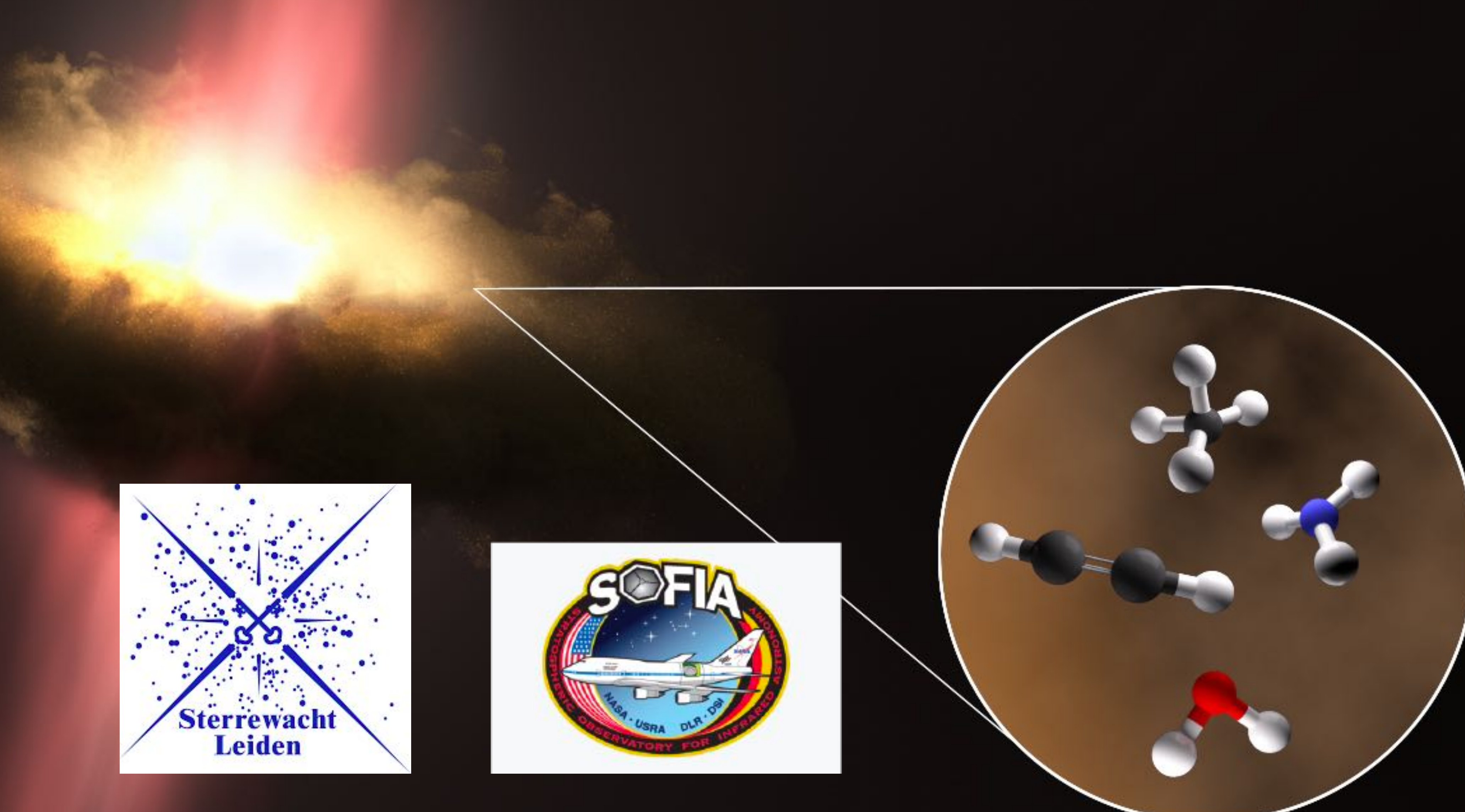
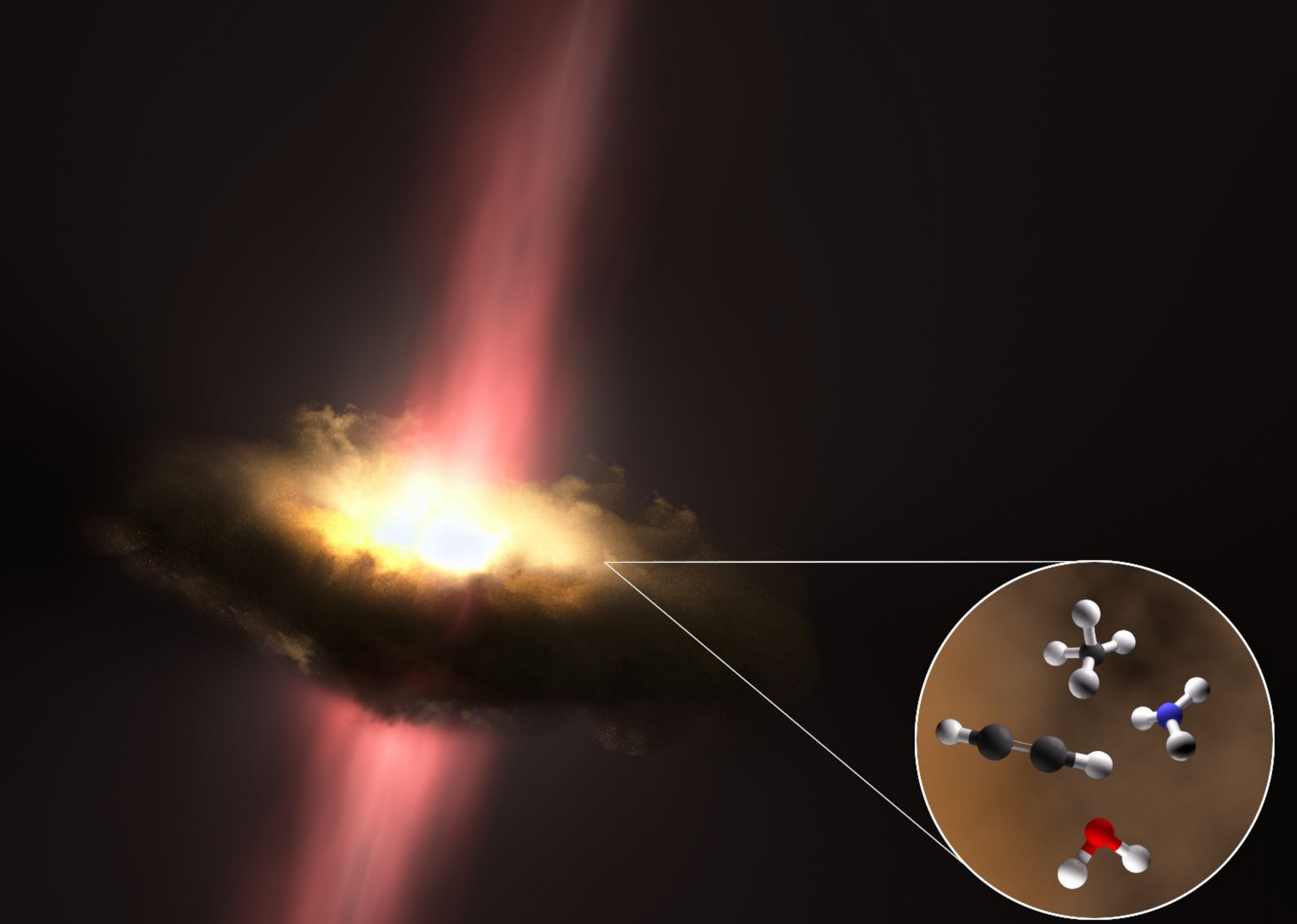
Accretion in the Inner Regions of Massive Circumstellar Disks: AFGL 2136 and AFGL 2591



Andrew Barr
SOFIA Tele Talk
12/09/20

Credit: NASA/SOFIA



Credit: NASA/SOFIA

THE ASTROPHYSICAL JOURNAL, 900:104 (35pp), 2020 September 10
https://doi.org/10.3847/1538-4357/abab05

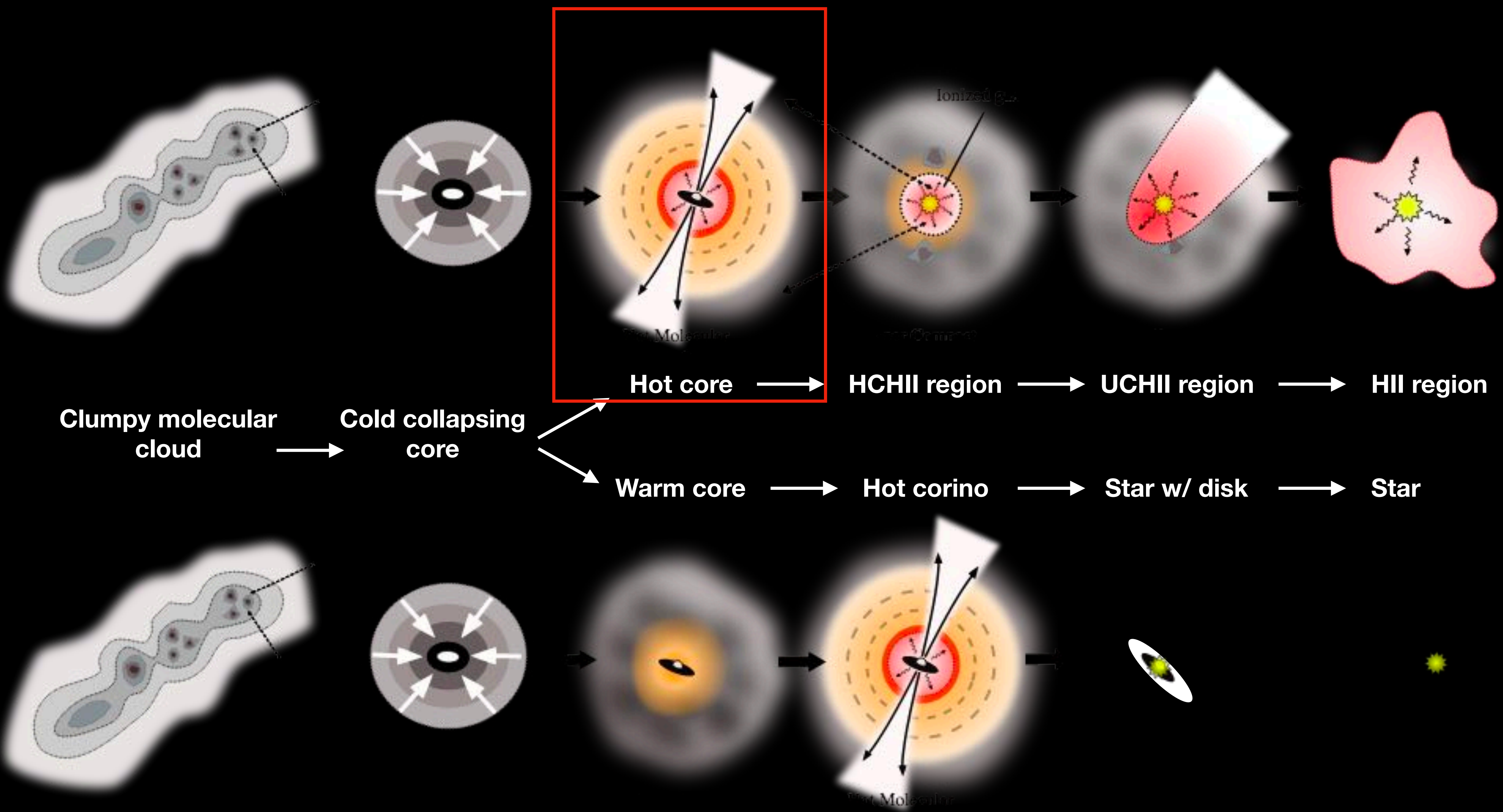
CrossMark

High-resolution Infrared Spectroscopy of Hot Molecular Gas in AFGL 2591 and AFGL 2136: Accretion in the Inner Regions of Disks around Massive Young Stellar Objects

Andrew G. Barr[1], Adwin Boogert[2,10], Curtis N. DeWitt[3], Edward Montiel[3], Matthew J. Richter[4], John H. Lacy[5], David A. Neufeld[6], Nick Indriolo[7], Yvonne Pendleton[8], Jean Chiar[9], and Alexander G. G. M. Tielens[1]

Credit: NASA/SOFIA

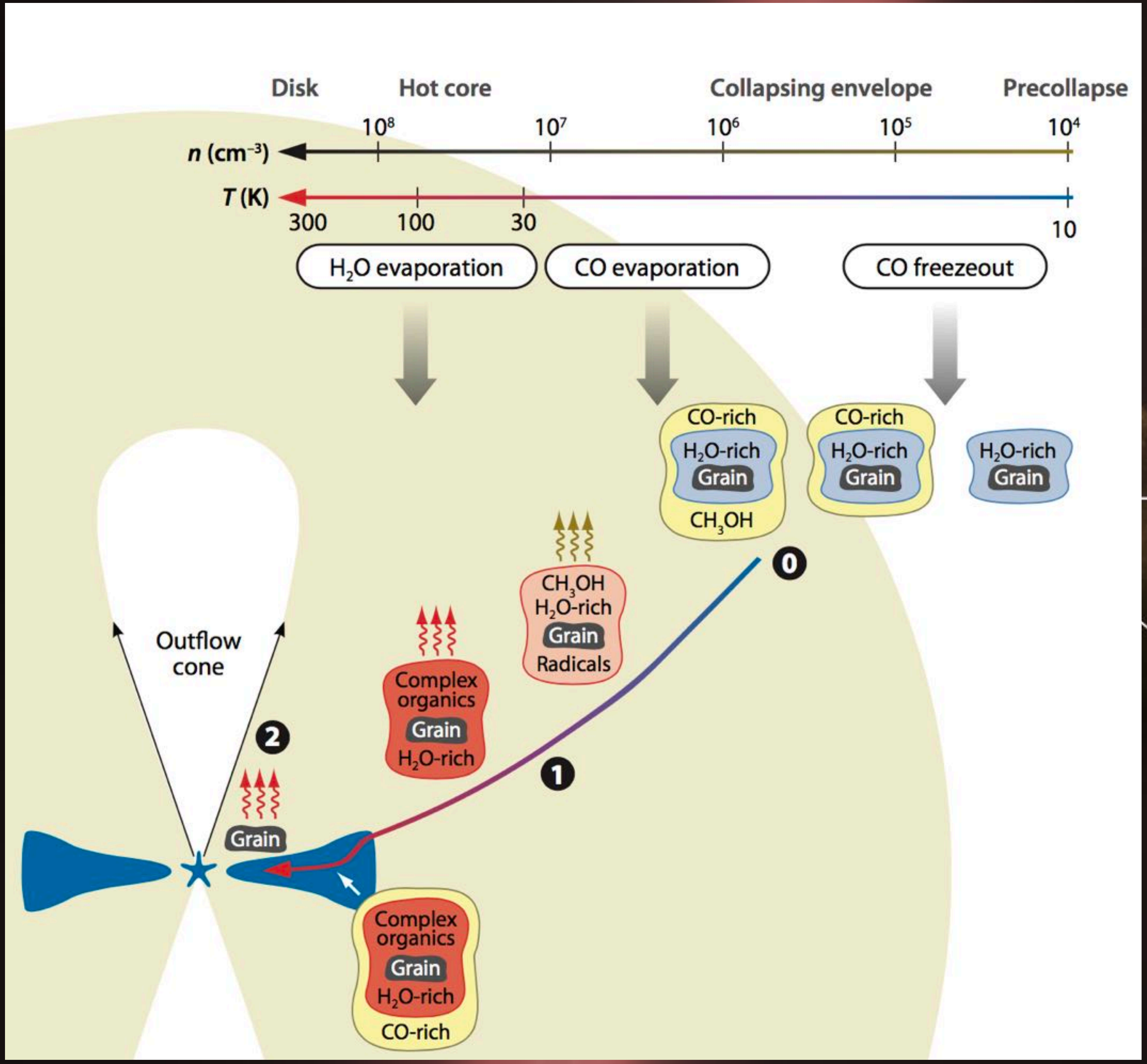
High Mass Star Formation



Low Mass Star Formation

Credit: Adam Ginsburg

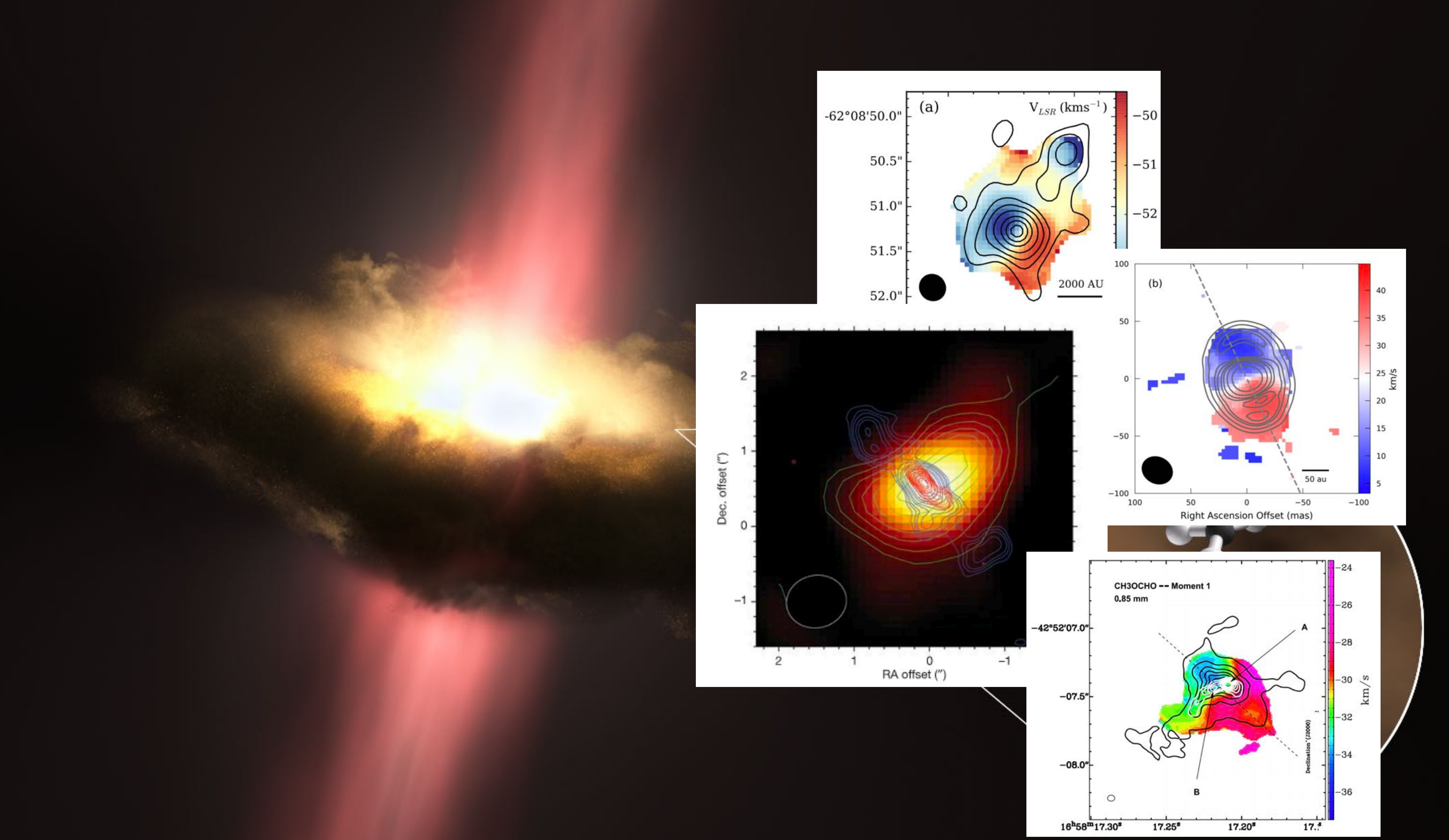
Hot Core Phase



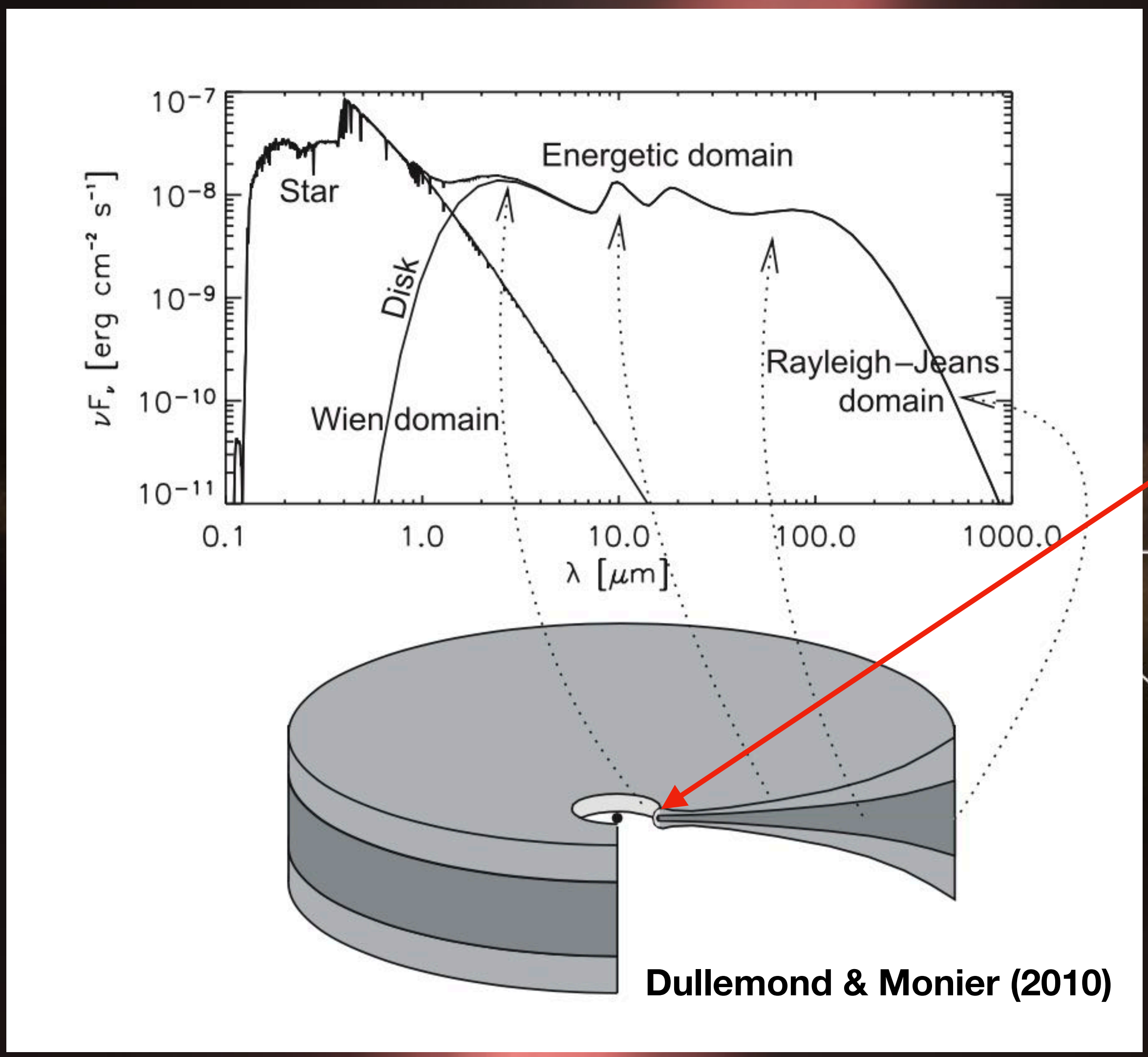
van Dishoeck & Herbst 2009

- Intermediate objects in high mass star formation
- Complex environment with evaporation of ice mantles
- Chemically rich objects
- Structure and chemistry well studied at sub-mm wavelengths. Not so much for infrared: CH_4 & C_2H_2

