Shocks in the inner 100 AU of low-mass protostars

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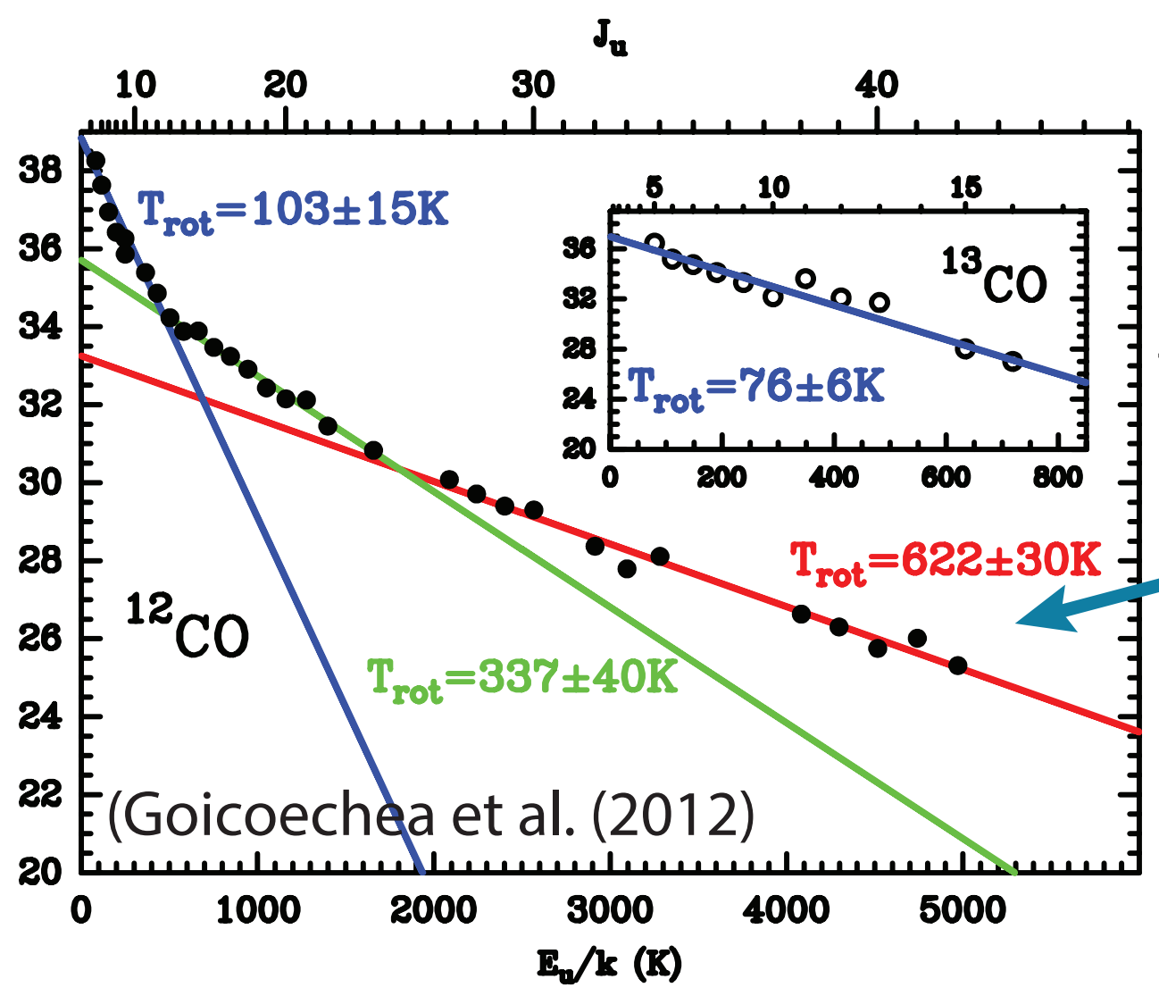
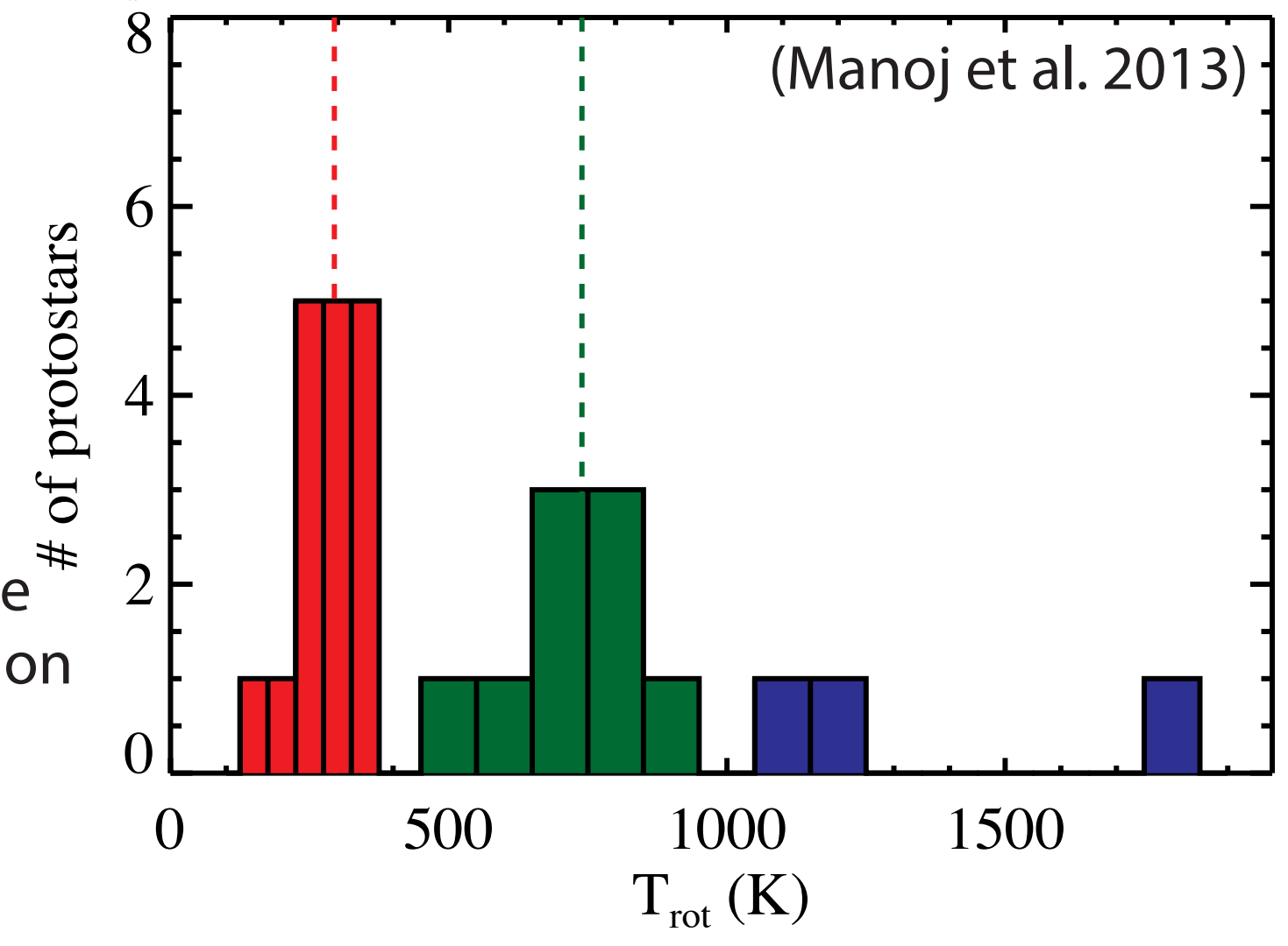
1: Hot gas exists in all low-mass protostars



