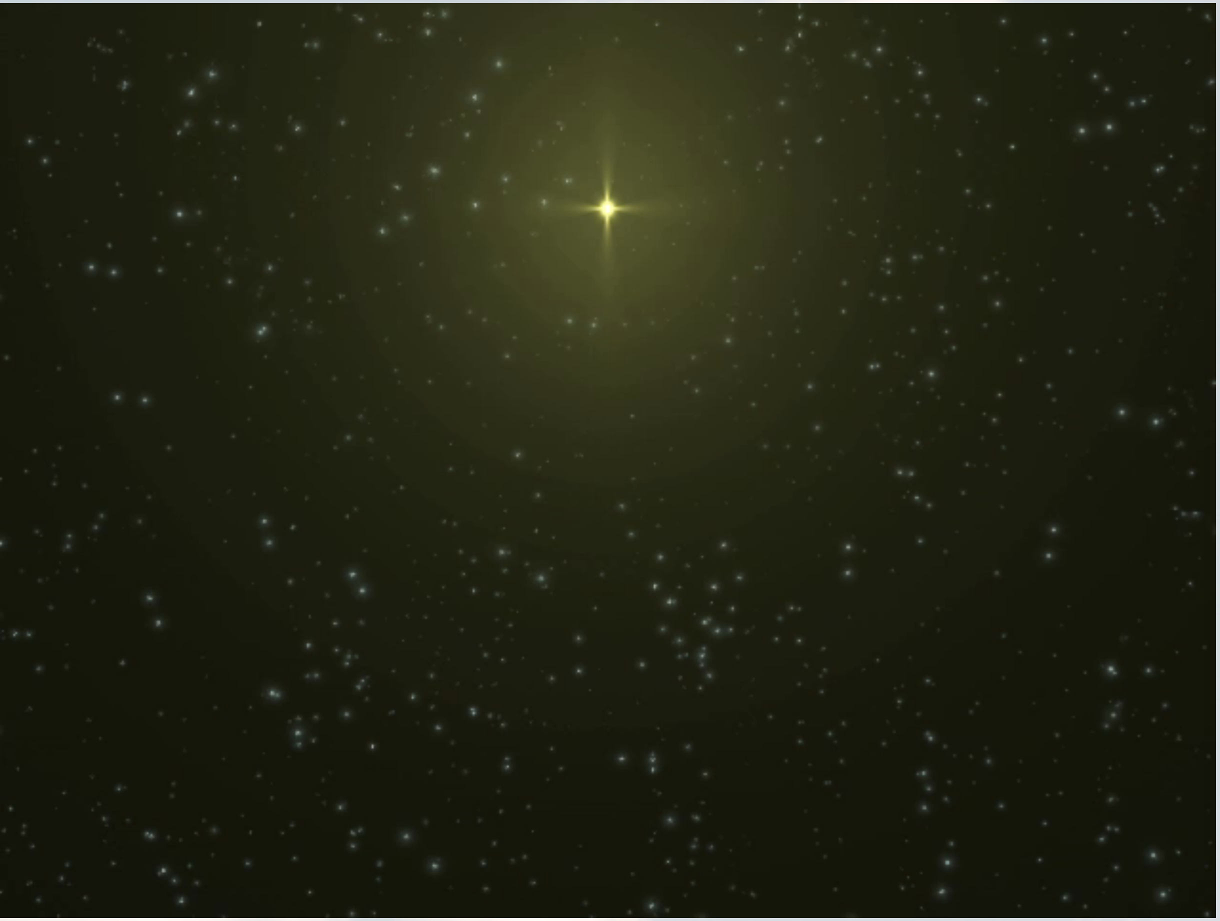
Hot, Metastable Hydronium Ion in the Galactic Center

Darek Lis (Caltech)

Peter Schilke (U. Cologne), Ted Bergin (U. Michigan), M. Emprechtinger (Caltech) and the HEXOS Team

Chicheley, February 10, 2012

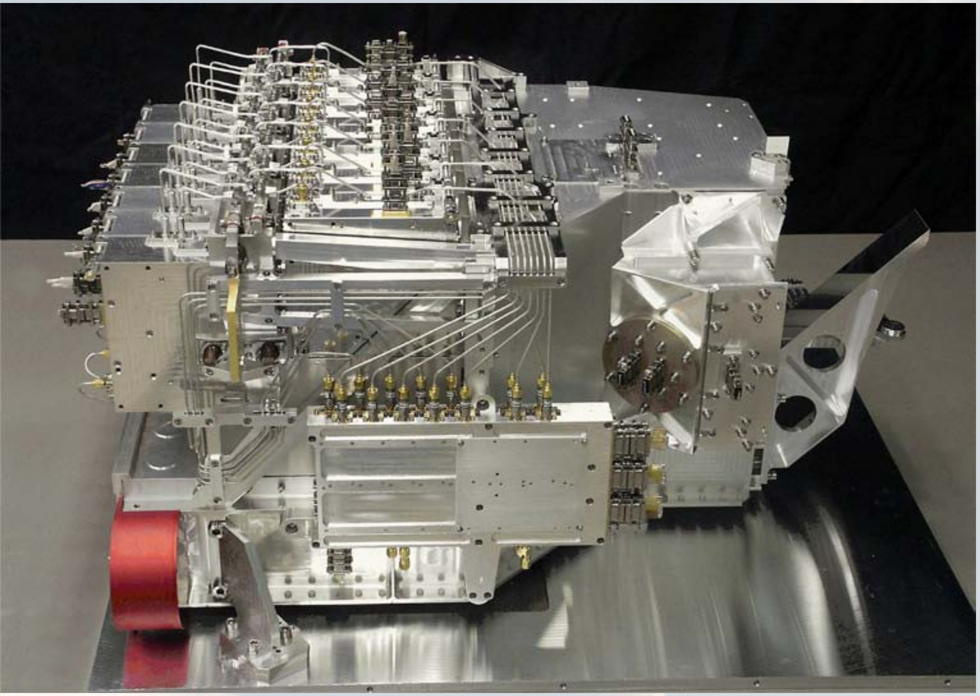
Herschel Space Observatory



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

- Launched on May 14, 2009; first space facility to completely cover the 60–670 μm spectral range
- Telescope: 3.5 m diameter, passively cooled to ~80 K
- Larger telescope than other missions (IRAS, ISO, SWAS, Spitzer, Akari…)
- Orbit: Lissajous around L2; very stable and low background
- Colder aperture, better 'site', more observing time than balloon or airborne instruments
- Lifetime: >3 years (until early 2013)
- Three cryogenically cooled instruments, PACS, SPIRE (bolometers), and HIFI (heterodyne)
- All three instruments have spectroscopic capabilities

Heterodyne Spectroscopy: HIFI

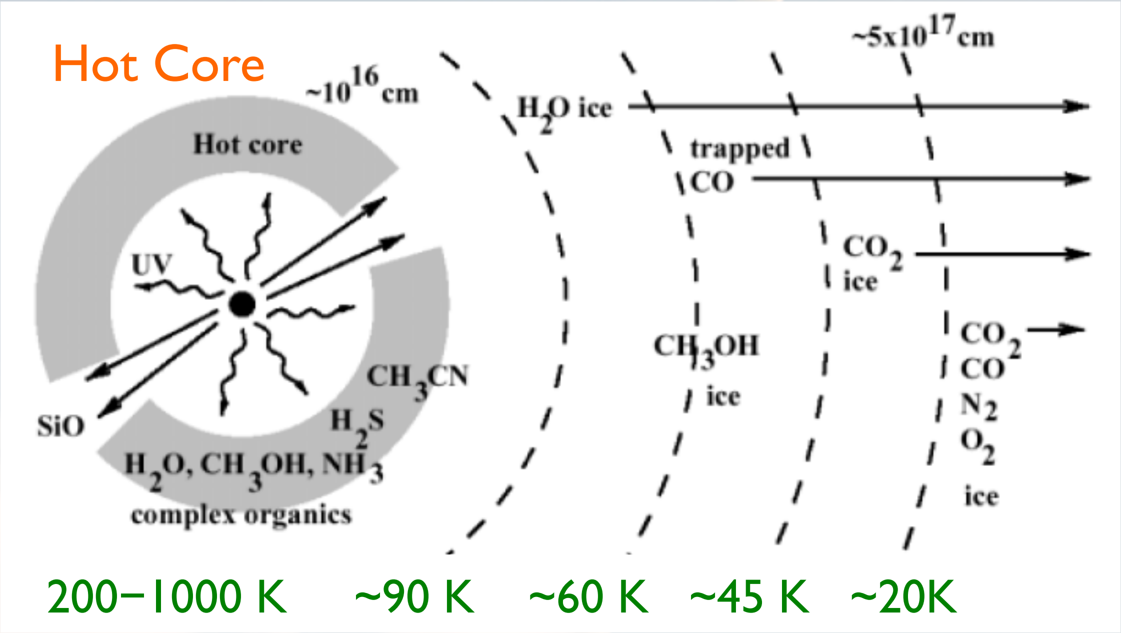


- Heterodyne spectrometer
- Wide frequency coverage:
  - Bands 1–5 (SIS mixers) : 480–1250 GHz (625–240 μm)
  - Bands 6-7 (HEB mixers): 1410–1910 GHz (212–157 μm)
- Wide instantaneous IF bandwidth:
  - 4 GHz in 2 polarizations (2.4 GHz for Bands 6-7)
- High frequency resolution:
  - WBS: 1 MHz (0.63 km/s at 480 GHz, 0.16 km/s at 1910 GHz)
  - HRS: 140/280 kHz
- High sensitivity (state of the art mixers; T_{sys}~160—2500 K SSB)
- Powerful line survey machine!

