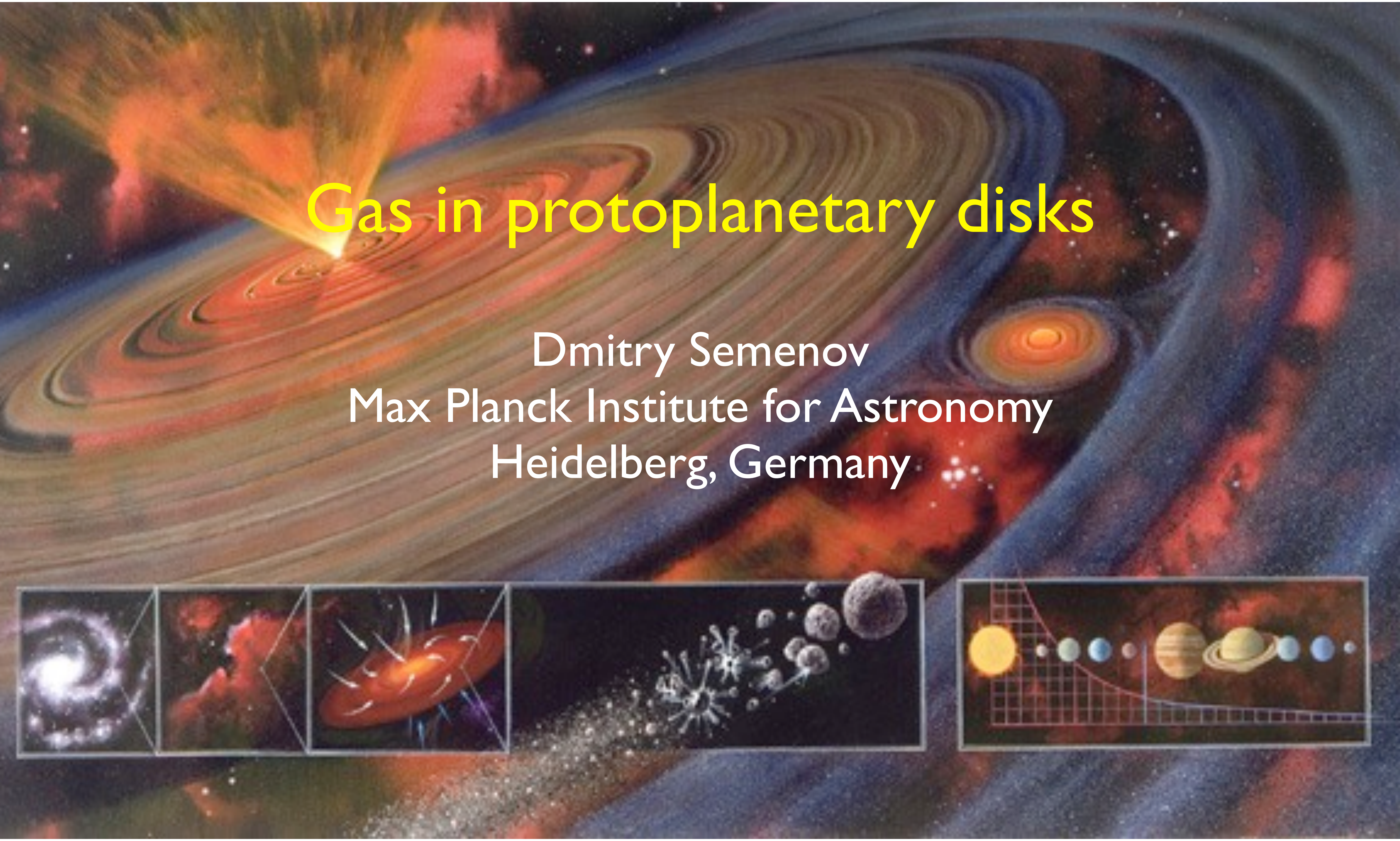

Gas in protoplanetary disks

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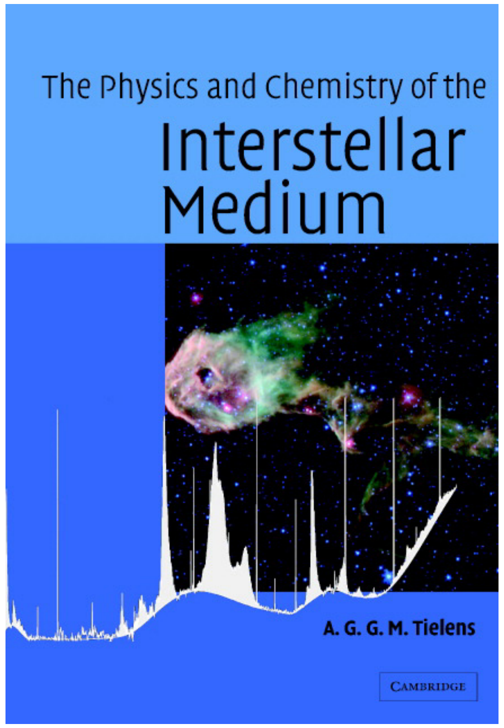
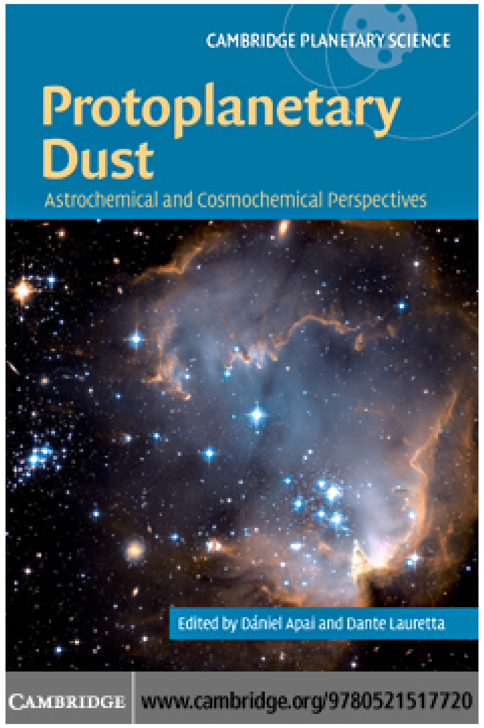
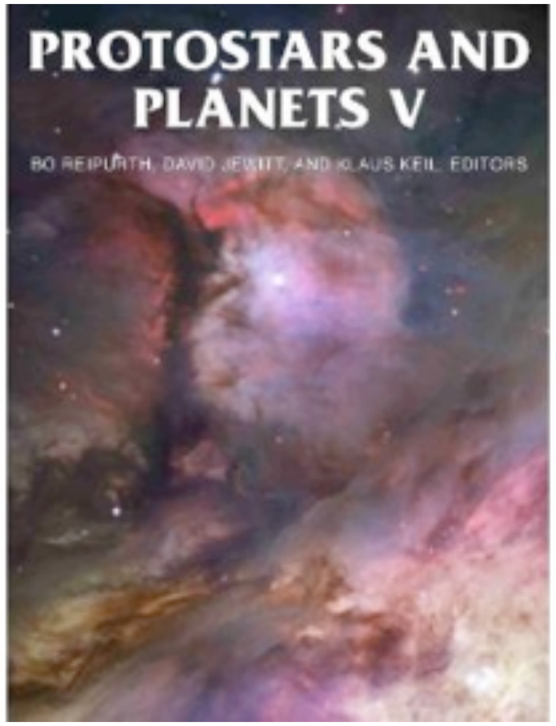
Suggested literature

- A. G.G.M. Tielens, "The Physics and Chemistry of the ISM" (2007), CUP
- "Protoplanetary Dust" (2010), eds. D. Apai & D. Lauretta, CUP
- "Protostars & Planets V" (2005), Part VI, eds. B. Reipurt et al., Univ. Arizona P.
- D. Semenov, "Chemistry in protoplanetary disks", Encyclopedia of Astrobiology, Springer Ver. ISBN: 978-3-642-11279-9

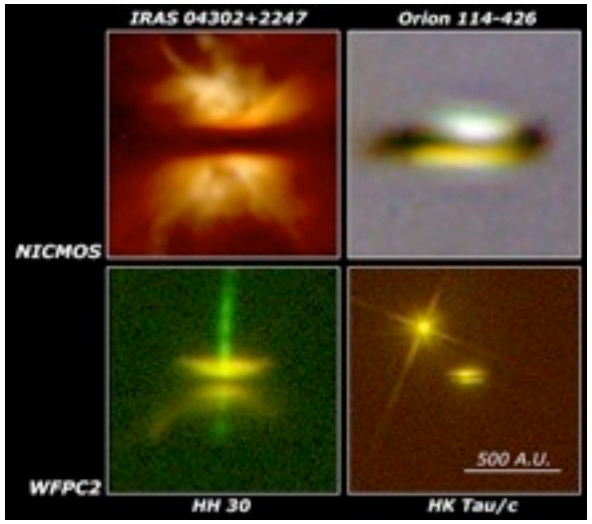


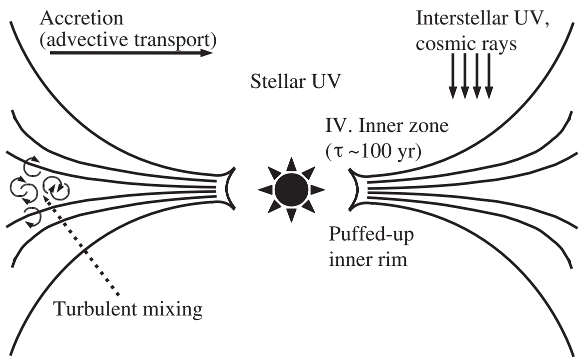


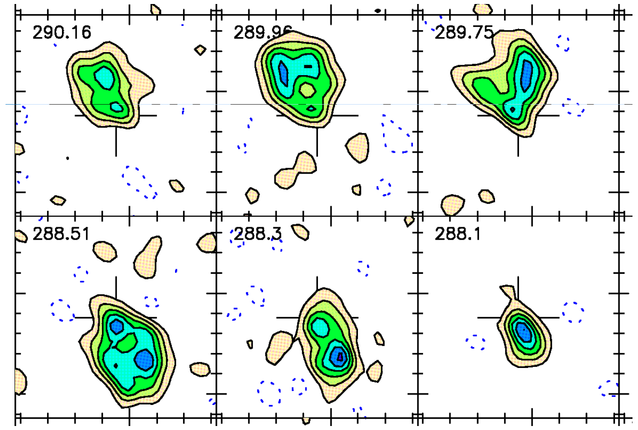


Outline

- Formation of molecular lines
- Molecules as disk probes
- Disk chemical structure
- Observations of molecules in disks
- Modeling disk chemical evolution with dynamics
- Predictions for ALMA







Advantages of millimeter observations

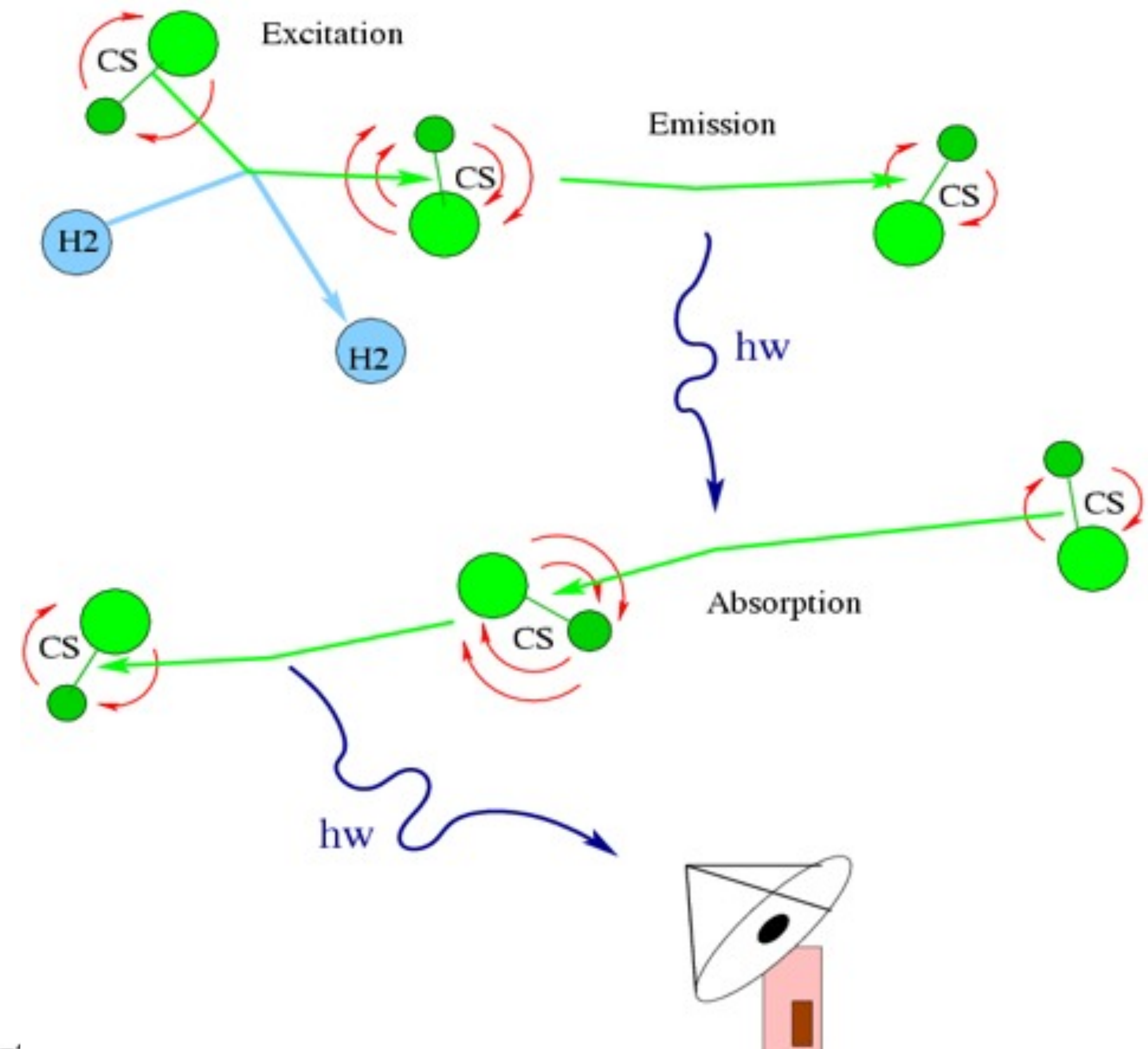
- Optically thin dust emission (outer disk)
- Rotational transitions of many molecules
- High frequency resolution: ~10^6 (~0.05 km/s)
- Sensitive to cold regions: T~10K
- Interferometers: sub-arsec resolution
- Many spectral lines within a bandwidth
- Day-time observations

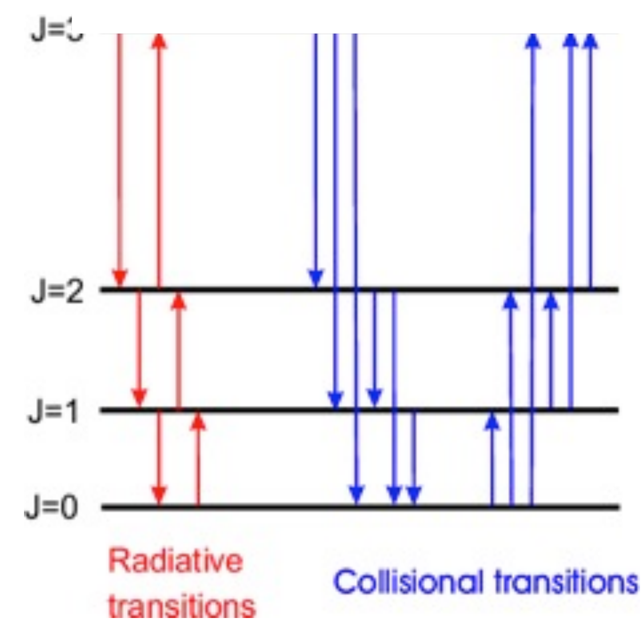
- Plateau de Bure interferometer, Submillimeter Array, Very Large Array, CARMA, ATCA
- IRAM 30-m, Apex 12-m, Effelsberg 100-m, Aresibo 100-m, JCMT 15m, Nobeyama 45-m

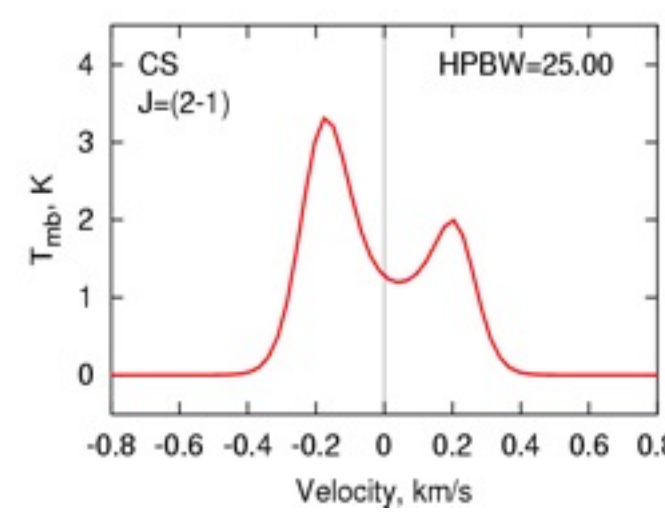
I. Basics of line excitation and line analysis

Analysis of emission line data

- n,T + chemistry + excitation + kinematics + radiative transfer: line
- Excitation: radiation & collisions
- Excitation & RT: non-local problem
- 6D: 3D n,T + 1D ν + 2D sky plane
- Incomplete coverage of (u,v) plane
- Optically thick lines: Intensity ~ T_{exc} (^{12}CO, H_2O)
- Optically thin lines: Intensity ~ $\tau * T_{exc}$



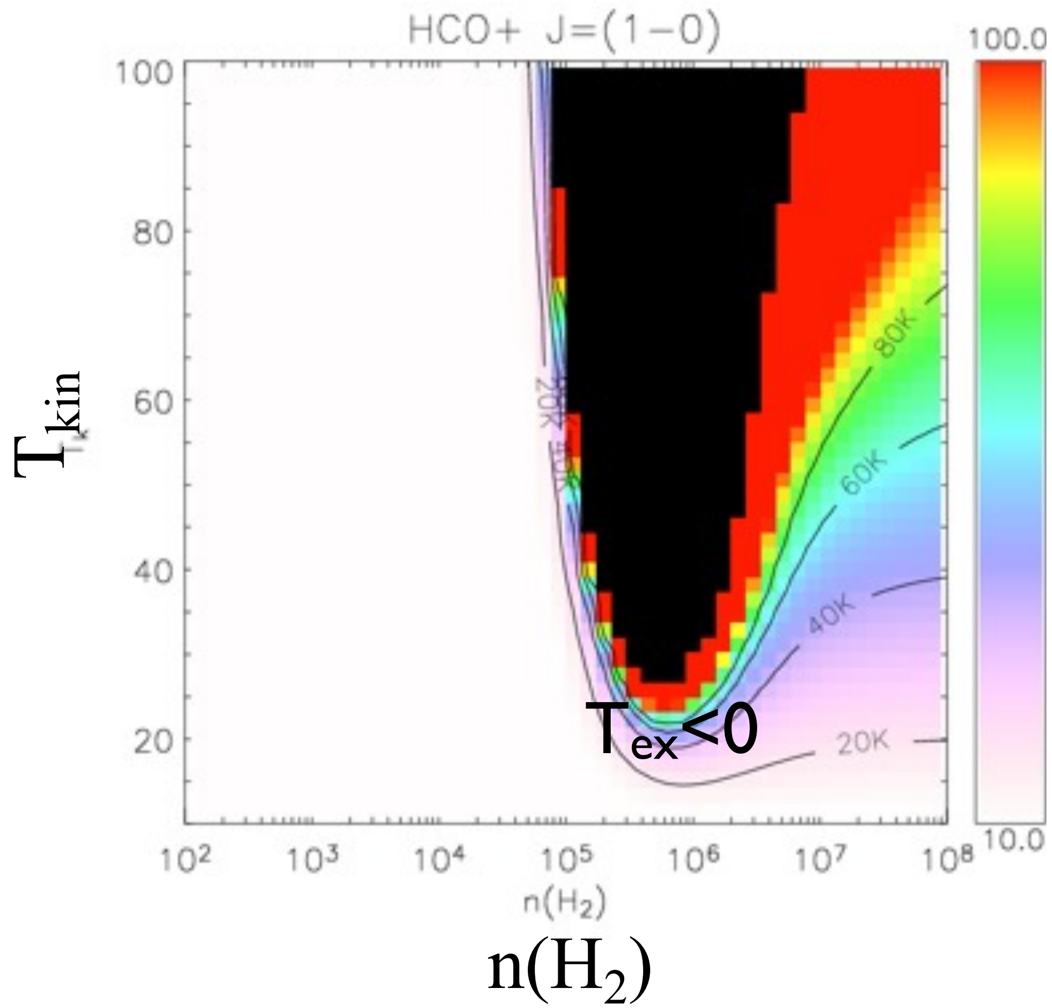




Courtesy: Ya. Pavlyuchenkov

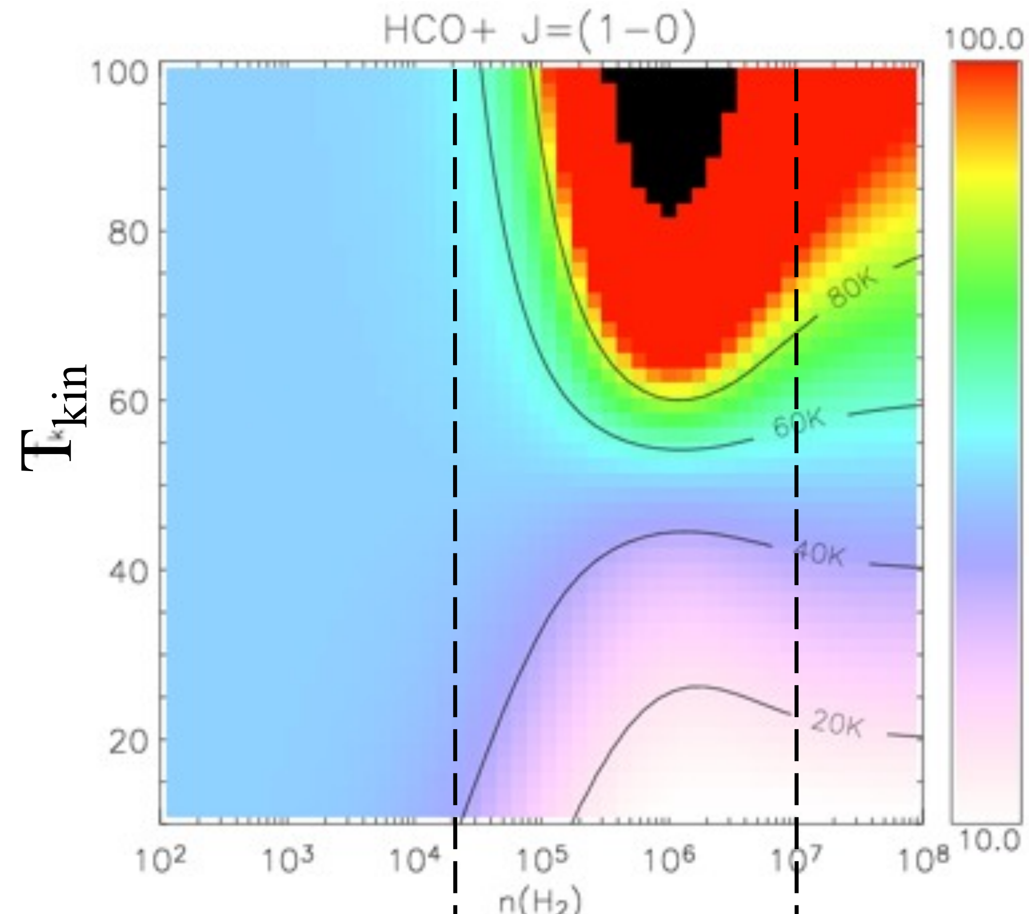
Excitation temperatures: HCO^+(1-0)

