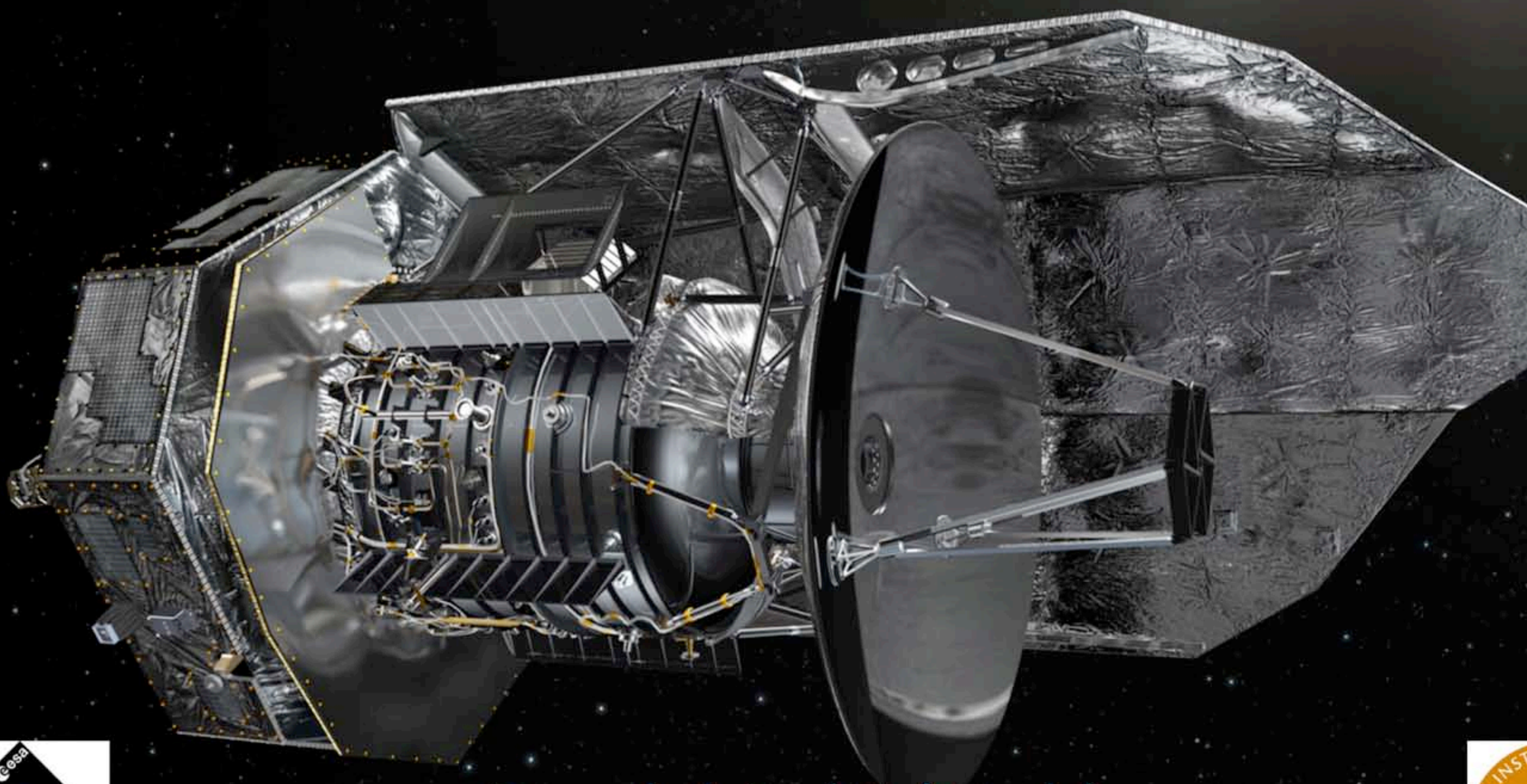
Star Formation and ISM:
The Herschel View



Darek Lis (Caltech)

Ithaca, November 13, 2010

Outline

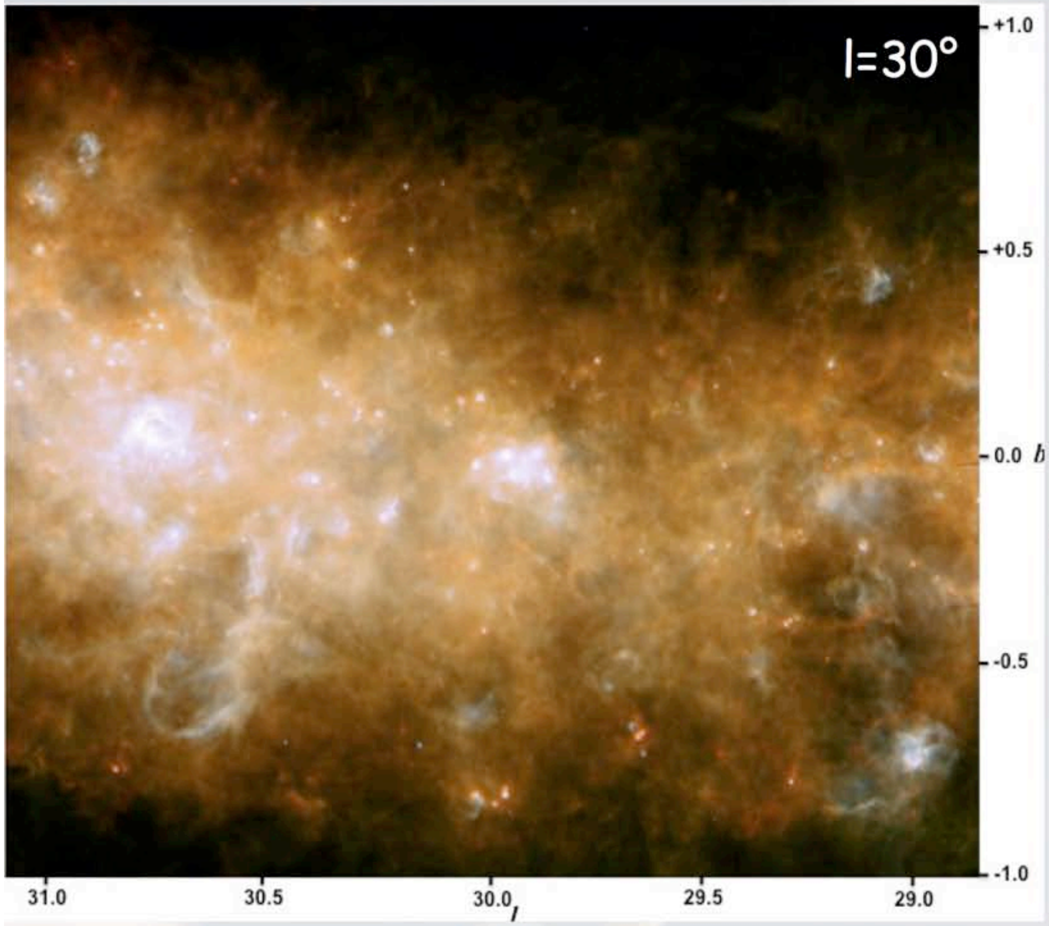
- Herschel was launched on May 14, 2009 and has been producing science data since summer 2009
- Early science results were presented at the *Herschel First Results Symposium at ESTEC* in May 2010 and published in the A&A Letters *Herschel* and *HIFI Special Issues* (Vol. 518 and 521)
- This talk: selected star formation (high-mass) and ISM highlights from the Science Demonstration Phase (SDP)
- SDP goal: demonstrate Herschel capabilities and show what can be expected when all observations from the approved GT and OT KPs are fully analyzed
- Start with imaging, move to spectroscopy
- Based on results from Hi-GAL, HOBYS, Gould Belt, HEXOS, WISH, CHESS, PRISMAS, GASPS KPs

Herschel Space Observatory

- ESA cornerstone mission; first space facility to completely cover the 60–670 μm spectral range
- Telescope: 3.5 m diameter, passively cooled to ~80 K
- Orbit: Lissajous around L2; very stable and low background
- Larger telescope than other missions (IRAS, ISO, SWAS, Spitzer, Akari…)
- Colder aperture, better 'site', more observing time than balloon and airborne instruments
- Lifetime: >3 years (until early 2013)
- Three cryogenically cooled instruments, PACS, SPIRE (bolometers), and HIFI (heterodyne)
- All three instruments have spectroscopic capabilities

http://herschel.esac.esa.int/overview.shtml

Wide-Field Imaging Surveys

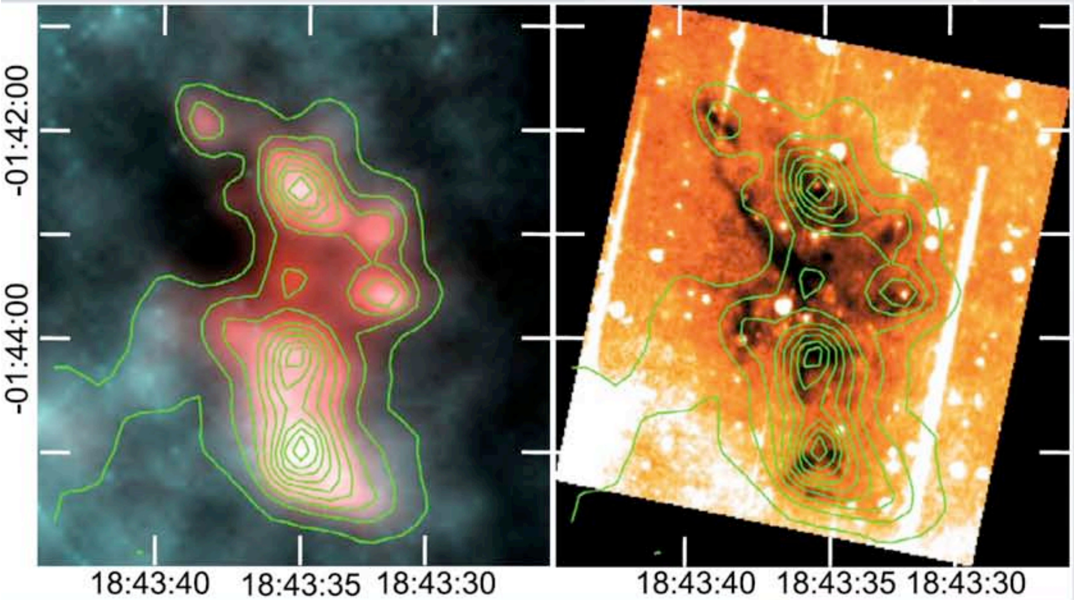


Blue 70 μm; Green 160 μm; Red 350 μm

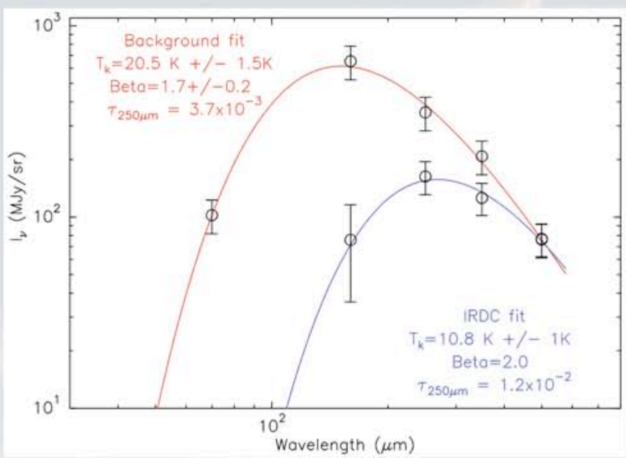
Molinari et al. 2010, A&A 518, L100

- Hi-GAL (PI. S. Molinari): mapping of the inner Galactic plane in 5 PACS and SPIRE bands (70–500 μm)
- Goals: study star formation over a full range of galactocentric radii, metallicities, and environmental conditions; distribution of cold dust in the galactic plane
- Two 2×2° fields at l=30° and 59° observed in the SDP
- Condensation of diffuse clouds into an extensive pattern of filaments
- Compact sources distributed mostly along brightest filaments
- Filaments fragment into cores where the column density has reached a critical level, A_V~1 (H_2 self-shielding)
- No apparent correlation between core mass and filament column density

