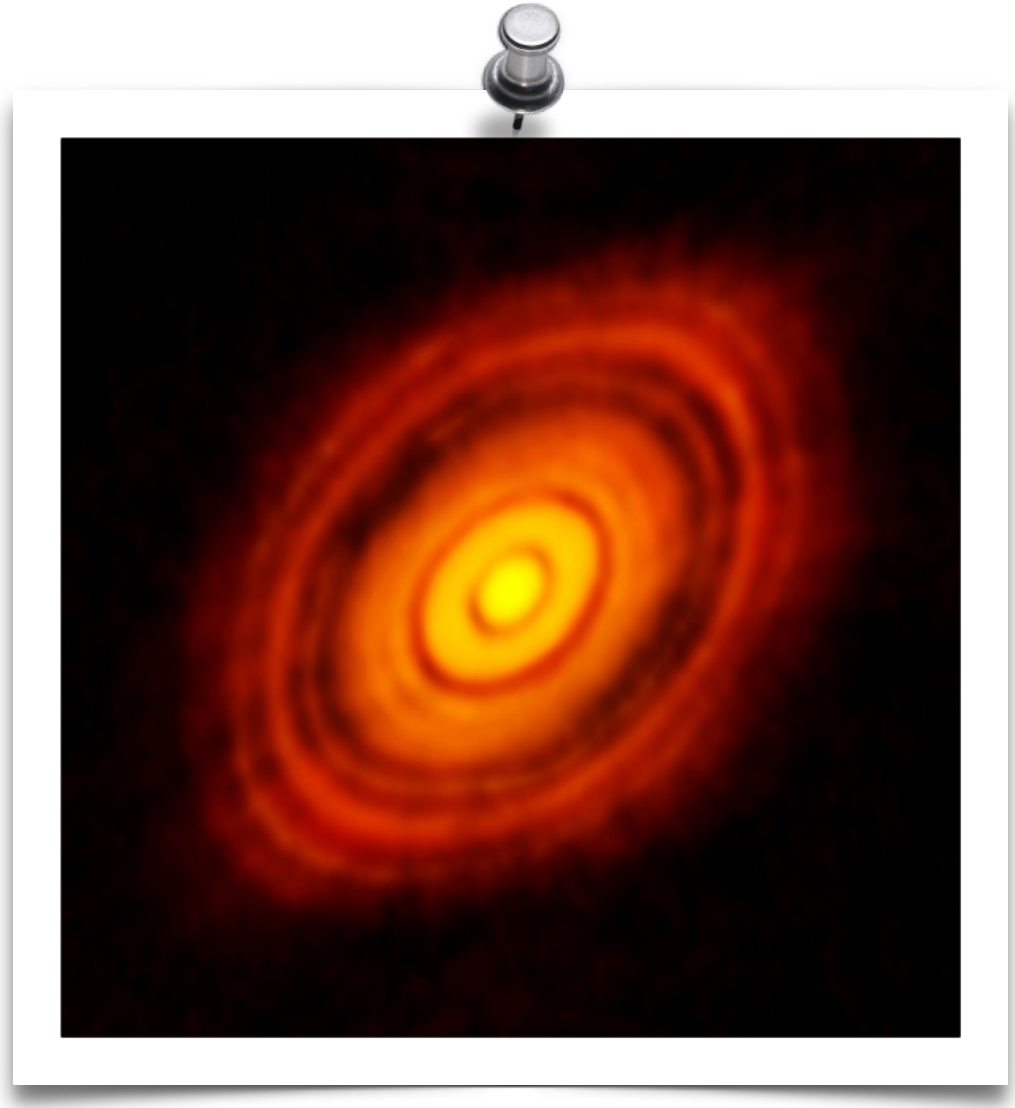
Towards the molecular complexity in protoplanetary disks



Cécile Favre

(INAF-OA Arcetri, Florence)

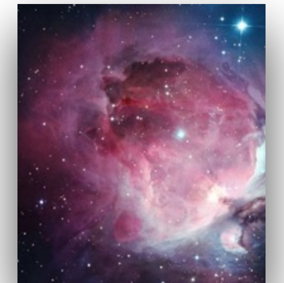
Davide Fedele (INAF-OAA), Dmitry Semenov (MPIA), Sergey Parfenov (Ural Federal Univ), Claudio Codella (INAF-OAA), Cecilia Ceccarelli (IPAG), Franck Hersant (LAB), E. Chapillon (LAB/IRAM), Linda Podio (INAF-OAA), Leonardo Testi (ESO), Edwin Bergin (Univ. Michigan)

