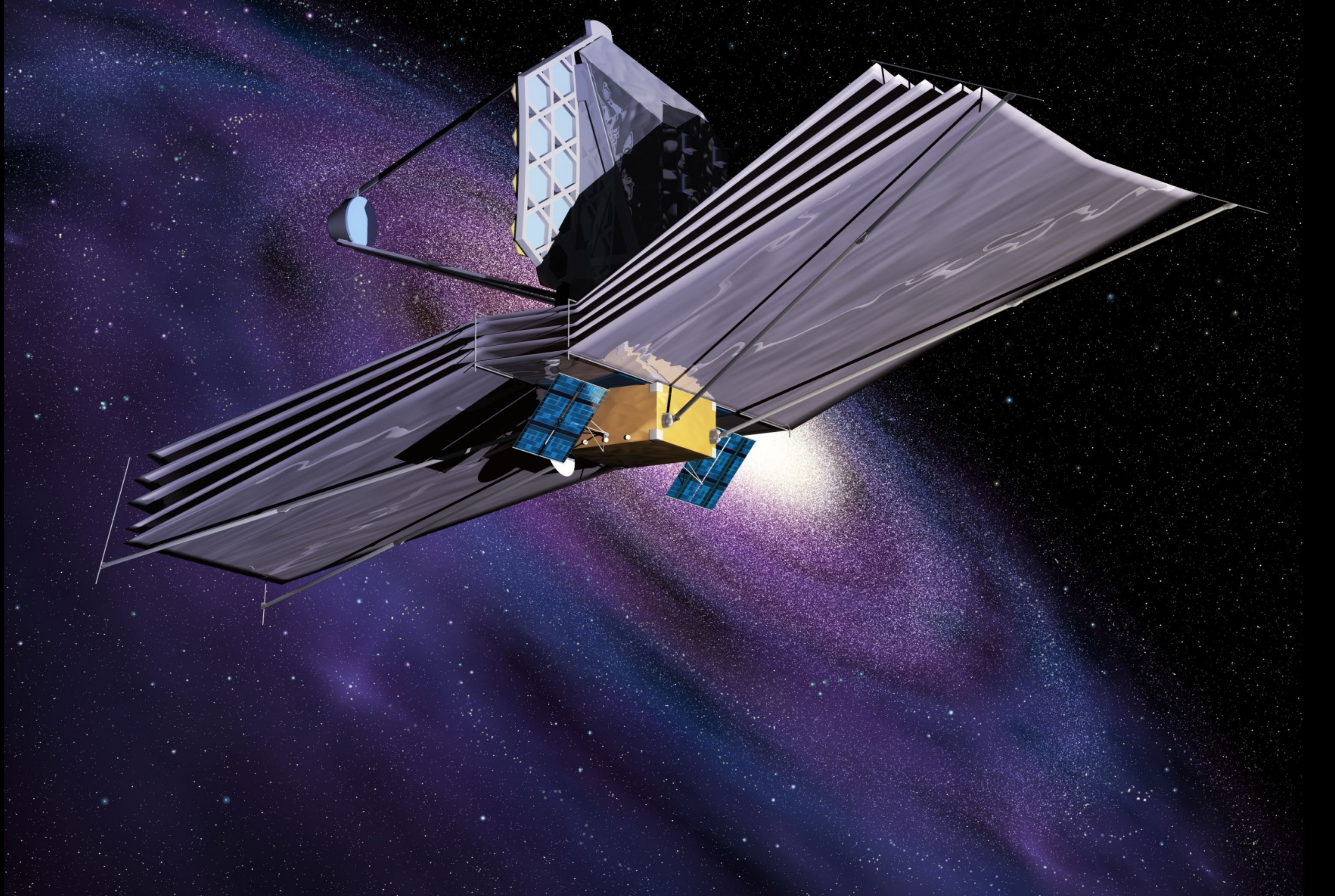
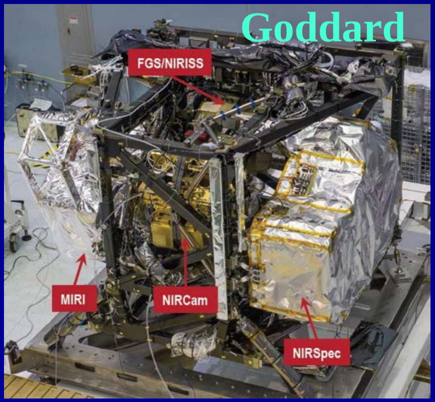
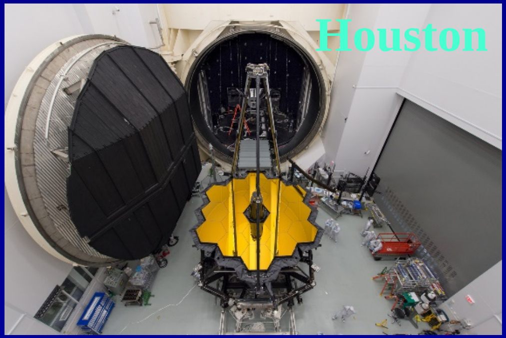
Mid-IR emission of protoplanetary disks



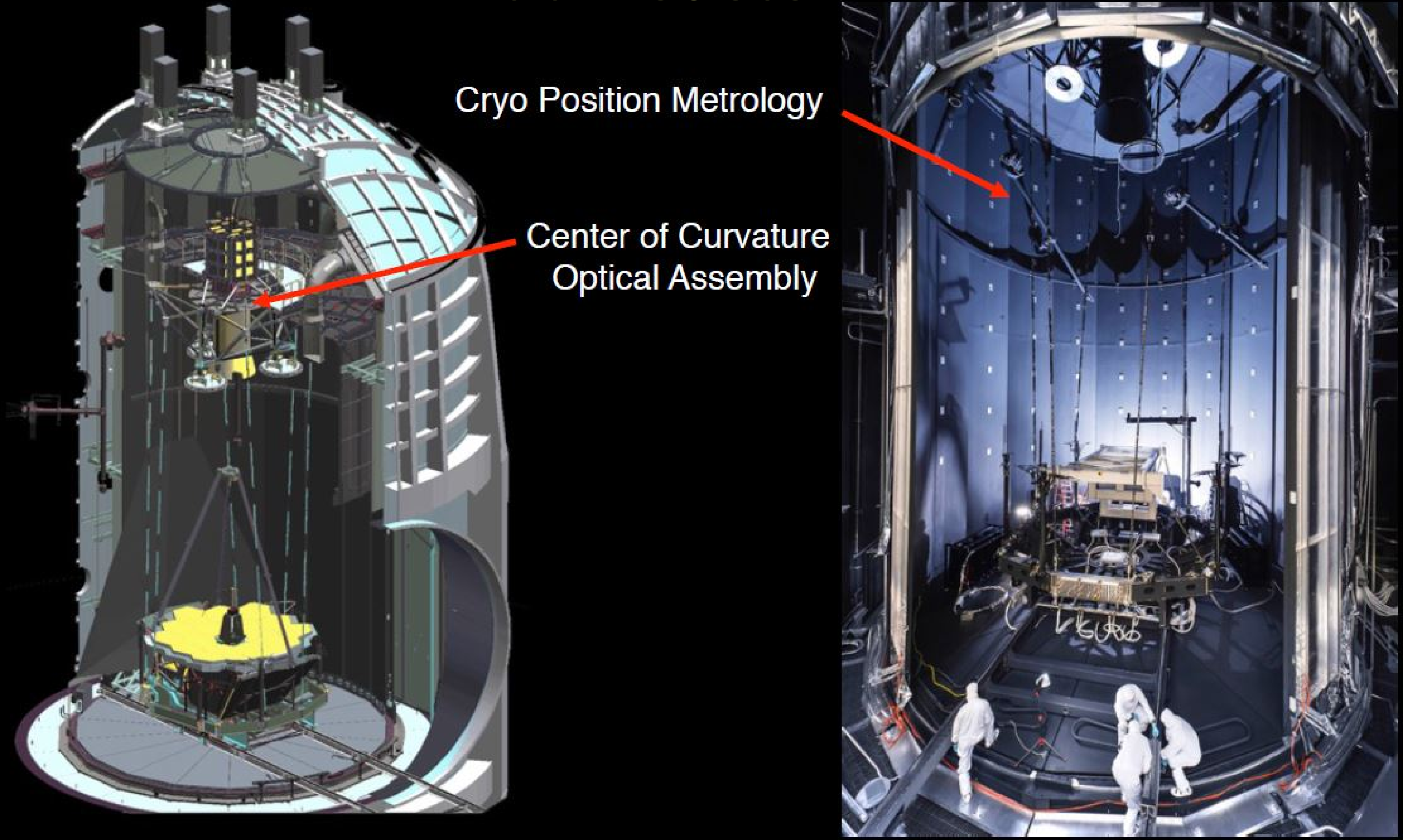
JWST-MIRI Project

- Instrument: 5-28 μm
  - Imager/coronagraph 1.25’x1.88’, 0.11’’/pix
  - Low resolution spectrometer 5-10 μm, R~100
  - Medium res spectrometer: IFU 3’’x3’’ at R~3000
- US-Europe: 50%-50%
  - Europe: Consortium of 10 countries
    - Major: UK (lead), Belgium, France, Germany, *Netherlands*
    - Minor: Denmark, Ireland, Spain, Sweden, Switzerland
- MIRI delivered to NASA in May 2012
  - Integrated in JWST, testing Goddard, Houston, launch March 2021



