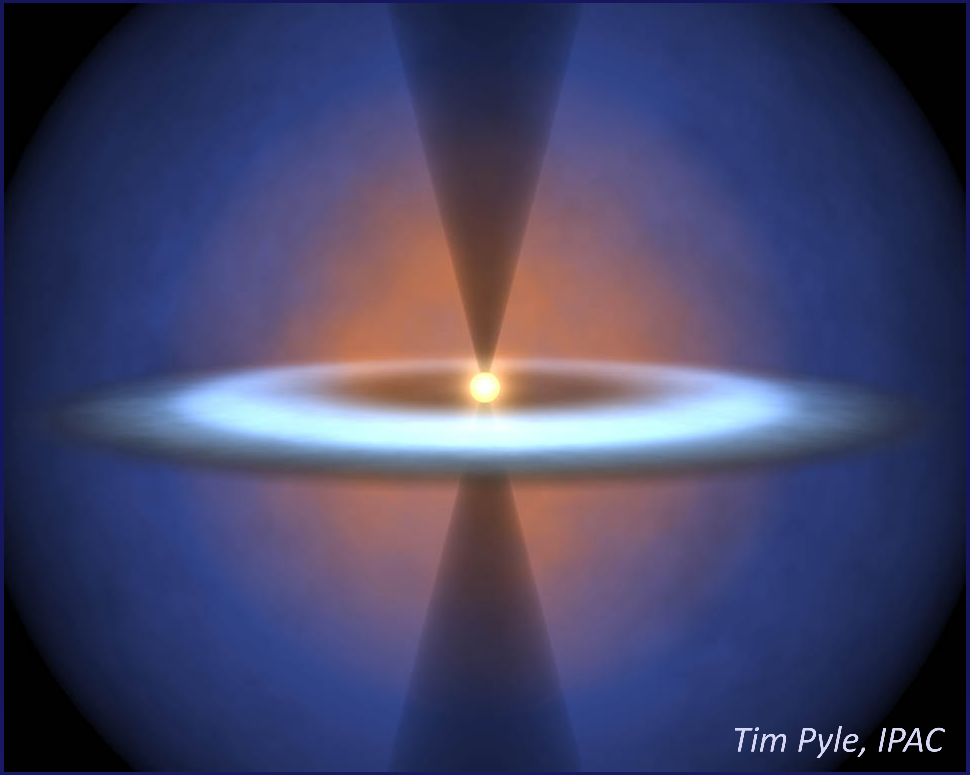
# Protostars and the IRS high-res legacy

## Star-formation feedback, outflows, and infall in Galactic young stellar objects: highlights of work by several groups.




**Dan Watson, University of Rochester**

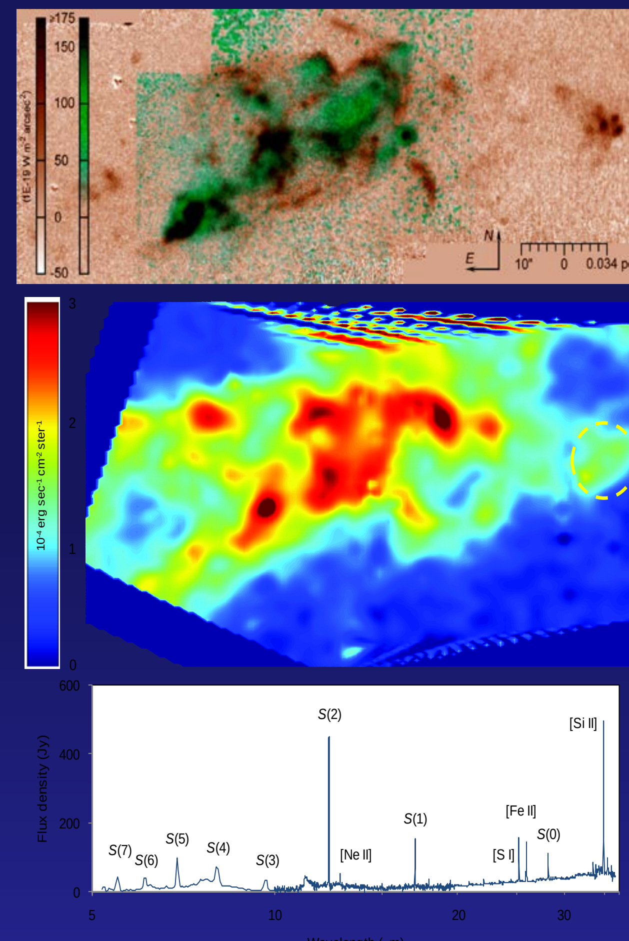
for the *Spitzer* IRS_Disks Team and the *Herschel* Orion Protostar Survey (HOPS).

Special thanks to David Neufeld, Ted Bergin, Gary Melnick, Charles Lawrence.

# Outline

*Spitzer*-IRS SH and LH were not designed for molecular spectroscopy or spectral-line mapping, but this did not prevent the making of substantial discoveries in the domain of star formation and outflow-cloud feedback.

- ❑ Access to good probes of **energetics**, enough spectral resolution to subtract stars accurately, allowed the harnessing of IRS's superb sensitivity.
- ❑ Atomic line emission in outflows: mass and momentum injection from protostars into clouds, and analysis of magnetocentrifugally-accelerated outflows.
- ❑ Pure-rotational $H_2$ in outflows: energy and momentum injection by protostars, and the ortho-para clock.

