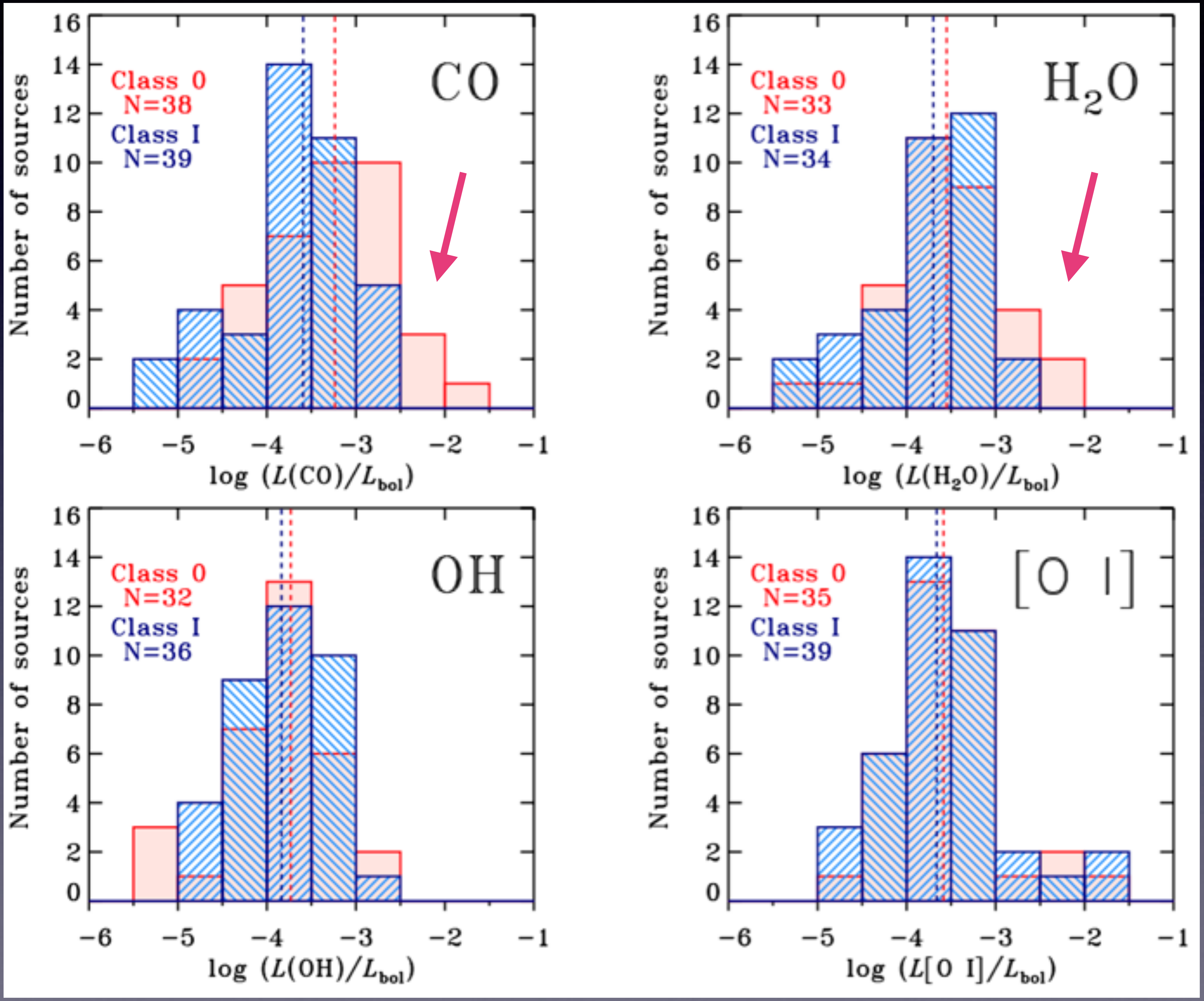


- calculated using only the lines in the PACS range

$L_{\mathrm{FIRL}}=L(\mathrm{CO})+L(\mathrm{H_2O})+L(\mathrm{OH})+L[\mathrm{OI}]$

- large variations in the fractions contributed by different species (no correlation with T_{bol} and L_{bol})

