Protostellar outflows:
Lessons from Herschel and ALMA

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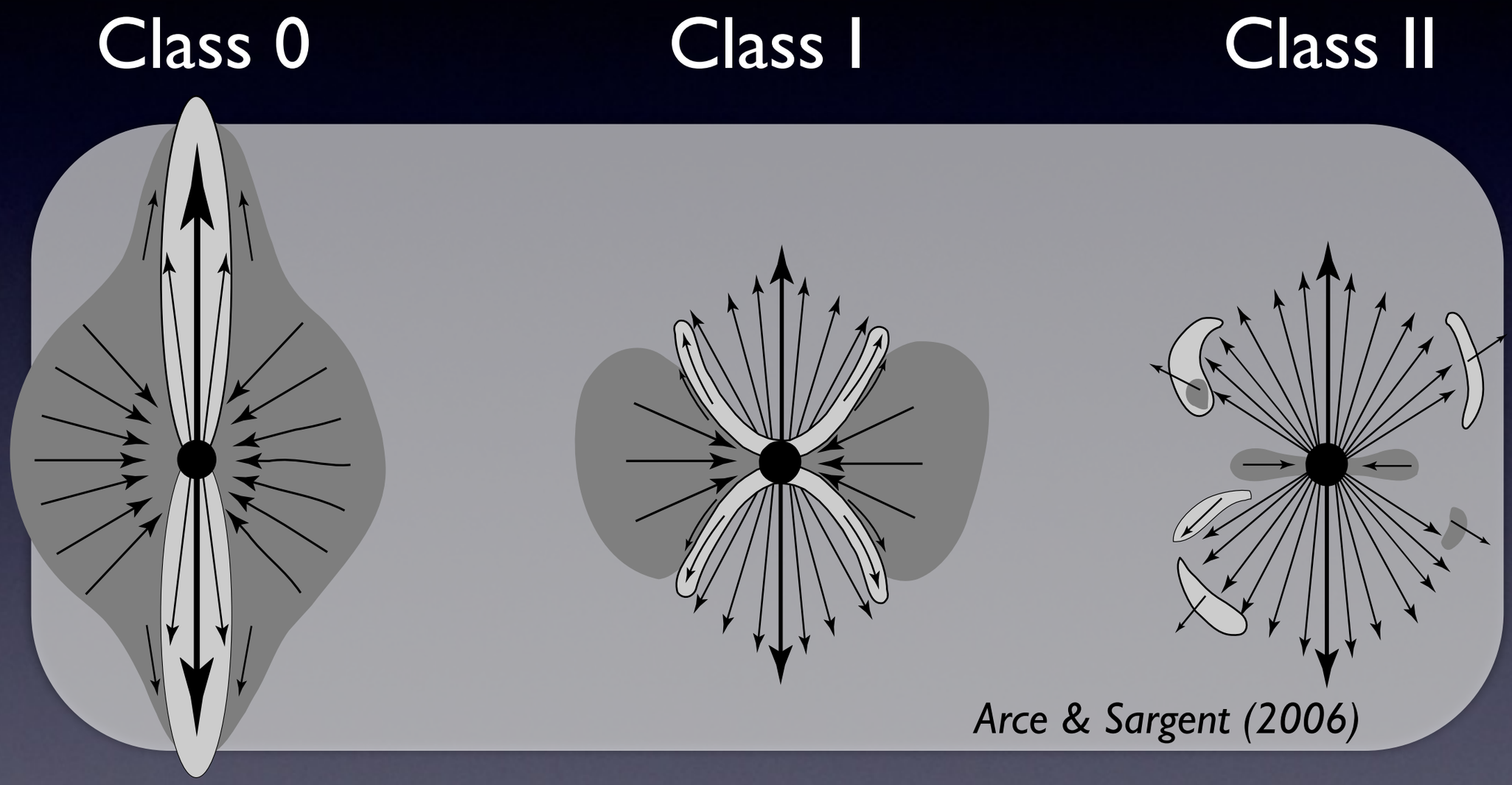
With many thanks to E.F. van Dishoeck, J.C. Mottram and the entire WISH team

Arce et al. 2012, ALMA CO + NTT optical image of HH46/47

Low-mass YSO evolution



Jet / wind driving outflow present at all evolutionary stages

Outflows matter

- **Feedback agent**: turbulent injection, open cavities where UV escapes, heat surrounding material, …
- **Determines IMF**: removes angular momentum from collapsing protostar, removes mass, changes disk dynamics, …
- **Chemical catalyst**: through heating + UV changes chemical properties, ice composition, …

Lesson 1:

Water is the best shock/outflow tracer we currently know of: it traces a 300K component not seen from the ground

Lesson 2:

Outflows are more energetic than pre-Herschel/ALMA observations revealed and shocks are predominant

Lesson 3:

High angular resolution + sensitivity required for completing the dynamical picture of winds + outflows

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Why is water so effective a shock tracer?

O

H_2O

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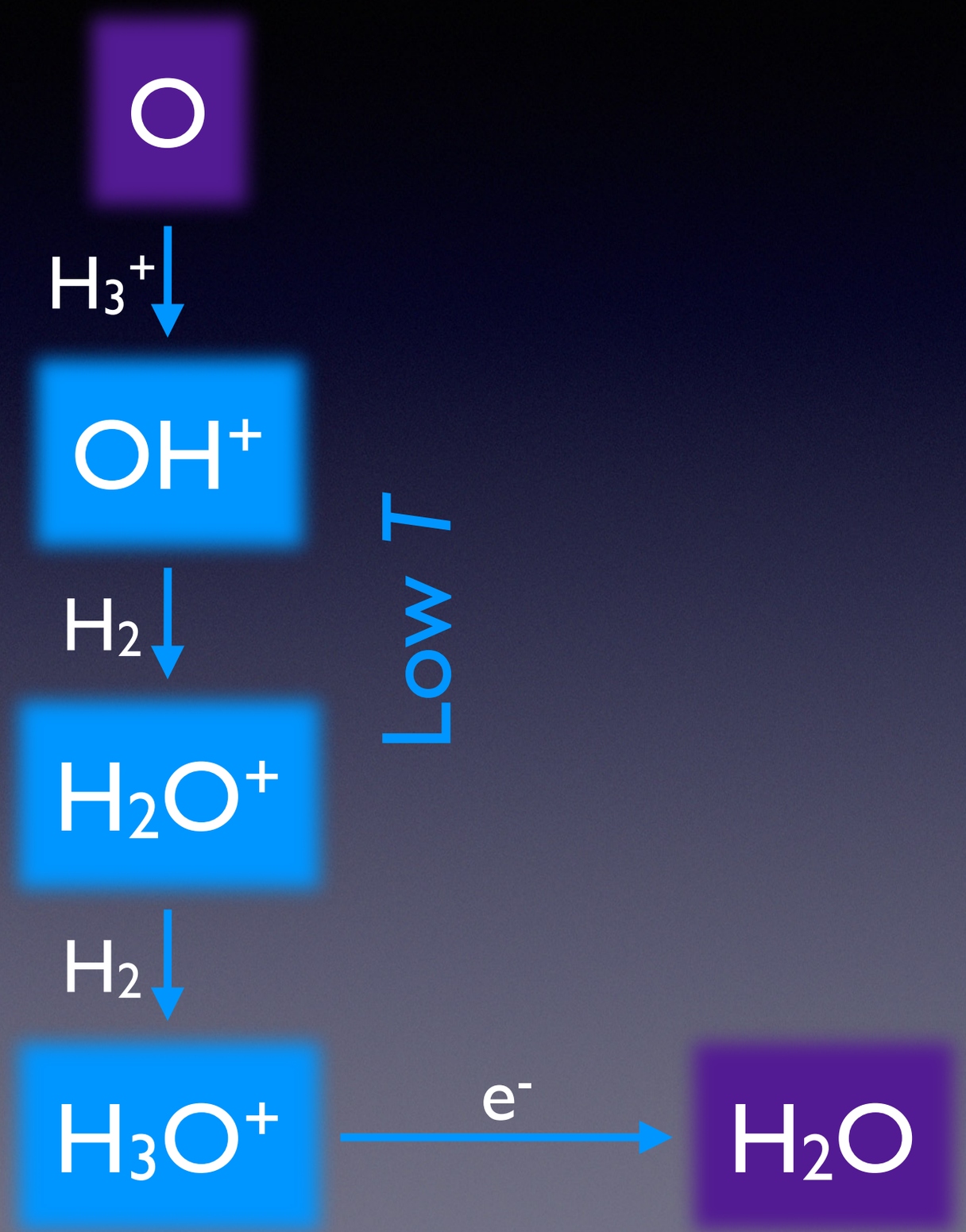

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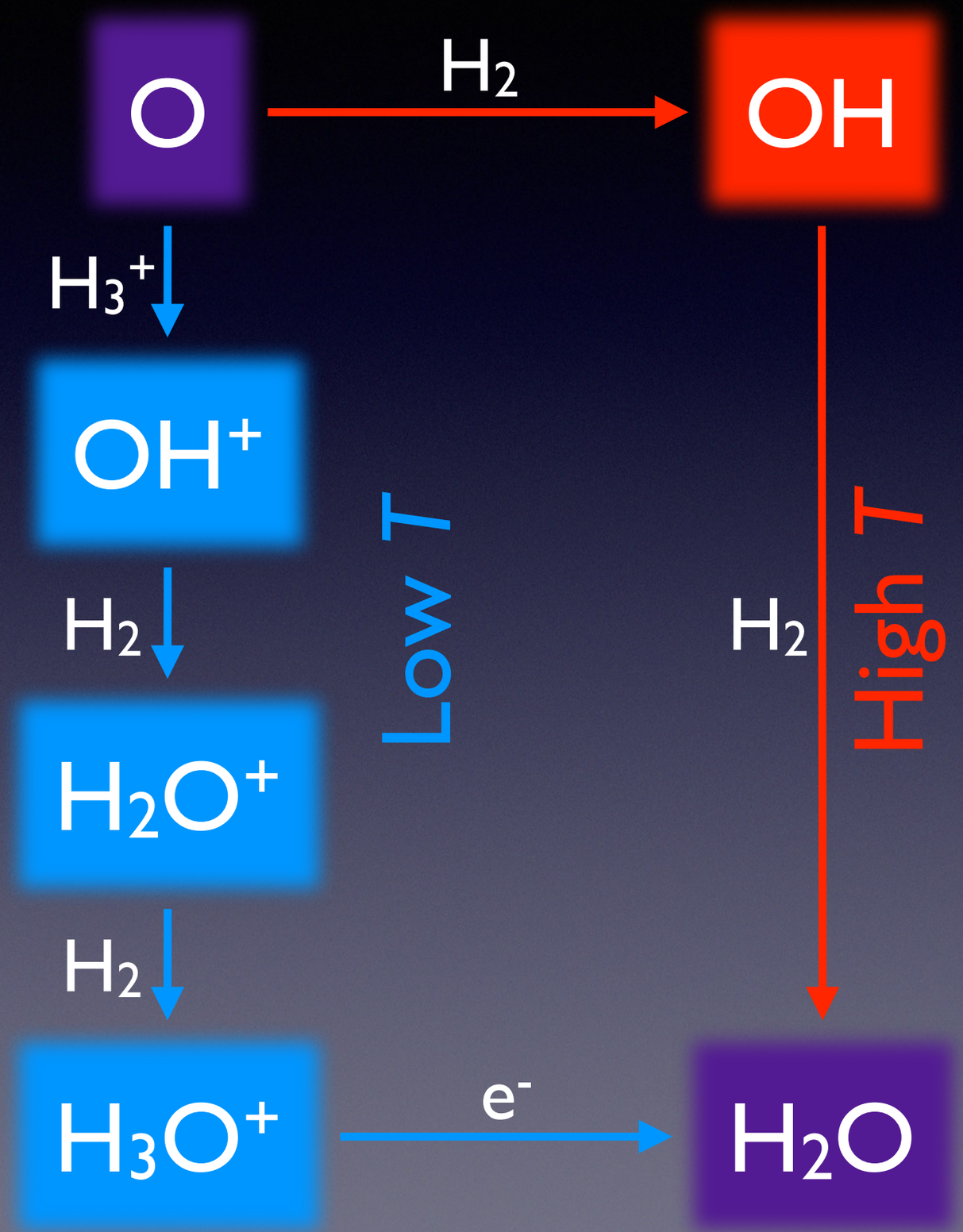

