Spitzer Observations of Outflow Destruction of Cores

Spitzer looking forward to Herschel

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DENSE CORES IN DARK CLOUDS. I. CO OBSERVATIONS AND COLUMN DENSITIES OF HIGH-EXTINCTION REGIONS

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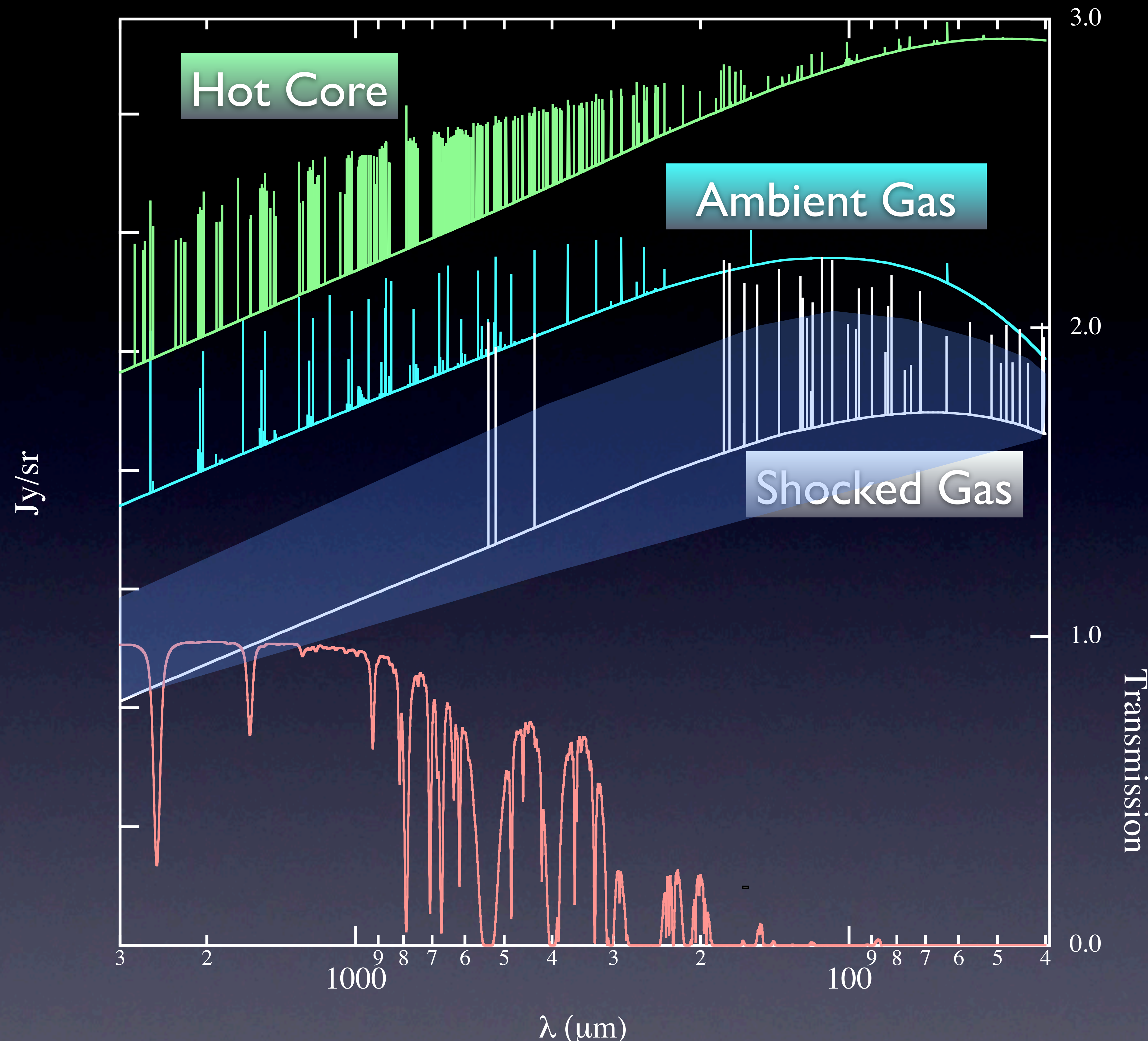
ABSTRACT

Ninety small ($\sim 5'$) visually opaque regions have been selected from Palomar Sky Atlas prints and surveyed in the 2.7 mm $J = 1 \rightarrow 0$ lines of $C^{18}O$ and ^{13}CO. The regions are primarily in complexes of obscuration, including those in Taurus and Ophiuchus. The typical $C^{18}O$ emission region has $C^{18}O$ line width 0.6 km s^{-1}, optical depth 0.4, excitation temperature 10 K, and column density 2×10^{15} cm^{-2}. It has size 0.3 pc, visual extinction ~ 11 mag, and mass ~ 30 $M_{\odot}$. Comparison with equilibrium and collapse models indicates that purely thermal supporting motions are consistent with the present data, but unlikely. If the full $C^{18}O$ line width reflects turbulent supporting motions, nearly all of the observed clouds are consistent with stable equilibrium. If only part of the $C^{18}O$ line width reflects supporting motions, many clouds are also consistent with turbulent contraction. More than half of the clouds have significant departures from Gaussian line shape. The most common asymmetry is a blueshifted peak in the ^{13}CO line, which is consistent with contracting motion.

Subject headings: interstellar: molecules — nebulae: general



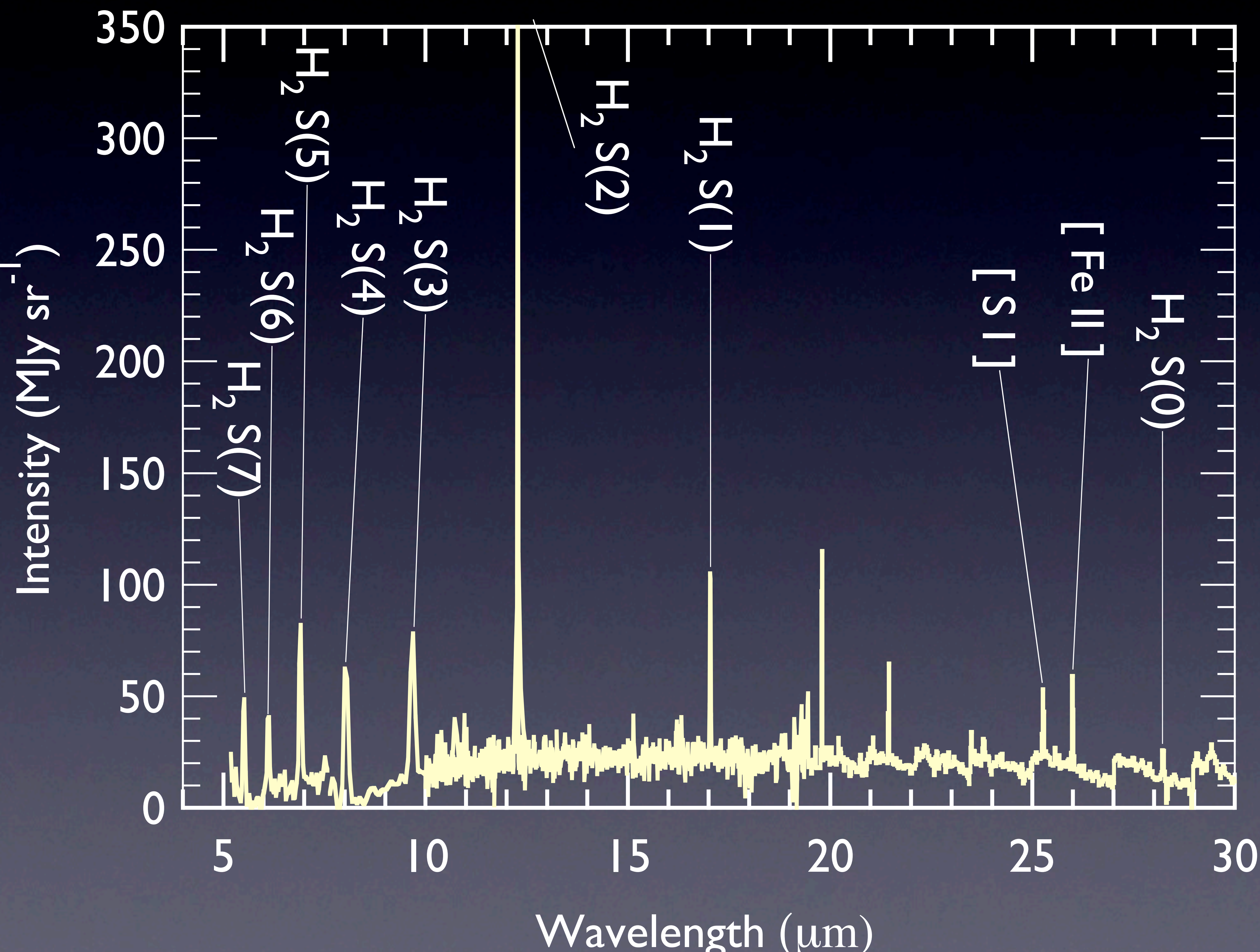
What can you do when you observe most (if not all) the cooling luminosity?

