Infrared Detection of CS in the Hot Core AFGL 2591 with SOFIA/EXES

SOFIA Tele-Talk

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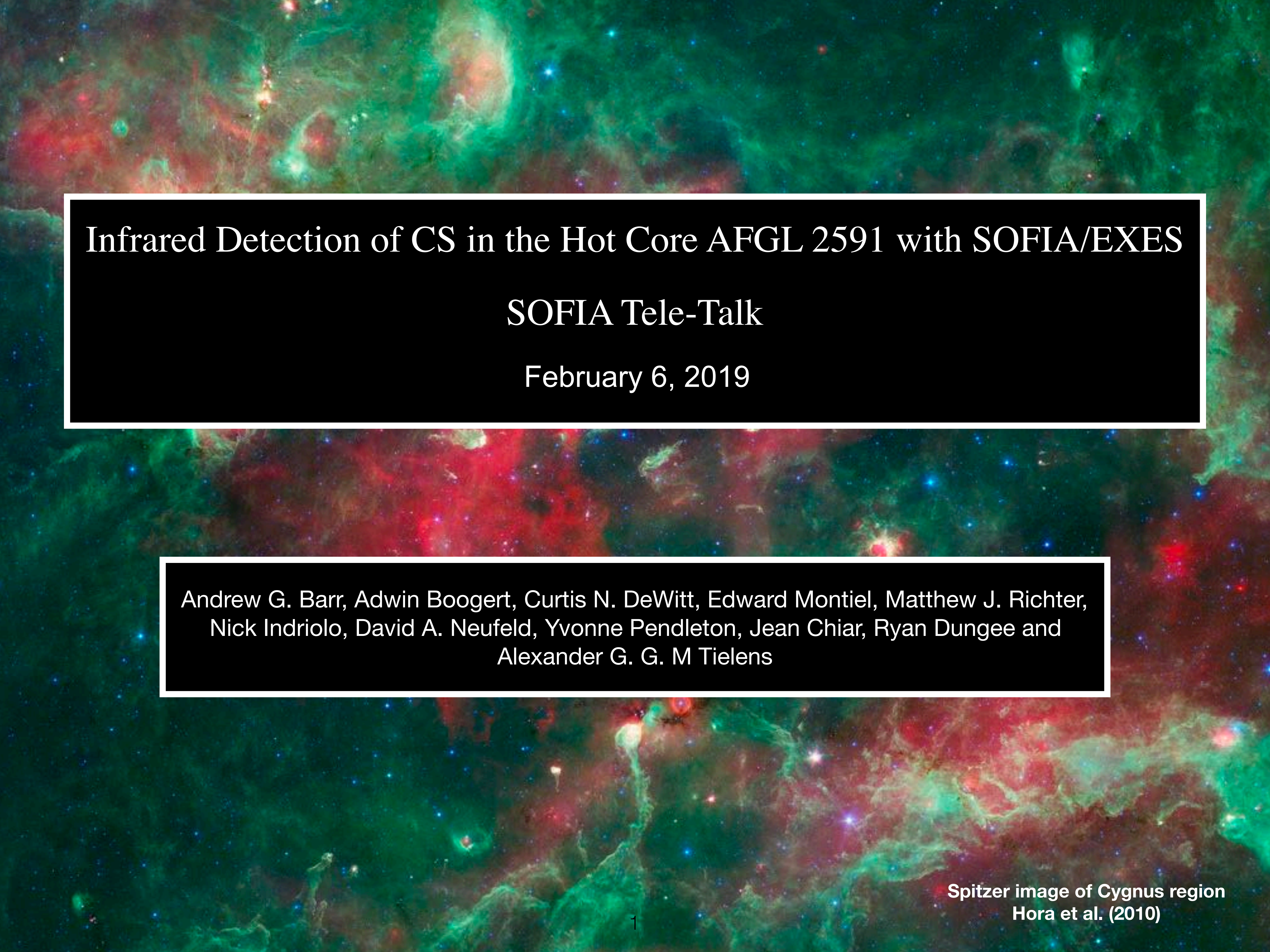
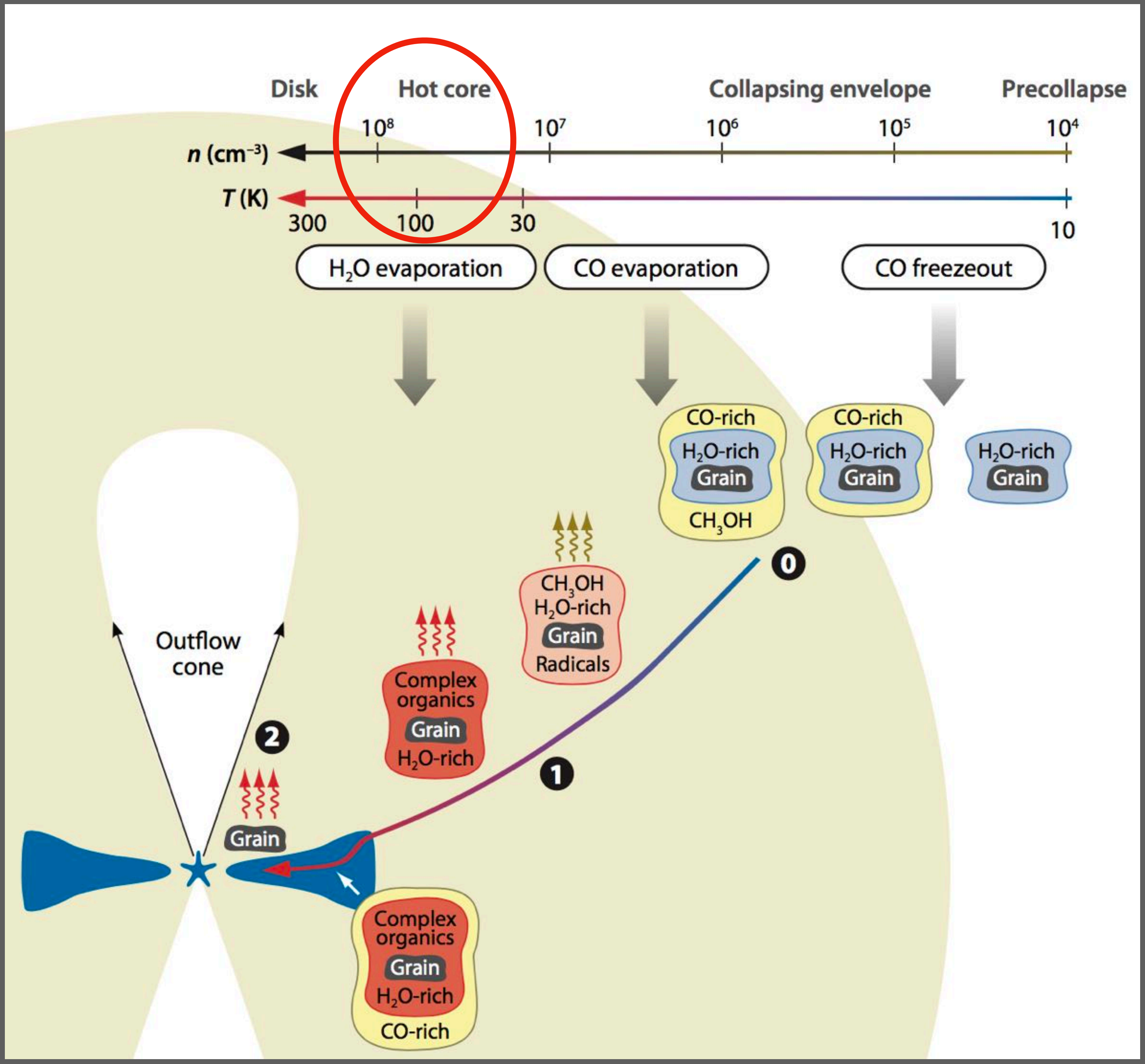


Spitzer image of Cygnus region
Hora et al. (2010)

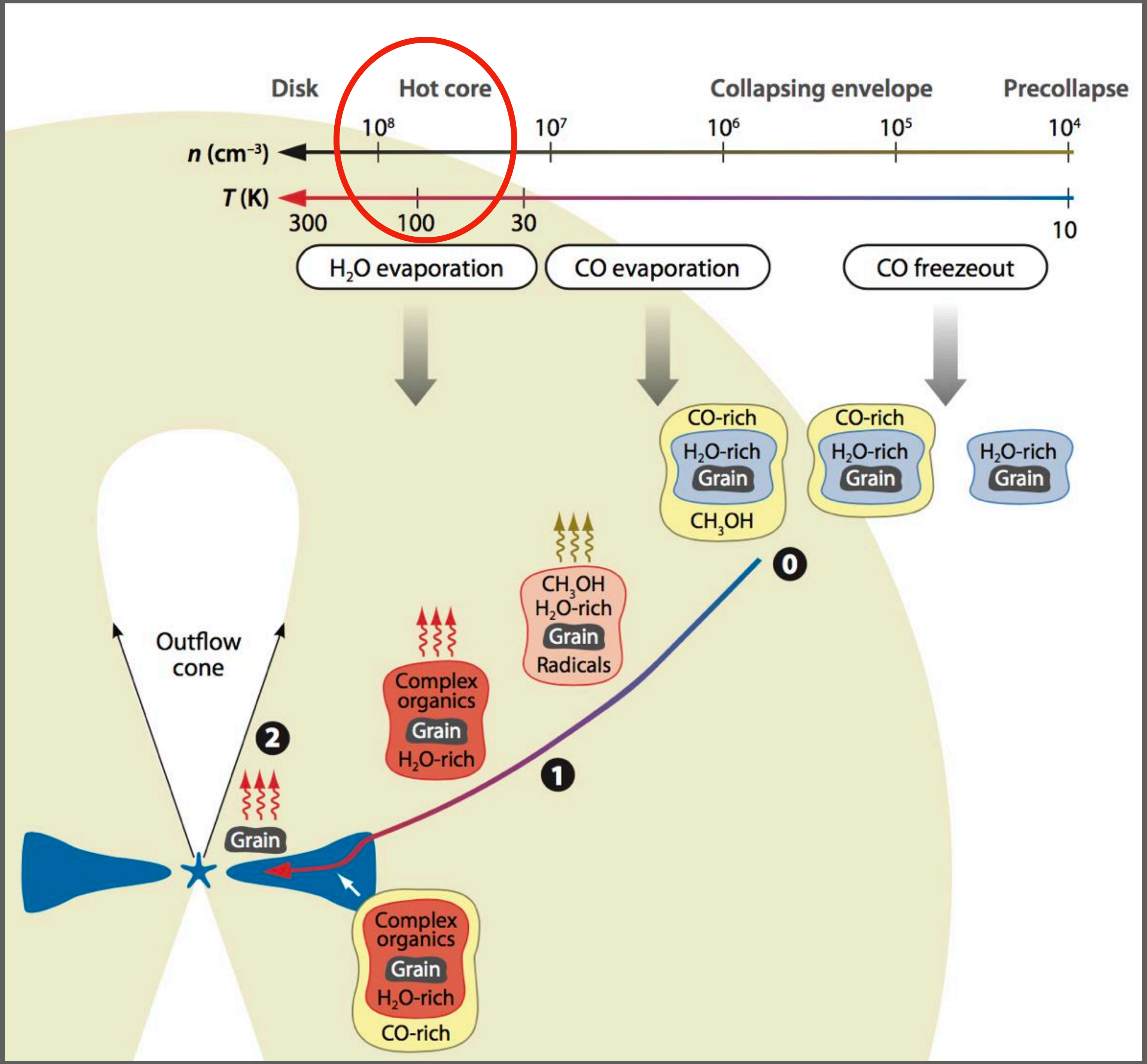
Introduction - Hot Cores



Van Dishoeck & Herbst 2009

- Embedded intermediary phase of high mass star formation
- Evaporation of ice mantles
- Chemically rich objects