T_{bg}= 2.73 K



$$\frac{n_u}{n_l} = \frac{g_u}{g_l} \exp\left(-\frac{\Delta E}{kT_{ex}}\right),$$

T_{bg}= 50 K

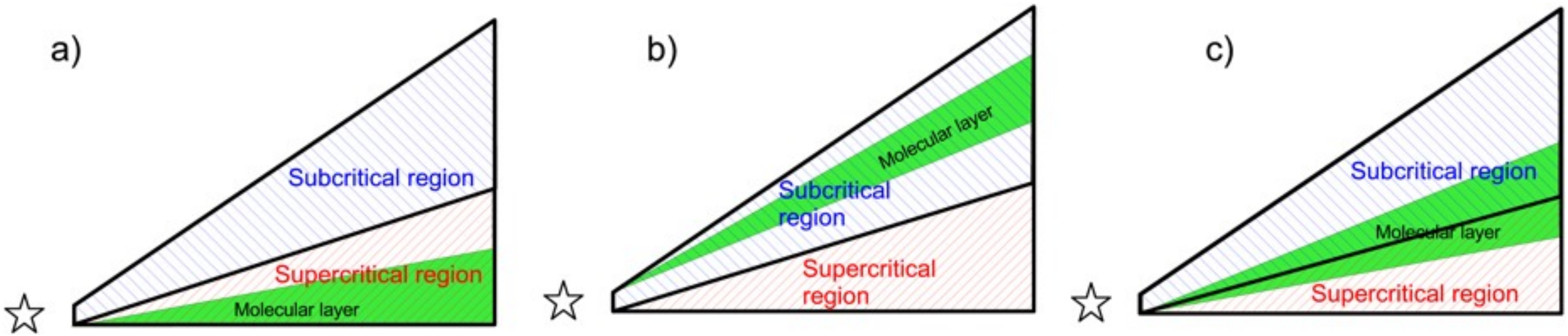


radiatively dominated	?	thermalized zone
$T_{exc}=T_{bg}$		$T_{exc}=T_{kin}$
Non-LTE		LTE

Courtesy: Ya. Pavlyuchenkov

Excitation conditions in PPDs

Rotational transition: thermally, sub-thermally, or super-thermally excited



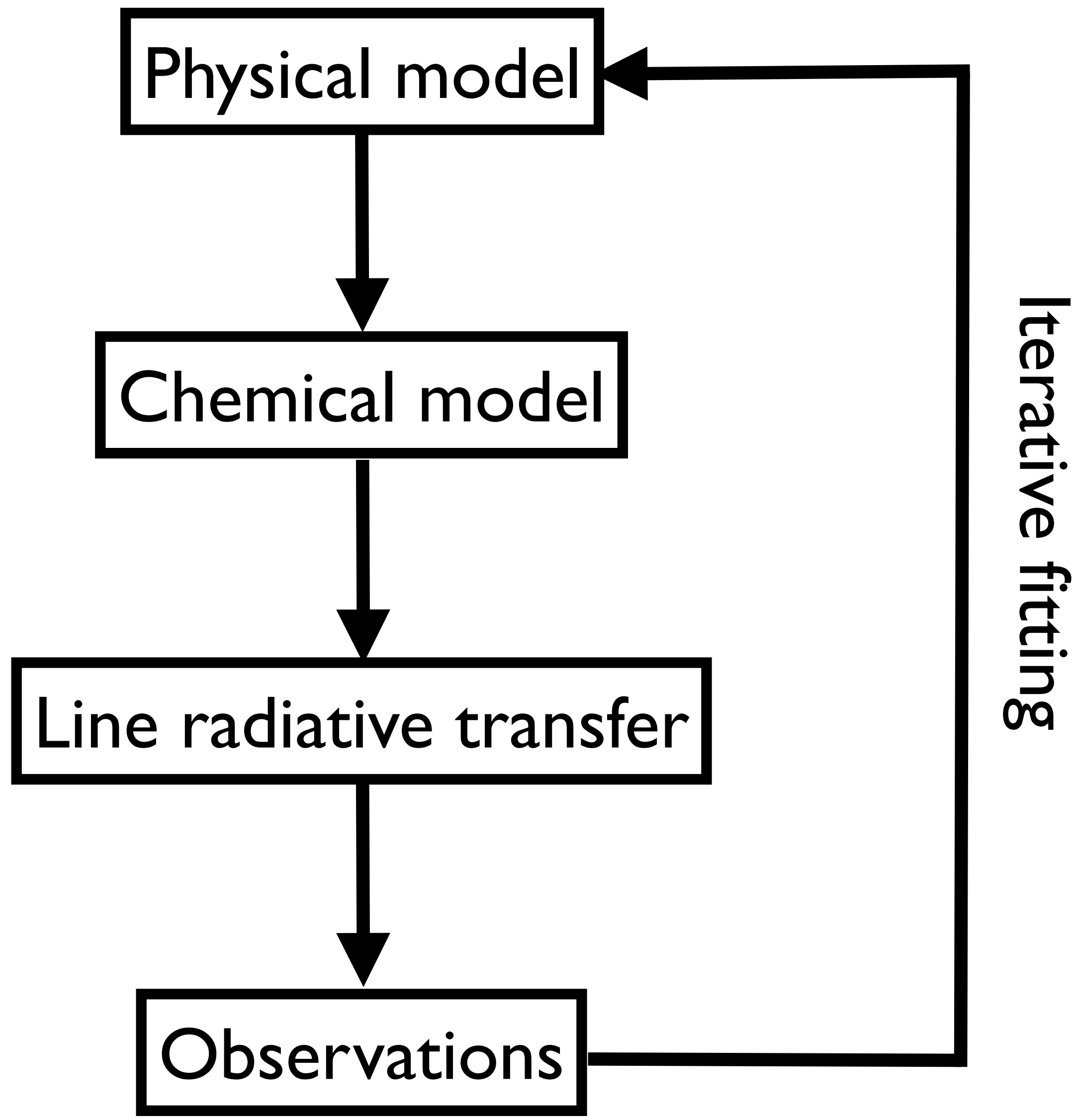
Line is thermalized

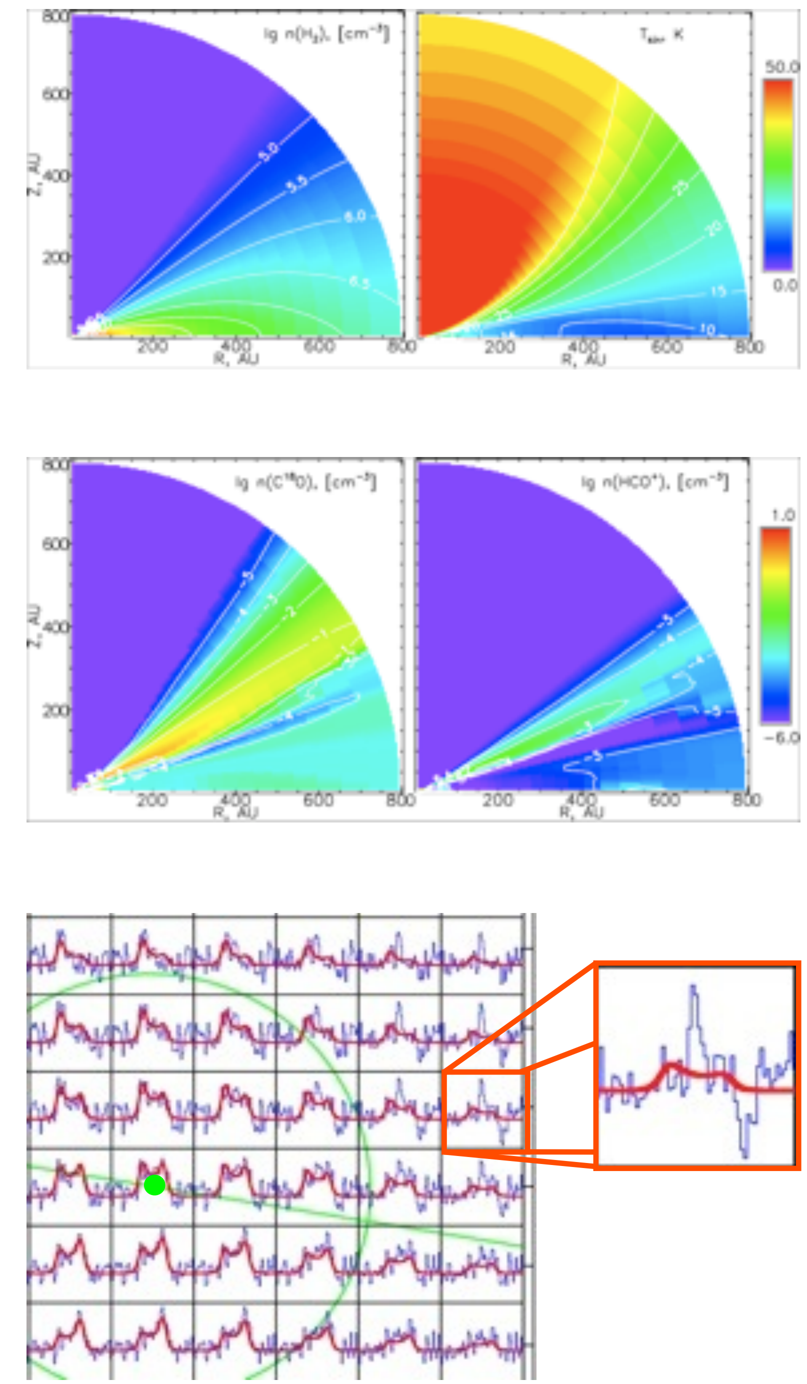
Line formation depends on chemistry

- Molecules in disks populate dense regions: $n_H > 10^5 – 10^6$ cm^{-3}
- Thermalized: low-lying transitions of observed molecules
- Asymmetric molecules have perplex level structure: H_2O
- High-lying transitions: LTE or non-LTE?

Pavlyuchenkov et al. (2007)

Analysis of emission line data





- LTE assumption
- T_{kin} is often fixed
- Chemistry is often ignored: fixed abundances
- Optical thin approx./LVG/escape probability

LRT tools & databases:

- 1/2/3D Line Radiative Transfer codes:
    - RADEX/RATRAN (F. van der Tak, M. Hogerheijde)
    - URANIA (Ya. Pavlyuchenkov)
    - RADLITE (K. Pontoppidan)
    - RADMC-3D (C. Dullemond)
    - LIME (C. Brich & M. Hogerheijde)
    - Photon-Dominated Region (PDR) code (F. Le Petit)
- Collisional rates: Leiden Atomic & Molecular Database:

  http://www.strw.leidenuniv.nl/~moldata/

- Line frequencies:
- Cologne Database for Molecular Spectroscopy: http://www.astro.uni-koeln.de/cdms/
- NIST, JPL, ...

I. LRT basics: Summary

- Formation of emission in molecular lines is a tricky problem
- LTE/non-LTE
- Observed molecules: T_{exc}~T_{kin}
- High-lying lines may reach τ>1
- Complex molecules: T_{exc}=?
- LRT codes & databases (limited)
- Full modeling cycle to fit interferometric data

II. Molecules as probes

Molecules in space (~170)

Number of Atoms										
2	3	4	5	6	7	8	9	10	11	13
H_2	C_3	c-C_3H	C_5	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N?	HC_9N	$HC_{11}N$
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN	$HCOOCH_3$	CH_3CH_2CN	$(CH_3)_2CO$		
AlCl	C_2O	C_3N	C_4Si	C_2H_4	CH_3C_2H	CH_3COOH?	$(CH_3)_2O$	NH_2CH_2COOH?		
C_2	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH			
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	$HCOCH_3$	H_2C_6	HC_7N			
CH^+	HCN	C_2H_2	CH_2CN	CH_3OH	NH_2CH_3		C_8H			
CN	HCO	CH_2D^+?	CH_4	CH_3SH	c-C_2H_4O					
CO	HCO^+	HCCN	HC_3N	HC_3NH^+						
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO						
CP	HOC^+	HNCO	HCOOH	NH_2CHO						
CSi	H_2O	HNCS	H_2CHN	C_5N						
HCl	H_2S	$HOCO^+$	H_2C_2O							
KCl	HNC	H_2CO	H_2NCN							
NH	HNO	H_2CN	HNC_3							
NO	MgCN	H_2CS	SiH_4							
NS	MgNC	H_3O^+	H_2COH^+							
NaCl	N_2H^+	NH_3								
OH	N_2O	SiC_3								
PN	NaCN									
SO	OCS									
SO^+	SO_2									
SiN	c-SiC_2									
SiO	CO_2									
SiS	NH_2									
CS	H_3^+									
HF										

Note that observations suggest the presence of large PAHs and fullerenes in the interstellar gas (Tielens et al 1999, Foing & Ehrenfreund 1997).

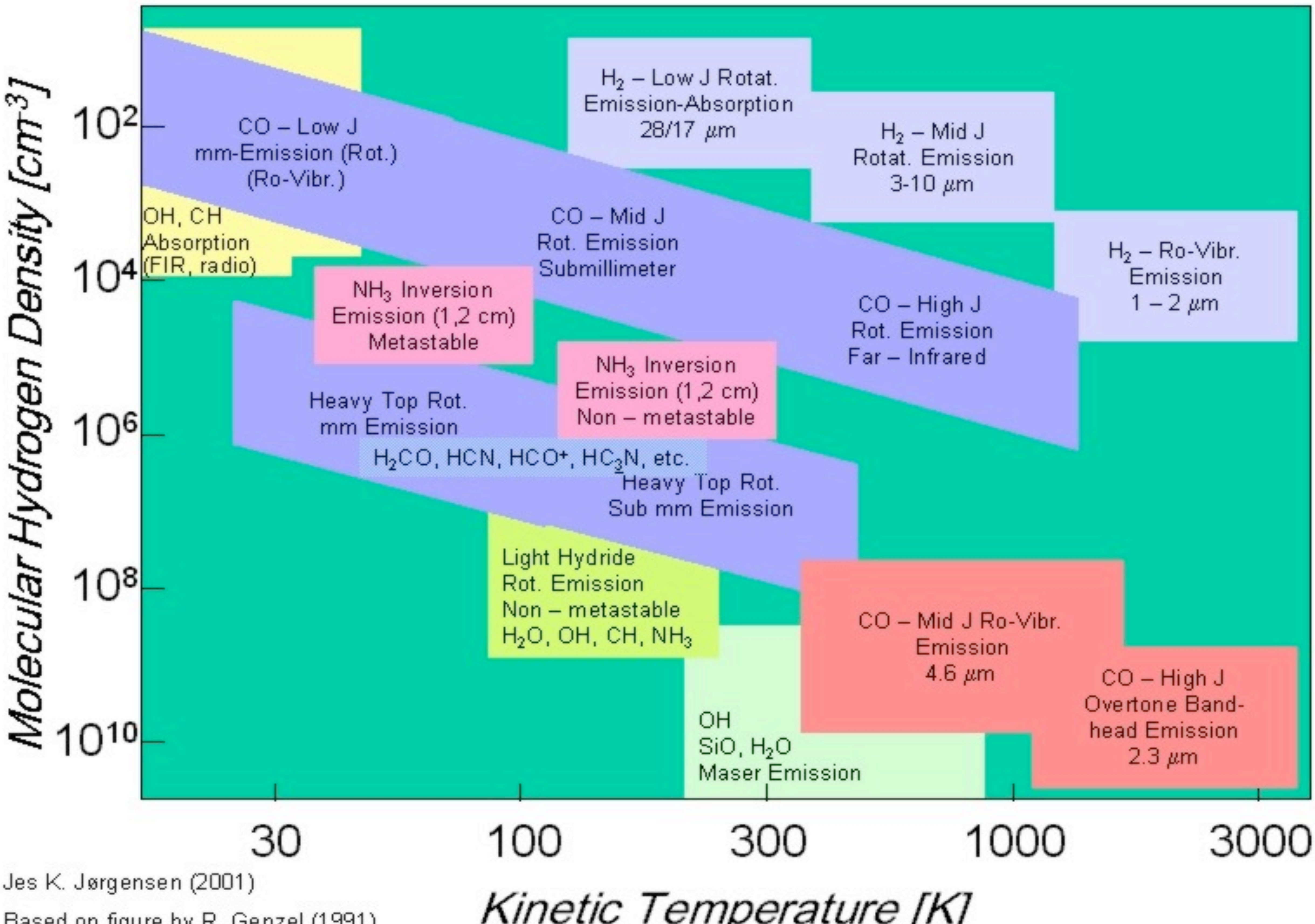
http://www.astrochymist.org/astrochymist_mole.html

http://www.astro.uni-koeln.de/cdms/molecules

Detected in disks: CO, HCO^+, DCO^+, CN, HCN, DCN, HNC, N_2H^+,

H_2CO, CS, HDO, C_2H_2, CO_2, OH, H_2O, Ne, Fe, Si, H_2

Molecules as probes of T and n_H



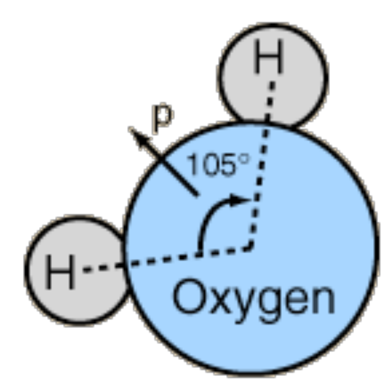
Jes K. Jørgensen (2001)

Based on figure by R. Genzel (1991)

Other molecular tracers

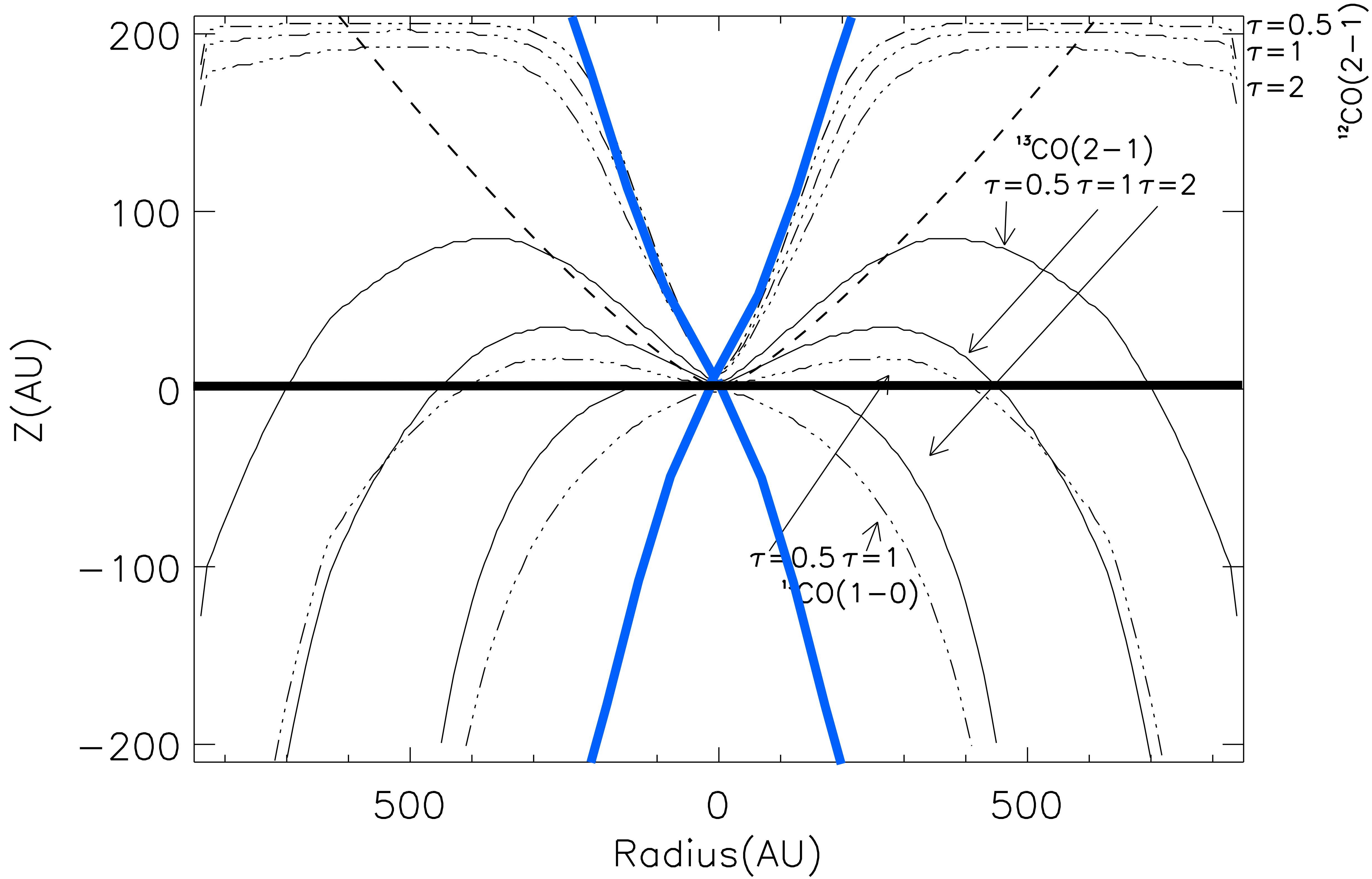
Tracer	Quantity
^{12}CO, ^{13}CO	Temperature
H_2	—
NH_3	—
CS, H_2CO	Density
CCH, HCN, CN	Photochemistry
HCO^+	Ionization
N_2H^+, H_2D^+	—
C^+	—
Metal ions	—
Complex organics	Surface processes
DCO^+, DCN, H_2D^+	Deuterium fractionation

