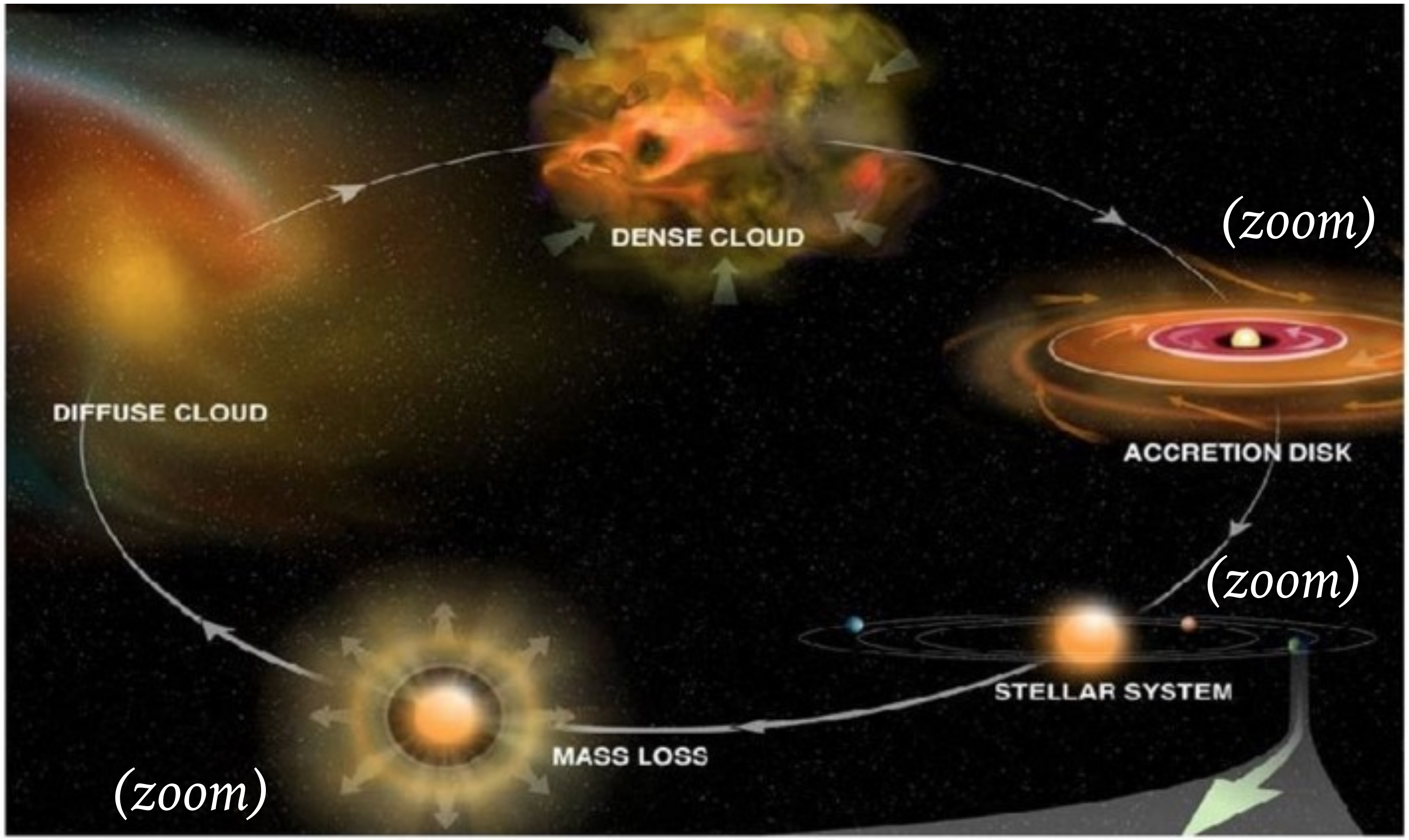
CHEMISTRY WITH ALMA

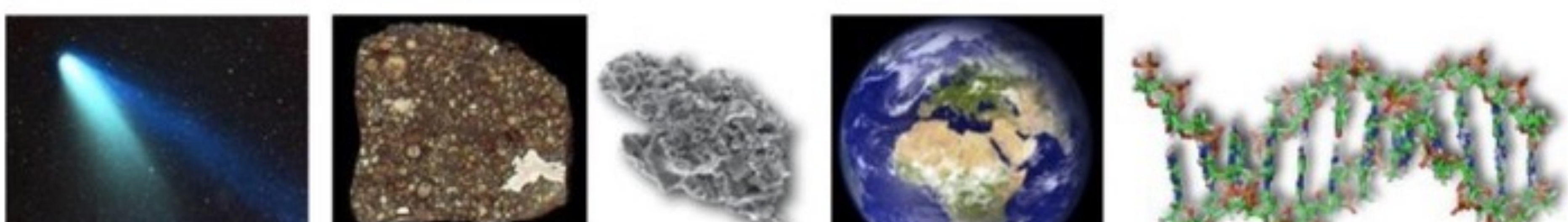
Kazi Rygl, IRA, Italian ALMA Regional Center

OVERVIEW

- (extremely brief) Introduction to astrophysics and astronomy
- Molecular lines in radio-submm astronomy
- ALMA interferometer
- Chemistry of star and planet formation done with ALMA
- Public ALMA data in the ALMA Archive

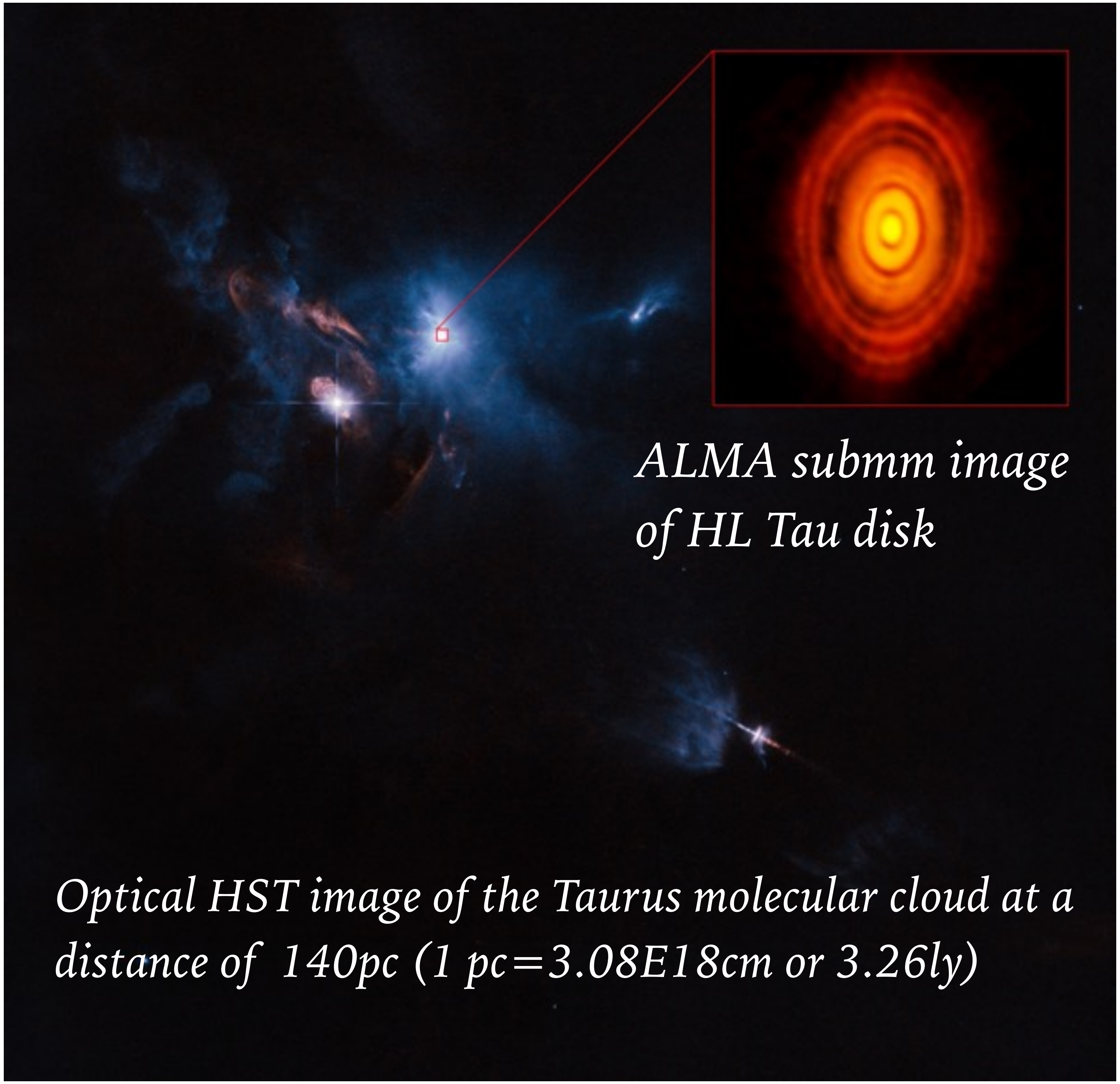
STAR AND PLANET FORMATION





source: phys.org

ALMA OBSERVATIONS OF HL TAU (SUN-LIKE STAR)



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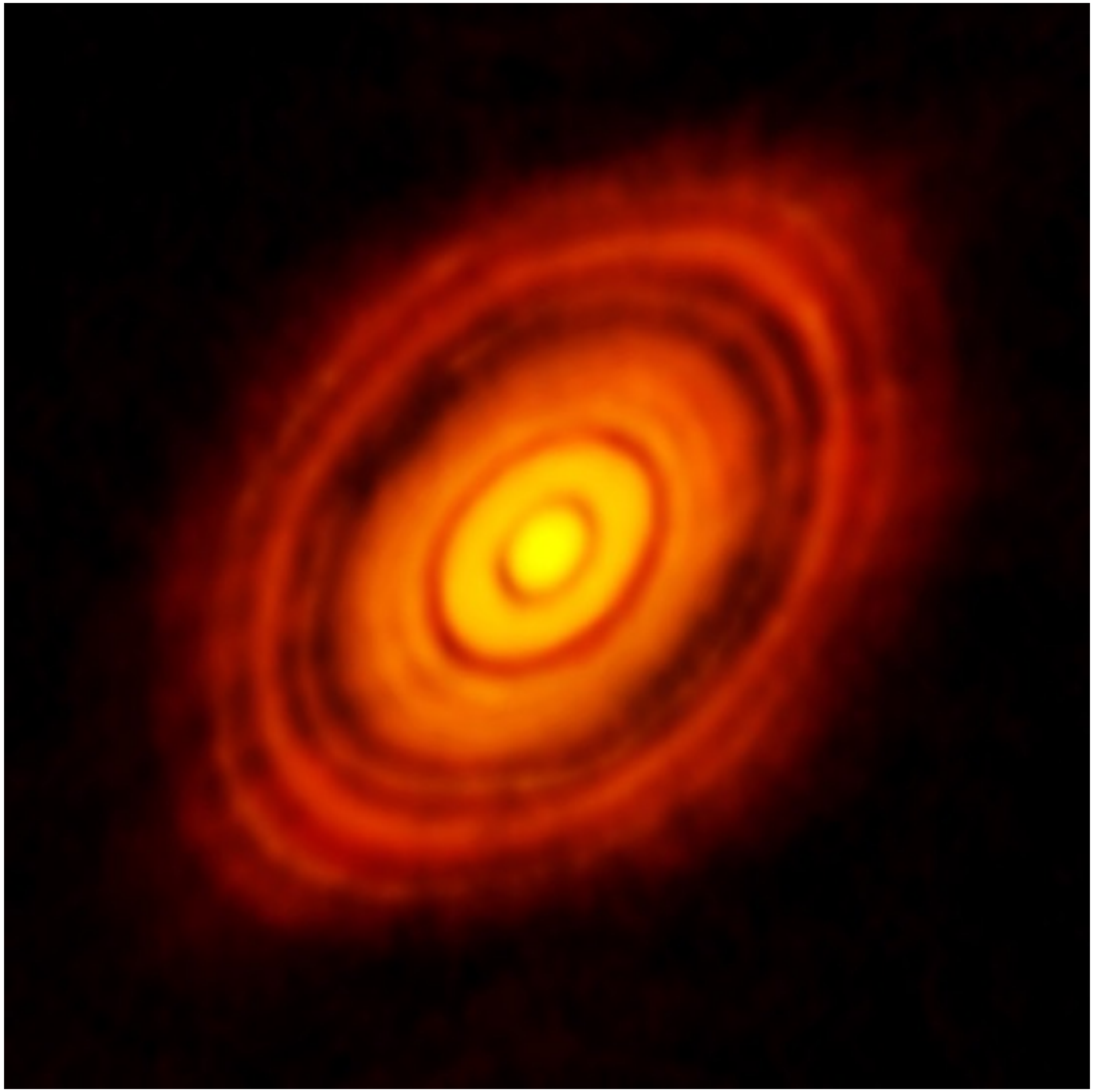
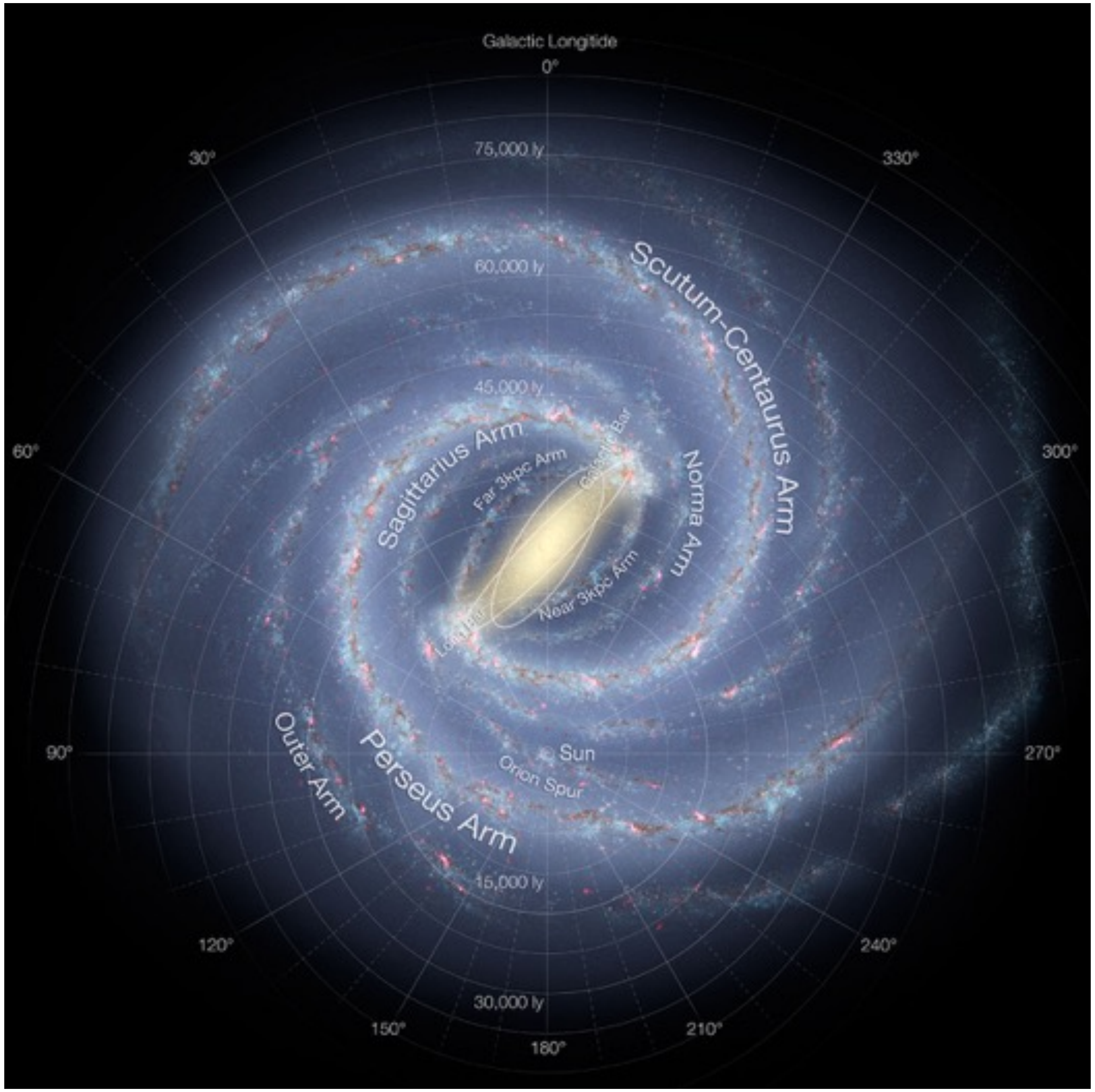


Stellar disk visible thermal emission from heated dust grains organized in concentric rings with gaps.

As planets and asteroids form in the disk, they reshape this disk, sweeping up the material in their orbit, thus creating a disk structure as observed in HL Tau.

STAR-FORMING CLOUDS IN THE MILKY WAY



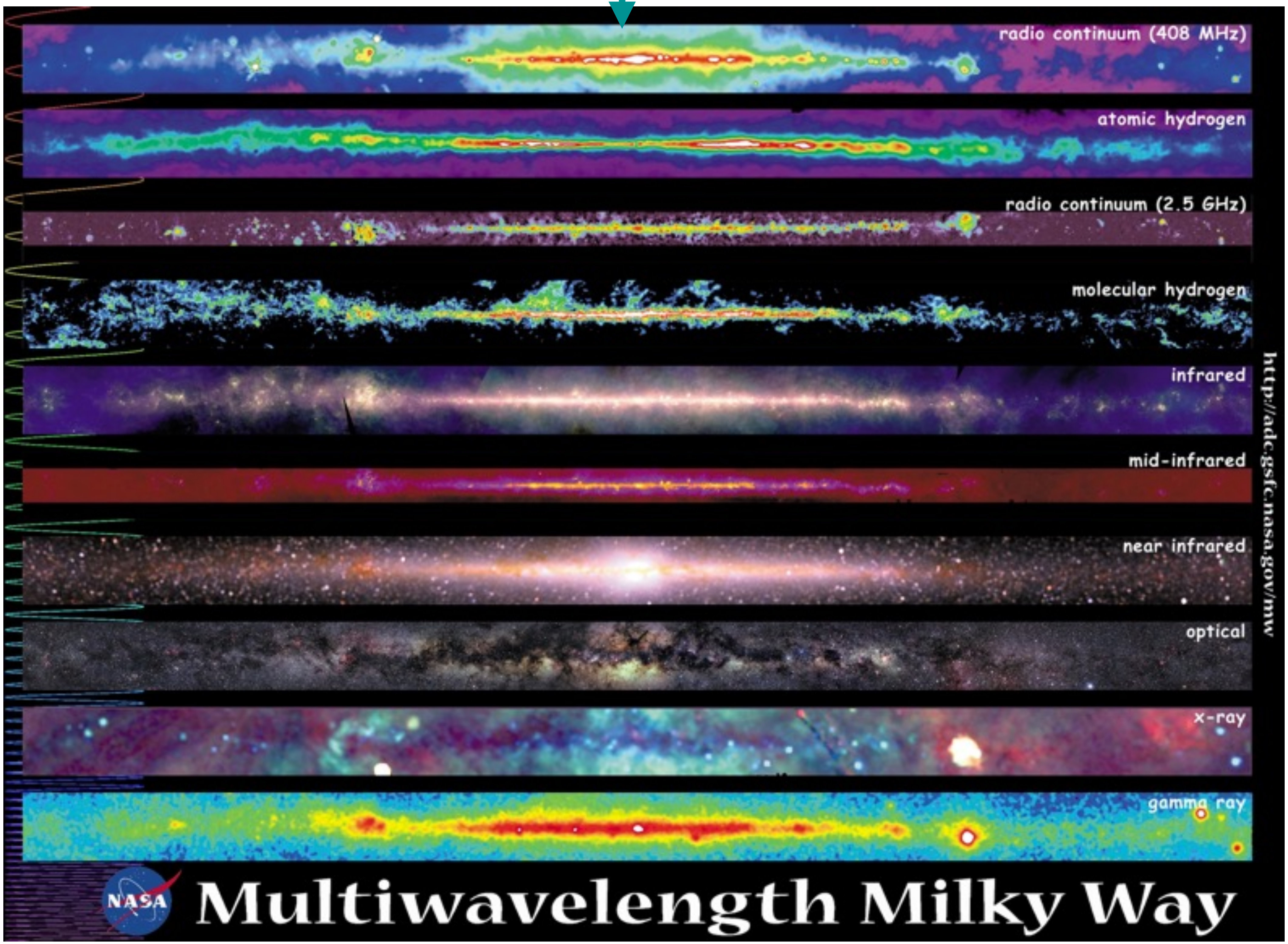
Our Sun is located in the Galactic disk, in outer region of the Milky Way.

The Milky Way's disk has a spiral arm structure, a central bar and a massive Black Hole (1E6Msun, 1Msun=2E33 g) in the center.

Dense molecular clouds are formed preferentially on the spiral arms (and bar) where the gravitational potential aids the accumulation of gas and dust.