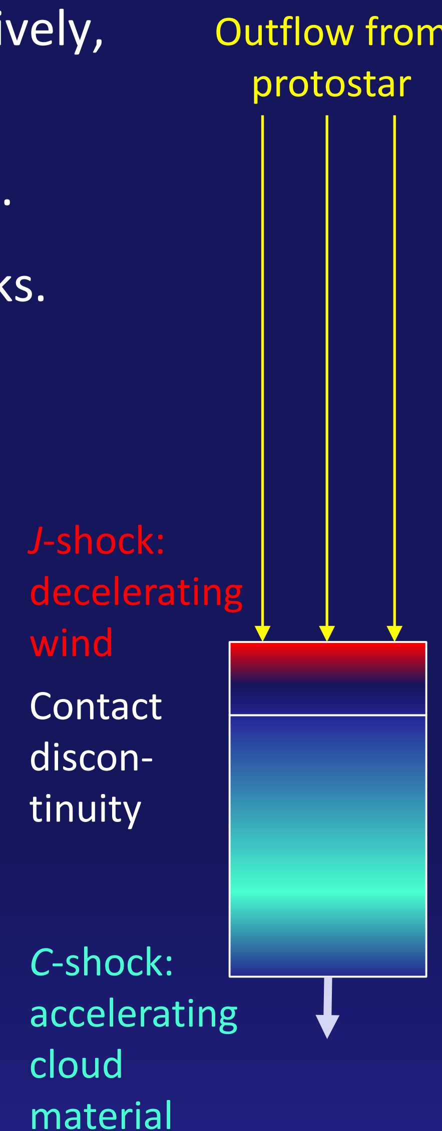



Joel Green, 2009

# What IRS SH-LH were good at detecting in protostars

Molecular and atomic spectral-line fluxes from **shocks**: respectively, *C*-type cloud shocks, and *J*-type wind shocks.

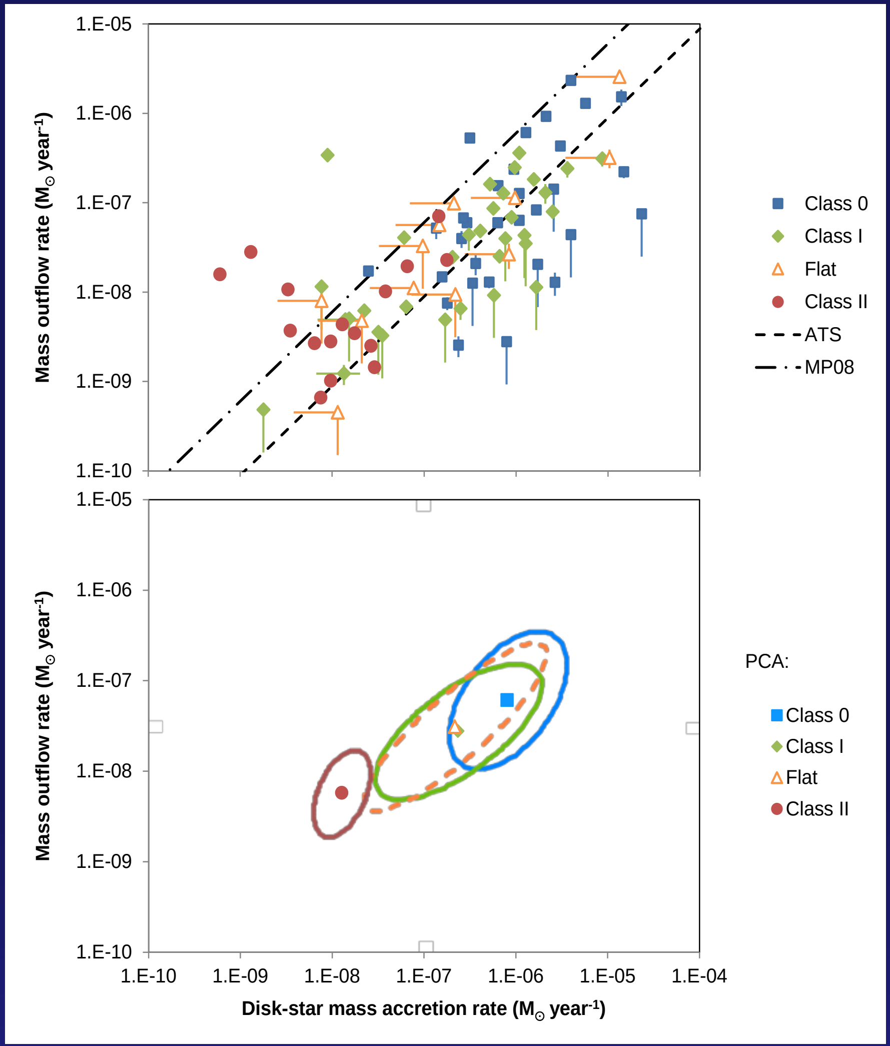
- Molecular lines: pure rotational $H_2$, HD, $H_2O$, OH; ro-vib $CO_2$.
  - These $H_2$ lines are the dominant coolant in cloud shocks.
    - Yield *T* and mechanical-energy injection rates.
  - In well-resolved outflows, get ortho-para ratio.
  - Abundance ratios, particularly $HD/H_2$.
- Atomic fine structure lines, primarily from low-ionization species: [S I], [Si II], [Fe II] (five lines), [Ni II], [Ne II].
  - Higher ionization states in more massive protostars.
  - [Fe II]: good constraints on preshock density, shock speed.
  - [Fe II] 26.0 μm and [Si II] 34.8 μm good proxies for dominant coolant, and allow estimates of dust grain sputtering.



# What we learned about protostars

## 1. Accretion and outflow footpoints

- Protostellar mass ejection rates $\dot{M}_w$ track accretion rates $\dot{M}_a$ as they evolve through YSO classes 0, I and II.
- Typically the bipolar outflows seen in mm-wave CO are 90-99% entrained matter.
- Large range of branching ratio, $\dot{M}_w / \dot{M}_a$, may indicate that all three proposed magnetocentrifugal acceleration mechanisms are represented among protostars.
  - Accretion-powered stellar winds (e.g. Matt & Pudritz 2008)
  - X winds (e.g. Shu et al. 2000)
  - Disk winds (e.g. Königl et al. 2000)