Mapping Shocks with Spitzer IRS

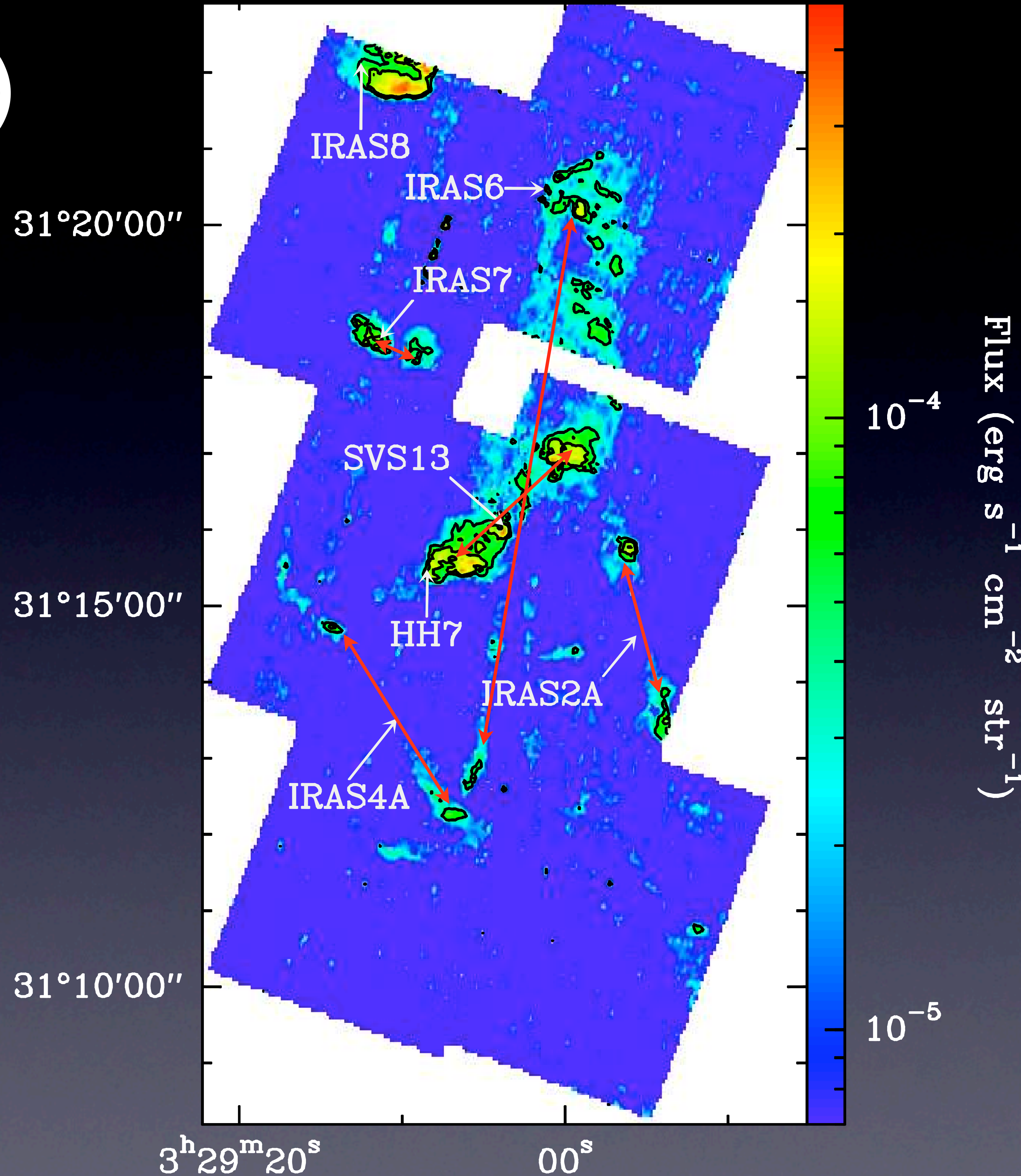
- 8 pure rotational transitions of H_2: 0-0 S(0)-S(7)
- maps of a 6′ x 10′ field in the central region of NGC1333
- Well studied source with a young protocluster and numerous outflows.
- Transitions probe of warm (T > 200 K) and hot (T ~ 1000-2000 K) gas seen in shocks -- and trace the dominant constituent.

R. Gutermuth (CfA)

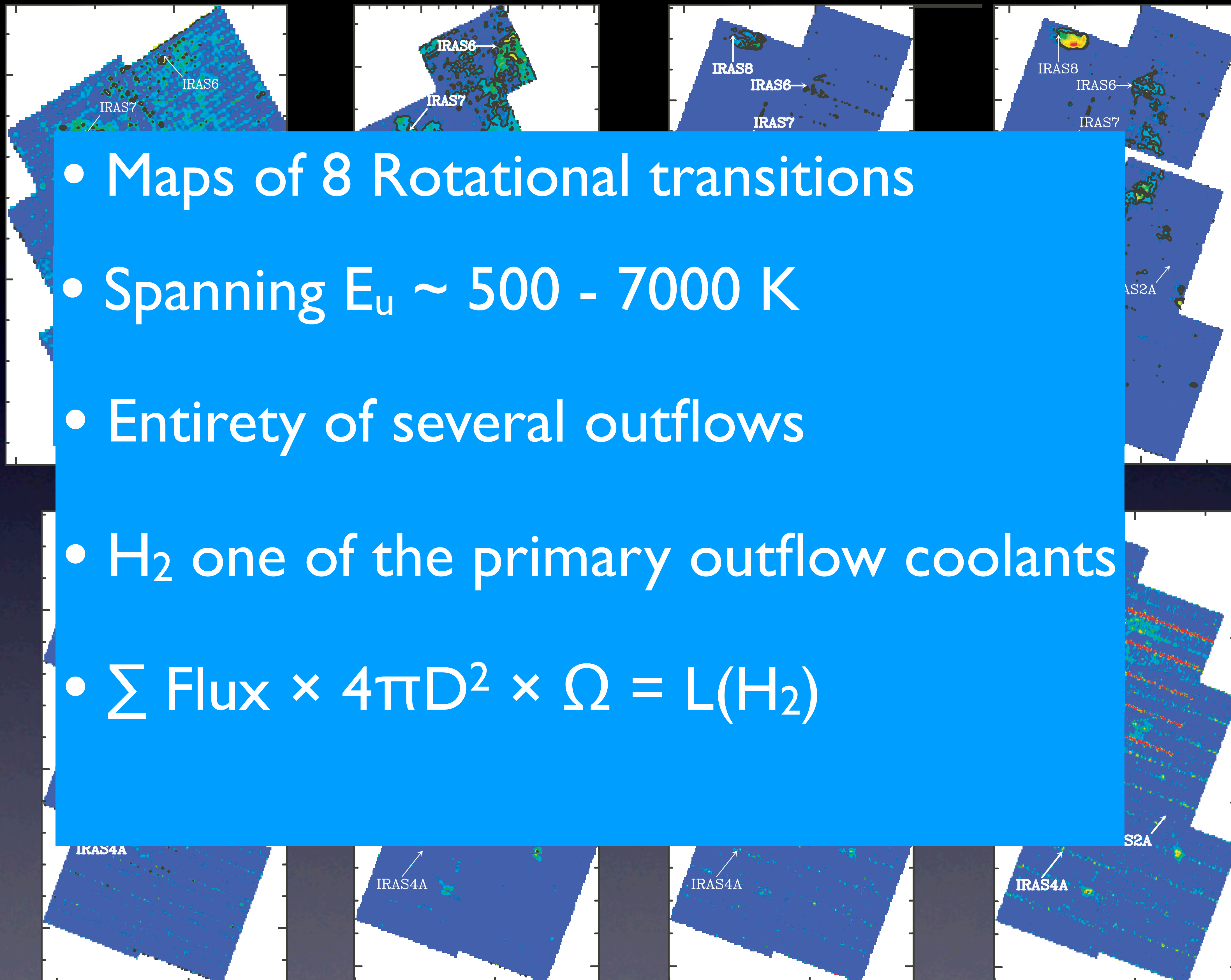
Typical Spectra



H_2 S(3)



$E_u/k = 2504$ K
5″ Resolution
~60,000 pixels



- Maps of 8 Rotational transitions
- Spanning $E_u \sim 500 - 7000$ K
- Entirety of several outflows
- H_2 one of the primary outflow coolants
- $\sum$ Flux $\times\, 4\pi D^2 \times \Omega = L(H_2)$

Line Cooling by Species
Fraction contributed as percentage of $1/2\rho v^2$

v_s	$H_2O(R)$	$H_2O(V)$	$H_2(R)$	$H_2(V)$	$CO(R)$	$CO(V)$
20 km/s	22.66	0.01	44.95	0.11	7.17	0.00
30 km/s	14.14	0.03	63.12	3.45	3.91	0.00

Kaufman & Neufeld 1996

confimed by CO/O I ISO observations

$$\frac{1}{2}\dot{M}_w v_s^2 = (1 - f_m) L_{tot} = (1 - f_m)\frac{1}{f_c} L_{\mathrm{H}_2}$$

$1 - f_m$ = fraction of energy flux given to cooling

f_c = H_2 cooling fraction

Physics of Outflow Core Interaction

- Based on our luminosity we derive:

$$\dot{M}_w \sim 0.6 - 2 \times 10^{-6}\ M_\odot\ yr^{-1}$$

- Can also estimate the total injected momentum flux:

$$\dot{P} = \dot{M}_w v_s = 2 - 6 \times 10^{-6}\ M_\odot\ yr^{-1}\ km\ s^{-1}$$

- total momentum injected by outflow into core

  ➡ $P = \dot{P}\tau_{dyn} = 0.06$ to $0.4\ M_\odot\ km\ s^{-1}$

- if similar level of outflow actively persists during the entire embedded phase (~5×10^5 yrs; Evans et al. 2008):

  ➡ inject ~$6 - 30\ M_\odot\ km\ s^{-1}$

Physics of Outflow Core Interaction

- when flows slow down to 1 km s^{-1} will have swept up 6 - 30 $M_\odot$
- Typical core mass ~ 1 - 5 $M_\odot$
- *Outflow is primary destruction mechanism for the core (within the outflow cone)*
- Also impact on the cloud -- but do not disrupt the cloud