WE ARE IN THE MILKY WAY DISK…

towards Galactic center



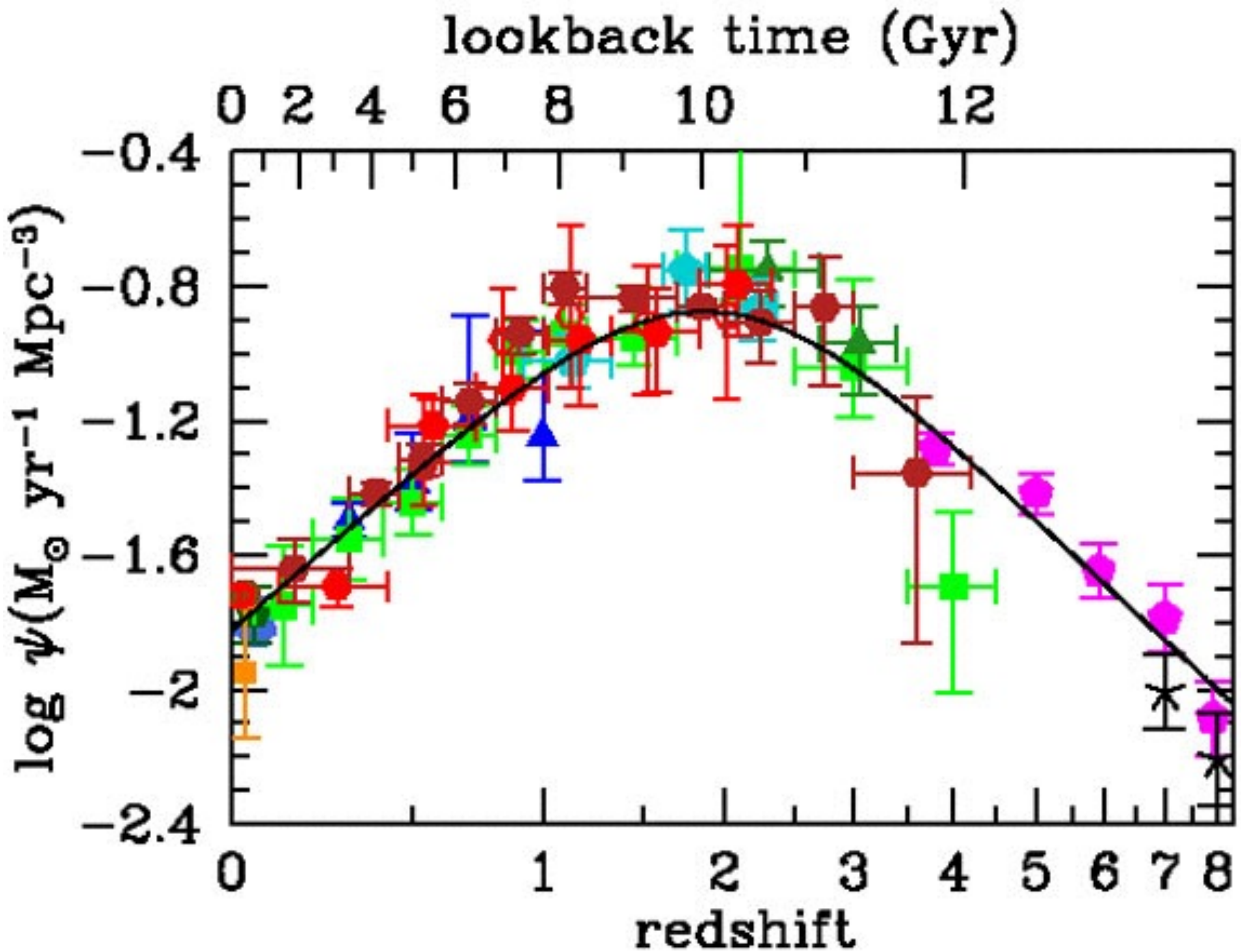
BUT OUR GALAXY IS JUST ONE OF MANY

source: scienceblog.com

LOOKING BACK IN TIME: COSMIC STAR FORMATION HISTORY

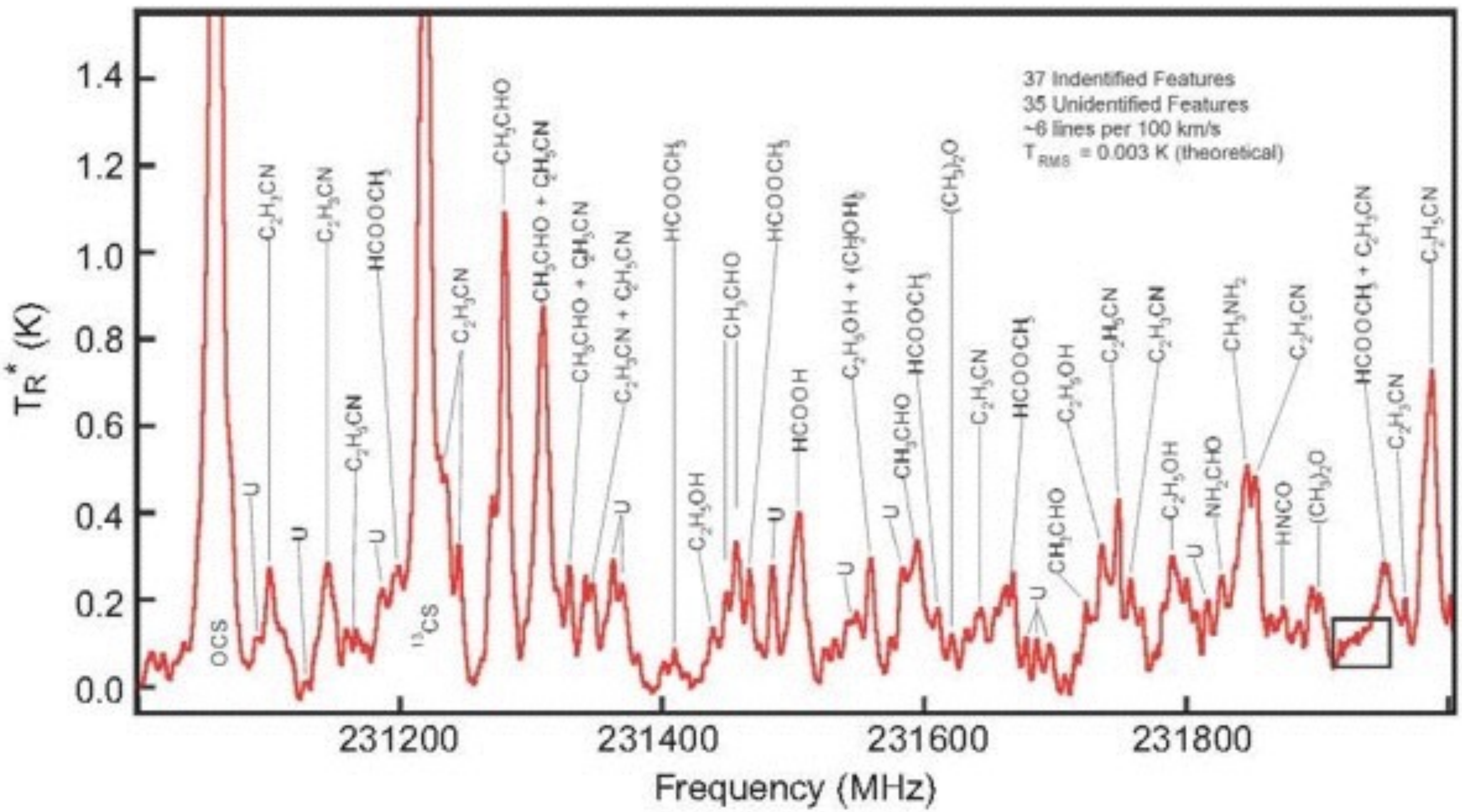
Apparent star formation peak at redshift z~2

$$z = \frac{\Delta\lambda}{\lambda_0}$$



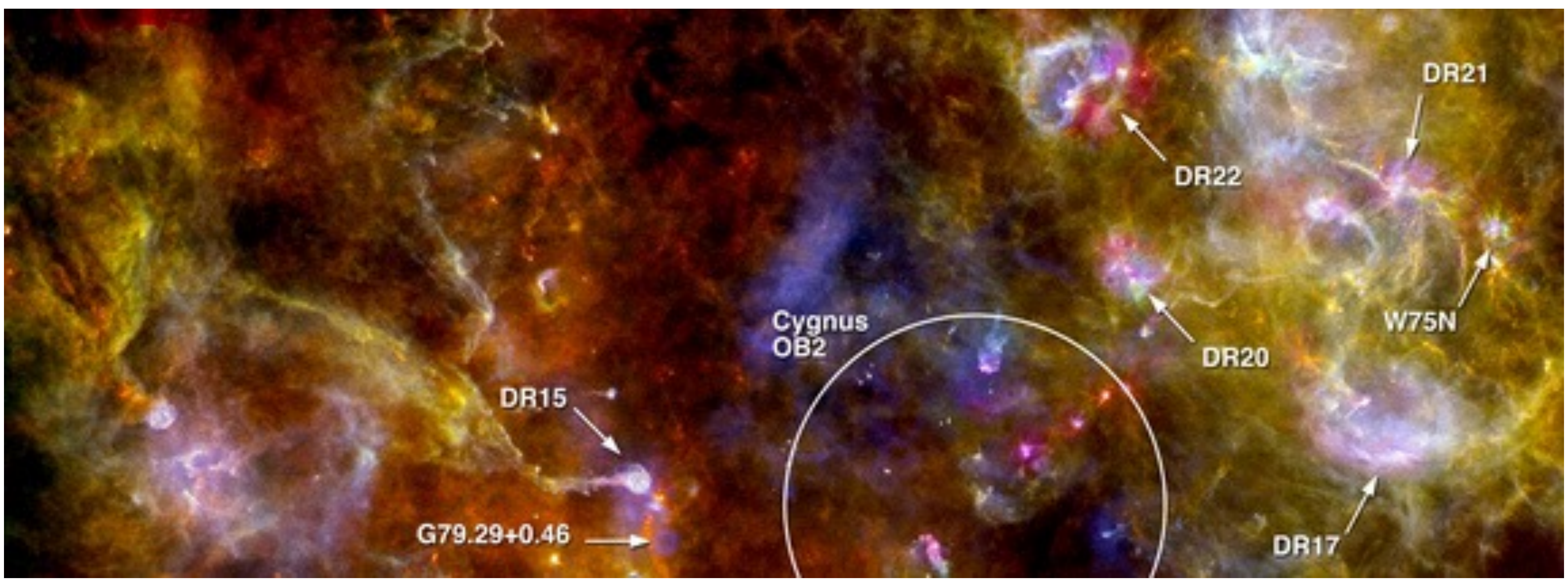
Madau et al. 2014

MOLECULAR LINES IN SUBMM ASTRONOMY



ISM ENVIRONMENTS IN THE GALAXY

- cold, dense atomic and molecular gas
  - temperatures from ~10K (at high density, shielded gas) to 5000 K (tenuous gas, not shielded)
  - hydrogen densities from 10 cm^{-3} (tenuous gas) to 10^6 cm^{-3} (densest location in molecular clouds)
- warm/hot, ionized gas near hot stars



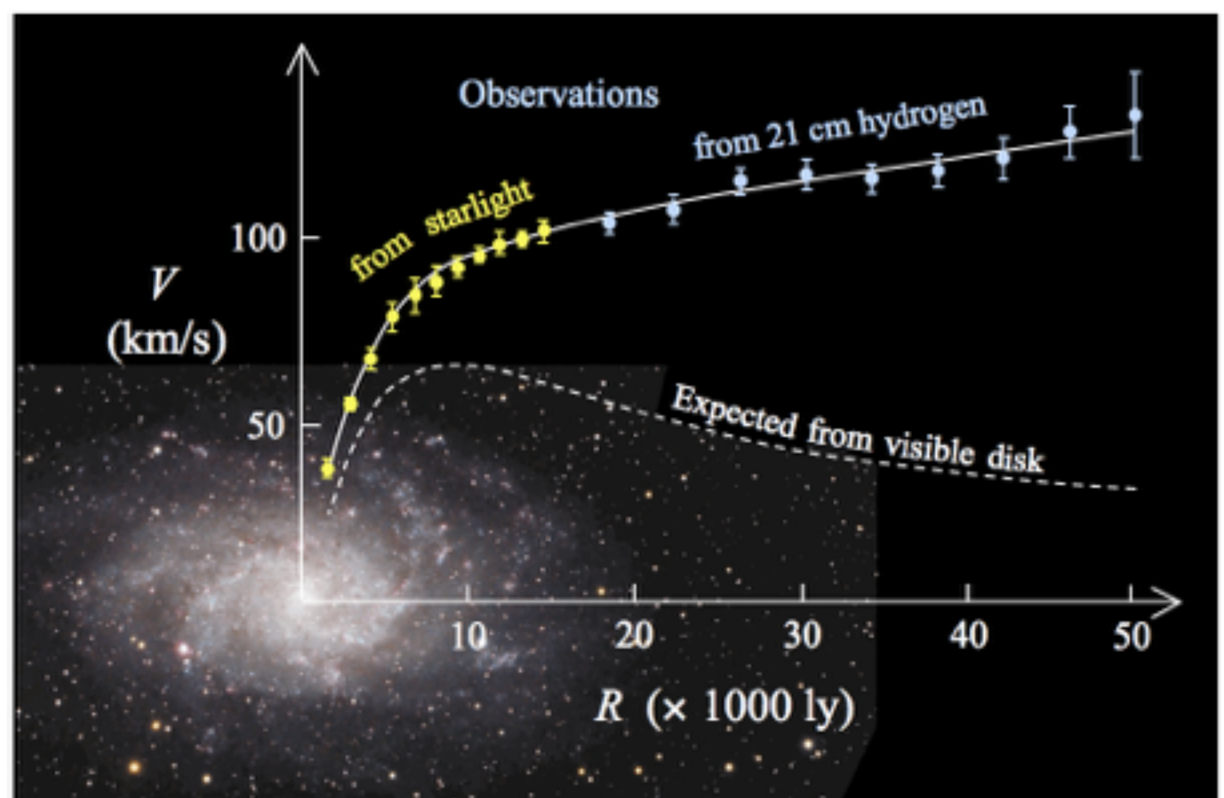
Herschel dust continuum map showing the cold dense medium in red/yellow, and the dust heated by young stars (blue shells) Image: Henneman et al. 2012, ESA

ISM CONSTITUTION AND MASS OF OUR GALAXY

- ~20% of mass is in stars, gas and dust (ISM: 99% gas, 1% dust)
- Most gas is HI (atomic) or H_2 (molecular)
- H_2 radiates inefficiently in cold ISM, because the molecule is light and has no permanent dipole moment: H_2 densities are inferred from dust emission or CO emission.
- ~80% of mass is not visible > dark matter, discovered through HI rotation curves

$$\frac{mv^2}{r} = \frac{GmM}{r^2}$$

$$M \propto R, v = constant$$
$$M = constant, v \propto r^{-0.5}$$



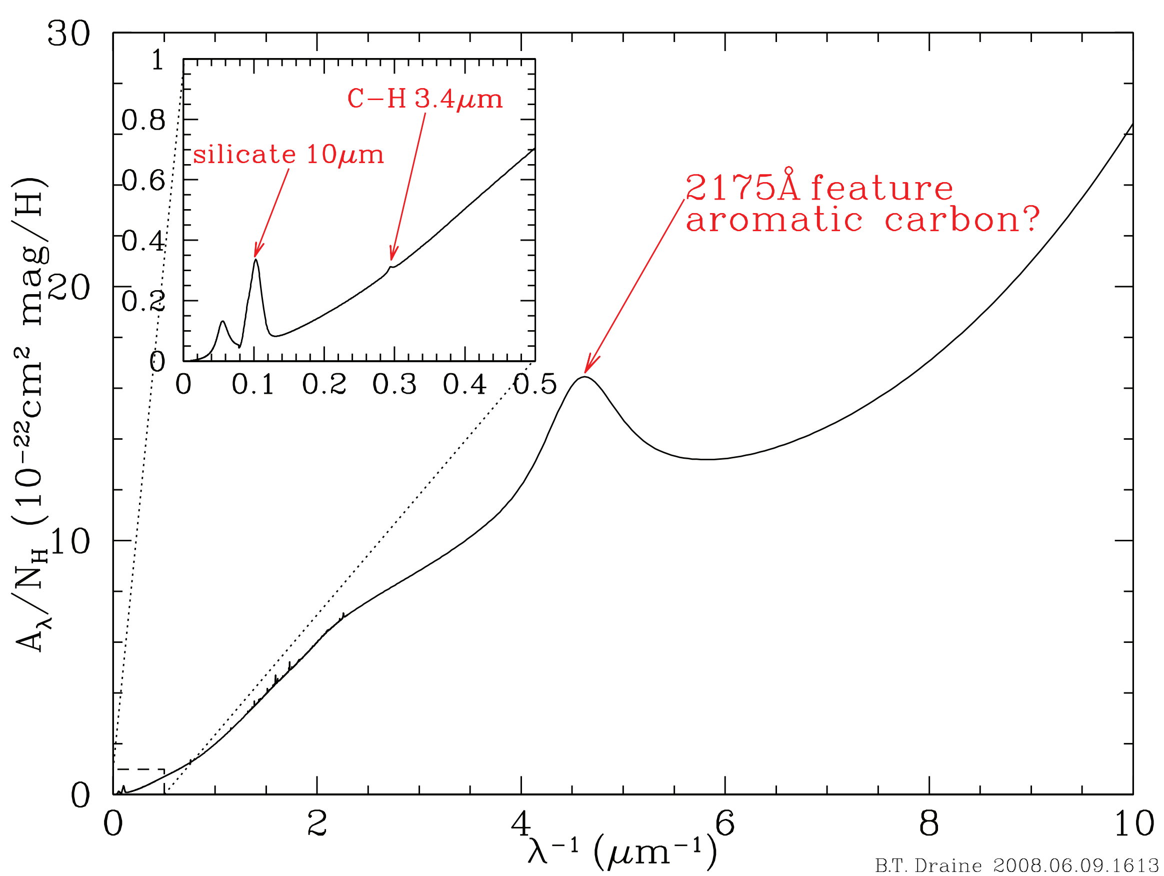
Rotation curve of Galaxy M33, Corbelli et al. 2001

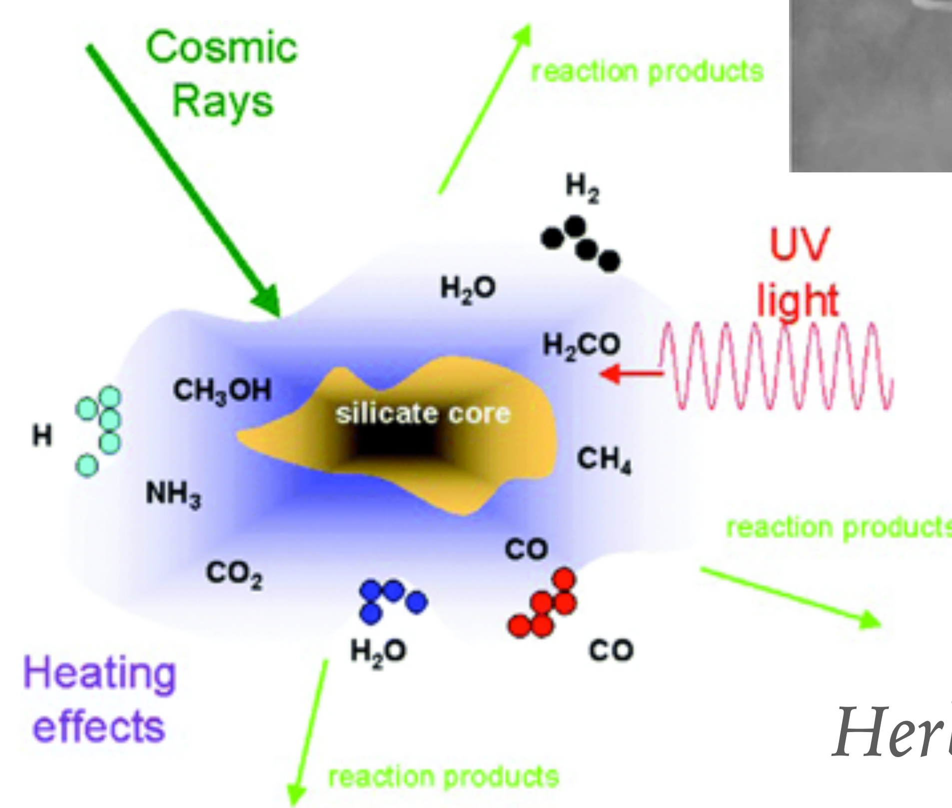
EMISSION PROCESSES IN SPACE OBSERVABLE IN THE CM-SUBMM REGIME

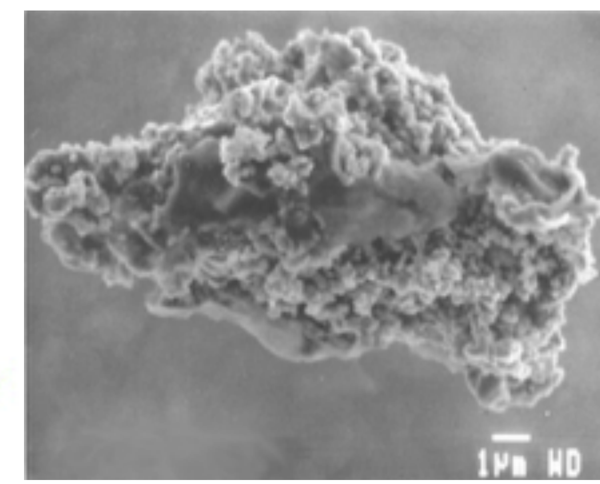
- synchrotron emission
- bremsstrahlung
- thermal emission of heated dust
- cosmic microwave background
- spectral line transitions
  - atomic transitions (electronic, radio recombination lines)
  - molecular transitions (rotational, vibrational states)
  - molecular masers (population inversion)
  - electronic nuclear spin transitions (21cm line of Hydrogen)

DUST GRAINS: EXTINCTION AND SURFACE FOR CHEMISTRY

- Dust is very effective at absorbing and scattering high frequency photons, prohibiting to measure signals from the dense regions at optical wavelengths
- Radio to FIR frequencies are free of dust extinction
- Dust grain surfaces are important for complex chemistry:
  - Also most of molecular hydrogen formed on grains (in cold temperatures)