IRDCs

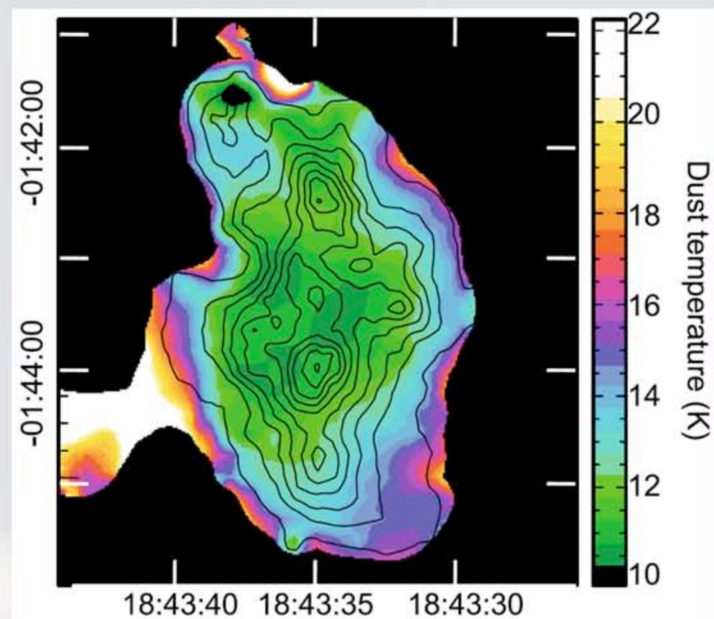


Left: 160 and 250 μm; Right: Spitzer 8 μm

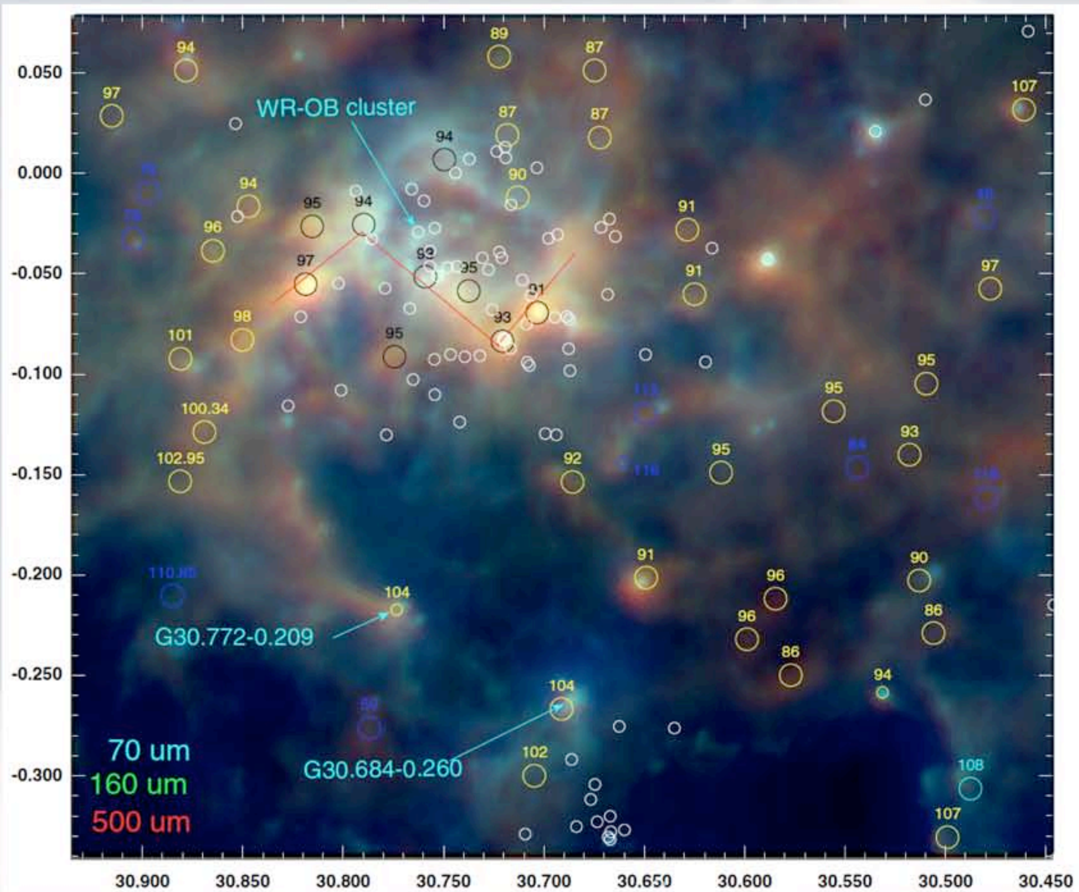


Peretto et al. 2010, A&A 518, L98

- Cold and dense reservoirs of gas potentially available to form (massive) stars
- Hi-GAL goal: construct and analyze accurate column density and temperature maps of IRDCs
- Pixel-by-pixel SED fitting method; a sample of 22 IRDCs in the SDP fields
- Dust temperature decreases significantly within IRDCs, from 20–30 K to 8–15 K in the interiors



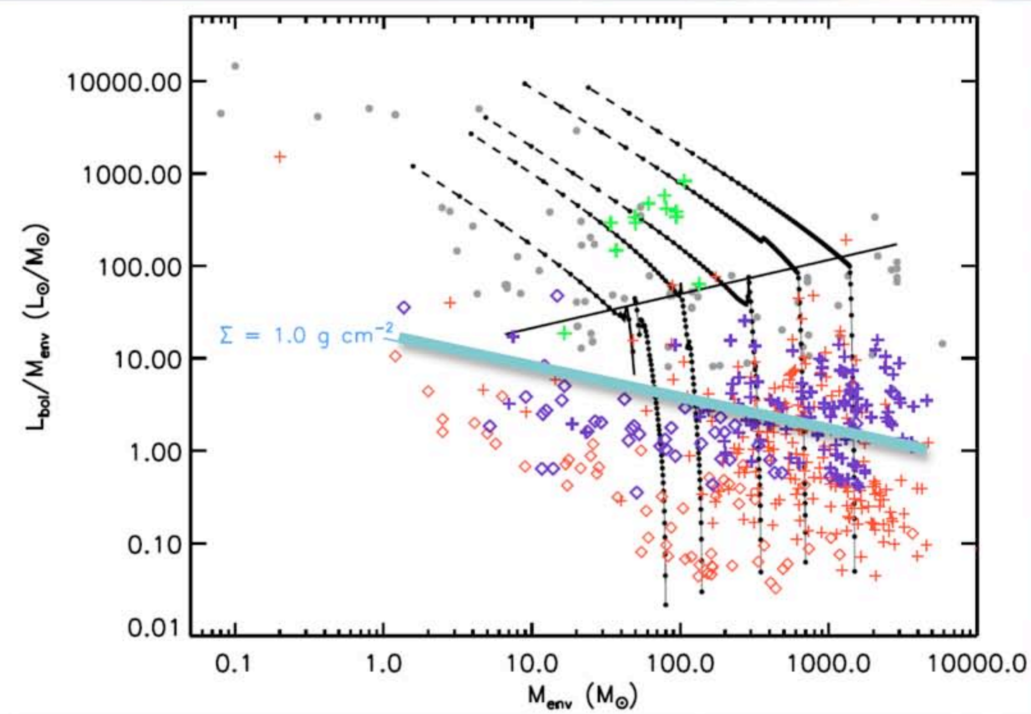
W43 Mini-Starburst



- One of the most luminous star forming complexes in the Galaxy
- Complex resolved into a dense cluster of protostars, IRDCs, and ridges of warm dust heated by massive stars
- A dozen embedded massive protostars with $L>10^4\ L_\odot$ which contribute only ~5–8% of the total FIR luminosity ($3.6\times10^6\ L_\odot$)
- Total mass ~$10^6\ M_\odot$
- Cometary dust clouds, compact 6 cm sources (white circles) and warm dust mark the locations of older populations of massive stars
- Energy release has created a cavity blowing out below the galactic plane

Bally et al. 2010, A&A 518, L90

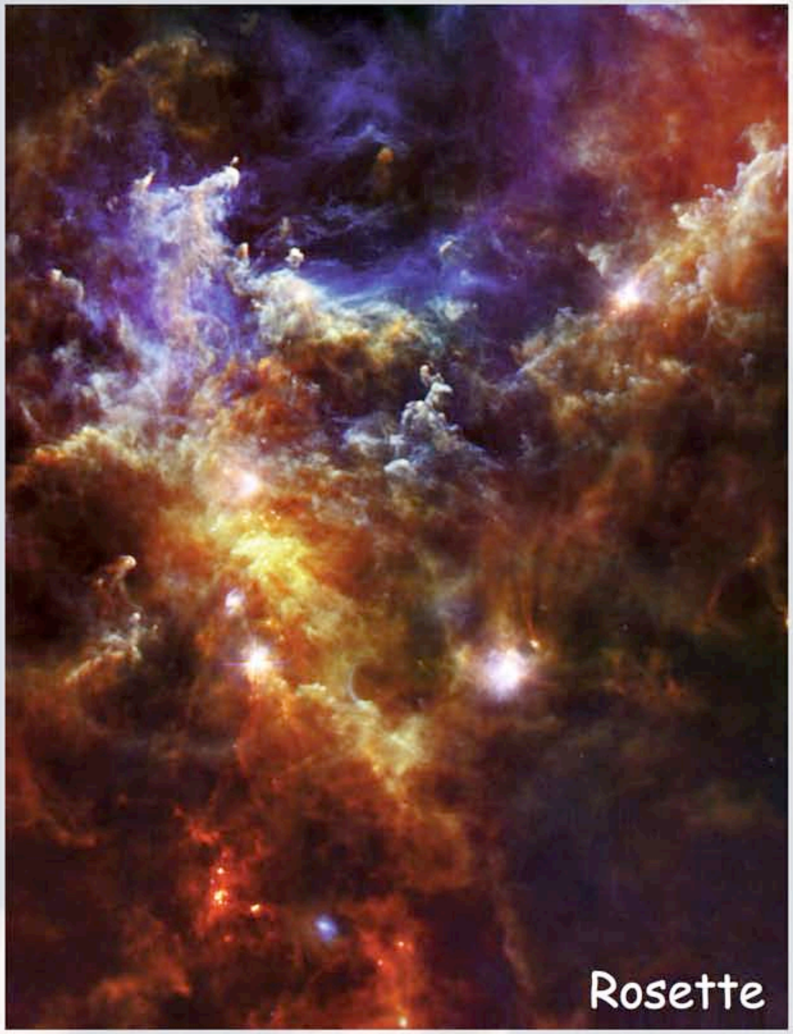
Compact Sources in Hi-GAL Fields



Crosses l=30°, diamonds l=59°
Blue and red: Robitaille et al. and SED models
Green: compatible with a central ZAMS star
Elia et al. 2010, A&A 518, L90

- 528 and 444 sources in the l=30° and 59° fields
- SED modeling: mass, luminosity, temperature, dust properties
- L_{bol}/M_{env} vs. M_{env} compared to collapse models in turbulence-supported cores (McKee & Tan 2003)
- Most points in the accretion phase (vertical part)
- Clear distiction between l=30° and l=59° fields
- Distance effects, but almost all sources from l=59° have luminosities below 10^3 $L_\odot$ despite a wide range of masses
- Global difference between the two populations—star formation at a more advanced stage in the l=30° field?
- Most cores have surface densities well below the critical value of 1 g cm^{-2} (Krumholtz & McKee 2008)

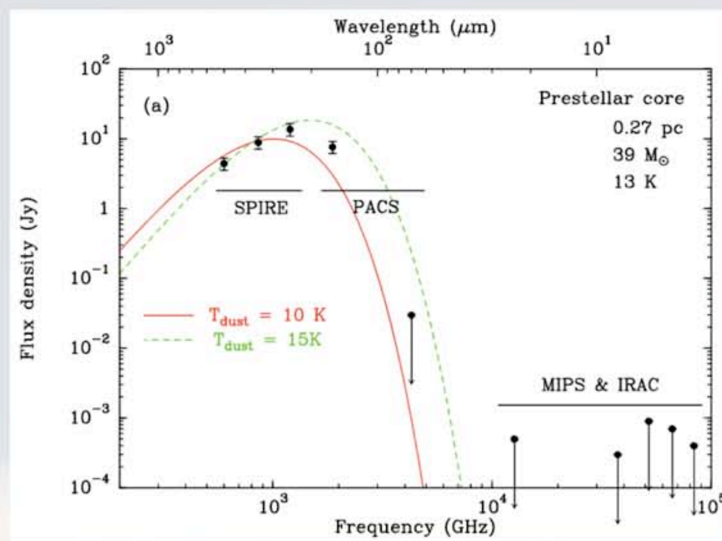
Imaging Survey of OB YSOs



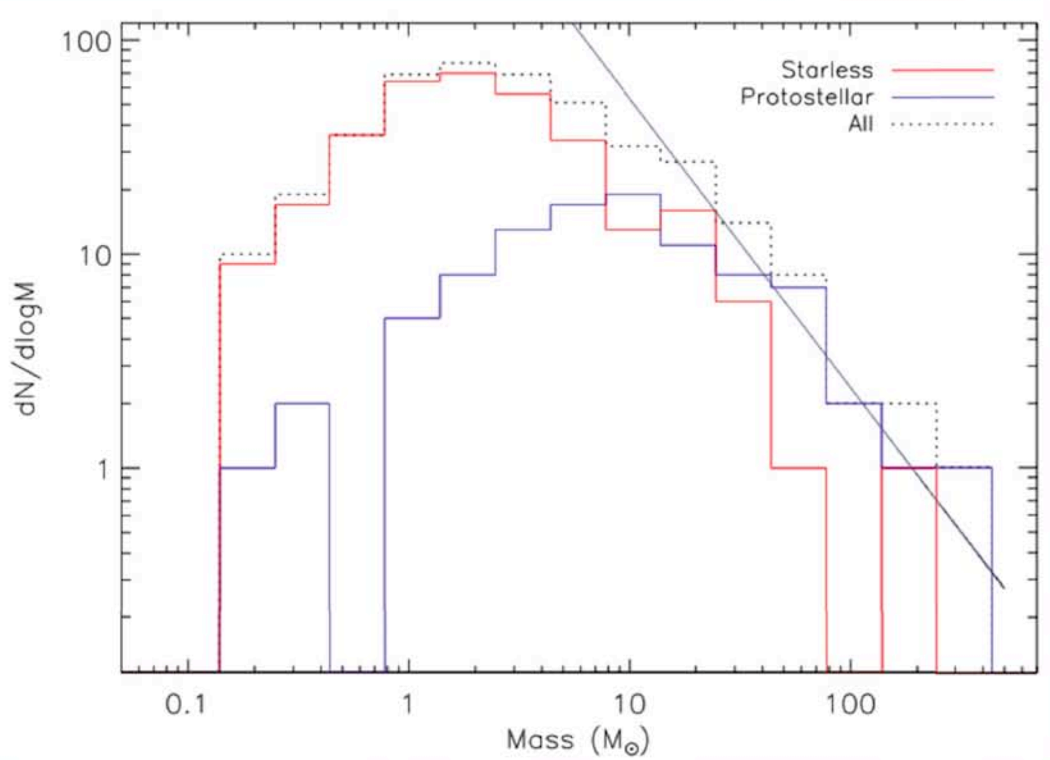
Blue 70 µm, green 160 µm, red 350 µm

Motte et al. 2010, A&A 518, L77

- HOBYS (PI. F. Motte): all OB complexes within 3 kpc
- How do high-mass stars form: quasi-static or dynamic scenario? Accretion or coalesence?
- SDP: Rosette molecular complex and RCW120 HII region
- Rosette: ~4000 sources at 70 µm and 900 at 500 µm
- SEDs, bolometric luminosities
- 6 protostellar and 3 prestellar cores, ~20–40 $M_\odot$; survey complete to ~8$M_\odot$