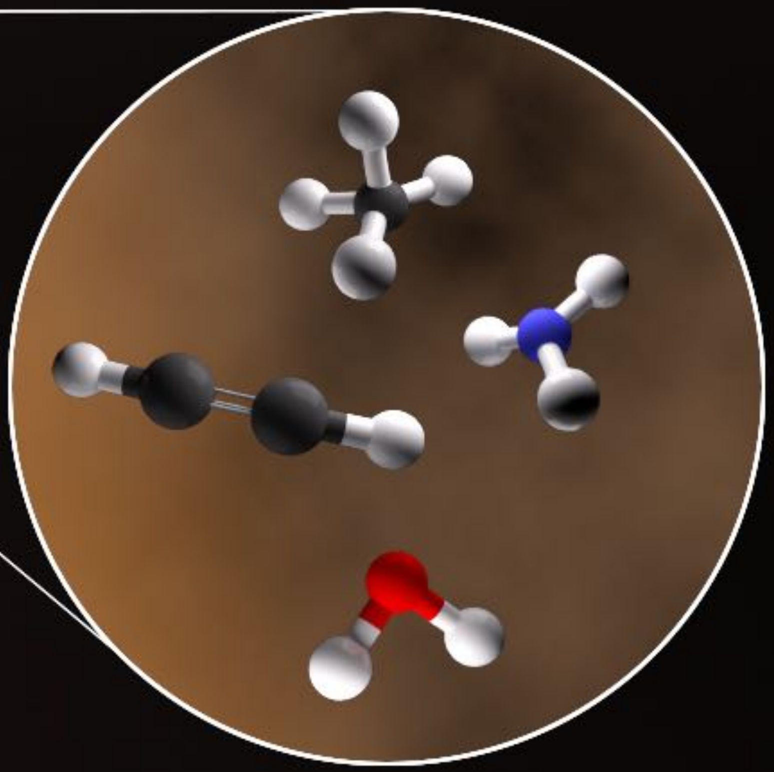
Disks in Massive Star Formation



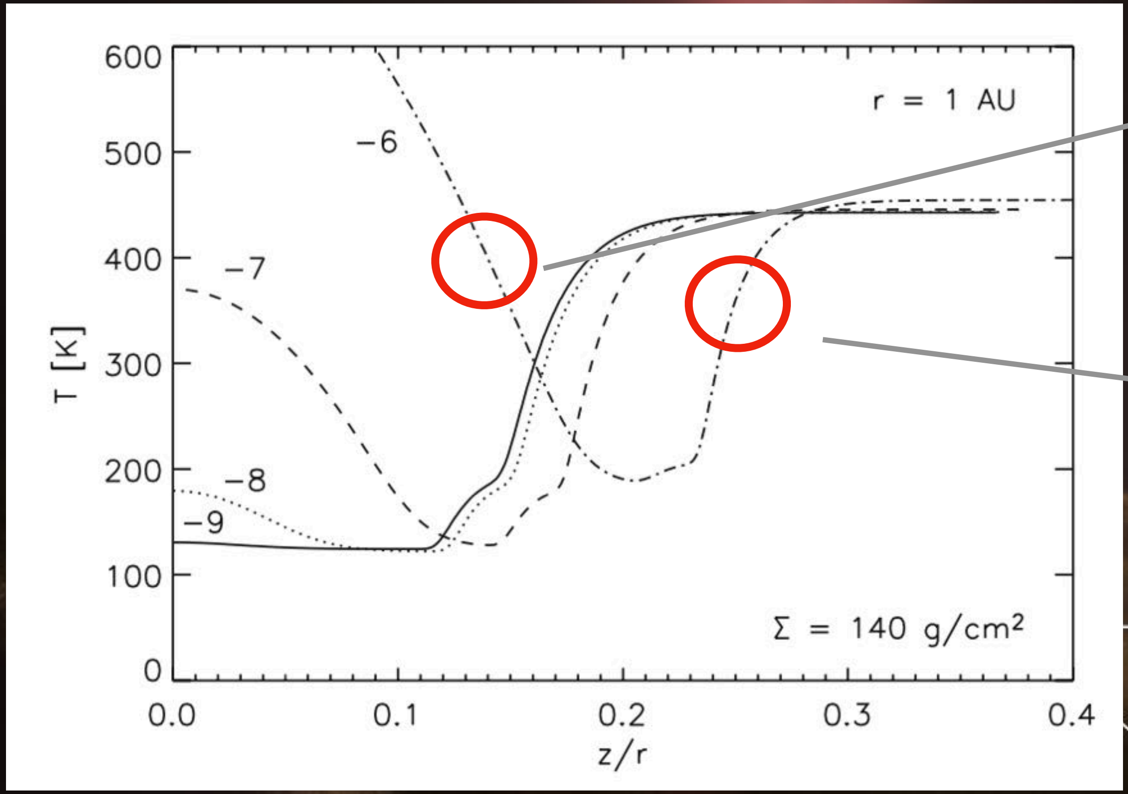
Disks in Massive Star Formation



CO emission

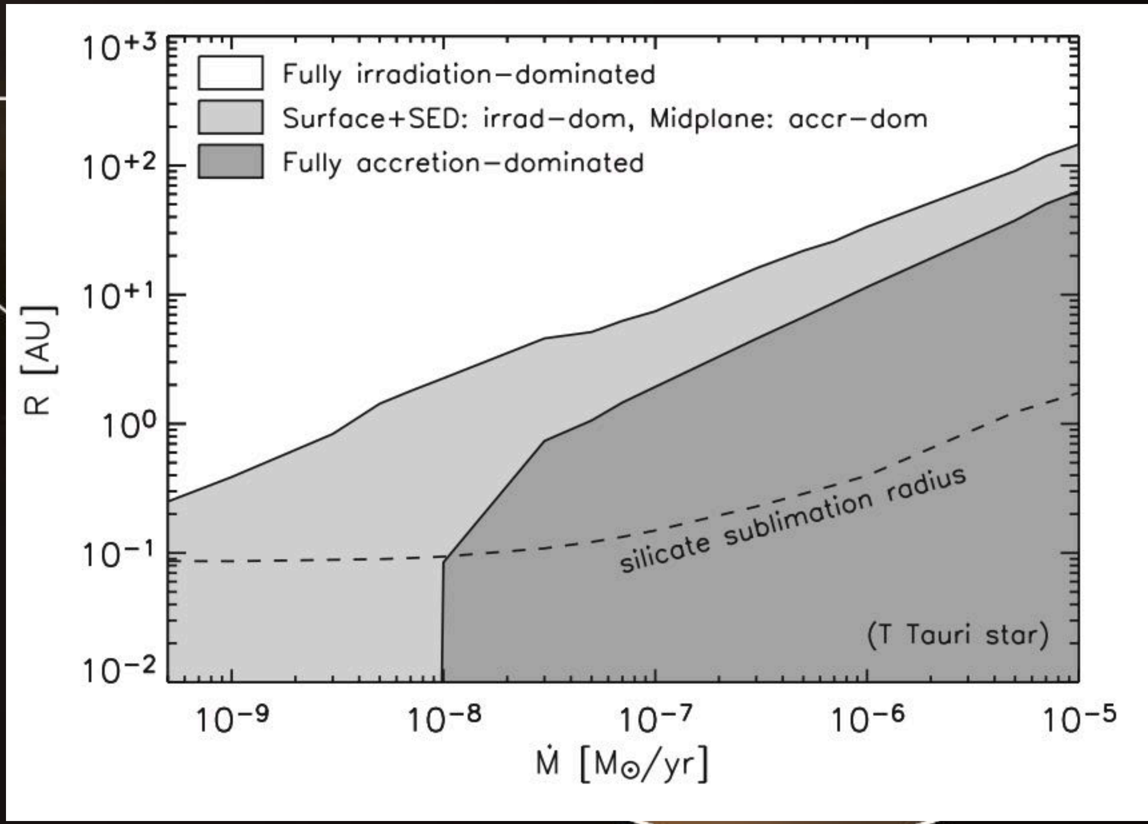


Disks in Massive Star Formation



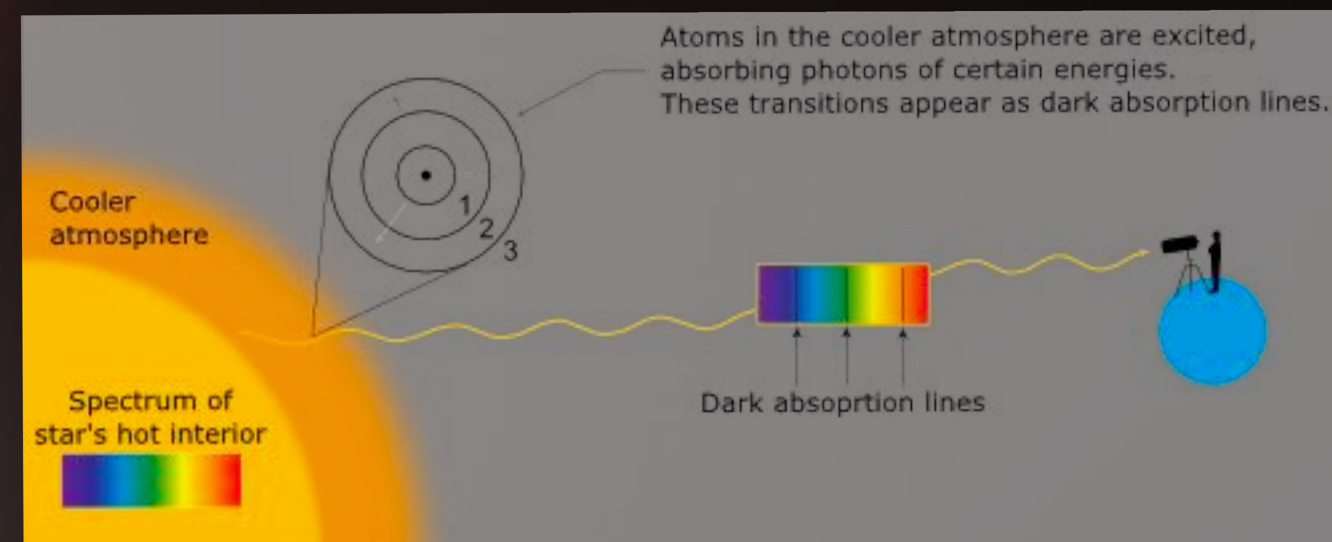
-ve temperature gradient outward

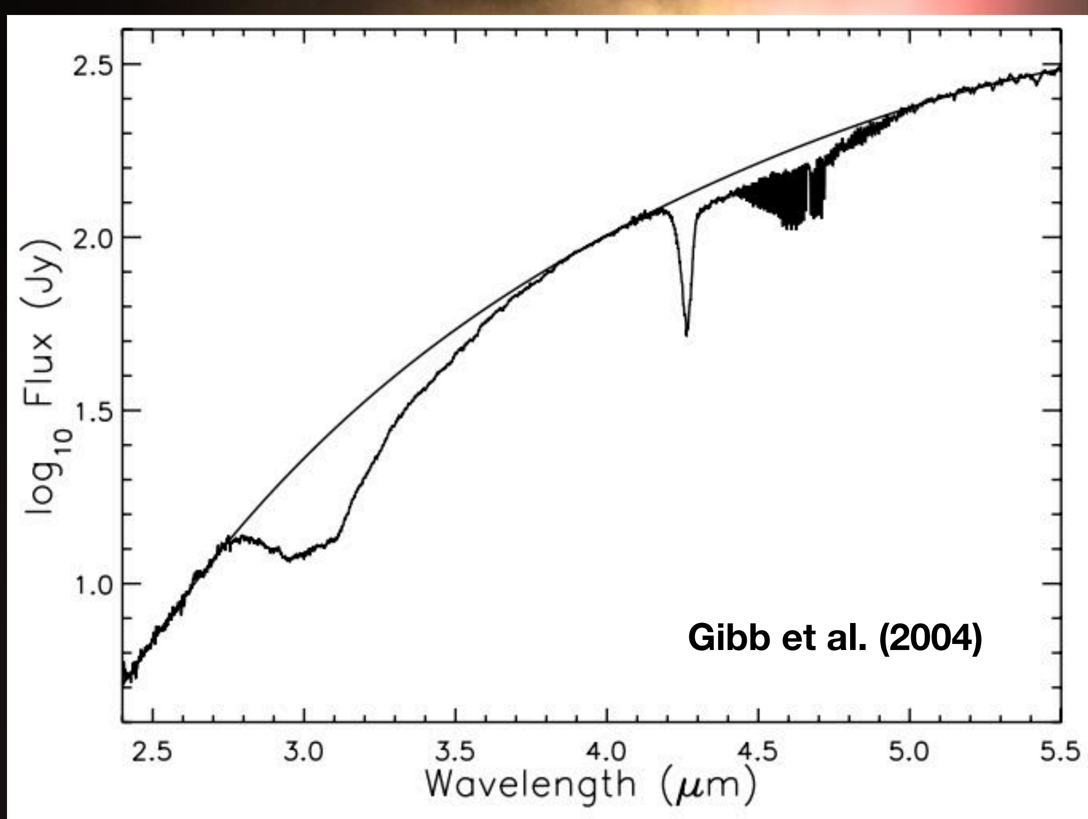
+ve temperature gradient outward

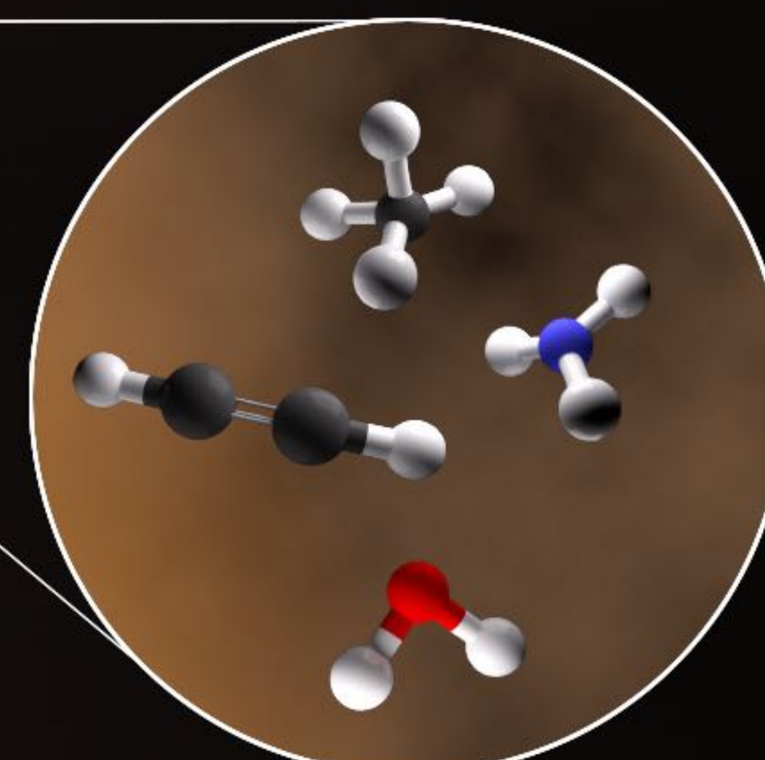


d'Alessio et al. (1998)