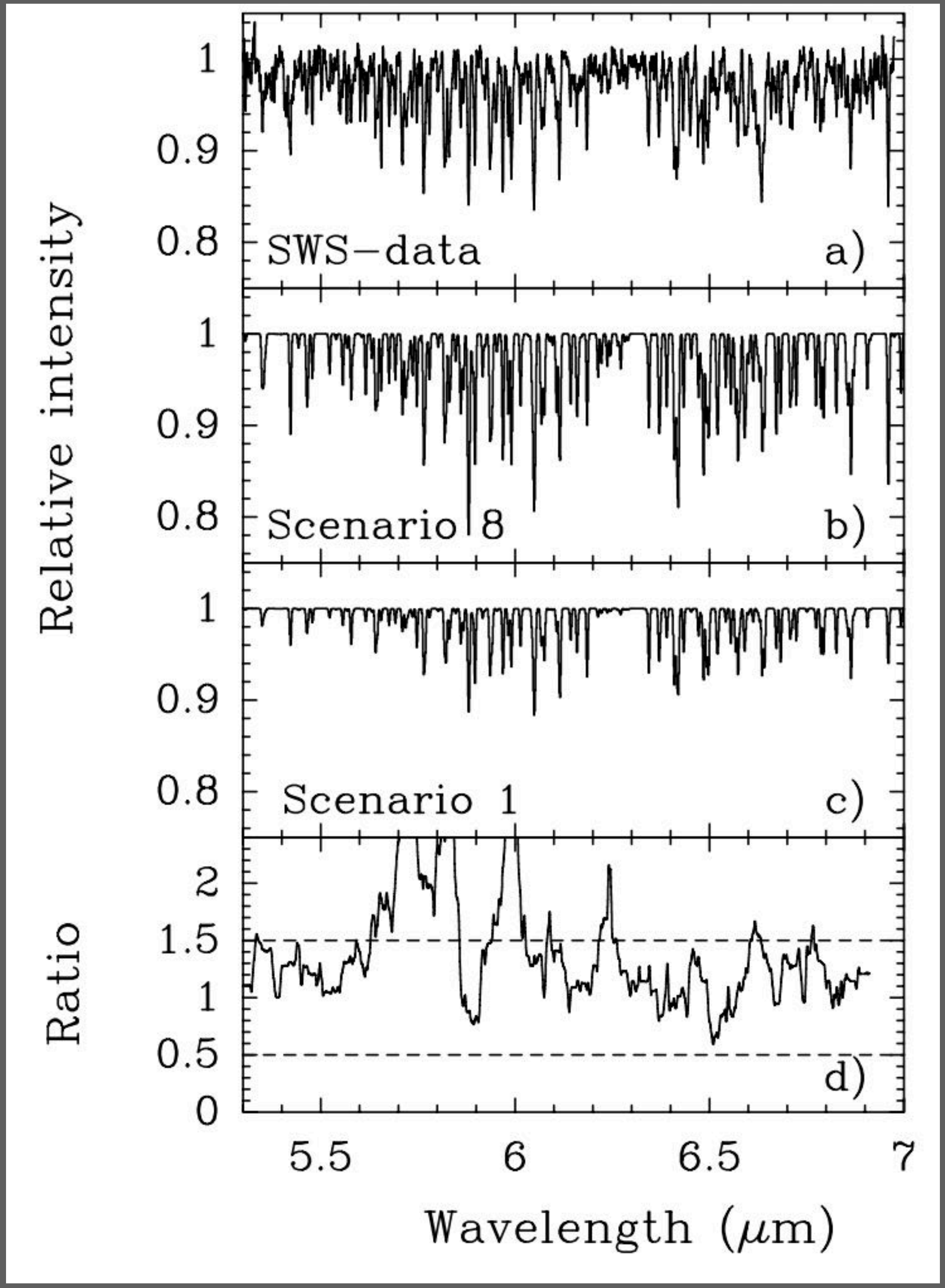
Hot Cores



Van Dishoeck & Herbst 2009

- Large amounts of molecular lines - COMs
- Low mass hot corinos
- Gas-phase chemistry well studied at sub-mm wavelengths but not so much for MIR: CH_4 & C_2H_2

IR Observations of AFGL 2591: H_2O



- Absorption lines
- Low spectral resolution of ISO/SWS
- Radiative transfer model fitted to data
- Chemical structure of envelope probed
- Ice evaporation is important

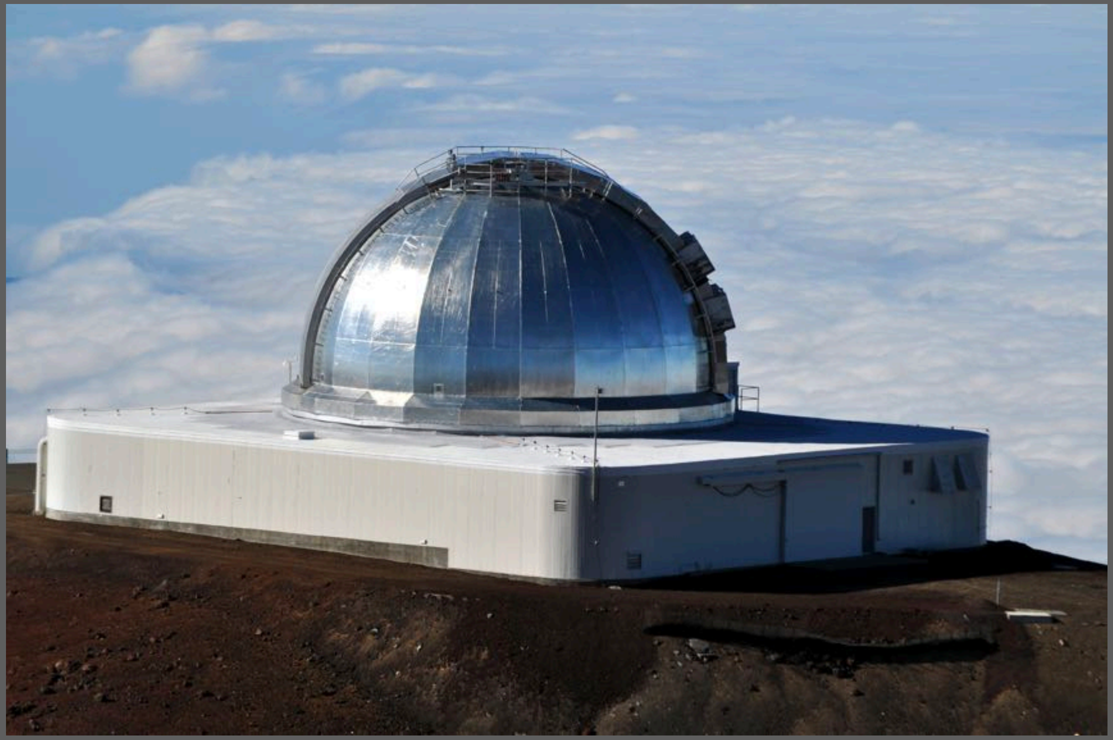
Boonman et al. 2003

Sulphur Chemistry

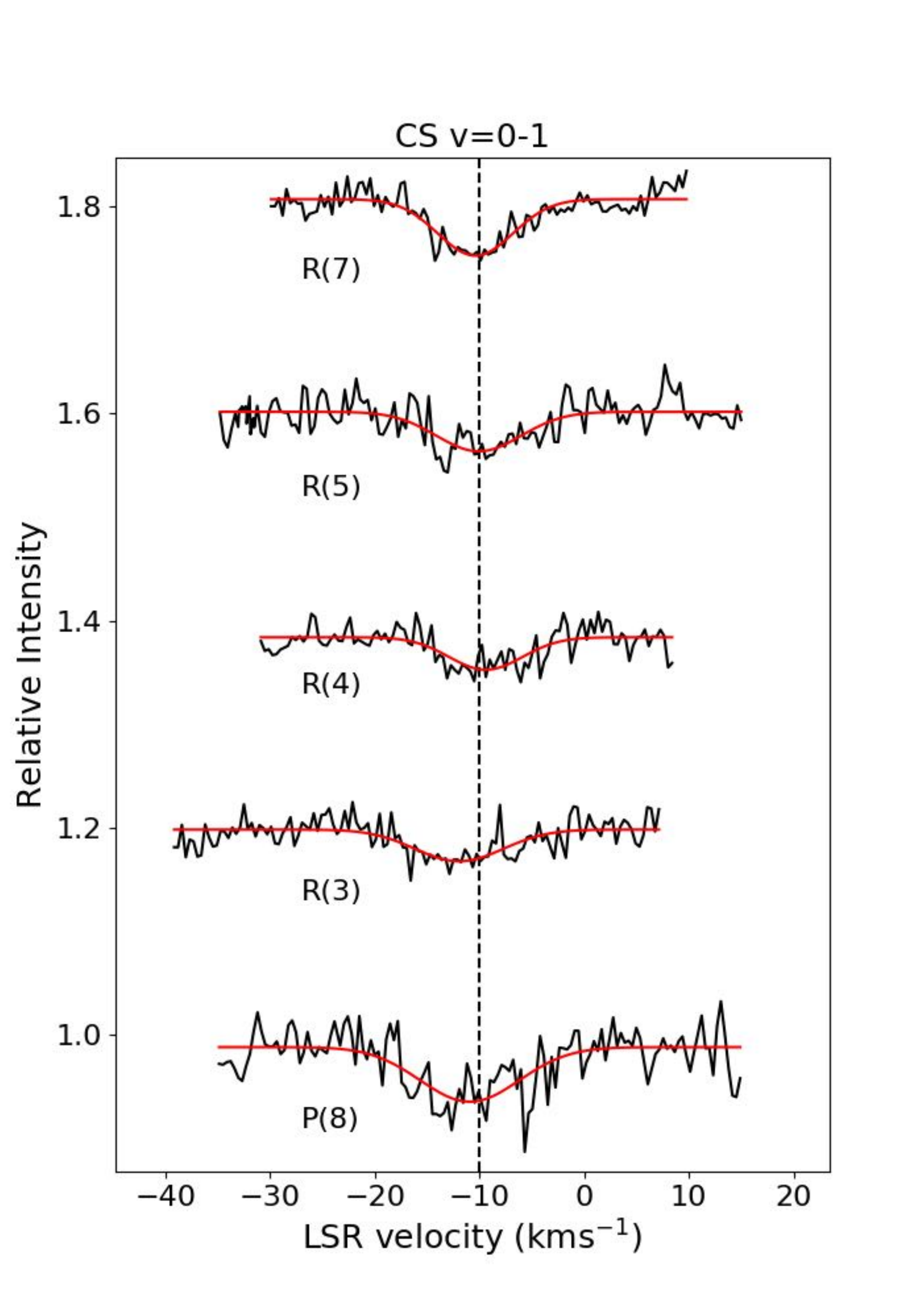
- S-bearing species very sensitive to physical conditions
- Sulphur is known to be heavily depleted in dense regions
- Large discrepancies exist between IR & Sub-mm
- Only detected in one other hot core in MIR (Knez et al. 2009)

Observations

- Full spectral survey of 4.5-13 μm region at R=50,000 (6kms^{-1})
- IRTF/iSHELL and TEXES ; SOFIA/EXES