Rosette—Compact Sources



Blue: protostellar; Red: starless

Di Francesco et al. 2010, A&A 518, L91

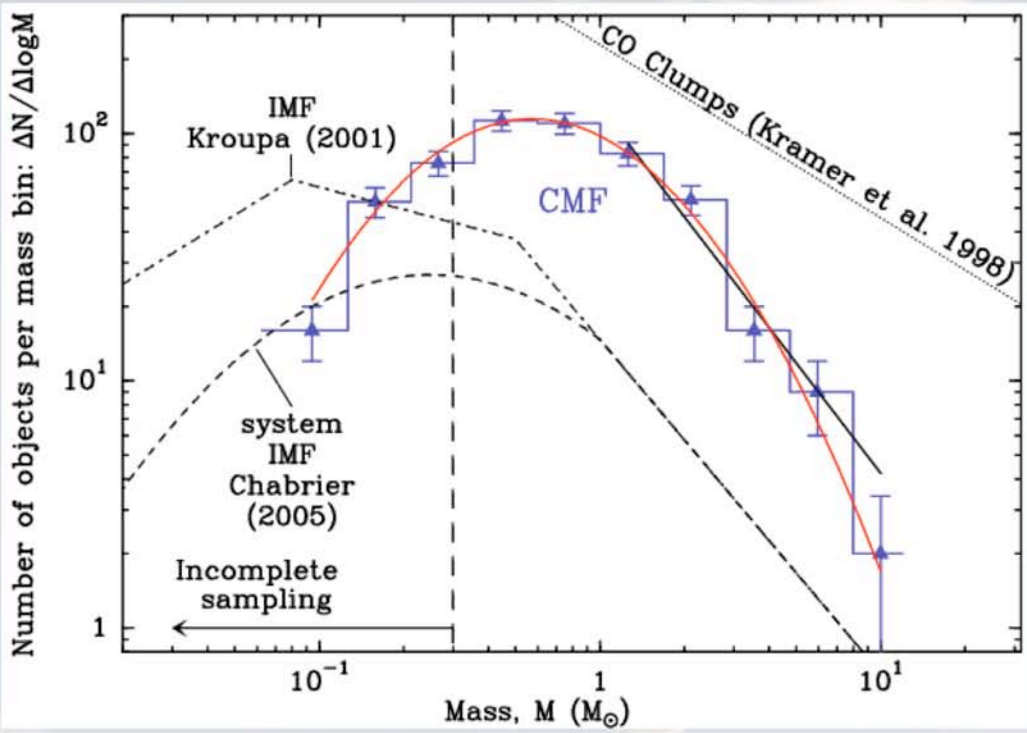
- Identified 473 clumps, with sizes up to ~1 pc, using a new structure identification algorithm
- 371 starless, 102 protostellar
- $-0.75 \leq \log (M_c/M_\odot) \leq 2.5$
- Clump mass spectra have slopes consistent with those found for high-mass clumps identified in CO emission
- Slope: -0.65±0.01 (-0.8 Dent et al. 2009 CO 3–2; -0.6 Schneider et al. 1998 CO 2–1)
- Starless and protostellar clumps have similar slopes, but over a different mass range
- *Herschel unable to resolve individual cores at 1.6 kpc?*

Gould Belt Survey

Aquila, 11 deg^2, PACS/SPIRE 70/160/500 μm
Andre et al. 2010, A&A 518, L102

- Gould Belt: a giant (0.7×1 kpc) flat structure inclined ~20° to the Galactic plane
- Nearest cloud complexes in the Galaxy (d≤0.5 kpc)
- Herschel angular resolution adequate for probing 0.01-0.1 pc star-forming cores
- Aquila rift and Polaris Flare observed in SDP
- Complex networks of long, thin filaments form first within molecular clouds
- Densest filaments fragment into cores via gravitational instability

Aquila—Compact Sources

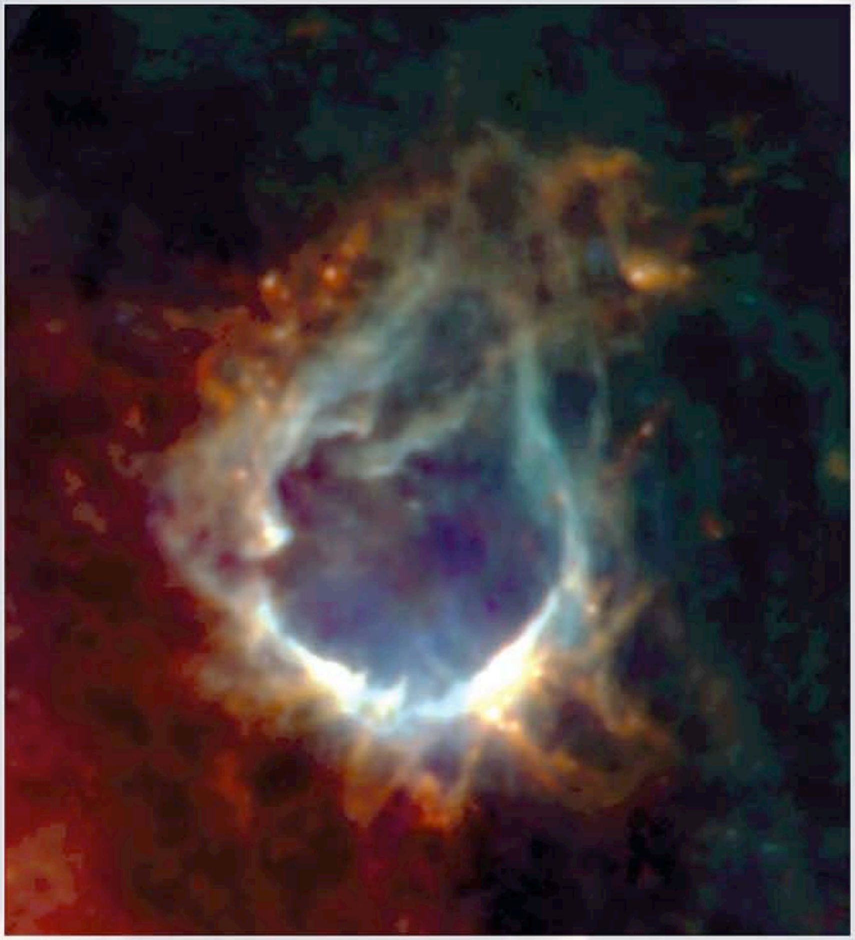


Blue: observed CMF; Red: lognormal fit; Black: power-law fit

Andre et al. 2010, A&A 518, L102

- ~350-500 prestellar cores and ~45-60 class 0 protostars identified in the Aquila field
- ~300 unbound starless cores and no protostars observed in the Polaris field
- Prestellar core mass function in Aquila bears strong resemblance to the stellar IMF
- Power-law fit to the high-mass end gives a slope of -1.5±0.2 (Salpeter -1.35)
- Much steeper than the slope derived from CO clumps
- Is the difference between the CMF in Rosette and Aquila simply a distance effect (260-400 pc vs. 1.6 kpc)?
- Need a factor of ~6 improvement in angular resolution (25/3.5=7!)

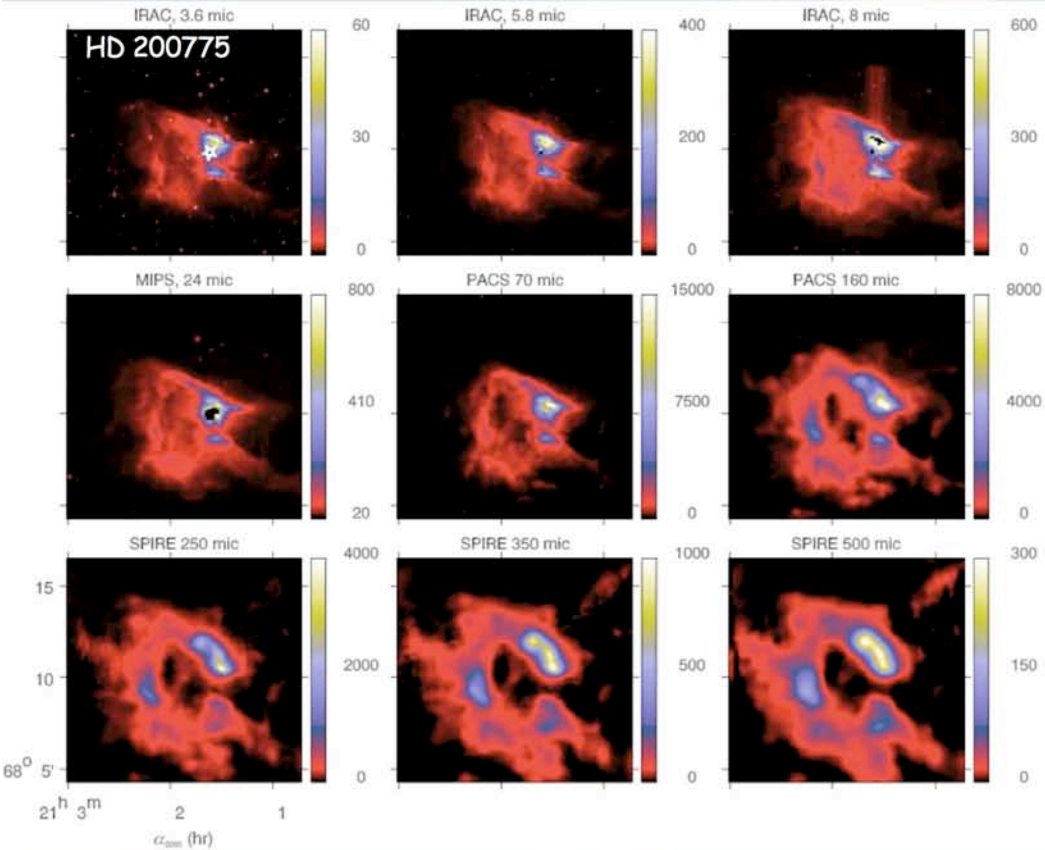
RCW 120



Blue 70 µm; Green 160 µm; Red 350 µm
Zavagno et al. 2010, A&A 518, L91

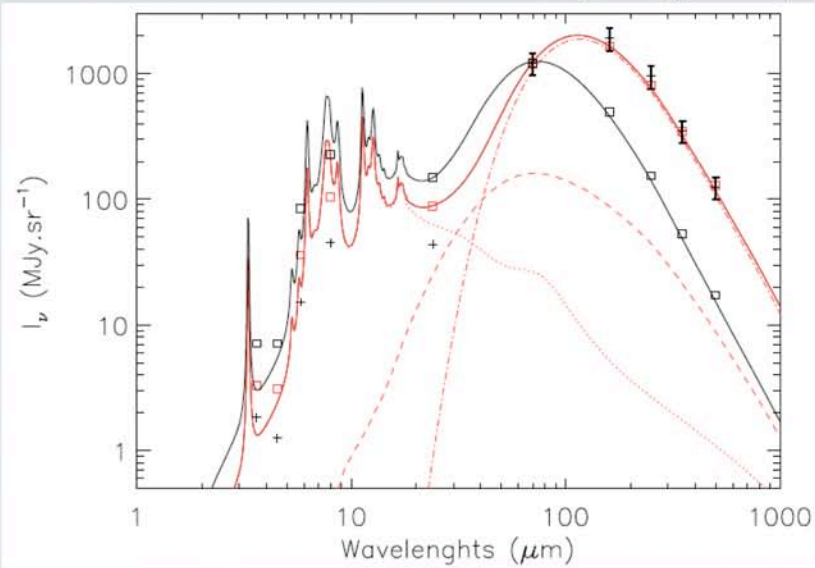
- Bubble-shaped HII region, 1.3 kpc from the Sun
- PACS and SPIRE images reveal a population of embedded YSOs
- They confirm the existence of an 8–10 $M_\odot$ YSO, surrounded by a massive (10^3 $M_\odot$), cold (18 K) envelope with a high accretion rate (10^{-3} $M_\odot$ yr^{-1})
- Stellar ages of the detected sources span between 10^3 and 5×10^4 yr (SED fits), well below the 2.5 Myr age of the RCW120 ionizing star
- Many sources detected are far away from the ionization front—triggered star formation by means of tunneling of radiation from the ionizing star into the ambient medium

Evolution of Interstellar Dust



Abergel et al. 2010, A&A 518, L96

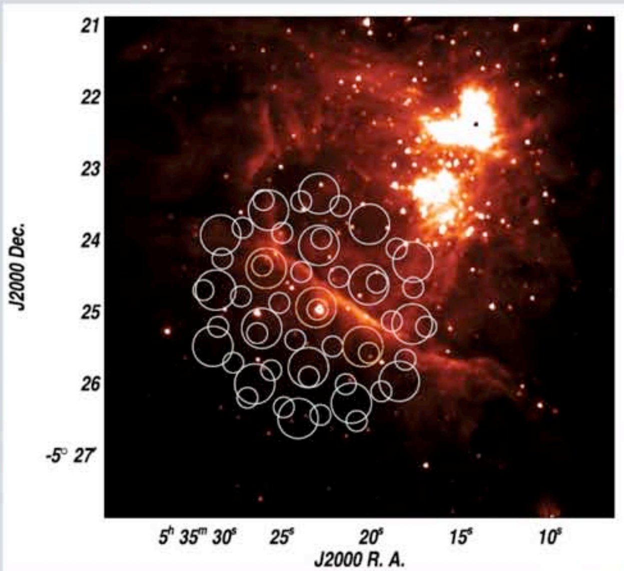
- FIR to submm emission properties of dust particles in a wide range of galactic environments (PI A. Abergel)
- Focus on PDRs; SDP—NGC 7023 (3 edge-on PDRs)
- Combination of SPIRE, PACS and Spitzer data provides full emission spectra of all dust particles that can be compared with radiative transfer models (PAHs, VSGs, BGs)
- Possible variations in β? (β–T)

