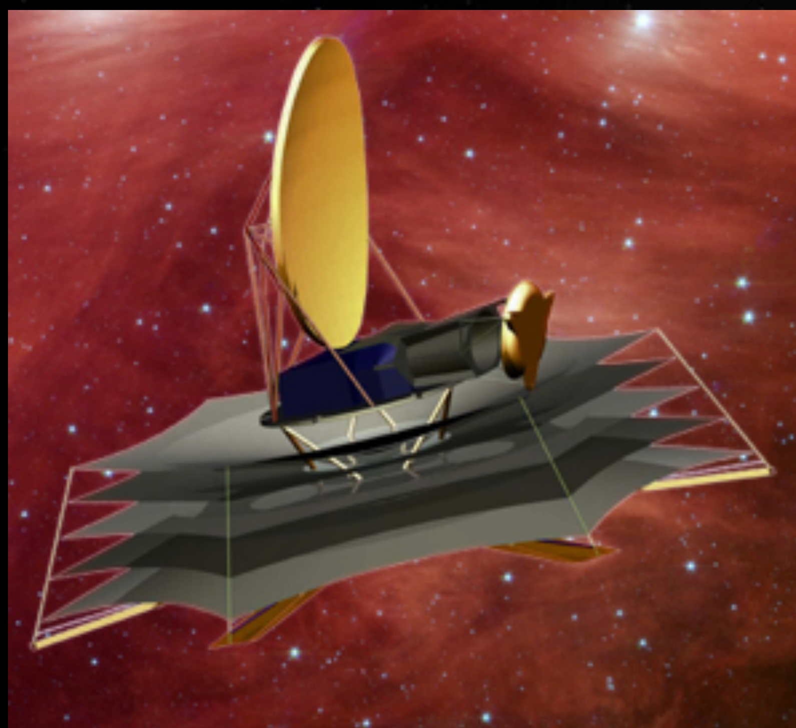
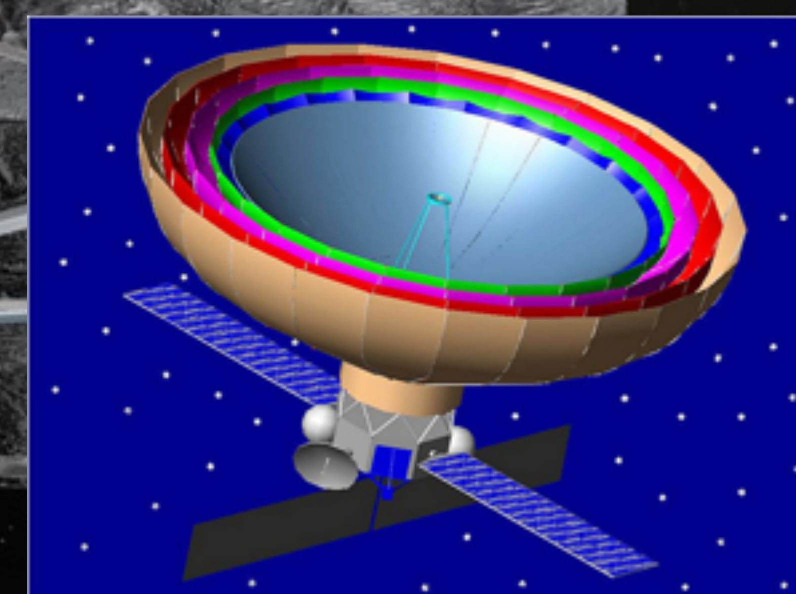
Far-Infrared Spectroscopy and Astrochemistry after Herschel

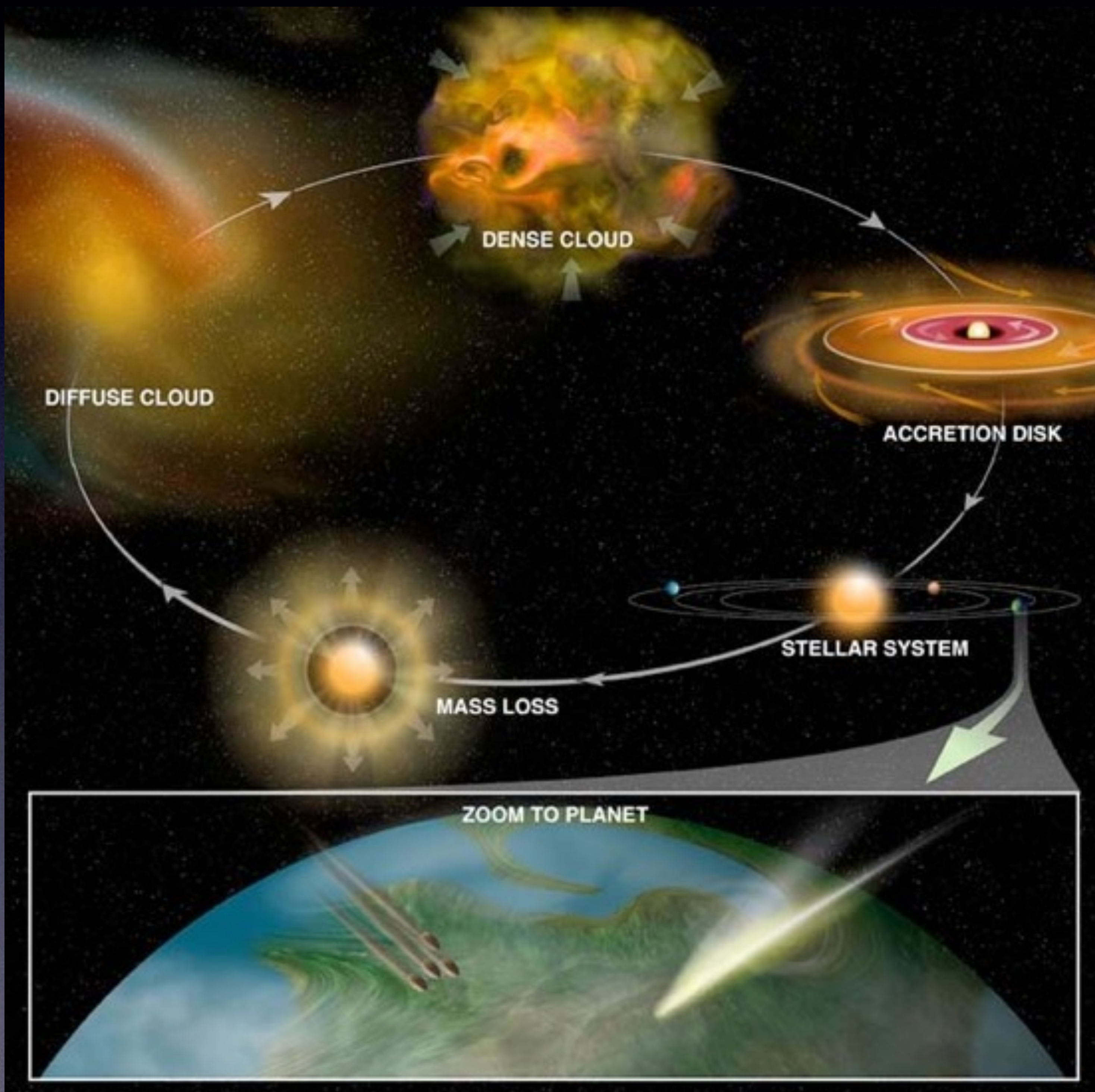




Darek Lis (LERMA/Caltech)

Pasadena, June 4, 2015

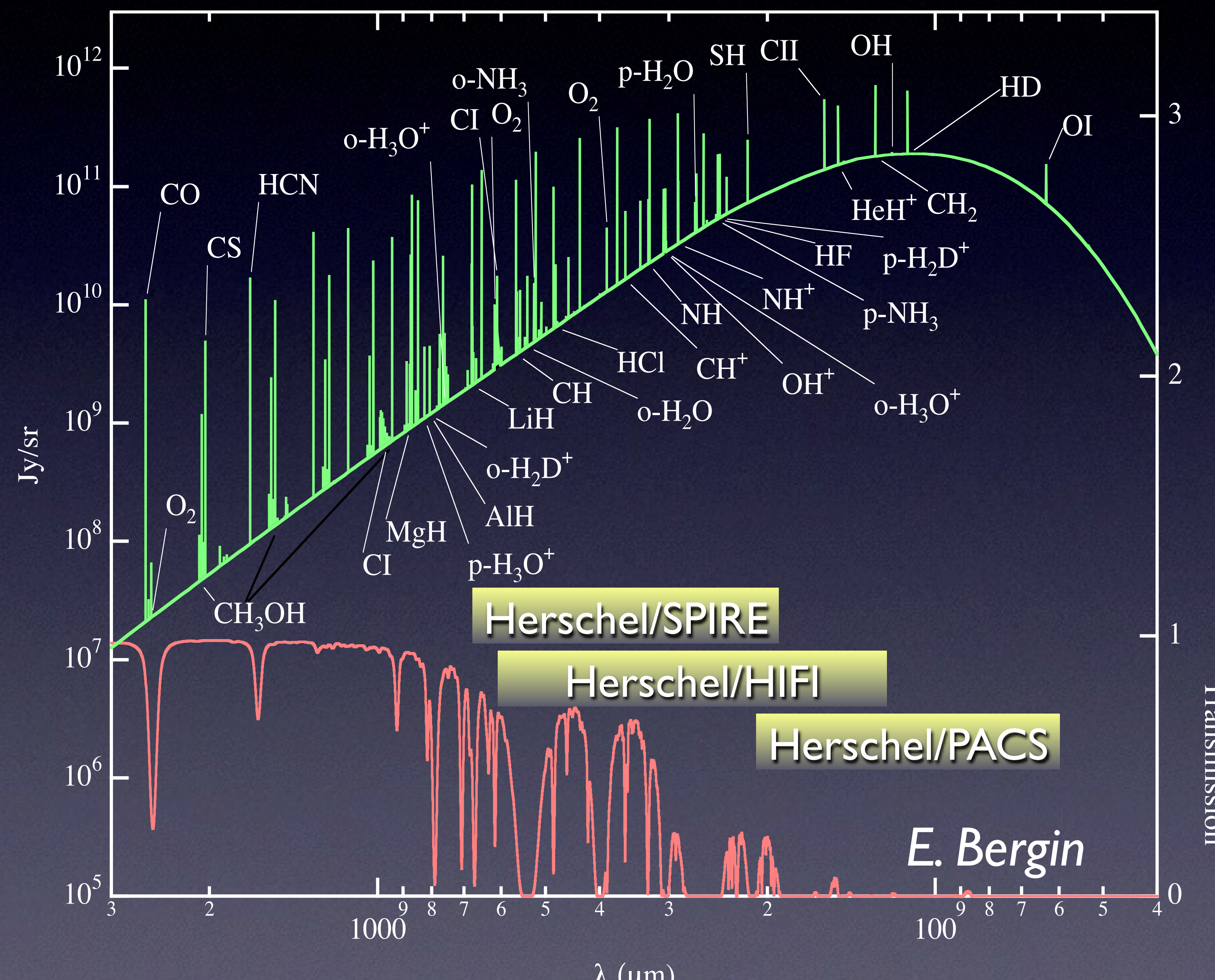
Broad Perspective



- Molecular clouds exhibit a high degree of chemical complexity — water, carbon monoxide, carbon dioxide, organics
- Gas phase chemistry, catalytic chemistry on grain surfaces, gas-grain interactions
- Delivery to the planet-forming disks and to young planets
- Molecules as tracers of *physical conditions* in the ISM and star-forming regions (e.g., density, temperature, UV field, ionization fraction…)