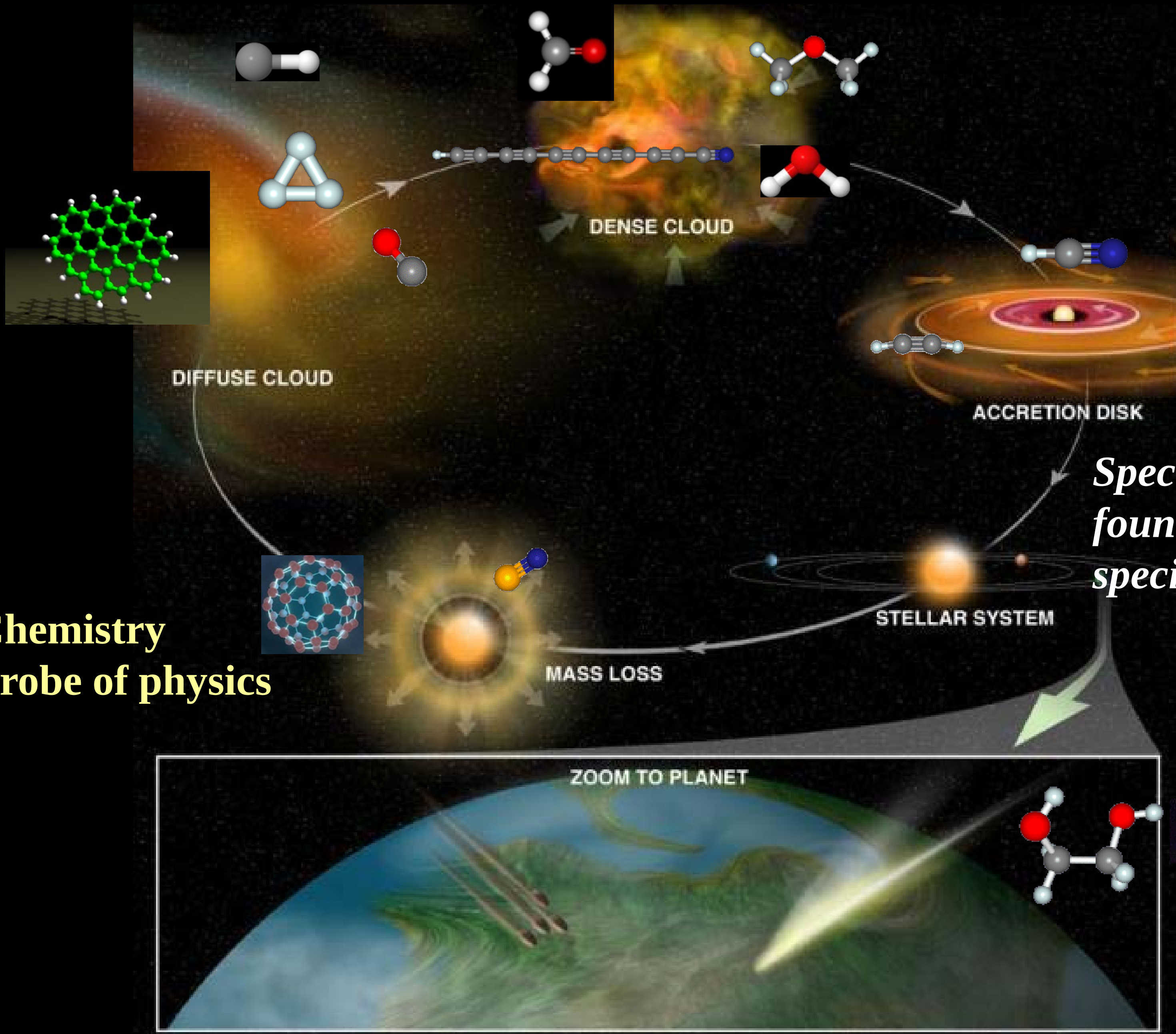


End-to-end cold testing with telescope at Houston



May 9 - Sept. 15 2017, survived Hurricane Harvey flooding!

From clouds to stars and planets



Specific molecules found under specific conditions

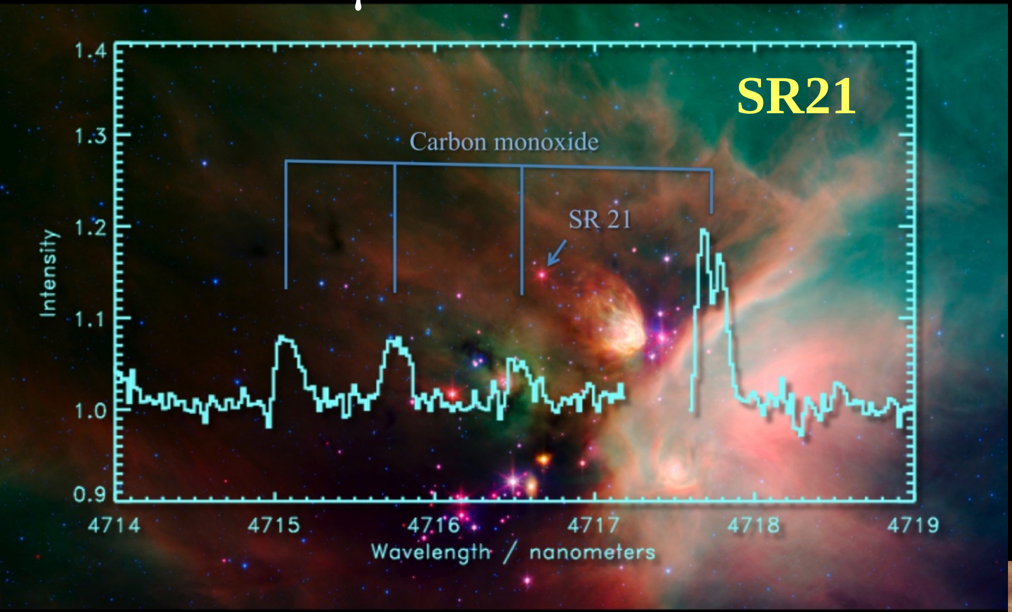
- Chemistry
- Probe of physics

Molecule images: The Astrochymist

B. Saxton
NRAO

Hot gas in the planet-forming zones of disks (<10 AU)

CO 4.7 μm v=1-0 VLT-CRIRES

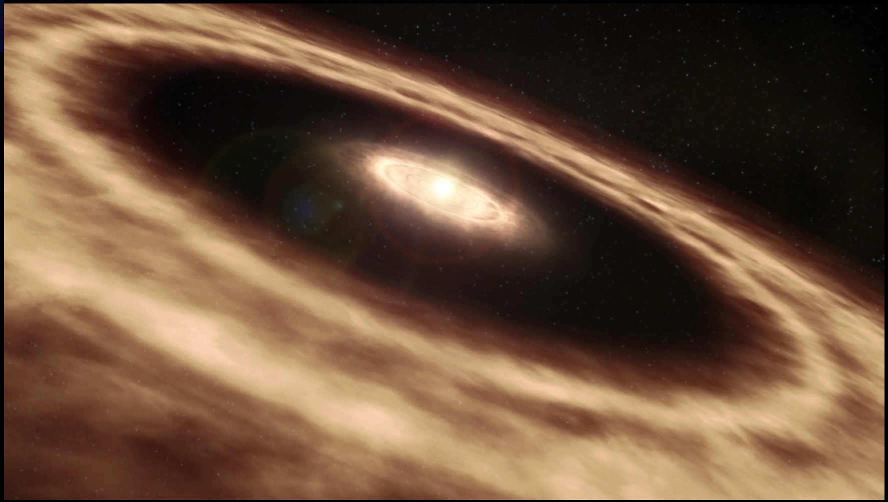


- Large surveys of CO v=1-0 in disks

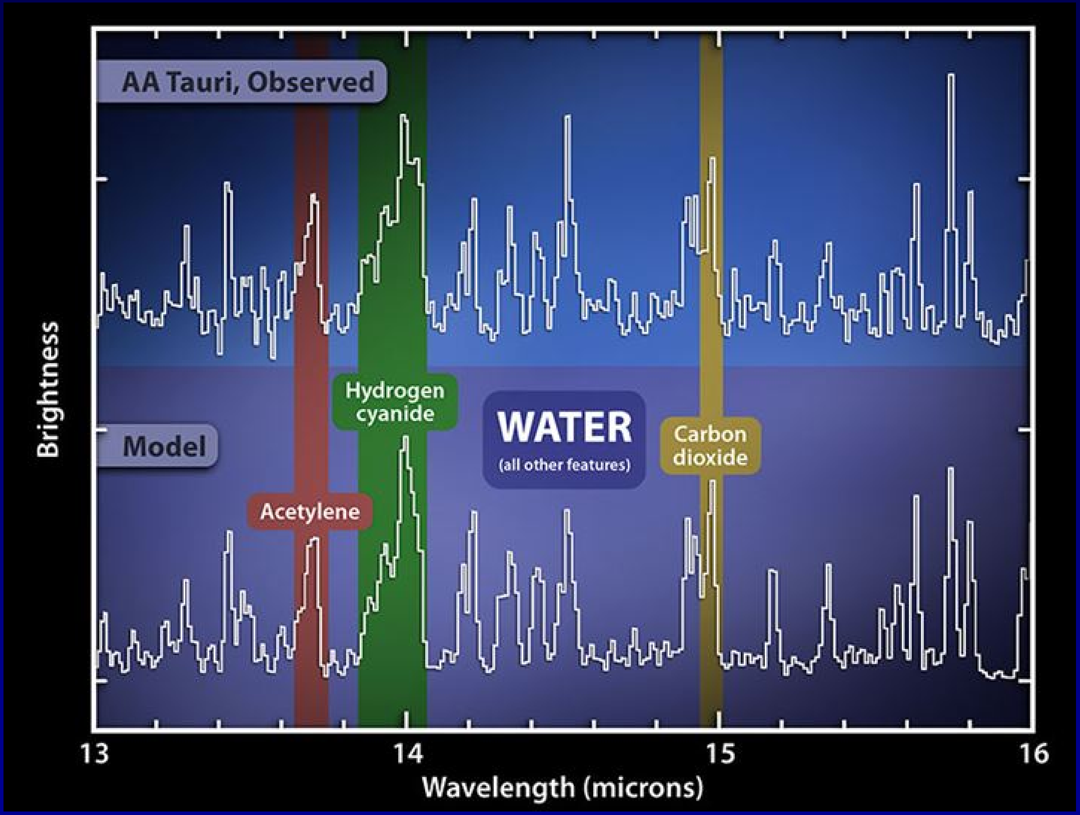
- Gas present in (dust) gaps where planets may be forming

Pontoppidan et al. 2008, van der Plas et al. 2009
Bast et al. 2010, Brown et al. 2013,
Banzatti & Pontoppidan 2017