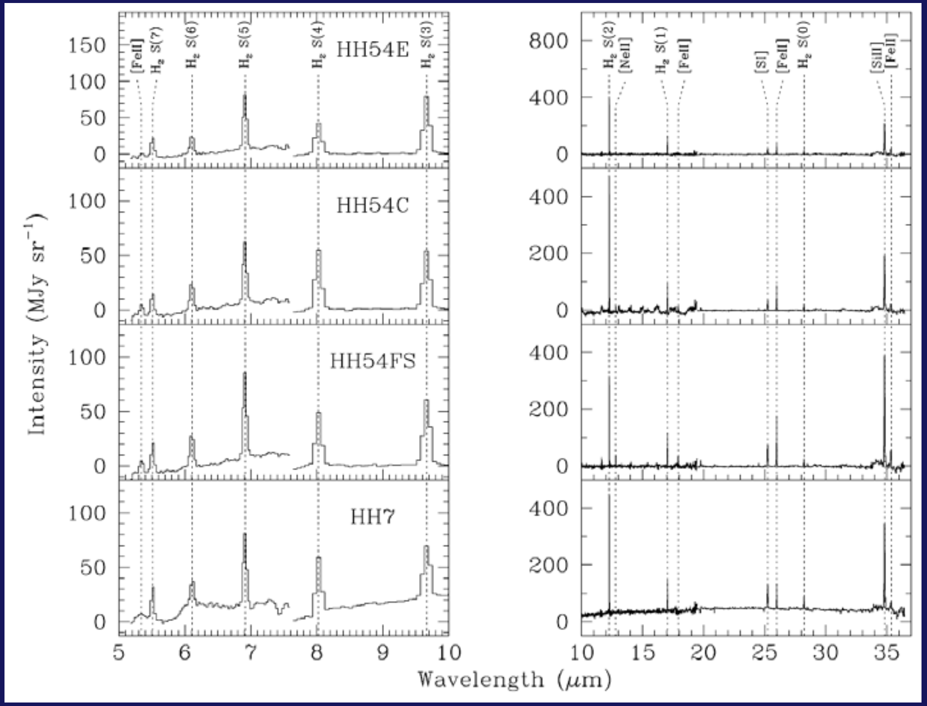



Watson et al. 2016

# What we learned about protostars (continued)

**2. How molecular shocks are cooled**

- In ordinary outflows, **>50% of the cooling is done by the mid-IR, pure rotational, lines of $H_2$** (e.g. Neufeld et al. 2009, 2014).
  - Most of the rest is done by CO.
  - Less cooling is done by $H_2O$ than we thought, pre-*Spitzer*.
- But in a few extraordinary objects, ~80% of the cooling is by $H_2O$.
  - Additional component: envelope-disk accretion shock? Compare Watson et al. 2007, Herczeg et al. 2012. Accretion-shock and outflow-shock models are degenerate…




HH 54, HH 7: $L(H_2) \sim 10L(H_2O)$
Neufeld et al. 2006a

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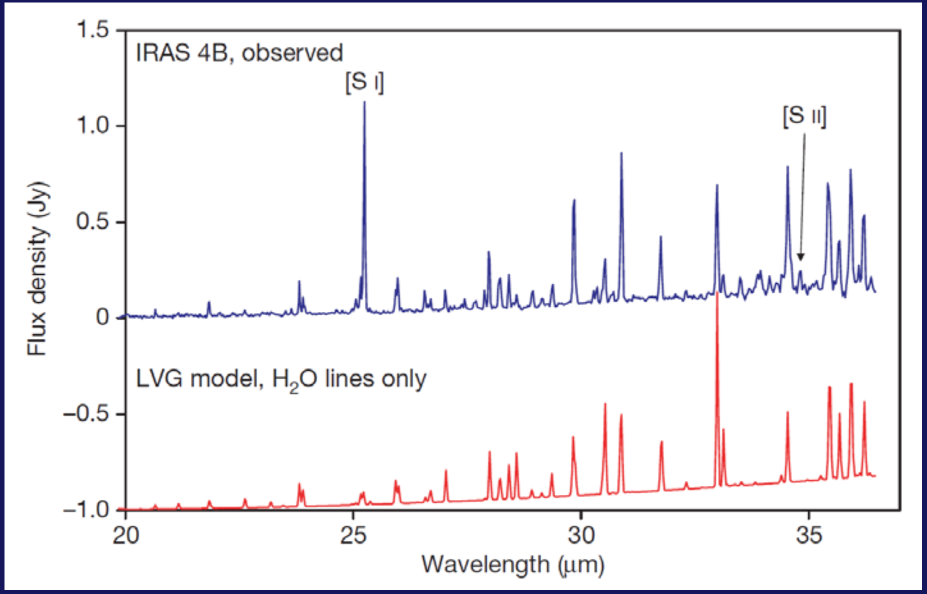
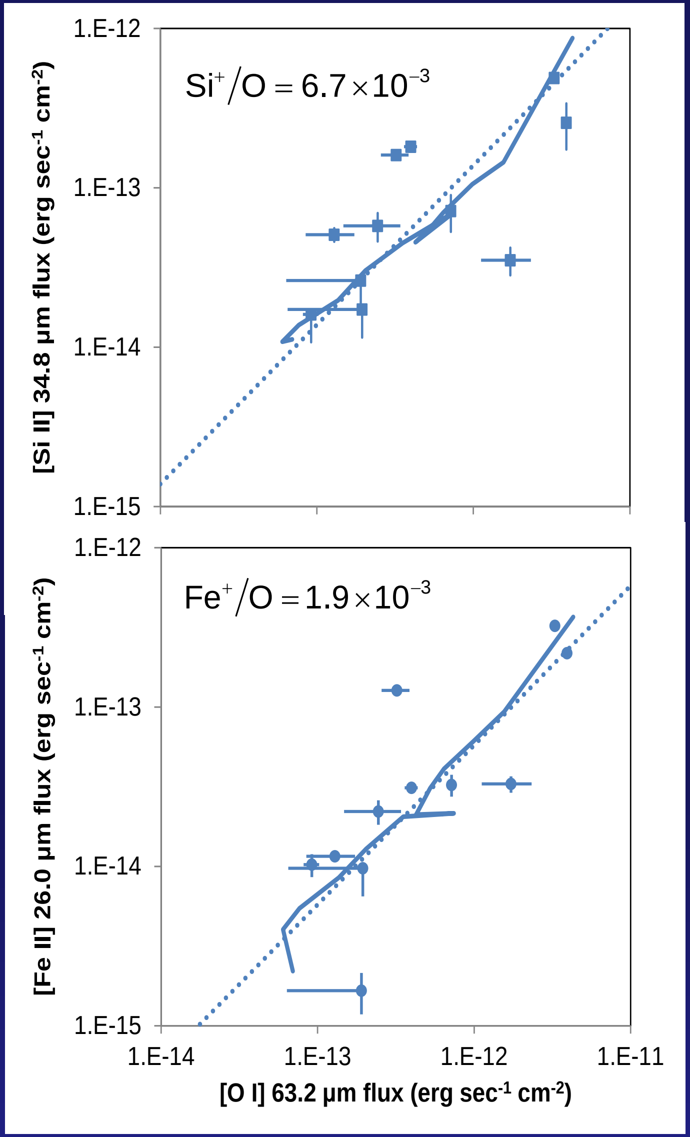