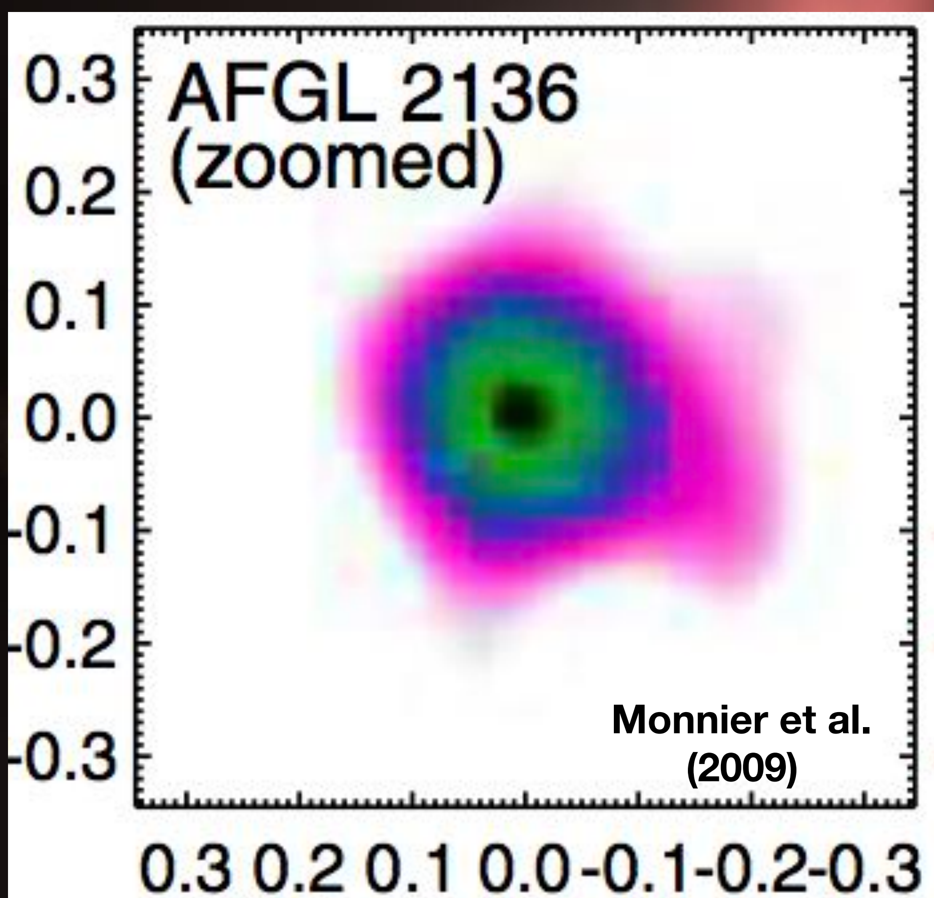
Absorption Spectroscopy

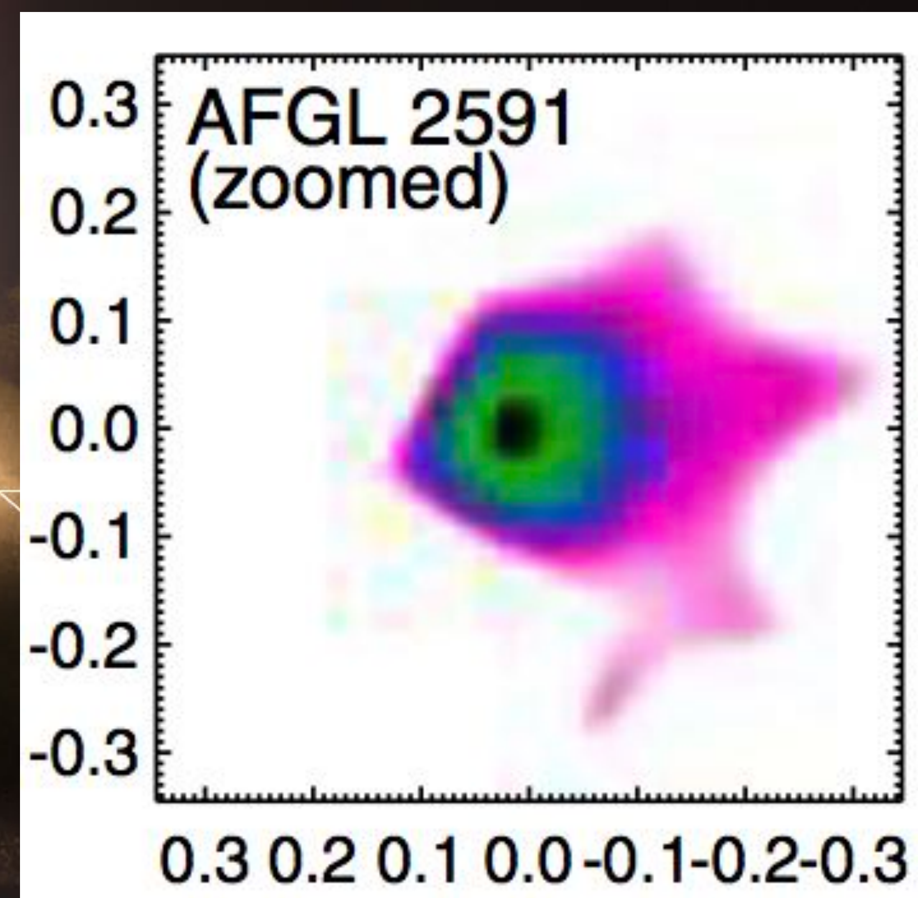


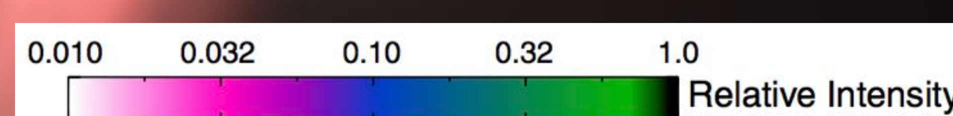


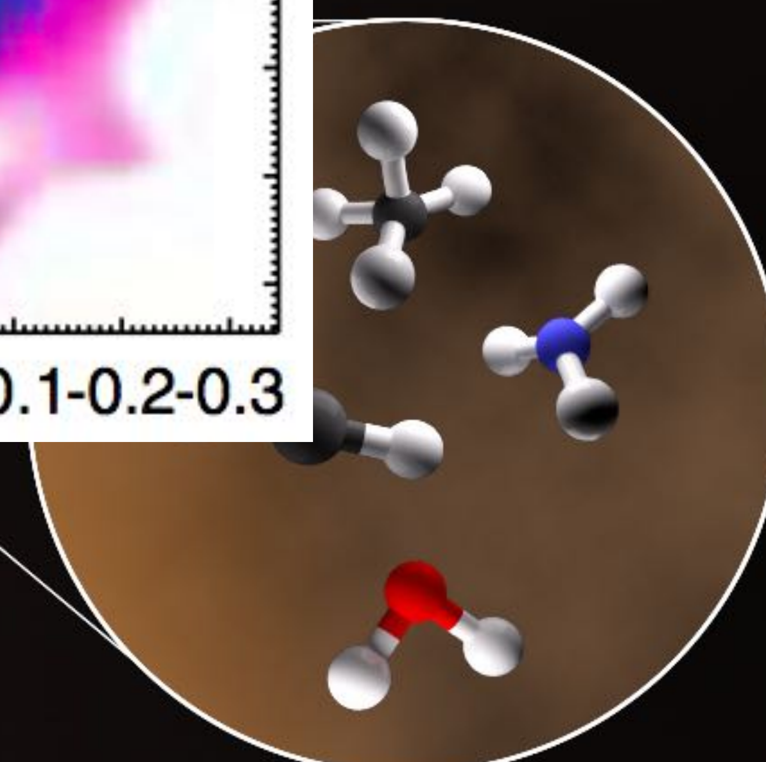


Absorption Spectroscopy

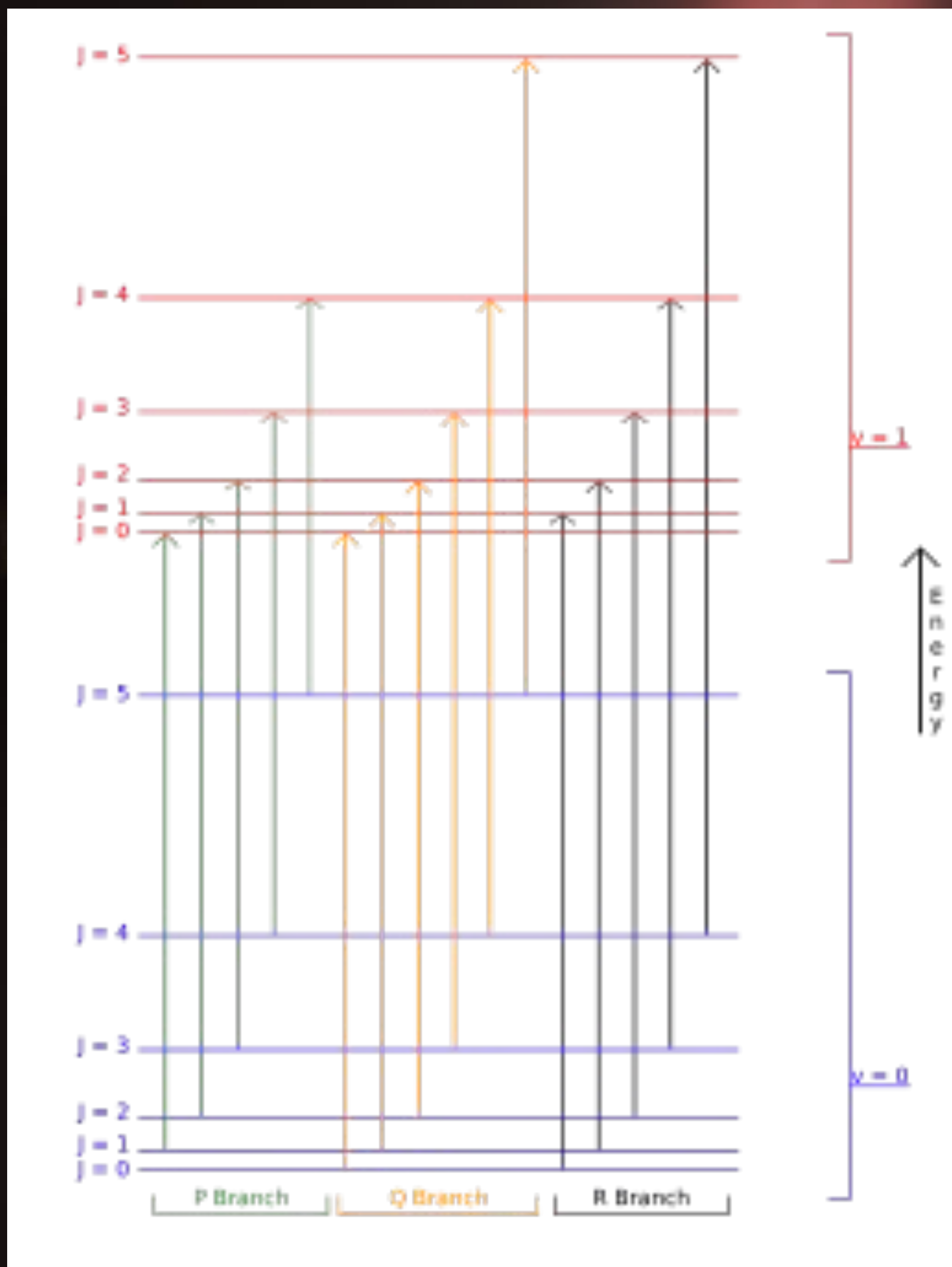


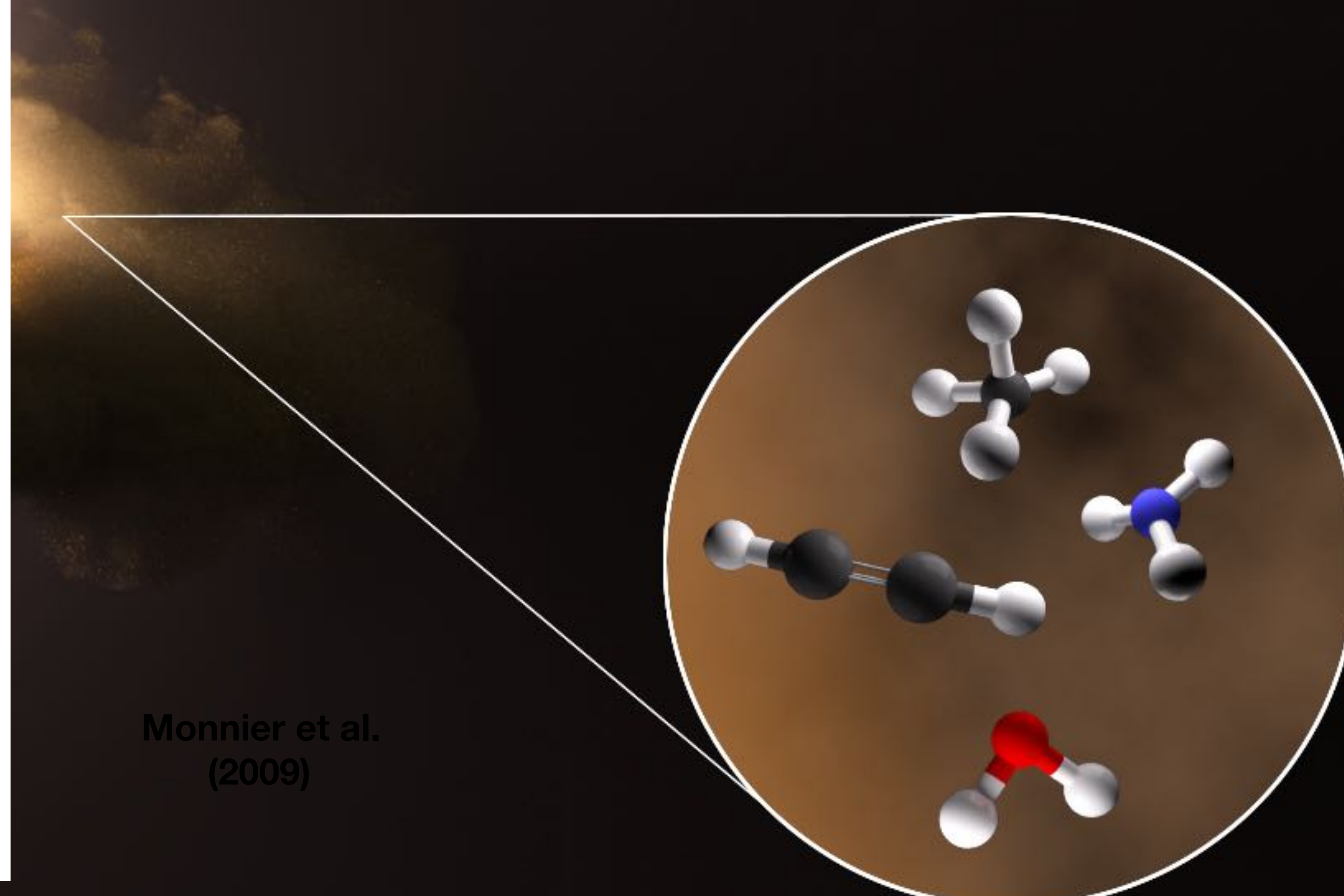






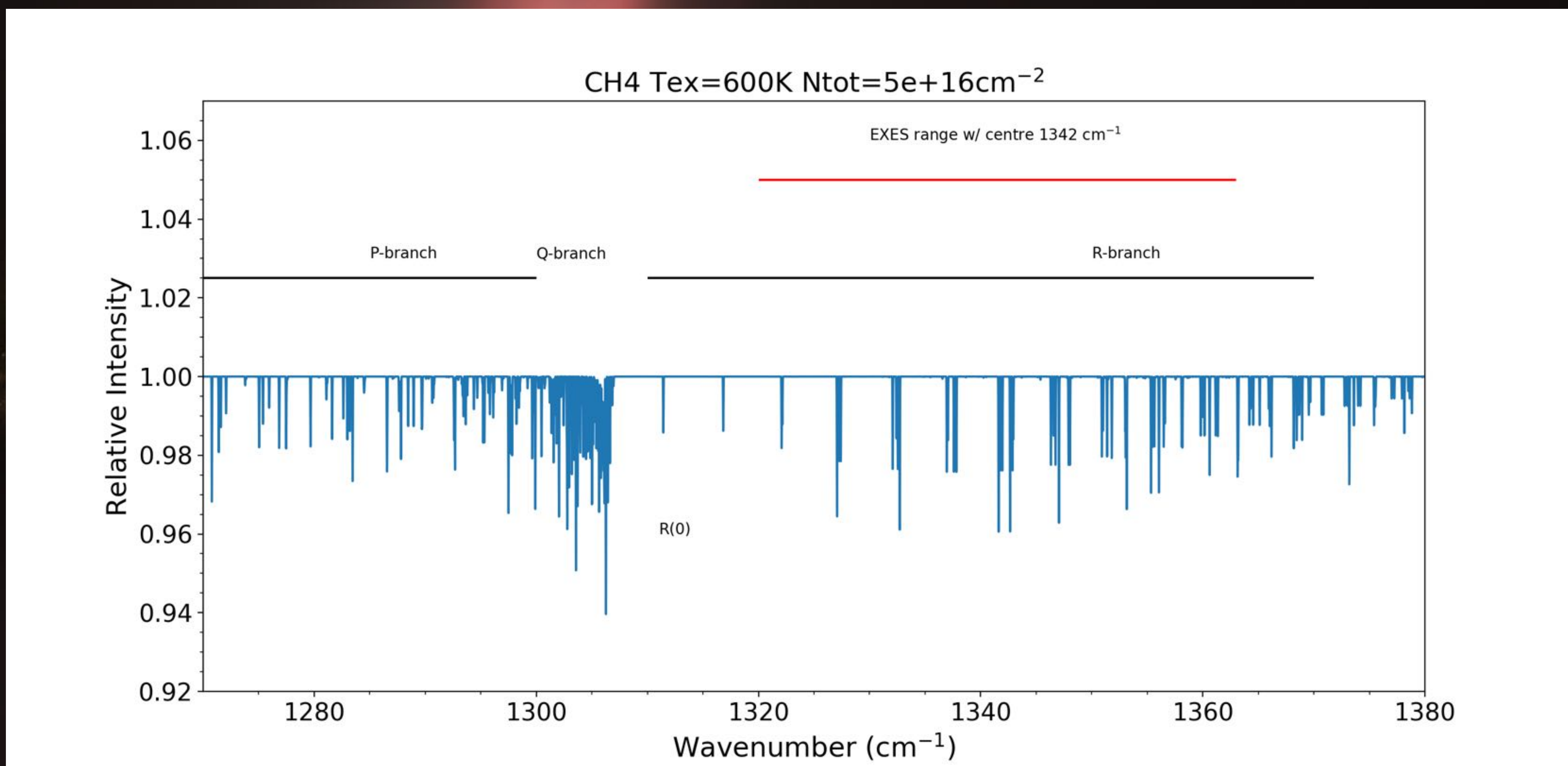
Ro-vibrational Spectra

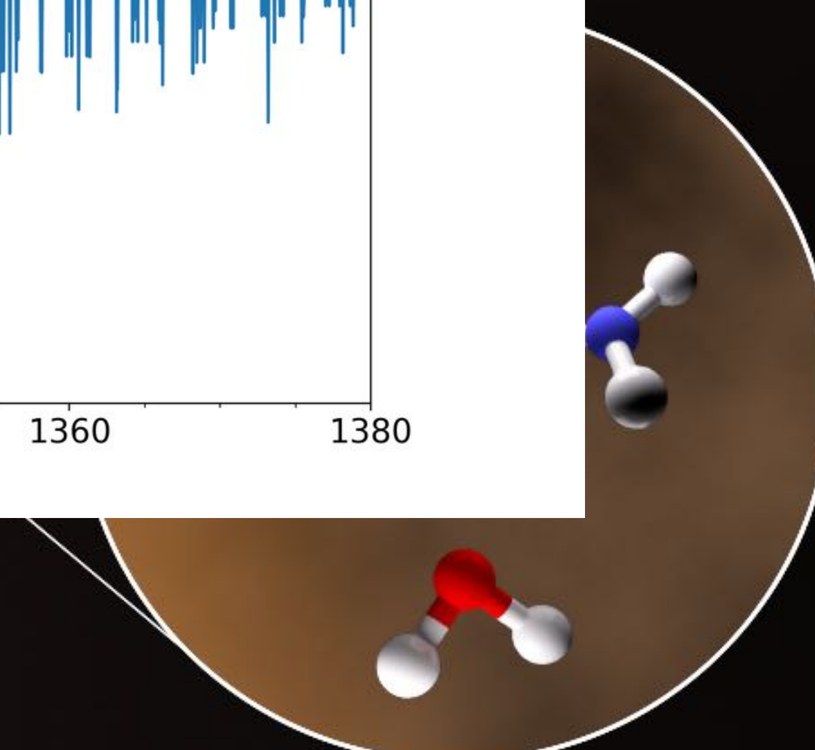




Monnier et al.
(2009)

Ro-vibrational Spectra



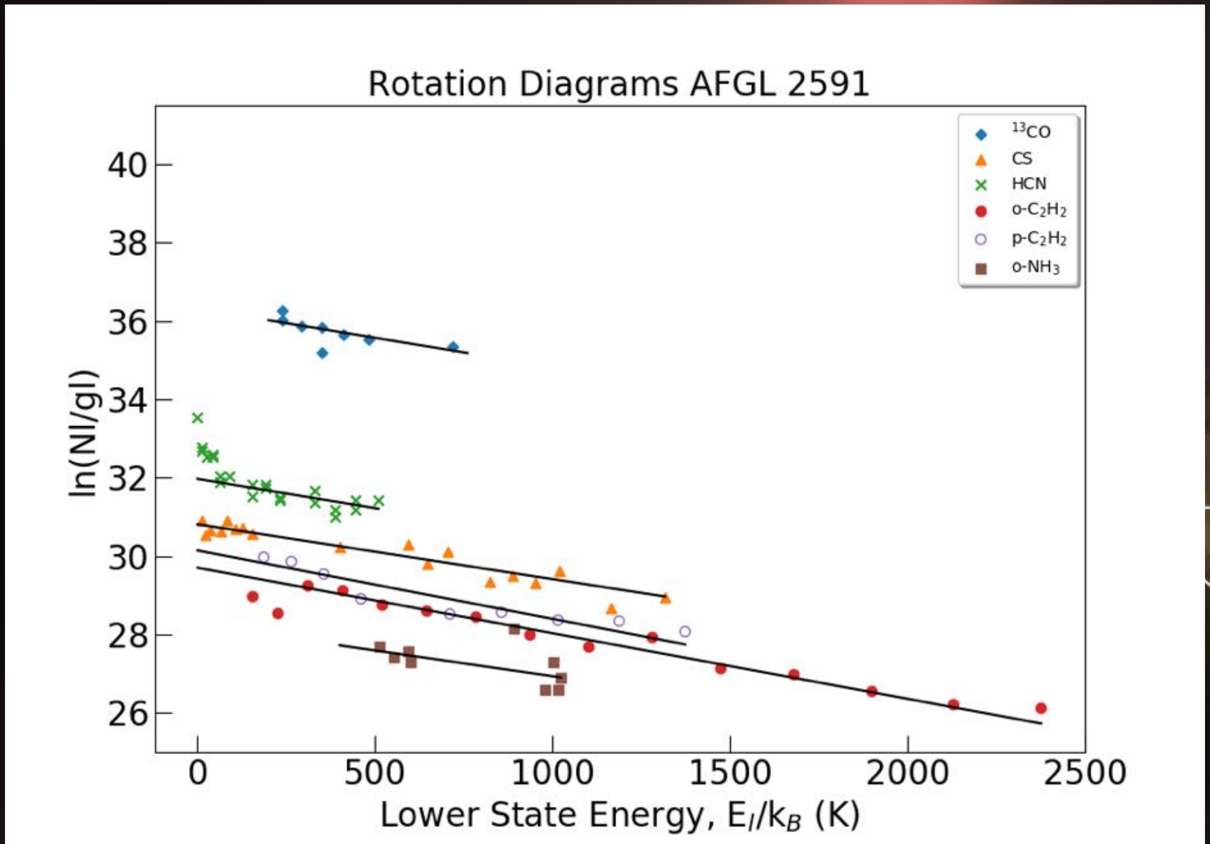


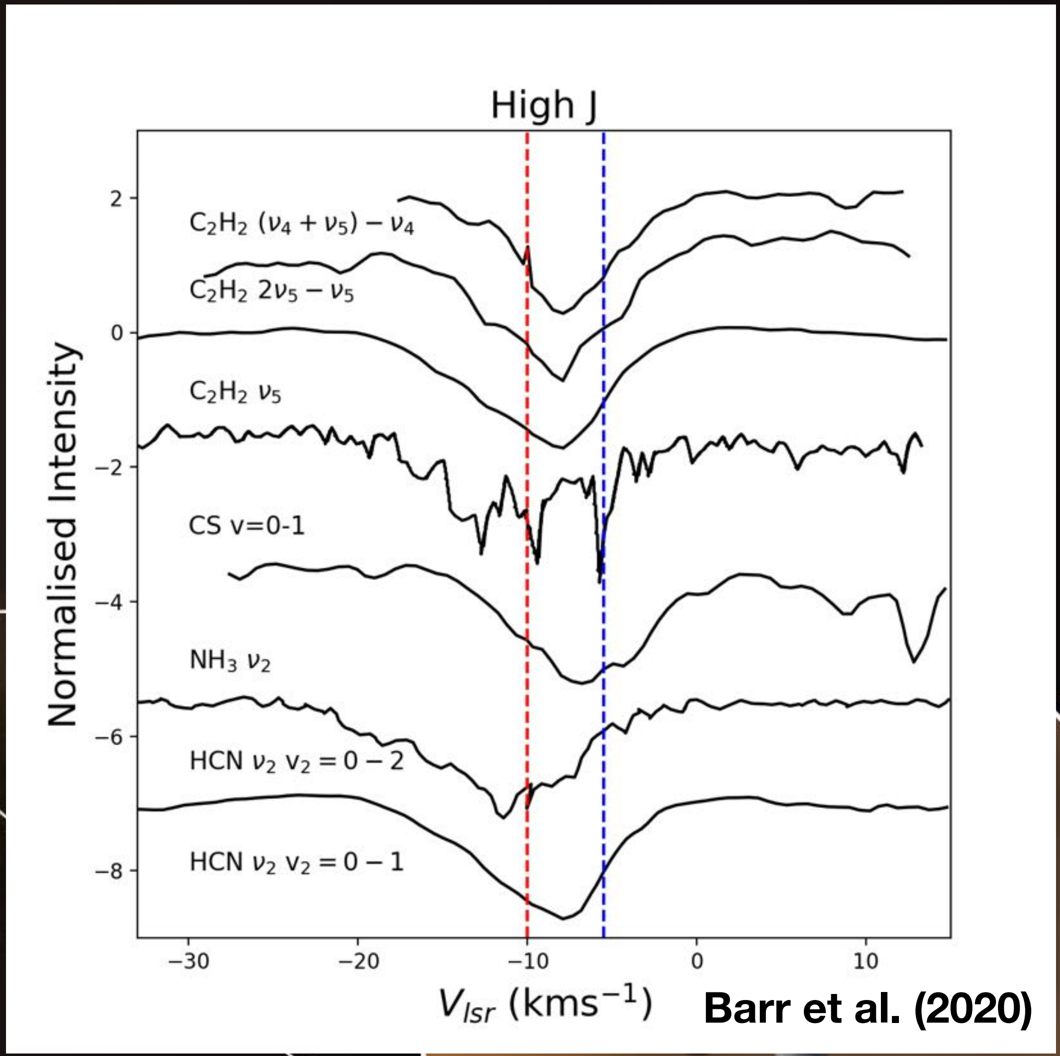
Monnier et al. (2009)

Observations

- Full spectral survey of 4.5-13 μm region at **R=50,000** (6kms^{-1})
- 2 Hot cores AFGL 2591 and AFGL 2136
    - 4.5 - 5.2 μm - iSHELL/IRTF
    - 6.7 - 8.0 μm - EXES/SOFIA
    - 8.0 - 13.3 μm - TEXES on GEMINI & IRTF
    - 3 μm - iSHELL/IRTF