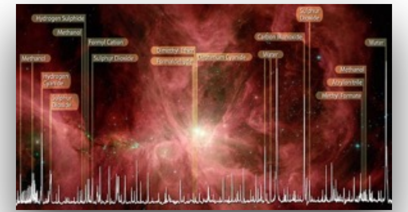
JEDI meeting

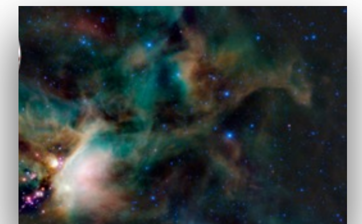
Proto-planetary disks

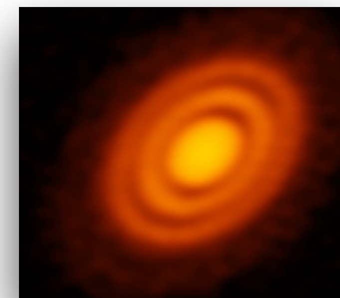
June 27, 2018

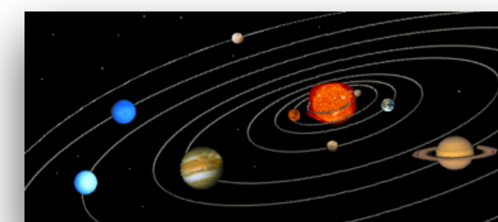
Star formation & chemical evolution


molecular clouds


High-mass star forming regions


Low-mass star forming regions


proto-planetary disks


planetary system

- **Production/Destruction of molecules associated with the different stages of star formation**
- **Evolution and Delivery of interstellar material**

- ***Were they altered?***
- ***Or formed in the protoplanetary nebula?***
- ***Or are they a direct ISM heritage?***
- ***Which processes at the icy surface of grains / in gas phase prevail?***

Molecular inventory of protoplanetary disks

Atoms	
C^+, O	Meeus et al. (2012)
Ions	
HCO^+, $H^{13}CO^+$, DCO^+, N_2H^+, CH^+	Dutrey et al. (1997, 2007), van Dishoeck et al. (2003), Thi et al. (2011), Qi et al. (2008, 2013a), Öberg et al. (2015a)
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	Dutrey et al. (1997), Guilloteau et al. (2013)
N-bearing molecules	
CN, HCN, HNC, DCN	Dutrey et al. (1997), Qi et al. (2008)
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), Podio et al. (2013)
O-bearing molecules	
H_2CO	Qi et al. (2013a),Loomis et al. (2015) Öberg et al. (2017), Carney et al. (2017)
t-HCOOH	Favre et al. (2018)
Complex organic molecules	
CH_3OH	Walsh et al. (2016)
CH_3CN	Öberg et al. (2015b),Bergner et al. (2018),Loomis et al. (2018)

Outline

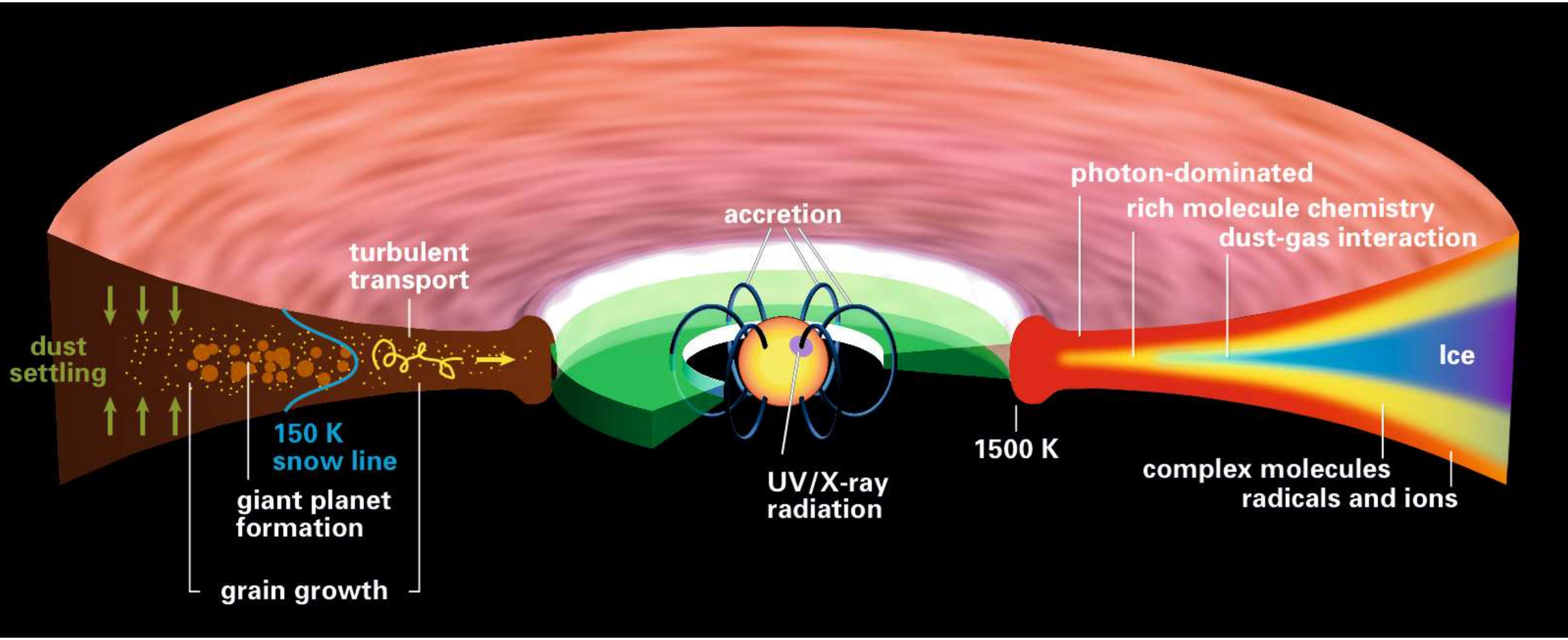
1. **Protoplanetary disks**
   - Interferometry for astrochemical studies: ***sensitivity*** & ***resolution***