Summary and Looking to the Future

- Presented observations of 8 rotational transitions of molecular hydrogen in NGC1333
- Constrained the total H_2 cooling luminosity and provided estimates of the wind mass loss rate
- Based on outflow momentum (and energetics), the flow is the main destruction mechanism of the core
- *Herschel (in some cases combined with Spitzer) will observe all the primary coolants - can perform this for many more flows but also in PDR's, on disk surfaces....*

Context: How is this usually done

- CO Emission
  - ➡ provides velocity, but need inclination correction
  - ➡ mass if adopt CO/H_2
  - ➡ low velocity outflow emission is hidden by core emission
  - ➡ emission is optically thick - not a good mass tracer

- Cooling (H_2 or far-IR)
  - ➡ need to know shock velocity
  - ➡ lines are optically thin
  - ➡ in case of H_2 tracing the main constituent and coolant
  - ➡ does not emit in core and is independent of inclination

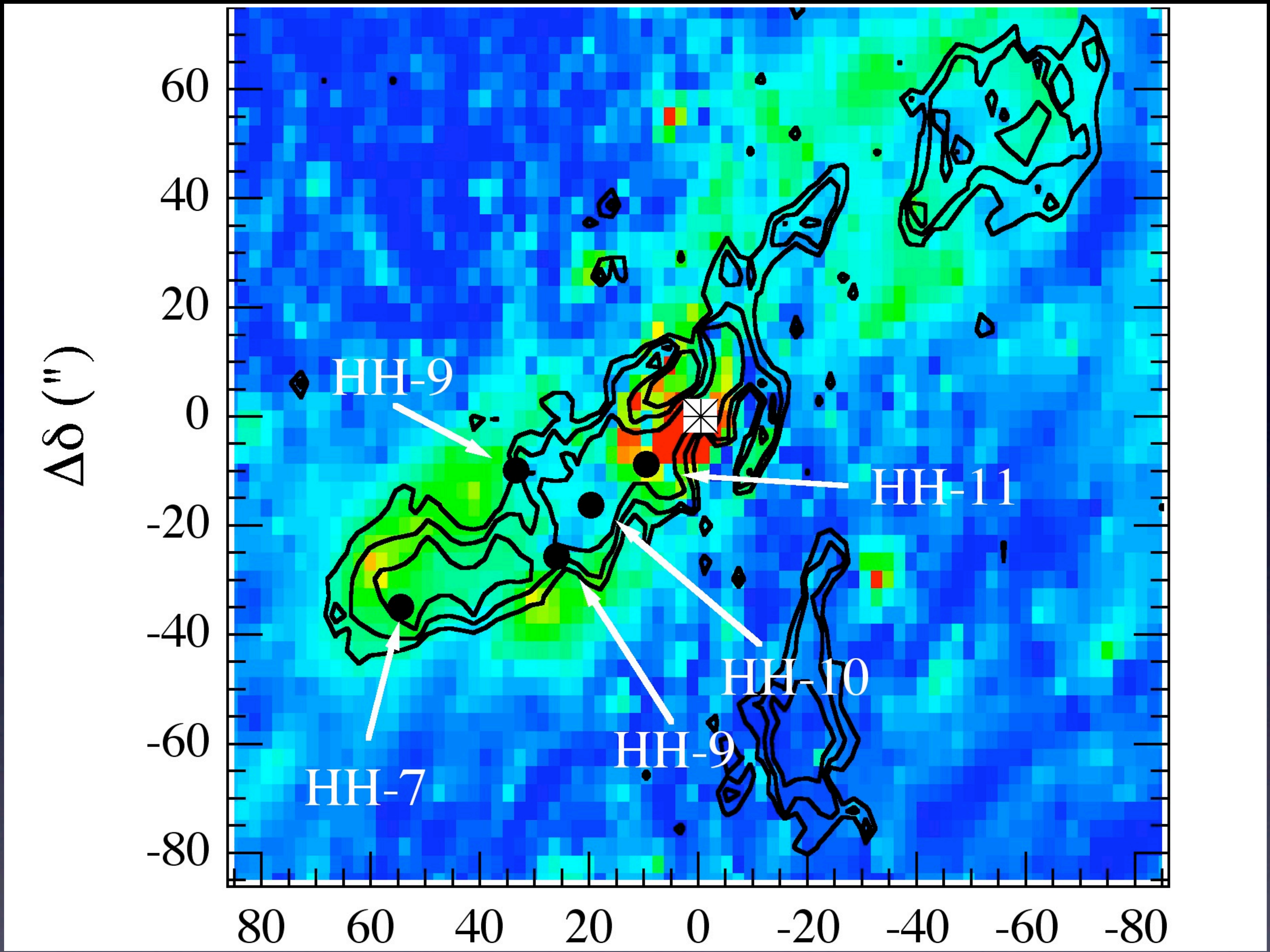
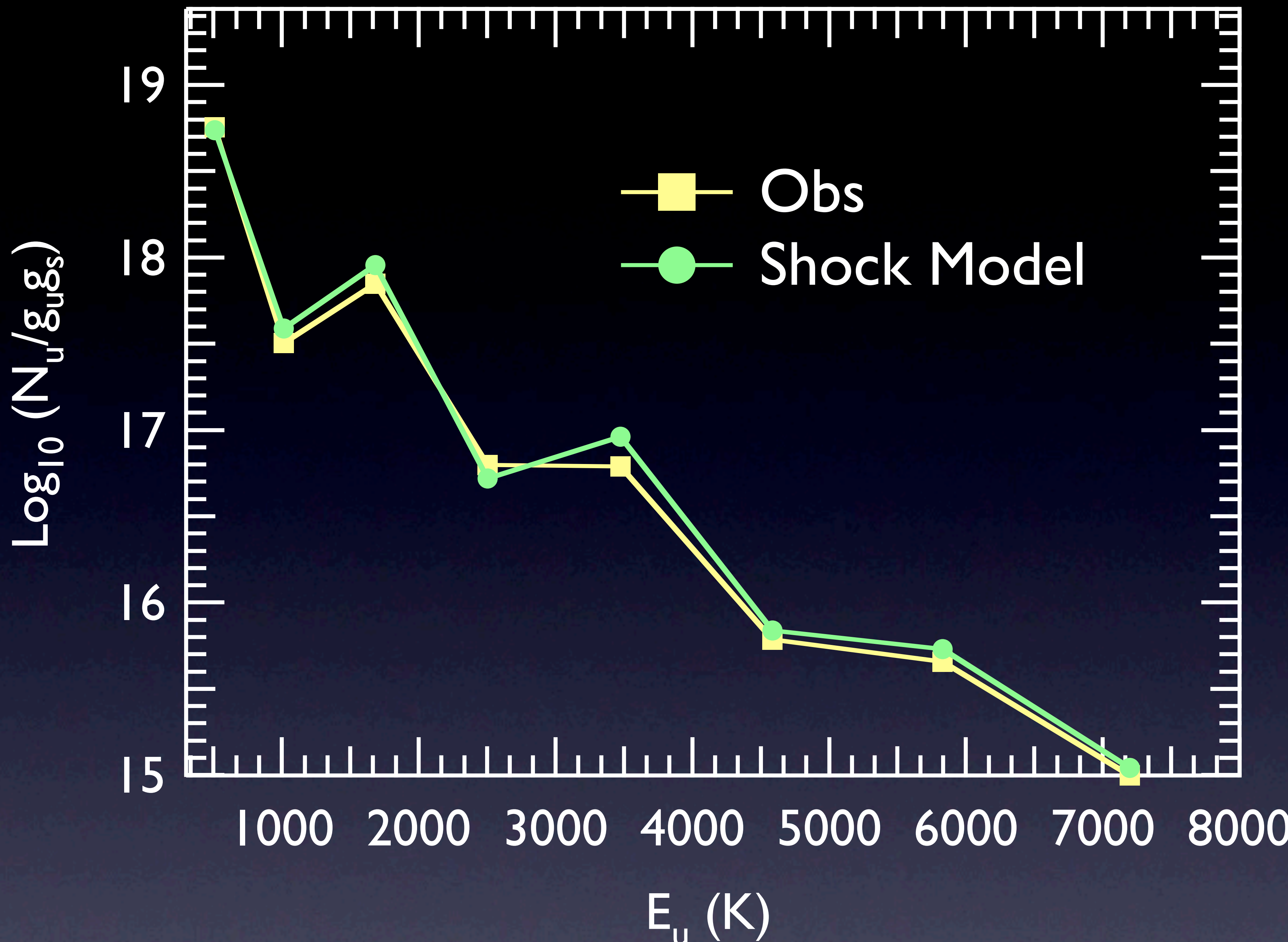


Image: S(0)