NGC 1333 IRAS 4B: $L(H_2) \sim 0.2L(H_2O)$
Watson et al. 2007, Arnold et al. 2011

# What we learned about protostars (continued)

## 3. Some abundances of note

- HD $R(3)$ and $R(4)$ lines are detected in molecular shocks, yielding D/H = $7.5\times10^{-6}$ (e.g. Neufeld et al. 2006b).
  - A factor of 2-3 below that of atomic gas in the local bubble and the Galactic halo, but similar to that in Galactic-plane sightlines.
- **$Fe^{+}$/O and $Si^{+}$/O are both larger by a factor of about 4 than Fe/O and Si/O in the ISM and quiescent molecular clouds (Watson et al. 2016).** $\Rightarrow\Rightarrow$
  - Moderate sputtering: this is 3.6% and 20% of the solar abundances.
  - Grains survive YSO outflow shocks.

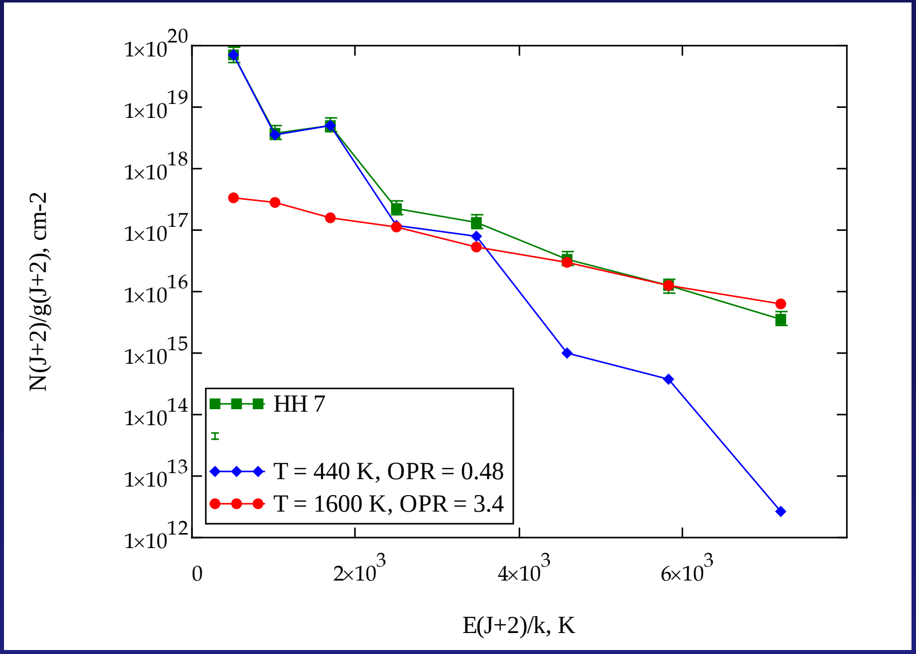


# What we learned about protostars (continued)

## 4. To read the $H_2$ ortho-para clock

- Molecular shocks at the heads of jets have **$H_2$ ortho/para (odd *J*/even *J*) abundance ratios much smaller (0.2-0.3) than the equilibrium value (3) for their temperature (500-1000 K).**
  - Thus the **preshock** $H_2$ has $T$ = 30-50 K.
  - No widespread warm $H_2$ outside outflows (Maret et al. 2009).
  - Postshock equilibration: H-$H_2$ chemical reactions at high $T$ (Neufeld et al. 2006b). For typical shock speeds in nearby clouds, the conversion time is several LH pixels wide.

NGC 1333 SVS13 outflow (HH 7-11)
RGB = $H_2$ S(1), S(3), S(5)
Watson et al. 2017



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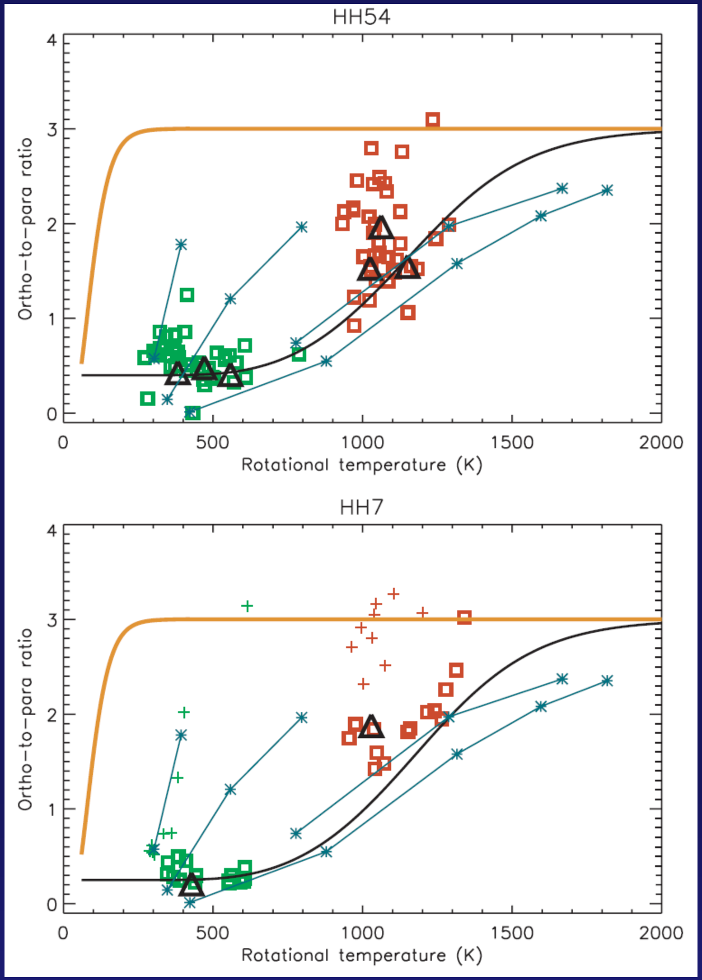