2. **O-bearing and S-bearing molecules in disks**
   - A rich organic chemistry
   - A non solar C/O ratio in T Tauri disks

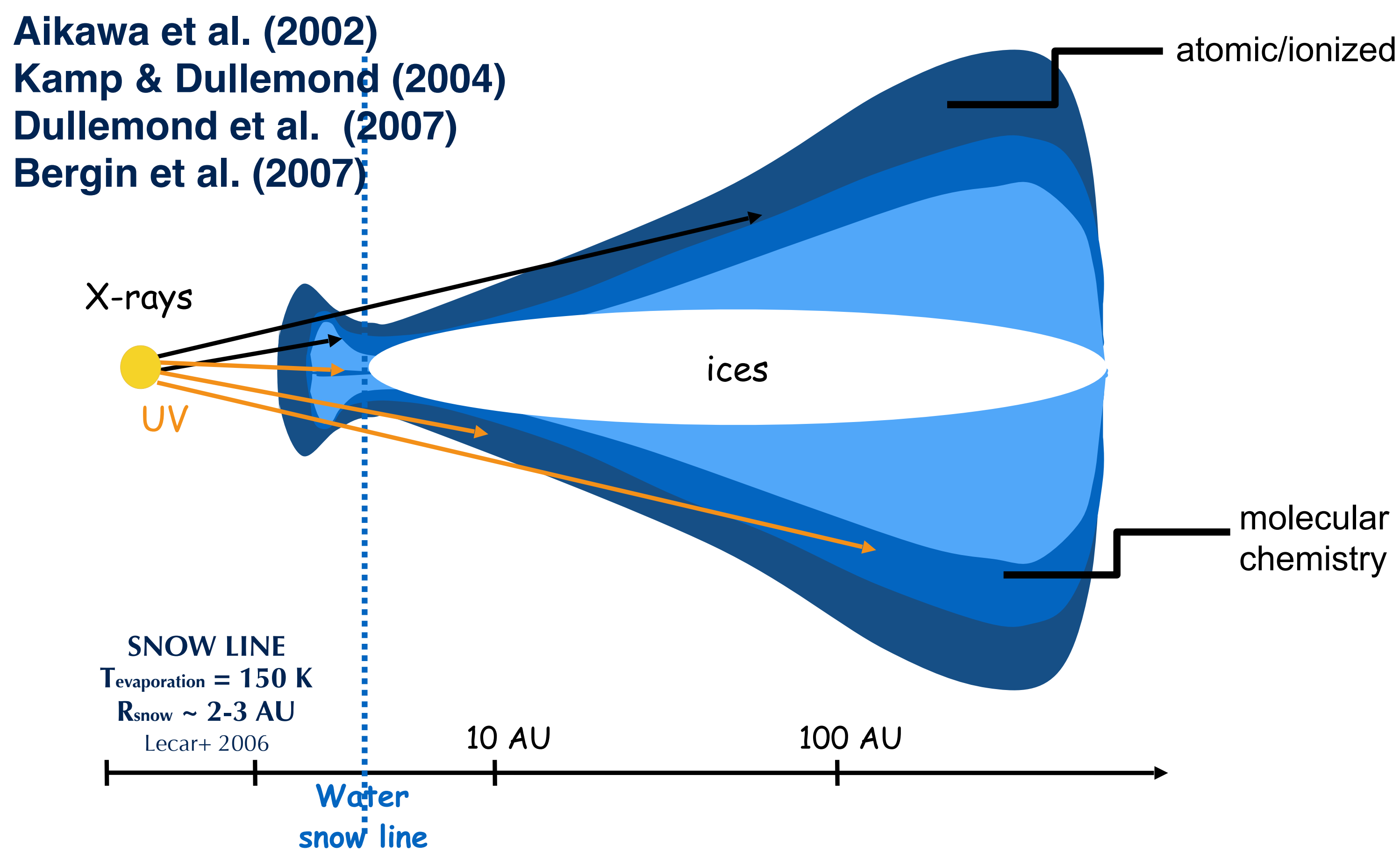
3. **Planet formation & molecules**
   - Observations of the molecular content that will be partly inherited by the planet(s)