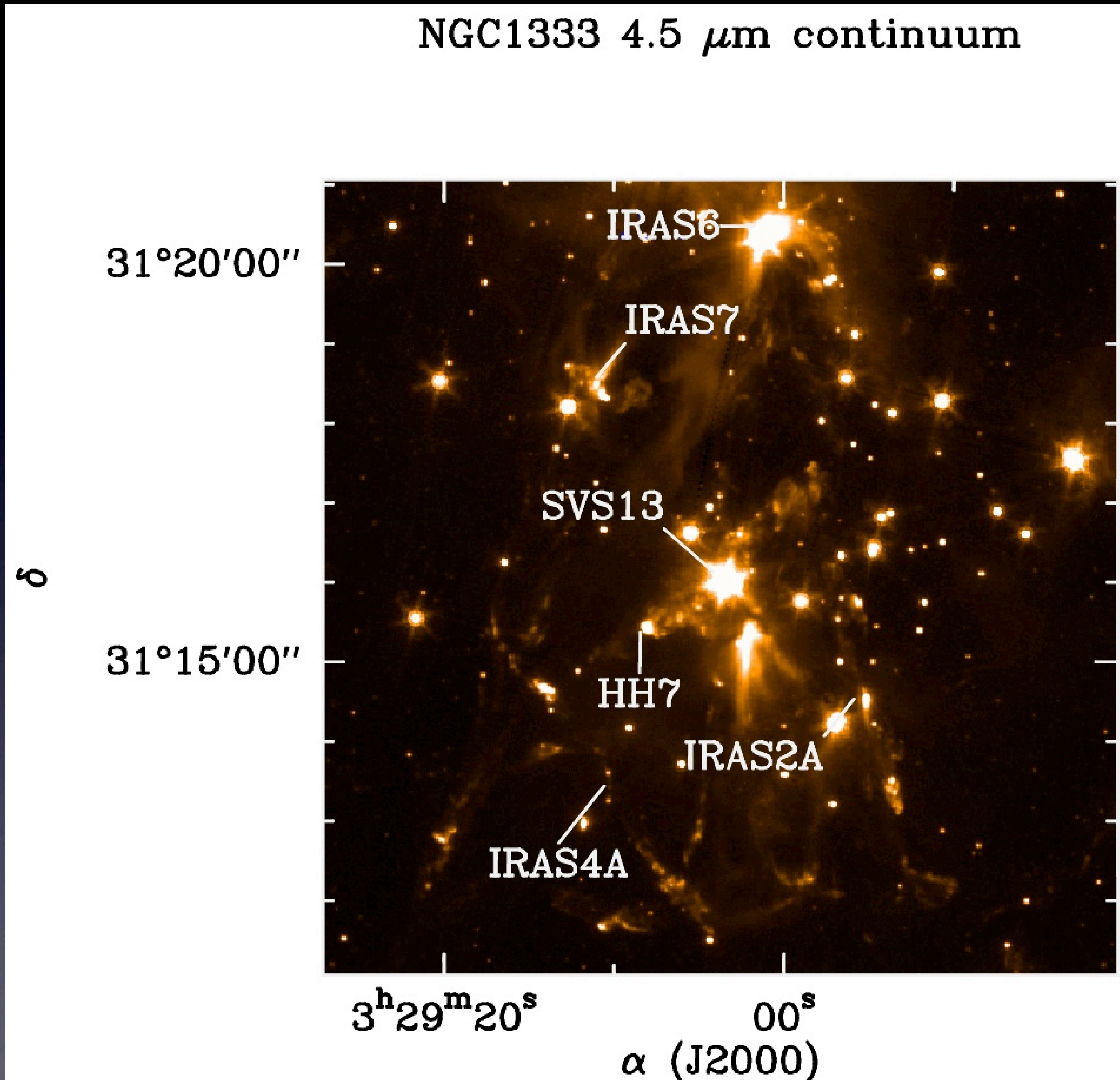
Contours: 35 μm

$[Si^{+}]$ $^{2}P_{3/2}$-$^{2}P_{1/2}$

Rotation Diagram



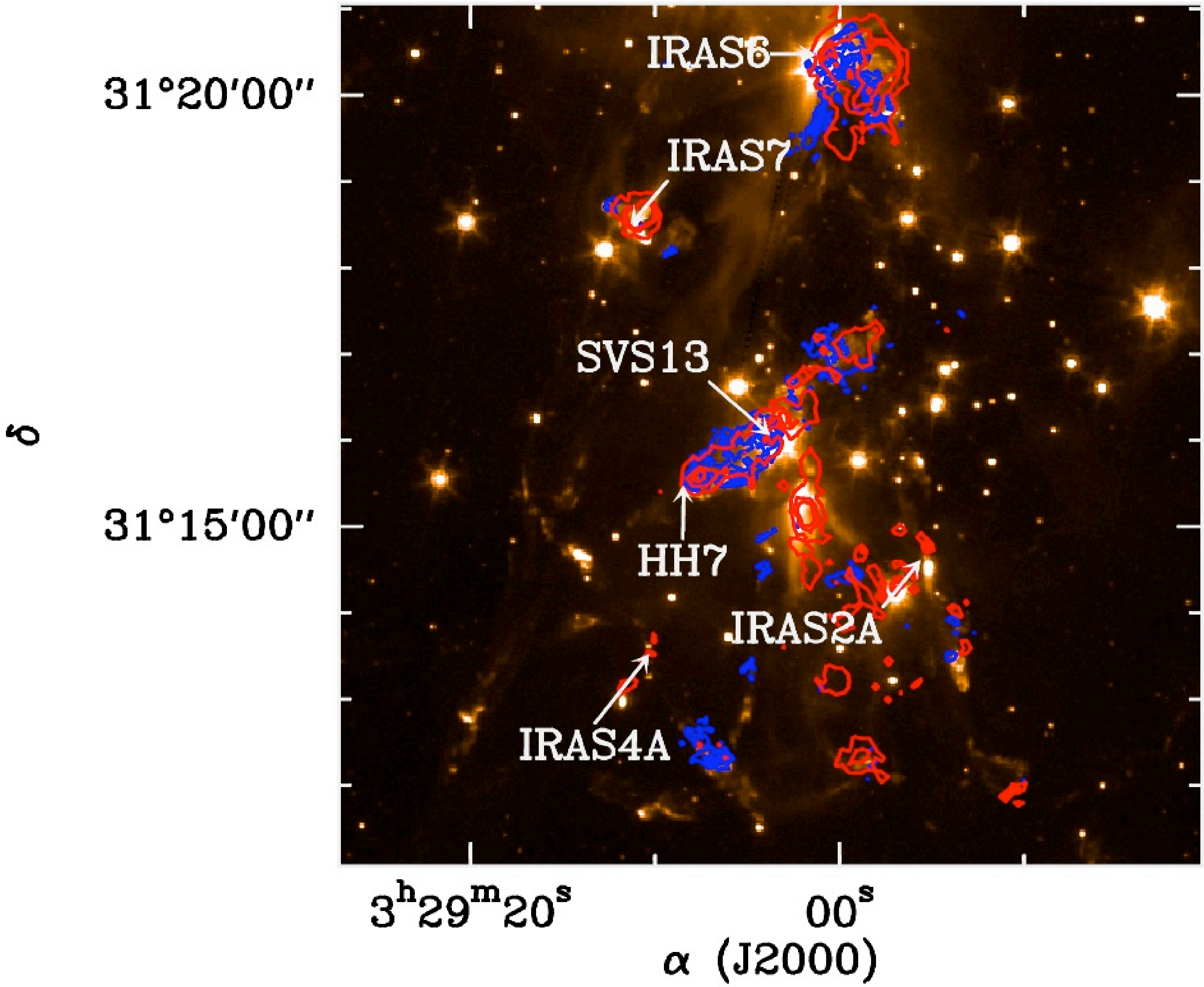
- zig-zag behavior -- non-equilibrium ortho/para ratio
- H_2 emission well fit with shock models provided v_s ~ 20-30 km/s
- covered peak of excitation.
- *we KNOW the H_2 cooling luminosity*



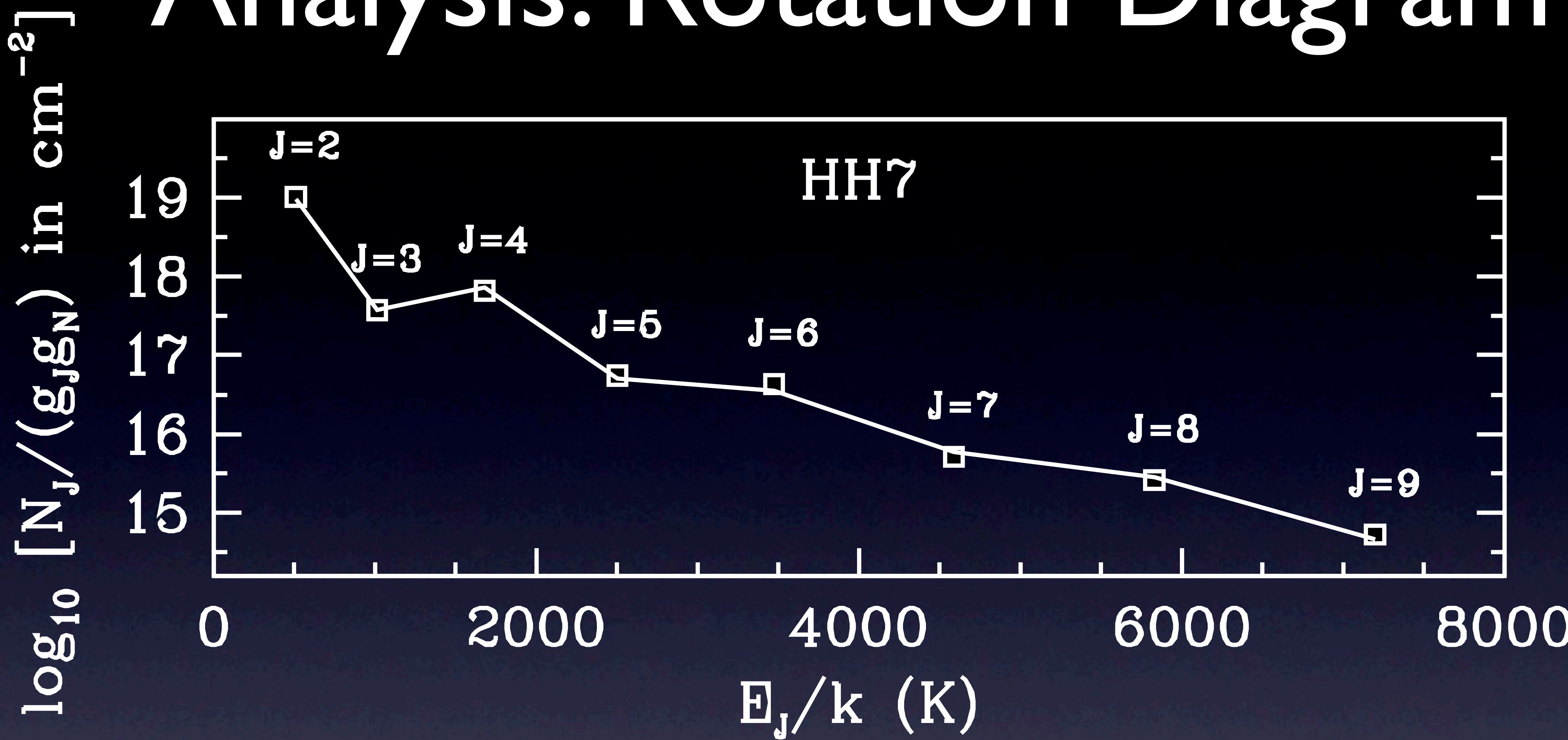
NGC1333 4.5 μm continuum
IRAS6
IRAS7
SVS13
HH7
IRAS2A
IRAS4A
31°20'00"
31°15'00"
δ
3h29m20s
00s
α (J2000)

