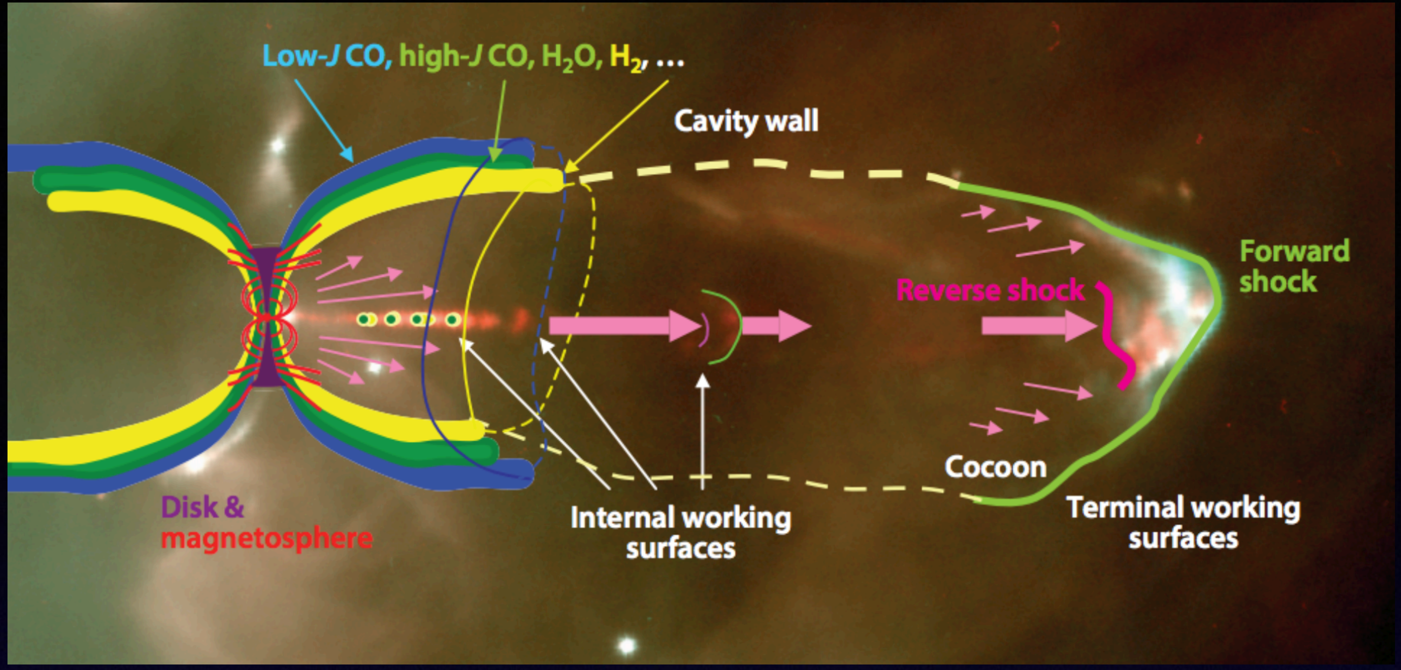
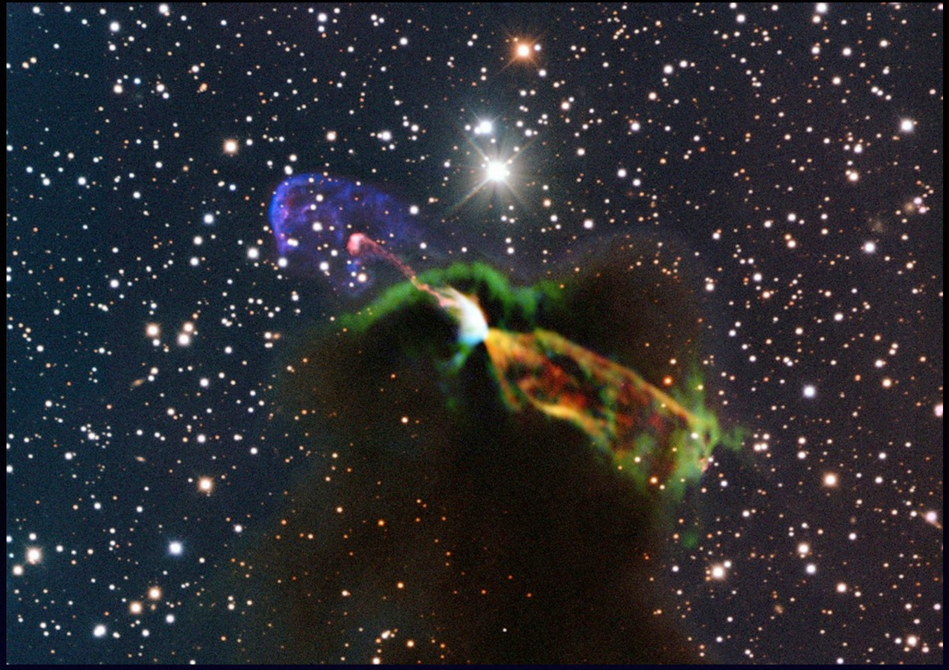




Shocks in protostellar outflows: observational constraints

Agata Karska

Center for Astronomy, Nicolaus Copernicus University in Torun, Poland

L. Kristensen, M. Kaufman, E. F. van Dishoeck, WISH, WILL and DIGIT teams

Low-mass protostars: laboratories of outflow shocks

Many nearby regions (<500 pc) driving large-scale outflows (up to ~pc) allow spatially-resolved observations