- Need collisional rate coefficients and photodissociation rates to quantitatively interpret data



Inner disk (<1 AU): hot chemistry

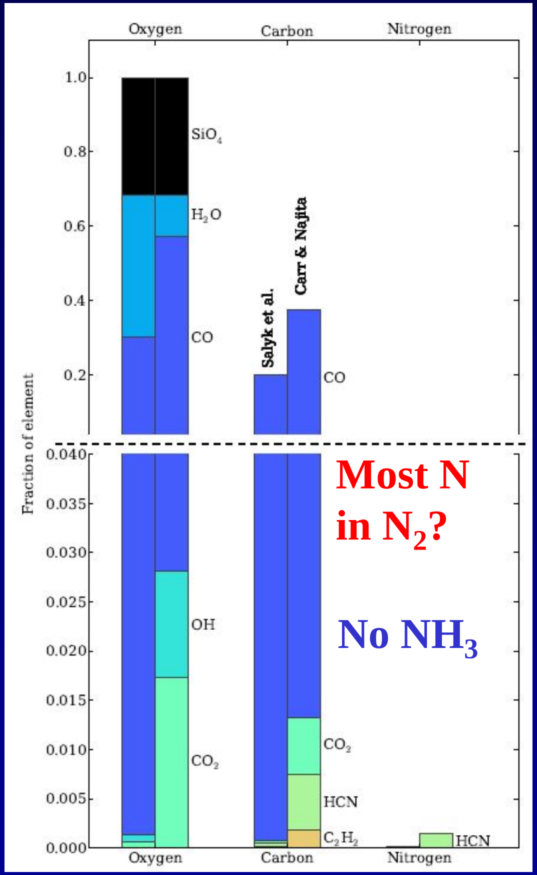


Note low line / continuum ratio at R~600; will be much better with JWST

Carr & Najita 2008, Salyk et al. 2008, 2010, Lahuis et al. 2006, Pontoppidan et al. 2014

- **Probe physical conditions**
- **High temperature (300-1000 K) chemistry** (e.g., Walsh et al. 2015)

Goal: C, N and O budget

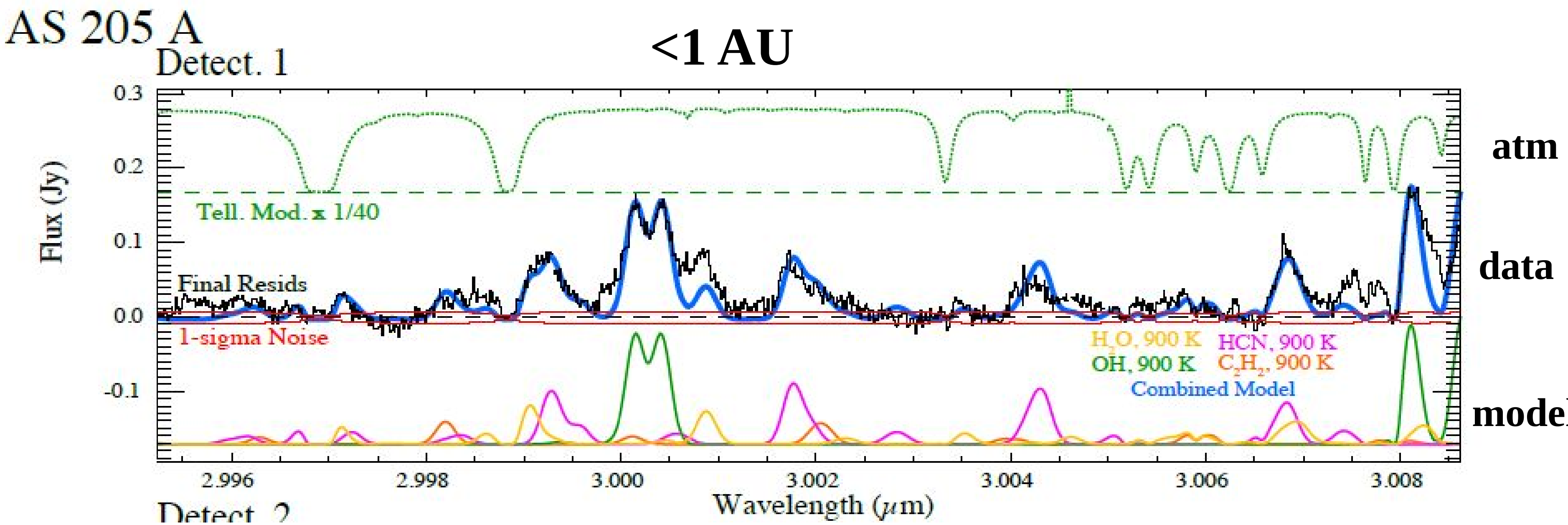


Pontoppidan et al. 2014

- Where are carbon and nitrogen?

JWST-MIRI will greatly improve sensitvity, spectral resolution, wavelength, especially CH_4 and NH_3

Near-IR detection of organics



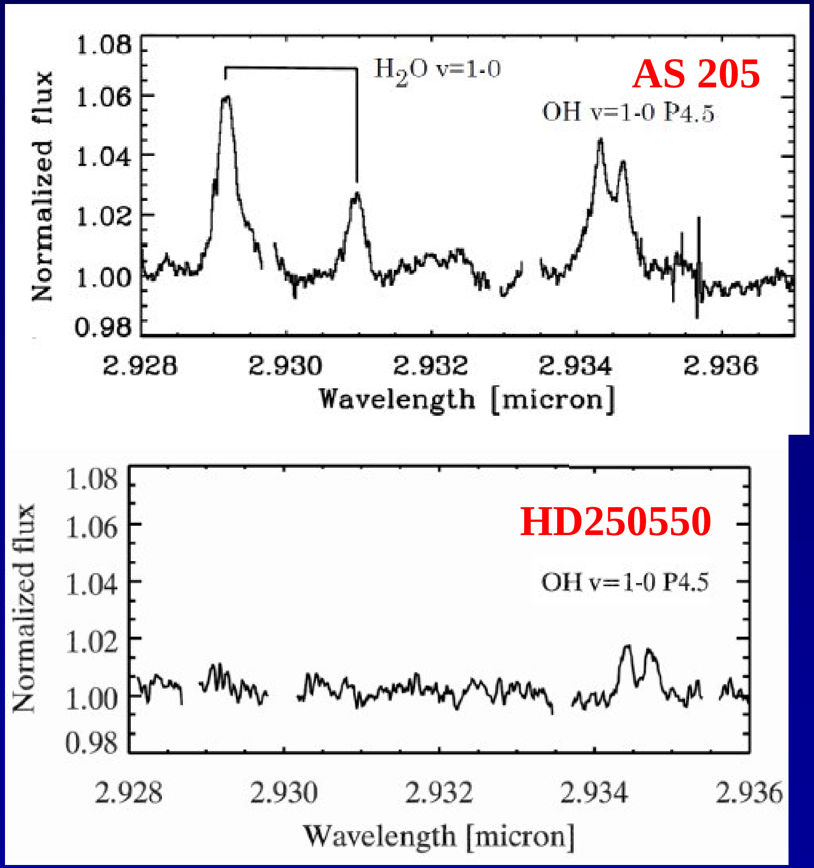
Mandell et al. 12

- CO, HCN and C_2H_2 detected in inner AU, plus H_2O, OH
- CH_4 and NH_3 not convincingly found

Implications for chemistry, C and N budget

Pontoppidan et al. 2014, PPVI

Near-IR Herbig vs T Tau stars: H_2O vs OH in inner disk



M star
$OH/H_2O=10^{-3}$

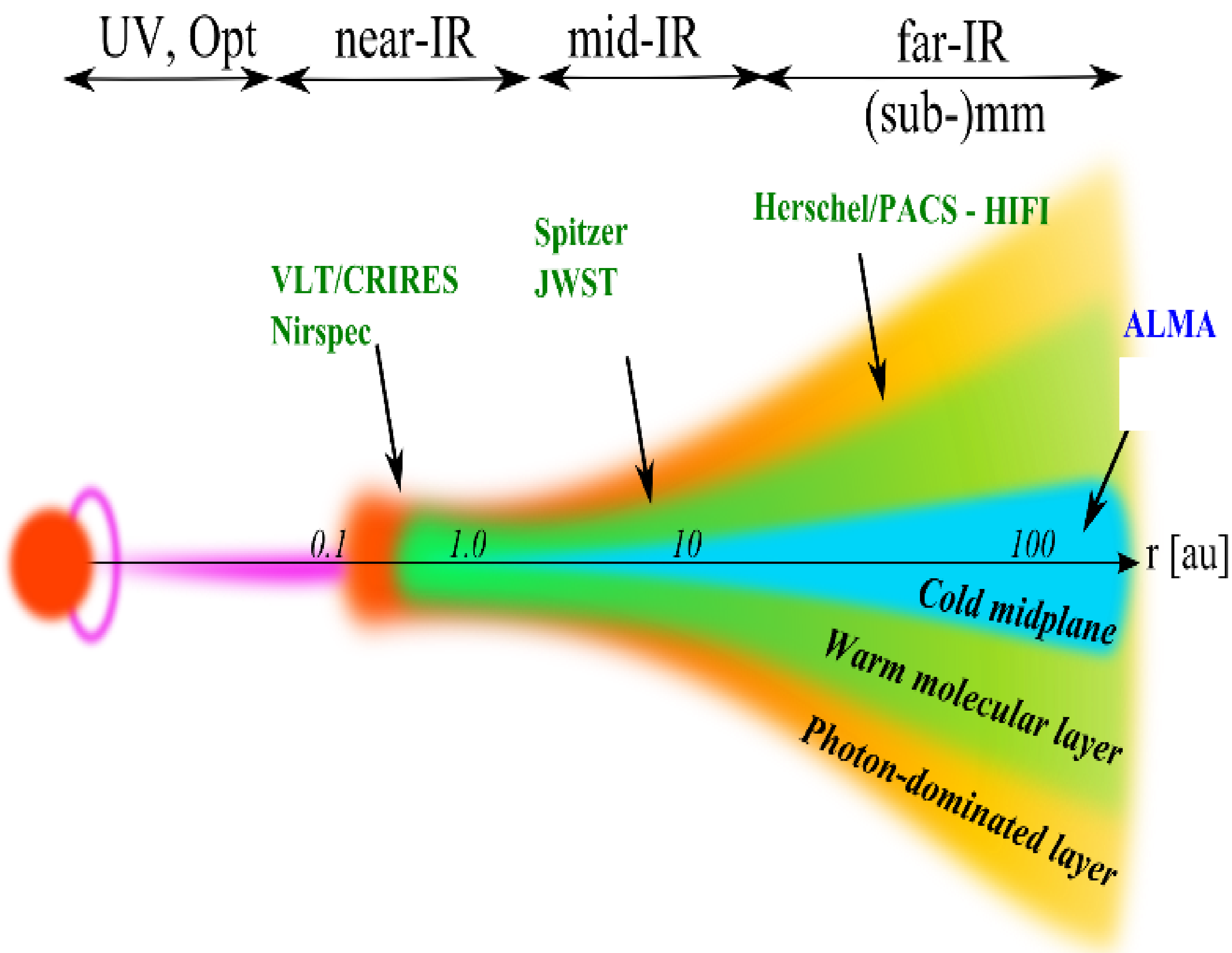
Salyk et al. 2008, Pontoppidan et al. 2010