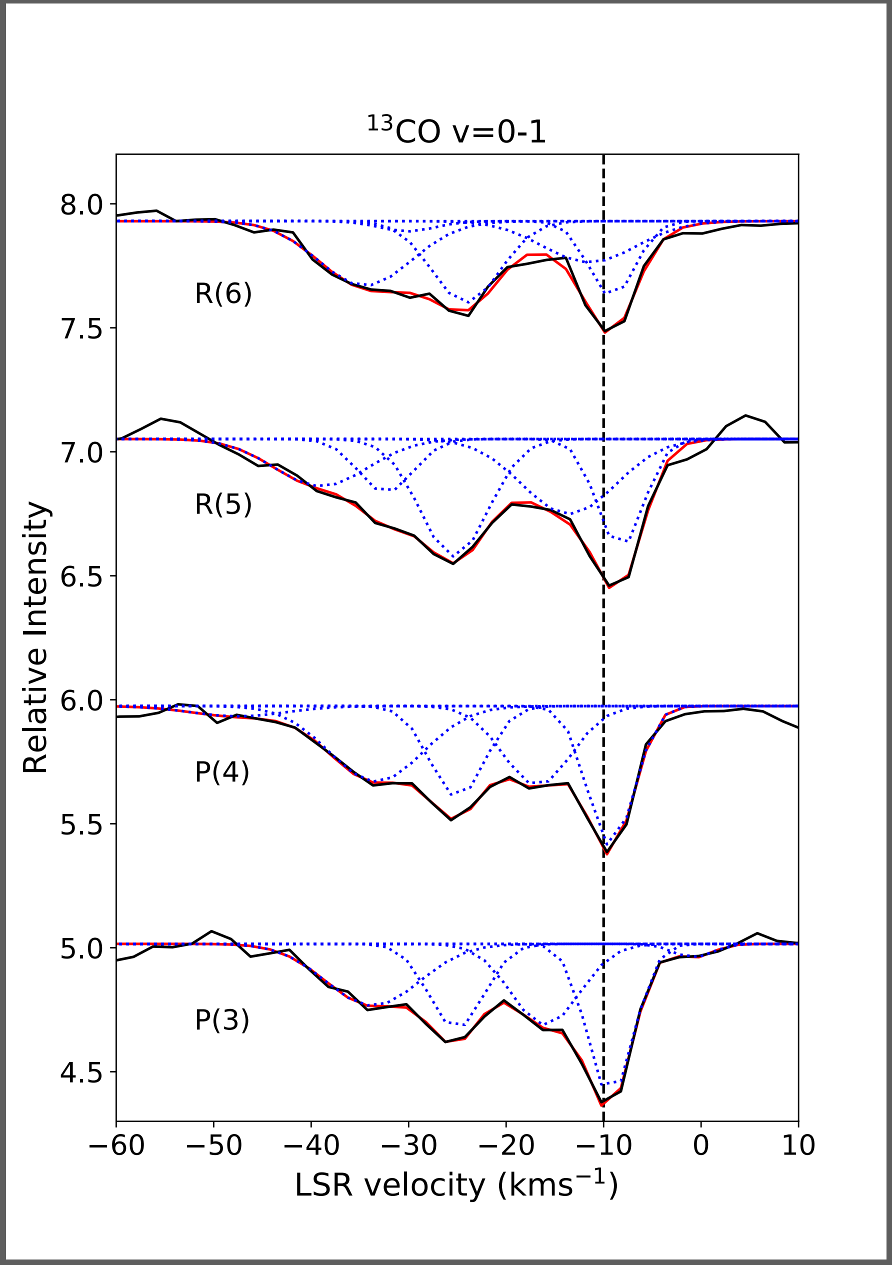


Results - Line Profiles

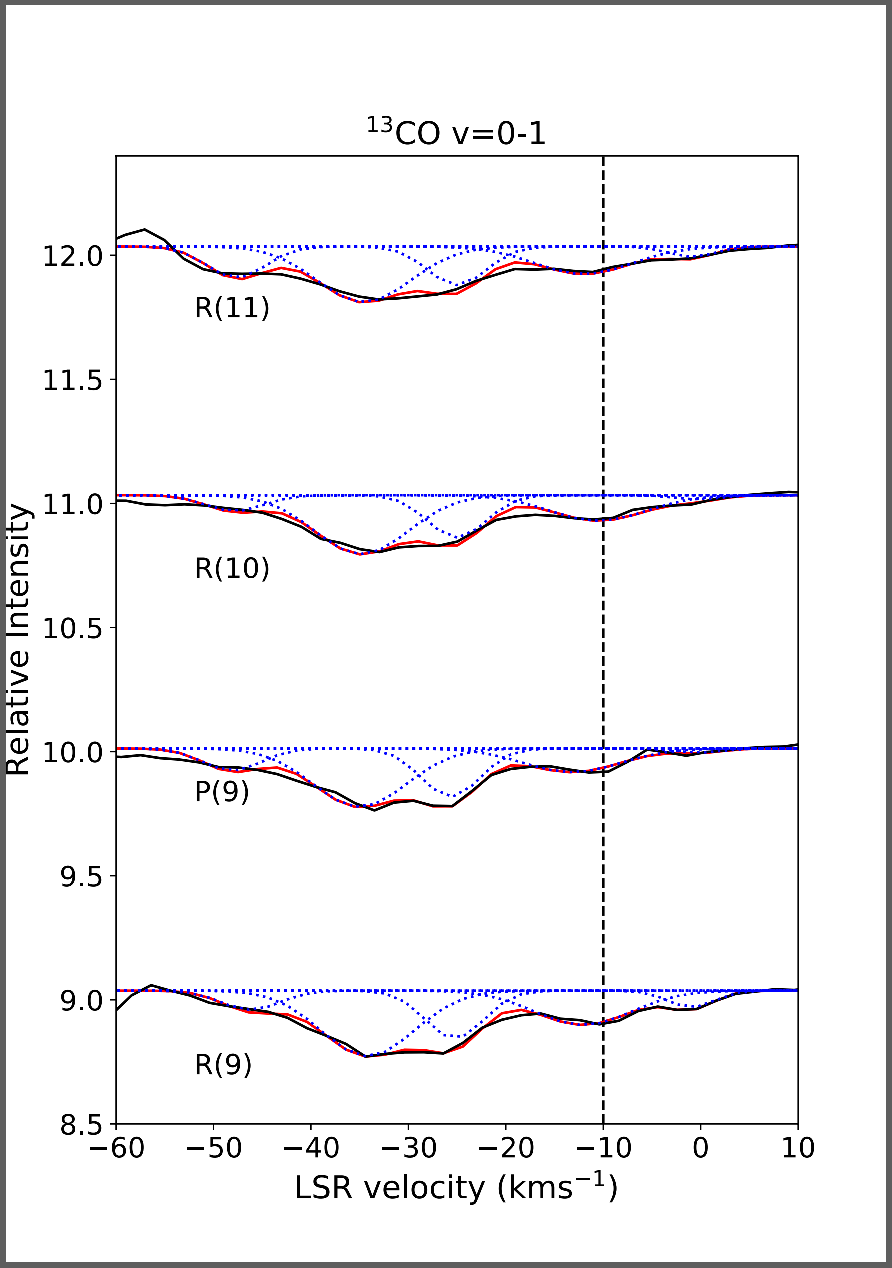


- 18 lines v=0-1
- Energy range 14 to 1317 K
- Single velocity component at -10 kms^{-1}

Line Profiles



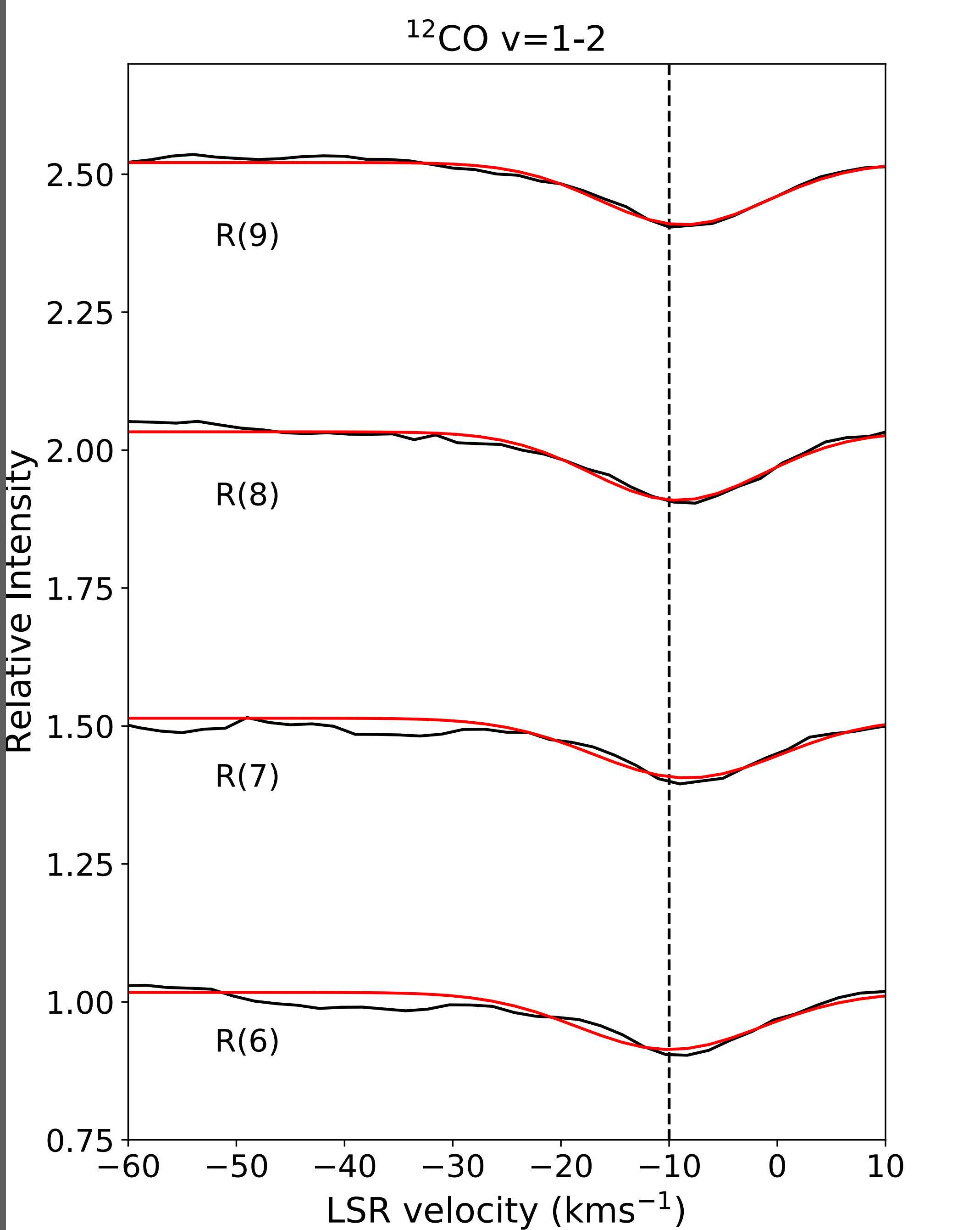
Low J level



High J level

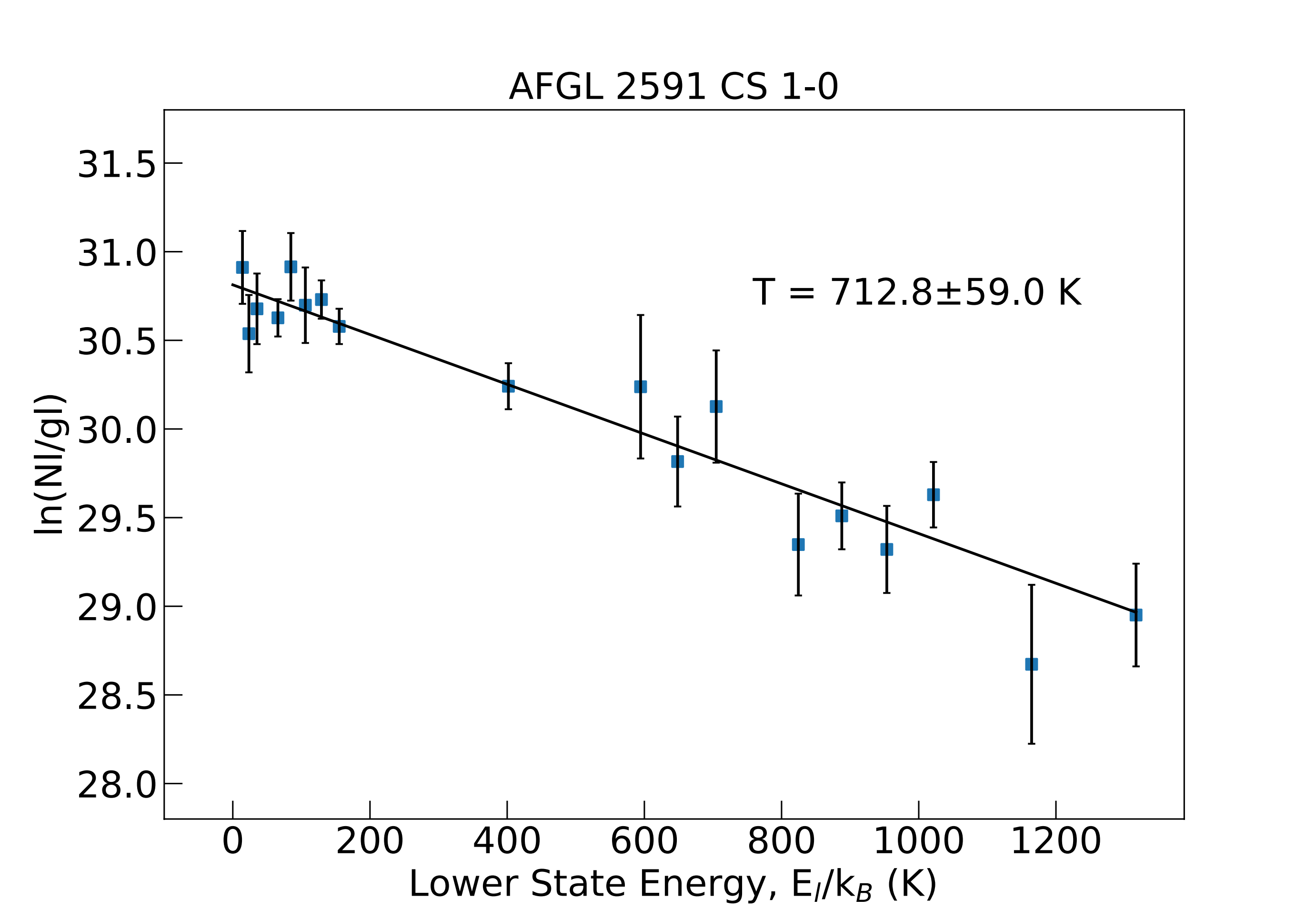
- 16 lines v=0-1
- 5 velocity components
- Clear shift from low to high J level
- Change in line width
- For high-J we adopt the CS line width in fitting at -10 kms^{-1}