Low-mass protostars: laboratories of outflow shocks

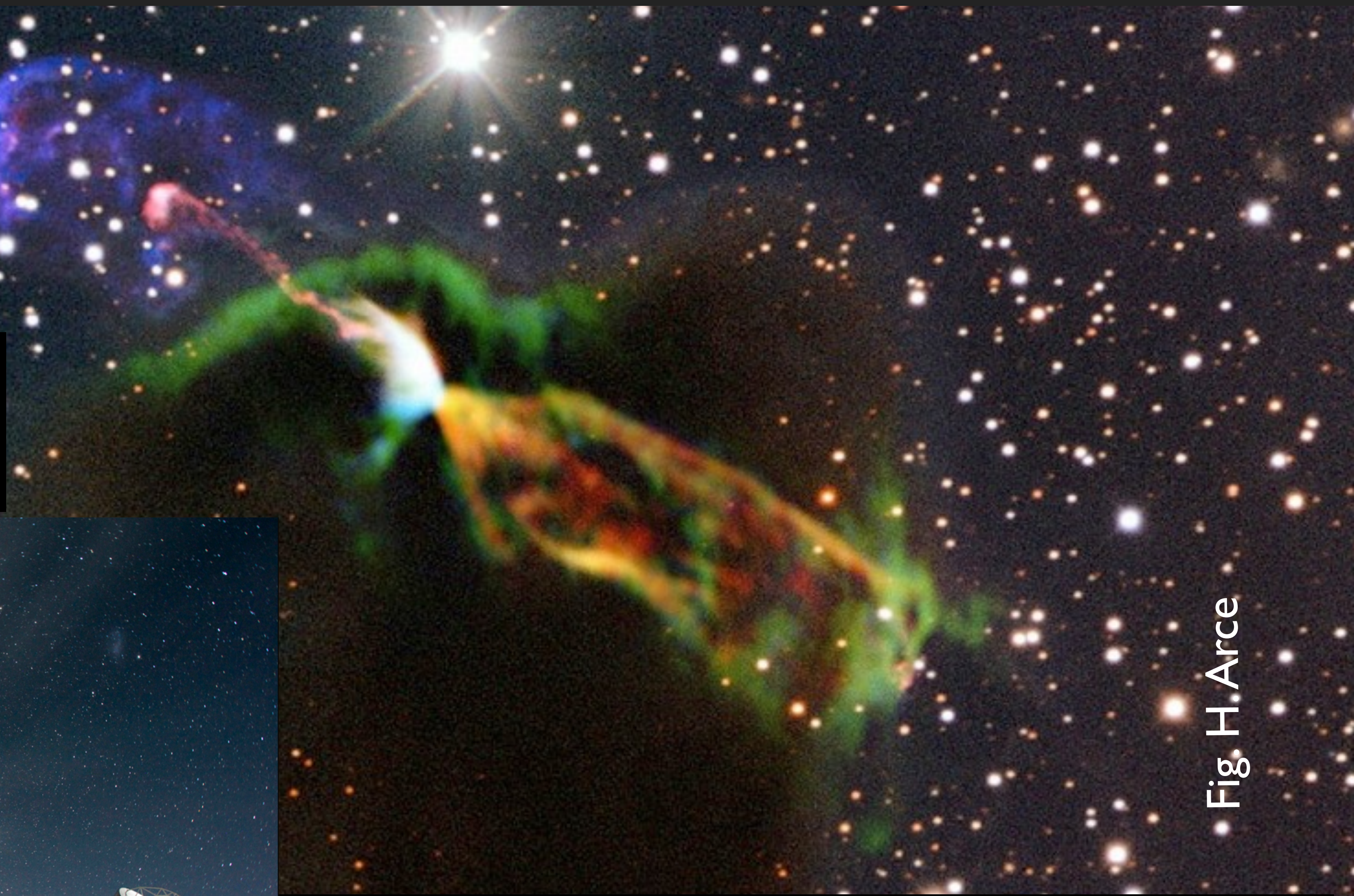
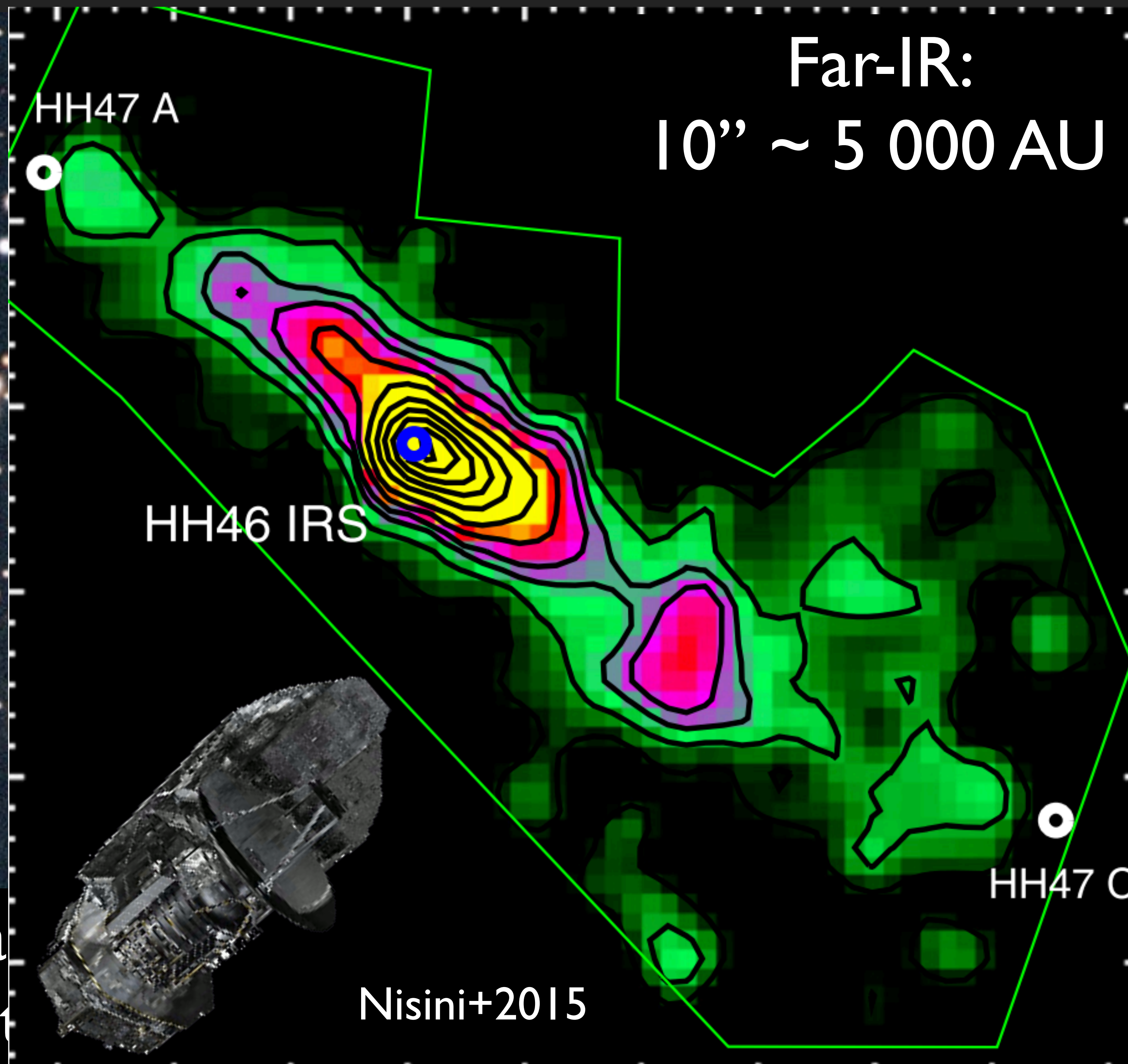


Fig. H. Arce

Sub-mm / radio:
1" ~ 500 AU

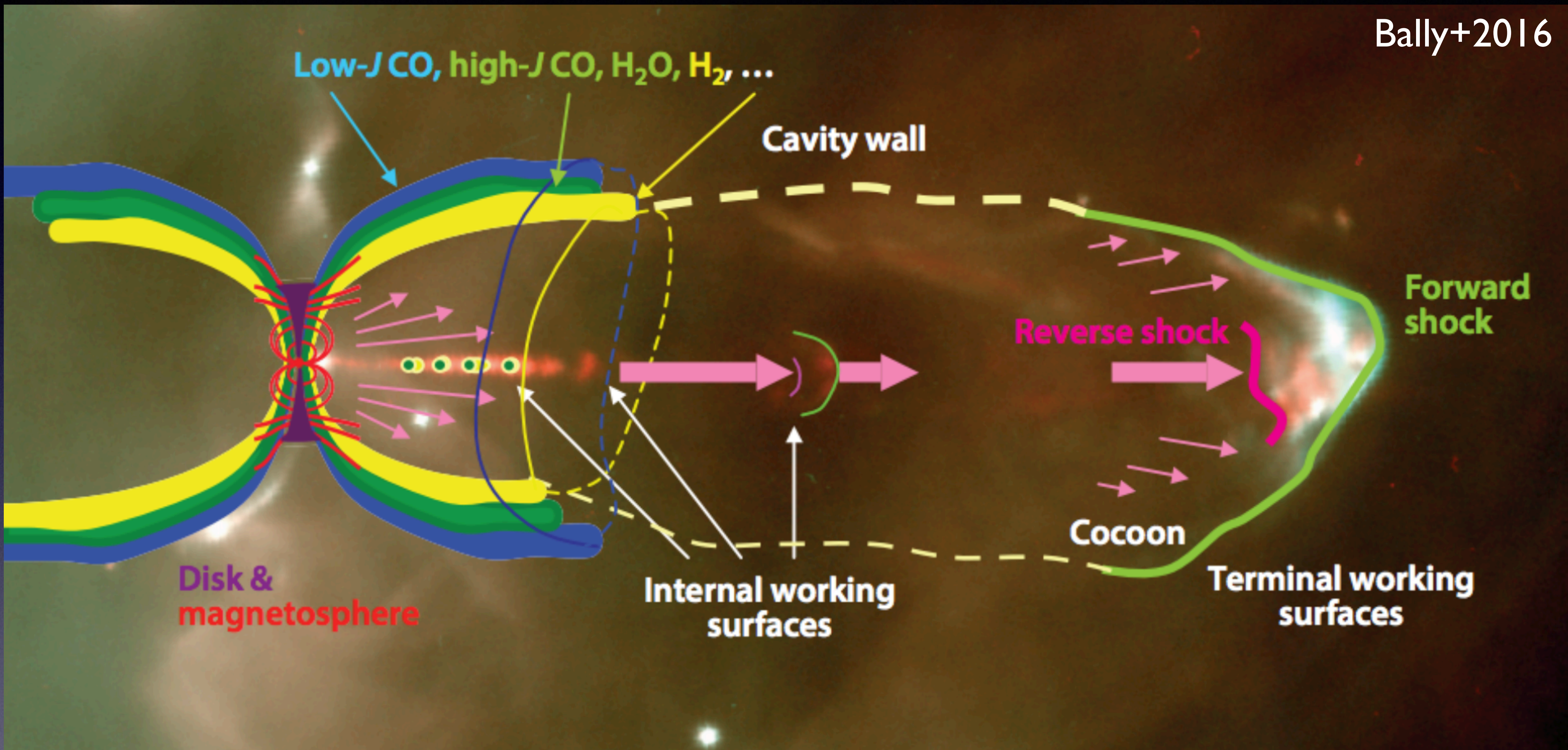
00 pc) driving large-scale outflows
patially-resolved observations