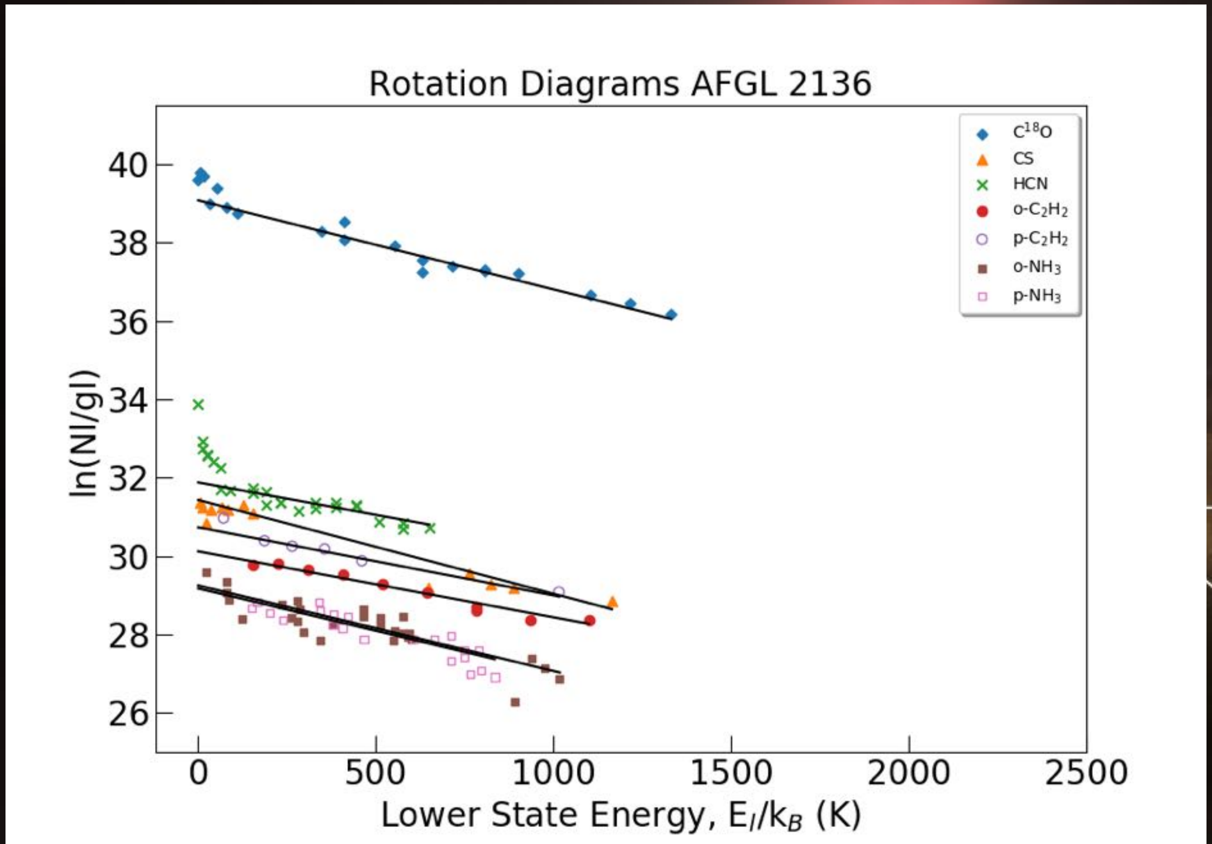
Results:
AFGL 2591

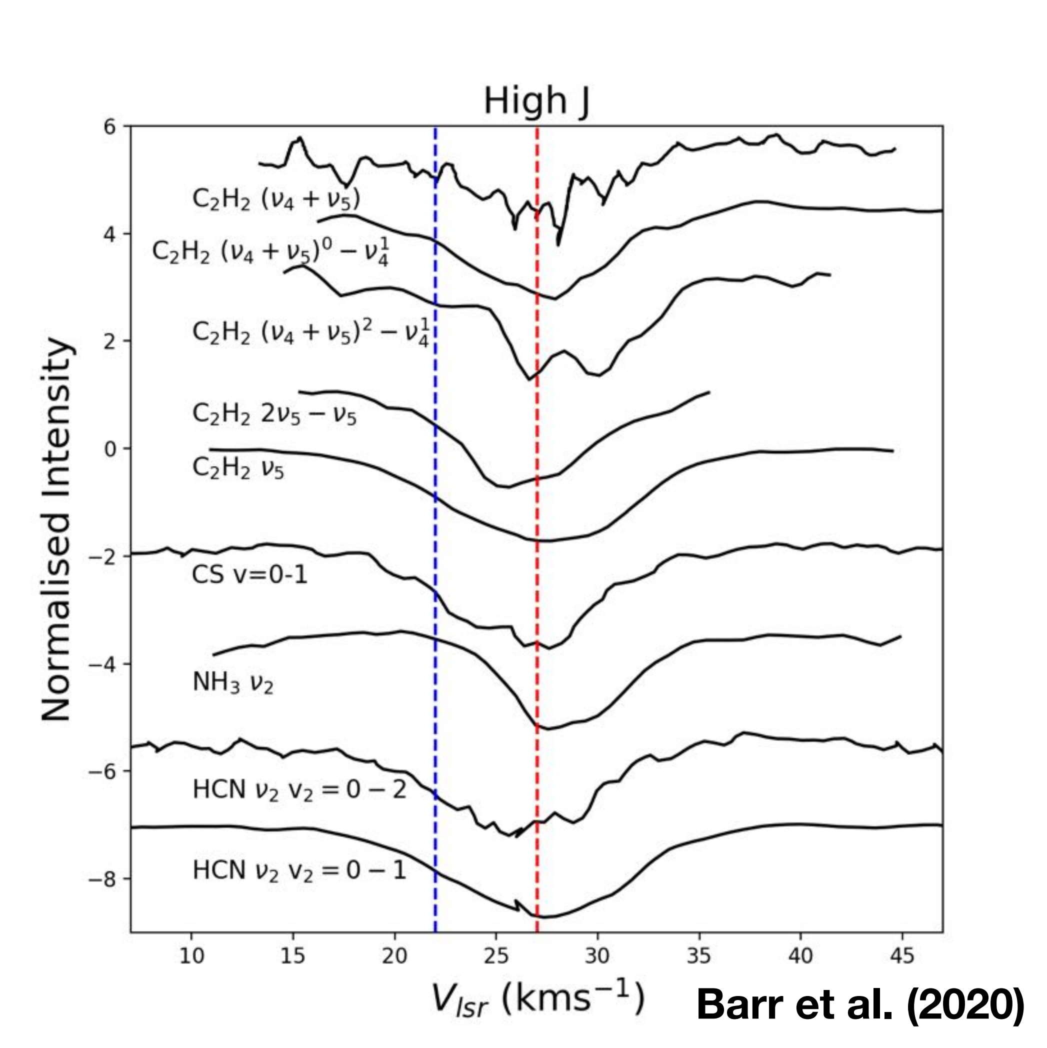




Barr et al. (2020)

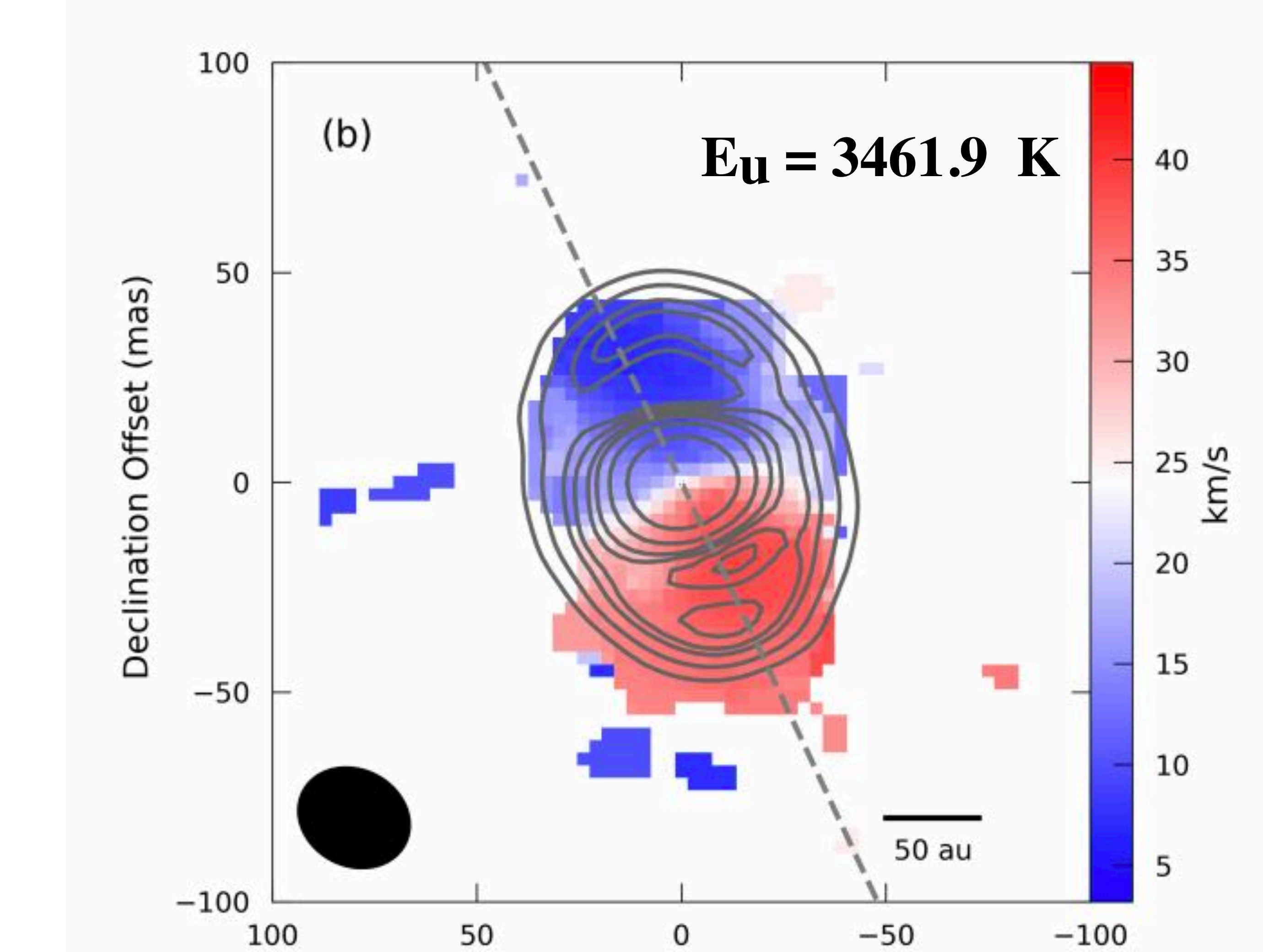
Results:
AFGL 2136



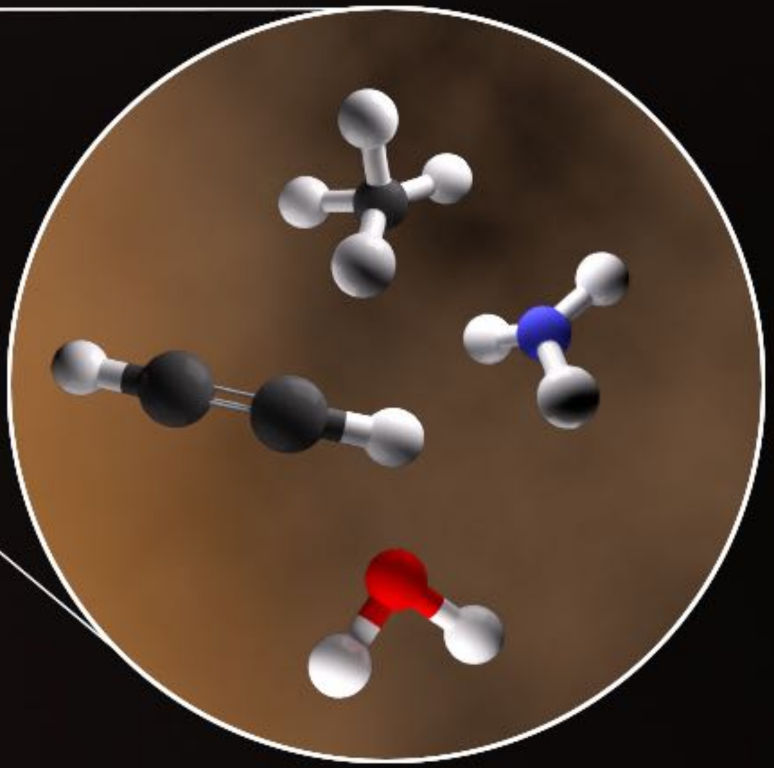


Circumstellar Disk

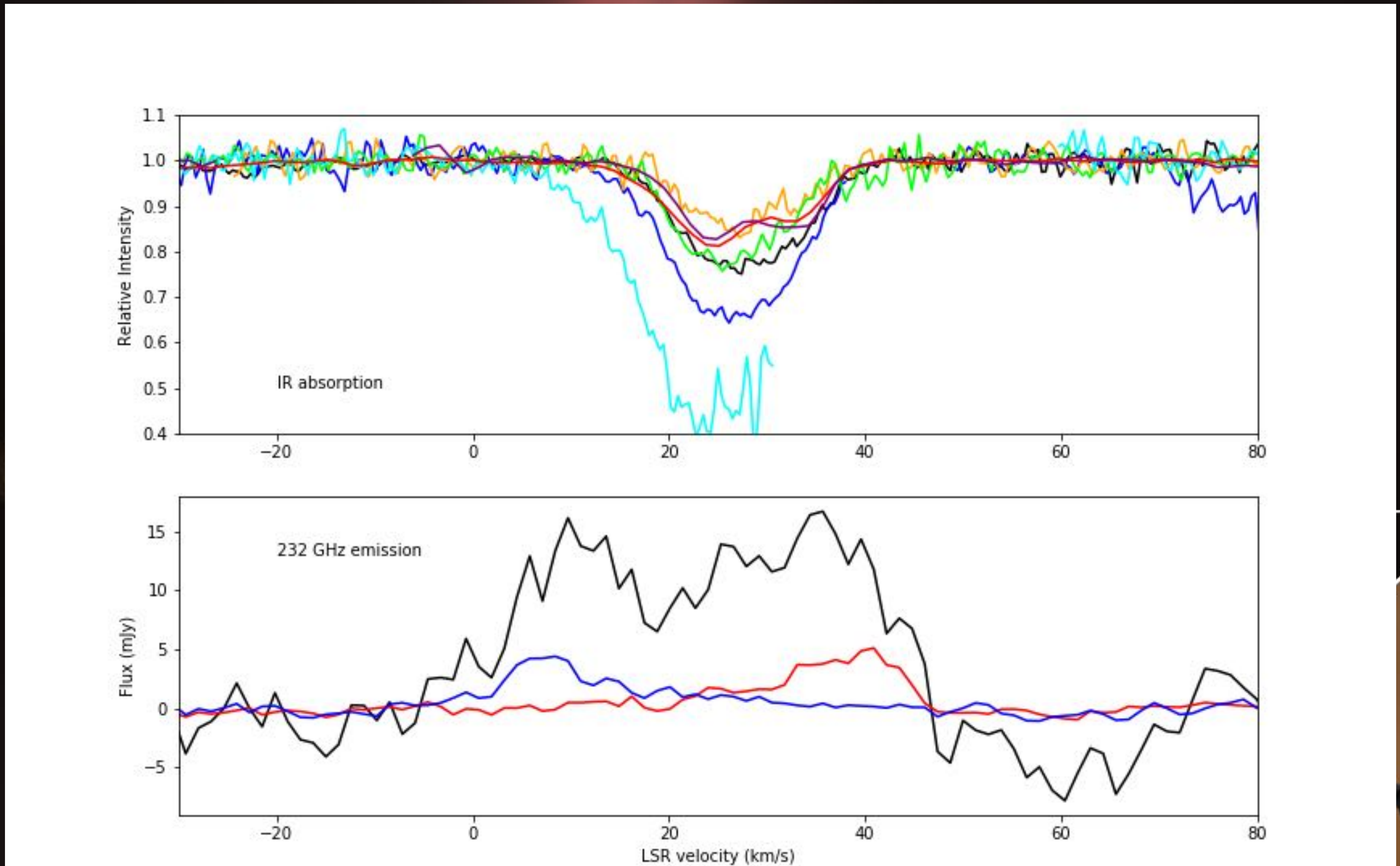
AFGL 2136 with ALMA ; ang res = 20x15 mas



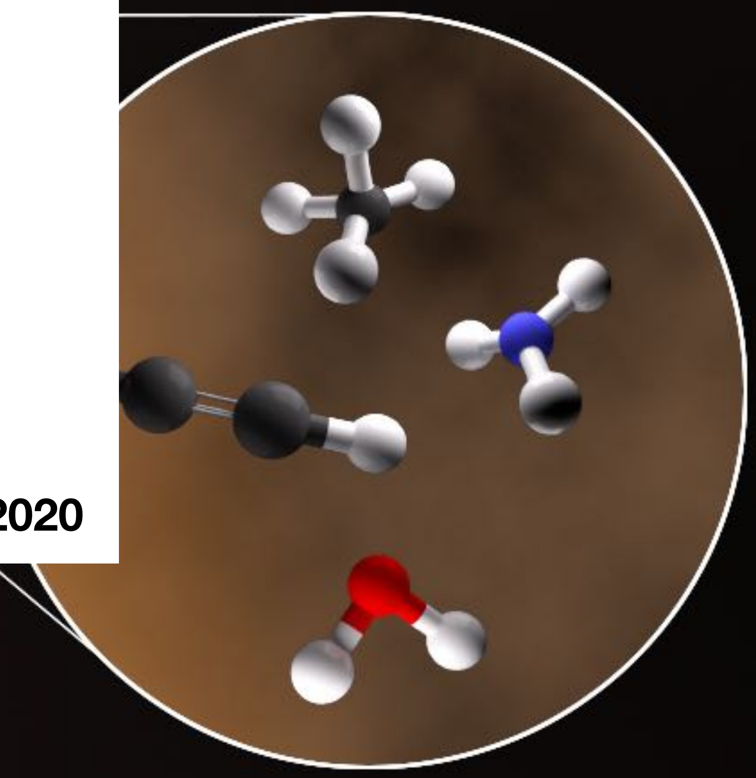
Maud et al. (2019)