Complete CO ladder towards Ser SMM1.

High-*T* component



CO T_{rot} distribution in the HOPS sample of protostars in Orion

Herschel-PACS observations of CO reveal a hot component (*T* > 500 K) in all low-mass protostars (Manoj et al. 2012, Karska et al. 2013, Green et al. 2013), typically originating in shocks associated with the outflow driver (jet and wind; van Kempen et al. 2010, Visser et al. 2012, Herczeg et al. 2012, Goicoechea et al. 2012, Kristensen et al. 2012, 2013b).

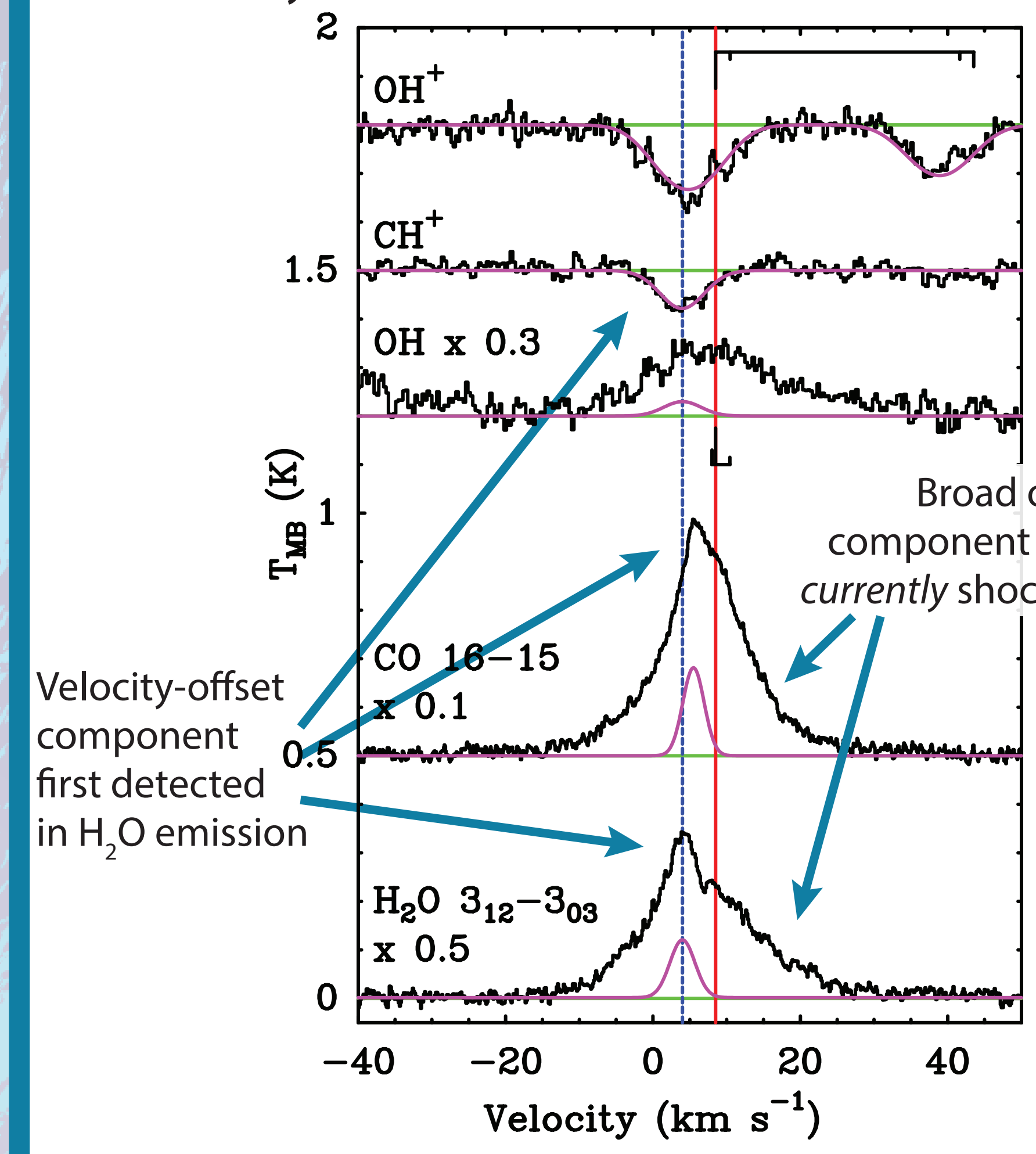
Take-home messages:

Dissociative shocks exist in the dense inner envelopes of low-mass protostars; whether the dissociation is caused by the shocks themselves or dissociating UV/X-ray radiation from the accreting star is an open question (*boxes 1, 2*).