Low-mass protostars: laboratories of outflow shocks



Many nea… le outflows
(up t… ations

Complexity of outflow shocks



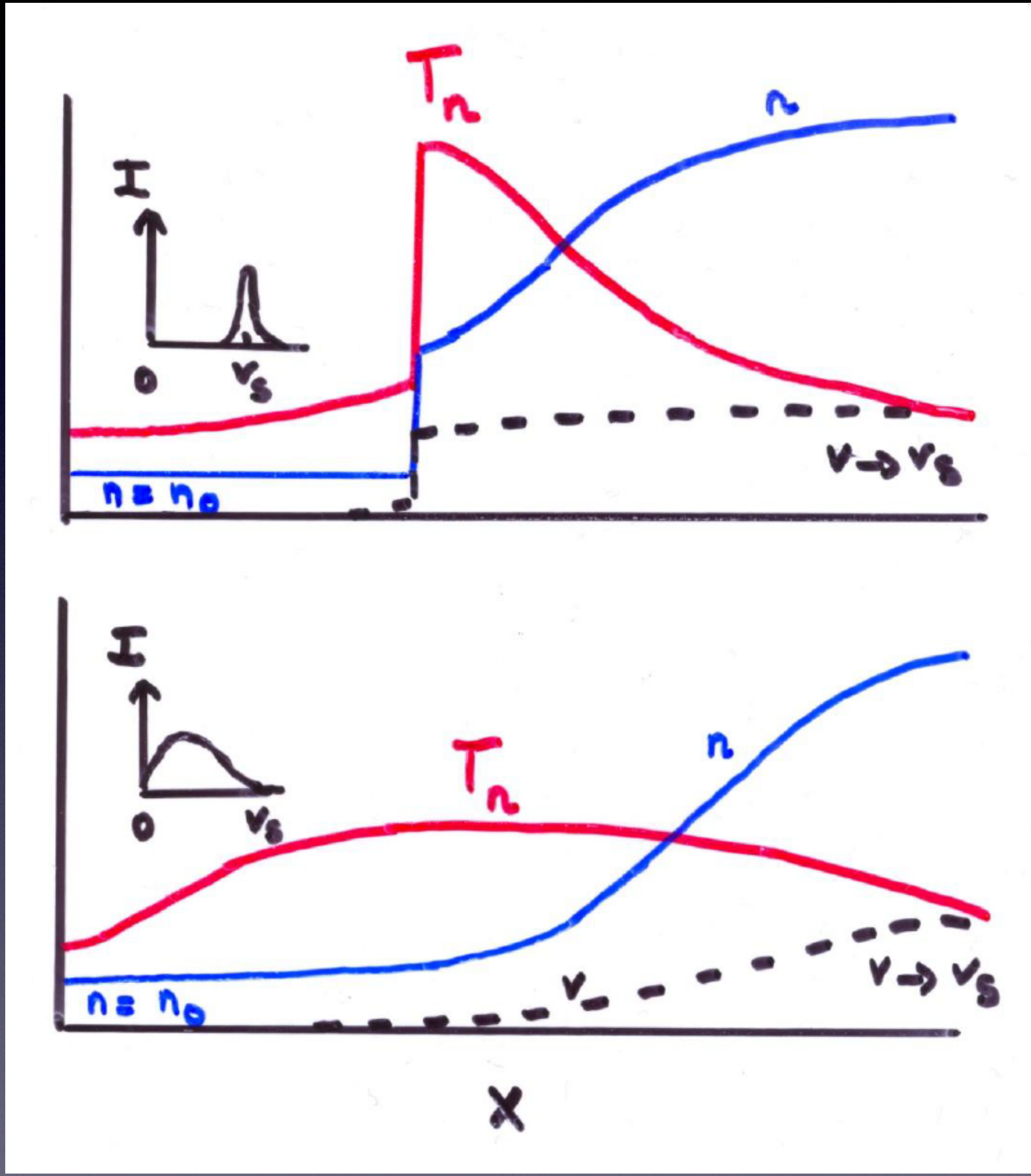
Multiple shocks due to the action of narrow jets and wide-angle winds, complex 2D / 3D geometry

Shock models: 1D

Draine 80
Hollenbach 97

'Jump'
(*J*-type)

'Continuous'
(*C*-type)



- $n_{post\text{-}shock}/n_{pre\text{-}shock}$~100
- T_{peak} ~10^4-10^5 K
- b=0.1

- n_{post}/n_{pre} ~ 10
- T_{peak} ~10^3-10^4 K
- b=1

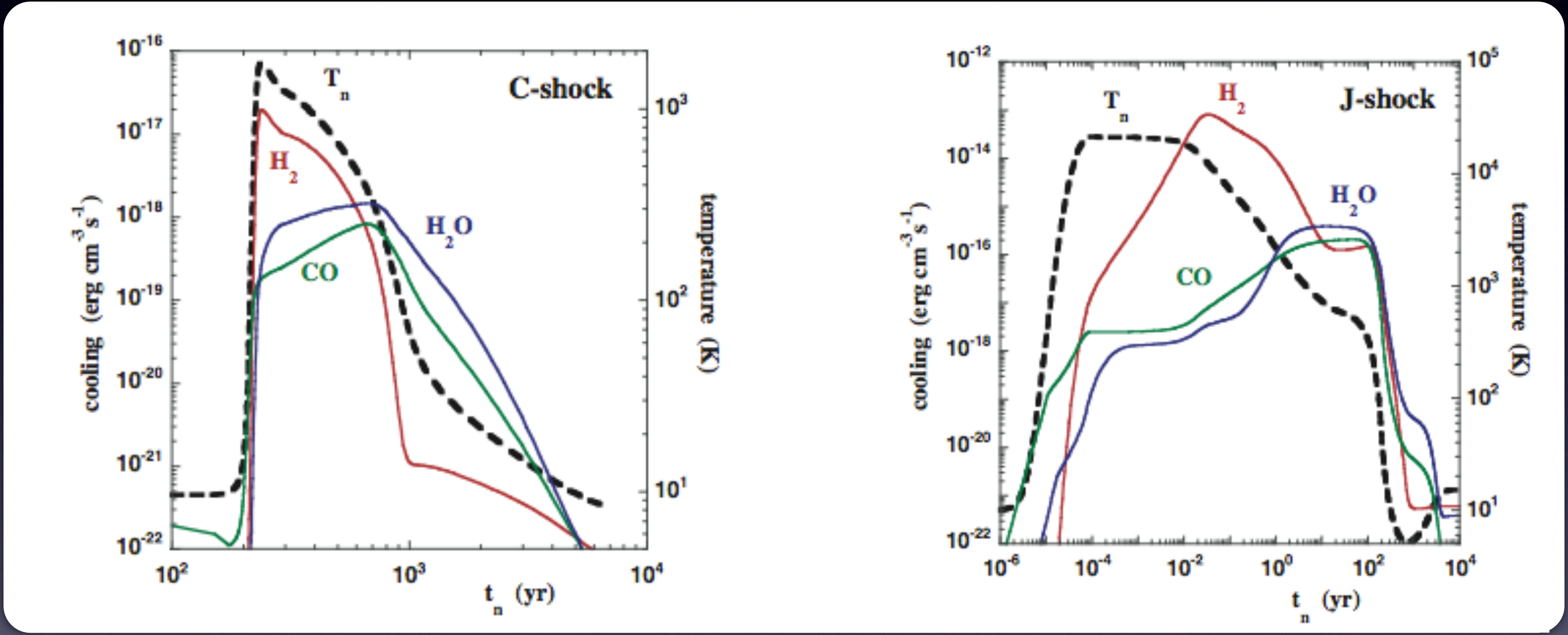
B=b sqrt(n_{pre})

Shock's type depends on magnetic fields strength, shock velocity, density and level of ionization

Chemistry plug-in

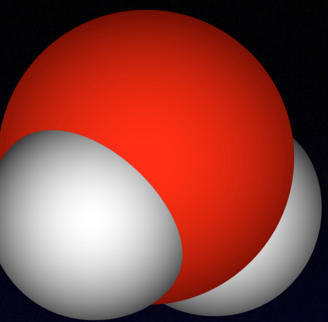
Kaufman & Neufeld 1996
Flower & Pineau des Forets 2015

C - shocks *J* - shocks



- Line cooling dominated by H_2, H_2O and CO for typical densities n_{H_2}~10^3-10^6 cm^{-3} and v_{sh} ~10-40 km s^{-1}
- Infrared line emission - a useful diagnostic of shocks