Line Profiles



- Vibrationally excited ^{12}CO
- 8 lines v=1-2
- Energy range 3200 - 4234 K
- Optically thin
- Single velocity component at -10 kms^{-1}

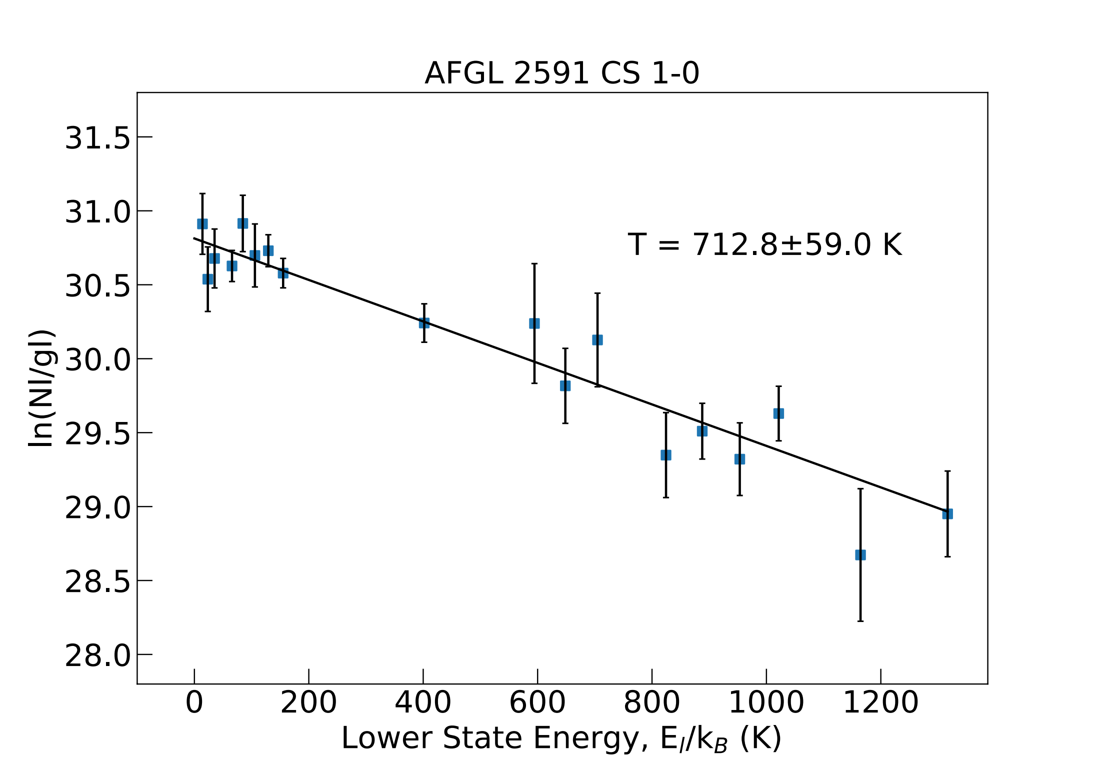
Rotation Diagrams

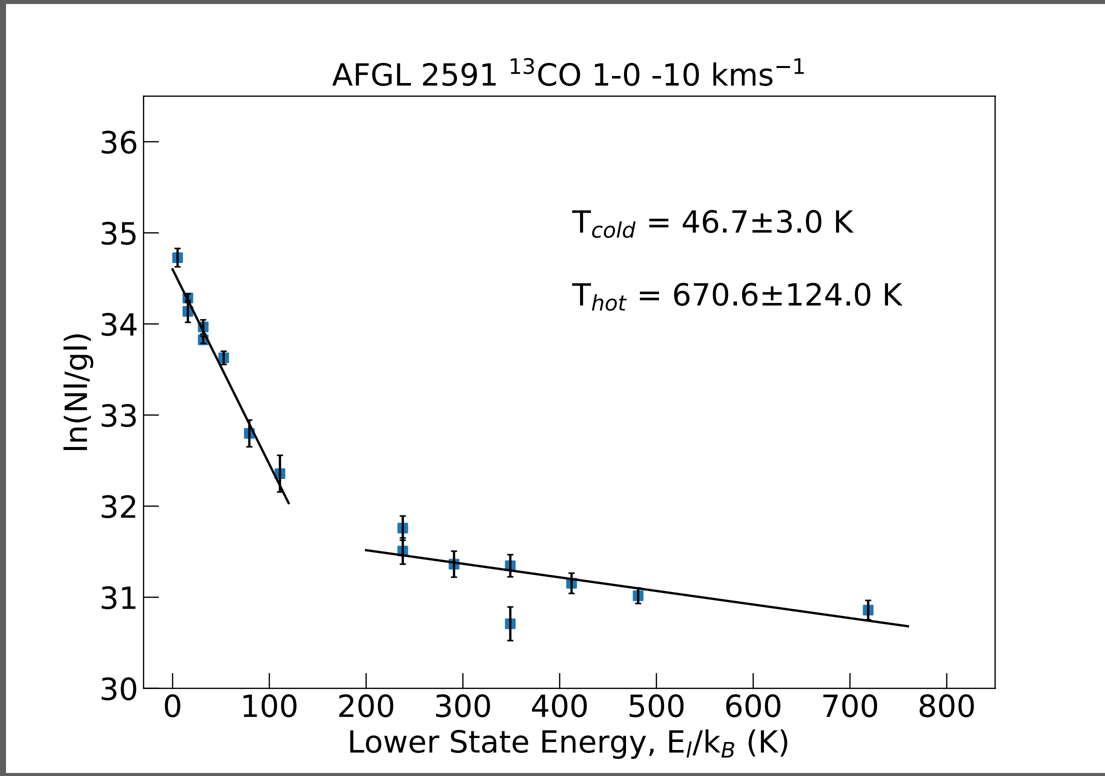


$$\ln \frac{N_u}{g_u} = \ln N - \ln Z - \frac{E_u}{kT}$$

- Straight line suggests LTE and optically thin
- No evidence for partial covering
- Single temperature component of ~700 K