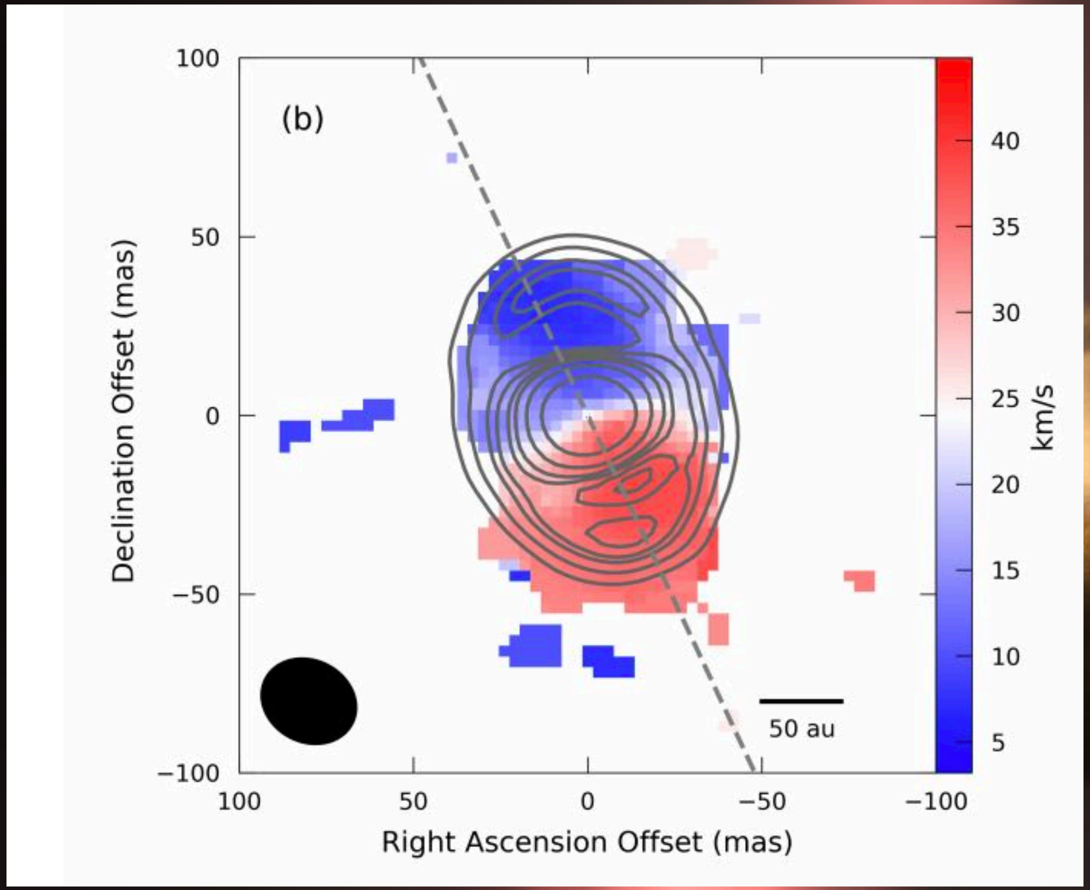
Circumstellar Disk

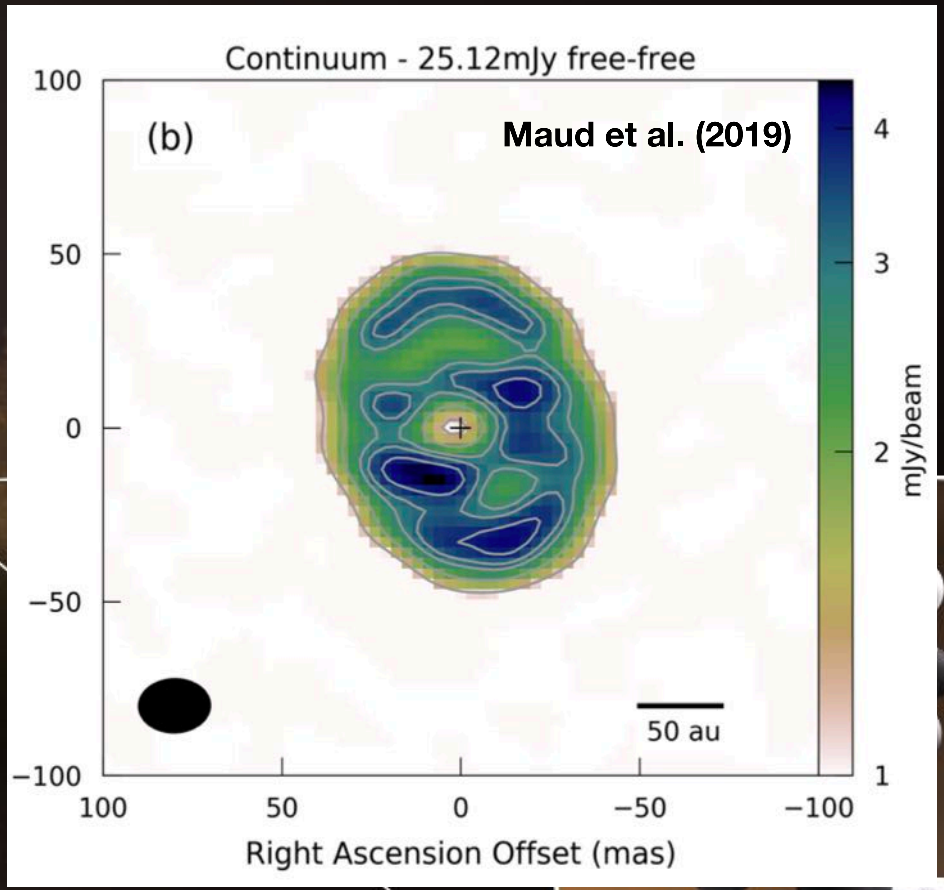


Indriolo et al. 2020

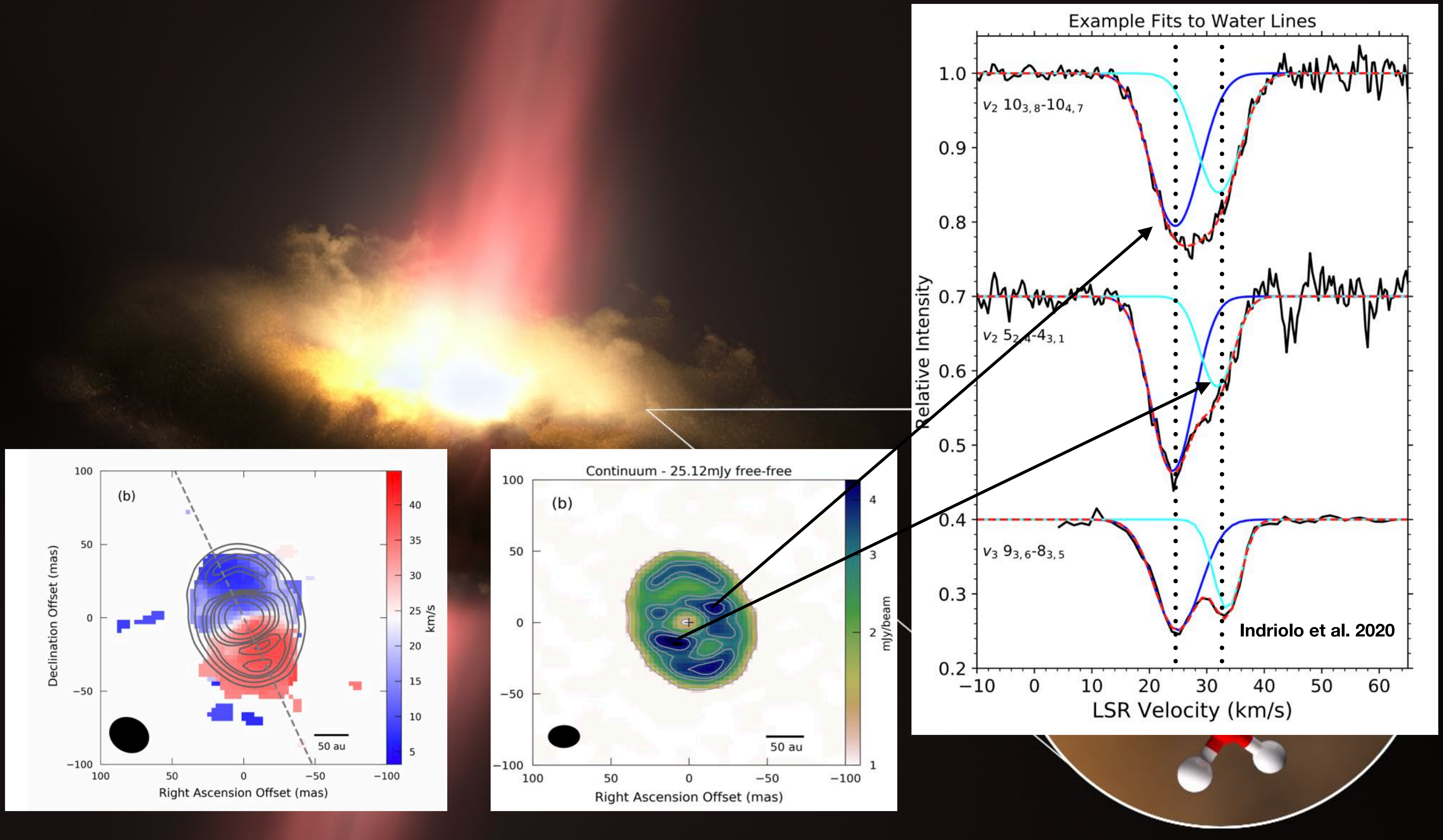


Circumstellar Disk



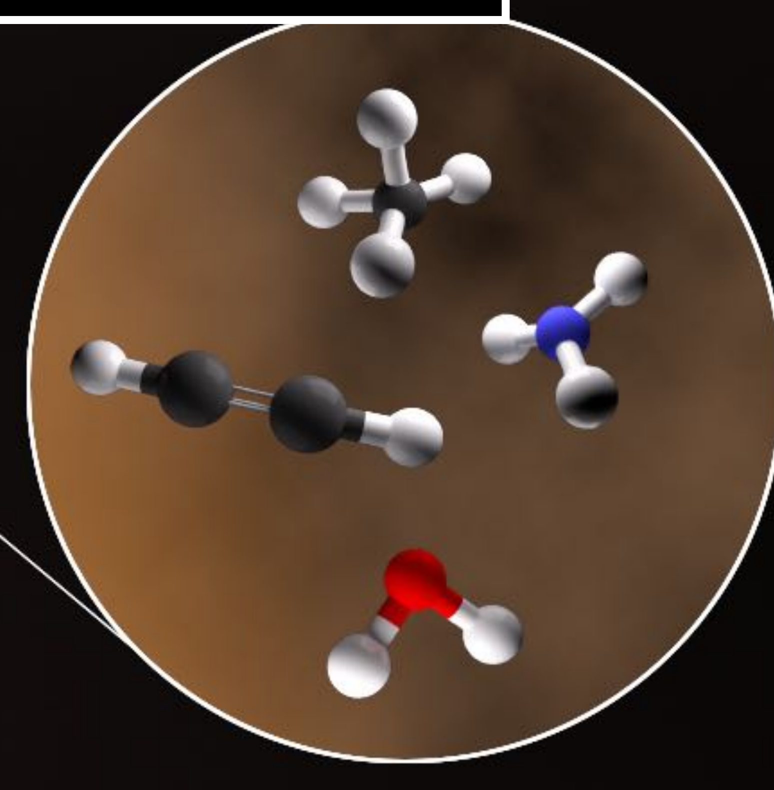


Circumstellar Disk

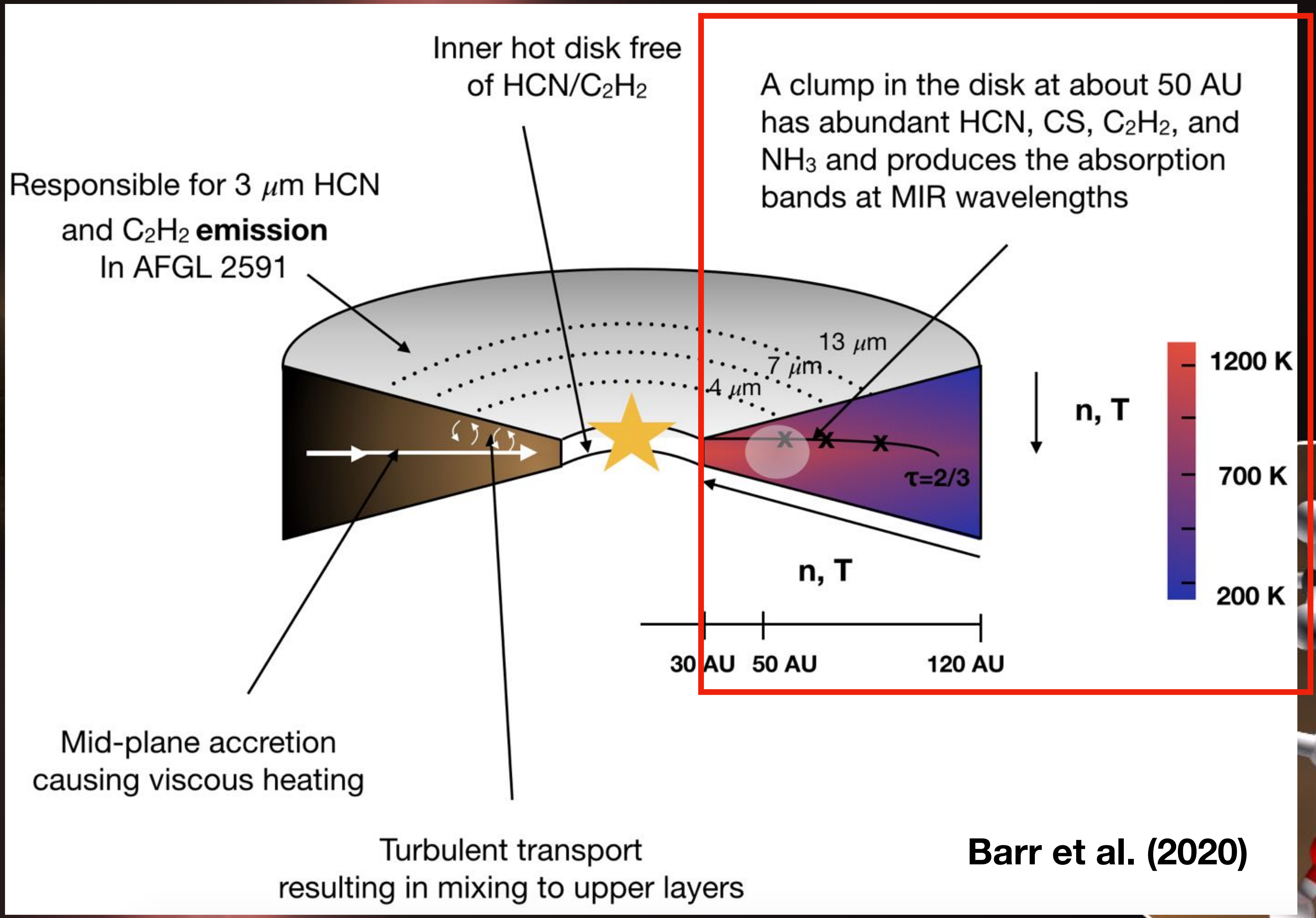


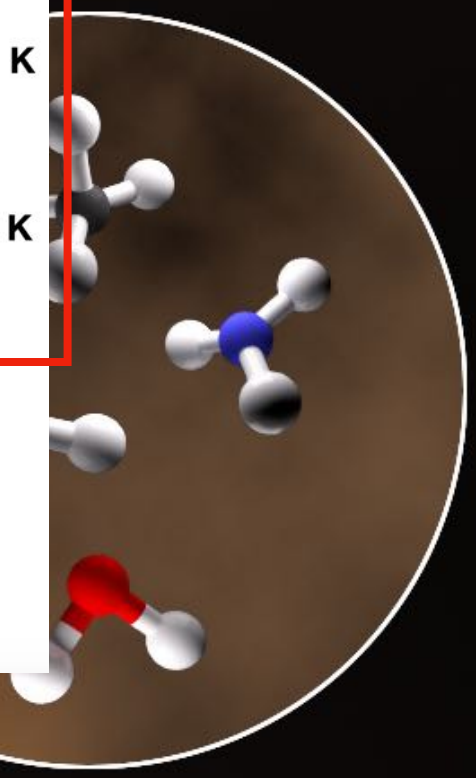
Circumstellar Disk

- We propose this scenario for *both* AFGL 2136 and AFGL 2591
- In AFGL 2591 size of absorbing region constrained to < 130 AU (Barr et al. 2018)
- Gieser et al. (2019) confirmed this with temperature modelling of CH_3CN suggesting a radius of 50 AU from the star

