Origin of Life
Univ. Grenoble Alpes

Astrochemistry of protoplanetary disks from an observational point of view

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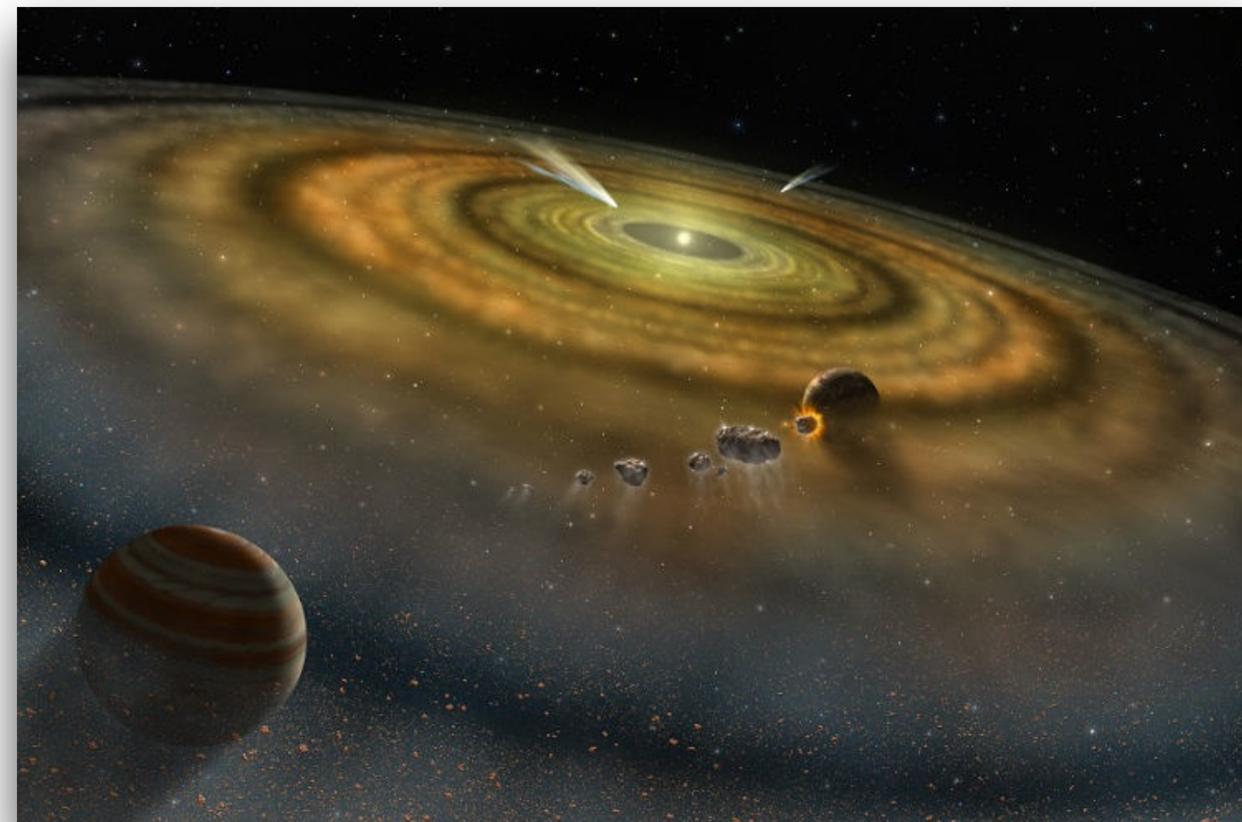
The Physics and Chemistry of the Interstellar Medium

Celebrating the first 40 years of Alexander Tielens' contribution to Science

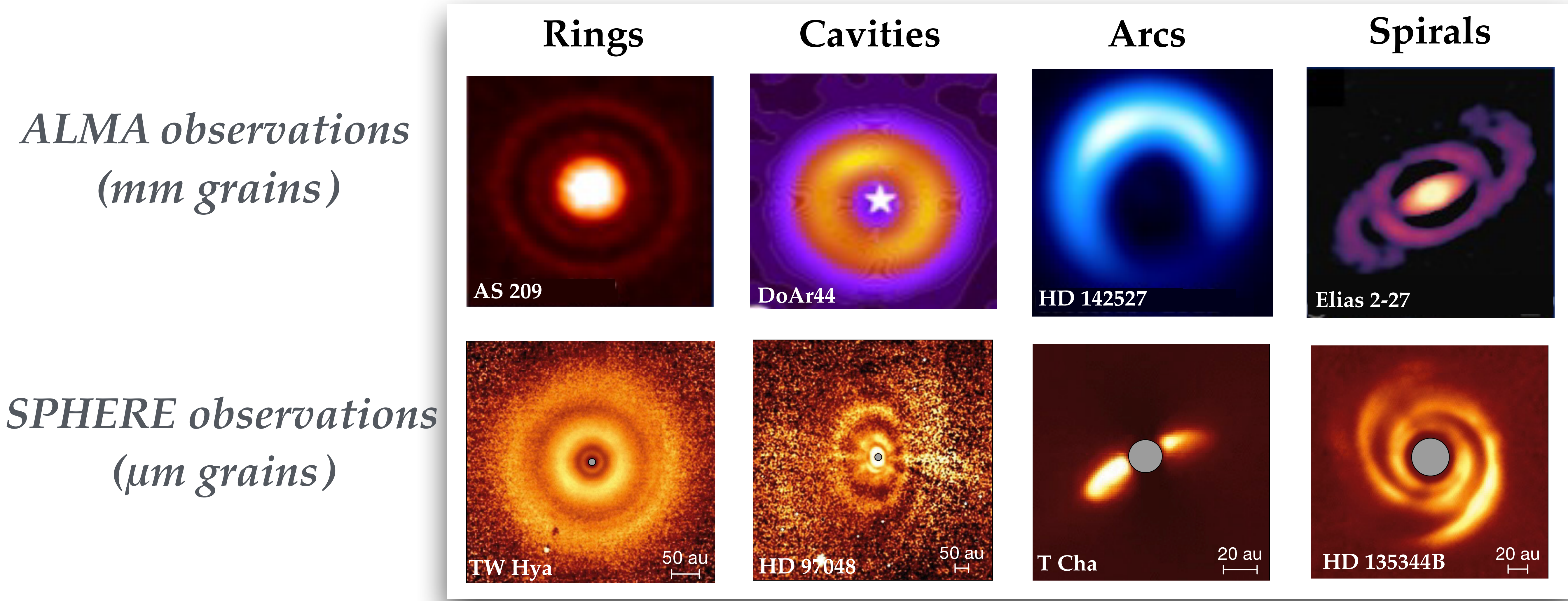
Avignon, France, Sept. 2-6, 2019

Protoplanetary disks are the birthplace of planets



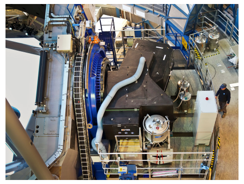
Study of the disk physical & chemical structure
is fundamental to understand the formation of
our ***own solar system & extra-solar planetary systems***

Morphological diversity of disks



Most of the disks display structures!

ALMA images: Fedele et al. (2018), van der Marel et al. (2016), Casassus et al. (2012) and Pérez et al. (2016)