Utility of H_2O



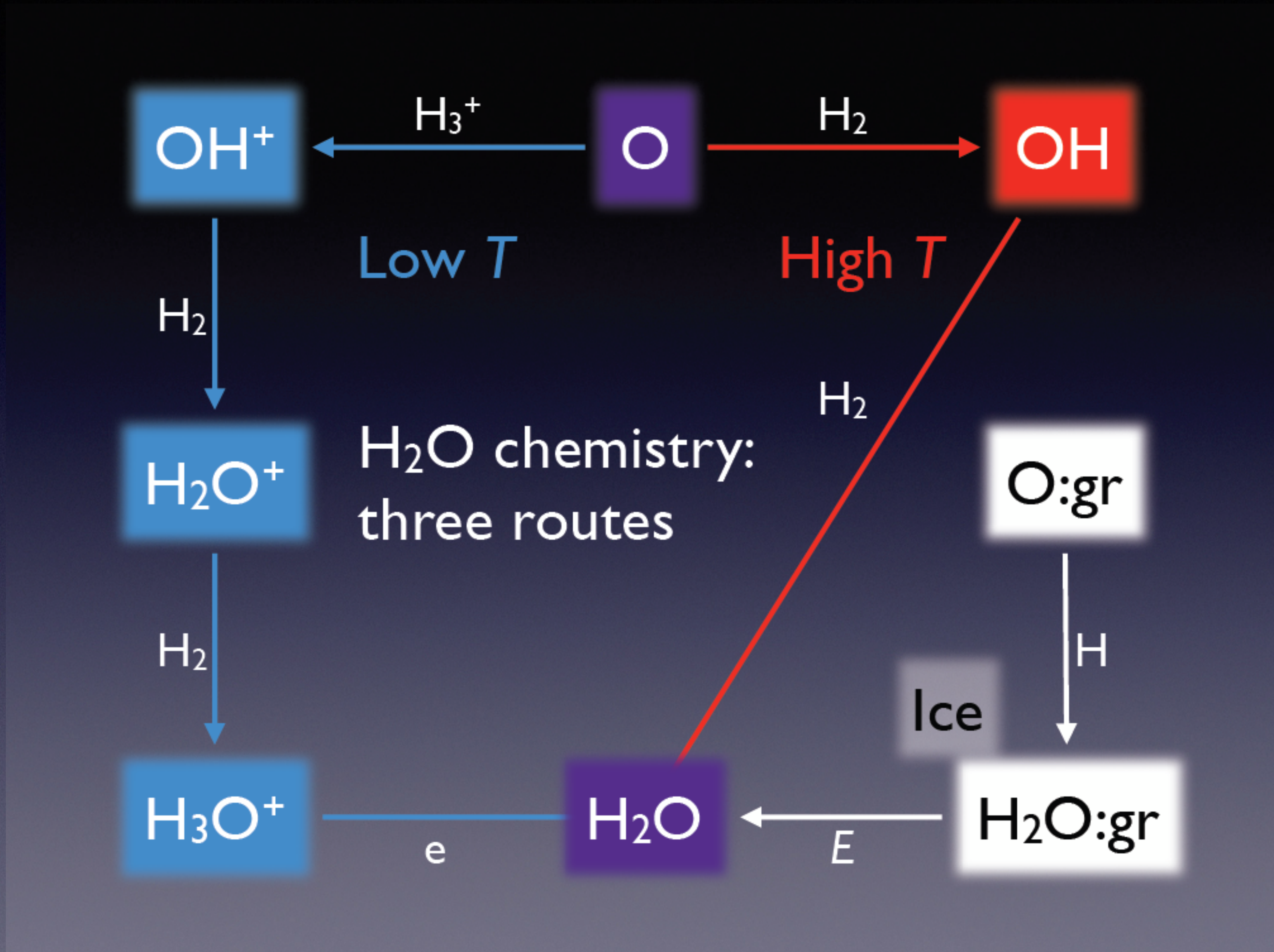


Fig. G. Melnick

Orders-of-magnitude variations in gas phase water abundances between cold and warm gas