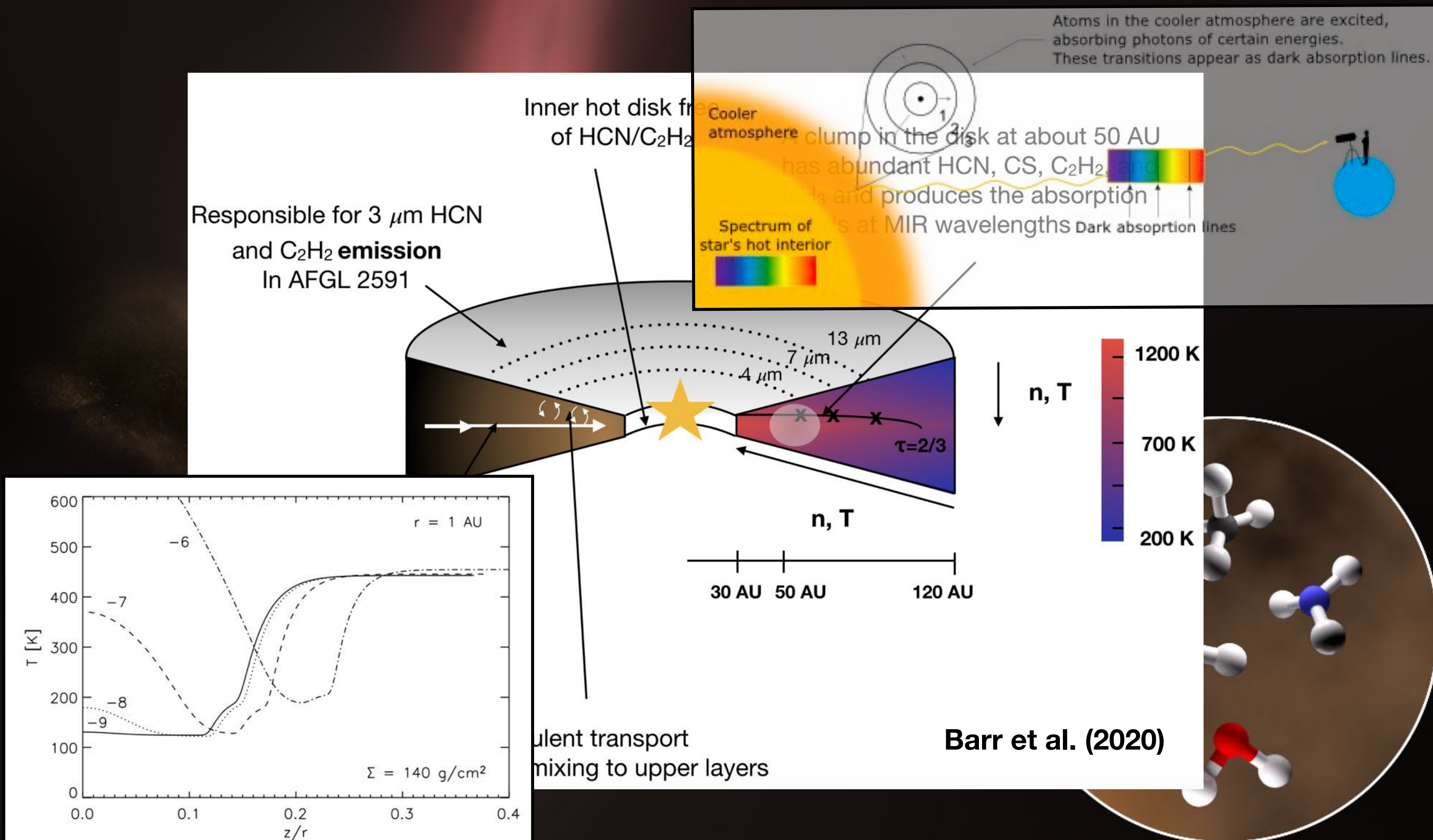


Viscously Heated Accretion Disk

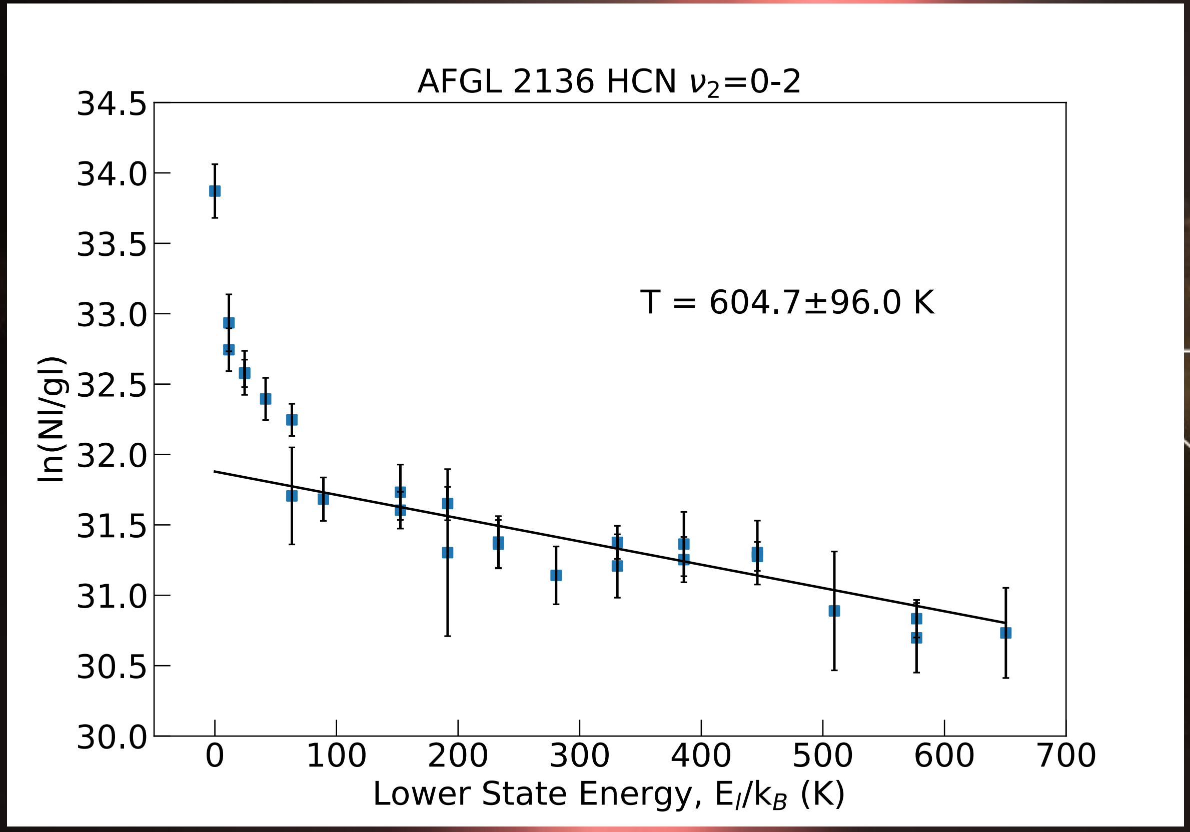


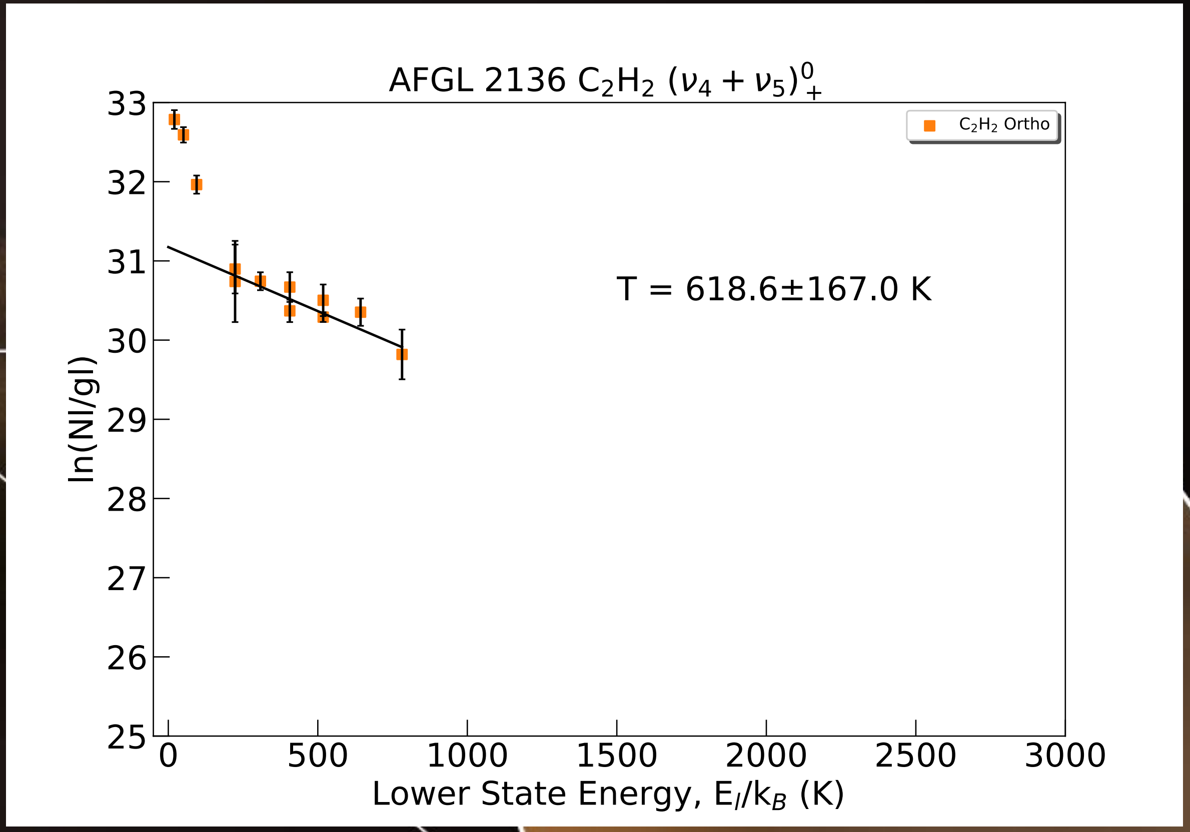


Viscously Heated Accretion Disk



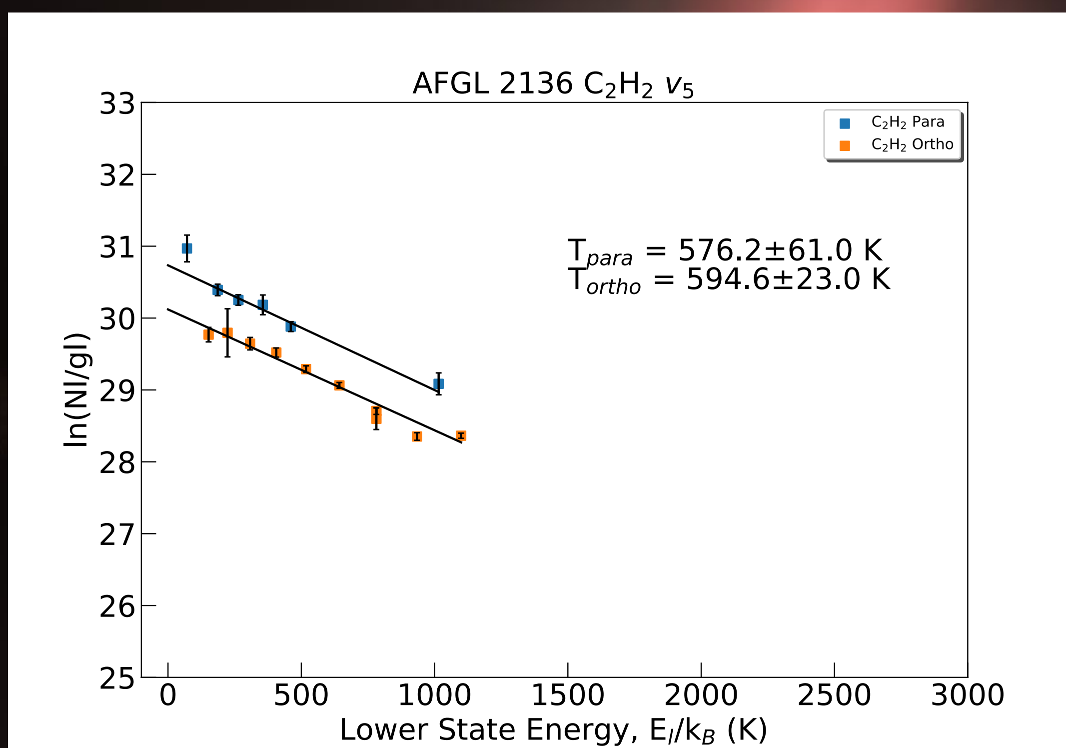
Viscously Heated Accretion Disk

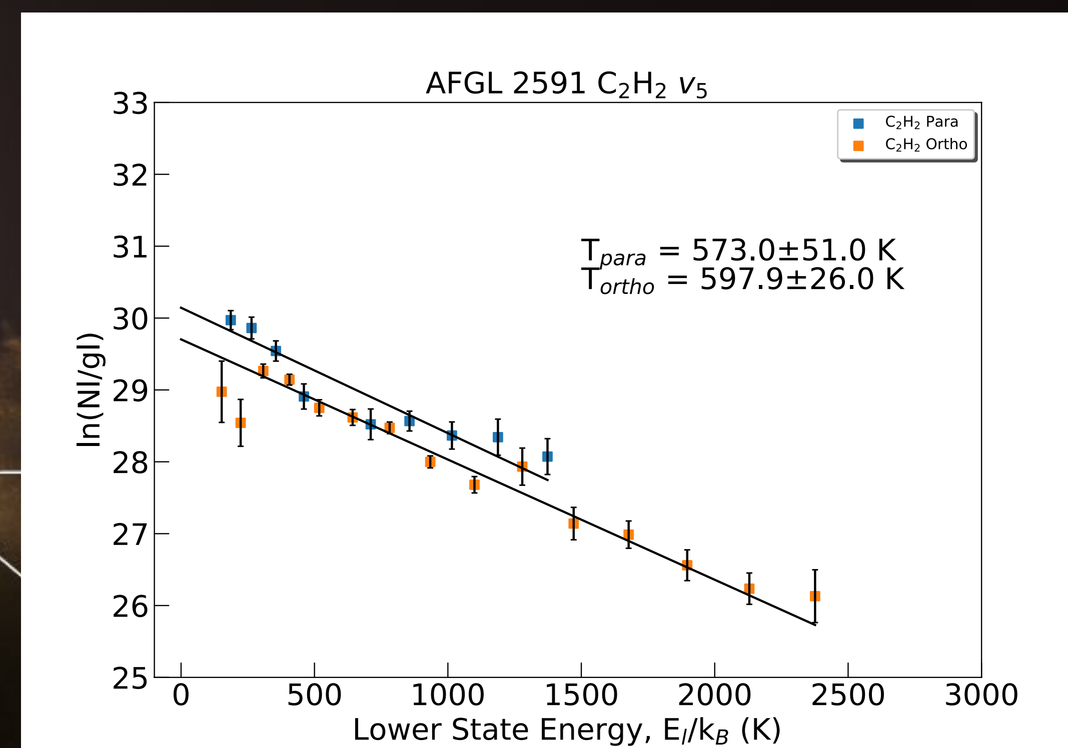


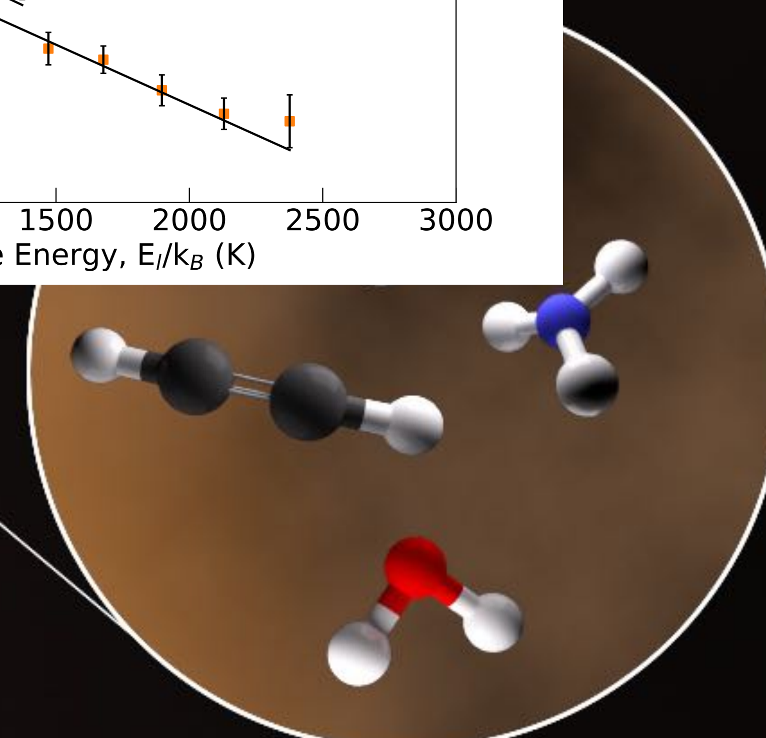


Barr et al. (2020)

Viscously Heated Accretion Disk







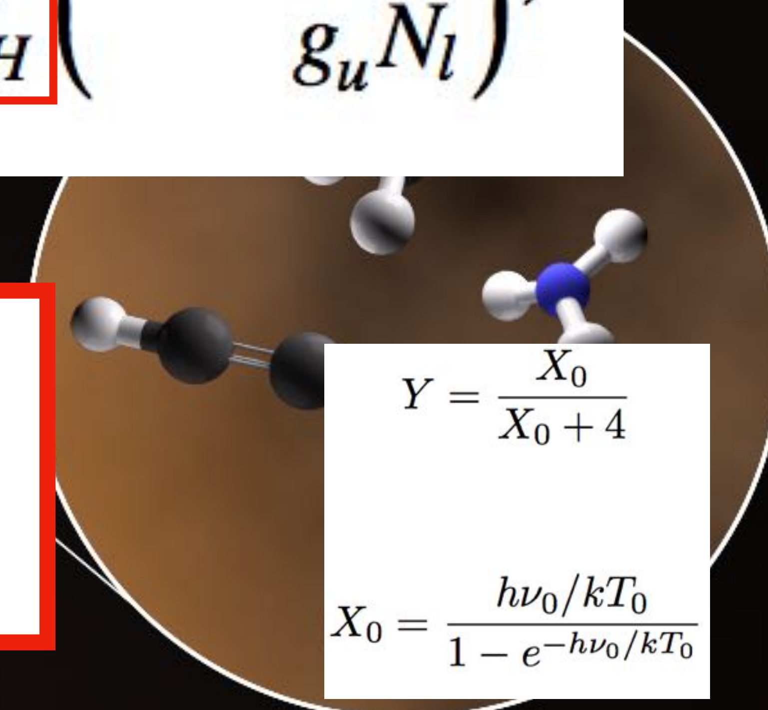
Barr et al. (2020)

Abundance Calculation

$$A_0 \simeq \frac{\eta_\nu}{1 + \sqrt{3}\,a/b}.$$

$$\eta_0 = \frac{\kappa_L(\nu = \nu_0)}{\kappa_c} = \frac{A_{ul}\lambda^3}{8\pi\sqrt{2\pi}\,\sigma_\nu}\frac{g_u}{g_l}\frac{N_l}{\boxed{\sigma_c N_H}}\left(1 - \frac{g_l N_u}{g_u N_l}\right),$$

$$\boxed{\frac{W}{2Y\Delta\nu} = \eta_0\frac{\sqrt{\pi}}{2},}$$

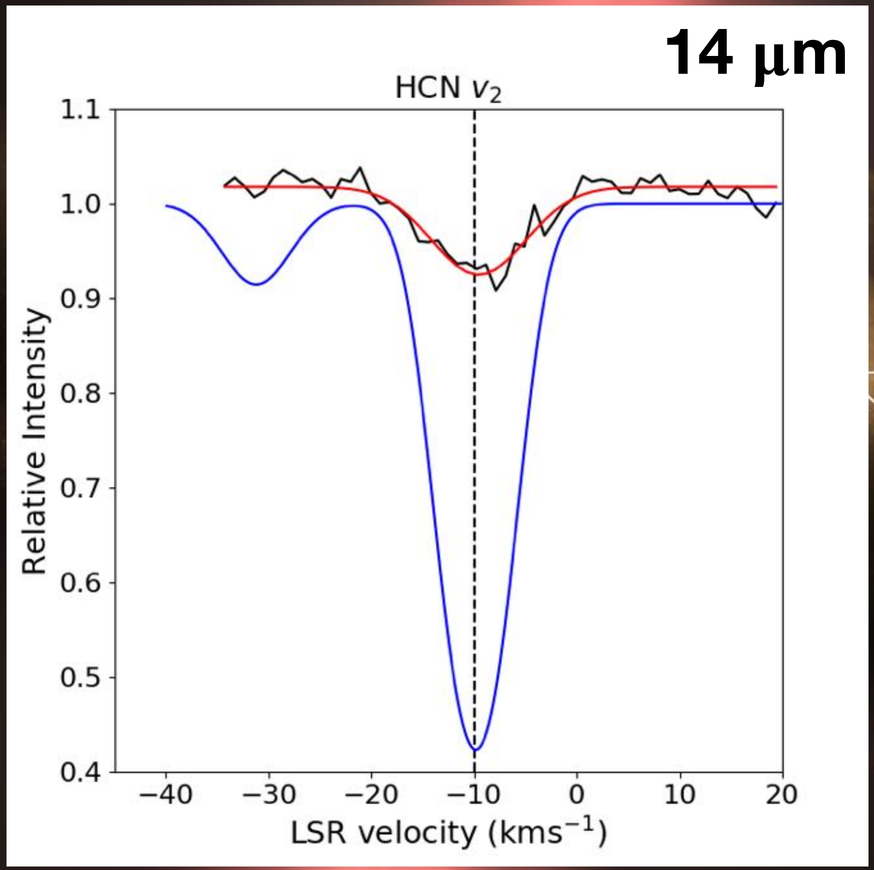


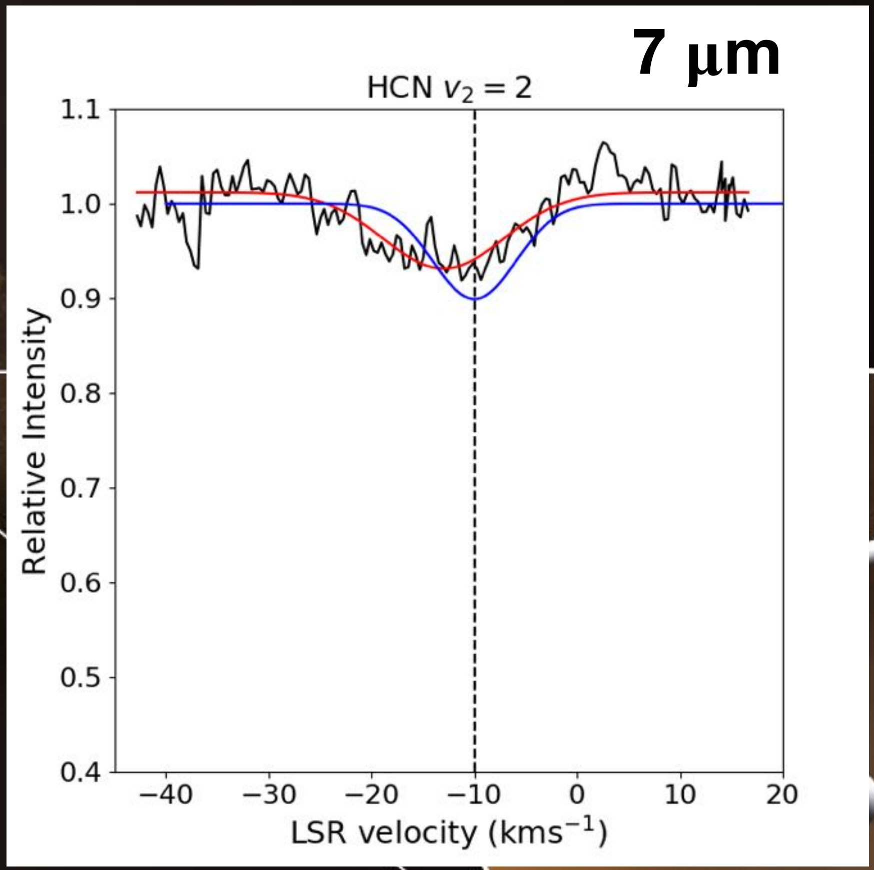
$$Y = \frac{X_0}{X_0 + 4}$$

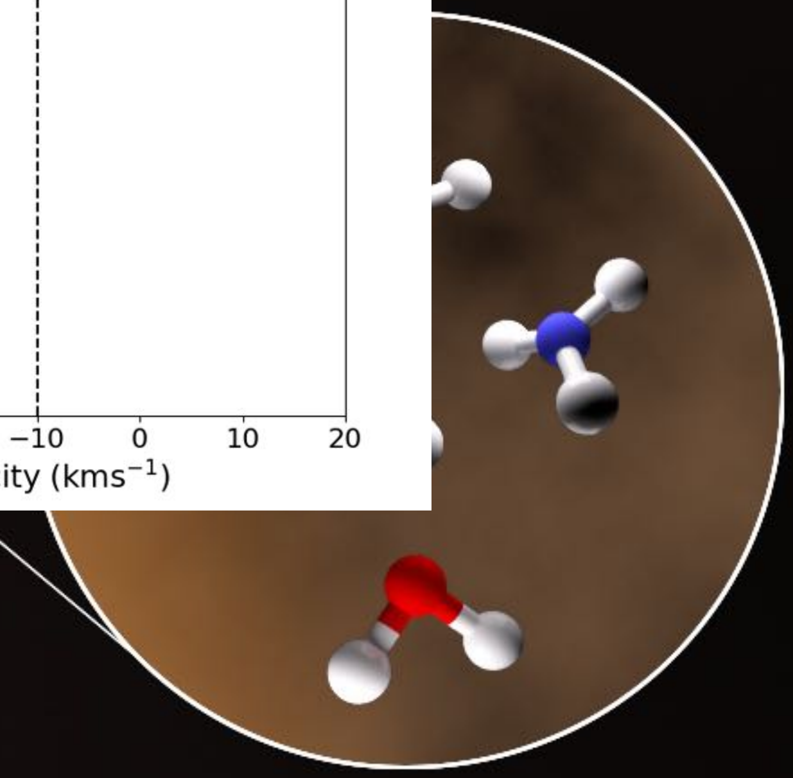
$$X_0 = \frac{h\nu_0/kT_0}{1 - e^{-h\nu_0/kT_0}}$$

Abundance Gradients

Blue - LTE model
Red - Fit to data
T = 670 K   N = 2.4e17 cm-2

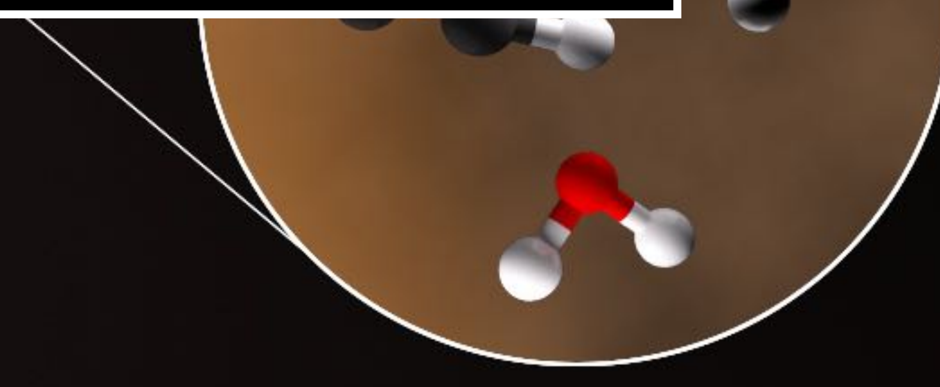




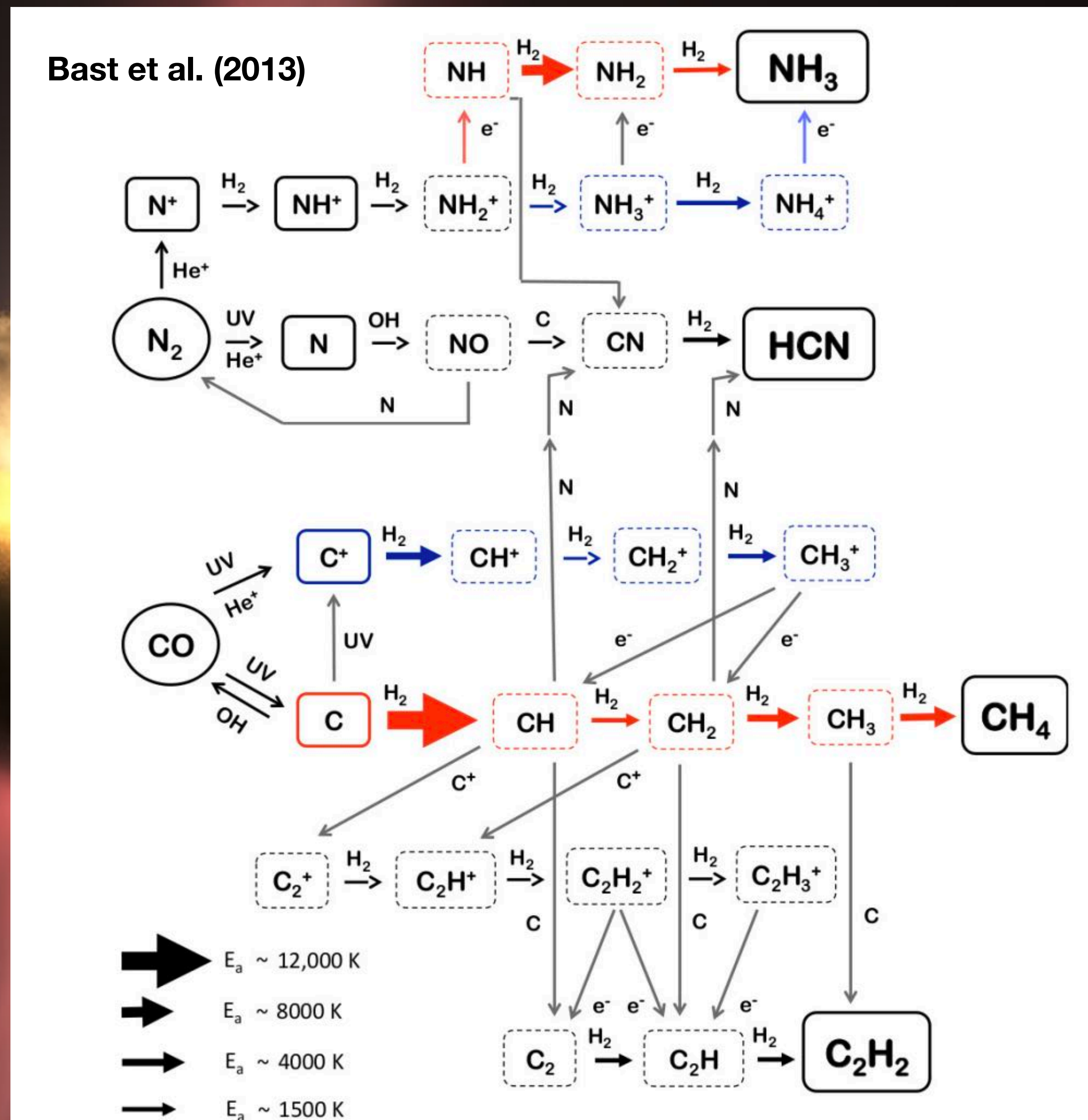


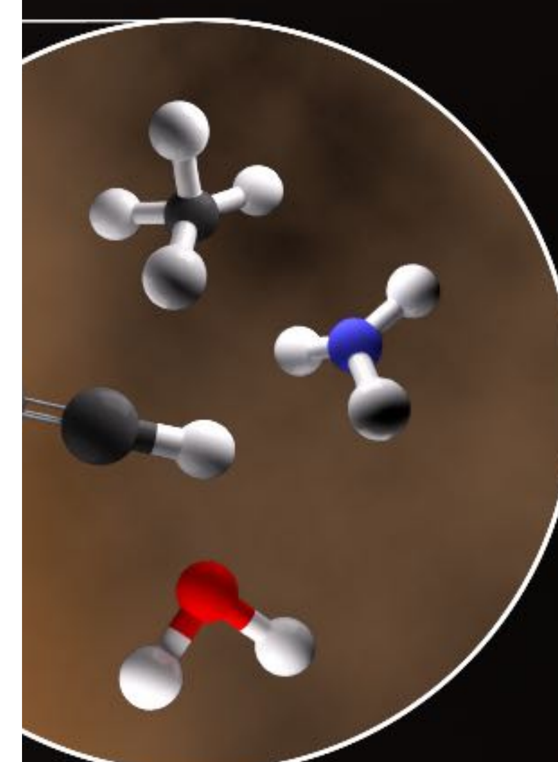
Abundance Gradients

- 1) The size of the continuum gets larger with wavelength
- 2) The temperature of the gas plays a role in the chemistry therefore if the temperature is not high enough no HCN/C_2H_2 will be formed
- 3) Non HCN/C_2H_2 containing parts of the disk will not contribute to the absorption line, but *will* contribute to the continuum emission - there is a trade off between the two

