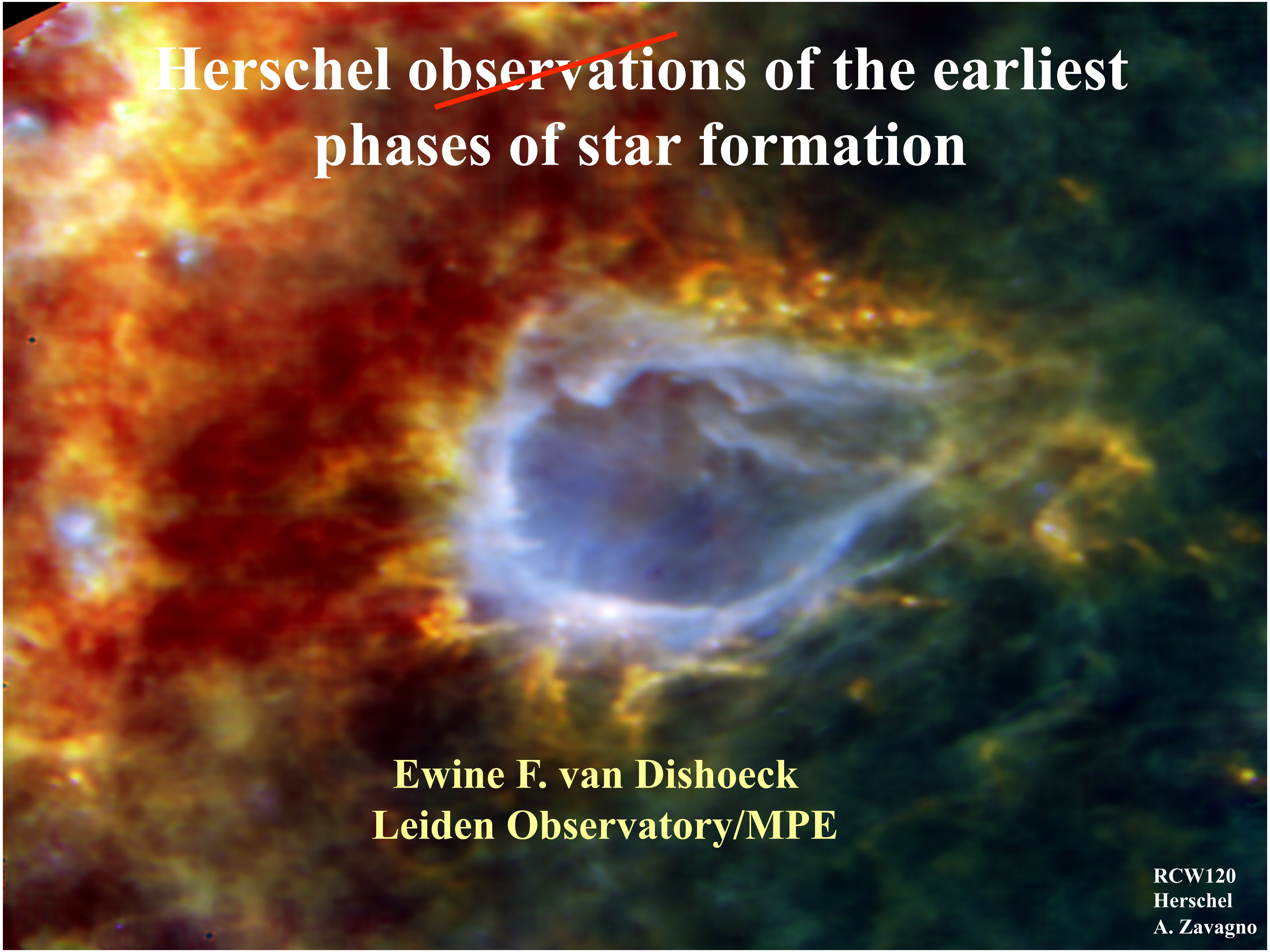
Herschel observations of the earliest phases of star formation

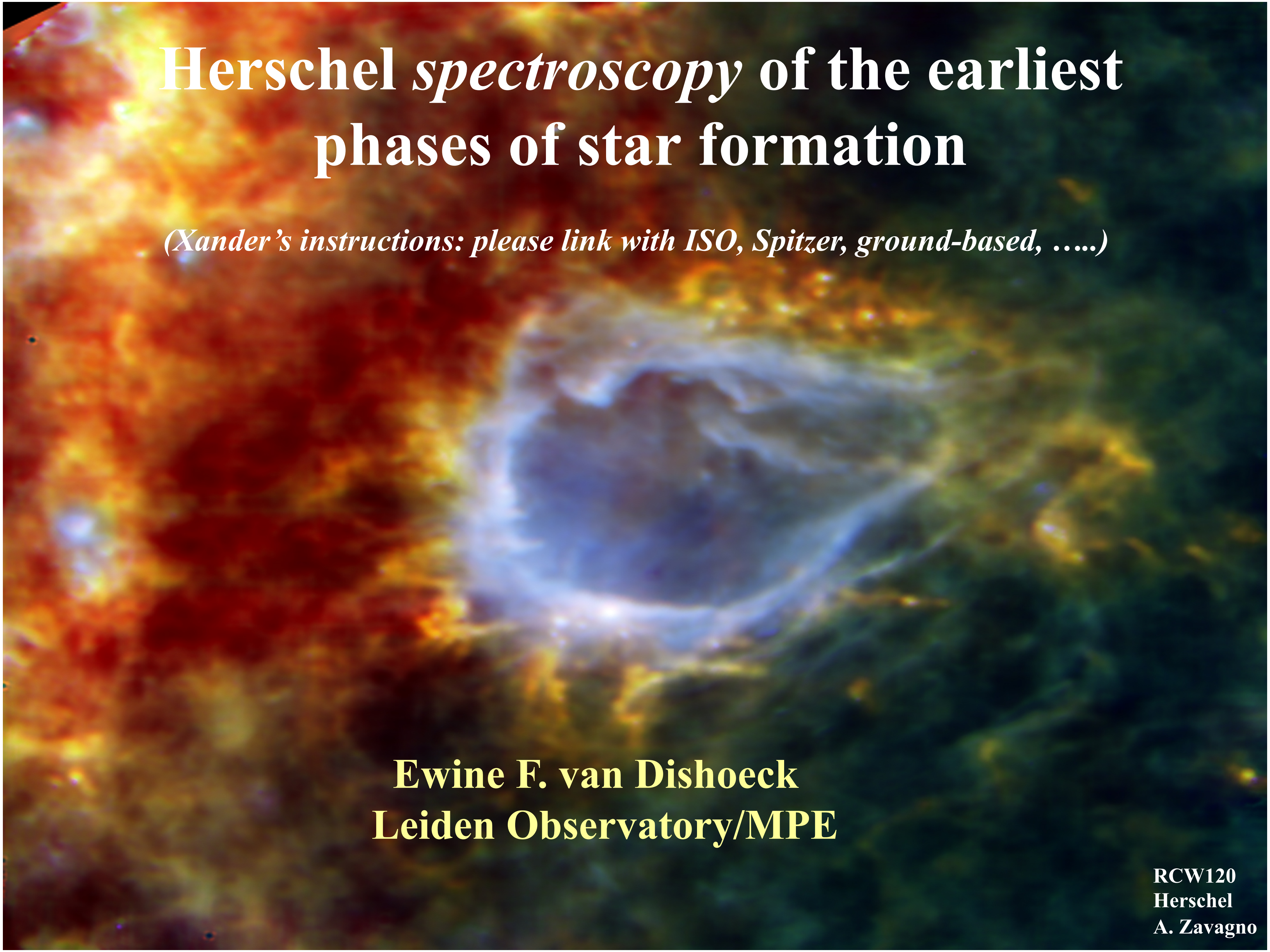
Ewine F. van Dishoeck
Leiden Observatory/MPE



RCW120
Herschel
A. Zavagno

Herschel *spectroscopy* of the earliest phases of star formation

(Xander's instructions: please link with ISO, Spitzer, ground-based, …..)



Ewine F. van Dishoeck
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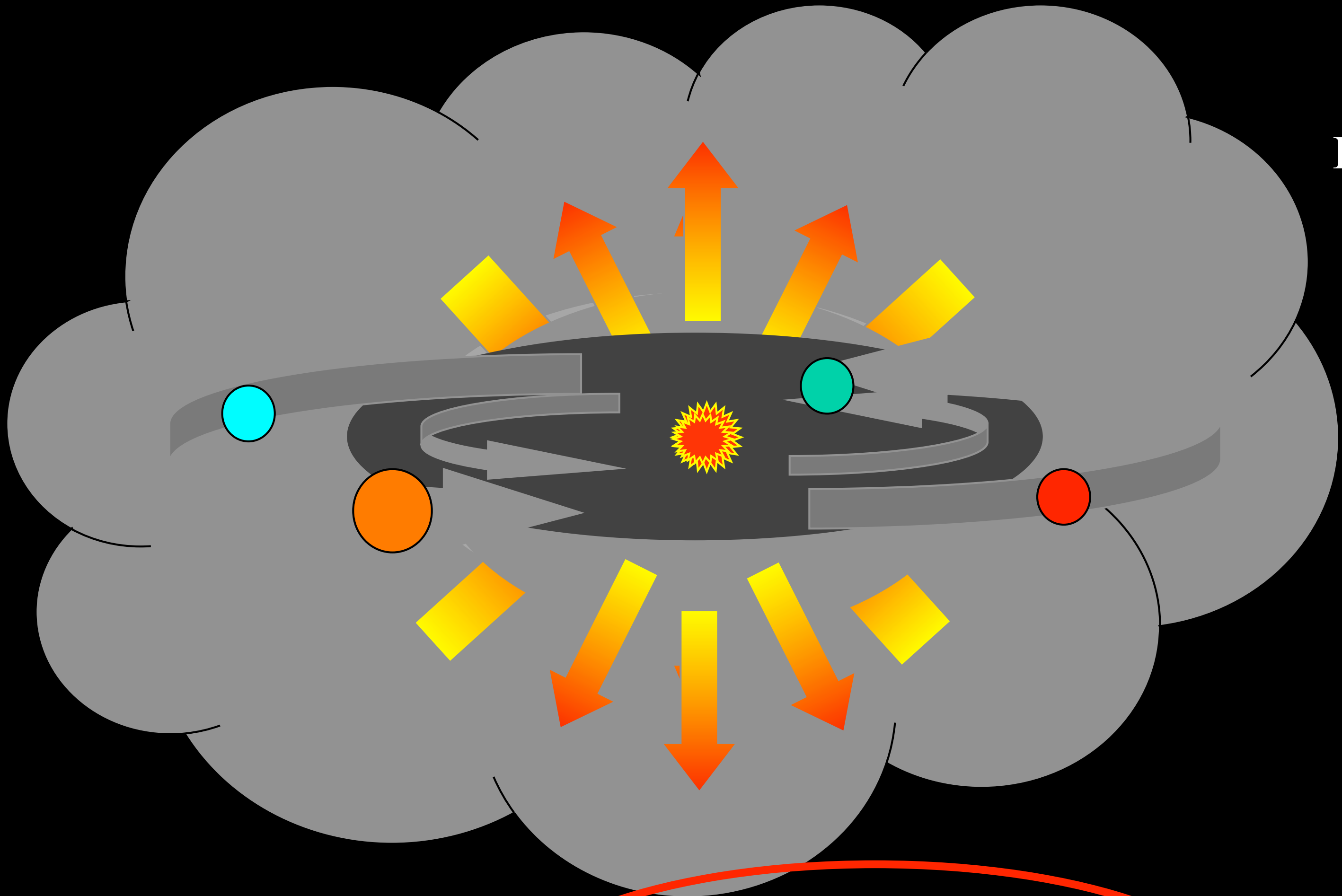
RCW120
Herschel
A. Zavagno

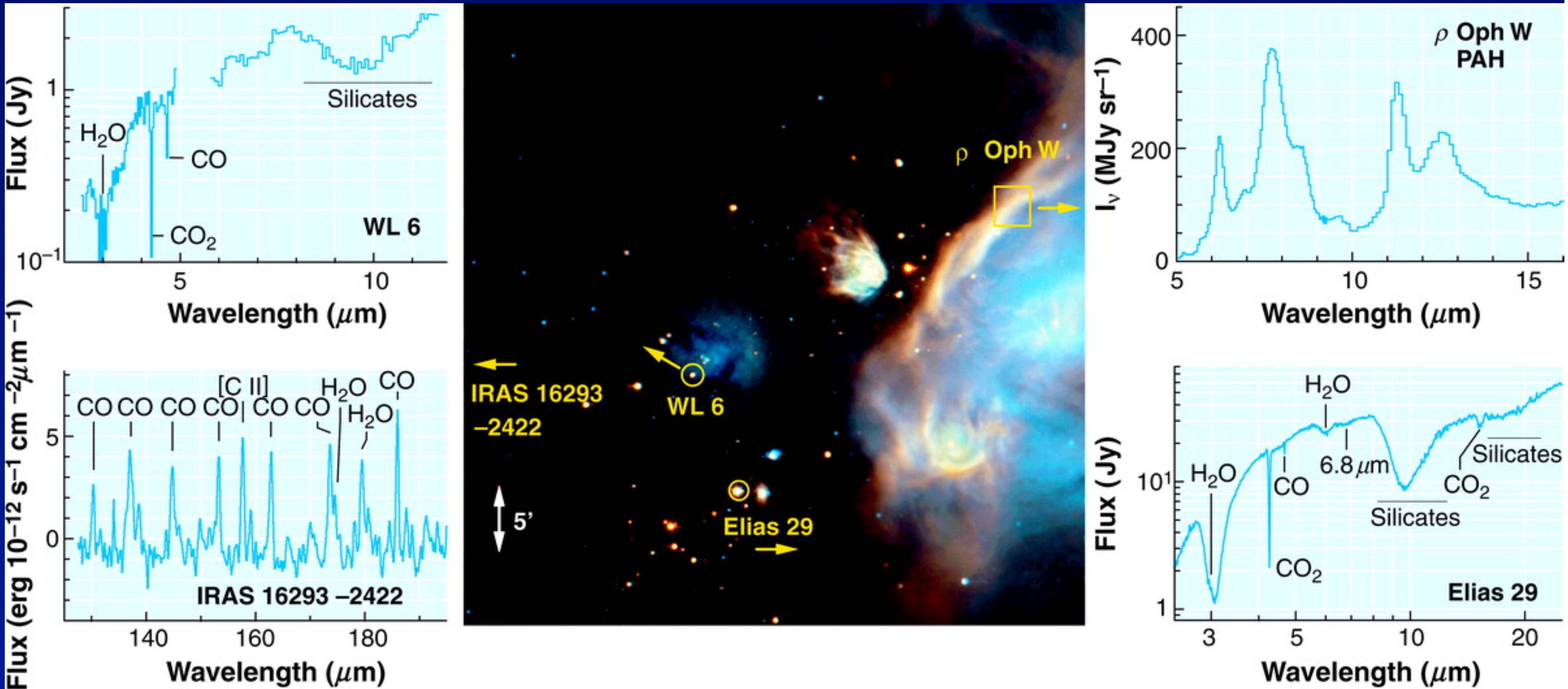
Follow molecules during star and planet formation



D. Lommen

Dark pre-stellar cores → Low-mass YSOs → Disks
Infrared dark clouds Intermediate mass YSOs
High-mass YSOs

ISO was great



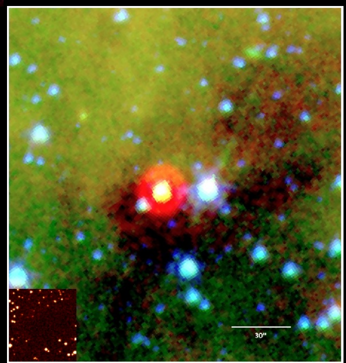
vD 2004, ARAA

- Opened up full 2.5 – 200 μm wavelength range: PAHs, ices, silicates, atomic and molecular lines
- Unmatched spectral resolution (R=2000 or higher) at mid-IR
- Limited to brightest objects; poor angular resolution

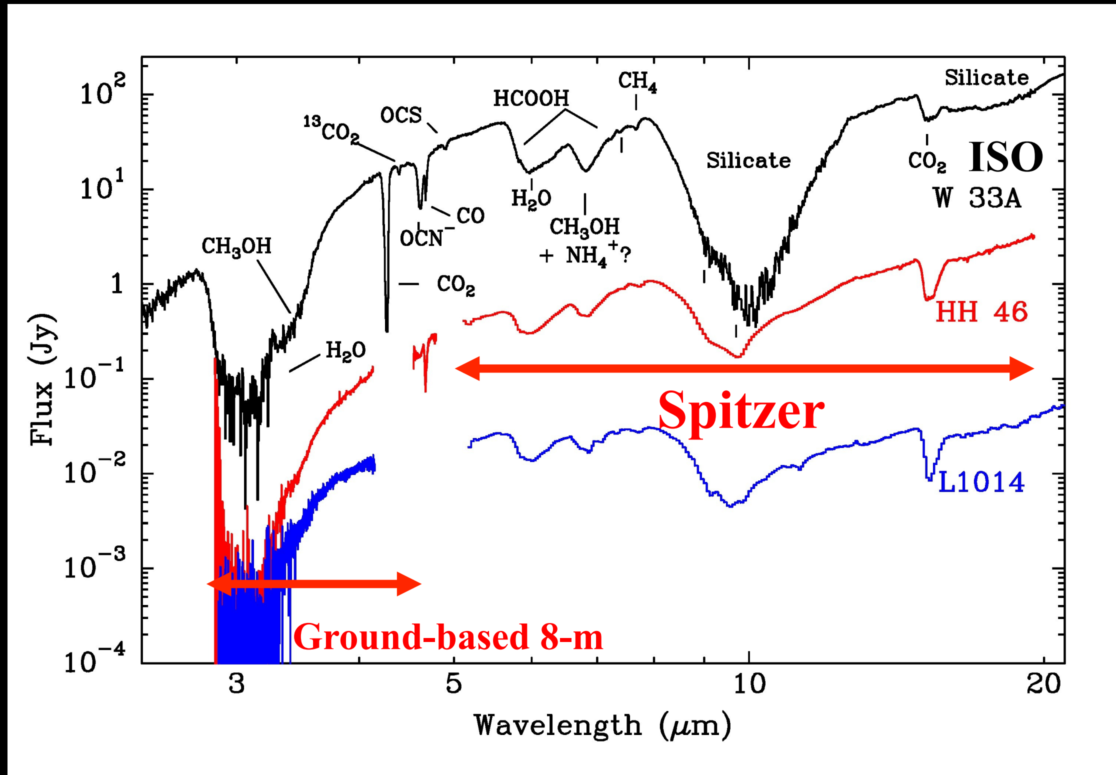
Spitzer was great

HH 46: solar-mass YSO

L1014: substellar YSO



From 10^5 to <0.1 L_{sun} objects!

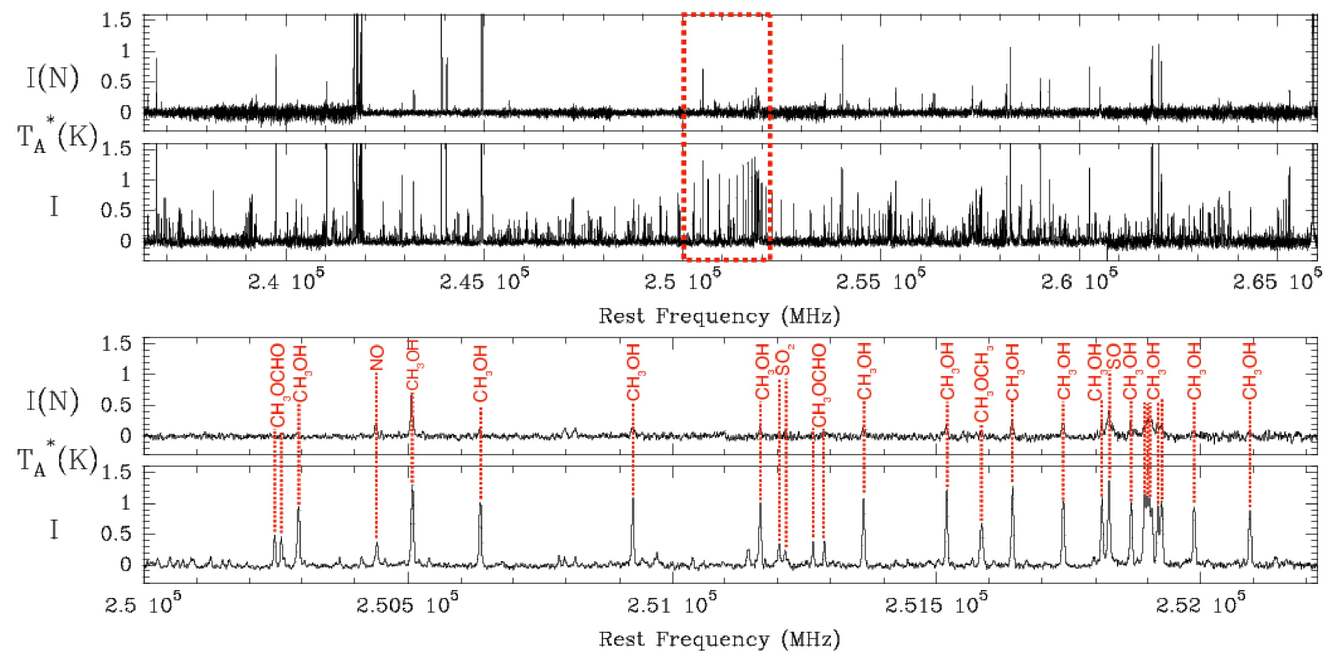


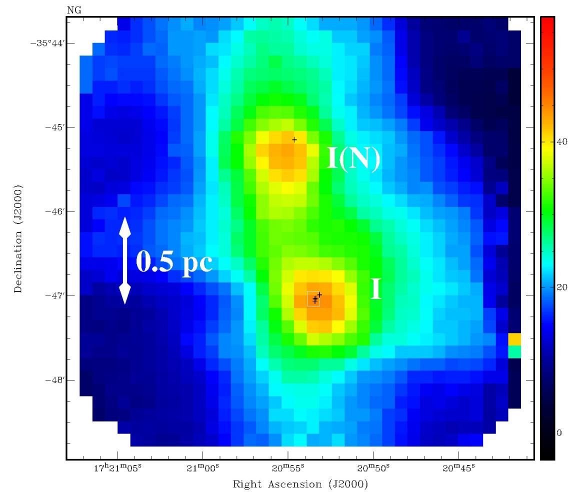
- Raw sensitivity ⇒ *large* samples down to the brown dwarf limit: statistics
- Limited spectral resolving power: R=600 from 10-38 μm
  R~100 from 5-10 μm
- Limited spectral coverage

Noriega-Crespo et al. 2004
Boogert et al. 2004, 2007
Young et al. 2004

Groud-based submm telescopes are great
(and will soon be getting even better: ALMA!)