- Large-dipole moment molecules: density
- Optically-thick lines: temperature
- Ions: ionization
- Radicals: FUV/X-ray radiation
- Complex molecules: surface chemistry/ transport processes
- Isotopes: fractionation & thermal history



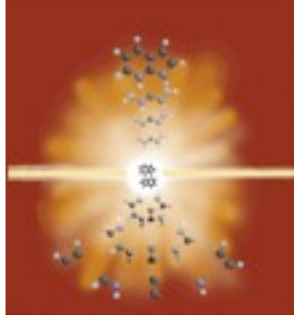
Semenov et al. (2010)

CO isotopologues in disks: T_{kin} (z)



Dartois et al. (2003)

Reactions in disks



Radiative association: $H + C \Rightarrow CH + h\nu$

Surface reactions: $H + O \Rightarrow OH$

Neutral-neutral: $CH + NO \Rightarrow HCN + O$

Ion-molecule: $H_3^+ + CO \Rightarrow H_2 + HCO^+$

Ionization: $H + h\nu, X, CRP \Rightarrow H^+ + e^-$

Photodissociation: $CH \Rightarrow C + H$

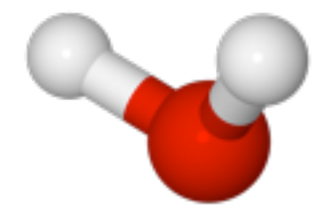
Charge exchange: $H^+ + O \Rightarrow H + O^+$

Dissociative recombination: $H_3O^+ + e^- \Rightarrow H_2O + H$

- ~600 species & ~6000 reactions (no isotopes)
- Only ~10-20% of accurate rates
- Uncertainty in abundances: ~0.5 dex

Gas-phase formation of complex molecules

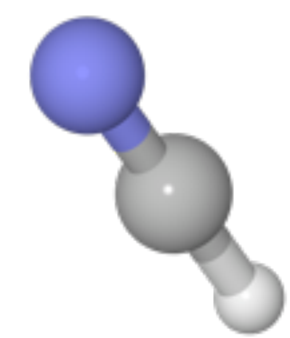
$C^+ + H_2 \Rightarrow CH_2^+$



$CH_2^+ + H_2 \Rightarrow CH_3^+ + H$

$CH_3^+ + H_2/O \Rightarrow CH_5^+/HCO^+ + H_2$

$CH_5^+ + e- \Rightarrow CH_3 + H_2$



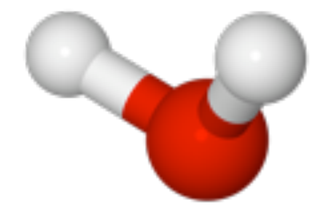
$CH_3 + O \Rightarrow H_2CO$

$CH_3^+ + H_2O \Rightarrow CH_3OH_2^+$

$CH_3OH_2^+ + e- \Rightarrow CH_3OH + H$

Gas-phase formation of complex molecules

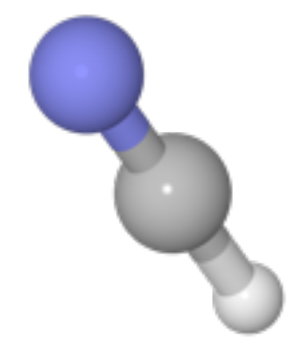
$C^+ + H_2 \Rightarrow CH_2^+$



$CH_2^+ + H_2 \Rightarrow CH_3^+ + H$

$CH_3^+ + H_2/O \Rightarrow CH_5^+/HCO^+ + H_2$

$CH_5^+ + e- \Rightarrow CH_3 + H_2$



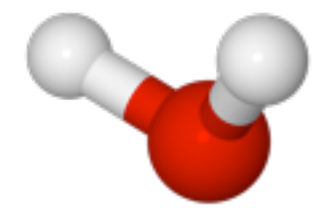
$CH_3 + O \Rightarrow H_2CO$

$CH_3^+ + H_2O \not\Rightarrow CH_3OH_2^+$ (too low rate, Luca et al. 2002)

$CH_3OH_2^+ + e- \Rightarrow CH_3OH + H$

Gas-phase formation of complex molecules

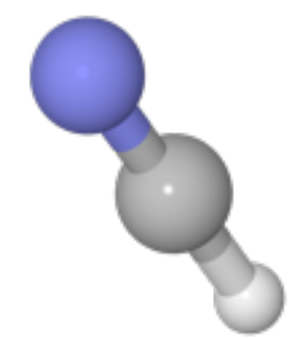
$C^+ + H_2 \Rightarrow CH_2^+$



$CH_2^+ + H_2 \Rightarrow CH_3^+ + H$

$CH_3^+ + H_2/O \Rightarrow CH_5^+/HCO^+ + H_2$

$CH_5^+ + e- \Rightarrow CH_3 + H_2$

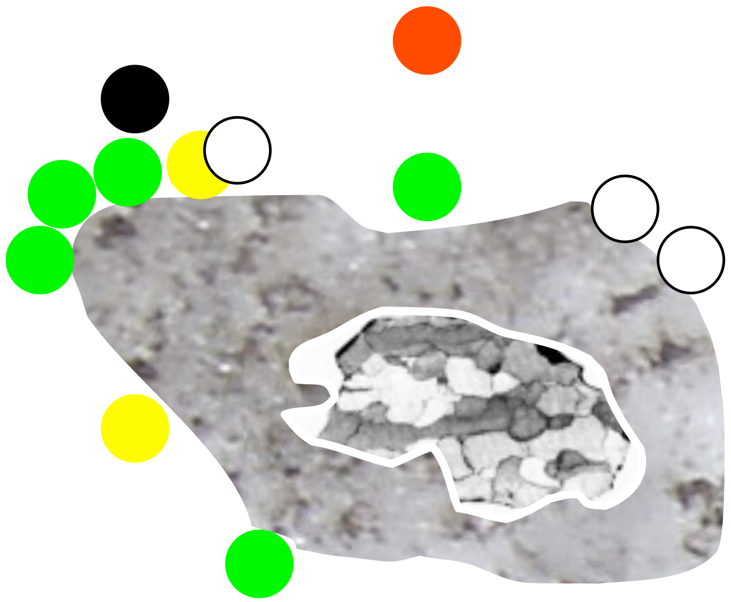


$CH_3 + O \Rightarrow H_2CO$

$CH_3^+ + H_2O \not\Rightarrow CH_3OH_2^+$ (too low rate, Luca et al. 2002)

$CH_3OH_2^+ + e- \Rightarrow CH_3OH + H$ (3 ± 2%, Geppert et al. 2006)

Surface formation of complex molecules



- Accretion
- Surface synthesis
- Photoprocessing of ices
- Desorption: T, UV, CRPs

Surface chemistry:

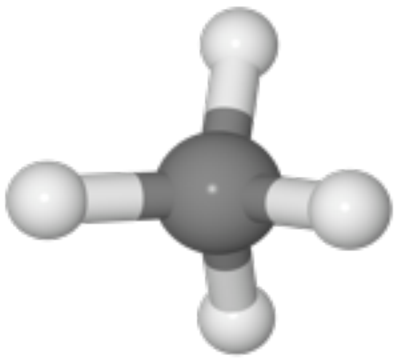
$O \Rightarrow OH \Rightarrow H_2O$

$N \Rightarrow NH \Rightarrow NH_2 \Rightarrow NH_3$

$C \Rightarrow CH \Rightarrow CH_2 \Rightarrow CH_3 \Rightarrow CH_4$

$CO \Rightarrow HCO \Rightarrow H_2CO \Rightarrow H_3CO \Rightarrow CH_3OH$

C + C, CO + OH, etc. in warm regions



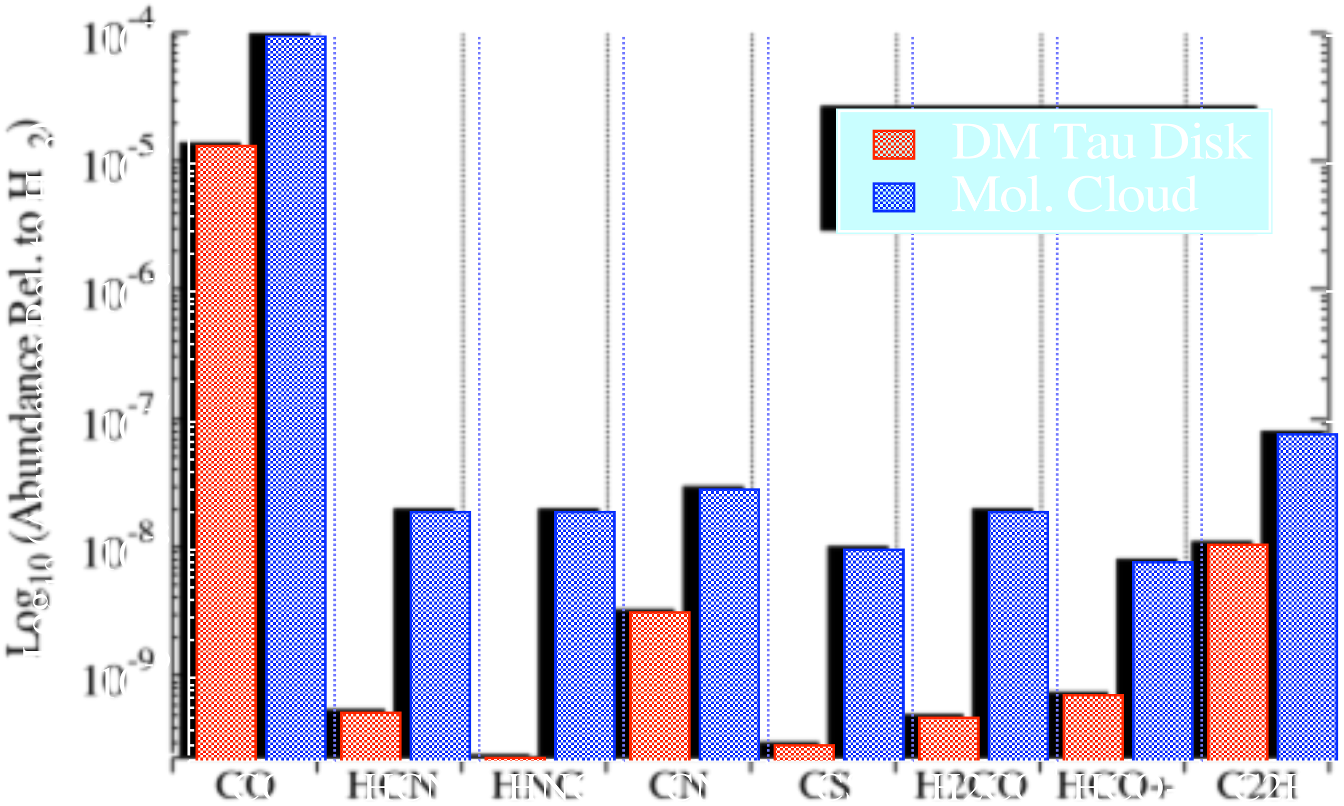
III. Observations of molecules in PPDs

- IR (space) spectroscopy:
  - inner regions: <20 AU
  - rotational/vibrational lines
  - absorption/emission
  - Boltzmann diagrams, LTE, T_{kin}

- (Sub-)millimeter observations:
  - outer regions: >50–100 AU
  - rotational/vibrational lines
  - emission lines
  - antennas: no spatial information, surveys
  - interferometers: resolved structures, restricted disk sample

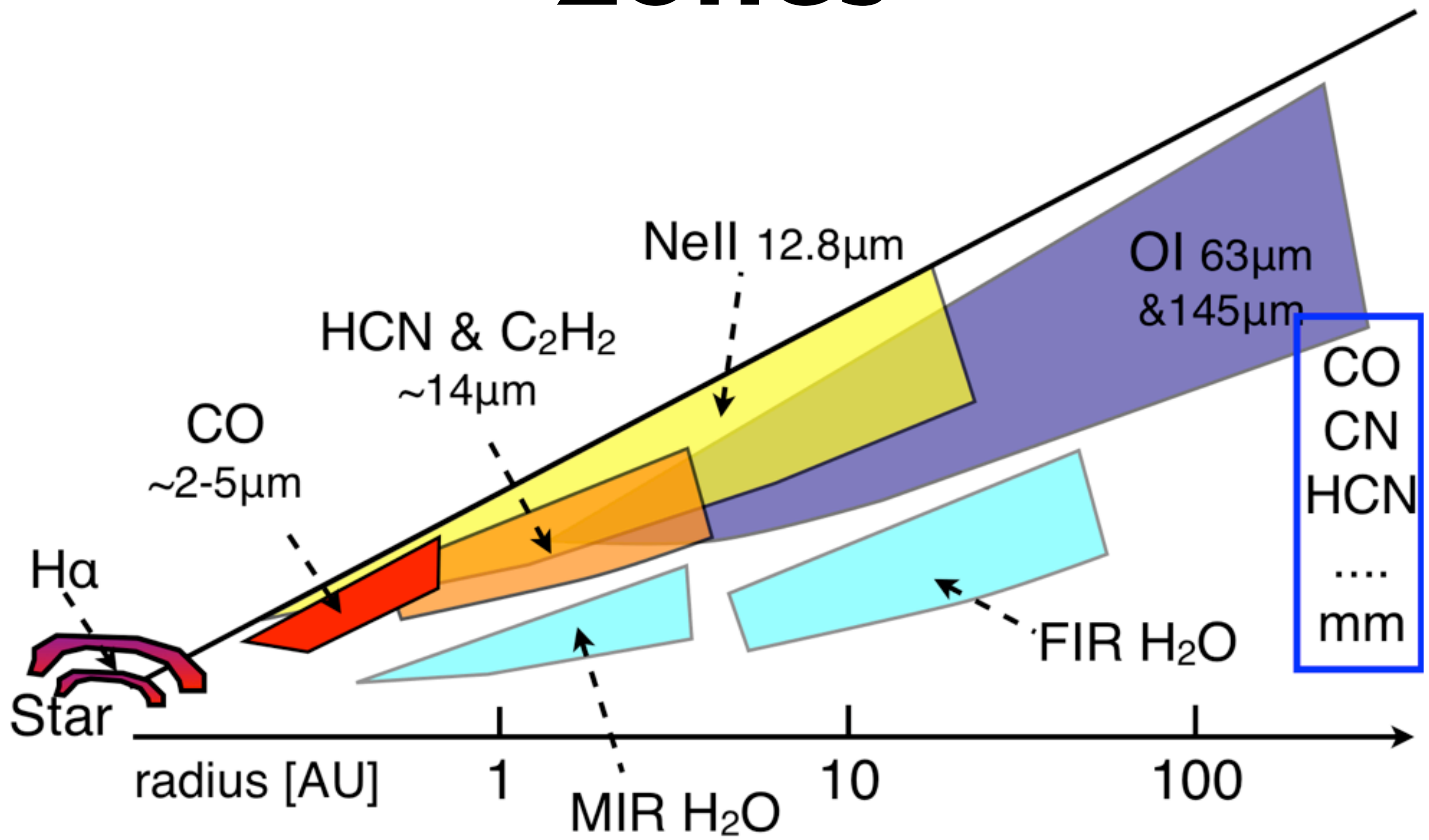
Observational findings: outer disks

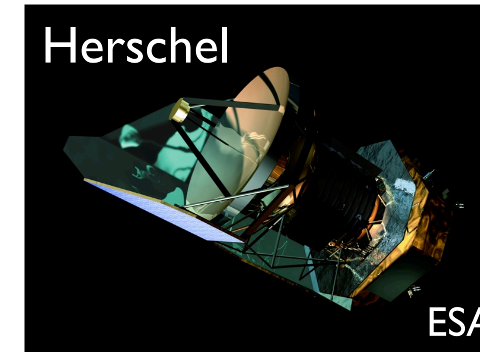
- Gas: depletion of molecules
- Ices: H_2O, NH_3, CH_4, H_2CO, CH_3OH
- Vertical gradients of T
- Photo-dominated chemistry
- Cold CO, CCH, HCN
- "Dry" interiors: where is water?
- Keplerian rotation
- Non-thermal line broadening



Bergin et al. (2007), Dutrey et al. (2007), Semenov et al. (2010)

IR revolution: molecules in planet-forming zones

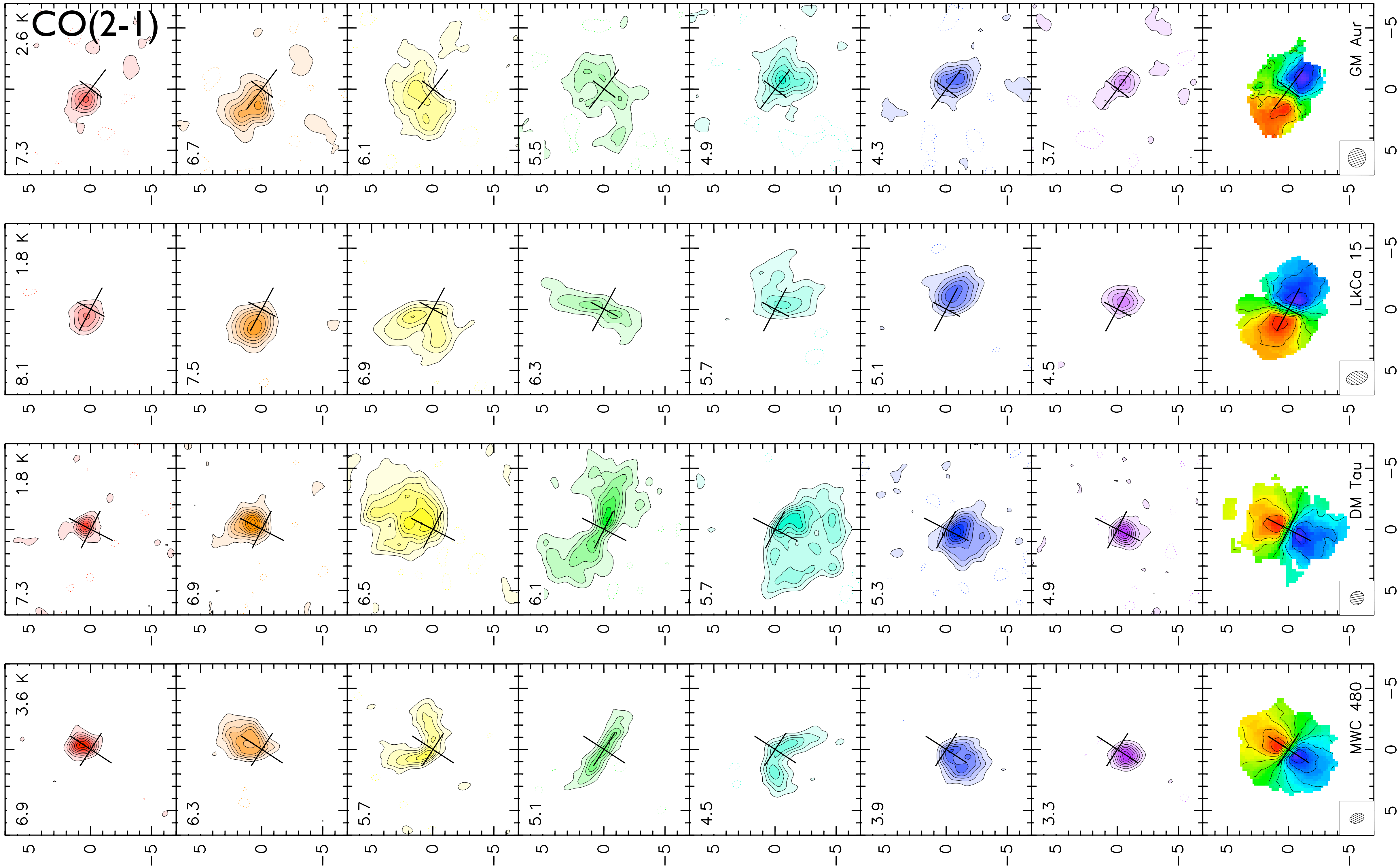




- NeII, FeII, OI, H_2, OH, H_2O, CO_2, HCN and C_2H_2
- Warm gas: T $\gtrsim$ 100 – 5000 K
- No depletion
- Non-Keplerian profiles: disk wind?
- Herbig Ae disks appears to be deficient in H_2O and organics

(Lahuis ++ 06, Pascucci ++ 07-11, Salyk ++ 08-11, Pontoppidan ++ 07-11, Carr & Najita 08, Kamp++11)

Kinematics: weighting stars



- M_* from high SNR measurements of Ω_K: evolutionary track models

Simon et al. (2000)