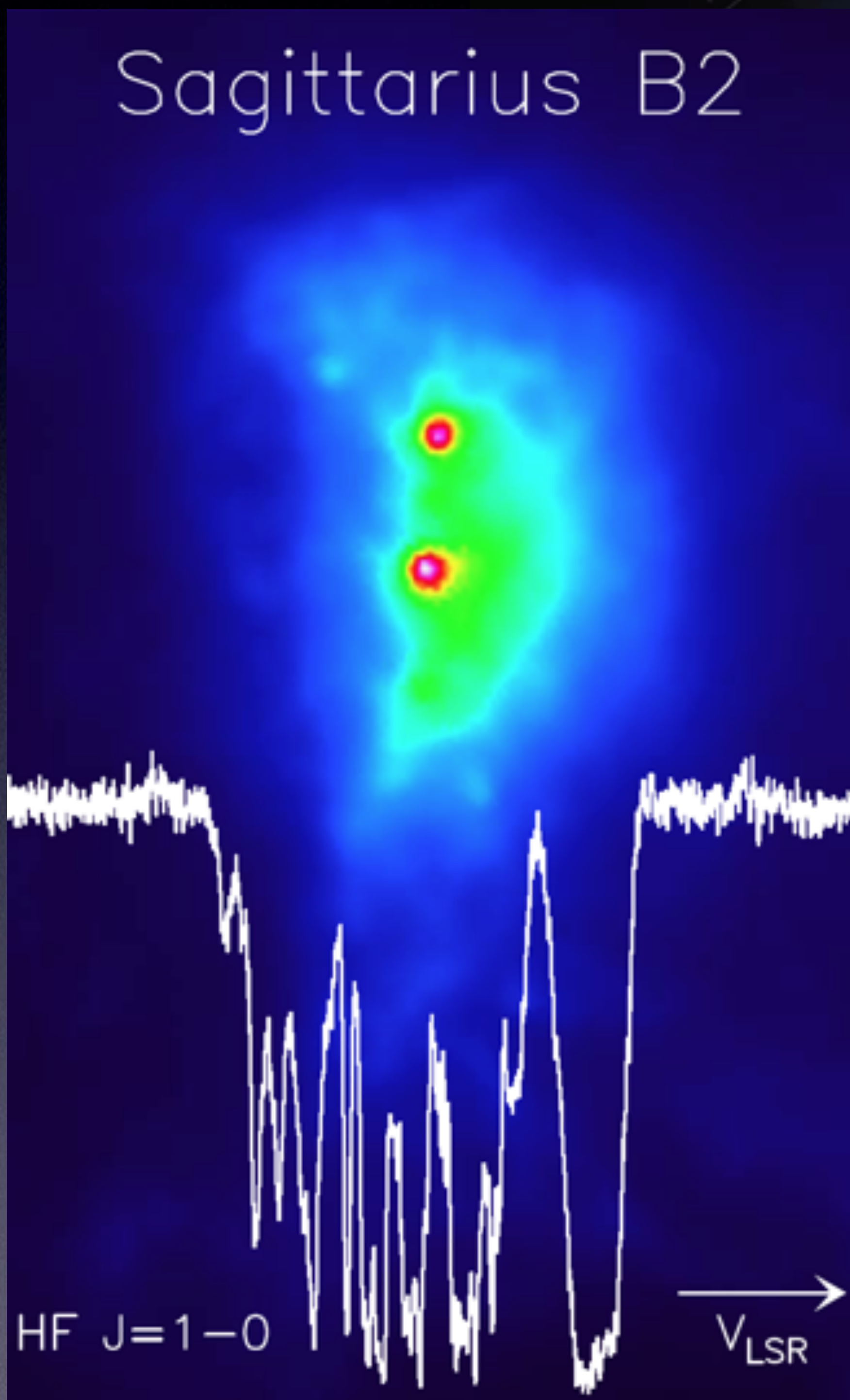
http://www.space.com

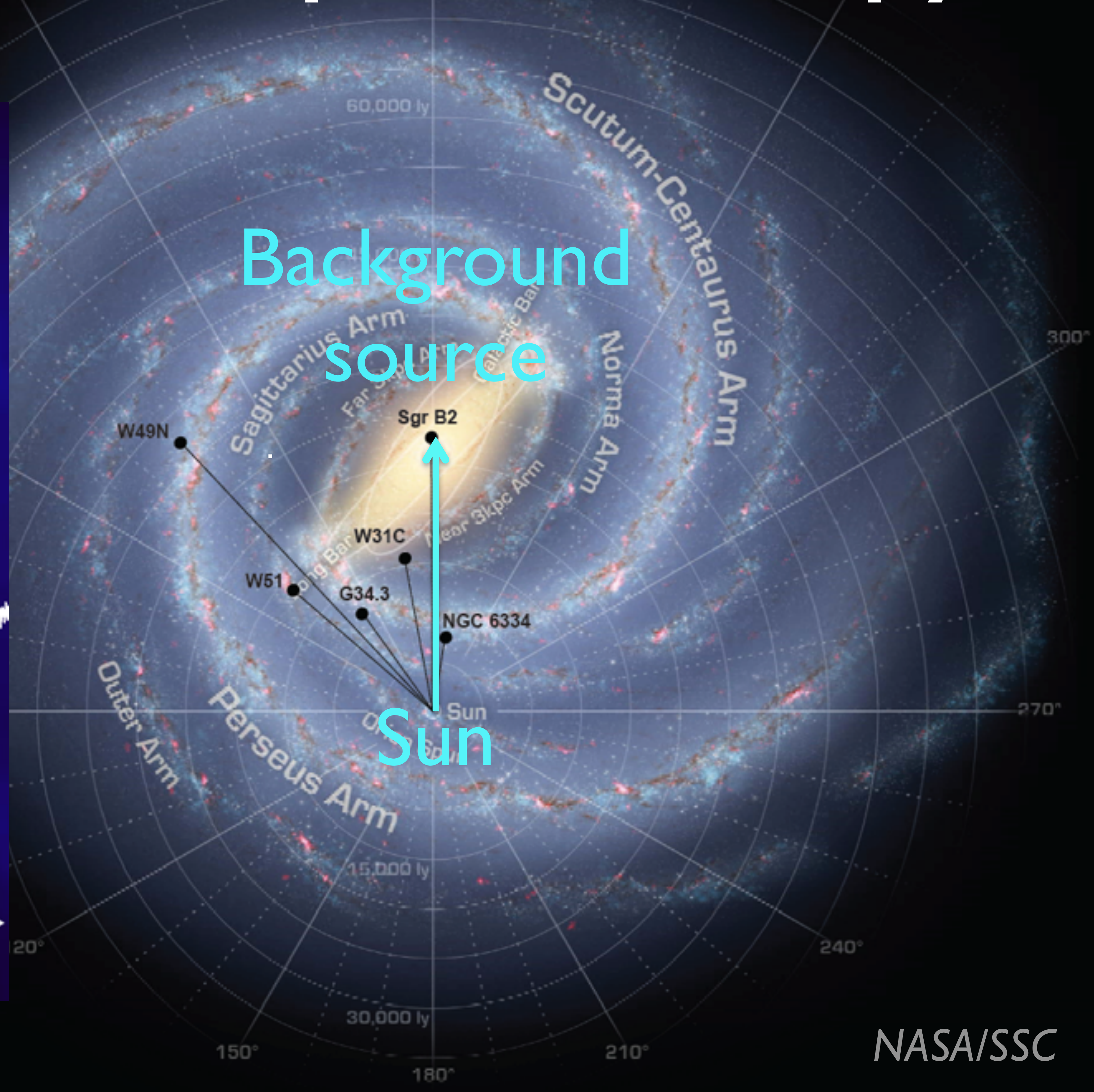
Submillimeter/FIR Astrophysics



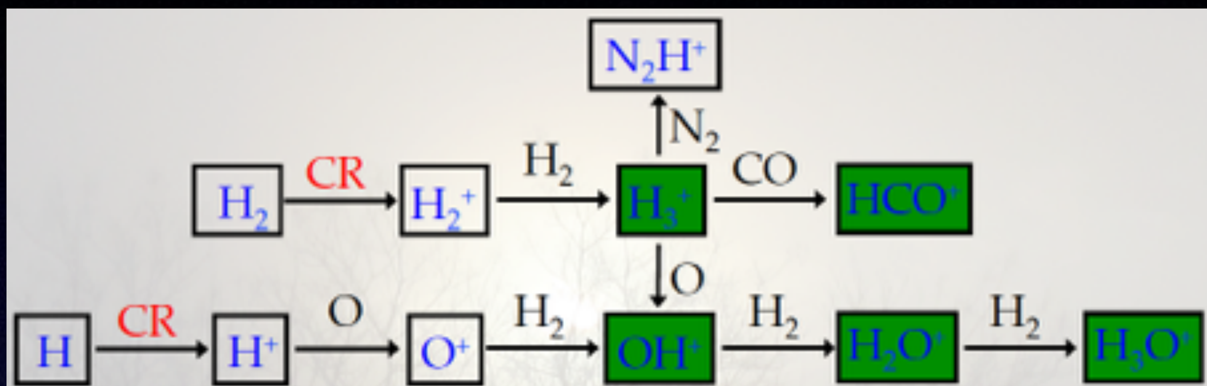
- Inability to view the entire spectrum of star forming gas — water, key coolants (e.g., [CII], [OI], high-J CO ladder)