A star
$OH/H_2O=1-30$

Fedele et al. 2011
Mandell et al. 2008

Water absent around A-type stars

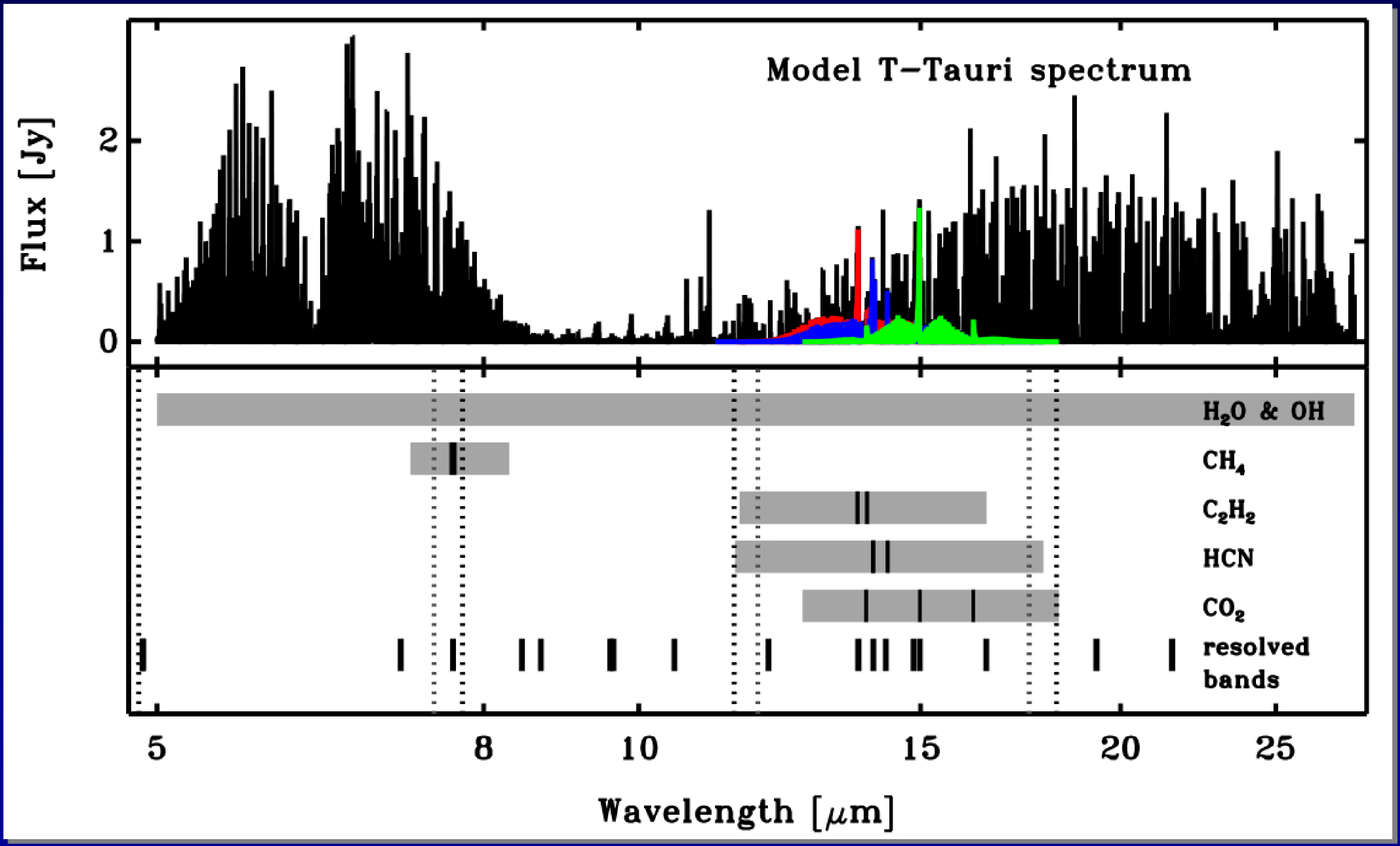
Probing protoplanetary disks



D. Fedele

Probing terrestrial planet-forming zones with JWST

MIRI GTO program (vD, Kamp)

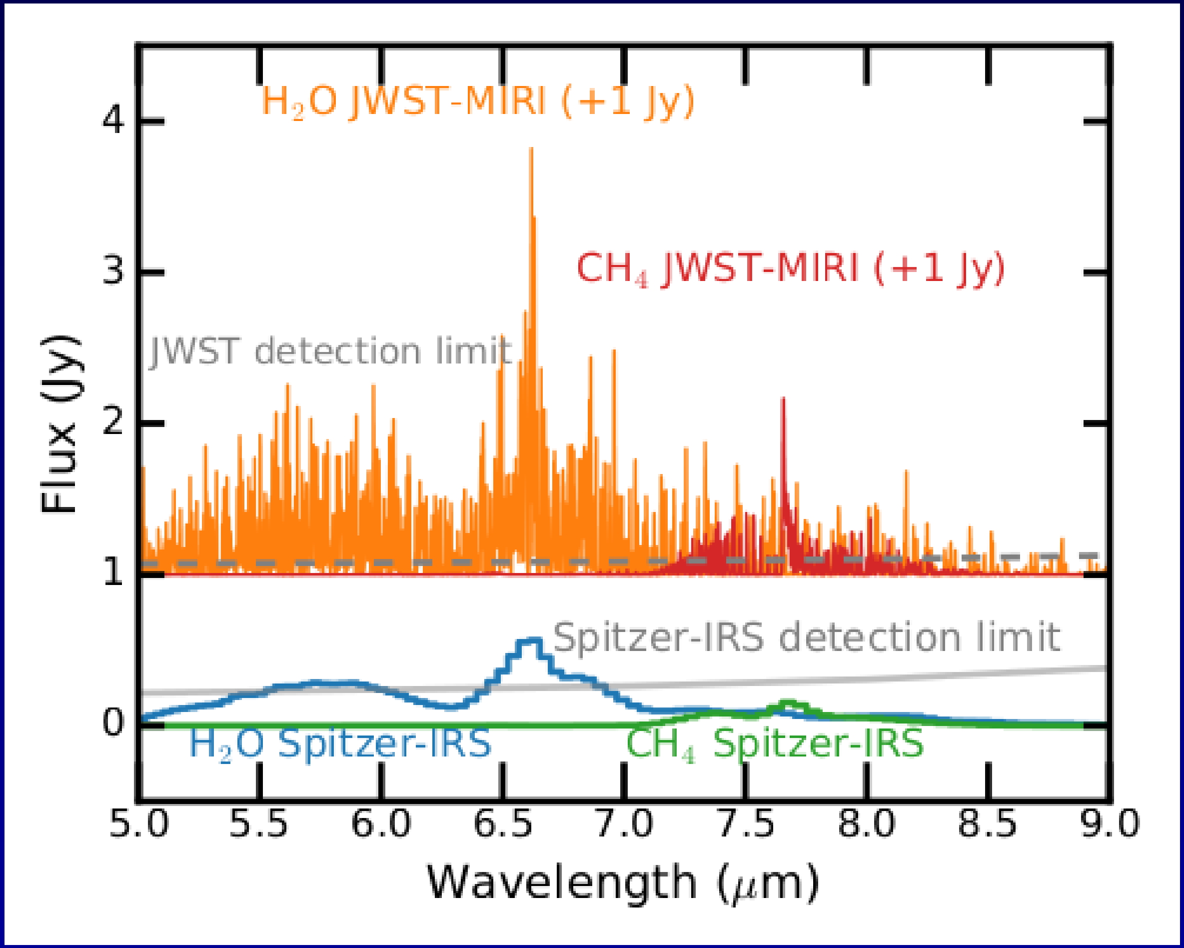


Mostly vibration-rotation bands

Lahuis et al.