SEST NGC 6334I 1 mm spectral line survey of massive YSOs



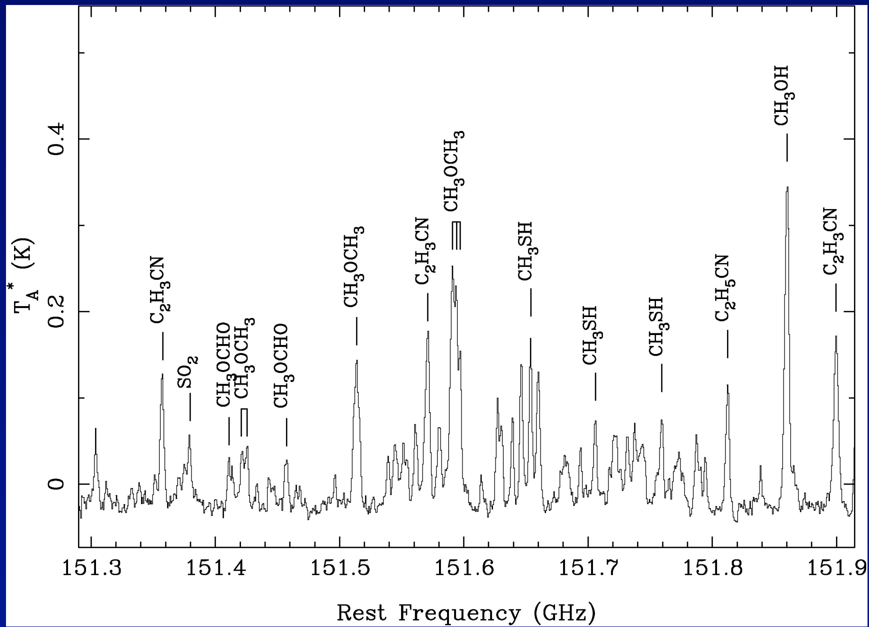


Thorwirth et al. 2003

- Rich spectra with lines from many complex organic molecules
- Large differences in line strengths between two hot cores <1 pc apart

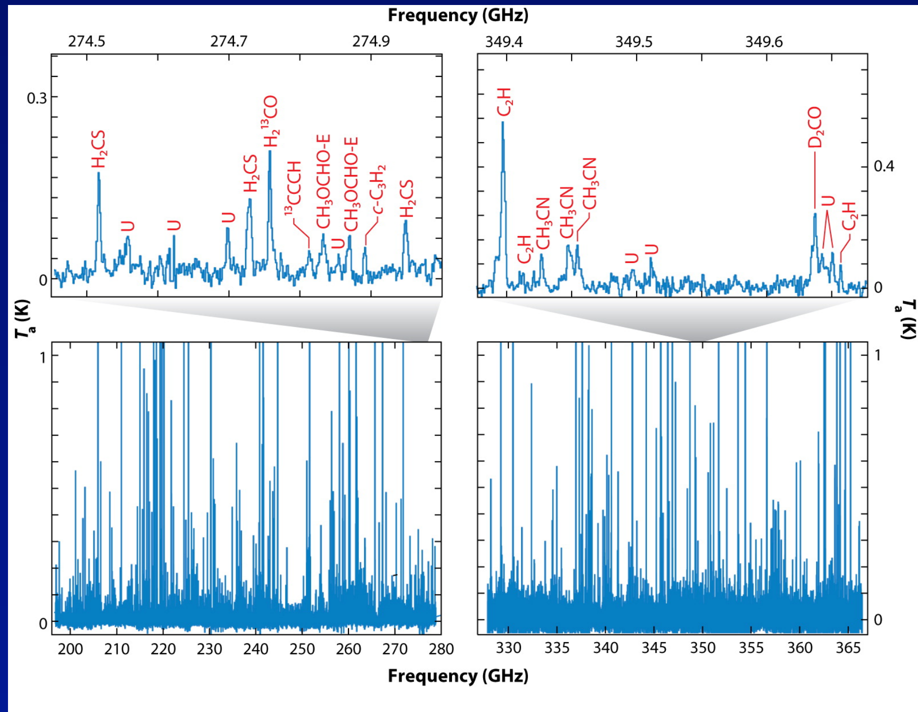
Rich spectra becoming confusion limited

G327.3: SEST



Gibb et al. 2000

IRAS 16293 -2422: IRAM 30m + JCMT

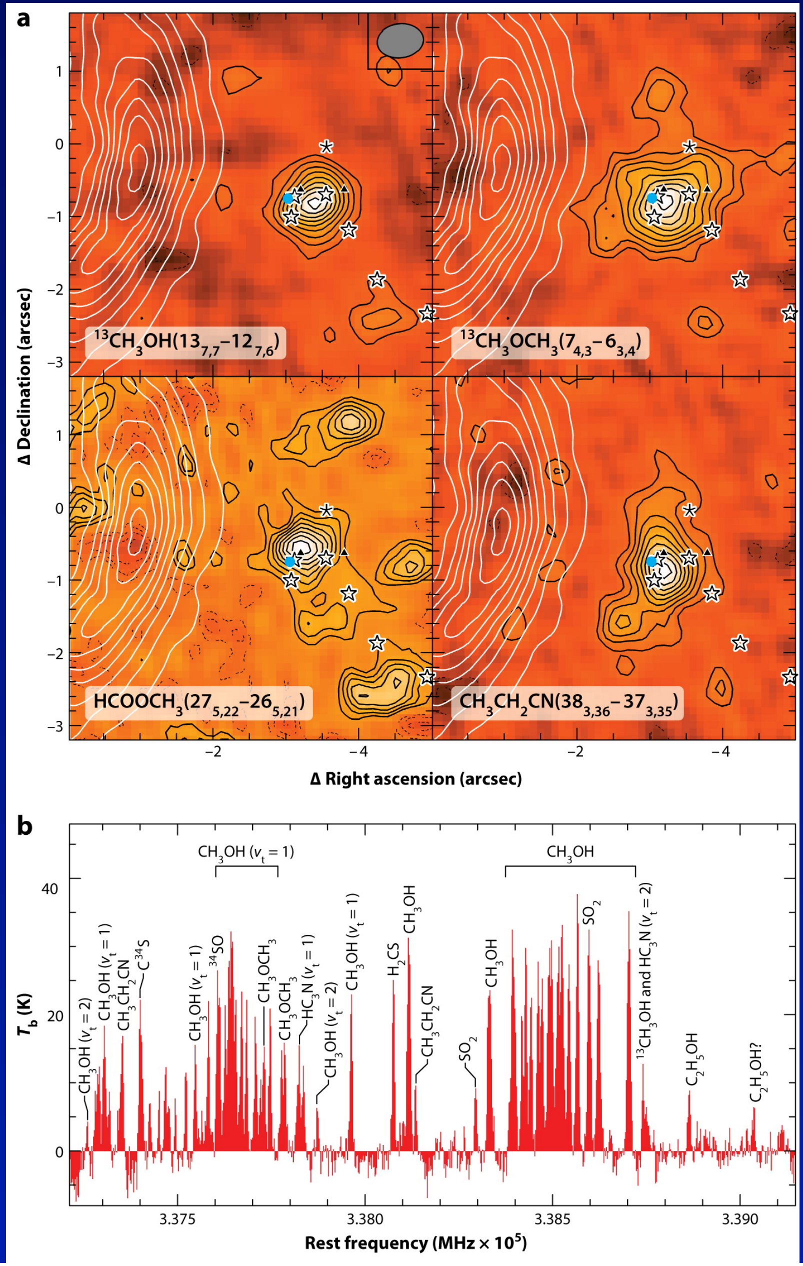


Herbst E, van Dishoeck EF. 2009.
Annu. Rev. Astron. Astrophys. 47:427–80

Caux et al. 2010

Inventory of organics: See talk Suzanne Bisschop

Starting to image the lines…



G29.96
-0.02

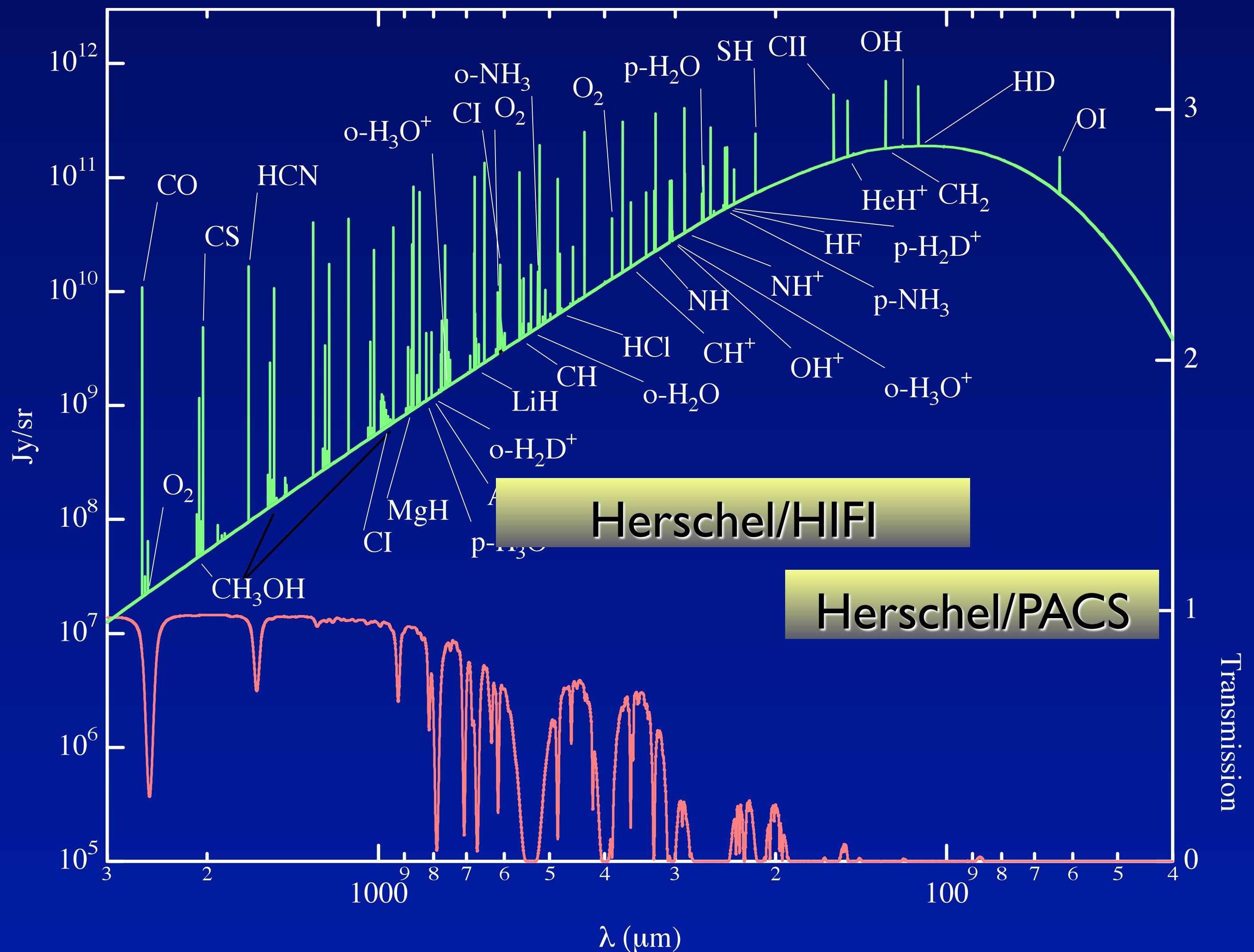
L=10^5 L$_{sun}$

- Various complex molecules have different distributions
- Sizes typically 1''

Beuther et al. 2007, SMA

Herbst E, van Dishoeck EF. 2009.

Potential of Herschel



E. Bergin, based on Philips et al.

- High spectral resolution and sensitivity at far-IR wavelength
- Large dish ⇒ spatial resolution much better matched to protostar
- *Unbiased*, complete surveys

Main strengths of Herschel

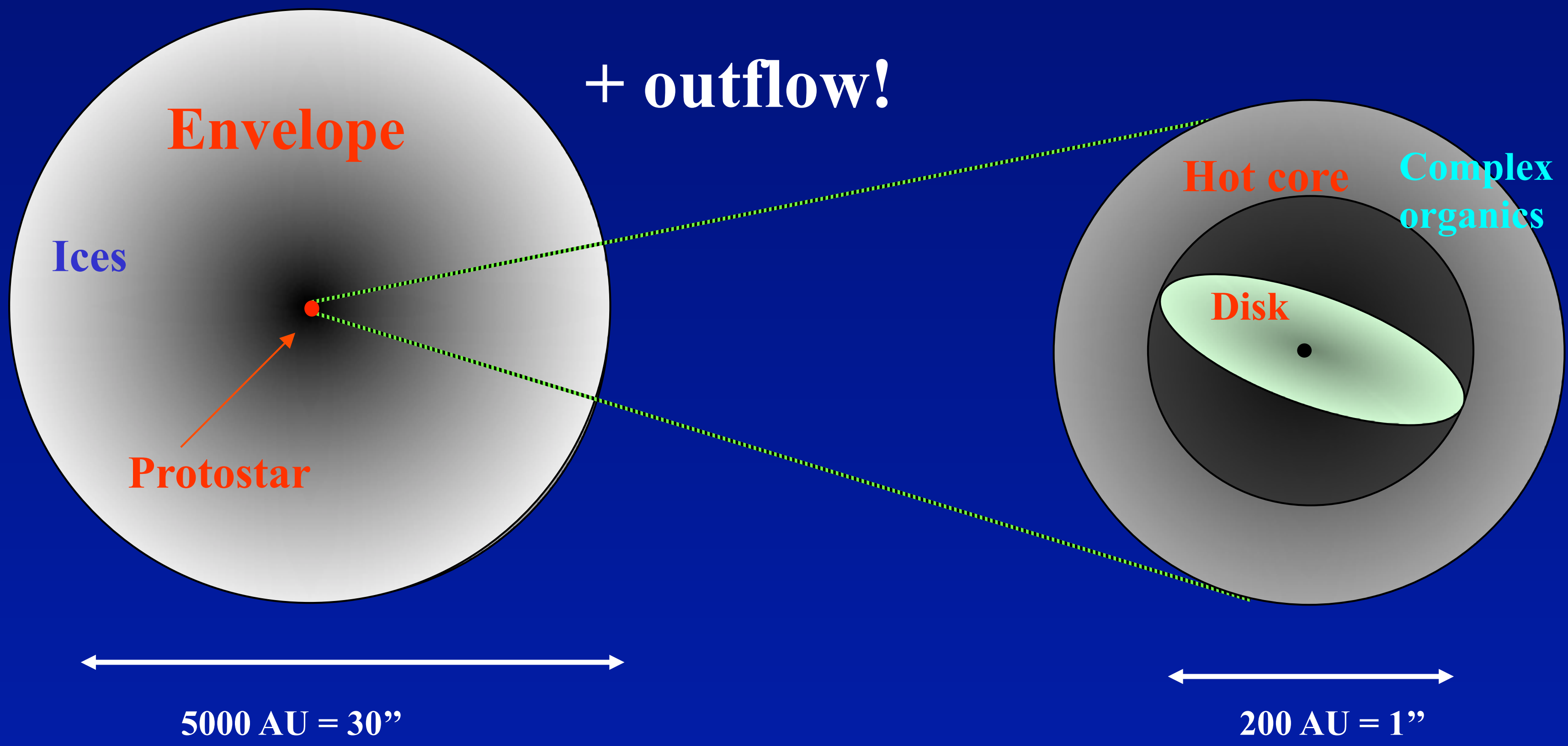
- Water
  - Building on ISO, SWAS, Odin heritage
- Cooling lines: high-*J* CO, OH, [O I], [C II]
- Hydrides
- Complex organic molecules
  - Lots of lines with very good relative calibration

These lines address key physical and chemical aspects

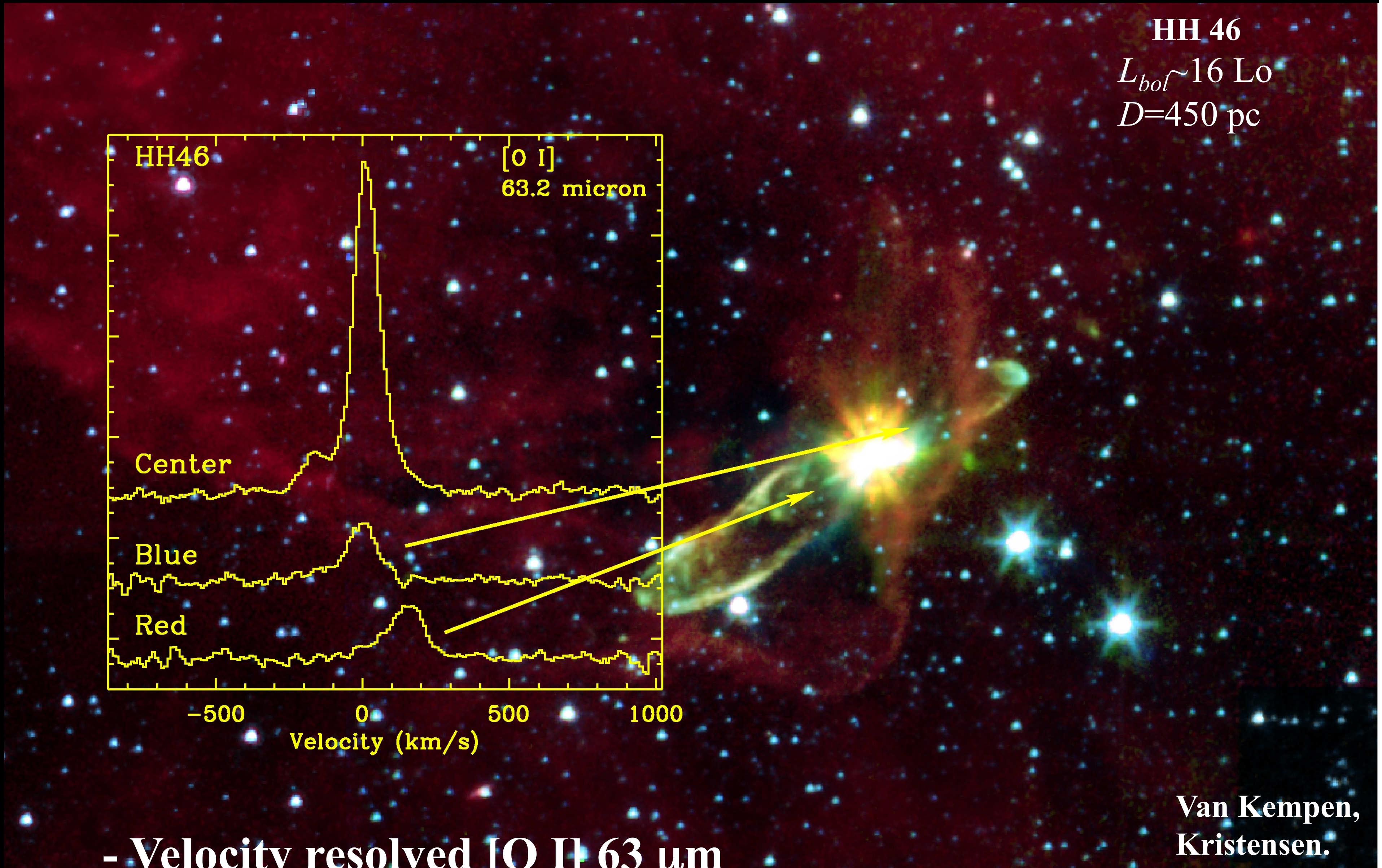
Anatomy of a low-mass YSO

(high mass similar but scaled up)

Herschel beam samples entire envelope



Physics: outflow



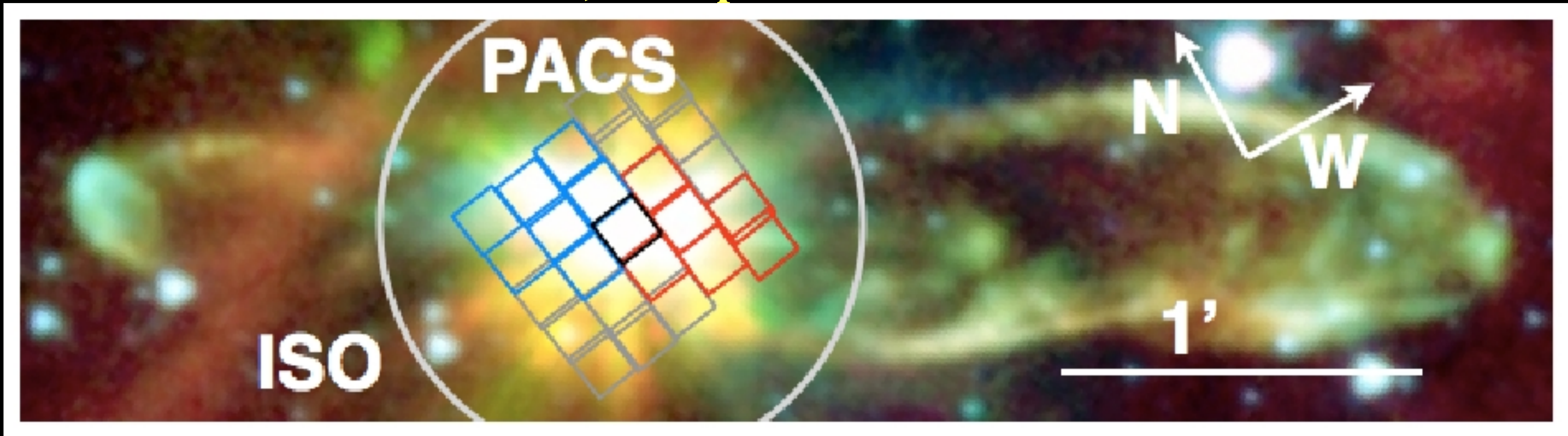
Van Kempen, Kristensen. Herczeg et al. 2010