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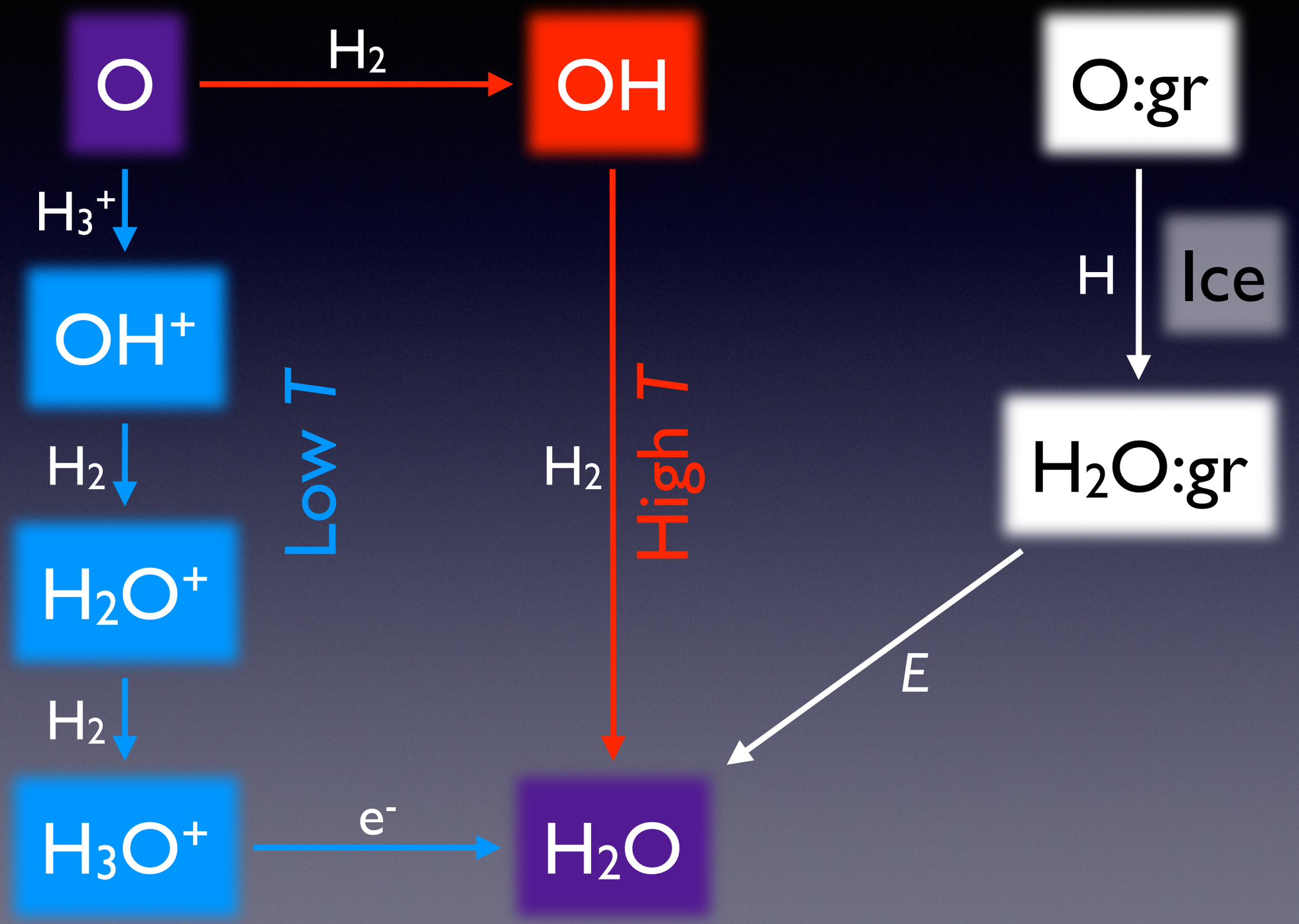

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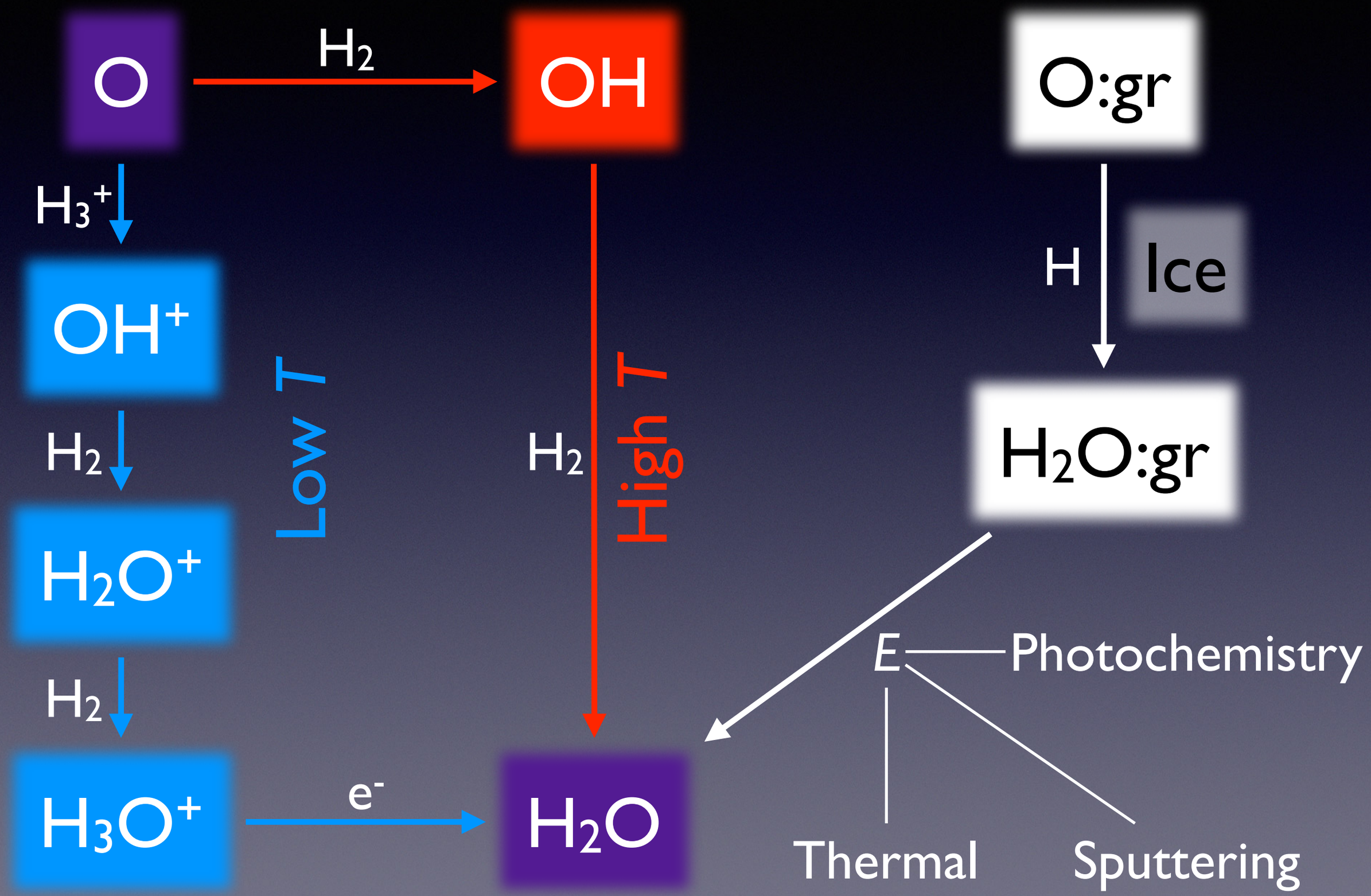