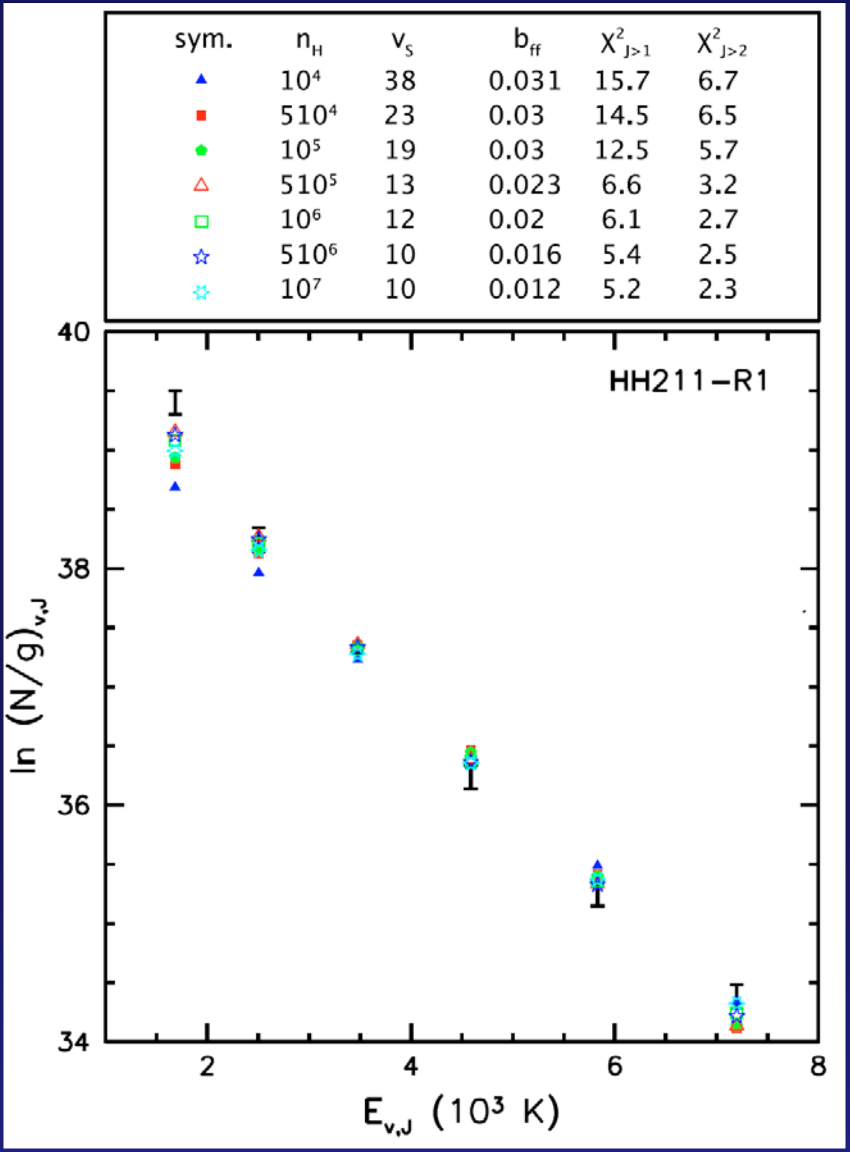

Neufeld et al. 2006b

# What we learned about protostars (continued)

## 5. Shock and feedback details

- Key, comprehensive constraints for detailed models of feedback between YSOs and their environs in nearby clouds.
- All inject enough energy to be important in the driving of turbulence (e.g. Quillen et al. 2006; Davis et al. 2008).
- The clouds richest in outflows could be disrupted by such outflows in a few hundred kyr if they remain numerous.

***C*-shock models of $H_2$ emission in HH 211; Dionatos et al. 2011.** ⇒⇒



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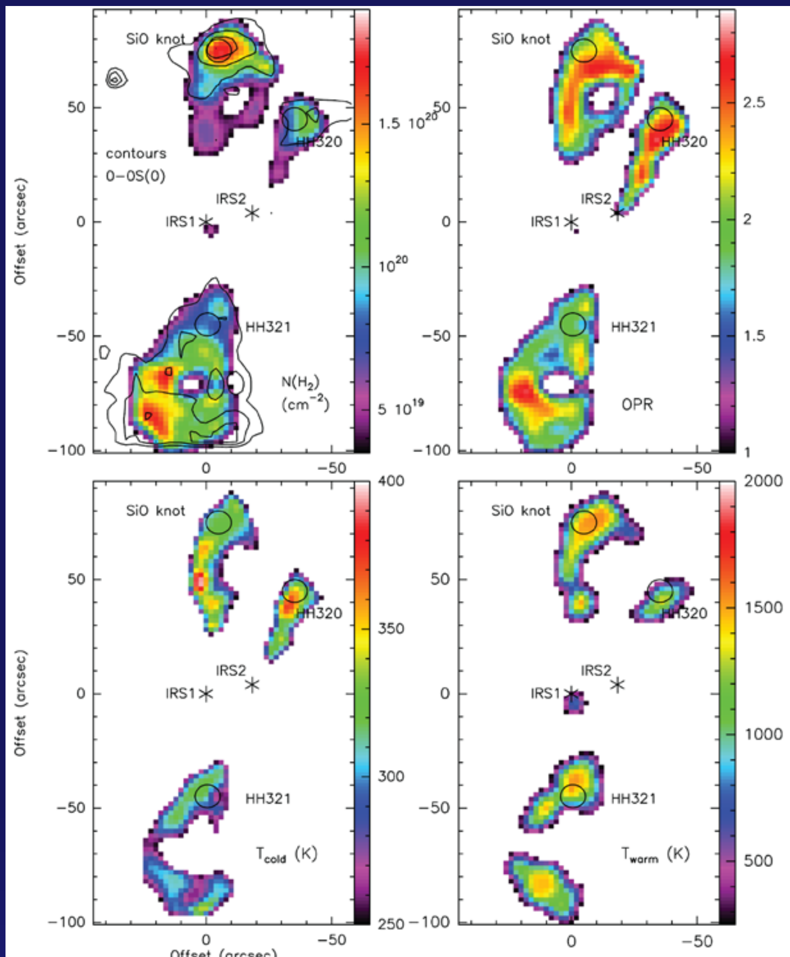