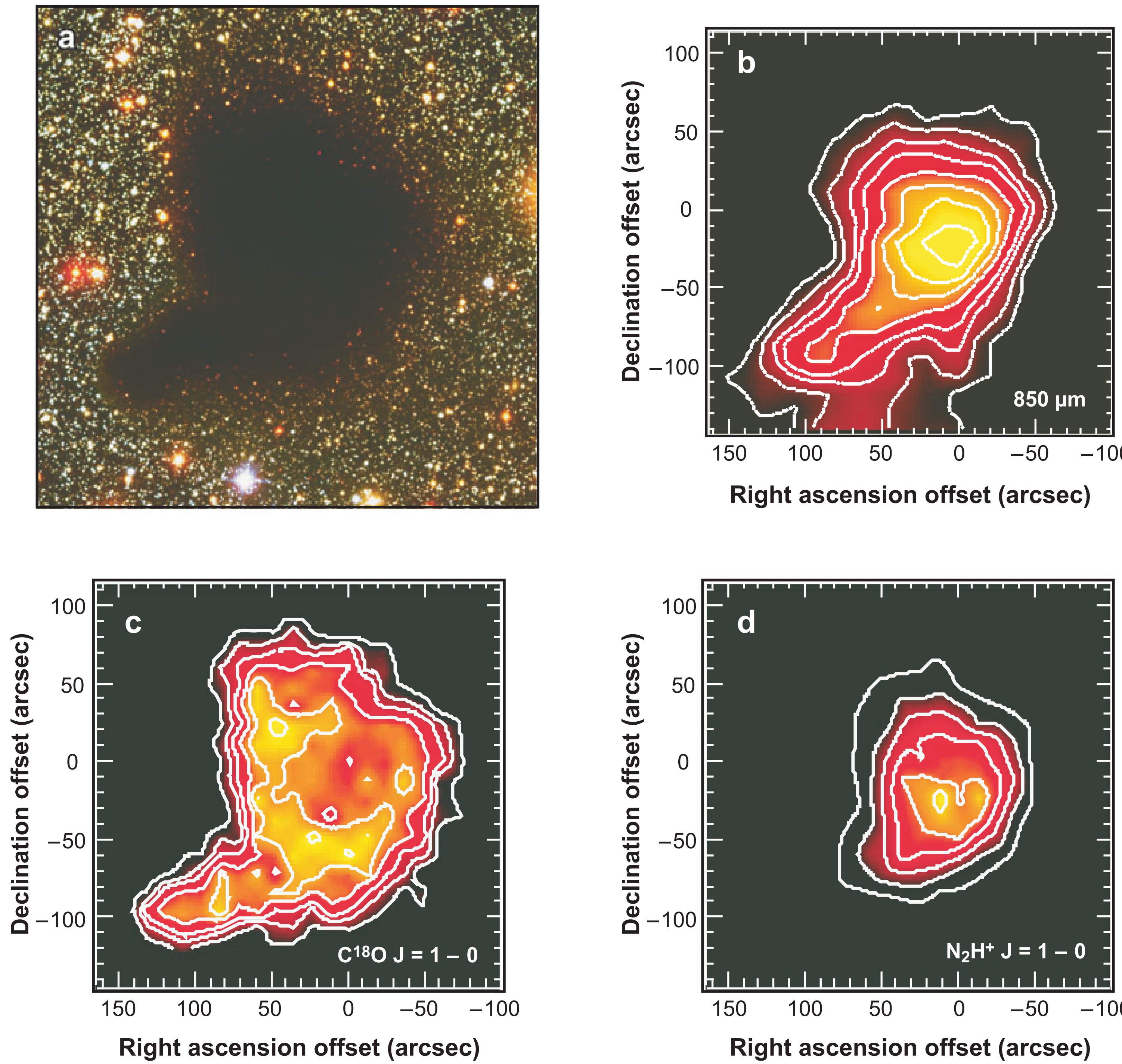


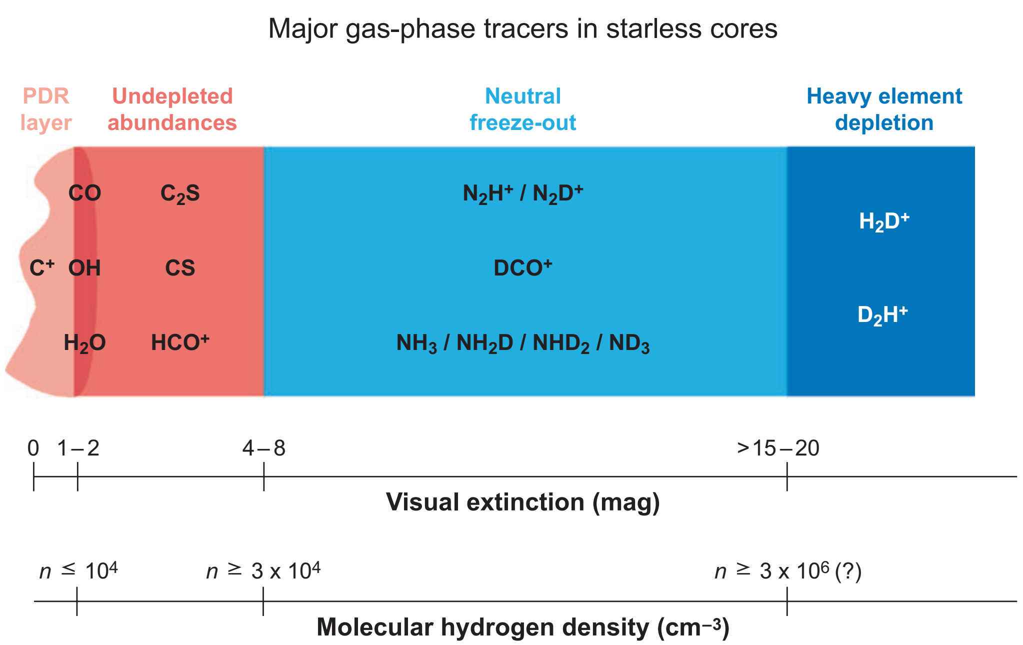
Herbst 2013

EXTINCTION BY DUST DOES NOT AFFECT RADIO & SUBMM

optical/NIR

Radio-mm spectral lines are thus ideal probes for the kinematics, temperatures and densities of dense regions with dust extinction





Star-forming regin Barnard 68, Bergin & Tafalla 2007

MOLECULES IN THE MILKY WAY (AS OF APRIL 2016 IN CDMS)

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	>12 atom
H_2	C_3 *	c-C_3H	C_5 *	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	c-C_6H_6 *	$HC_{11}N$
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN	$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	n-C_3H_7CN	C_{60} *
AlCl	C_2O	C_3N	C_4Si	C_2H_4*	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	i-C_3H_7CN	C_{70} *
C_2**	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO	$CH_3OC(O)CH_3$	$C_2H_5OCH_3$?	C_{60}^+ *
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	CH_3CHO	C_6H_2	HC_7N				
CH^+	HCN	C_2H_2*	H_2CCN	CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H				
CN	HCO	NH_3	CH_4 *	CH_3SH	c-C_2H_4O	l-HC_6H *	$CH_3C(O)NH_2$				
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	H_2CCHOH	CH_2CHCHO (?)	C_8H^-				
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO	C_6H^-	CH_2CCHCN	C_3H_6				
CP	HOC^+	HNCO	HCOOH	NH_2CHO	CH_3NCO 2015	H_2NCH_2CN	CH_3CH_2SH (?)				
SiC	H_2O	HNCS	H_2CNH	C_5N		CH_3CHNH					
HCl	H_2S	$HOCO^+$	H_2C_2O	l-HC_4H *							
KCl	HNC	H_2CO	H_2NCN	l-HC_4N							
NH	HNO	H_2CN	HNC_3	c-H_2C_3O							
NO	MgCN	H_2CS	SiH_4 *	H_2CCNH (?)							
NS	MgNC	H_3O^+	H_2COH^+	C_5N^-							
NaCl	N_2H^+	c-SiC_3	C_4H^-	HNCHCN							
OH	N_2O	CH_3 *	HC(O)CN								
PN	NaCN	C_3N^-	HNCNH								
SO	OCS	PH_3	CH_3O								
SO^+	SO_2	HCNO	NH_4^+								
SiN	c-SiC_2	HOCN	H_2NCO^+ (?)								
SiO	CO_2 *	HSCN	$NCCNH^+$ 2015								
SiS	NH_2	H_2O_2									
CS	H_3^+ (*)	C_3H^+									
HF	SiCN	HMgNC									
HD	AlNC	HCCO 2015									
FeO ?	SiNC										

(continued)

2 atoms	3 atoms
O_2	HCP
CF^+	CCP
SiH ?	AlOH
PO	H_2O^+
AlO	H_2Cl^+
OH^+	KCN
CN^-	FeCN
SH^+	HO_2
SH	TiO_2
HCl^+	C_2N
TiO	Si_2C 2015
ArH^+	
NO^+ ?	

Source: CDMS, https://www.astro.uni-koeln.de/cdms/molecules

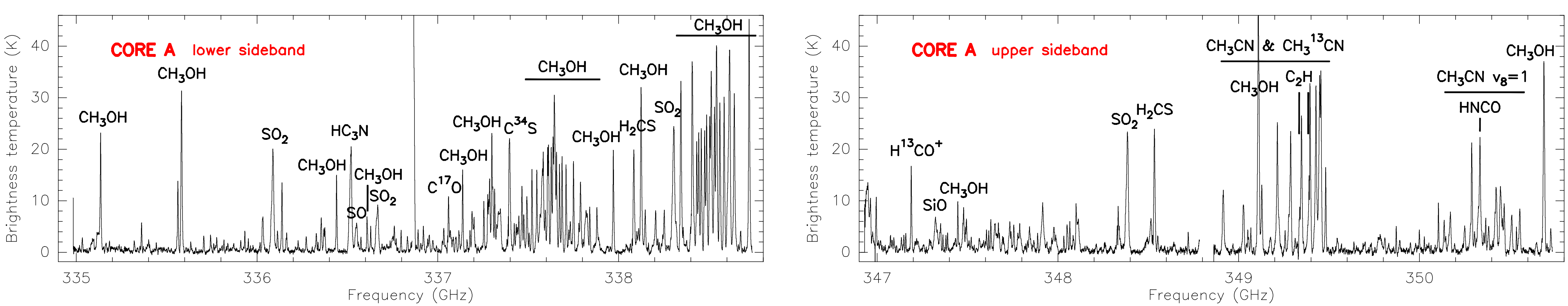
EXTRAGALACTIC MOLECULES (APRIL 2016, CDMS)

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	>8 atoms
OH	H_2O	H_2CO	*c*-C_3H_2	CH_3OH	CH_3CCH	HC_6H	*c*-C_6H_6 *
CO	HCN	NH_3	HC_3N	CH_3CN	CH_3NH_2		C_{60}* (?)
H_2 *	HCO^+	HNCO	CH_2NH	HC_4H *	CH_3CHO		
CH	C_2H	C_2H_2 *	NH_2CN	$HC(O)NH_2$			
CS	HNC	H_2CS ?	*l*-C_3H_2				
CH^+ **	N_2H^+	$HOCO^+$	H_2CCN				
CN	OCS	*c*-C_3H	H_2CCO				
SO	HCO	H_3O^+	C_4H				
SiO	H_2S	*l*-C_3H					
CO^+	SO_2						
NO	HOC^+						
NS	C_2S						
NH	H_2O^+						
OH^+	HCS^+						
HF	H_2Cl^+						
SO^+	NH_2						
ArH^+ 2015							
CF^+ 2016							

Source: Cologne Database for Molecular Spectroscopy, https://www.astro.uni-koeln.de/cdms/molecules

LINE RICHNESS

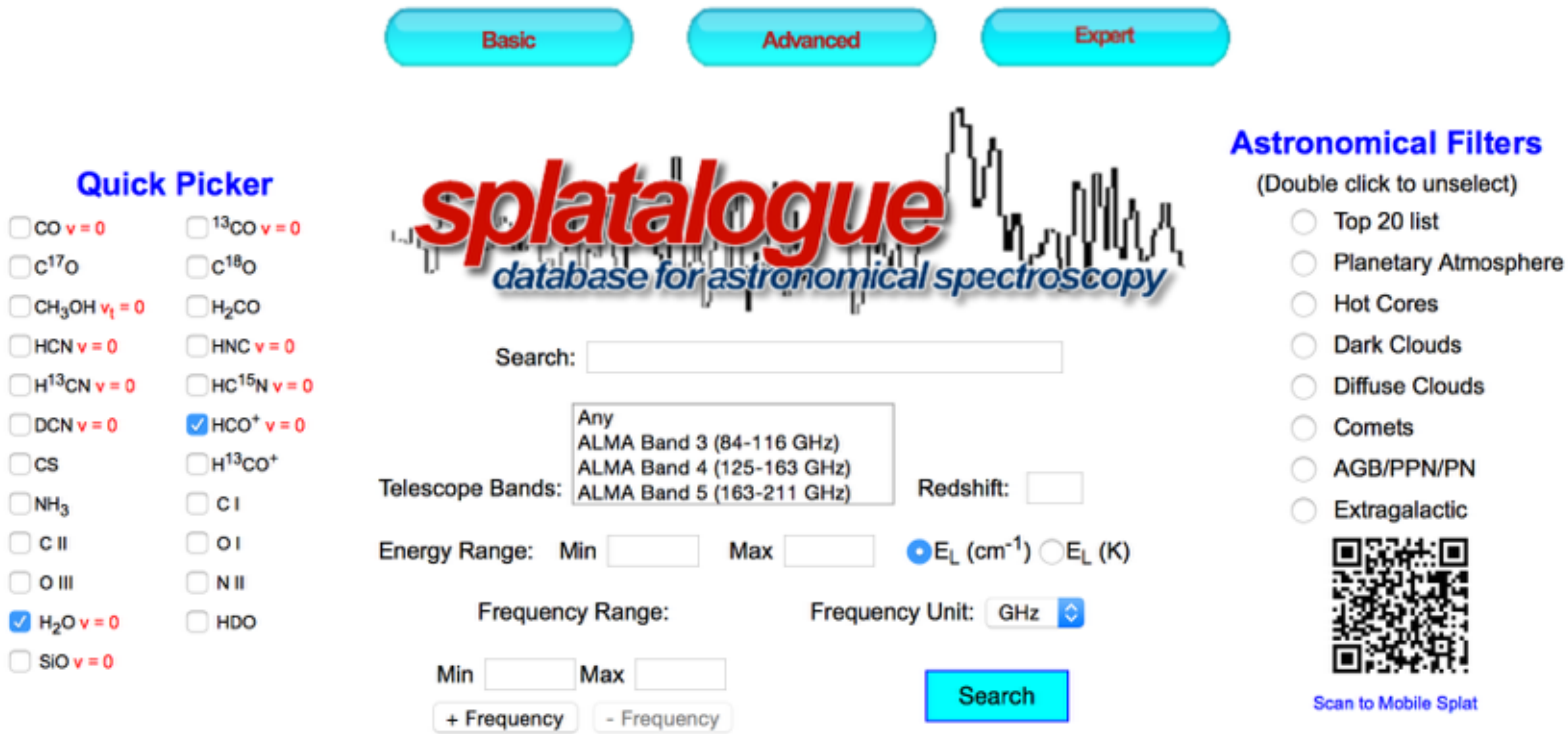
- ALMA observations of a star-forming core show a line forest
- To identify these molecular lines, knowledge of their rest frequencies, and upper (or lower) state energy is extremely important
- Spectral line identification in astronomy thus depends heavily on laboratory experiments



Beltran et al. 2014

SPLATOLOGUE: ONLINE MOLECULAR DATABASE

http://www.cv.nrao.edu/php/splat/



Found 4 lines in ALMA Band 6 (211-275 GHz), showing 1 - 4
Click on the chemical formula below for more information about that species.

$$h\nu = E_U - E_L$$

	Species	Chemical Name	Ordered Freq (GHz) (rest frame, redshifted)	Resolved QNs	CDMS/JPL Intensity	Lovas/AST Intensity	E_L (cm^{-1})	E_L (K)	Linelist
1	H_2O v=0	Water	247.44010, 247.44010	14(4,10) - 15(3,13)	-9.00970		2872.5806	4133.0296	JPL
2	H_2O v=0	Water	259.95218, 259.95218	13(6,8) - 14(3,11)	-8.66900		2739.4286	3941.4523	JPL
3	H_2O v=0	Water	266.57410, 266.57410	21(4,17) - 20(7,14)	-14.10890		5739.2279	8257.5225	JPL
4	HCO^+ v=0	Formylium	267.55763, 267.55763	3- 2	-0.85420	12.	8.9250	12.8410	CDMS

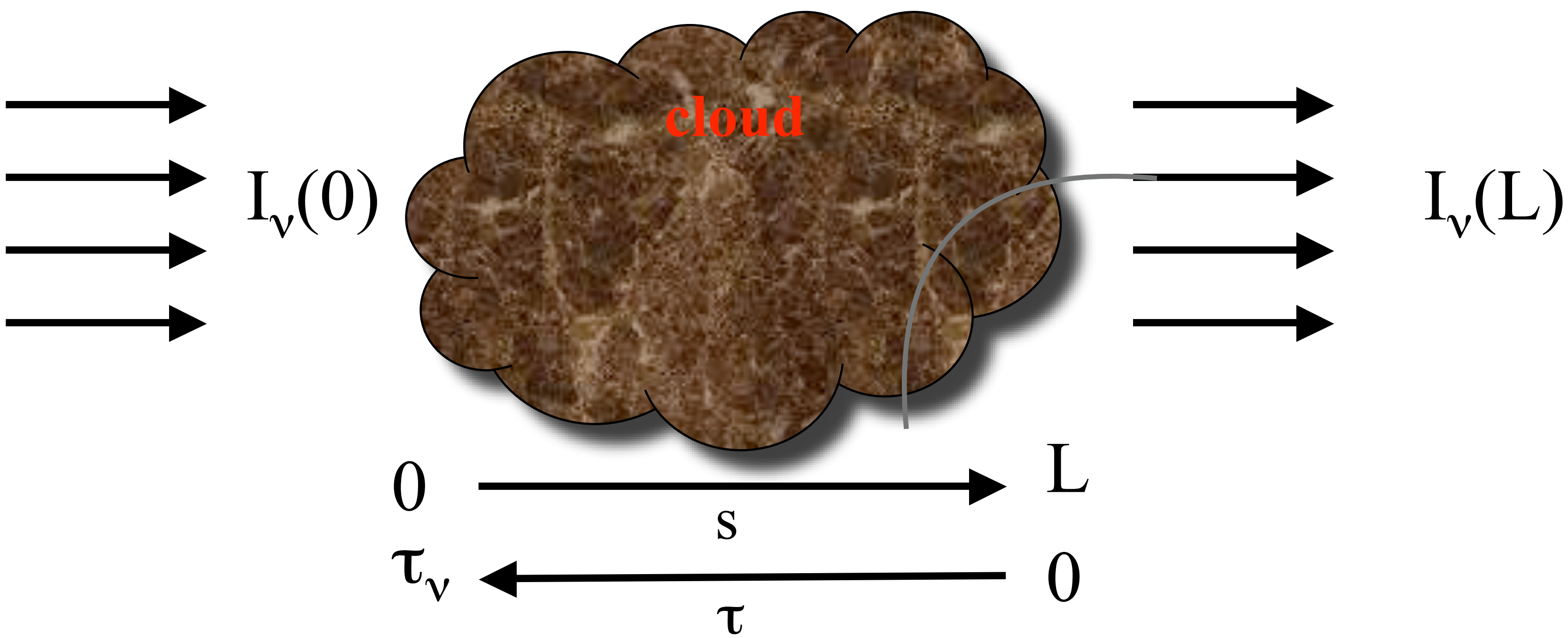
Found 4 lines in ALMA Band 6 (211-275 GHz), showing 1 - 4

RADIATIVE TRANSPORT

$$I_\nu = I_\nu(0)\exp(-\tau_\nu) + B_\nu(T_{ex})(1-\exp(-\tau_\nu))$$

absorption *emission, Planck radiation*

$$\frac{2h\nu^3}{c^2}\frac{1}{(\exp(h\nu/KT)-1)}$$



At radio-submm frequencies (hν/kT is small) the measured brightness temperature with the radio antenna can be approximated by

$$\tau_\nu \propto N/T$$

$$T_A = \underbrace{(T_{ex} - T_{bg})}_{T}(1-\exp(-\tau_\nu))$$

$\tau_\nu < 1$ *optically thin: measure column density:* $T_A \sim T\tau_\nu$

$\tau_\nu > 1$ *optically thick: measure temperature* $T_A \sim T$

MOLECULAR SPECTROSCOPY

Typical medium Temperature

Critical density proportional to A

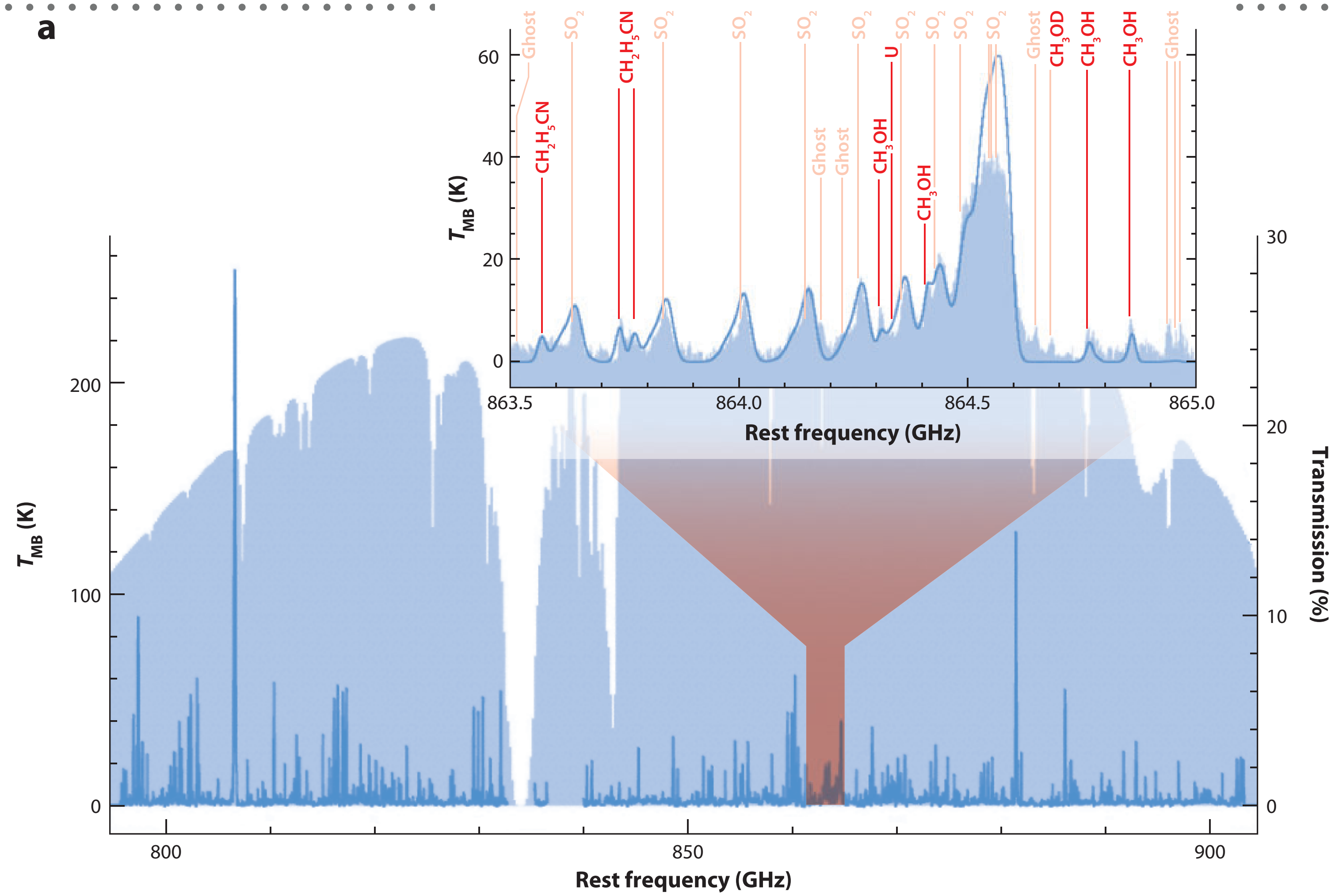
Table 2. Parameters of the commonly observed short cm/mm molecular lines

