The O budget in low-mass protostars:

The NGC1333-IRAS4A R1 shock observed in [O I] 63 μm with SOFIA-GREAT

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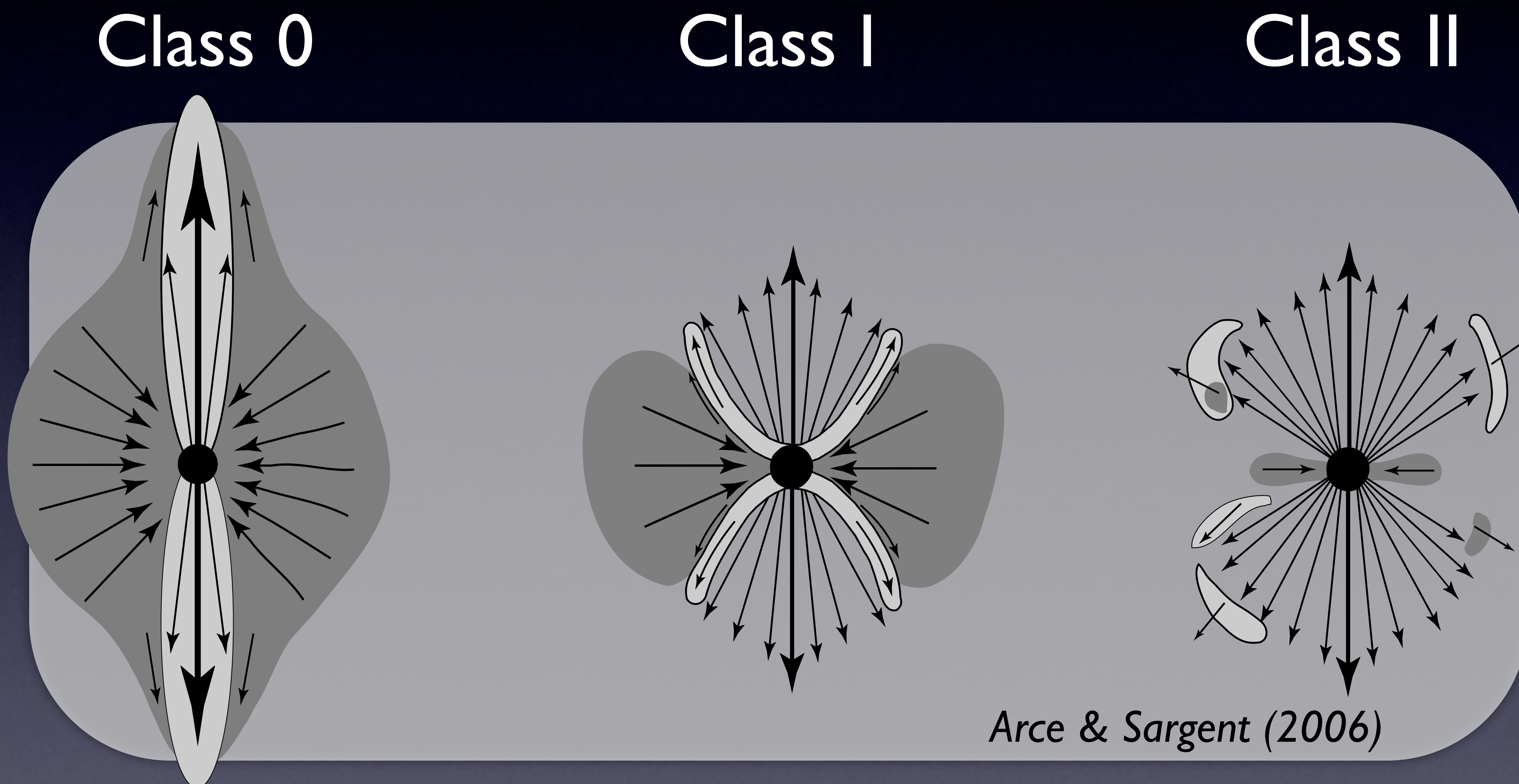
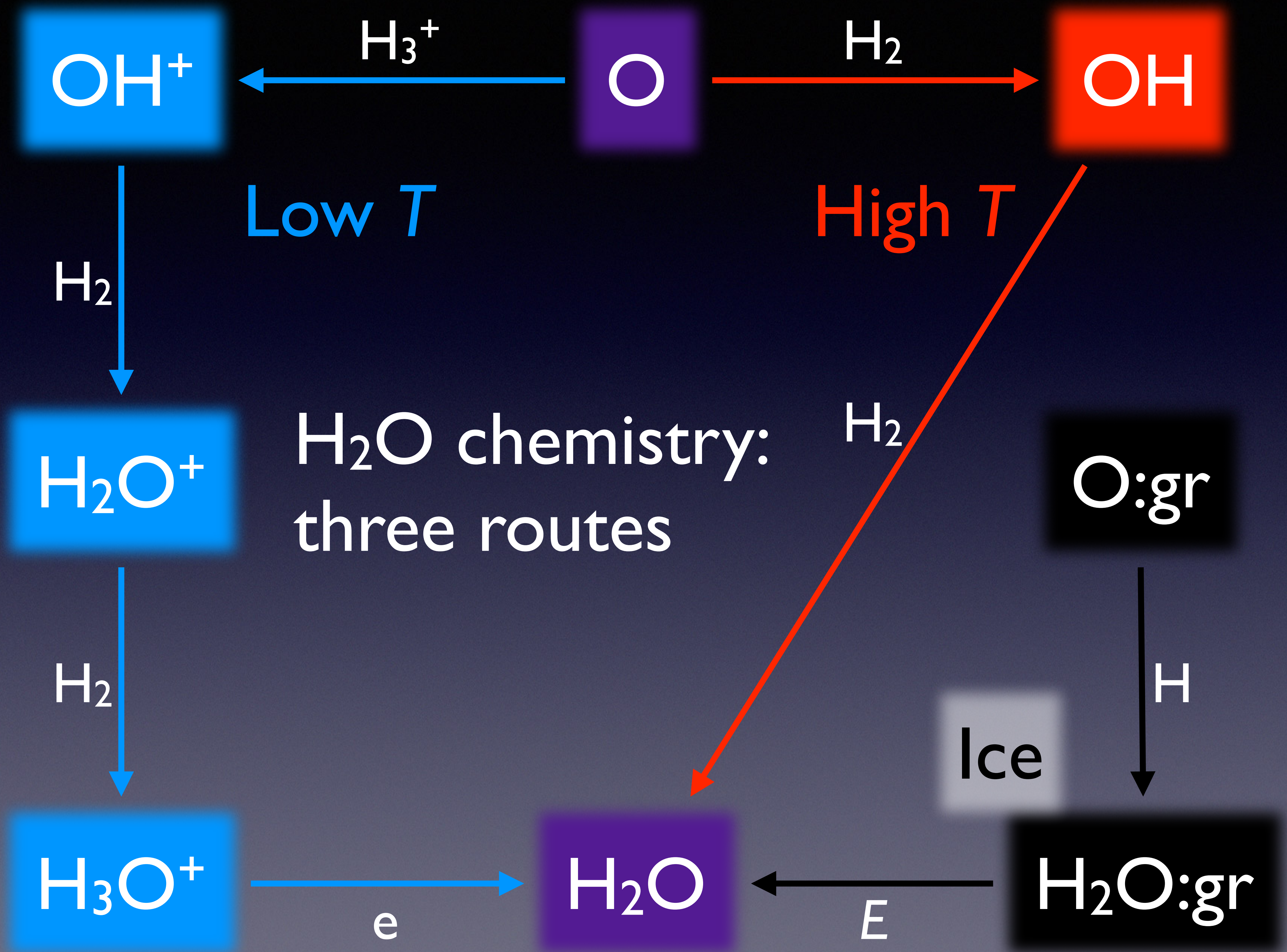
H. Wiesemeyer, R. Güsten, R. Simon and special thanks to G. Sandell

Low-mass YSO evolution



Jet / wind present at all evolutionary stages



OH+
H3+
O
H2
OH
Low T
High T
H2
H2O chemistry:
three routes
H2
H2O+
O:gr
H2
H
Ice
H3O+
H2O
H2O:gr
e
E