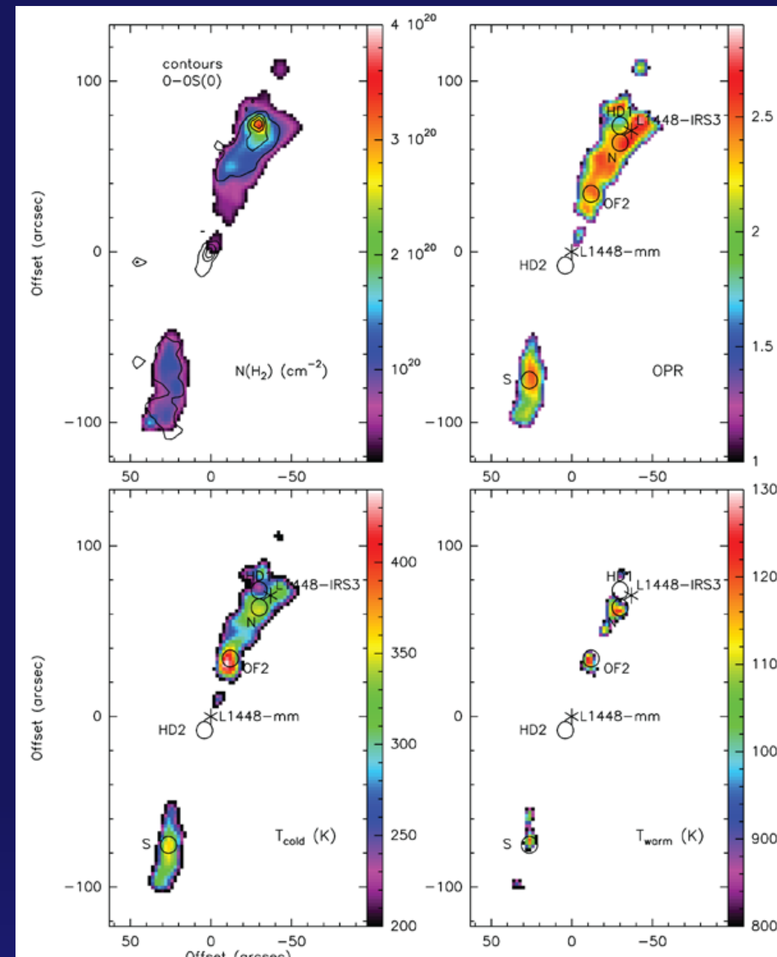


Detailed model results for BHR 71 (left) and L1448 (right): Giannini et al. 2011.

# Feedback example: jets and shocks in NGC 1333

- Mass of molecular cloud: 350 $M_\odot$.
- 17 outflows. (!)
- Binding energy: $10^{46}$ erg; turbulent energy ~$2 \times 10^{45}$ erg.
- Outflow momentum and energy injection rates: $1.4\times10^{-3}$ $M_\odot$ km sec$^{-1}$ year$^{-1}$, and $2L_\odot$ = $2\times10^{41}$ erg year$^{-1}$.
- Typical outflow lifetime: ~$10^4$ years.

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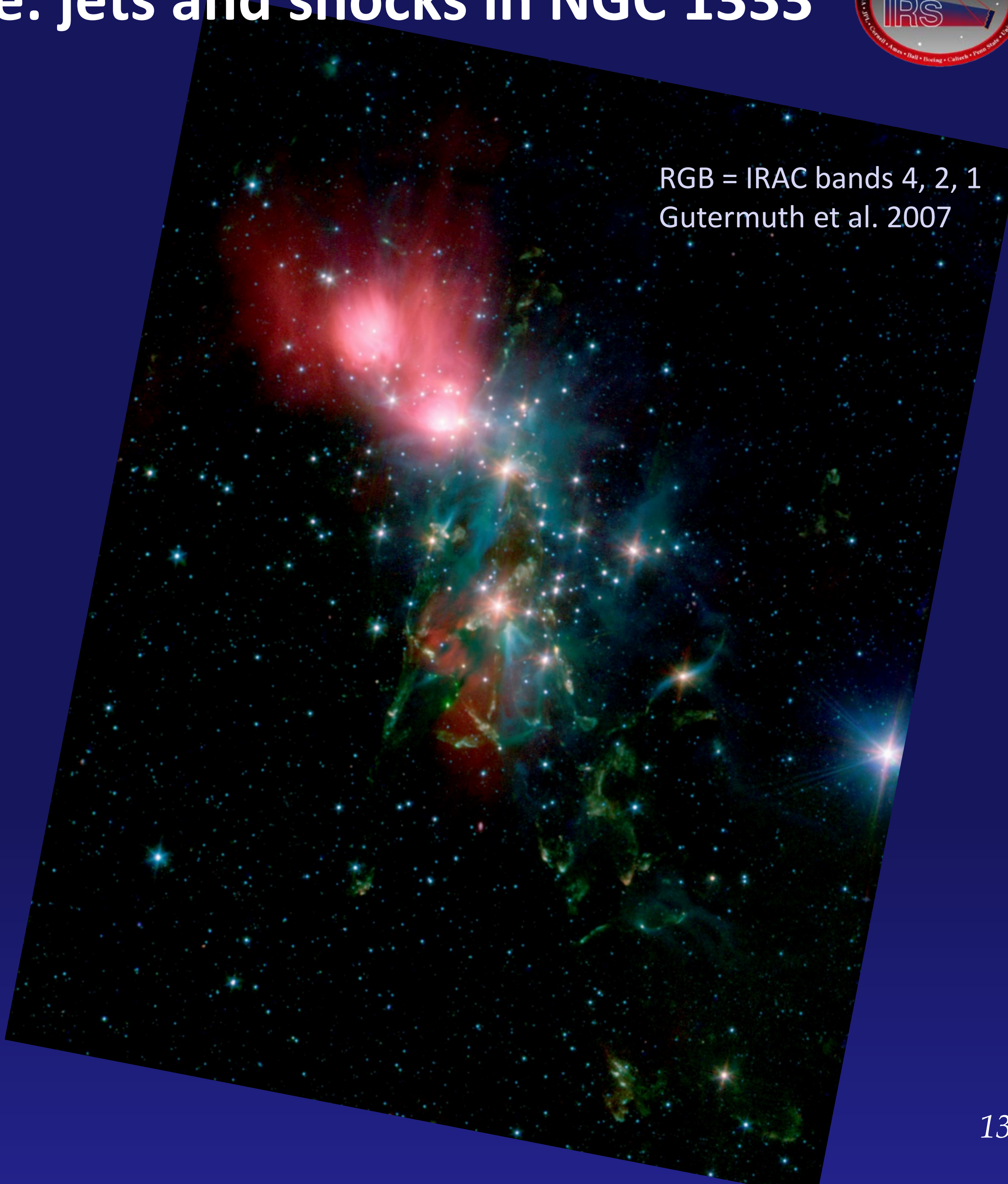