Chemical[a] formula	Molecule name	Transition	ν/GHz	E_u/K[b]	A_{ij}/s^{-1} [c]
H_2O	ortho-water*	$J_{K_a K_c} = 6_{16} - 5_{23}$	22.235253	640	1.9×10^{-9}
NH_3	para-ammonia	$(J, K) = (1,1) - (1,1)$	23.694506	23	1.7×10^{-7}
NH_3	para-ammonia	$(J, K) = (2,2) - (2,2)$	23.722634	64	2.2×10^{-7}
NH_3	ortho-ammonia	$(J, K) = (3,3) - (3,3)$	23.870130	122	2.5×10^{-7}
SiO	silicon monoxide*	$J = 1 - 0, v = 2$	42.820587	3512	3.0×10^{-6}
SiO	silicon monoxide*	$J = 1 - 0, v = 1$	43.122080	1770	3.0×10^{-6}
SiO	silicon monoxide	$J = 1 - 0, v = 0$	43.423858	2.1	3.0×10^{-6}
CS	carbon monosulfide	$J = 1 - 0$	48.990964	2.4	1.8×10^{-6}
DCO^+	deuterated formylium	$J = 1 - 0$	72.039331	3.5	2.2×10^{-5}
SiO	silicon monoxide*	$J = 2 - 1, v = 2$	85.640456	3516	2.0×10^{-5}
SiO	silicon monoxide*	$J = 2 - 1, v = 1$	86.243442	1774	2.0×10^{-5}
$H^{13}CO^+$	formylium	$J = 1 - 0$	86.754294	4.2	3.9×10^{-5}
SiO	silicon monoxide	$J = 2 - 1, v = 0$	86.846998	6.2	2.0×10^{-5}
HCN	hydrogen cyanide	$J = 1 - 0, F = 2 - 1$	88.631847	4.3	2.4×10^{-5}
HCO^+	formylium	$J = 1 - 0$	89.188518	4.3	4.2×10^{-5}
HNC	hydrogen isocyanide	$J = 1 - 0, F = 2 - 1$	90.663574	4.3	2.7×10^{-5}
N_2H^+	diazenylium	$J = 1 - 0, F_1 = 2 - 1, F = 3 - 2$	93.173809	4.3	3.8×10^{-5}
CS	carbon monosulfide	$J = 2 - 1$	97.980968	7.1	2.2×10^{-5}
$C^{18}O$	carbon monoxide	$J = 1 - 0$	109.782182	5.3	6.5×10^{-8}
^{13}CO	carbon monoxide	$J = 1 - 0$	110.201370	5.3	6.5×10^{-8}
CO	carbon monoxide	$J = 1 - 0$	115.271203	5.5	7.4×10^{-8}
$H_2{}^{13}CO$	ortho-formaldehyde	$J_{K_a K_c} = 2_{12} - 1_{11}$	137.449959	22	5.3×10^{-5}
H_2CO	ortho-formaldehyde	$J_{K_a K_c} = 2_{12} - 1_{11}$	140.839518	22	5.3×10^{-5}
CS	carbon monosulfide	$J = 3 - 2$	146.969049	14.2	6.1×10^{-5}
$C^{18}O$	carbon monoxide	$J = 2 - 1$	219.560319	15.9	6.2×10^{-7}
^{13}CO	carbon monoxide	$J = 2 - 1$	220.398714	15.9	6.2×10^{-7}
CO	carbon monoxide	$J = 2 - 1$	230.538001	16.6	7.1×10^{-7}
CS	carbon monosulfide	$J = 5 - 4$	244.935606	33.9	3.0×10^{-4}
HCN	hydrogen cyanide	$J = 3 - 2$	265.886432	25.5	8.5×10^{-4}
HCO^+	formylium	$J = 3 - 2$	267.557625	25.7	1.4×10^{-3}
HNC	hydrogen isocyanide	$J = 3 - 2$	271.981067	26.1	9.2×10^{-4}

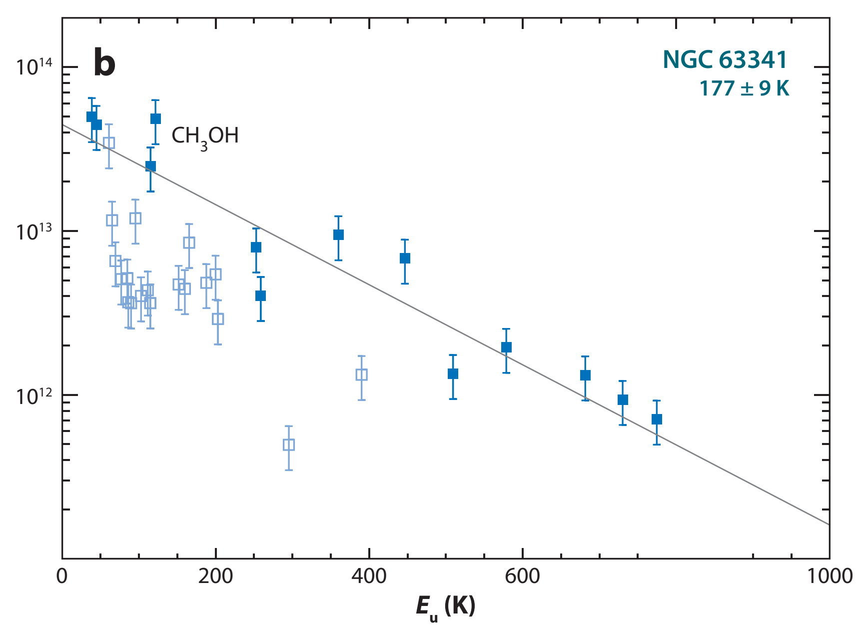
Choose molecular species depending on n, T of gas you want to probe. Also must consider expected strength of line, depends on intrinsic strength (prop to A) + chemical abundance. Must be strong enough to detect, but may want to avoid being optically thick

n> ncrit - collision dominated and the excitation temperature will close to the kinetic temperature of the gas

PHYSICAL PROPERTIES FROM MOLECULAR LINES



Ncol



Rotational diagram method:

using several level populations under the assumption that they all come from the same region, are characterized by one temperature and are optically thin allow to obtain the temperature and column density simultaneously

Herbst & van Dishoek 2009

COMPARE WITH CHEMICAL MODELS

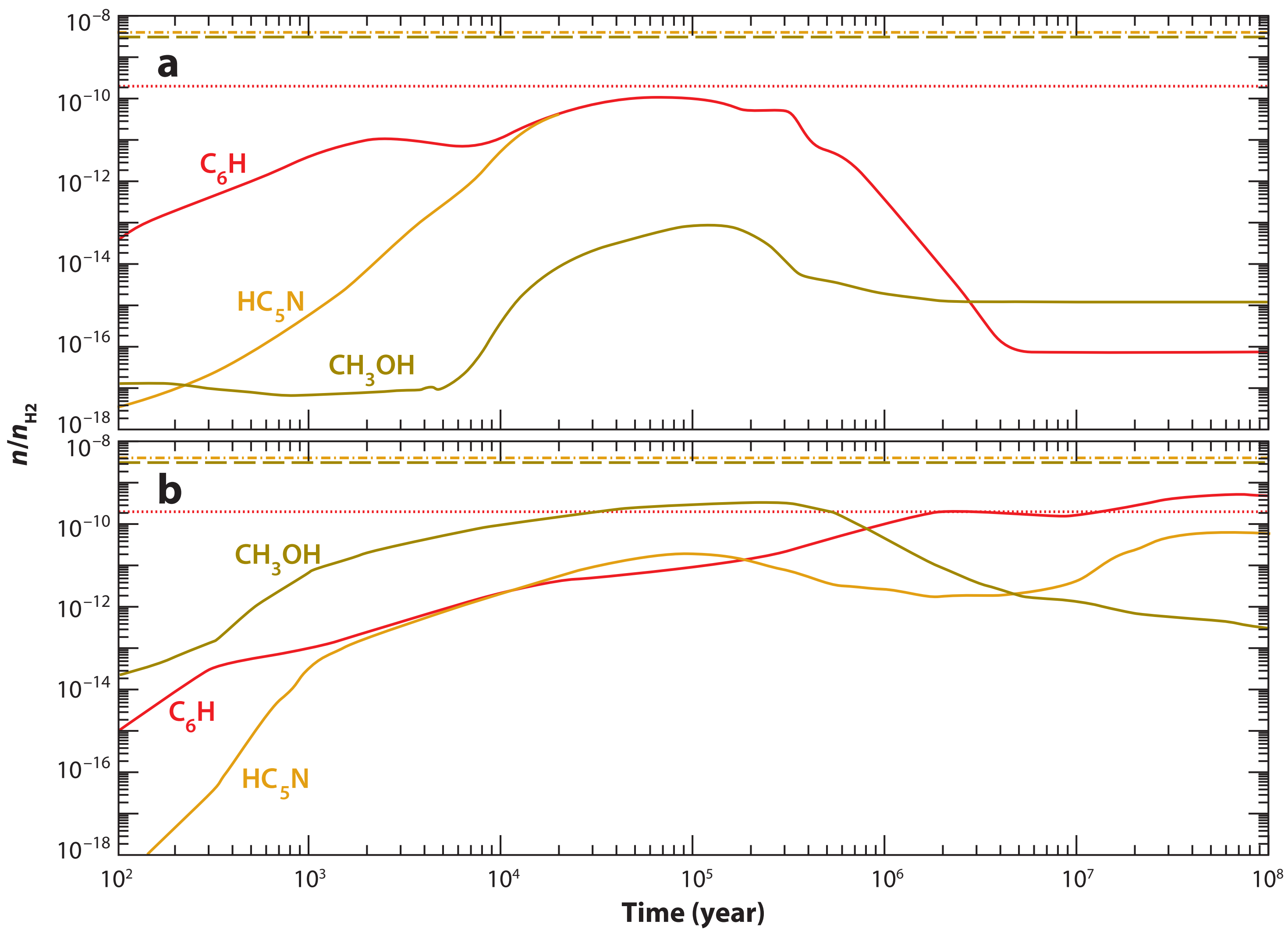


Figure 11

Comparison of fractional abundances calculated with gas-phase (*a*) and gas-grain (*b*) models for a cold core with oxygen-rich abundances (C/O = 0.4). The Ohio State networks were used without anions. The model parameters are $T = 10$ K, $n_H = 2 \times 10^4$ cm^{-3}, and the cosmic ray ionization rate per H_2 molecule of $\zeta = 1.3 \times 10^{-17}$ s^{-1}. Horizontal lines represent observed species in TMC-1. Provided by D. Quan.

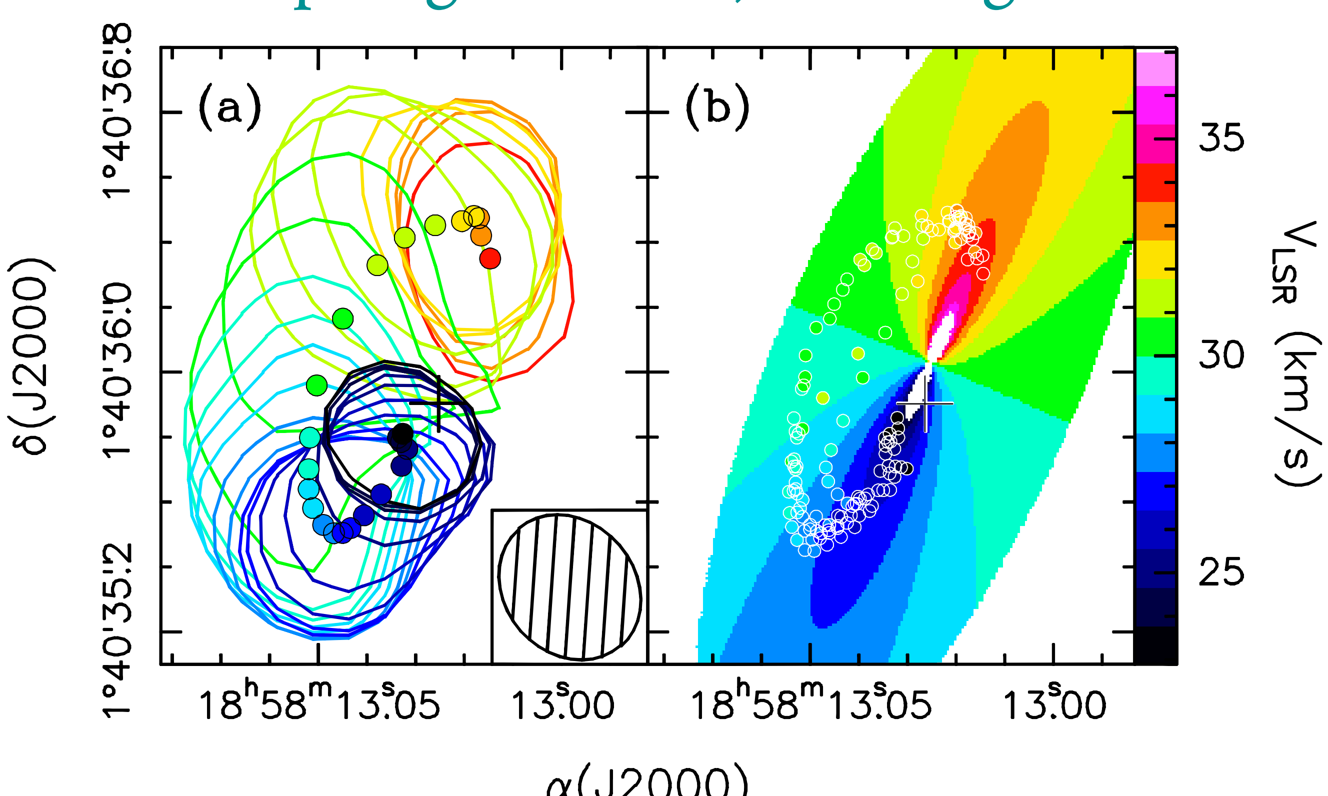
Measurements of molecular lines, especially if more transitions or species are involved can than be compared with chemical models (formation pathways) that predict abundances.

Herbst & van Dishoek 2009

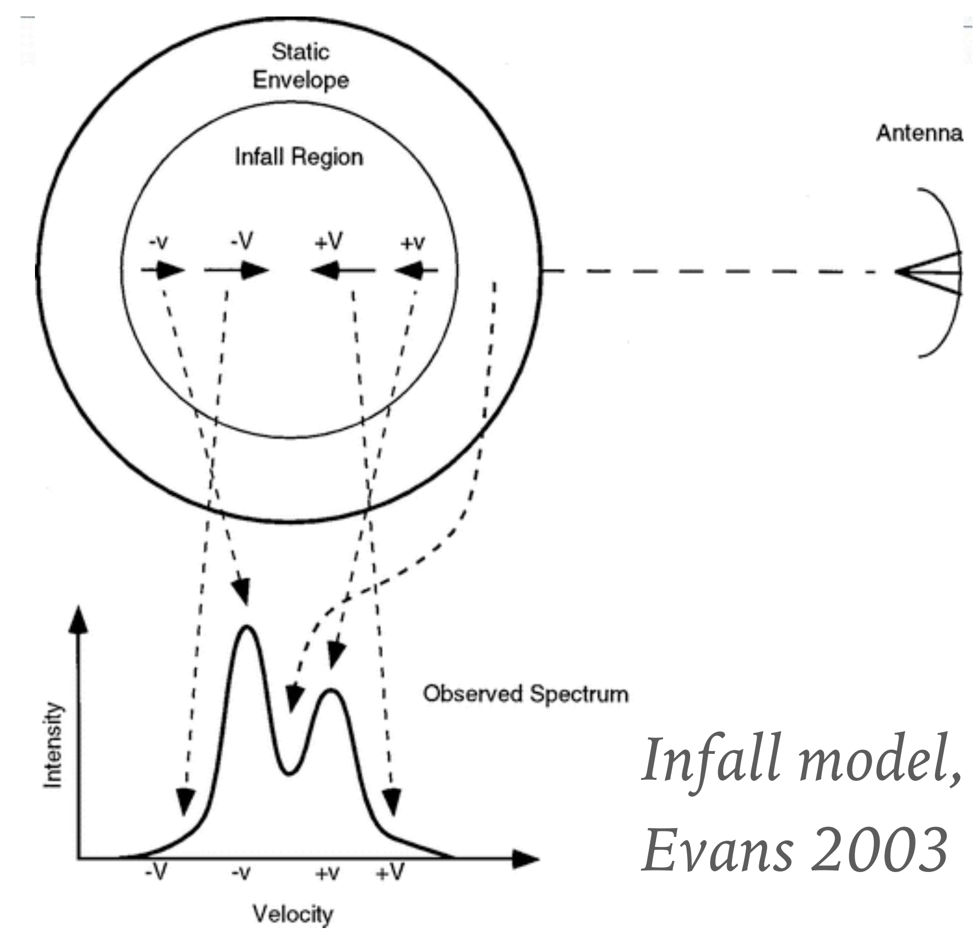
KINEMATICS FROM DOPPLER SHIFTS OF LINES

$$\frac{\Delta\nu}{\nu_0} = \frac{\Delta\lambda}{\lambda_0} = \frac{\Delta v}{c}$$

- redshift of the galaxy
- Rotational curves of Galaxies
- In our own Milky Way, most of the distances are based on their spectral line velocity under the assumption of a rotational model
- Collapsing motions, rotating disks around stars



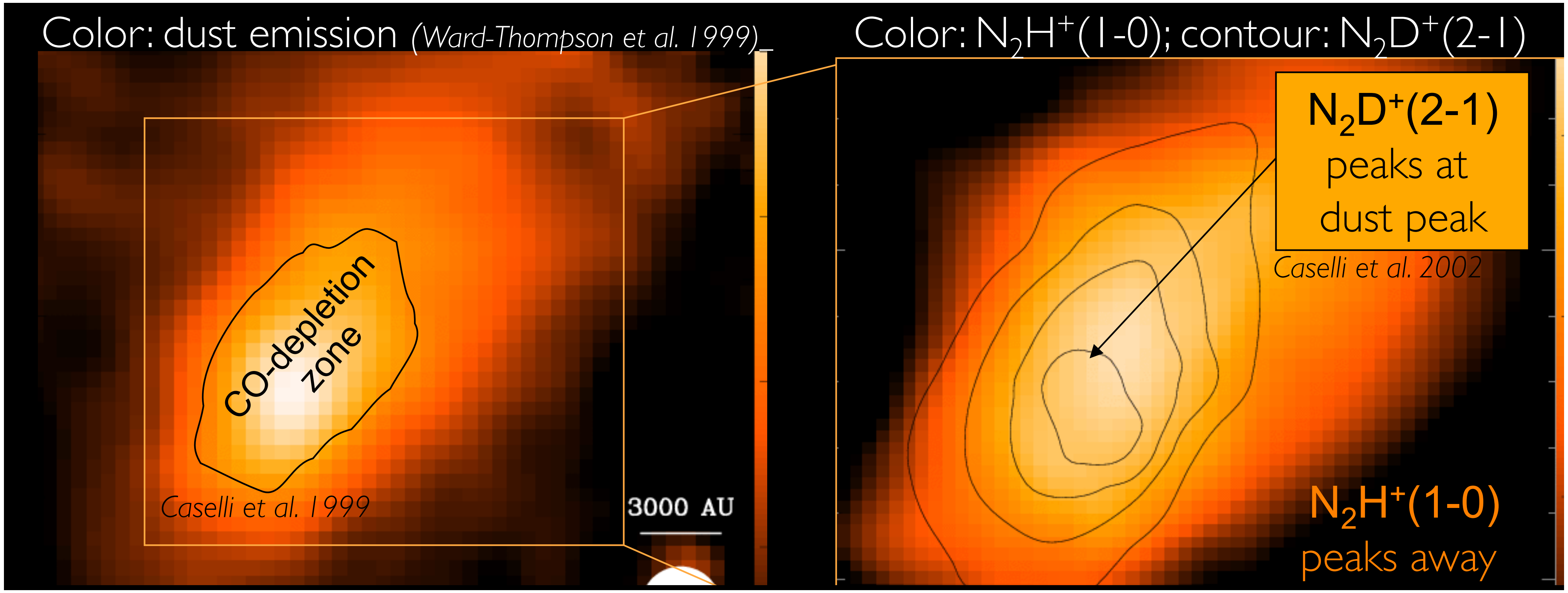
Rotating disk of high-mass protostar in CH_3CN, Sanchez-Monge et al. 2013