NGC1333 4.5 μm continuum

H_2 S(1) (blue) and FeII (red)

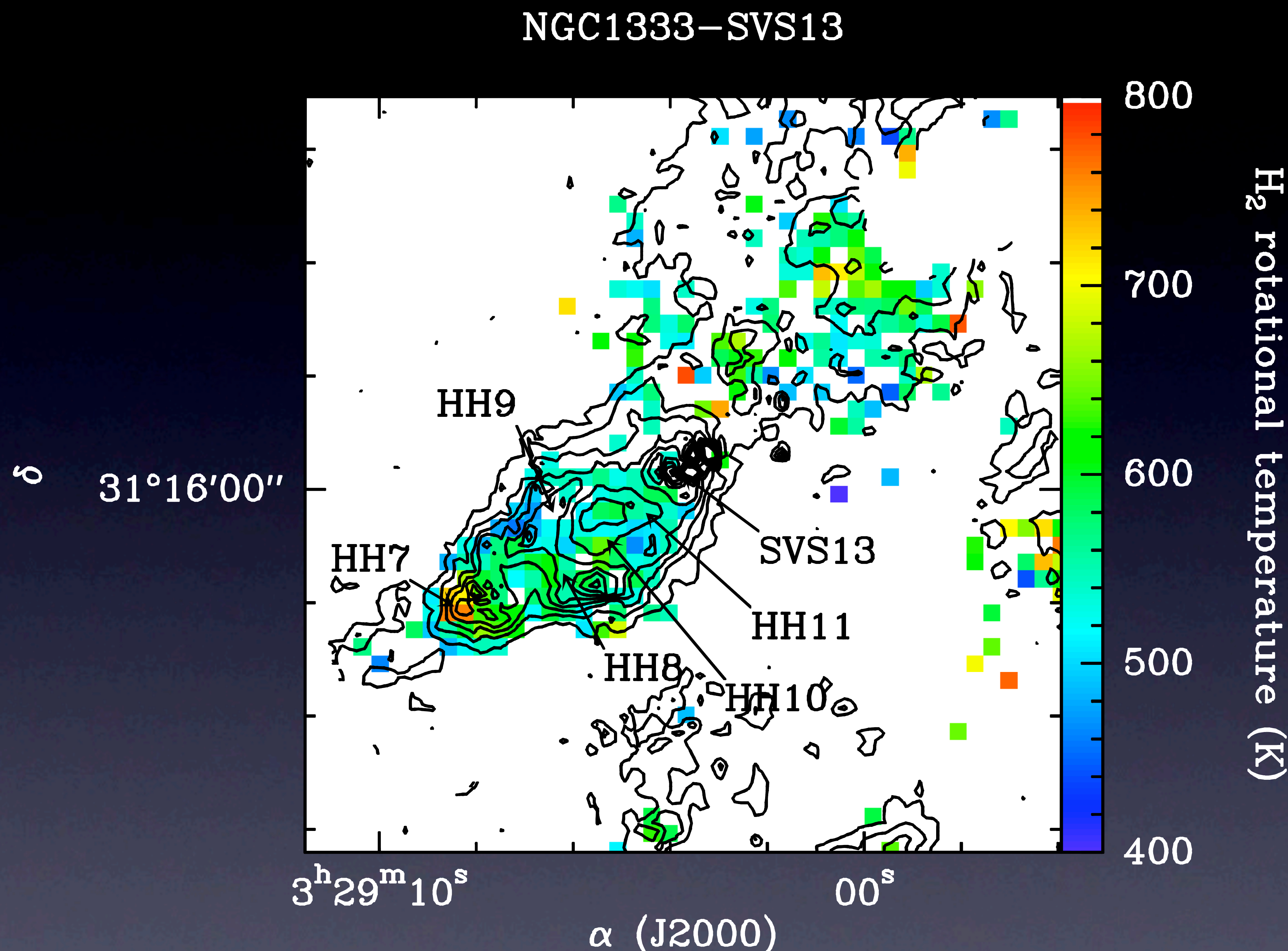


Analysis: Rotation Diagram



- Can derive rotational temperature and ortho/para ratio.
- Zig-Zag Behavior: o/p ratio not in equilibrium
- Is also some curvature in rotational diagram -- indicative of admixture of temperature