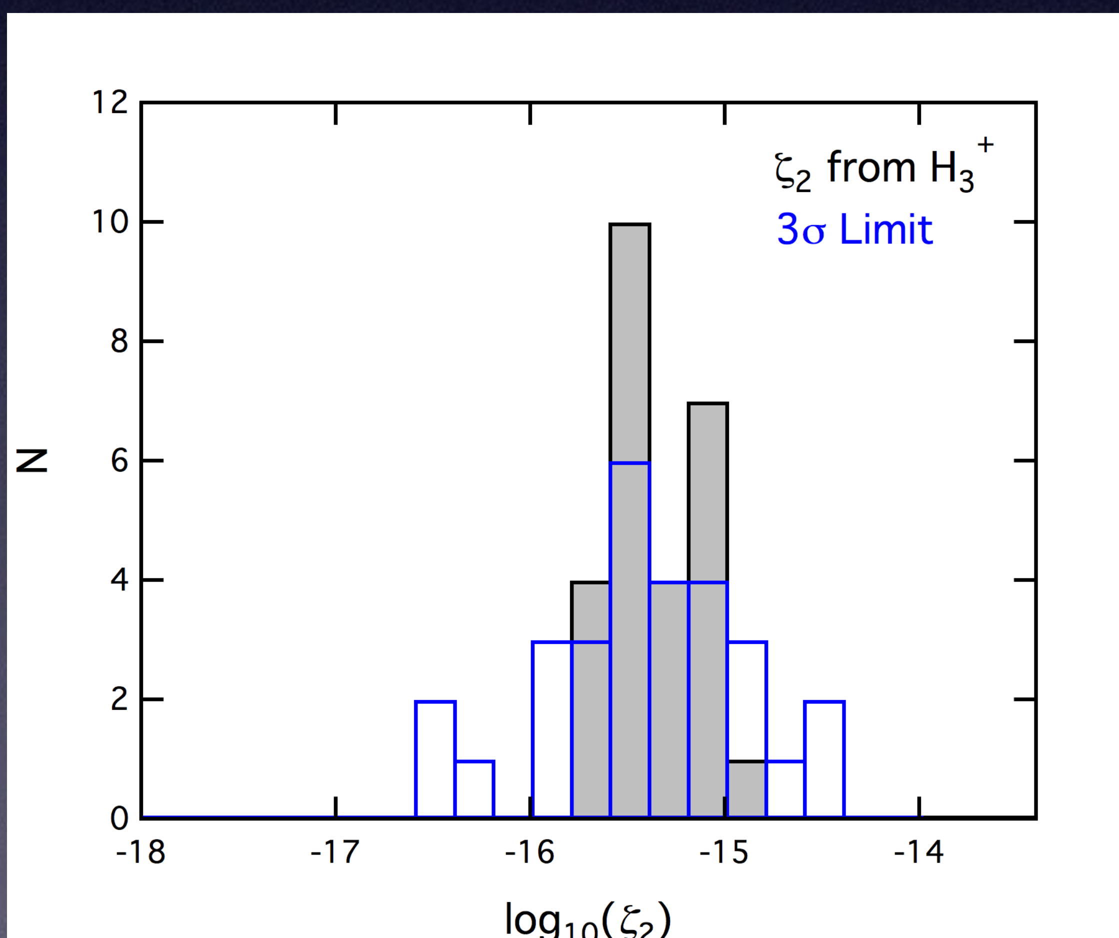
Absorption Spectroscopy





Cosmic Ray Ionization Rate

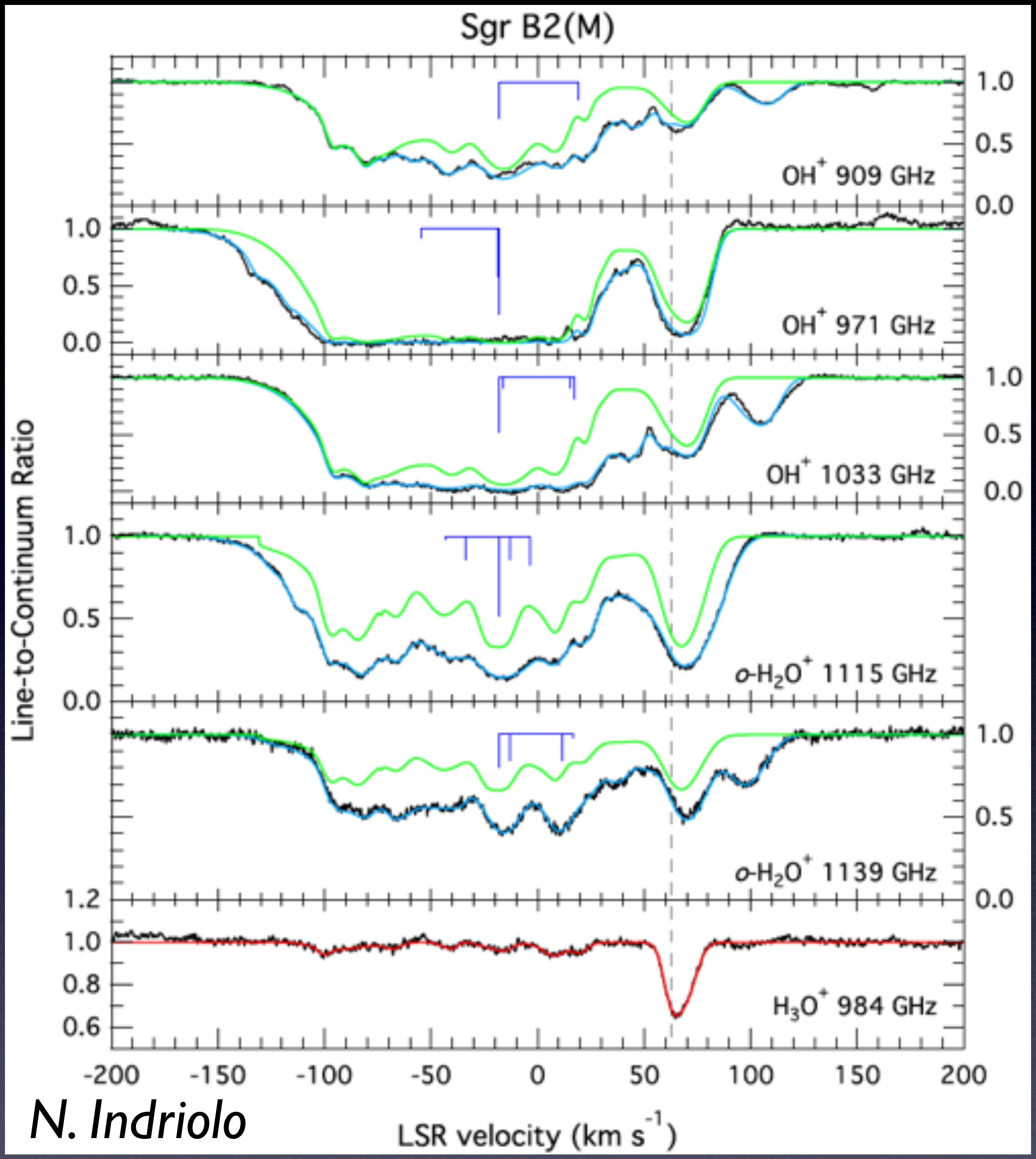


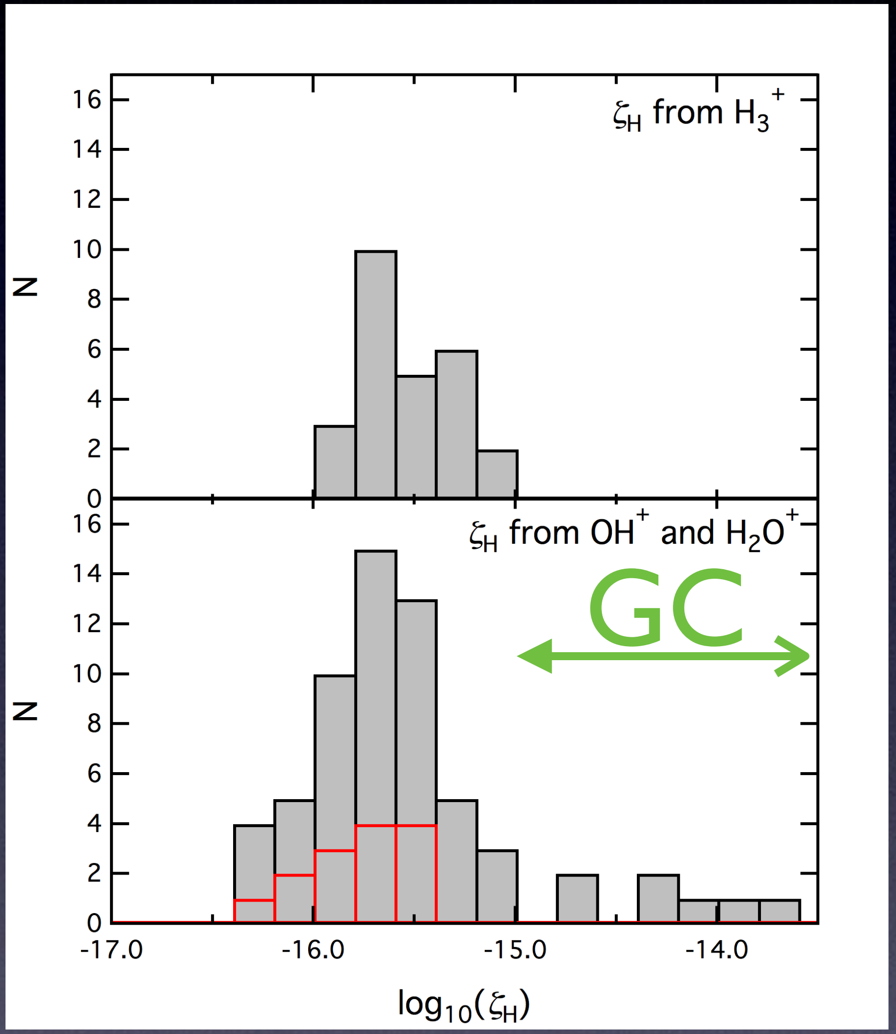


N. Indriolo

- Key parameter that regulates star formation in molecular clouds
- Coupling between the gas and the magnetic field — dynamics of the collapse through magnetic pressure support
- Abundances of molecular ions directly linked to the CR rate
- Particle spectrum poorly constrained below ~1 GeV — constraints on the low energy particle flux
- H_3^+ observable in the infrared, but difficult to detect

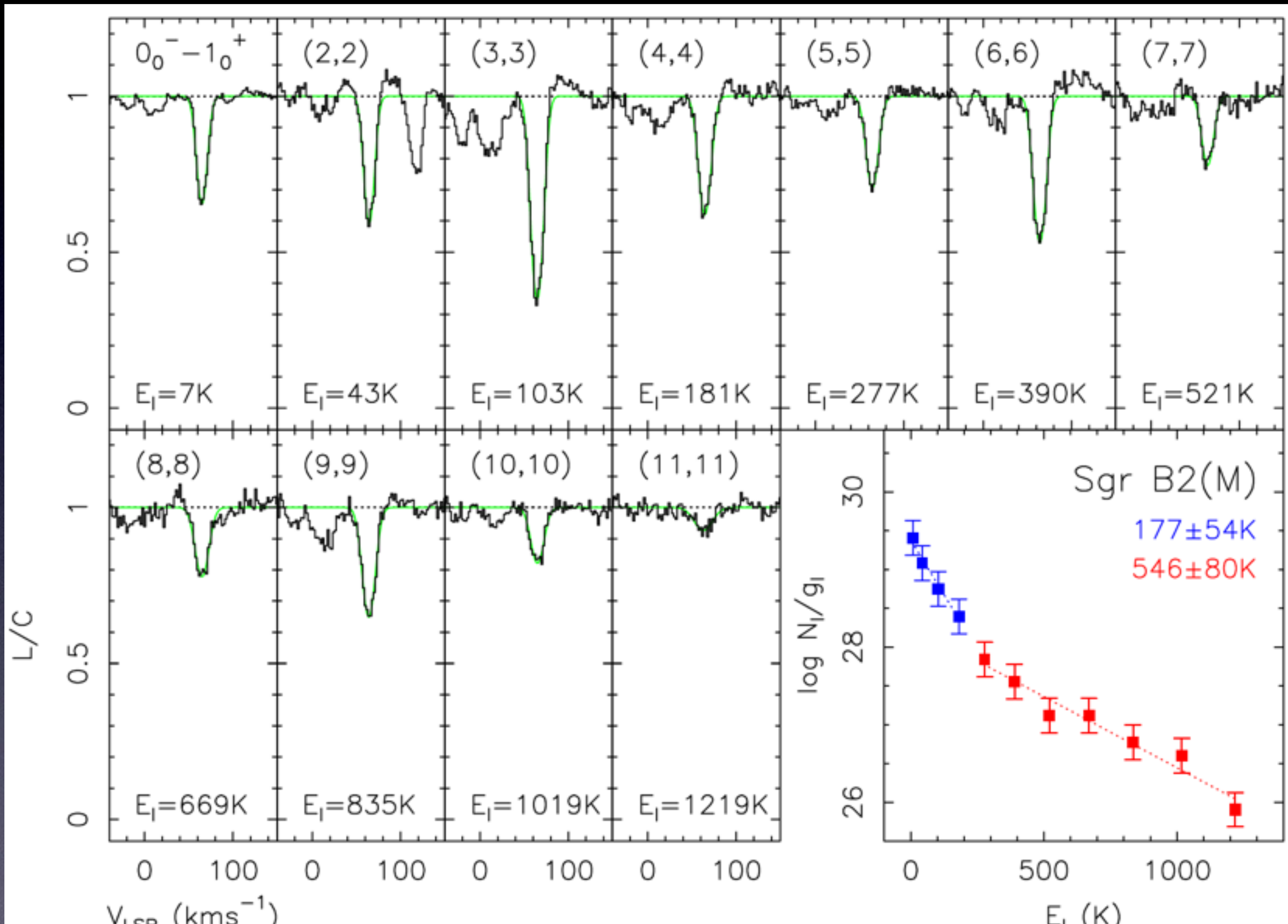
Oxygen Ions





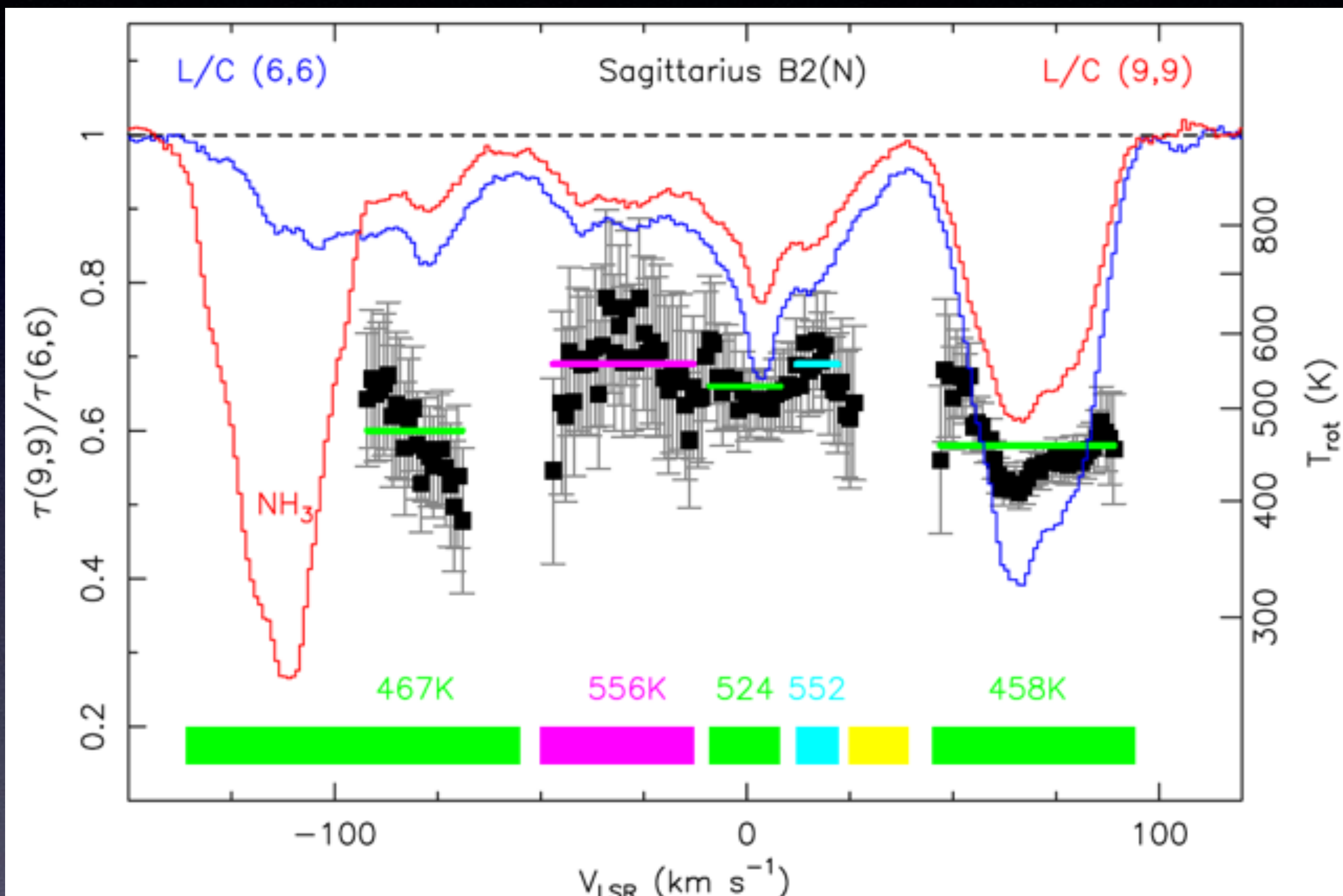
- Herschel: 20 Galactic lines of sight, 100 separate components
- Molecular fraction typically 3—8%
- Can calibrate with respect to H_3^+ to derive the "efficiency factor"
- Key transitions in the 970—1100 GHz range

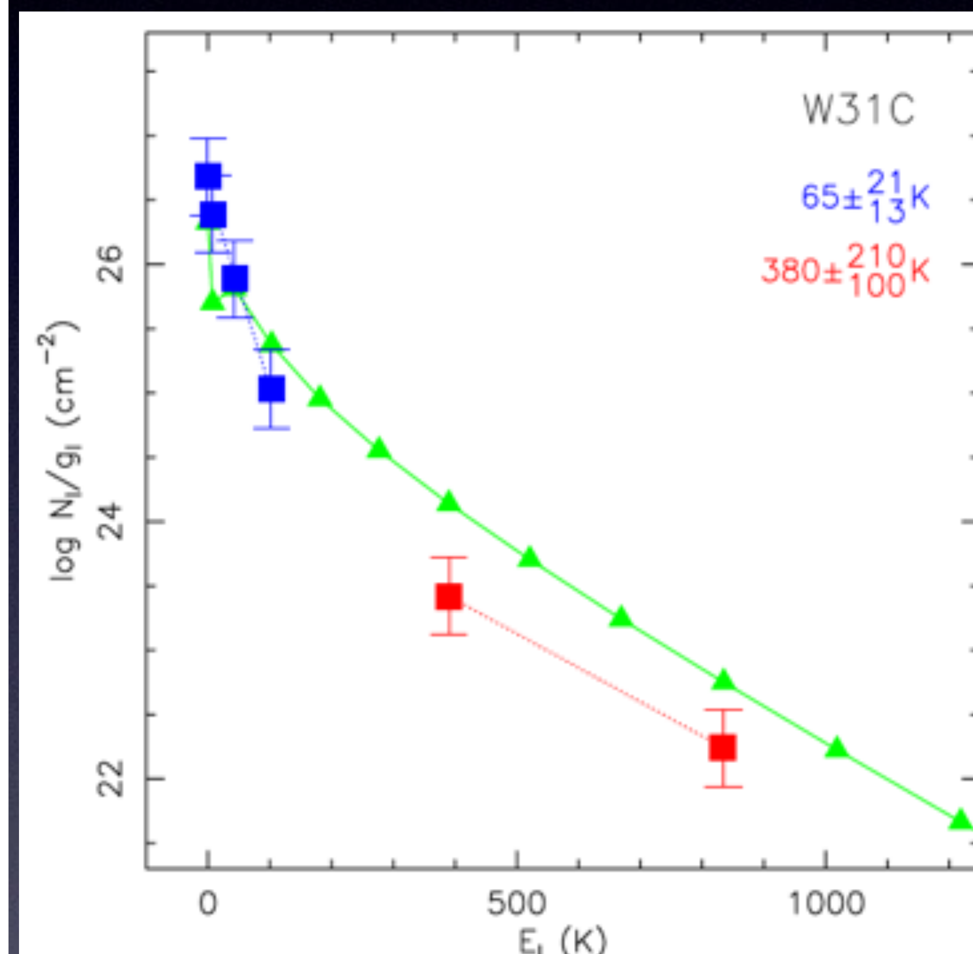
Metastable H_3O^+ in Sgr B2



- Unanticipated; shocked gas layer? Same T_{ex} in active galaxies (Arp 220)

Widespread Hot Gas Component?