Infall model, Evans 2003

VERY COLD CHEMISTRY: DEPLETION & DEUTERATION

- To study the prestellar cores, which centers are very cold <10K and dense ($>10^5$ cm^{-3}) one need to resort to deuterated molecules because common C-bearing molecules will be depleted

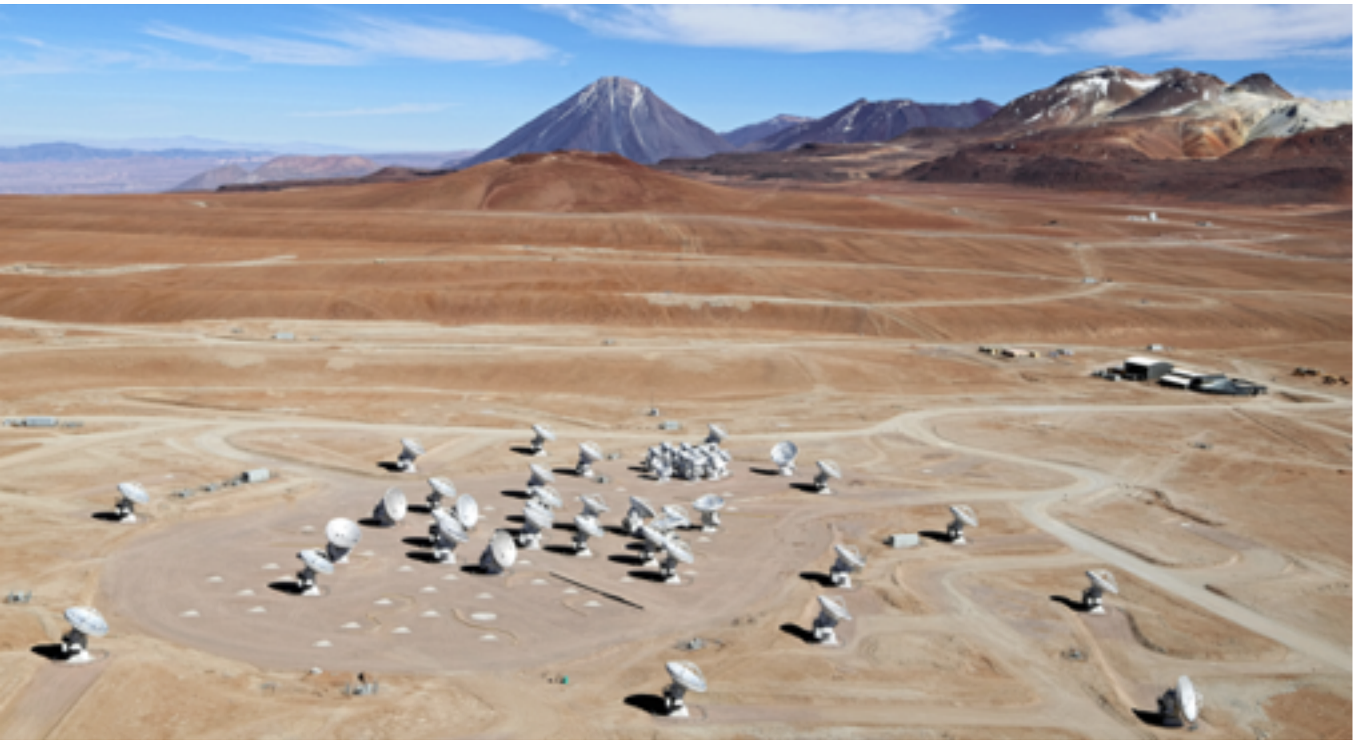


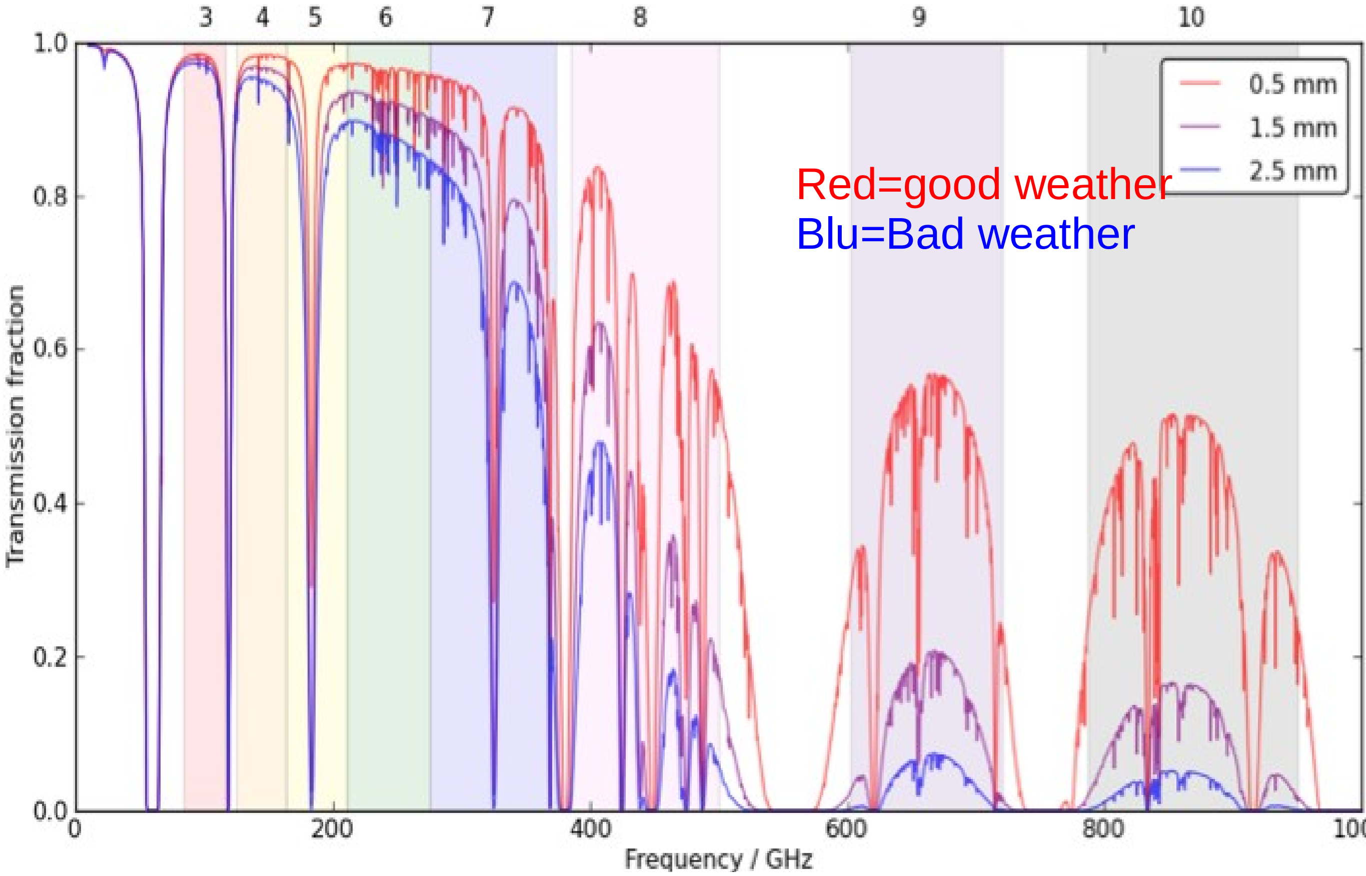
From Ceccarelli & Caselli, PPVI

THE ALMA INTERFEROMETER

ALMA

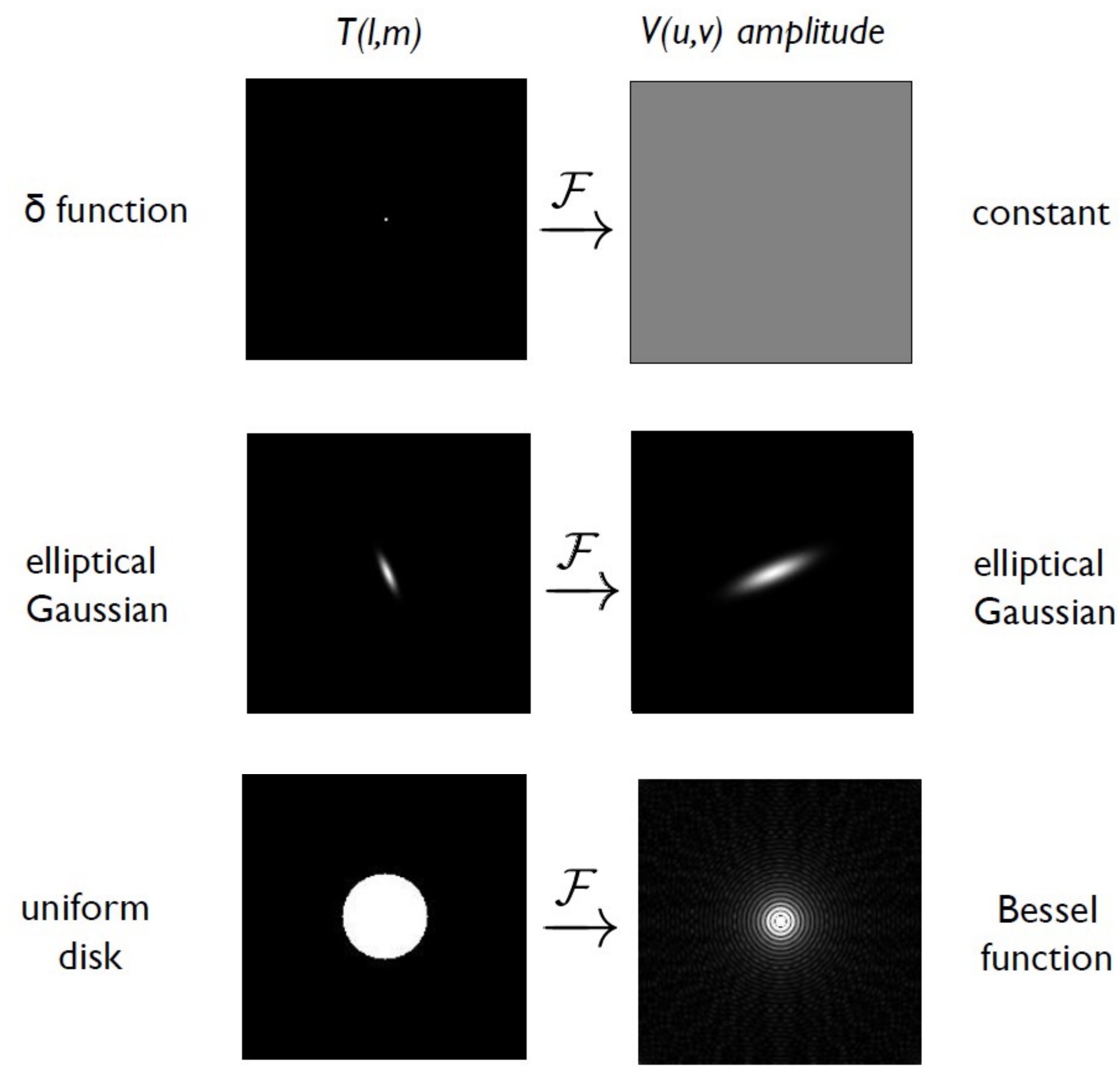
- high sensitivity in radio-submm regime
- located at the driest site on Earth: the Chilean Atacama desert





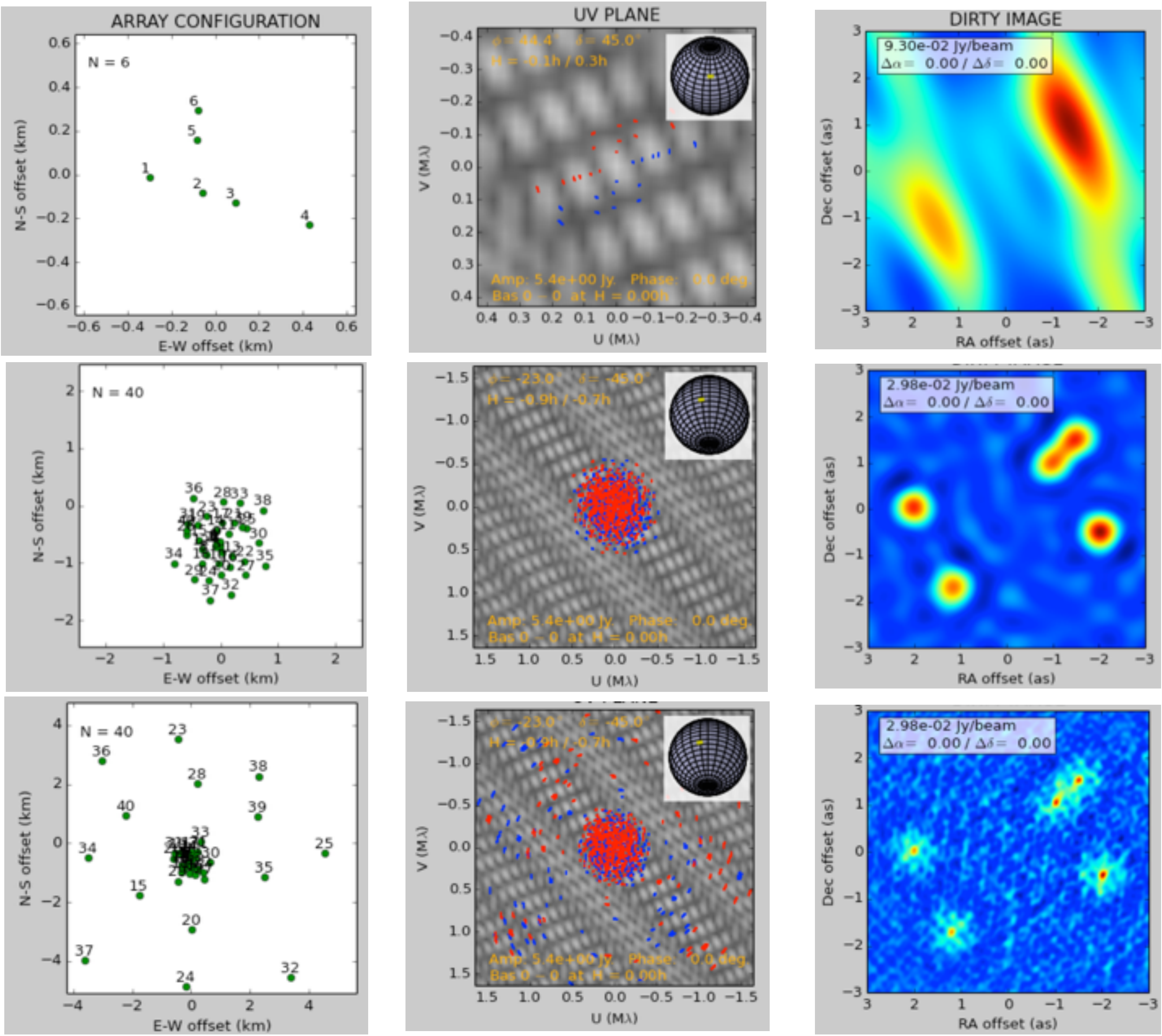
APERTURE SYNTHESIS

- An interferometer measures per each antenna pair (baseline) the source brightness distribution (visibility) at the spatial scale to which the baseline is sensitive.
- With a sufficient number of visibilities measured, one can reconstruct an image by Fourier inversion.
- The interferometer is filters out emission from structures bigger than the shortest baseline and cannot recover structures smaller than then the longest baseline



Images: APSYNSIM

EXAMPLE: OBSERVING 5 GAUSSIANS WITH



with 6 antennas
20min

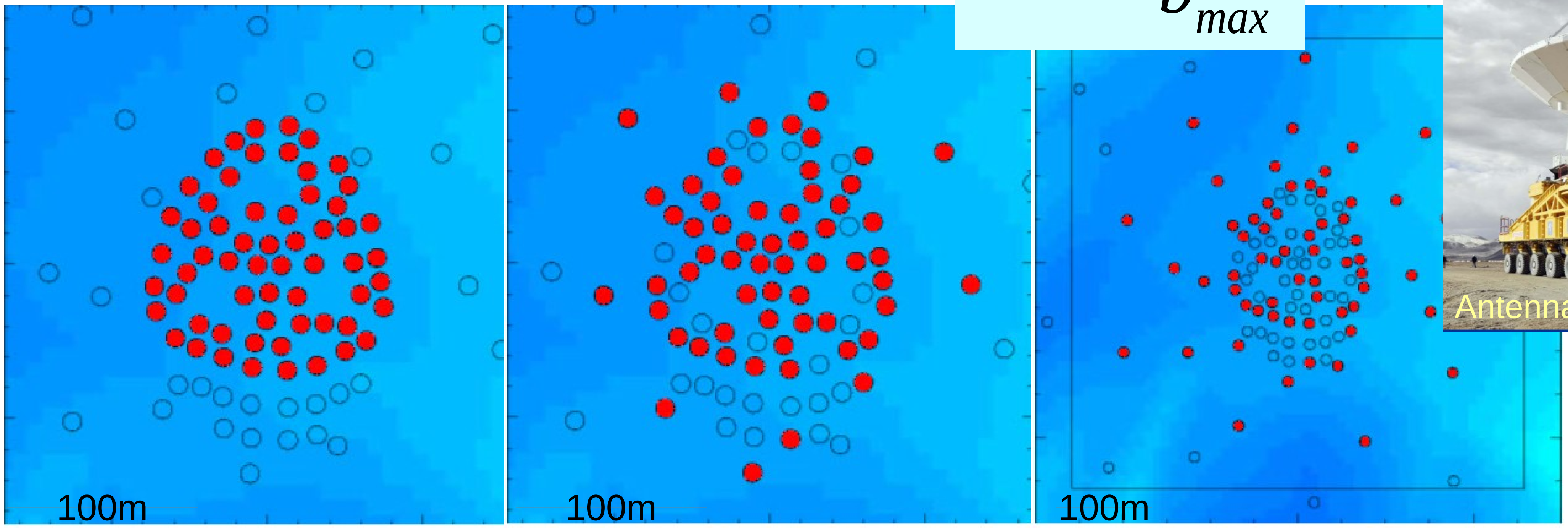
ALMA 12m array
baseline to ~2km
20min

ALMA 12m array,
baselines to ~8km
20min

ALMA: HIGH RESOLUTION IMAGING

- antennas are movable, allowing to change the angular resolution, which is proportional to the inverse of the antenna separation, baseline

$$\theta_{res} \propto \frac{\lambda}{b_{max}}$$

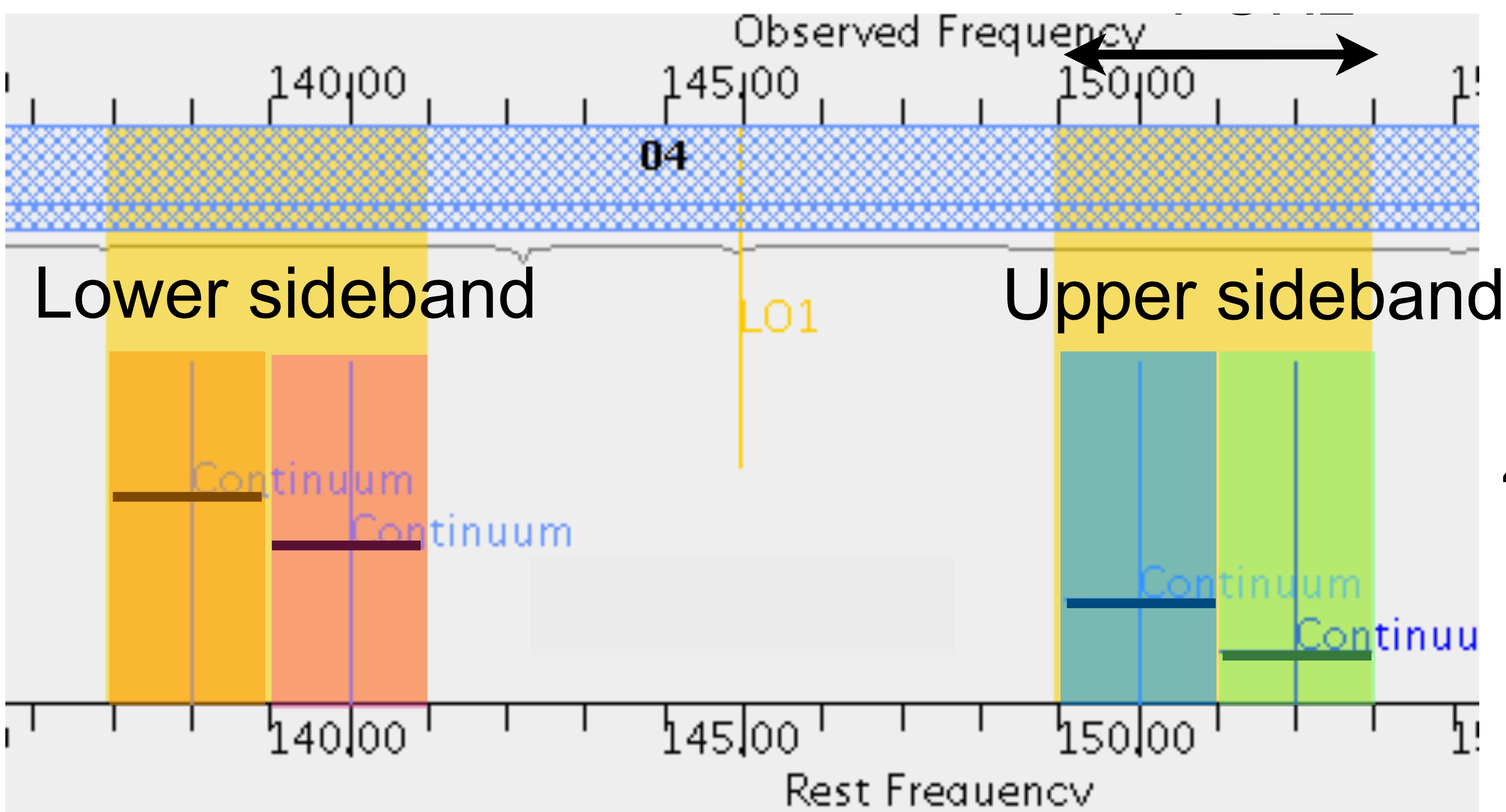


- the largest angular scale measurable with an interferometer depends on the shortest baseline

$$\theta_{max} \propto \frac{\lambda}{b_{min}}$$

ALMA SPECTROSCOPY

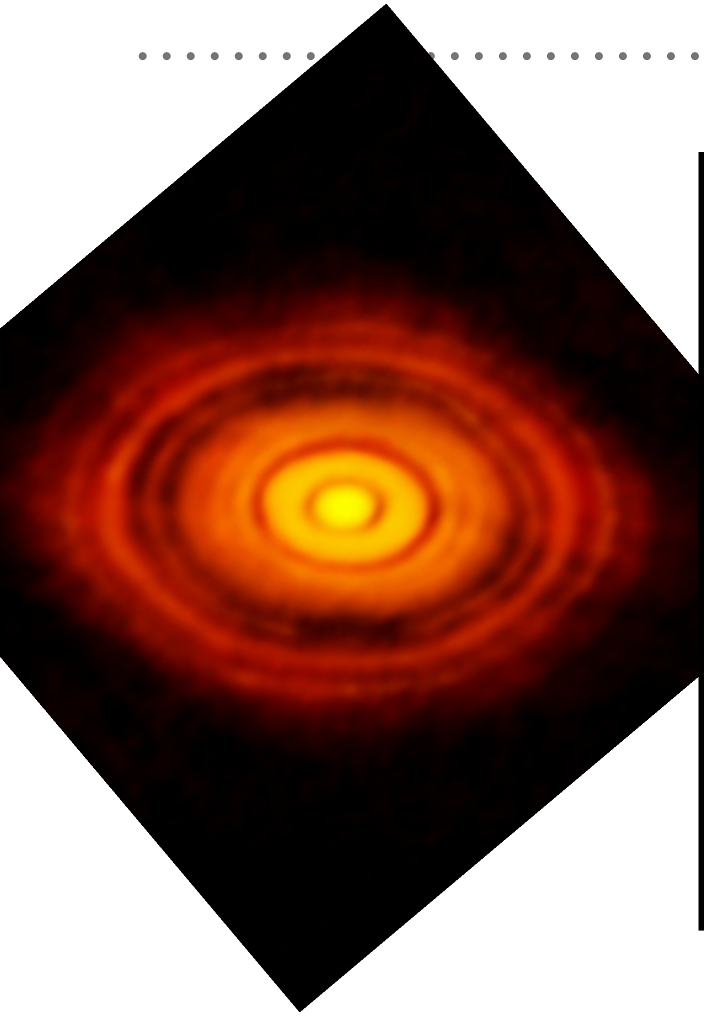
- ALMA will have 10 bands between 30 to 900 GHz
- can have up to 8GHz of instantaneous bandwidth, and allows high spectral resolution (up to 0.03MHz)
- full polarization measurements possible