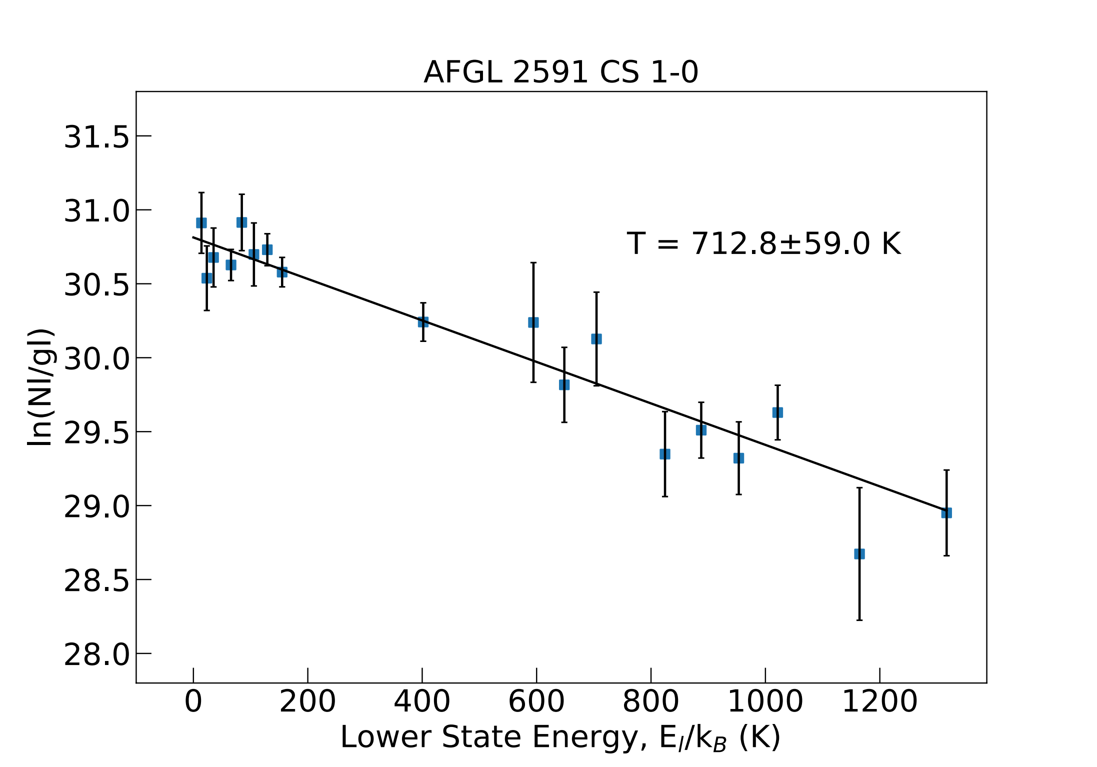
Rotation Diagrams

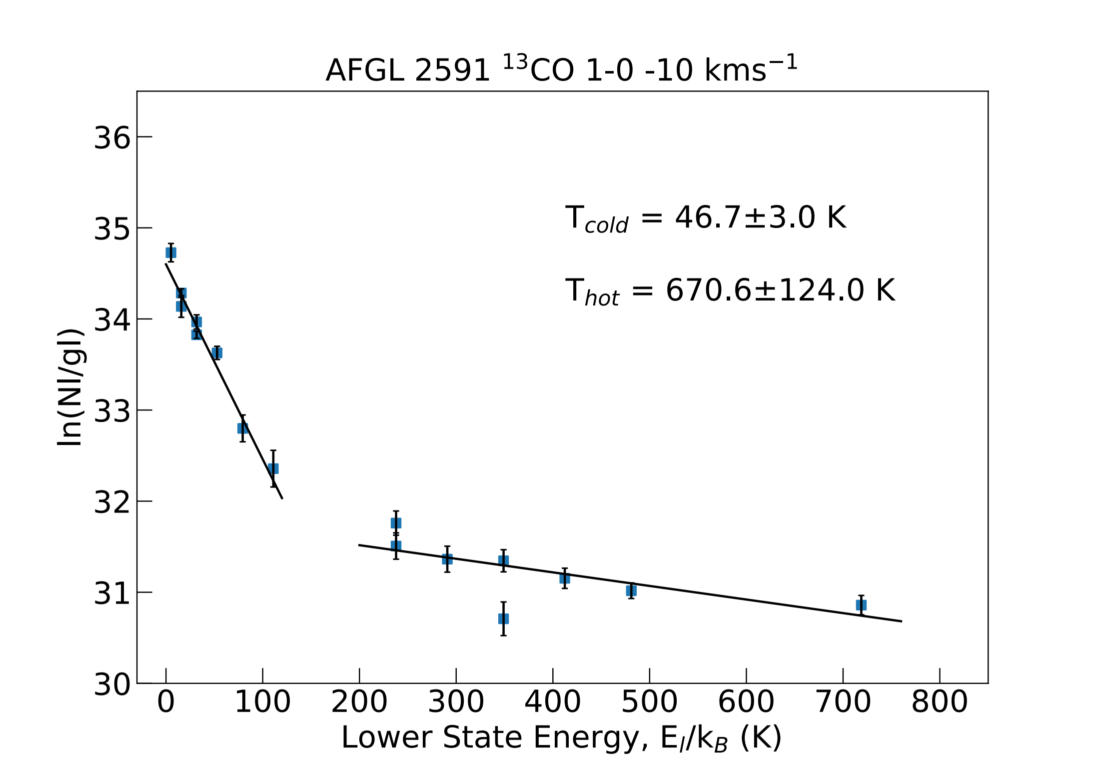


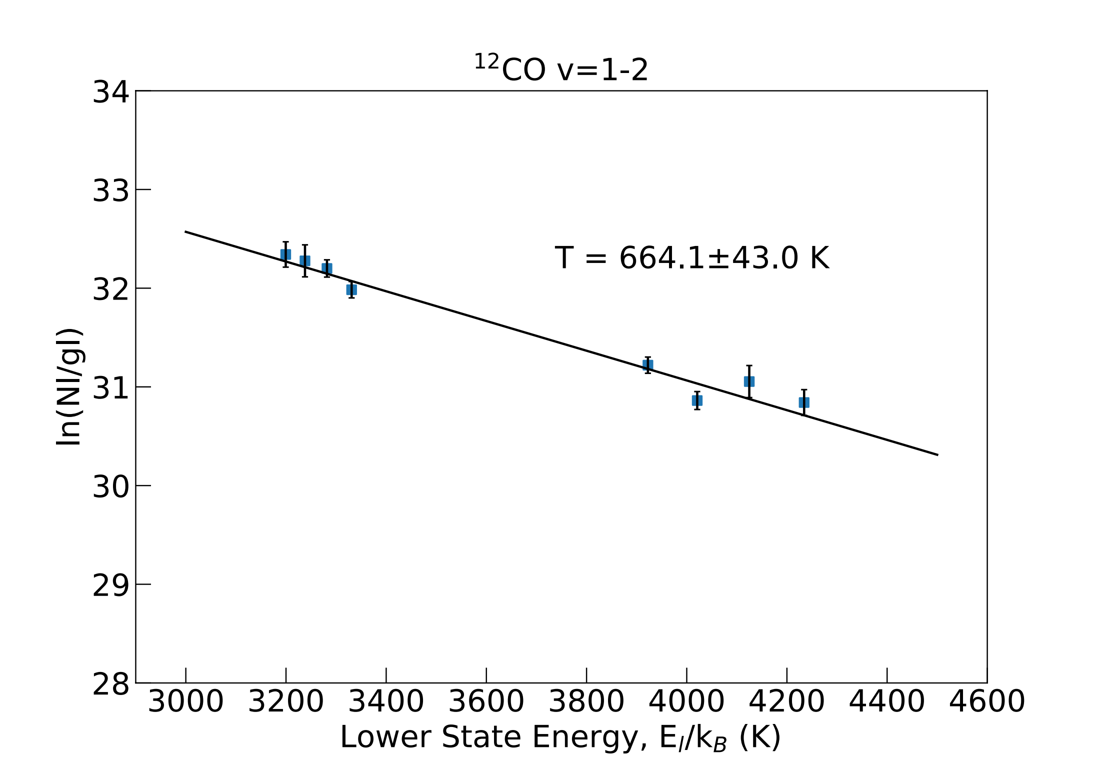


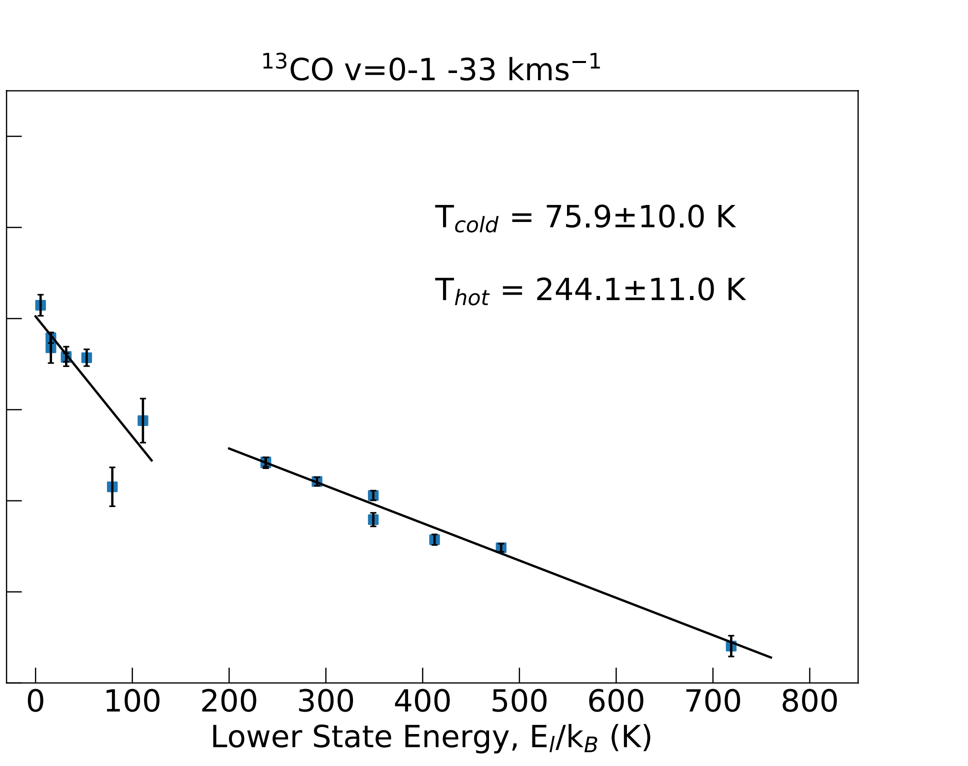
- ^{13}CO shows 2 temperature components at -10 kms^{-1}
- CO has very complicated spatial distribution
- CS and CO rotation temperatures agree well