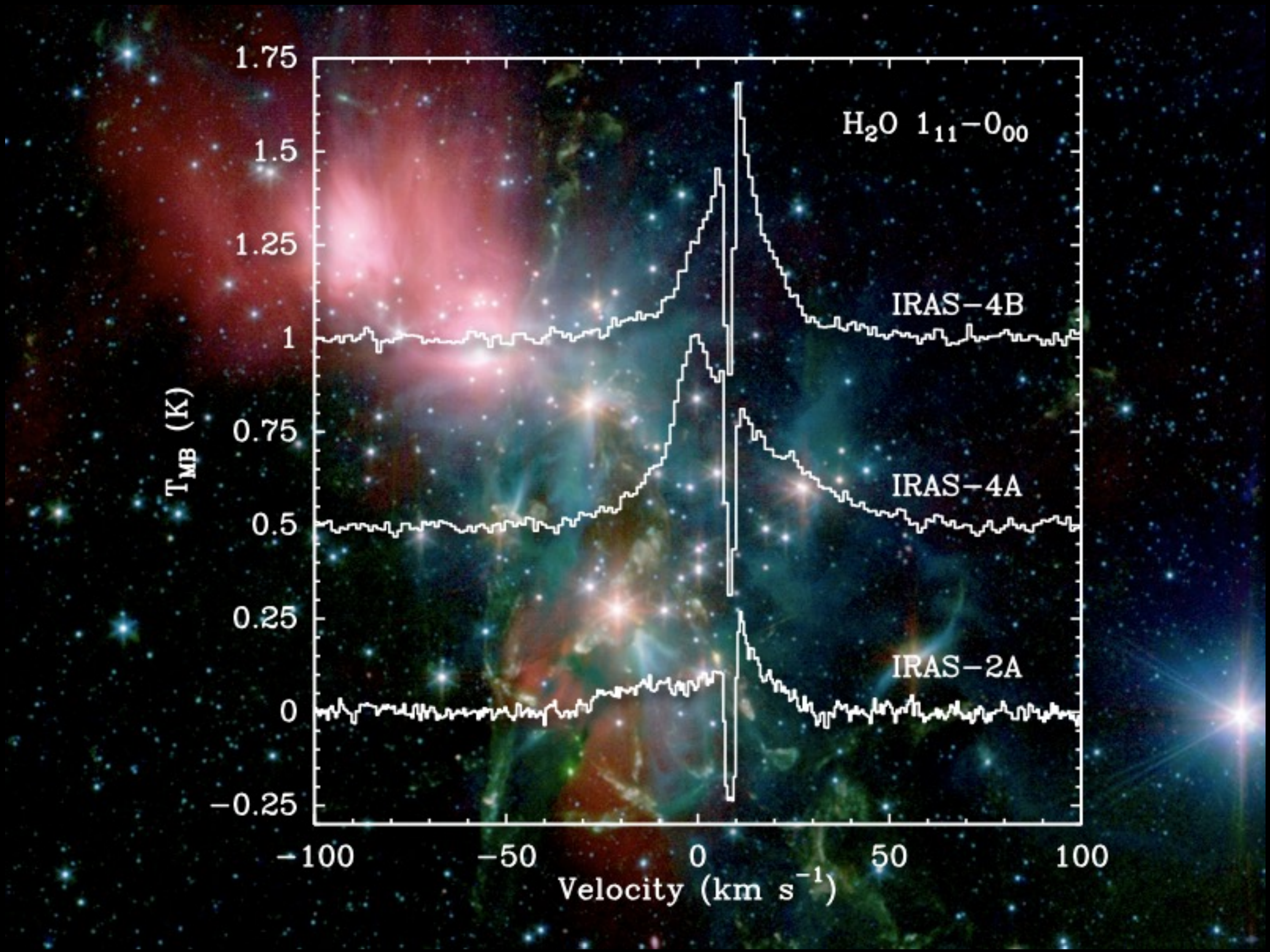
Observational constraints

1. Shock velocities
2. Densities of ambient medium
3. UV radiation
4. Magnetic fields (?)

Shock velocities

Herschel / HIFI

~160-600 μm
dv = 0.1 km/s

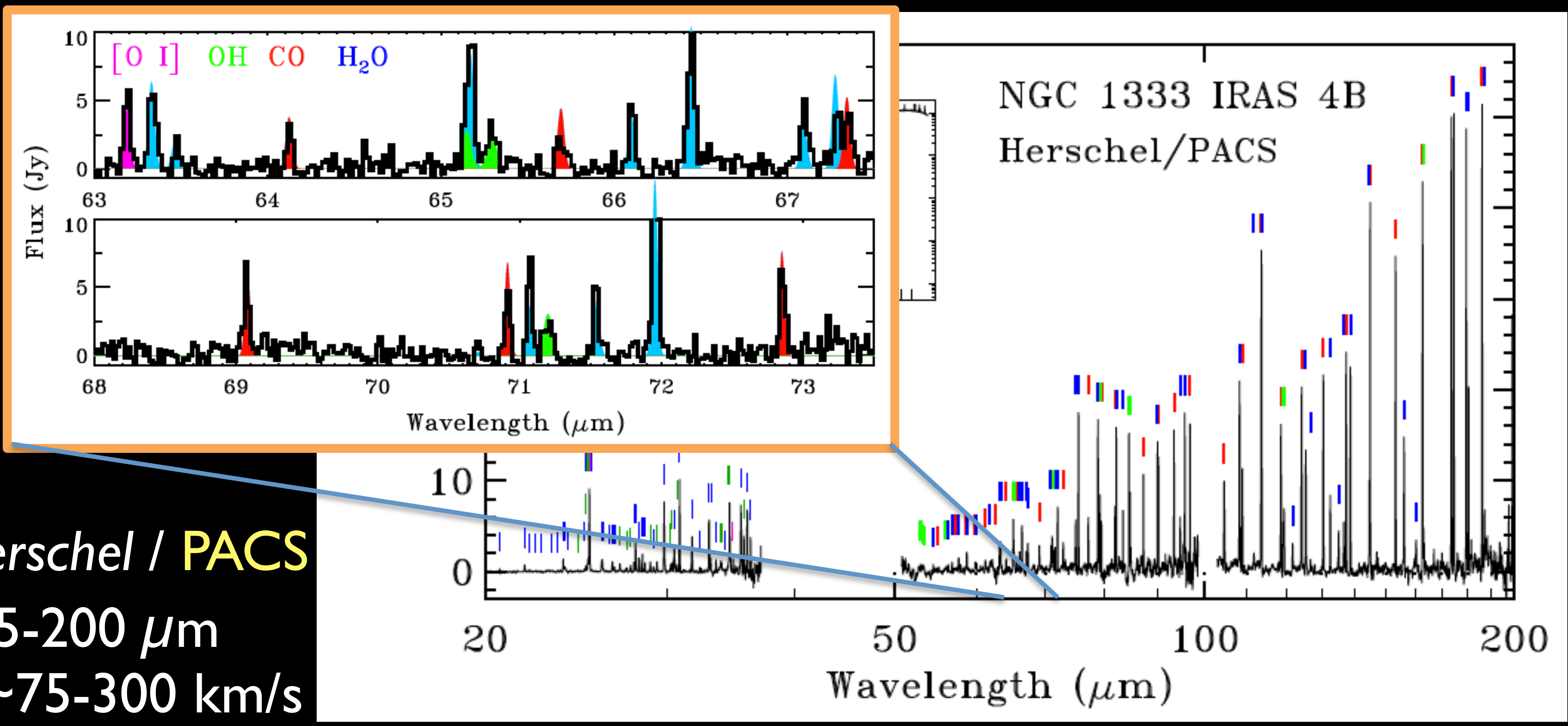


Kristensen+12,17
Mottram+14,17

- Broad far-IR H_2O line profiles due to bipolar outflows
- Gas radial velocities ~10-50 km s^{-1}

Gas densities, shock type

Herczeg, Karska+12
Karska+13



Herschel / PACS
~55-200 μm
dv~75-300 km/s

- Detections of highly excited CO and H_2O
- Comparisons to line fluxes predicted by shock models

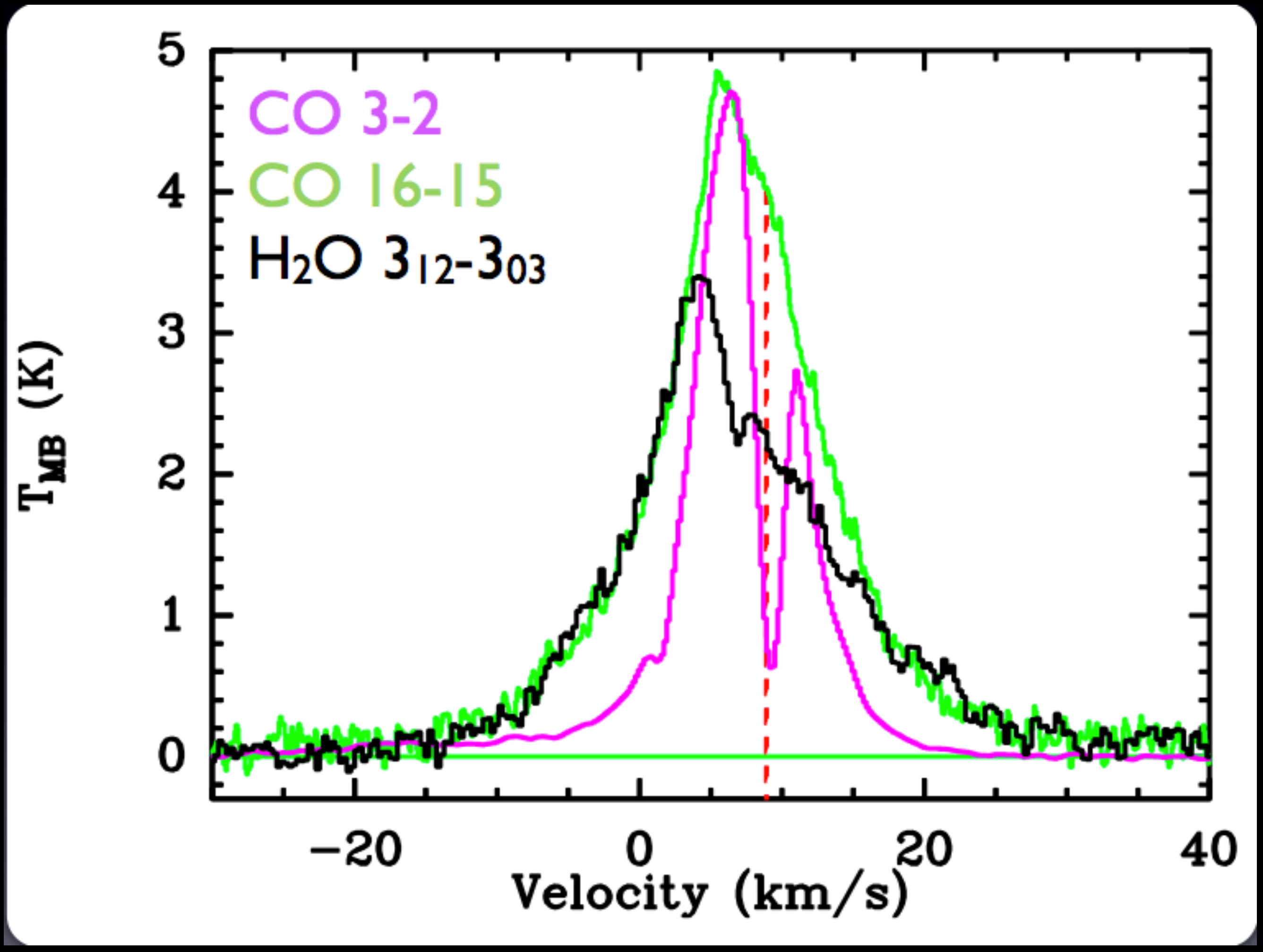
Single-source studies

<table>
<tr><th></th><th>H_2O</th><th>CO</th><th>OH</th><th>method</th></tr>
<tr><td>Ser SMM3
(Dionatos+13)</td><td>C shock,
v~30 km/s,
n~10^4 cm^{-3}</td><td>J shock,
v~20 km/s,
n~10^4 cm^{-3}</td><td>C shock,
v~30 km/s,
n~10^4 cm^{-3}</td><td rowspan="2">best fit to rotational diagrams</td></tr>
<tr><td>L1448-MM
(Lee+13)</td><td colspan="2">C shock, v~40 km/s,
n~10^5 cm^{-3}</td><td>-</td></tr>
<tr><td>L1448-R4
(Santangelo+12)</td><td>J shock,
v~20 km/s,
n~10^5 cm^{-3}</td><td colspan="2">-</td><td>HIFI line ratios</td></tr>
<tr><td>L1448-R4
(Santangelo+13)</td><td colspan="2">C shock, v>20 km/s,
n~10^5 cm^{-3}</td><td></td><td>PACS line ratios</td></tr>
<tr><td>L1157 B1
(Benedettini+12)</td><td>-</td><td colspan="2">dissoc. J shock,
v>30 km/s n~10^4 cm^{-3}
v>20 km/s n~10^5 cm^{-3}</td><td>OI fluxes, O/CO & OH/CO</td></tr>
<tr><td>L1157 B1
(Busquet+14)</td><td>non-dissoc.
J shock</td><td colspan="2">-</td><td>cooling in H_2O lines</td></tr>
</table>

Real differences between sources or different approaches?