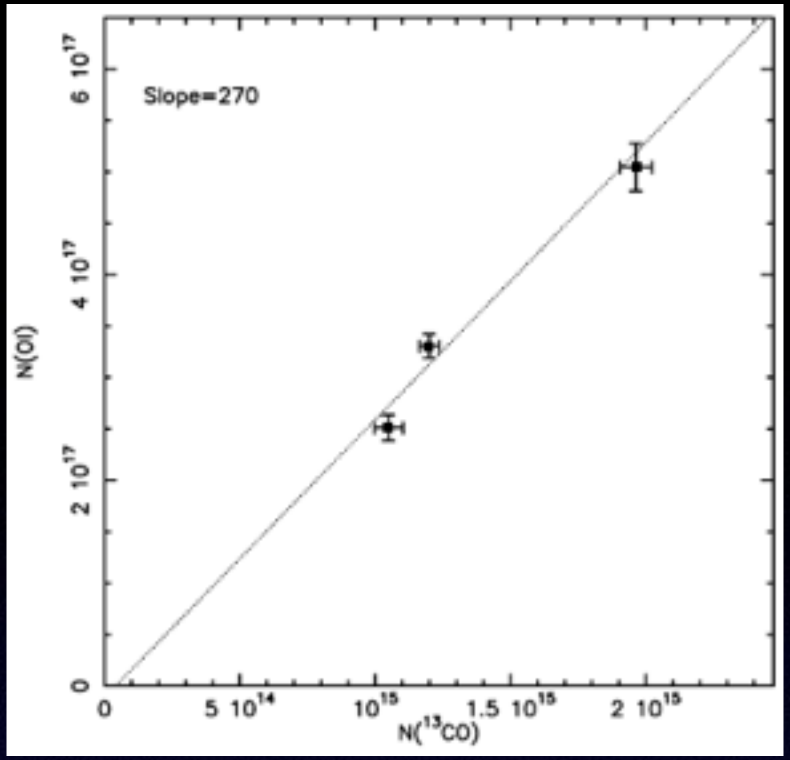


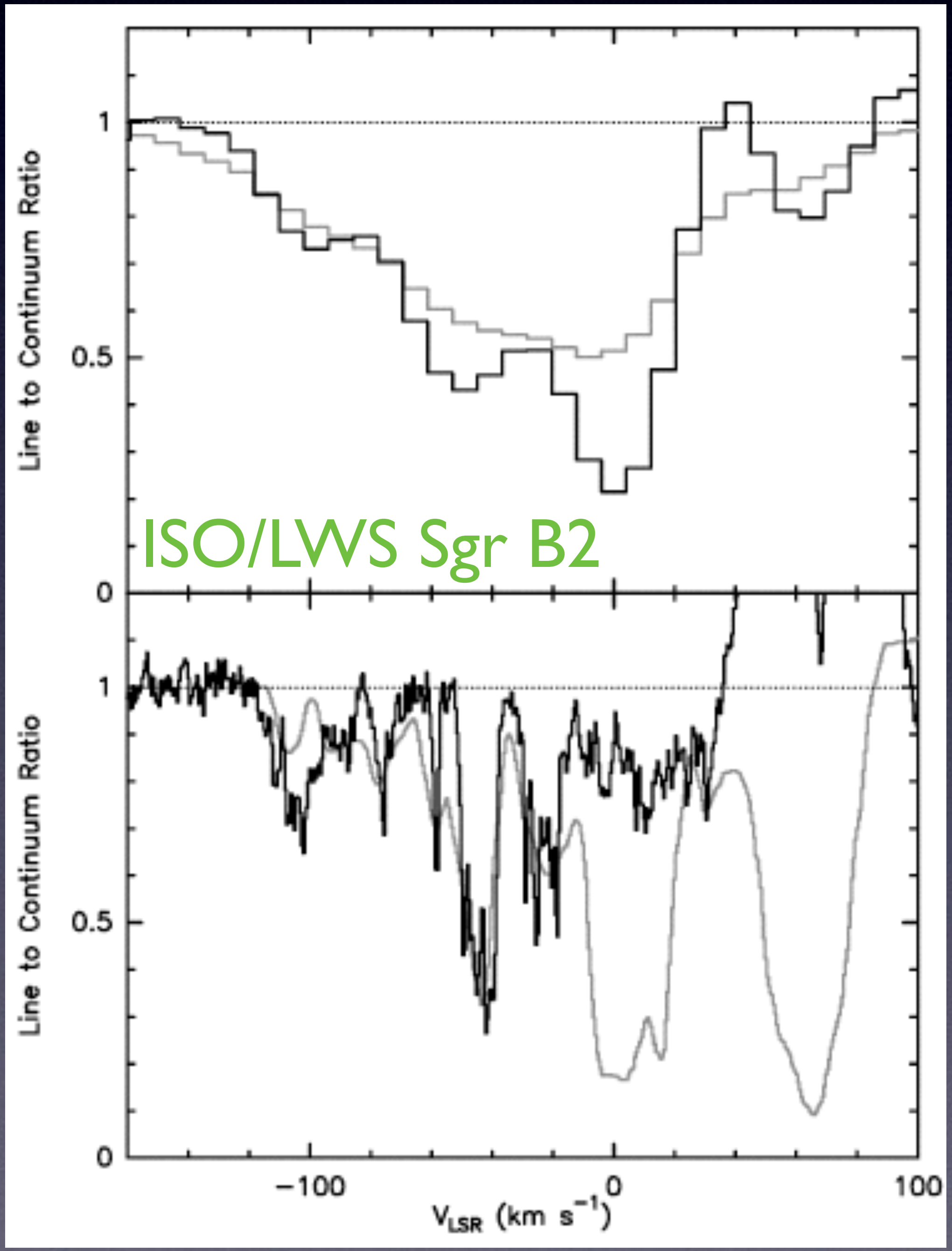


GC, Norma, Scuttum, Sagittarius Arm

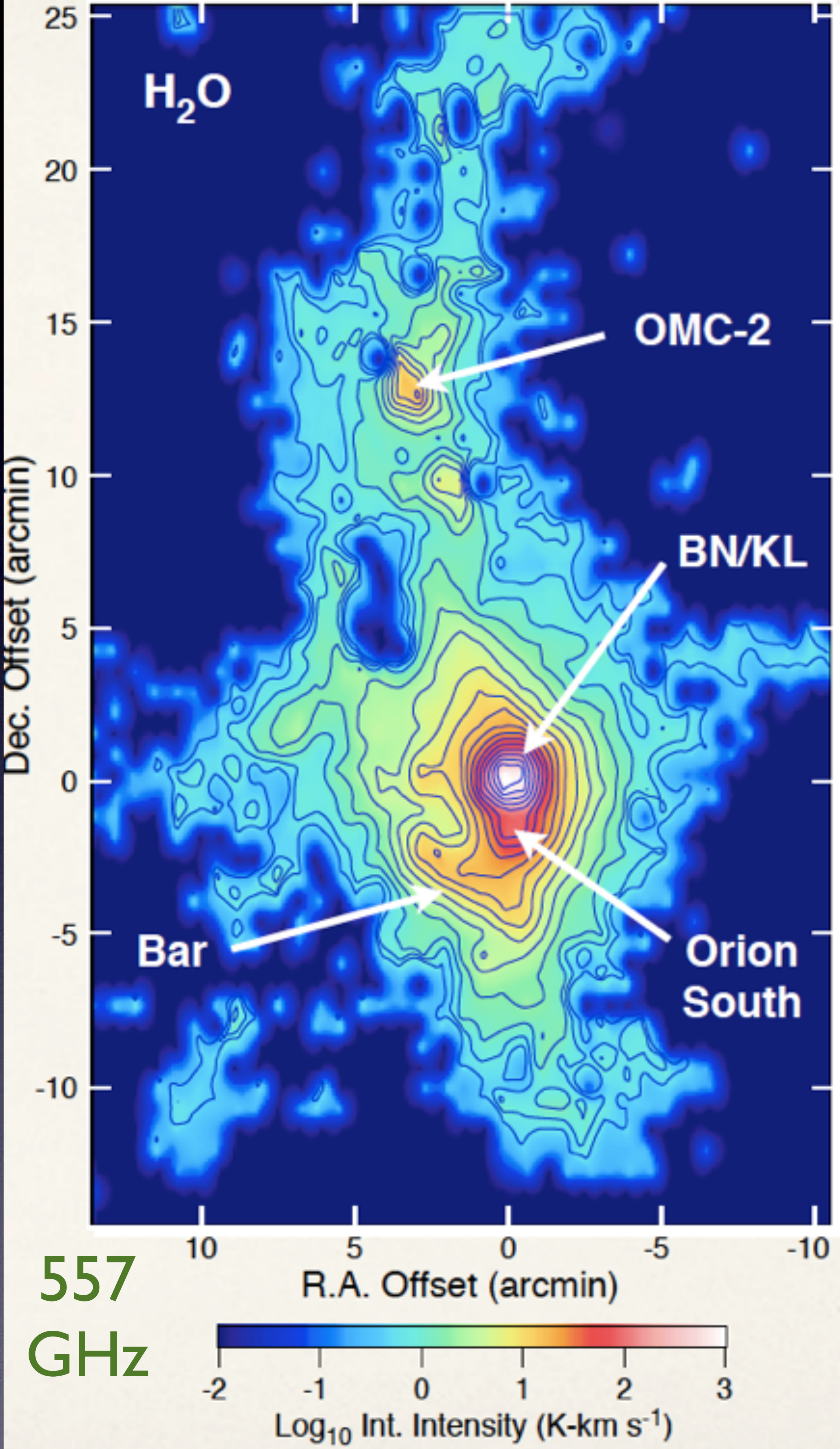
- Hot H_3O^+ not limited to "active" environments
- "Formation pumping" or a new phase of ISM?