Disks are complex systems

Strong T and n gradients, UV & X-ray



Sketch of physical and chemical structure of protoplanetary disks
Henning & Semenov (2013)



Courtesy Linda Podio

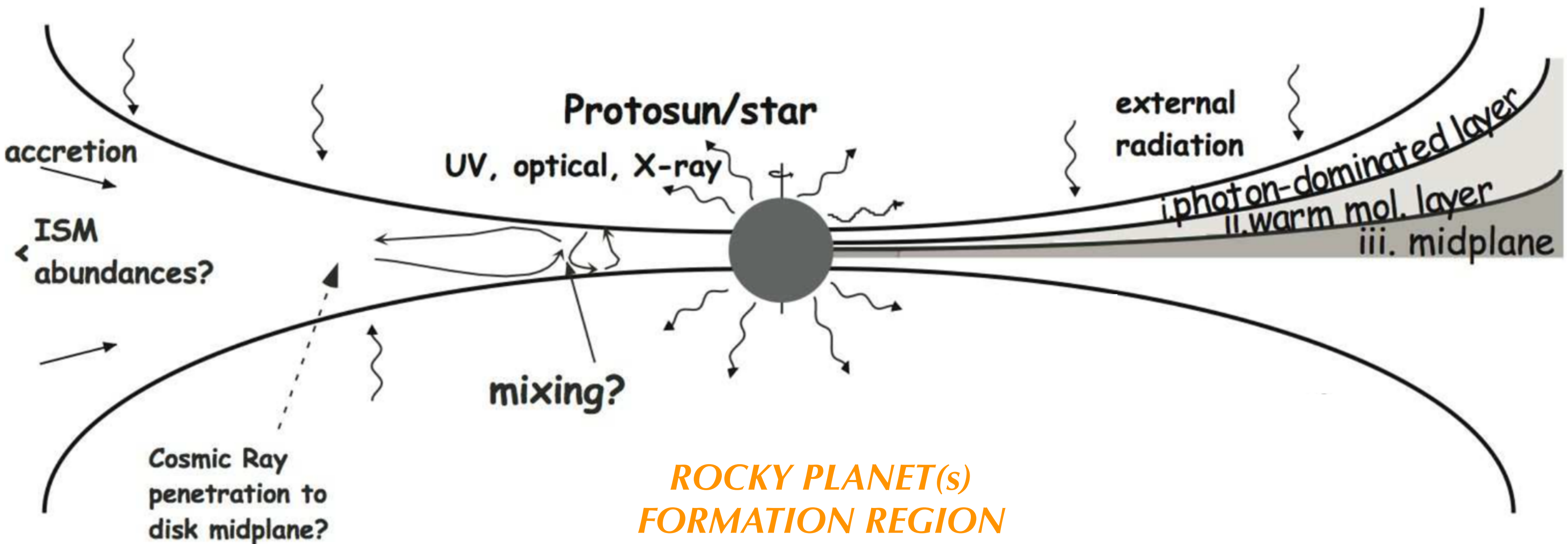
Complex organic molecules in protoplanetary disks

- **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!

Modica & Palumbo (2010)
Walsh et al. (2014)

Interferometry is needed to access the molecular content in disk



ROCKY PLANET(s)
FORMATION REGION

Bergin et al. (2007)