Rotation Diagrams

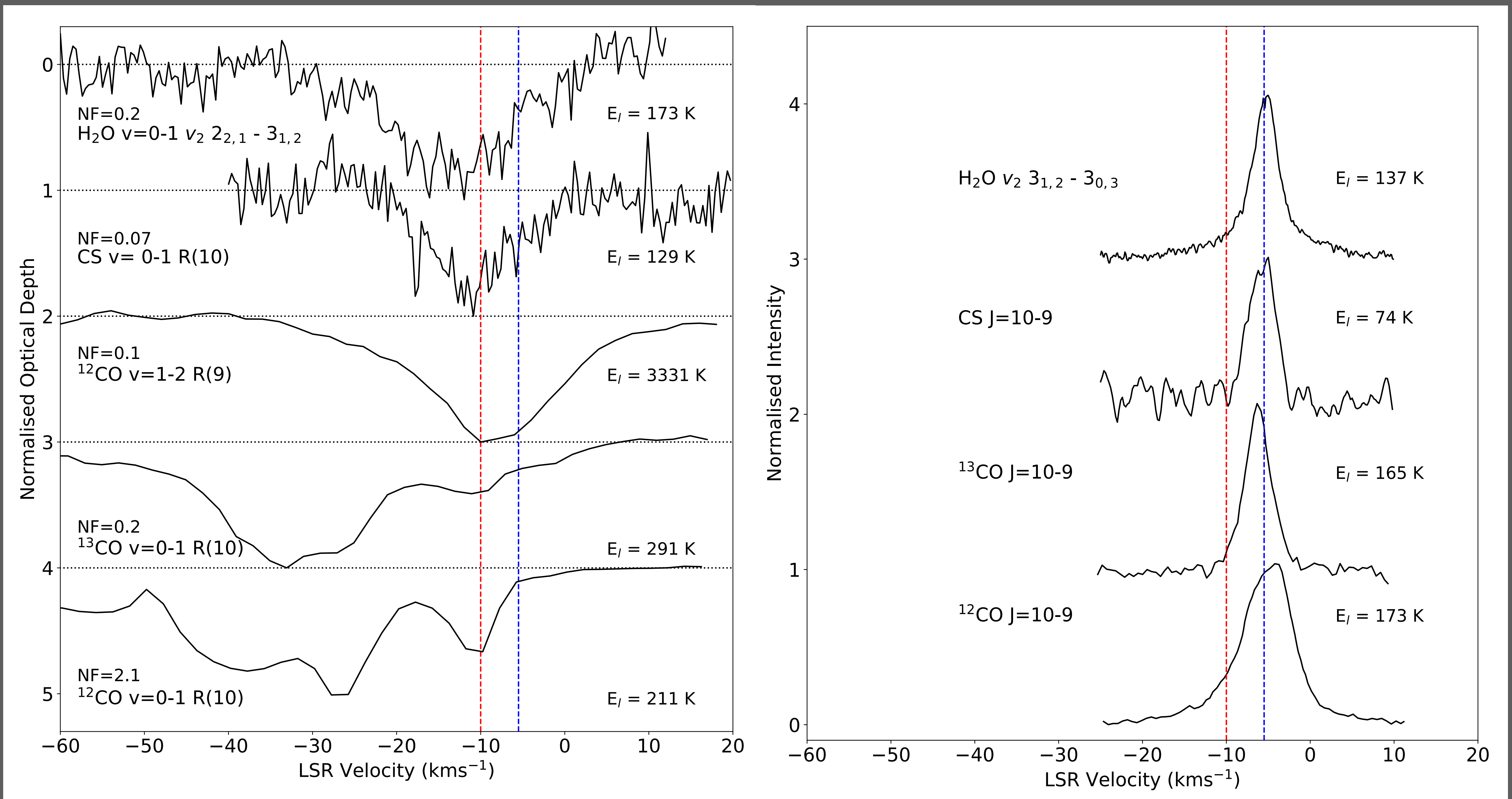






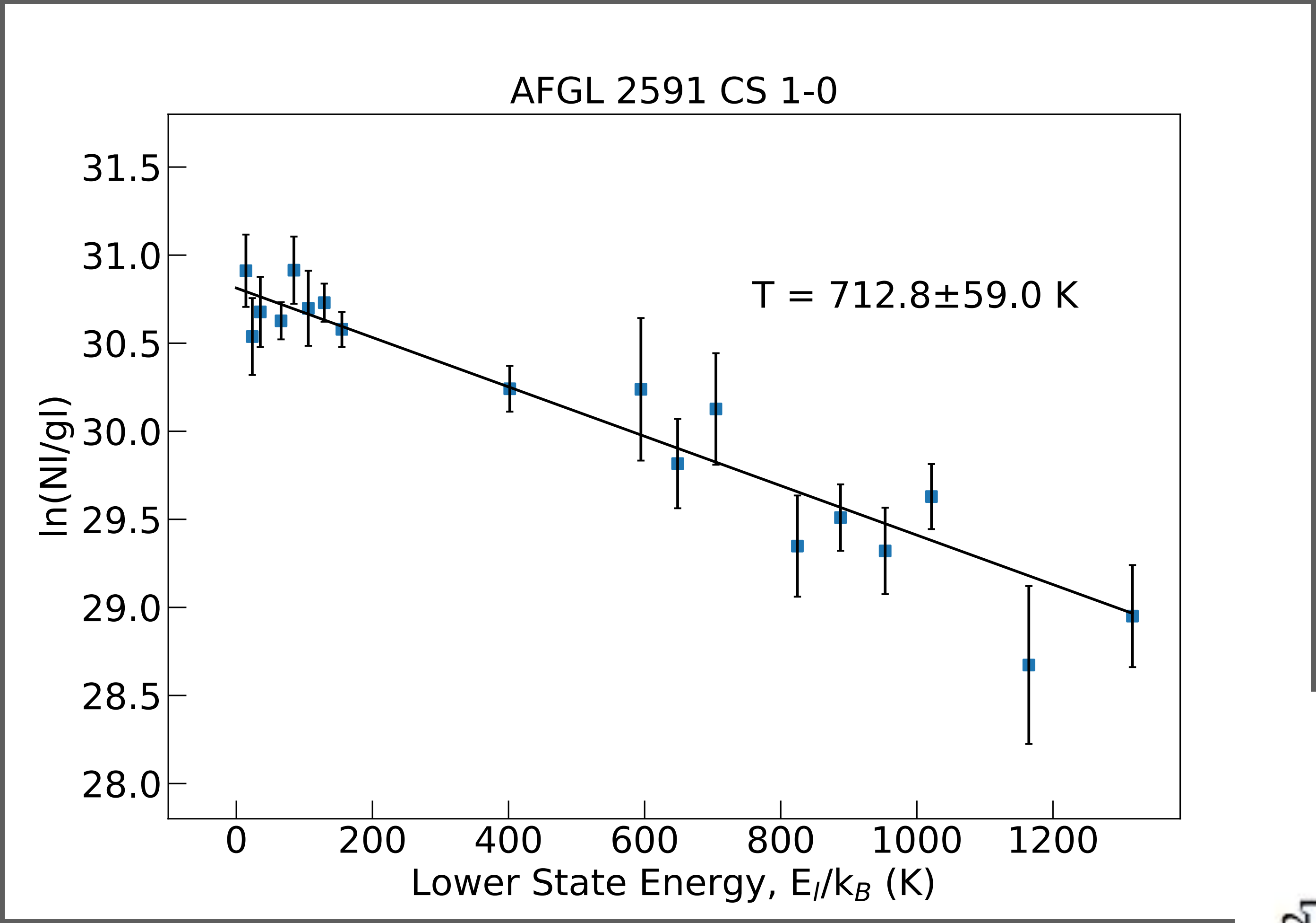


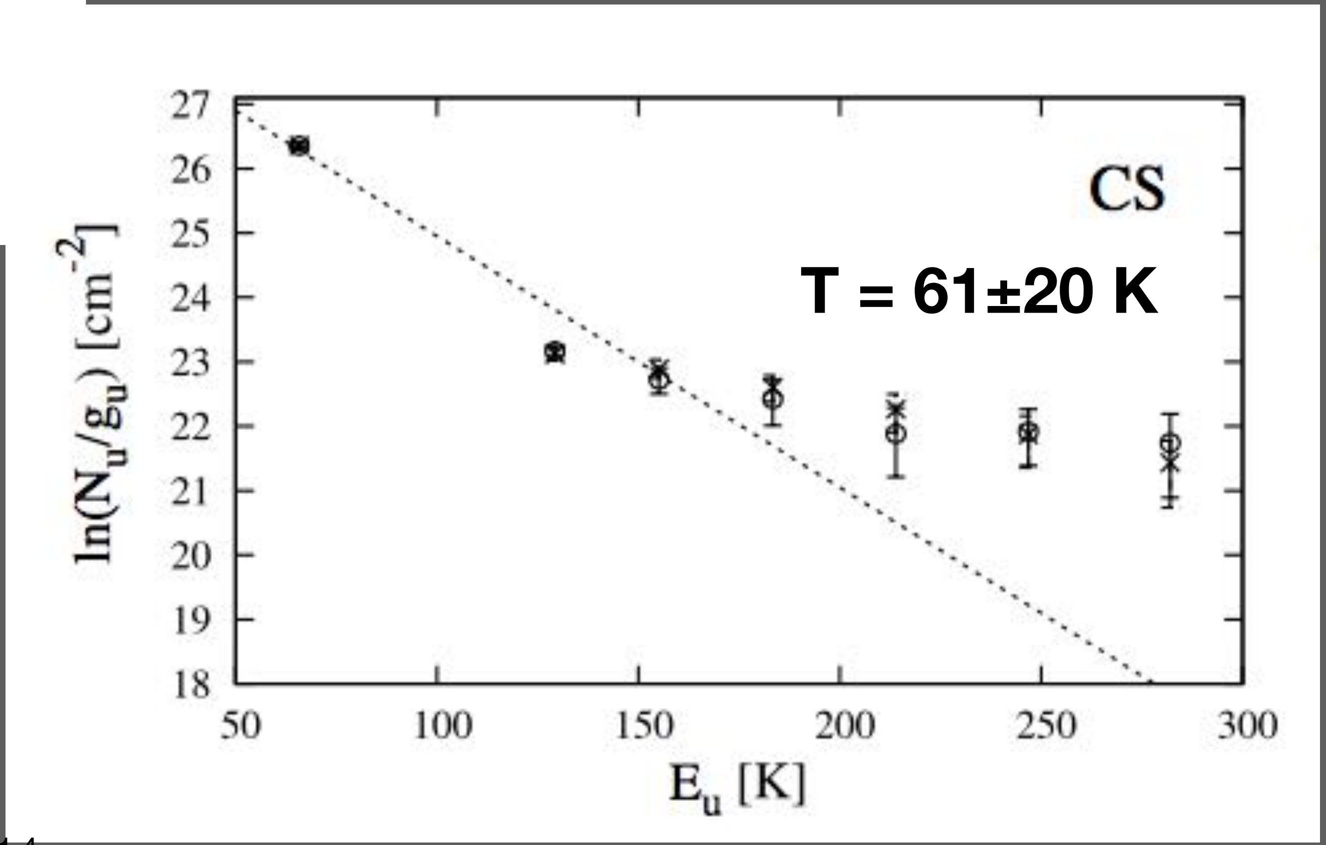
Discussion - Infrared vs Submillimeter



Kaźmierczak-Barthel et al. (2014)

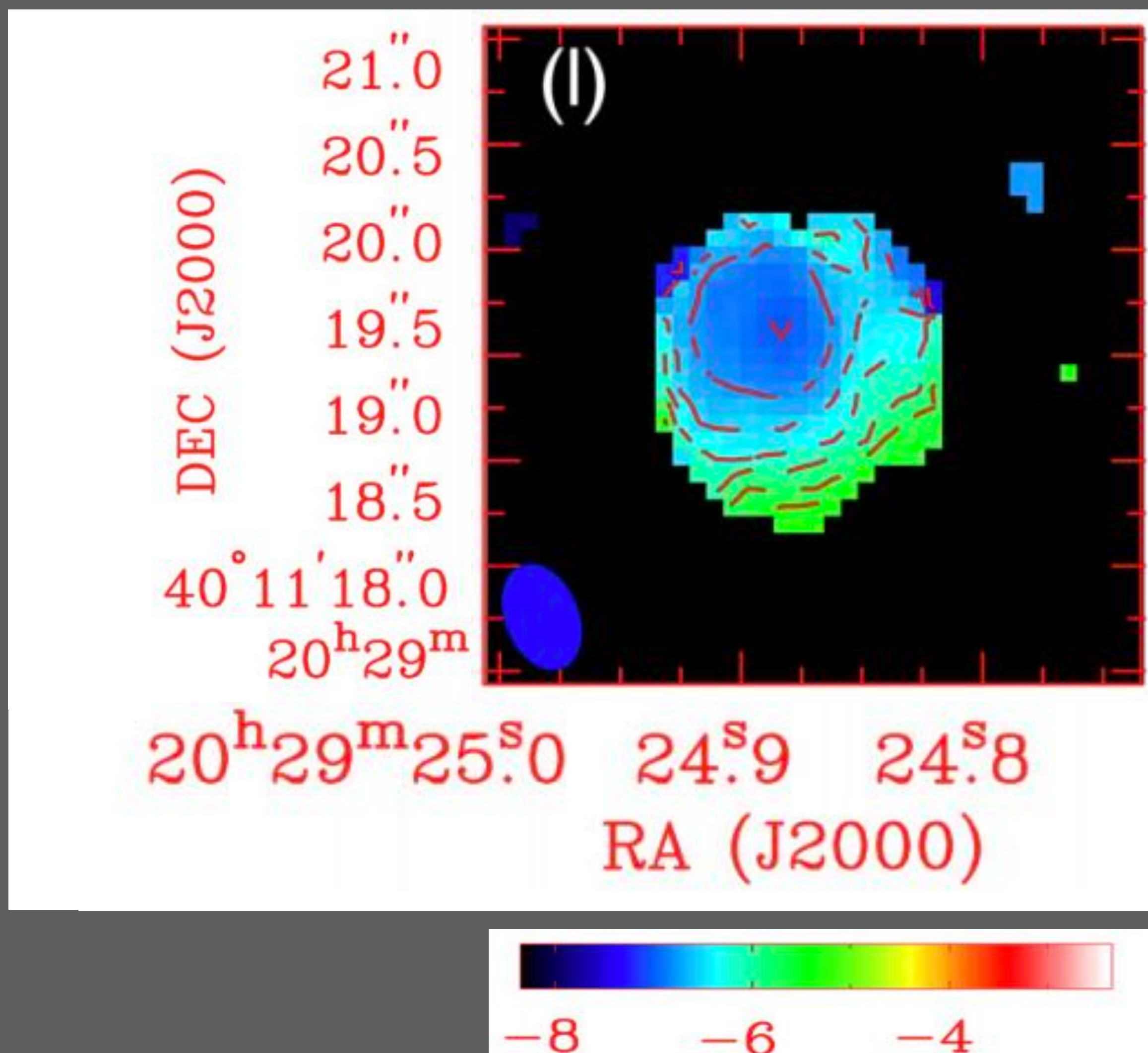
Infrared vs Submillimeter

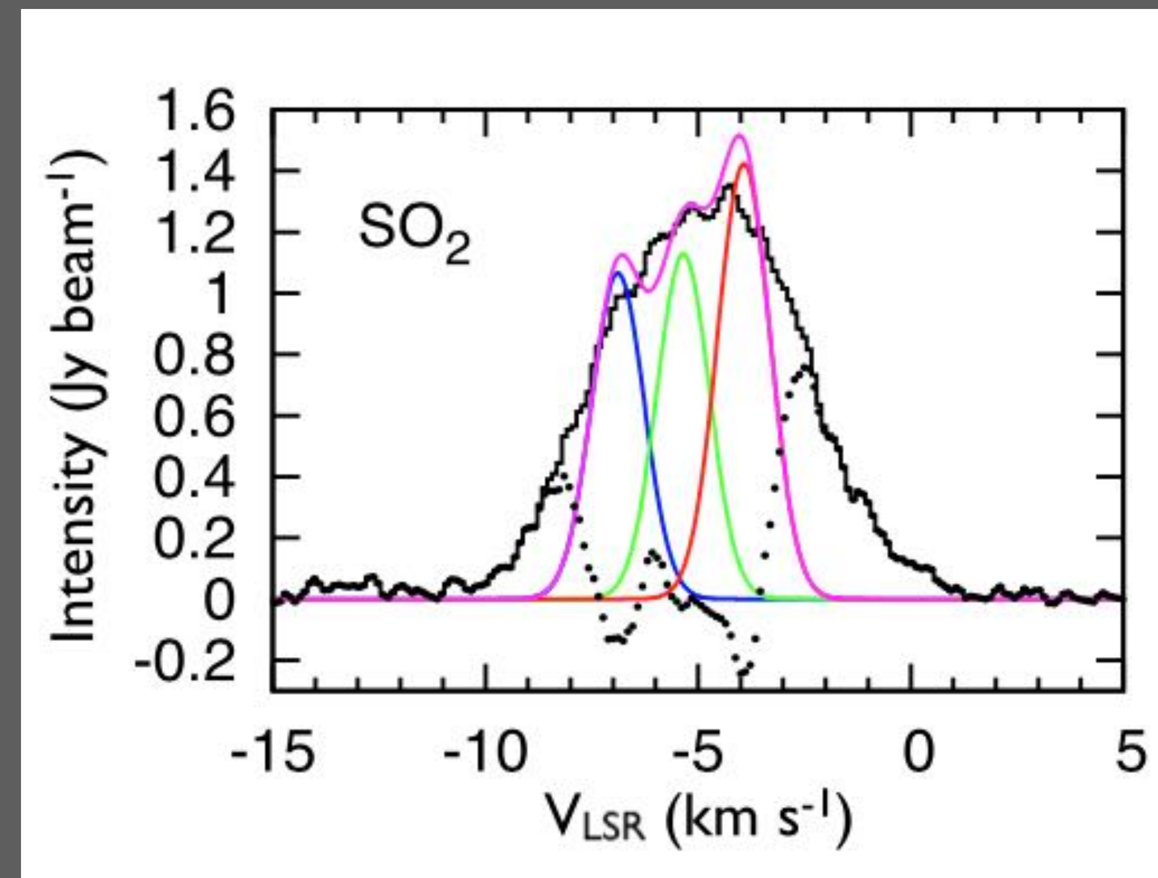




Kaźmierczak-Barthel et al. (2014)

Infrared vs Submillimeter: SO_2





Wang et al. (2012)

- Velocity map of blue shifted SO_2 shows minimum of -7 kms^{-1} towards centre of source
- Based on critical density of CS we derive a physical size of < 0.04″ (< 130 AU)
- This would not be picked up by previous sub-mm observations