Oxygen Budget



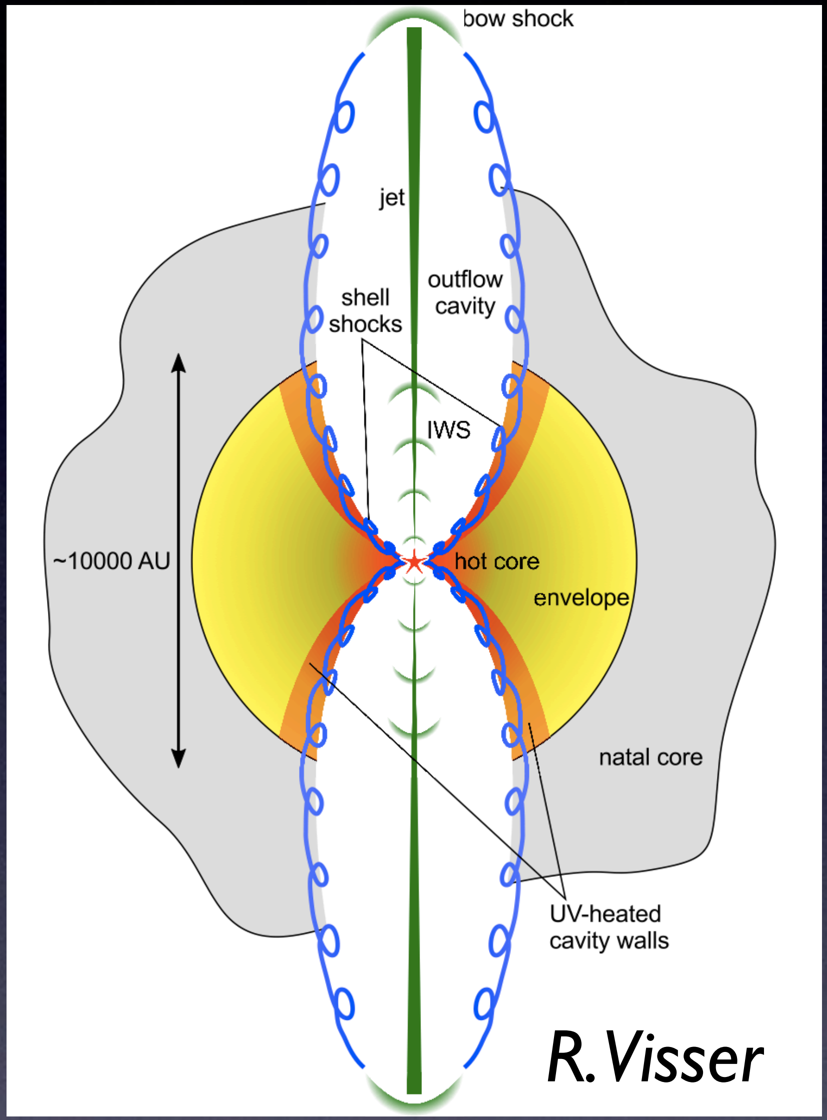


- Cosmic C/O abundance ratio ~0.5
- All C should be locked in CO, with plenty of O left for O_2, H_2O etc.
- O_2 abundance in the ISM is typically very low
- ISO/LWS: high OI abundances (a few 10^{-4}; OI/CO~10)
- In contradiction with recent laboratory measurements indicating a high O binding energy of ~0.15 eV
- Velocity-resolved OI 63 µm spectra needed (SOFIA/Up-GREAT)
- Herschel HF and CH spectra provide reference H_2 column densities



557 GHz

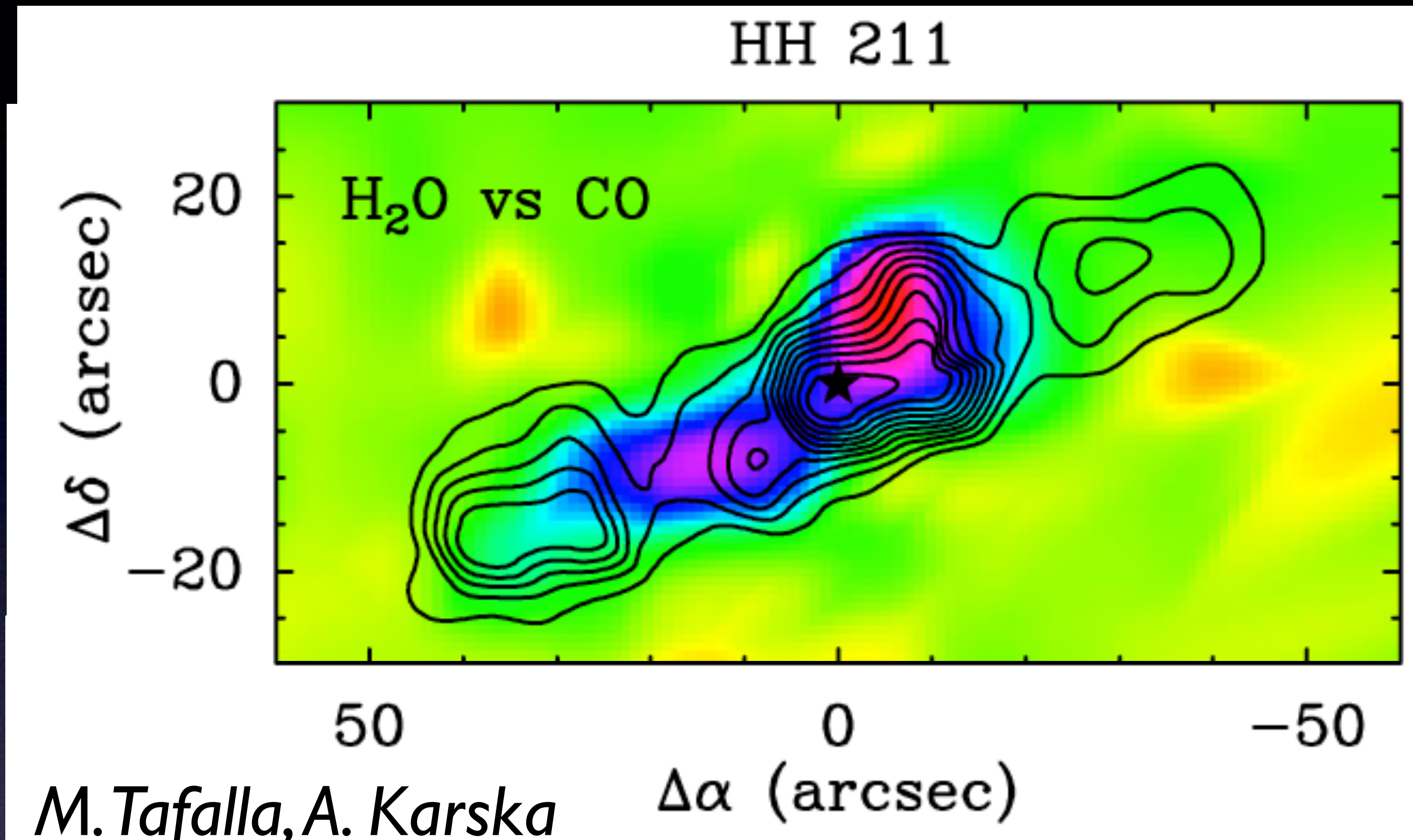
Water

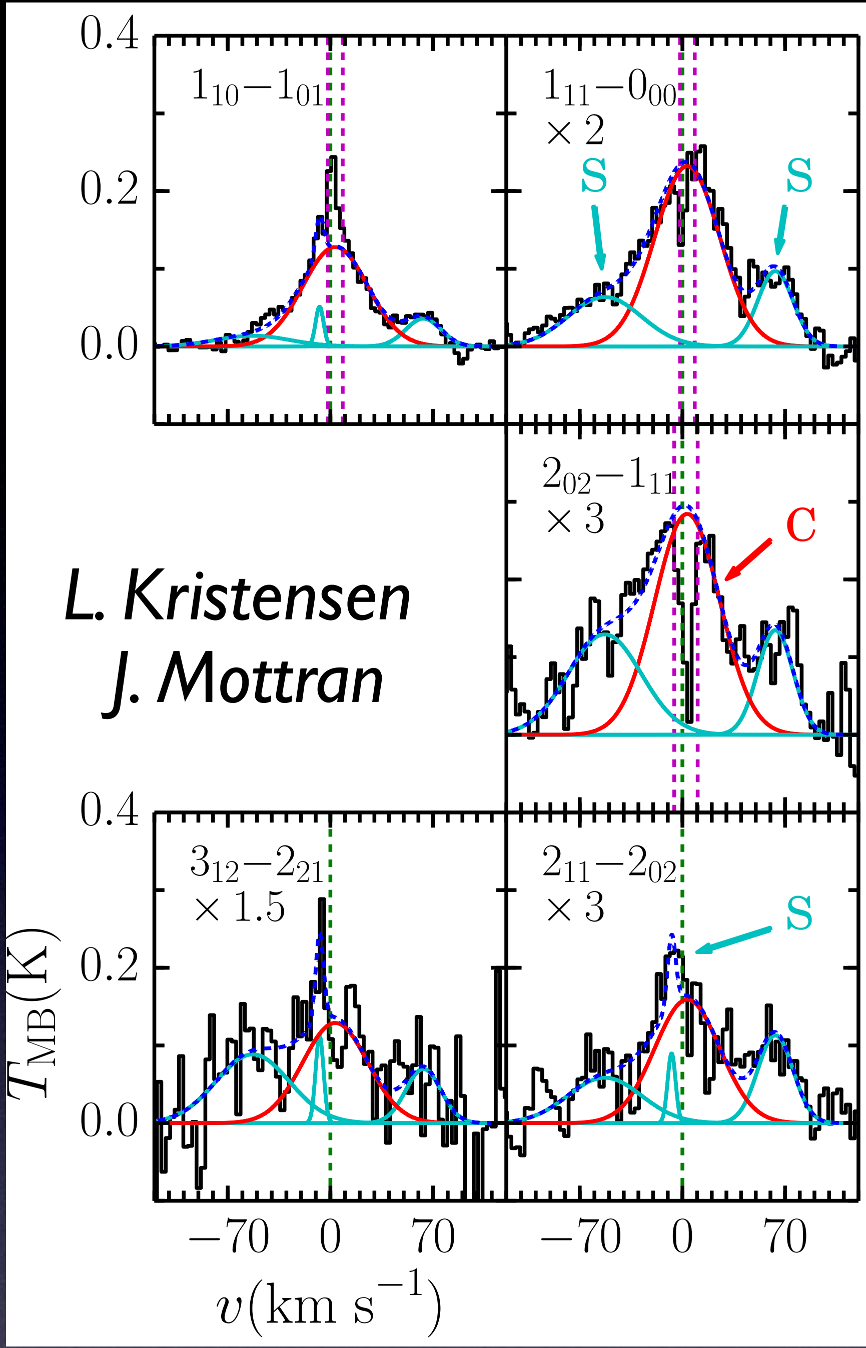


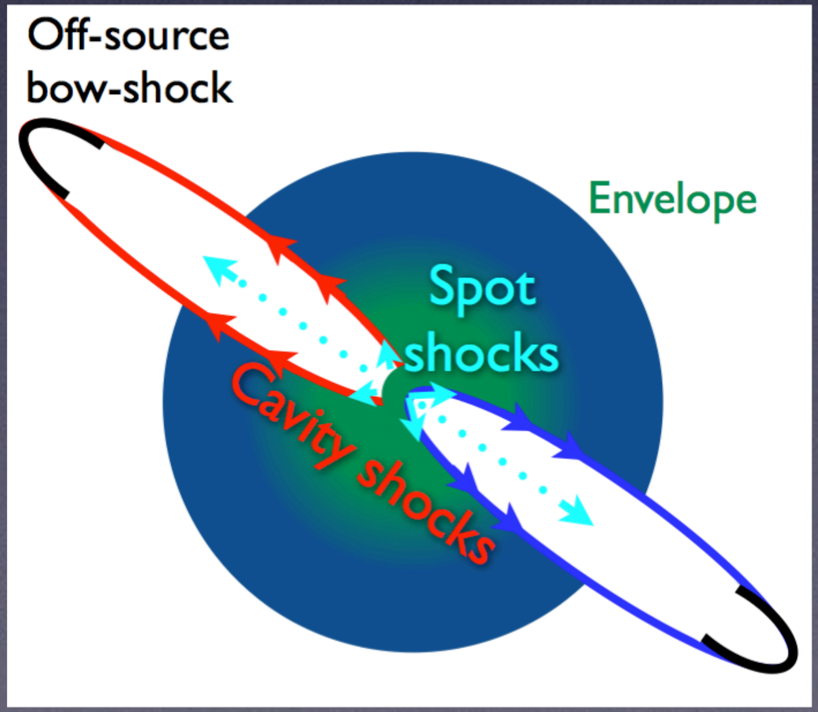
G. Melnick, V. Tolls

- Depletes on dust grains for T<100K
- Abundance enhanced in warm gas: outflows, hot cores
- Important for astrophysics, astrochemistry and astrobiology

Water — Outflows

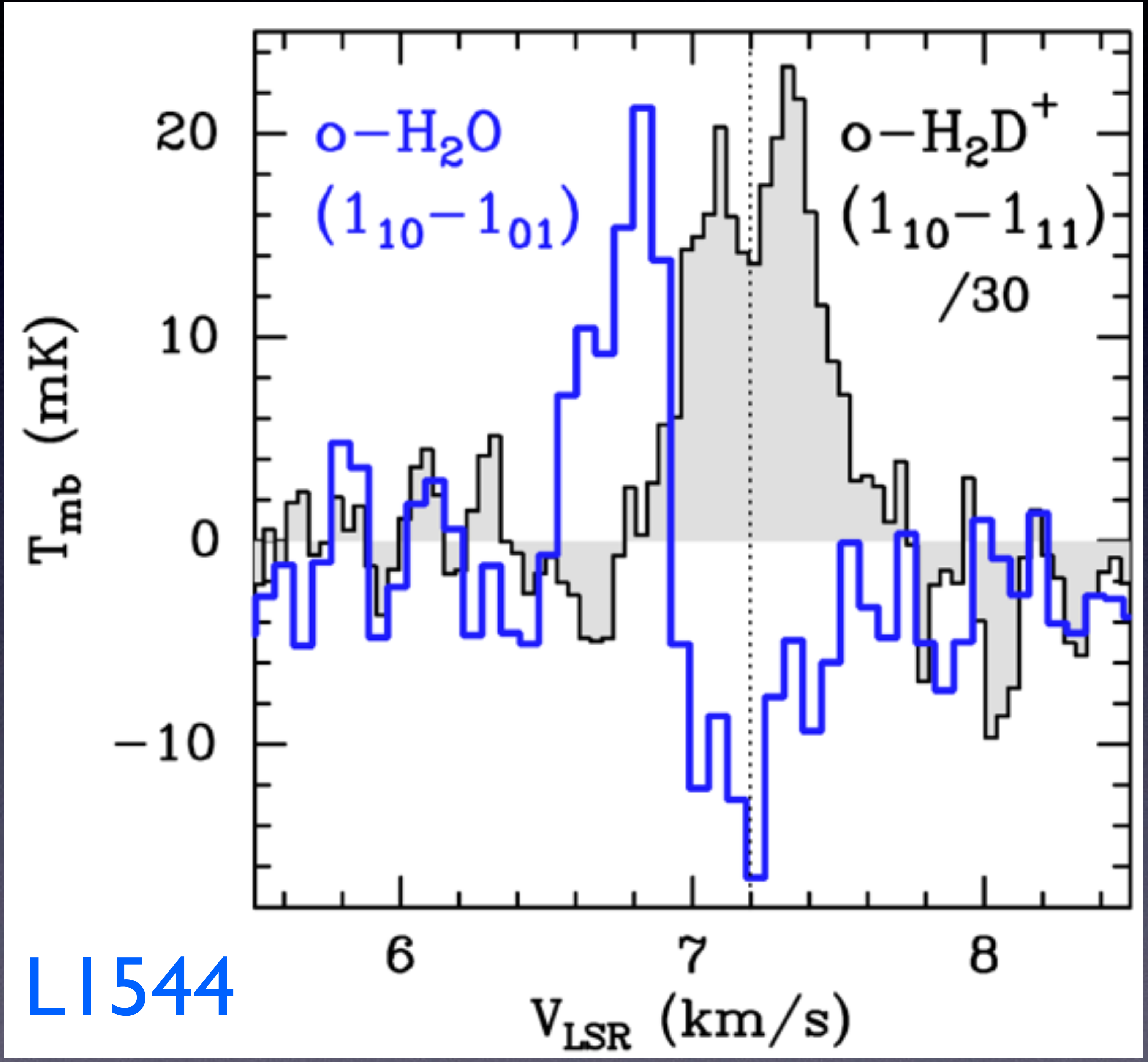






- Water and low-J CO trace different regions within the outflow—probing a new part of the protostellar system
- Complex line profiles—envelope emission/absorption, outflows, high-velocity bullets (spot shocks)
- Hot core and outflow water abundances often lower than the canonical value of 10^{-4} — oxygen budget?