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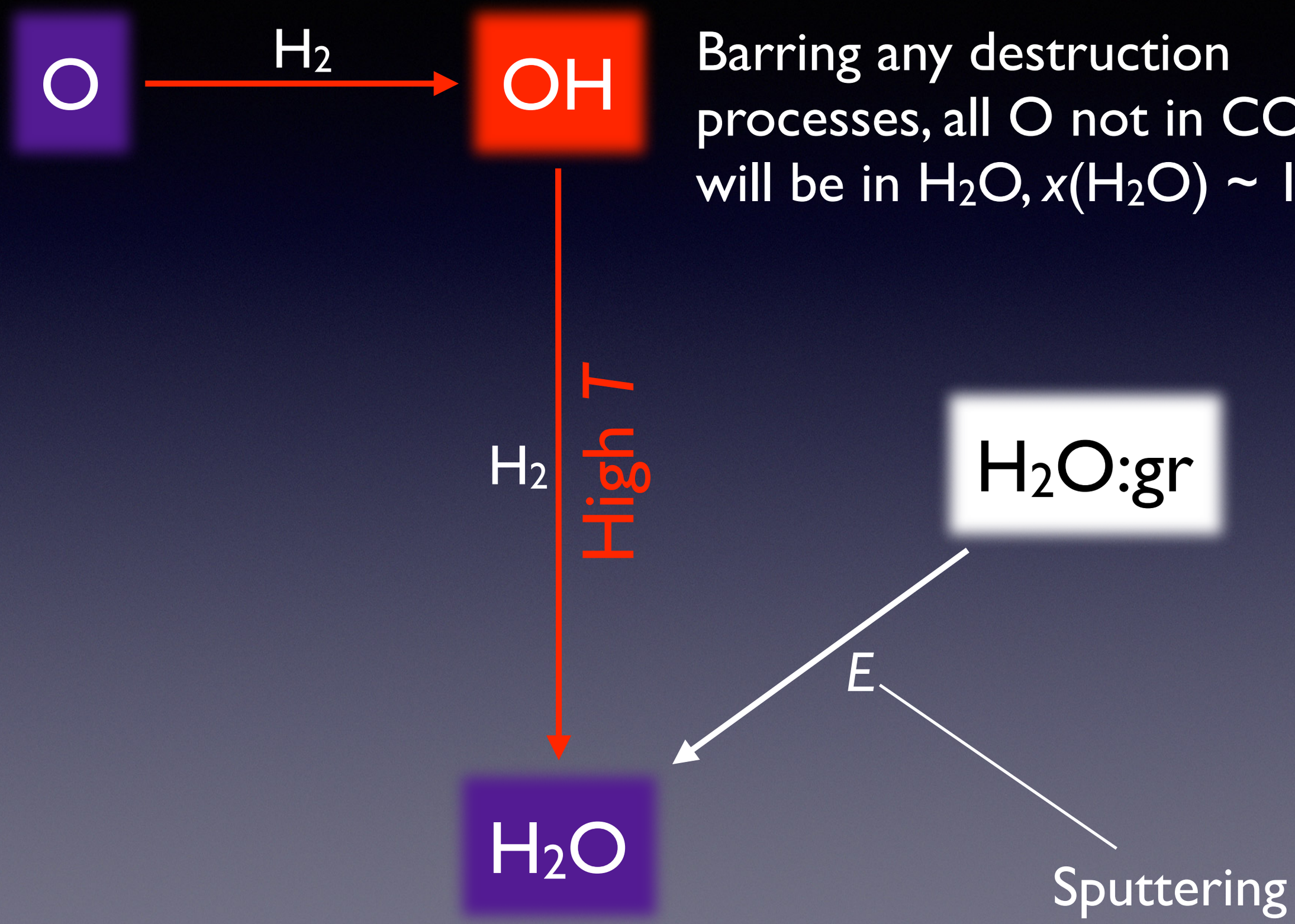
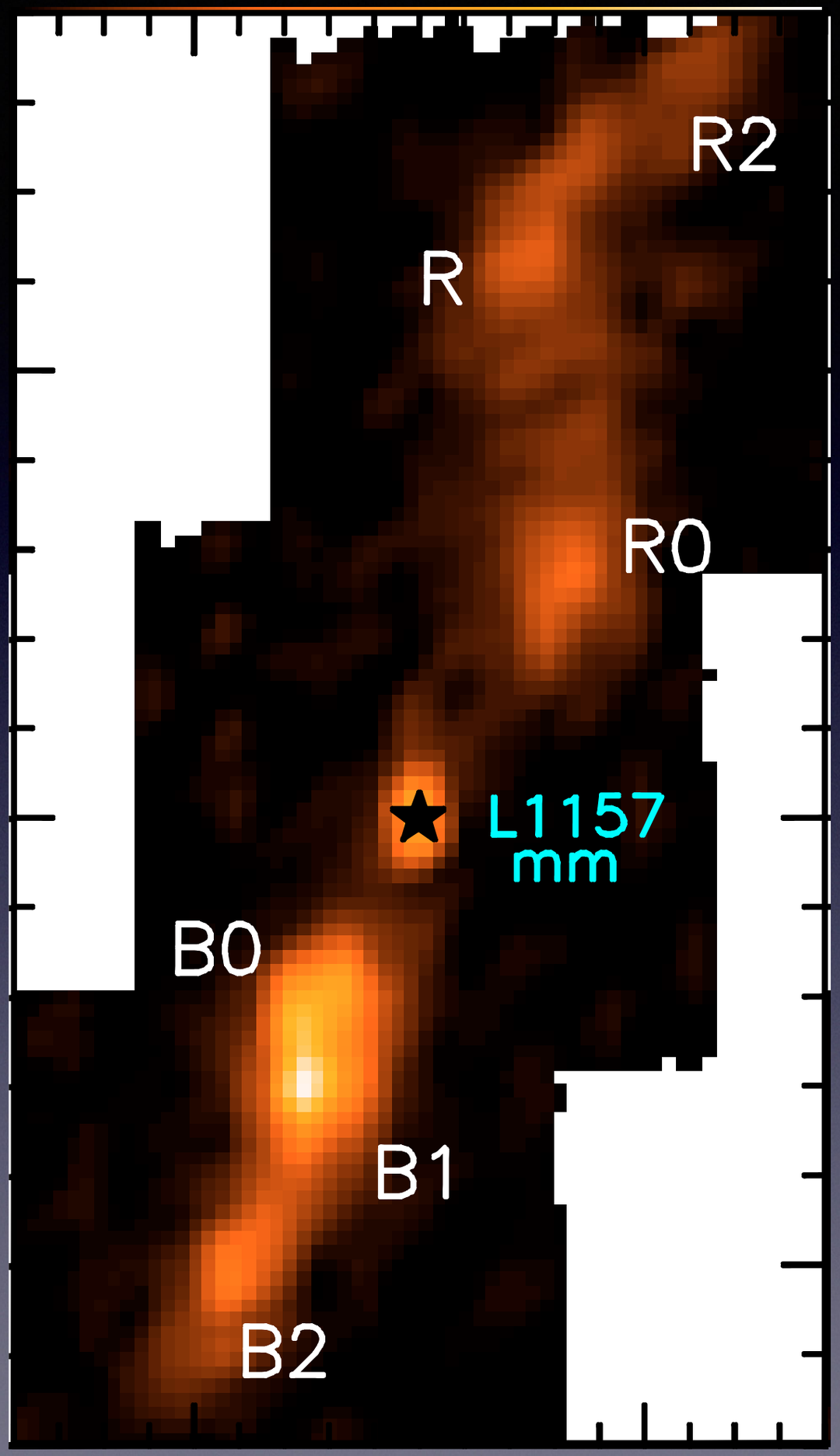


Barring any destruction processes, all O not in CO will be in H_2O, $x(H_2O) \sim 10^{-4}$

H_2O is not CO

- Low-J CO (E_{up}/k_B < 50 K) traces cold entrained outflow
- No spatial overlap between low-*J* CO and H_2O: not tracing same outflow component



Nisini et al. 2010, Bjerkeli et al. 2011, 2012, 2013, Santangelo et al. 2012, 2013, 2014, Vasta et al. 2012, Tafalla et al. 2012, Lefloch et al. 2010, Codella et al. 2010

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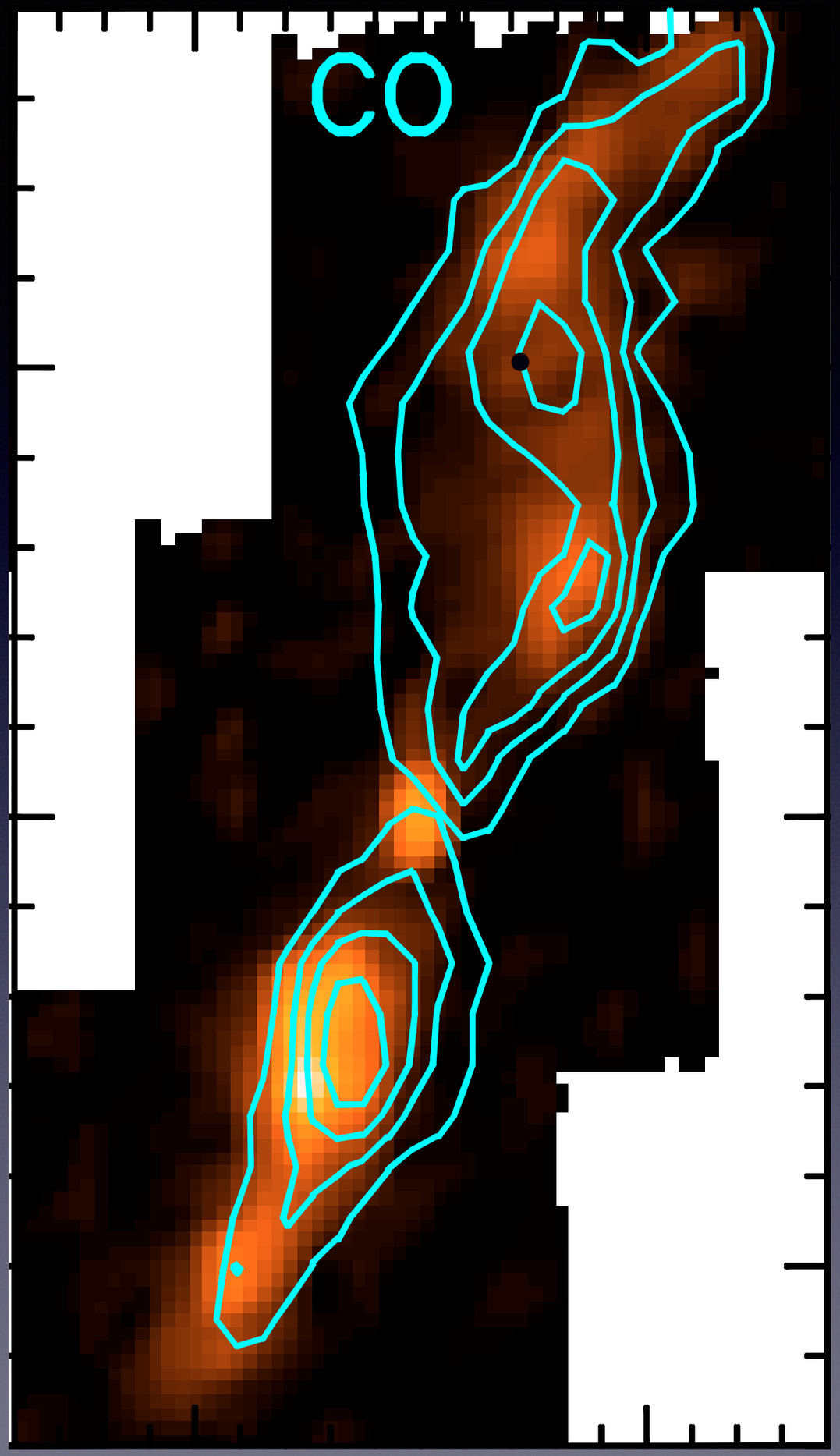