Low-mass protostellar systems are ideal testbeds for models of irradiated dense shocks; their proximity to us makes it possible to isolate the shock emission spatially and spectrally from the surrounding system (*boxes 2, 3, 4*).

A combination of irradiated shock models and observations at high angular resolution (< 0.5" ~ 100 AU) is required to constrain the effect these shocks has on the protostellar evolution on small scales (*boxes 3, 4*).

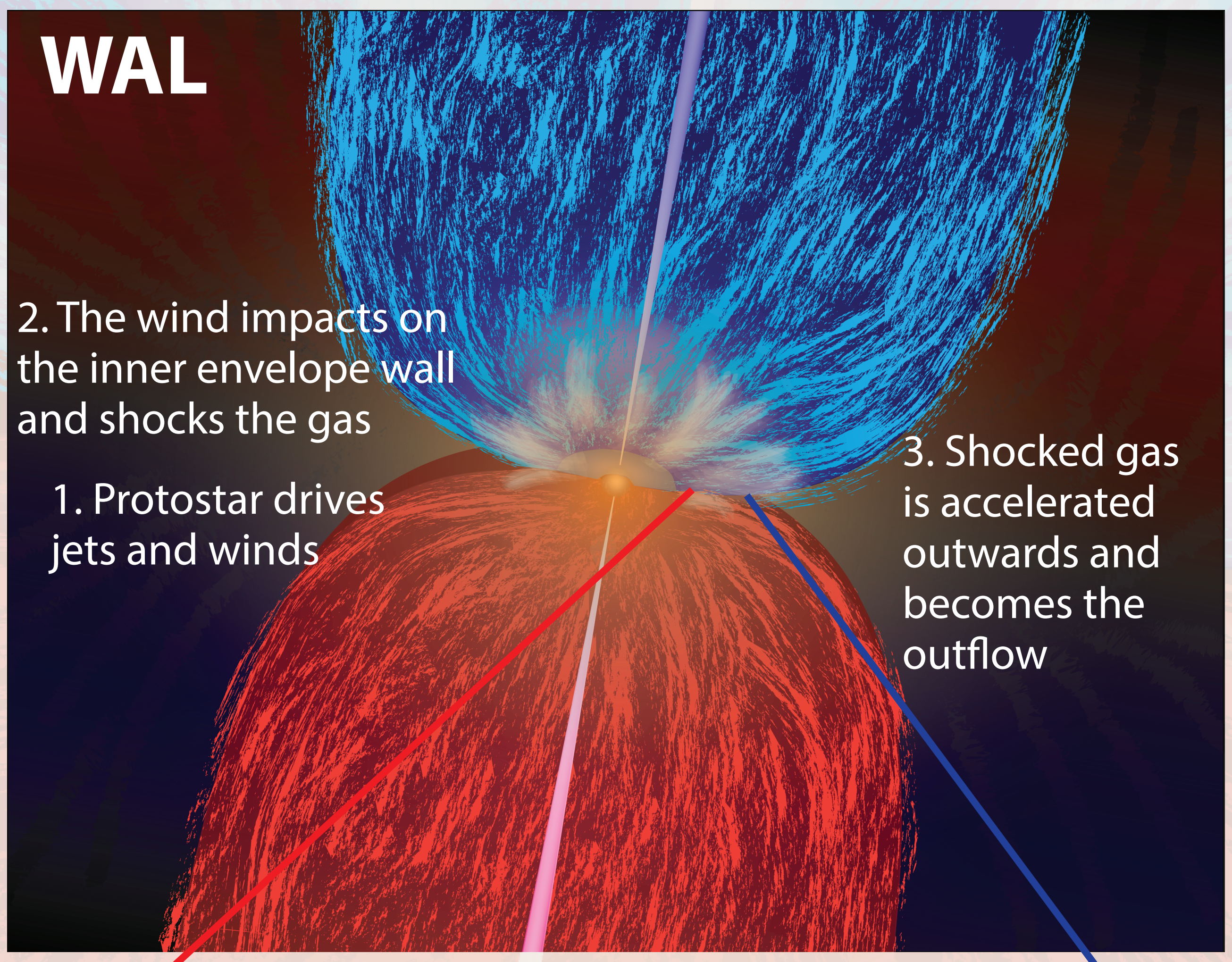
2: The chemical signature of the strongest shocks shows they are dissociative