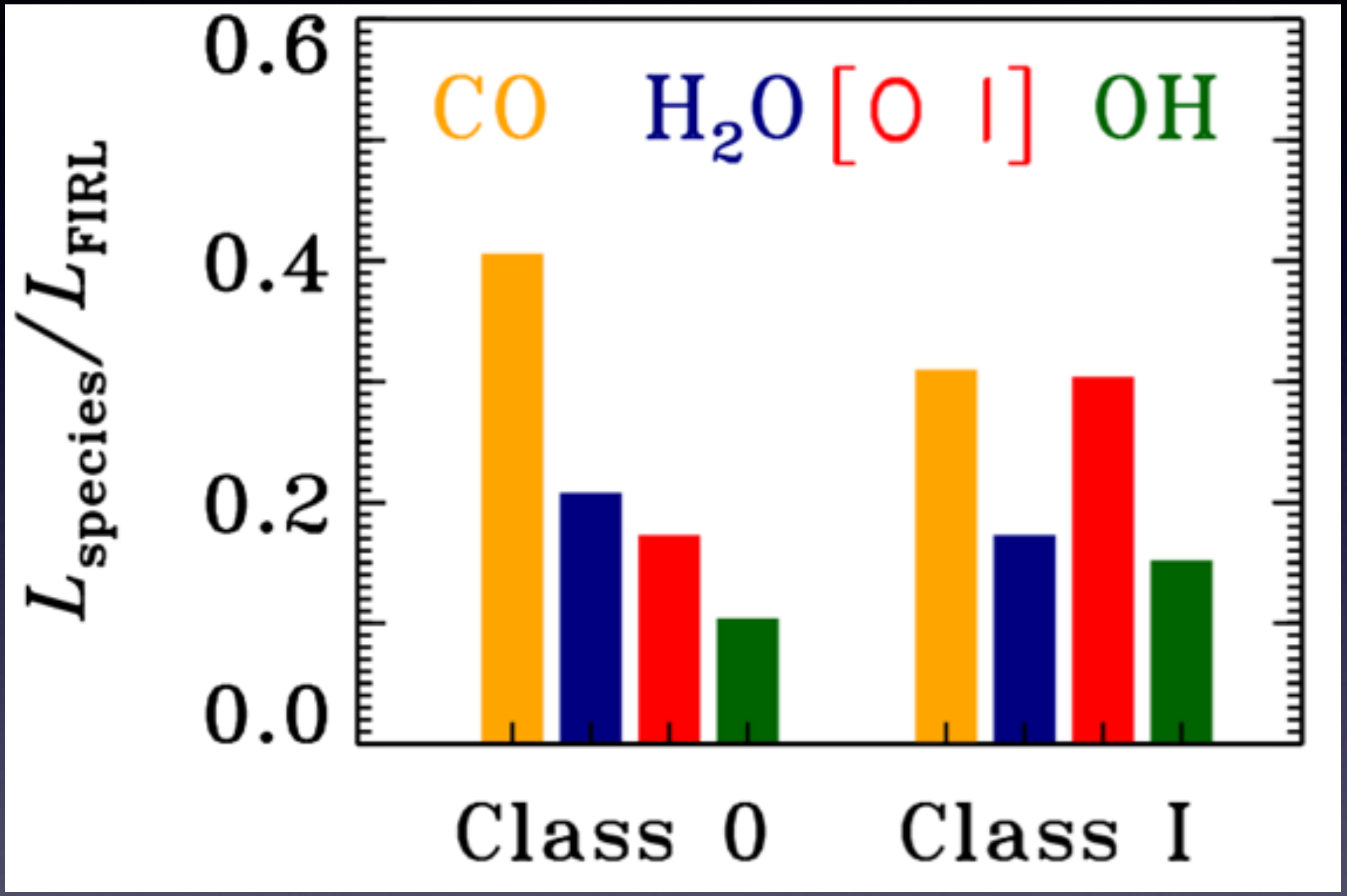
Line emission in Class 0/I

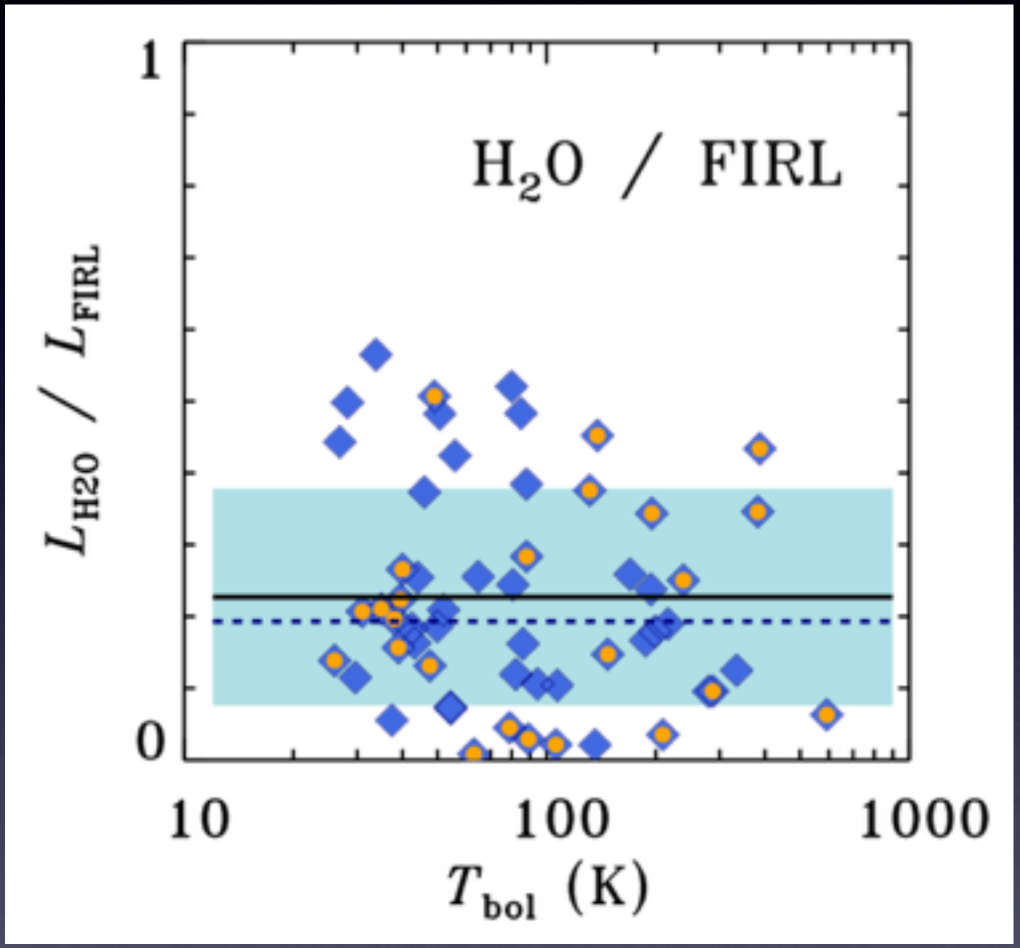


- surprisingly similar distributions for all protostars

- very similar absolute values (a few 10^{-4})