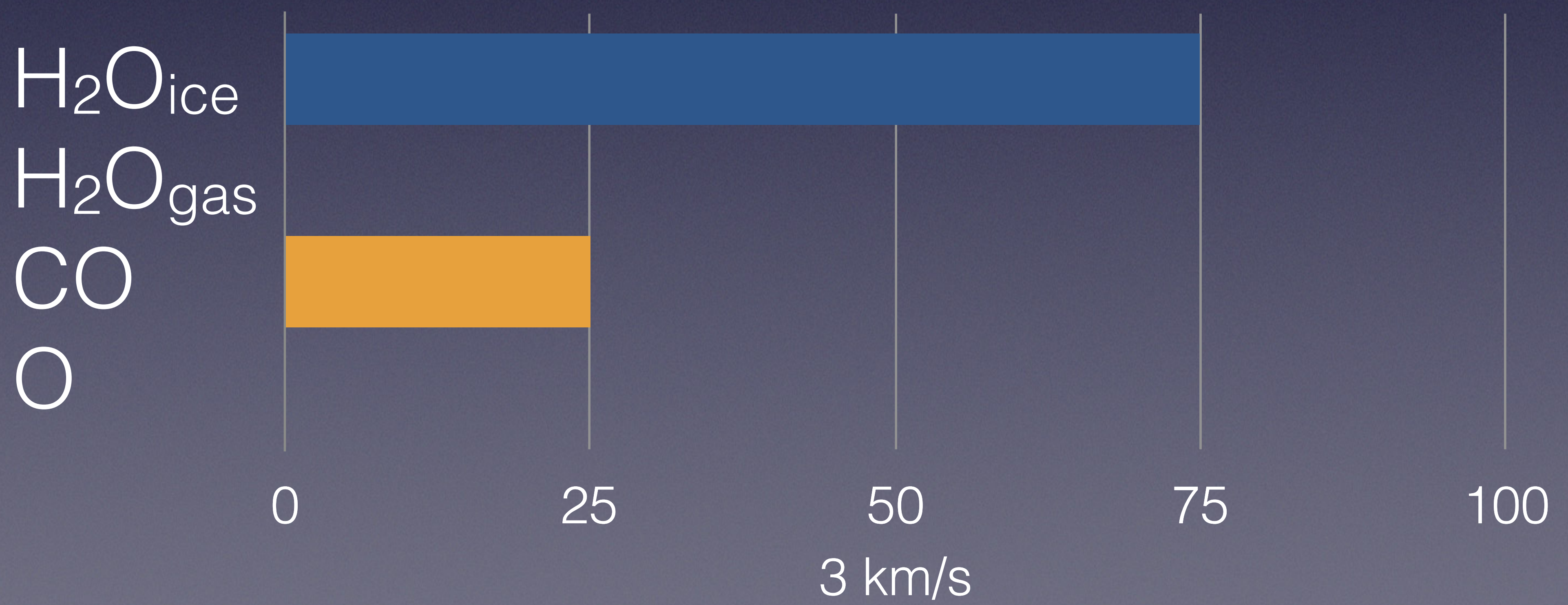
Shock chemistry 101

Volatile Oxygen budget

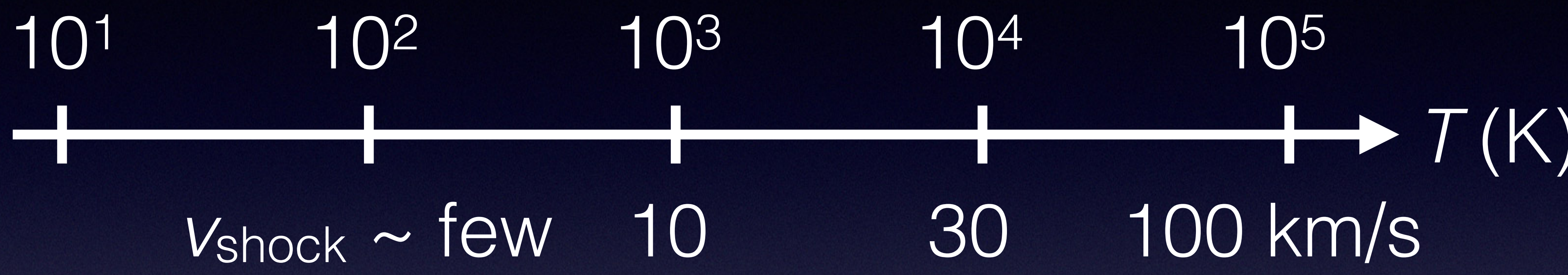
H_2O_{ice}
H_2O_{gas}
CO
O

Shock chemistry 101

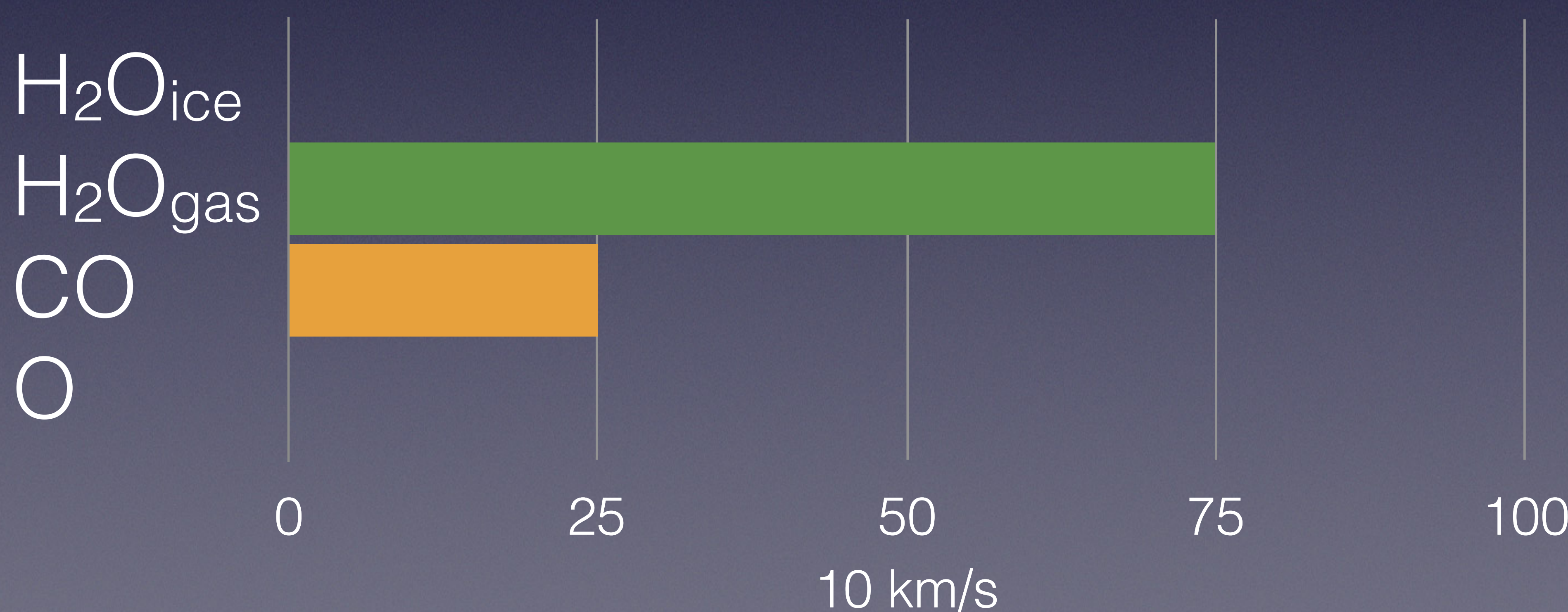
Volatile Oxygen budget



Shock chemistry 101

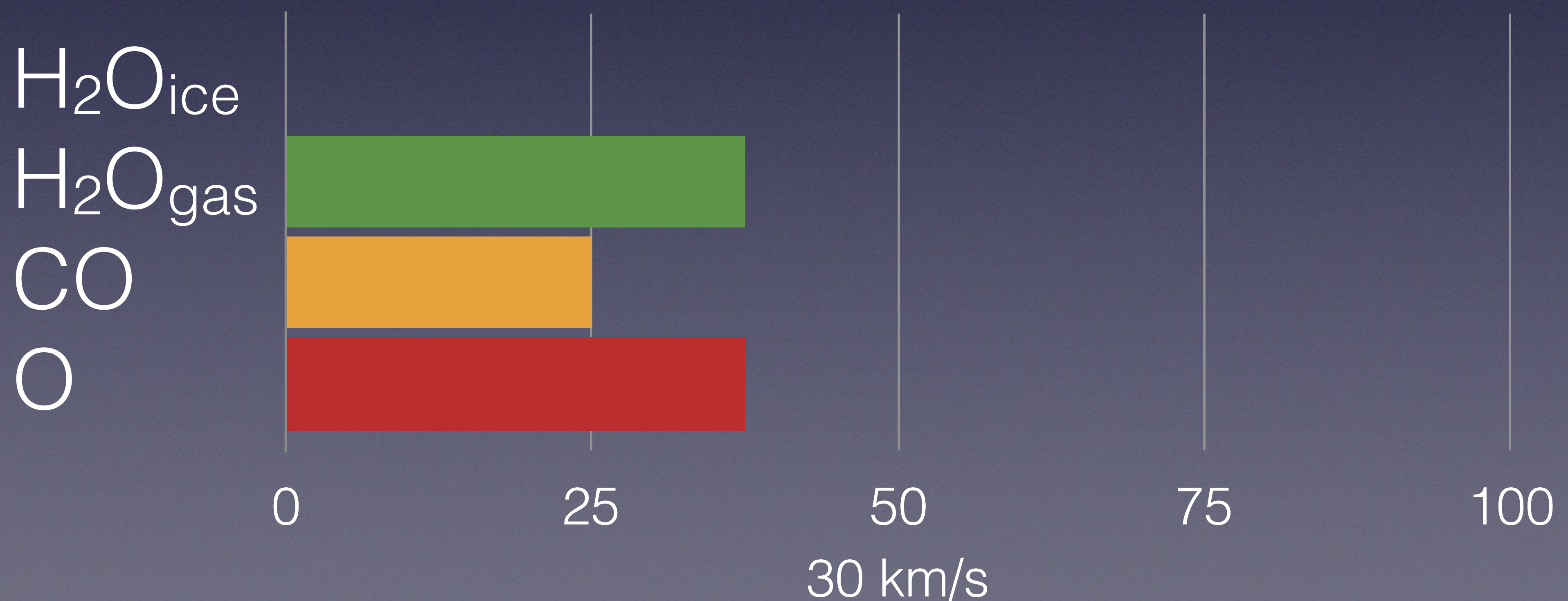


Volatile Oxygen budget



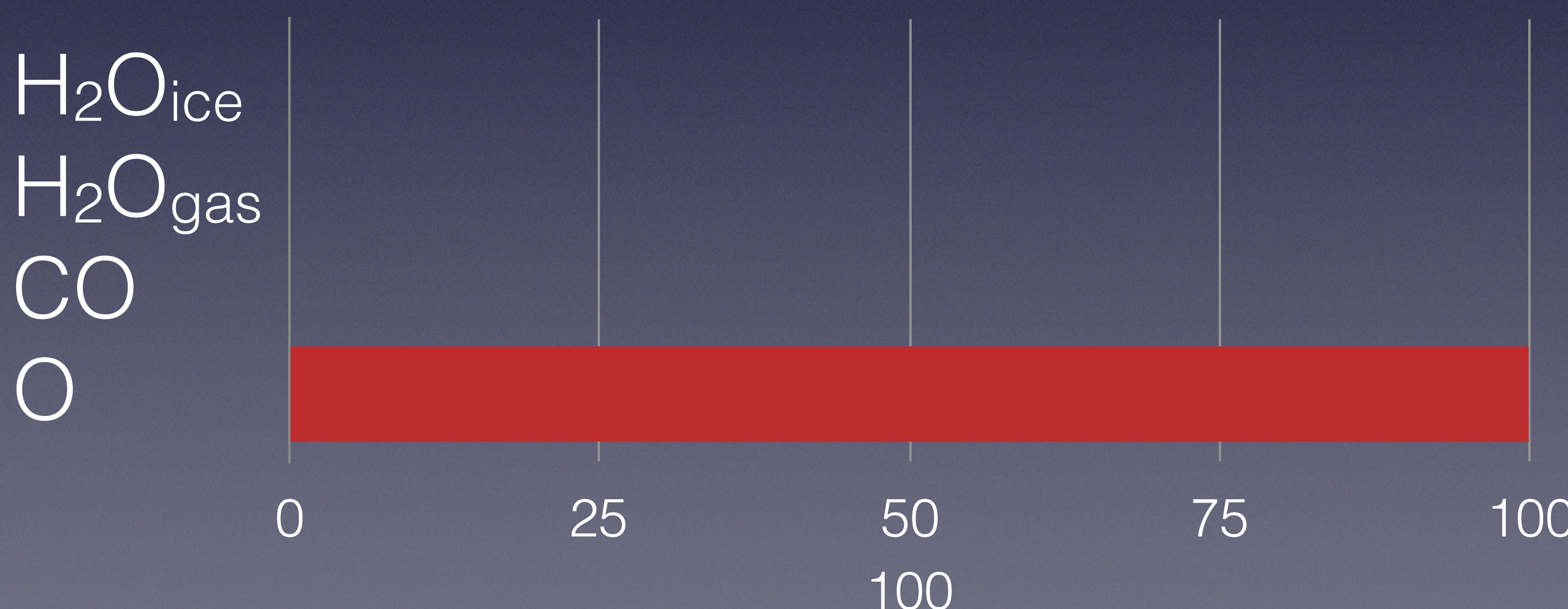
Shock chemistry 101