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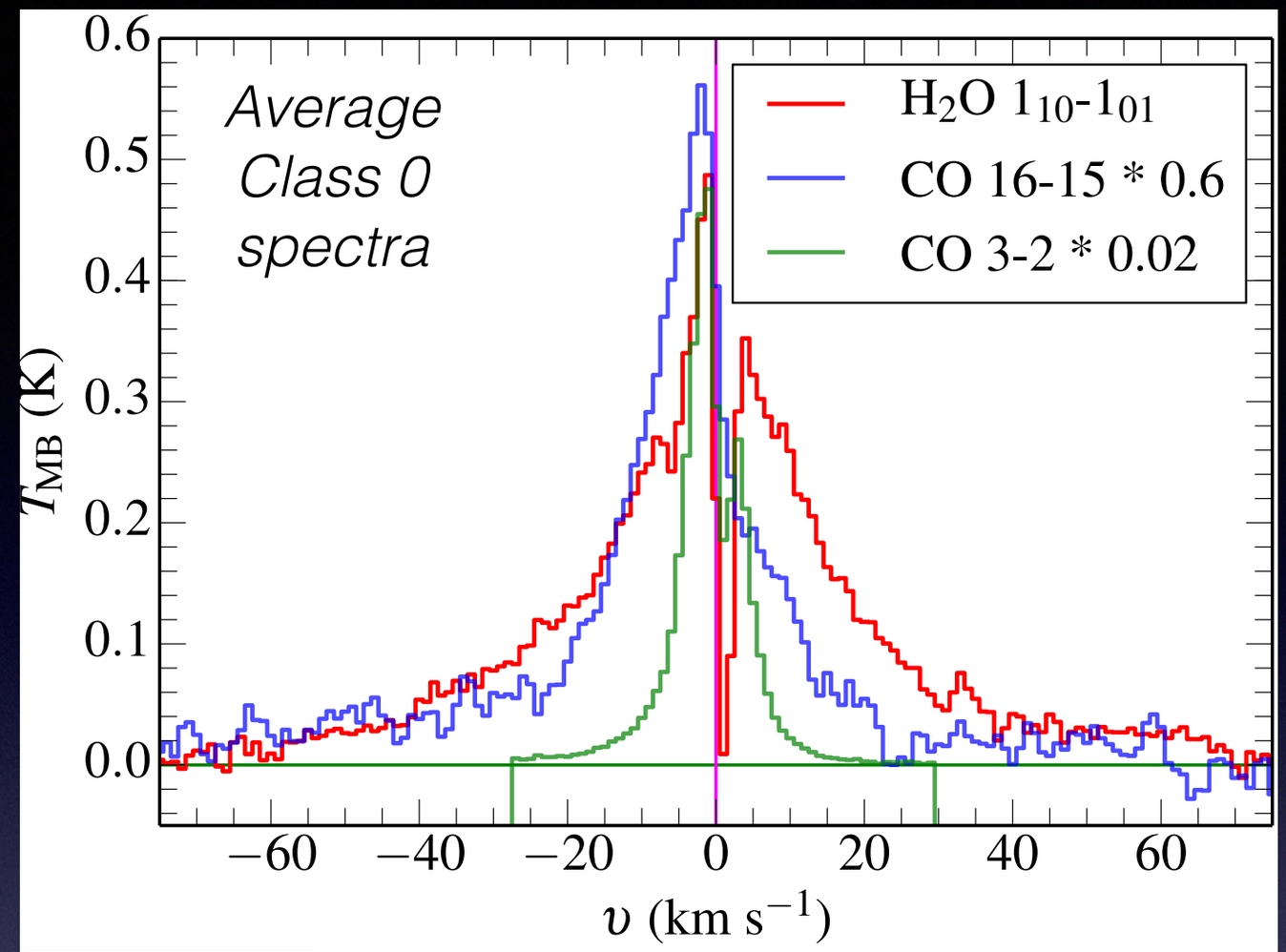
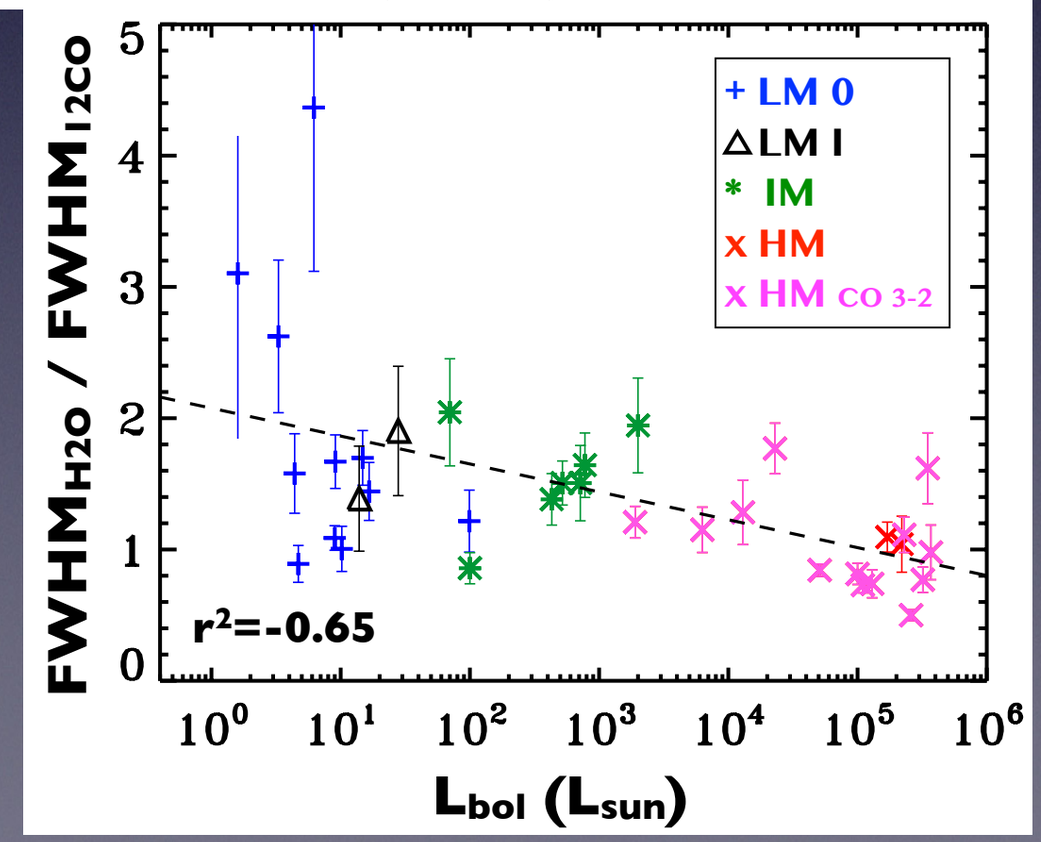
H_2O moves differently than CO

- Lower contrast between high- and low-v material
- CO varies with excitation: higher-*J* CO has more momentum and energy



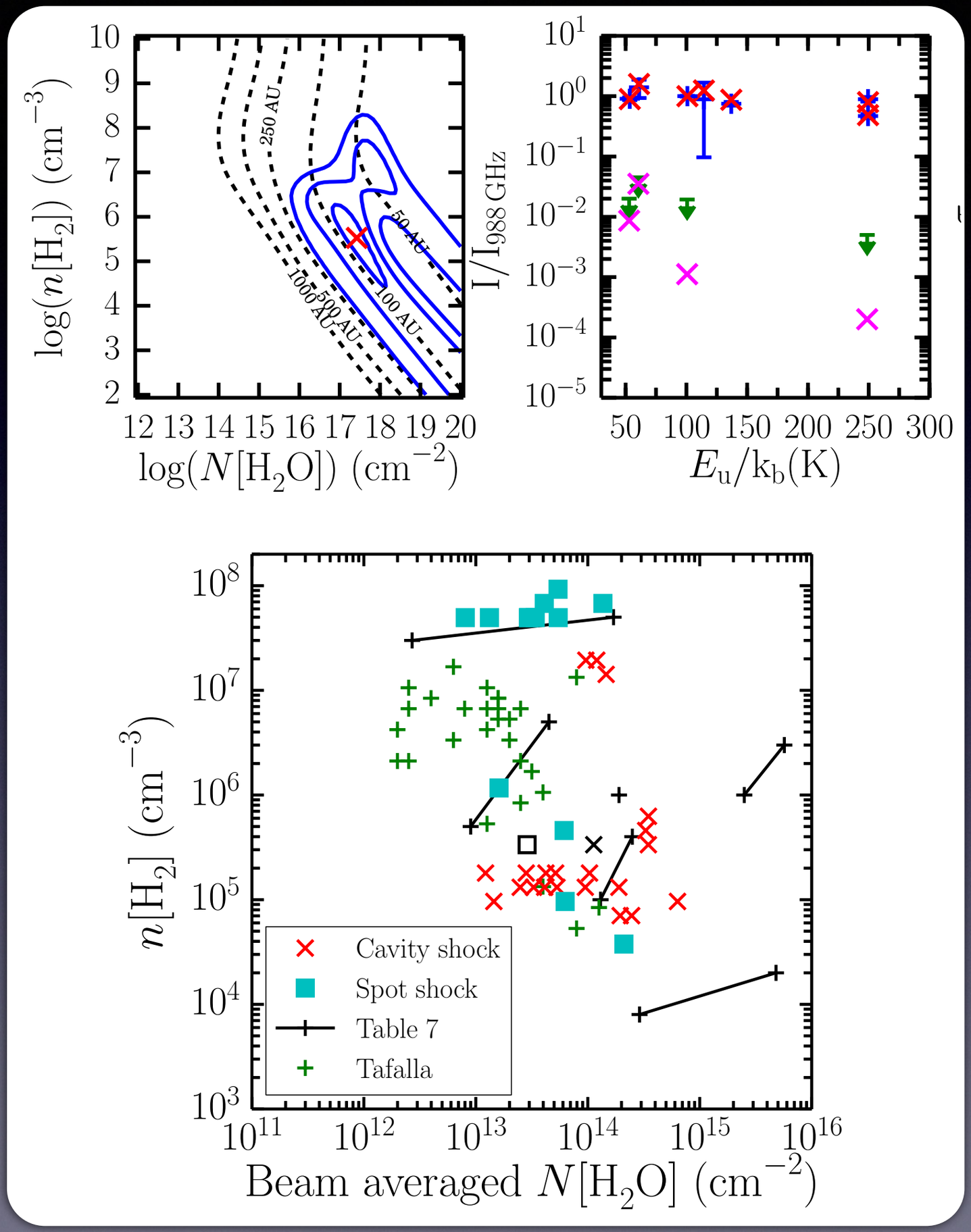


Kristensen et al. in prep.
San Jose-Garcia et al. 2012, in prep.

H_2O is warm and dense

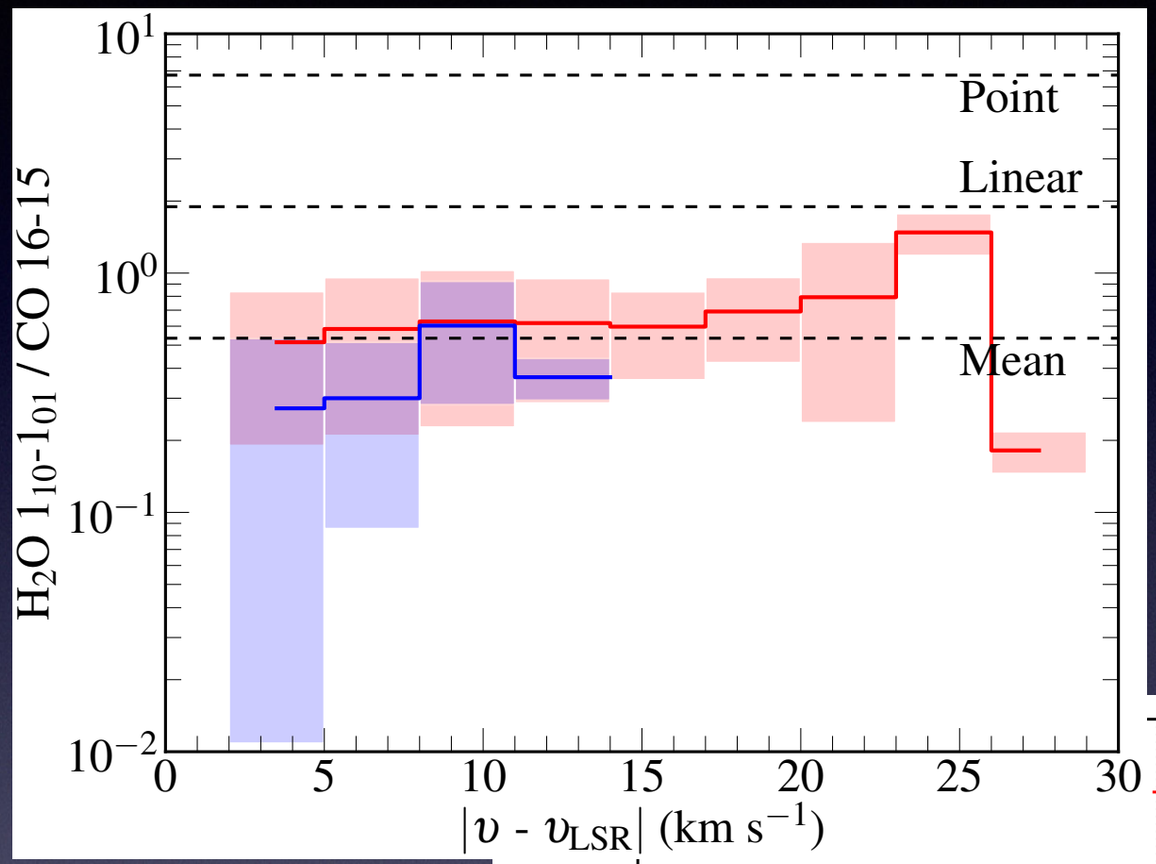
- H_2O follows CO 16-15: excitation in 300 K gas
- High dipole moment: excitation in dense gas
- Collisional excitation, even close to the central protostar