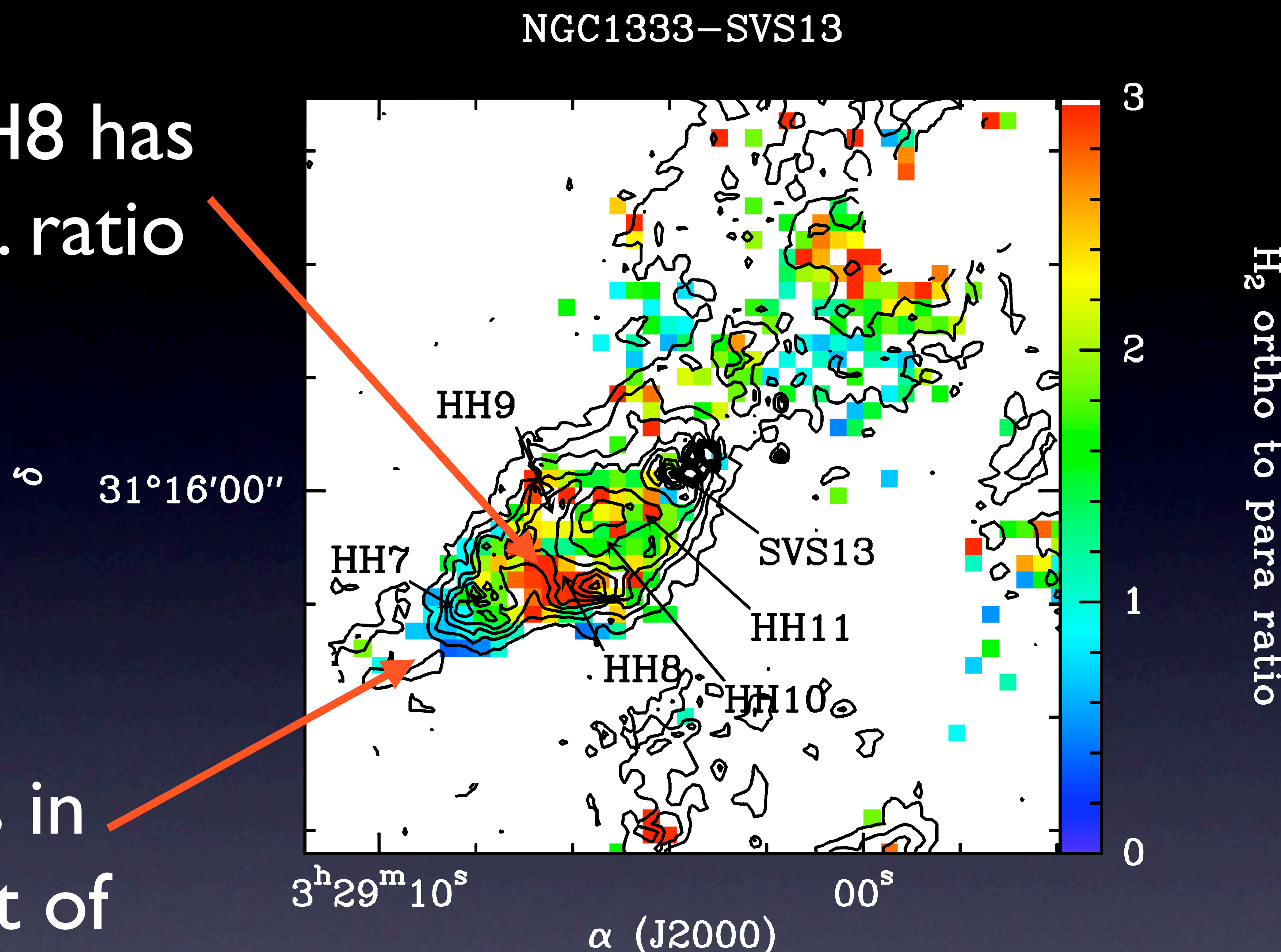
Measurement of H_2 Kinetic Temperature



➡ T ~ 400-800: Consistent with shock heating by 10-20 km/s shocks

Ortho/Para Ratio

HH8 has eq. ratio



Gas in front of shock has low o/p ratio

At T~600 K o/p should be 3:1 - But we measure o/p ~ 0.1-2

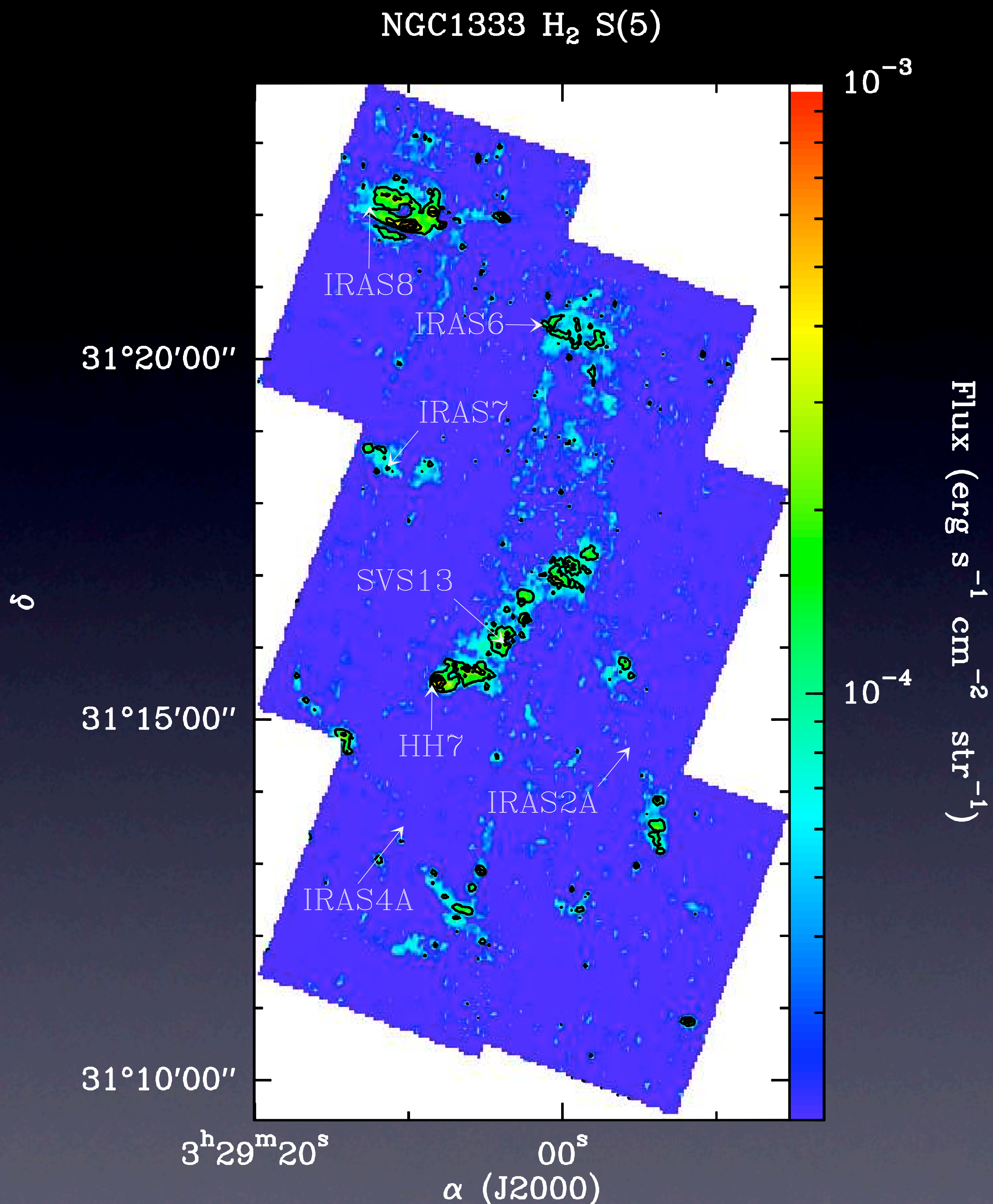
Interpretation of o/p ratios

- At observed temperature o/p should be 3
  - ➡ The gas is currently warm
  - ➡ The gas was previously cold (T < 50-100 K)
- Shocks heat gas temporarily (cooling time ~100 yrs)
  - ➡ gas has not been warm long enough to establish equilibrium o/p ratio
  - ➡ at T = 650 timescale is 5000 yrs! (shorter at higher T)
  - ➡ Observation of o/p of 3 indicates gas heated to T > few thousand K previously

H_2 in NGC1333

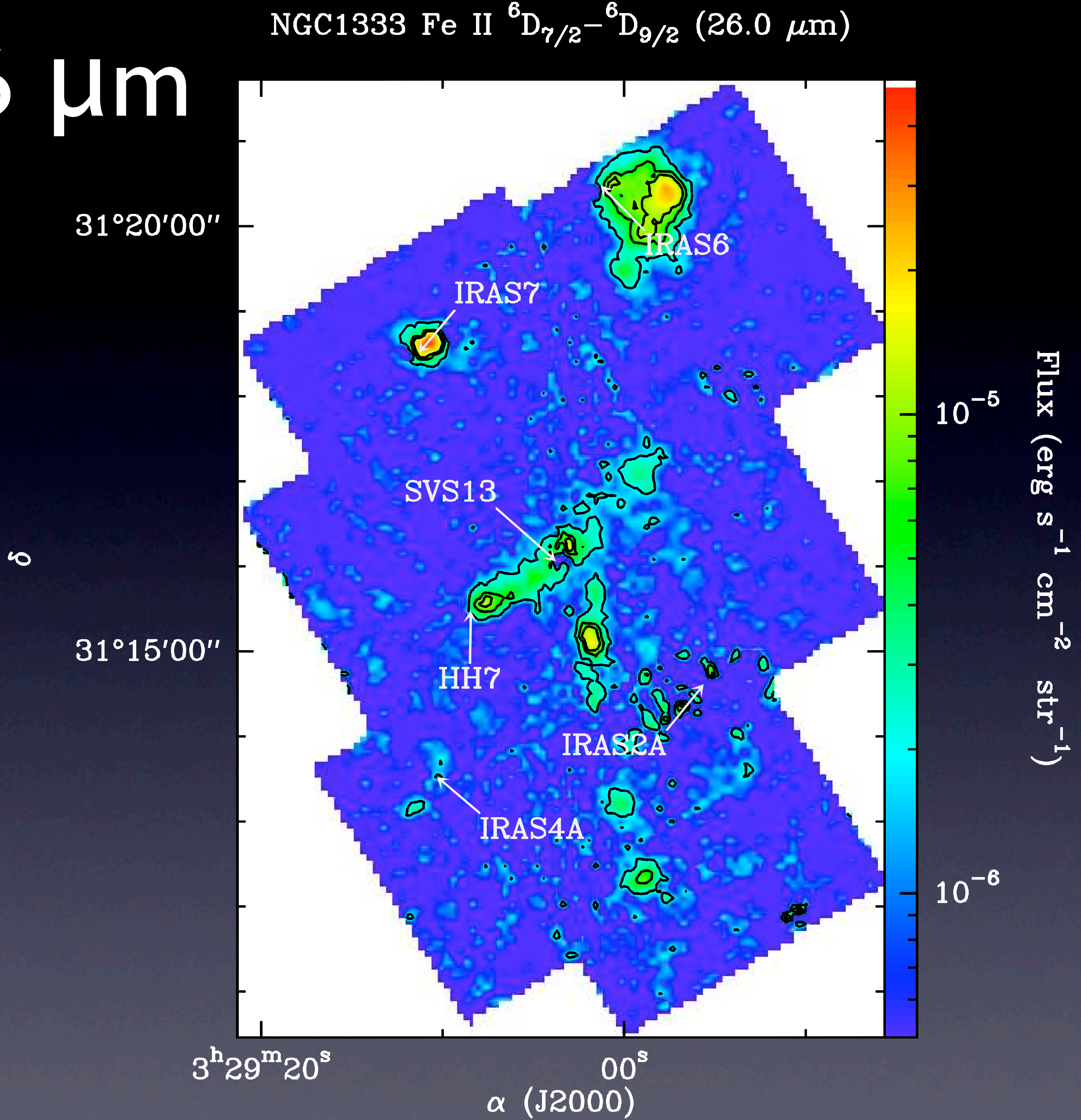
- o/p ratios provide a fossil memory
- lowest ratios (o/p $\leq$ 0.1) in front or on edges of shock - tracing pre-shock gas
  - ➡ o/p ratio in cold ISM is dominated by para-H_2
  - ➡ lowest ratios implying equilibrium below 30 K.