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

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 ("hot cores")
- Complex, high-T chemistry, molecules evaporating from grain mantles (e.g., methanol, methyl formate, dimethyl ether…)

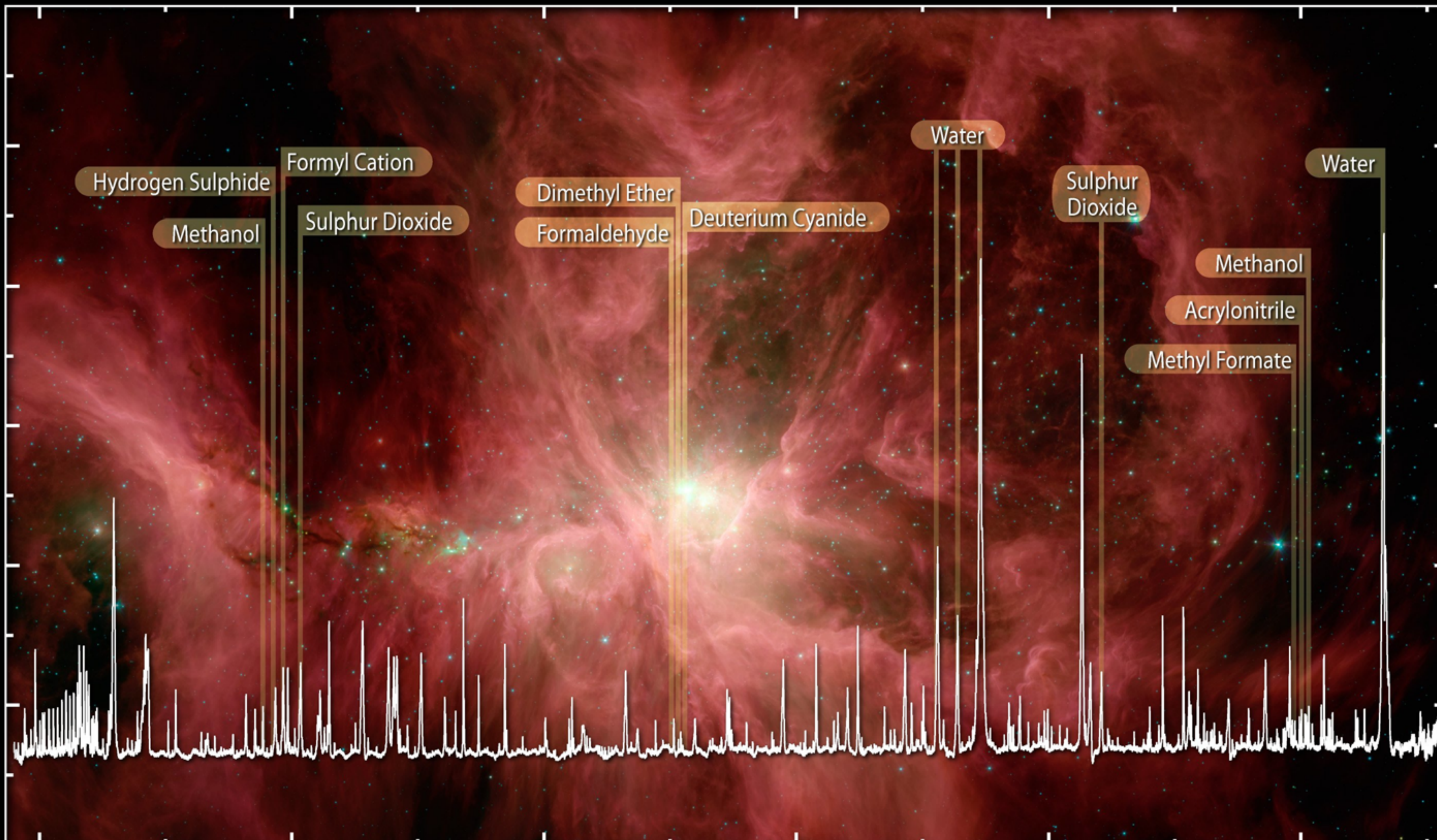


van Dishoeck et al. 1998

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

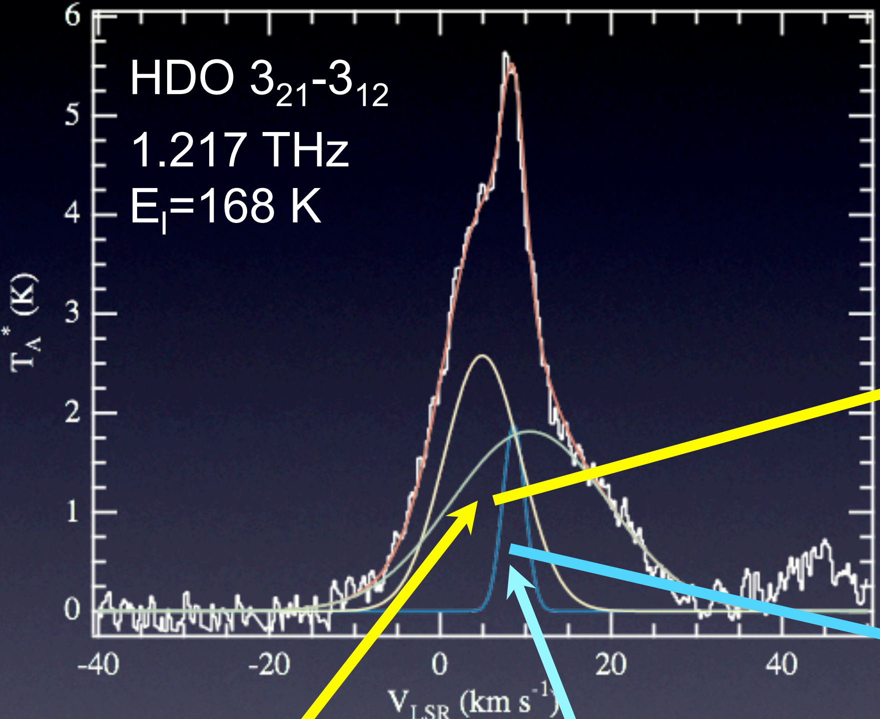


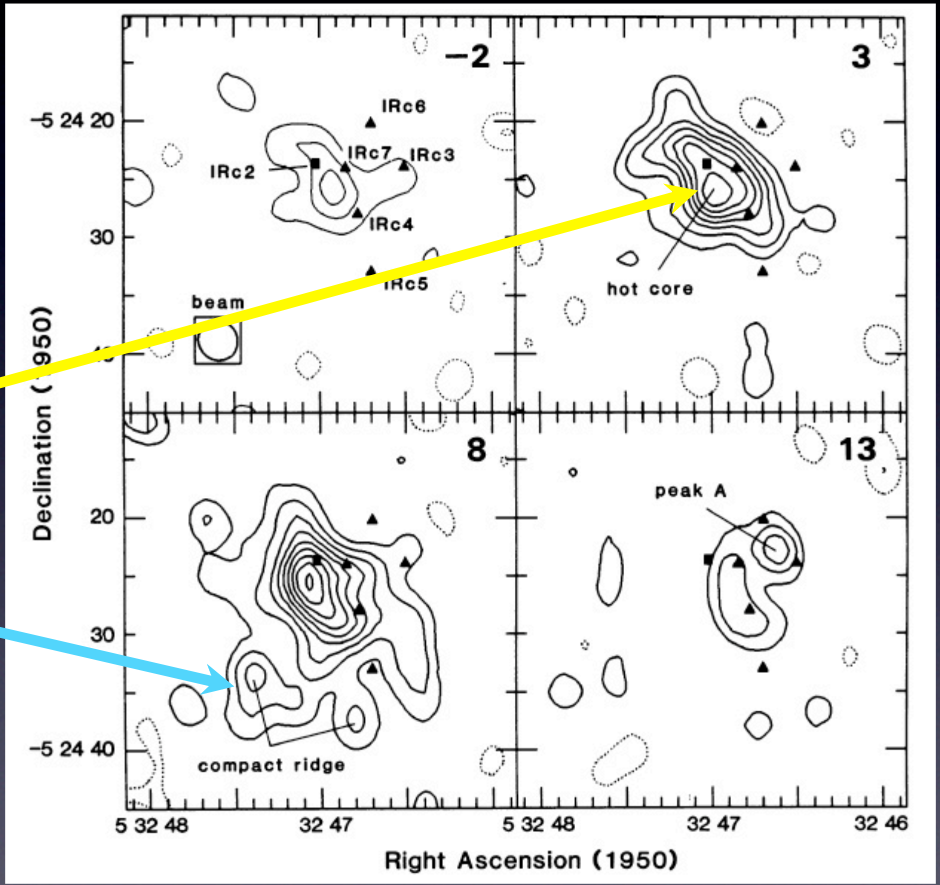
HIFI Spectrum of Water and Organics in the Orion Nebula