More robust comparisons

~20 low-mass protostars



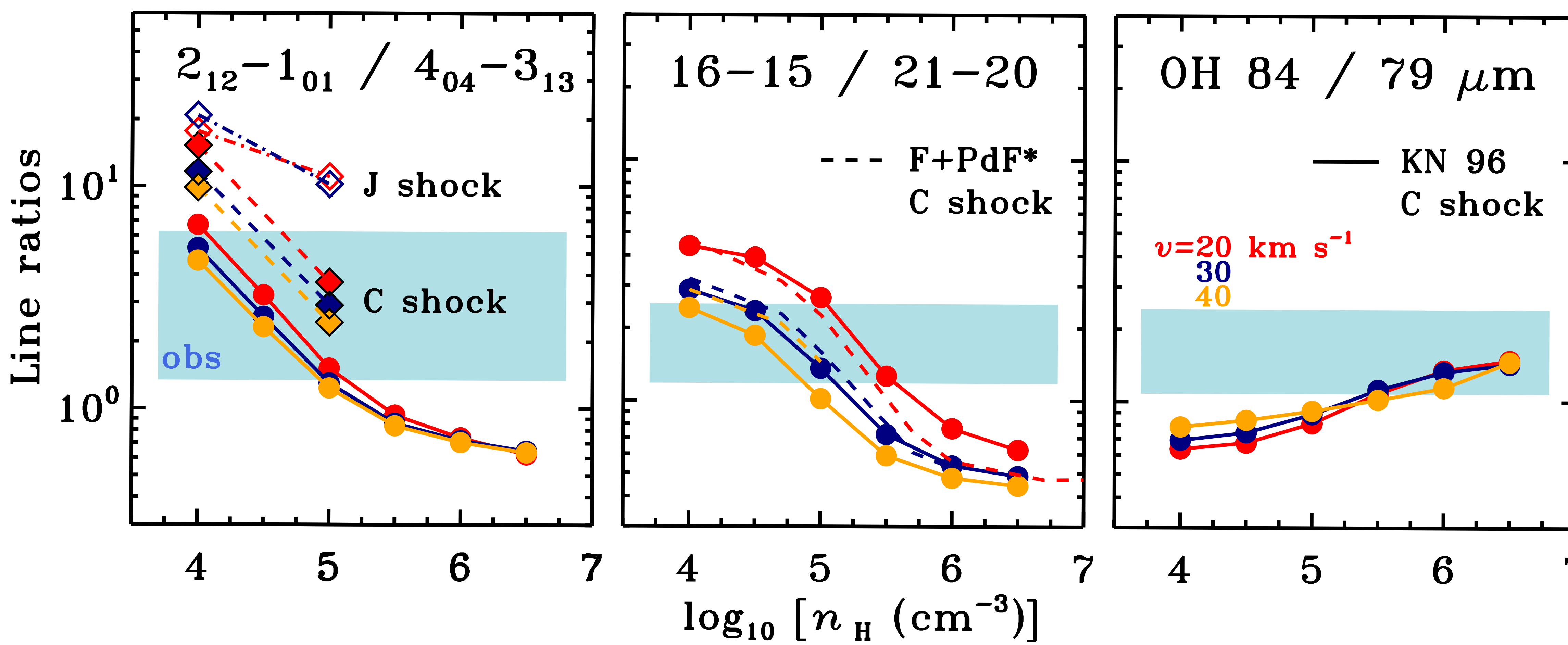
Kristensen+ 12,17, Mottram+14,17

- uniform sample of sources, at the same distance
- H_2O and high-J CO co-spatial, similar profiles - same component

Line ratios vs. shock models - excitation

Karska+2014

H_2O / H_2O CO / CO OH / OH

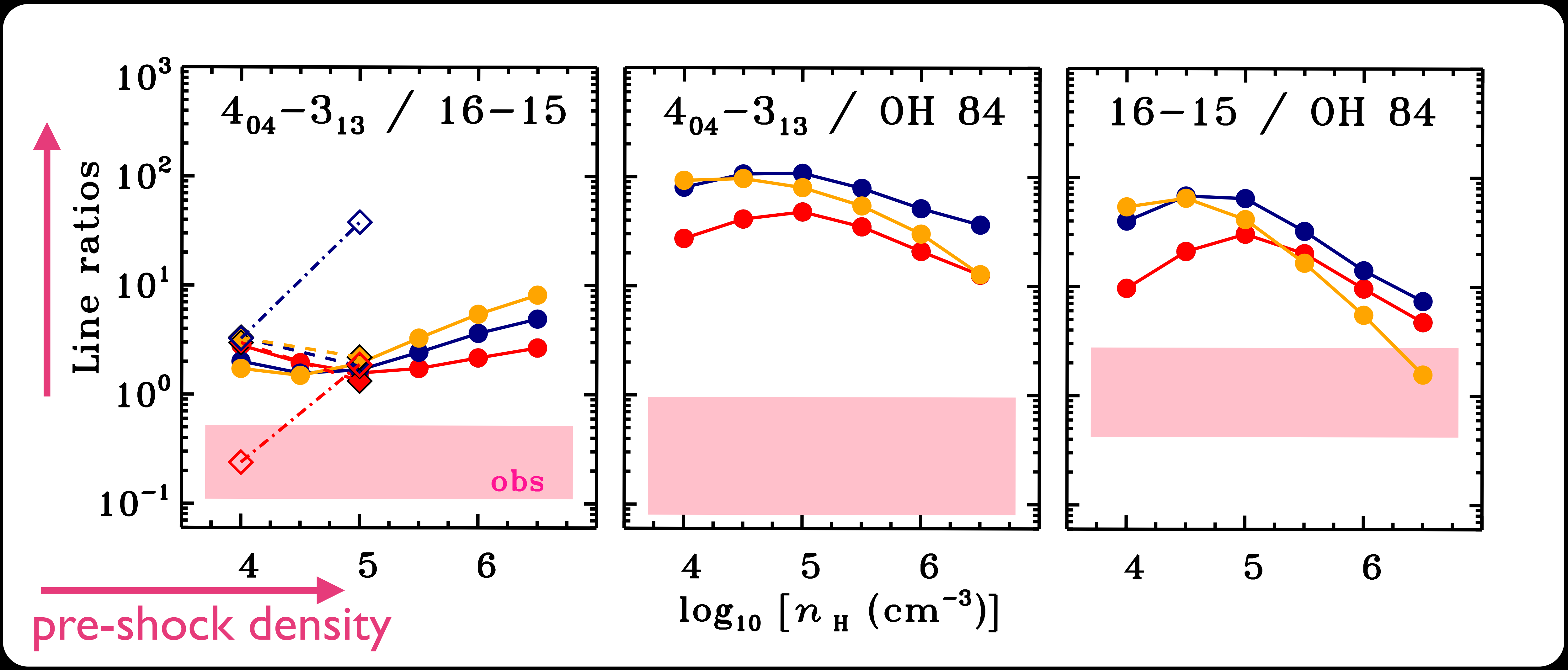


- Line ratios remarkably similar across the sample
- Velocities > 20 km s^{-1}, pre-shock densities of ~10^4-10^5 cm^{-3}