Chemistry in T Tau and Herbig Ae disks

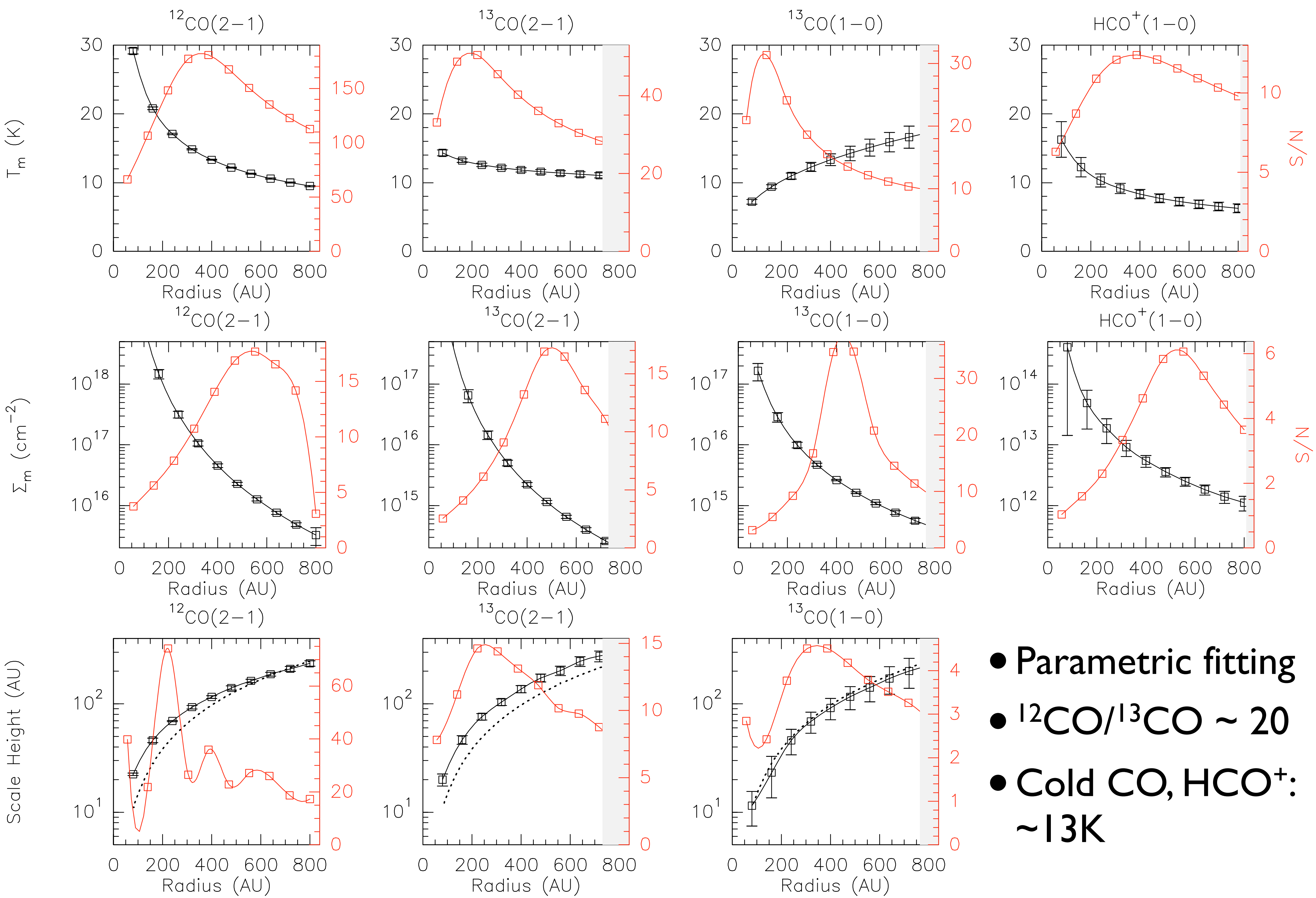
- Large programs: "Chemistry in Disks" (CID), Europe
- CID strategy: observations + modeling
- "Disk Imaging Survey of Chemistry with SMA" (DISCS), USA
- DISCS strategy: observations

- Limited sample: large, face-on disks (~6)
- Lines are weak: ~0.3–3K (0.1–1Jy)
- 1 line: ~1–10 hours

- Herbig Ae: CO, HCO^+, CN, HCN
- T Tau: CO, HCO^+, HCN, N_2H^+, CCH, CS, H_2CO, DCO^+, DCN

Dutrey et al. (2007), Schreyer et al. (2008), Henning et al.(2010), Öberg et al. (2010-11)

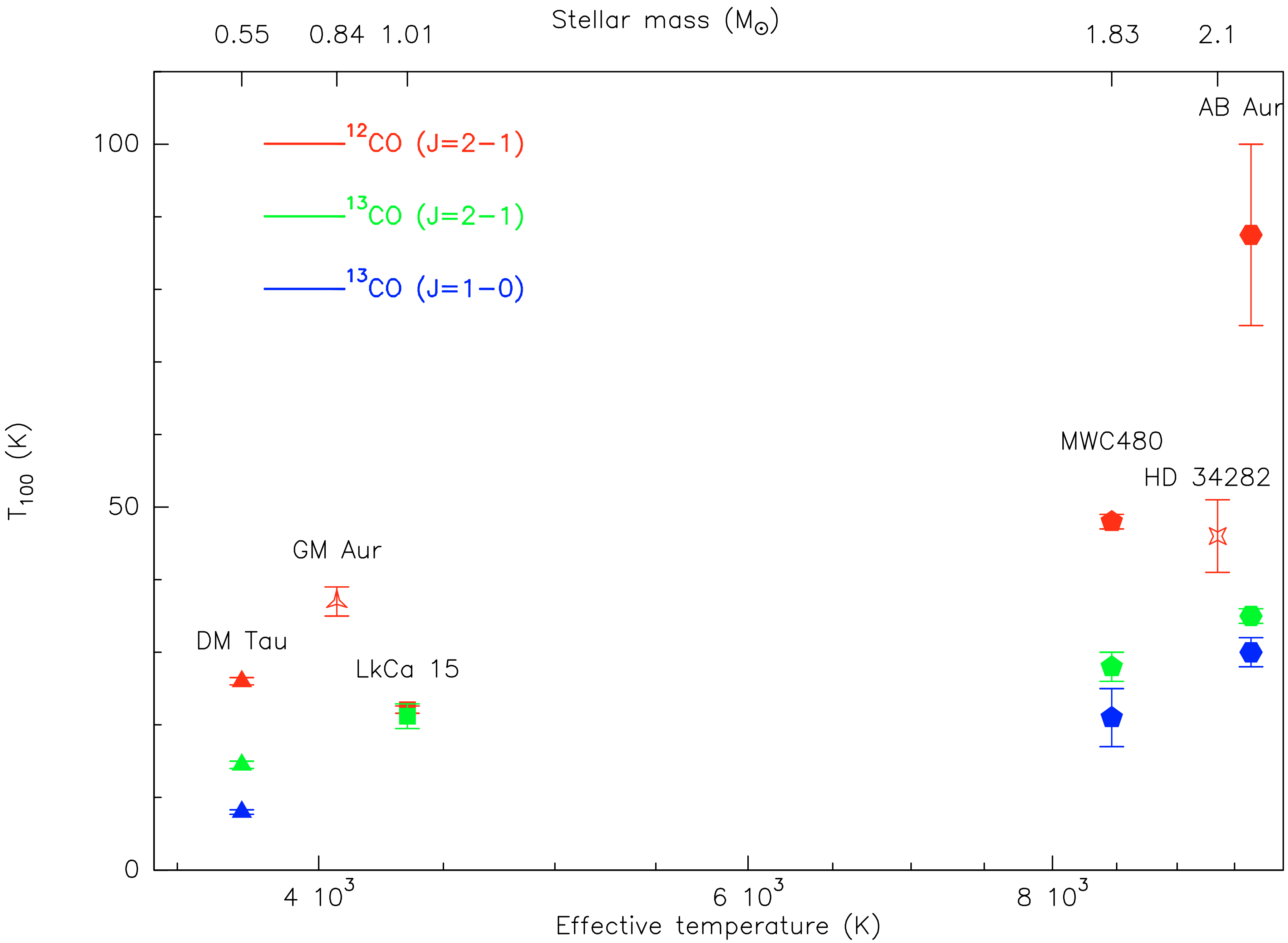
Resolved surface density & T: DM Tau



- Parametric fitting
- ^{12}CO/^{13}CO ~ 20
- Cold CO, HCO$^+$: ~13K

Pietu et al. (2007)

Temperature in T Tau and Herbig Ae disks

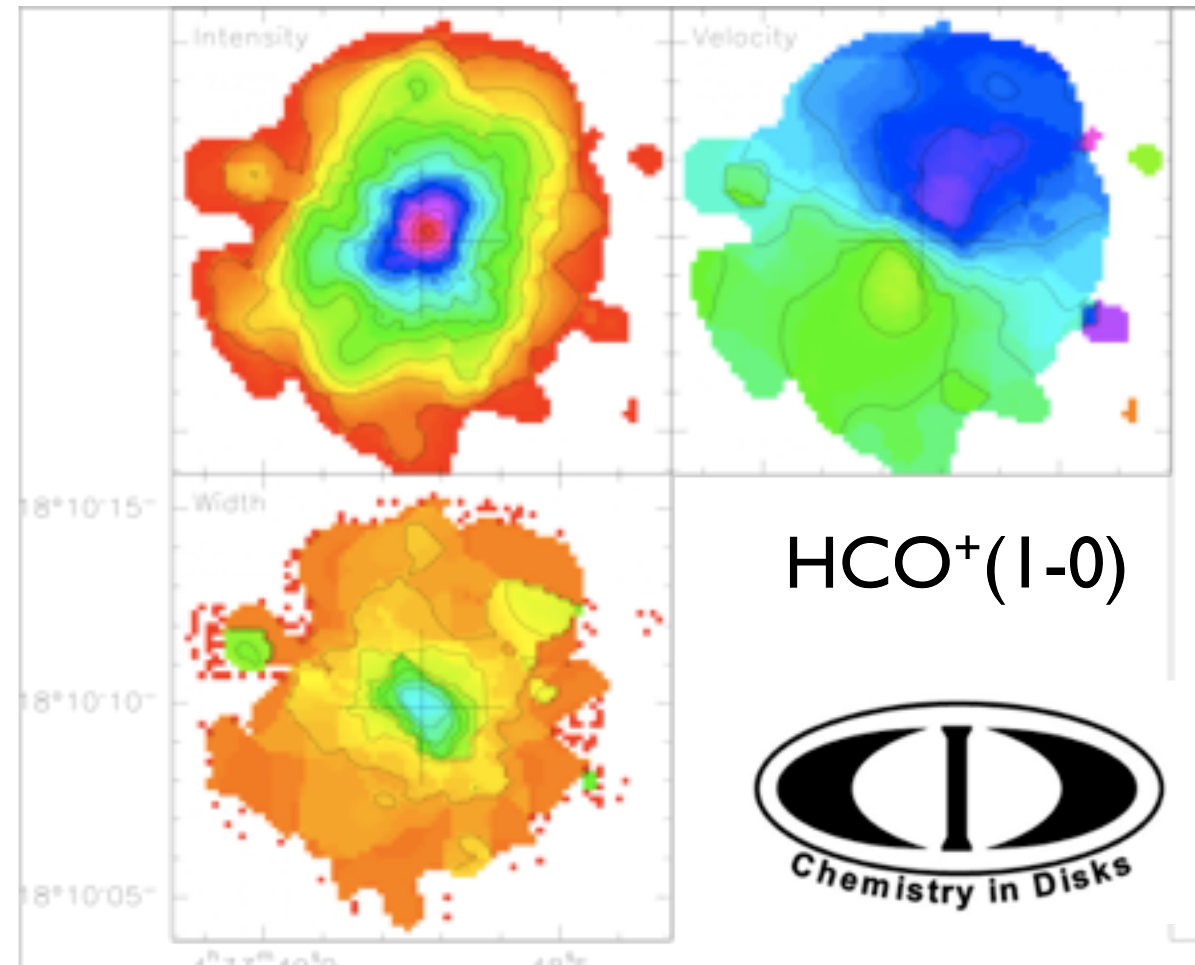


- "Warm" Herbig Ae disks: T_{kin} > 20–100K
- "Cool" T Tauri disks: T_{kin} ~ 10–30K
- No gradient in LkCa 15: inner hole of ~ 45 AU
- Are transitional disks peculiar?

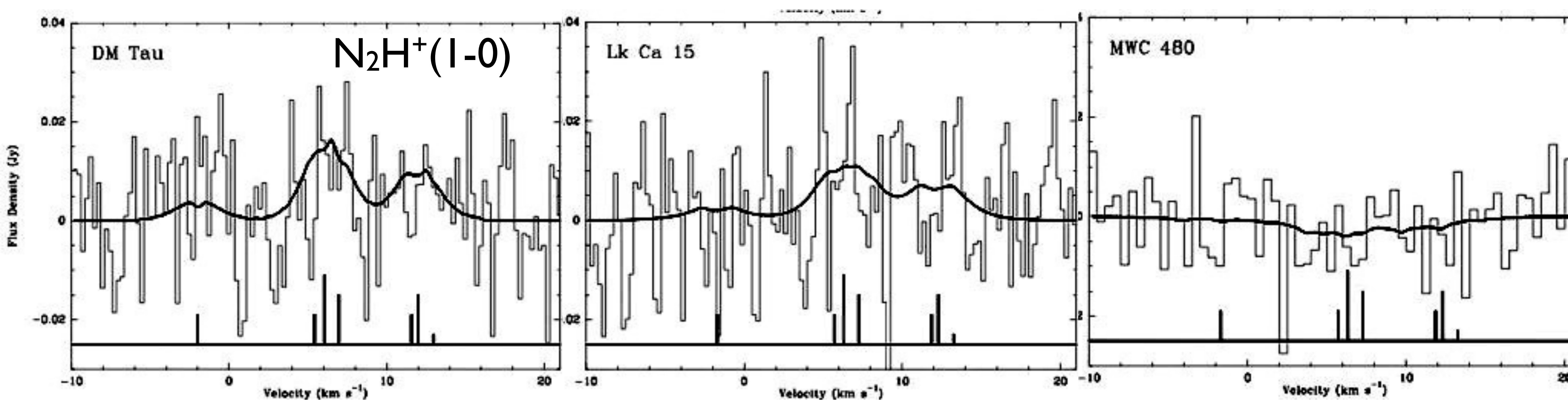
Pietu et al. (2007)

Ionization: HCO^+ and N_2H^+

- LkCa15 (K5), DM Tau (M1) and MWC480 (A4)
- J=1-0, 2-1
- Two 5σ detections: N_2H^+ in LkCa15 & DM Tau
- Upper limit: MWC480

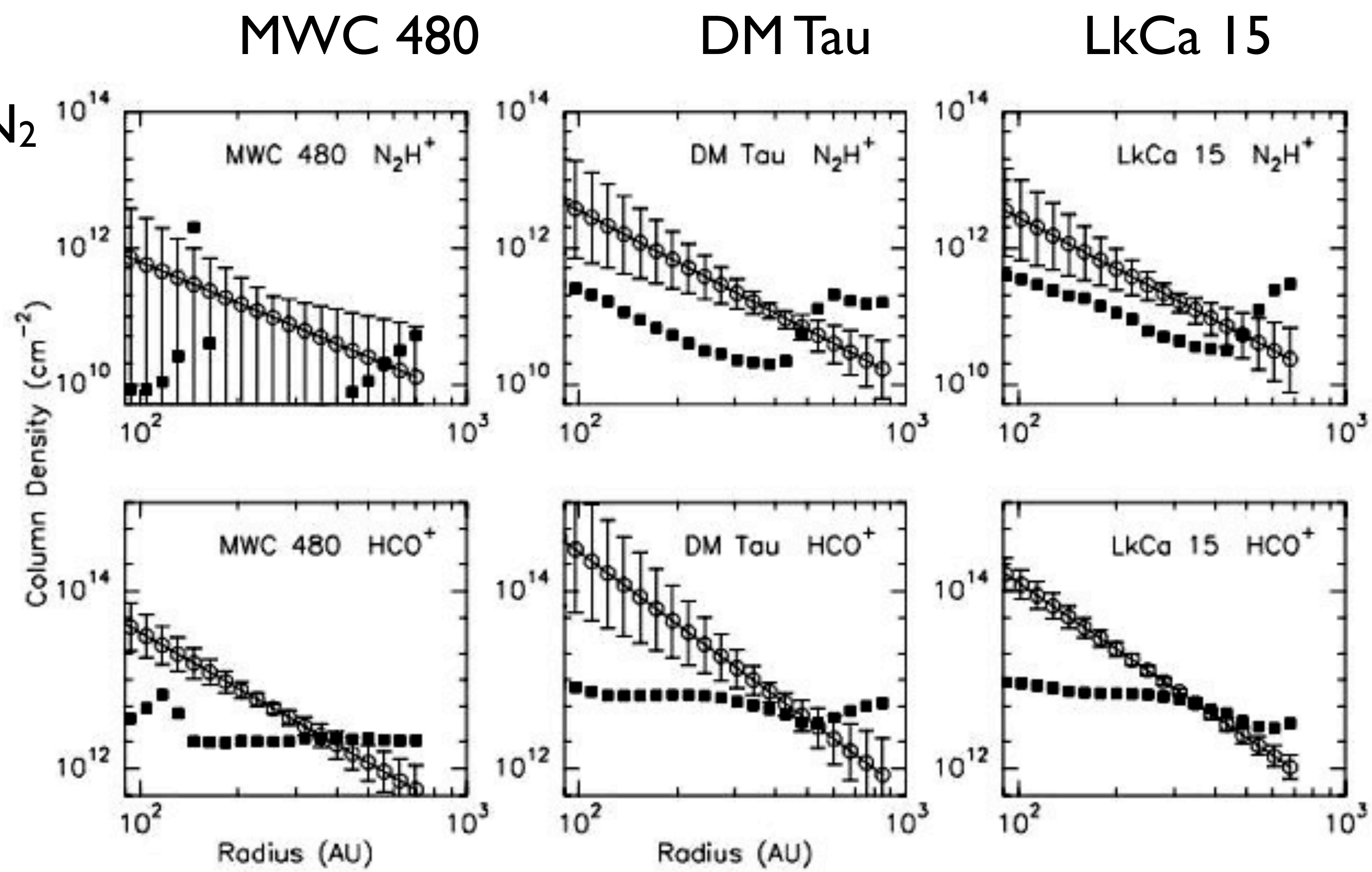


Dutrey et al. (2007)



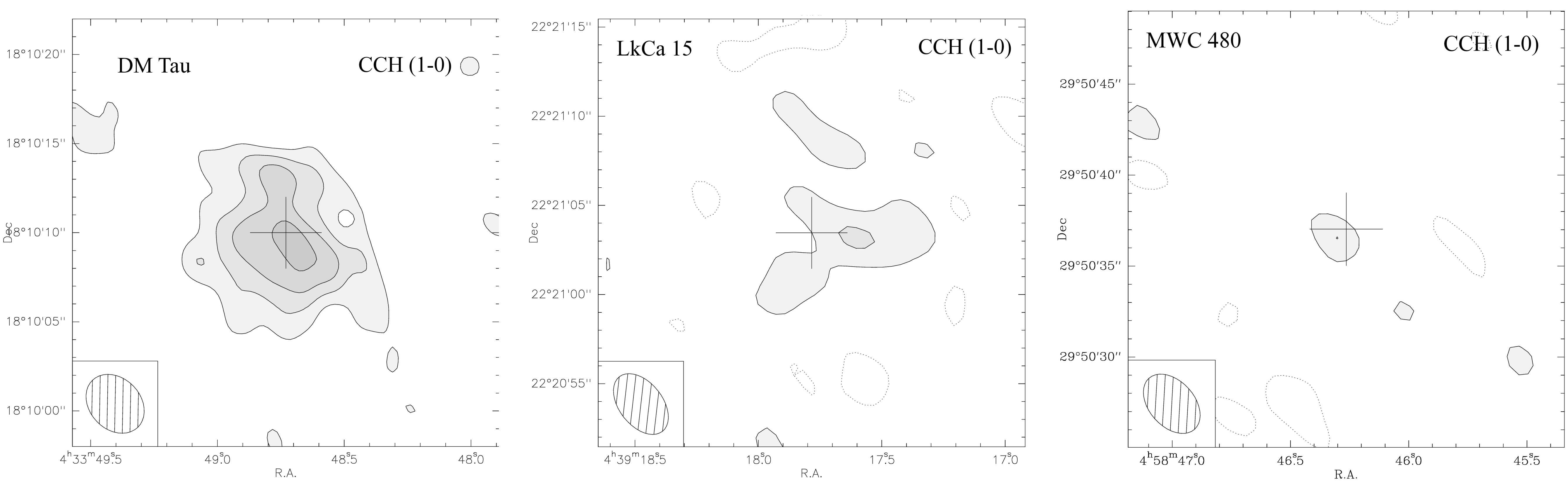
Ionization: HCO^+ and N_2H^+

- HCO^+ is dominant ion:
  $N_2H^+ + CO \Rightarrow HCO^+ + N_2$
- $[N_2H^+]/[HCO^+] \sim 2$–5%
- $X(e) > \sim 10^{-10}$
- Radial profiles are poorly reproduced
- Absolute values are in qualitative agreement



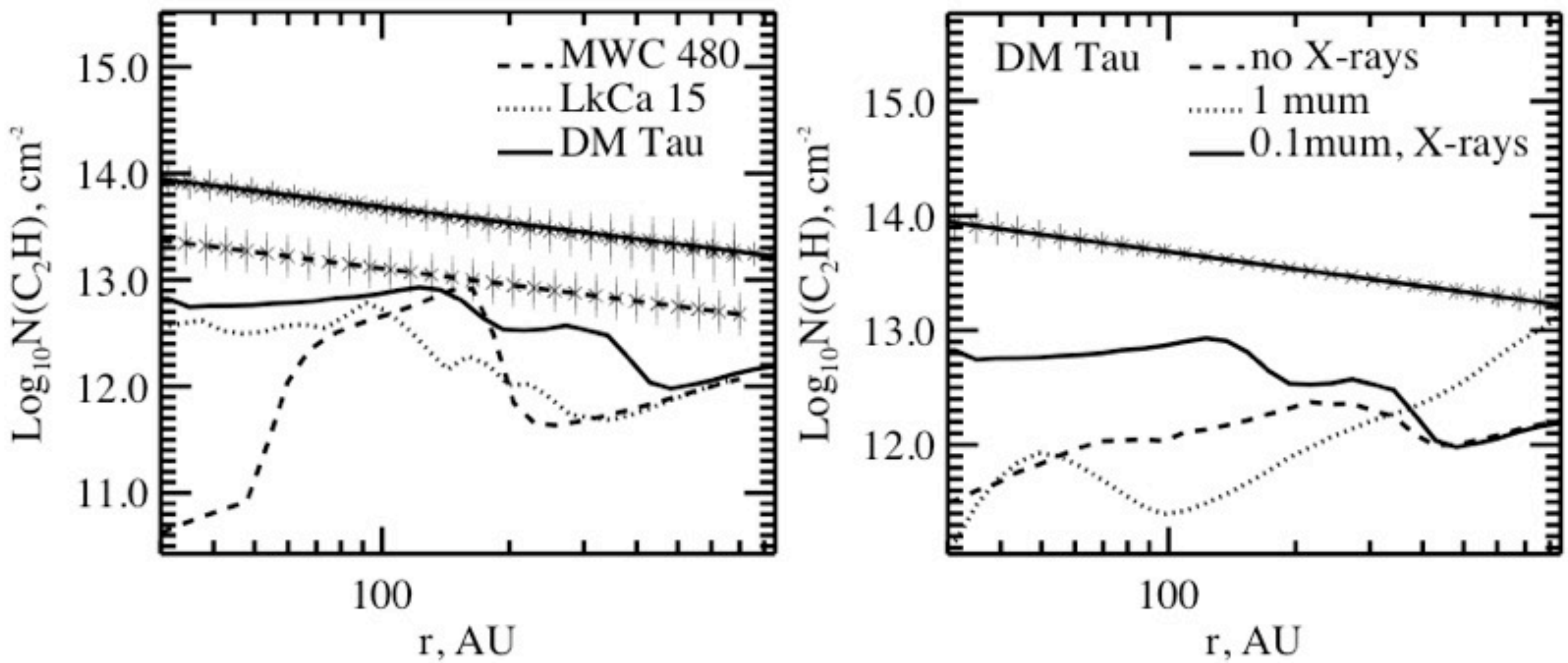
X-ray-driven chemistry in disks

- DM Tau (M1), LkCa 15 (K5), MWC 480 (A4)
- CCH (1-0) & (2-1)
- Hard to photodissociate
- Chemistry is known



Henning et al. (2010)

X-ray-driven chemistry in disks



- T_{exc}: ~6 K
- Large-scale mixing or sub-thermal excitation?
- Less CCH in MWC 480
- Strong photodissociation by the Herbig Ae star?
- Low L_X in MWC 480: less efficient ion-molecule chemistry?