Water — Prestellar Cores



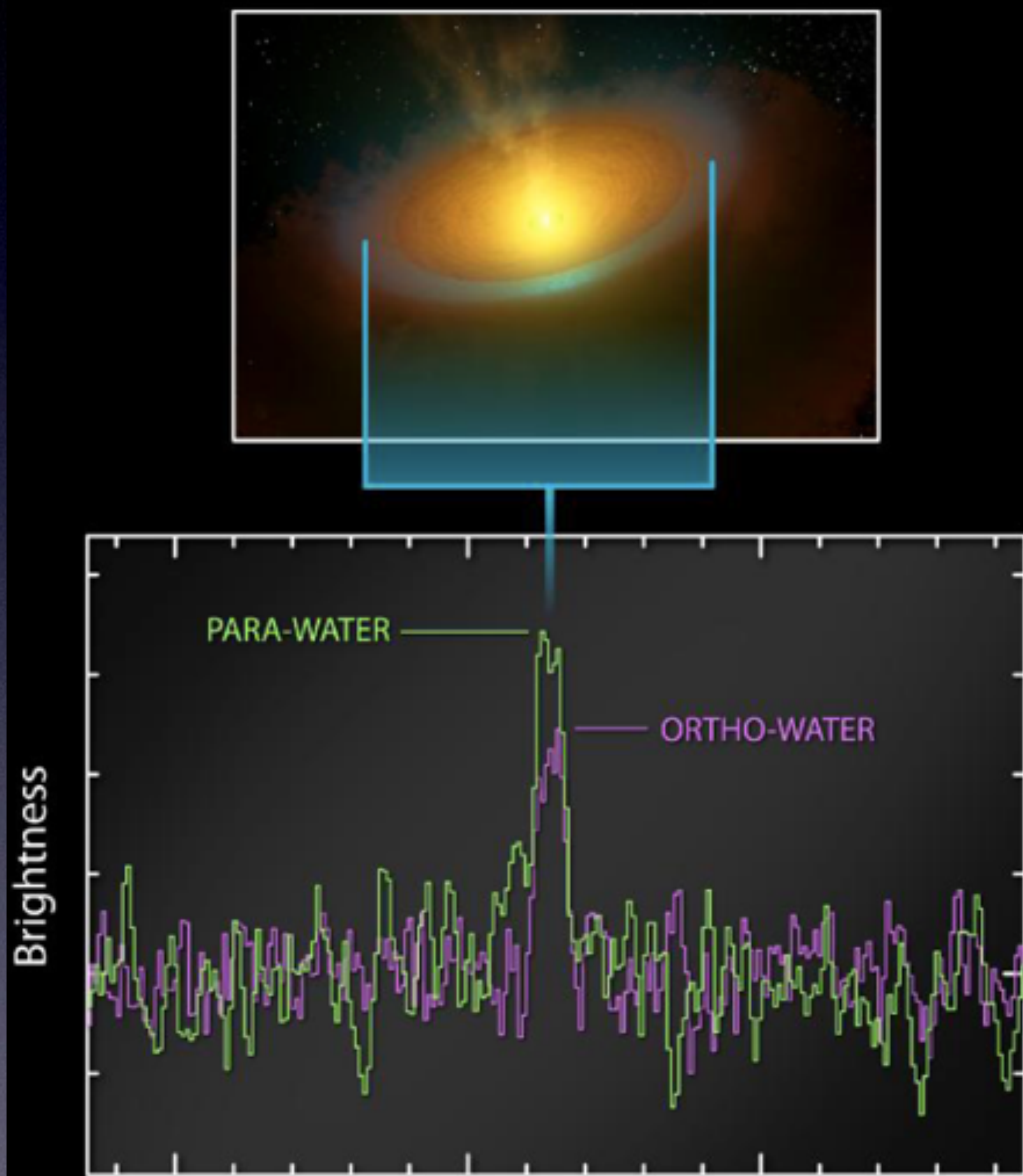
P. Caselli

- Inverse P-Cygni profile indicative of infall
- Water has to be present in the central few 1000 AUs
- Water abundance ($>10^{-9}$) maintained by FUV photons locally produced by interaction of CRs with H_2

- The simple "onion" structure of prestellar cores has to be carefully re-evaluated