Evolution in cooling

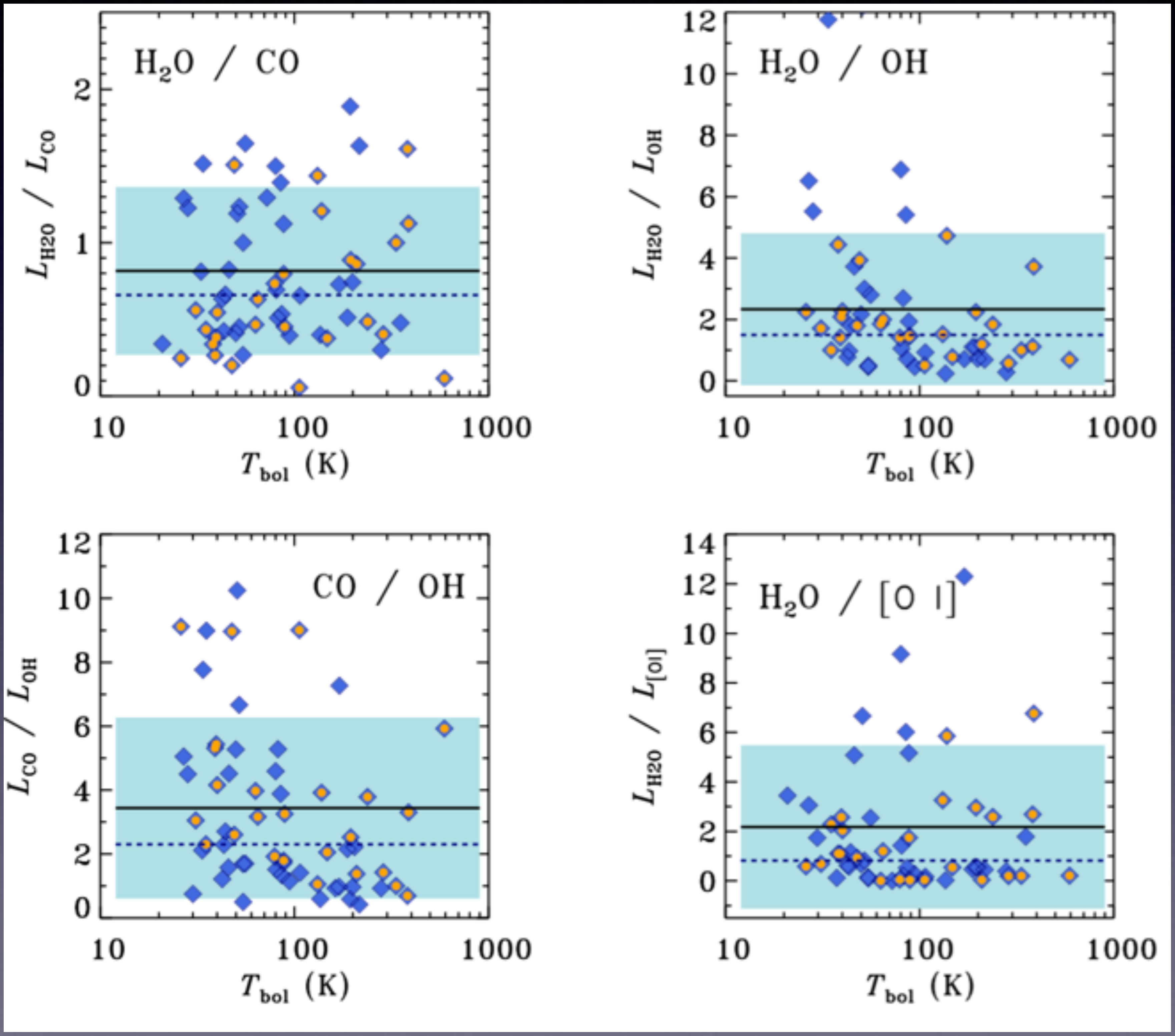




- large spread, but median contributions of CO and H_2O decrease, while [O I] and OH increase

- overall decrease in L_{FIRL}=L(CO)+L(H_2O)+L(OH)+L[OI] from 5.9 10^{-3} to 3.7 10^{-3} L_{bol} from Class 0 to I (not shown)