Chemistry in T Tau and Herbig Ae disks

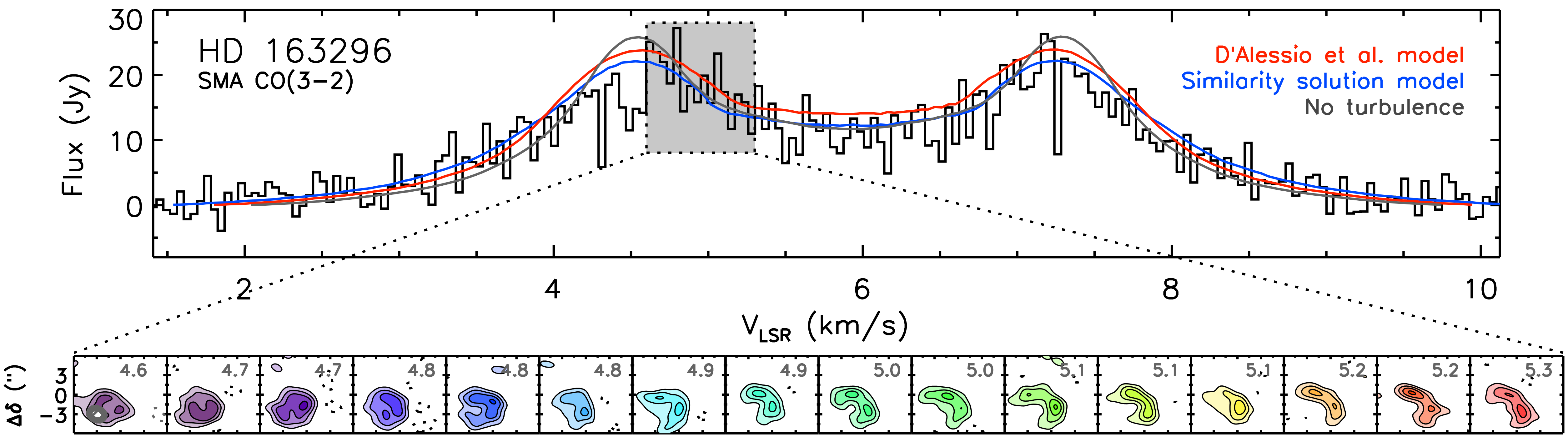
Molecule	χ^2-minimization method			Chemical model		DM Tau
	N [cm^{-2}]	1 σ error	$N/N(^{13}CO)^{(1*)}$	N [cm^{-2}]	$N/N(^{13}CO)^{(2*)}$	$N/N(^{13}CO)^{(1*)}$
H_2	$6\,10^{22}$	$1\,10^{22}$	$1.5\,10^{6}$	$5\,10^{22}$	$1.3\,10^{6}$	$1\,10^{7}$
$^{13}CO^{(*3)}$	$4\,10^{16}$	$5\,10^{15}$	1	$4\,10^{16}$	1	1
HCO^+	$6\,10^{12}$	$3\,10^{11}$	$1.5\,10^{-4}$	$1.5\,10^{13}$	$4\,10^{-4}$	$2\,10^{-3}$
HCN	$5\,10^{11}$	$3\,10^{11}$	$1.3\,10^{-5}$	$4\,10^{11}$	10^{-5}	$7\,10^{-4}$
CS	$3\,10^{12}$	$3\,10^{12}$	$< 8\,10^{-5}$	$2\,10^{11}$	$5\,10^{-6}$	$3\,10^{-4}$
C_2H	$2\,10^{13}$	$2\,10^{13}$	$< 5\,10^{-4}$	10^{10}	$2.5\,10^{-7}$	10^{-3}
CH_3OH	0	$7\,10^{15}$	$< 2\,10^{-1}$	0	0	0

- AB Aur: less amount of complex molecules per CO
- Are Herbig Ae disks "deserts" for complex molecules?

- No CO freeze-out in Herbig Ae disks: no surface chemistry
- Lower L_X: less efficient ion-molecule chemistry
- $CO + He^+ \Rightarrow C^+ + O + He^+$

Schreyer et al. (2009), Öberg et al. (2010-11)

Turbulence in disks



- Temperature from CO lines
- Keplerian velocity: M_*, r
- Subsonic components: ~0.1–0.4 km/s
- Comparable with MHD models

Dutrey et al. (2007), Hughes et al. (2011)

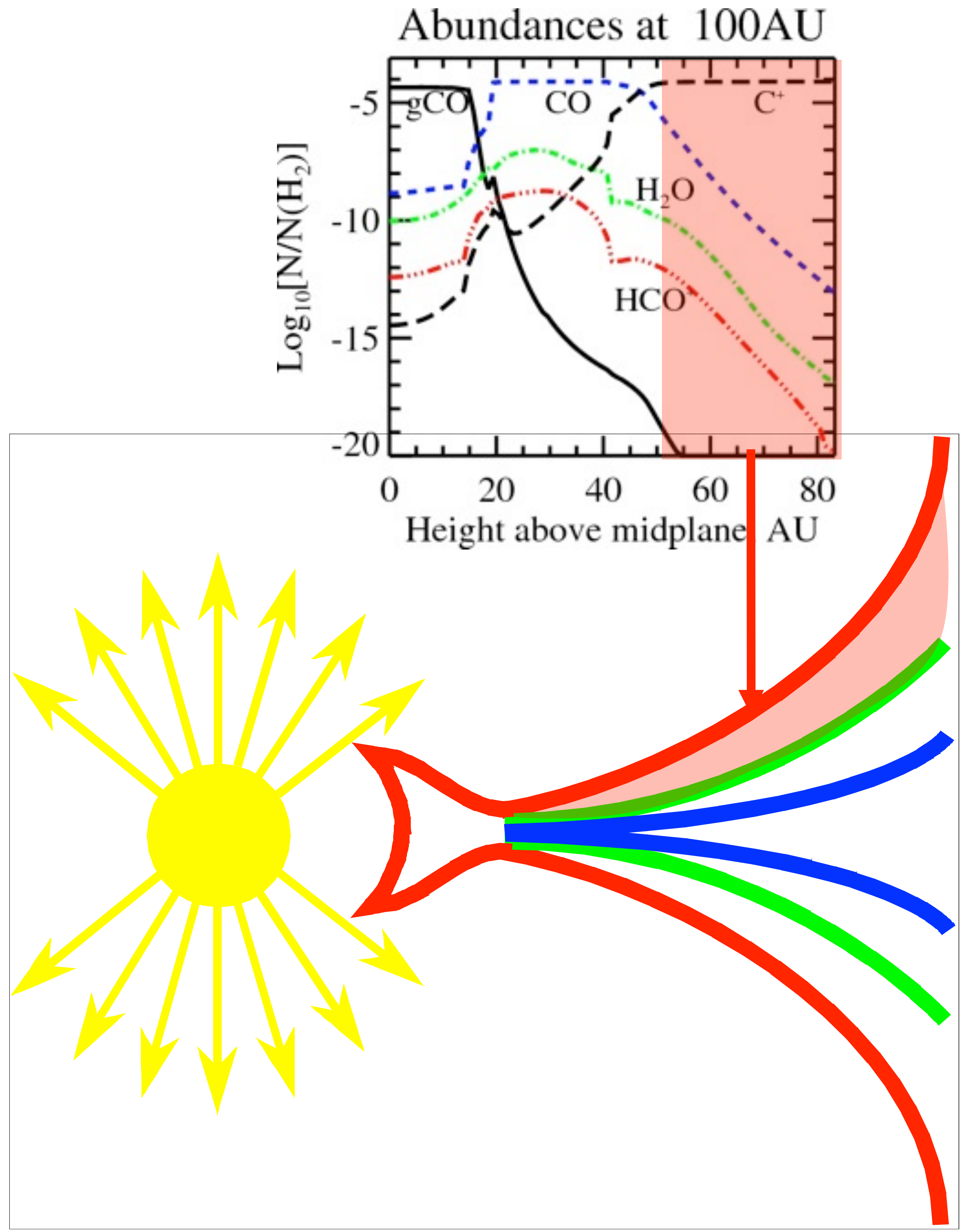
III. Observations of molecules in PPDs: Summary

- Probes of disk structure
- Analysis techniques are available
- Vertical gradients of T
- CO freeze-out in "cold" T Tauri disks
- "Warm" Herbig Ae disks are less rich in molecules
- High-energy stellar radiation
- Models are in "qualitative" agreement
- Turbulent line broadening
- Rich inner disk chemistry

IV. Disk chemical structure from modeler's perspective

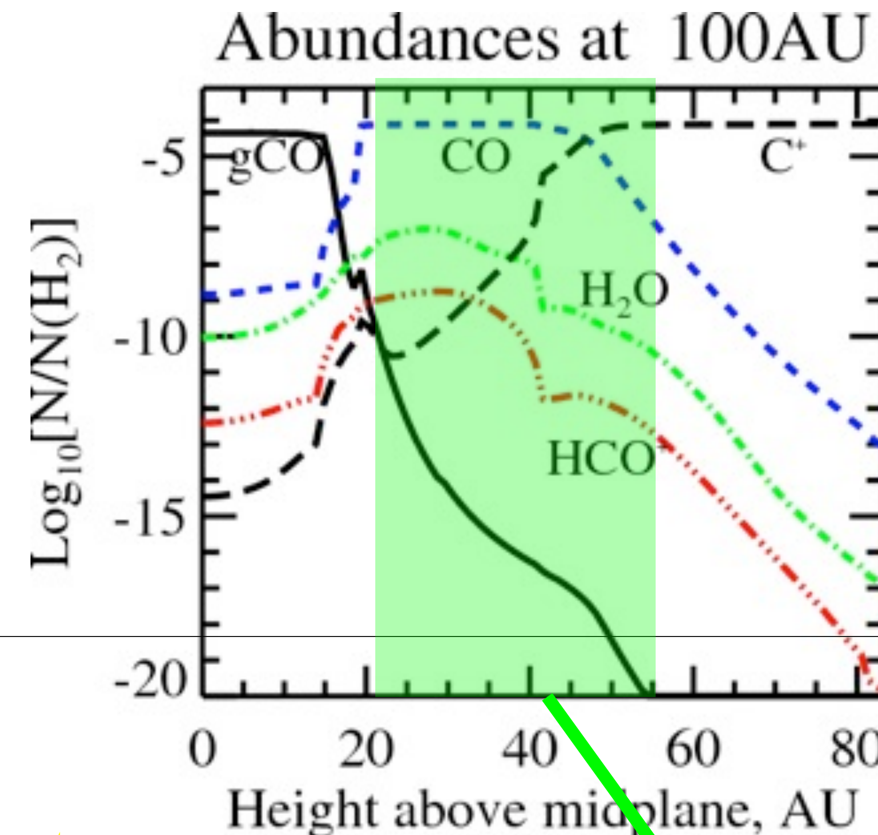
Zone of ions and radicals (atmosphere)

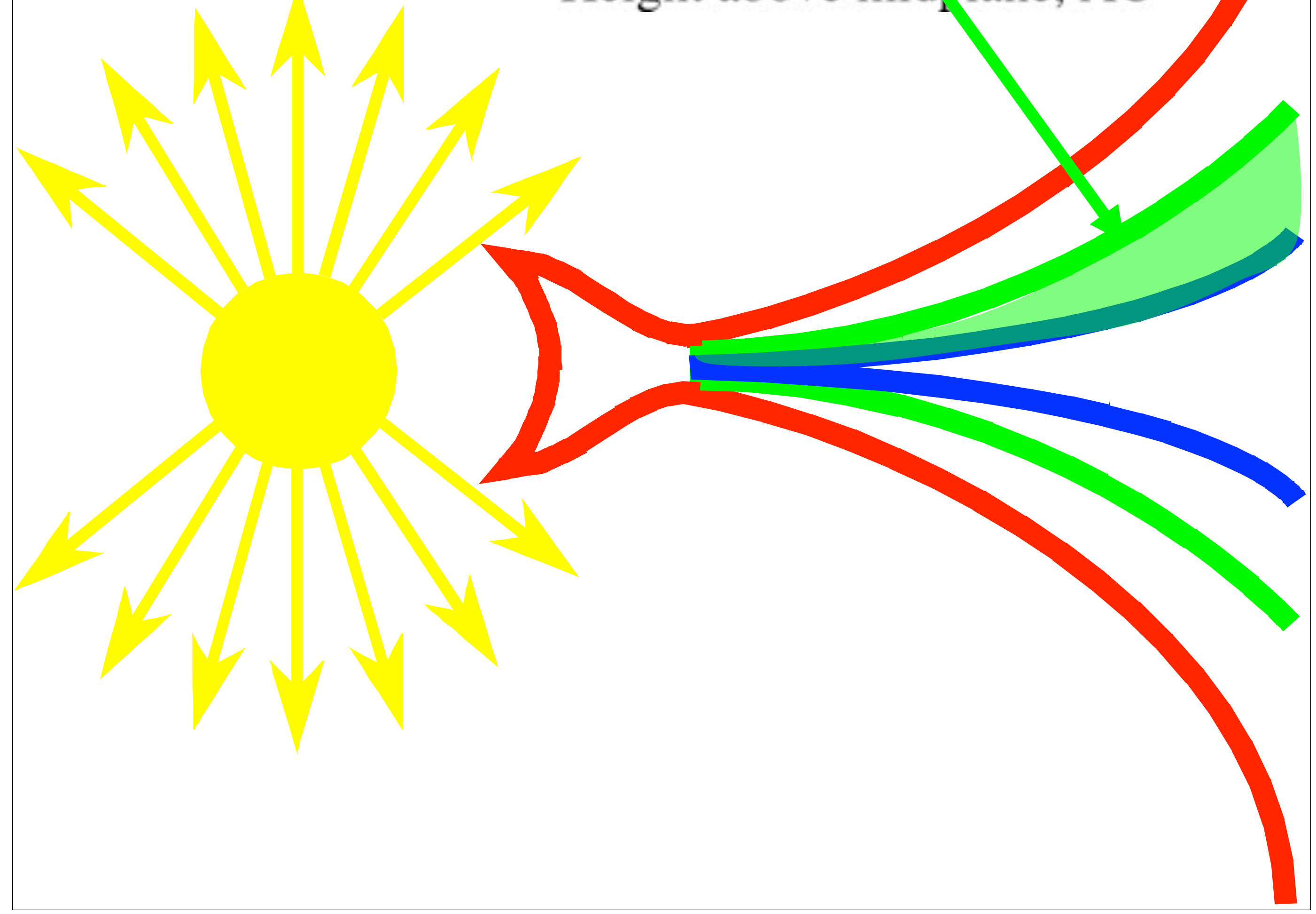
- Intense UV and X-rays
- Low densities
- High temperatures
- High ionization degree
- Limited gas-phase chemistry



Zone of molecules (intermediate layer)

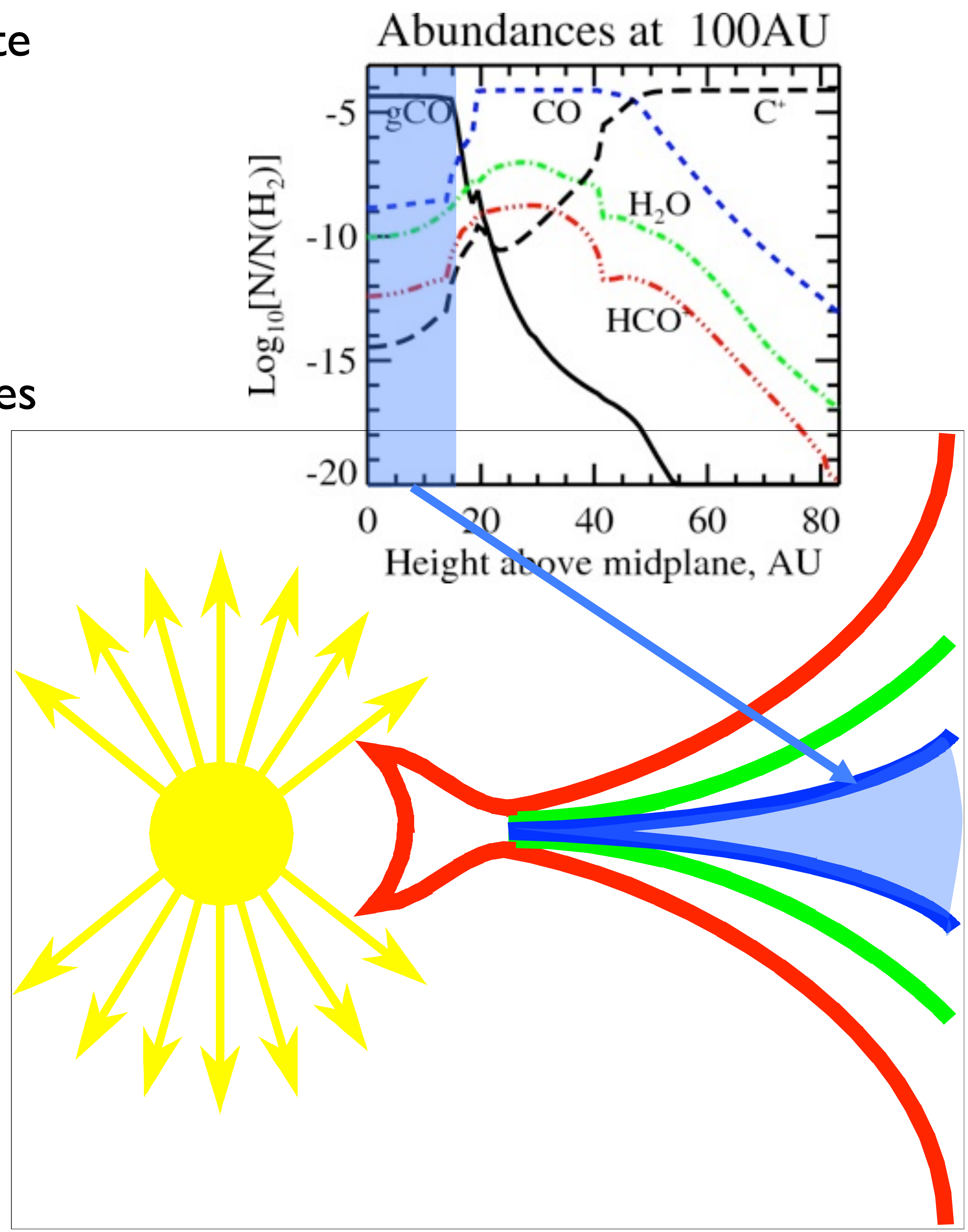
- Partly shielded from UV and X-rays
- Moderate densities
- Moderate temperatures
- Oasis of rich chemistry: gas-surface cycling, photoprocessing of ices
- Most molecular lines are excited here





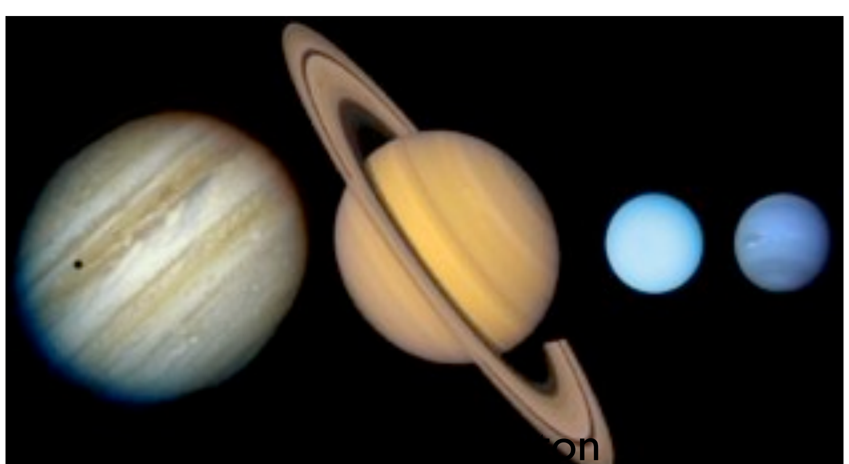
Zone of ices (midplane)

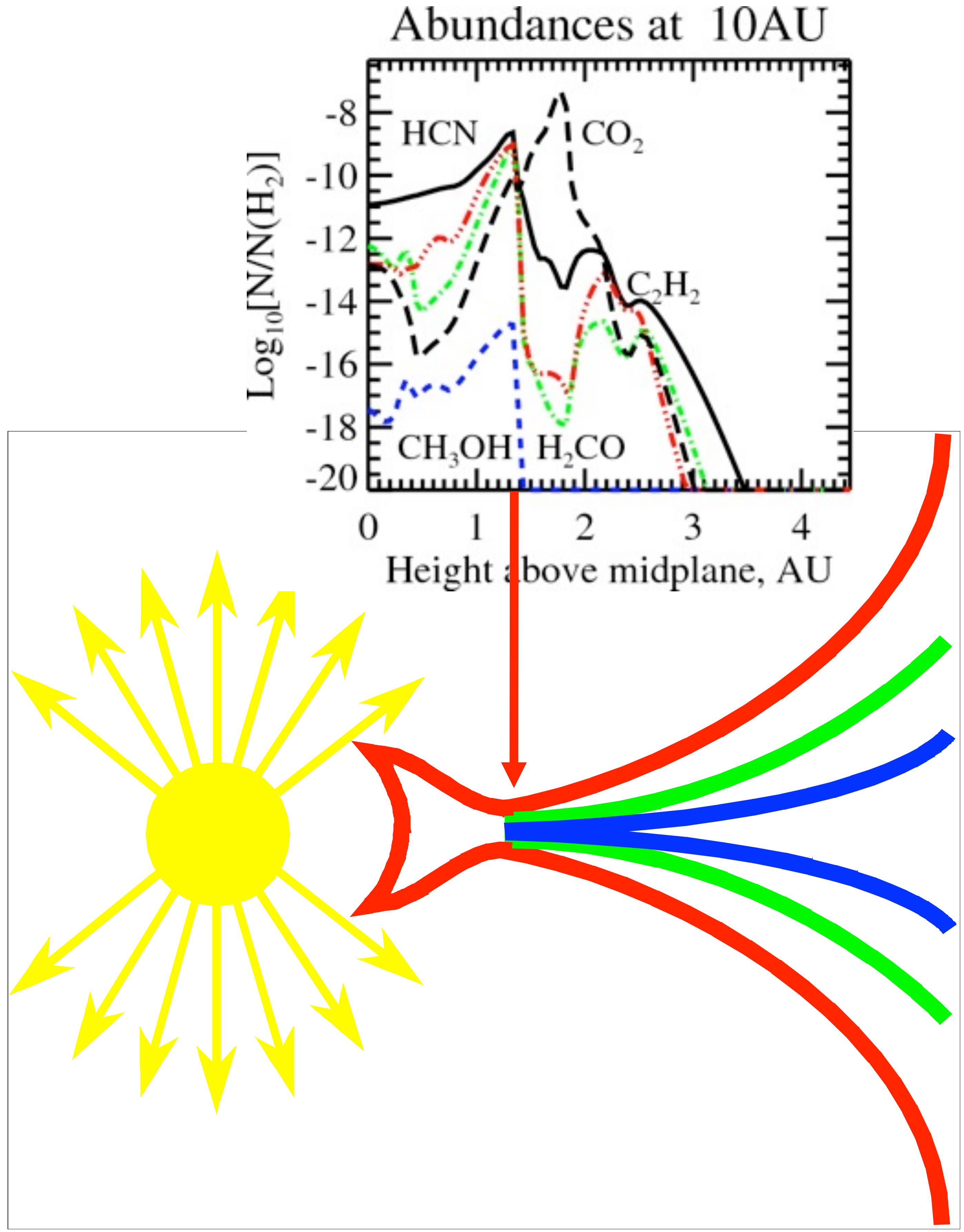
- Only cosmic rays can penetrate
- High densities
- Low temperatures
- Molecules are frozen out
- Rich chemistry on dust surfaces