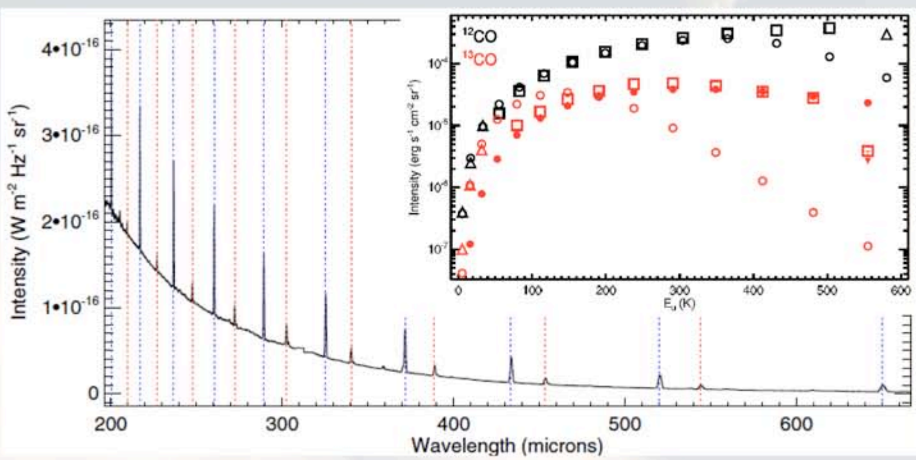


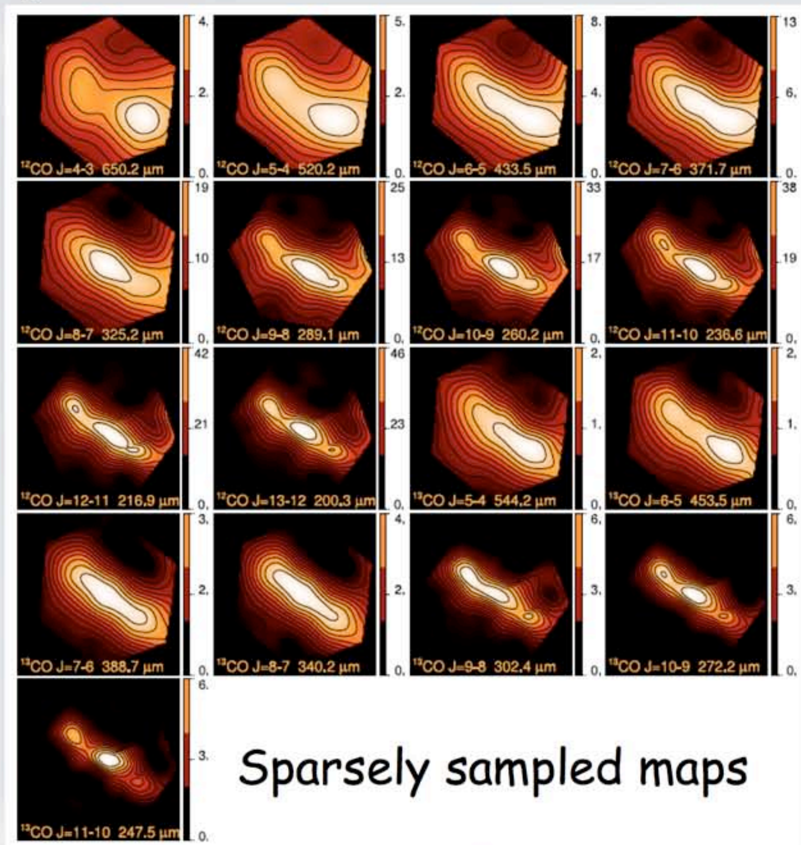
Black: DUSTEM + diffuse ISM dust grains
Red: different source geometry

SPIRE Spectroscopy

- SPIRE FTS: 19 pixel SLW array (303–671 µm), 37 pixel SSW array (194—313 µm); R~1000
- Orion Bar PDR: CO rotational ladder J=4–3 to J=13–12 + isotopologues, CH^+, H_2O, H_2S, HCO^+, HCN, CN, C_2H...
- Dense, warm (100–150 K) component required to reproduce $J_u \geq 9$ line intensities



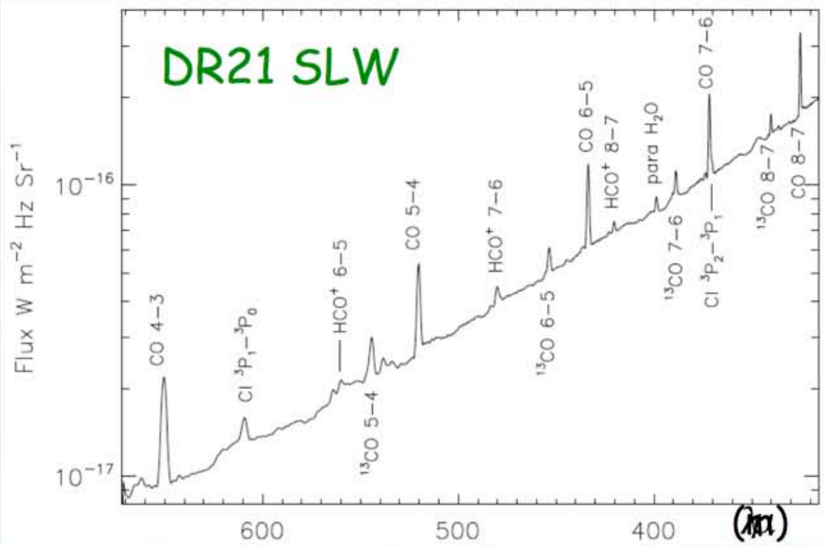


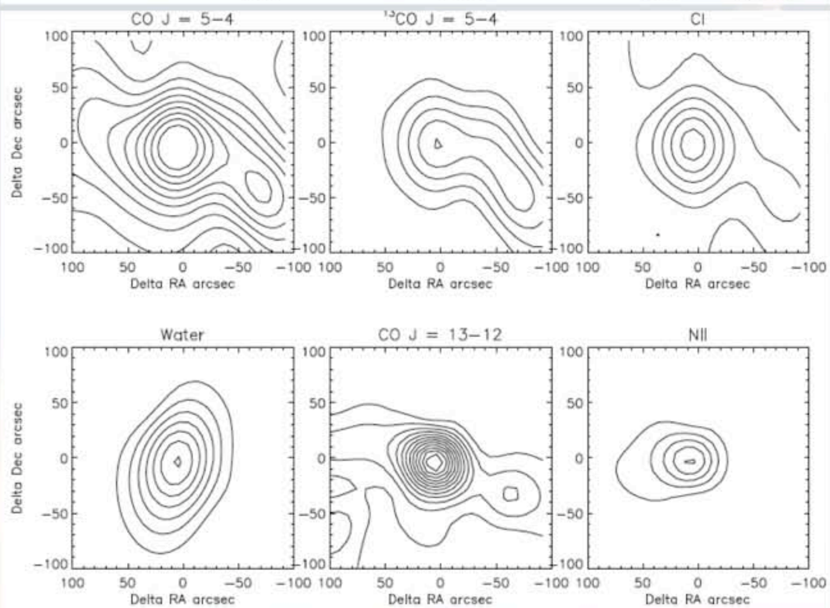


Sparsely sampled maps

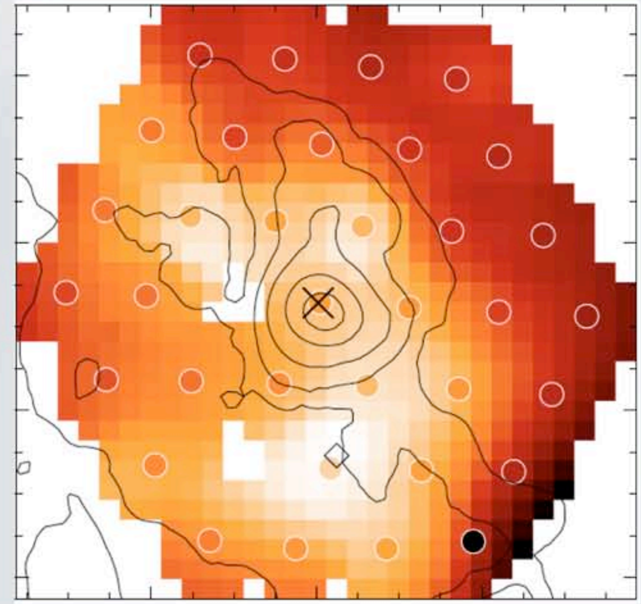
Habart et al. 2010, A&A 518, L116

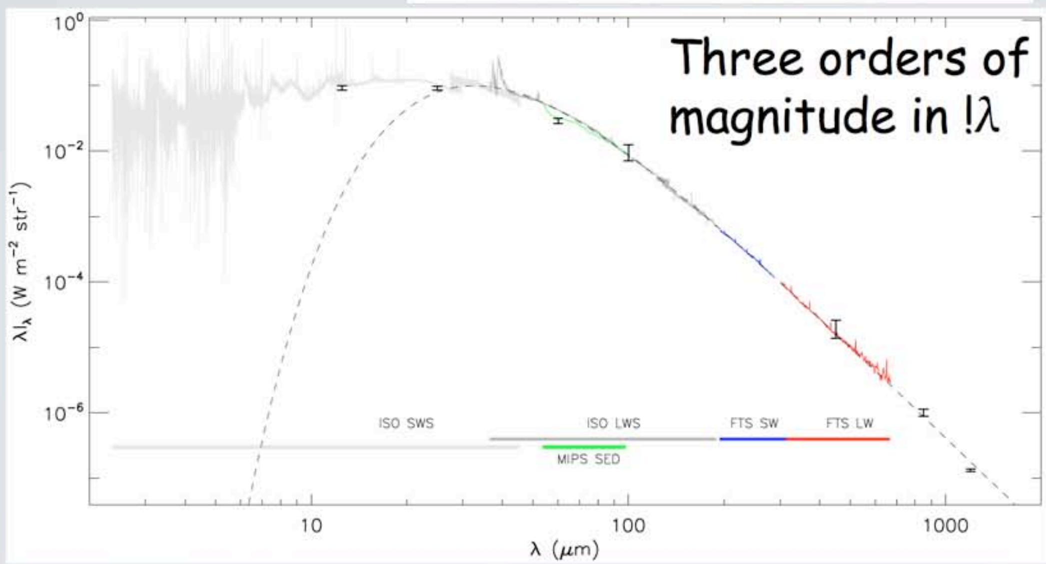
DR21 and G29.96-0.02





G29 [NII]
(850 µm)