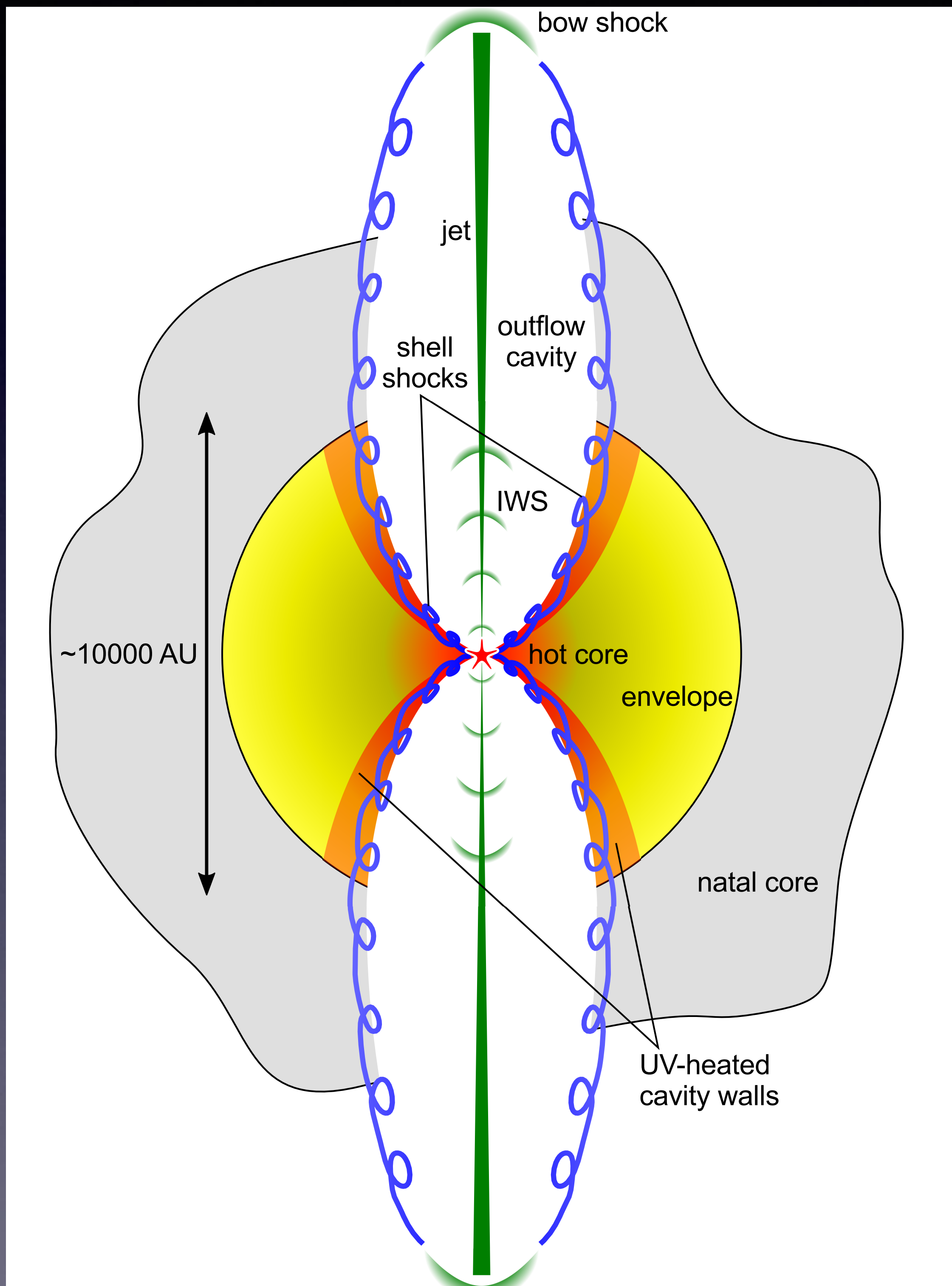
Luminosity ratios of various species



- very similar values for all sources (of the order of unity)

- useful for comparisons with the models

Origin of warm gas?



van Dishoeck+11

Well-resolved extended emission along the outflow direction

→ not an inner envelope, not a disk

Observed spatial scales

→ not a bow shock at the tip of a jet

Lack of very high velocity emission

→ not due to jet

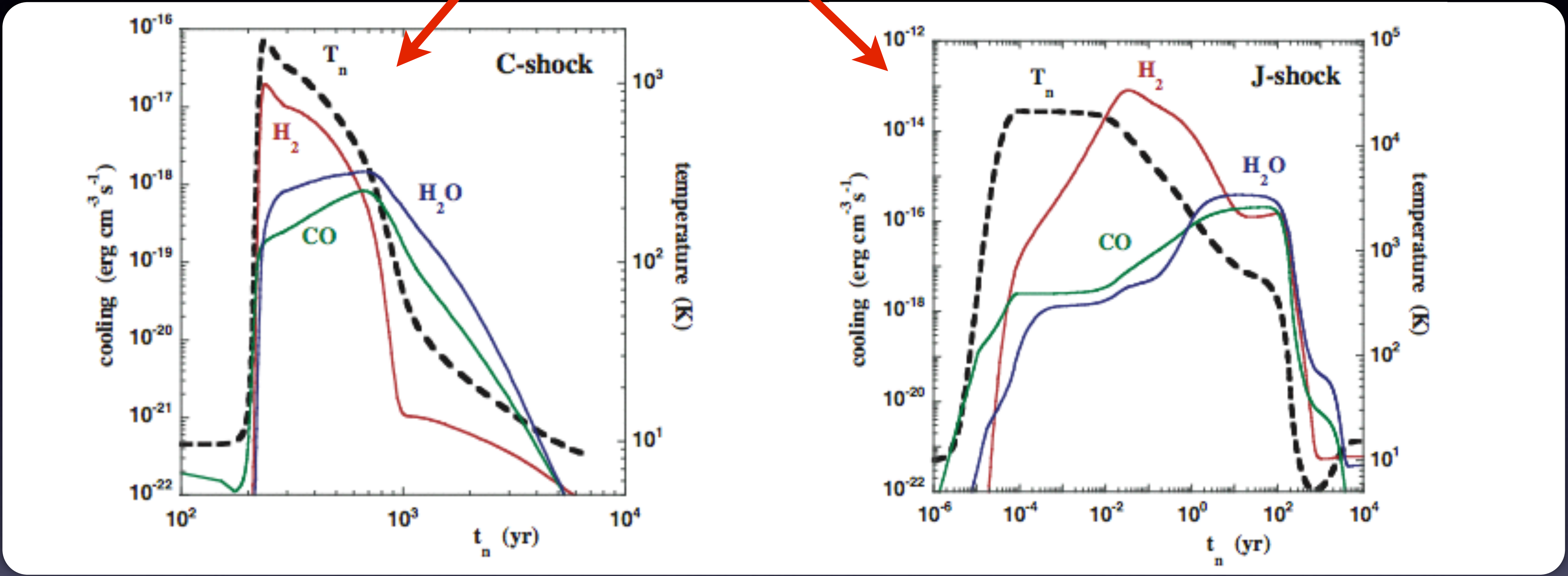
Temperatures well above 100 K

→ not an entrained outflow gas

shocks & UV

Molecular cooling in shocks

Non-dissociative C - shock & J-shock (Flower & Pineau des Forets)



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

$OH + H_2 \rightarrow H_2O + H$

v_{sh} > 15 km/s:

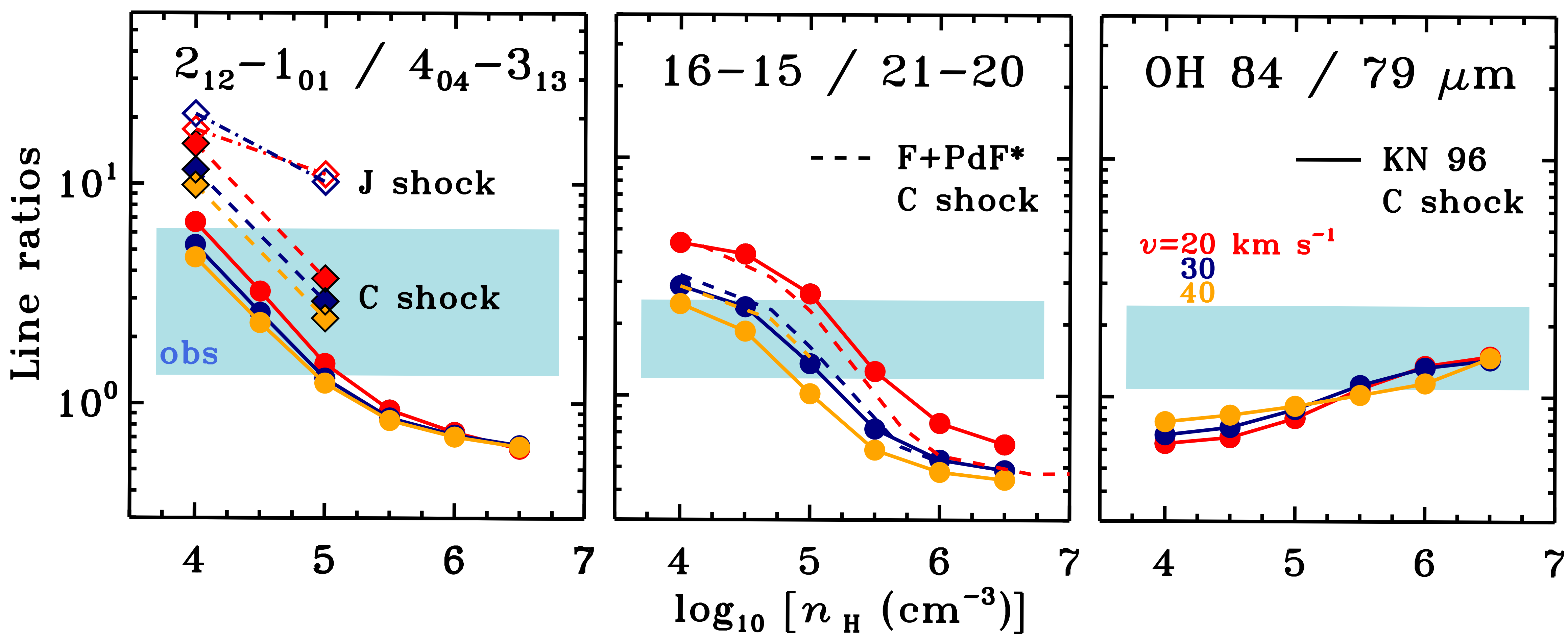
molecules released from grains

- molecules can survive the passage of C shock, but not all J shocks
- line cooling dominated by H_2, H_2O and CO

Line ratios vs. shock models
- excitation

Protostars in Perseus (22 sources)

Karska+14b

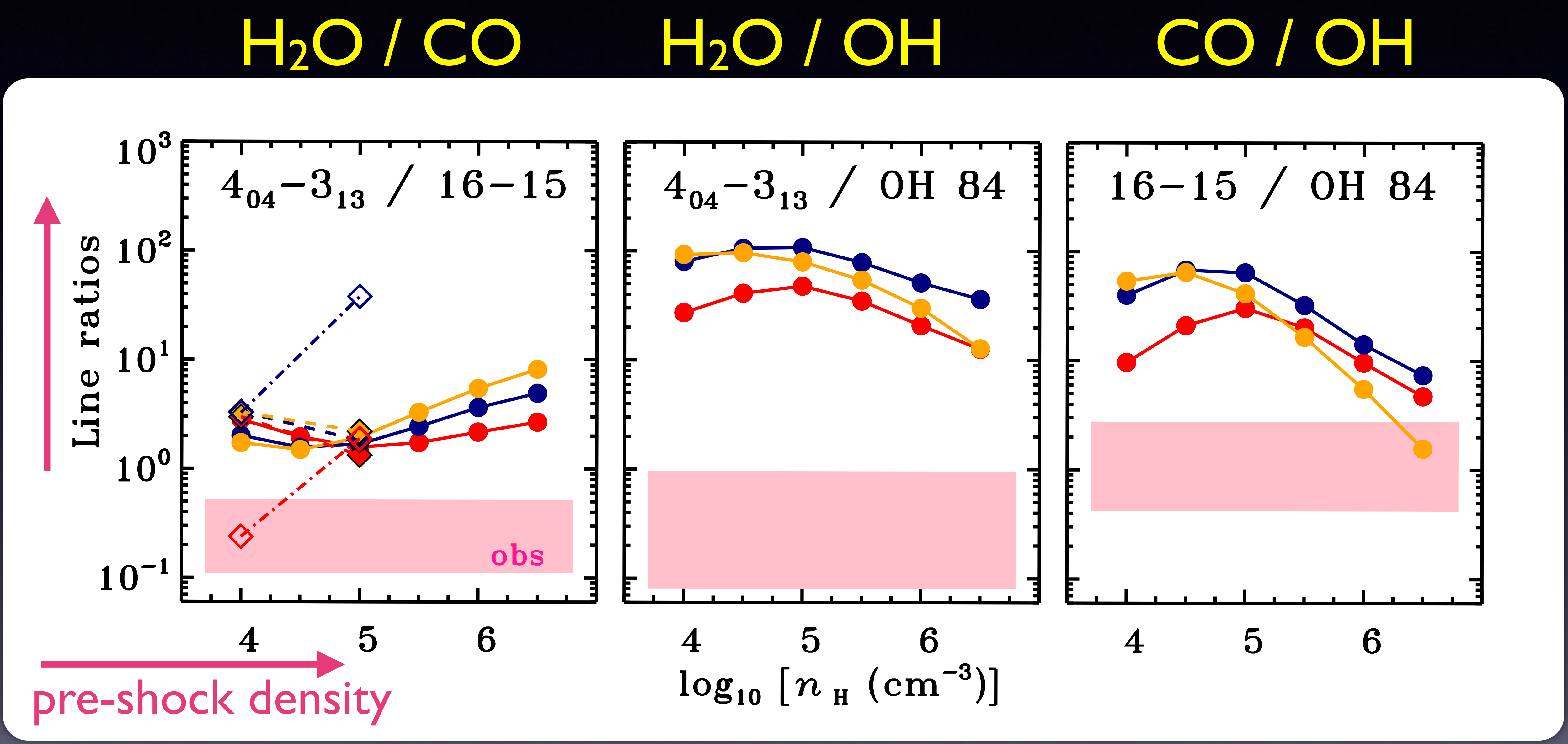


- Line ratios remarkably similar across the sample
- Velocities > 20 km s^{-1}, pre-shock densities of ~10^5 cm^{-3}