- Velocity resolved [O I] 63 µm
- Most of [O I] along outflow is in high-velocity jet

Cooling budget

van Kempen,Kristensen, Herczeg et al. 2010
Wampfler et al. 2010

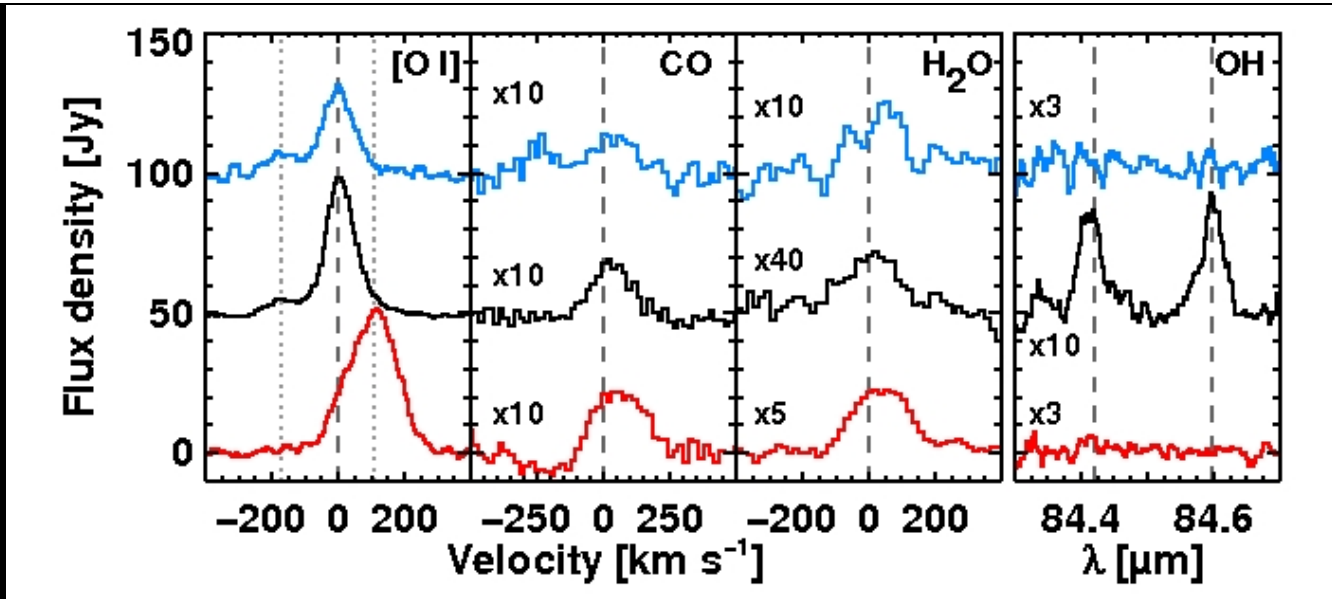
R=1500-4000, 9.4” pixels



Blueshifted Outflow

Inner envelope

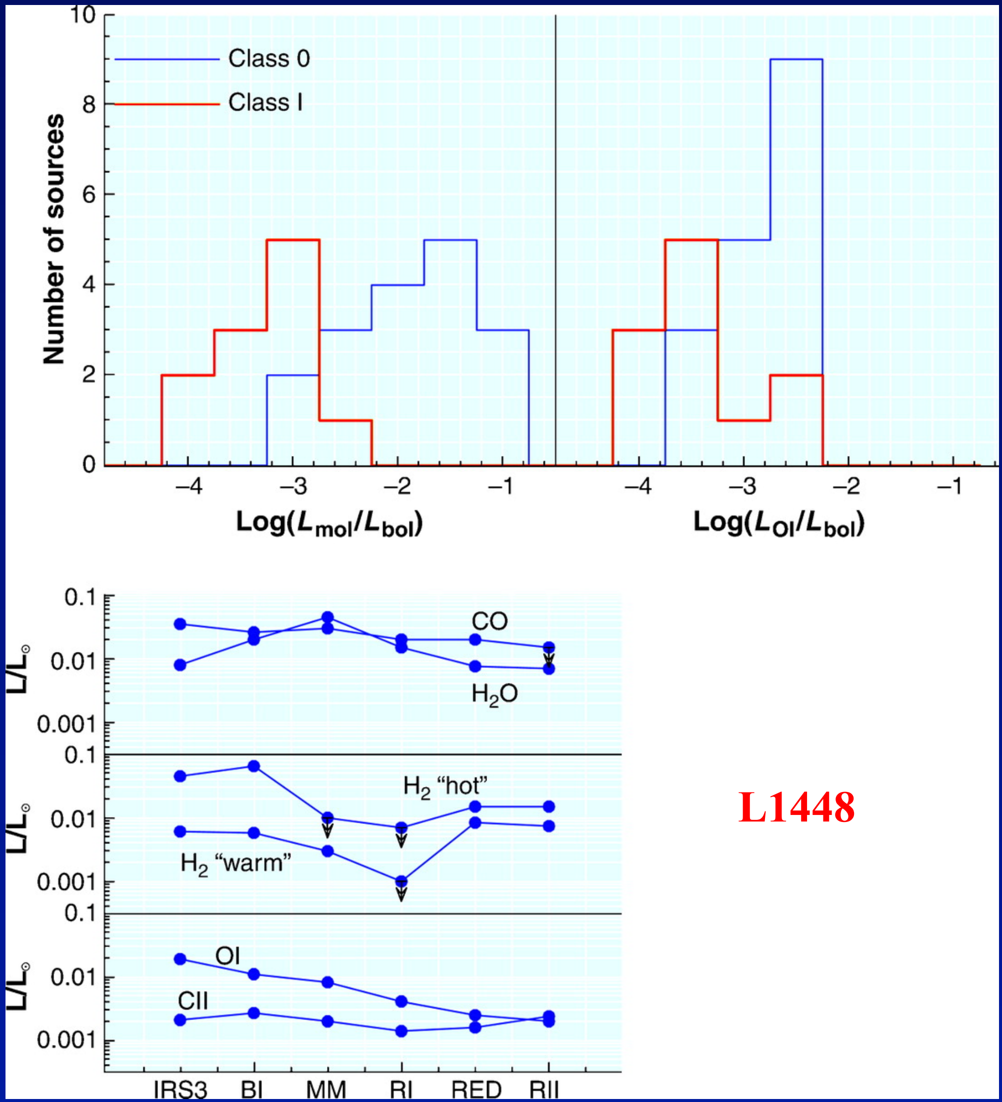
Red-shifted Outflow



H_2O accounts for 25% of far-IR cooling

O I and OH consistent with high density (>10^6 cm^{-3}) dissociative shock

Cooling budget: ISO

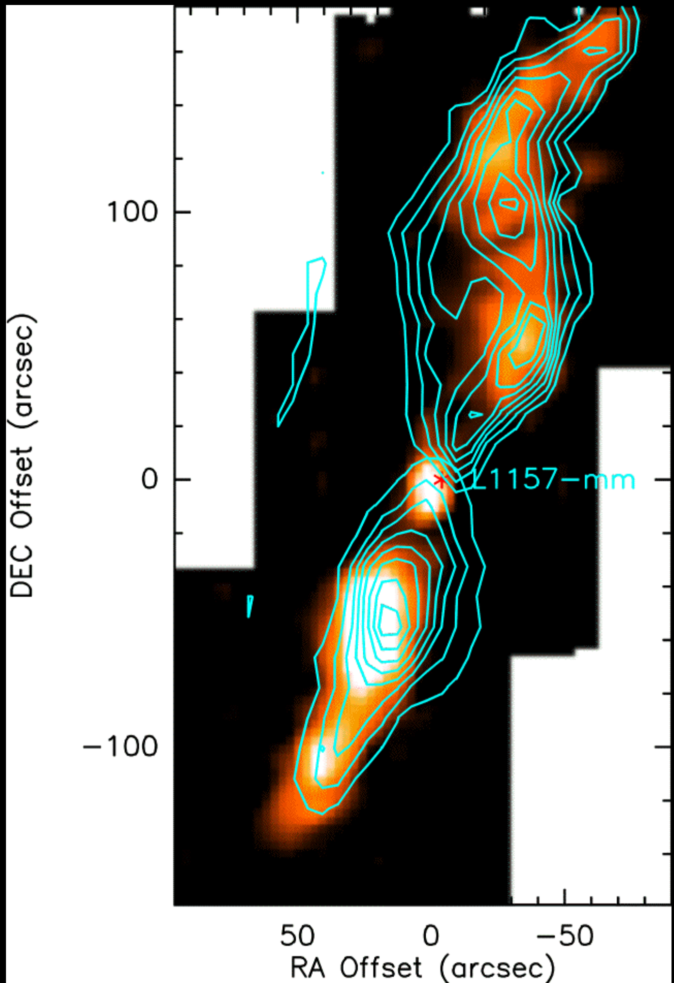


vD 2004, based on Nisini et al. 2000, 2002

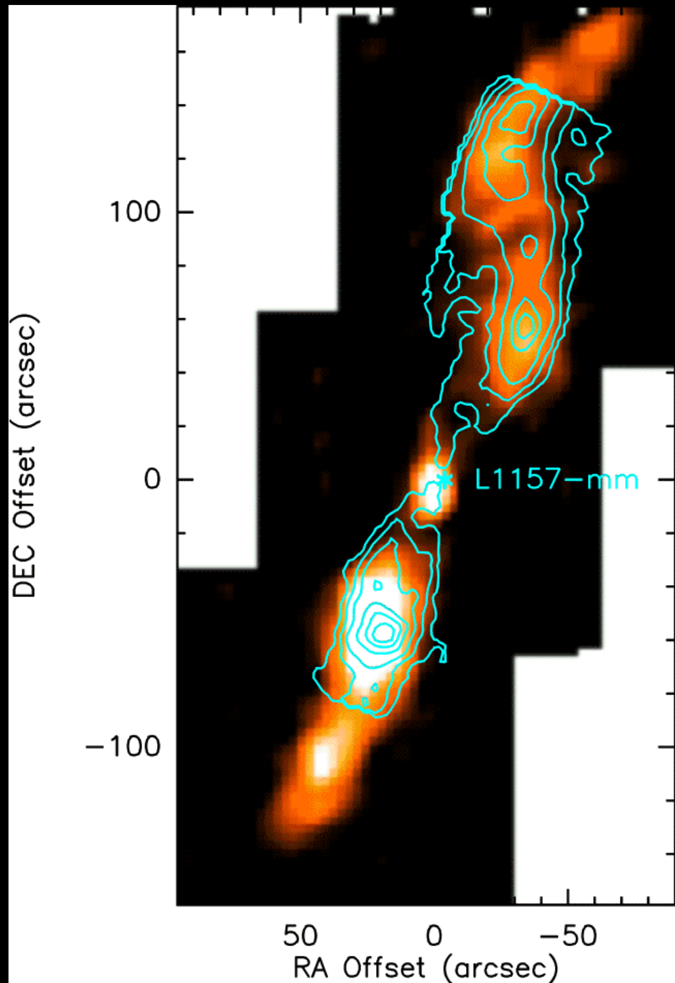
- ISO: H_2 dominates/very significant except on protostar
- Herschel + Spitzer can determine this on pixel-by-pixel basis

L 1157: Comparison with other gas main coolants

CO 2-1 | **H_2 0-0 S(1) 17μm**



Bachiller et al. 2001



Neufeld et al. 2009

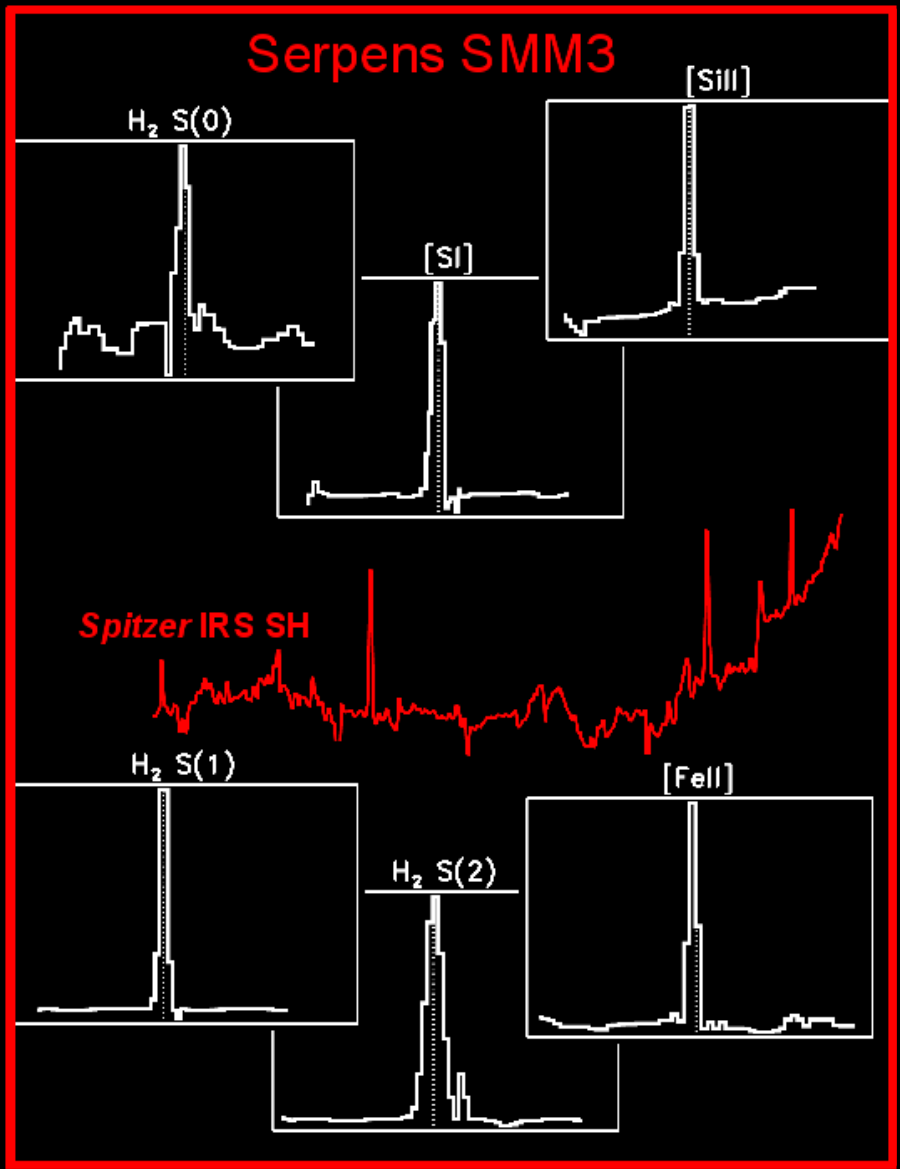
Color:
H_2O 179 μm

See also talk by Cabrit

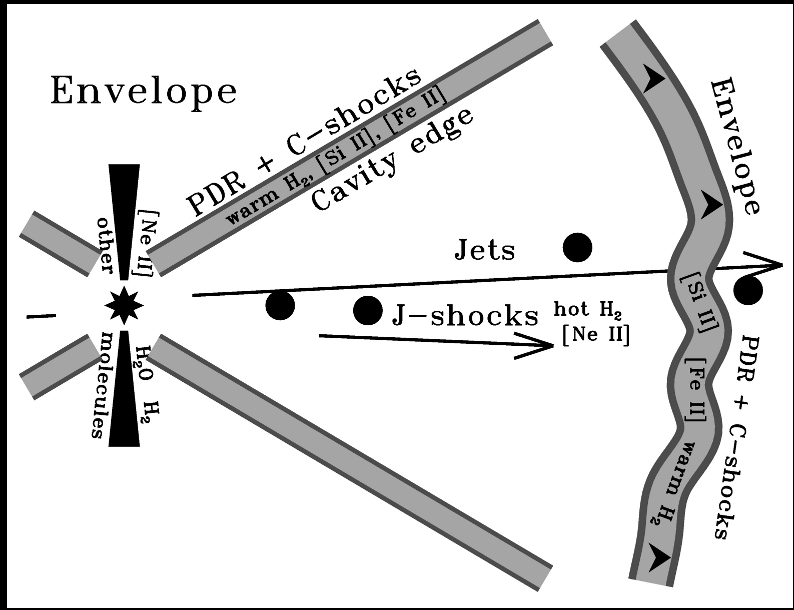
Nisini et al. 2010

- **Correlation between H_2O and H_2 warm gas at T ~ 300 K**
- **All coolants observed; H_2O about 25%**

Probing shocks and PDRs: Spitzer



Also: [Ne II] 12.8 μm

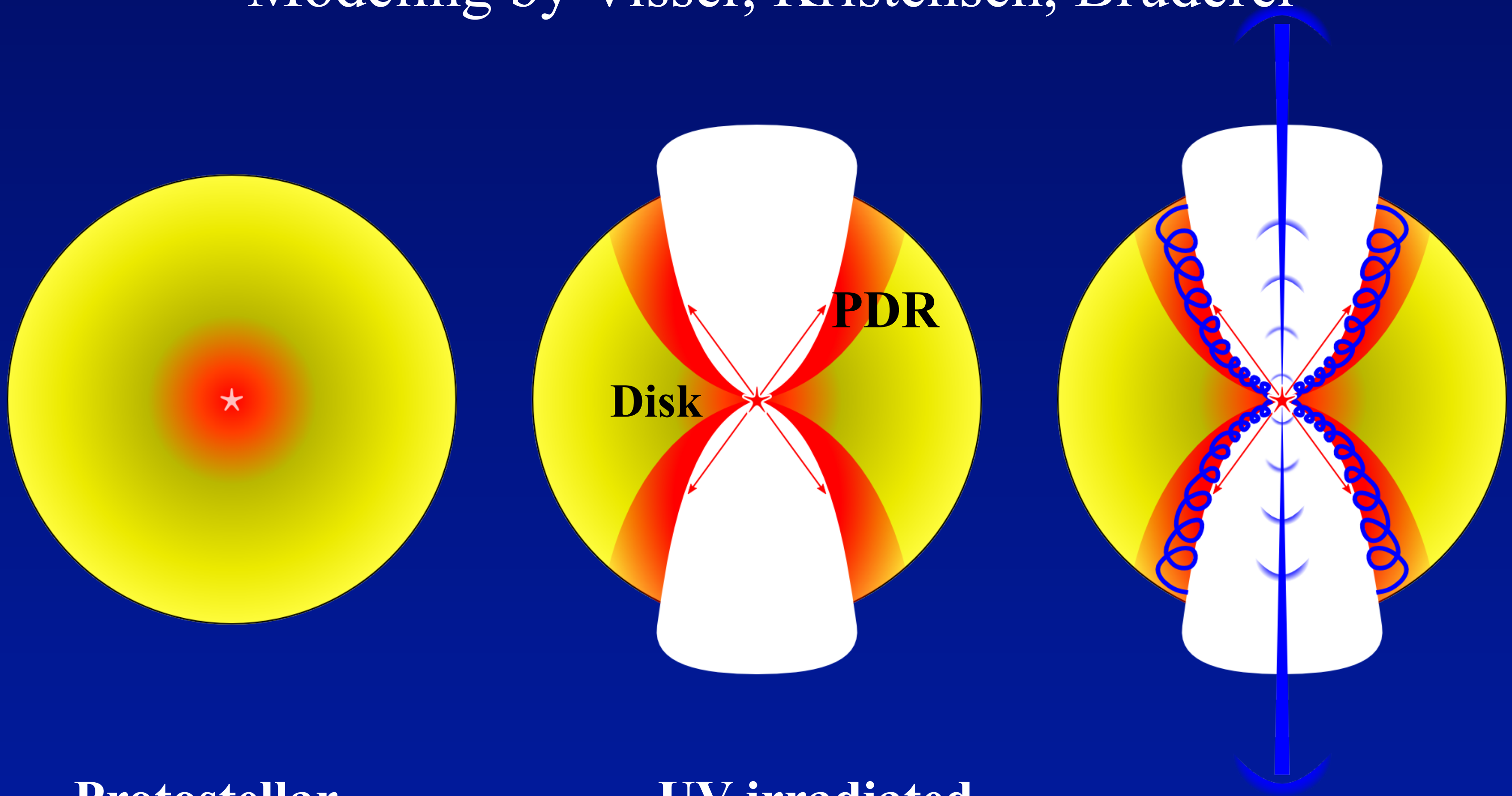


Lahuis et al. 2010
Baldovin-Saavedra et al. P10.1

Mid-IR contains unique, complementary atomic diagnostics of shocks, X-rays, …

Which physical component dominates which lines?