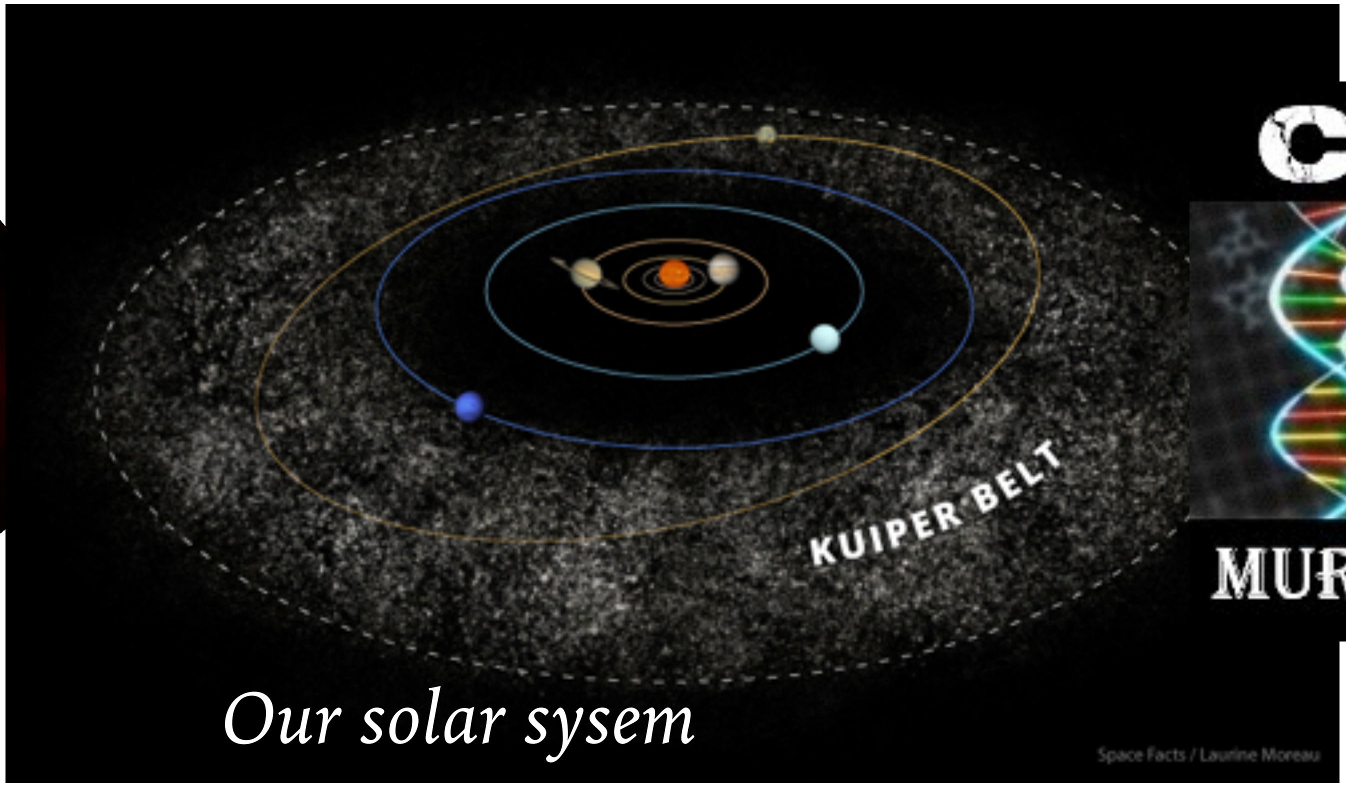


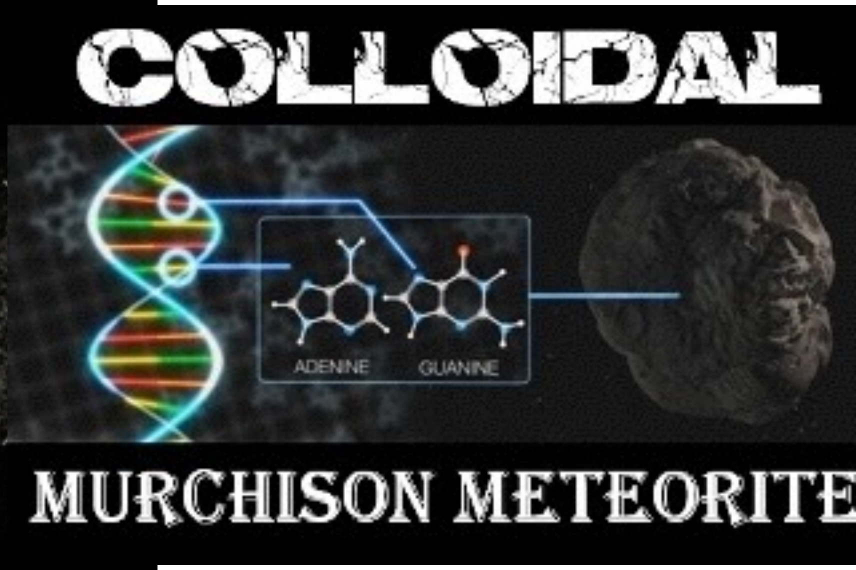
Four available basebands color coded

SCIENCE WITH ALMA

CHEMISTRY WITH ALMA: STAR AND PLANET FORMATION



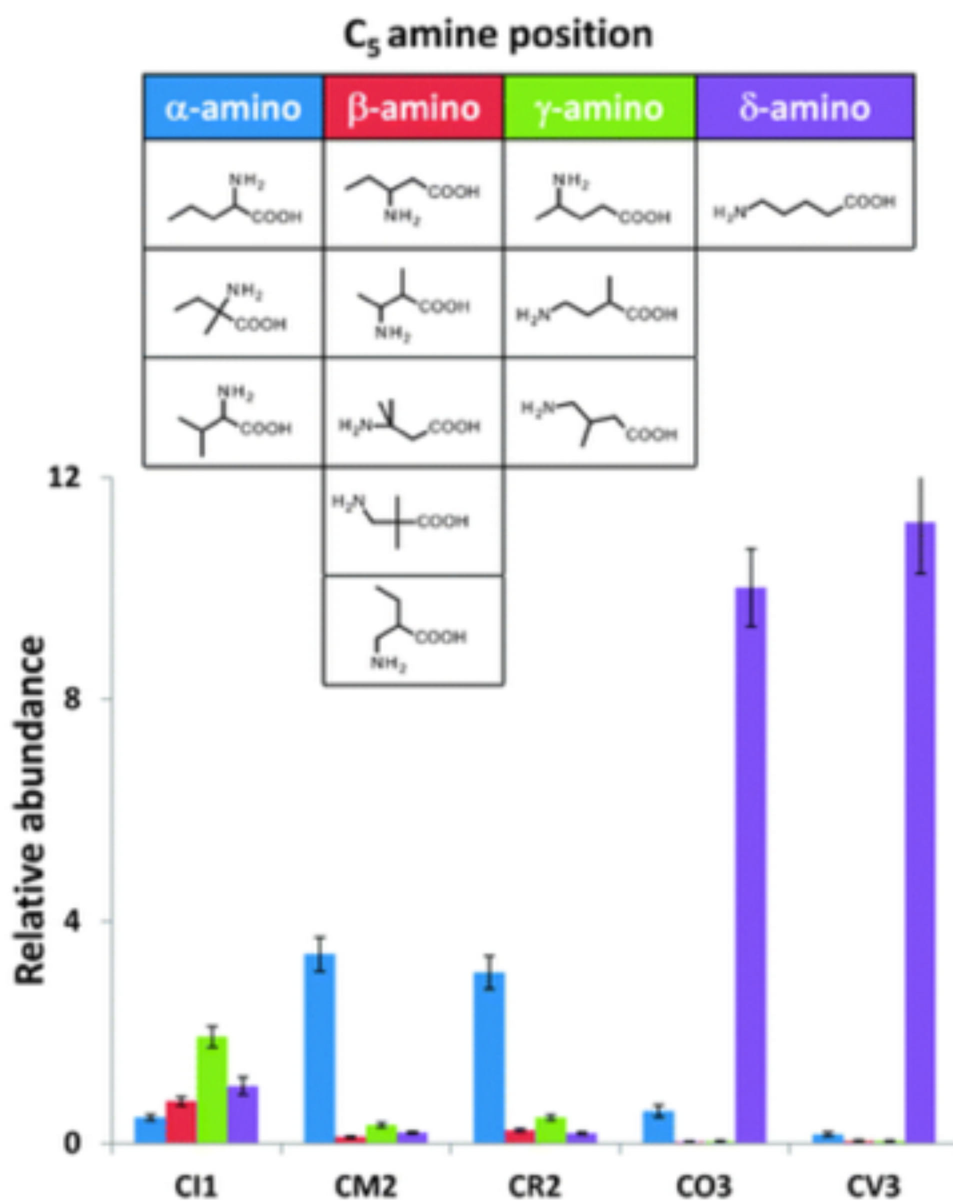




- branched alkyl molecules present in ISM
- cold gas reservoir from ice desorption in protostellar disk
- studying the Titan atmosphere

BRANCHED ALKYL MOLECULES IN ISM

Amino acids have been found in meteorites. It is not known whether the amino acids have been present in the ISM from which the meteorite formed (protostellar disk), or if they formed on the meteoroid/asteroid.

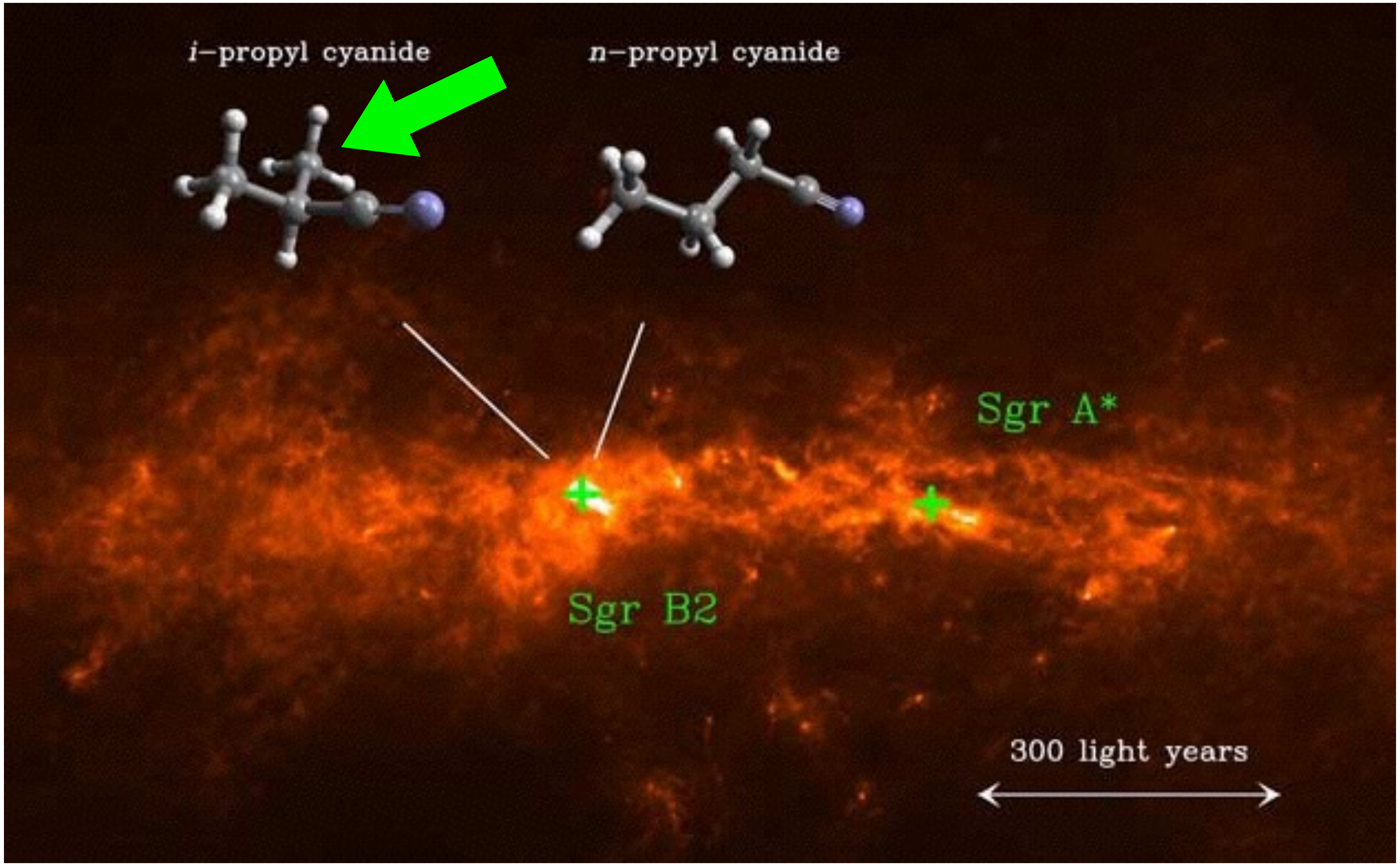


X-axis: various meteorites (Burton et al. 2012)

CM2: Murchinson meteorite

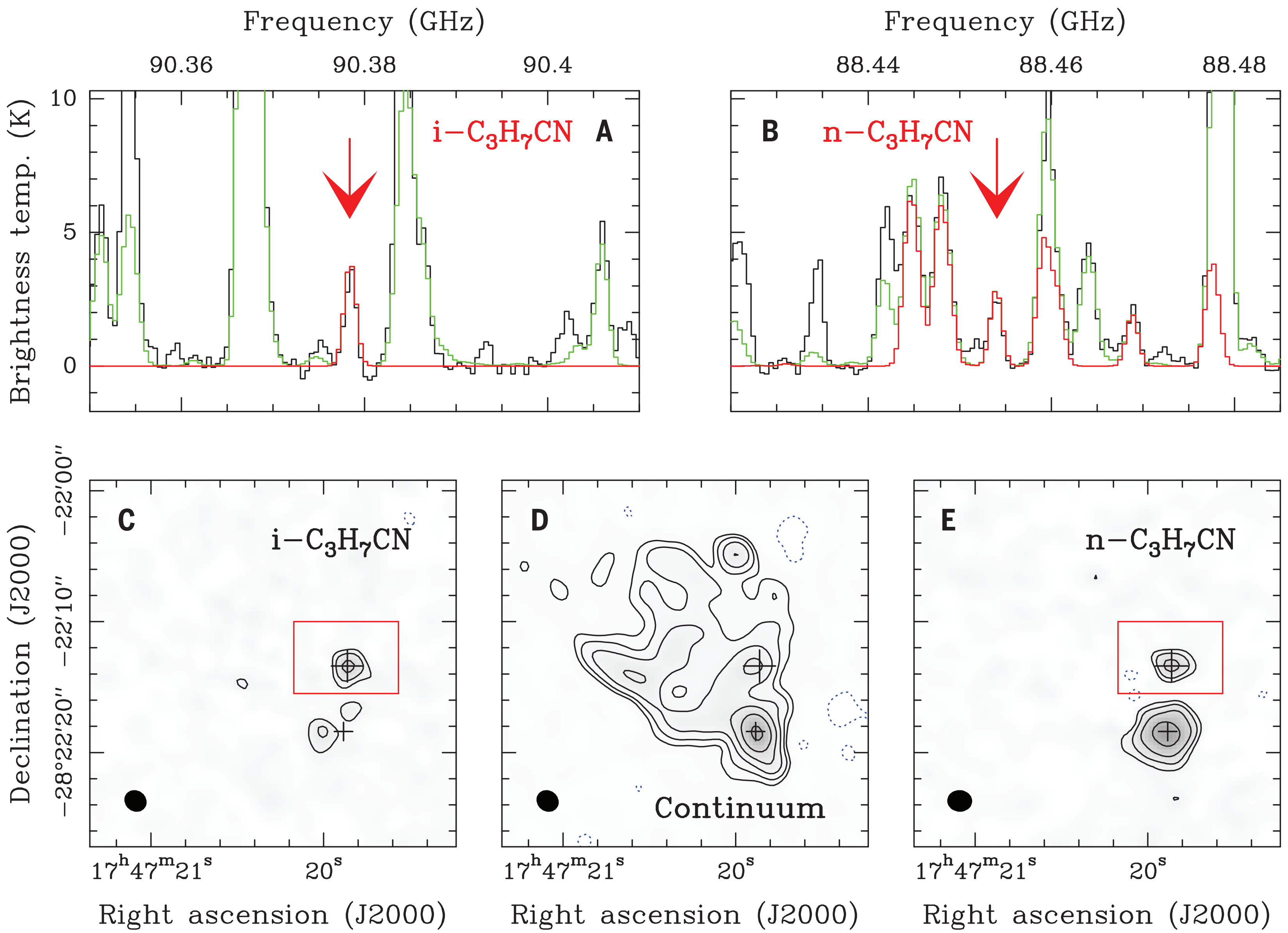
BRANCHED ALKYL MOLECULES WITH ALMA

Branched propyl cyanide detected in Sgr B2 (star-forming region near the Galactic Center) by Belloche et al. (2015). Due to the very high column density of Sgr B2 allowed the detection of this low-abundance species.



BRANCHED ALKYL MOLECULES WITH ALMA

The abundance of i- (branched) and n- (straight chain) propyl cyanide in Sgr B2 is 0.4:1. In meteorites the branched amino acids dominate over their straight chain isomers.

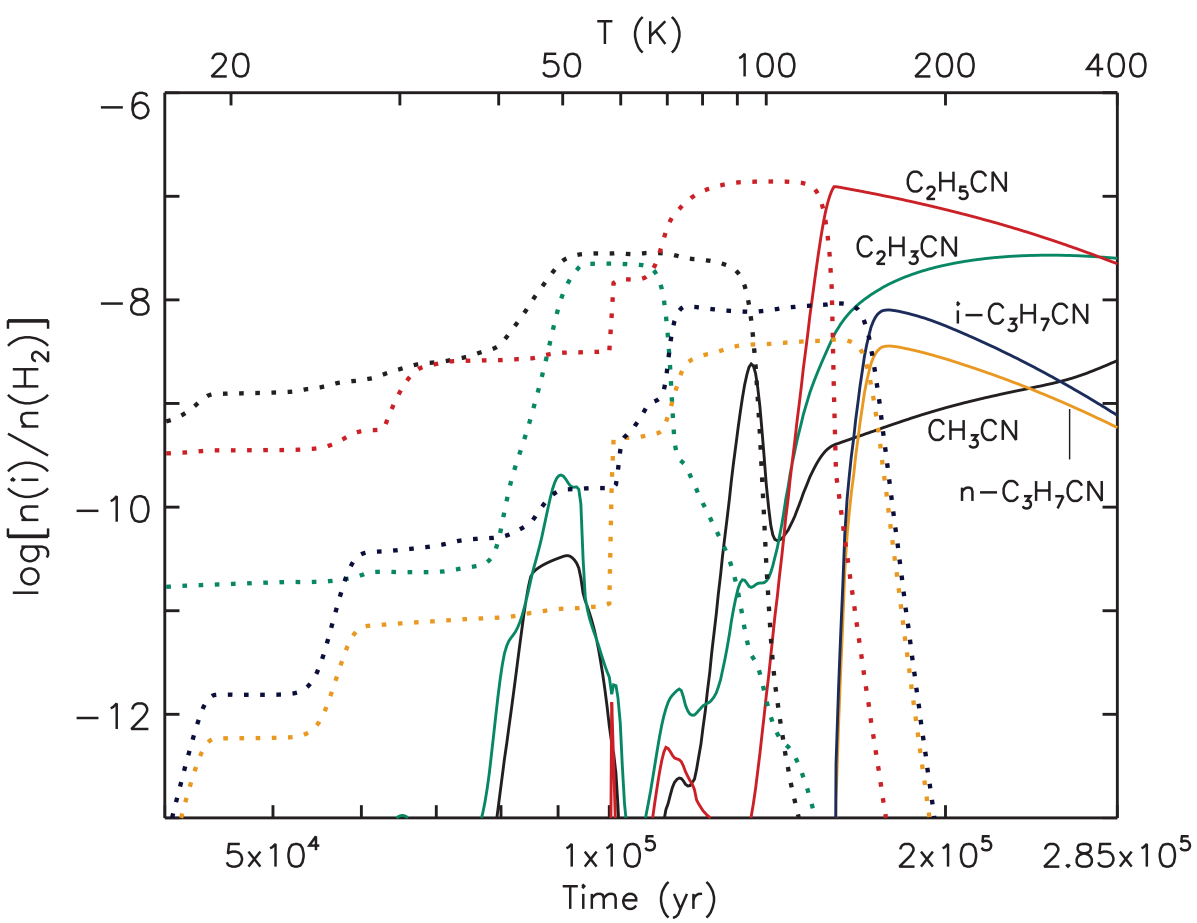


Belloche et al. 2015

BRANCHED ALKYL MOLECULES WITH ALMA

Chemical models favor a bias toward branched propyl cyanide (2.2:1), however there are several uncertainties regarding the chemistry on the surface of icy dust grains.