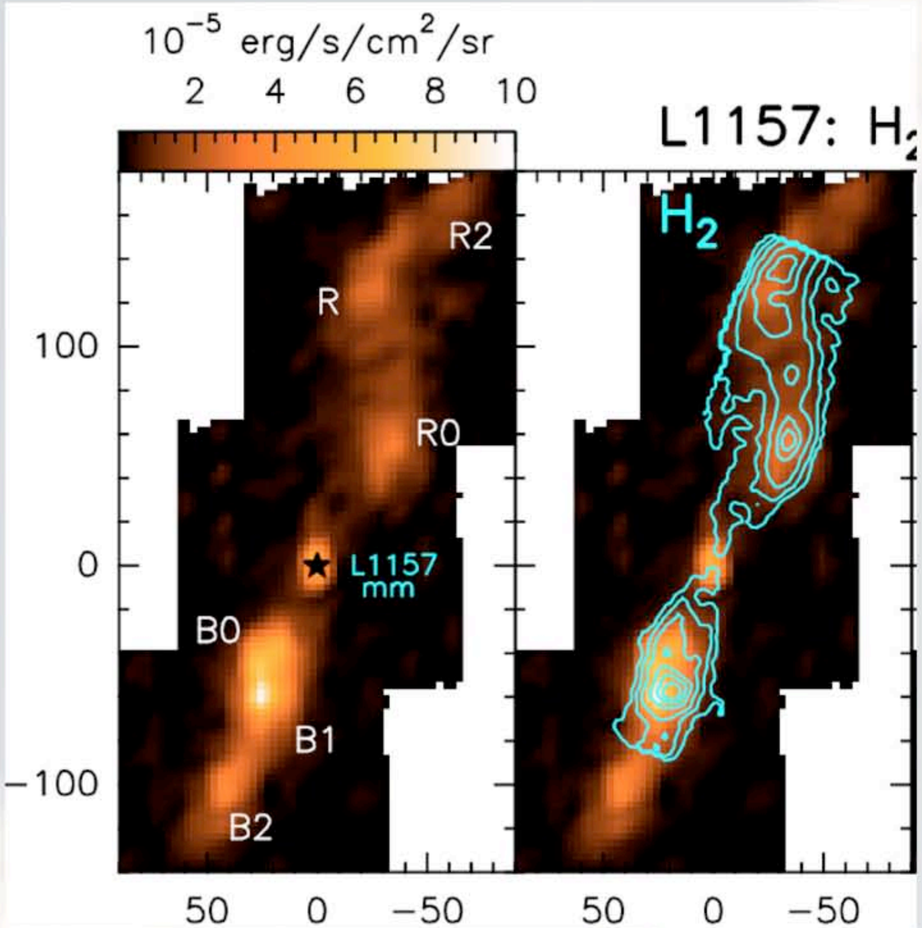




White et al. 2010, A&A 518, L114

Kirk et al. 2010, A&A 518, L82

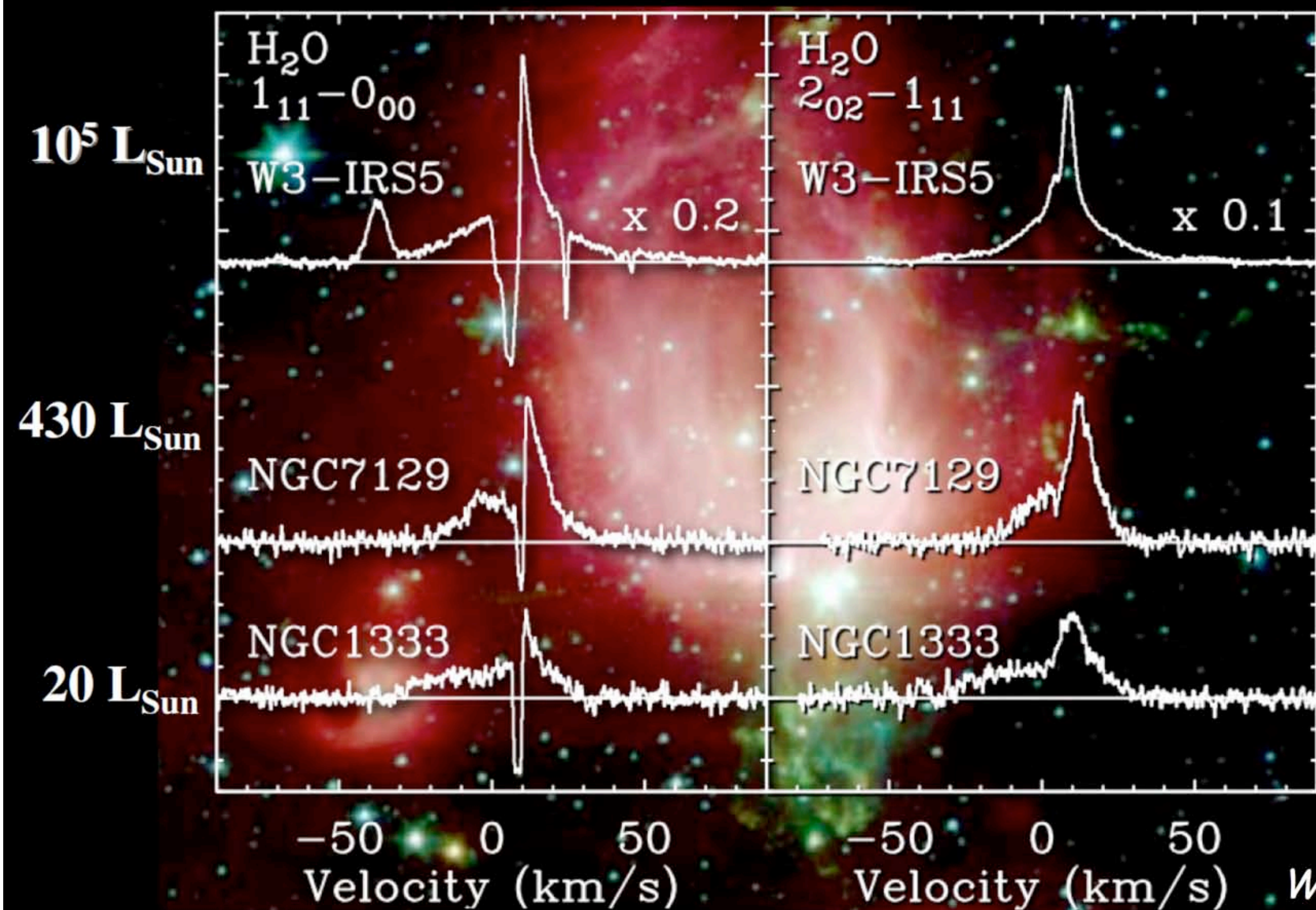
Water



Nisini et al. 2010, A&A 518, L120

- WISH (PI E. van Dishoeck): follow water trail during star and planet formation
  - Natural filter of warm gas
  - Main reservoir of oxygen
  - Important coolant of molecular gas
  - Necessary ingredient for life
- L1157, PACS spectroscopy: strong H_2O peaks at the shocked emission knots and the central source
- H_2O 179 μm emission correlated with mid-IR H_2 rotational lines—water abundance enhancements in shocks
- H_2O emission from compact clumps, spatially unresolved by PACS
- Water cooling: ~0.1 $L_{\odot}$, ~40% of H_2 cooling, ~23% of the total energy released in shocks along the outflow

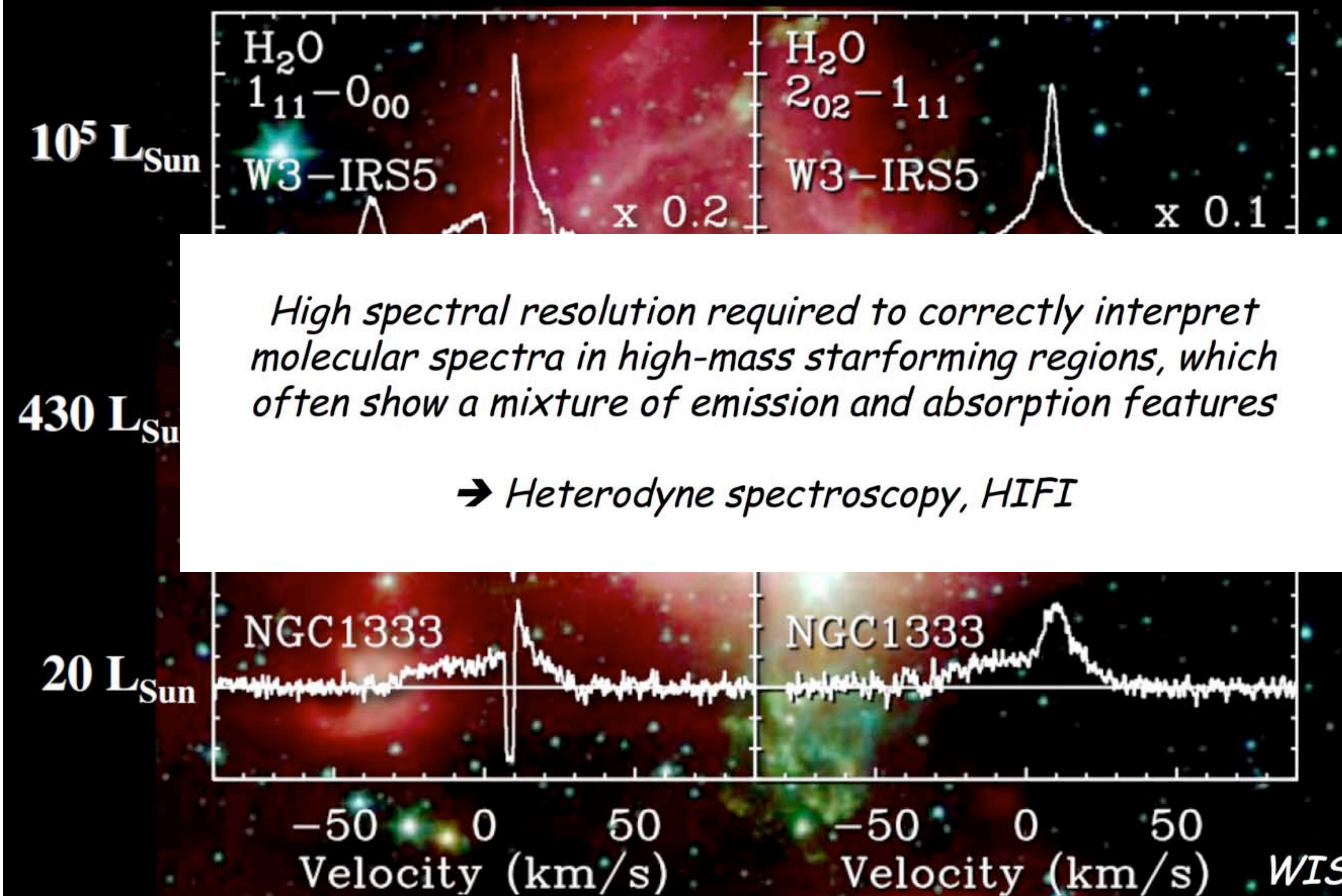
From low to high mass YSOs



Low and intermediate YSOs similar but high-mass lines much stronger and more complicated line profiles

WISH: E. van Dishoeck HIFI data

From low to high mass YSOs



High spectral resolution required to correctly interpret molecular spectra in high-mass starforming regions, which often show a mixture of emission and absorption features

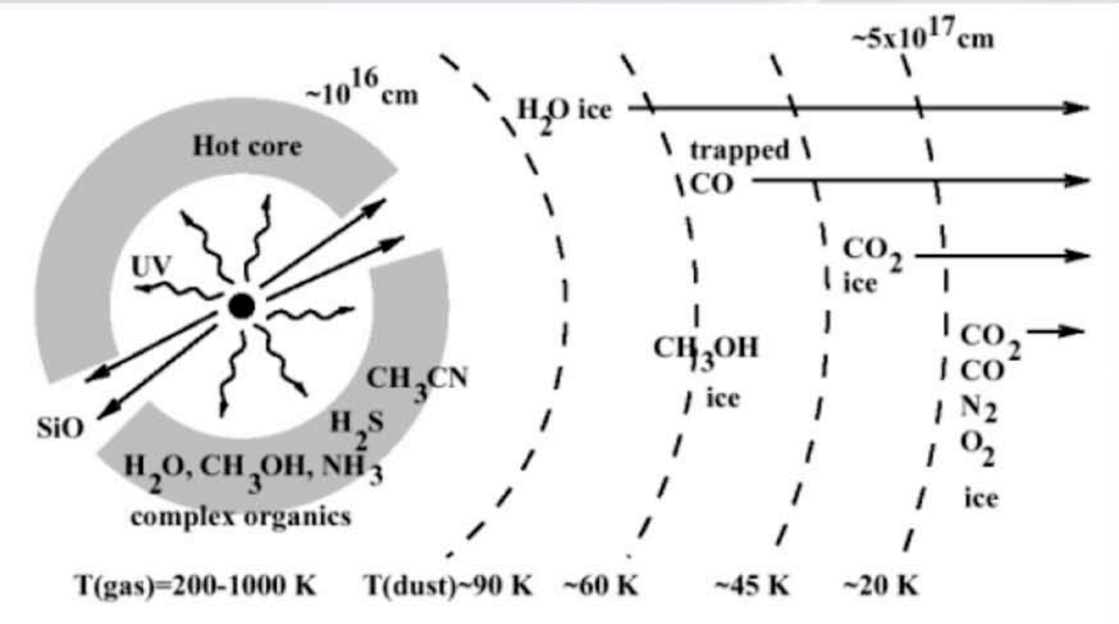
➔ *Heterodyne spectroscopy, HIFI*

Low and intermediate YSOs similar but high-mass lines much stronger and more complicated line profiles

WISH: E. van Dishoeck HIFI data

Spectral Line Surveys

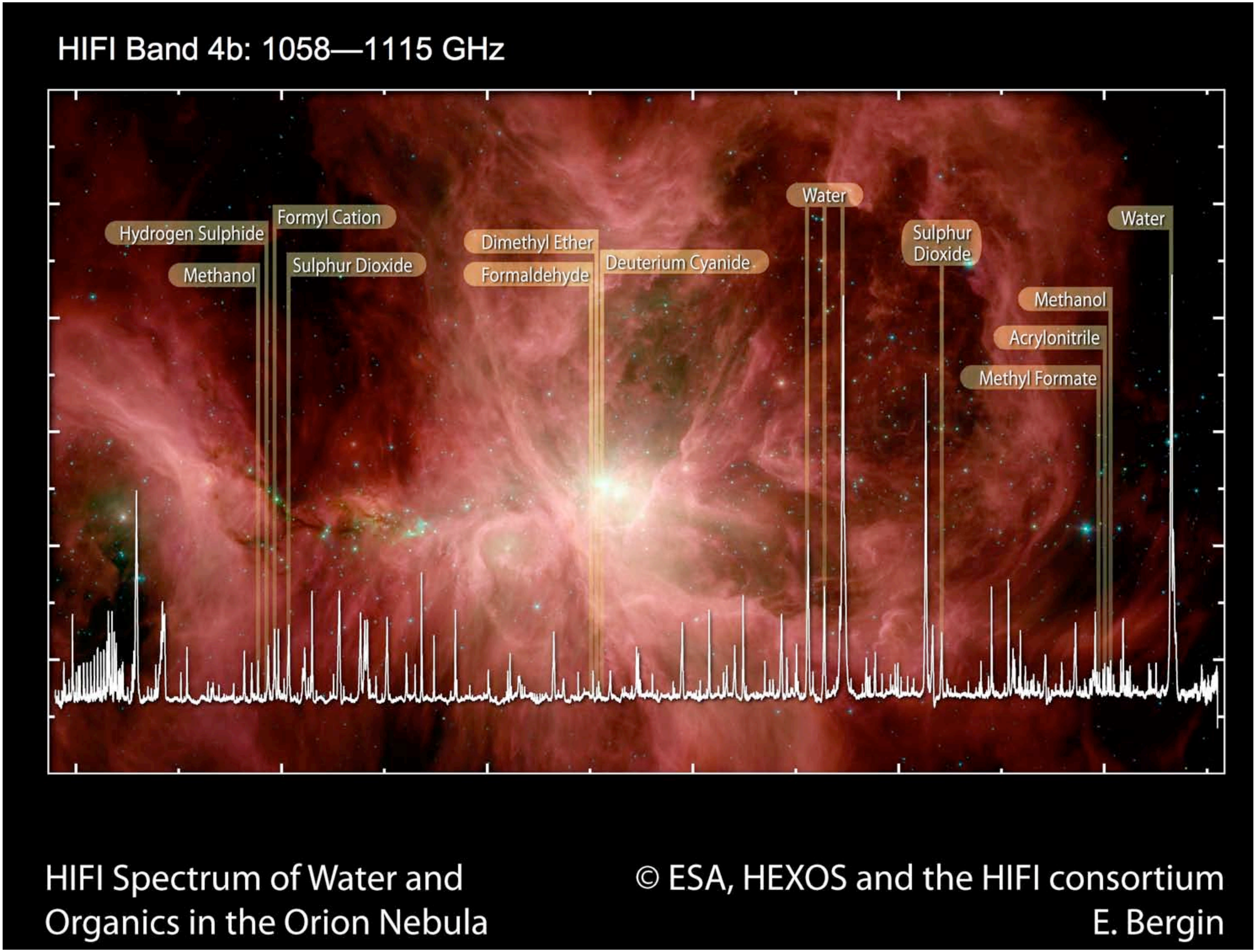
- Complete census of molecules in the ISM; in regions with high line confusion essential for identification
- Submm λs give access to high-energy transitions, excited only in the immediate vicinity of the newly formed stars
- Complex, high-T chemistry driven by molecules evaporating from grain mantles (e.g., methanol)