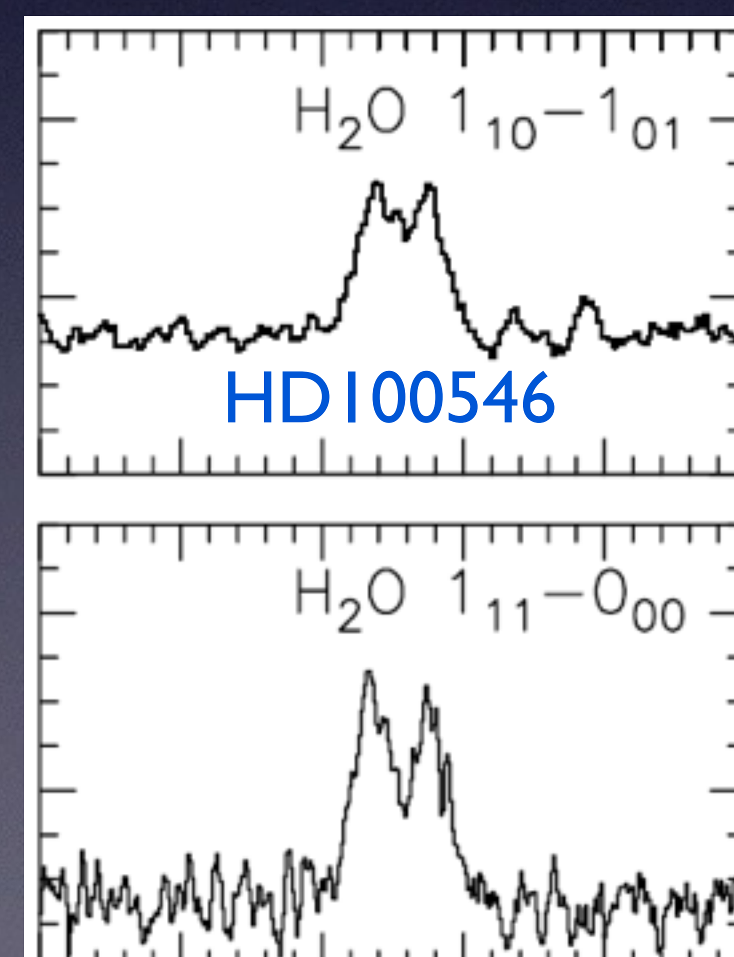
Water — Disks

TW Hya

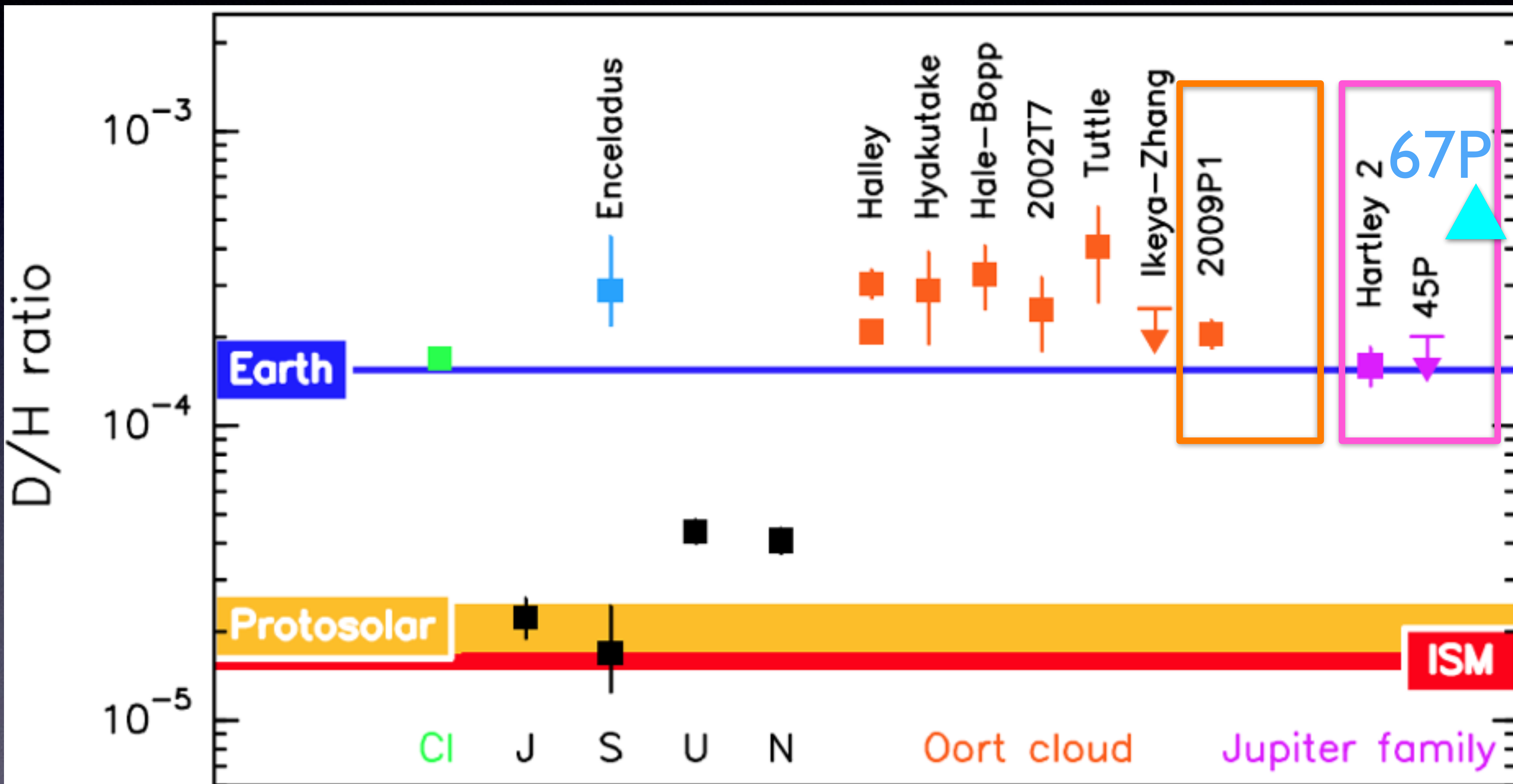


M. Hogerheijde

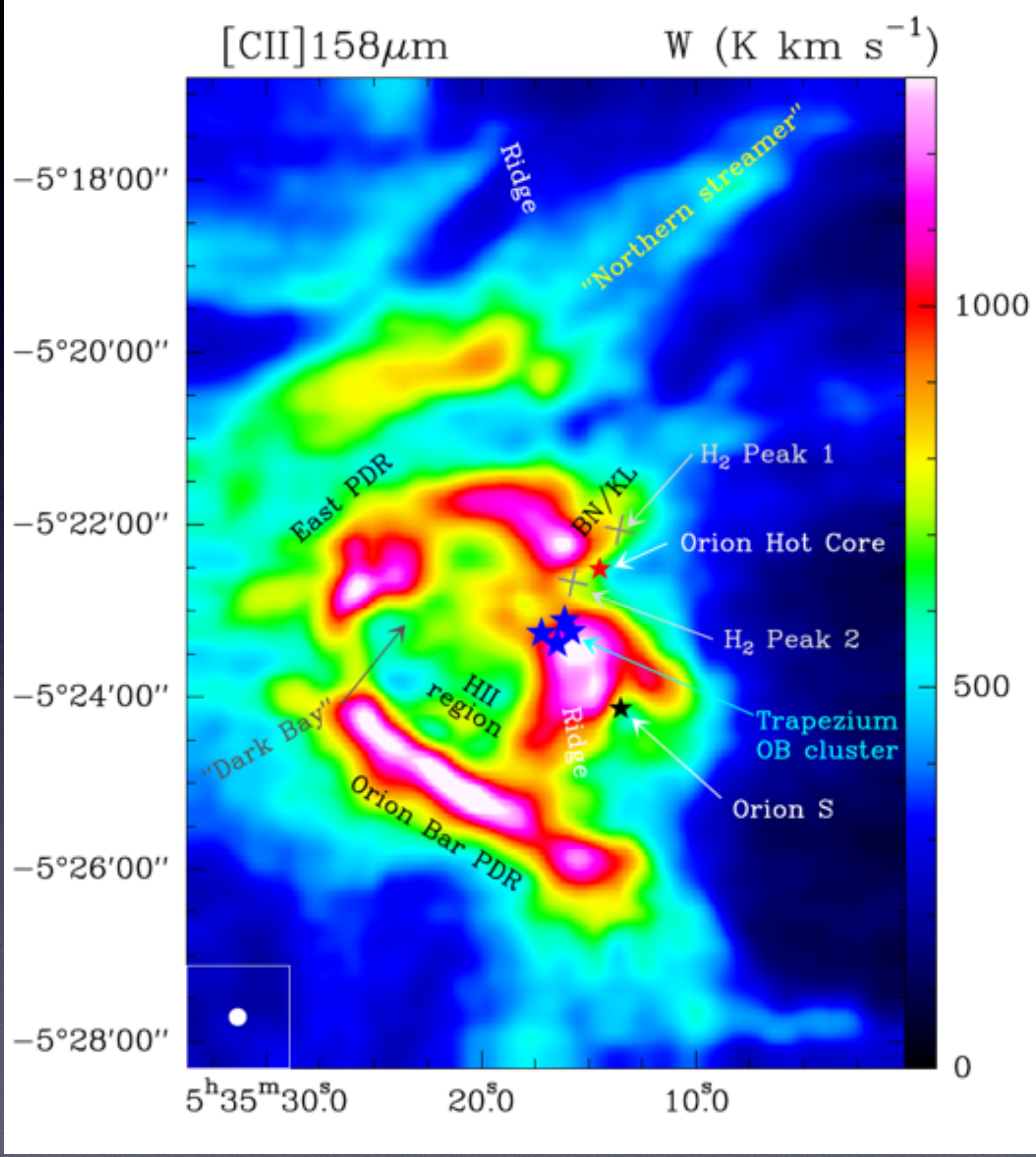
- Lines of ortho and para water detected for the first time with Herschel/HIFI in TW Hydrae
- 10 mln years old T Tauri star, 0.6 $M_\odot$ at 54 pc
- Several thousand oceans worth of *water ice*, at 100–200 AU from the star
- If other disks are similar to TW Hydrae, ample water exists in the outer disk, where comets form
- Some of them are, but not all



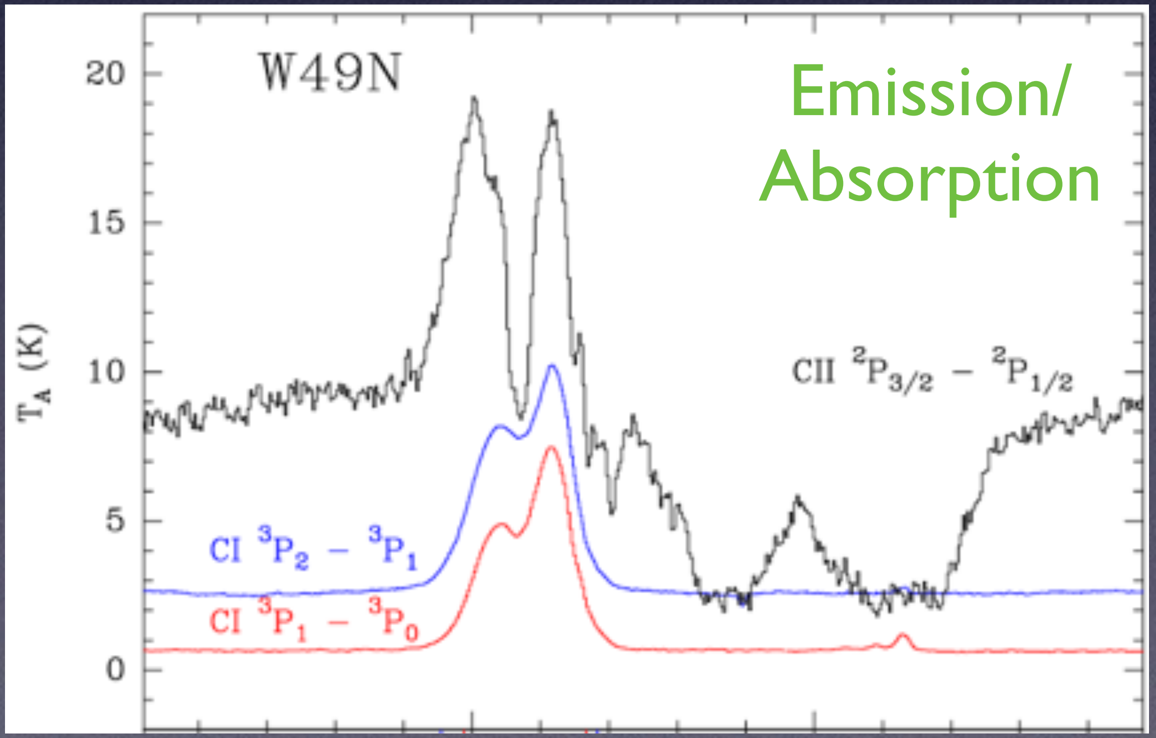
Water — Comets



CII Spectroscopy



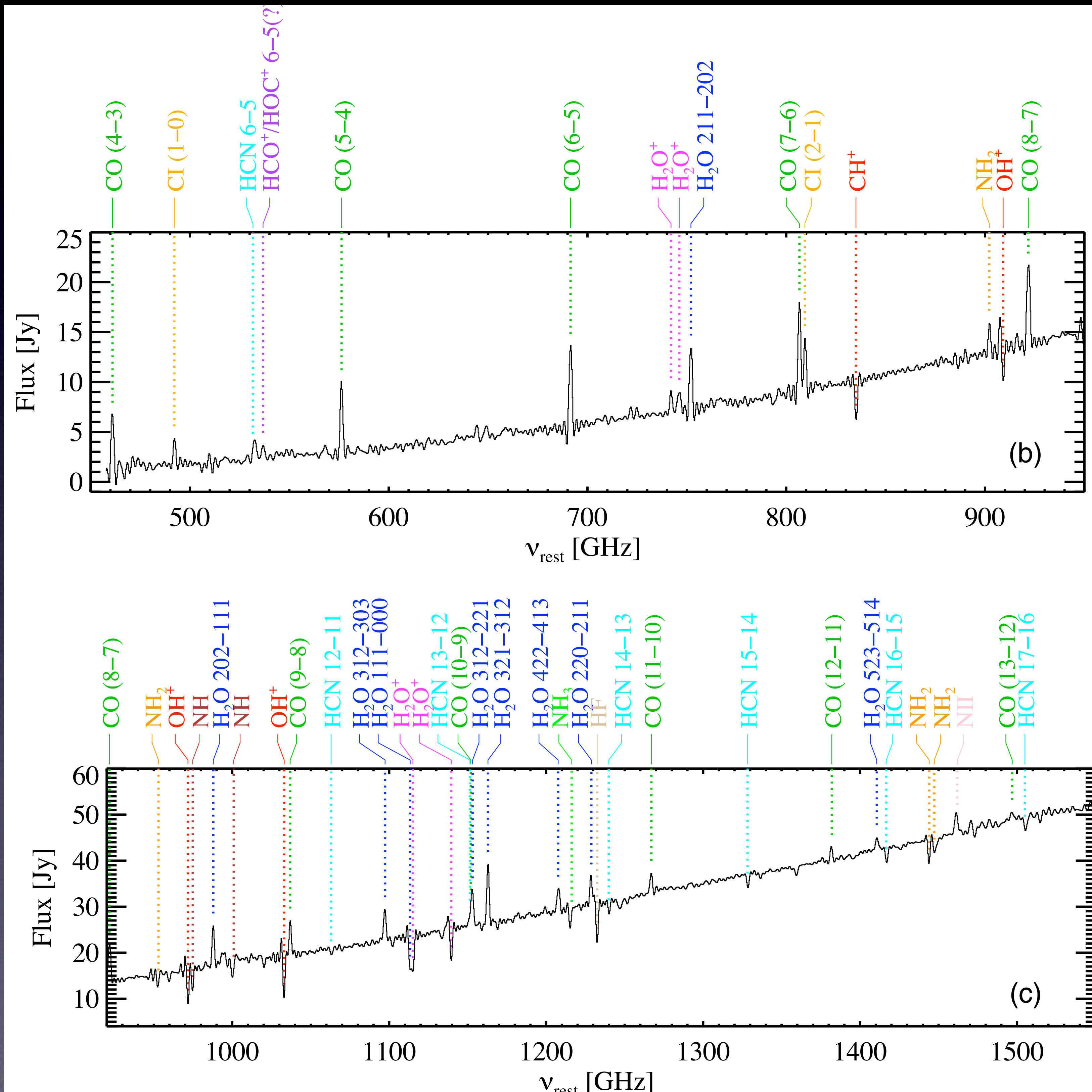
- Small-scale kinematics of the ionized/PDR/molecular gas interfaces and radiative feedback from massive stars
- 15% of CII without CO counterpart (CO dark gas)
- Strong variations of the $L[CII]/L_{FIR}$
- Lowest values reminiscent of the "CII deficit" in ULIRGs