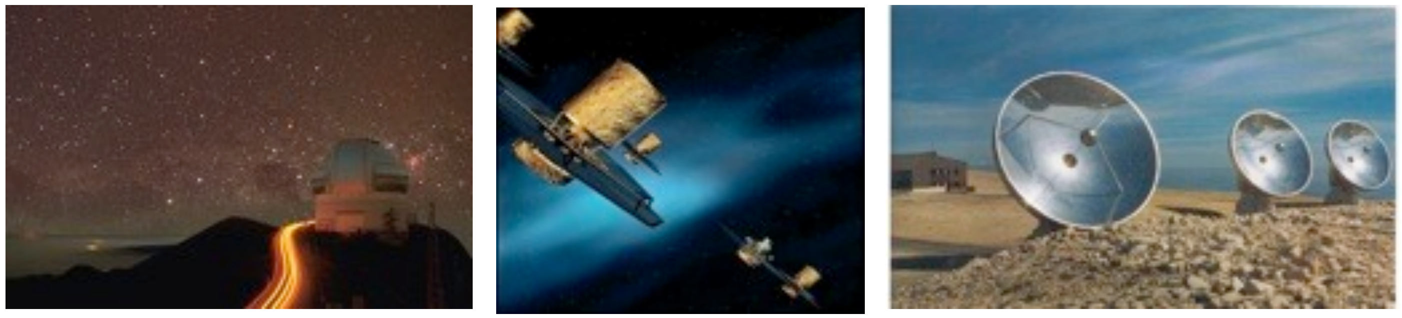
Inner, planet-forming zone

- High n, T
- Reactions with barriers
- 3-body collisions
- X-ray-driven processes
- No freeze-out
- Fast grain evolution

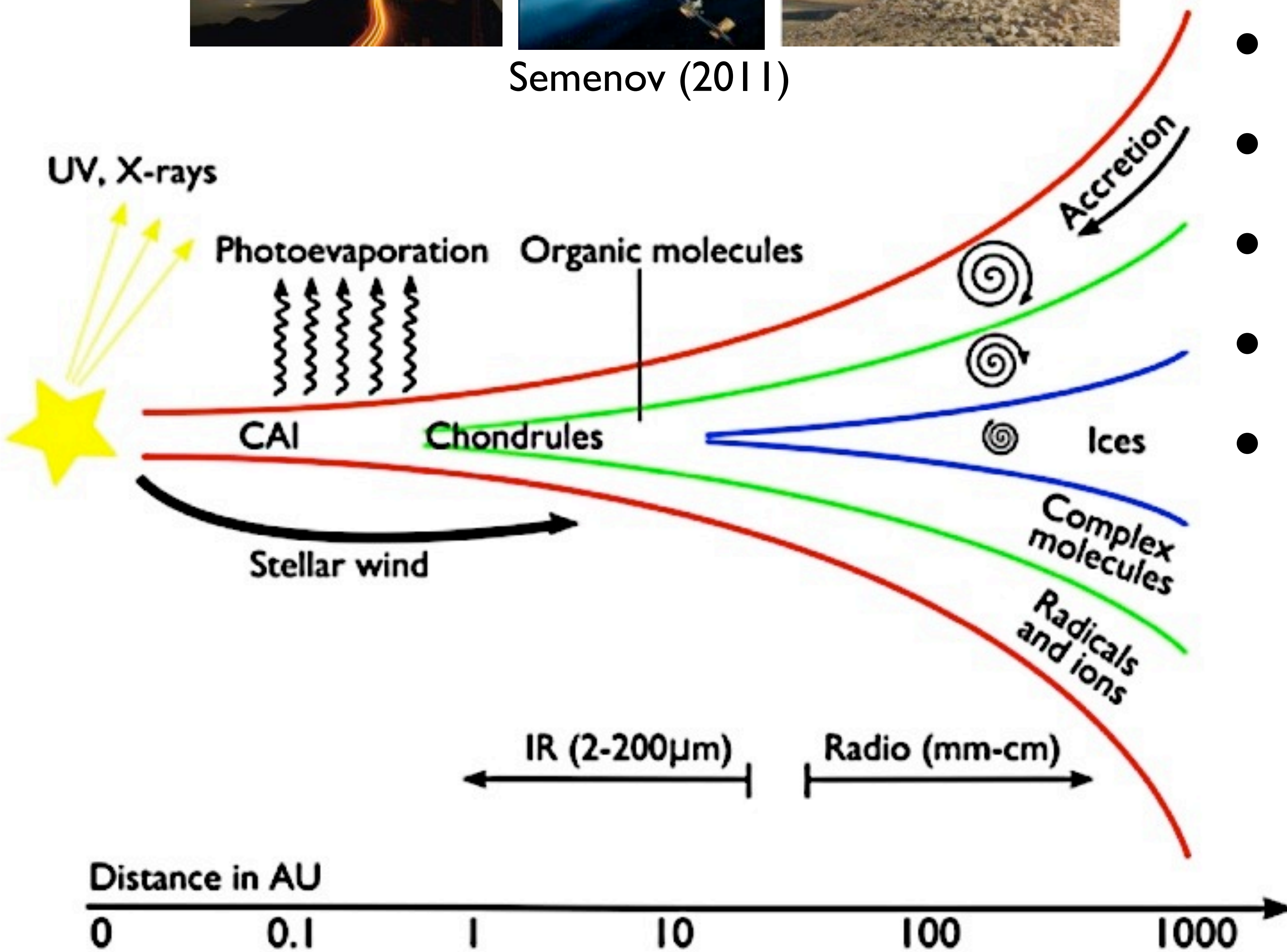




A scheme of disk structure



Semenov (2011)



- Wide range of T & n_H
- FUV, X-rays, cosmic rays
- Dynamical evolution
- Photoevaporation
- Grain evolution
- No equilibrium

IV. Disk chemical structure from modeler's perspective: Summary

- "Sandwich"-like chemical structure
- Cold midplane: freeze-out, thick ices, surface chemistry
- Hot atmosphere: dissociation/ionization, ions/radicals, gas-phase chemistry
- Warm molecular layer: oasis of molecules, UV-assisted gas-phase & gas-grain chemistry
- Dense planet-forming zone: endothermic neutral-neutral chemistry, X-ray-assisted ion-molecule chemistry

V. Modeling disk chemistry

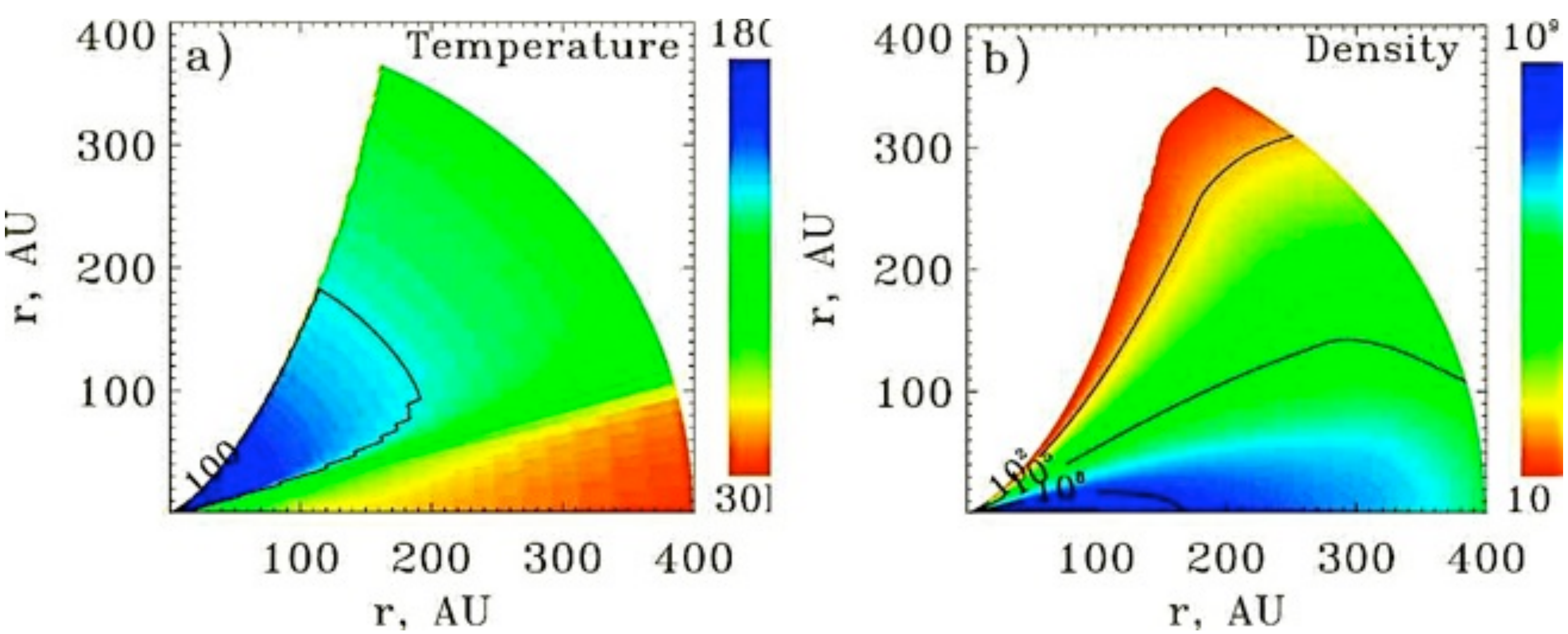
Chemical kinetics equations

$$\frac{\partial n_i}{\partial t} = \Sigma_{j,k\neq i} k_{jk} n_j n_k - n_i \Sigma_l k_l n_l + \nabla D n_{\rm H} \nabla n_i / n_{\rm H} - \nabla U n_i$$

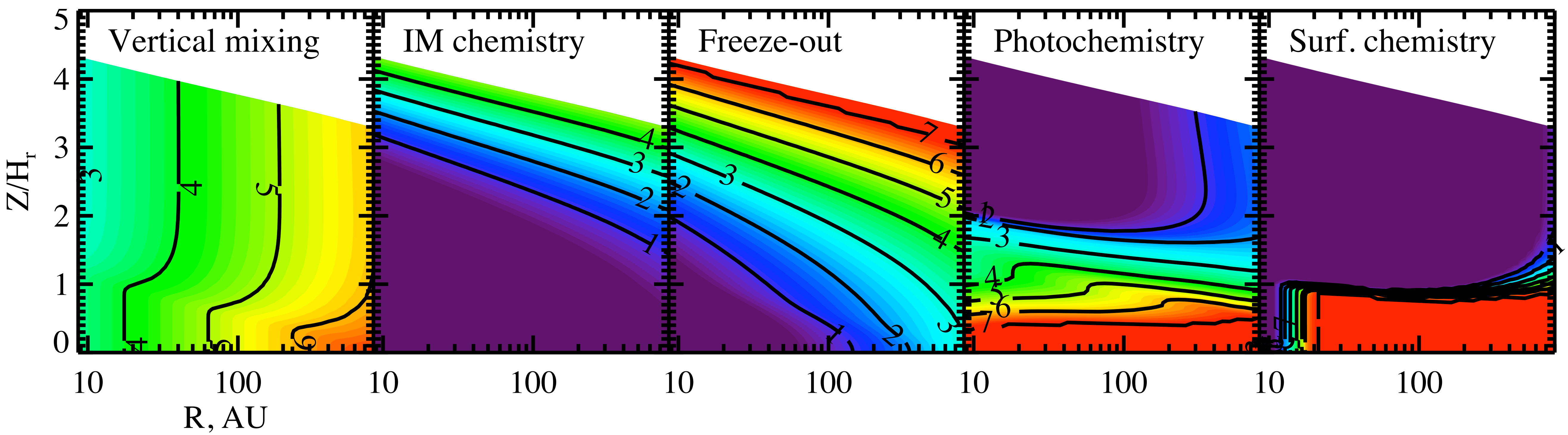
Evolution = Formation - Destruction + Diffusion + Advection

[Chemistry] [Dynamics]

- Physical conditions
- Initial abundances of molecules
- Grain properties
- Reaction data
- Chemical code



Timescales in disks: chemistry vs dynamics



Characteristic Timescales: Outer Disk (250 AU)

Processes	Midplane [yr]	Warm layer* [yr]	Atmosphere* [yr]
Mixing	1.0 (6)	2.5 (5)	1.4 (5)
Gas-phase	2.0 (-2)	1.8 (-1)	2.9 (0)
UV	>1.0 (7)	1.2 (6)	3.1 (1)
Accretion	2.7 (1)	1.8 (2)	2.3 (3)
Desorption	1.0 (6)	4.3 (0)	<1.0 (-7)
Surface	>1.0 (7)	>1.0 (7)	1.4 (5)

*

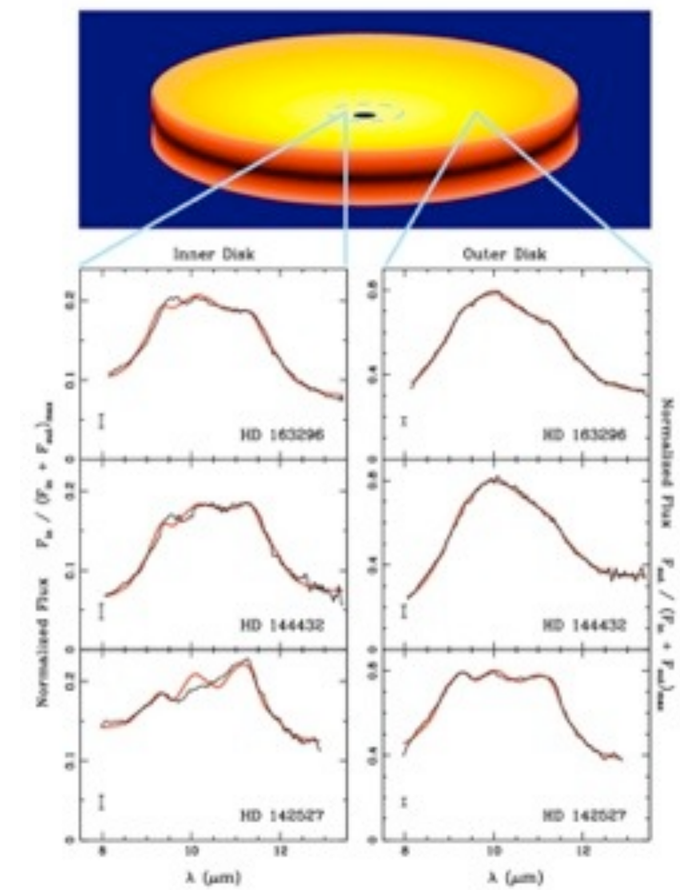
Semenov & Wiebe (2011)

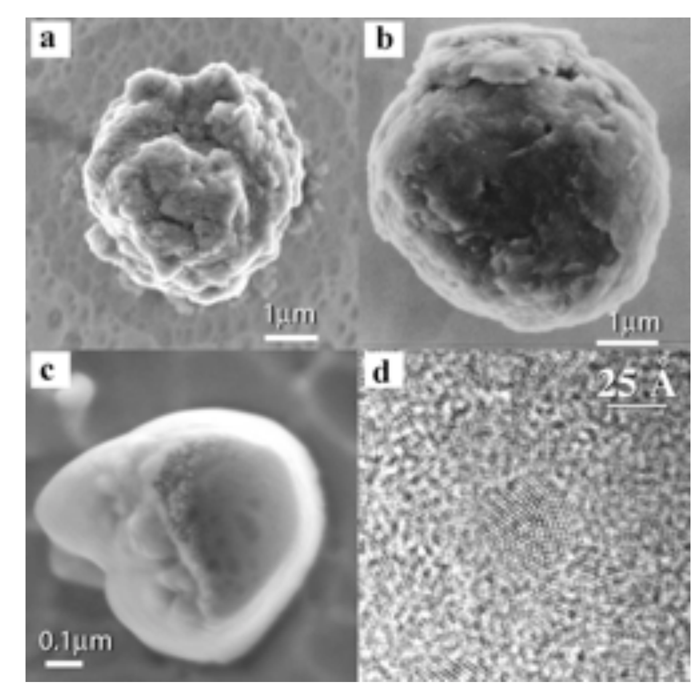
Chemistry with dynamics

- Turbulence & accretion
- Isotopic homogeneity of the Solar Nebula
- Crystalline silicates in comets and outer disk regions

- Extended gas-grain chemistry
- 1D/2D turbulent mixing
- "ALCHEMIC" code

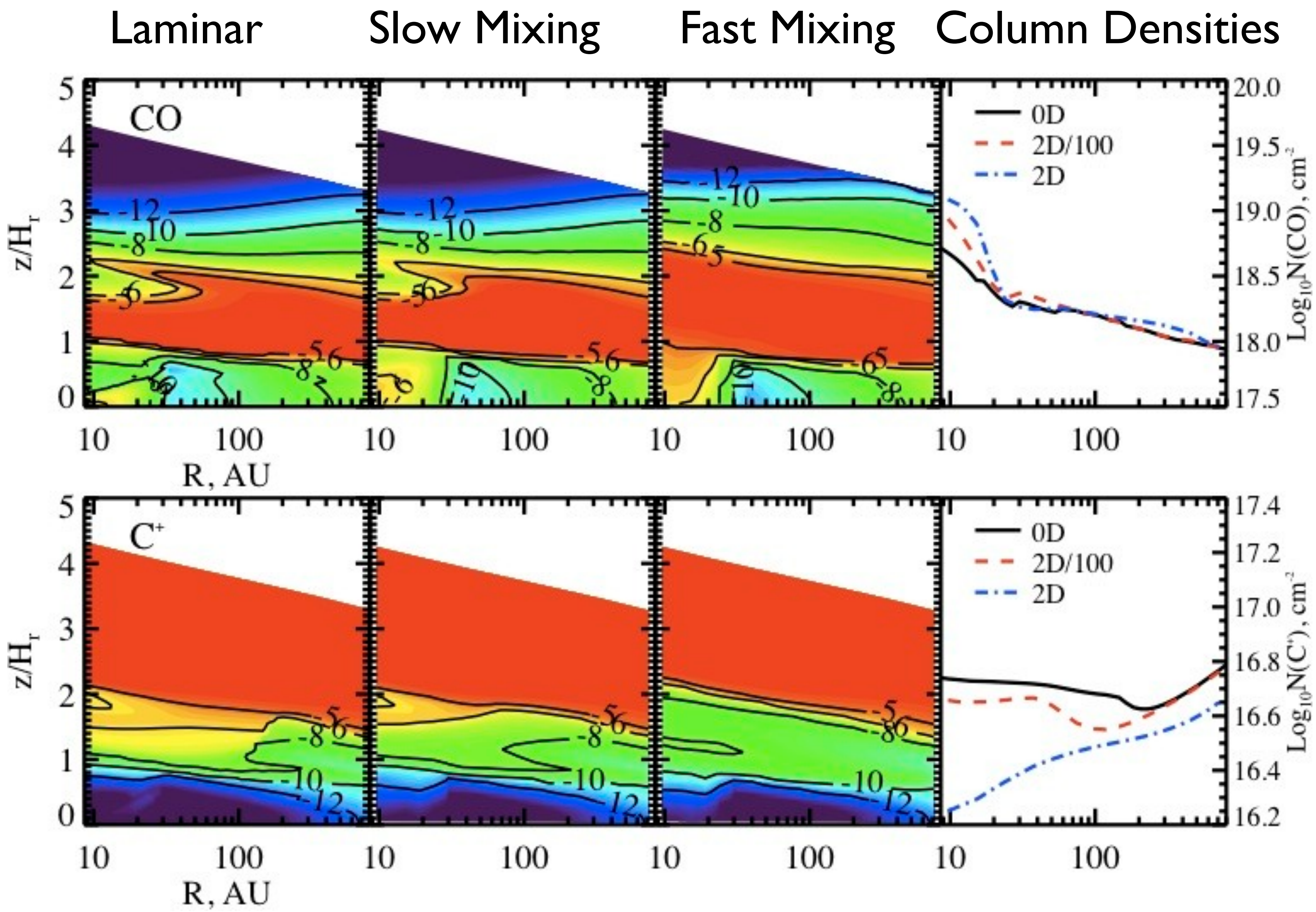
- "Qualification" fit to observations
- Reduced and oxidized ices in comets