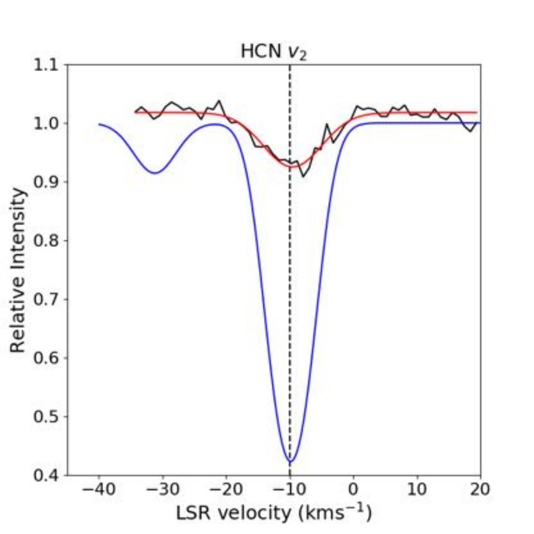


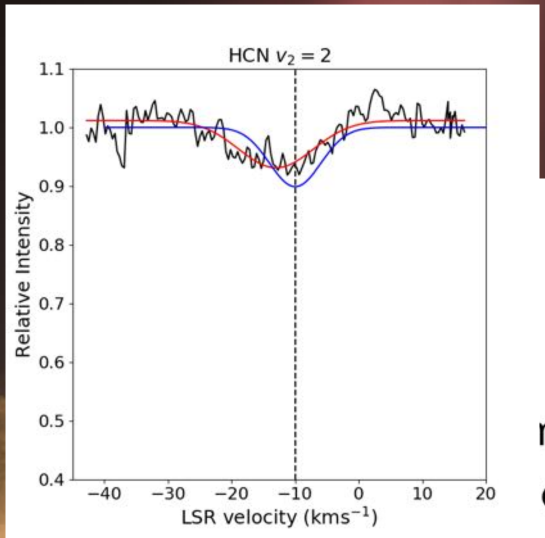
Abundance Gradients

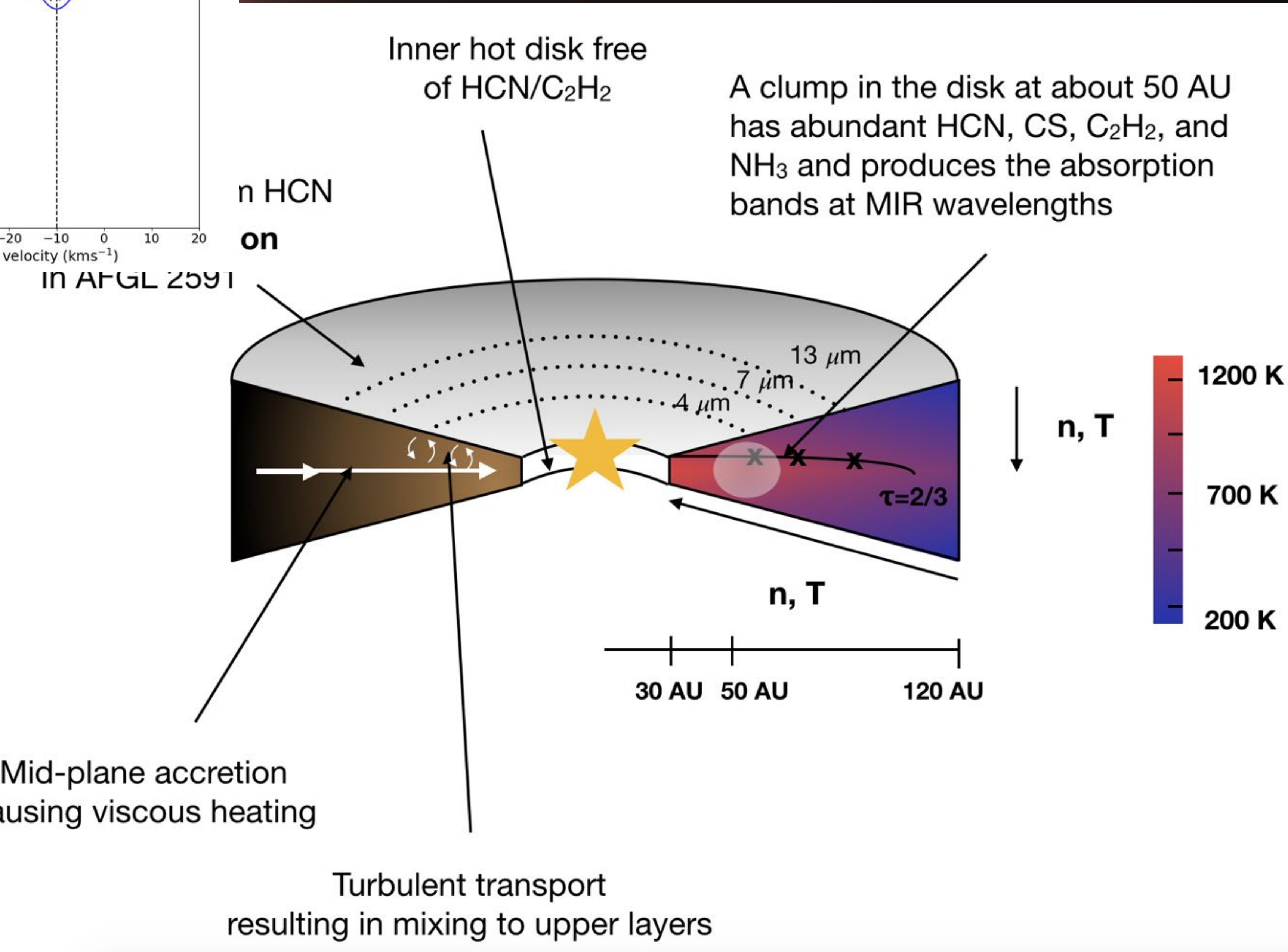




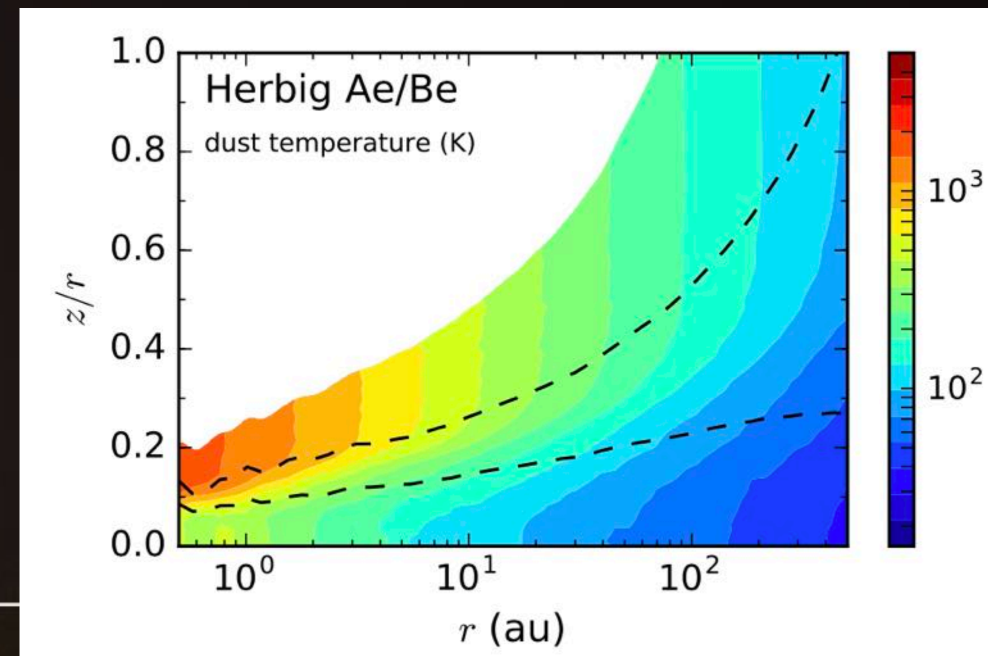
Abundance Gradients

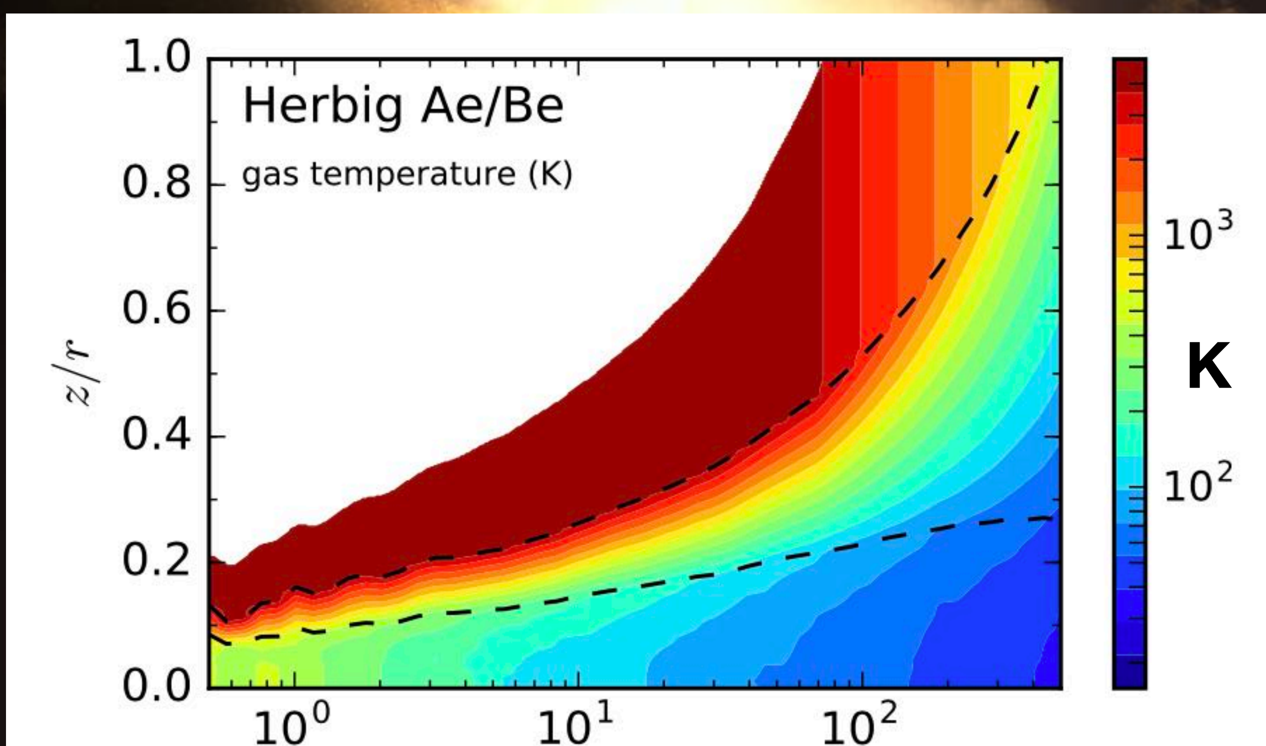




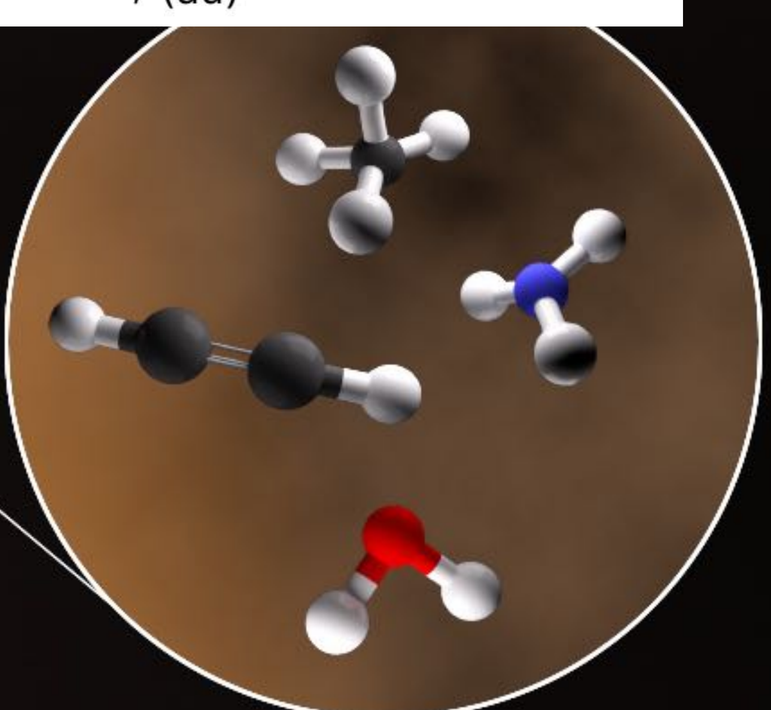


Chemical Models - Herbig Stars

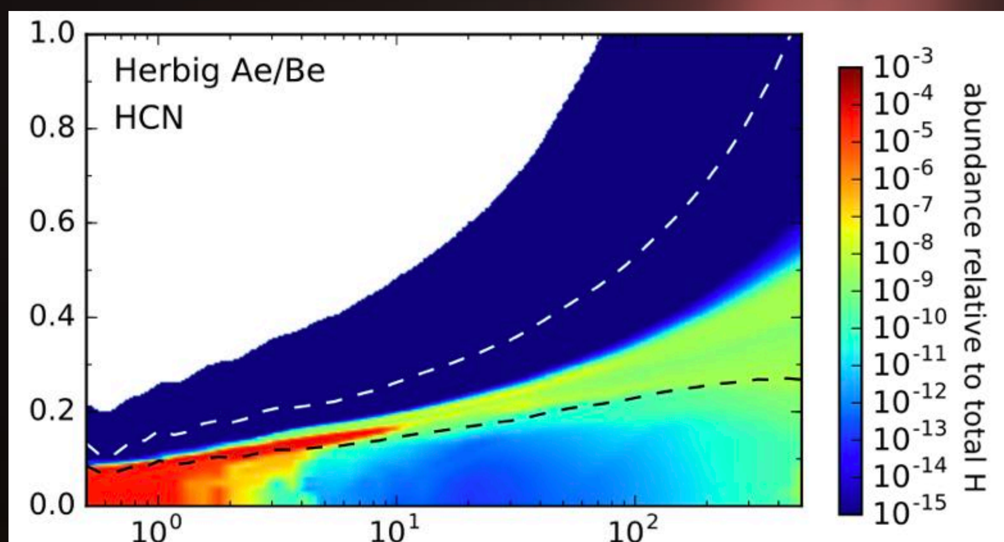


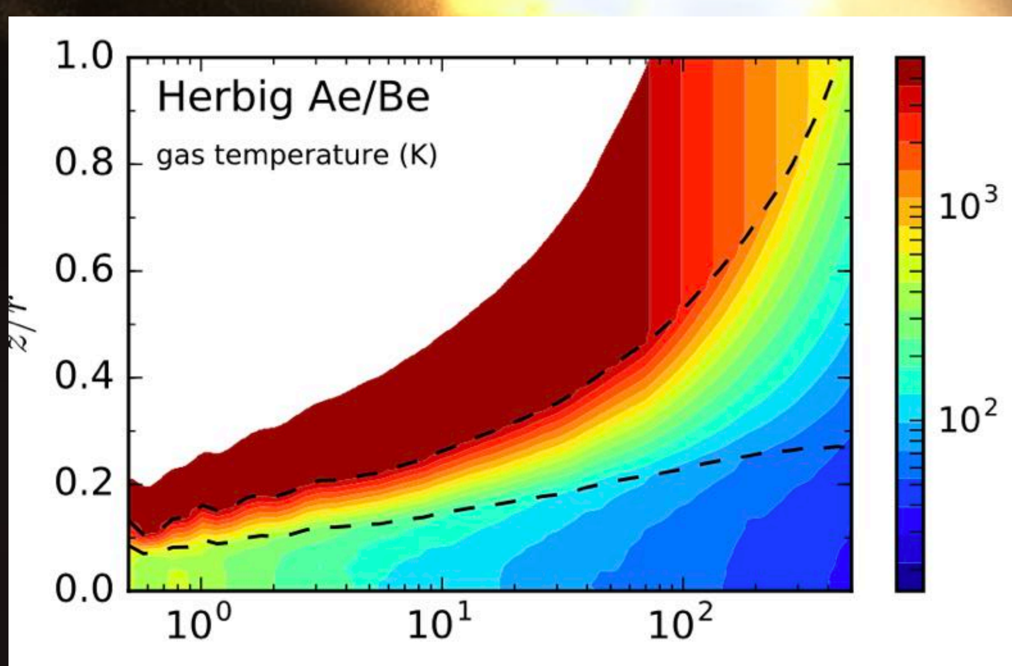


Agundez et al. (2018)

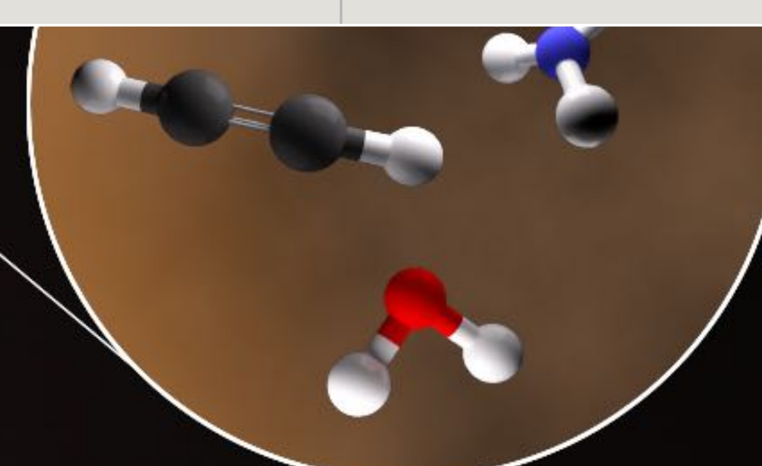


Chemical Models - Herbig Stars

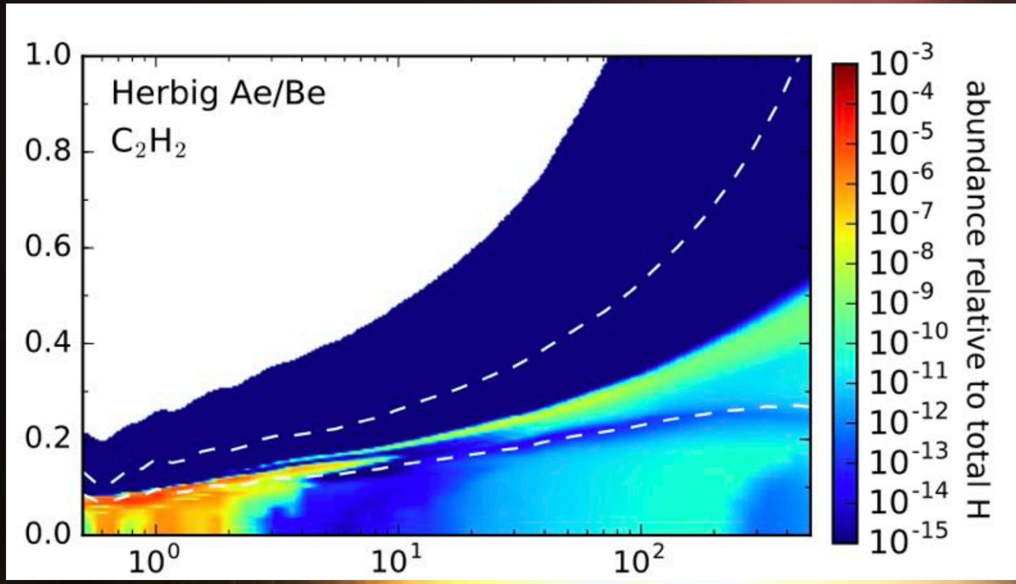


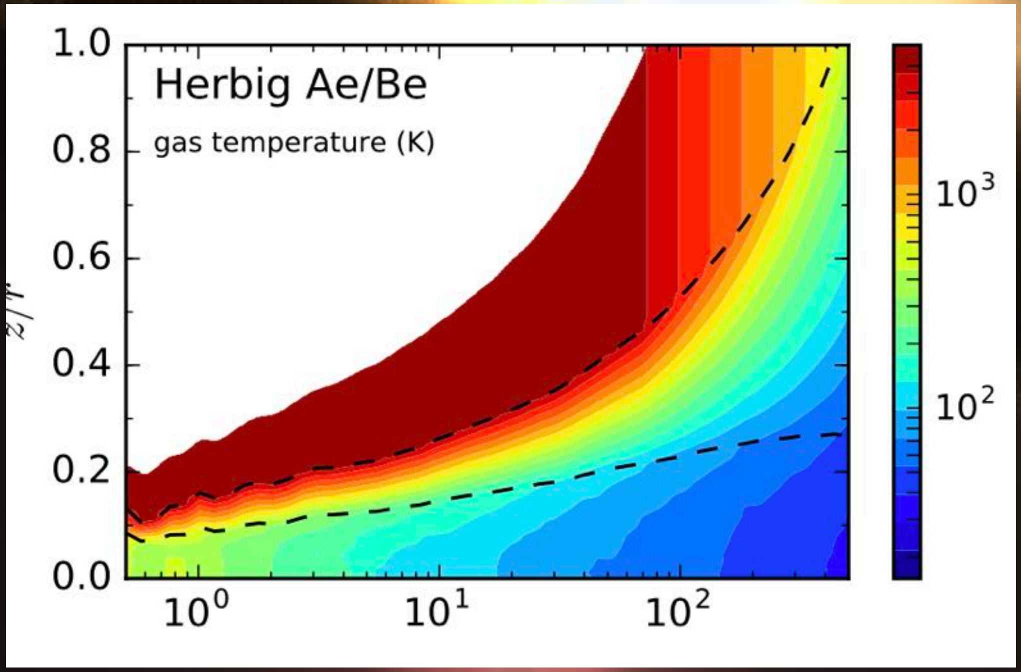


	AFGL 2591	AFGL 2136
T (K)	671 +/- 118	592 +/- 21
X_H(HCN) ($\times 10^{-5}$)	2.0 +/- 1.0	1.6 +/- 0.8