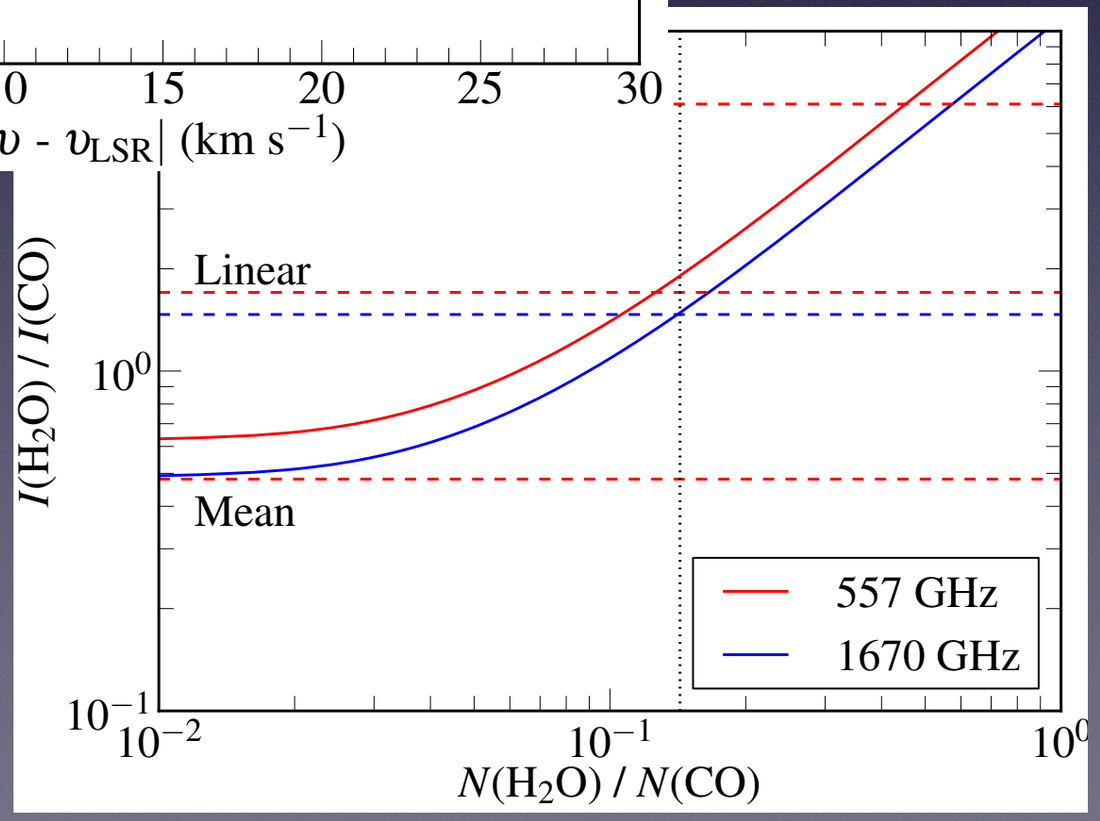
Kristensen et al. 2010, 2012, in prep., Mottram et al. 2014, Bjerkeli et al. 2011, 2012, 20213, Santangelo et al. 2012, 2013, 2014, Vasta et al. 2012, Tafalla et al. 2012, Lefloch et al. 2010, Codella et al. 2010



Water abundance

- CO 16-15 as reference frame: x(H_2O) constant with velocity
- At source position: x(H_2O) ~ 10^{-5}
- At outflow position: x(H_2O) ~ 10^{-7} - 10^{-5}
- Lower than expected: UV photodissociation?





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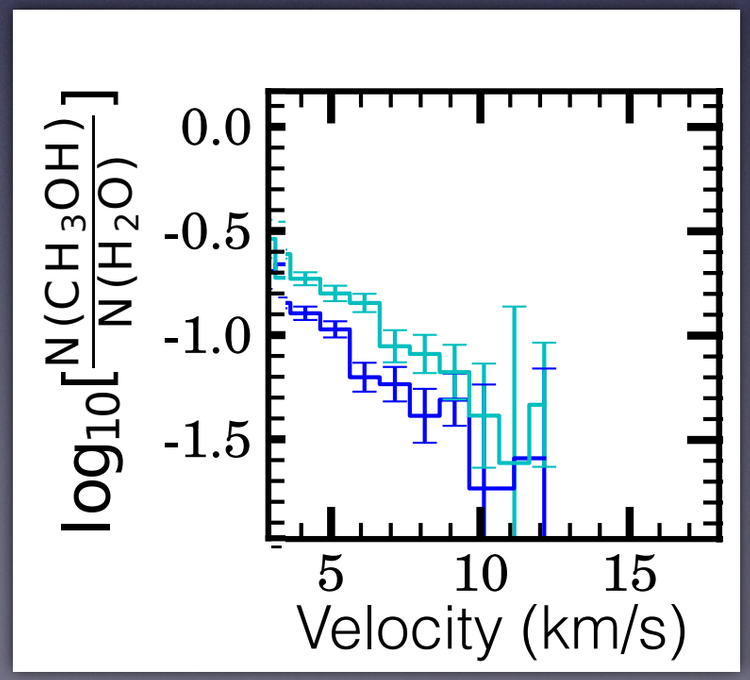
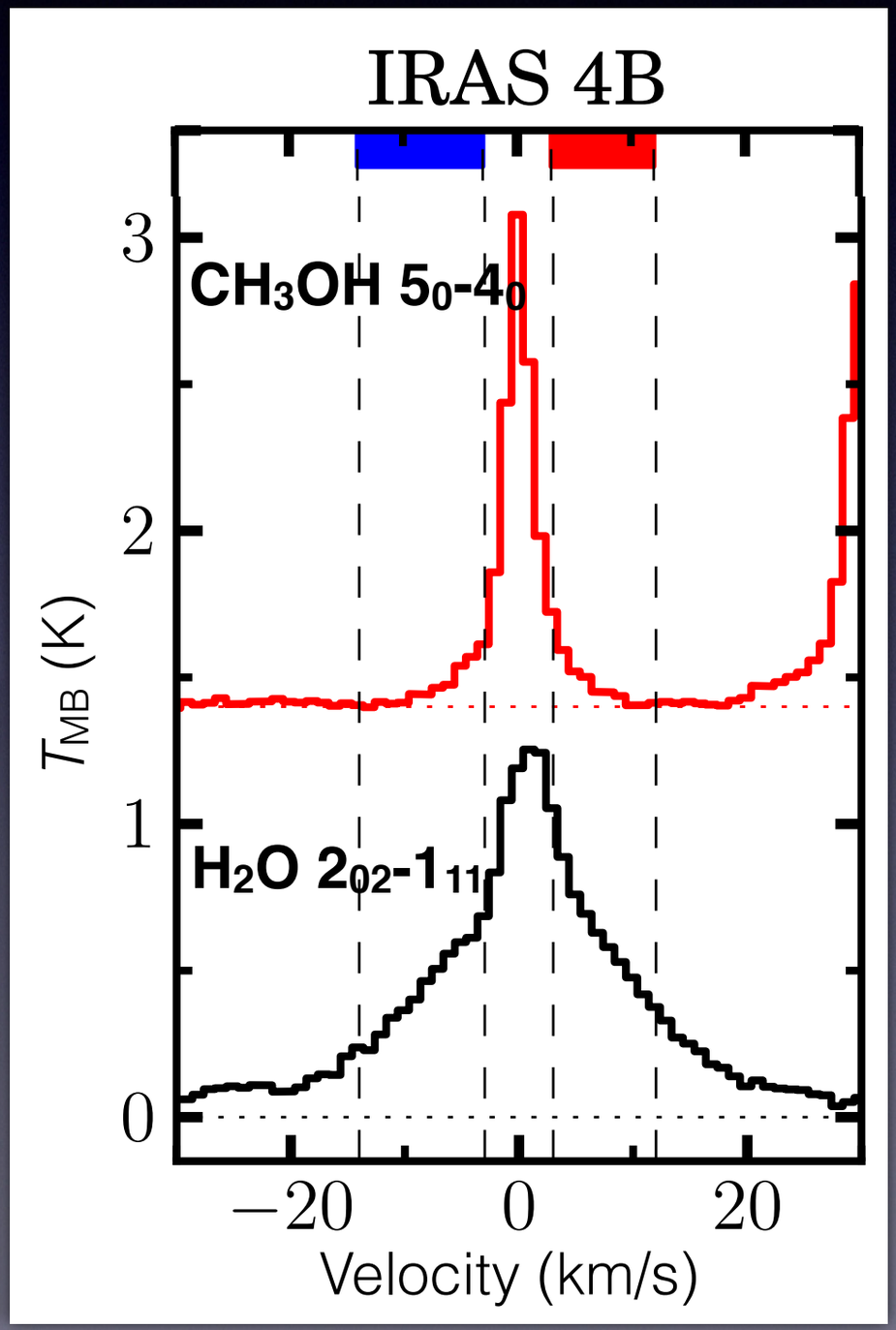
Water chemistry: sputtering & gas-phase synthesis

- CH_3OH and H_2O: grain products released through sputtering
- H_2O: also efficient gas-phase route
- Comparison: 90-99% of molecules destroyed in sputtering process, H_2O reforms at high velocities



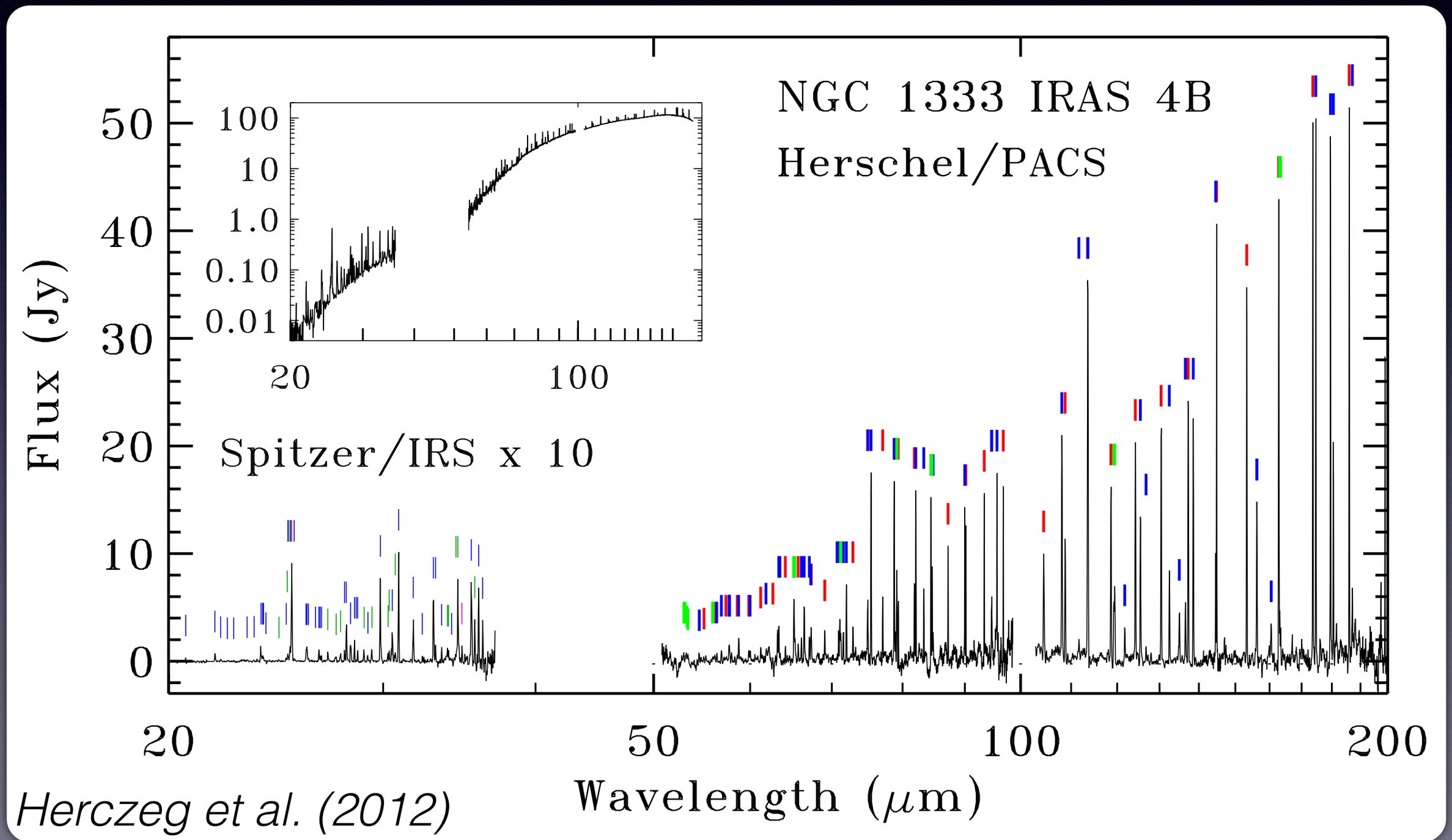


Suutarinen et al. 2014

Lesson 2:

Outflows are more energetic than pre-Herschel/ALMA observations revealed and shocks are predominant

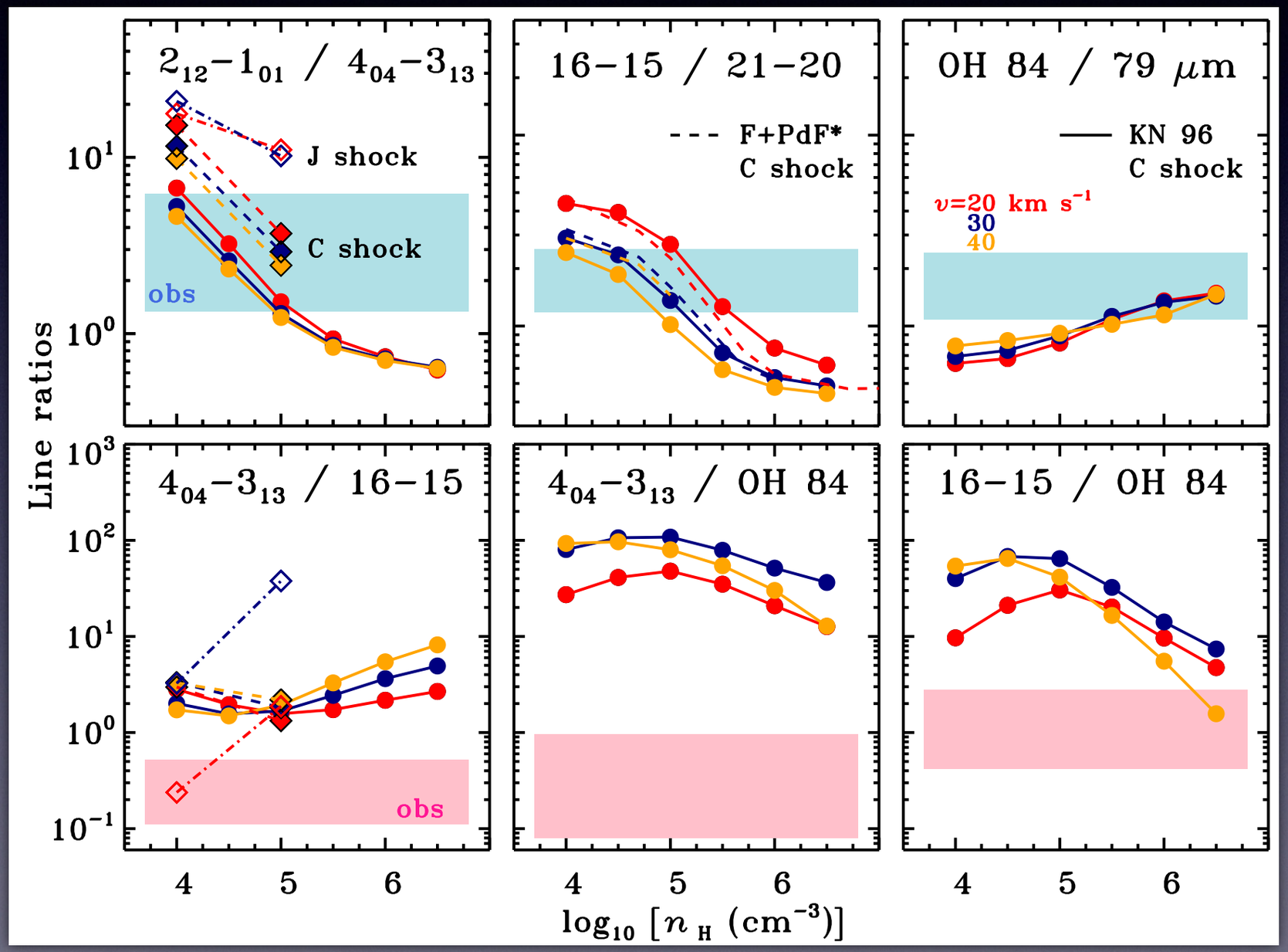
CO, H_2O, OH: dominant coolants and probes



Herczeg et al. (2012)

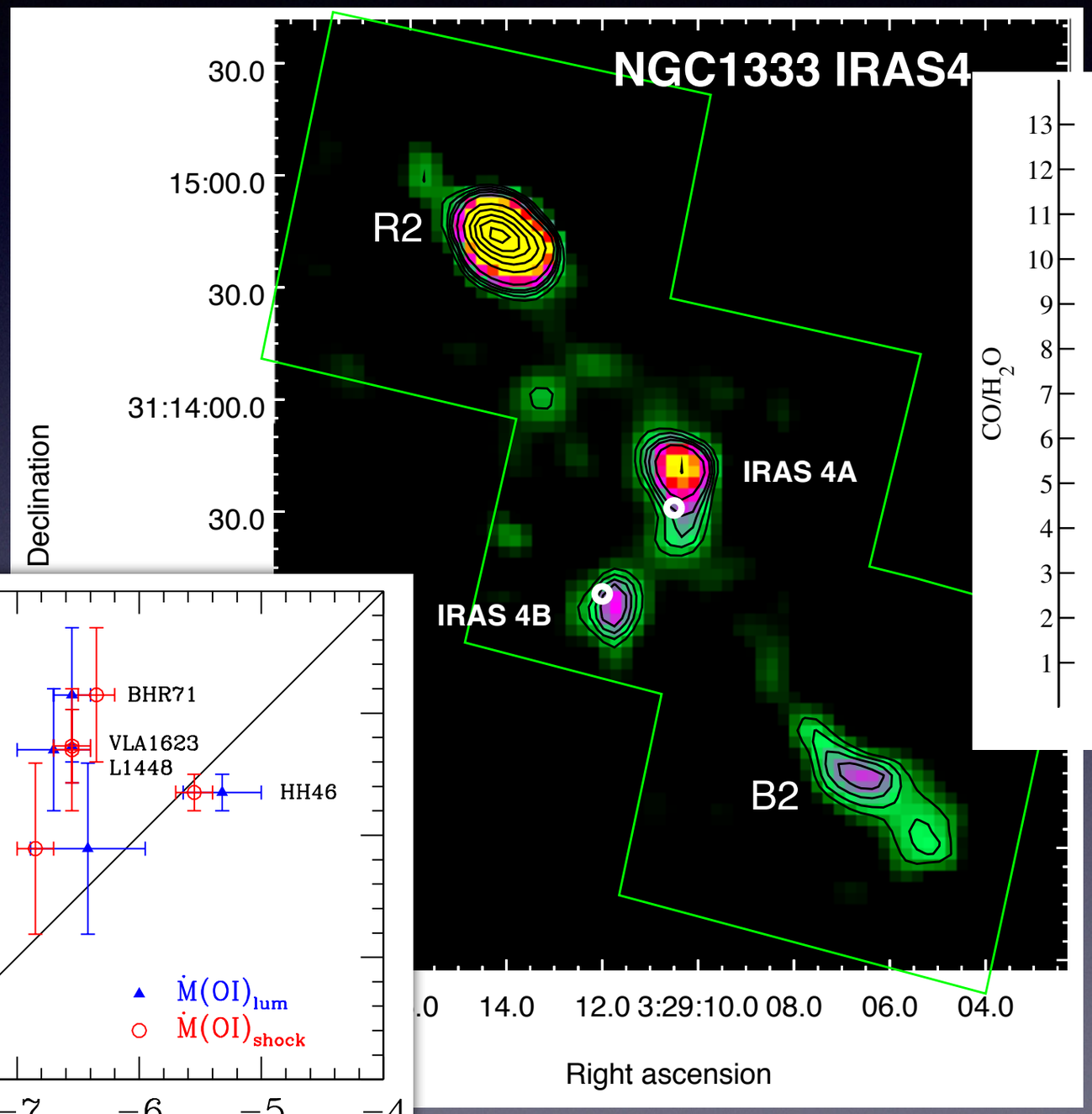
Shocks dominate FIR cooling lines

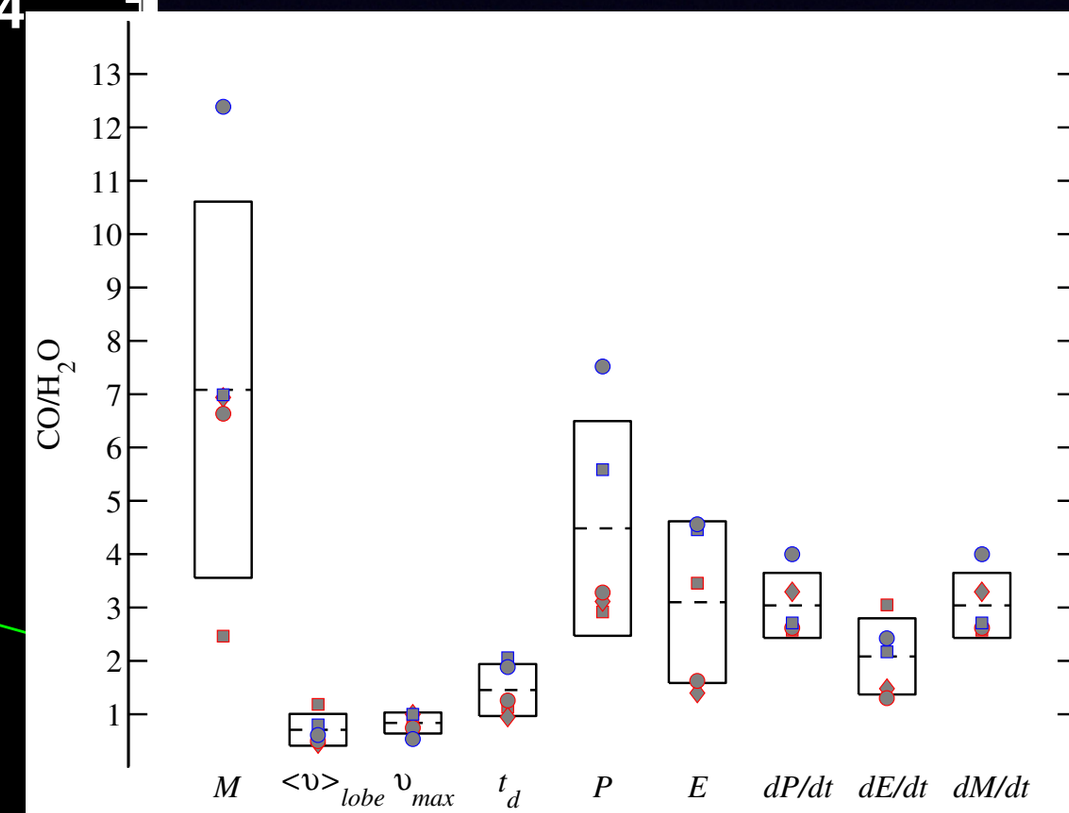
- FIR spectra dominated by H_2O, CO, OH and O
- Shock models reproduce excitation: UV needed to reproduce chemistry