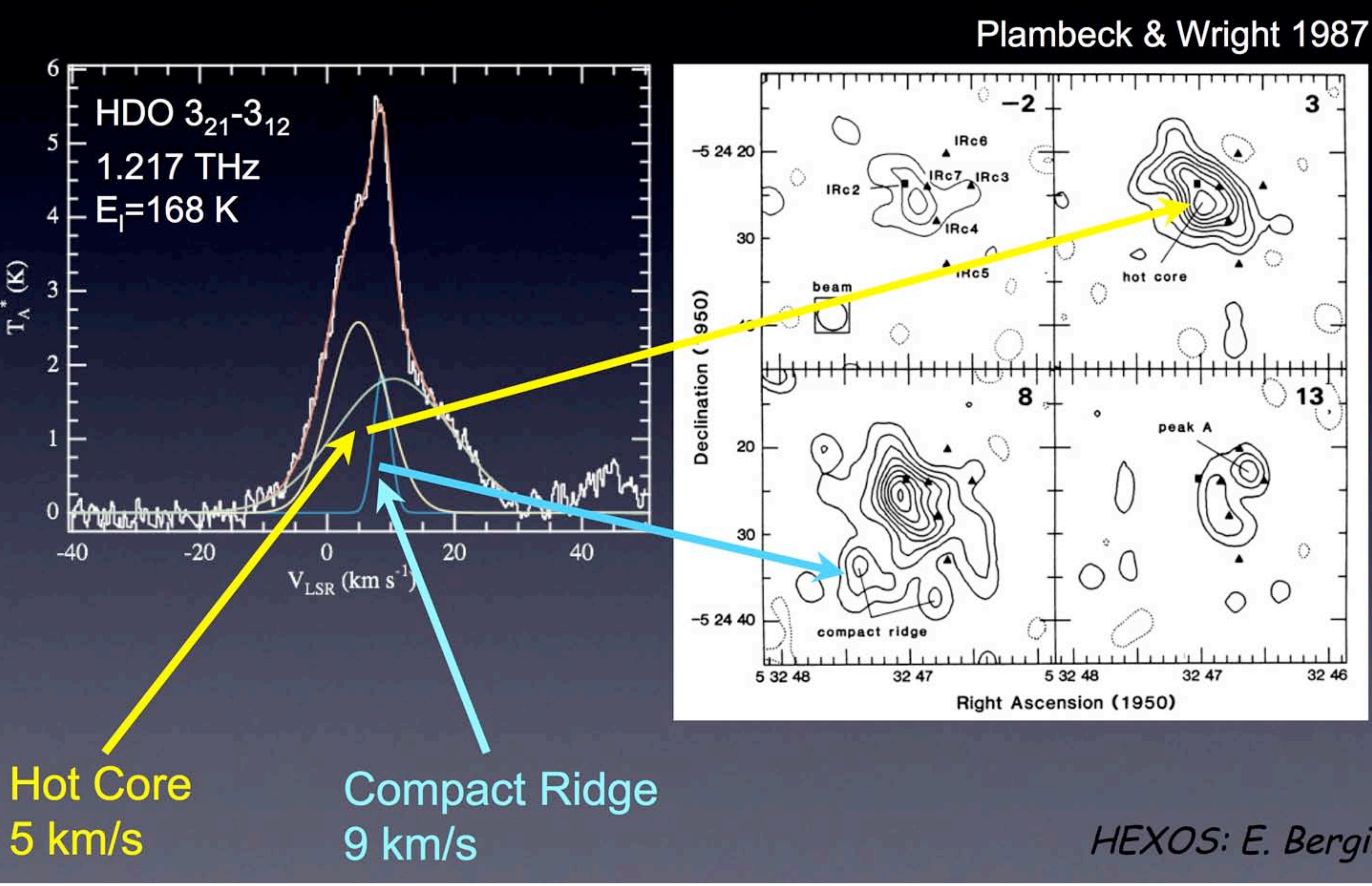
van Dishoeck et al. 1998

Fundamental questions:

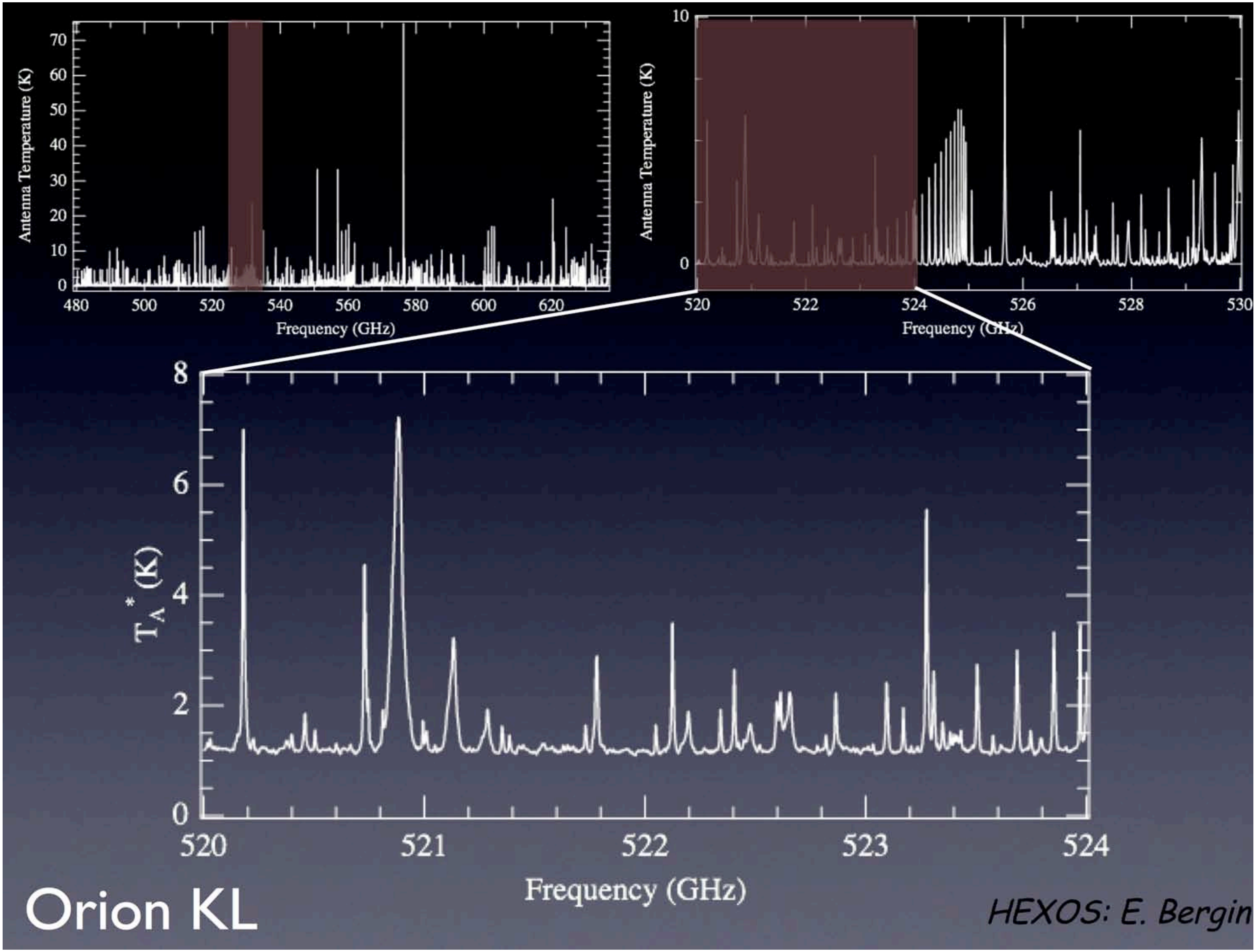
- Grain-surface vs. gas-phase processes
- Formation of large organic molecules → small grains (PAHs)
- Time scales (molecular clocks)
- Dependence on the mass, luminosity etc.


HIFI Band 4b: 1058—1115 GHz
Hydrogen Sulphide
Methanol
Formyl Cation
Sulphur Dioxide
Dimethyl Ether
Formaldehyde
Deuterium Cyanide
Water
Sulphur Dioxide
Methanol
Acrylonitrile
Methyl Formate
Water
HIFI Spectrum of Water and Organics in the Orion Nebula
© ESA, HEXOS and the HIFI consortium
E. Bergin

Spatial/Velocity Structure

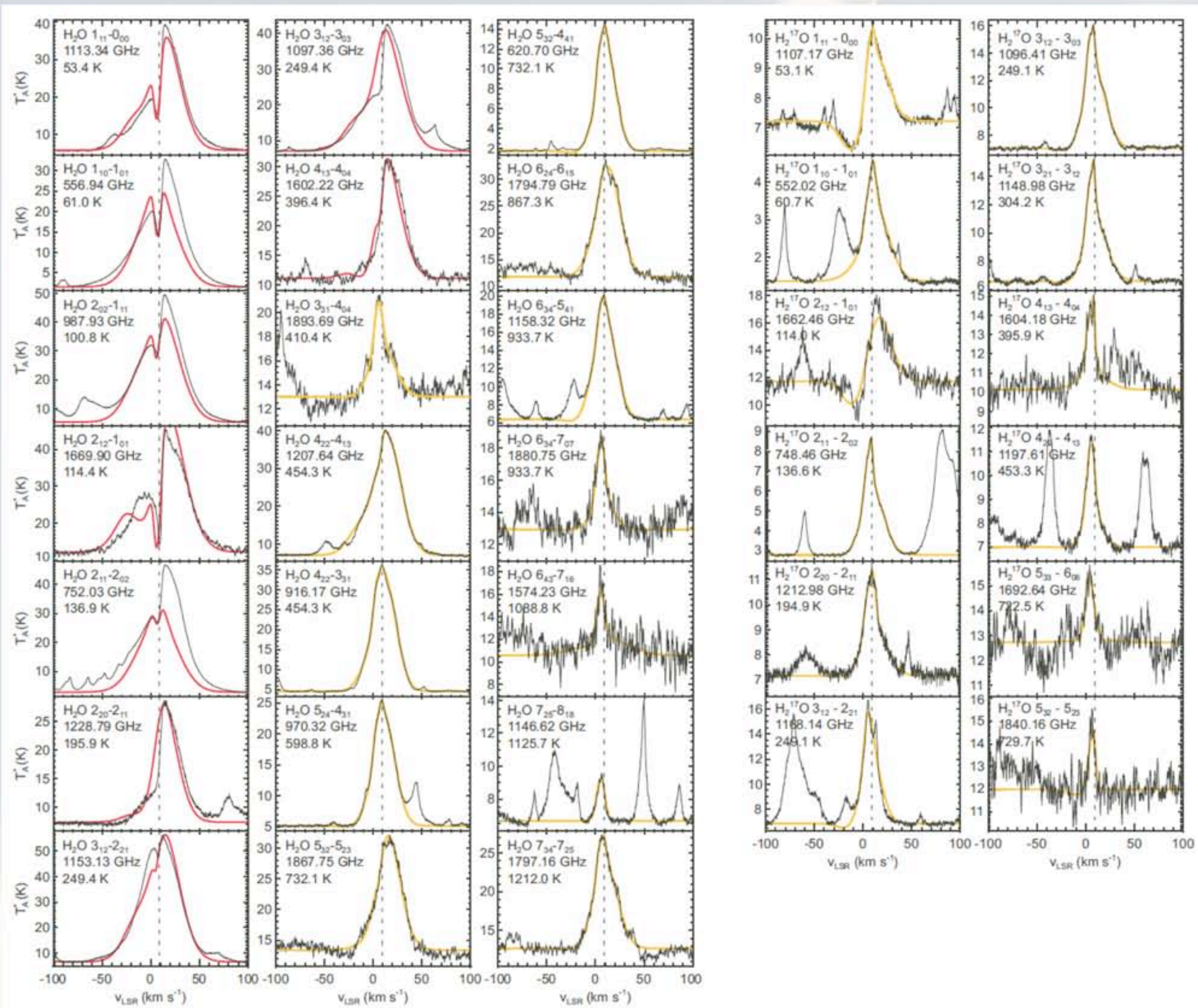


HEXOS: E. Bergin



Antenna Temperature (K)
Frequency (GHz)
Antenna Temperature (K)
Frequency (GHz)
T_A^* (K)
Frequency (GHz)
Orion KL
HEXOS: E. Bergin

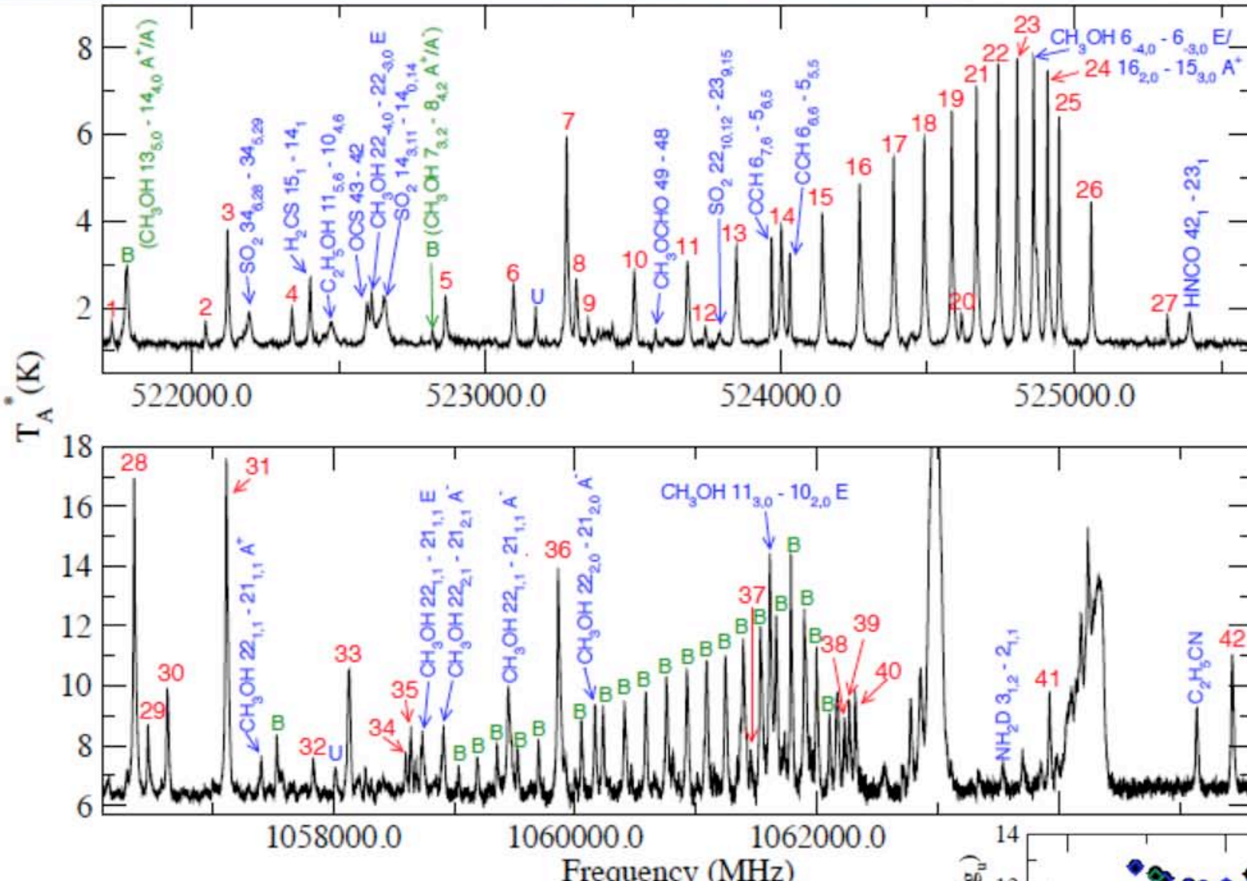
Orion KL- Water



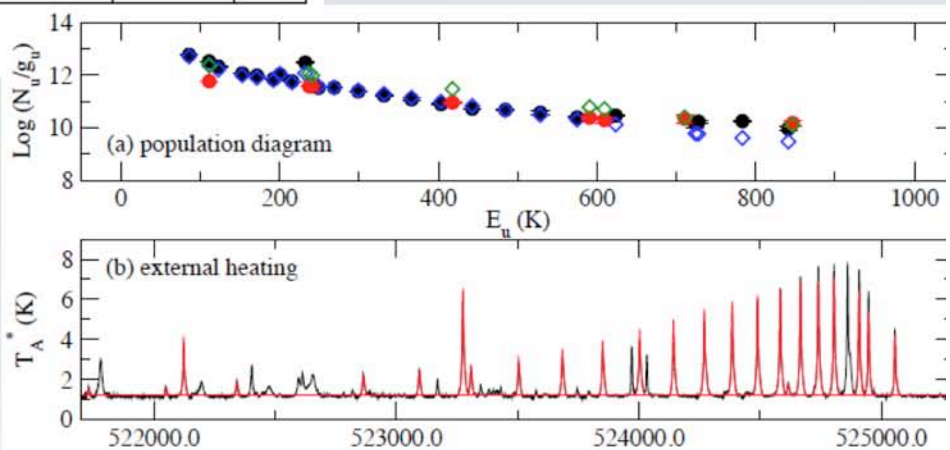
- 48 velocity resolved transitions of $H_2{}^{16}O$, $H_2{}^{18}O$ and $H_2{}^{17}O$
- Simple fit matching the known emission and absorption components along the line of sight in excellent agreement with the observed spectra
- Water abundances in the hot core and extended warm gas an order of magnitude higher than in the quiescent gas
- Enhanced sublimation of water ice in warm gas