Modeling by Visser, Kristensen, Bruderer

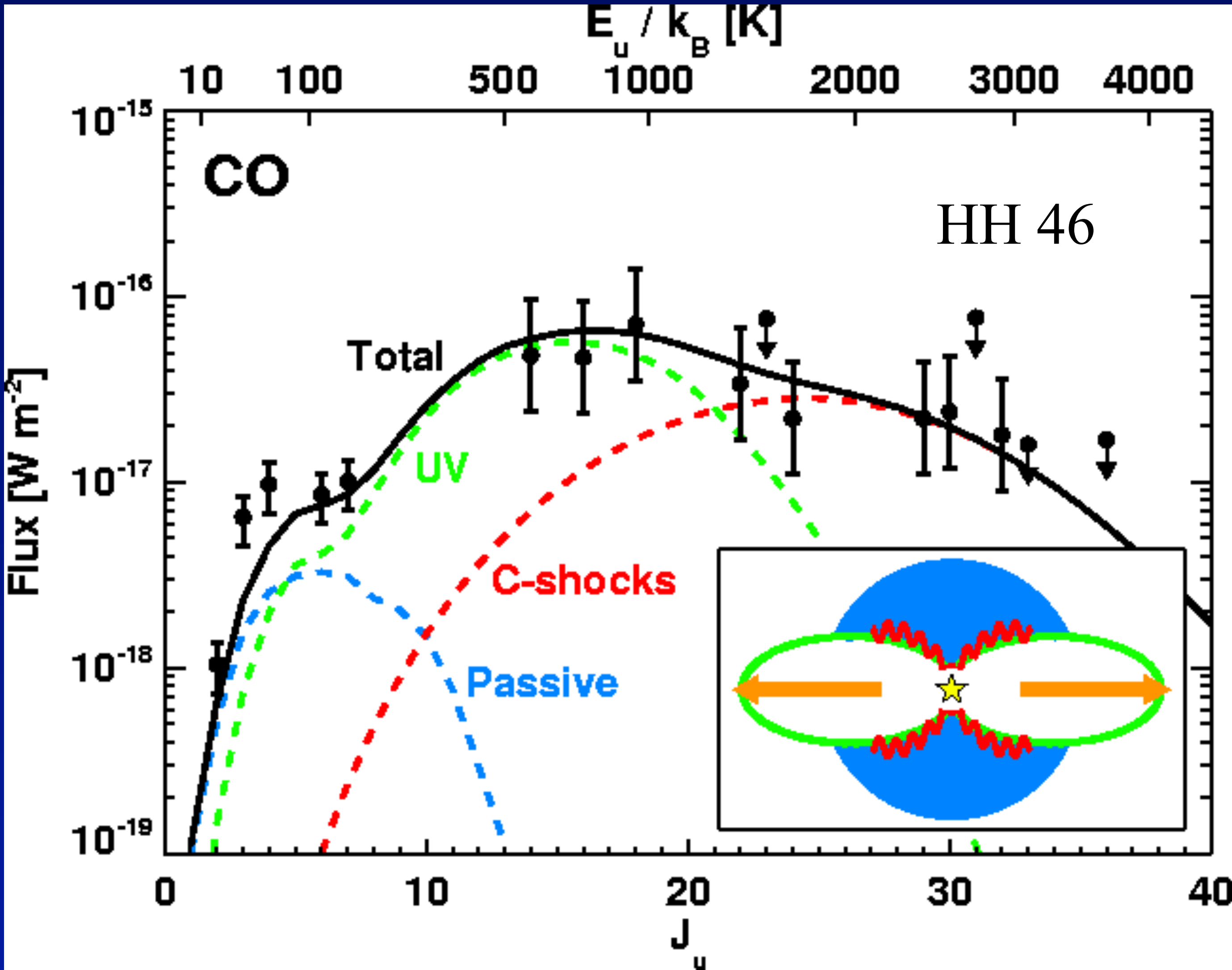


Protostellar envelope with hot core:
Low-J CO

UV irradiated cavity walls, disk surface:
Mid-J CO
Hot water?

Outflow shocks:
High-J CO,
Hot water?
High velocity O I

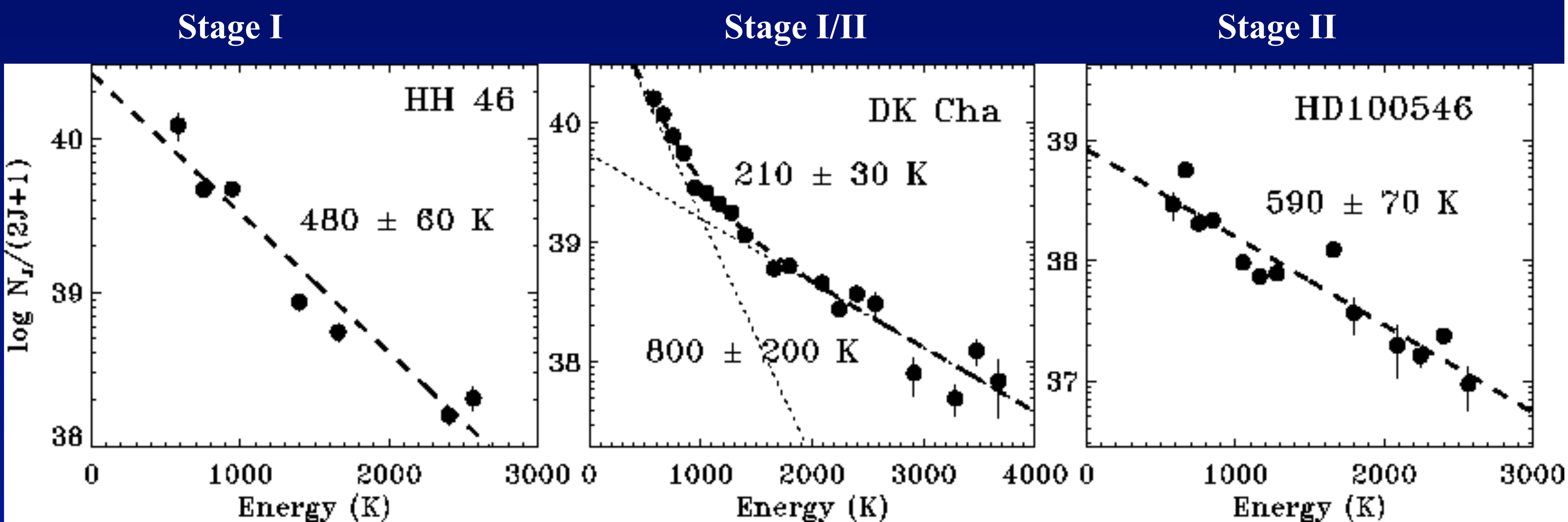
Origin of hot CO



Only parameters: UV field G_o and v_{shock}
Is this solution unique?

Visser, Bruderer, Kristensen, van Kempen et al. 2010

Can CO rotation diagram capture this?

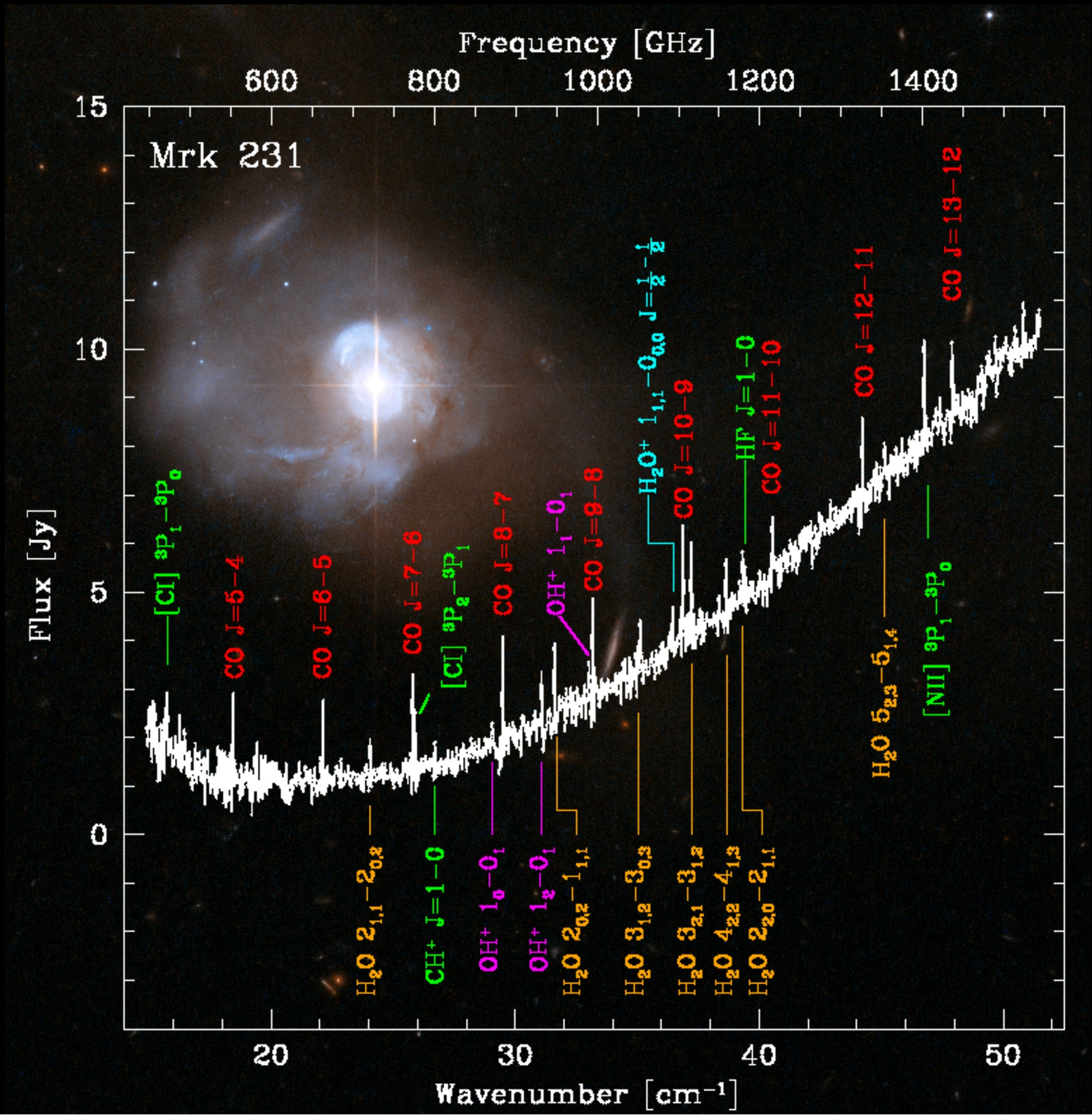


G. Herczeg, prelim.

- What do rotational diagrams tell us?
  two components, temperature gradient, or optical depth effects?

- How do they compare with diagrams over much larger scales, e.g., extragalactic?

Observing the entire CO ladder

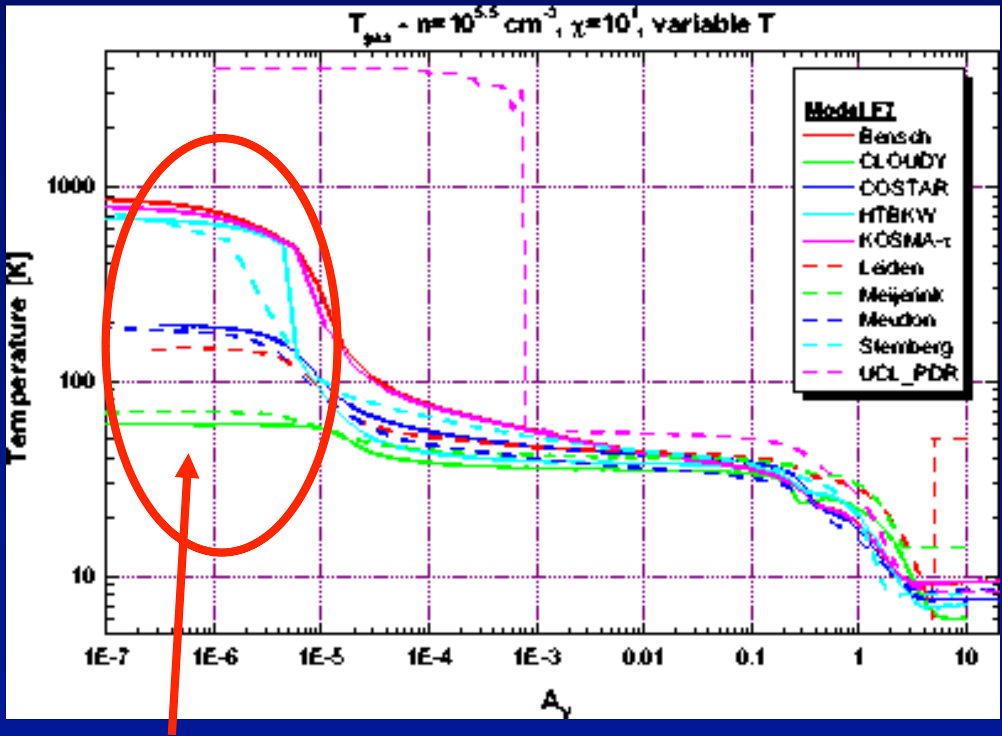


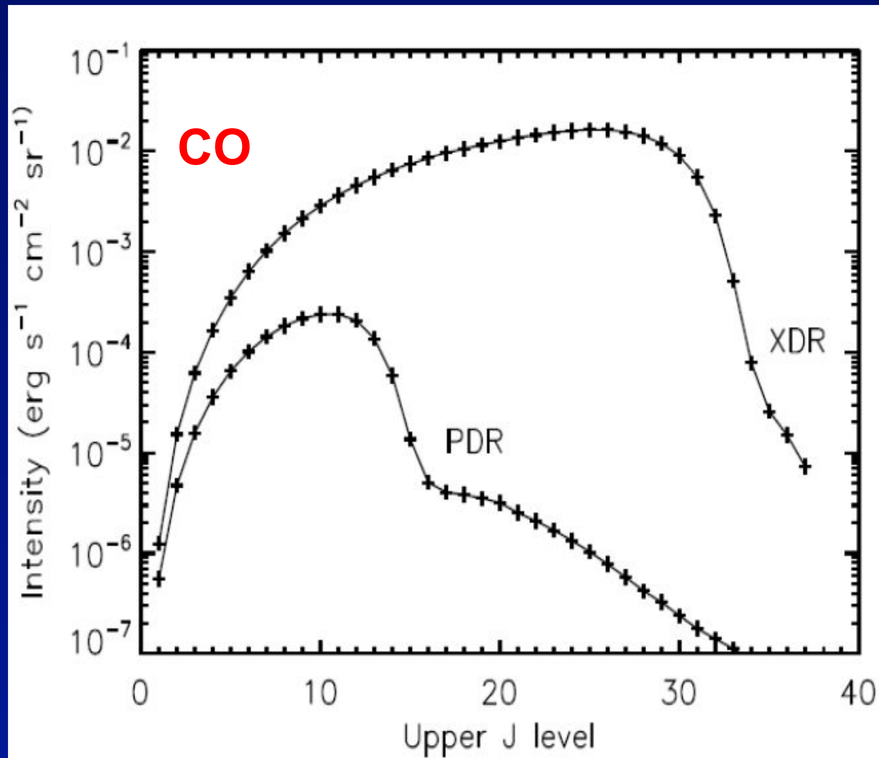
SPIRE-FTS

Van der Werf et al. 2010

What does high-J CO tell us?

Temperature structure: PDR comparison





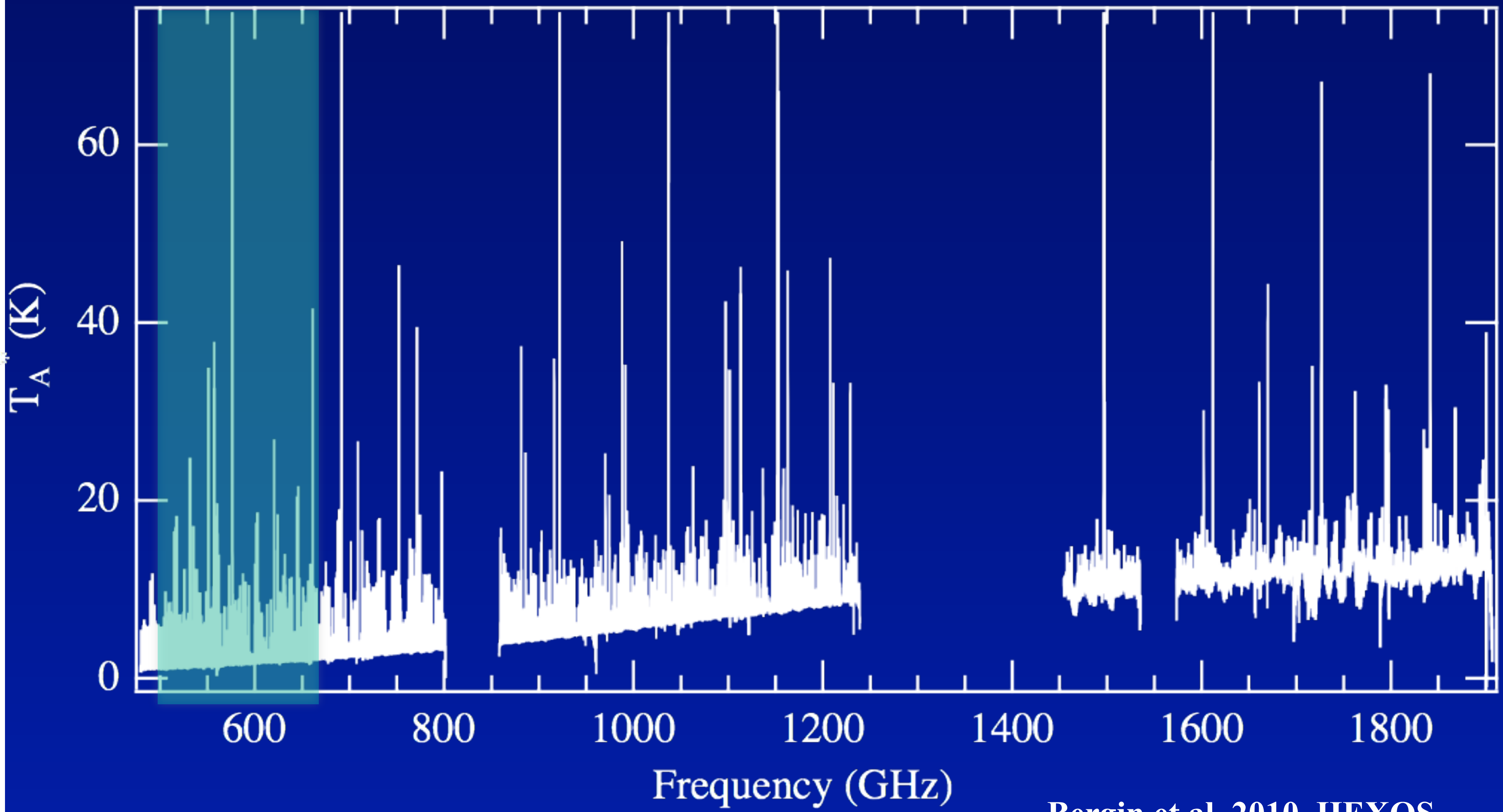
Note discrepancy!

Roellig et al. 2007

Meijerink & Spaans 2005, 2008

-Need to observe CO ladder in many more (well defined) galactic sources to calibrate PDR models (WADI?)

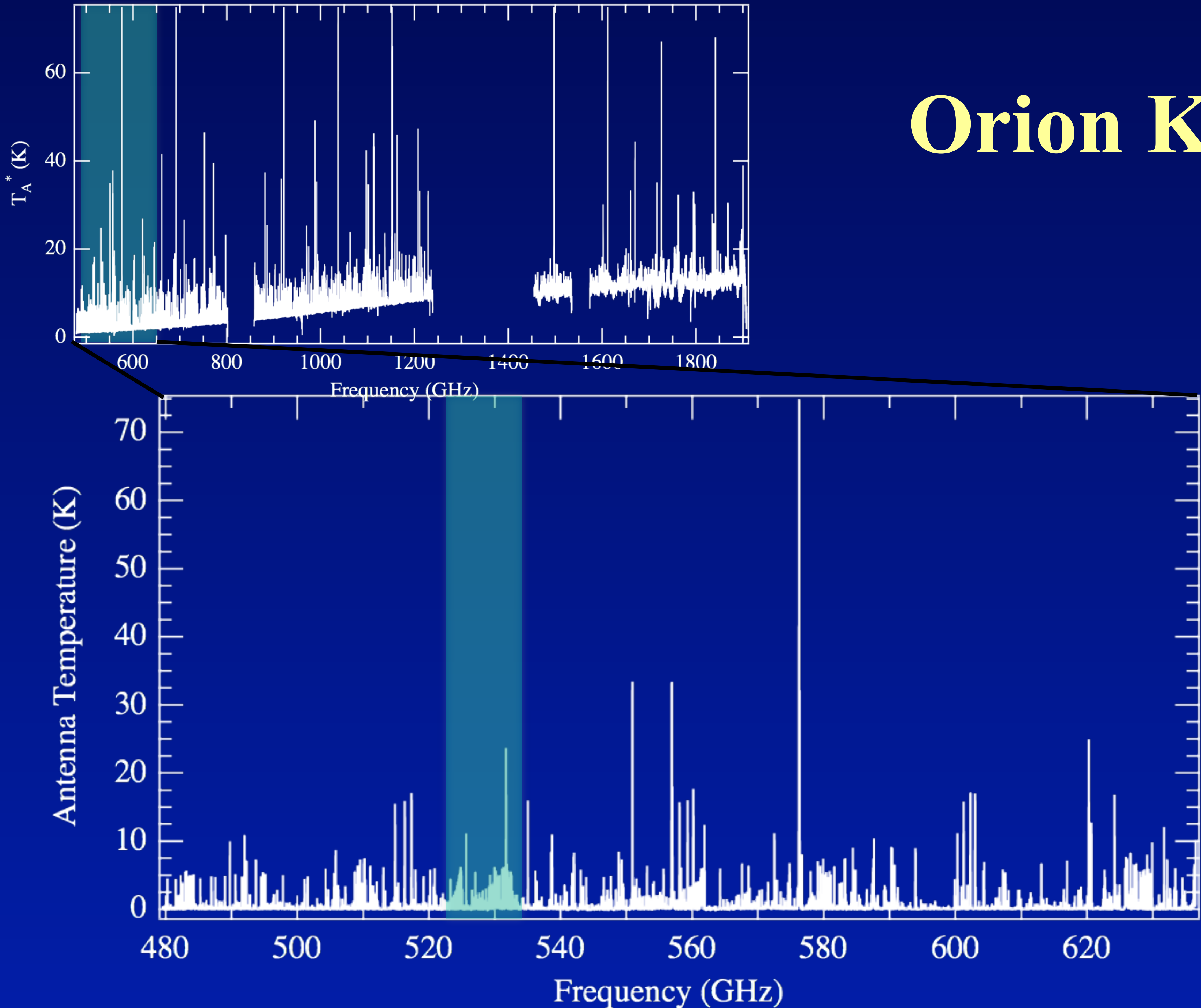
Chemistry: HIFI forest of lines in Orion