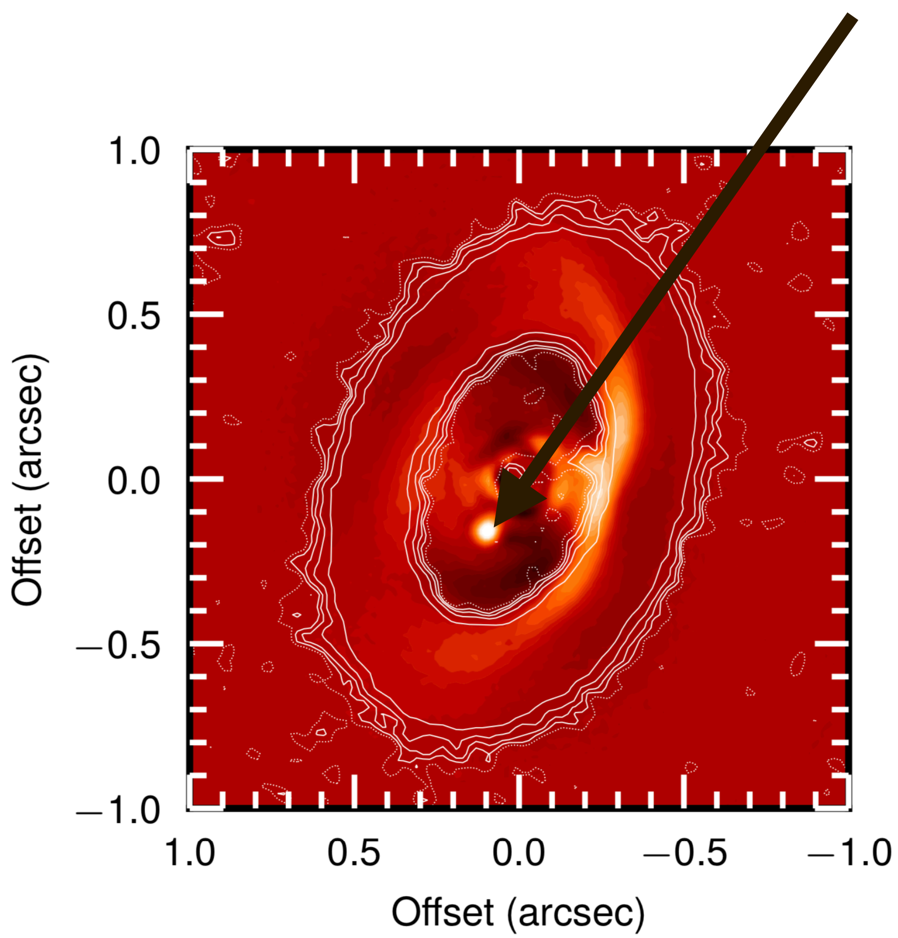


SPHERE images: Garufi et al. (2017), van Boekel et al. (2017), Ginski et al. (2016), Pohl et al. (2017) and Stolker et al. (2016)

Planet Formation

Direct Imaging

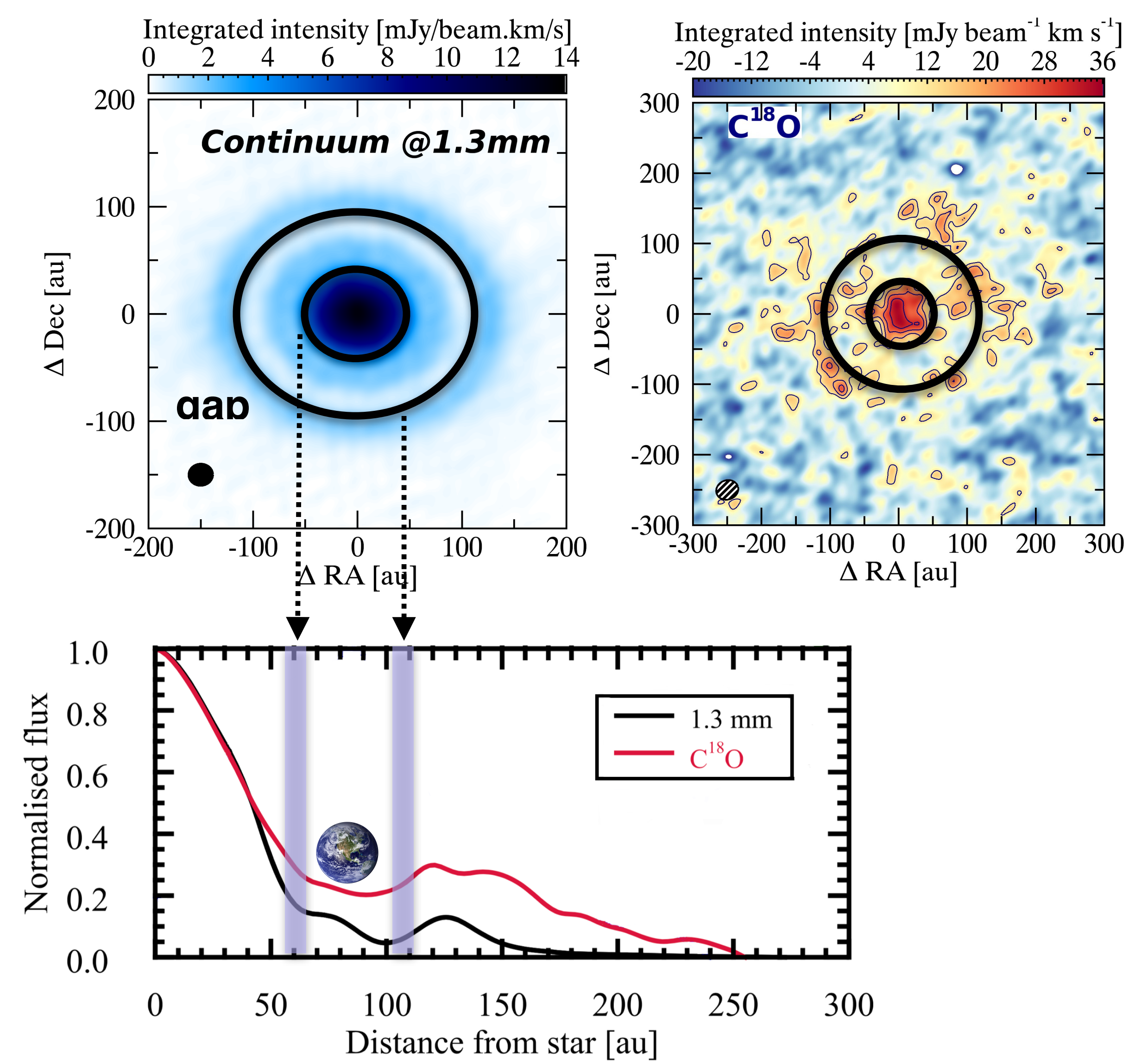
SPHERE obs. (0.96–3.8 μm) of PDS 70 transition disk!



Kepler et al. (2018)
Müller et al. (2018)