Line ratios vs. shock models

- abundances

H_2O / CO H_2O / OH CO / OH



- Observed ratios with H_2O much lower than models

- UV photons needed to decrease the H_2O abundances

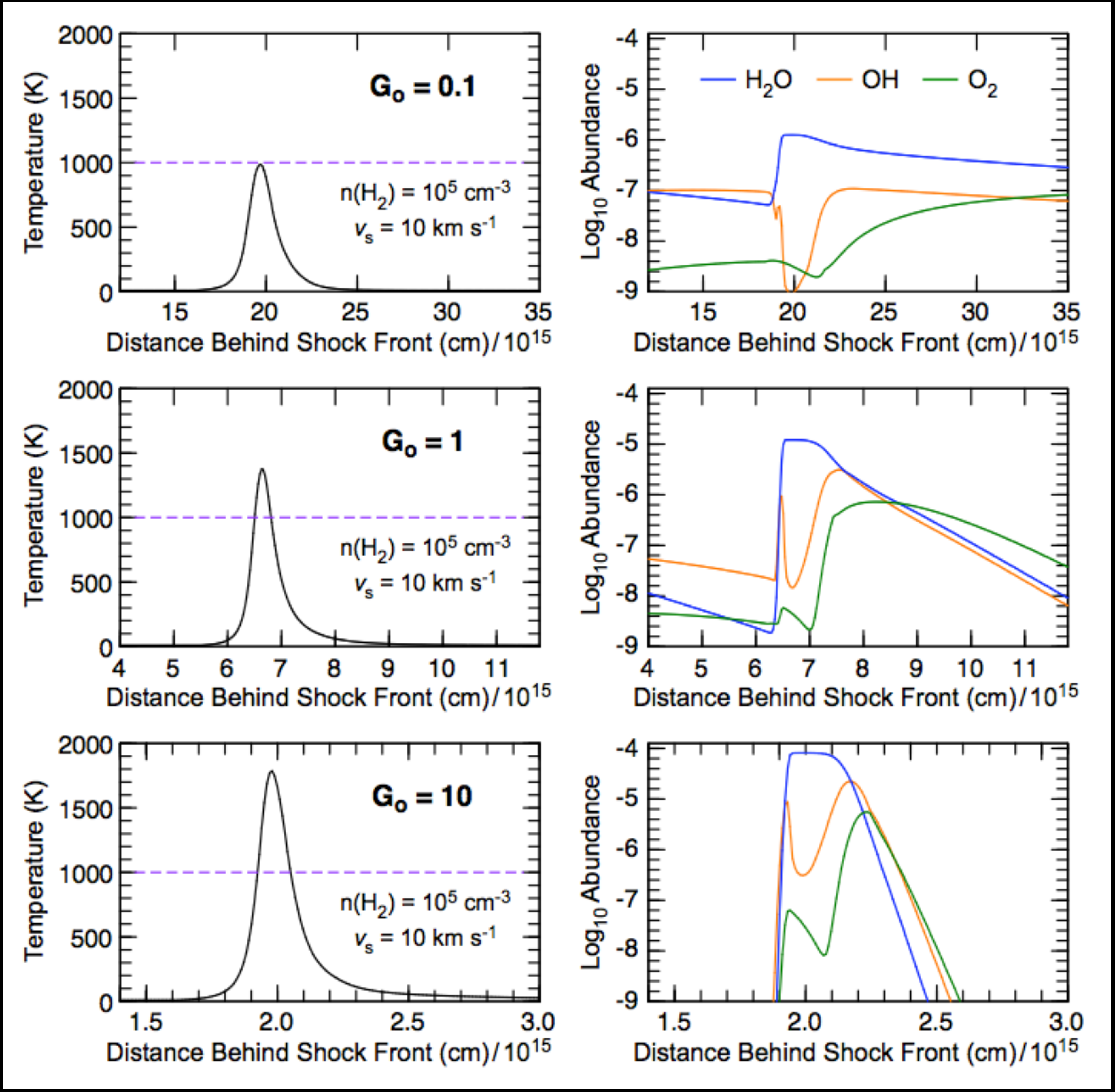
Missing H_2O and O_2

Santangelo+15,
Kristensen+ 13,17

Yildiz+14, Chen+14,
Melnick & Kaufman 15

- Low abundances of H_2O and O_2, high of ionic species
- Arguments in favour of the presence of UV photons

- As FUV field is increased, T_{max} goes up
- As FUV field is increased, available gas-phase oxygen goes up
- As FUV is increased, post-shock gas is more dissociated



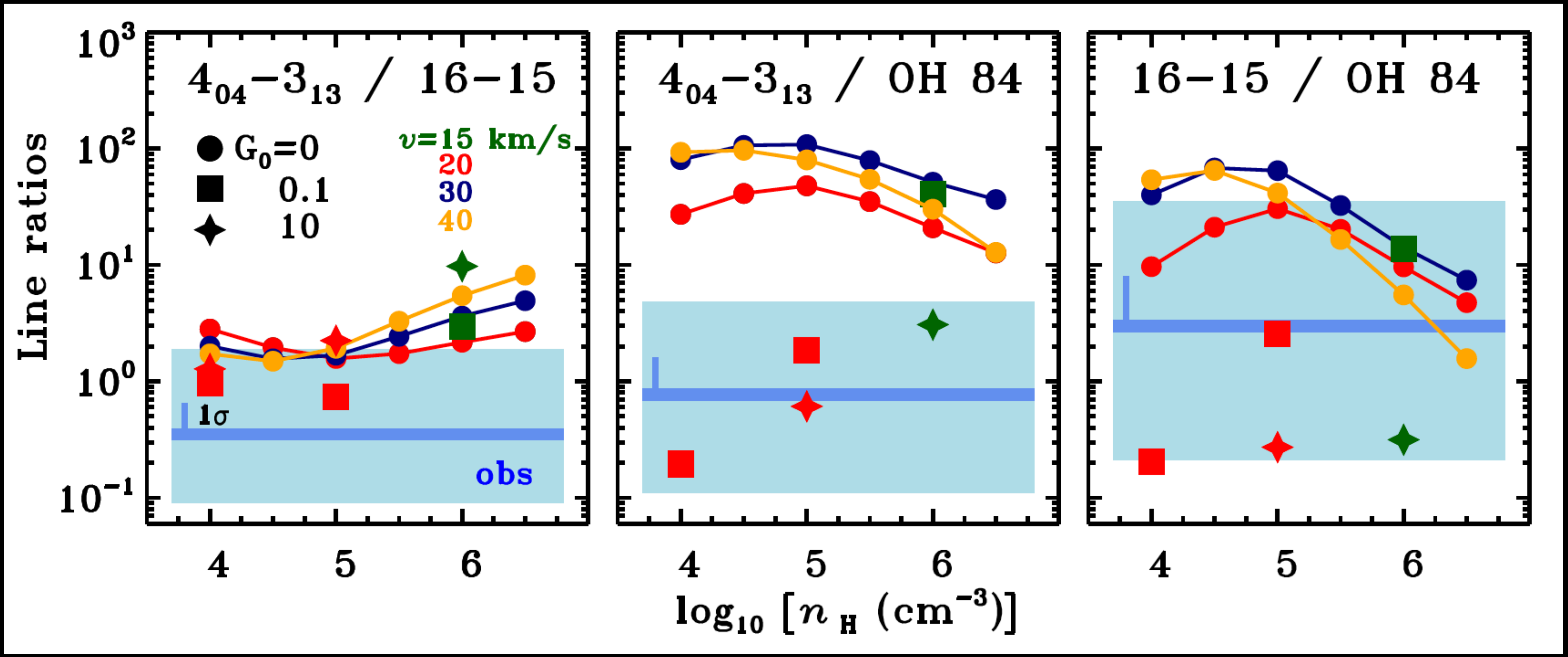
Melnick & Kaufman 15, see also Lesaffre+13