E. Bergin

Spatial/Velocity Structure

Plambeck & Wright 1987



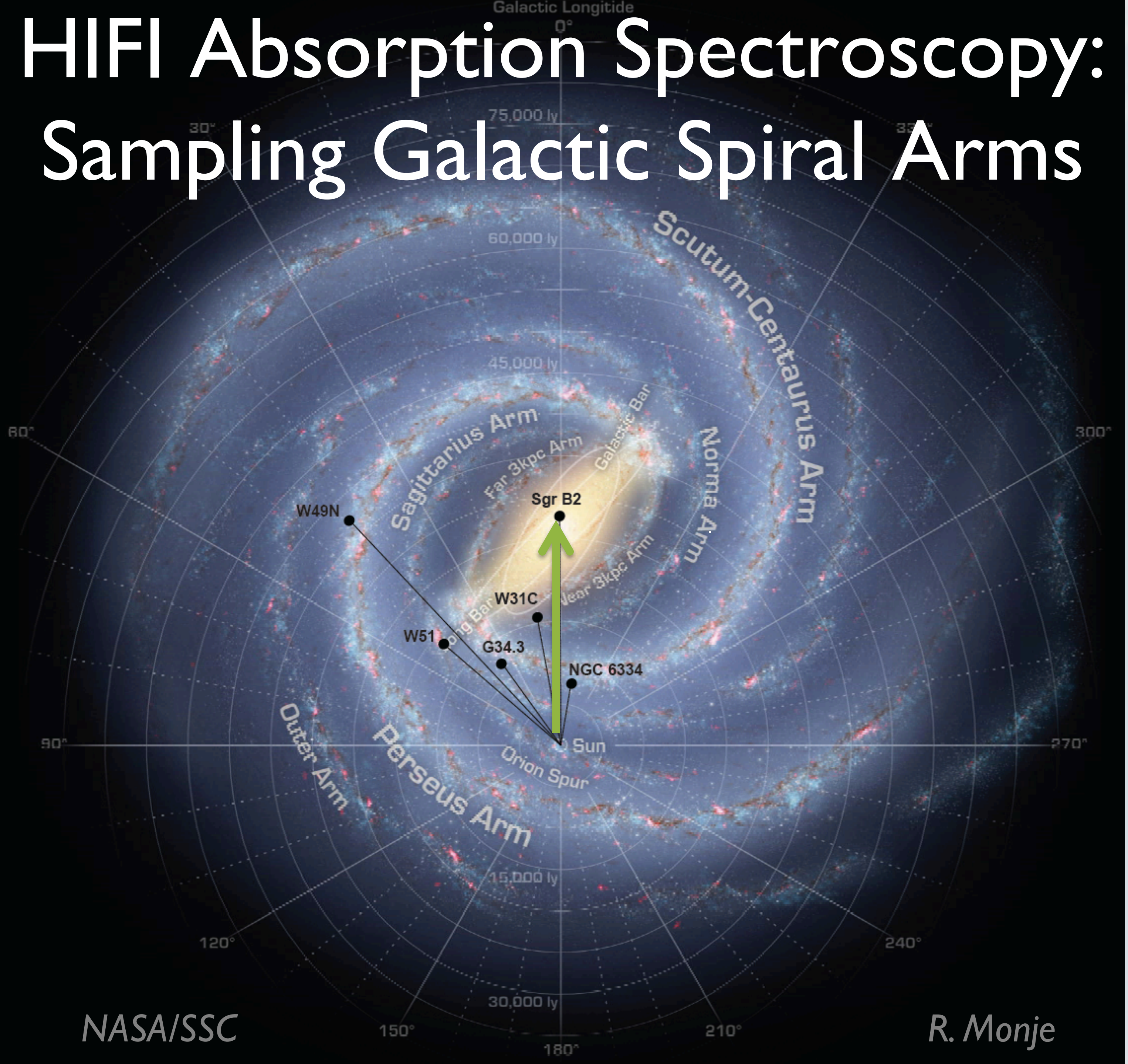


Hot Core
5 km/s

Compact Ridge
9 km/s

HEXOS: E. Bergin

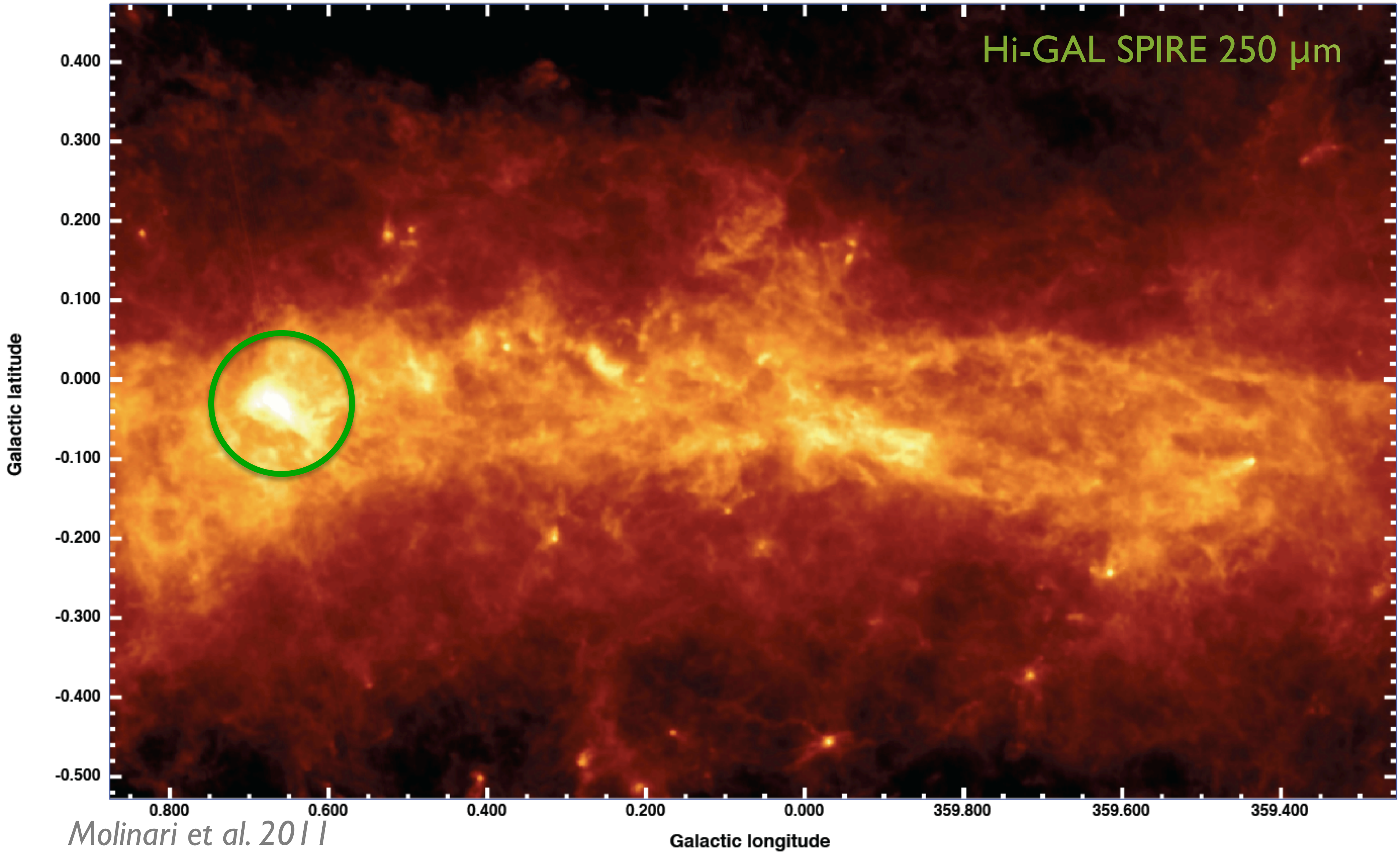
HIFI Absorption Spectroscopy: Sampling Galactic Spiral Arms



Hydrides

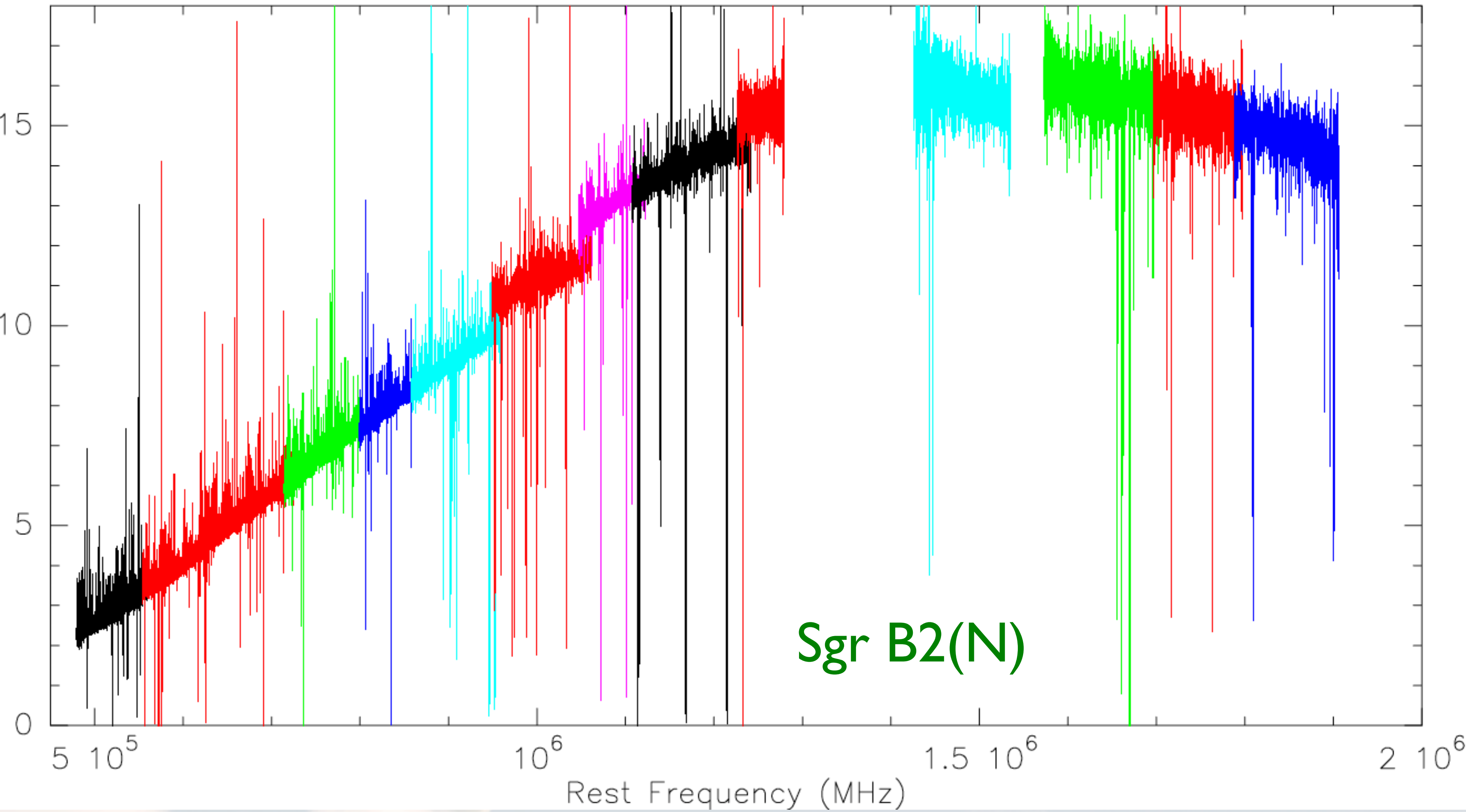
- OH^+
- H_2O^+
- H_3O^+
- H_2O
- HDO
- HF
- CH^+
- CH
- H_2S
- SH^+
- NH
- ND
- NH_2
- NH_3
- HCl
- HCl^+
- H_2Cl^+
- …
- *NH^+*