3 AU = 0.02” at 140 pc

10 AU = 0.07” at 140 pc

50 AU = 0.4” at 140 pc

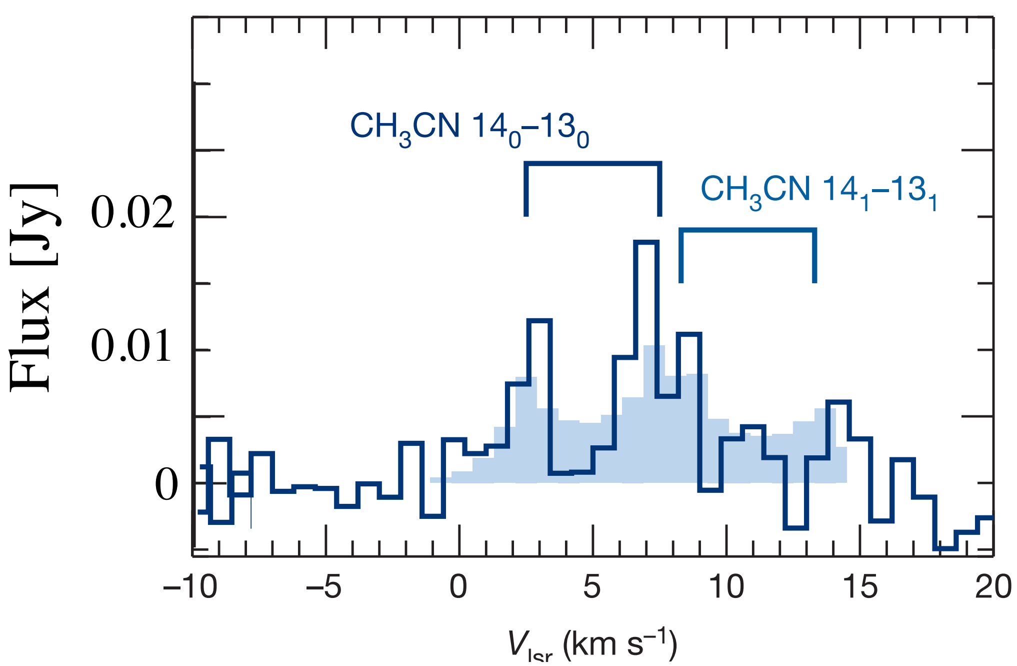
100 AU = 0.7” at 140 pc

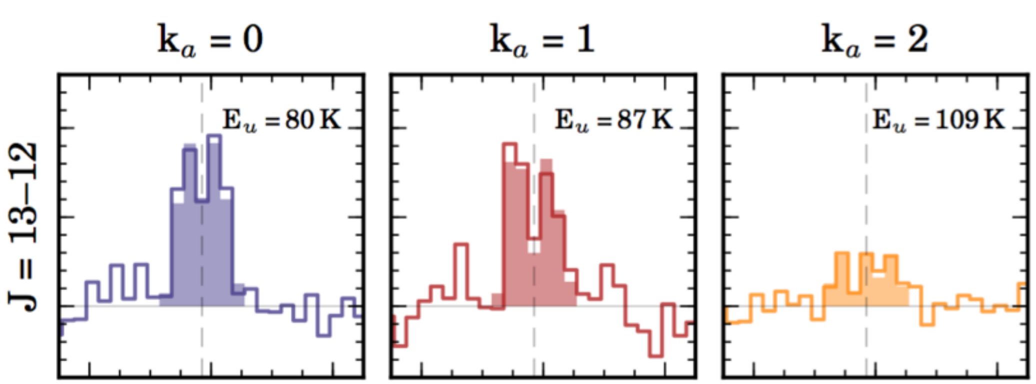
High angular resolution!

1 AU = Distance between the Sun and the Earth

Interferometry is needed to access the molecular content in disk

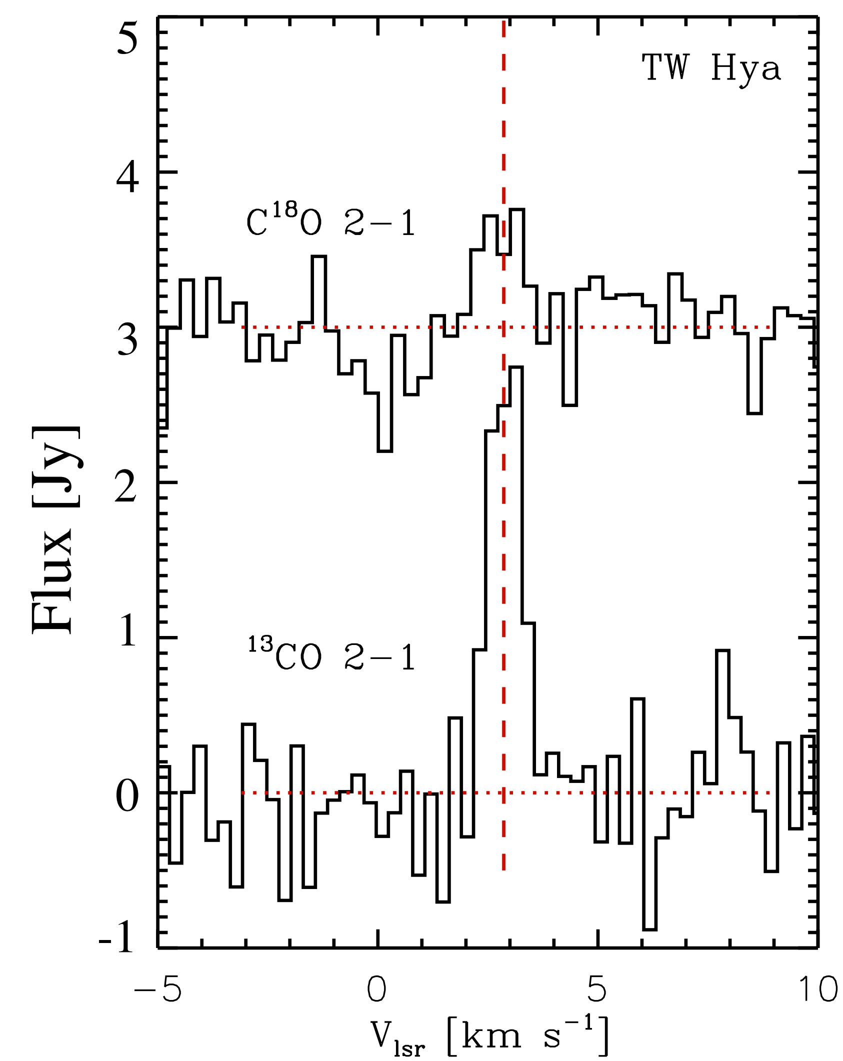
The emissive area is expected to be small
(and might be closed to the central object)
It is really hard to detect a not intense transition