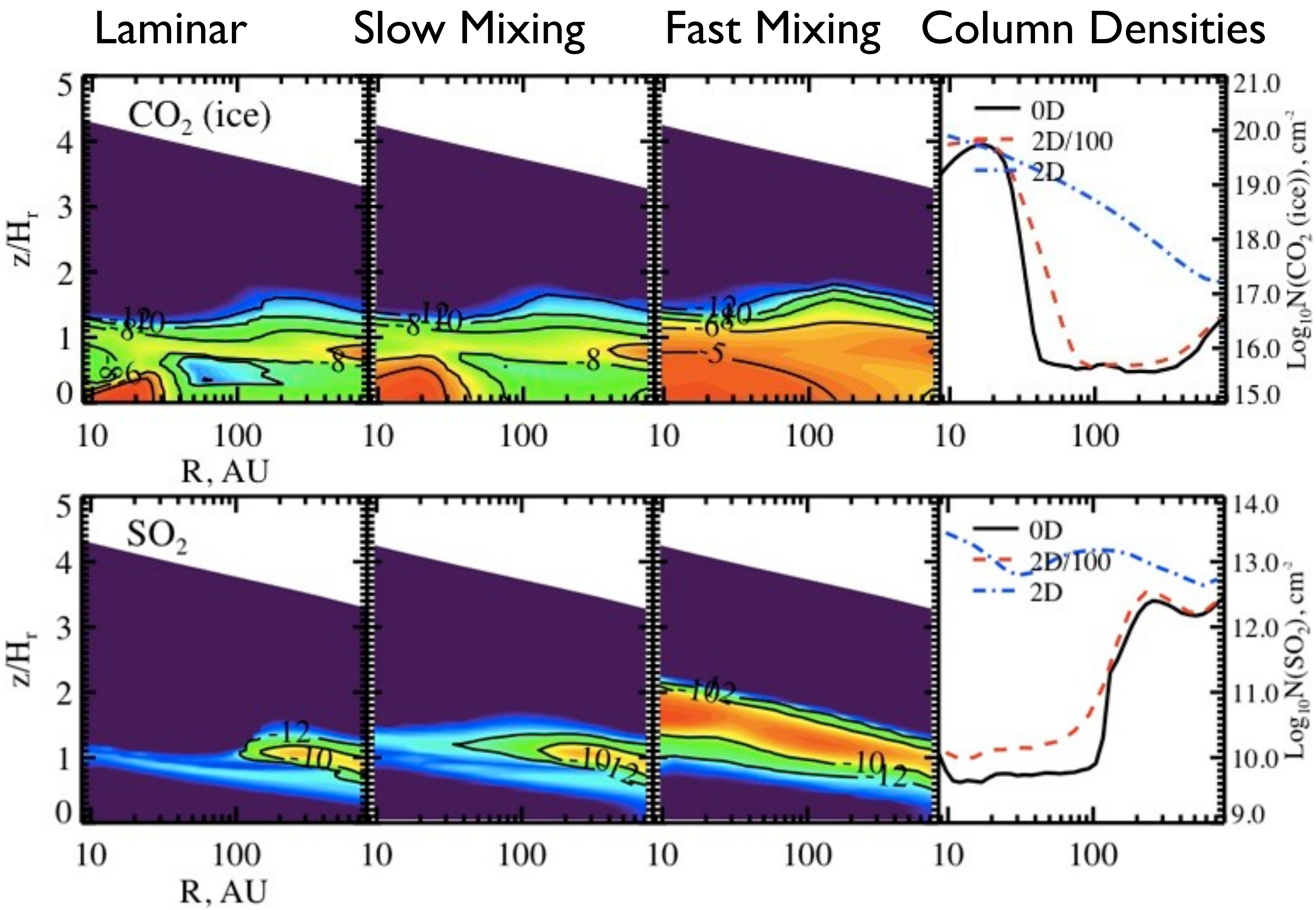
Semenov & Wiebe (2011)

Turbulence: Steadfast species



- Fast gas-phase formation and destruction
- t: Gas-phase chemistry < Dynamics
- Example: CO, OH, H_2O ice, CCH, C^+, CN, HCN

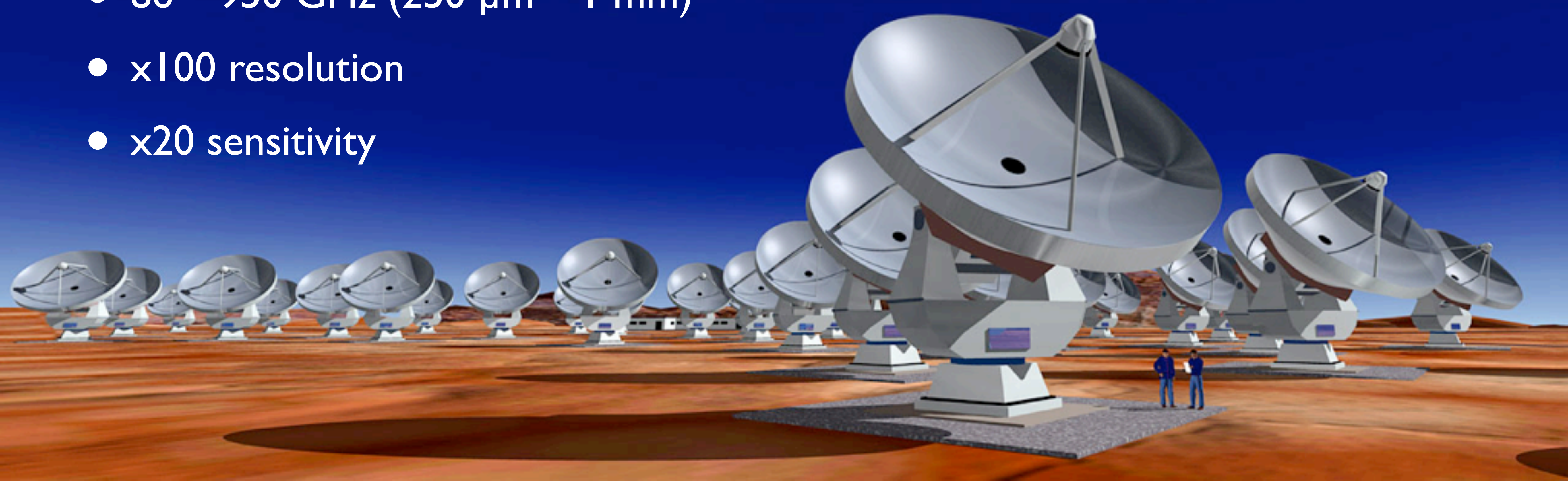
Turbulence: Sensitive species



- Slow surface formation & desorption
- t: Surface chemistry > Dynamics
- Hydrocarbons (C_2H_2), organics (HCOOH), SO, SO_2,C_2S, C_3S

VI. The Brave New World: ALMA

- Atacama Large Millimeter Array (2013)
- 50 x 12m + 12x7m + 4x12m
- Spatial resolution: 0.005″
- Spectral resolution: <0.05 km/s
- 8 GHz bandwidth for continuum
- 86 – 950 GHz (250 μm – 1 mm)
- x100 resolution
- x20 sensitivity



Credit: ALMA (ESO)

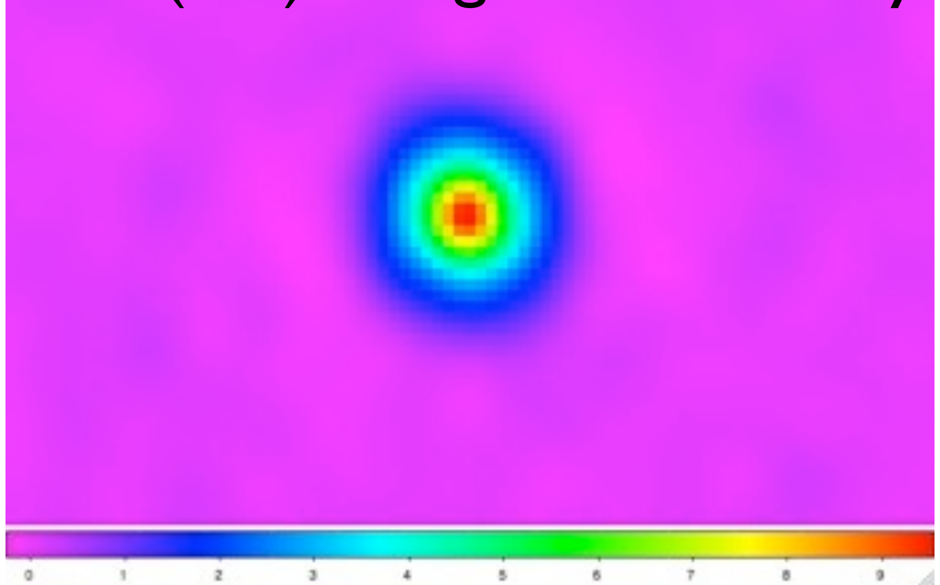
ALMA imaging of gas in PPDs:

- "Hot core/corinos"-like complex molecules: >CH_3OH, C_nH_m
- Molecules with S, P, Si, Cl, ...
- Anions: C_8H^-
- Isotopologues: ^{15}N, ^{34}S, $^{17,18}O$, D, ^{13}C
- Ionization structure
- Planet-forming inner regions
- Molecular layers
- Large- and small-scale dynamics
- Large surveys

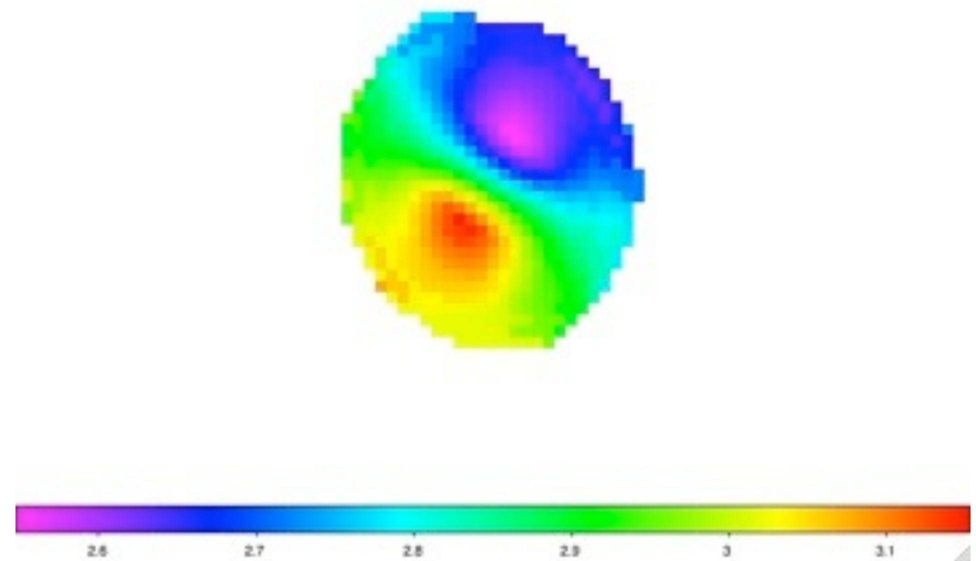
- Unknown unknowns!

ALMA is working: TW Hya

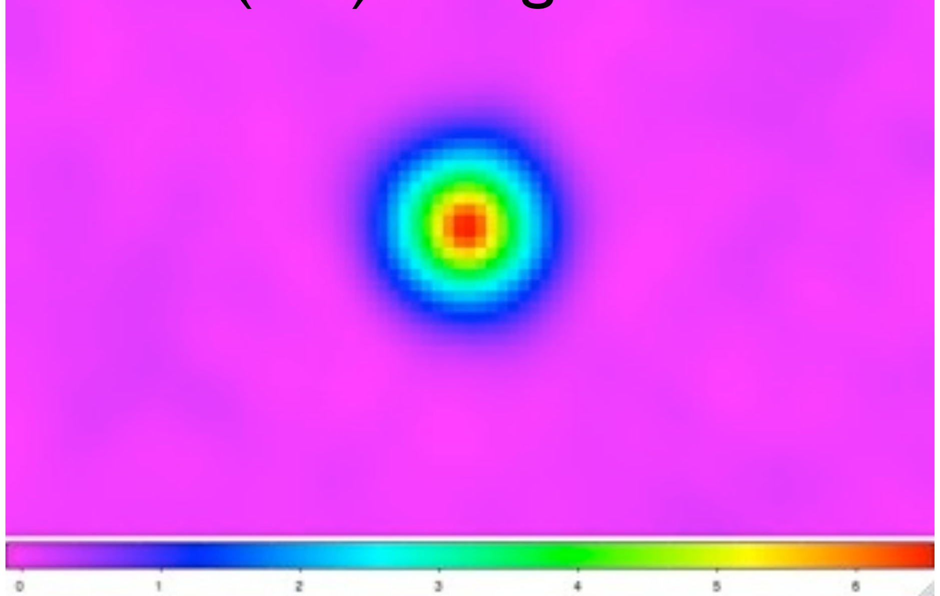
CO (3-2): Integrated intensity



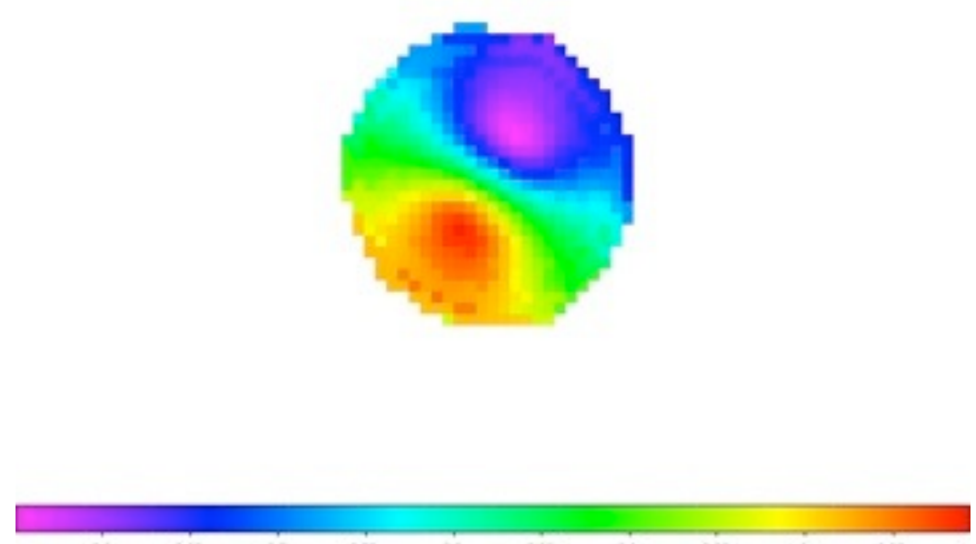
CO (3-2): Rotation



HCO^+ (4-3): Integrated intensity



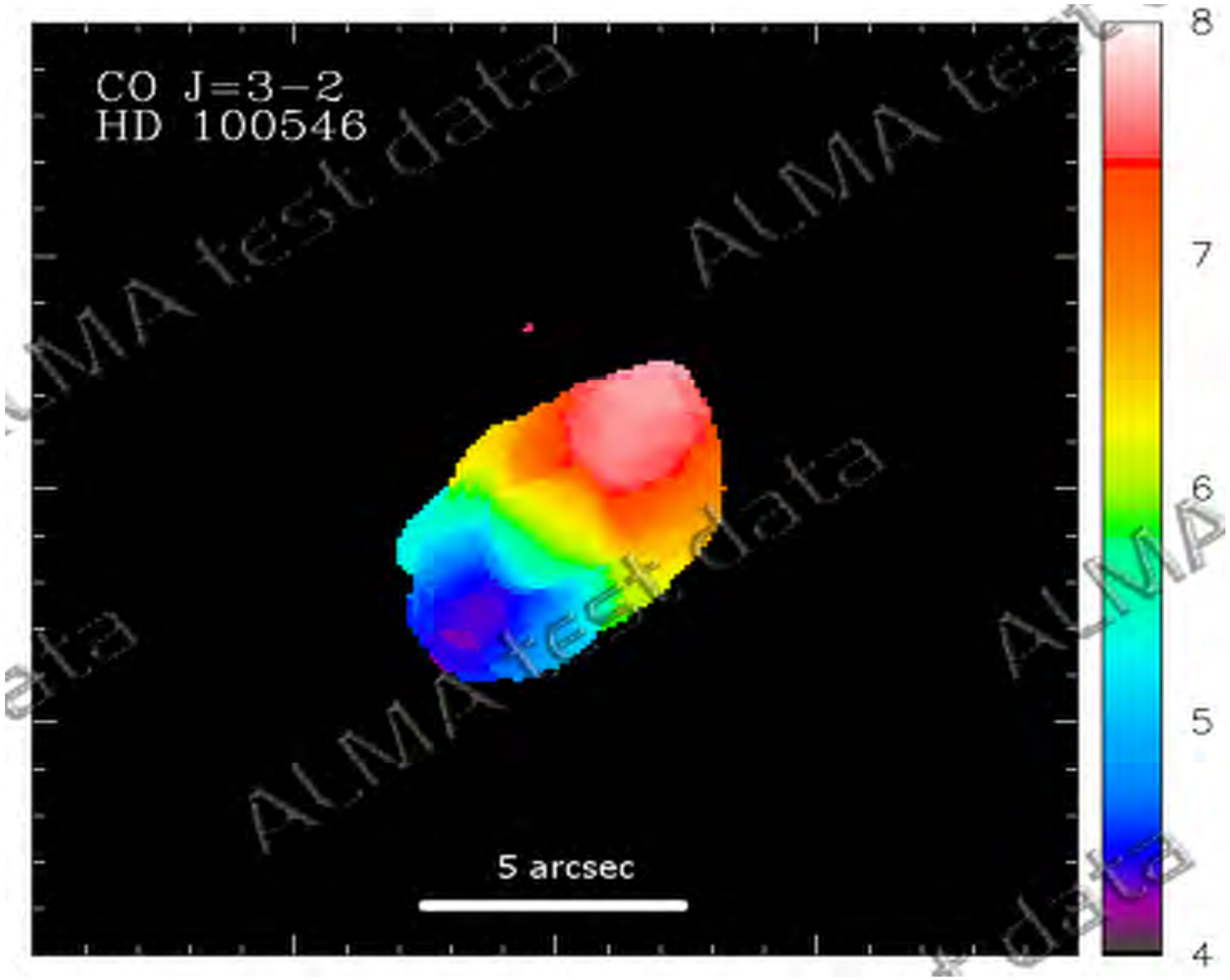
HCO^+ (4-3): Rotation



Science Verification observations of TW Hya at 345 GHz

ALMA is working: HD 100546

CO (3-2): Rotation



ALMA commissioning

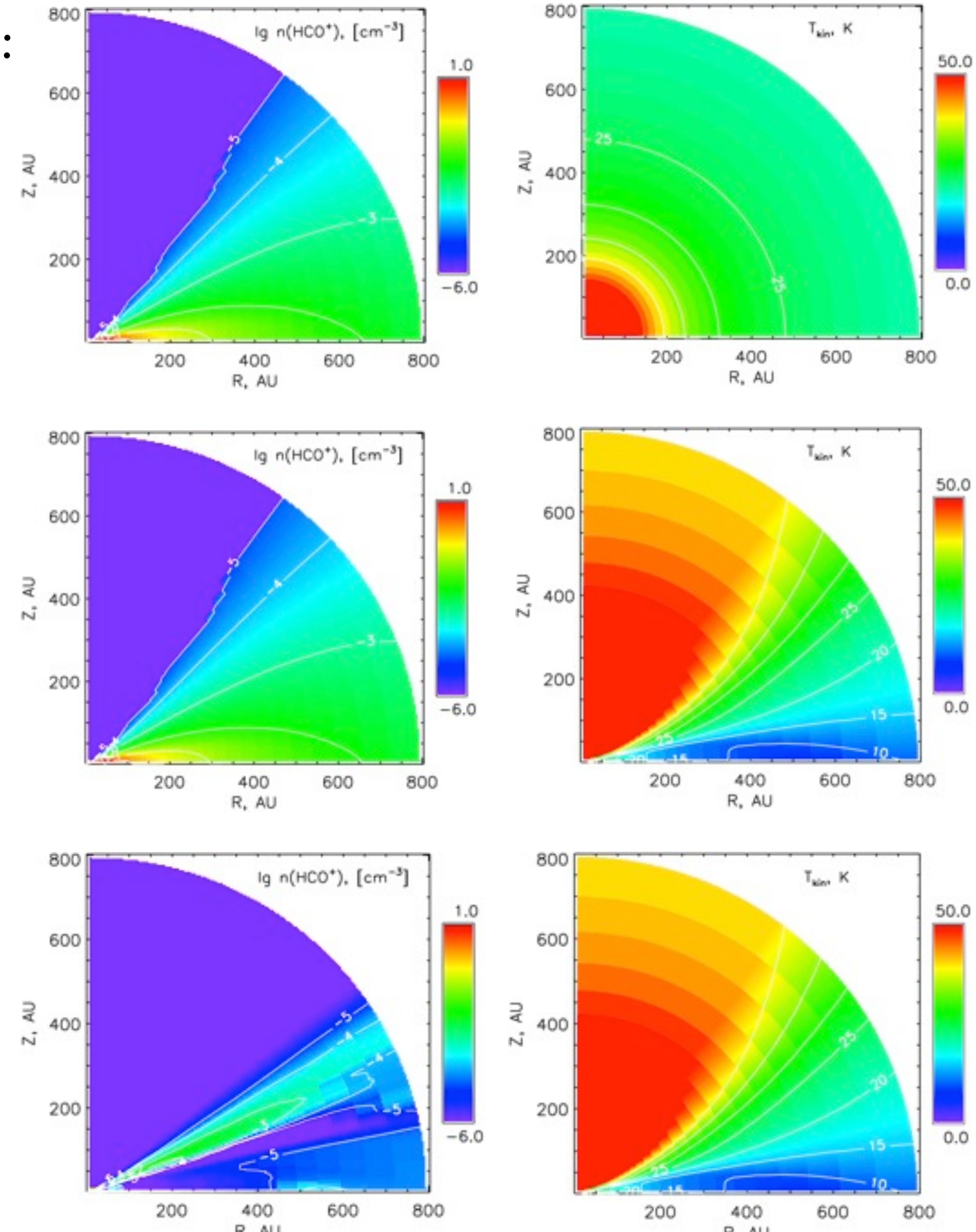
Disk models for ALMA: HCO^+ (4-3)

2D Monte-Carlo LRT calculations:

Uniform abundances,
radial T-gradient

Uniform abundances,
2D T-gradient

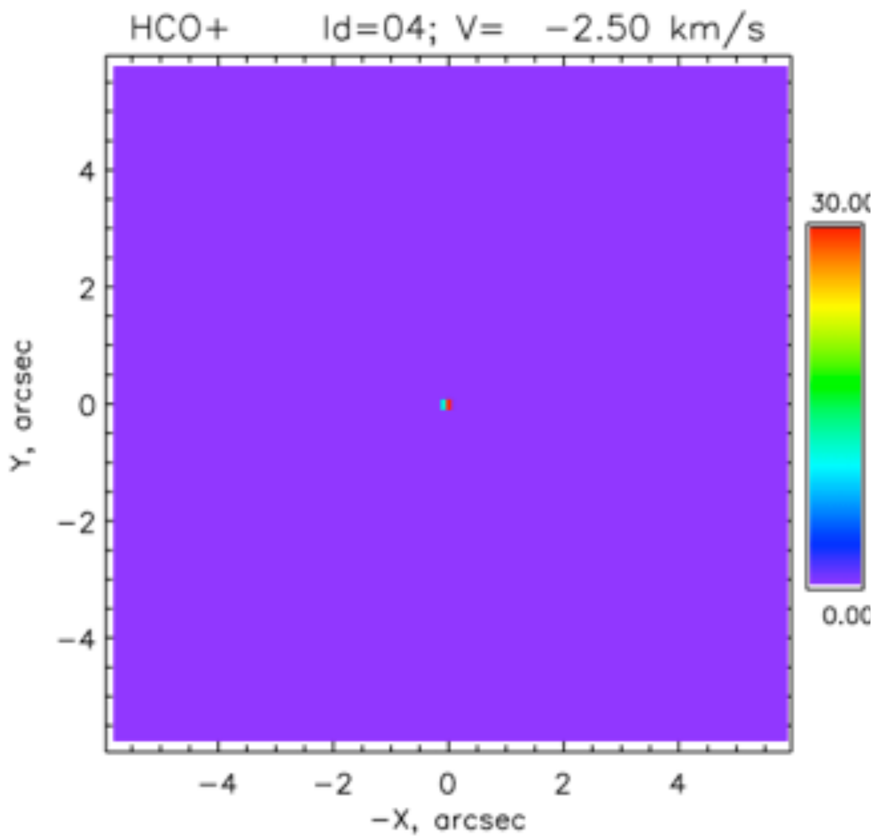
Chemical abundances,
2D T-gradient



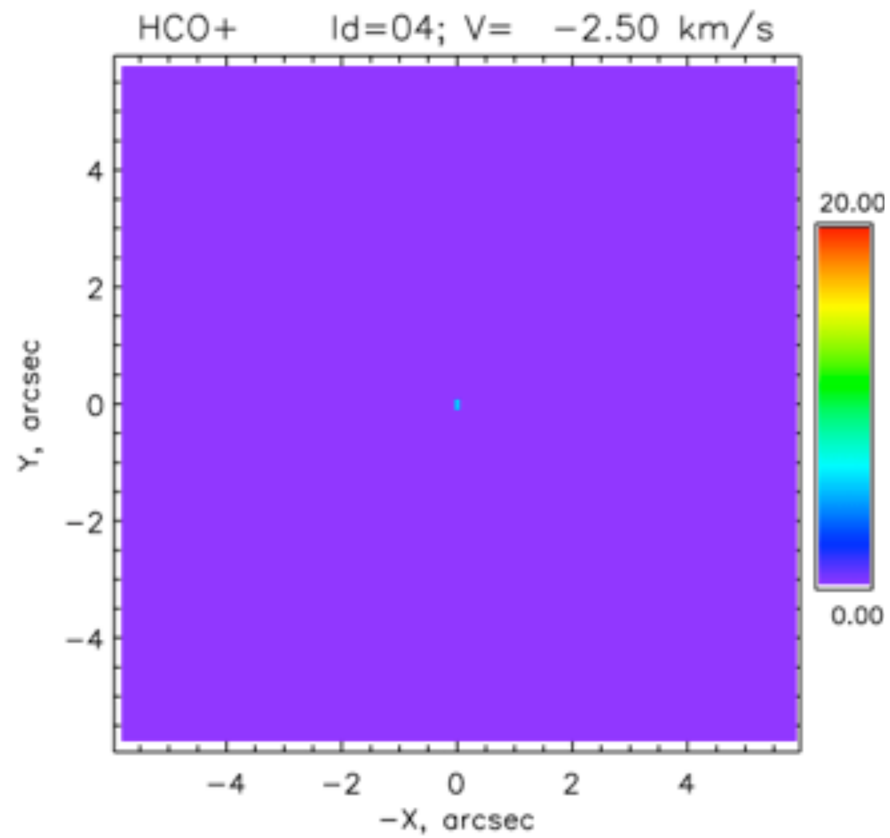
Semenov et al. (2008)

Channel maps of HCO^+ (4-3)@ 20°

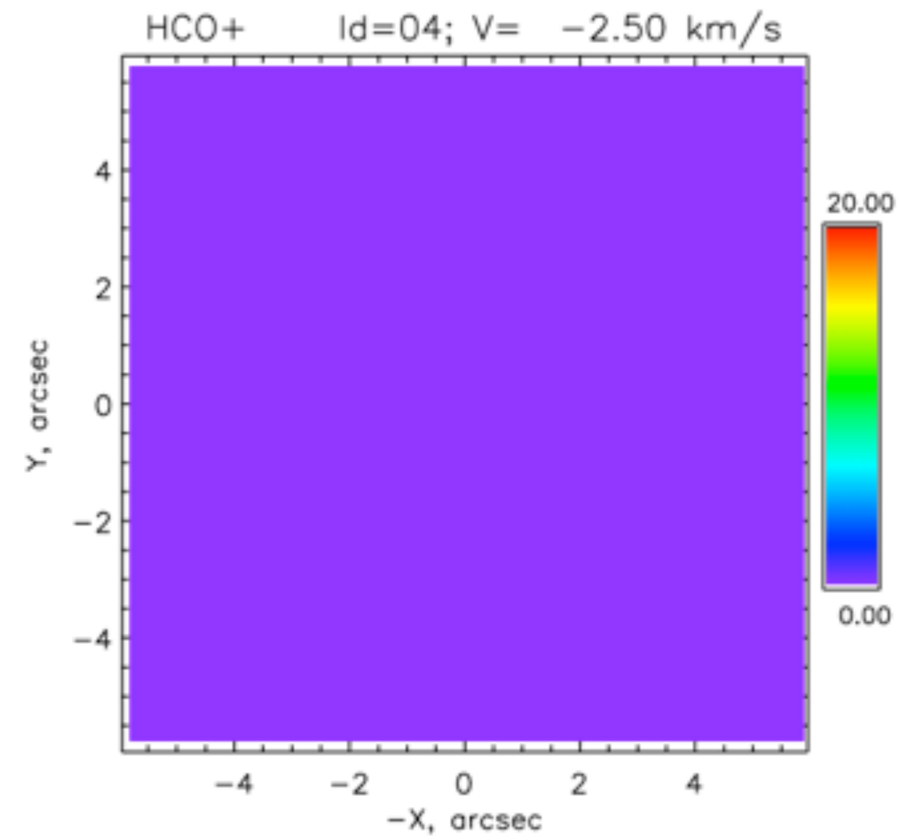
"UNIFORM"



"THERMAL"



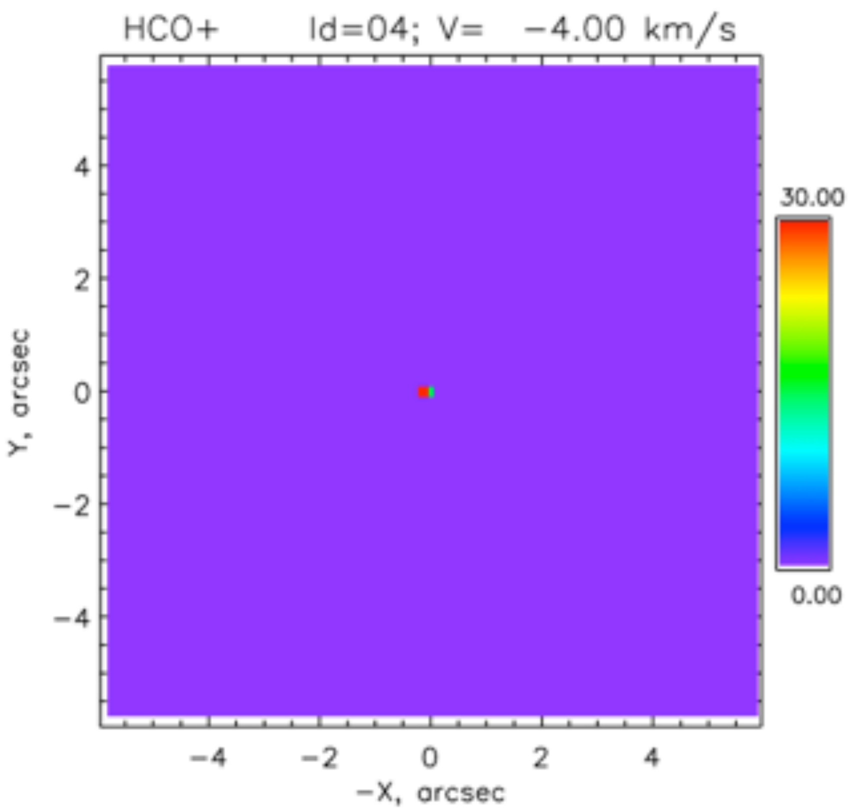
"CHEMICAL"



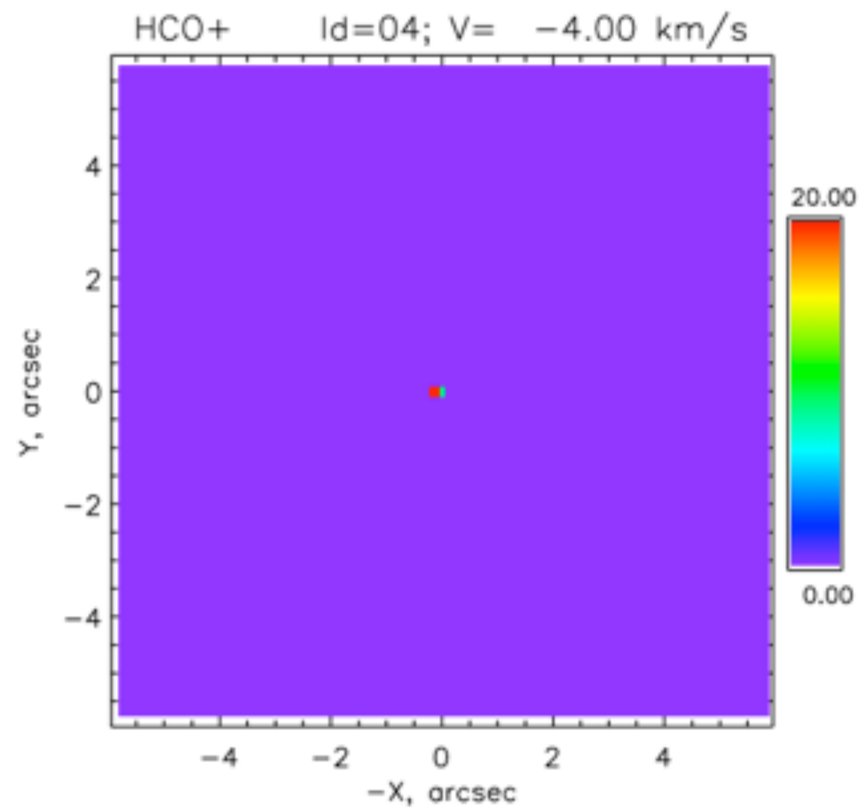
Face-on disks: no big difference

Channel maps of HCO⁺ (4-3)@ 60°

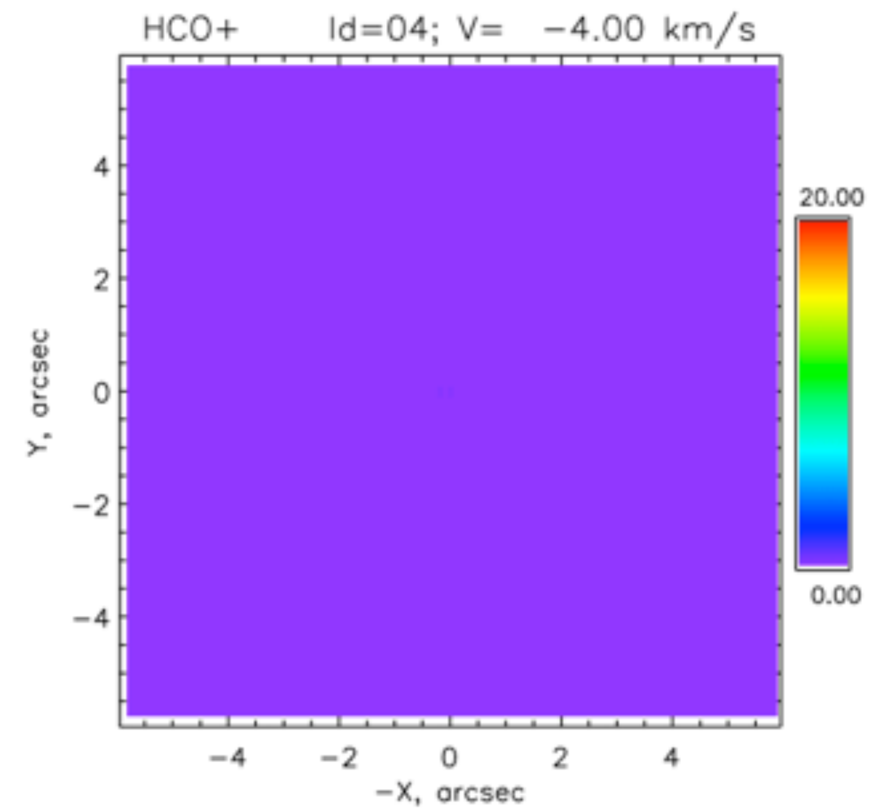
"UNIFORM"



"THERMAL"

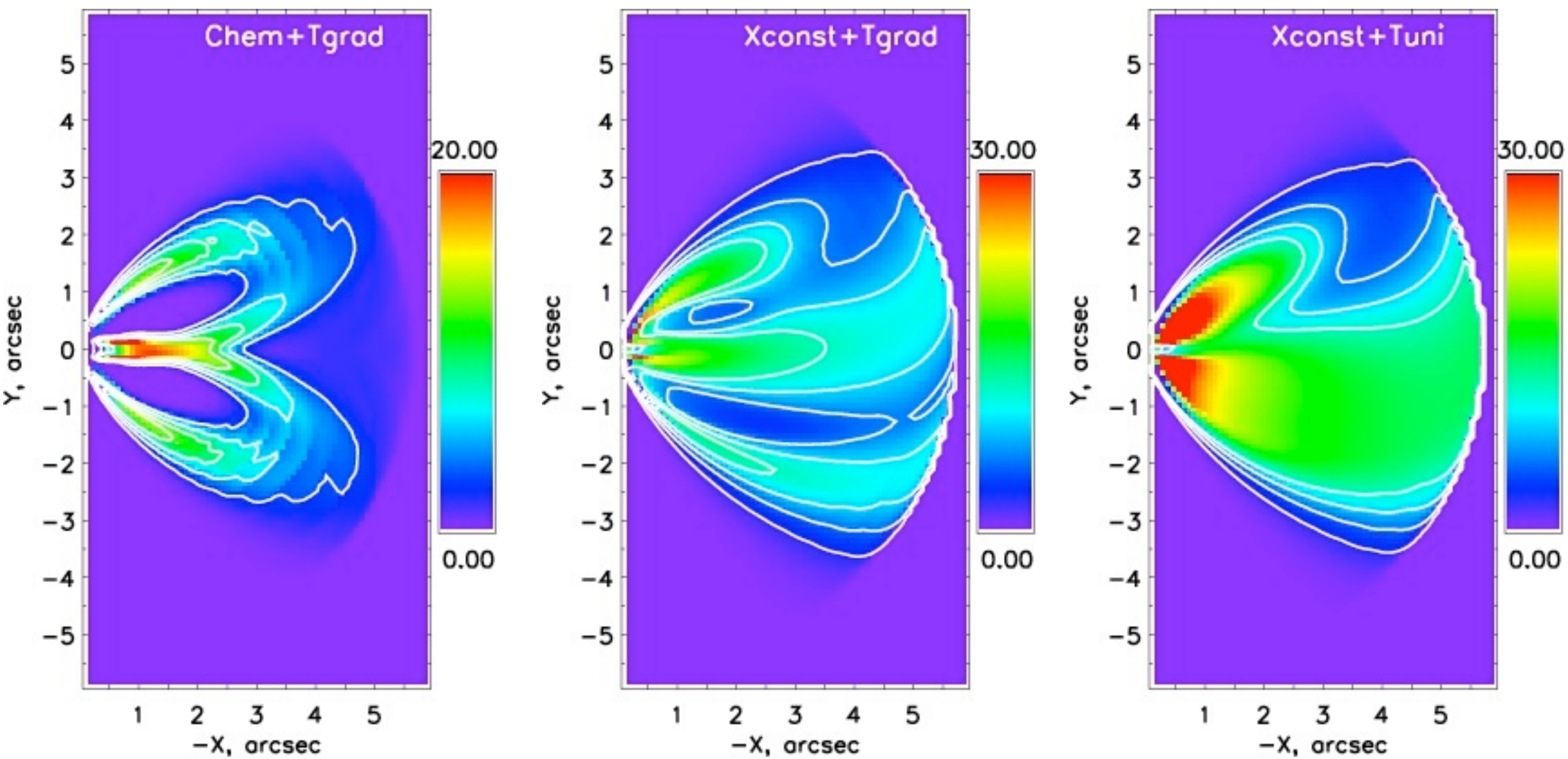


"CHEMICAL"

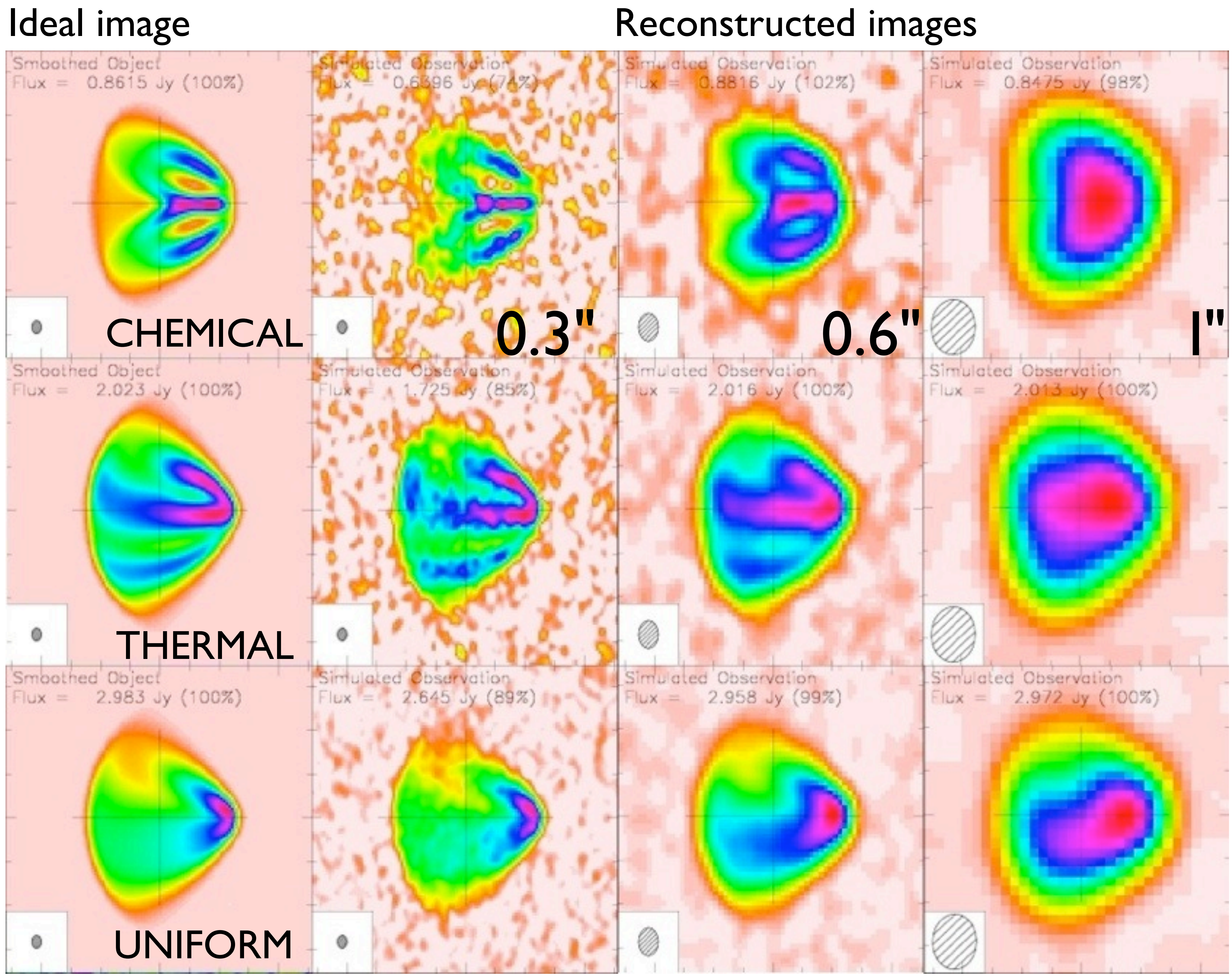


Edge-on disks: molecular layers & T-gradients become visible

Chemical vs. Temperature Gradients: 0.68 km/s channel of HCO+ (4-3)@ 60°



ALMA simulations



Semenov et al. (2008)

ALMA simulations (other transitions, disk sizes,and inclinations)

Species	Frequency (GHz)	Bandwidth (kHz)	R_{disk} = 800 AU		R_{disk} = 250 AU	
			i = 20°	i = 60°	i = 20°	i = 60°
HCO^+(1–0)	89	30	Zoom-c (4 hr)[a]	Zoom-c (10 hr)	Zoom-a/b (>12 hr)	Zoom-a/b (>12 hr)
$C^{18}O$(2–1)	220	75	Zoom-d (1 hr)	Zoom-c (<0.5 hr)	Zoom-c (4 hr)	Zoom-c (10 hr)
^{13}CO(2–1)	220	75	Zoom-d (<0.5 hr)	Zoom-d (<0.5 hr)	Zoom-c (2 hr)	Zoom-c (3.5 hr)[a]
CS(5–4)	245	80	Zoom-e (3 hr)	Zoom-d (12 hr)	Zoom-b (>12 hr)	Zoom-b (>12 hr)
HCN(3–2)	266	90	Zoom-e (<0.5 hr)	Zoom-d (1 hr)	Zoom-c (4 hr)	Zoom-b (>12 hr)
HCO^+(4–3)	357	120	Zoom-d (<0.5 hr)	Zoom-e (<0.5 hr)	Zoom-c (2 hr)	Zoom-c (3 hr)
HCO^+(7–6)	624	210	Zoom-e (<0.5 hr)	Zoom-e (1.5 hr)	Zoom-c (12 hr)	Zoom-d (>12 hr)
^{13}CO(6–5)	661	220	Zoom-e (<0.5 hr)	Zoom-e (1 hr)	Zoom-d (1 hr)	Zoom-c (6 hr)

Thermal gradients and chemical stratification in disks will become observable