Herschel View of the Galactic Center



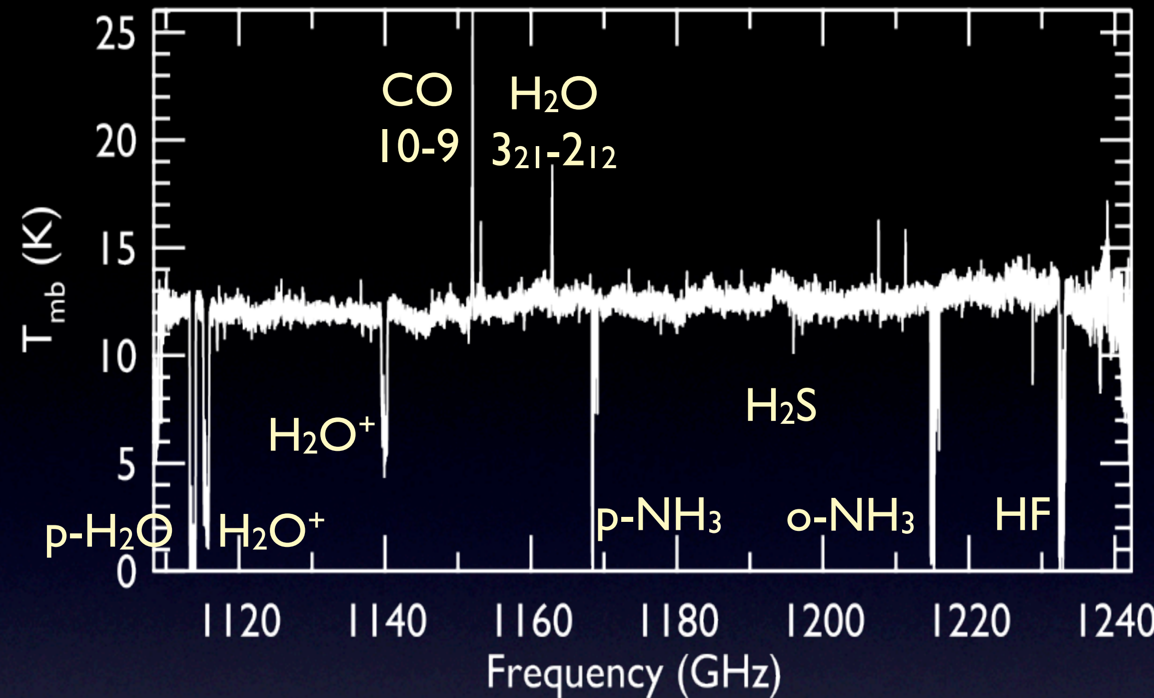
Molinari et al. 2011

HEXOS Sagittarius B2 Program

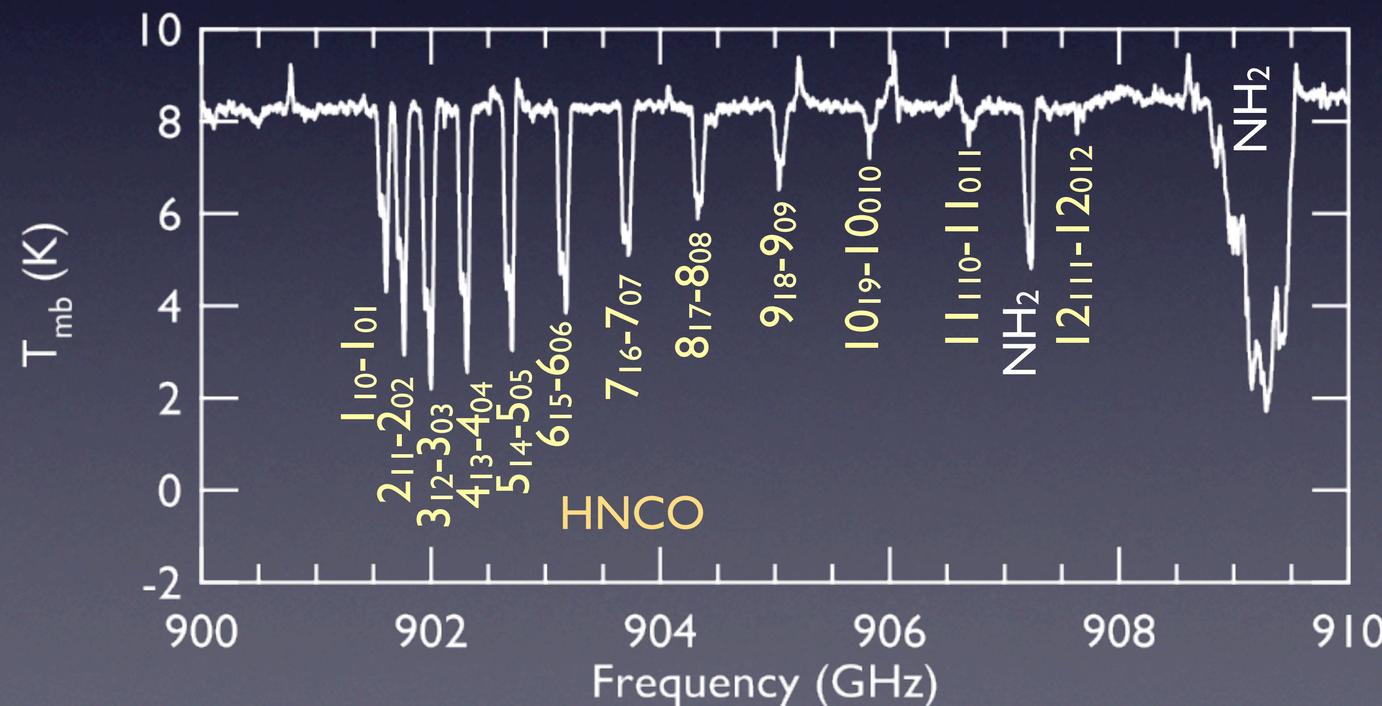


- Complete HIFI scans of Sgr B2(N) and (M); excellent continuum stability

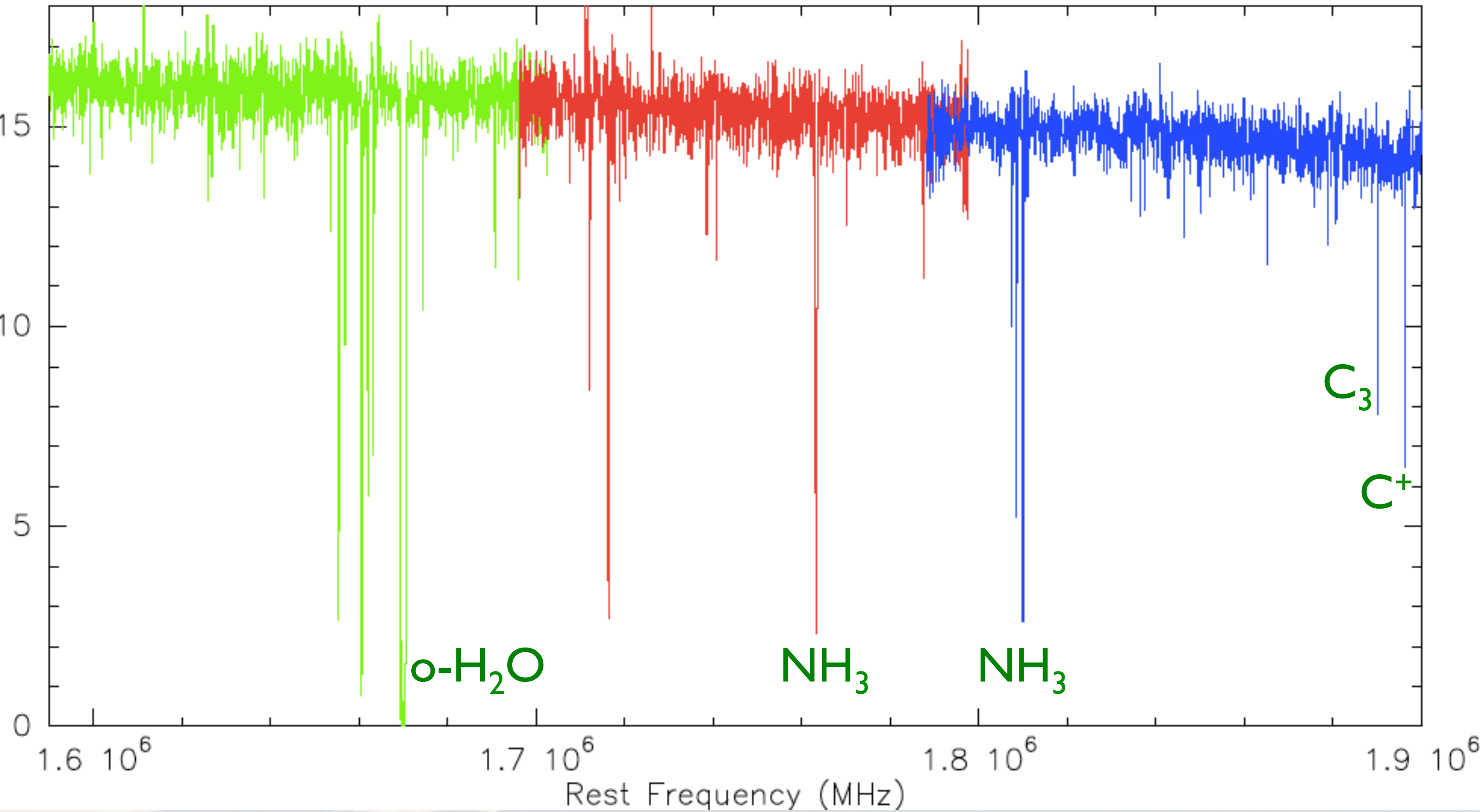