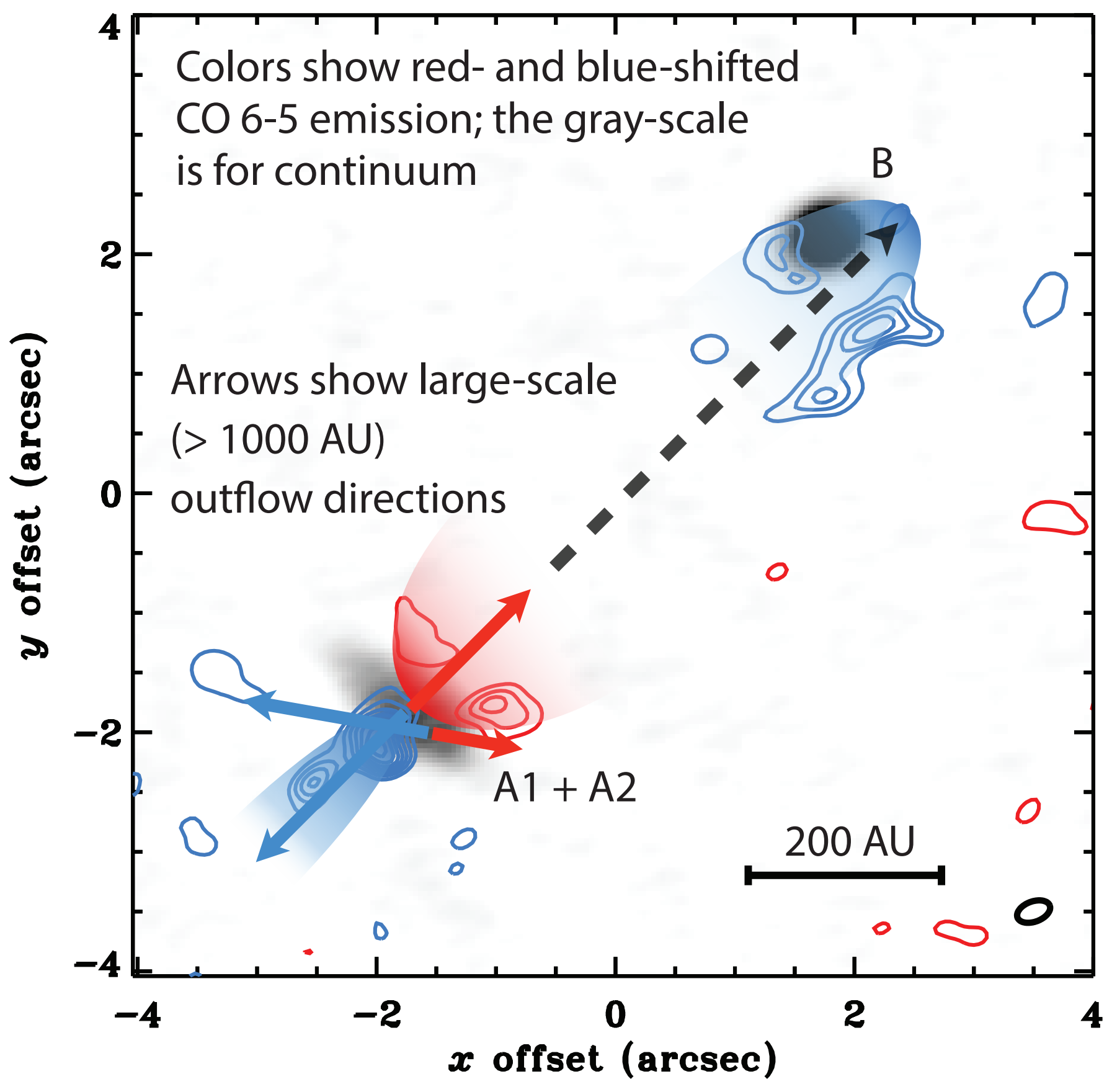
Broad outflow component tracing *currently* shocked gas