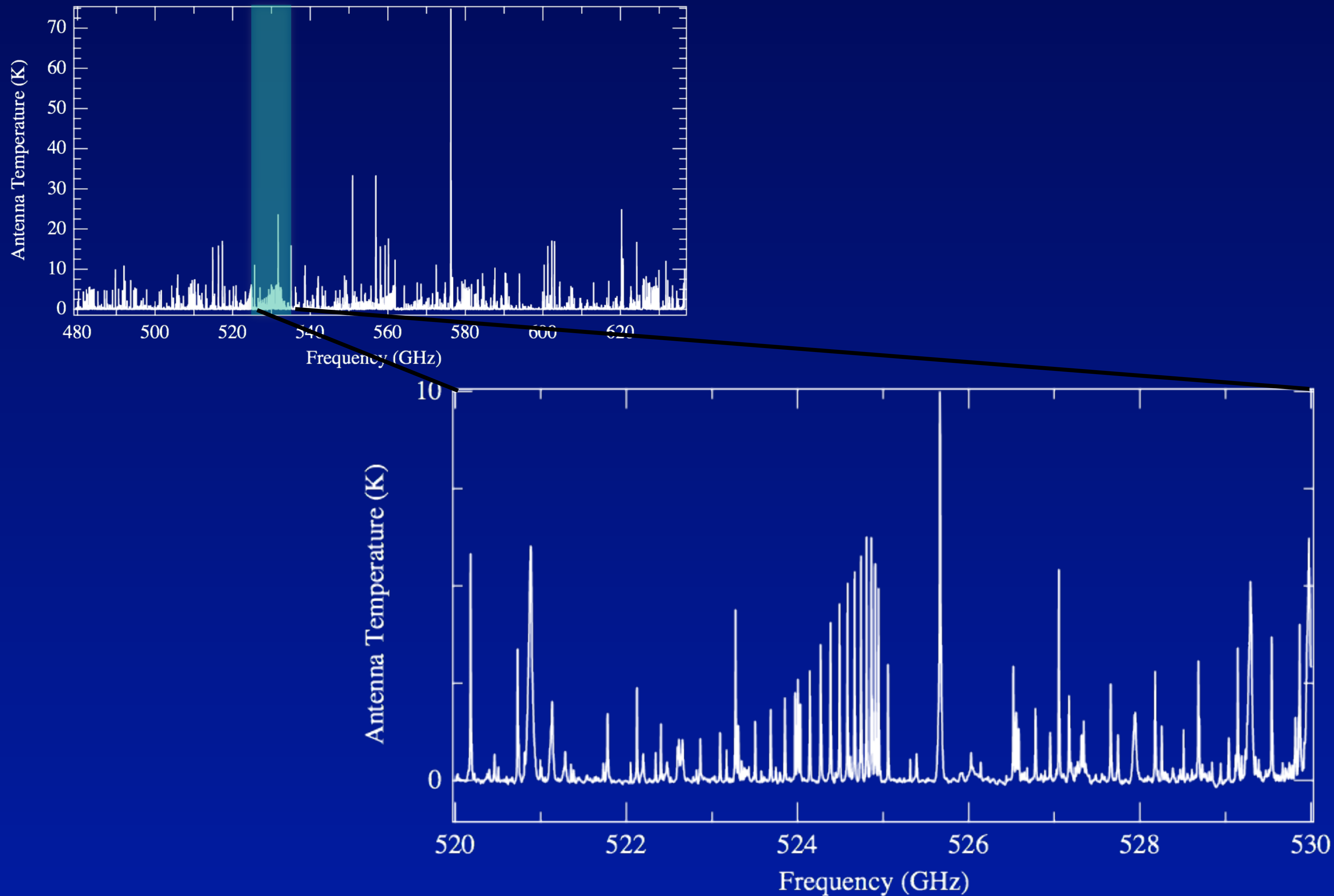
Bergin et al. 2010, HEXOS

Entire spectrum in just tens of hours!

Orion KL

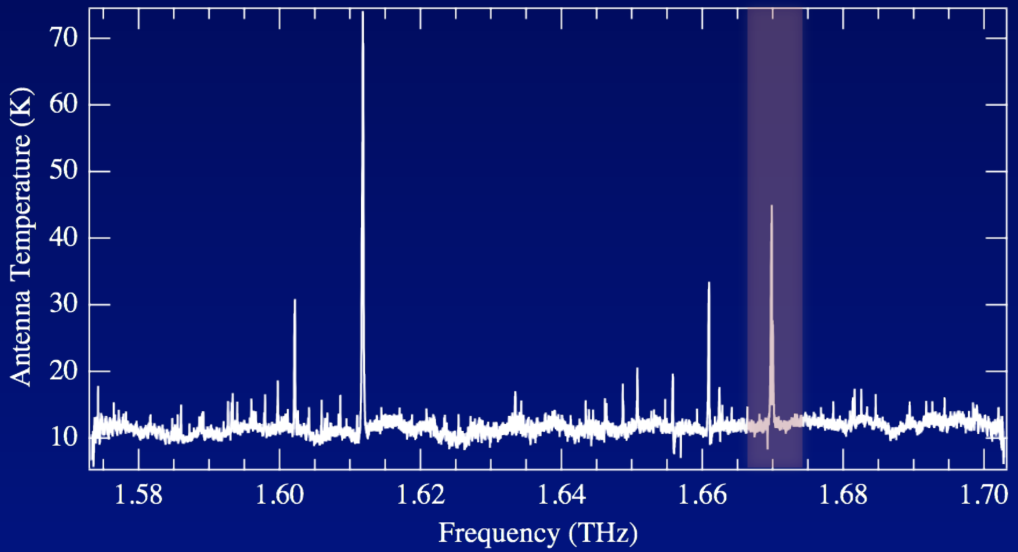


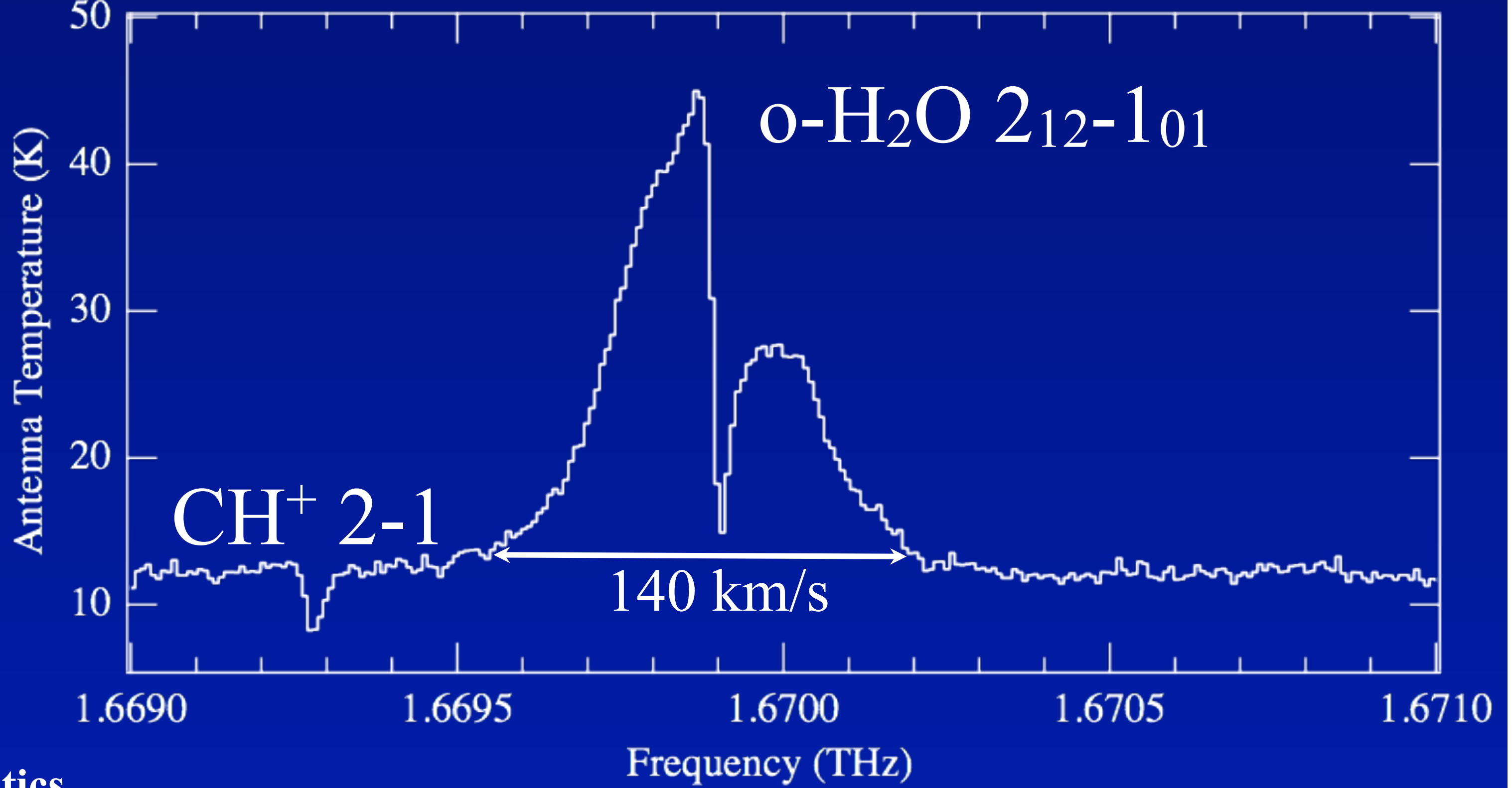
T_A^* (K)
0
20
40
60
600
800
1000
1200
1400
1600
1800
Frequency (GHz)
Antenna Temperature (K)
0
10
20
30
40
50
60
70
480
500
520
540
560
580
600
620
Frequency (GHz)



Orion KL - Band 1

Orion KL Band 6b



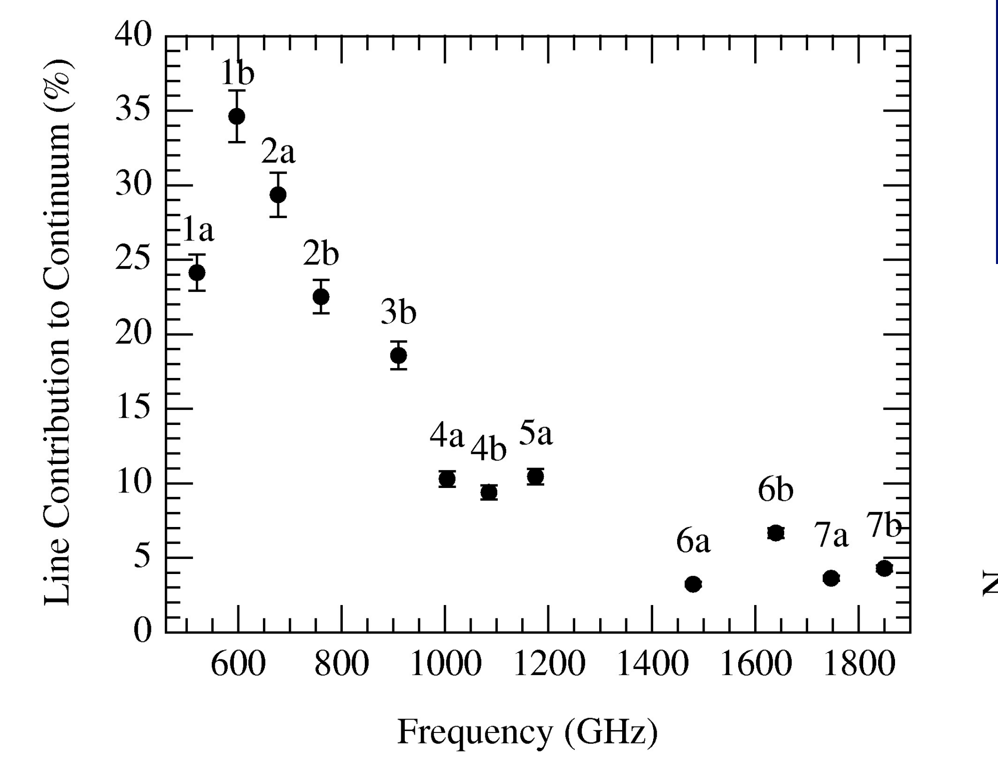


Note complex kinematics

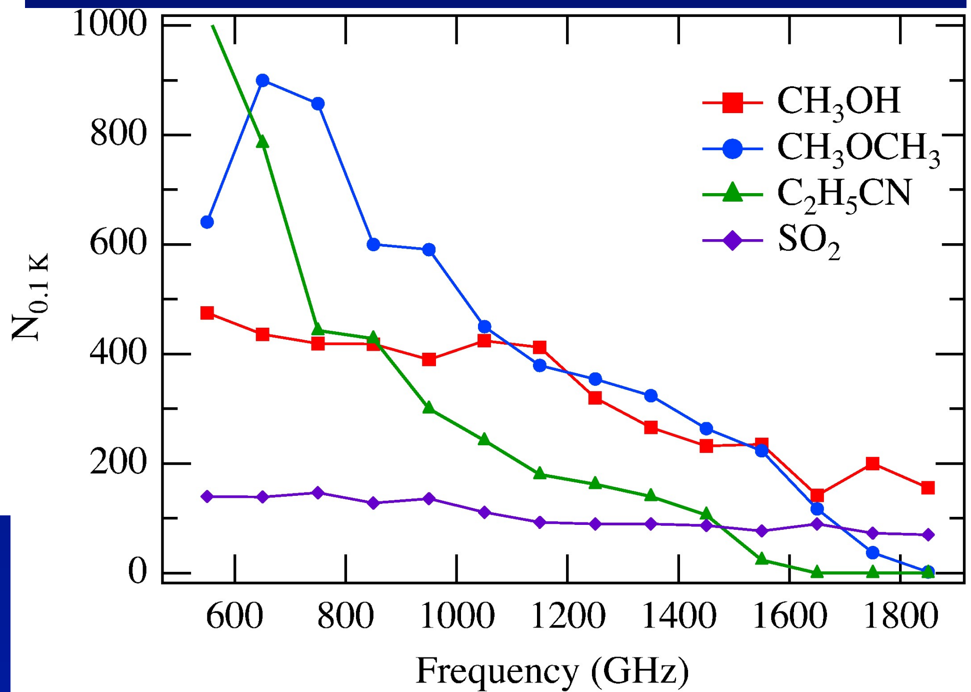
Crockett et al. 2010

Line surveys: statistics Orion

Line contribution continuum



'Weeds' at high frequency



Peaks around 30-35% at 500-600 GHz

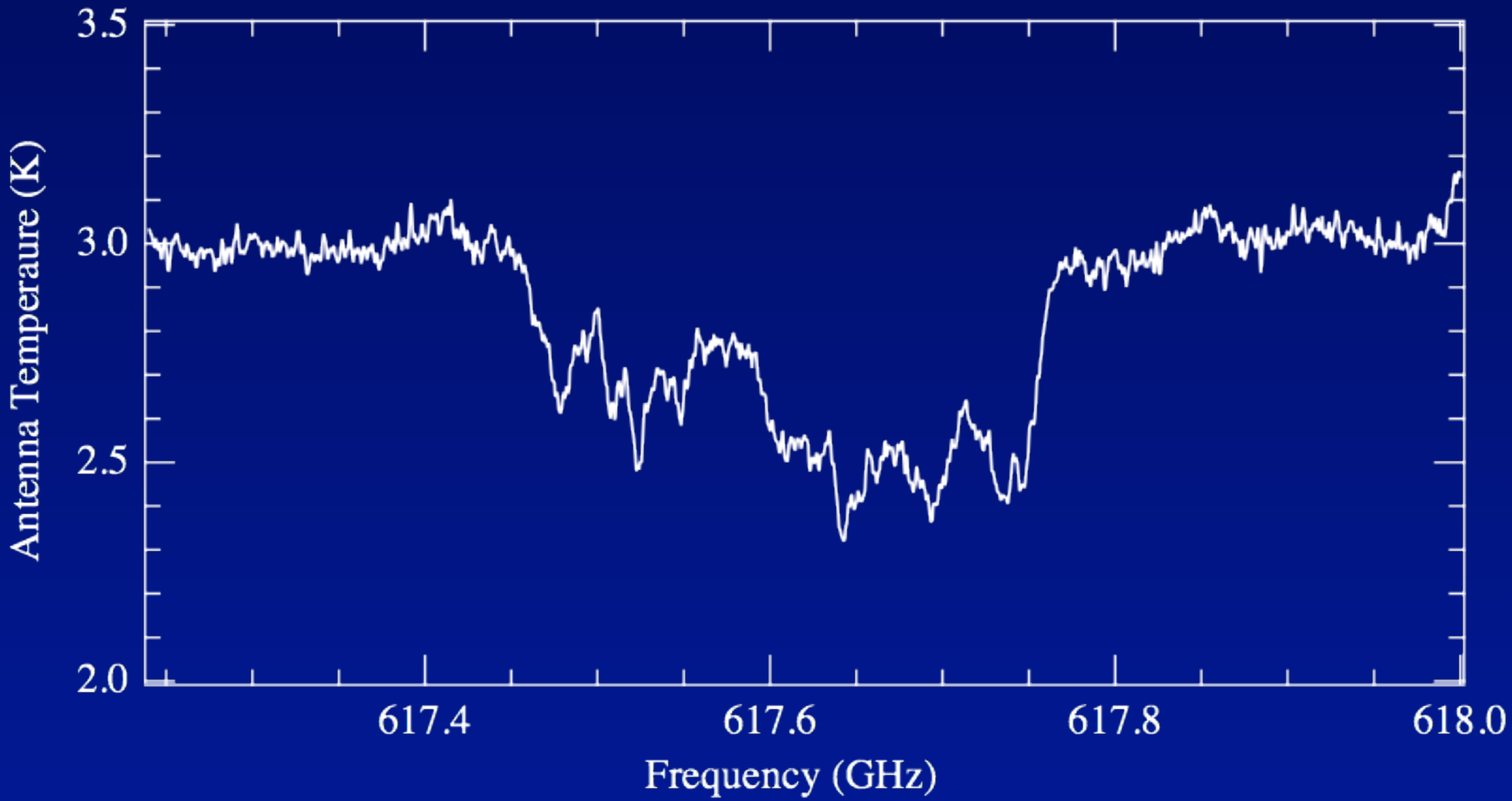
Bergin et al. 2010, Groesbeck 1995 lower freq

This high freaction does not hold for all high-mass sources!