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

High sensitivity!



Favre et al. (2013)

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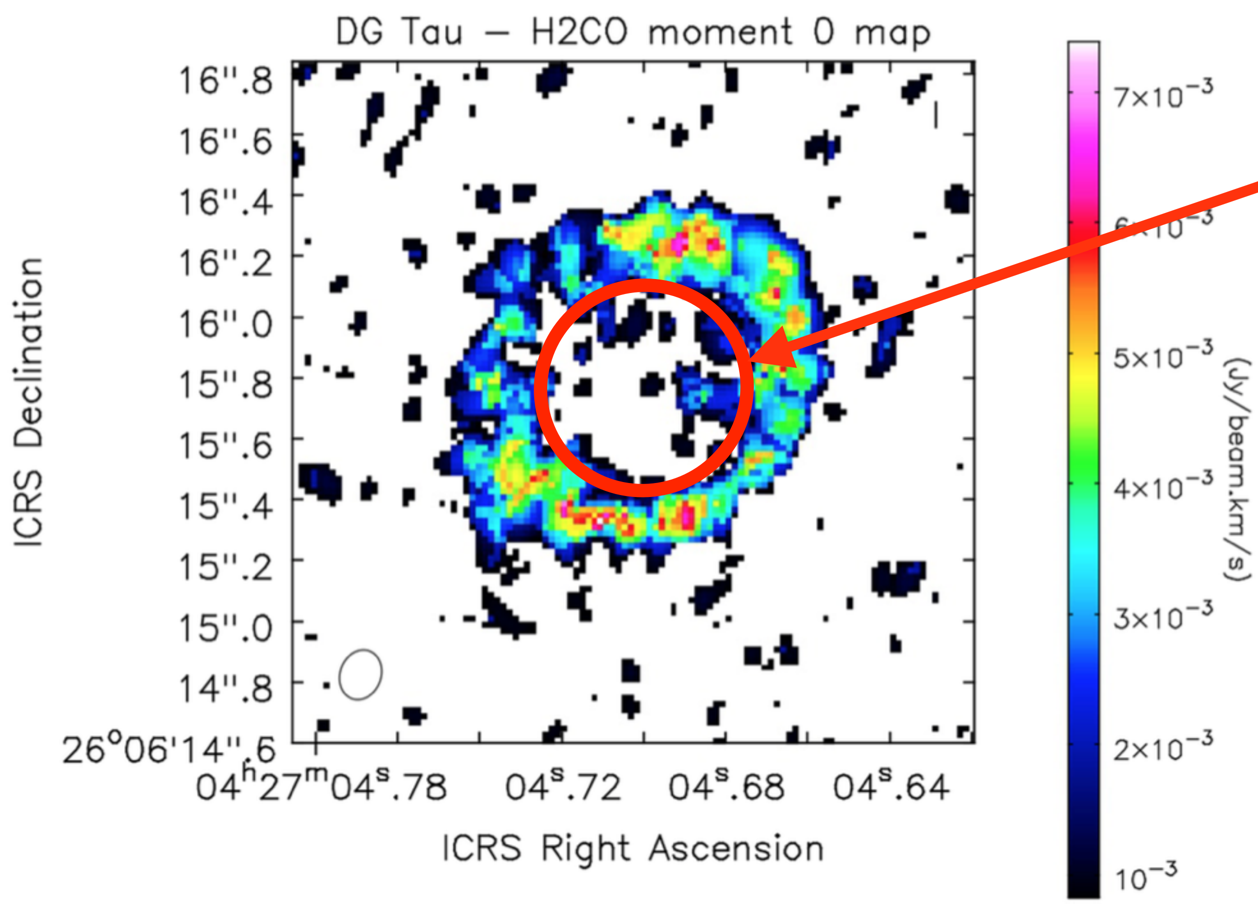
Towards O-bearing molecules in protoplanetary disks