Seen via gas and dust density perturbations

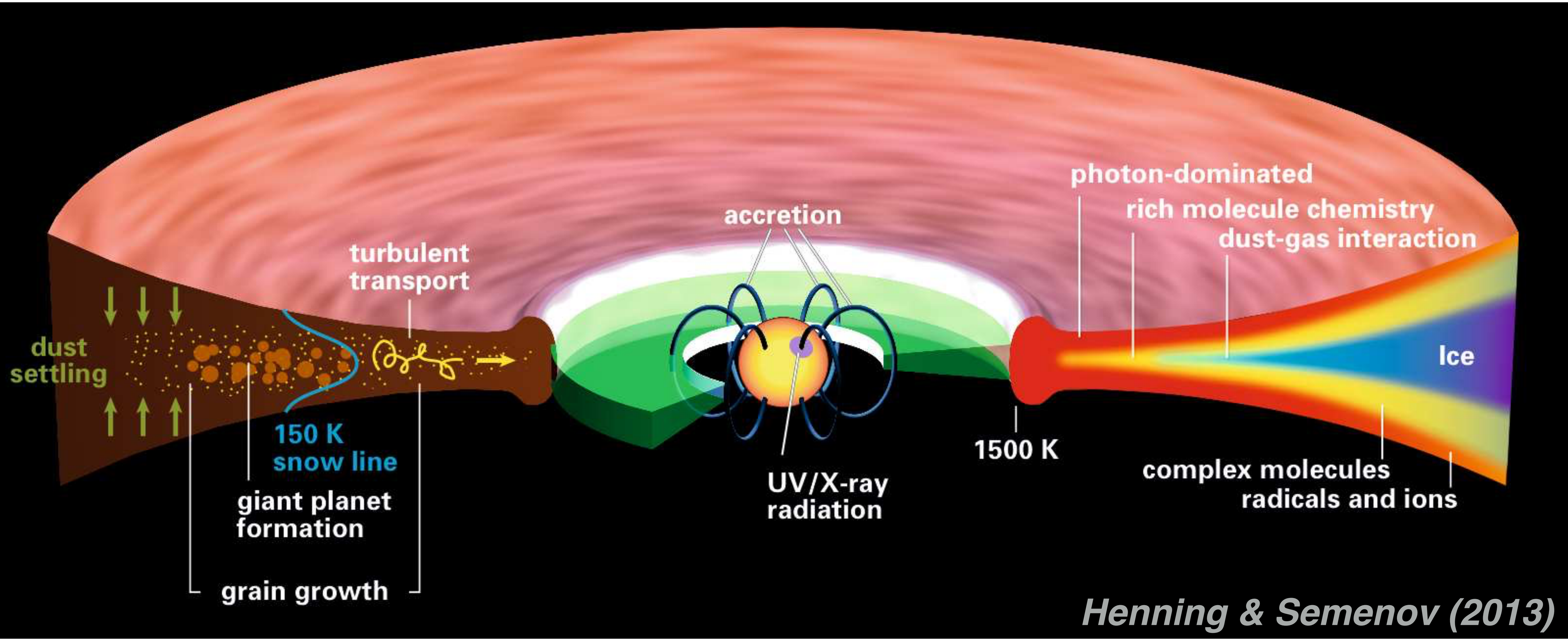
ALMA obs. (1.3mm) of AS 209



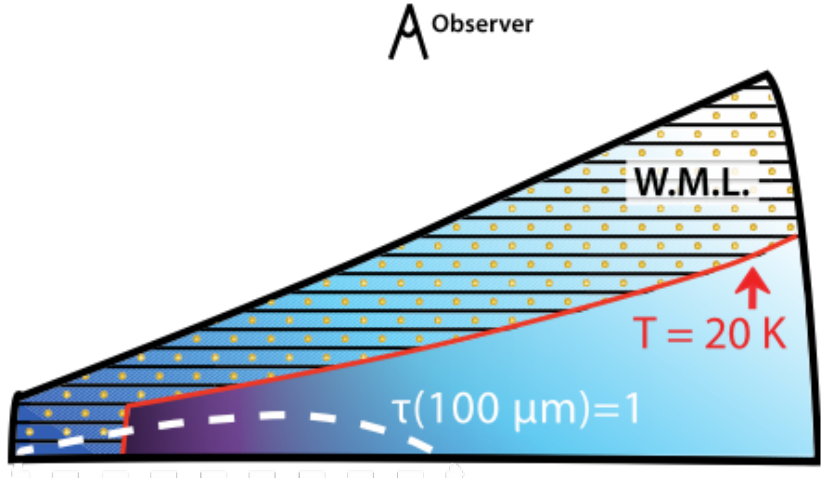
Favre et al. (2019)

Disks are complex systems

Strong T & n gradients, UV & X-ray



- "Inhomogeneous" chemistry
- Gas/ice reservoirs are likely affected



A depletion of elemental C in Solar Type (T Tauri) disks

Favre et al. (2013)
Schwarz et al. (2016)
Kama et al. (2016)
Nomura et al. (2016)
Miotello et al. (2017)

CO abundance relative to H_2 : $(0.1\text{-}3)\times10^{-5}$ *in the disk's warm molecular layers (T>20K)*, **lower than the canonical value of $\chi(CO) = 10^{-4}$)**

Carbon chemistry?
(Aikawa et al. 1997, Reboussin et al. 2015)

CO chemical destruction via reactions with He^+

+

Followed **by rapid formation of carbon chains** (C_xH_x) or CO_2

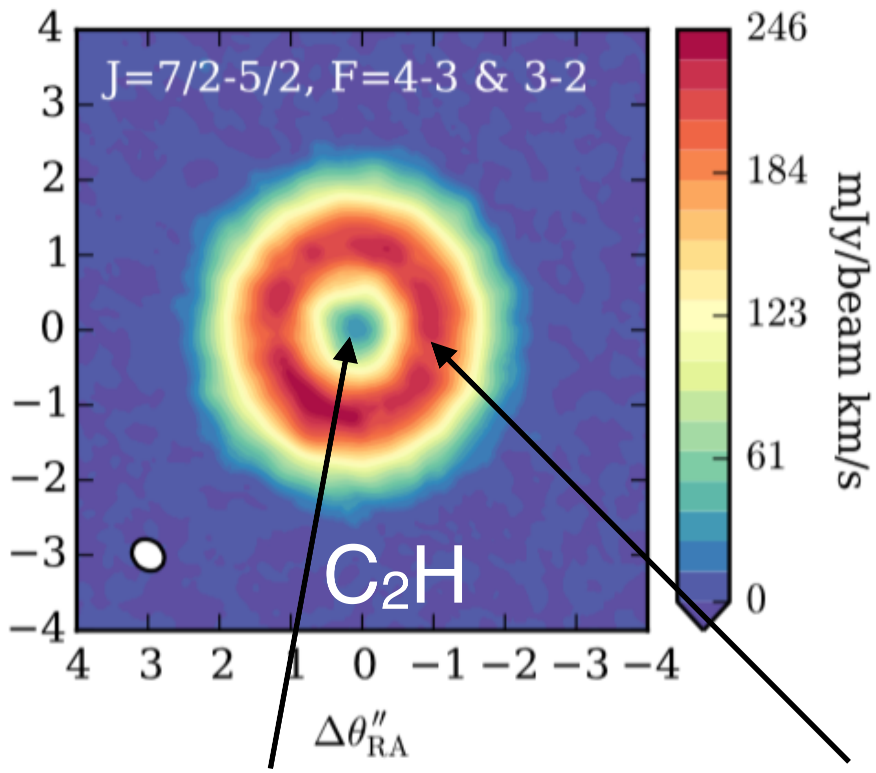
+

Freeze-out T higher than CO —> trap the carbon in ices

- **Carbon reservoir in gas?**
- **CO an unreliable tracer of the disk H_2 gas mass**

Kastner et al. (2015)
Bergin et al. (2016)

A depletion of elemental O in Solar Type (T Tauri) disks

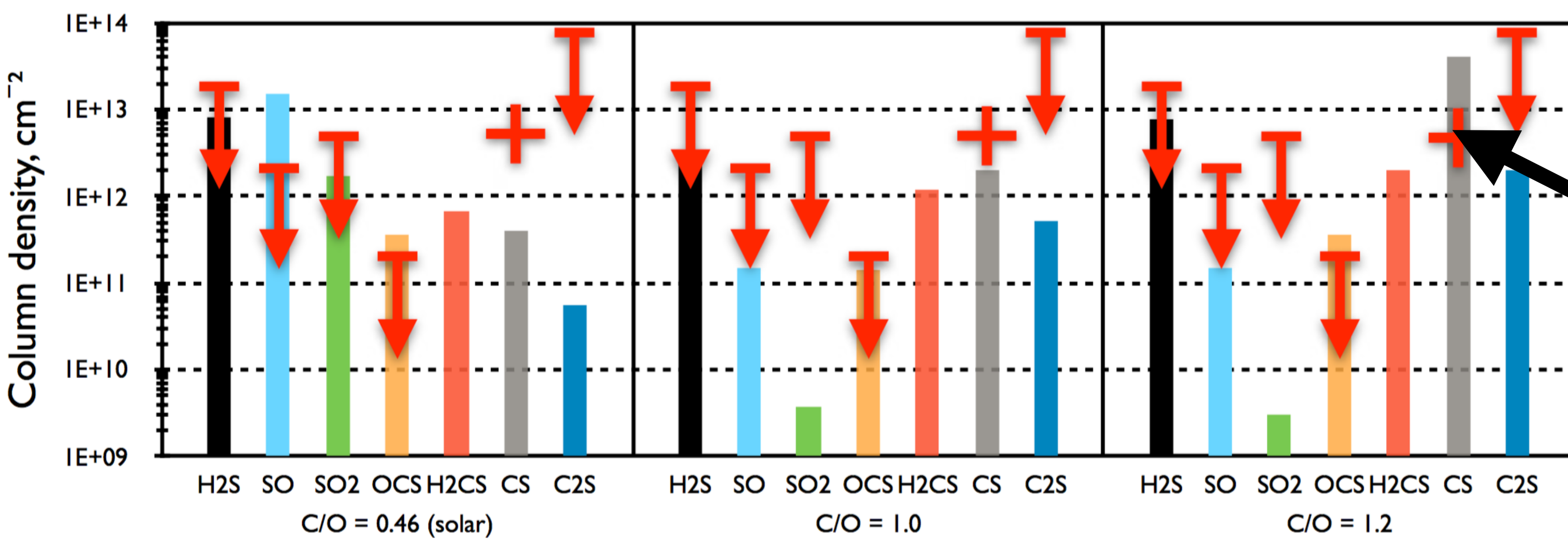


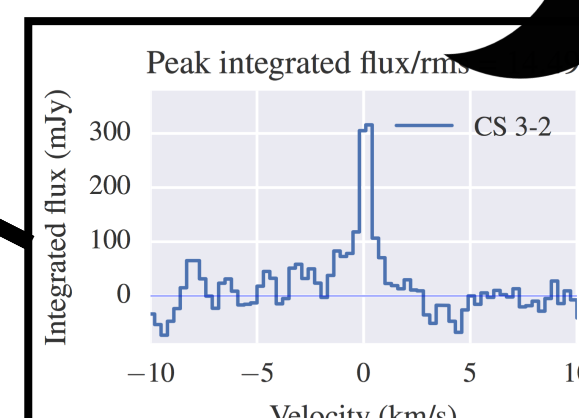
Carbon chemistry

Oxygen chemistry
(Bergin et al. 2016)