Infrared vs Submillimeter

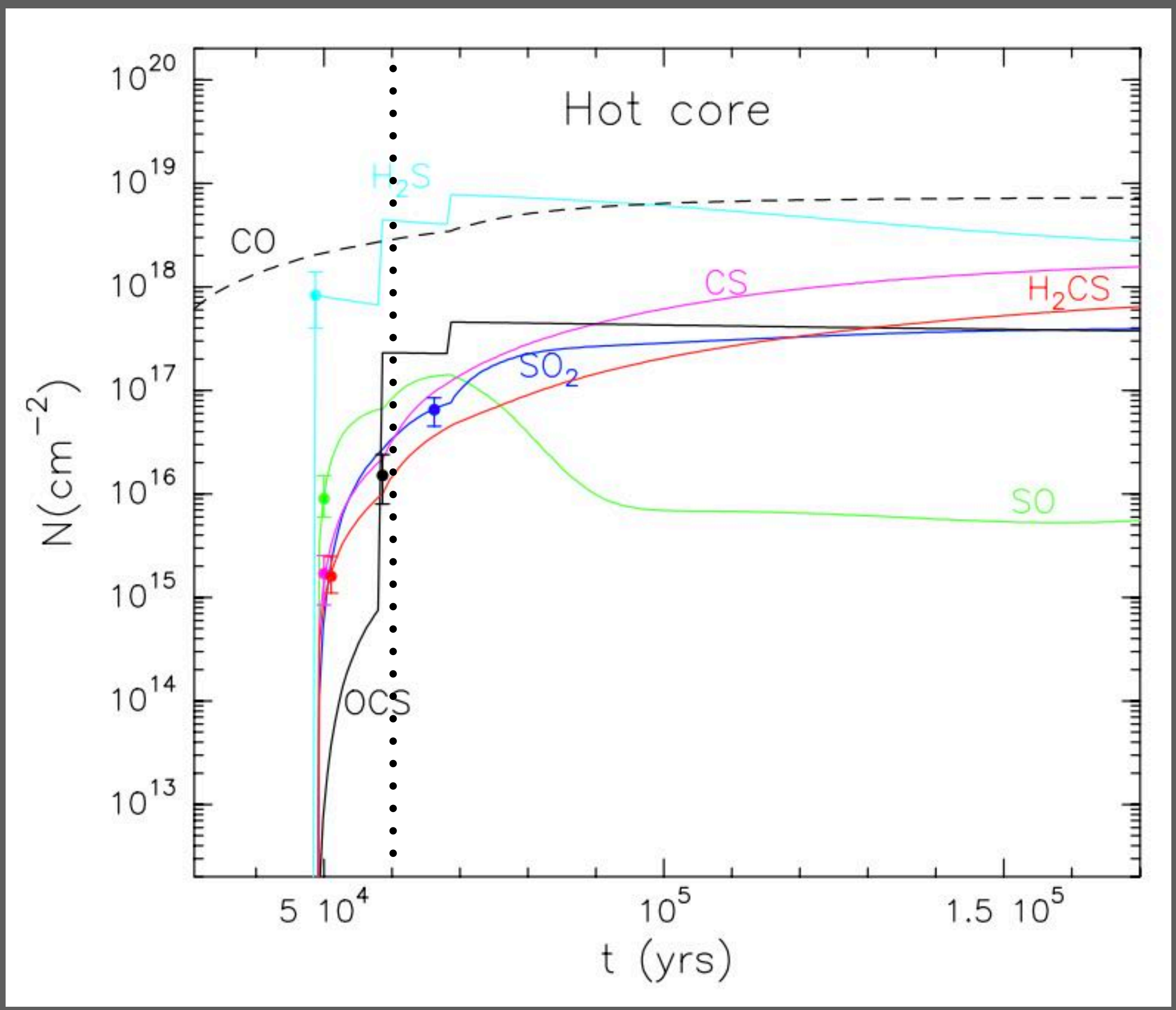
- IR and sub-mm are tracing different regions of the hot core
- IR probes more turbulent gas at the base of the outflow very close to the protostar
- Sub-mm traces more quiescent extended gas in the envelope

High temperatures and broad line profiles suggest gas is close to protostar

Chemistry of CS

- CS/CO abundance = $8x10^{-3}$
- CS/H_2 abundance = $2x10^{-6}$
- Over 2 orders of magnitude higher than sub-mm observations!
- Abundance also very high compared to Orion Hot Core with CS/CO = $4x10^{-4}$ (Tercero et al. 2010)

Chemistry of CS



Esplugues et al. (2014)

- After ~6x10^4 yr our observed CS abundance is reached
- S formed by abstraction of H_2S
- CH_2 formed by cosmic ray breakdown of CO
- CS, H_2CS and SO_2 become the most abundant S-bearing species for an evolved hot core

$CH_2 + S \rightarrow CS + H_2$

Chemistry of CS

I. AFGL 2591 is an evolved hot core

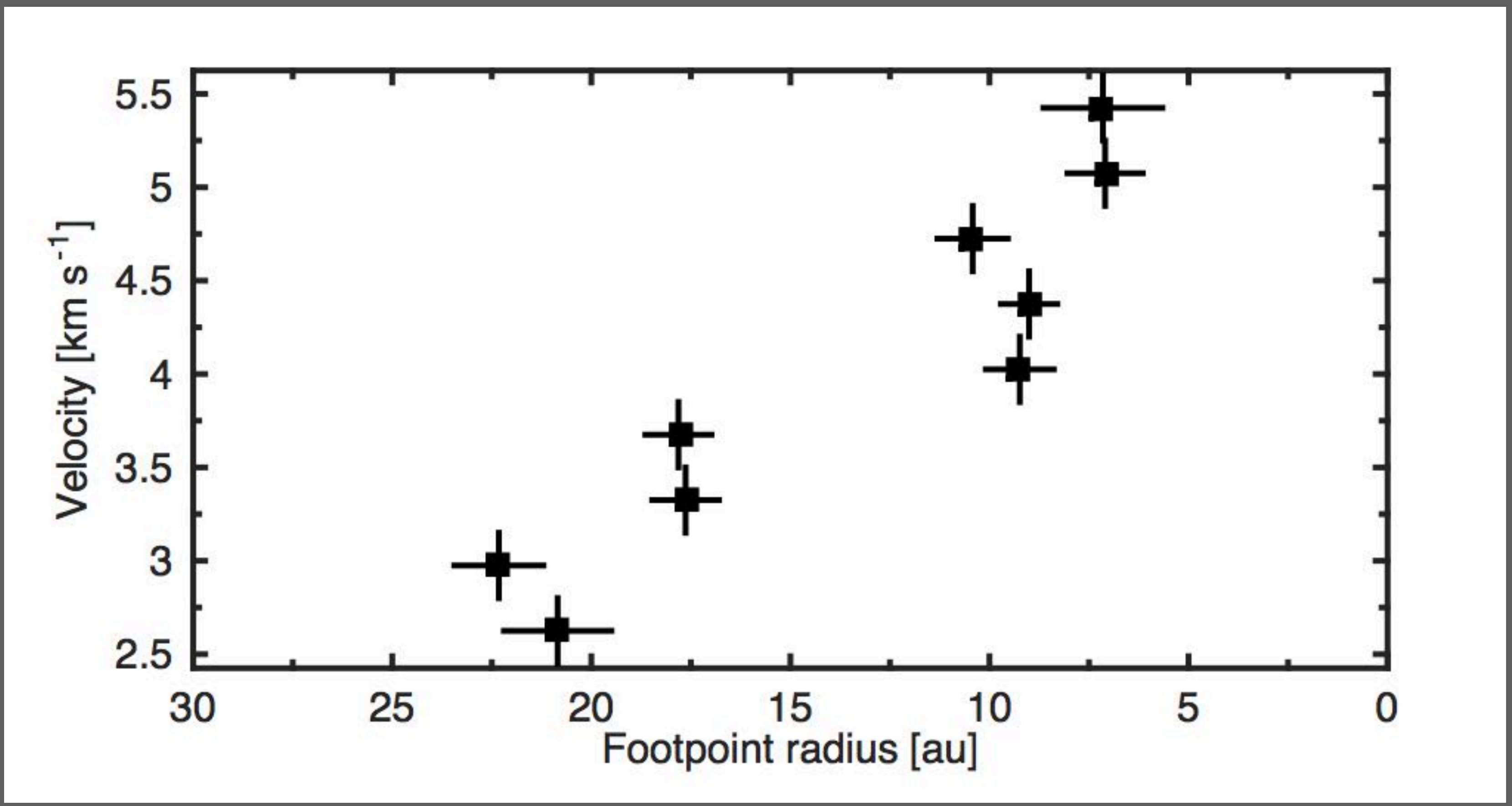
- All S converted to H_2S on grain surfaces then converted back to S in gas phase after sublimation
- At long timescales enough CS is produced to explain our observations
- H_2S is not observed in ice toward massive protostars so deeper searches needed to clarify
- Hot core models have not been optimised to conditions of AFGL 2591

Chemistry of CS

II. IR observations trace disk-wind interaction zone

- Cosmic ray ionisation very high favouring breaking up of CO
- Again atomic S produced via abstraction of H_2S
- Grain sputtering becomes important in shocks ~15 kms^{-1} (May et al. 2000). Might release S from grain surfaces

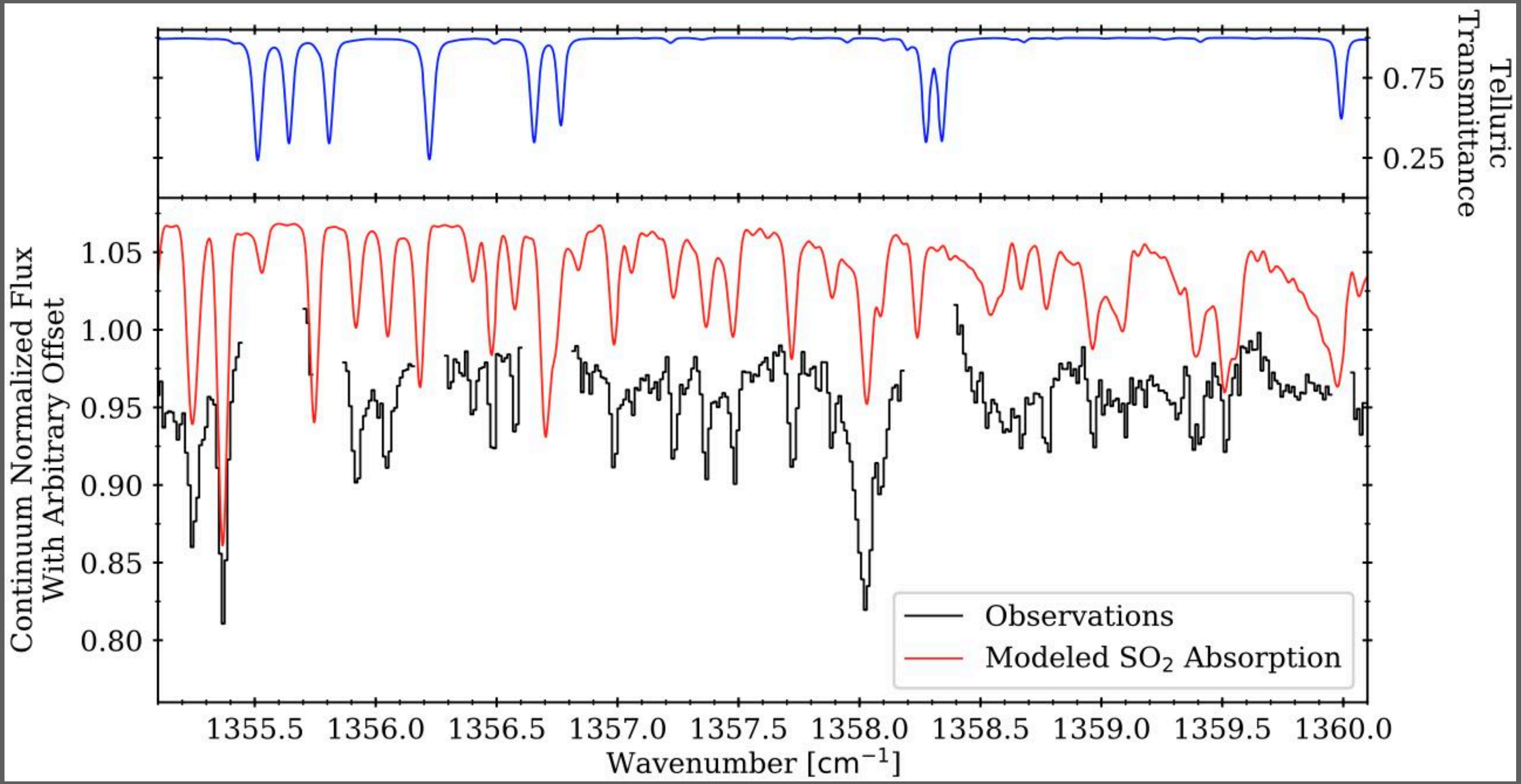
Disk Wind Launching-point



Bjerkeli et al. (2016)

- Low mass protostar TMC1A
- CO observations with ALMA
- Extended launching mechanism of outflow