H_2CO emits from beyond the CO snowline

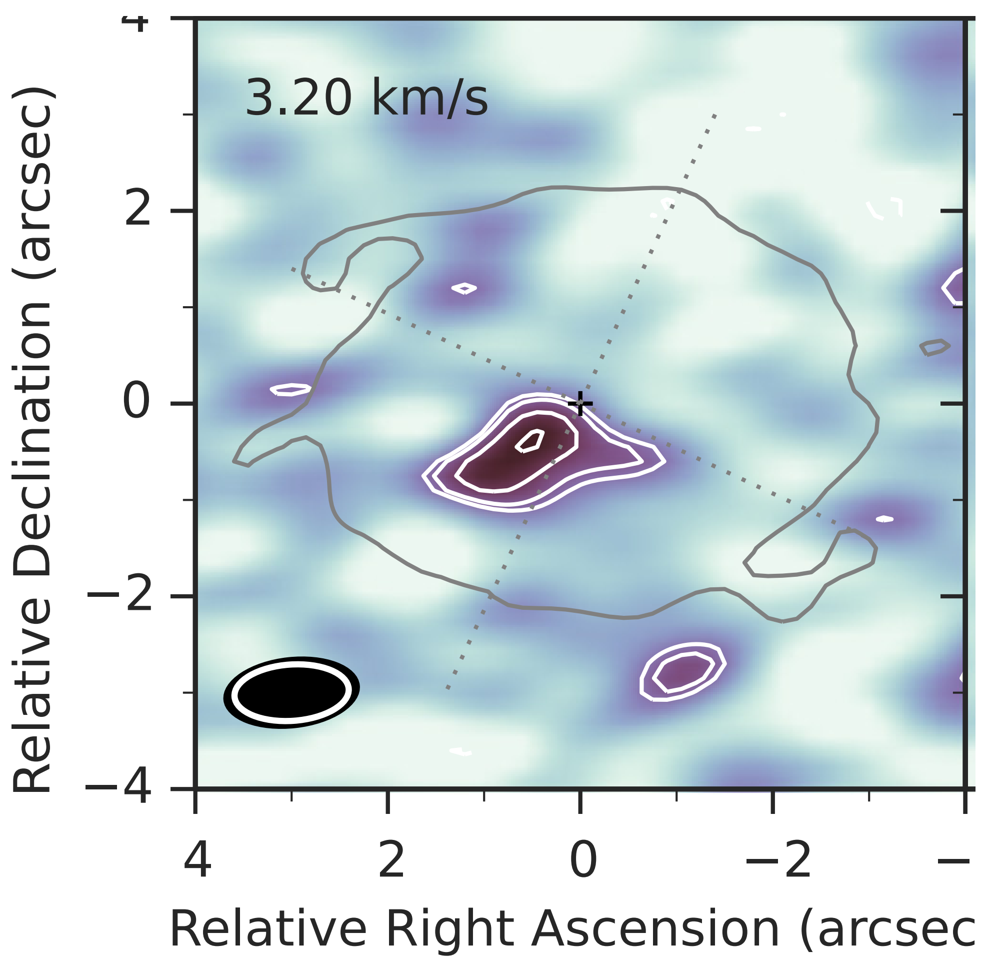
Efficient formation of organics on icy grain for R> R_{CO} to explain the H_2CO ring

Podio et al., in prep.
Qi et al. (2013)
Carney et al. (2016)
Öberg et al. (2017)

Towards complex molecules in protoplanetary disks

Complex Organic Molecules

CH_3OH: ***a key molecule in the formation routes to larger O-bearing molecules***