# of lines of complex mol drops with freq not due to continuum optical depth

Crockett et al. 2010

U-line SgrB2

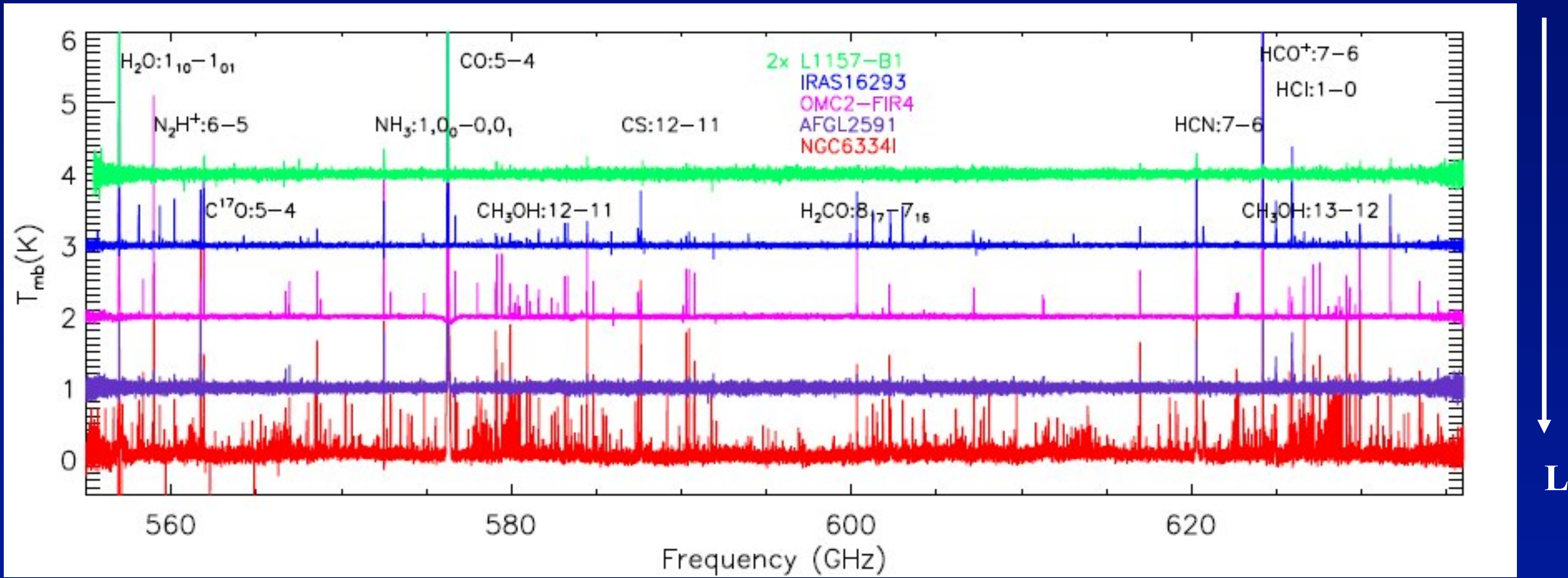


Molecule present in *all* spiral arm clouds between us and the galactic center

E. Bergin

Spectral surveys: other sources

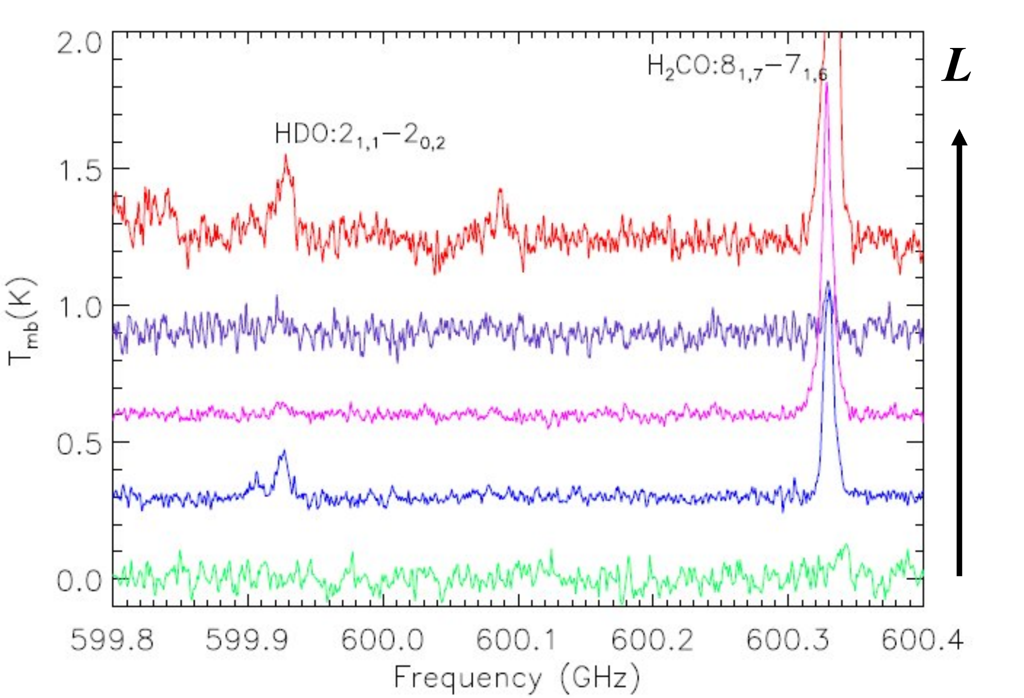
CHESS



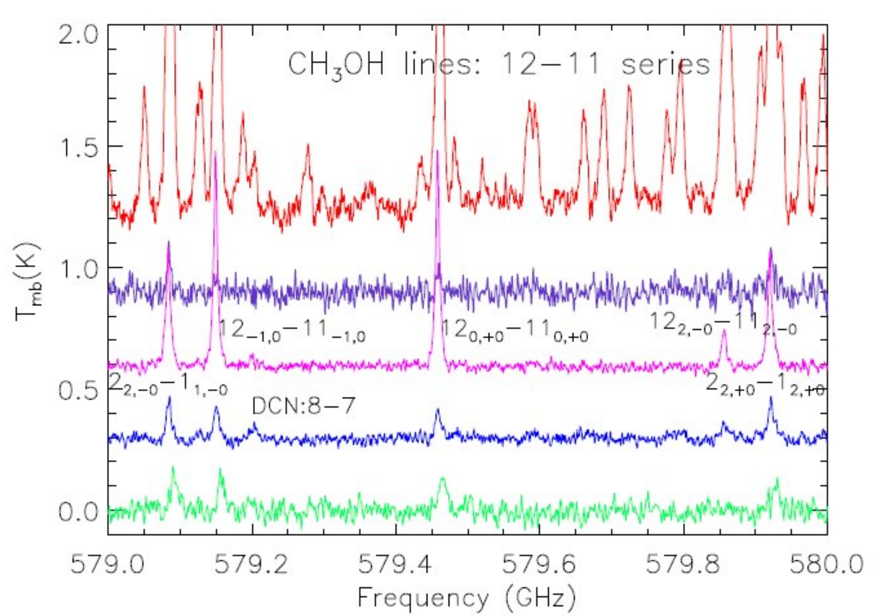
Ceccarelli et al. 2010
Kama et al. 2010

Spectral surveys: zoom in

HDO



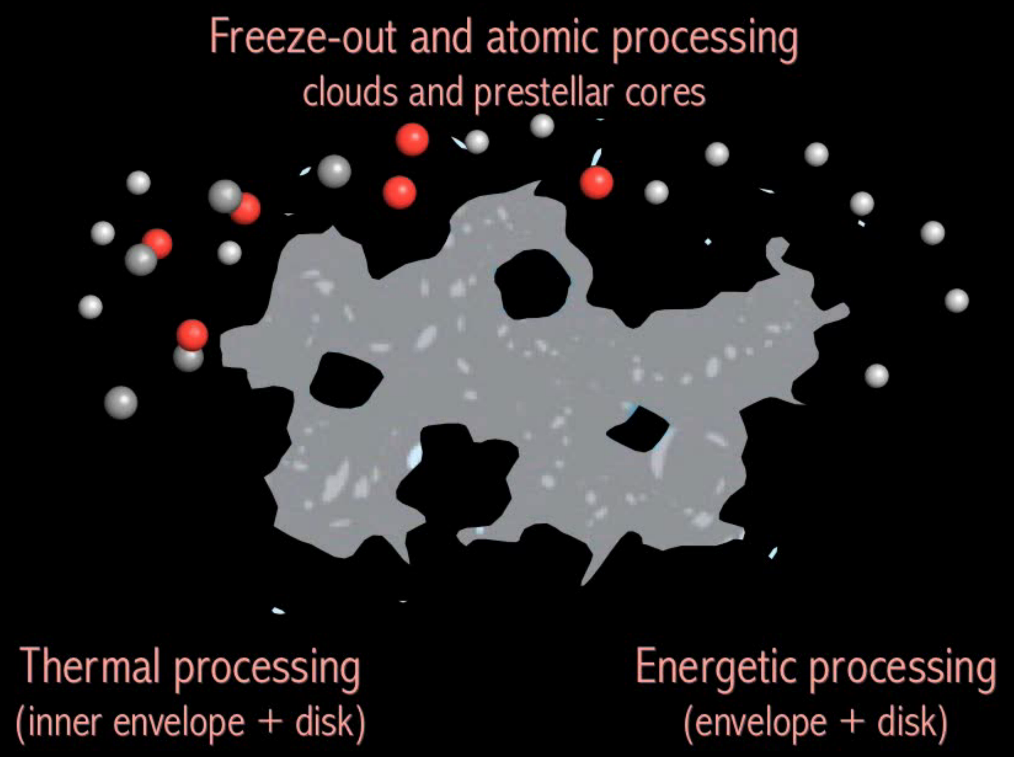
CH$_3$OH



Strength of water, complex molecules varies from source to source

- **Not related to luminosity**
- **Evolutionary state?**
- **Beam filling factor warm gas?**

Importance of gas-grain chemistry

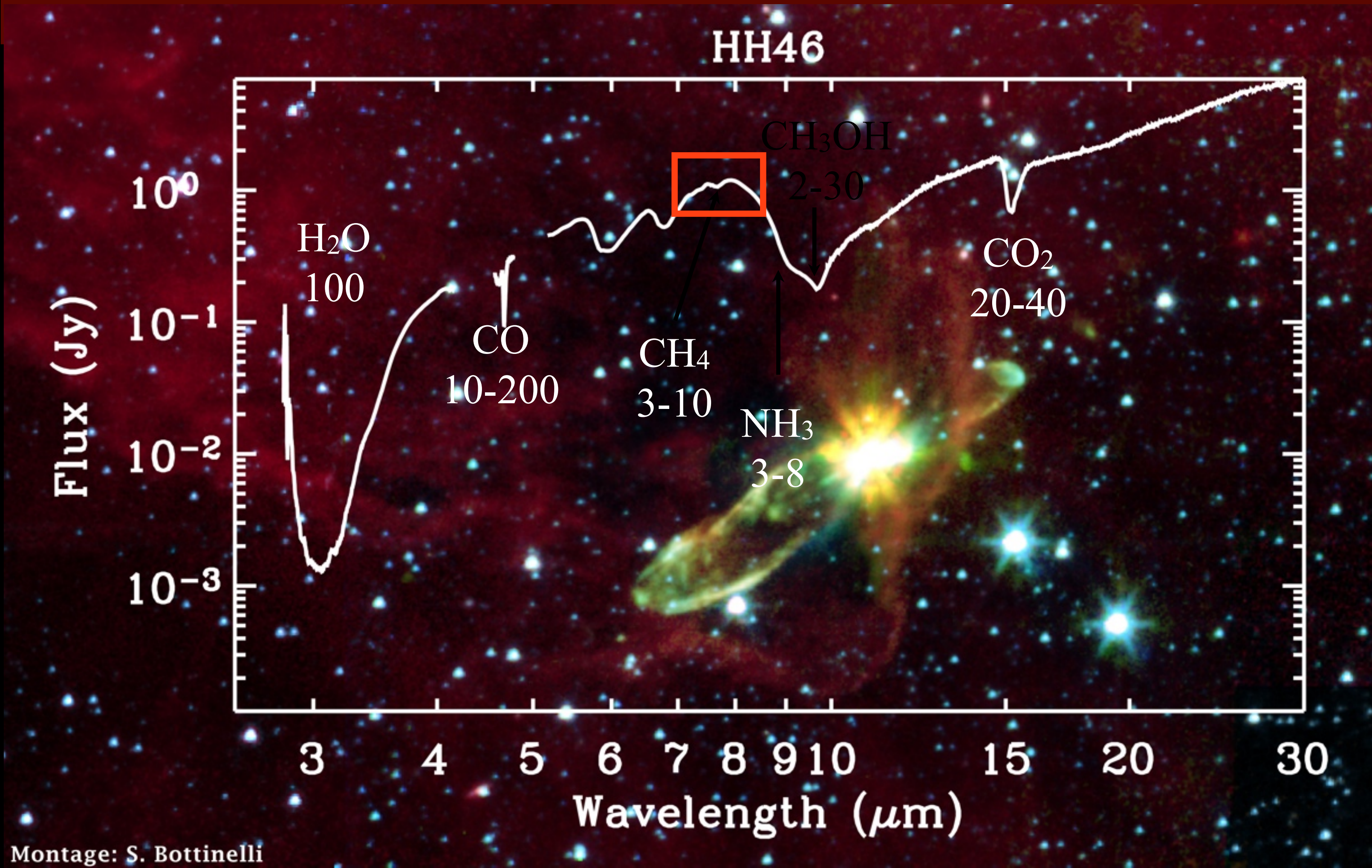


Complex organics formed on and in the ices

K. Öberg 2009

See talk Garrod

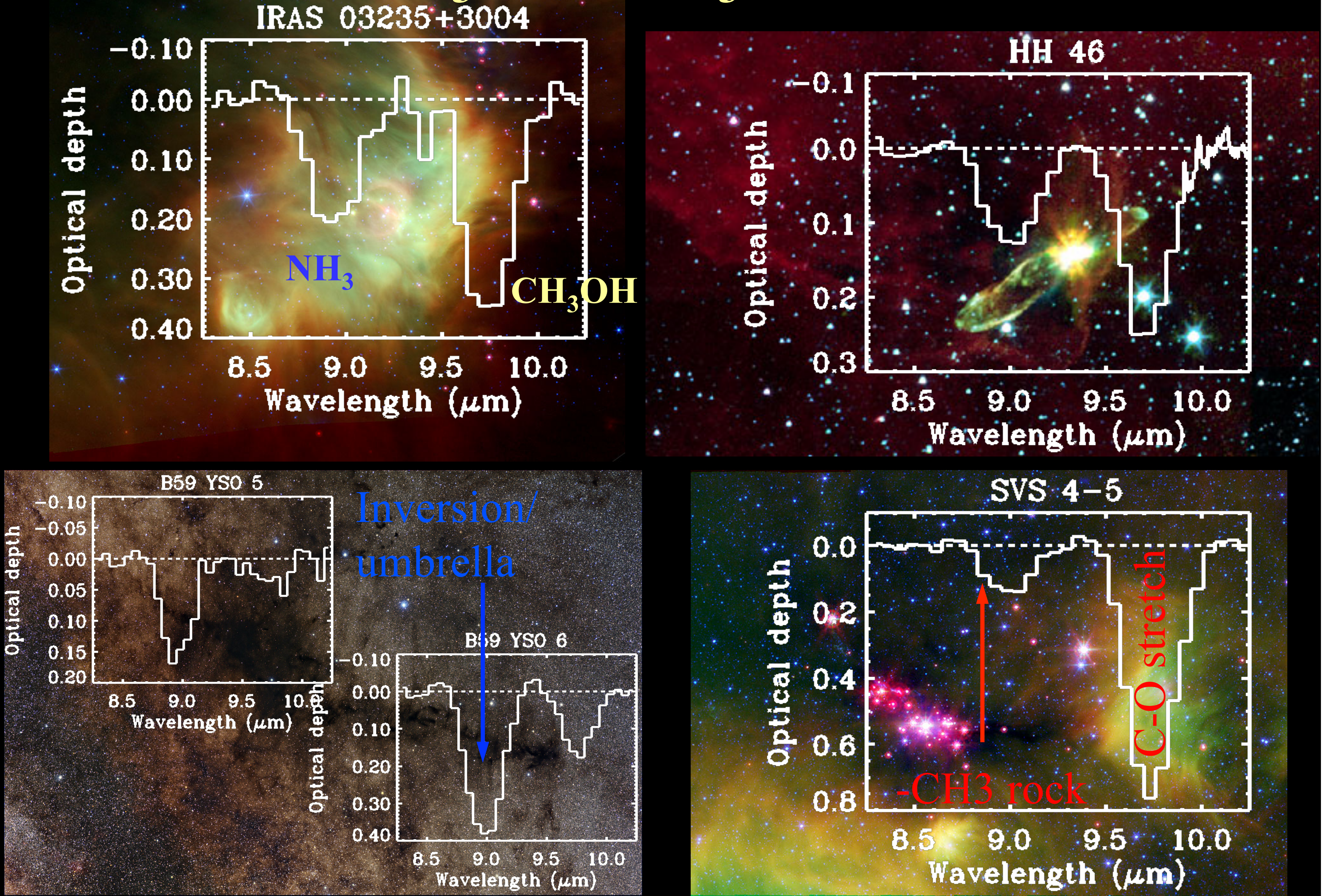
Ices are abundant and common!



- Ices can contain significant fraction of heavy elements (50% or more)

Boogert, Pontoppidan
Öberg et al. 2008

NH_3 and CH_3OH ice



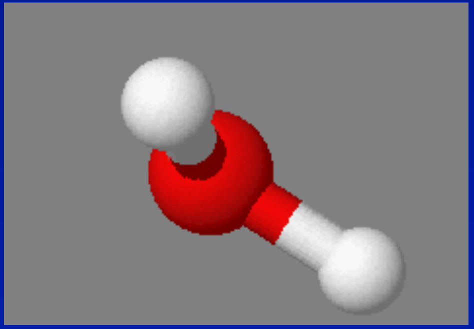
Ingredients for complex organics!

Bottinelli et al. 2010

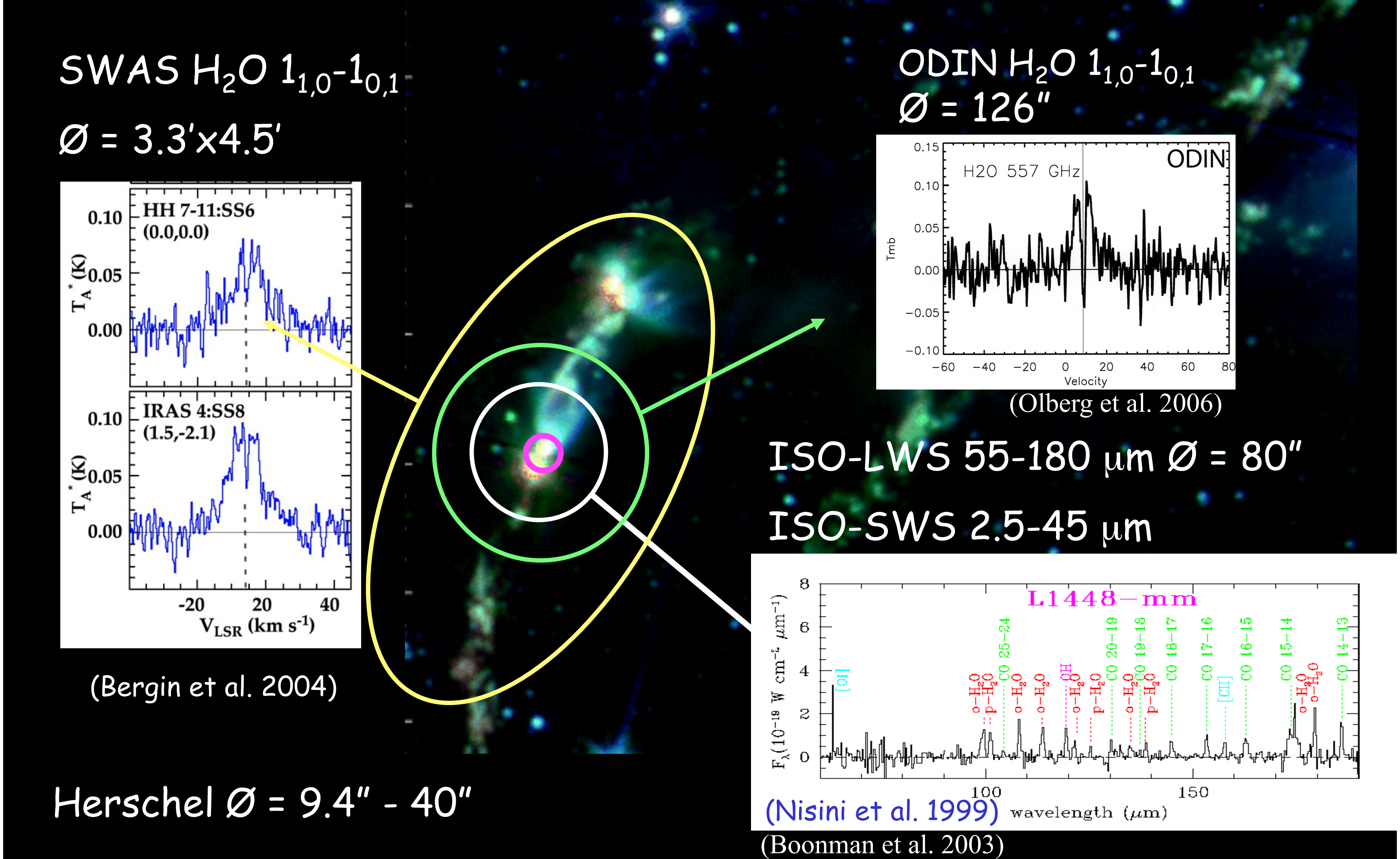
Water

- **Unique probe of different physical regimes and processes → natural filter of warm gas**
  - **H_2O abundance shows large variations: <10^{-8} (cold) – 3. 10^{-4} (warm)**
- **Main reservoir of oxygen → affects chemistry of all other species including complex organics**
  - **Traces basic processes of freeze-out onto grains and evaporation, which characterize different stages of evolution**
- **Astrobiology: water associated with life on Earth → characterize water 'trail' from clouds to planets, including origin of water on Earth**