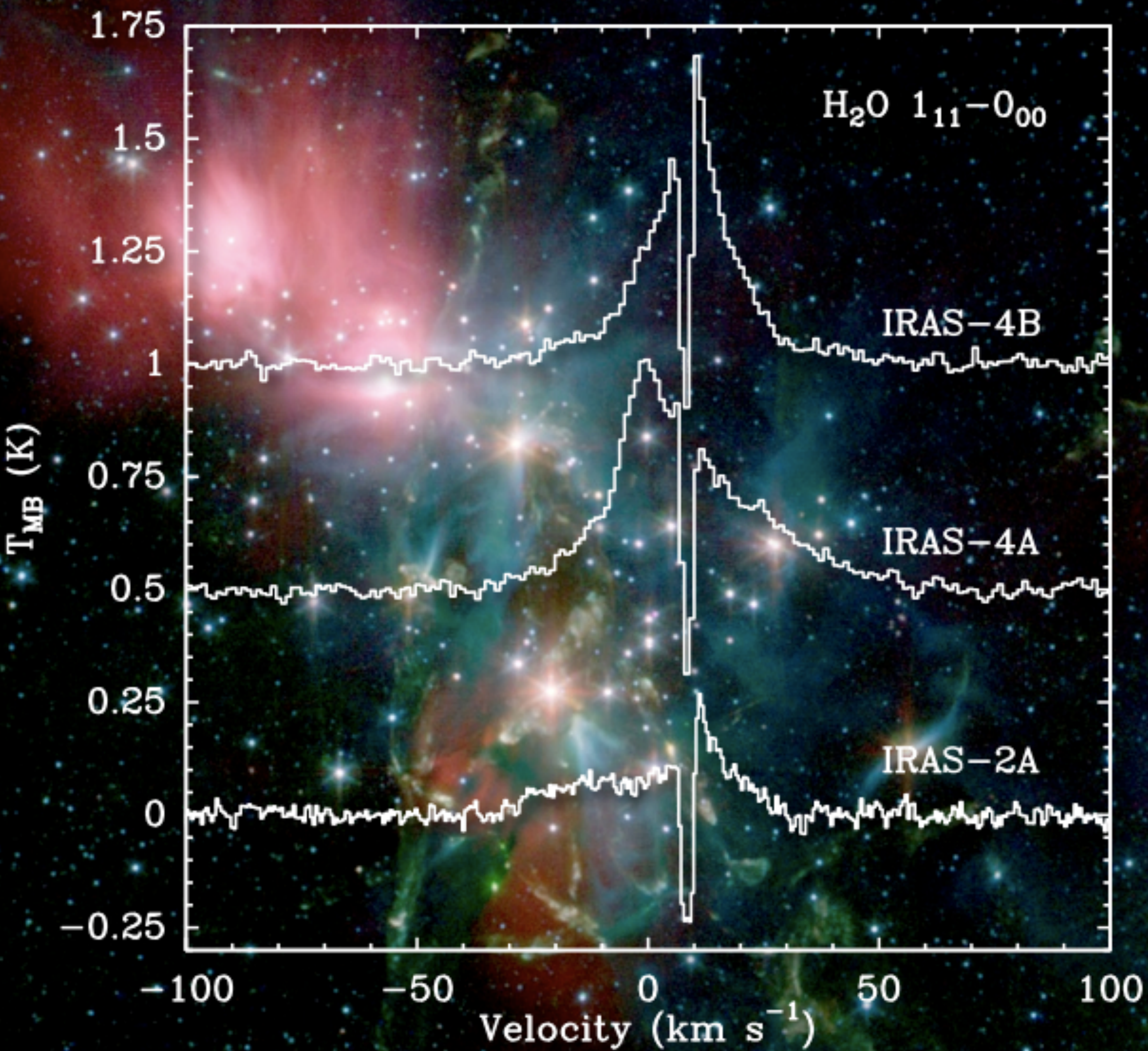
Volatile Oxygen budget



Shock chemistry 101

Volatile Oxygen budget

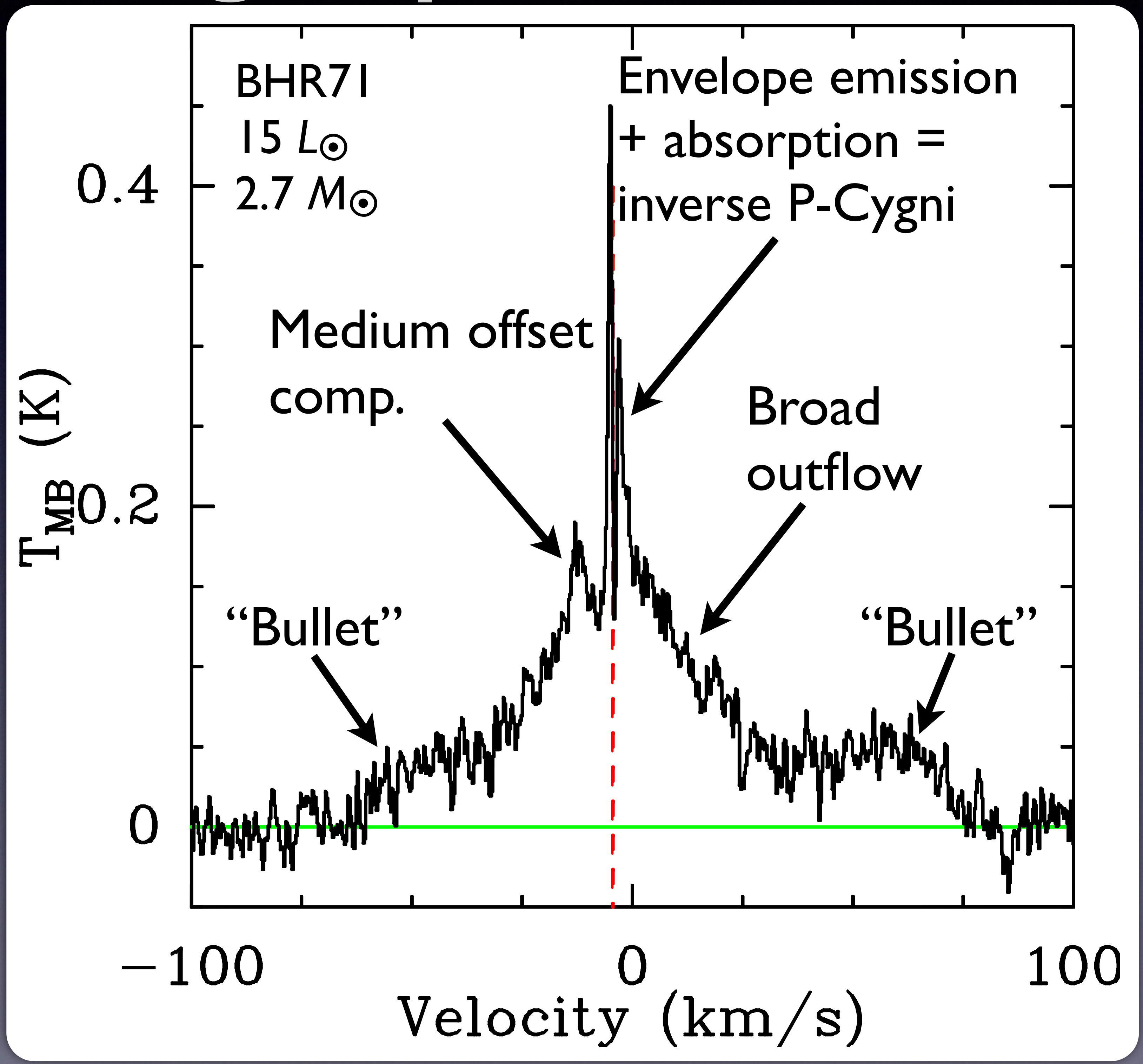




Kristensen et al. (2010, 2012), Mottram et al. (2014)

Dissecting a profile

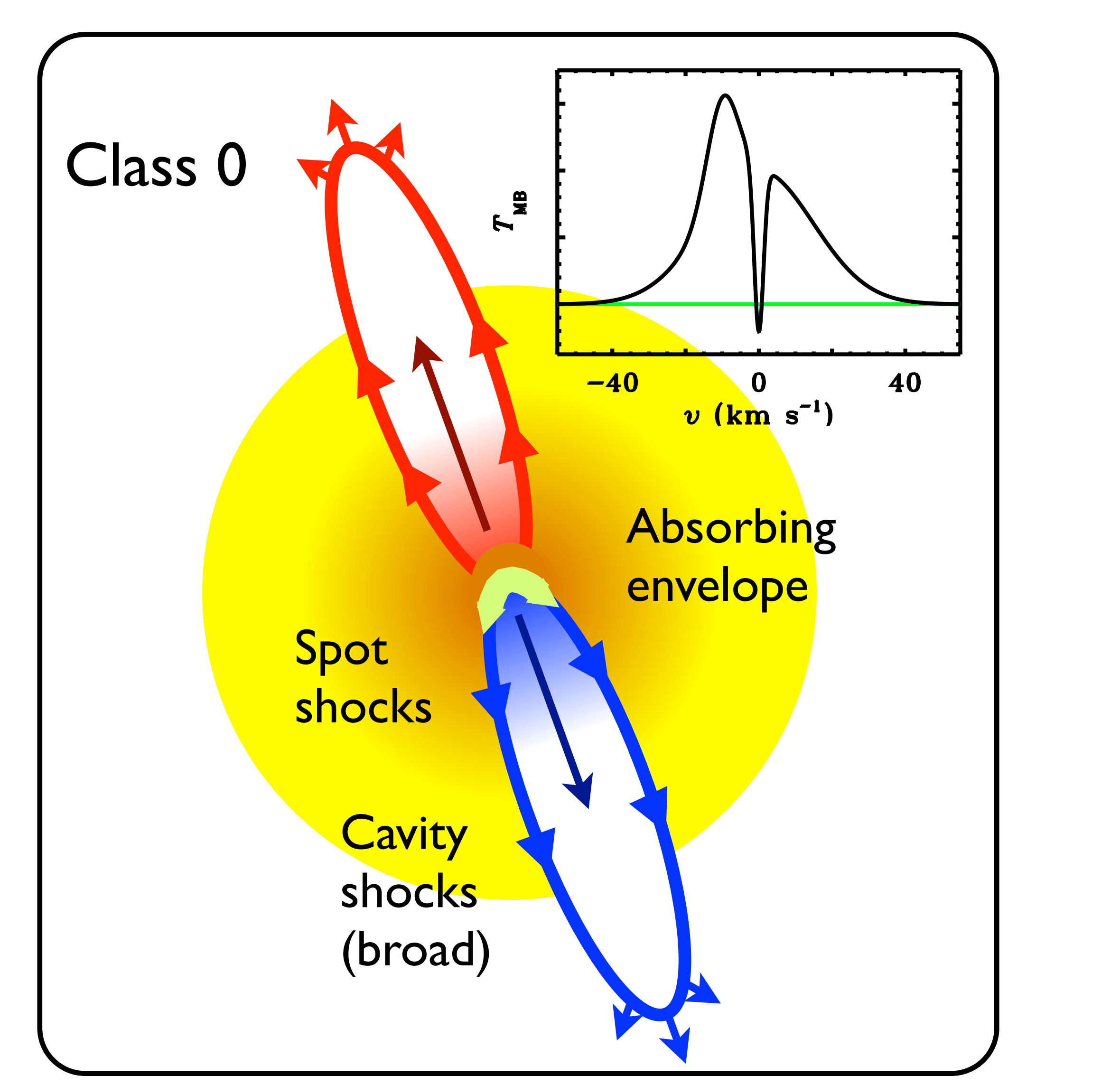
- One profile: lots of H_2O moving!
- Bulk of emission in three components
- *Velocity resolution allows for decomposition*