Melnick et al. 2010, A&A, 521, L27

Orion KL-Methanol

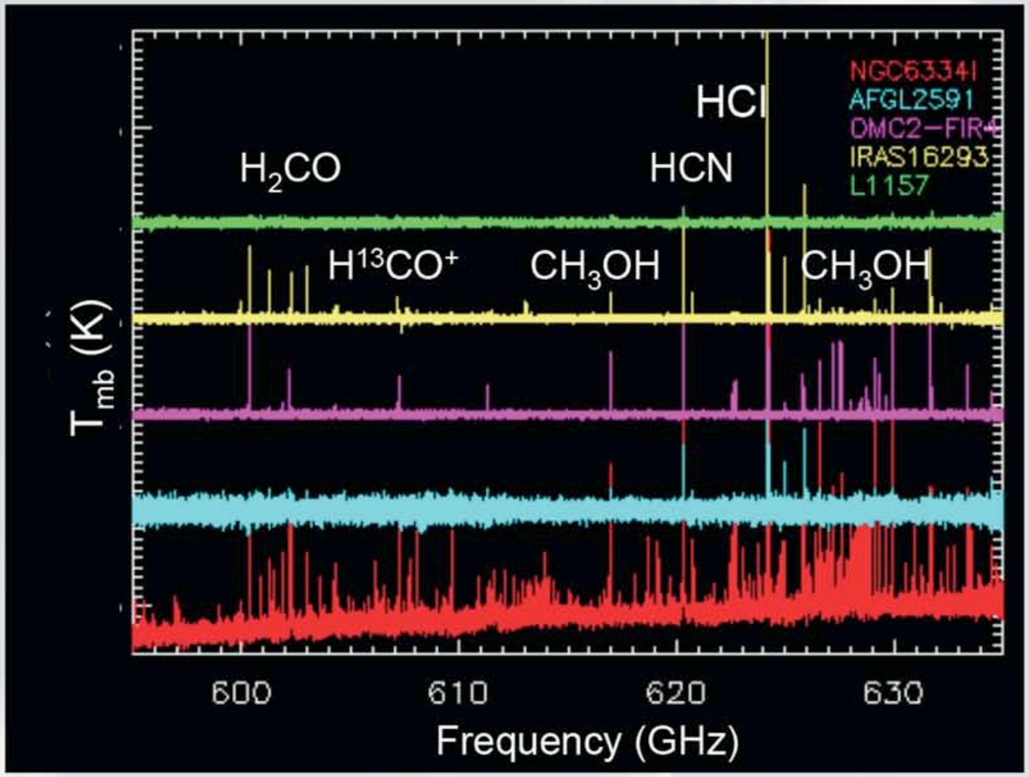


- Hundreds of lines of methanol in the spectra
- Weed or flower?
- Explore physical conditions in various components (hot core, low velocity flow, compact ridge)
- Upper level energies up to 900 K—thermal structure
- Compact ridge externally heated



Wang et al. 2010, A&A, submitted

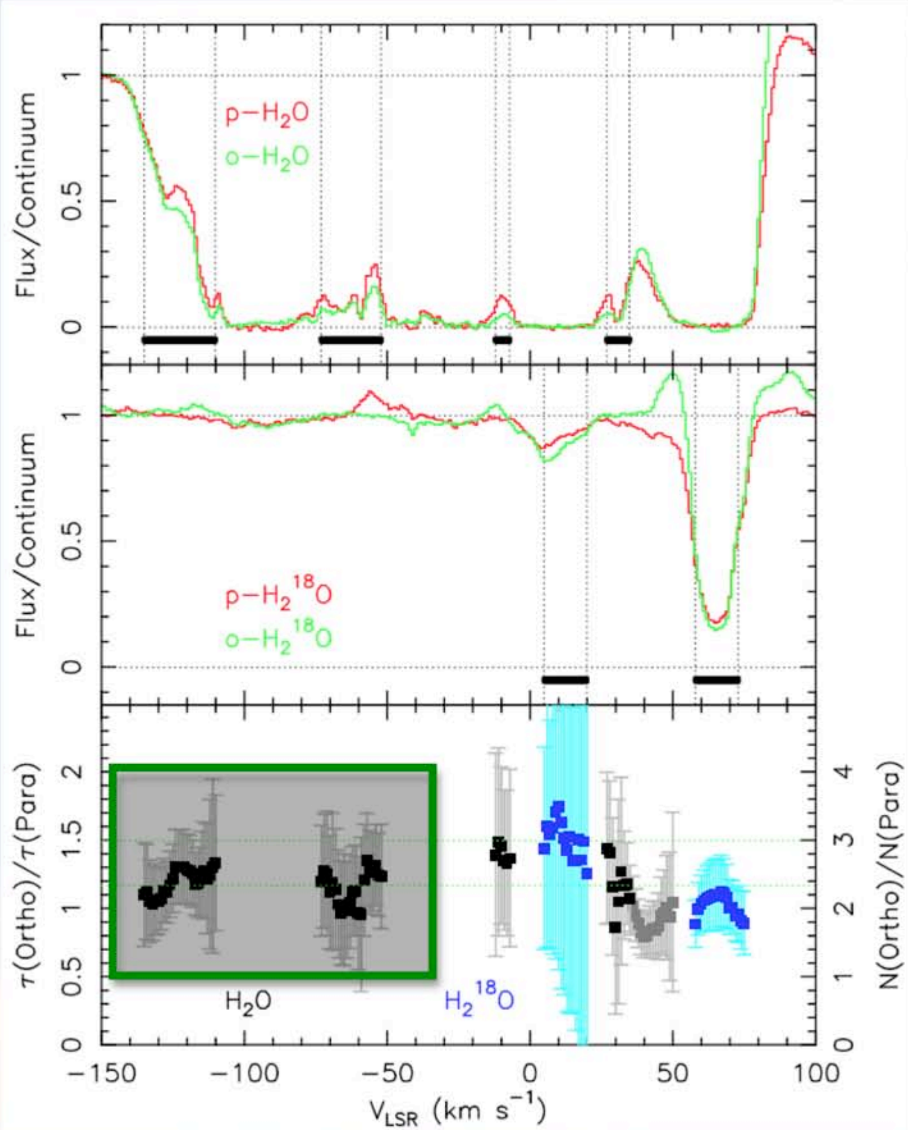
Herschel Chemical Surveys



Ceccarelli et al. 2010, A&A, 521, L22

- CHESS (PI C. Ceccarelli): a coherent study of astrochemistry in starforming regions
- Molecular lines as diagnostics of physical conditions
- Chemical composition affects the physical and dynamical evolution (e.g., cooling, ionization degree)
- Complete molecular census of molecule in low-to-high mass protostars
- NGC6334I—spectrum rich in complex organics (methanol, dimethyl ether…)—temperature effects
- Large differences in abundances of sulfur bearing molecules (age differences, e.g. SO/SO_2?)
- Different deuteration levels—IRAS16293 undisputed winner (ND, D_2O)

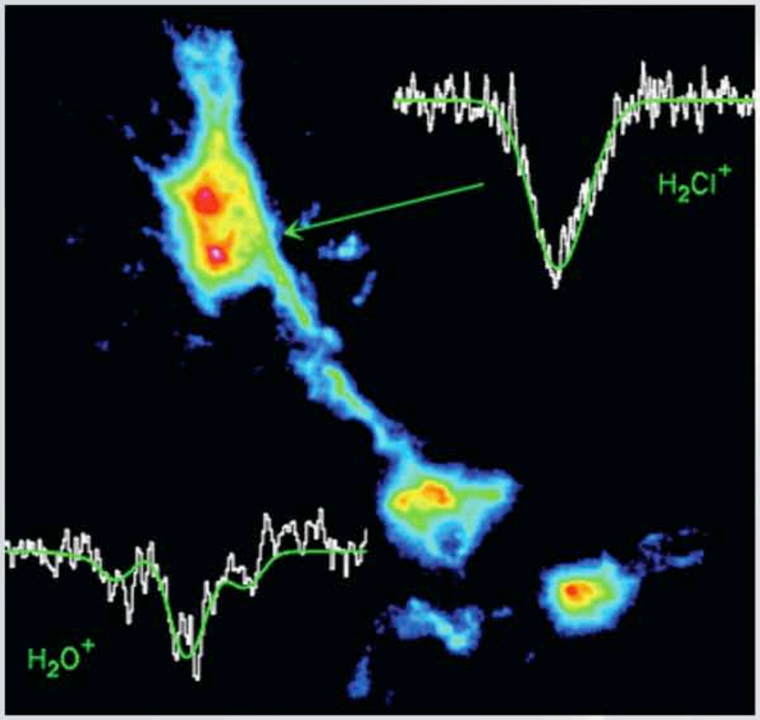
Water o/p Ratio

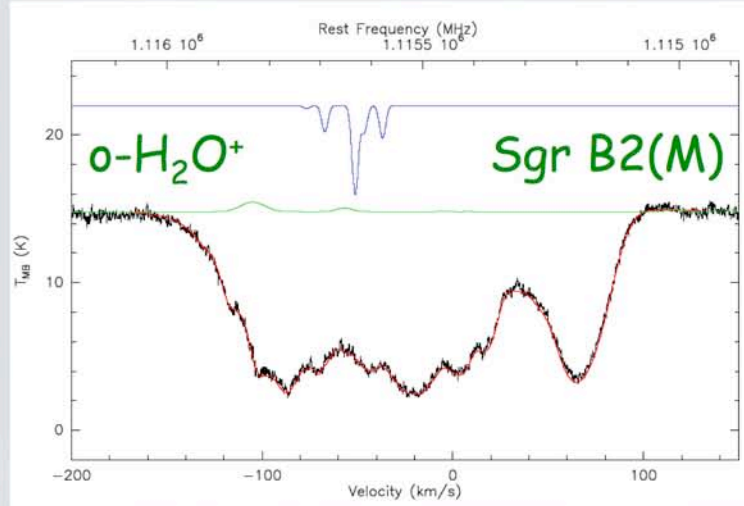


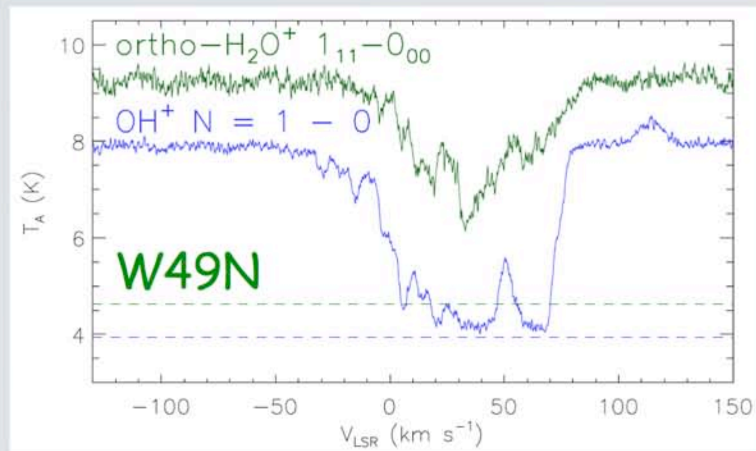
Lis et al. 2010a, A&A, 521, L26

- HIFI allows velocity-resolved observations of the fundamental p-H_2O line at 1113 GHz
- Water o/p ratio is temperature dependent and, in principle, the temperature of the medium in which the spin state populations last equilibrated can be deduced
- The o/p ratio in foreground clouds on the l-o-s toward Sgr B2 and W31C generally consistent with the statistical high-temperature ratio of 3
- A low o/p ratio of 2.35±0.35 (3σ) measured in Sgr B2 at velocities corresponding to the expanding molecular ring (T_{spin}~27 K)
- Even lower o/p ratio also derived toward NGC6334I (Emprechintger et al.)
- Water molecules formed with, or relaxed to, an o/p ratio close to the value corresponding to the local temperature of the gas and dust