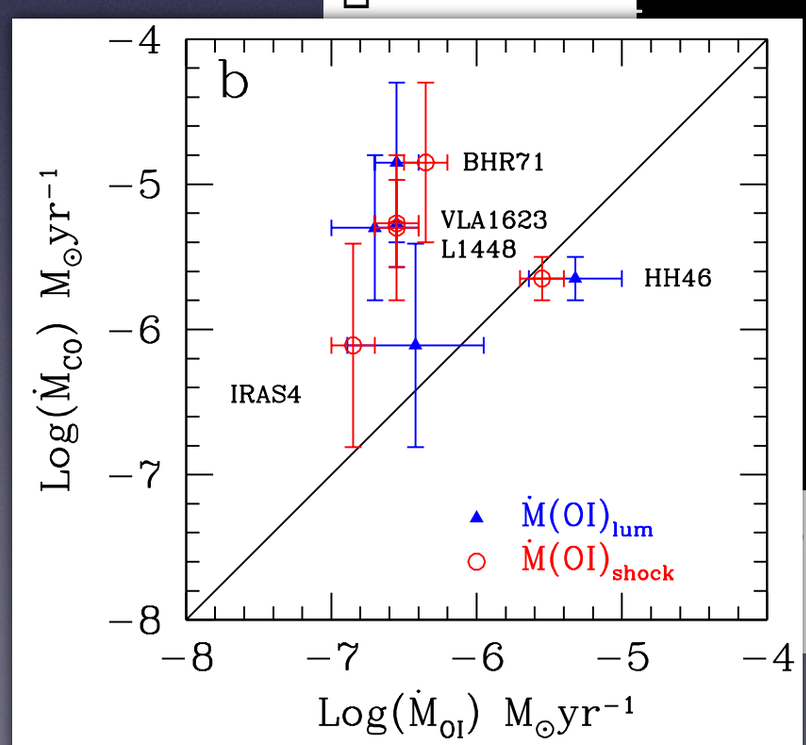


Karska et al. 2015, Kristensen et al. in prep.

Shock energetics as important as outflow energetics







- [O I] 63 micron observations velocity-resolve jet emission

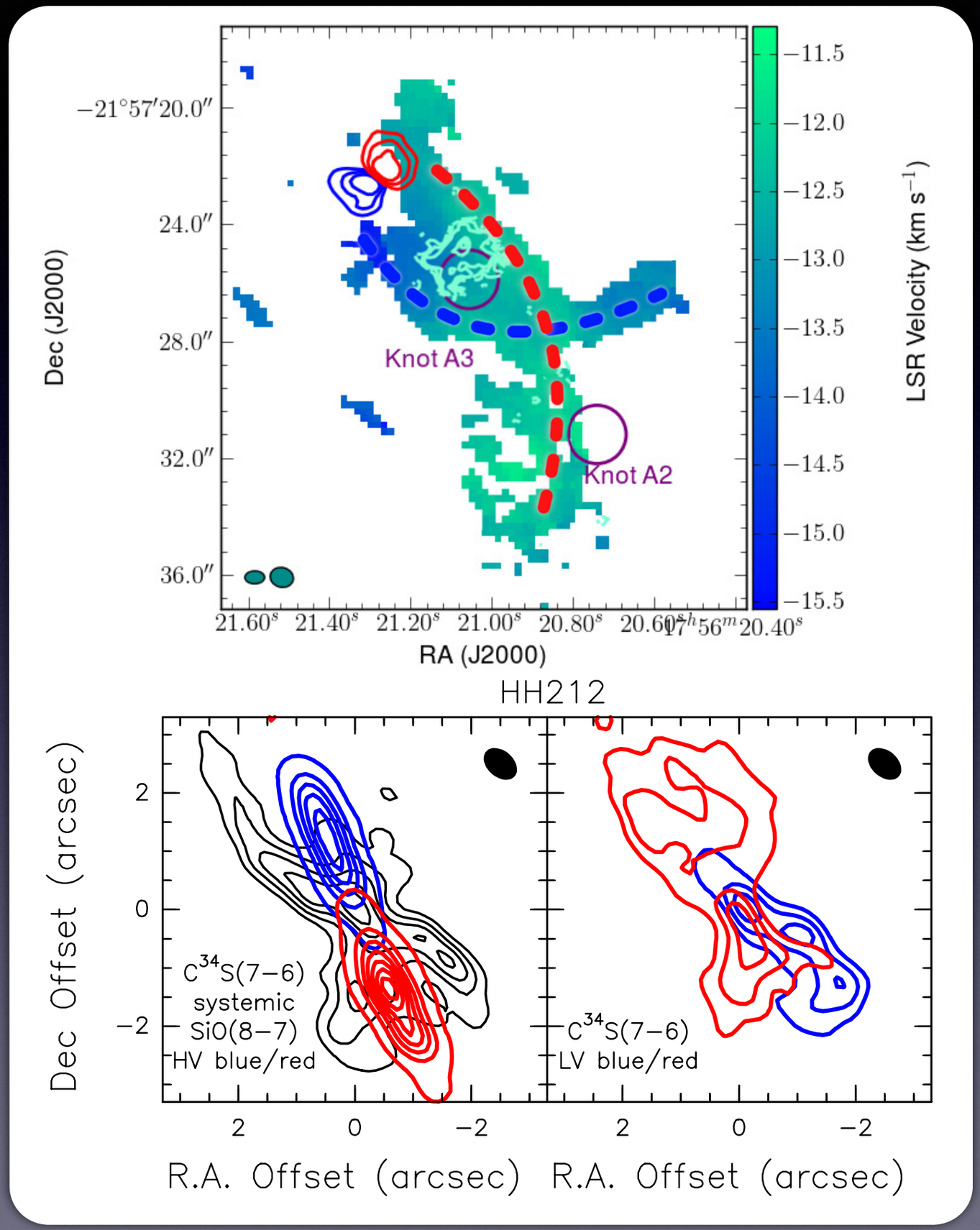
Bjerkeli et al. 2012, 2013, Nisini et al. 2015

Lesson 3:

High angular resolution + sensitivity required for completing the dynamical picture of winds + outflows

Winds rotate

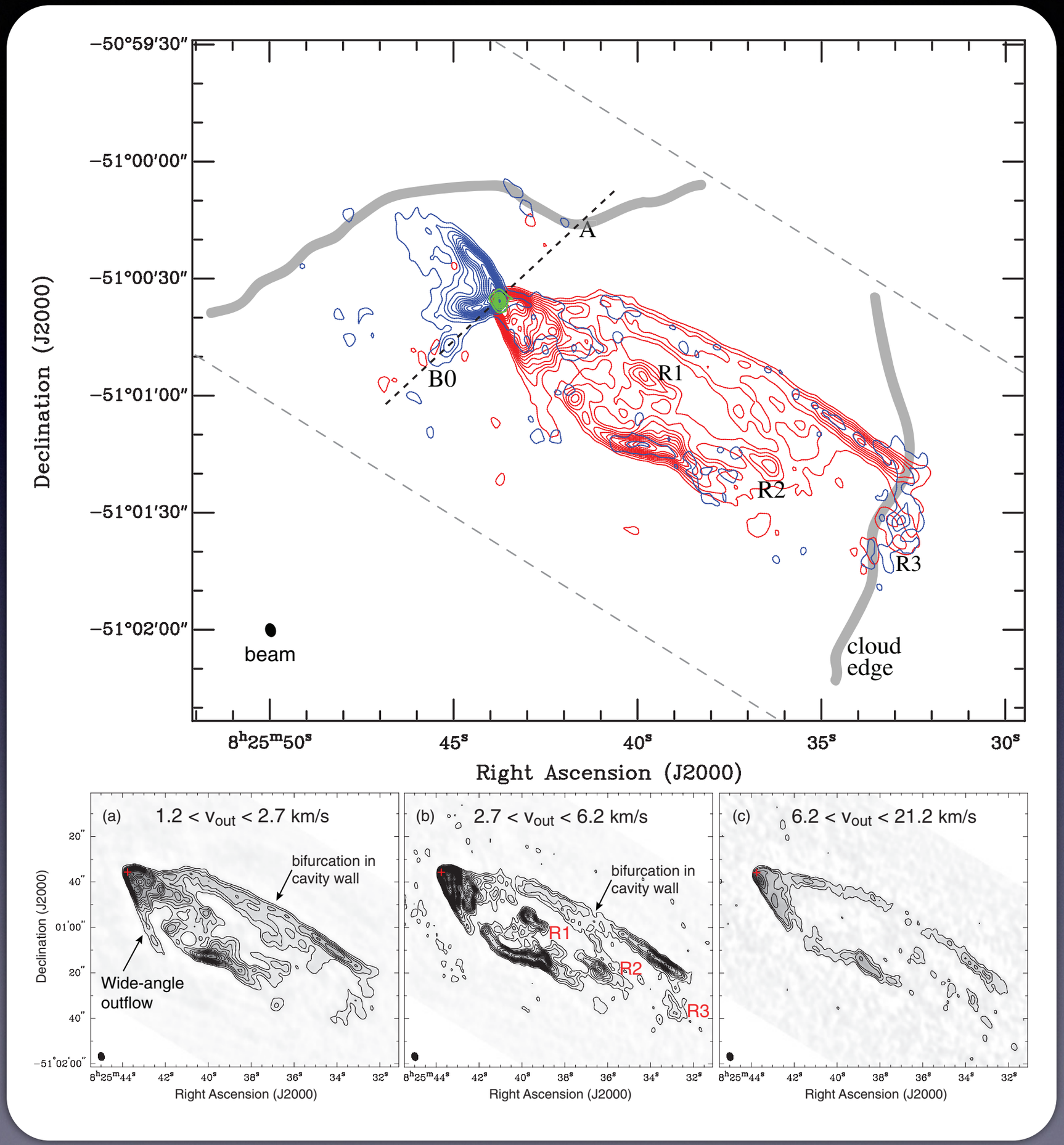
- Winds + outflows remove angular momentum: constraining the rate constrains the launch mechanism
- Observations difficult: require high sensitivity + resolution
- ALMA delivers!