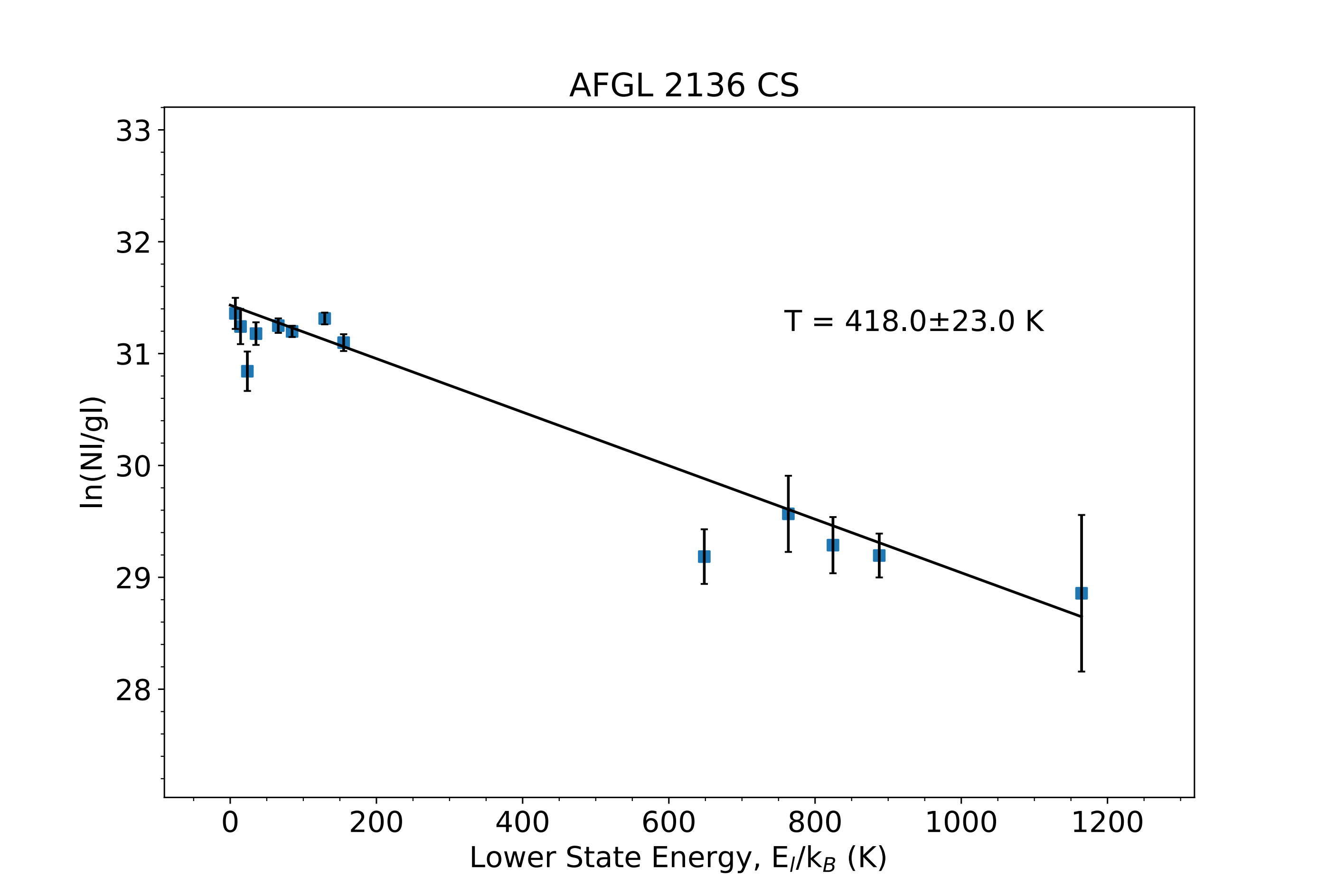
EXES Detection SO_2



Dungee et al. (2018)

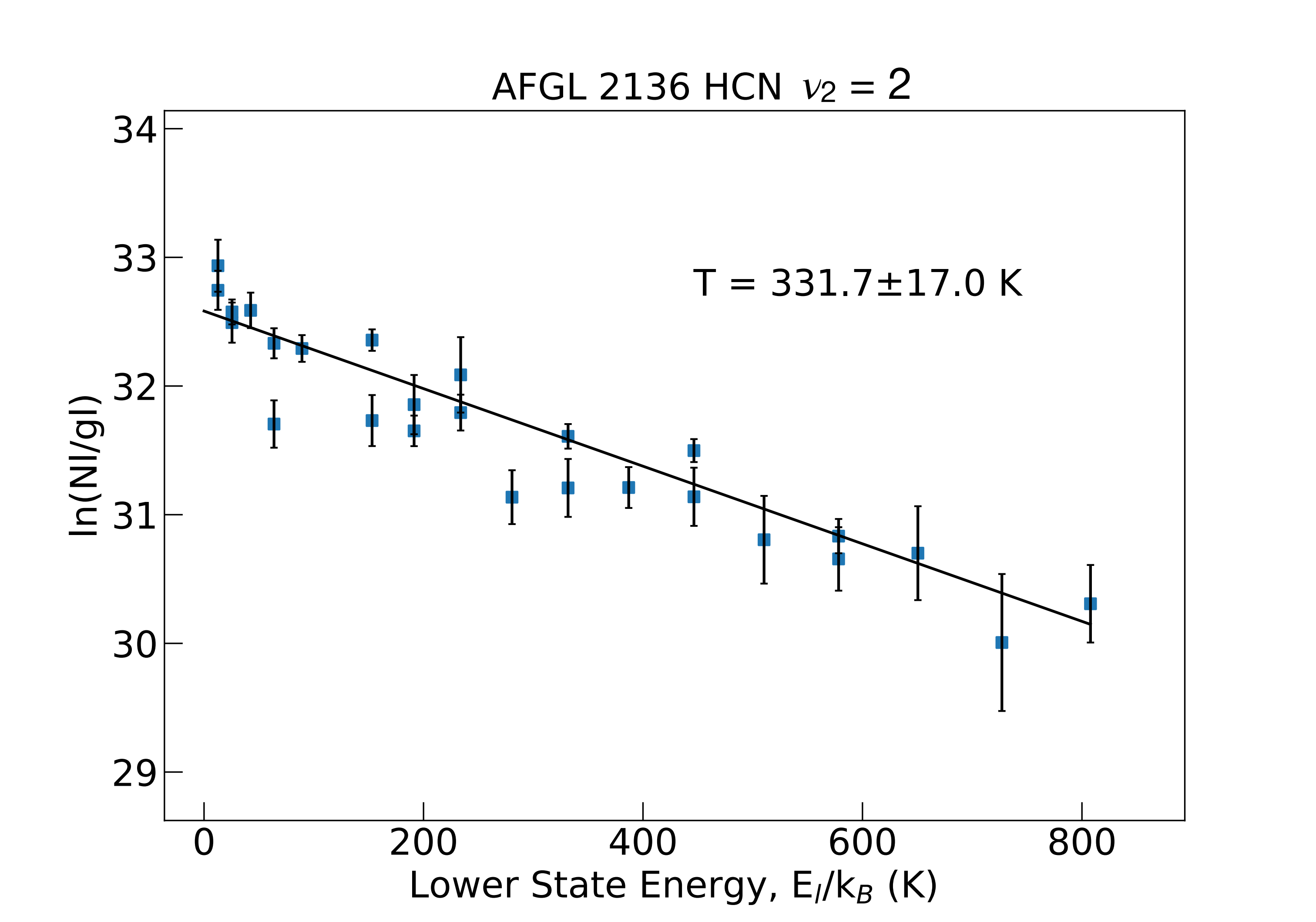
- Hot core MonR2 IRS3
- High abundance of warm SO_2 suggests large amount of S in hot cores only visible at IR wavelengths

AFGL 2136 - CS



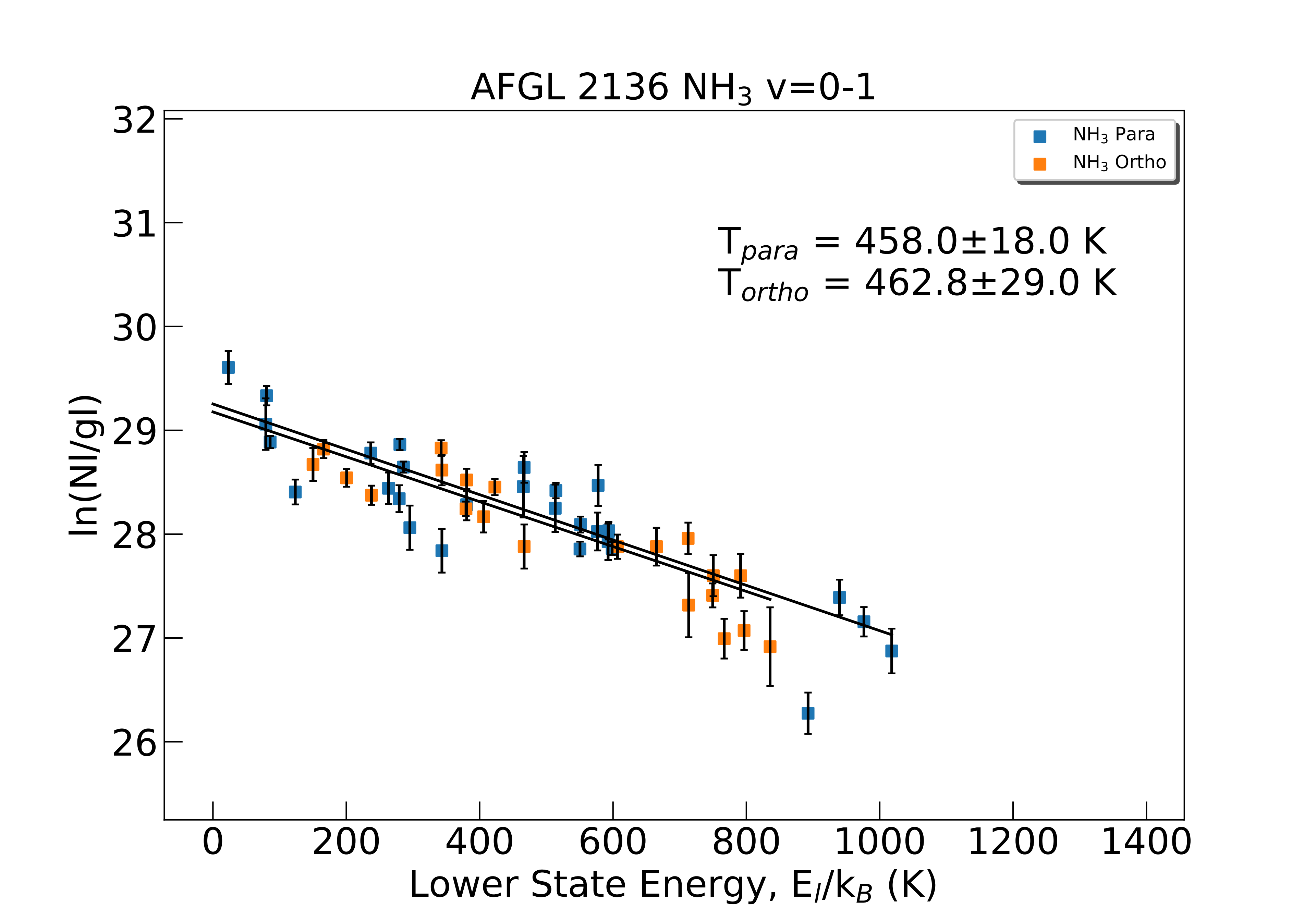
- CS/CO = 1.2×10^{-3}
- 60 times higher than sub-mm
- Velocity derived is 3 kms^{-1} more red-shifted compared to sub-mm
- Disk-wind proposed to explain ALMA observations in SiO (Maud et al. 2018)

AFGL 2136 - HCN



- HCN important for initiating complex chemistry and understanding where cold mid-plane molecules come from
- HCN/CO = 1×10^{-2}
  $HCN/H_2 = 2 \times 10^{-6}$
- v_{lsr} consistent with other molecules observed with EXES

AFGL 2136 - NH_3



Challenges and Future

- Ways forward:
  - Identification of new species in IR
  - Identify chemical signatures in IR that trace different parts of hot cores
- Challenges:
  - Better atmospheric models
  - Better line lists for IR spectroscopy

Conclusions

- First detection of CS in AFGL 2591 at IR wavelengths
- Temperatures and line profiles suggest CS and CO gas in same region
- IR and sub-mm observations trace different components of the hot core
- High densities, temperatures, velocity and abundance suggests that CS observations probe the base of the outflow very close to protostar
- Chemical models support CS abundance if AFGL 2591 is an evolved hot core
- Alternatively observations trace onset of disk wind at base of outflow
- There is work to be done in developing molecular databases in IR