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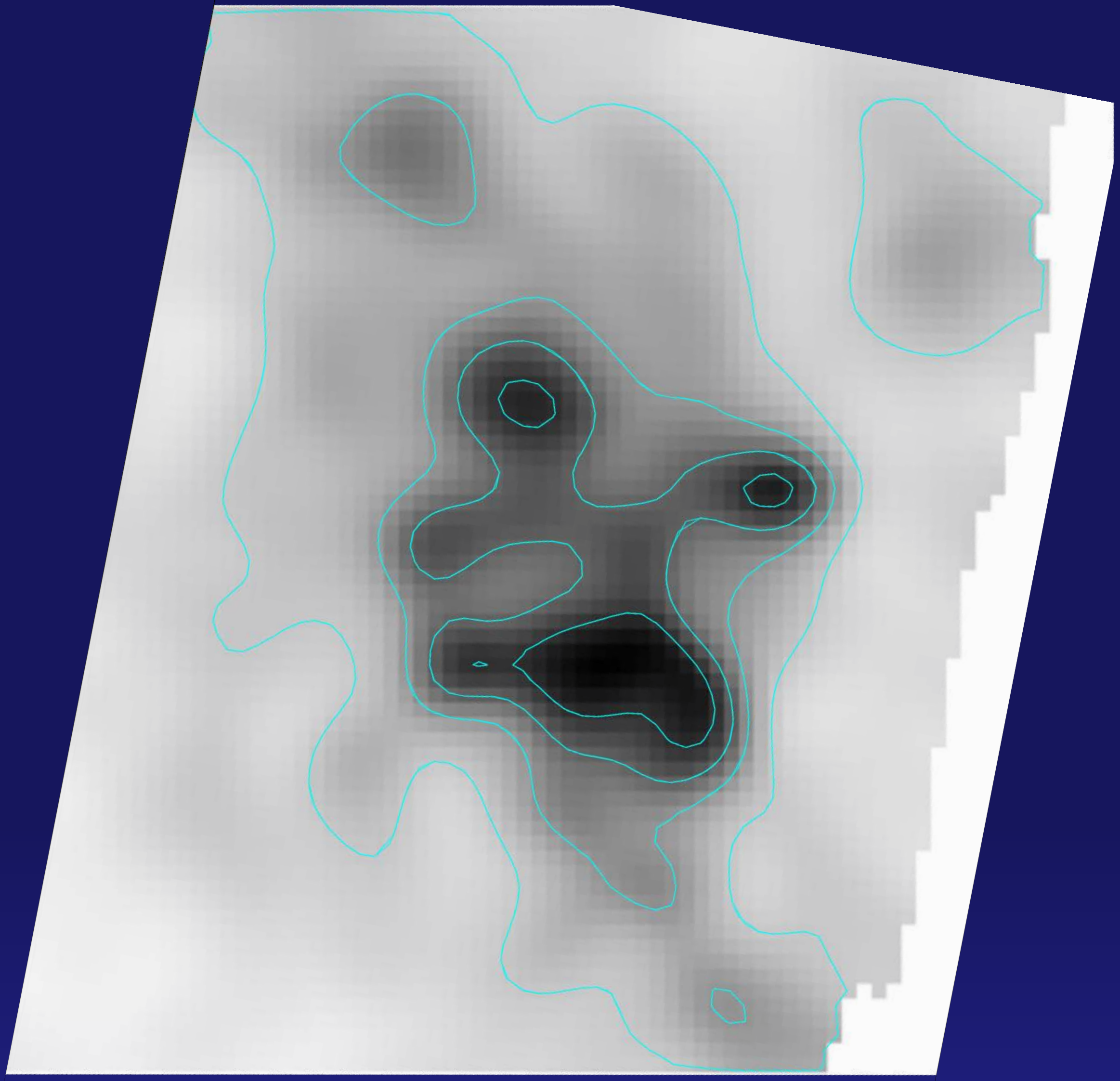