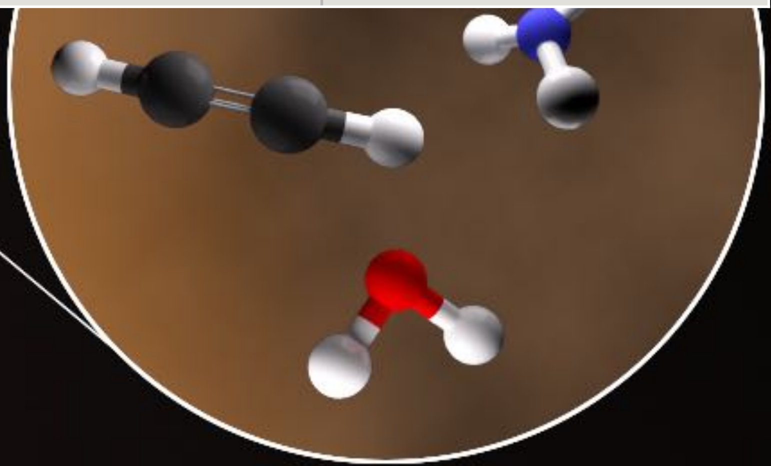


Chemical Models - Herbig Stars

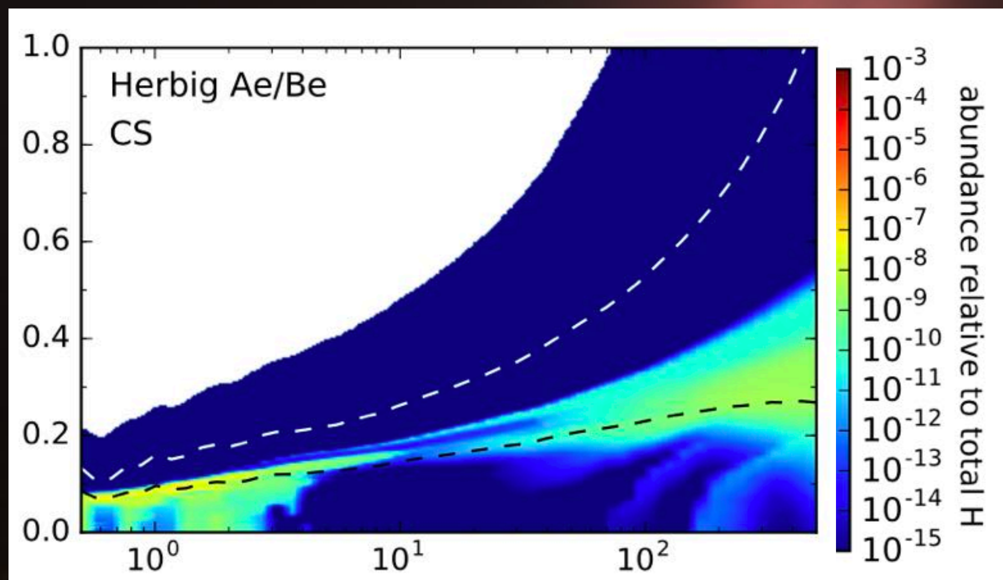


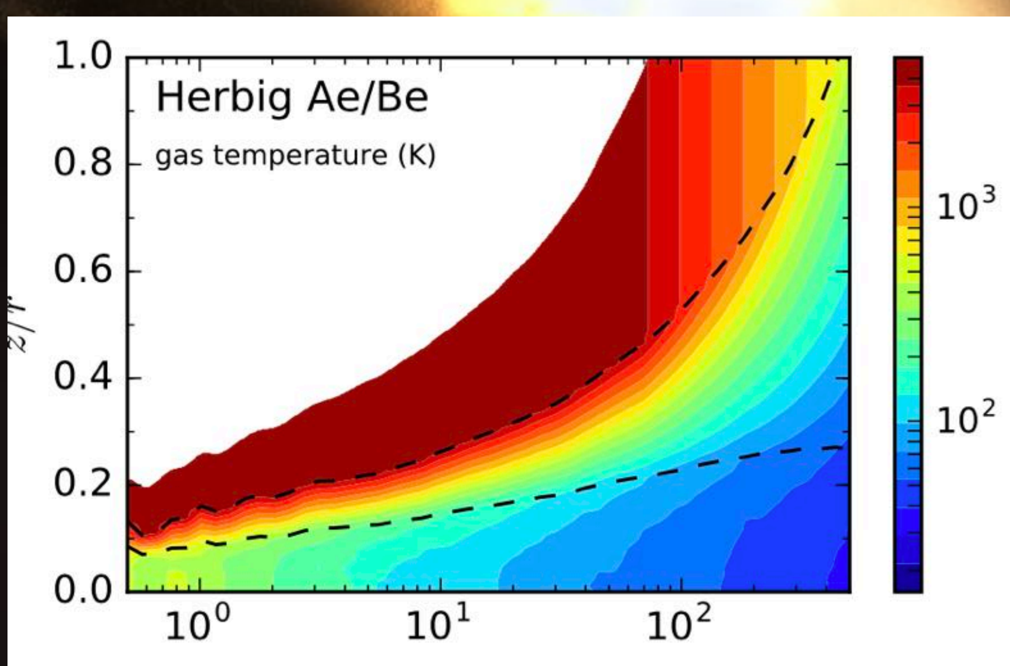


	AFGL 2591	AFGL 2136
T (K)	598 +/- 51	618 +/- 176
$X_H(C_2H_2)$ ($\times 10^{-6}$)	1.8 +/1 0.2	7.0 +/- 0.8

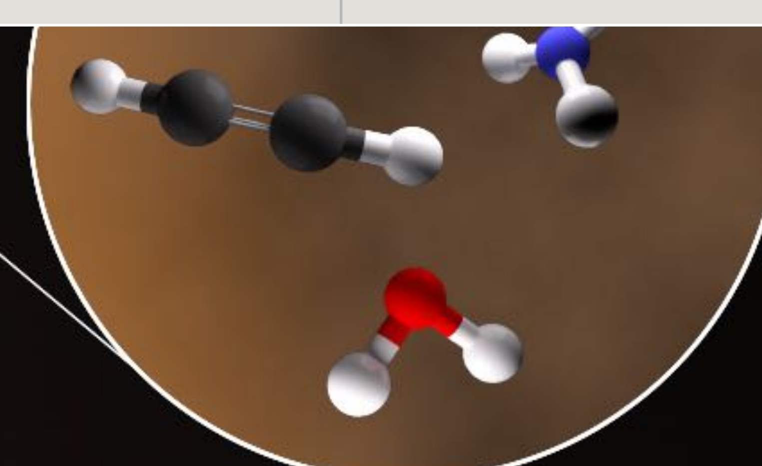


Chemical Models - Herbig Stars

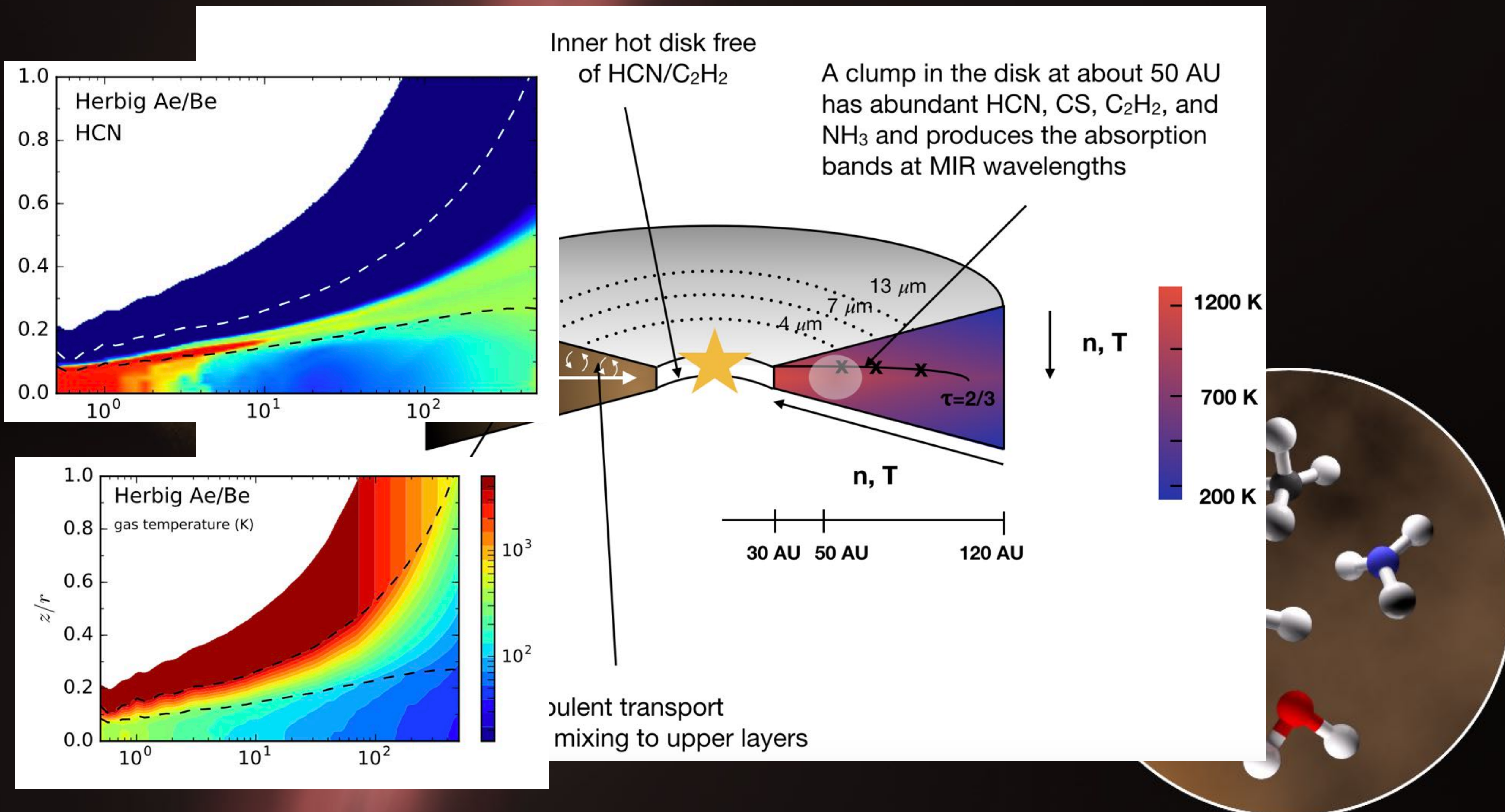




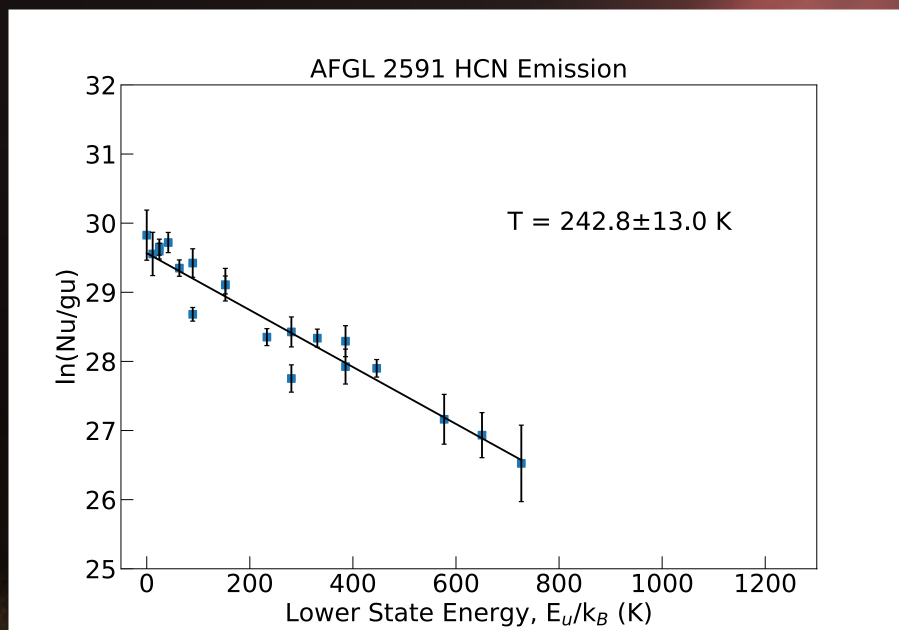
	AFGL 2591	AFGL 2136
T (K)	713 +/- 59	418 +/- 23
X_H(HCN) ($x10^{-6}$)	1.5 +/- 0.3	1.2 +/- 0.1

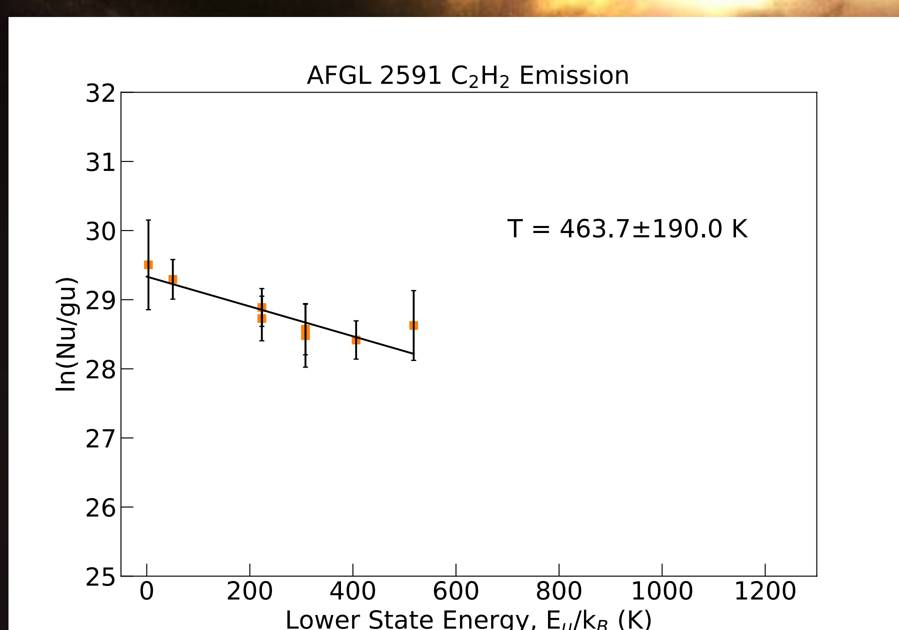


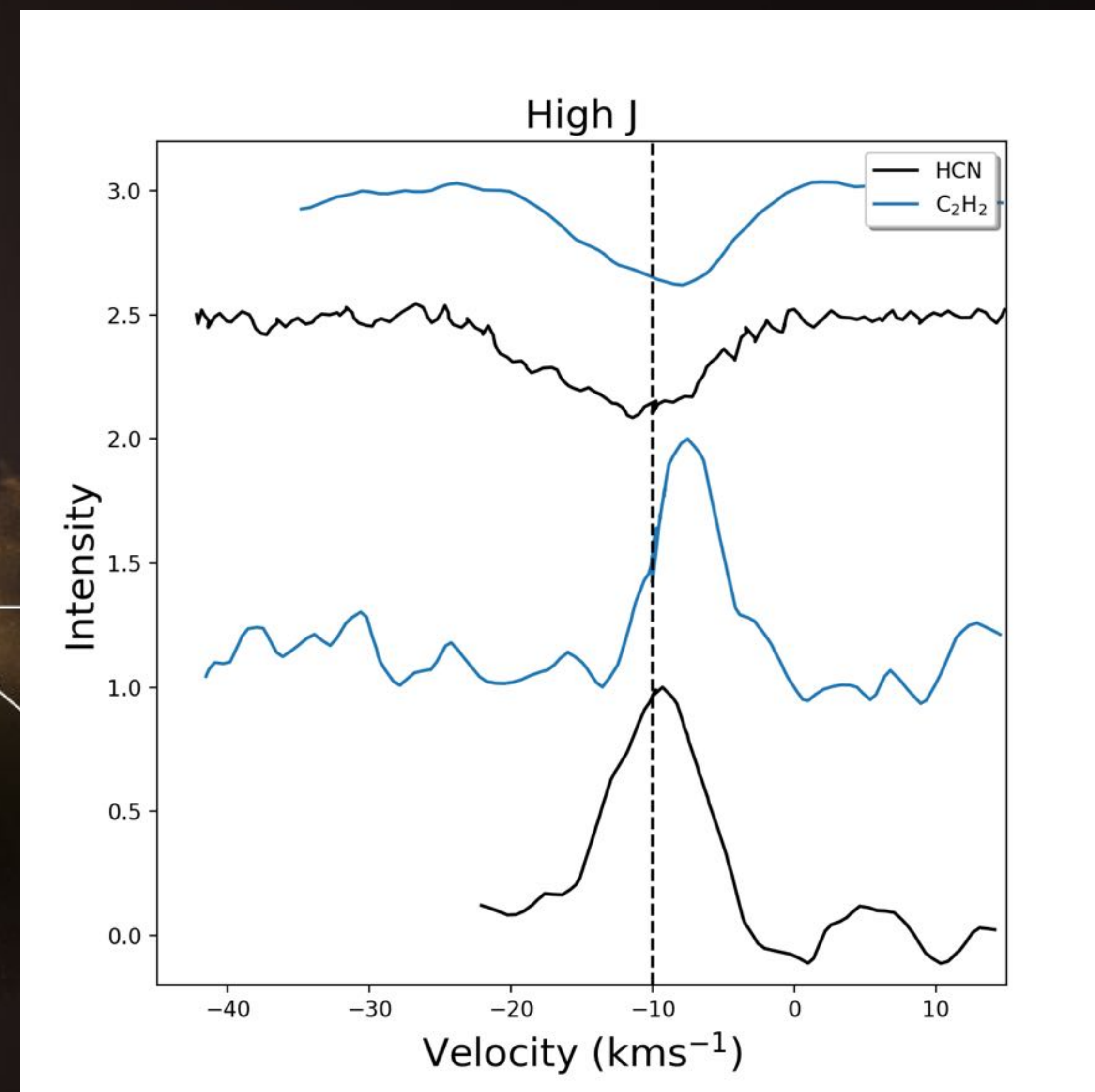
Chemical Models - Herbig Stars



Emission Lines in L-band







Barr et al. (2020)

Other Hot Cores

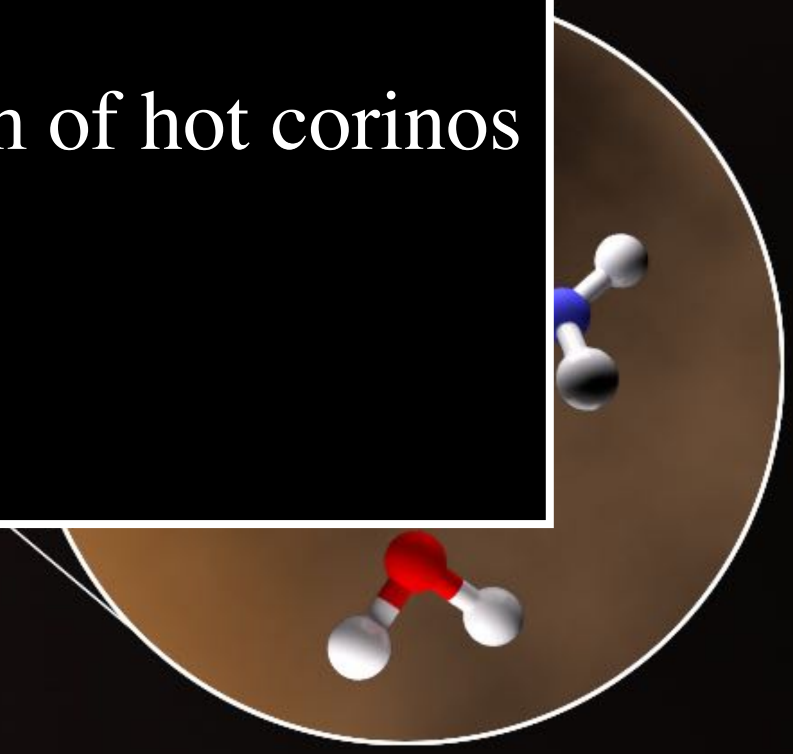
- Absorption lines seen towards other luminous hot cores ($>10^5$ $L_{\odot}$)
- NGC 7538 IRS1, MonR2 IRS 3, W3 IRS5, Orion IRc2
- These may be characteristic of O-type stellar disks in most early embedded phase where UV flux from star cannot irradiate disk
- Orion IRc2 shows OPR<3 for C_2H_2

Conclusions

- Absorption lines in the MIR are a further signpost of disk accretion towards embedded high mass protostars
- OPR< 3 is evidence for a disk photosphere
- Hot corinos may also reveal MIR absorption lines which would suggest the presence of actively accreting embedded disks
- Similarity in chemistry implies that the formation of massive stars may well be a scaled up version of low mass star formation
- Lower detection rate of H_2O and simple organics in Herbig disks is likely an observational effect not a chemical effect

James Webb Space Telescope

- SOFIA can guide JWST/MIRI observations which will lack high spectral resolution
- JWST can clarify whether the MIR spectrum of hot corinos has absorption lines



Conclusions

- ❖ Absorption lines are known to be associated with disks
- ❖ These imply the presence of a viscously heated accretion disk
- ❖ Line profiles and high temperatures of absorption lines imply that the absorption arises in clumps in the disk
- ❖ Using stellar atmosphere theory we derive abundances of the detected species w.r.t H, which are high (10^{-6})
- ❖ Temperatures and abundances are consistent with chemical models of TTauri and Herbig disks of the inner 1 or 5 AU respectively
- ❖ There is evidence for abundance gradients of HCN and C_2H_2