Kristensen et al. (2012), Mottram et al. (2014)

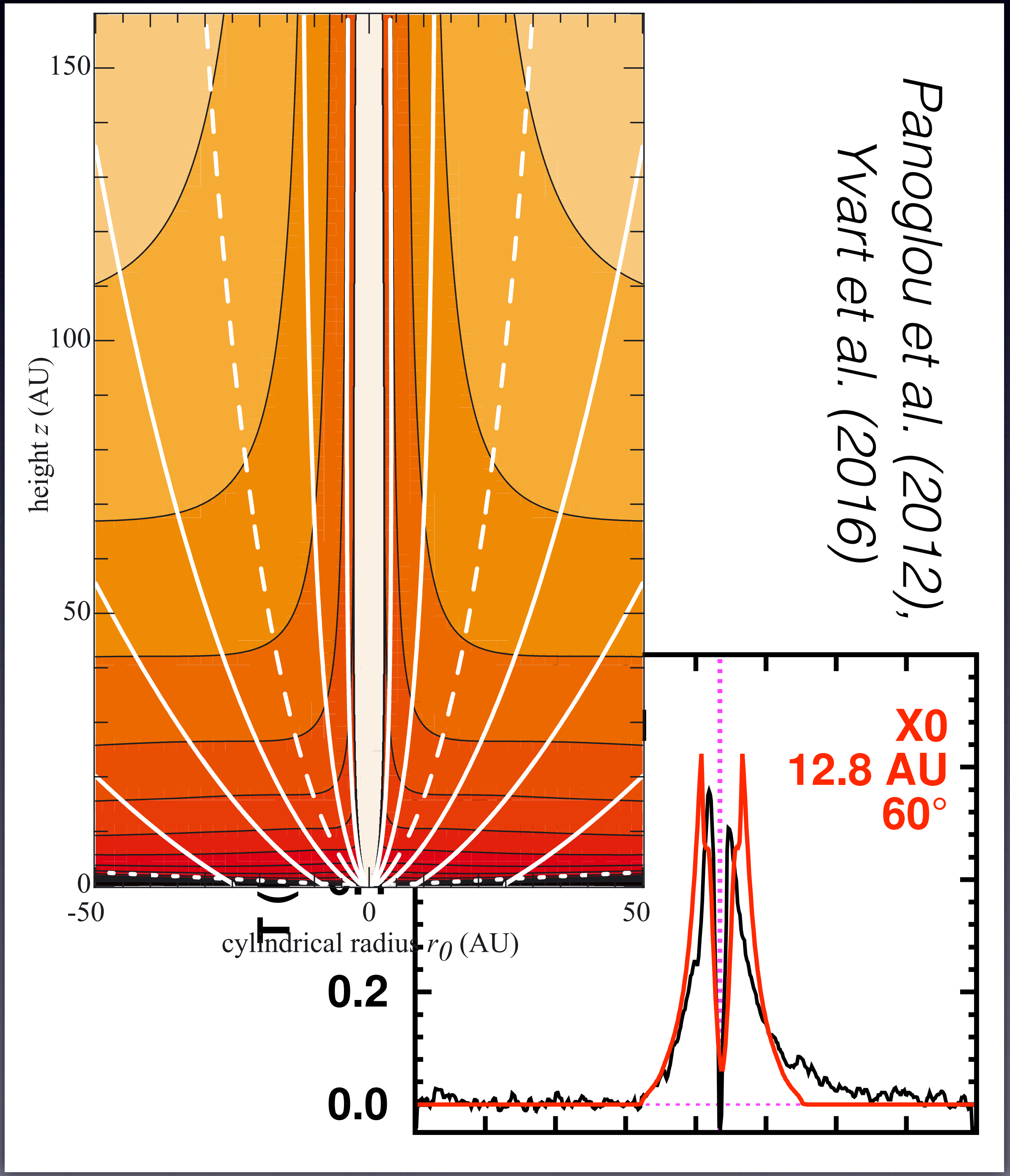
Physical components

Cavity shocks



Kristensen et al. (2010, 2012, 2013), Mottram et al. (2014, 2017), Visser et al. (2012)

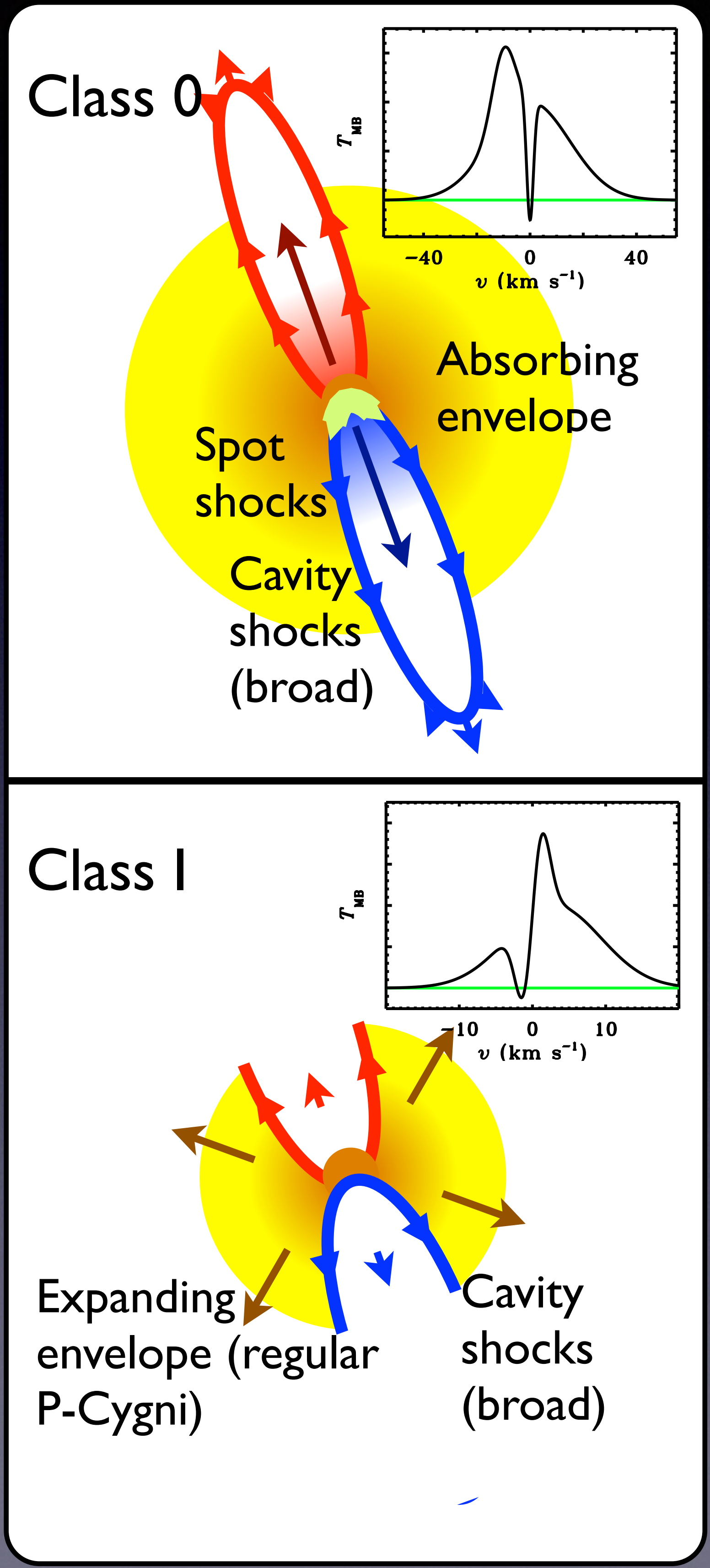
Protostellar wind



Panoglou et al. (2012), Yvart et al. (2016)

Evolutionary scheme

- *Class 0*: H_2O tightly linked to outflow, infall, molecular jet, profiles are the broadest + brightest
- *Class I*: envelope opens, outflow force decreases, expansion, profiles decrease in width + intensity



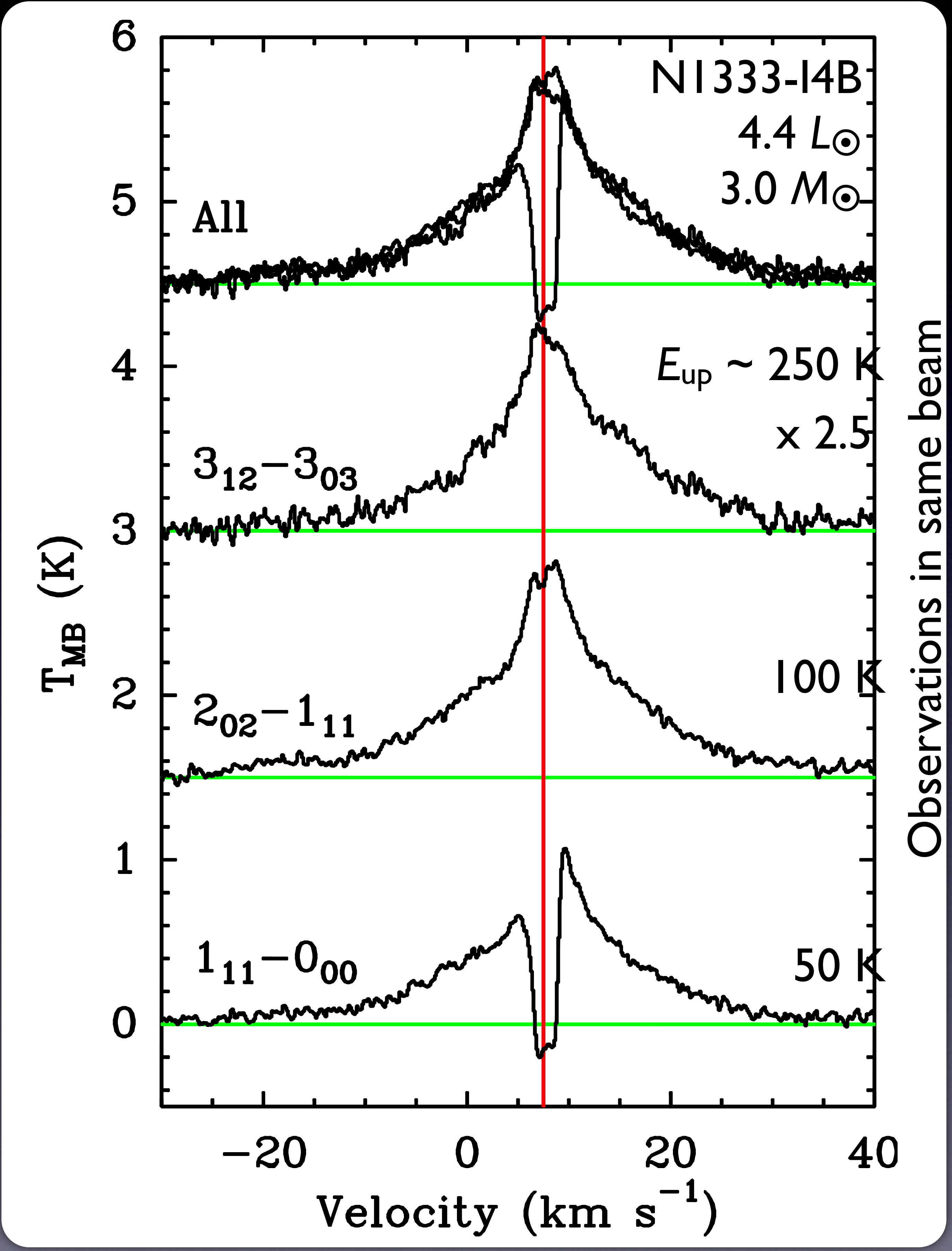
(Visser et al. 2012, Kristensen et al. 2012, Mottram et al. 2014)