pre-stellar cores → YSO's → disks → comets

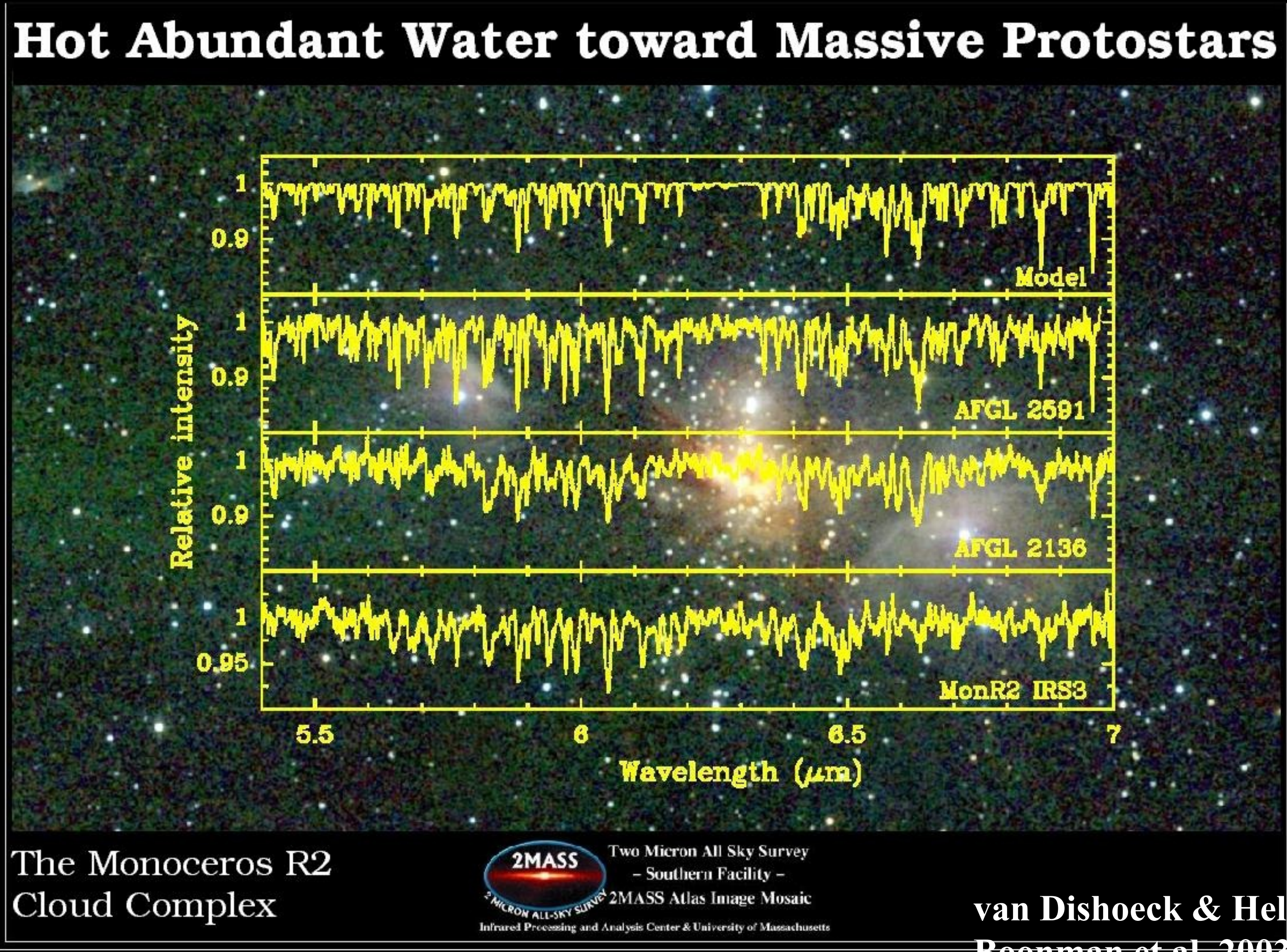


Building on the heritage of previous missions



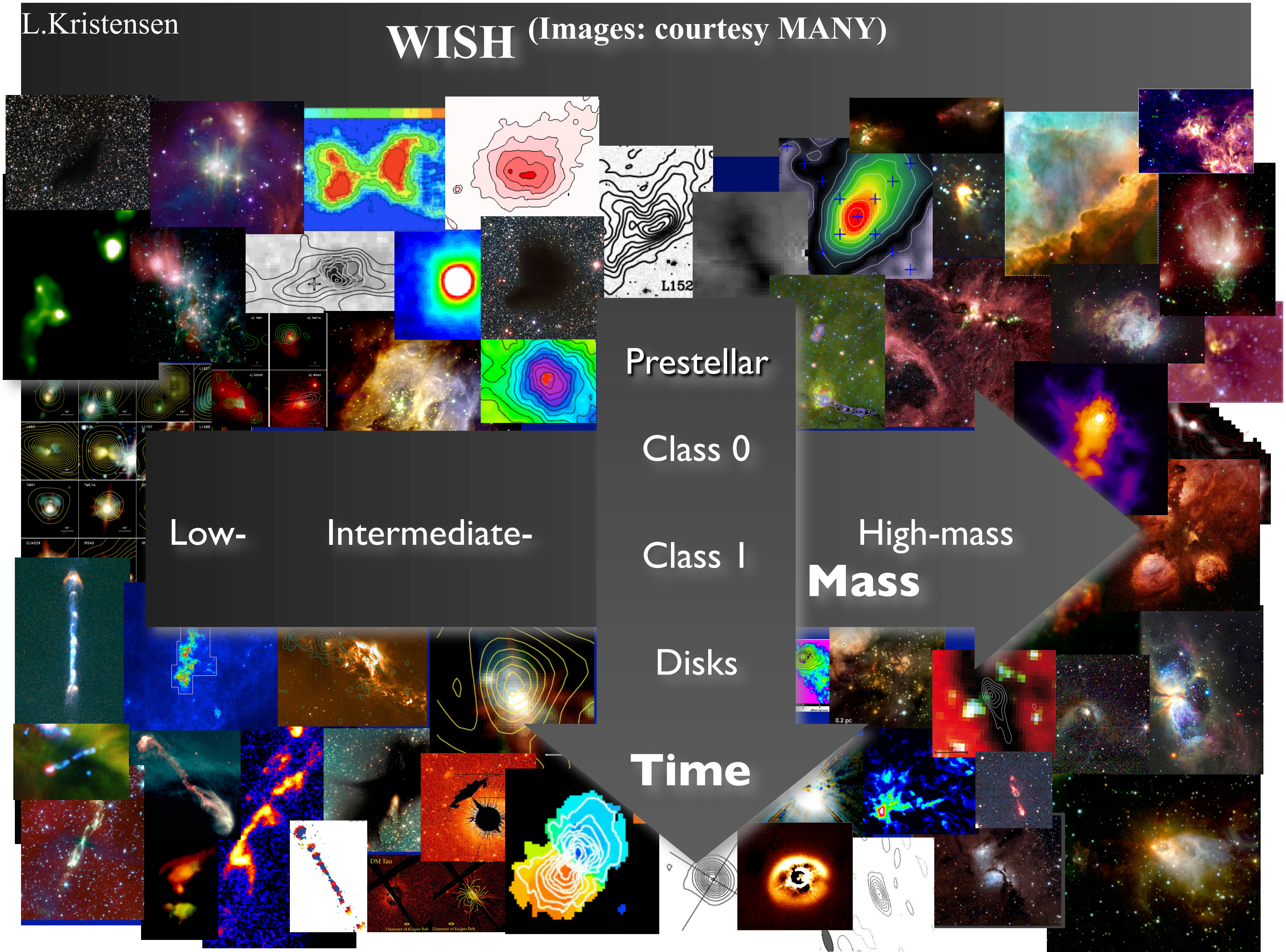
⇒ ***provides orders of magnitude increase in spatial and/or spectral resolution and sensitivity***

Hot cores probed by ISO-SWS 6 μm absorption

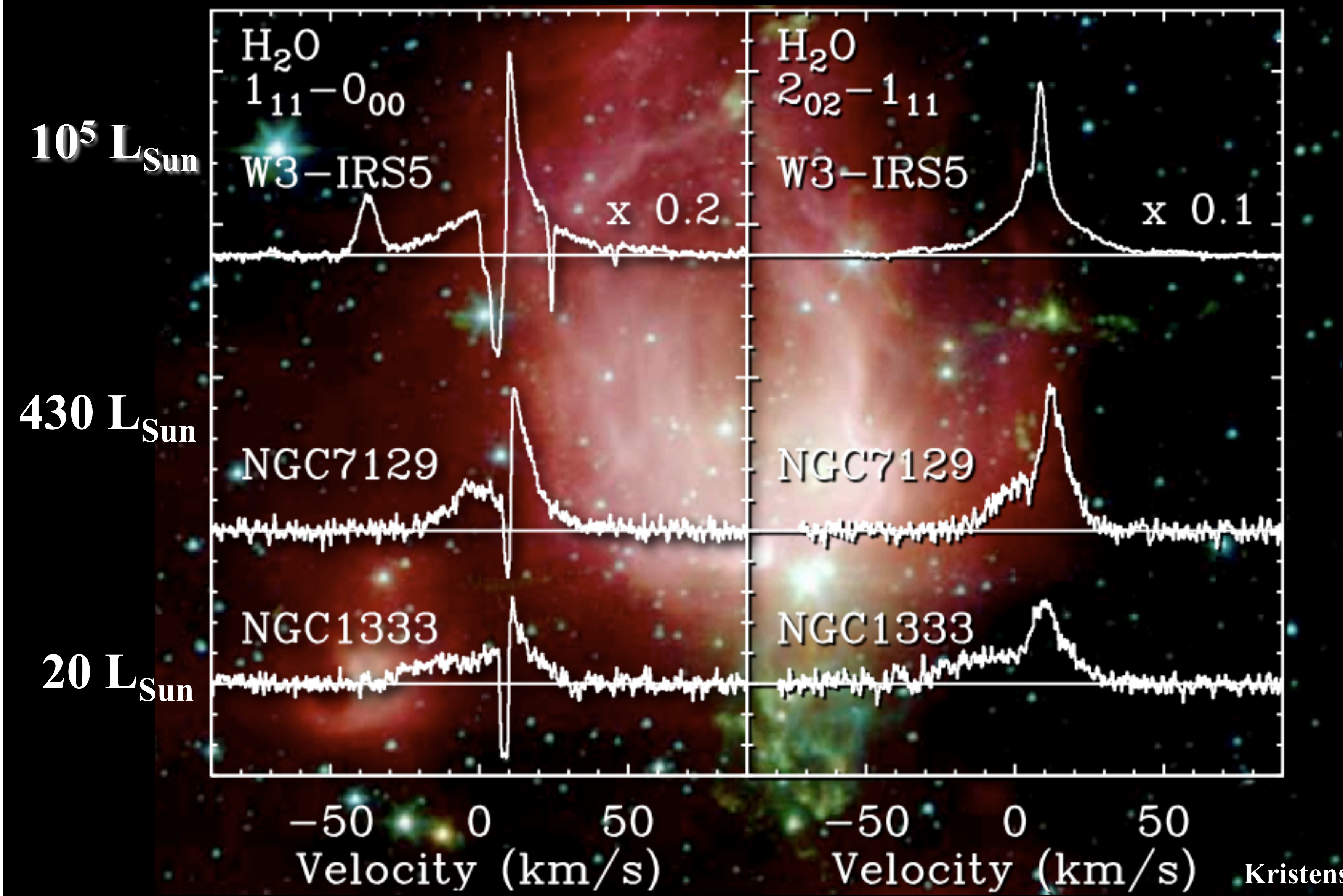


van Dishoeck & Helmich 1996
Boonman et al. 2003

Only JWST (and partly SOFIA) can do this


L.Kristensen
WISH (Images: courtesy MANY)
Prestellar
Class 0
Class I
Disks
Time
Low-
Intermediate-
High-mass
Mass
L152
DM Tau
0.2 pc

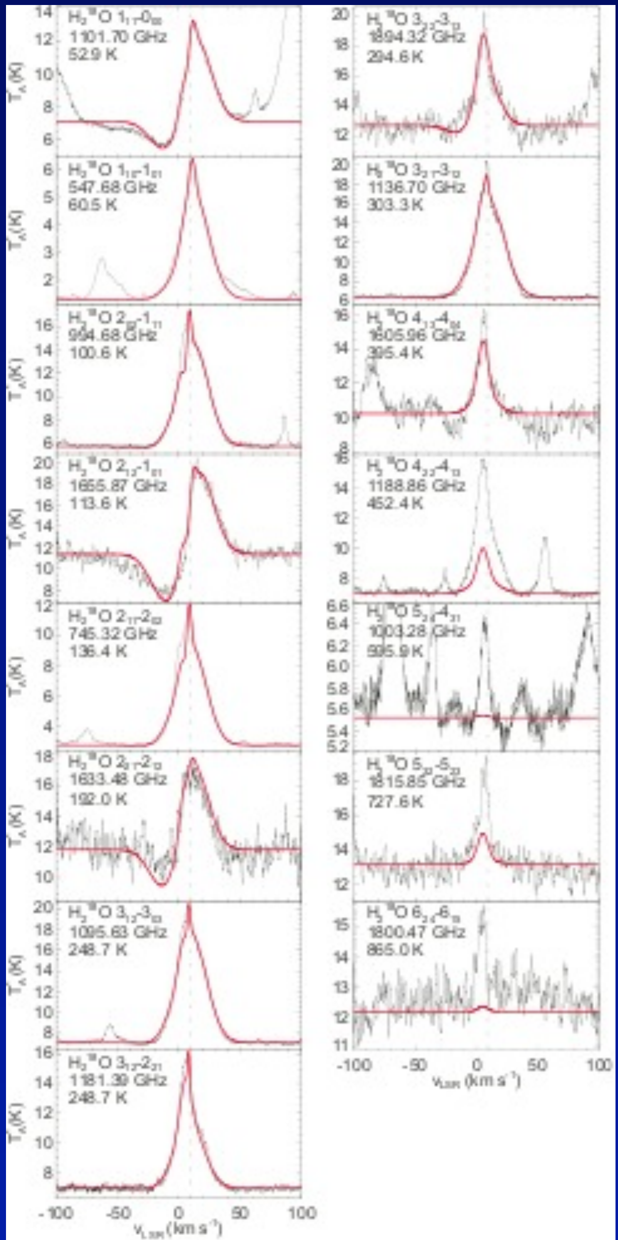
From low to high mass protostars



Note similar profiles: medium-broad and broad outflow components

Kristensen et al. 2010
Johnstone et al. 2010
Chavarria et al. 2010

Water in massive protostars



- DR 21 (OH): p-H_2O 1_{11}-0_{00} line
  - Foreground clouds, outer envelope, outflow
  - Van der Tak et al. 2010
- Orion: analysis of 15 $H_2^{18}O$ lines various components ⇒ H_2O/H_2 = (1-7)x 10^{-5}
  - Melnick et al. 2010
- NGC 6334 I: analysis of 12 H_2O, $H_2^{18}O$ and $H_2^{17}O$ lines
  - Foreground clouds: 10^{-8}
  - Hot core: ~2x10^{-6} (uncertain)
  - Outflow: 4x10^{-5}
  - Emprechtinger et al. 2010

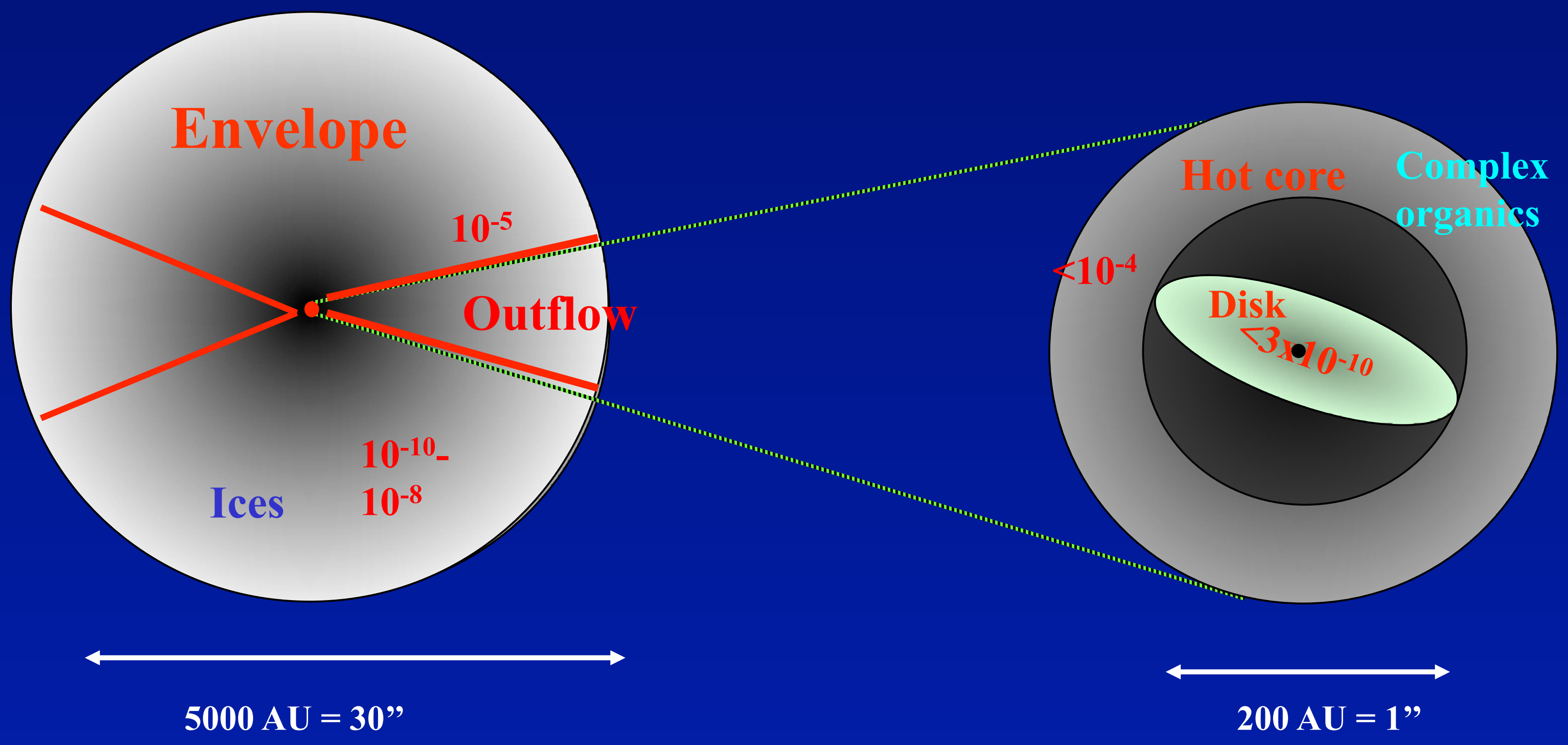
Also: Chavarria et al. 2010, Marseille et al. 2010

Water results

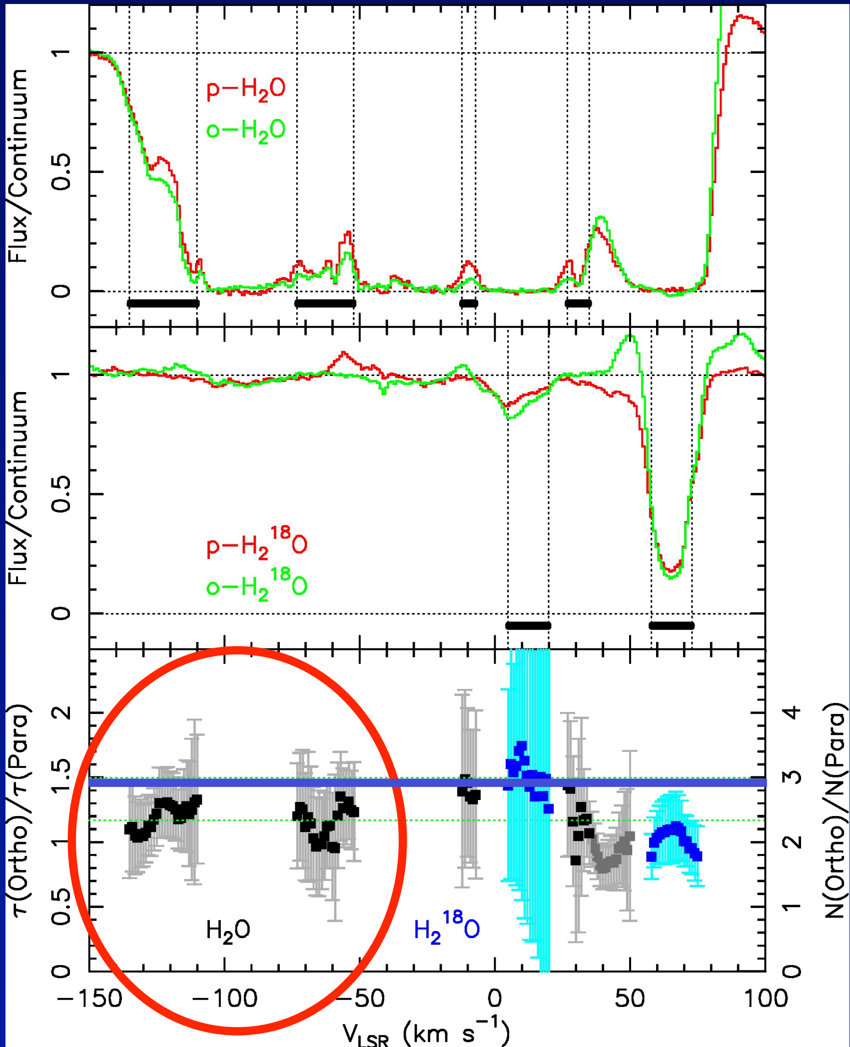
- **Gaseous water abundance in cold regions is very low: 10^{-8} or lower**
  - **Lower than thought before (unless 'dark')**
  - **Water (vapor) is *not* everywhere!**
- **Warm H_2O emission is dominated by shocks + UV photon heated component along outflow walls: $\sim 10^{-5}$**
  - **Hot cores only seen for a few massive YSOs: $<10^{-4}$**
- **Herschel CO and H_2O lines require models beyond spherical symmetry**

See talks Kristensen, Visser, …

Where is the water?



Water o/p ratio

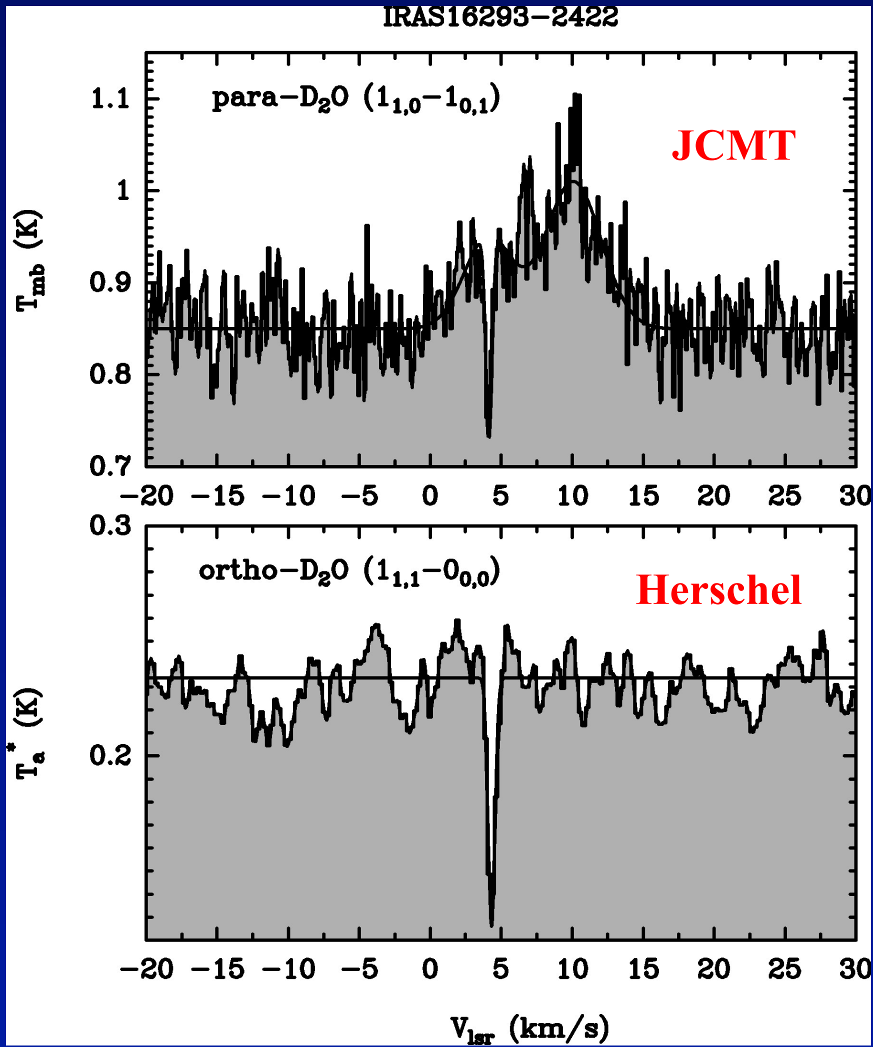


SgrB2(M)

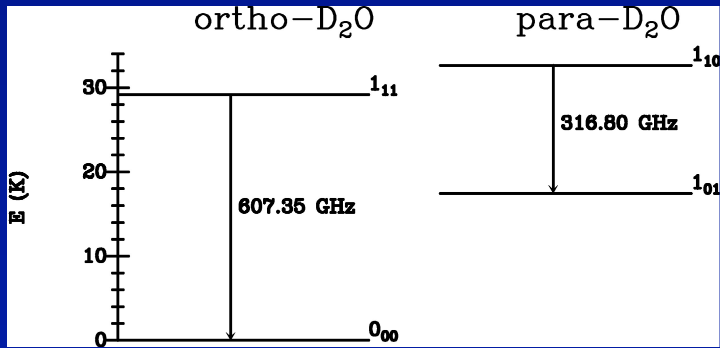
Lis et al. 2010

- **o/p ratio generally consistent with high temperature value of 3**
- **o/p=2.35±0.35 for expanding molecular ring ⇒ T_{spin}~27 K**