Antonelli , Kamp et al. 2016

Model disk spectra: LTE slab



Note that Spitzer was not able to see these bands at ~R<100

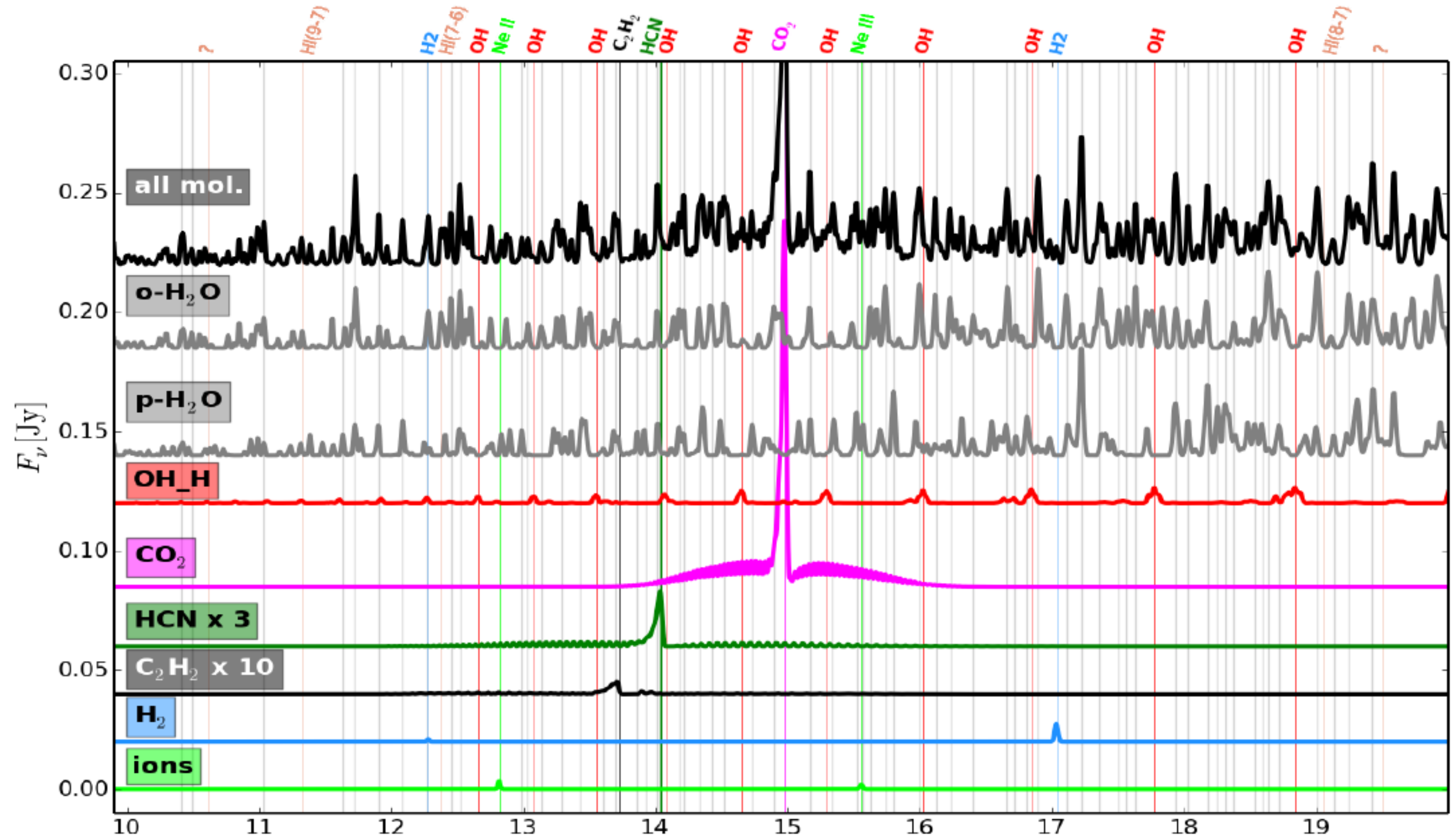
Bosman, priv. comm

Beyond LTE slab models

Astronomy & Astrophysics manuscript no. FLiTs
July 26, 2018

Modelling mid-infrared molecular emission lines from T Tauri stars

P. Woitke[1,2], M. Min[3], W.-F. Thi[4], C. Roberts[1], A. Carmona[5], I. Kamp[6], F. Ménard[7], C. Pinte[7]



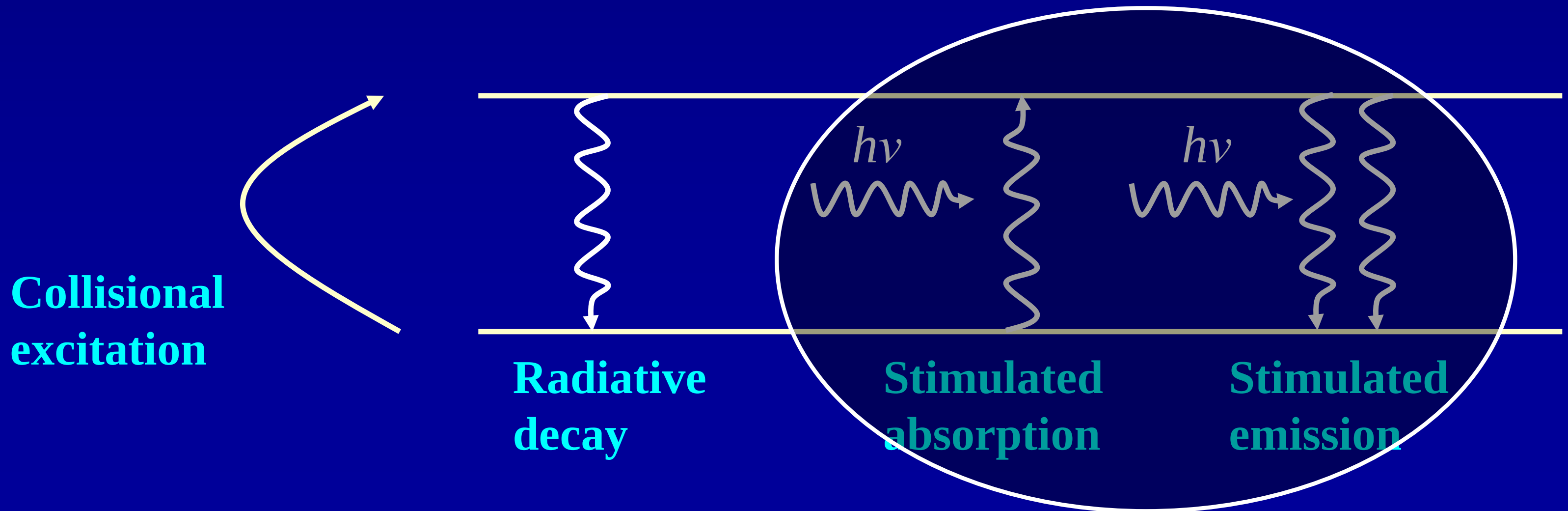
Full thermo-chemical modeling, LTE excitation

Molecular excitation

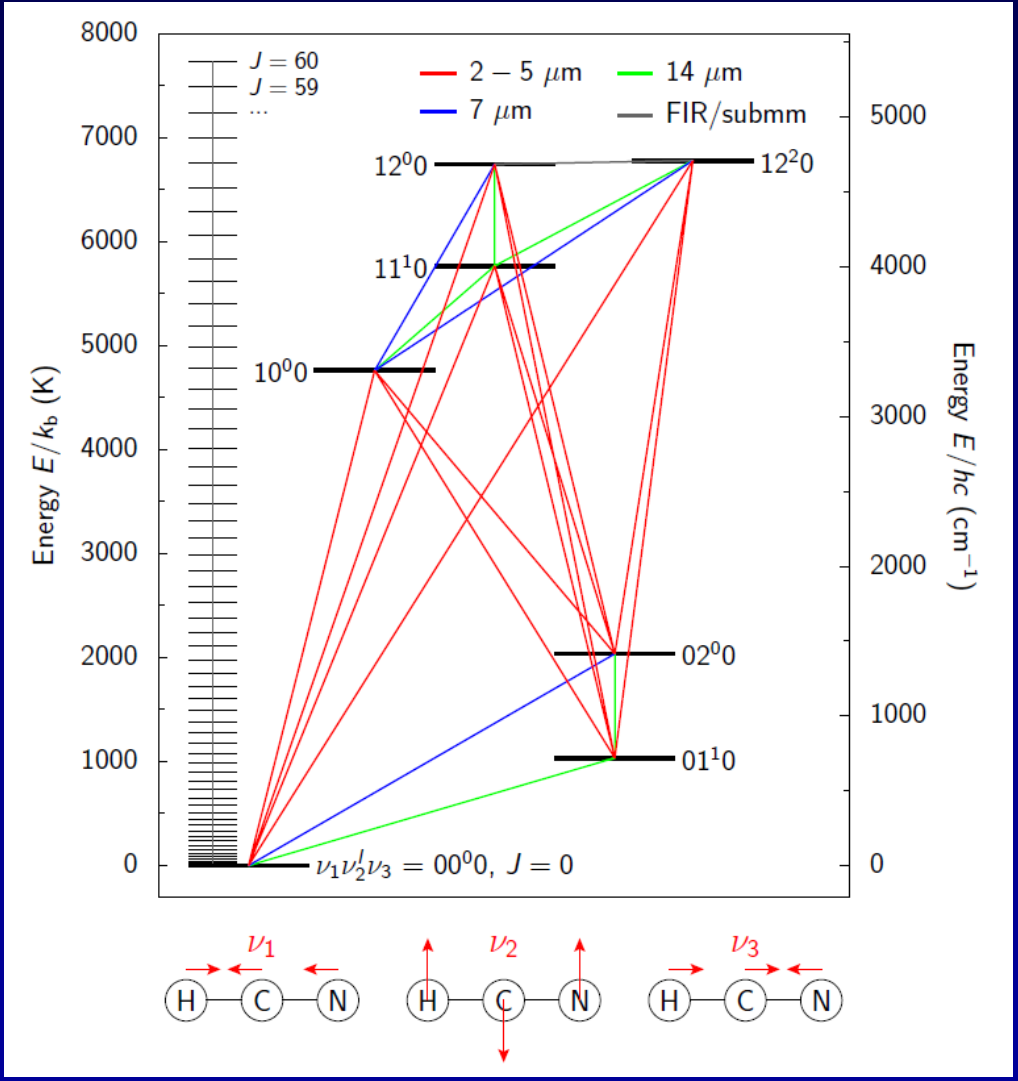
- Line emission results from collisional excitation followed by emission of a photon, where the photon can escape