Velocity-offset component first detected in H_2O emission

Herschel-HIFI observations of H_2O, CO 16-15 and hydrides (CH^+, OH^+, OH) reveal distinct velocity components not seen from the ground; these components are identical to the hot CO gas observed with PACS (box 1, Kristensen et al. 2013b). The chemical signature points to an origin in dissociative shocks in dense gas ($n > 10^7$ cm^{-3}) and the profile shape indicates the shocks are moving perpendicular to the outflow direction.



3: ALMA pinpoints where outflowing gas is first shocked and entrained

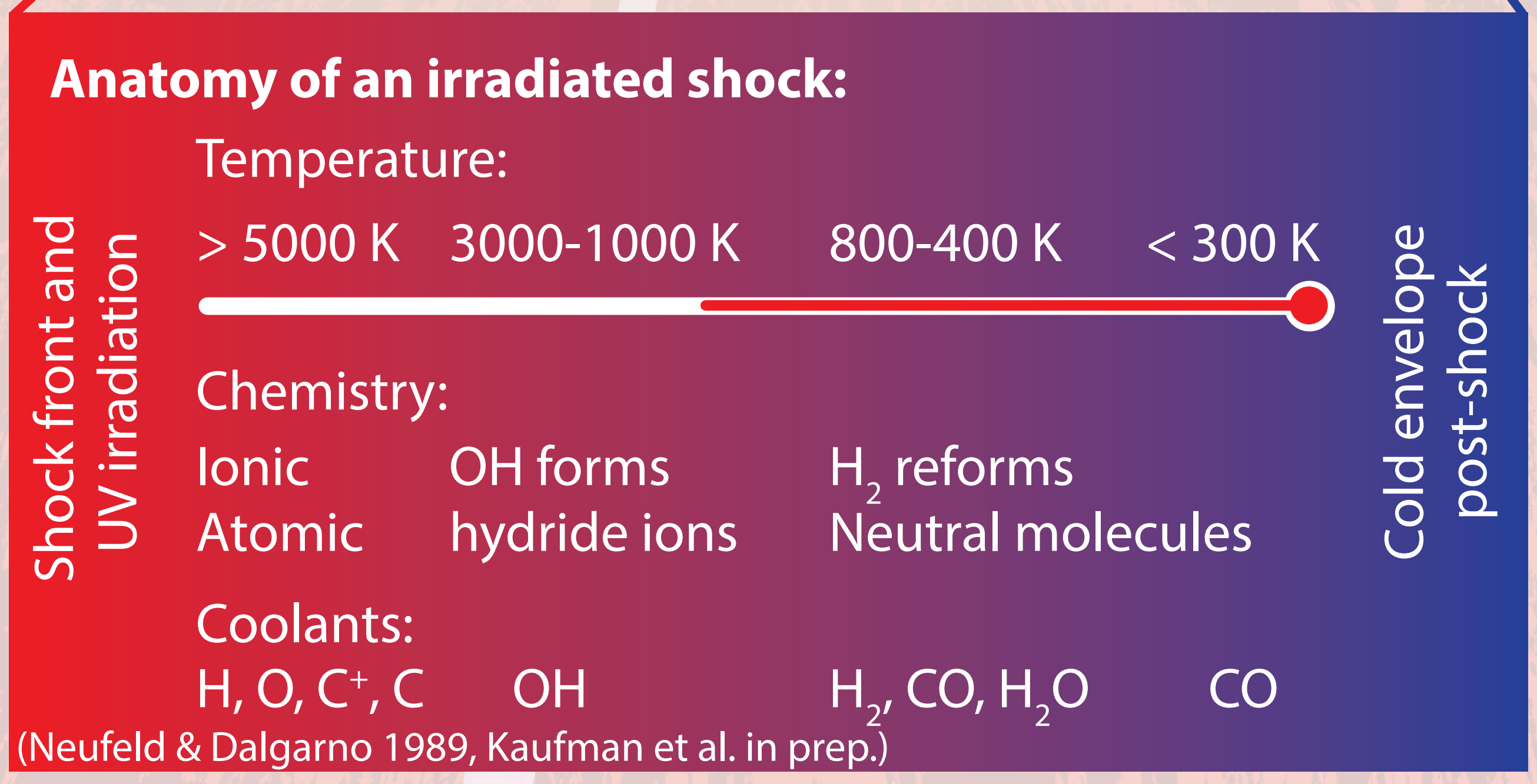


Colors show red- and blue-shifted CO 6-5 emission; the gray-scale is for continuum