Line ratios vs. shock models

- abundances

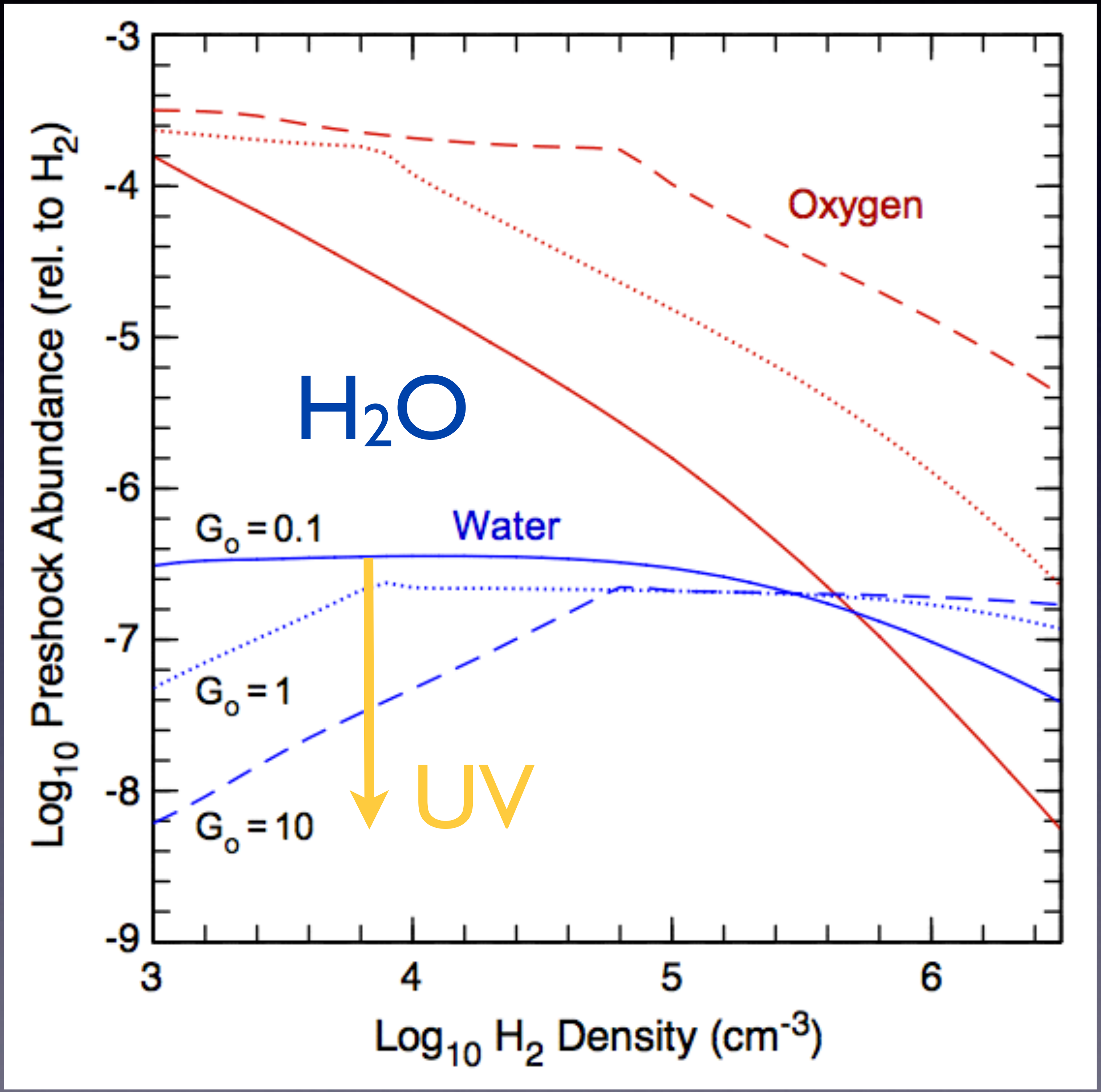
Karska+14b



- Observed ratios with H_2O much lower than models

- We postulated to use irradiated shock models to decrease the H_2O abundances

FUV irradiated C shocks



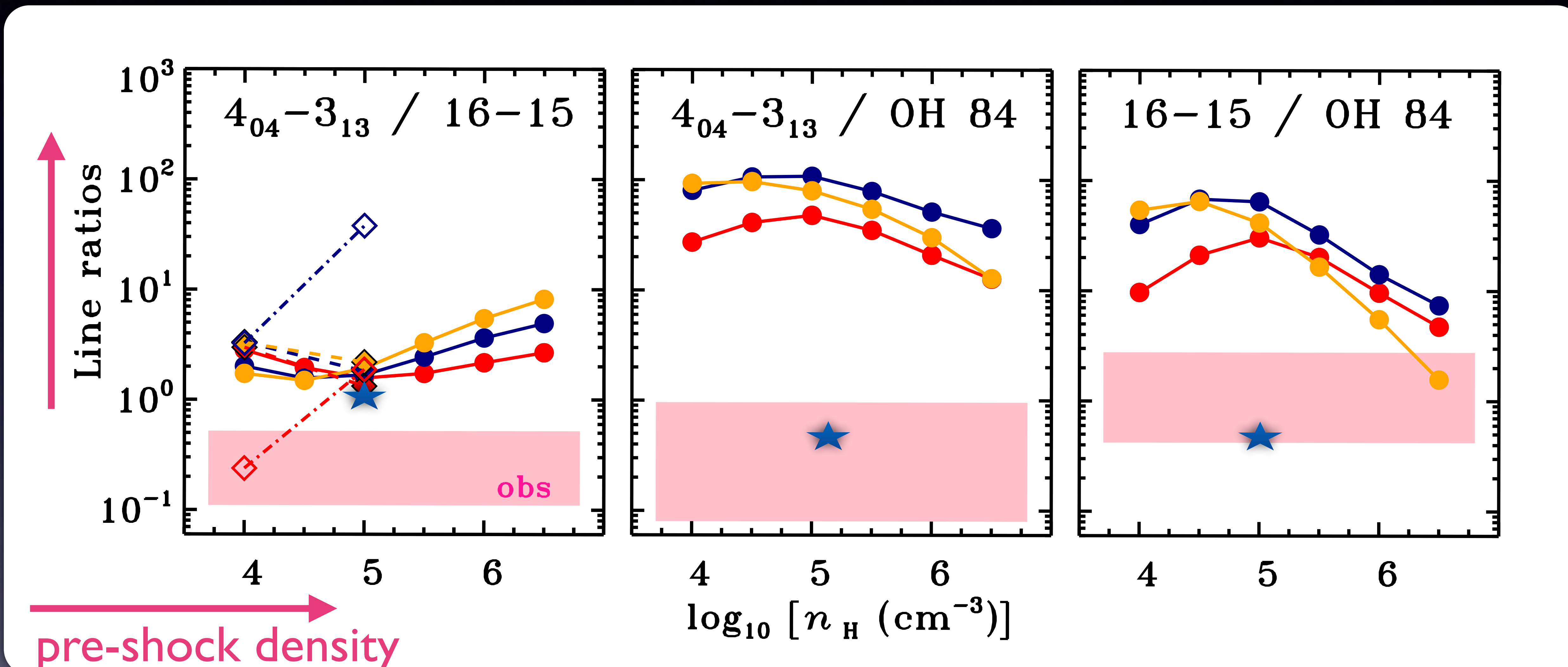
Melnick & Kaufman 2015, talk by M. Kaufman