Oxygen locking from the disk molecular layer by the **freeze-out of water** onto **sedimenting large dust grains**

C/O ≥ 1 in the outer upper disk layers





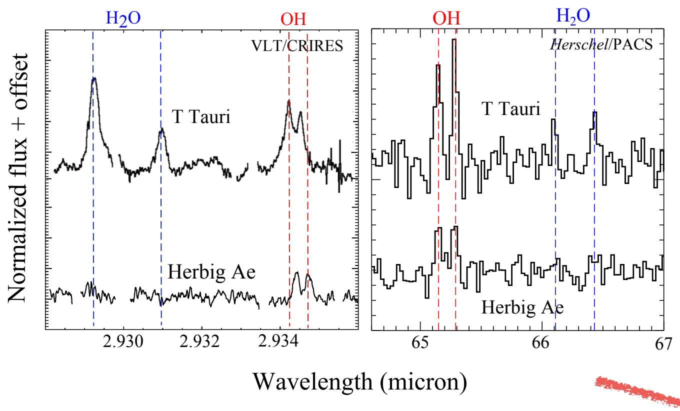
Semenov, Favre et al. (2018)

Molecular inventory of protoplanetary disks

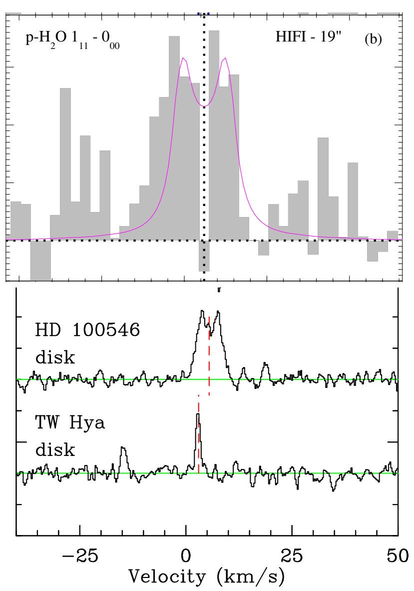
Atoms	
C_I, C_{II}, O_I	Sturm et al. (2010),Meeus et al. (2012),Du et al. (2015), Kama et al. (2016)
Ions	
HCO^+, $H^{13}CO^+$, DCO^+, N_2H^+, CH^+ N_2D^+	Dutrey et al. (1997, 2007), van Dishoeck et al. (2003), Thi et al. (2011) Qi et al. (2008, 2013a), Öberg et al. (2015a), Huang & Öberg (2015)
Carbon reservoirs?	
CO, CO_2	Koerner & Sargent (1995), Pontoppidan et al. (2010)
Simple species	
^{13}CO, $C^{18}O$, OH, HD	Dutrey et al. (1996), Pontoppidan et al. (2010), Bergin et al. (2013), Favre et al. (2013), McClure et al. (2016)
S-bearing molecules	
CS, SO, H_2S ^{13}CS, $C^{34}S$, H_2CS	Dutrey et al. (1997), Guilloteau et al. (2013), Phuong et al. (2018) Le Gal et al. (2019)
N-bearing molecules	
CN, HCN, $HC^{15}N$, $H^{13}CN$, HNC, DCN, NH_3	Dutrey et al. (1997), Qi et al. (2008), Salinas et al. (2016) Guzmán et al. (2017), Booth et al. (2019)
Carbon chains	
CCH, C_2H_2, c-C_3H_2, HC_3N	Dutrey et al. (1997), Pontoppidan et al. (2010), Henning et al. (2010), Chapillon et al. (2012), Qi et al. (2013b), Öberg et al. (2015b),Bergner et al. (2018)
Water	
H_2O	Bergin et al. (2010), Hogerheijde et al. (2011), Fedele et al. (2012), Podio et al. (2013)
O-bearing molecules	
H_2CO t-HCOOH	Qi et al. (2013a),Loomis et al. (2015), Öberg et al. (2017) Carney et al. (2017), Guzmán et al. (2018),Podio et al. (2019) Favre et al. (2018)
Complex organic molecules	
CH_3OH CH_3CN	Walsh et al. (2016) Öberg et al. (2015b),Bergner et al. (2018),Loomis et al. (2018)

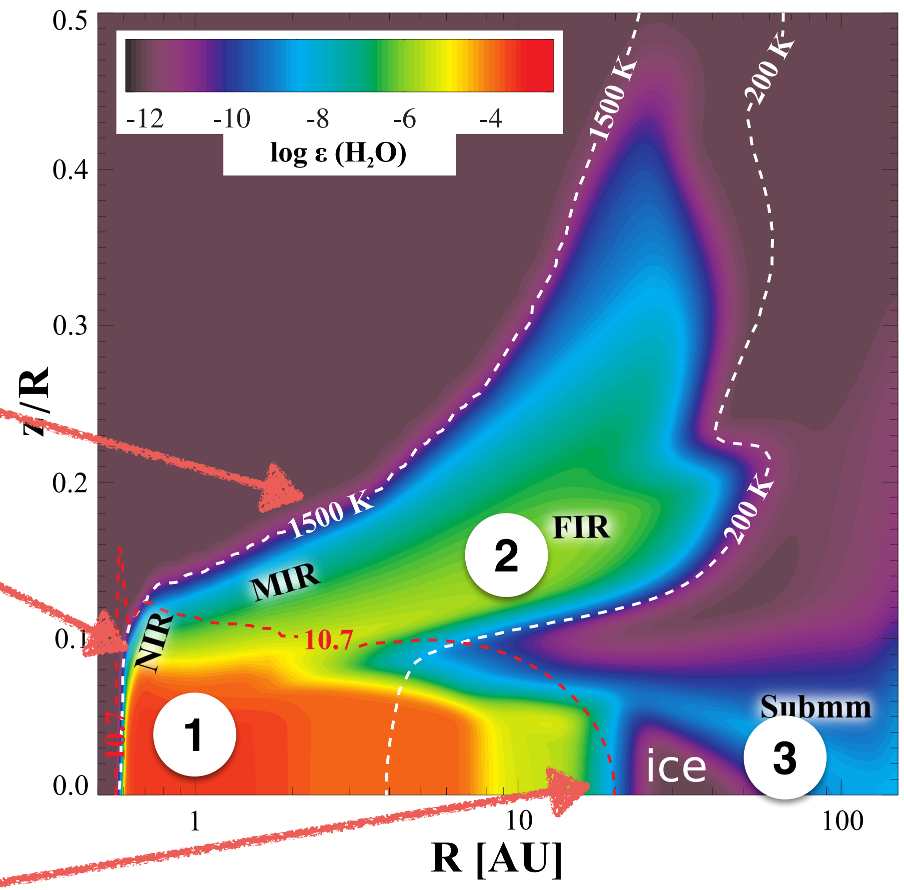
Water reservoirs in disks

Infrared



sub-mm





Terada et al (2007)
Carr & Najita (2008)
Salyk et al. (2008)
Glassgolf et al. (2009)
Woitke et al. (2009)
Honda et al. (2009)
Pontoppidan et al. (2010a,b)
Hogerheijde et al. (2011)
Bruderer et al. (2012)
Fedele et al. (2011, 2012, 2013)
Podio et al. (2013)
Van Dishoeck (2014)