UV radiation

Karska, Kaufman+18

Herschel legacy of low-mass protostars: ~ 90 objects

H_2O / CO H_2O / OH   CO / OH

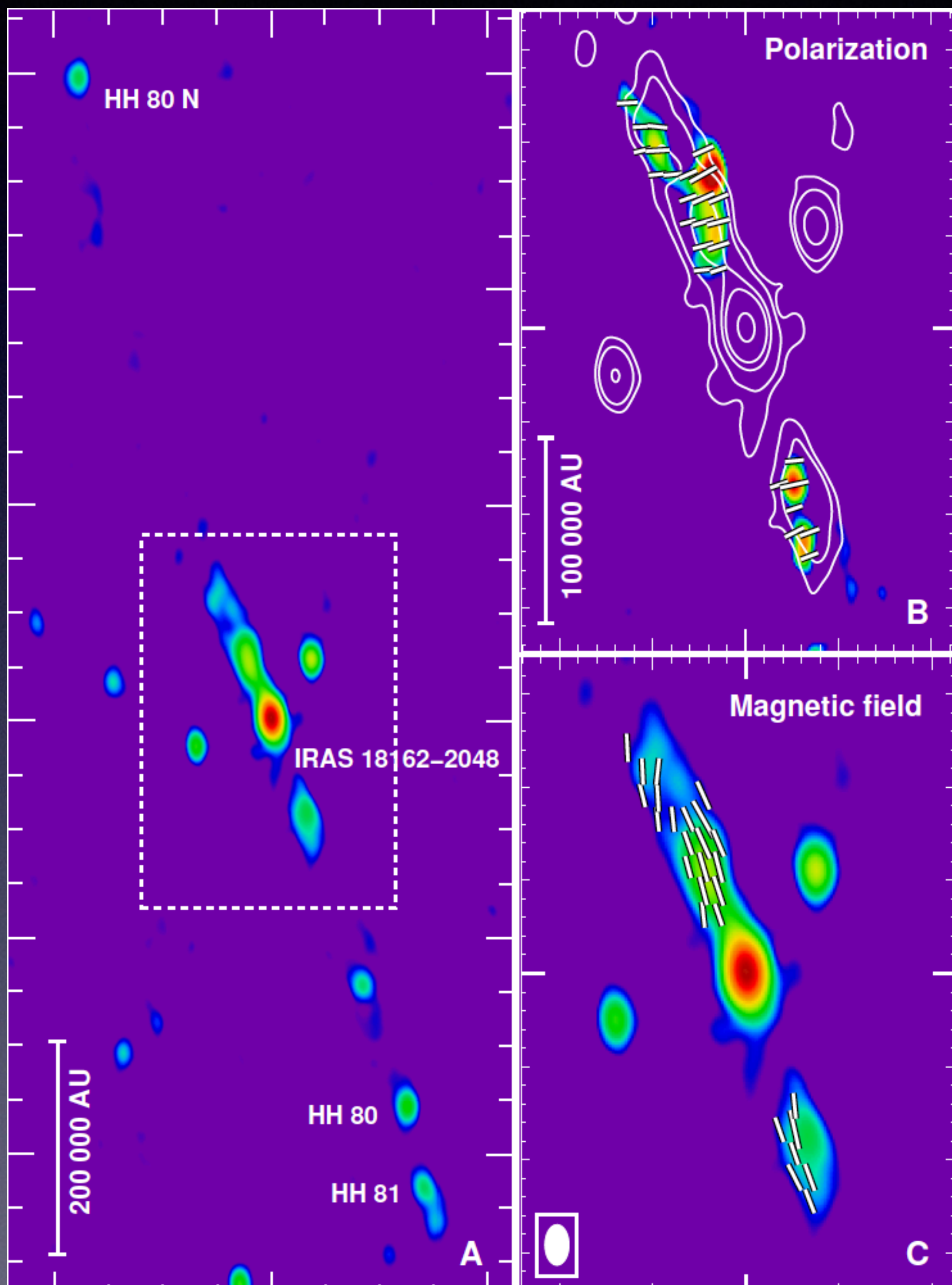


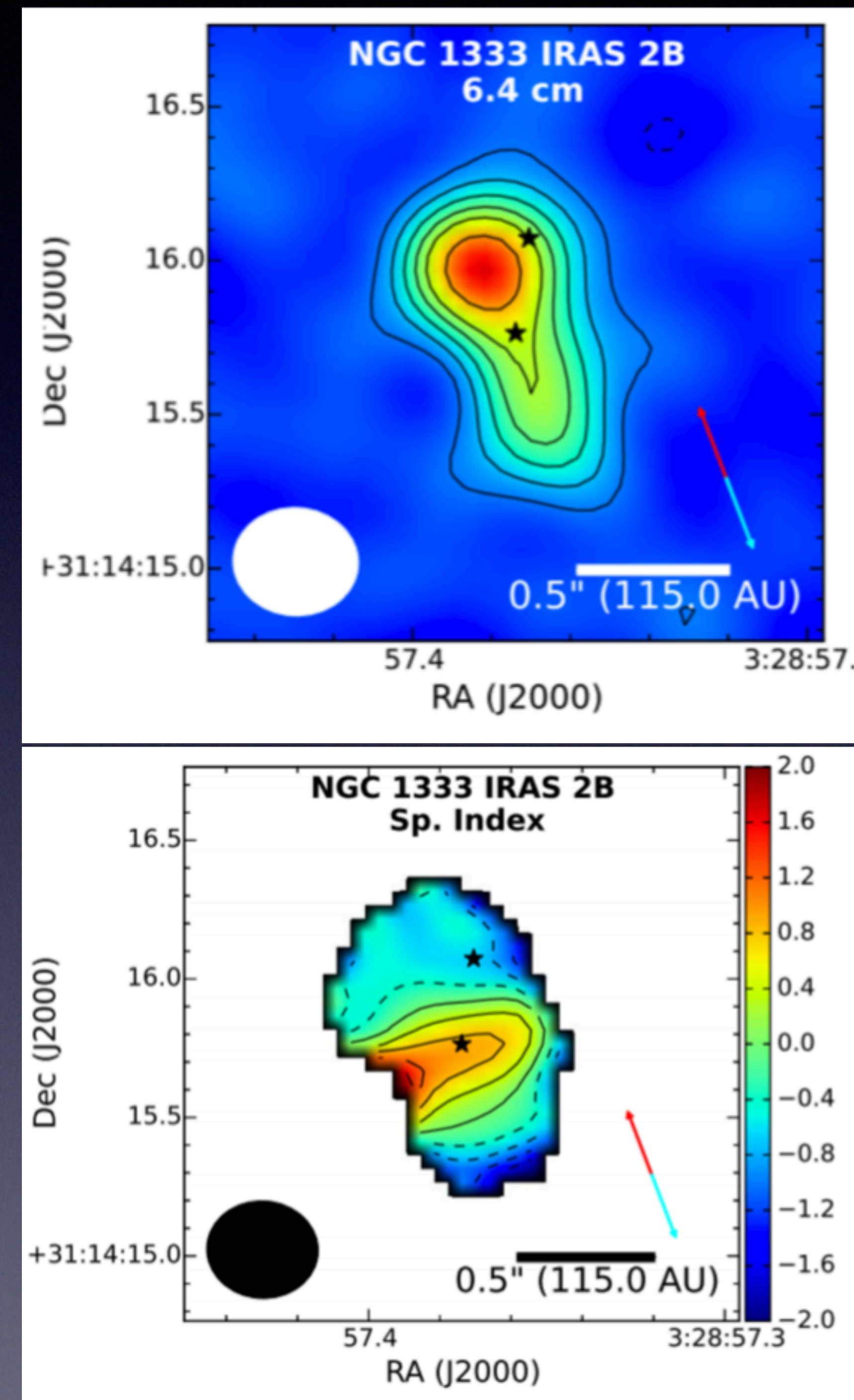
- Irradiated C-shock models agree with observations for pre-shock log n ~ 5 and G_0 ~0.1-10
- UV photons irradiate outflows and influence chemistry

Magnetic fields

Jet from a high-mass protostar

Carassco-Gonzalez+2010, 6 cm, 0.2 mG

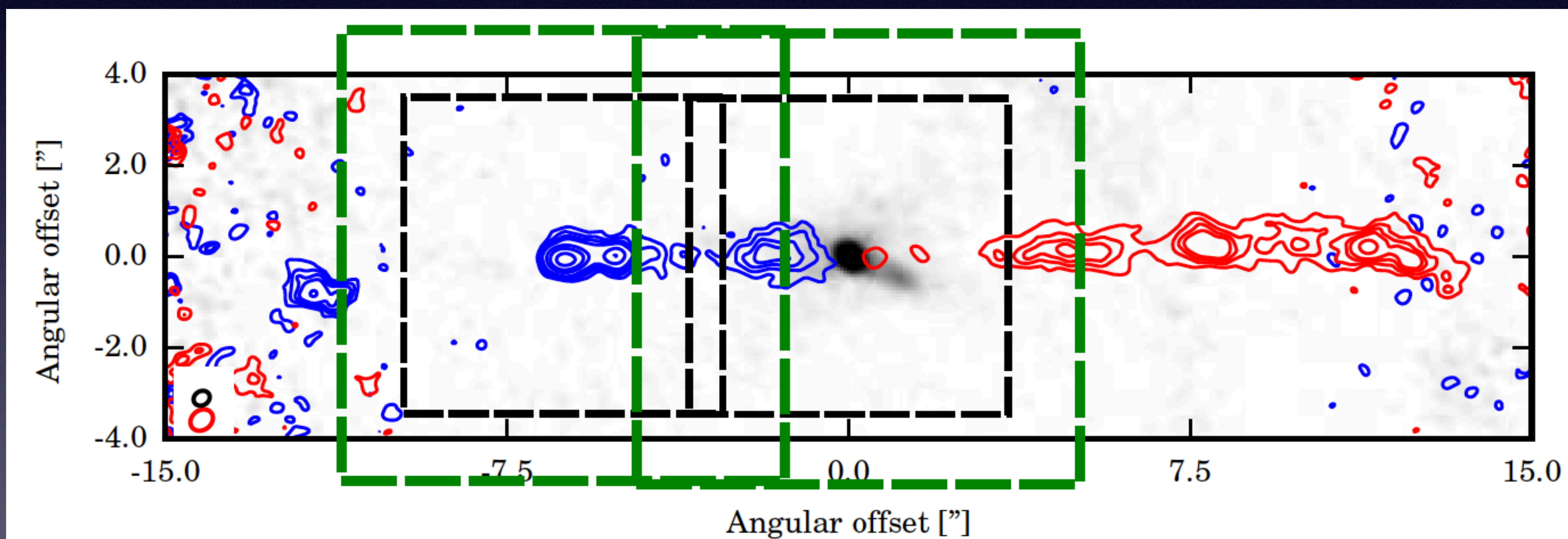




Tychoniec, Tobin, Karska+2018

- Resolved radio jets from protostars with spectral indices in mm/cm tracing free-free and synchrotron emission

Cosmic-ray acceleration



- Combined radio and sub-mm data at 100 AU scales should soon shed light on the cosmic-ray acceleration in jets (see talk by M. Padovani)

Conclusions

1. Infrared observations reveal ubiquitous slow shocks in outflows ($v < 50$ km s^{-1}) propagating in partly ionised, magnetised medium

2. UV photons influence the physics and chemistry of shocks even around low-mass protostars

3. Current radio / sub-mm arrays starts to reveal the interaction between shocks and magnetic fields

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