Sagittarius B2(N) Zoom-In



Complex mixture of emission and absorption lines

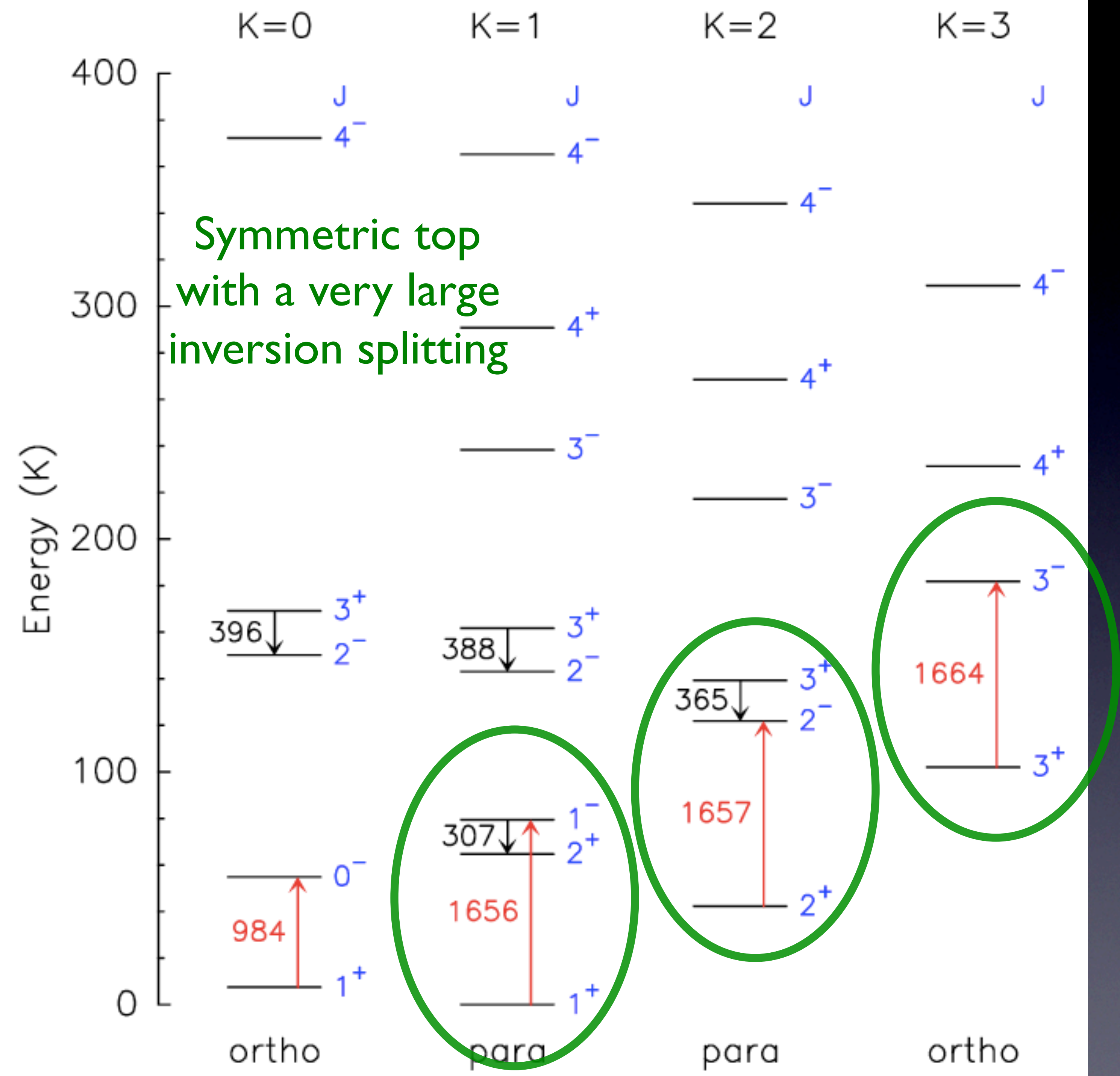


Sagittarius B2(N) HEB Spectrum

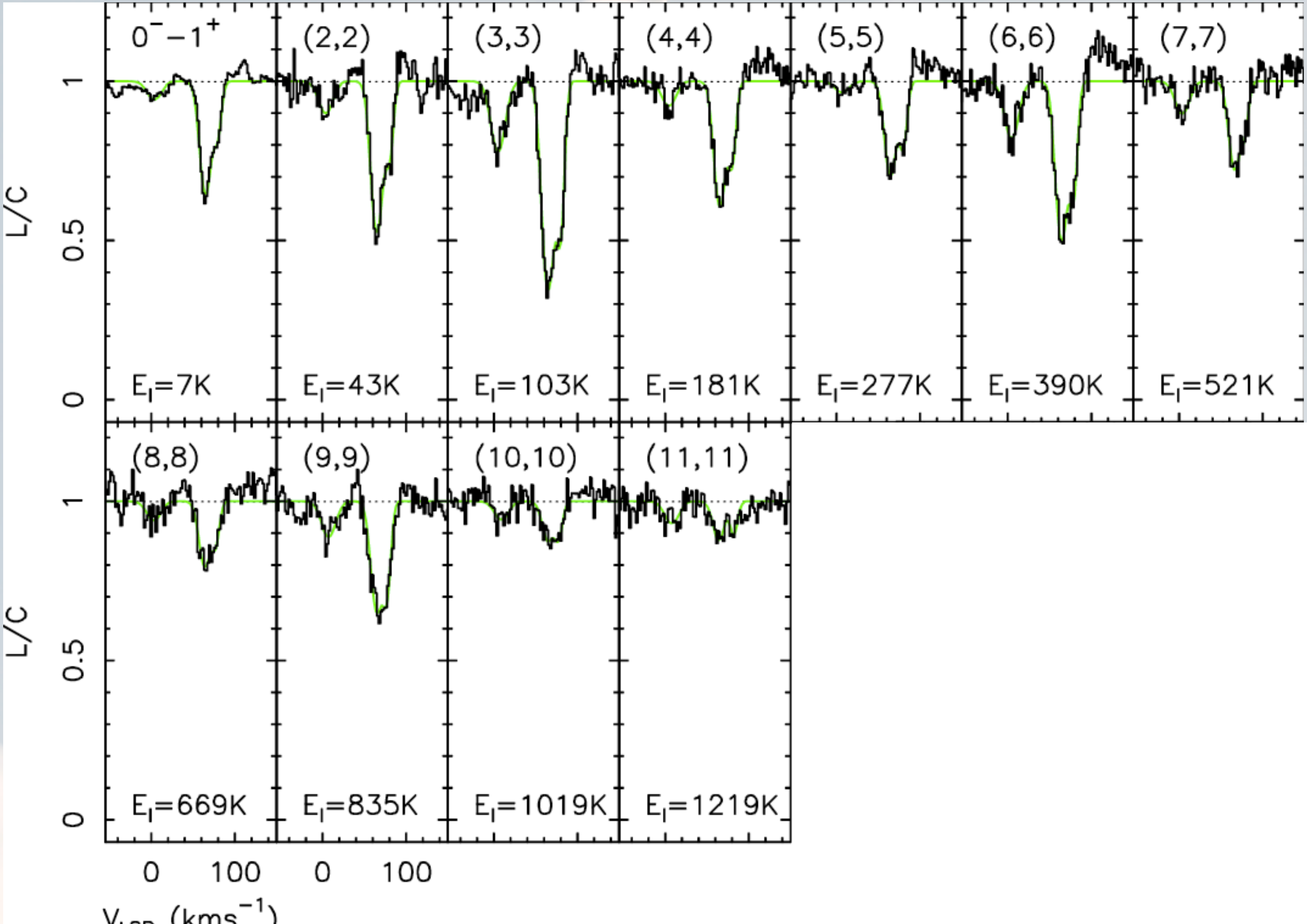


- HEB bands dominated by absorption lines—water isotopologues, low energy ammonia lines, C_3, C^+…