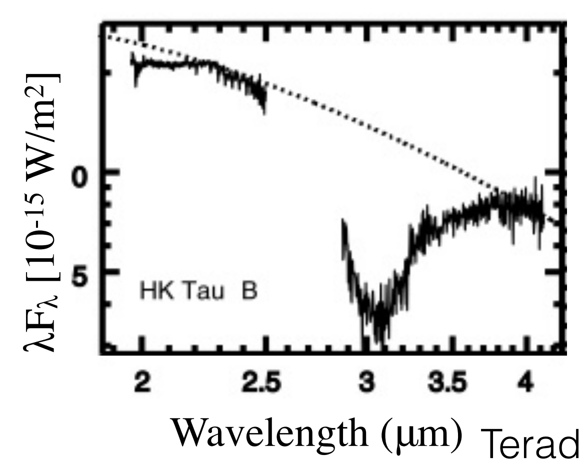
Courtesy Davide Fedele

Planetesimal with H_2O form in the outer disk (water ice reservoir)

Water Vapor

1. Hot water chemistry & evaporation
2. Hot water chemistry
3. Photodesorption of water ice

Water ice



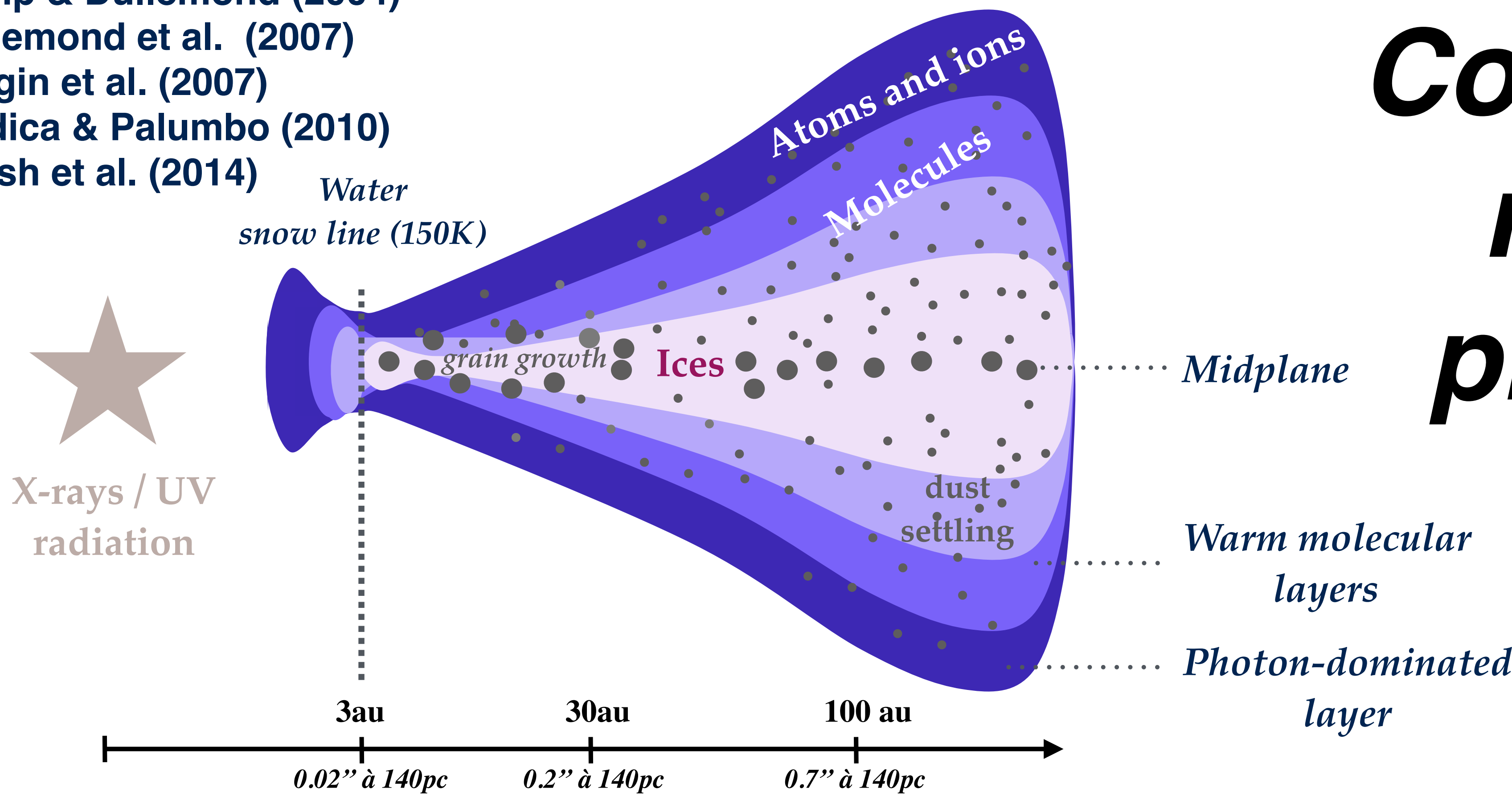
Terad

Tielens & Hagen (1982):

reaction scheme to form water ice

Aikawa et al. (2002)
Kamp & Dullemond (2004)
Dullemond et al. (2007)
Bergin et al. (2007)
Modica & Palumbo (2010)
Walsh et al. (2014)

Complex organic molecules in protoplanetary disks

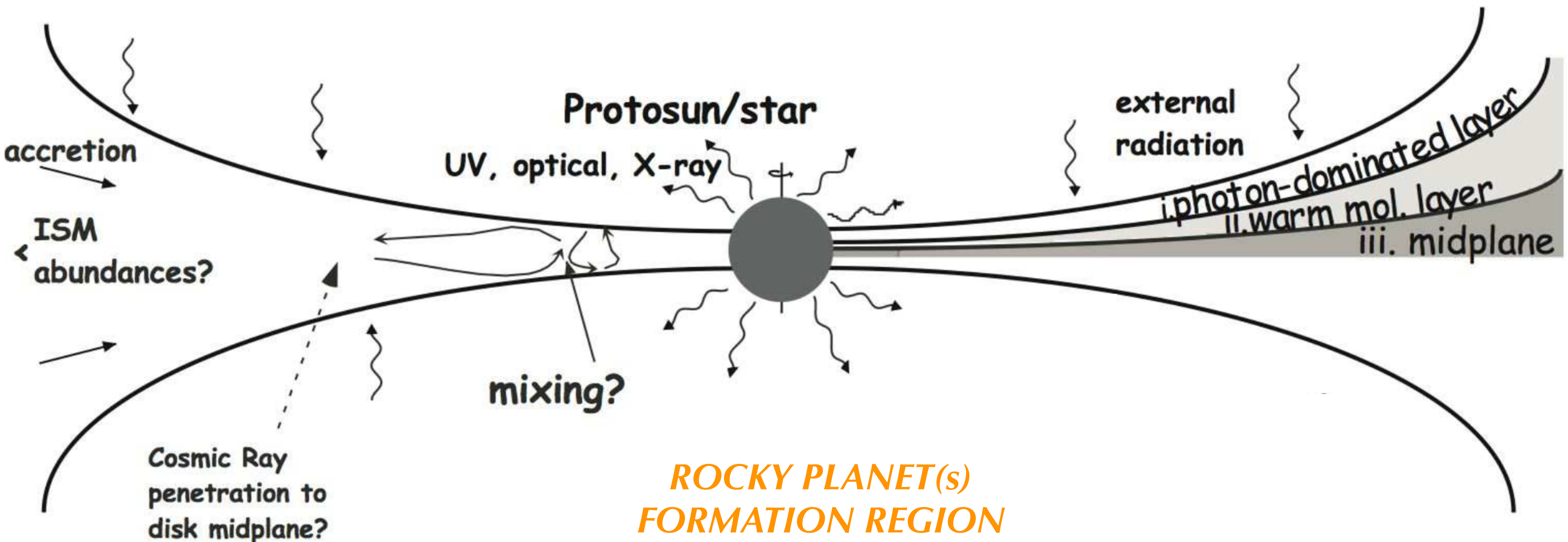


(1 AU = Distance between the Sun and the Earth)

- **Surface layers:** molecules destroyed by UV photodissociation
- **Inner (r <50 AU -100 AU, T >50-100K):** molecules present in warm molecular layers. Production via gas phase chemistry or formation on ices and then release into the gas phase
- **Outer disk / Mid plane (r >100-200 AU, T <50K):** molecules are locked into the icy surface of dust grains (χ_{H2}~10^{-6}-10^{-4}), ***Only*** a few percent are in gas-phase (χ_{H2}~10^{-11}-10^{-7})

The chemical composition of disks is hidden in ices!