Quest for H_2O abundance

- Step I: determine excitation conditions, particularly $N(H_2O)$
- Step II: Choose appropriate reference frame to get $N(H_2)$
- Step III: Calculate $x(H_2O) = N(H_2O) / N(H_2)$

Profile shape vs. excitation

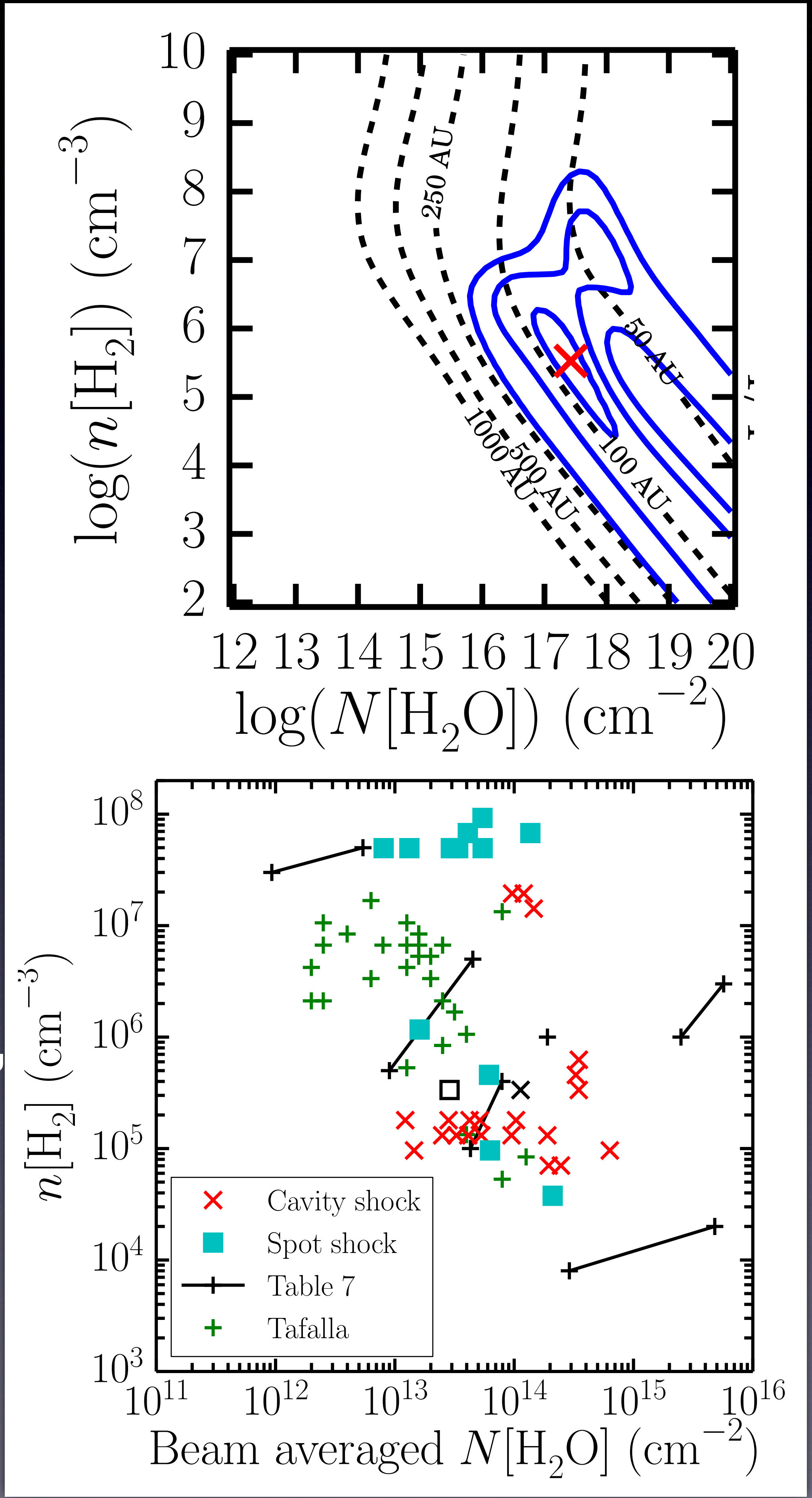
- Similarity in profile shapes independent of excitation
  (different at outflow positions)
- *Excitation conditions constant with v in each component*



Kristensen et al. (2010)
Mottram et al. (2014)