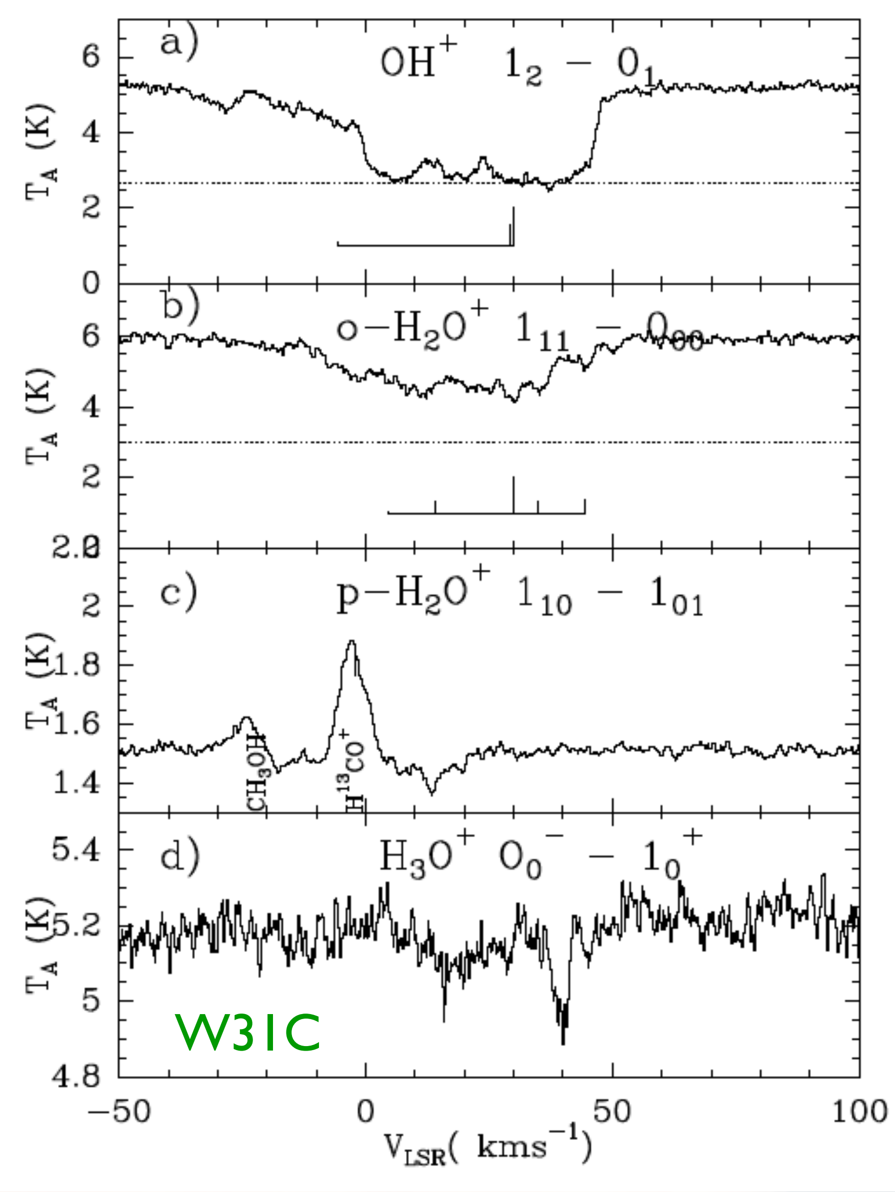
H_3O^+


K=0
K=1
K=2
K=3
Energy (K)
400
300
200
100
0
J
Symmetric top
with a very large
inversion splitting
396
388
365
307
984
1656
1657
1664
ortho
para
para
ortho

Metastable H_3O^+ in Sgr B2(N)

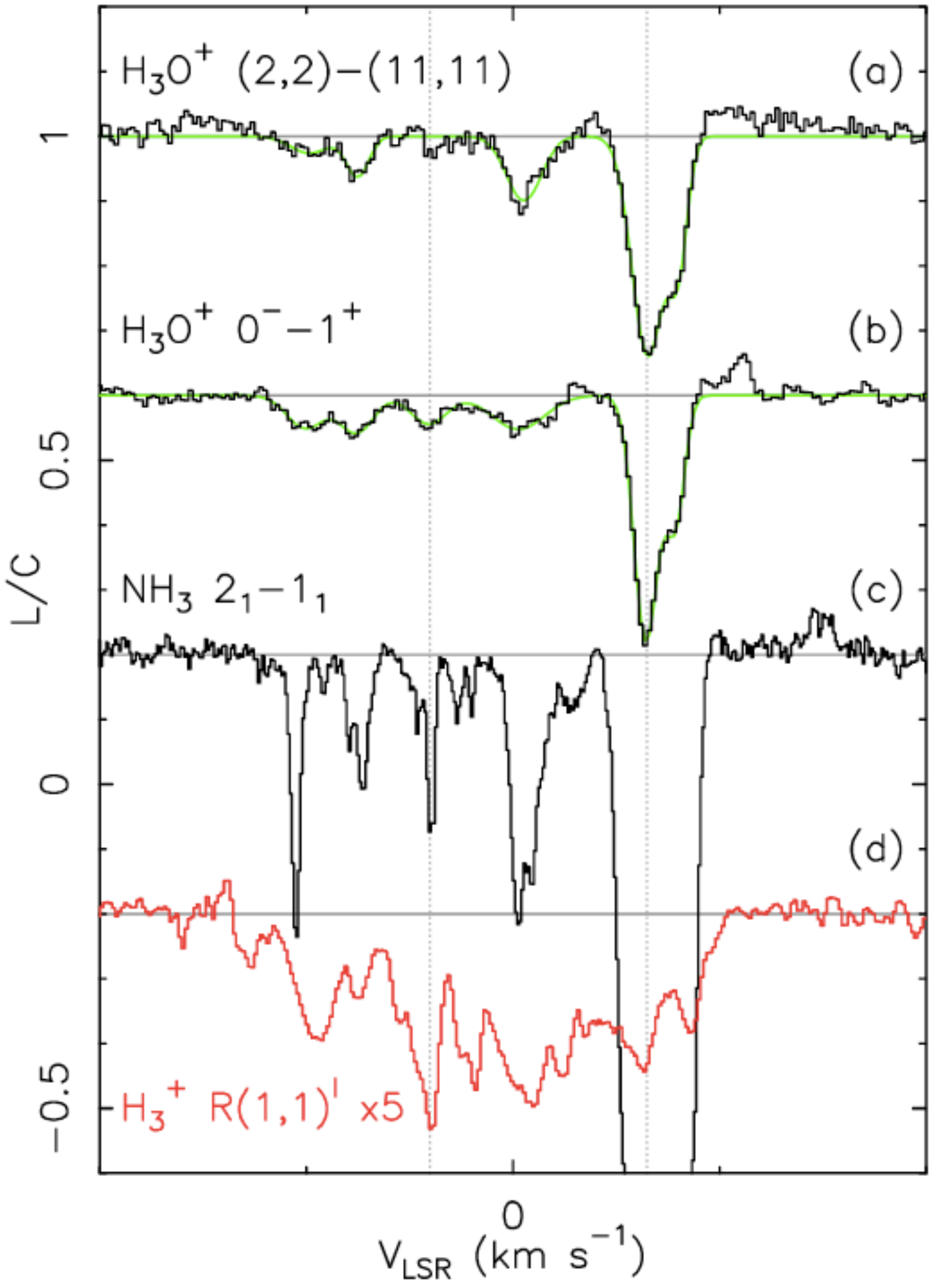


Herschel/HIFI: OH^+, H_2O^+, H_3O^+



- PRISMAS: W31C (Gerin et al. 2010) W49N (Neufeld et al. 2010)
- Strong OH^+ and H_2O^+ absorption, but only weak H_3O^+
- Observations probe primarily diffuse gas
- If the ratio of electron density to H_2 is sufficiently high, the pipeline leading from O^+ to OH^+ to H_2O^+ to H_3O^+ can be "leaky"
- In dense gas the H^+ abundance and T are too low to to produce O^+ by charge transfer; dominant source of OH^+ is reaction of H_3^+ with O
- Conversion from OH^+ to H_3O^+ proceeds with high efficiency
- Nevertheless, H_3O^+ not detected in Orion KL (Gupta et al. 2010)