Interferometry is needed to access the molecular content in disk



Bergin et al. (2007)

ROCKY PLANET(s)
FORMATION REGION

3 AU = 0.02” at 140 pc

10 AU = 0.07” at 140 pc

50 AU = 0.4” at 140 pc

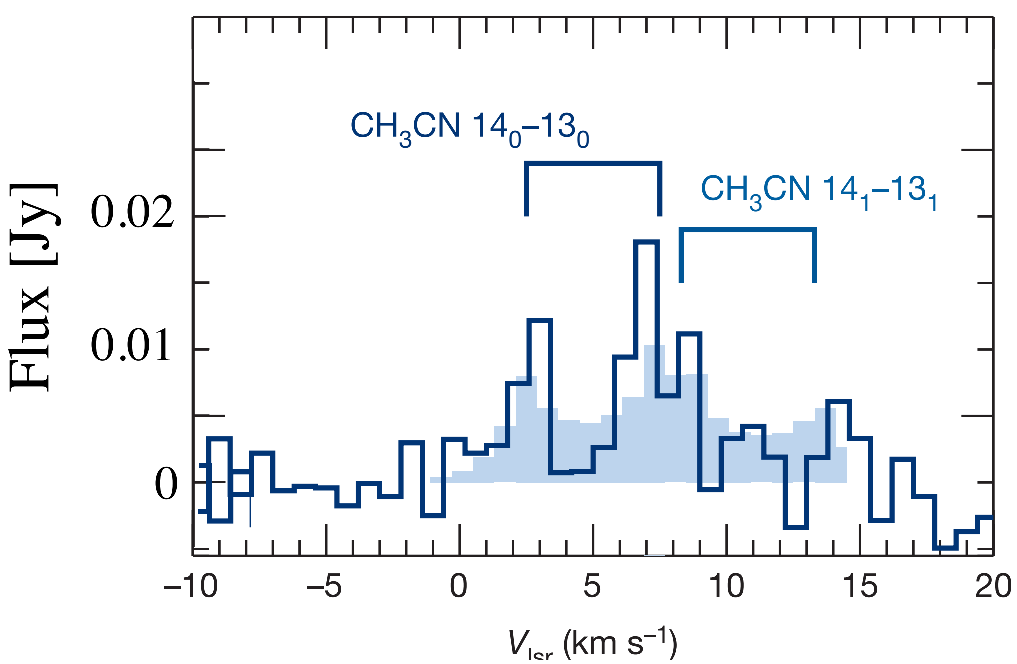
100 AU = 0.7” at 140 pc

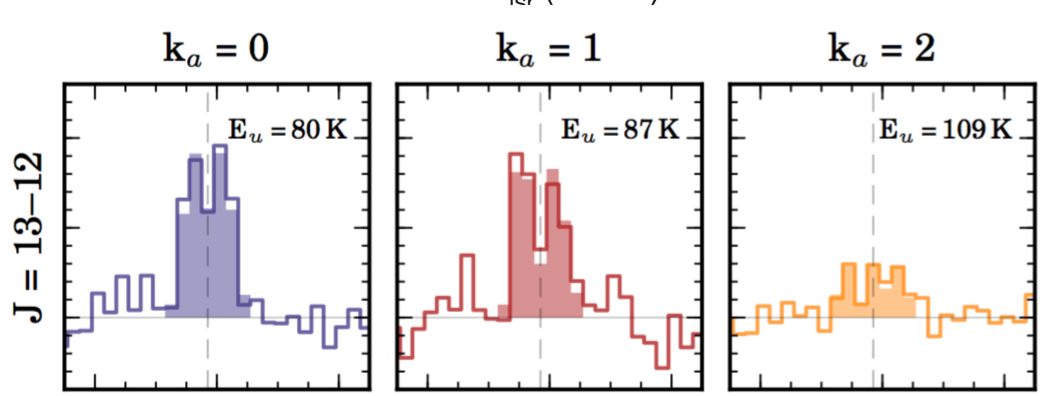
High angular resolution!

1 AU = Distance between the Sun and the Earth

Interferometry is needed to access the molecular content in disk

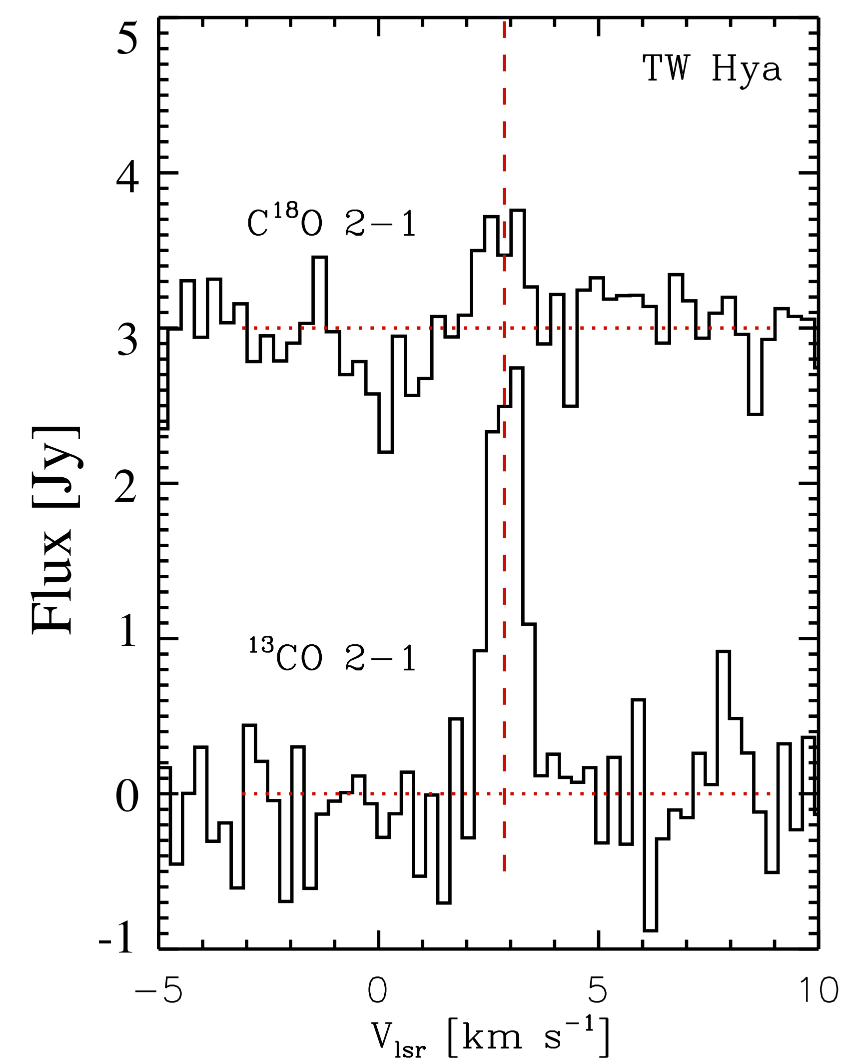
The emissive area is expected to be small
(and might be close to the central object)
It is really hard to detect a not intense transition





Öberg et al. (2015a)
Loomis et al. (2018)

High sensitivity!