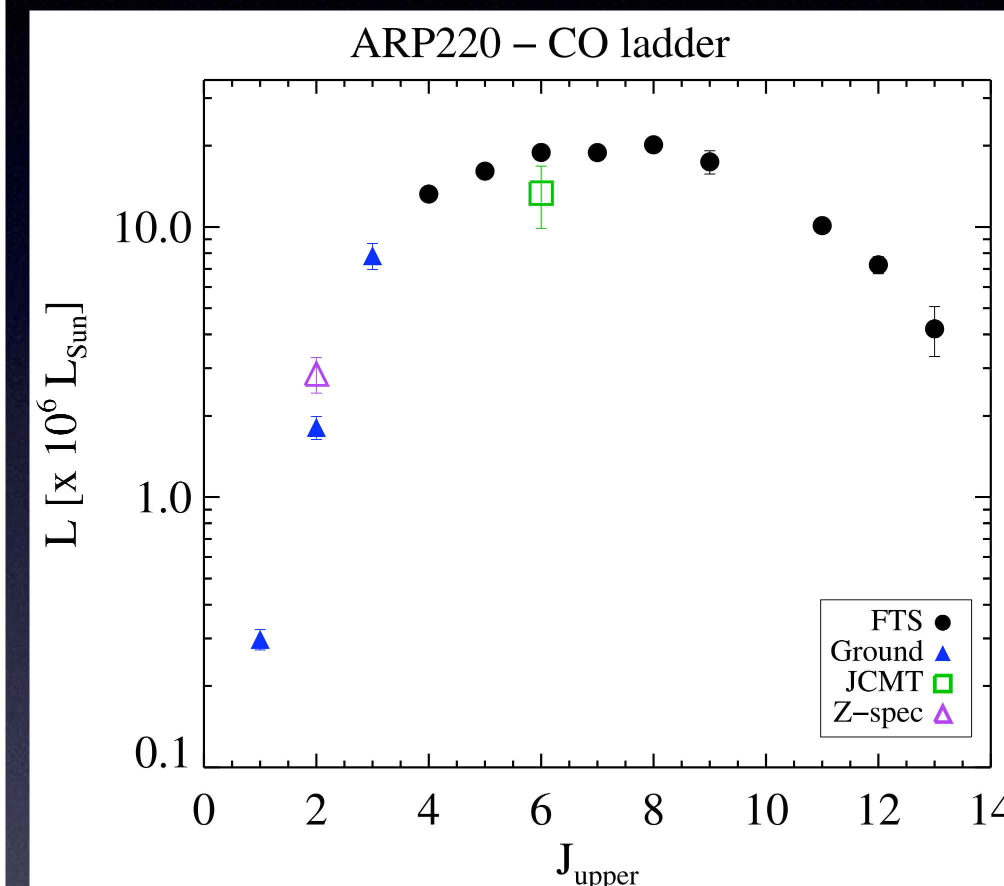


J.Goicoechea

M. Gerin

Extragalactic Spectroscopy





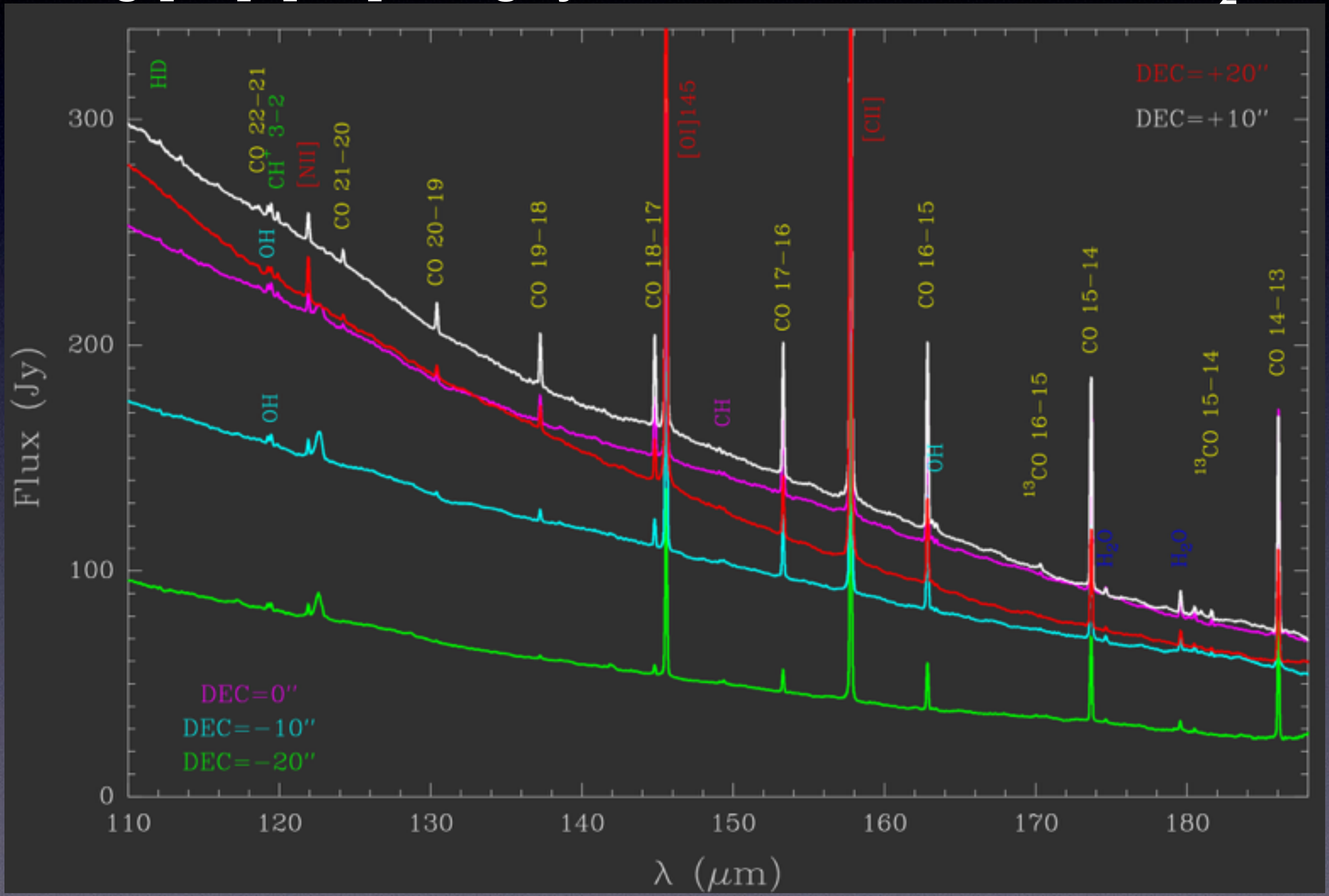
N. Rangwala

- SPIRE/FTS — CO SLEDs
- Such studies are no longer possible in the local Universe!

Low-Resolution Spectroscopy

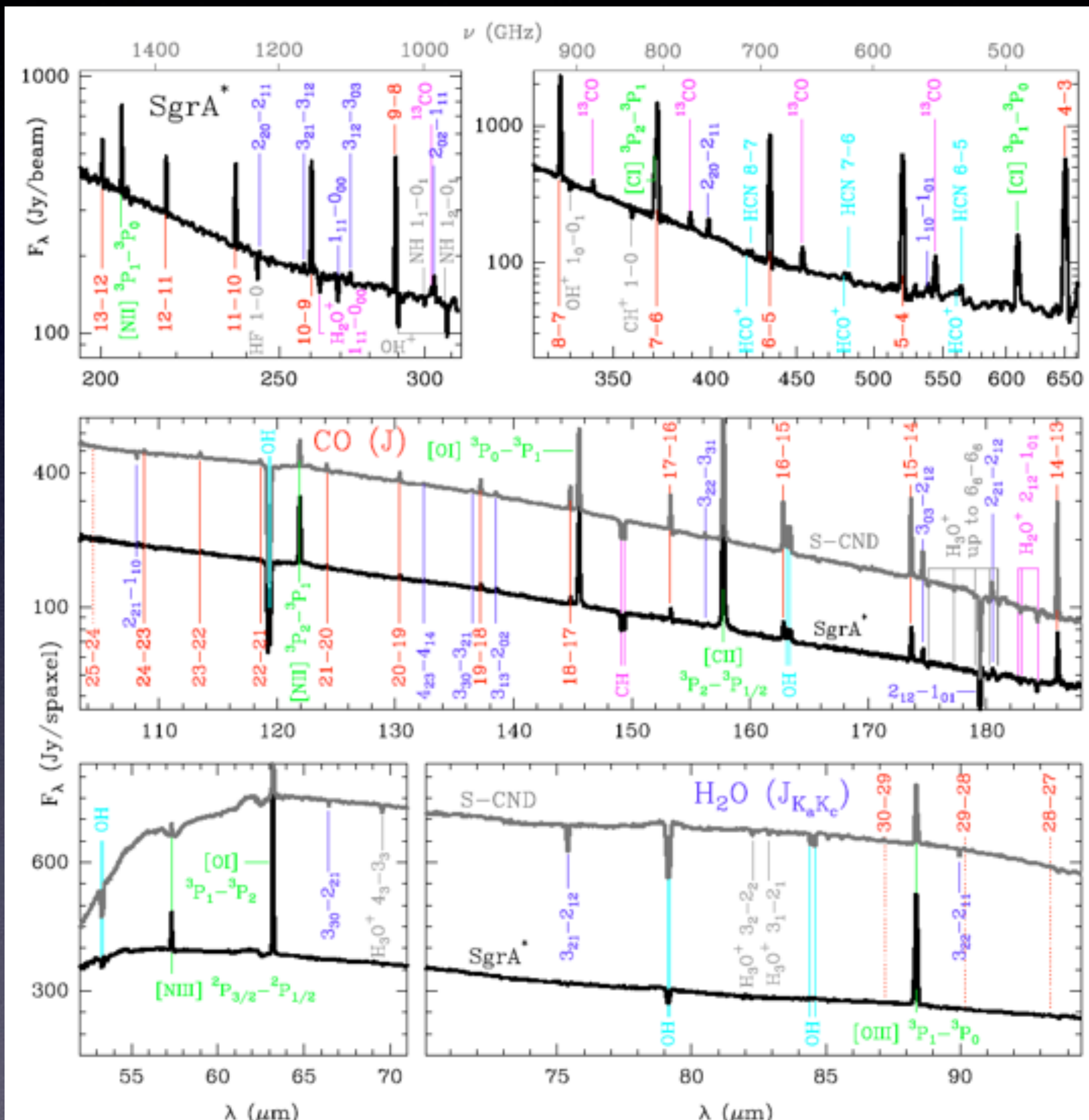
Orion Bar, PACS: Cooling and PDR Chemistry

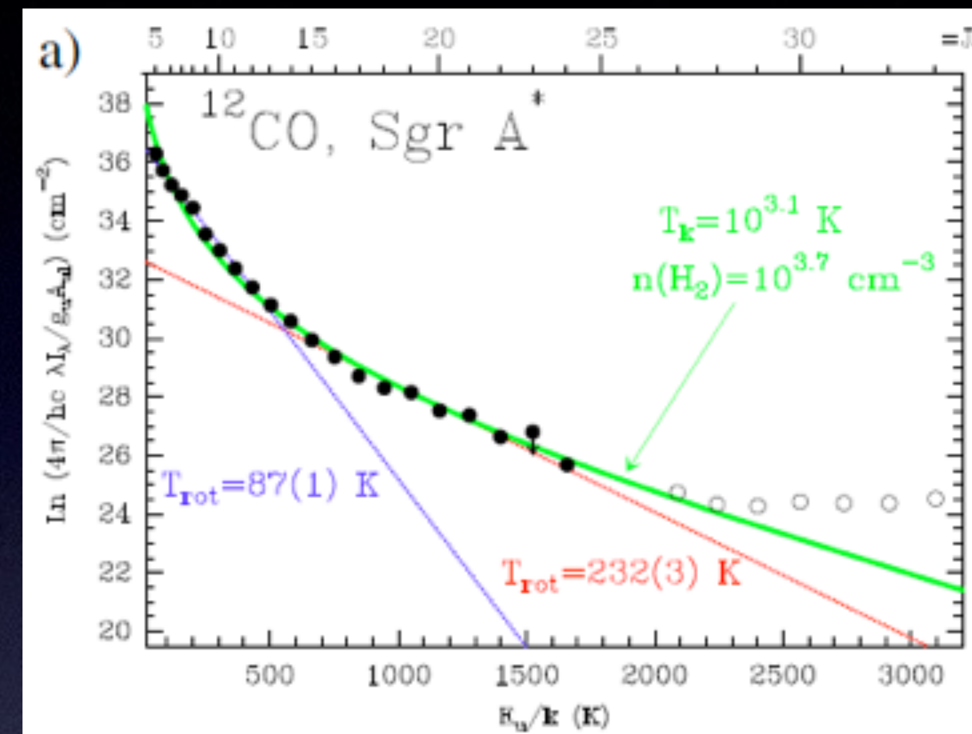
Strong [OI], [CII] + high-*J* CO + excited OH, CH^+, H_2O…



C. Joblin, J. Goicoechea, A. Contursi

PACS/SPIRE Sgr A*





- Separate emission from the central cavity and the CND
- X-rays or CRs do not play a dominant role in the energetics of the hot molecular gas
- Shocks or the related supersonic turbulence dissipation and magnetic viscous heating dominate

J. Goicoechea

Requirements: Spectral Resolution and Frequency Coverage

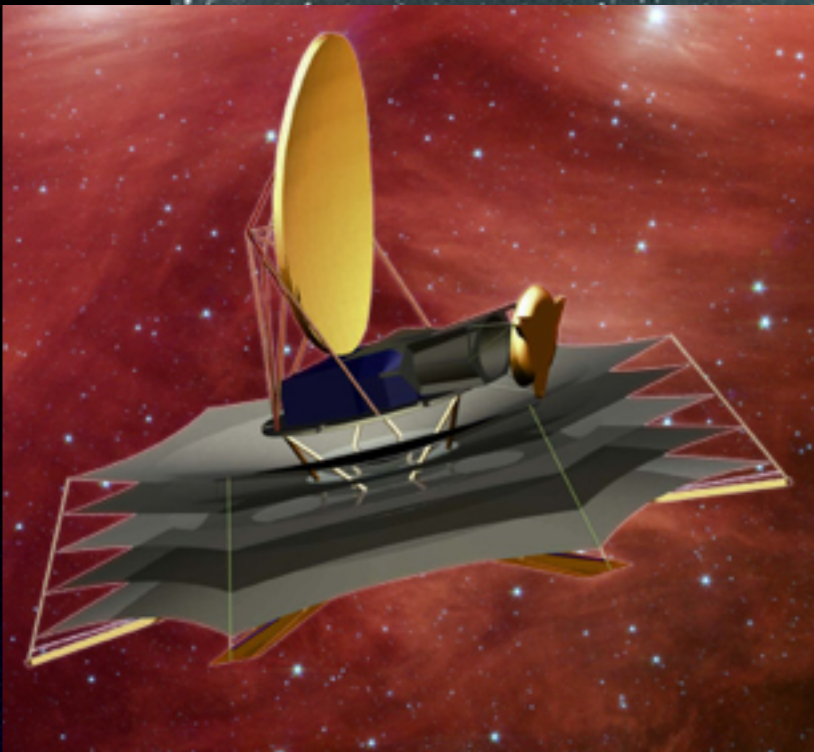
- Heterodyne instrumentation ($R \sim 10^6$) required to spectrally resolve the lines in the Galactic ISM and solar system objects and to separate emission and absorption components (lines widths <1 km/s)
- A direct-detection interferometer ($R \sim 3000$) does not satisfy this requirement — a heterodyne interferometer or a large single-dish telescope is needed
- JWST will not cover many key atomic fine structure and molecular lines (MIRI spectral coverage down to 28 µm, low spectral resolution)
- No need to cover the full spectral range
- Frequency coverage should be optimized to address the priority science goals (e.g., water isotopologues 500–570 GHz; many lines of interest at 900–1150 GHz; CII, H_3O^+ 1.6–1.9 THz; HD 2.7 THz, OI 4.8 THz)

Requirements: Angular Resolution and Mapping Requirements

- A factor of ~3 improvement in angular resolution compared to Herschel would be a big step forward (single dish), but <0.1" is required to resolve the snow line in disks (implies km baselines)
- A single pixel receiver largely sufficient for absorption studies (limited by the angular extent of the background continuum sources; ~a few arcs) and solar system observations
- Array receivers required for mapping the extended emission (e.g., water, CII, OI)
- Passively cooled surface sufficient for heterodyne spectroscopy (a follow-up "warm mission"?)
- Any space interferometer will need a large single-dish telescope element to provide the short spacings

Conclusions

- Herschel has left unanswered many questions concerning the chemistry of the Galactic interstellar medium (e.g., chlorine chemistry)
- A large single-dish telescope would have the sensitivity and angular resolution needed to address the specific open questions discussed here:
  - How does the cosmic ray ionization rate vary across the Galactic disk?
  - What is the oxygen budget in the ISM?
  - What is the origin of the hot (400–600 K) gas component in the Galactic and extragalactic ISM?
  - What is the water trail from the molecular clouds to the planets in habitable zone?
- Some of these questions can be addressed by SOFIA — what is the future?
- Science case for water particularly compelling — astrophysics + planetary science; cannot be done from SOFIA



Water: From Clouds to Oceans