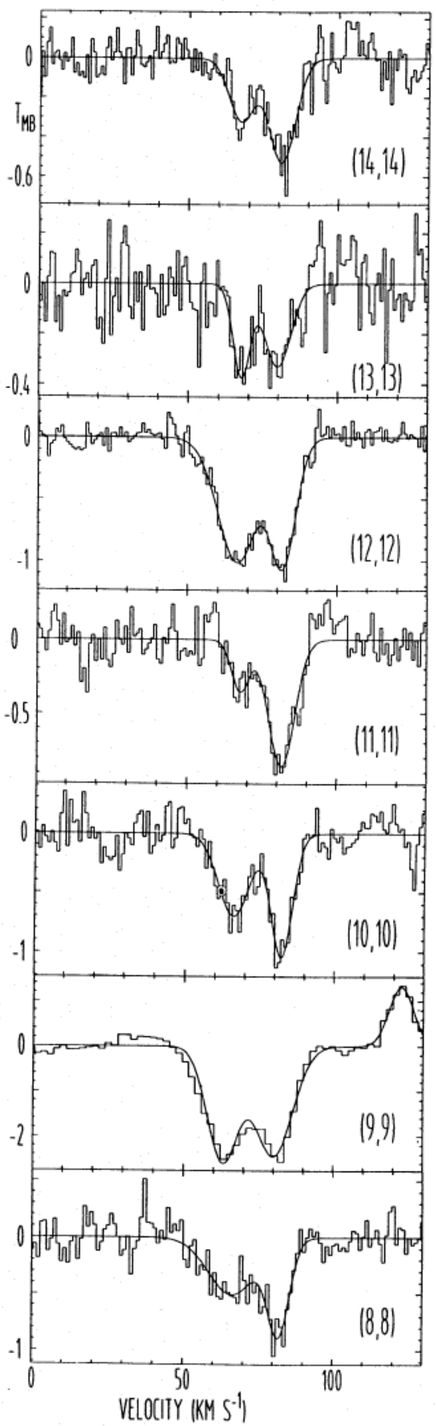
- *What is special about Sagittarius B2?*

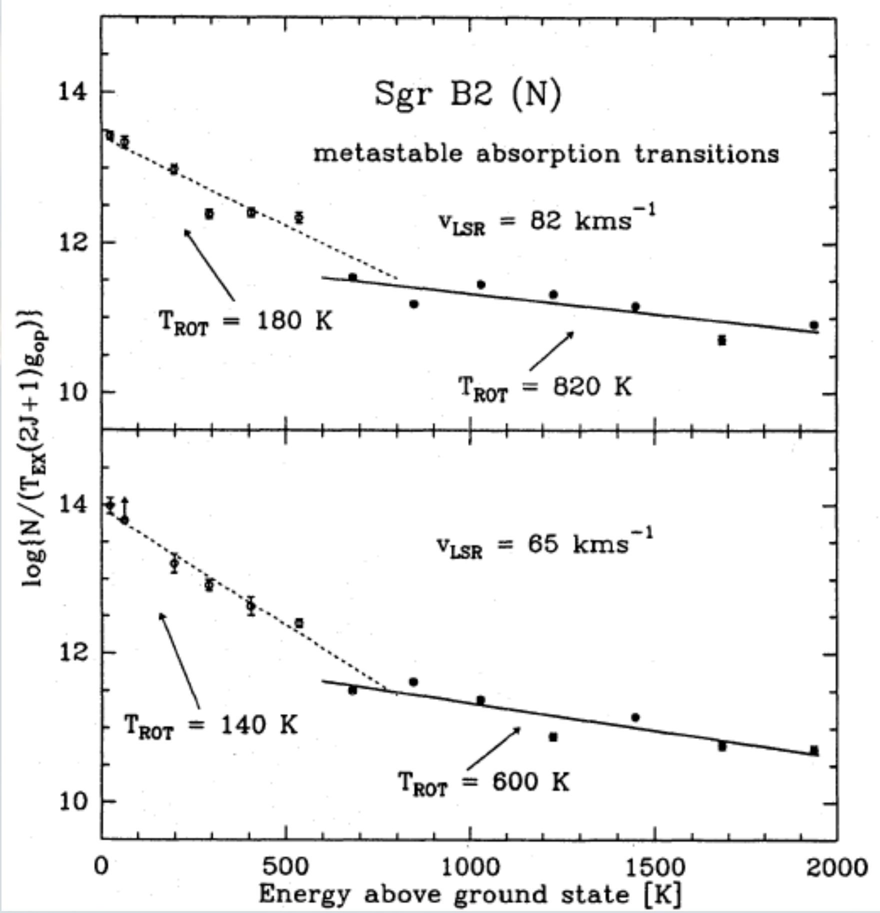


Comparison with Other Tracers

- Several velocity components seen in metastable H_3O^+: -75, 6, 65, and 80 km s^{-1}
- All in the Galactic Center
- Some velocity components prominent in other tracers (e.g. NH_3) weak or not seen: -104, -40 km s^{-1}
- All velocity components seen in H_3O^+ also seen in H_3^+ (Geballe & Oka 2010)
- Many additional H_3^+ velocity components (e.g. -40 km s^{-1}) not seen in metastable H_3O^+

Comparison with Ammonia Inversion Lines





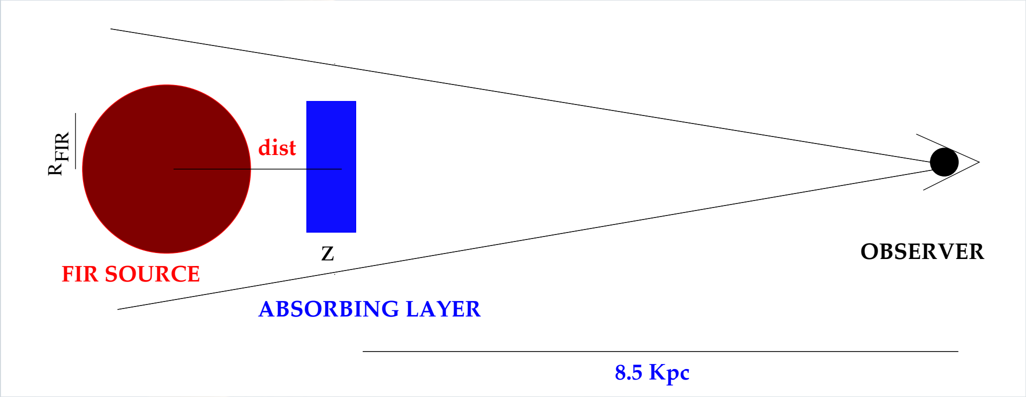
Hüttemeister et al. (1995)

Shocked Gas Layer toward Sgr B2

- Earlier evidence of hot gas in the Galactic center from ground-based observations of the ammonia inversion lines (Hüttemeister et al. 1995; Flower et al. 1995)
- ISO LWS observations of 21 ammonia lines, both ortho and para, metastable and non-metastable (Ceccarelli et al. 2002)

- Absorbing gas layer: temperature (700±100) K, density < 10^4 cm^{-3}, NH_3 column density $(3\pm1)\times10^{16}$ cm^{-2}, H_2 column density 3×10^{22} cm^{-2}

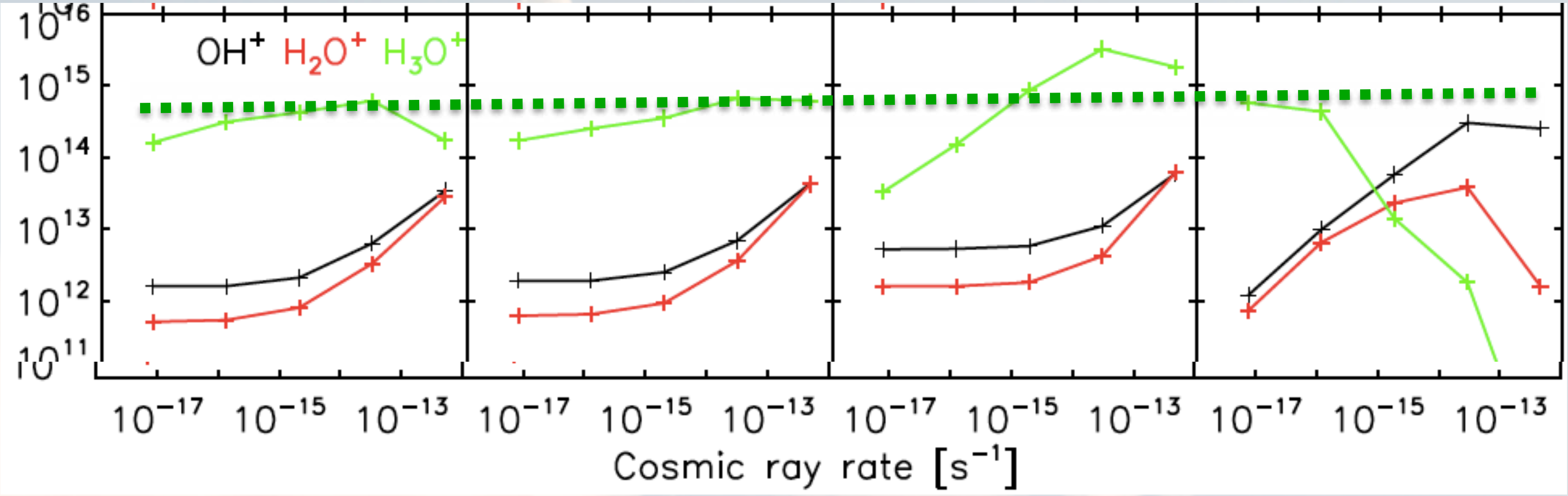
- Interpreted as a layer of *shocked gas* between us and Sgr B2



- Size ~30", but the 60 kms^{-1} component seen toward both Sgr B2(M) and (N)
- Why is the velocity of the shocked layer the same as the dense cores?