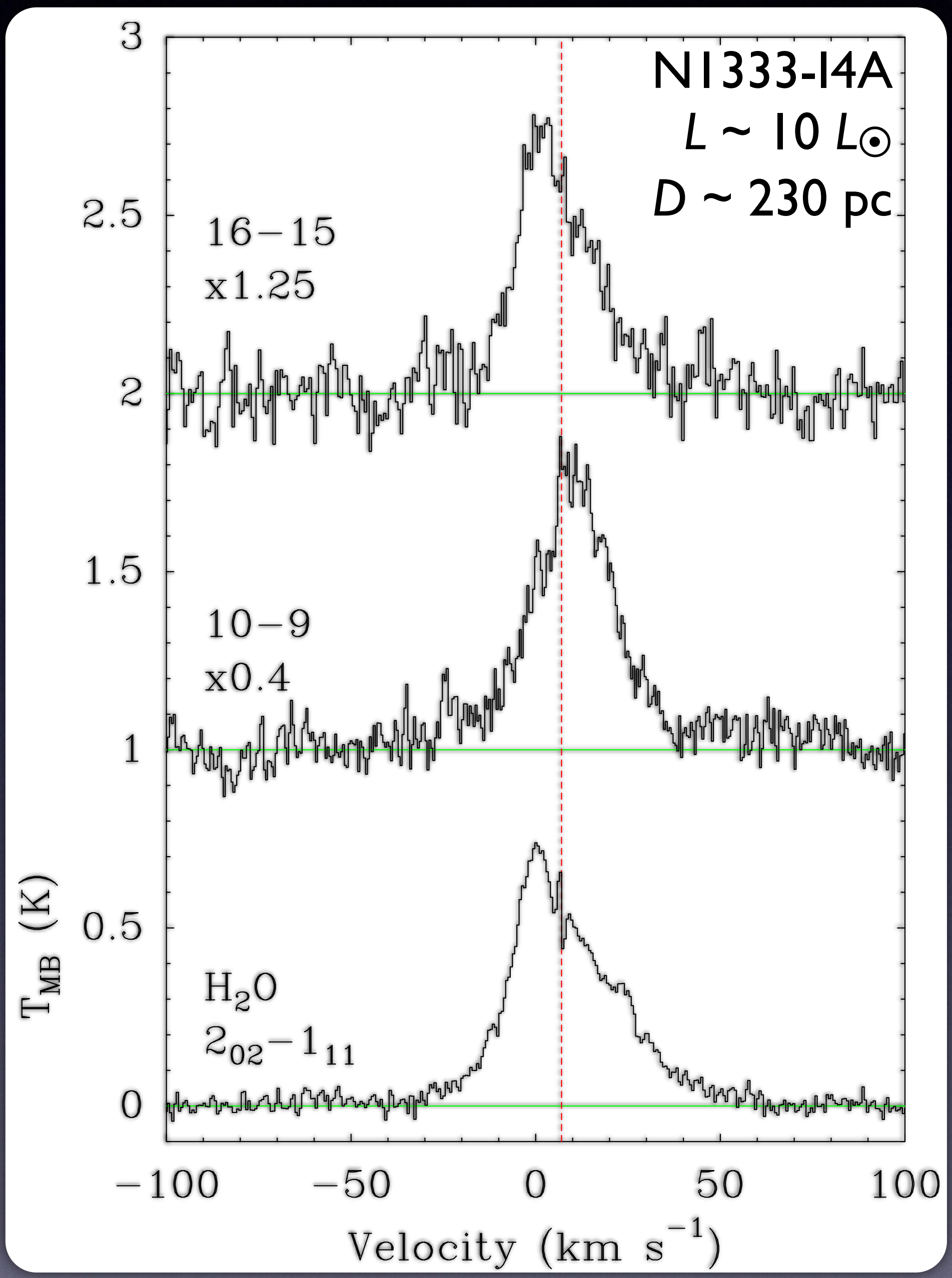
H_2O: subthermally excited

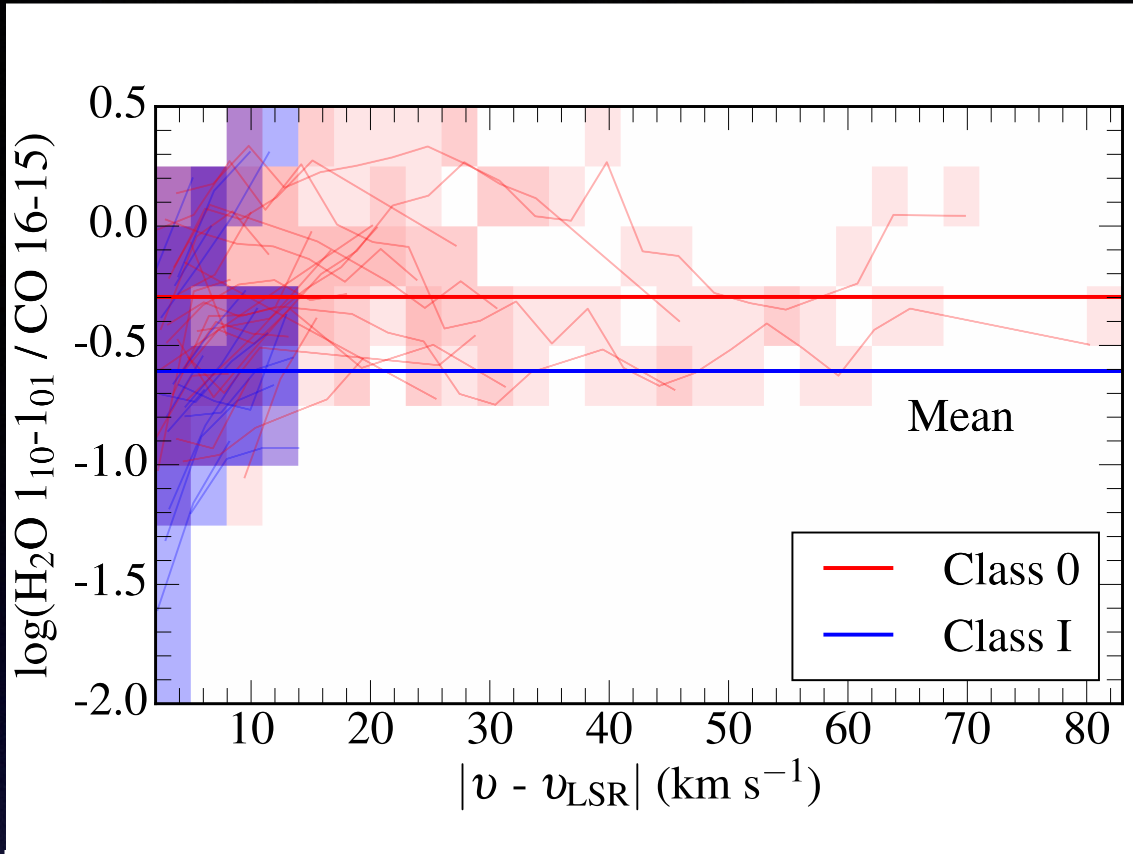
- RADEX excitation analysis
- Conclusion:
  small emitting area (10^2 AU),
  high temperature (~ 300 K),
  high column density (~10^{18} cm^{-2}),
  high density (10^5-10^8 cm^{-3})

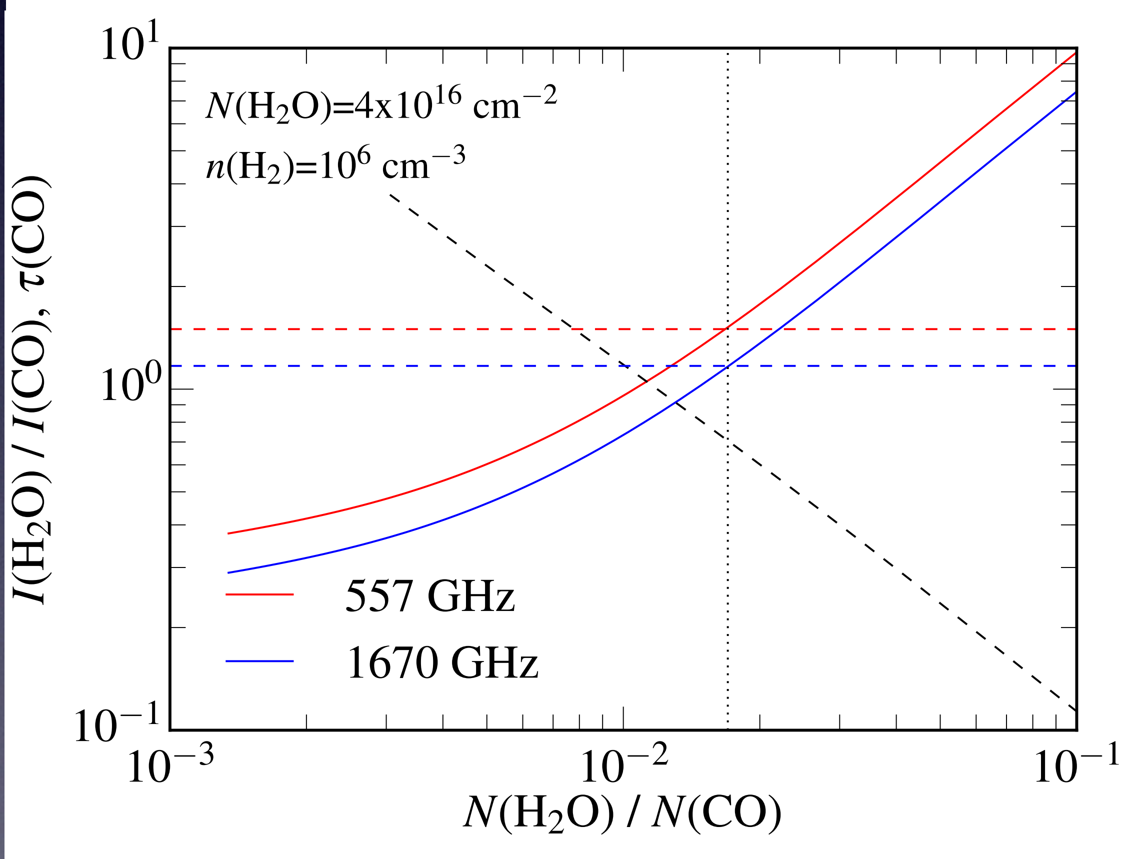


Mottram et al. (2014)

Surprisingly low $X(H_2O)$: ~10-100 times "too little"?



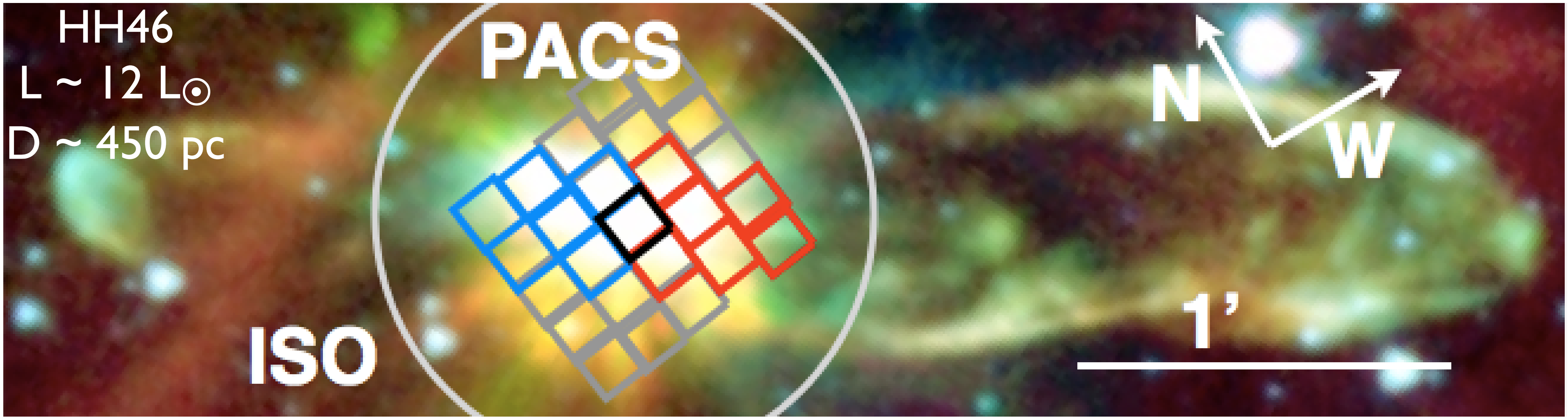




Kristensen et al. 2012, 2017b, Santangelo et al. 2013, 2014, Tafalla et al. 2013, Neufeld et al. 2014

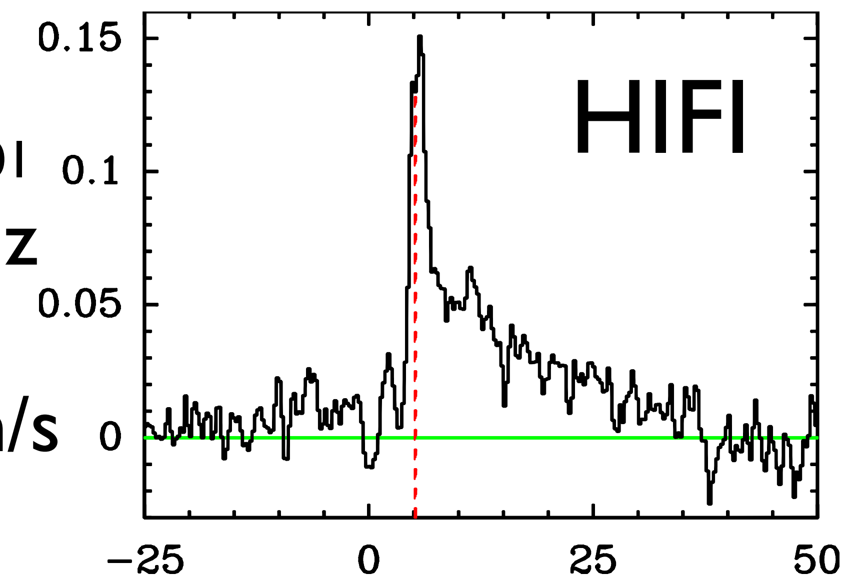
- Where is the oxygen?