Fig. 3. Simulated fractional chemical abundances of alkyl cyanides with respect to molecular hydrogen, H_2. These abundances represent the warm-up phase of hot-core evolution. Solid lines indicate gas-phase species; dotted lines of the same color indicate the same species in the solid phase. The main phase change from solid to gas for each molecule is caused by thermal desorption from the grain surfaces, according to species-specific binding energies.

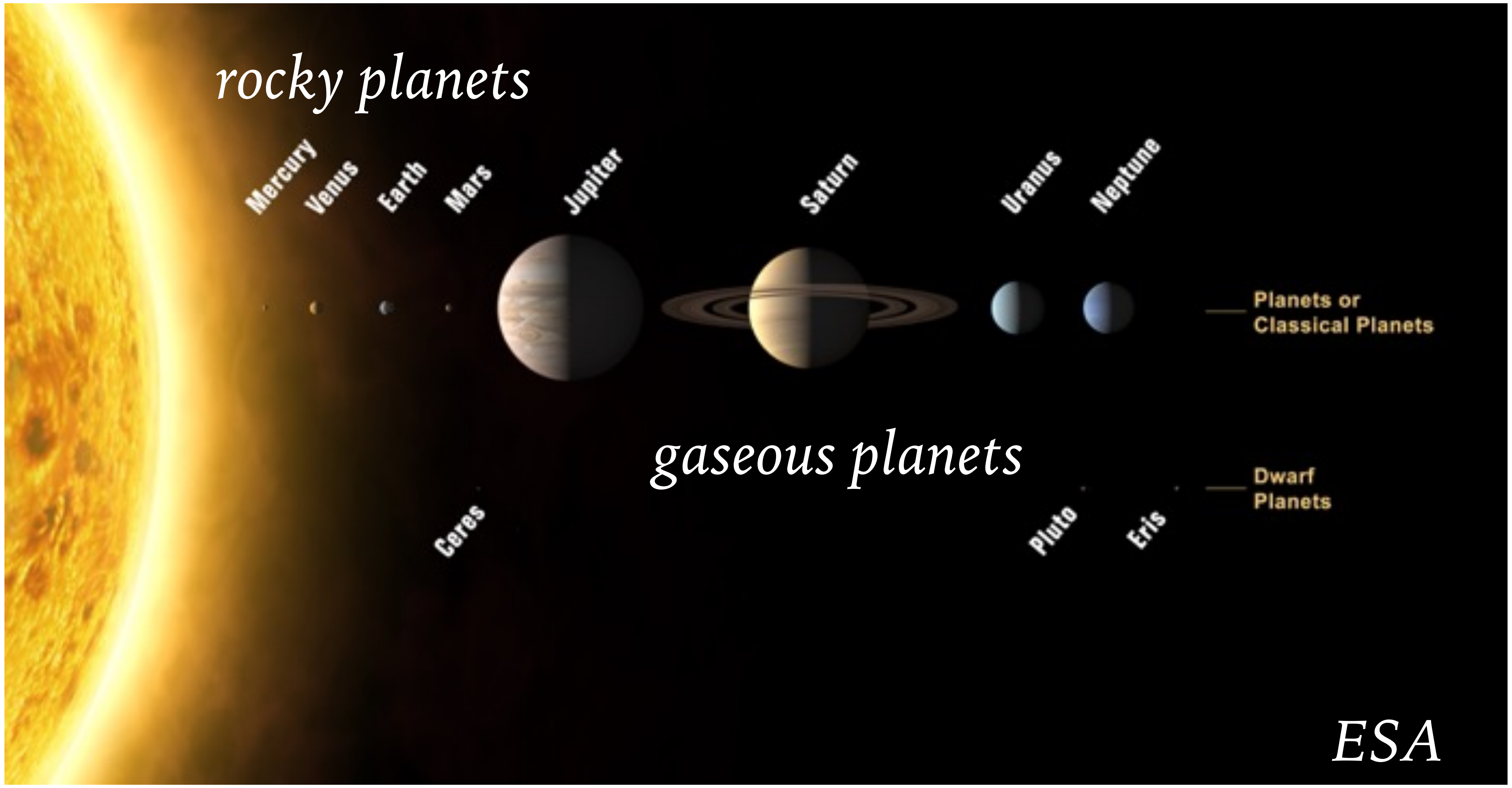


The detection of this branched iso-propyl cyanide suggests that there is a link between interstellar chemistry in star-forming regions and the molecular composition of meteors.

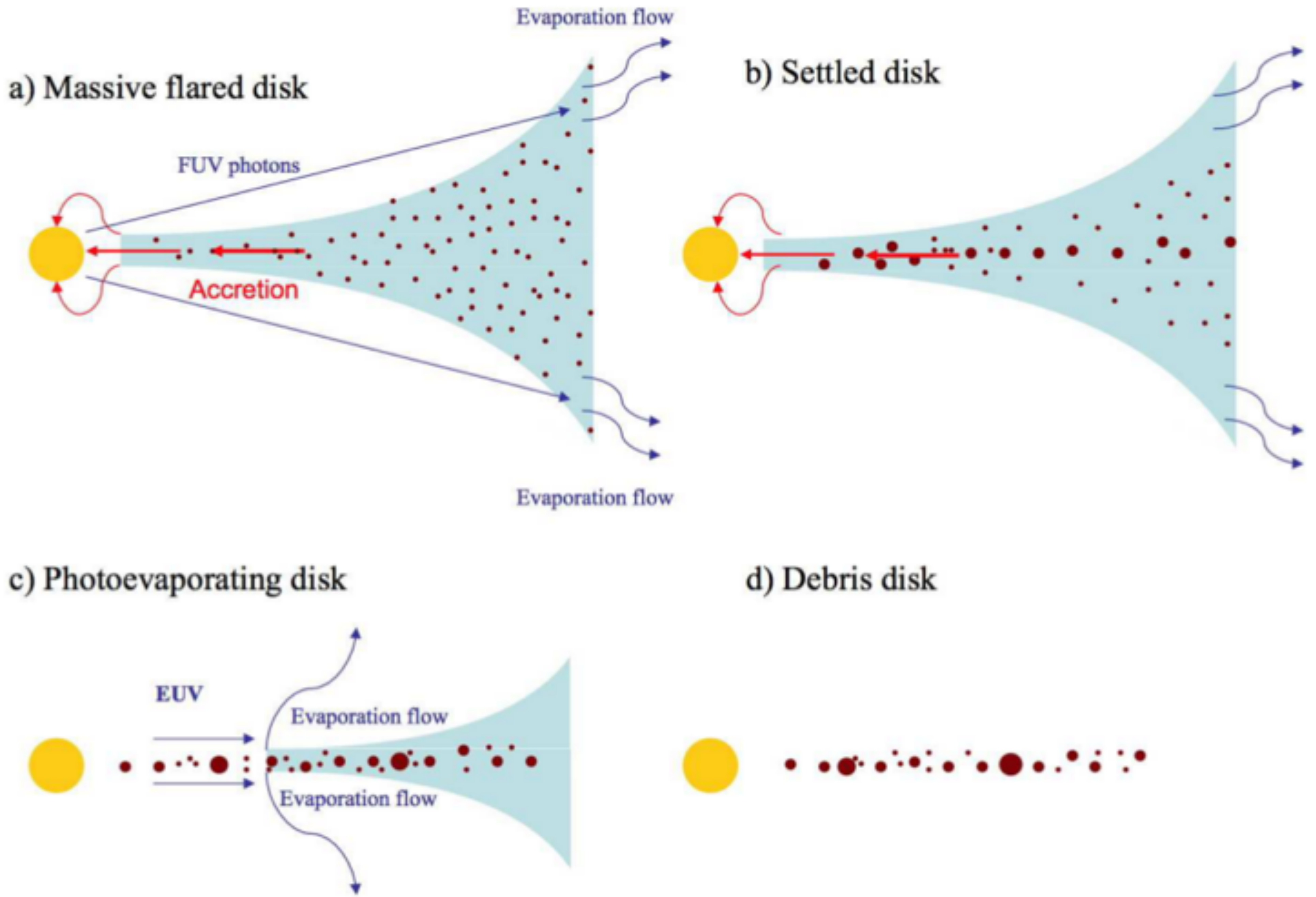
Belloche et al. 2015

GAS/DUST DISTRIBUTION IN PROTOSTELLAR DISKS

- planet formation occurs in the protostellar disk from the refractionary dust, volatile (chemical compounds with low boiling points, e.g. CO, CO_2, NH_3,H_2O) ice, and gas
- spatial distribution of volatile abundances helps to determine the composition of nascent planets at different disk radii

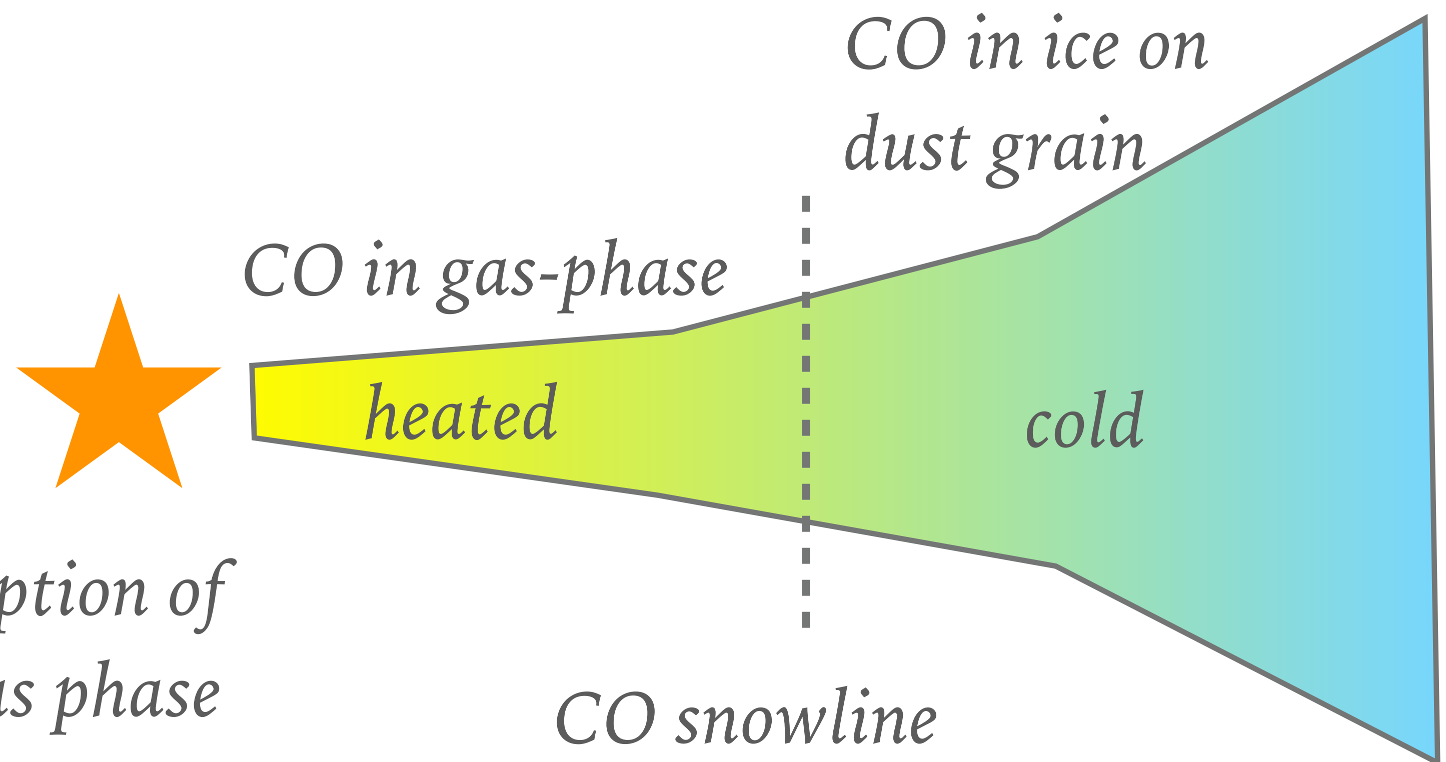


EVOLUTION OF A PROTOSTELLAR DISK

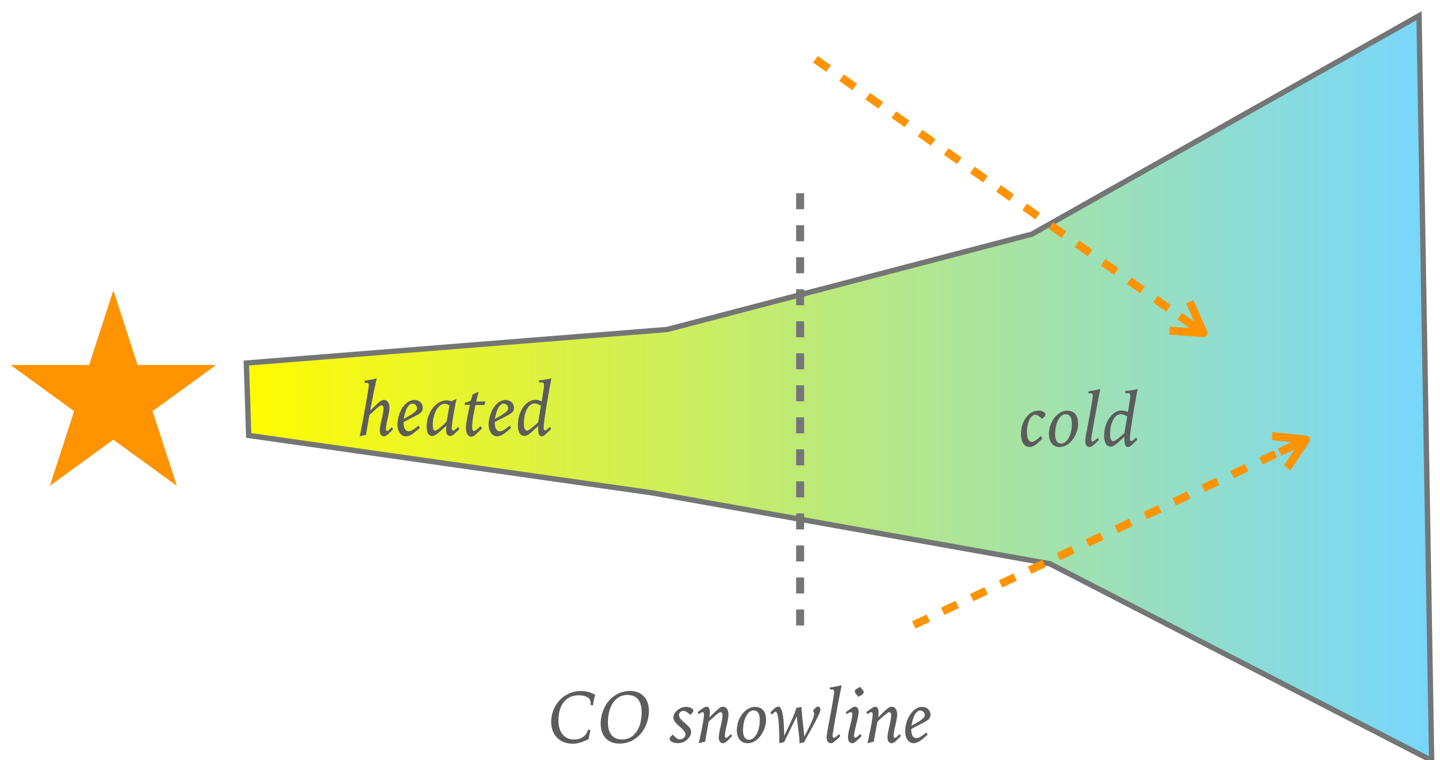


Williams & Cieza (2011)

DISK TEMPERATURE AND MOLECULAR EMISSION



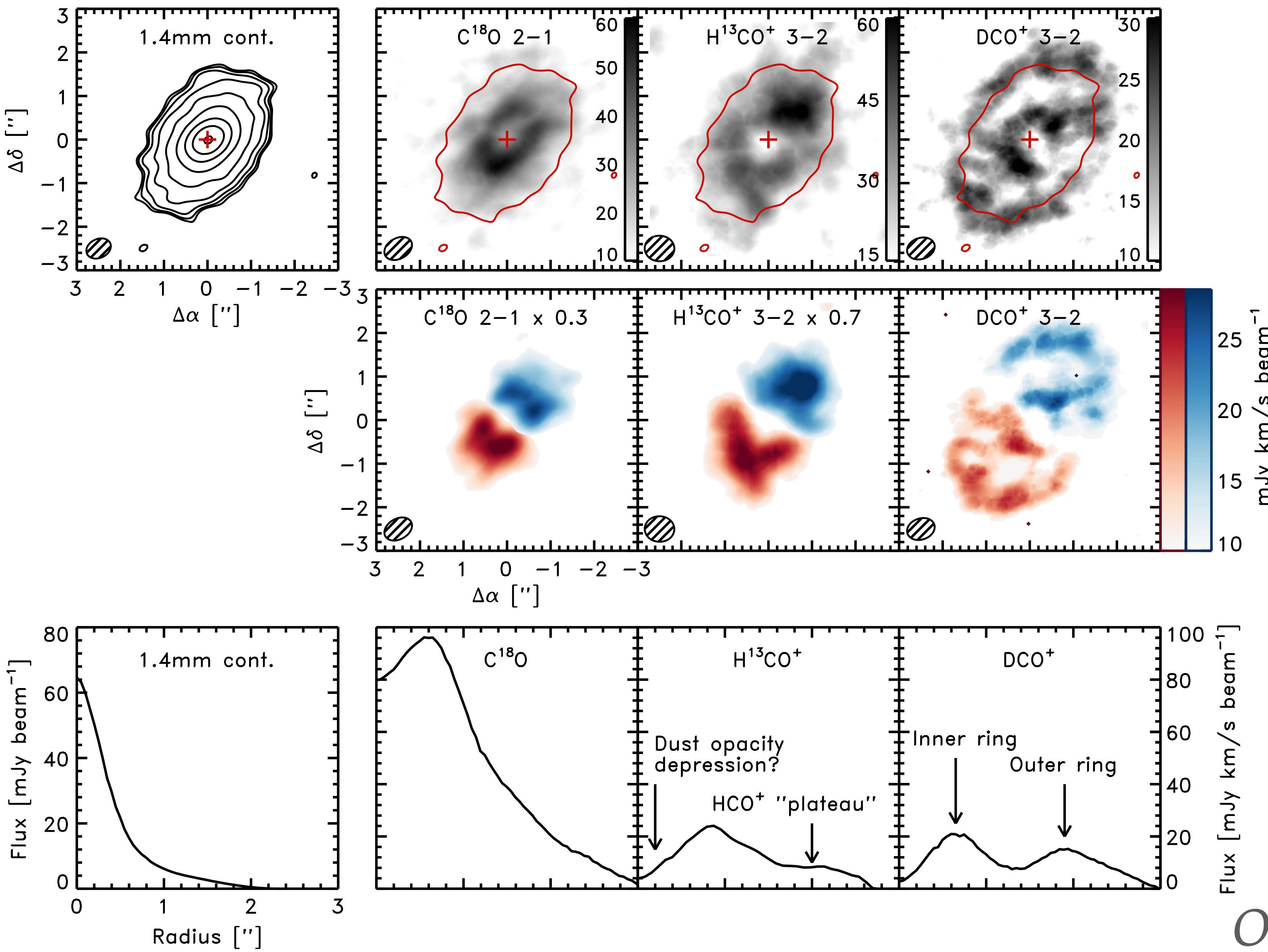
thermal desorption of CO back to gas phase by heating from star



desorption of CO back to gas phase by interaction with high energy photons due to decrease of density