Klaassen et al. 2013, Codella et al. 2014

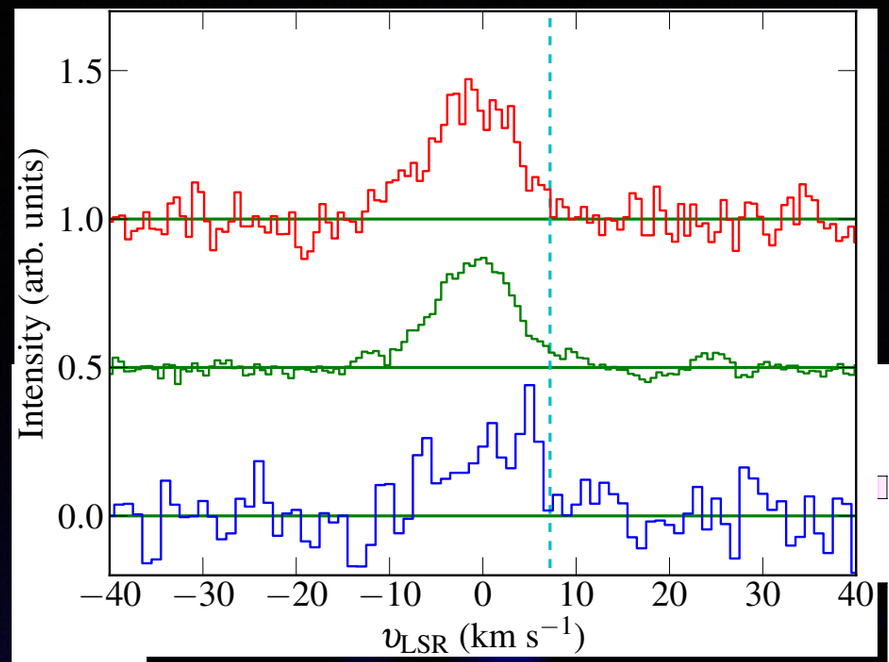
ALMA confirms: outflows are energetic

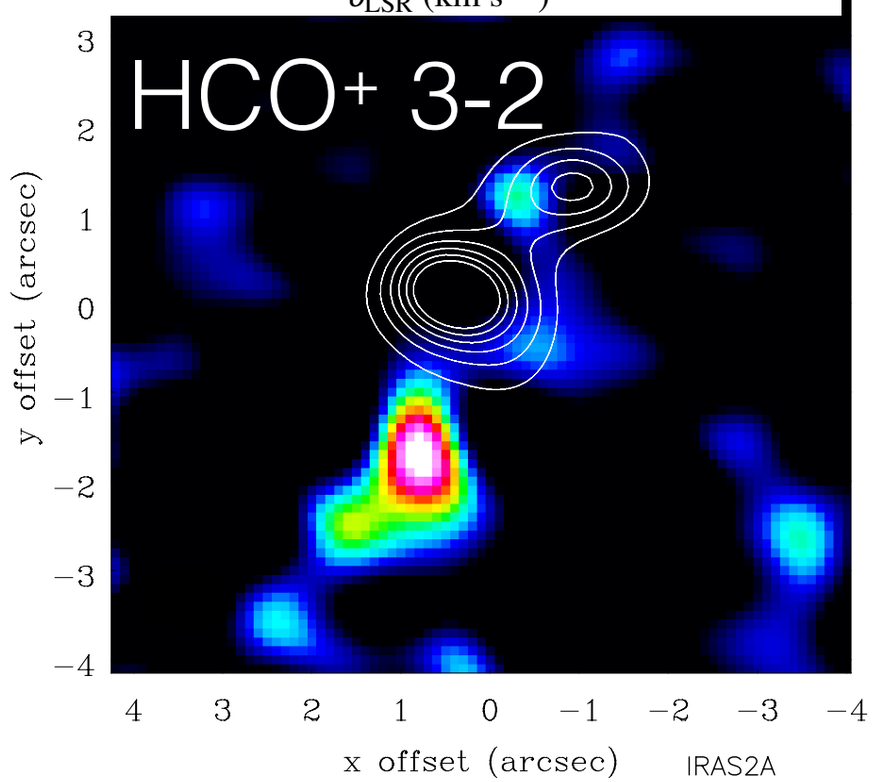
- High-sensitivity CO 1-0 observations reveal higher-v material than previously observed
- Outflows contain more mass and energy than previously assumed
- Follows Herschel conclusions but now with spatial resolution

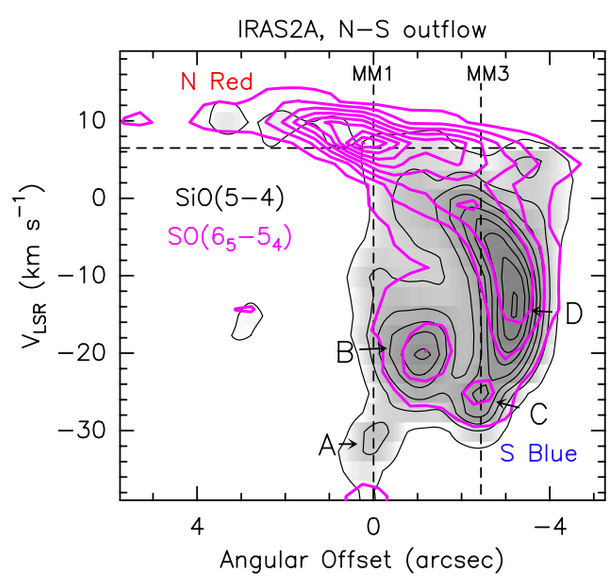


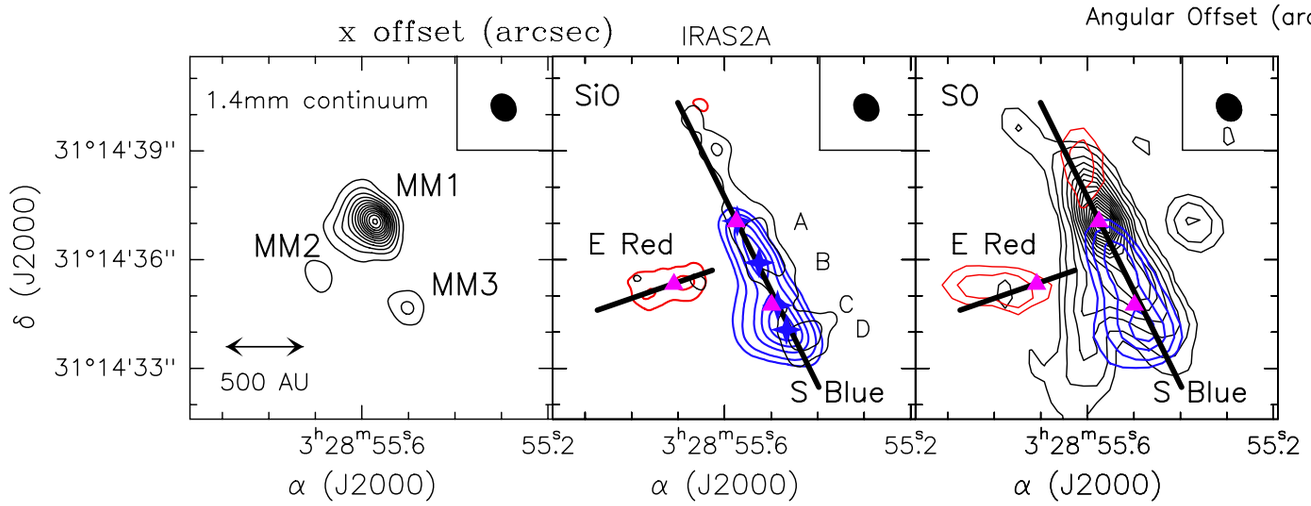
Arce et al. 2013

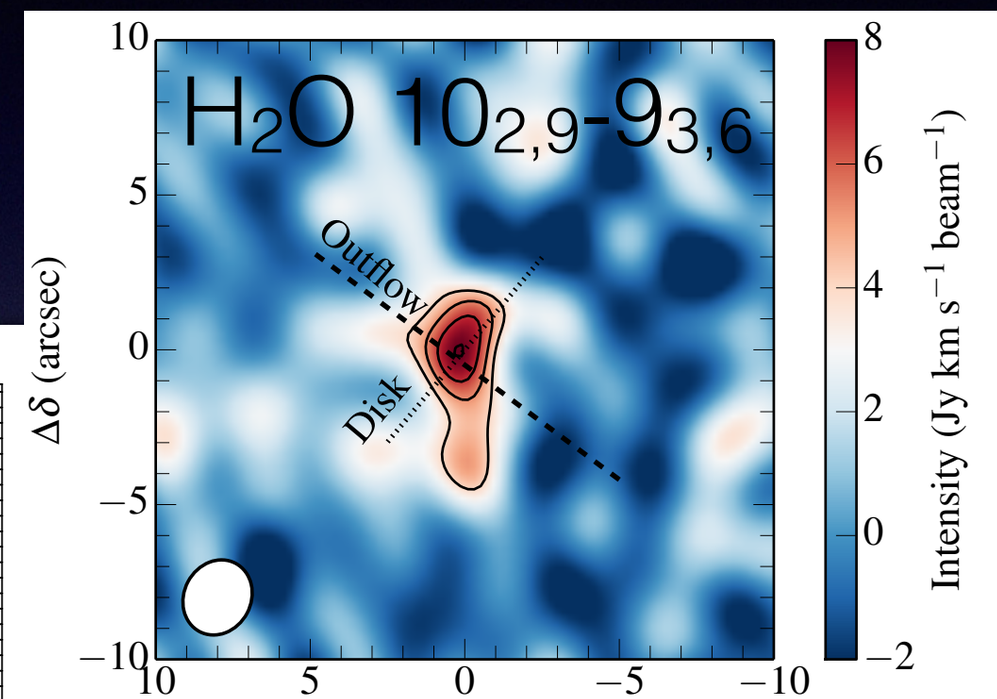
Smaller arrays still useful: SMA and PdBI pinpoint shock locations

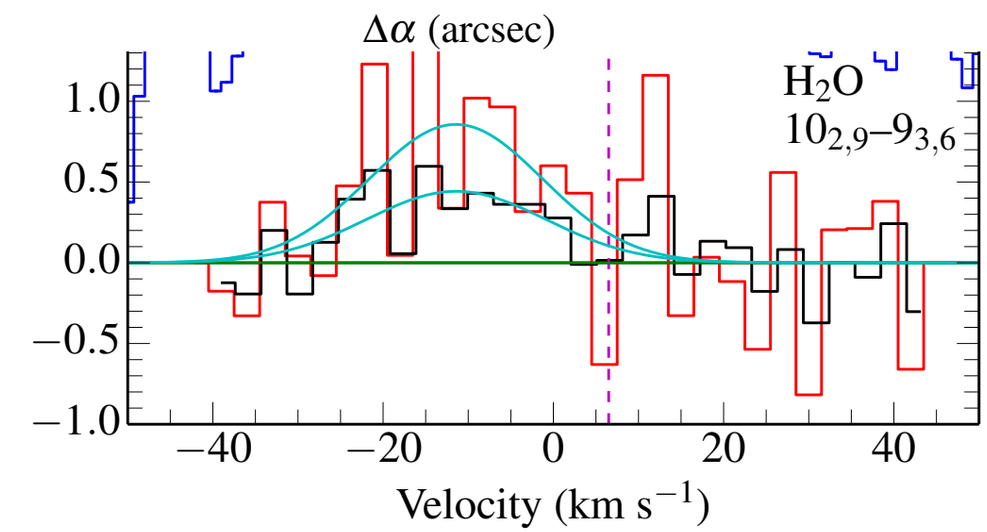












Codella et al. 2014, Kristensen et al. in prep.

Summary

- Herschel was, and ALMA is fantastic new toys for outflow studies: complementary capabilities
- Herschel revealed where the momentum and energy are, ALMA reveals the total mass and location
- Future: constrain the launch mechanism, pinpoint where and how outflow entrainment takes place, establish the elemental budgets, expand initial ALMA observations to full surveys