D_2O and H_2O^+ o/p ratio



- D_2O toward IRAS 16293
  - o/p=1.1 (<2.6) vs 2 statistically ⇒ T_{spin}>15 K
- H_2O^+ toward SgrB2(M) (Schilke et al. 2010)
  - o/p=4.8 ⇒ T_{spin}~21 K



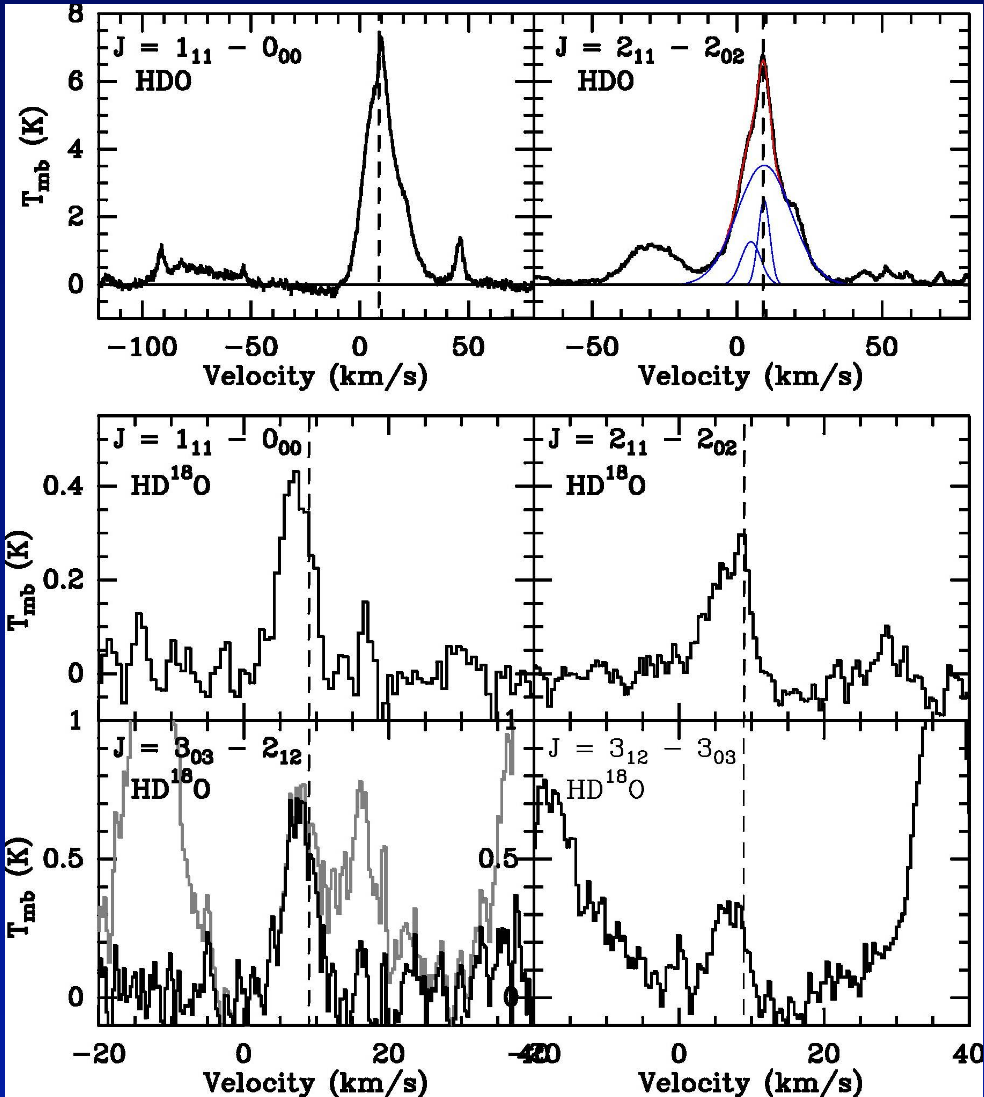
Vastel et al. 2010

Origin o/p ratio

- Exothermic reactions
  - e.g. $H_3O^+ + e \rightarrow H_2O$
- Gas-phase reactive collisions with H^+, H_3^+ or H
  - Timescale few x 10^5 yr
- Ice desorption
  - But excess energy shared with surface
- Equilibration at grain temperature
  - Mechanism not well understood (do not need magnetic interactions?) but can happen
  - Lab experiments under way in Paris, Japan

Good, but complicated molecular physics involved!

Detection $HD^{18}O$ in Orion



Use $HD^{18}O$ to better constrain HDO in Orion

$\Rightarrow HDO/H_2O = 0.01$

Consistent with Persson et al. 2007, but higher than previous estimates

Bergin et al. 2010

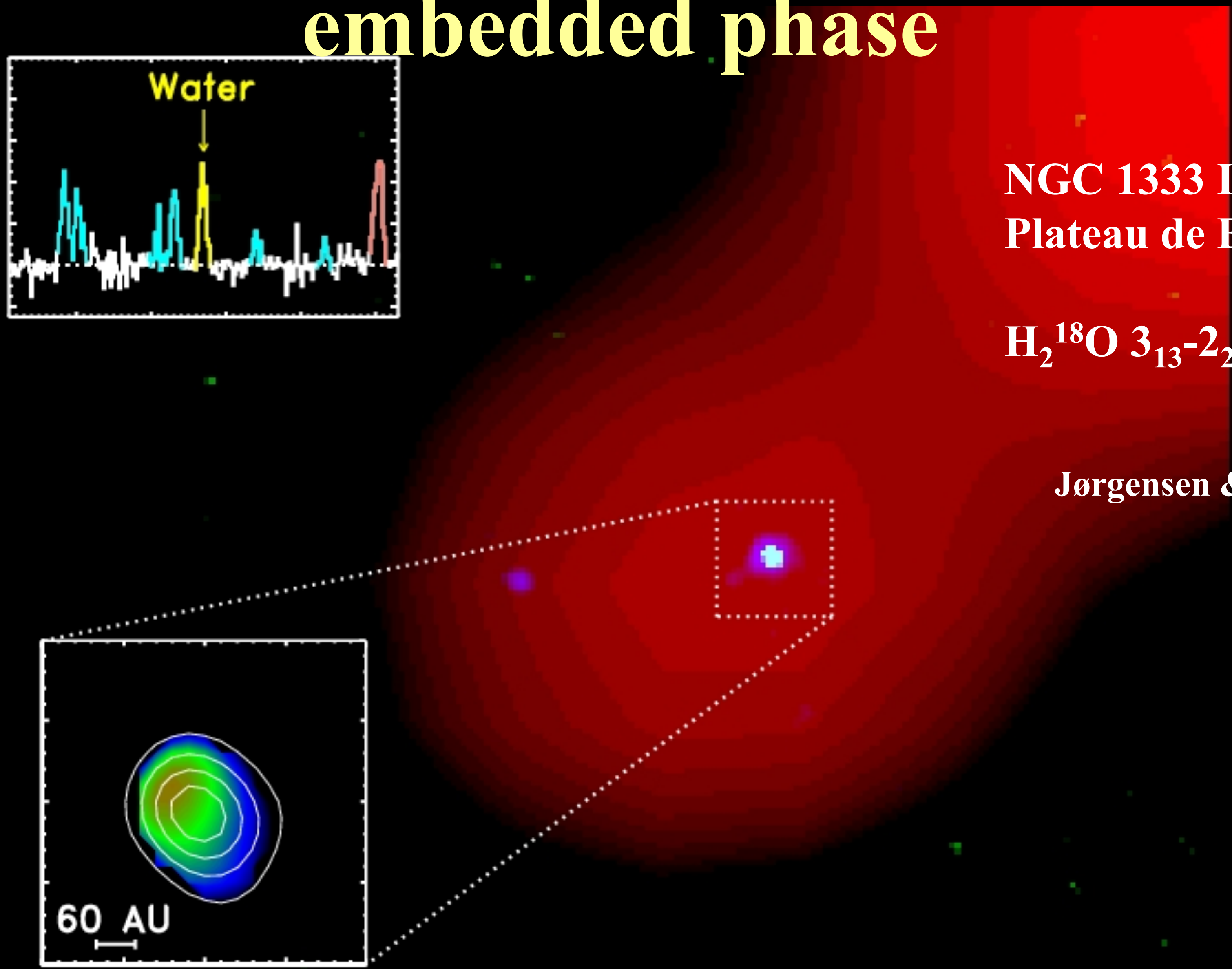
Puzzling HDO/H_2O ratios

- **High-mass hot cores: 0.01 vs. 0.001?**
- **Low mass protostars:**
  - **IRAS 16293 -2422: 0.03**
    - **Parise et al. 2005**
  - **NGC 1333 IRAS2A: 0.01**
    - **Liu et al. 2010**
  - **NGC 1333 IRAS4B: <0.0006**
    - **Jørgensen et al. 2010, see poster**

Probling is determining H_2O rather than HDO

see also Comito et al. 2010 for SgrB2(M)

Hot water in a disk in the deeply embedded phase



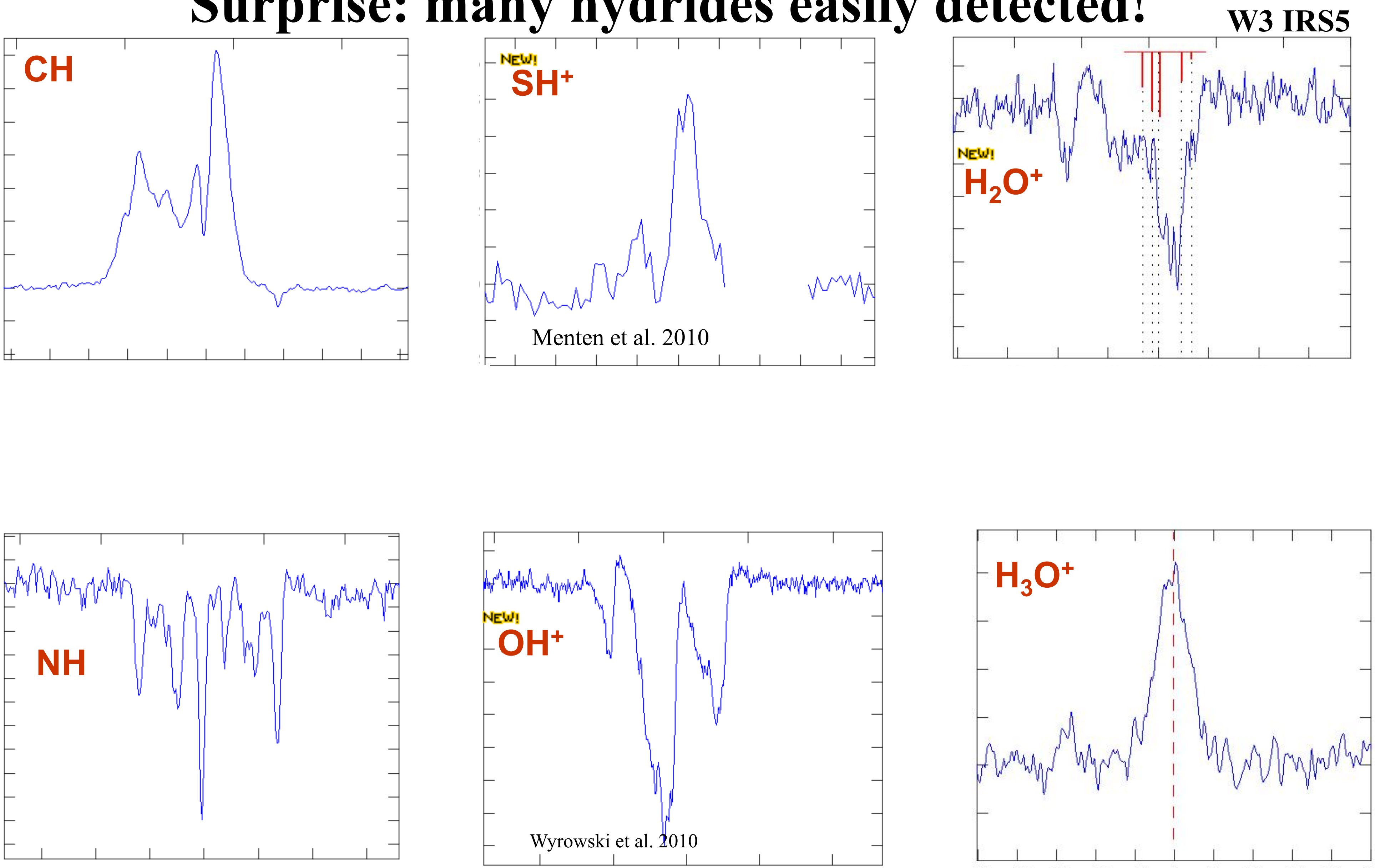
NGC 1333 IRAS4B
Plateau de Bure

$H_2{}^{18}O$ 3_{13}-2_{20} 203 GHz

Jørgensen & vD 2010

Interferometer can image water at 50-100 times higher angular resolution
HDO data available from SMA (Jørgensen et al., in prep)

Surprise: many hydrides easily detected!

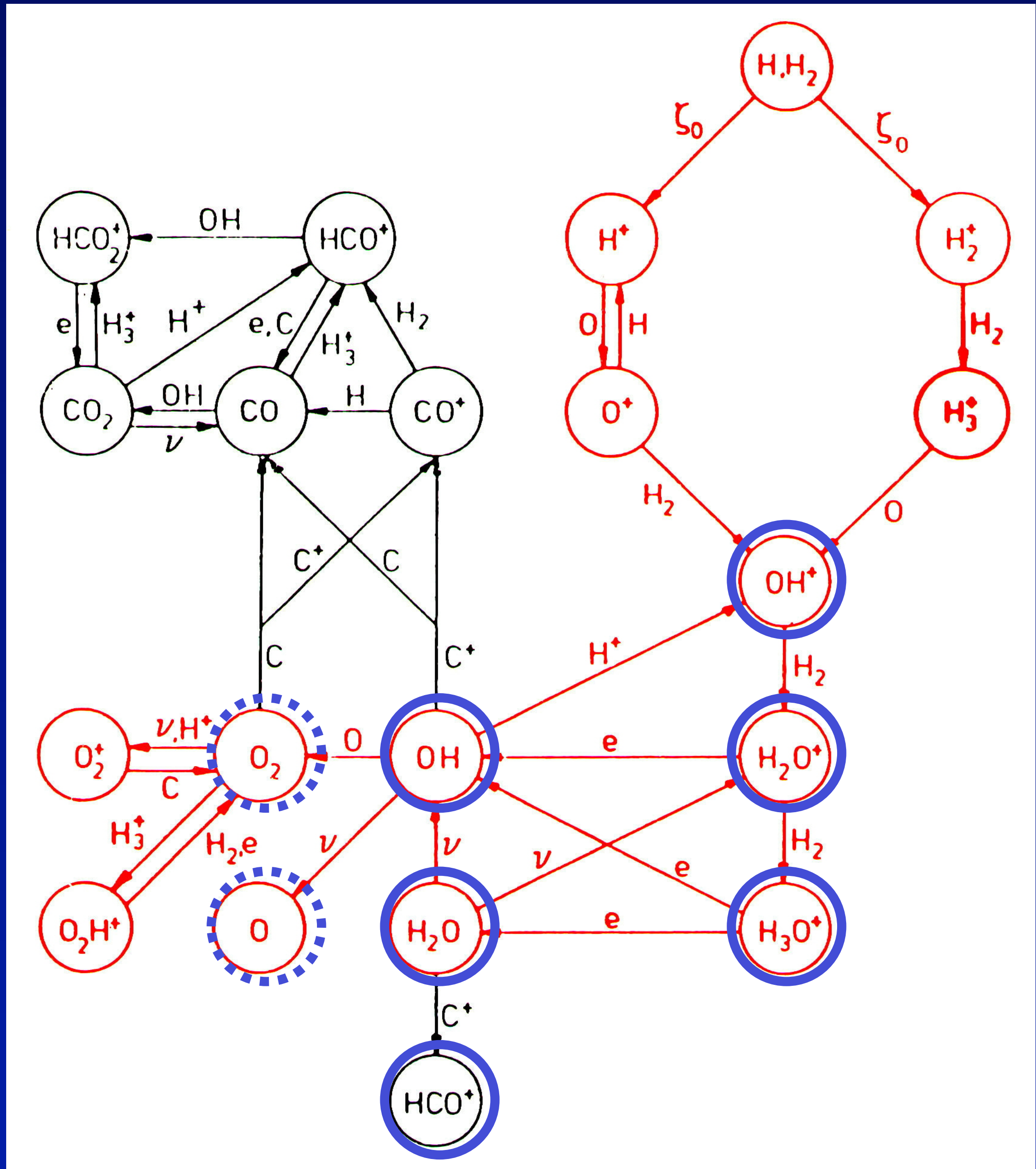


Also: HF: **Phillips, Neufeld et al. 2010**

H_2Cl^+: Neufeld et al. 2010

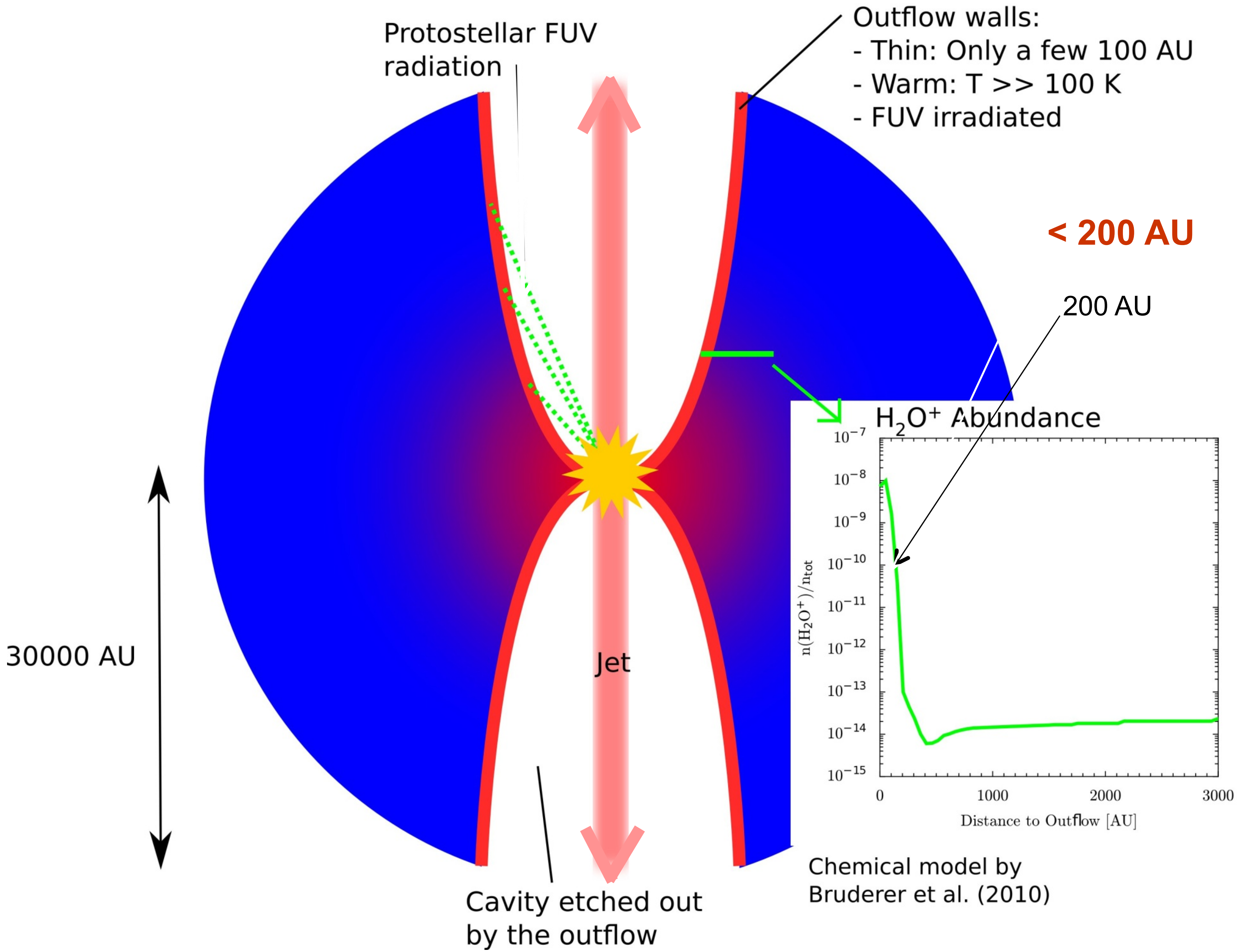
Benz et al. 2010

All key species in oxygen chemistry detected!



Widespread H_2O^+

- Widespread H_2O^+ and OH^+ observations, from diffuse clouds to massive star-forming regions
    - Gerin et al. 2010, Ossenkopf et al. 2010, Bruderer et al. 2010, Benz et al. 2010, Wyrowski et al. 2010, Neufeld et al. 2010, Schilke et al. 2010, Gupta et al. 2010
  - Even seen in SPIRE-FTS external galaxies
    - Van der Werf et al. 2010
  - H_2O^+ columns are largest in outflow sources, no H_2O^+/H_2O trends
    - Wyrowski et al. 2010
- Diffuse clouds: gas with low H_2/H ratio (low *n*, high G_0)
  - Gerin et al. 2010
  - Link with CH^+ mystery?
- Dense clouds: UV-heated outflow cavity walls
  - Bruderer et al. 2010



H_2O^+, OH^+, CH^+, and SH^+ are the paint on the outflow wall

Conclusions

- Herschel is producing fantastic data
- Water and other molecules abundantly seen
- Physical structure
  - Cooling budget
  - Importance of outflows
  - Multi-D models needed
- Chemical structure
  - Oxygen network, including hydride ions (H_2O^+): roots of the chemistry
  - Water abundance variations
  - HDO/H_2O
  - Complex organics: precision analysis, new species?
- Strong synergy with other facilities: Spitzer, ALMA, …