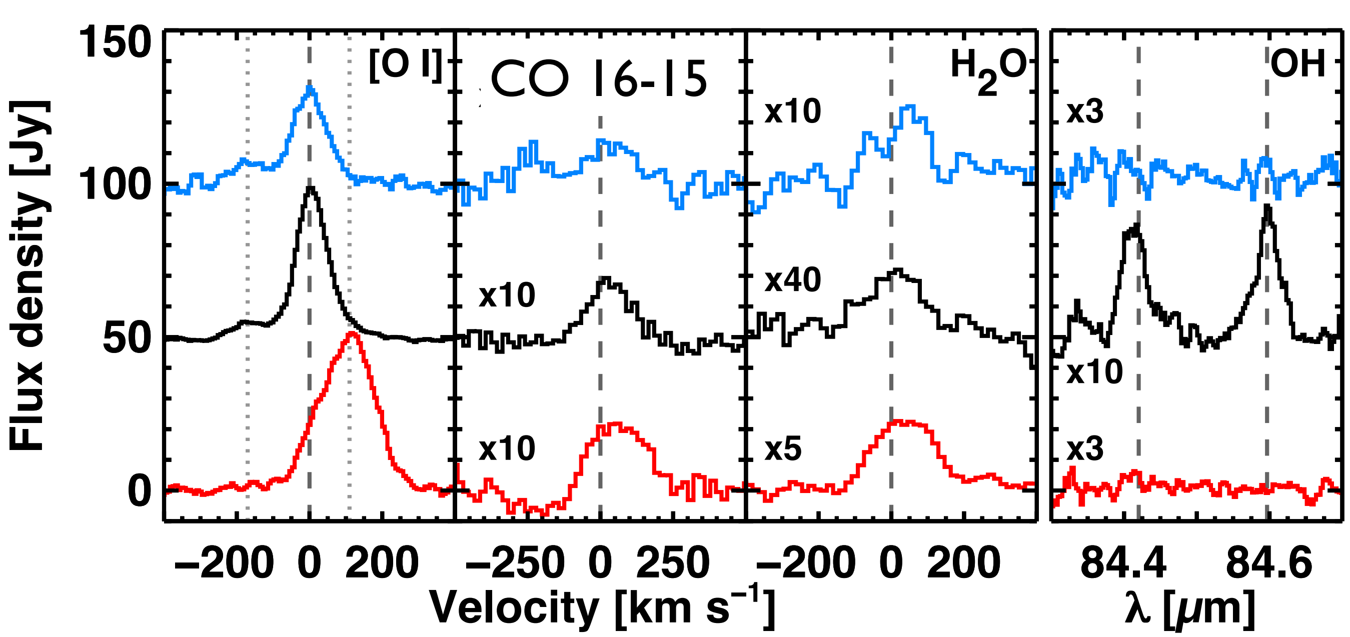
HH46



H_2O 1_{10}-1_{01}
@ 557 GHz

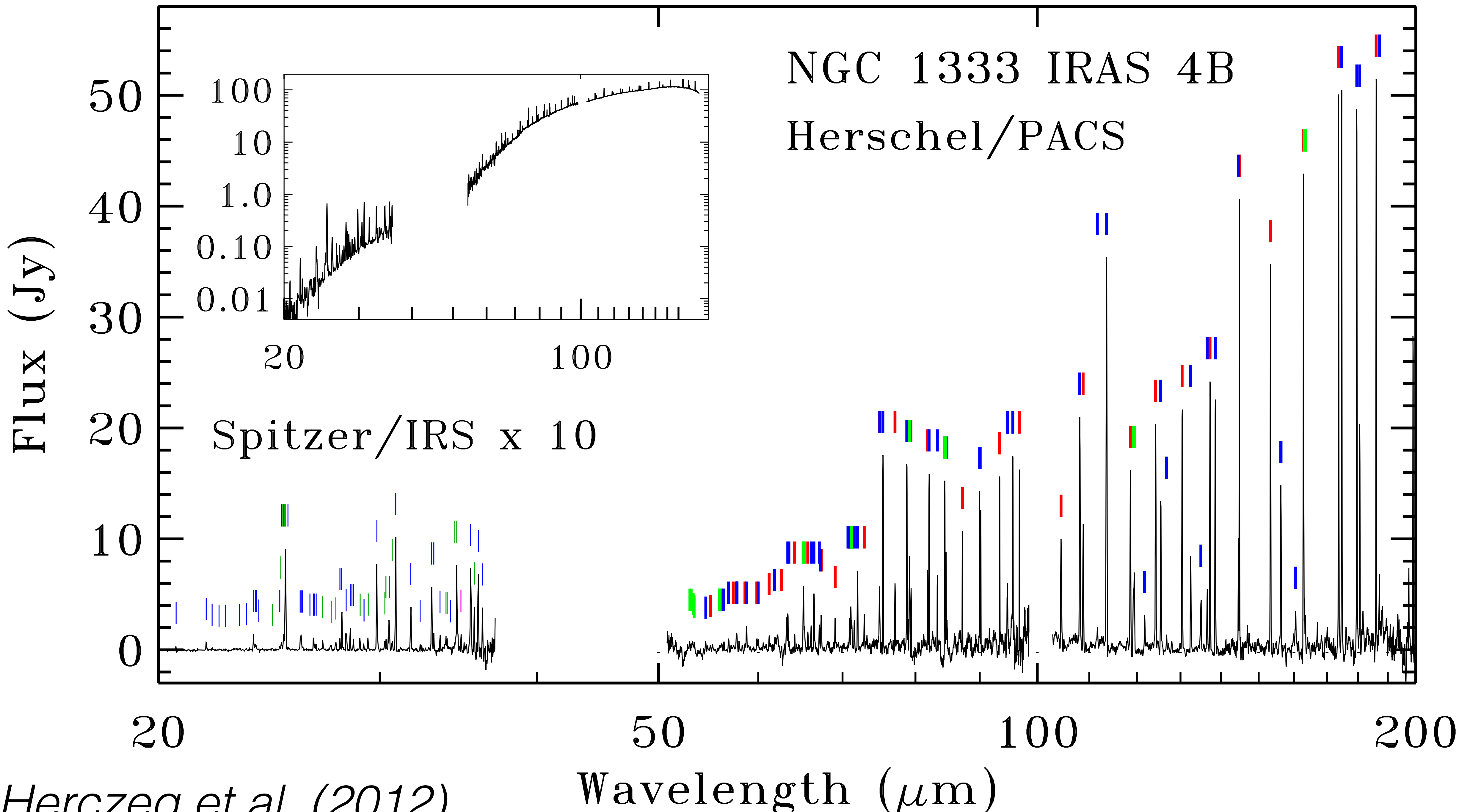
Δv ~ 35 km/s





Kristensen et al. 2012; van Kempen, Kristensen et al. (2010)

Herschel-PACS: FIR inventory



Herczeg et al. (2012)

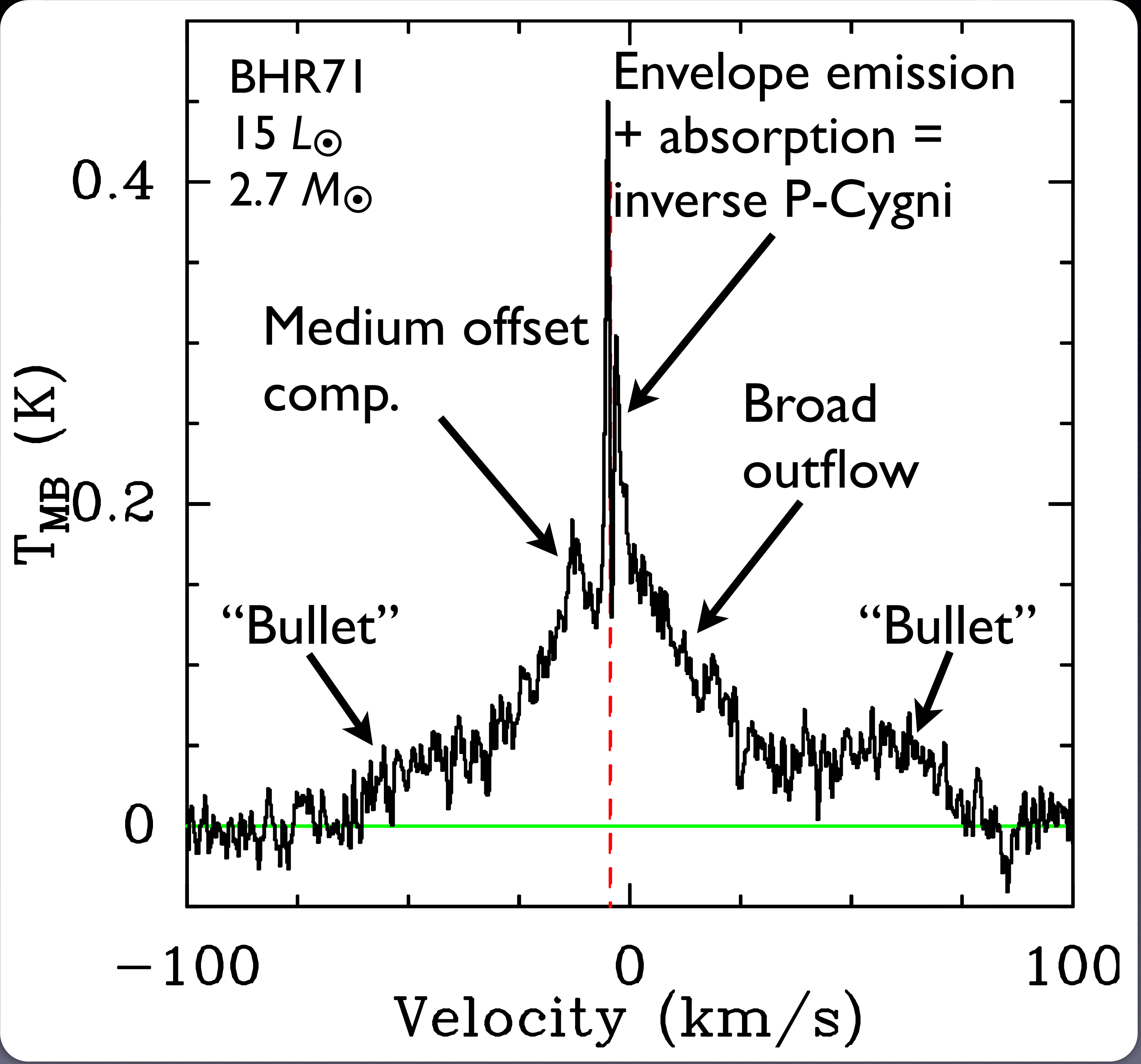
FIR line cooling budget

FIR cooling dominated by O-species
Cooling not chemistry!