- decrease of H_2O pre-shock abundances at low densities

- increase of the pre-shocks O available for the post-shock OH and H_2O

Line ratios vs. shock models

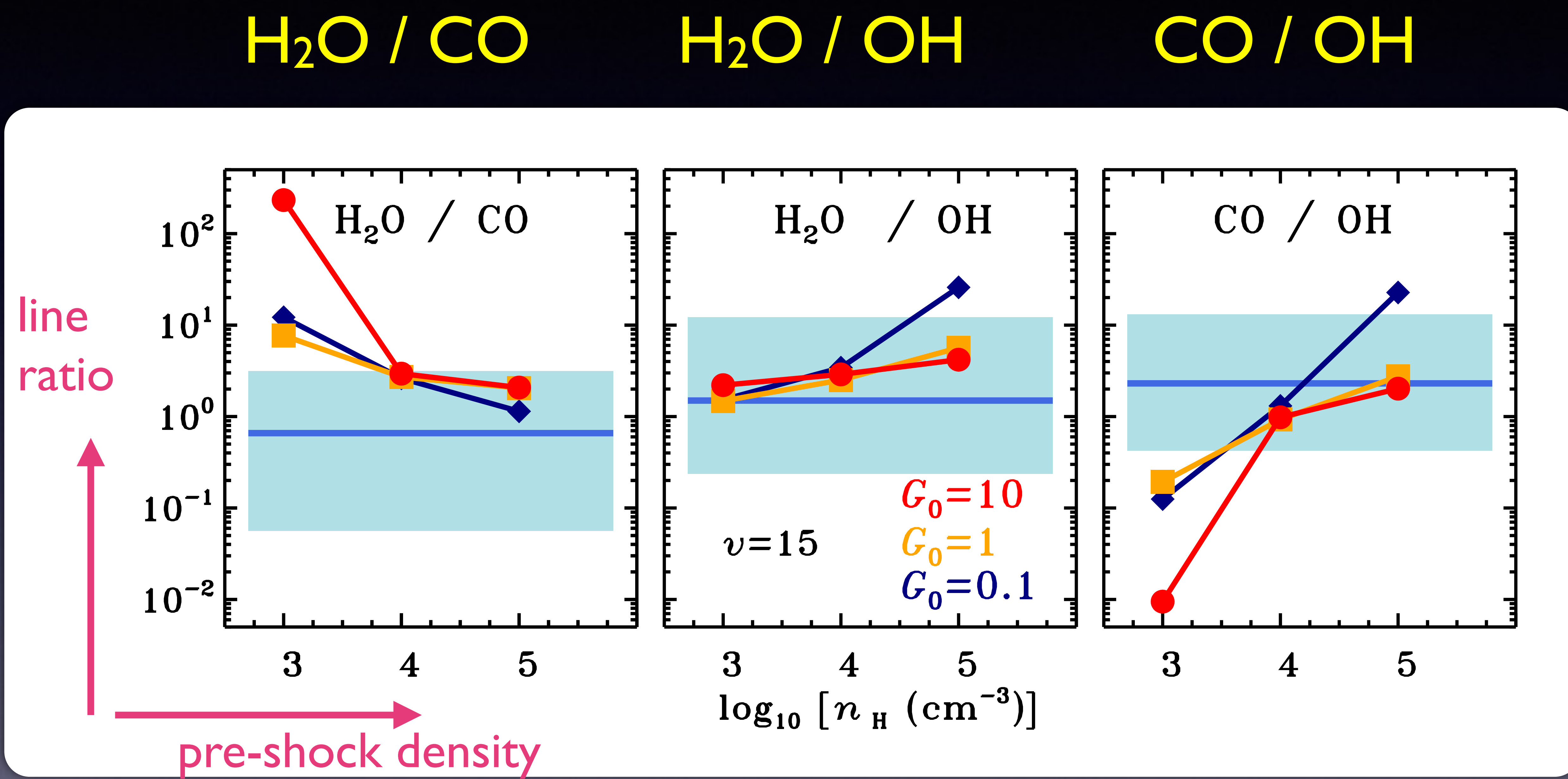
H_2O / CO H_2O / OH   CO / OH



- Observed ratios with H_2O much lower than models

- We postulated to use irradiated shock models to decrease the H_2O abundances

Irradiated shock models



- Irradiated shock models agree with observations for pre-shock log n ~ 4-5 and G_0 ~1-10

Outflow parameters

- total energy loss is a direct measure of mechanical luminosity

c.f. Maret, Bergin+09

$$1/2\ dM/dt\ v_{sh}^2 = (1\text{-}f_m)\ 1/f_x\ L_{FIRL}$$

,f_m - fraction of shock mechanical energy translated into excitation

f_x - fraction of cooling due to CO, H_2O, OH, [O I]