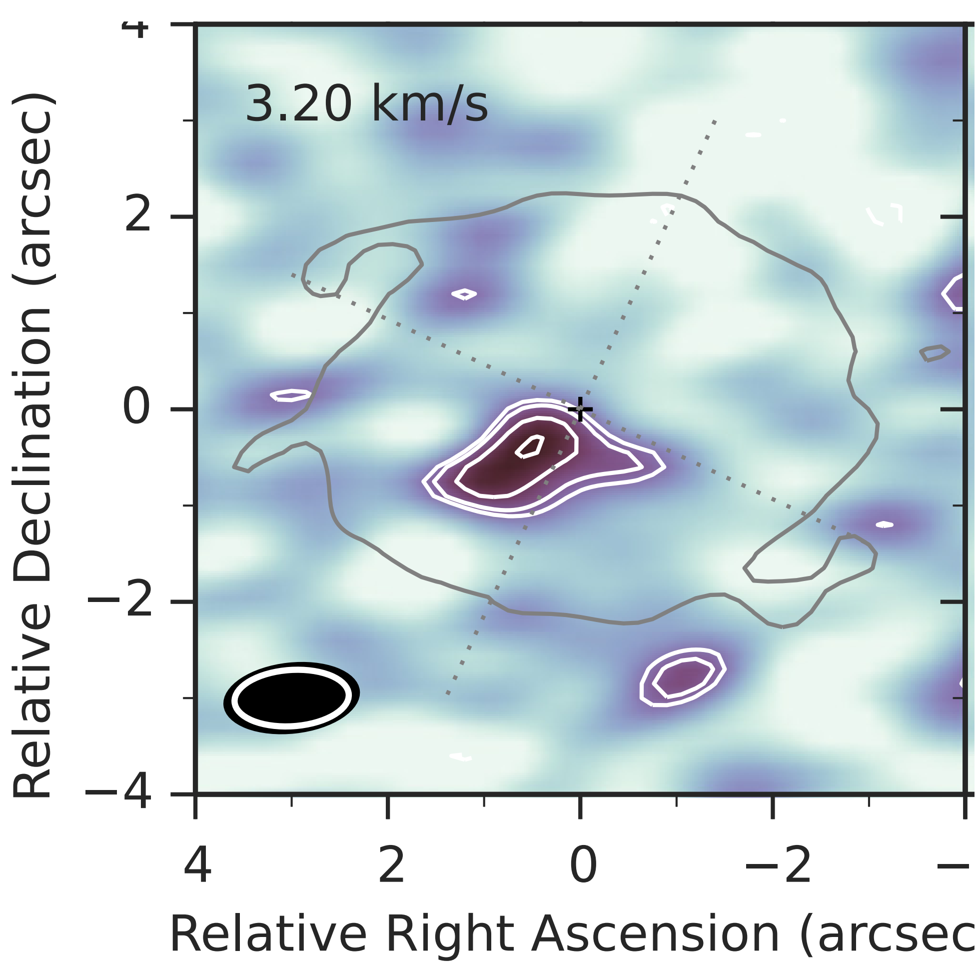


Favre et al. (2013)

Towards complex molecules in protoplanetary disks

Methanol (CH_3OH)

Key molecule in the formation routes to larger O-bearing molecules



STACKING!

Table 1
Methanol Transitions

Transition	Frequency (GHz)	Upper Level Energy (K)
$2_{11}-2_{02}$ (A)	304.208	21.6
$3_{12}-3_{03}$ (A)	305.473	28.6
$4_{13}-4_{04}$ (A)	307.166	38.0
$8_{17}-8_{08}$ (A)	318.319	98.8

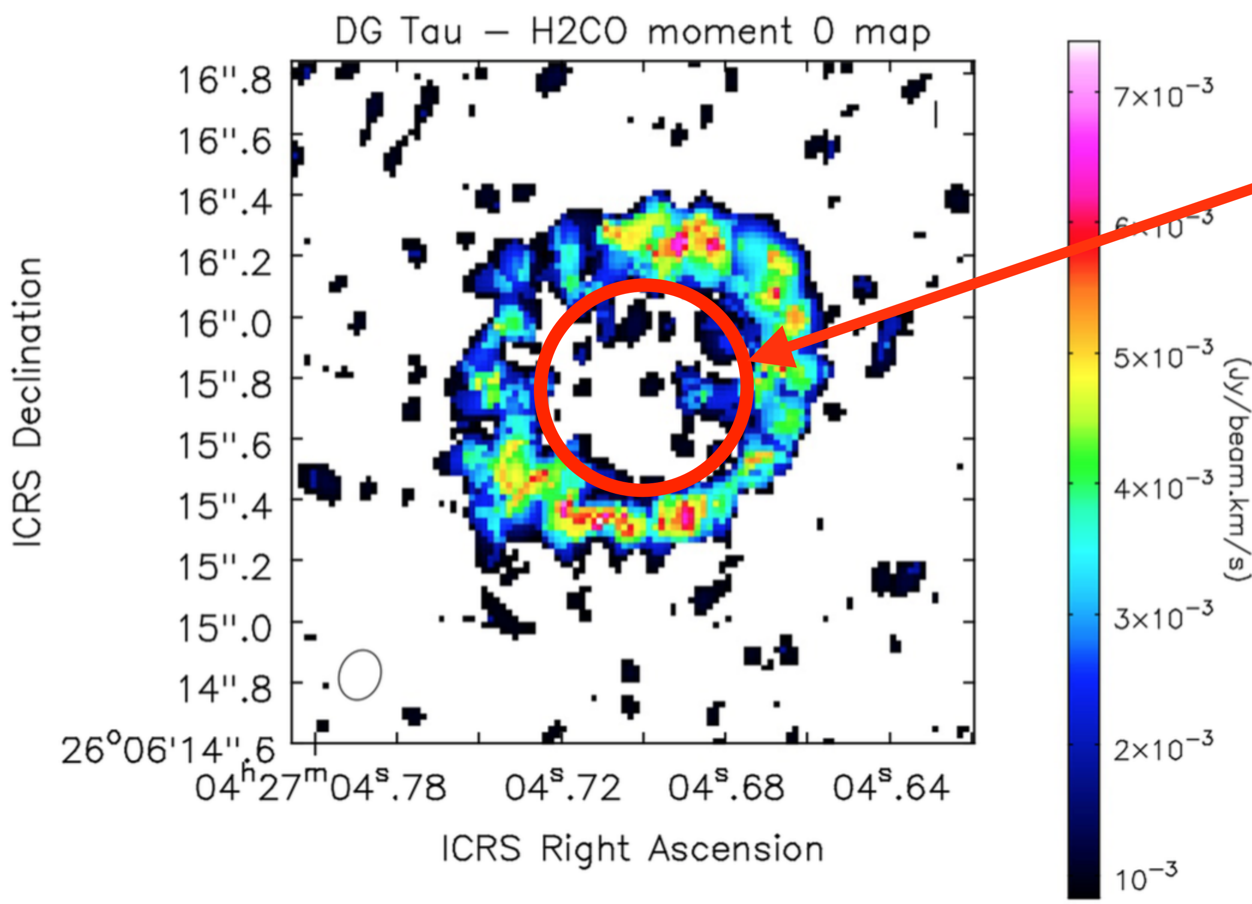
Cold reservoir of CH_3OH in TW Hya

non-thermal desorption

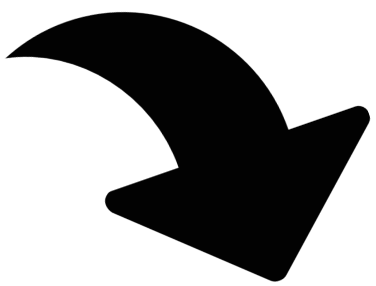
(i.e. induced photo-desorption and/or chemical desorption)

Walsh et al. (2016)

Towards O-bearing molecules in protoplanetary disks



H_2CO emits from beyond the CO snowline



The H_2CO ring?

Efficient formation of **organics on icy grains** for R> R_{CO} and then desorption ?

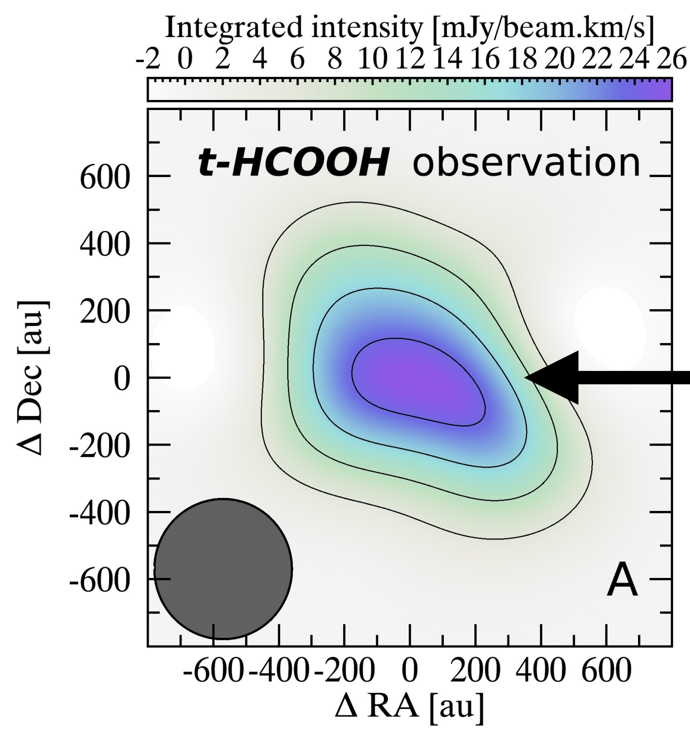
Or **gas phase** chemistry?