$$A + B \rightarrow A^* + B$$

$$A^* \rightarrow A + h\nu$$

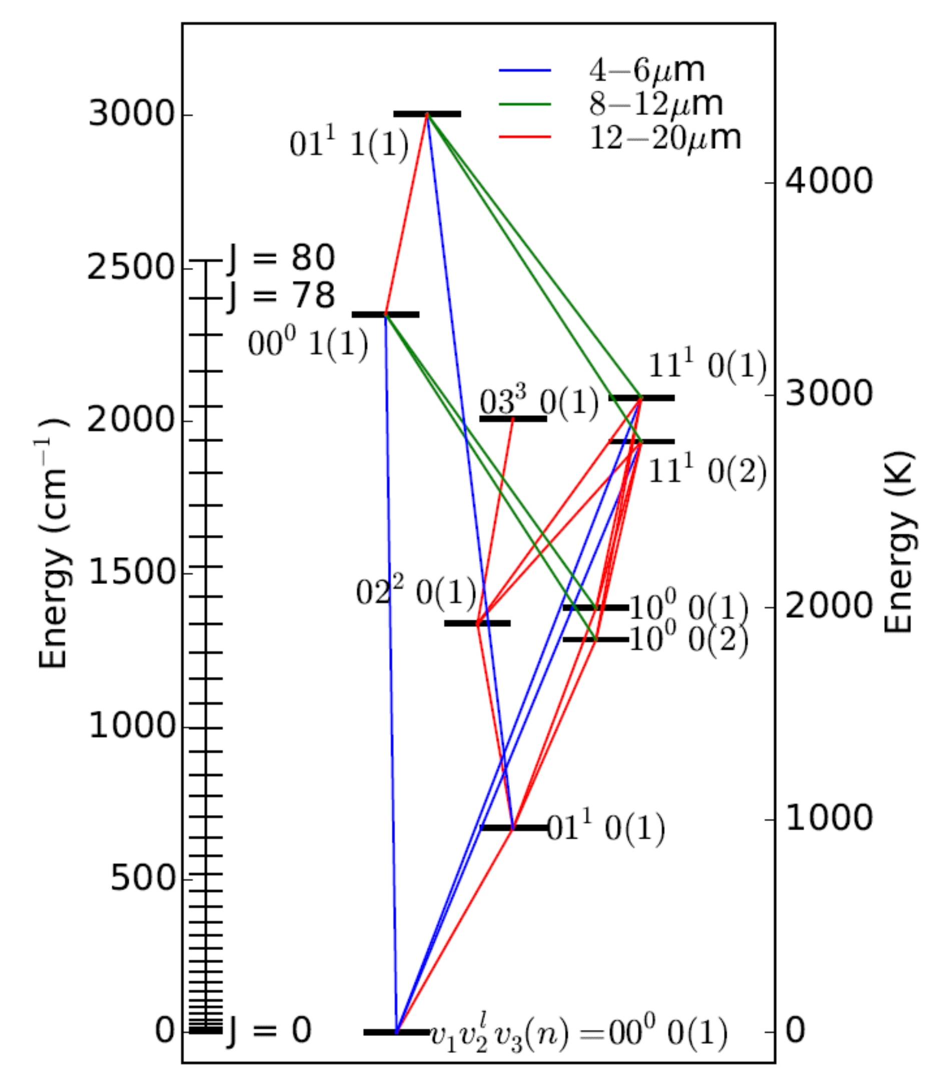


Non-LTE excitation: HCN



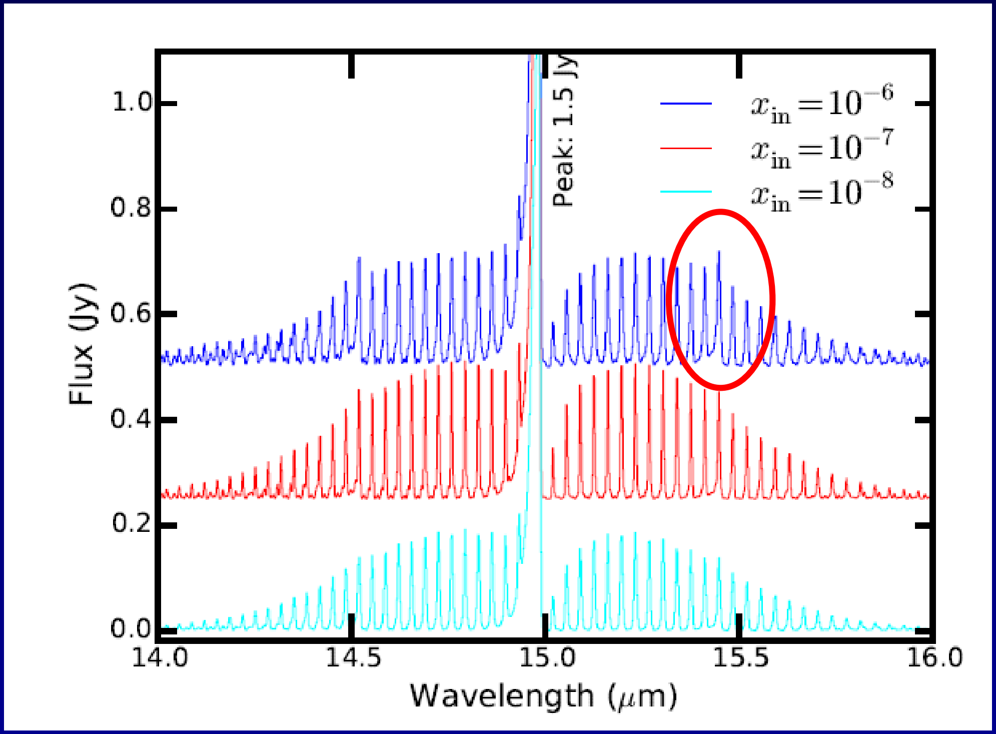
Bruderer et al. 2015

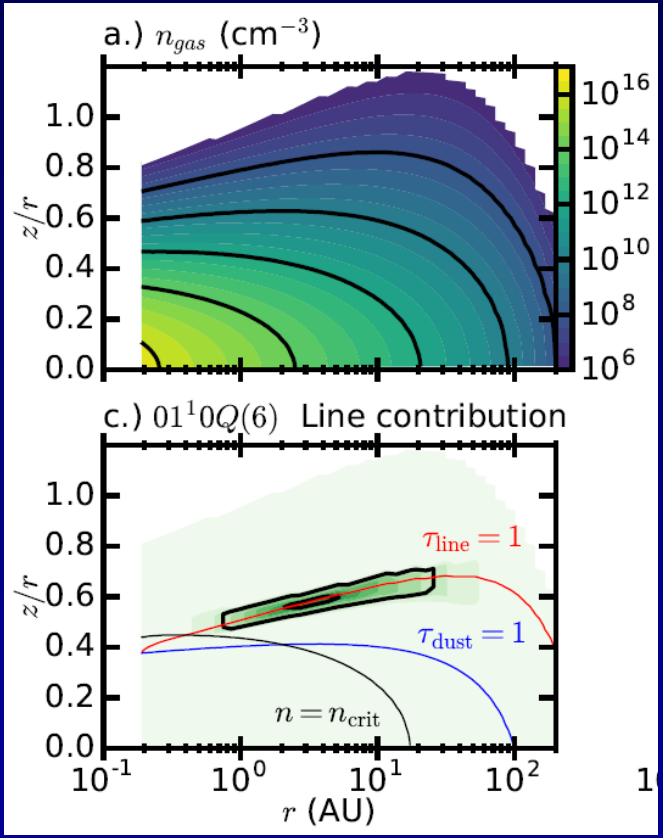
CO_2 energy level diagram



Bosman et al. 2017

Some simulated CO_2 spectra

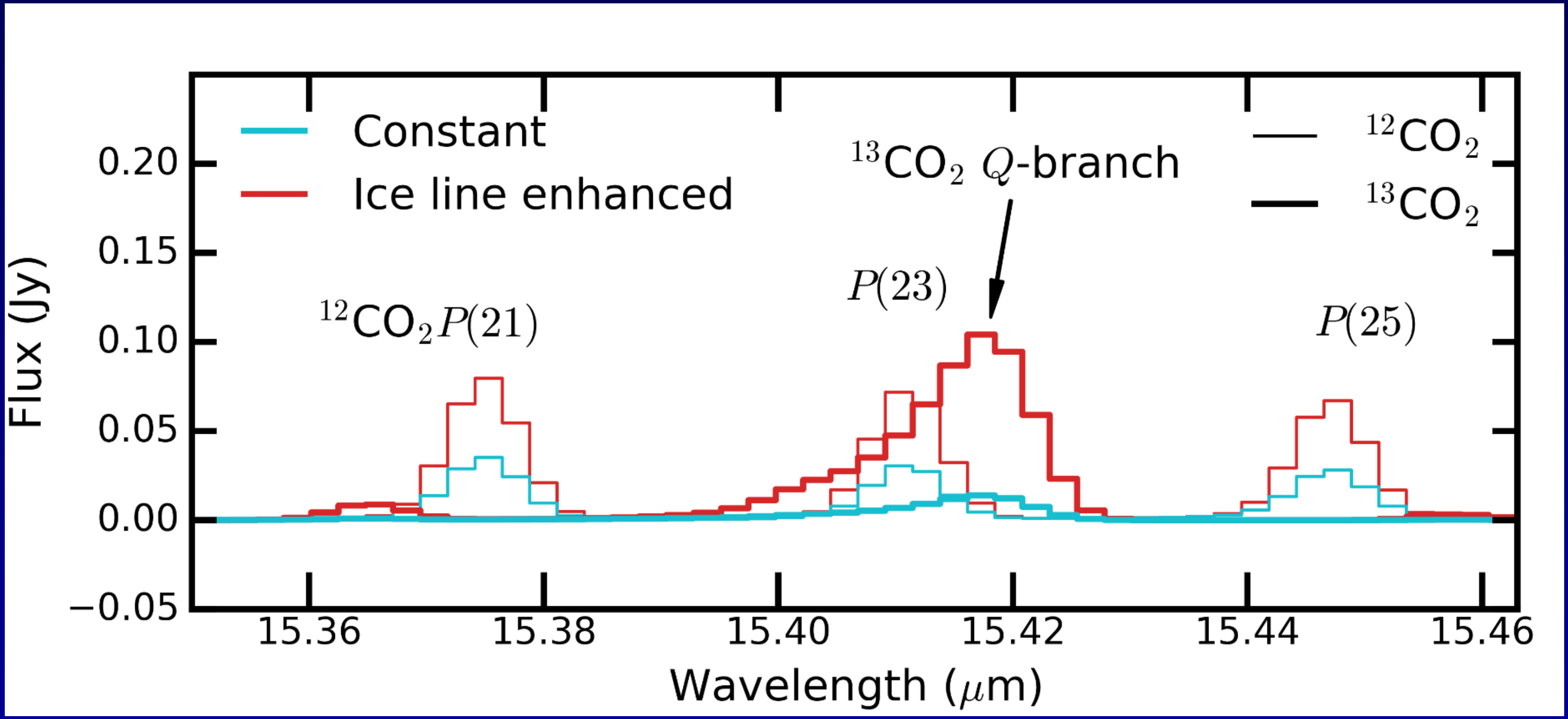




Bosman et al. 2017

Sublimating planetesimals at icelines

Importance of isotopologs as probes: $^{13}CO_2$



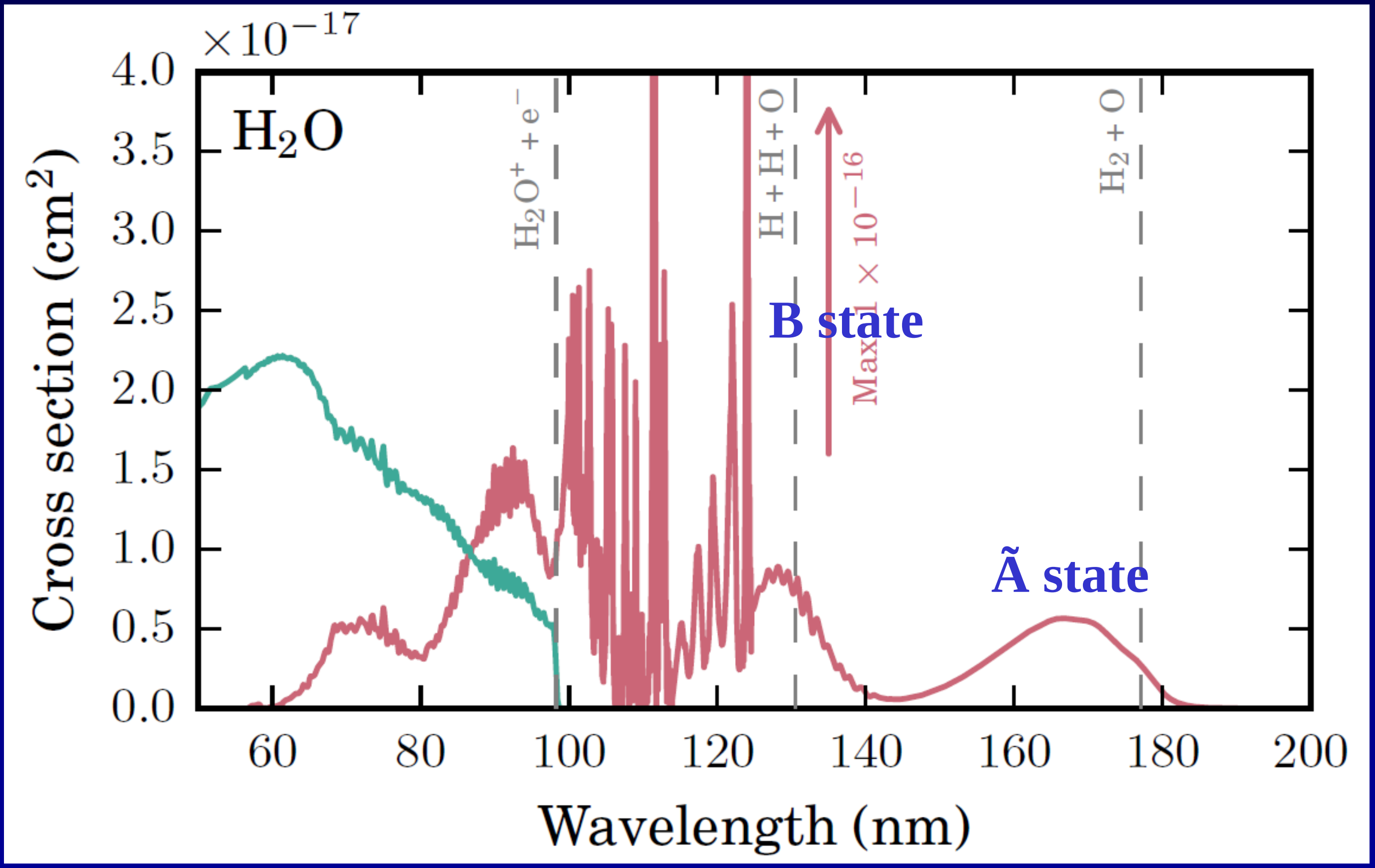
Bosman et al. 2017

General conclusions non-LTE

- IR pumping important
- Collisions important
  - Both H_2 and H relevant

Affects fluxes, inferred abundances at factor of few level

Prompt emission following photodissociation



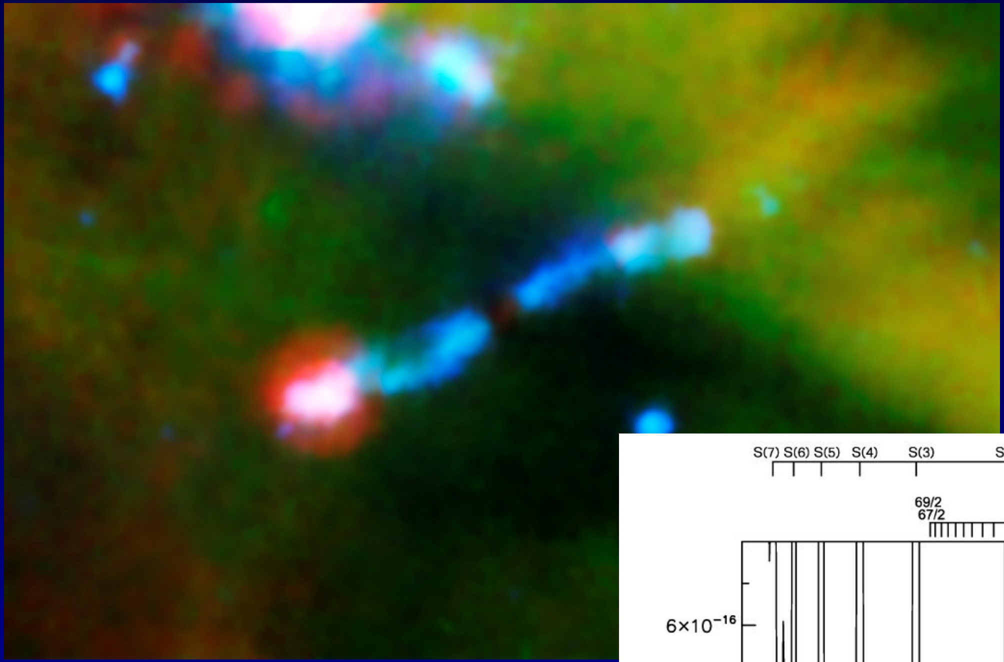
Heays, Bosman, vD 2017

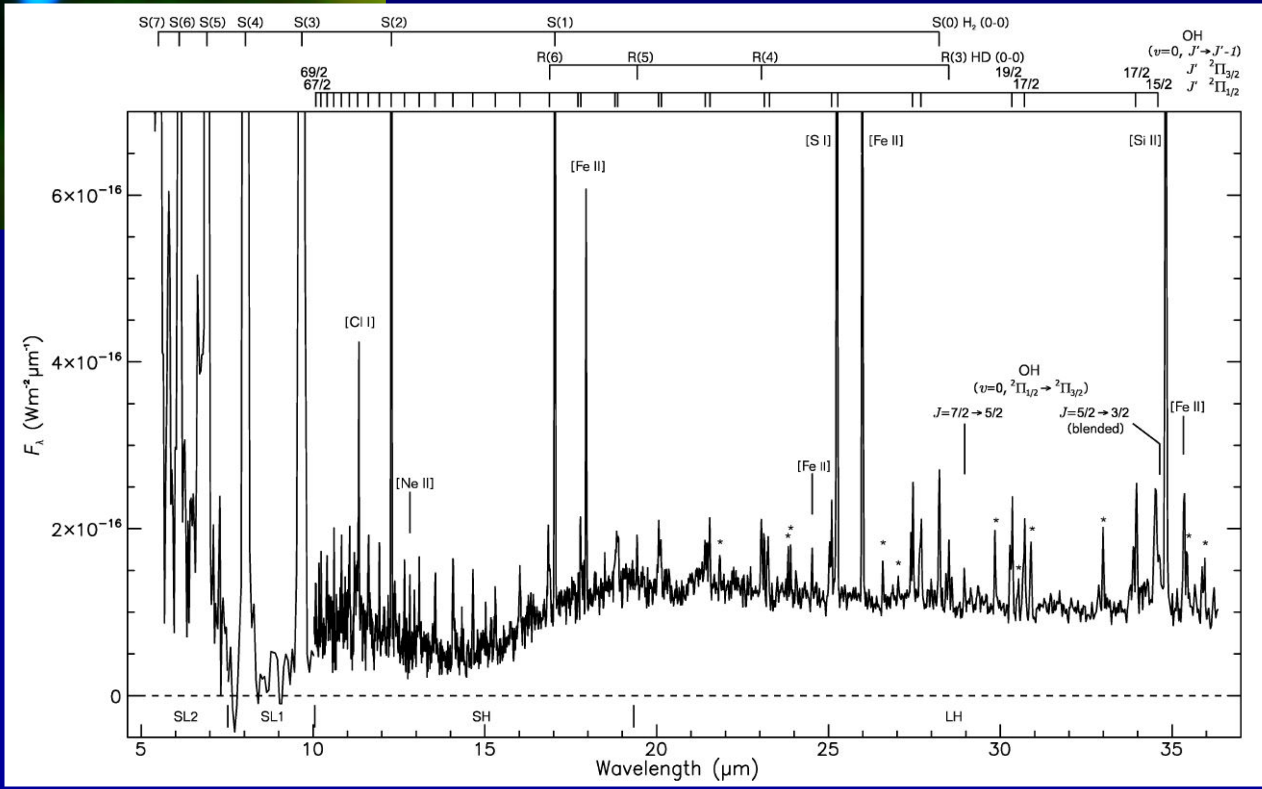
$H_2O \longrightarrow OH(v,J) + H$

Use calculations from van Harrevelt & van Hemert

Include in disk models: Benoit Tabone

Prompt OH emission in shocks





Tappe et al. 2008

Prompt OH emission in disks

Table 1
Measured OH Transitions and Fluxes

λ (μm)	N_{up}	Flux (10^{-17} W m^{-2})	E_{up} (K)	OH Transitions