Cosmic Rays

- Hot H_3O^+ column density: $N(H_3O^+) \sim 4 \times 10^{14}$ cm^{-2}, $X(H_3O^+) \sim 1.3 \times 10^{-8}$
- In shocks, main source of ionization are UV photons
- H_3O^+ abundance in UV irradiated regions $<3 \times 10^{-9}$ (van der Tak et al. 2008)
- Rolffs et al. 2010, high-J HCN transitions: infall reversal in Sgr B2(M)—shock at the interface between the cores and the infalling envelope? Higher density gas!
- Meijerink et al. (2011): effect of cosmic rays and mechanical heating
- H_3O^+ abundance can reach $\sim 10^{-8}$ in *high density* gas (few x 10^5 cm^{-3}; inconsistent with the density of the ammonia layer)
- H_3O^+/H_2O ratio ~0.01, similar to that measured in Sgr B2 (Comito et al. 2003)



Galactic Center Chandra Composite

Energy: Red (1-3 keV); Green (3-5 keV); Blue (5-8 keV)

- Strong 6.4 keV Fe line and hard X-ray emission: Sgr B2 illuminated by an X-ray flash originating from the GC black hole (Sunyayev et al. 1993; Koyama et al. 1996)
- X-ray emission now fading quickly (~8 yr timescale; Terrier et al. 2010)

H_3O^+ Formation Pumping

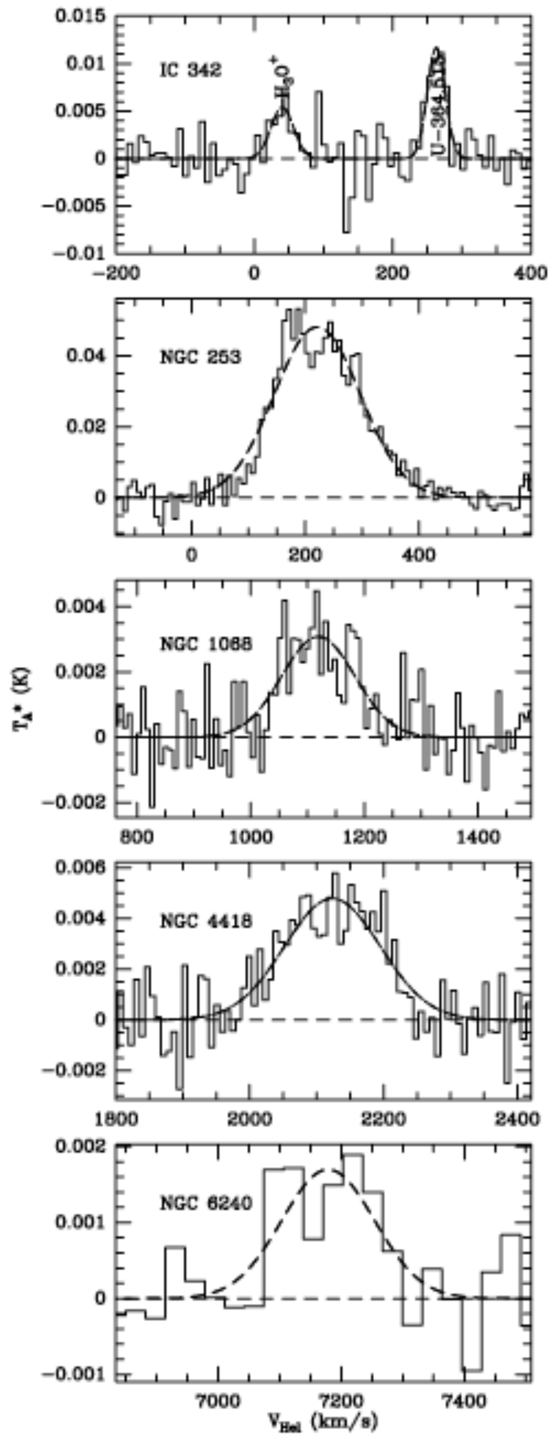
- How do you populate the metastable levels up to 1200 K?
- Cosmic/X-ray + $H_2 \rightarrow H_3^+$ (widespread in the Galactic Center region, Oka et al.)

$$H_3^+ + O \rightarrow OH^+ + H_2$$
$$OH^+ + H_2 \rightarrow H_2O^+ + H$$
$$H_2O^+ + H_2 \rightarrow H_3O^+ + H + 1.69 \text{ eV}$$

- Also

$$H_3^+ + H_2O \rightarrow H_3O^+ + H_2 + 2.81 \text{ eV}$$

- If we assume 1/2 of the excess energy change goes into rotation then we can match observations (J. Black, private comm.)
- Need high ionization rate ~ 10^{-14} s^{-1}
- Collisional relaxation time has to be long compared to recombination/reformation of H_3O^+ molecules to maintain the population
- Question: can the hot ammonia also be explained by formation pumping? (More stable, long lived—more time to relax through collisions?)

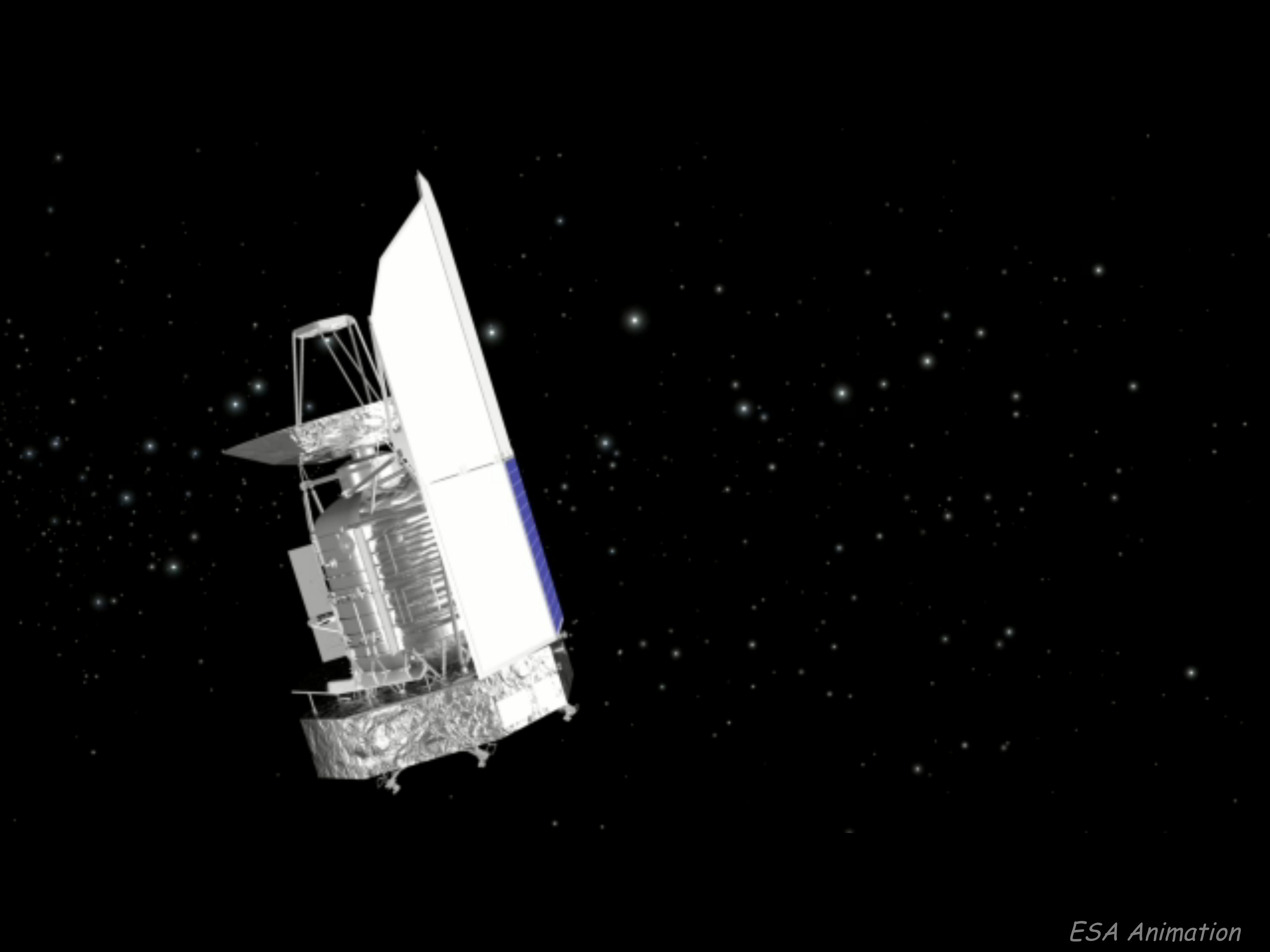


Extragalactic H_3O^+

- Galactic Center can be considered the closest active galactic nucleus
- Impact of starburst and AGN activity on the ISM chemistry?
- Aalto et al. (2011) observed H_3O^+ toward the centers of seven active galaxies
- High H_3O^+ abundances, in excess of 10^{-8}, in four galaxies: NGC 253, NGC 1068, NGC 4118, and NGC 6240
- Only in the case of IC 342 the H_3O^+ abundance is an order of magnitude lower—can be explained by PDR chemistry
- The high abundances in the remaining galaxies consistent with XDR models, but alternative explanation may be H_3O^+ formation from H_2O evaporating from dust grains and reacting with HCO^+ in warm, dense gas

Summary

- Herschel is providing a comprehensive view of the FIR universe, not obscured by the Earth's atmosphere
- Unbiased HIFI spectral line surveys are the key for investigations of the chemical complexity of ISM sources (new species, e.g., H_2O^+, OH^+, H_2Cl^+, HCl^+, O_2, …)
- H_3O^+ targeted in PRISMAS and shown to be weak on sightlines in the Galactic disk
- Strong H_3O^+ absorption from metastable levels up to 1200 K toward Sagittarius B2 came in as a surprise
- Related to the unique environment in the Galactic Center (closest active galactic nucleus)
- Formation pumping in X-ray irradiated gas is an attractive explanation, but detailed modeling needed


ESA Animation