H_2 S(5)



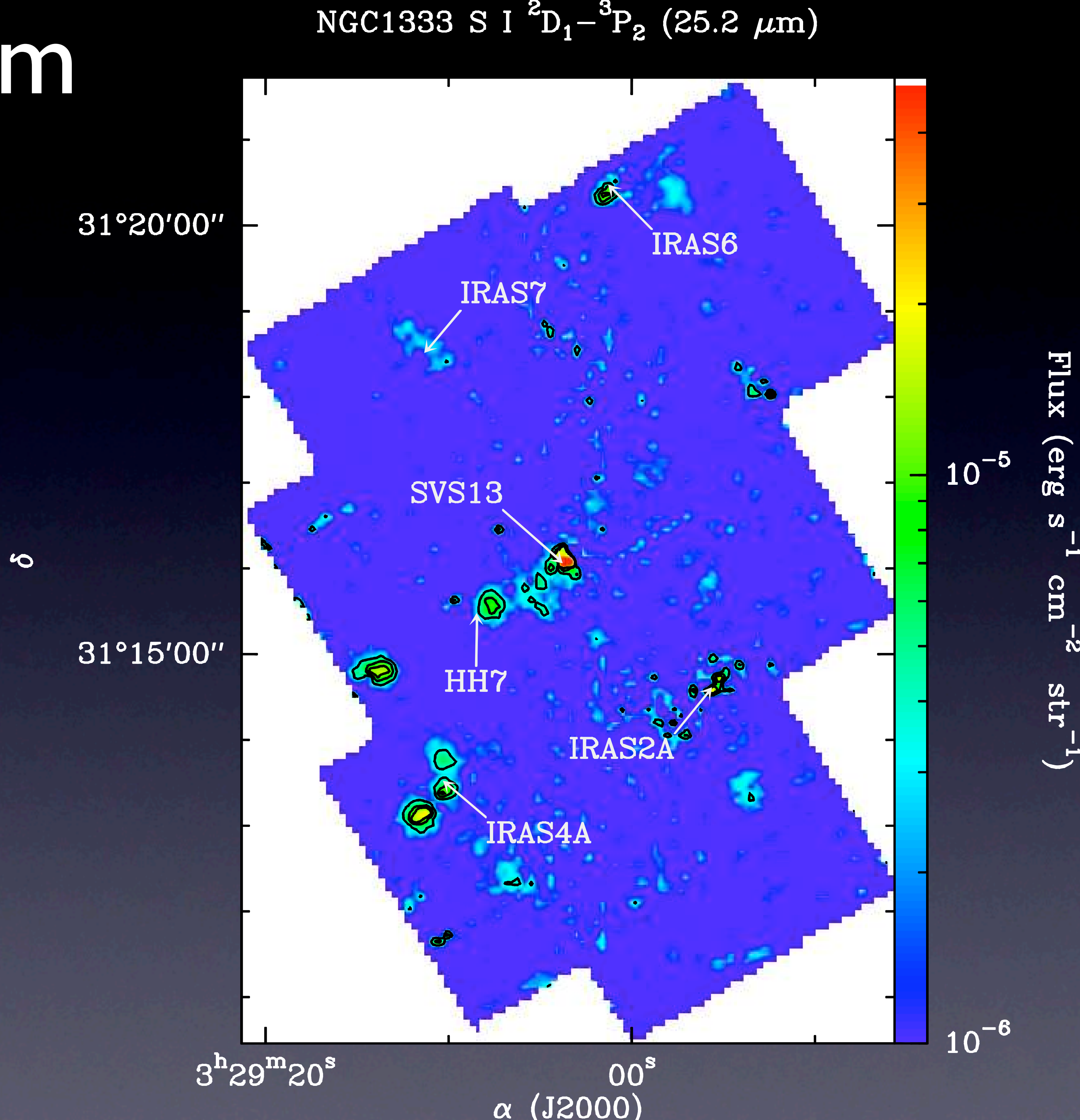
NGC1333 H2 S(5)
IRAS8
IRAS6
IRAS7
SVS13
HH7
IRAS2A
IRAS4A
31°20′00″
31°15′00″
31°10′00″
δ
3h29m20s
00s
α (J2000)
10−3
10−4
Flux (erg s−1 cm−2 str−1)

Fe^+ 26 µm



Wednesday, November 18, 2009

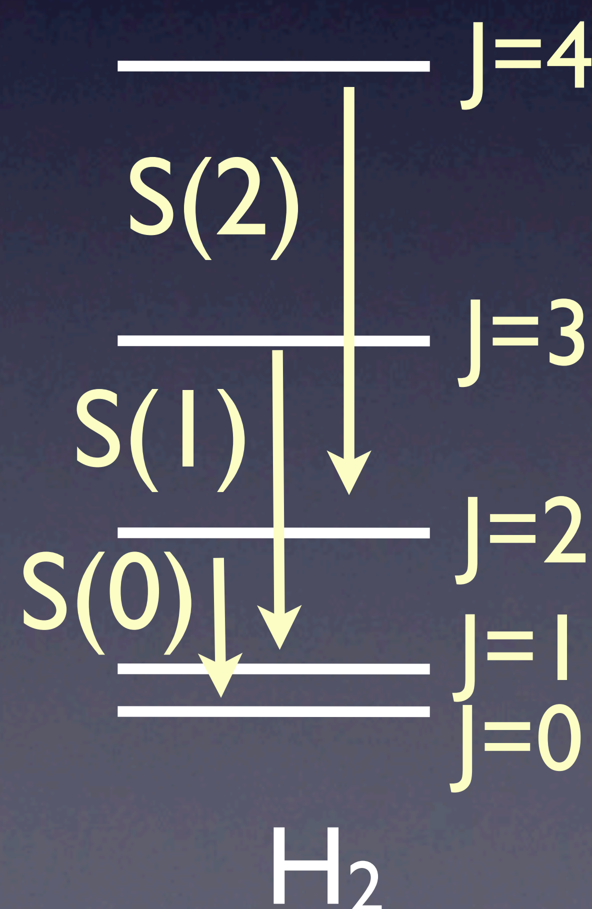
S I 25 µm



NGC1333 S I $^2D_1-^3P_2$ (25.2 μm)
31°20′00″
31°15′00″
δ
IRAS6
IRAS7
SVS13
HH7
IRAS2A
IRAS4A
$3^h29^m20^s$
00^s
α (J2000)
10^{-5}
10^{-6}
Flux (erg s^{-1} cm^{-2} str^{-1})

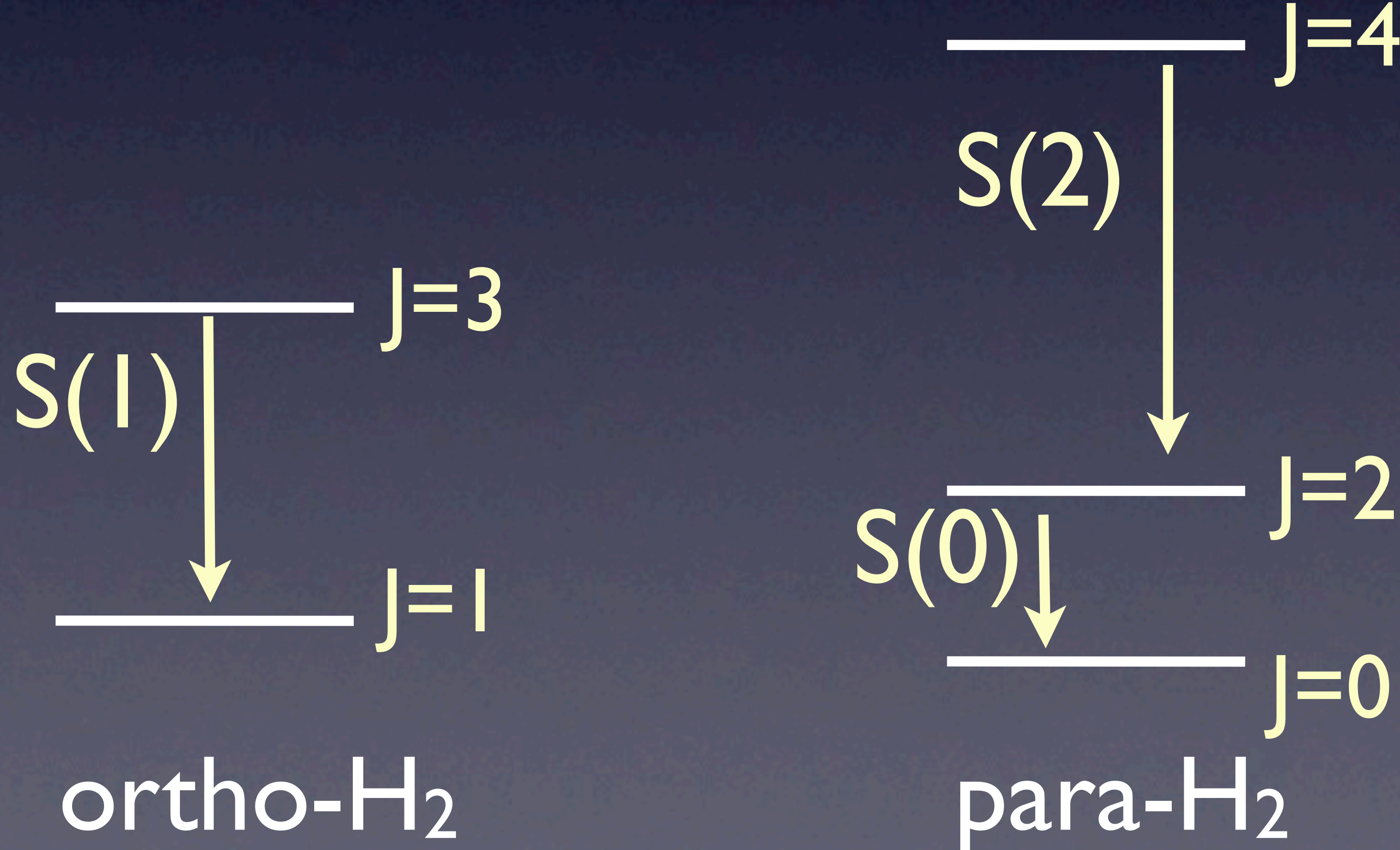
H_2 Rotational Transitions

- homonuclear molecule → no permanent dipole moment
- quadrupole transitions with $|\Delta J| = 2$