10.07	34	1.33 ± 0.48	28182	3/2 R33.5ef, 1/2 R32.5ef
10.23	33	1.80 ± 0.46	26752	3/2 R32.5ef, 1/2 R31.5ef
10.40	32	3.09 ± 0.40[a]	25344	3/2 R31.5ef, 1/2 R30.5ef
10.60	31	1.15 ± 0.32	23961	3/2 R30.5ef, 1/2 R29.5ef
10.82	30	3.02 ± 0.31	22608	3/2 R29.5ef, 1/2 R28.5ef
11.06	29	3.49 ± 0.35[b]	21274	3/2 R28.5ef, 1/2 R27.5ef
11.30	28	4.29 ± 0.35[c]	19976	3/2 R27.5ef, 1/2 R26.5ef
11.60	27	2.15 ± 0.46	18702	3/2 R26.5ef, 1/2 R25.5ef
11.92	26	5.76 ± 0.44[b]	17463	3/2 R25.5ef, 1/2 R24.5ef
12.65	24	4.10 ± 0.42	15084	3/2 R23.5ef, 1/2 R22.5ef
13.08	23	3.12 ± 0.39	13944	3/2 R22.5ef, 1/2 R21.5ef
13.54	22	4.51 ± 0.54	12844	3/2 R21.5ef, 1/2 R20.5ef
14.06	21	2.12 ± 0.57	11784	3/2 R20.5ef, 1/2 R19.5ef
14.64	20	6.70 ± 0.66	10760	3/2 R19.5ef, 1/2 R18.5ef
15.29	19	5.77 ± 0.58	9775	3/2 R18.5ef, 1/2 R17.5ef
16.02	18	8.20 ± 0.63[a]	8836	3/2 R17.5ef, 1/2 R16.5ef
16.84	17	6.92 ± 0.69	7943	3/2 R16.5ef, 1/2 R15.5ef
17.77	16	6.10 ± 0.98	7082	3/2 R15.5ef, 1/2 R14.5ef
18.84	15	5.85 ± 1.23	6273	3/2 R14.5ef, 1/2 R13.5ef
20.06	14	7.82 ± 1.56	5513	3/2 R13.5ef, 1/2 R12.5ef
21.44	13	7.30 ± 1.04	4773	3/2 R12.5ef
21.53	13	3.85 ± 1.03	4817	1/2 R11.5ef
23.07	12	2.65 ± 0.56	4105	3/2 R11.5f
23.12	12	3.48 ± 0.56	4092	3/2 R11.5e