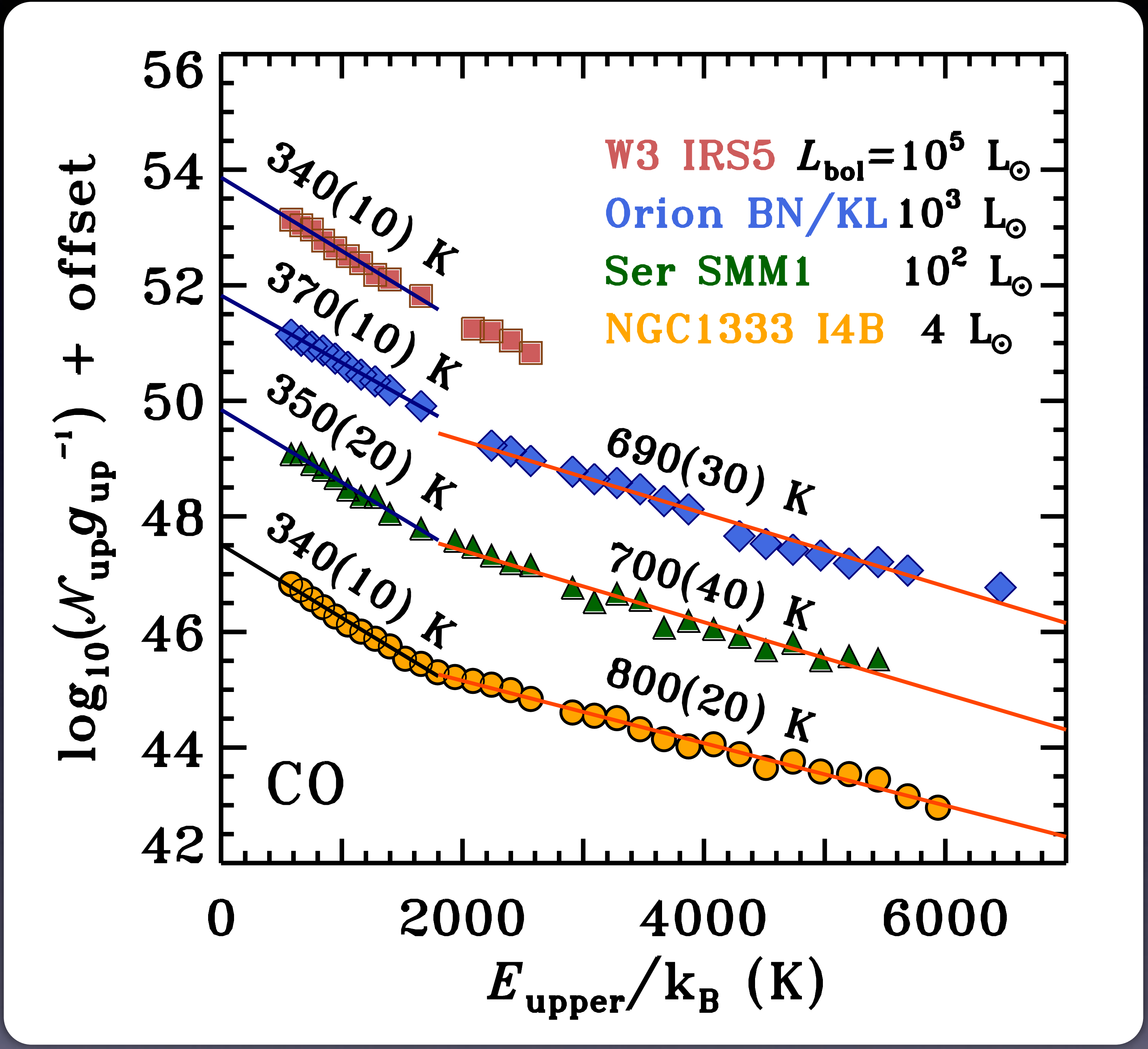
- assuming $(1\text{-}f_m) \sim 0.75$ and $f_x \sim 0.25$ and $v_{sh} \sim 15$ km s^{-1} (G_0=1, log$n$=5) and $L_{FIRL} = 4.7\ 10^{-3}\ L_{bol}$ (observations)

Mass loss by outflows: $dM/dt \sim 5.2\ 10^{-7}\ M_{sun}\ yr^{-1}$

Caution: we may not observe the full extent of the outflow

High-mass protostars

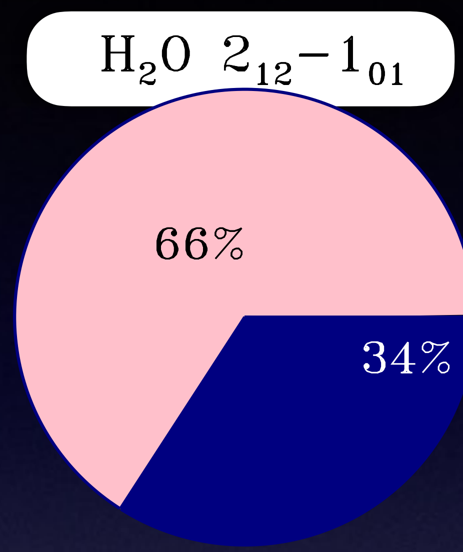
Goicoechea+15
Matuszak+15
Karska+14



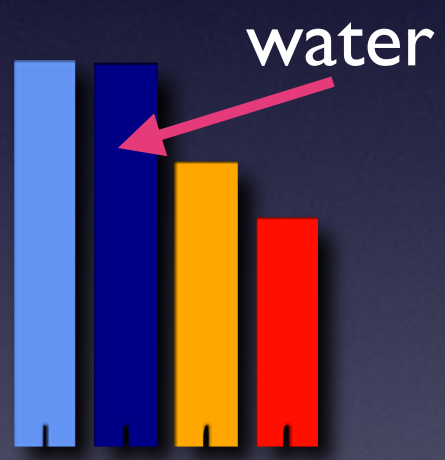
see talks by
Mottram (LM-HM)
and Herpin (cooling)

The same processes responsible for far-IR emission from low- to high-mass star forming regions?

Conclusions



1. Water is ubiquitous in deeply-embedded protostars and follows closely the highly-excited CO lines (physical conditions)



2. Water is one of the key coolants of the gas in Class 0/I protostars

3. Water originates from a hot and dense gas likely associated with the FUV illuminated outflow shocks