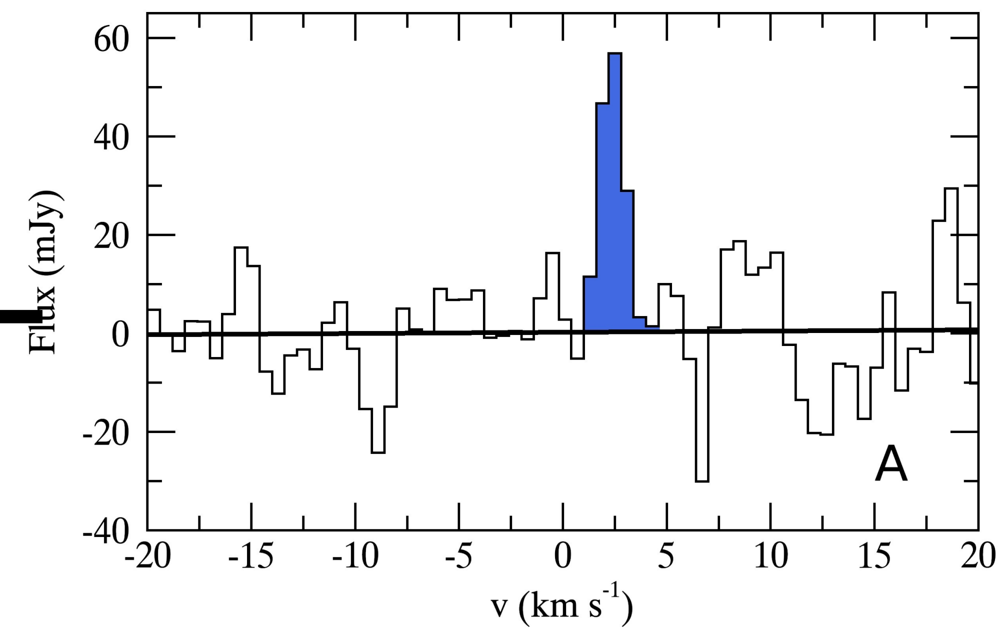
Podio,…, Favre et al. (2019)
Qi et al. (2013)
Carney et al. (2016)
Öberg et al. (2017)

Towards O-bearing molecules in protoplanetary disks

Formic acid (HCOOH)

Key molecule as the carboxyl group (C(=O)OH) *is one of the main functional groups of amino acids*



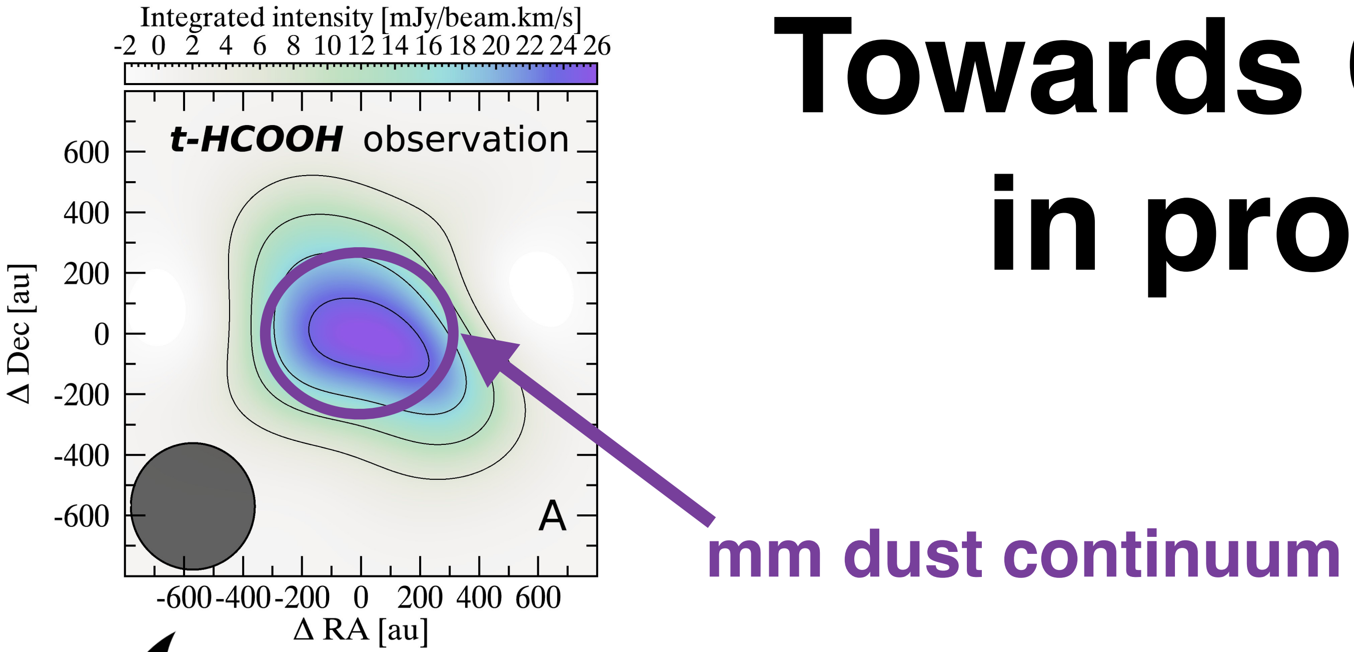


First detection of HCOOH at the 4σ level without stacking!

Rich organic chemistry: (that can lead to larger organic molecules), likely **takes place** at the verge of planet formation in protoplanetary disks

Favre, Fedele, Semenov et al. (2018)

Towards O-bearing molecules in protoplanetary disks

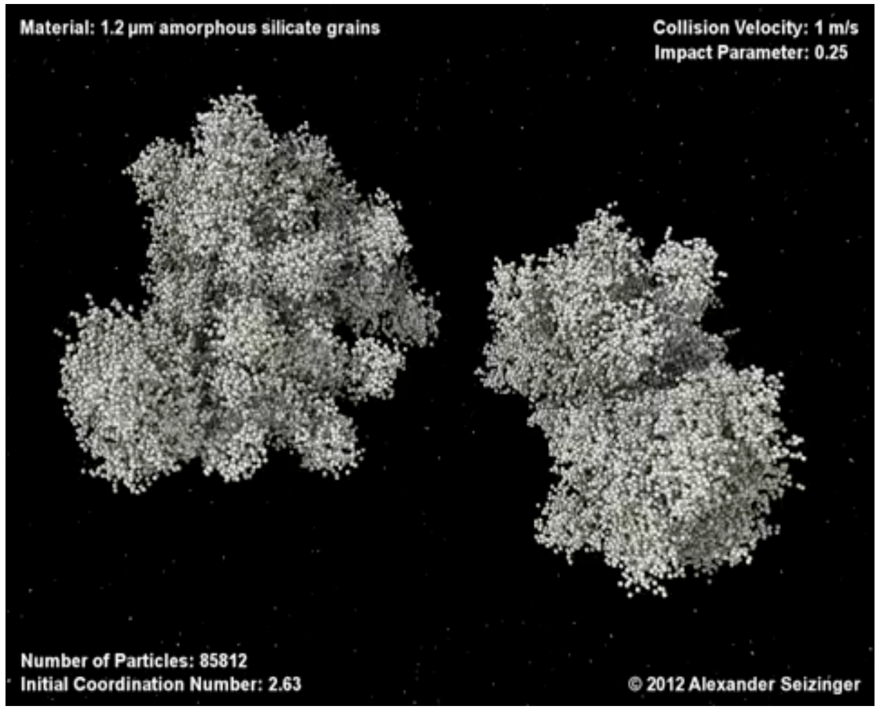


HCOOH emission extends beyond 200 AU (mm dust continuum)

Formation of planets via coagulation of dust grains:

Size & time

1. *Dust (μm)*
2. *Pebbles (mm-cm)*
3. *Planetesimals (10-1000km)*
4. *Planets (10000km)*



Courtesy C.Dominik

Summary

Water (warm and cold) & complex organic molecules (N- and O-bearing)
are present in protoplanetary disks

Observations suggest that chemistry leading to molecular complexity likely takes place in protoplanetary disks where planets might form

- ISM inheritance?

- Reprocessed?

→ **ALMA & NOEMA**

(resolution and sensitivity)

key interferometers for astrochemical studies

But still it will be difficult to detect larger species

Acknowledgements

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