$A_V$ from 2MASS star counts
Gutermuth et al. 2007

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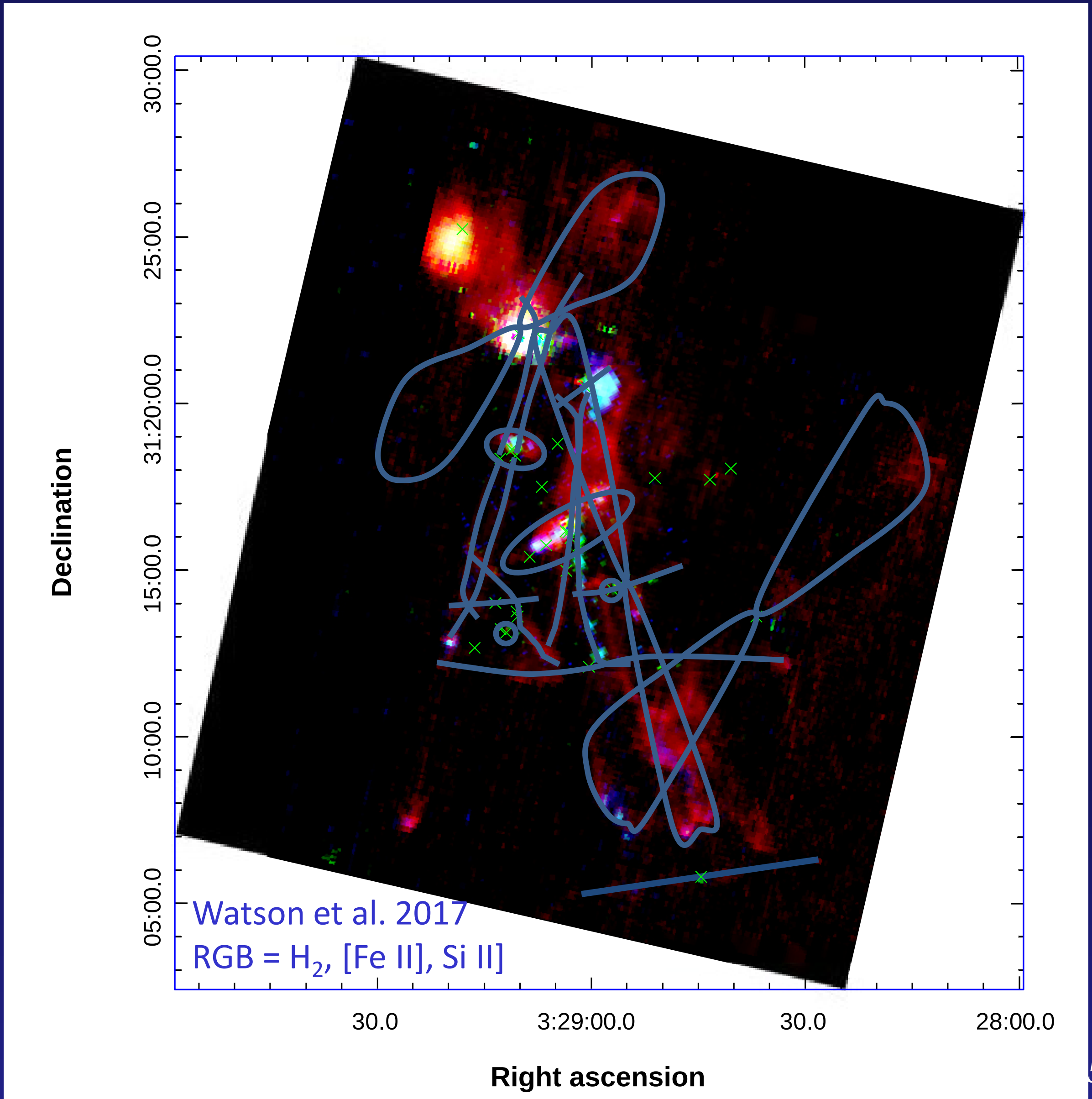
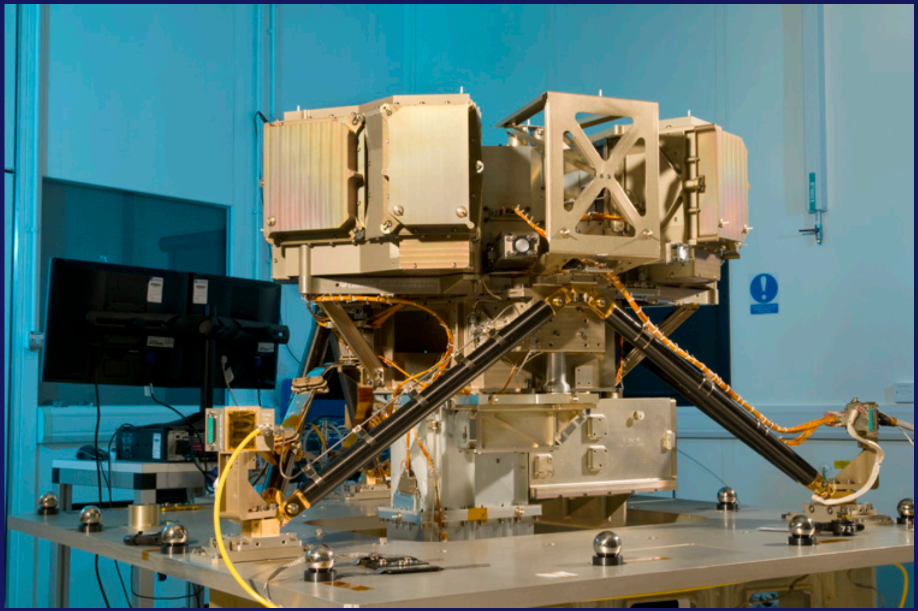


# The IRS protostar and outflow legacy

So we pass on some 300 IRS staring mode observations, and dozens of spectral images, to get outflow and feedback studies started on JWST.

For example, JWST-MIRI can

- spatially resolve *C* shocks and contact discontinuities in nearby star-formation regions $\Rightarrow$ details of *B*, and of turbulence driving.
- spatially resolve oblique shocks in protostellar envelopes $\Rightarrow$ the role of outflows in determining the duration of a protostar's accretion phase.



The JWST Mid-Infrared Instrument (MIRI)