H_2 Rotational Transitions

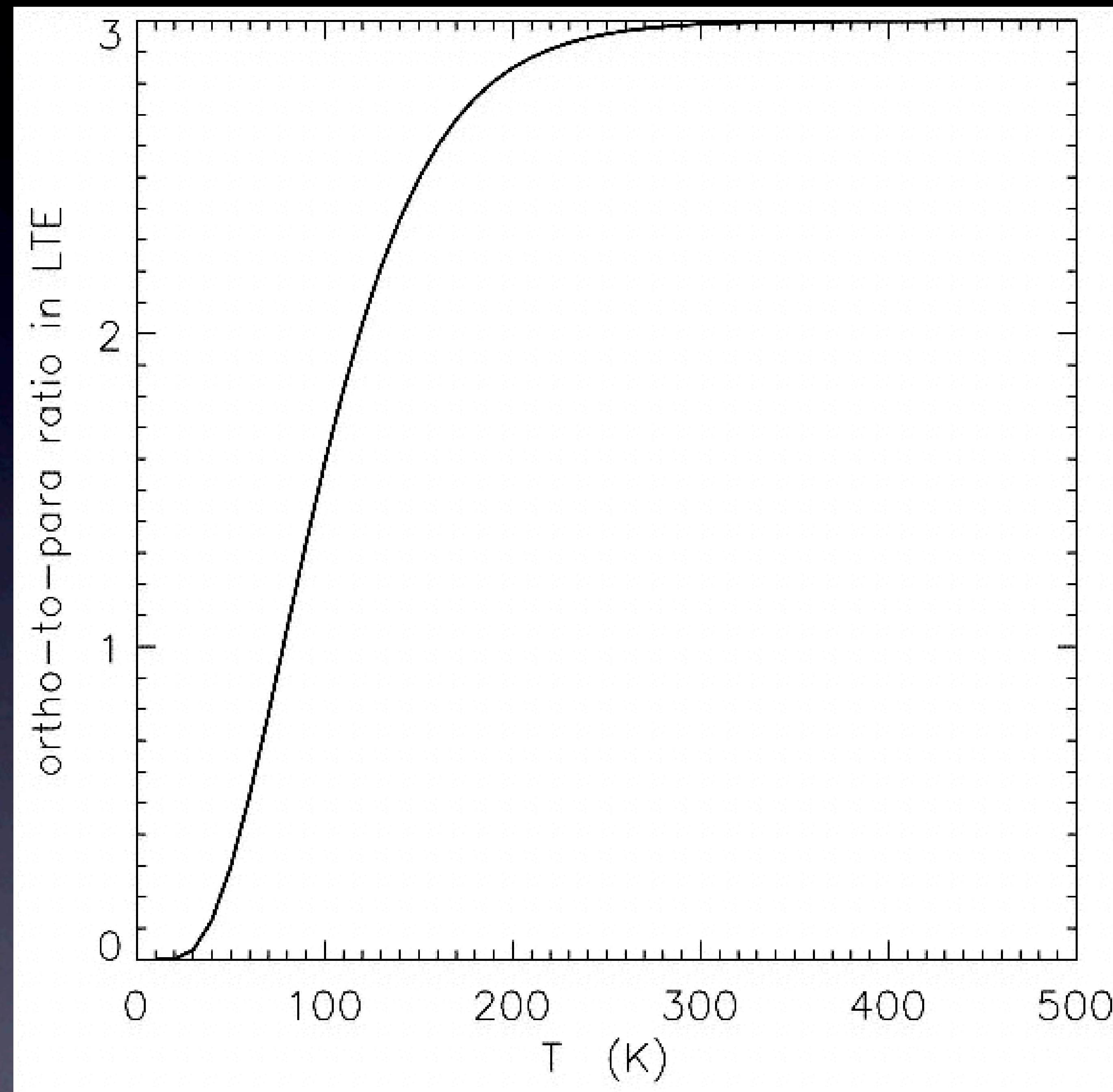
- H_2 nuclei each have spin I = 1/2 - can form a triplet and singlet nuclear function
- Fermi-Dirac statistics (total wave-function must be anti-symmetric to interchange of any 2 particles):
  - ➡ ortho (spins of nuclei parallel)
  - ➡ para (spins of nuclei anti-parallel)



Equilibrium Ratio

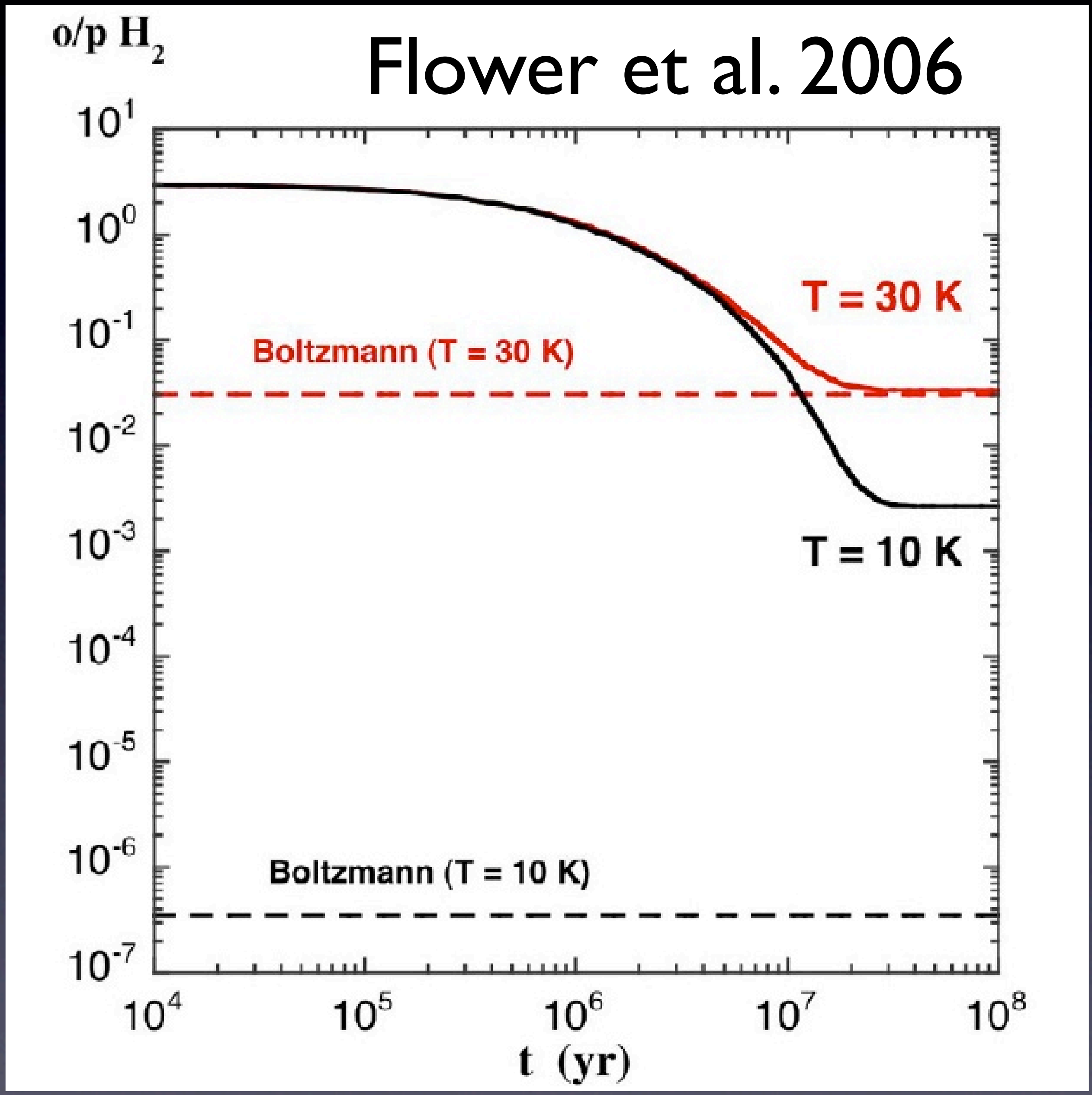
- At high temperature (T > 250 K) the equilibrium ratio is 3:1

- At low temperature
  ➡ ortho-H_2/para-H_2 = $n_{J=1}/n_{J=0} = 9 \exp(-171/T)$



Ortho-to-Para Conversion

- Cold Gas:
  - ➡ Formation on grains produces 3:1
  - ➡ slow conversion via gas-phase reactions (~10^5 yrs)
  - ➡ expectation o/p is low in cold gas
- Warm Gas:
  - ➡ o/p can change behind shocks via reaction with H
  - ➡ para-H_2 + H + 4000 K ↔ ortho-H_2 + H
  - ➡ at 650 K get 3:1 in 5000 years
  - ➡ expectation o/p can be high depending on Temp and time



Observations of H_2 o/p Ratio

- o/p ratio known in diffuse clouds (H_2 detected in UV) and from ISO observations of shocks - but never mapped with across a shock
- o/p ratio in cold, dense ISM is unclear
  - ➡ implications for equation of state
  - ➡ can affect gas chemistry
  - ➡ collision rates are stronger with ortho-H_2 and some polar species (e.g. H_2O)

Summary

- Results from two Spitzer studies of dense ISM
  - ➡ Isolated structure within IR dark clouds
  - ➡ Objects are pre-stellar and have a clump mass function significantly steeper than stellar IMF -- earliest stages of fragmentation
  - ➡ Mapped the emission of H_2 and atoms in numerous outflows
  - ➡ Temps ~ 600 K, consistent with v ~ 10 - 20 km/s
  - ➡ o/p ratios trace heating history of gas and are likely low in quiescent material

Molecular Outflows in the ISM

- Energetic flows from young stars are an intrinsic part of the star formation process
- They interact with the natal cloud producing shocks which alter the physics and chemistry of the surrounding material
  - ➡ can elevate gas temperatures from 10-30 K to > 1000 K
  - ➡ fast shocks (> 40 km/s) can dissociate molecules
  - ➡ weaker shocks (10-40 km/s) can alter cloud chemistry