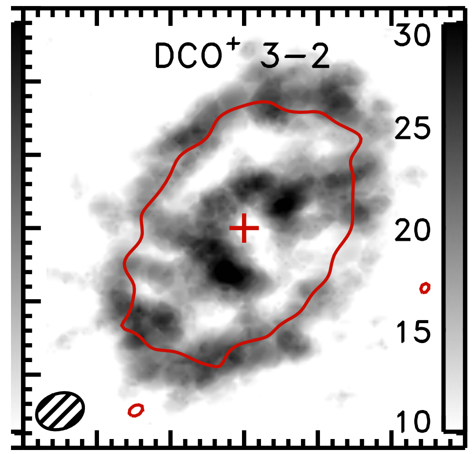
COLD GAS RESERVOIR IN PROTOSTELLAR DISK VIA ICE DESORPTION

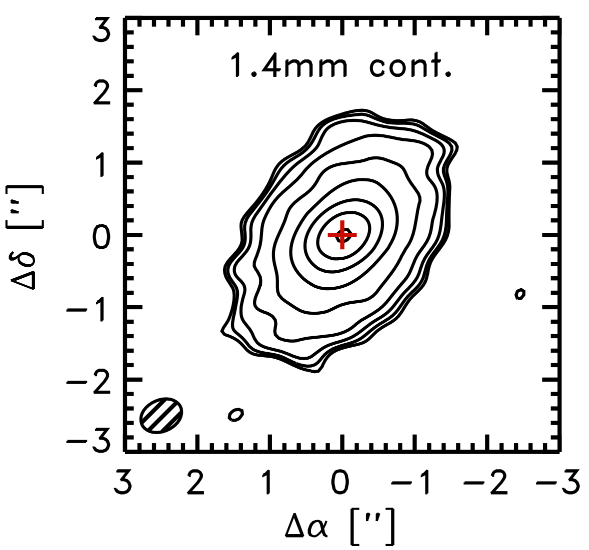
DCO^+ is found in two concentric rings, an inner ring (warm CO, small dust grains present) and an outer ring (cold CO, no small dust grains)



Oeberg et al. 2015

COLD GAS RESERVOIR IN PROTOSTELLAR DISK VIA ICE DESORPTION





- inner ring: in balance with CO thermal desorption due to radial decrease in disk temperature
- outer ring: evidence of non-thermal desorption of CO and the efficient formation of DCO^+ via :

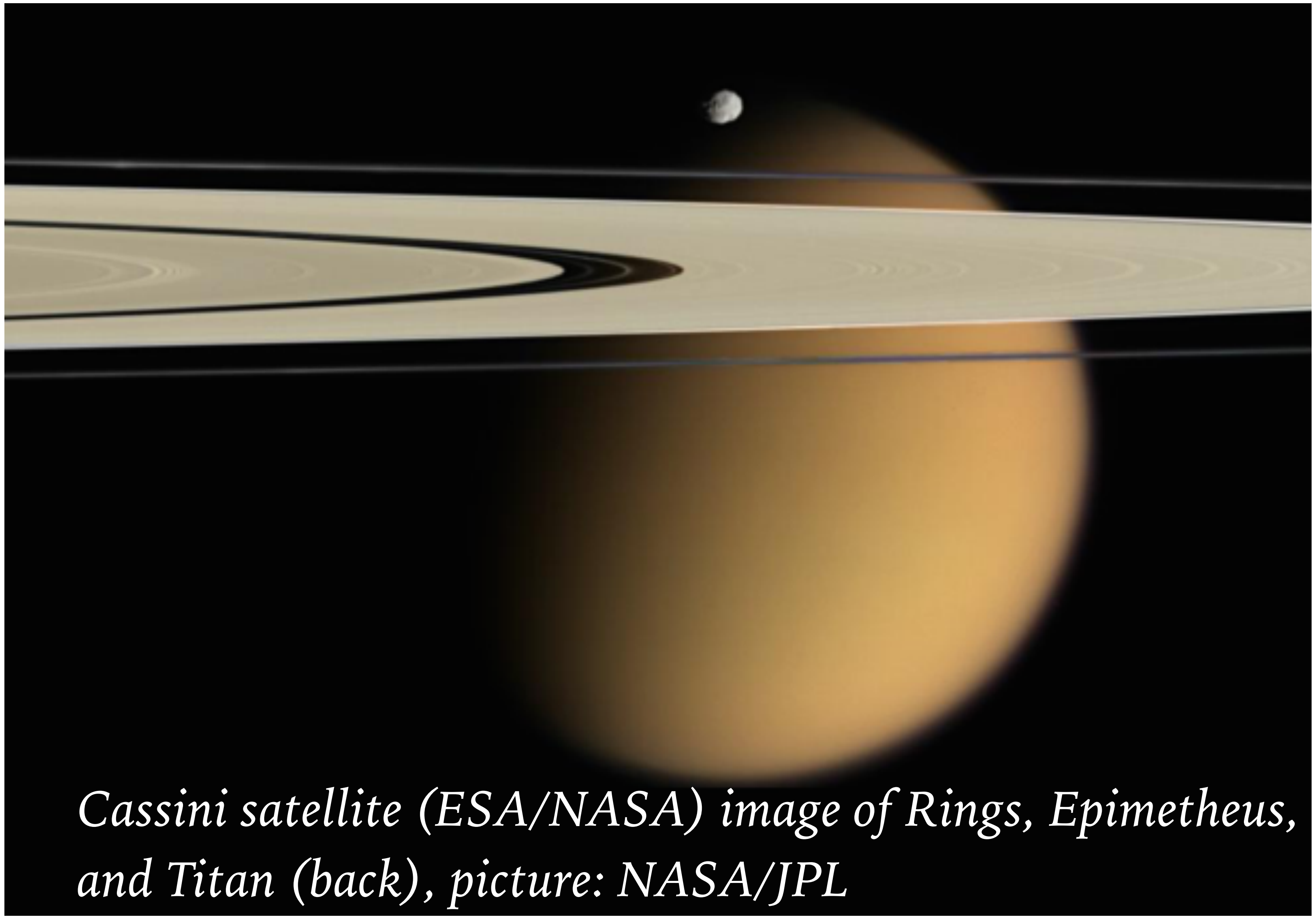
$$\mathbf{H2D^+ + CO \text{ -> } H_2 + DCO}$$

- outer ring is not coincident with dust continuum emission, meaning that the density of small dust grain have decreased - also grain growth would explain the decrease in dust continuum emission and UV shielding.

Oeberg et al. 2015

TITAN ATMOSPHERE

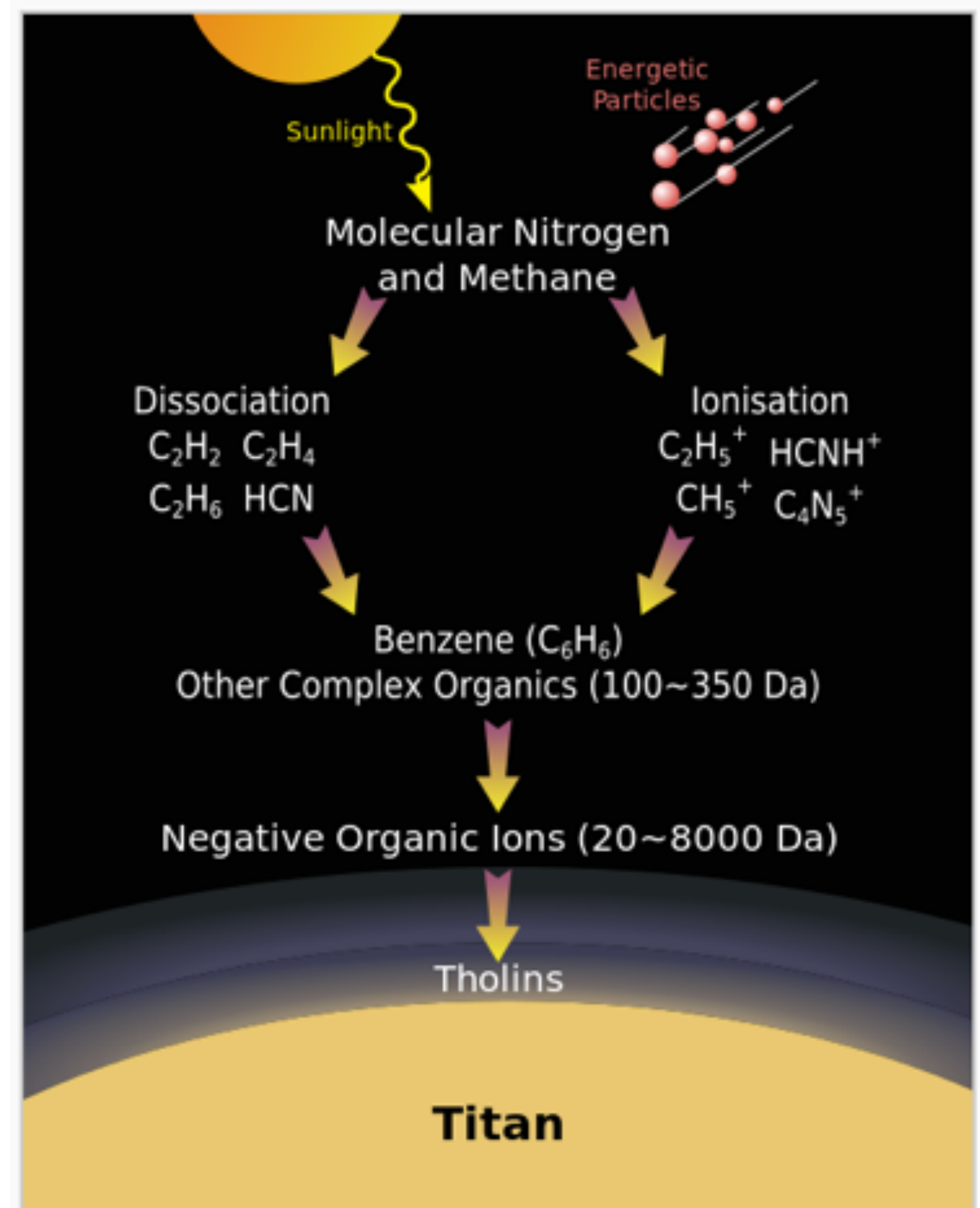
- Titan (Mass$\sim$2M_{moon}) is the only moon with a dense atmosphere in our Solar system and the only other body which has a liquid surface (Stofan et al. 2007)
- Atmosphere: 98% Nitrogen, 2% methane (earth: 78% nitrogen, 21% oxigen, 0.9 argon)



Cassini satellite (ESA/NASA) image of Rings, Epimetheus, and Titan (back), picture: NASA/JPL

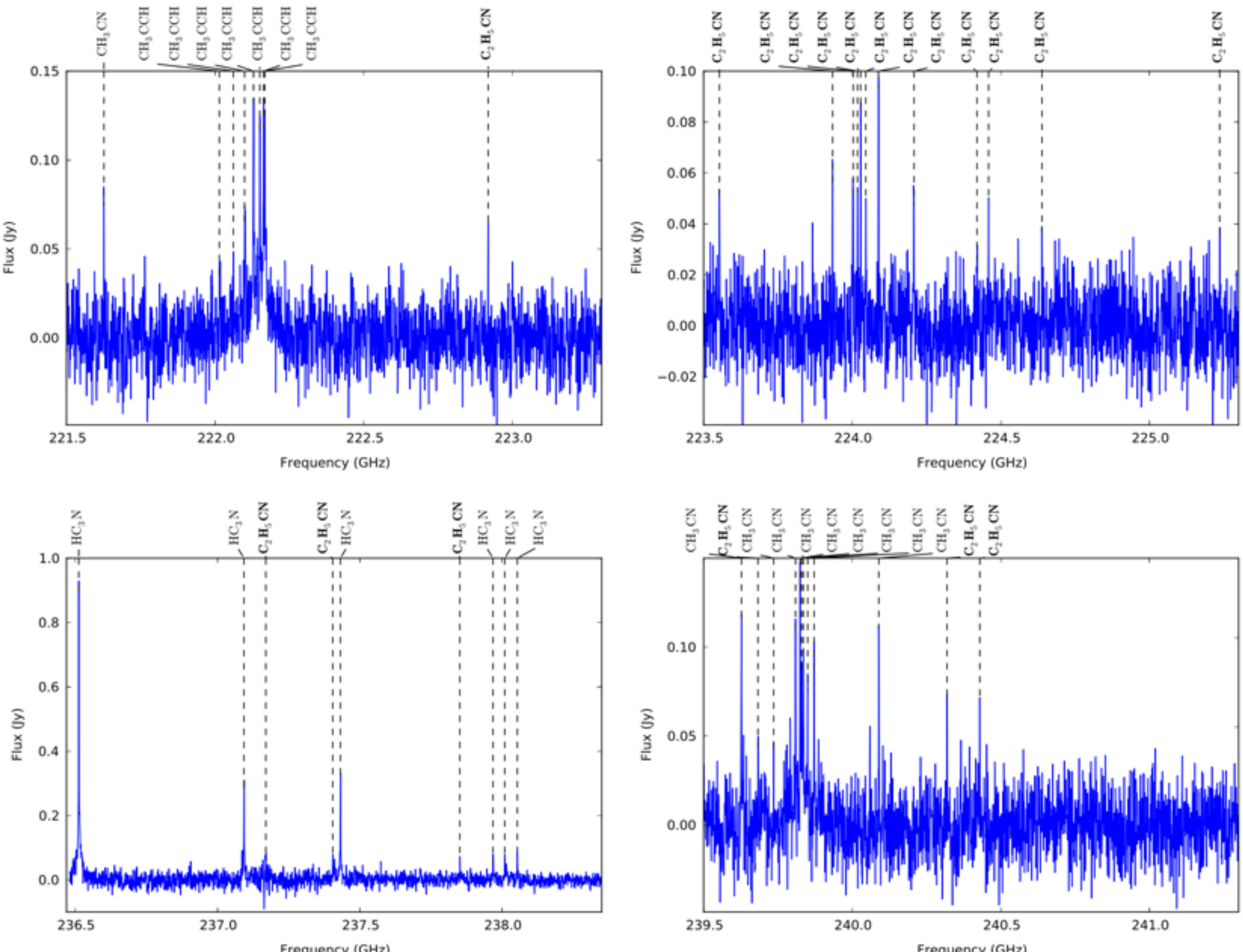
ETHYL CYANIDE (C_2H_5CN) TO CONSTRAIN TITAN CHEMISTRY

- From lab plasma-discharge experiments expected to be highly abundant (e.a. Thomson et al. 1991)
- $C_2H_5CNH^+$ found by Cassini satellite (Vuitton et al. 2007)
- Measures of C2H5CN necessary to constrain formation pathways, and constrain models for for the formation of nitriles and other large organic molecules



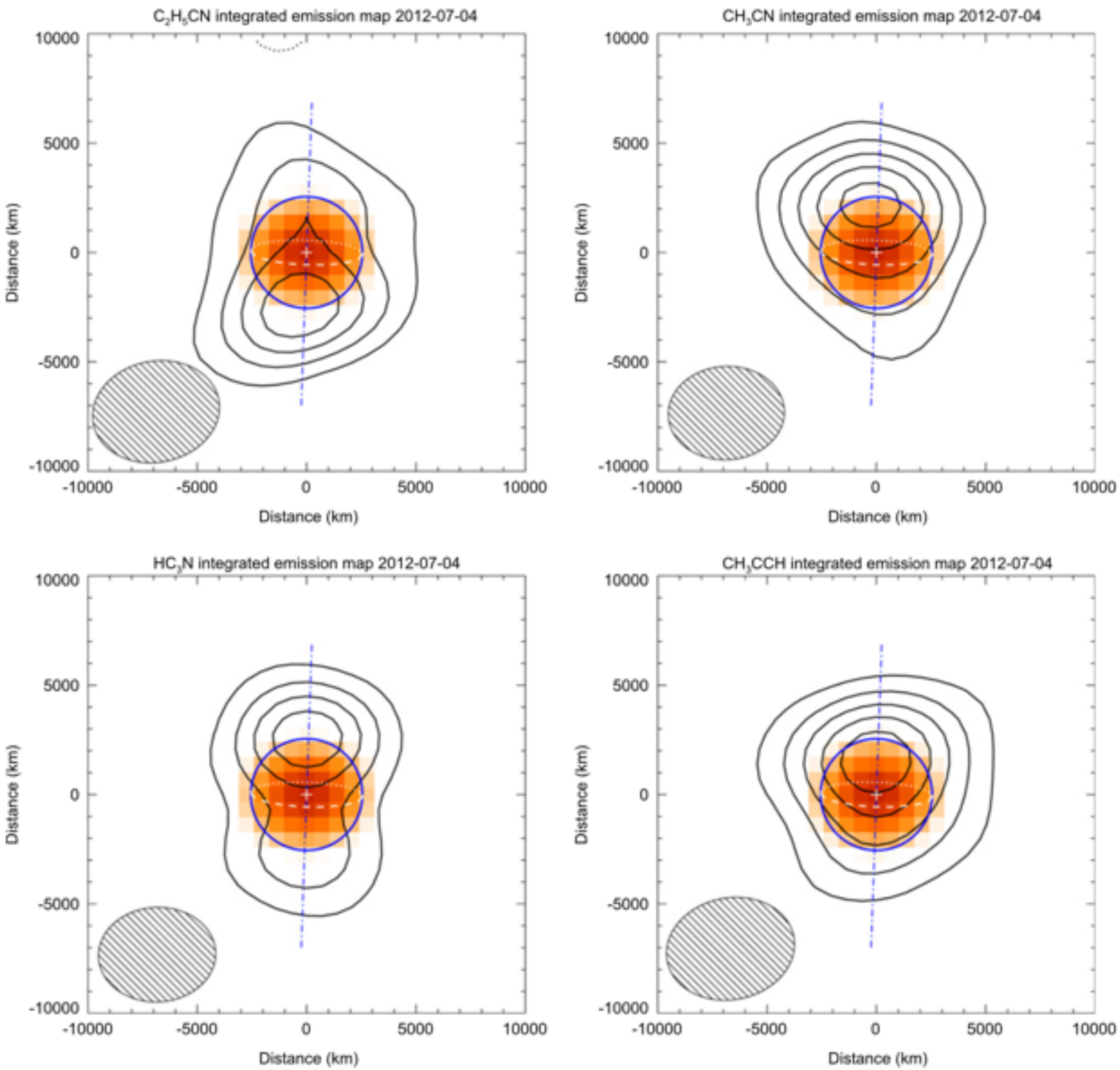
ETHYL CYANIDE (C_2H_5CN) WITH ALMA

ALMA's four spectral windows:



Cordiner et al. 2015

ETHYL CYANIDE (C_2H_5CN) WITH ALMA



Southern hemisphere ethyl cyanide peak

Titans seasons cause a reversal (N-S) of the atmospheric circulation: the disappearance of ethyl cyanide in the north implicates a shorter chemical lifetime than that of the CH3CN, HC3N, and CH3CCH

color: Titan continuum emission, contours: molecular line emission

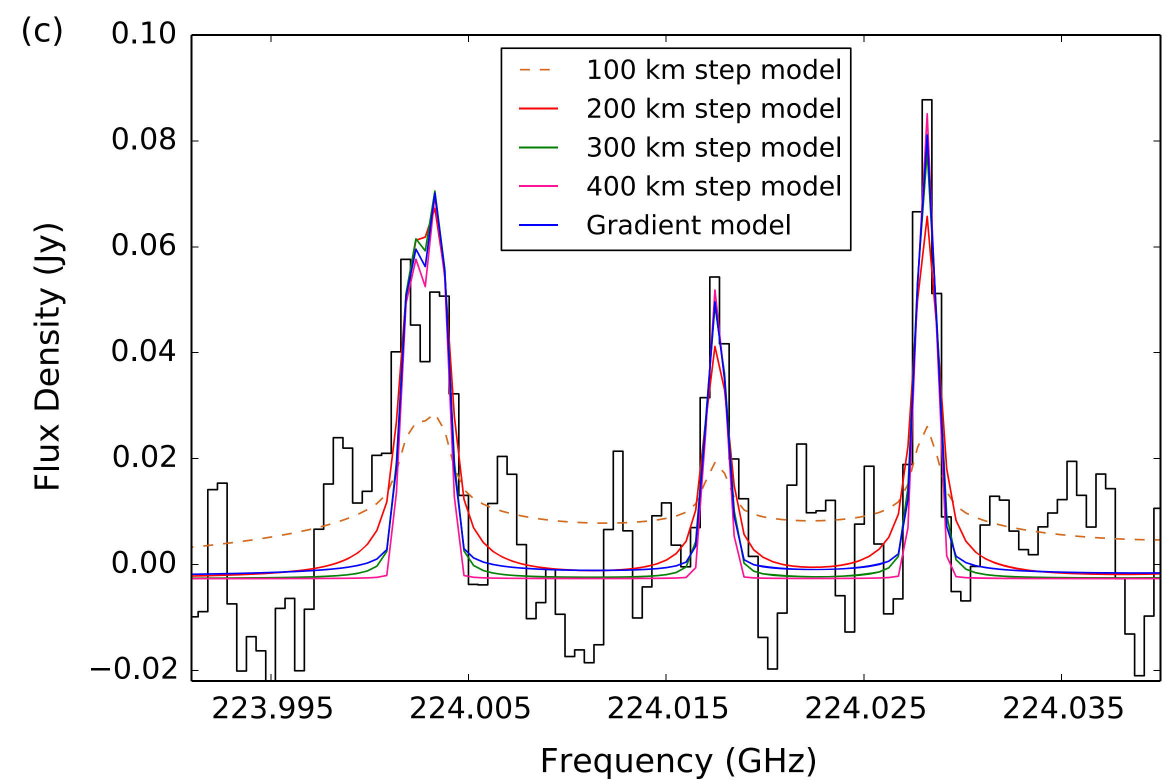
Cordiner et al. 2015

ETHYL CYANIDE (C_2H_5CN) WITH ALMA

Table 2
Best-fitting C_2H_5CN Model Abundances and Vertical Column Densities

Model	Abundance (ppb)	z_r^a (km)	χ^2	N (cm^{-2})
Step (100 km)	0.79	100	1.43	1.3×10^{15}
Step (200 km)	3.24	200	1.01	4.6×10^{14}
Step (300 km)	9.25	300	0.97	1.7×10^{14}
Step (400 km)	73.1	400	0.98	2.1×10^{14}
Gradient	1.30	292	0.97	3.6×10^{14}

[a] Reference altitude for abundance.



Comparing various radiative transfer models with ALMA measure of ethyl cyanide it can be deduced that methyl cyanide is most concentrated at altitudes of 200km and higher.

Cordiner et al. 2015

CALIBRATED ALMA DATA IN ARCHIVE

- 1 year after delivery to PI, data are publicly available on the ALMA archive
- You can download raw data with a reduction script in CASA (ALMA data reduction software)
- You can always ask help to the Italian ARC @ IRA :)