Arrows show large-scale (> 1000 AU) outflow directions

IRAS16293-2422 is a low-mass trinary (sources A1+A2 and B); only A1 + A2 are currently driving outflows (although this is debated; Loinard et al. 2013)

High angular resolution observations are required to image the origin of these shocks; ALMA observations of CO 6-5 towards one low-mass protostars reveal where material is accelerated (shocked) and subsequently entrained into the molecular outflow observed in, e.g., CO 3-2 (Kristensen et al. 2013a).



Anatomy of an irradiated shock:

Shock front and UV irradiation

Temperature:
> 5000 K 3000-1000 K 800-400 K < 300 K

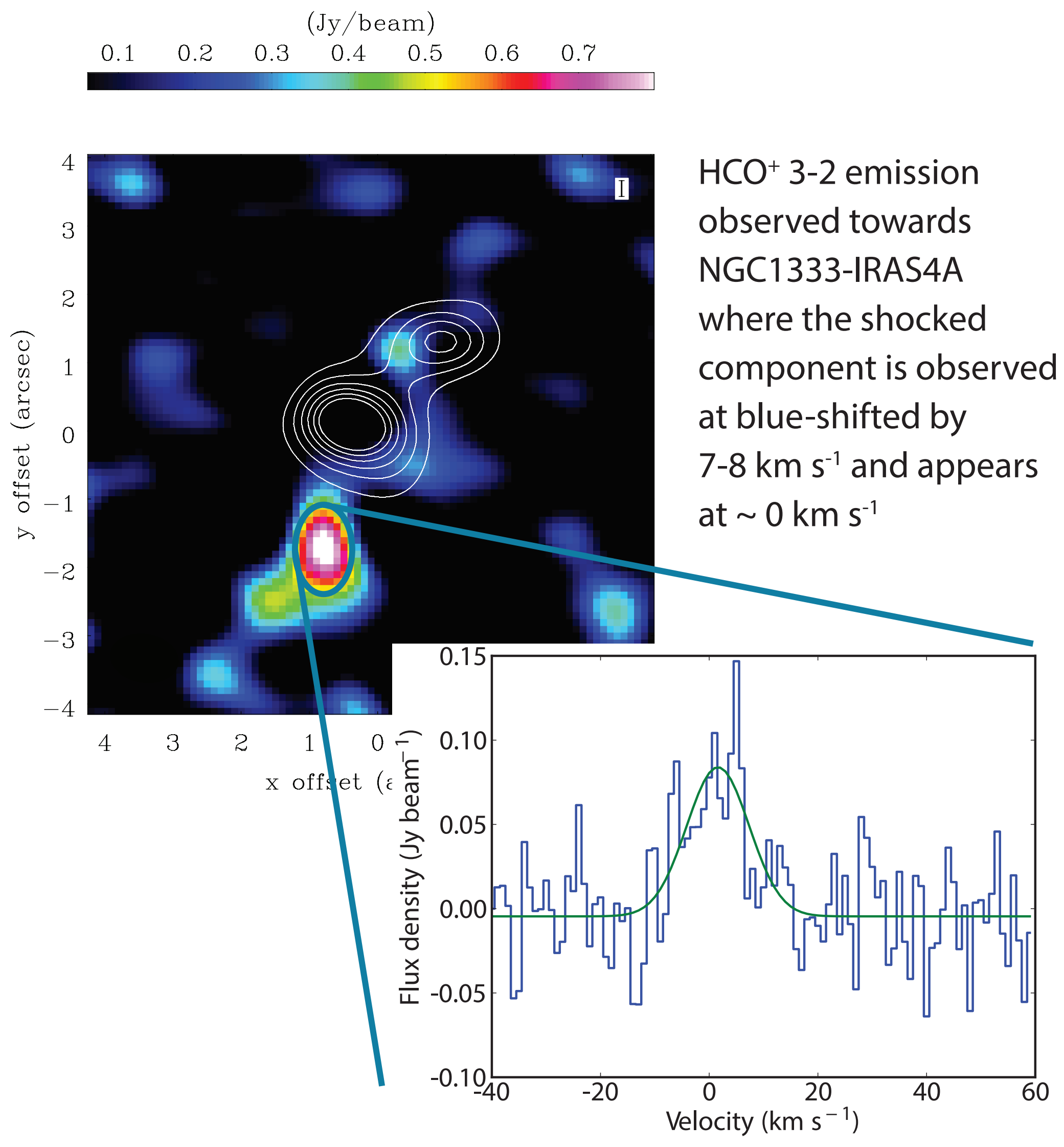
Chemistry:
Ionic OH forms H_2 reforms
Atomic hydride ions Neutral molecules