23.22	12	8.84 ± 1.06	4147	1/2 R10.5ef
25.04	11	3.54 ± 0.57	3476	3/2 R10.5f
25.09	11	5.19 ± 0.57	3475	3/2 R10.5e
25.24	11	8.65 ± 0.89	3529	1/2 R9.5ef
27.39	10	3.79 ± 0.68	2904	3/2 R9.5f
27.45	10	6.40 ± 0.68	2903	3/2 R9.5e
27.67	10	10.10 ± 1.02	2957	1/2 R8.5ef
30.28	9	3.33 ± 0.78	2378	3/2 R8.5f
30.35	9	5.07 ± 0.78	2377	3/2 R8.5e
30.68	9	9.52 ± 1.24	2442	1/2 R7.5ef
33.88	8	6.24 ± 2.32	1910	3/2 R7.5f
33.95	8	8.68 ± 2.31	1898	3/2 R7.5e
34.48	8	12.07 ± 2.65	1972	1/2 R6.5ef

Carr & Najita 2014

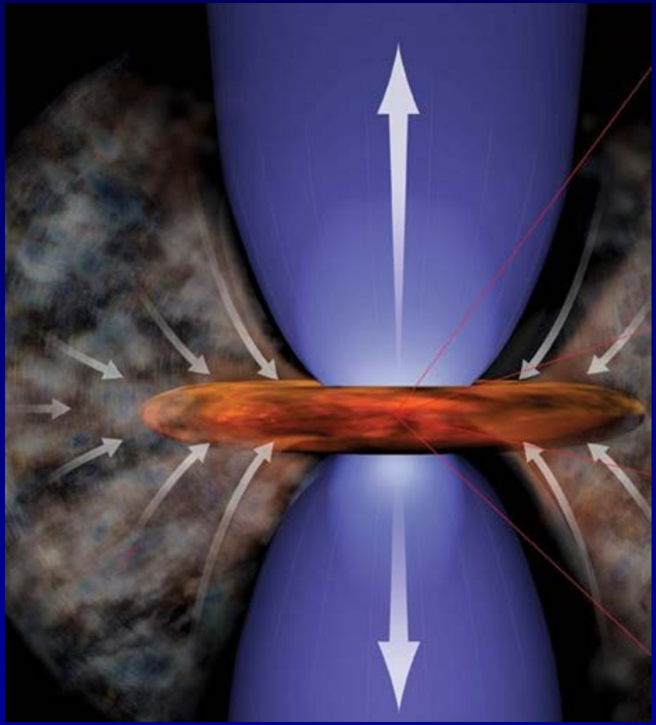
Boltzmann diagram: 200, 6000 K components

Summary

- JWST GTO, ERS and open time programs will target many disks (and protostars)
- Modeling preparation before launch 2021 needed
  - OH, H_2O: pure rotation, ro-vibration
  - HCN, CO_2, C_2H_2, CH_4, NH_3, ...

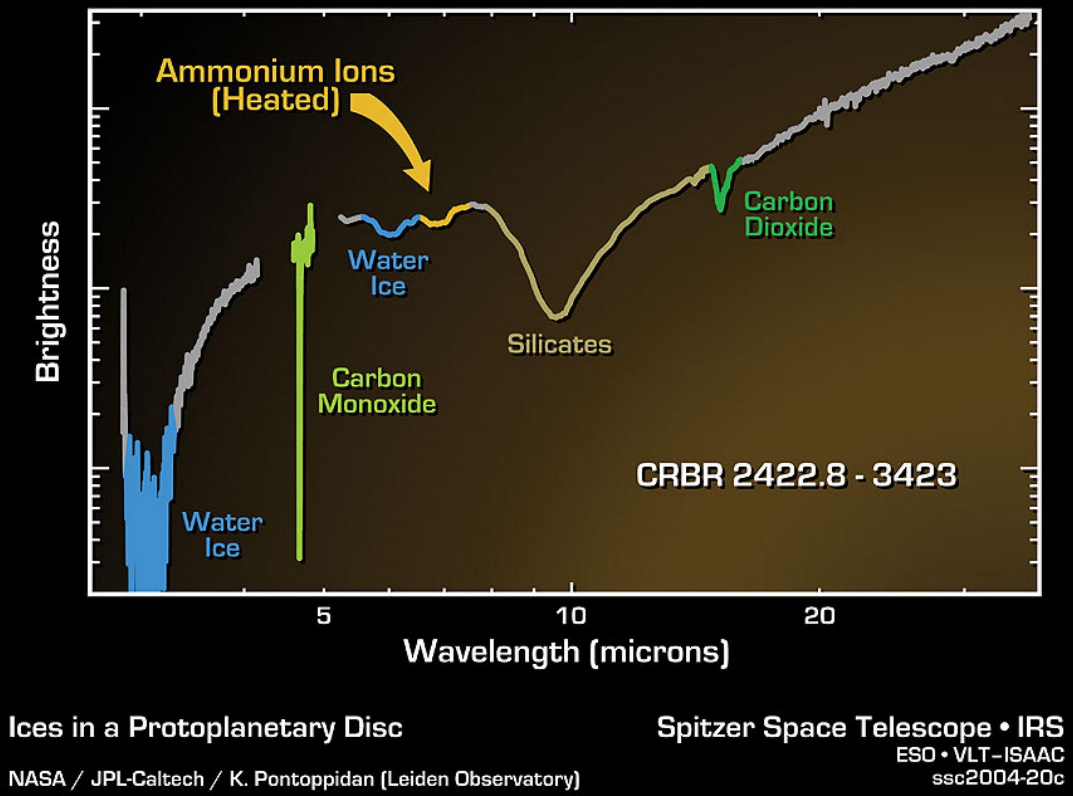
Young disks and envelopes with MIRI

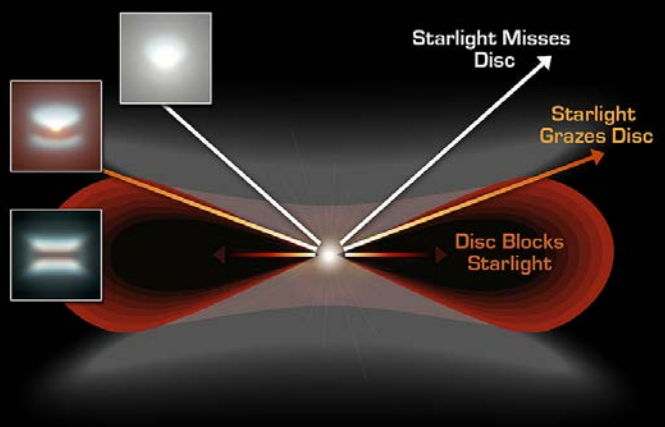
NIRSPEC



Protostar GTO program: dozen low-mass protostars with MRS (+ another dozen together with US partners; also ERS program M. McClure)

Ices in edge-on disks





Measure CO_2, CH_4 ice in disks for the first time; O_2 search

Pontoppidan et al. 2005