New Molecules: H_2Cl^+, H_2O^+, OH^+

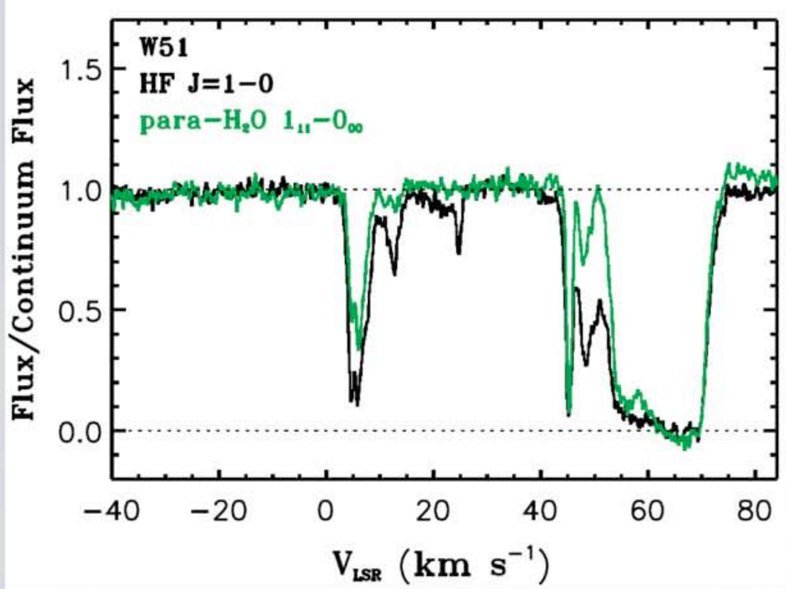


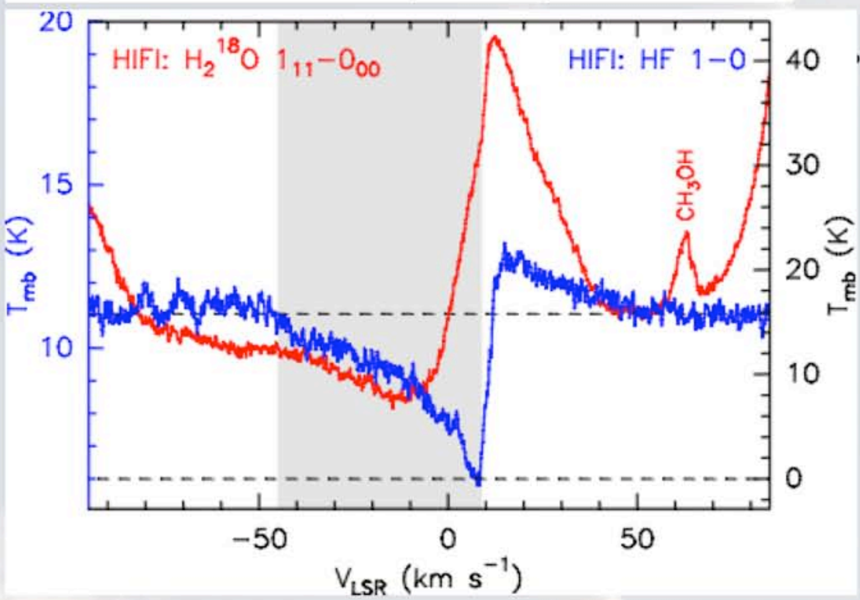




- Chloronium detected in absorption toward NGC6334I and Sgr B2(S)
- Predicted by chemical models, but column densities ~100 times higher
- OH^+ and H_2O^+: reactive cations that play key role in the oxygen chemical network in UV irradiated regions
- Key constraints for astrochemistry

Lis et al. 2010b, A&A, 521, L9
Ossenkopf et al. 2010, A&A 518, L111
Neufeld et al. 2010, A&A 521, L10
Schilke et al. 2010, A&A, 521, L11

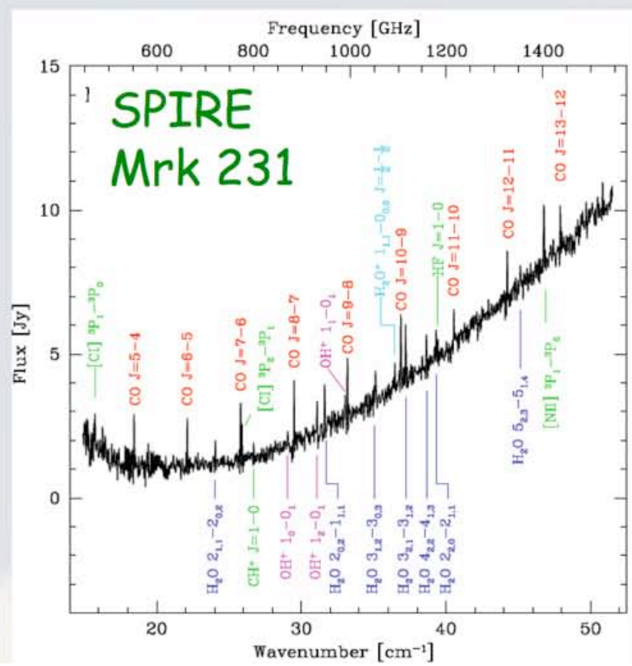


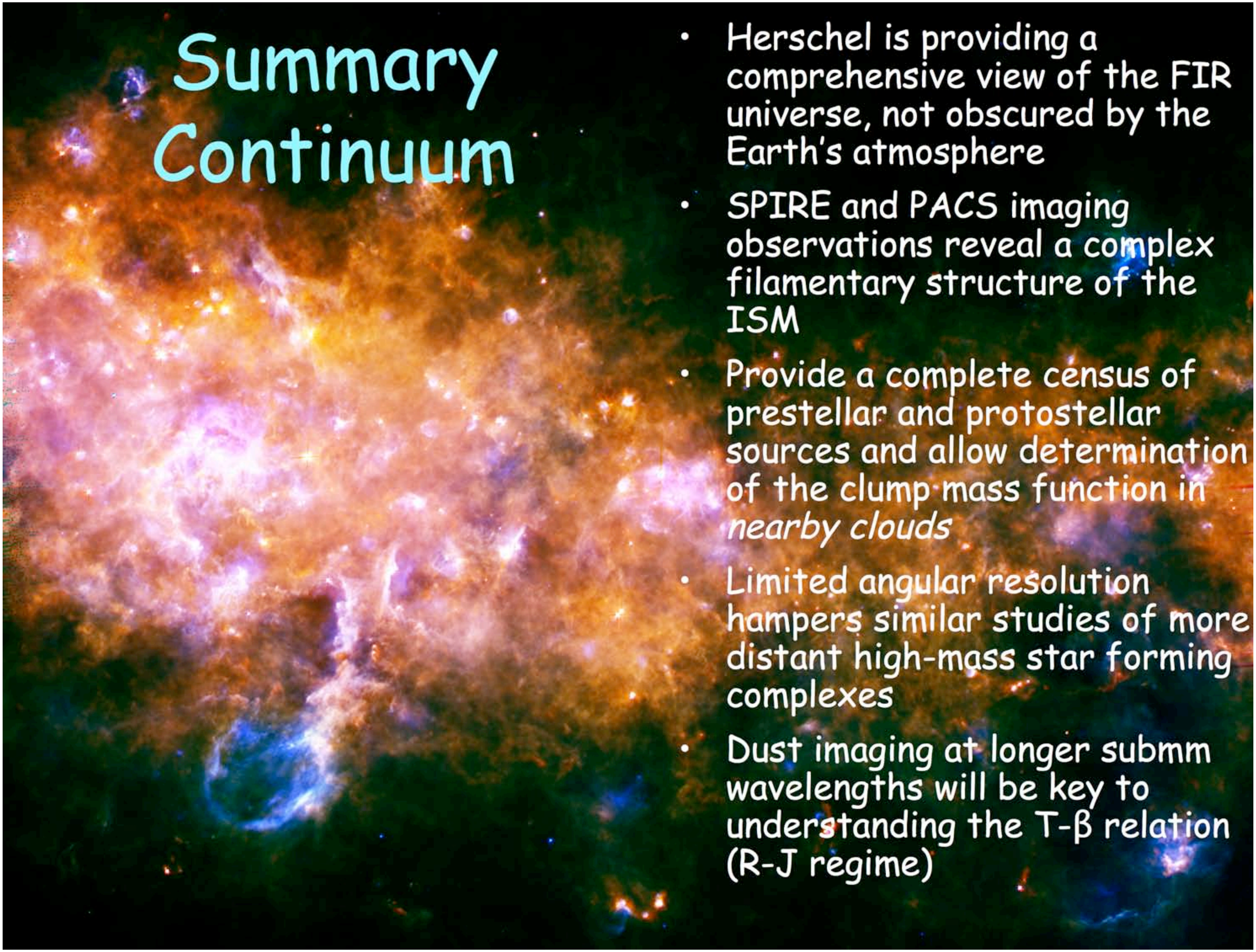


Phillips et al. 2010, A&A, 518, 109
Neufeld et al. 2010, A&A, 518, 108
Sonnentrucker et al. 2010, A&A, in press
van der Werf et al. 2010, A&A, 518, L42

HF

- Widespread HF J=1—0 absorption detected by Herschel in a *variety of galactic environments*
- HF column densities typically comparable with those of H_2O
- HF main reservoir of gas-phase F
- Potentially important new tracer of H_2 in high redshift Universe

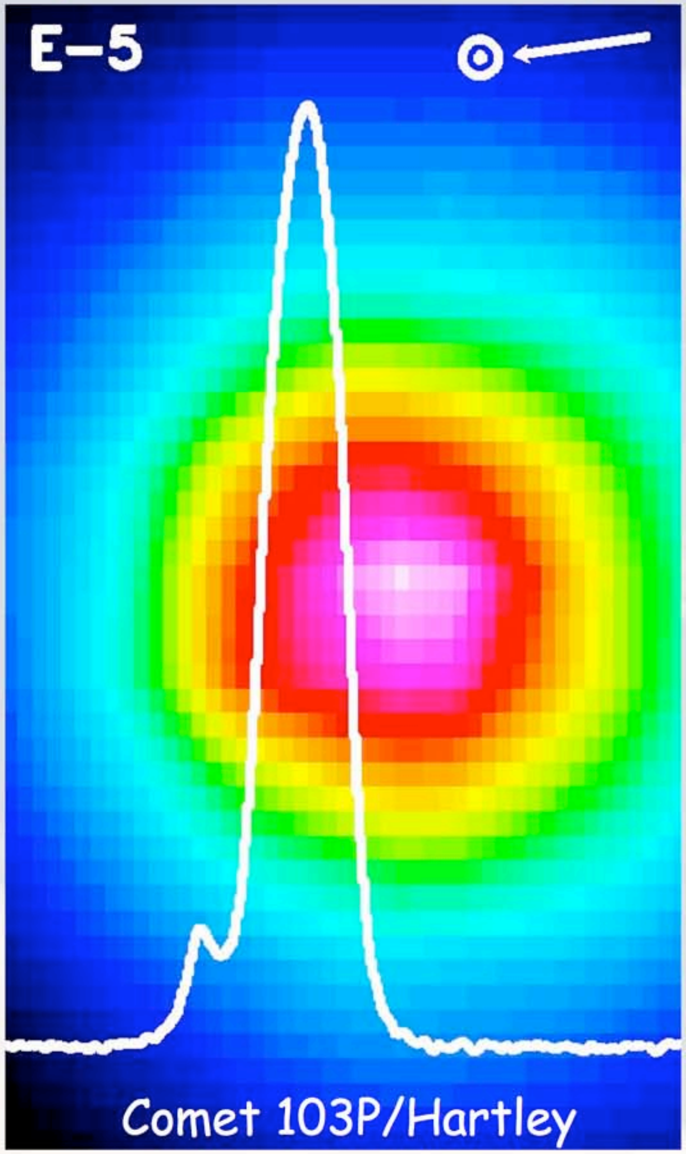




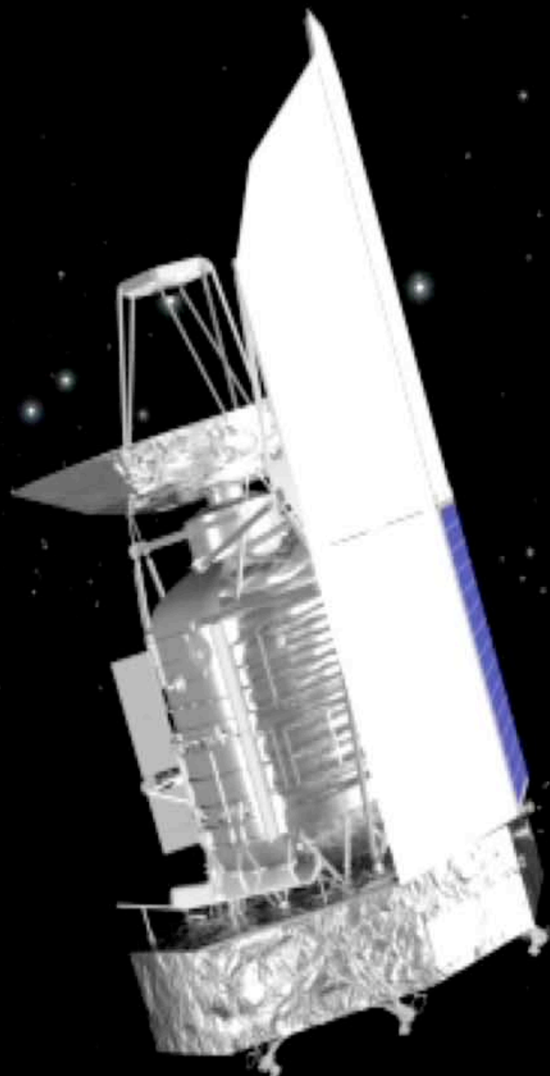
Summary Continuum

- Herschel is providing a comprehensive view of the FIR universe, not obscured by the Earth's atmosphere
- SPIRE and PACS imaging observations reveal a complex filamentary structure of the ISM
- Provide a complete census of prestellar and protostellar sources and allow determination of the clump mass function in *nearby clouds*
- Limited angular resolution hampers similar studies of more distant high-mass star forming complexes
- Dust imaging at longer submm wavelengths will be key to understanding the T-β relation (R-J regime)

Summary Spectroscopy



- HIFI is a single pixel instrument, excellent for line surveys, but slow for mapping
- HIFI imaging has been limited to lines not observable from the ground (e.g., water, CII)
- To fully understand the ISM energy balance we need imaging heterodyne arrays at 350 and 450 μm
- High-J *CO, CI* (SPIRE spectral resolution too low for kinematic studies of galactic sources)
- HIFI will not observe lines that can be studied from the ground: HCl, CI, *HDO*
- Even line surveys will only be carried out in a small sample of sources that may or may not be representative and do not cover the full range of luminosities, ages, environments…



There will be plenty left to do in the fields of star formation and ISM studies after Herschel!