Karska et al. 2013, in prep., Podio et al. 2013

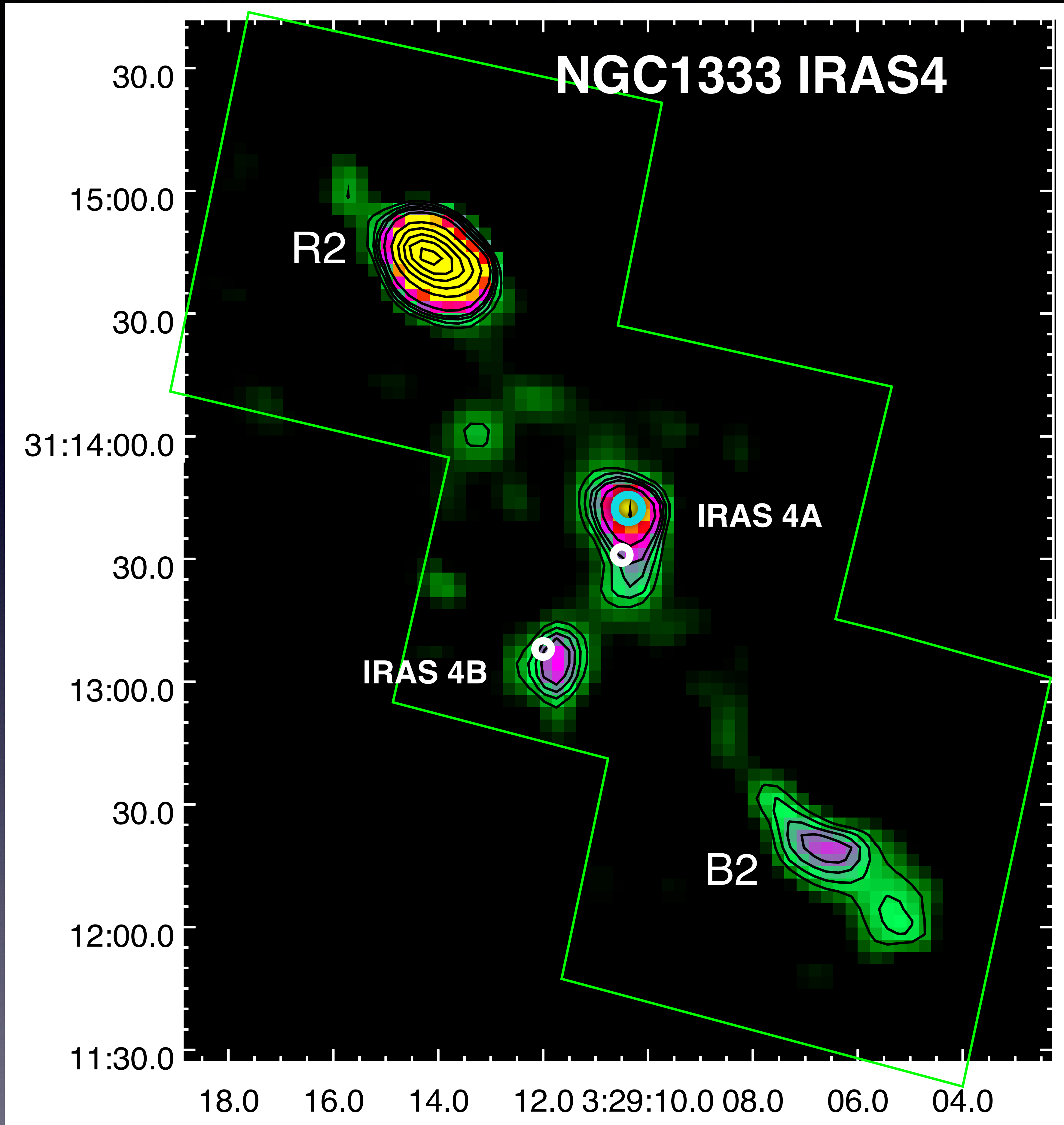
Complex water line profiles

Herschel-HIFI



Kristensen et al. (2012), Mottram et al. (2014)

- Velocity resolution: identifying physical components



[O I] emission lights up at shock spots

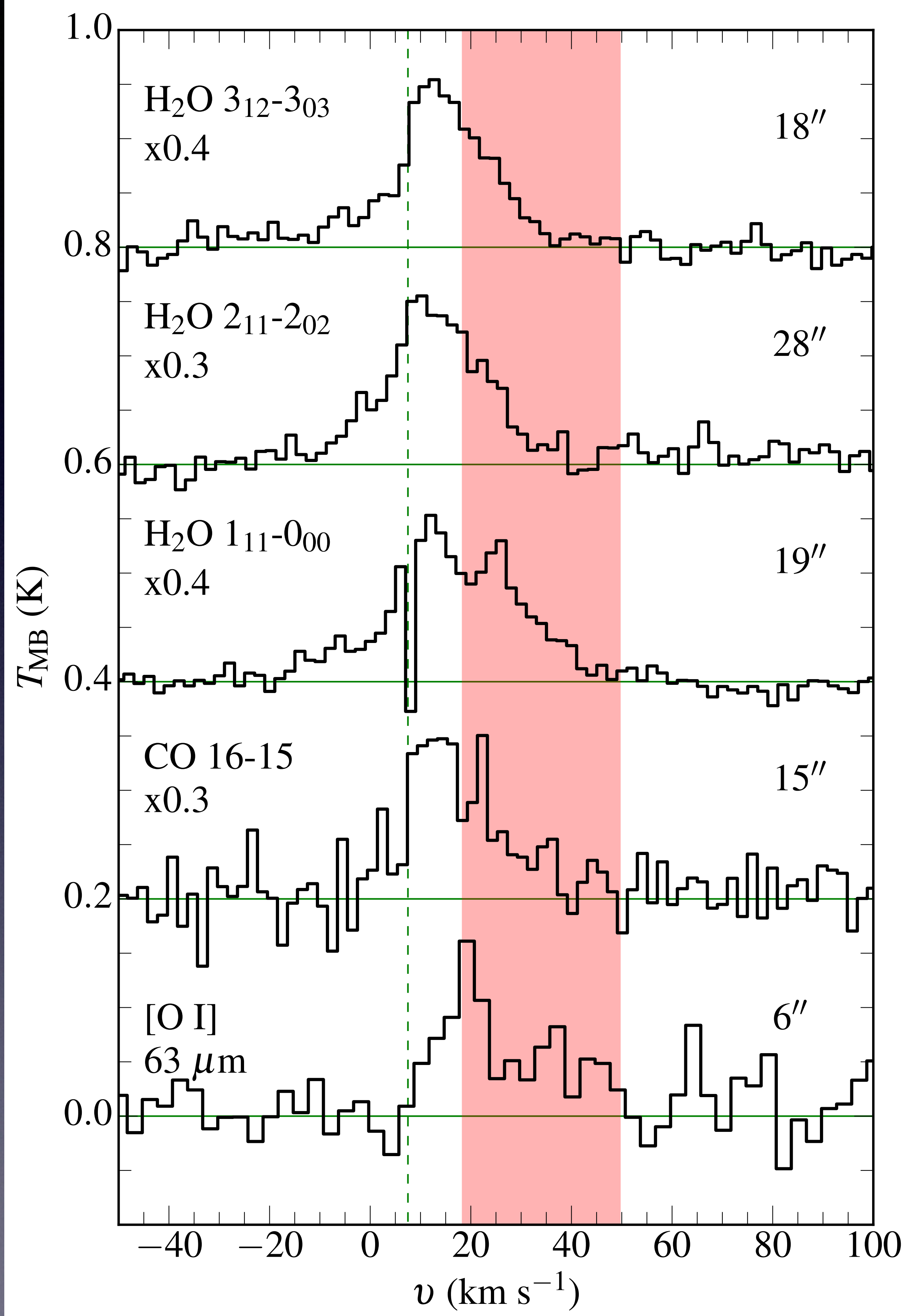
-

but where does [O I] emission come from?

Nisini et al. 2015

Enter SOFIA-GREAT!

- [O I] 63 μm detected at R1 position
- *Only* seen in high-velocity component!
- HV component also seen in CO 16-15 (GREAT) and H_2O (HIFI)



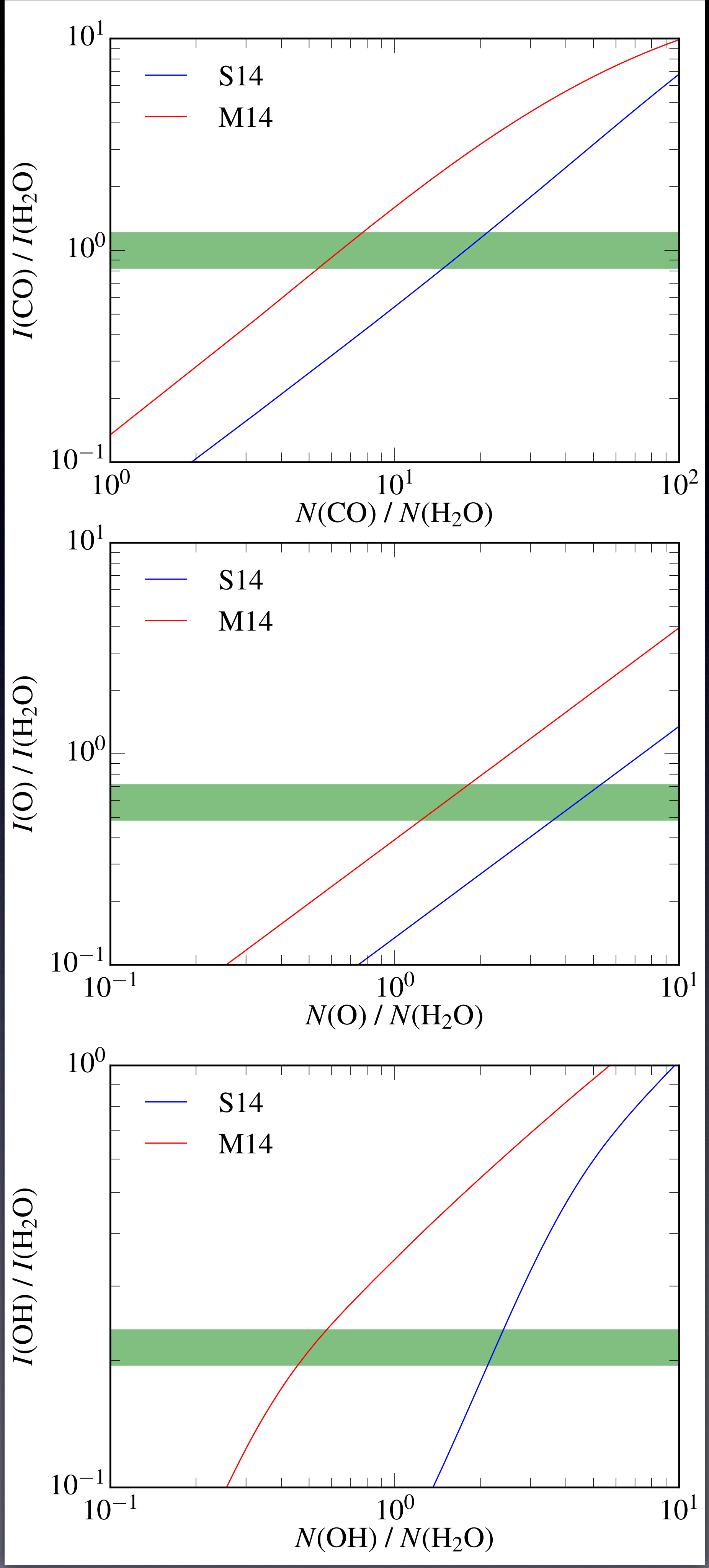
Kristensen et al. 2017a

Excitation -> Oxygen budget

- **Recipe**:
  Assume excitation from H_2O
  Apply to CO, < OH, and O
  Get *N*(CO), *N*(OH), *N*(O)
  Assume $X(O)_{volatile} = 3\ 10^{-4}$
  Calculate *X*(M)

- $X(H_2O) \sim 3\ 10^{-5}$
  $X(CO) \sim 2\ 10^{-4}$
  $X(OH) < 2\ 10^{-5}$
  $X(O) \sim 5\ 10^{-5}$

Kristensen et al. 2017a



Low *X*(O) at high v: what does it mean?

- Atomic O is ~15% of total O budget at high v, ~85% molecular and primarily CO
- Volatile C/O ratio ~0.7
- Do the youngest sources host atomic/ionic jets? Why so much molecular material? Reformation, or molecular from the start? Implications for outflow energetics? mass loss rates and infall rates? ***One spectrum, one paper, many new questions!***

What have we learnt?

- **Lesson I:** SOFIA-GREAT is delivering beautiful [O I] 63 μm spectra!
- **Lesson II:** Toward one shock position, [O I] traces only the high-velocity component and the bulk of O is in molecular form
- **Lesson III:** Systematic surveys are needed: do lessons from one source apply elsewhere?
(Accepted C5 proposal: two new spectra not yet delivered, two more papers?)