Coolants:
H, O, C$^+$, C OH H_2, CO, H_2O CO

Cold envelope post-shock

(Neufeld & Dalgarno 1989, Kaufman et al. in prep.)

4: HCO$^+$ traces irradiated shocks directly



HCO^+ 3-2 emission observed towards NGC1333-IRAS4A where the shocked component is observed at blue-shifted by 7-8 km s^{-1} and appears at ~ 0 km s^{-1}

Models of dissociative shocks predict that HCO^+ is a possible lower-frequency tracer. SMA observations reveal this to be true and opens up a window for following the temporal evolution of dense dissociative shocks in low-mass protostars (see also poster 1B072, Kristensen et al. in prep.).

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Herschel observations (box 1 and 2):

The Herschel-HIFI observations are presented in Kristensen and Benz et al. in prep. They were obtained in the framework of the 'Water in star-forming regions with Herschel' key program (WISH; van Dishoeck et al. 2011). All spectra were obtained in dual-beam-switch mode and data reduction followed the standard pipeline. The shocked component described here was detected in 6 / 29 sources, 5 of which are Class 0. These sources arethe ones with the highest mass of hot CO as detected by PACS.

ALMA + SMA observations (box 3 and 4):

The ALMA observations were performed as part of the science verification (ADS/JAO.ALMA#2011.0.00007.SV). See the CASA guides and Kristensen et al. (2013) for details on the data reduction.

The SMA observations were done under excellent weather conditions in Dec. 2012 at 267 and 356 GHz corresponding to the HCO^+ 3-2 and 4-3 transitions, respectively. The data were obtained in the extended configuration and the corresponding reconstructed beams are 1" and 0.7", respectively. Data reduction was done in CASA. The shocked component is detected in both transitions and the line ratio corresponds to a rotational temperature of ~ 500 K, consistent with model predictions.

Models (box 2 and 4):

Excitation conditions were modeled using the 1D non-LTE radiative transfer code RADEX (van der Tak et al. 2007). In particular, the H2O transitions were used to constrain the local H2 density and the CO transitions and limits were used for the temperature.

The modeled column densities were compared to the fast, dissociative shock model of Neufeld & Dalgarno (1989). For shock velocities in excess of 60 km/s, the agreement between the models and observations was excellent (better than a factor of 3).

References:

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