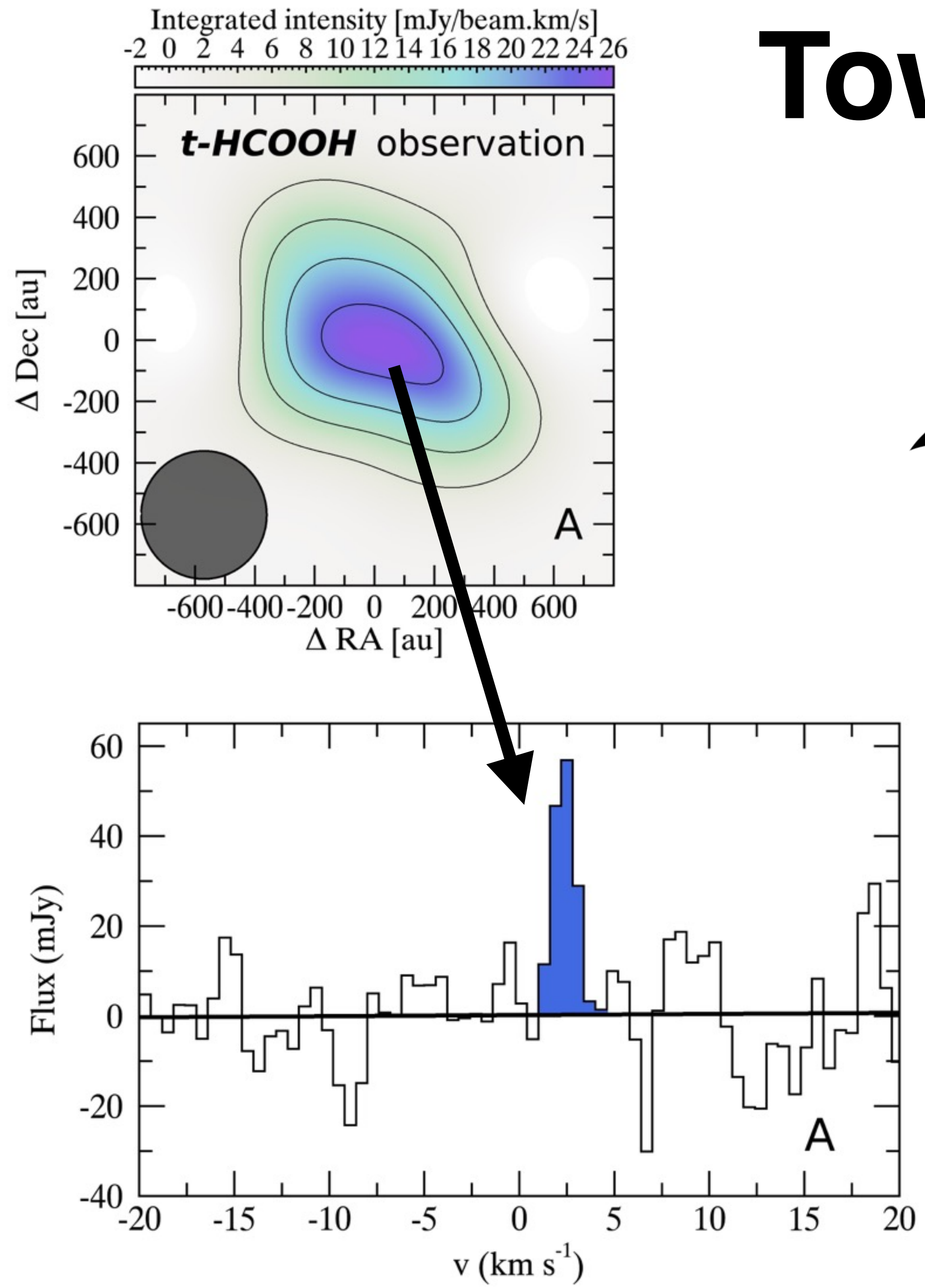
Walsh et al. (2016)

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

STACKING!

Towards O-bearing molecules in protoplanetary disks

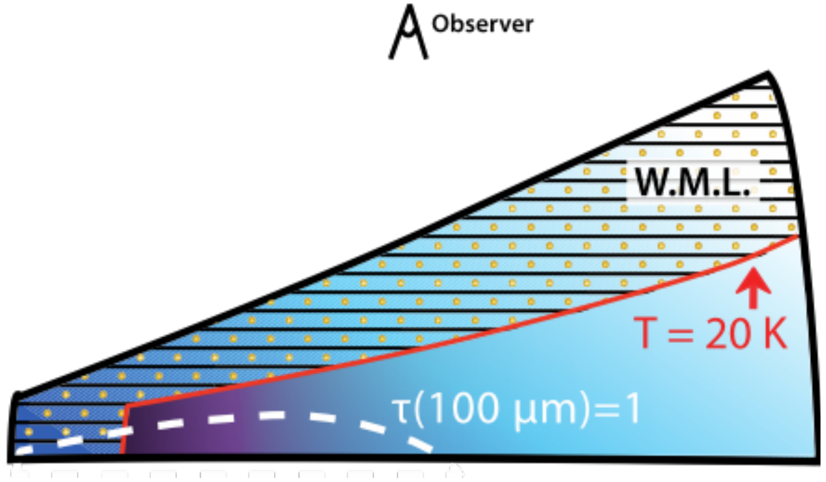


$N(HCOOH) \sim (2\text{-}4) \times 10^{12}\ cm^{-2}$
$HCOOH/CH_3OH \leq 1$

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)
- **HCOOH emission extends beyond 200 AU (mm dust continuum):** contribution of small grains likely contribute to the HCOOH production

Favre, Fedele, Semenov et al. (2018), ApJL, in press



A depletion of elemental C in T Tauri disks

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

CO abundance relative to H_2 : (0.1-3)x10^{-5} *in the disk's warm molecular layers (T>20K),* **lower than the canonical value of χ(CO) = 10^{-4})**

Carbon chemistry?

(Aikawa et al. 1997, Reboussin et al. 2015)

CO chemical destruction via reactions with He^+

+

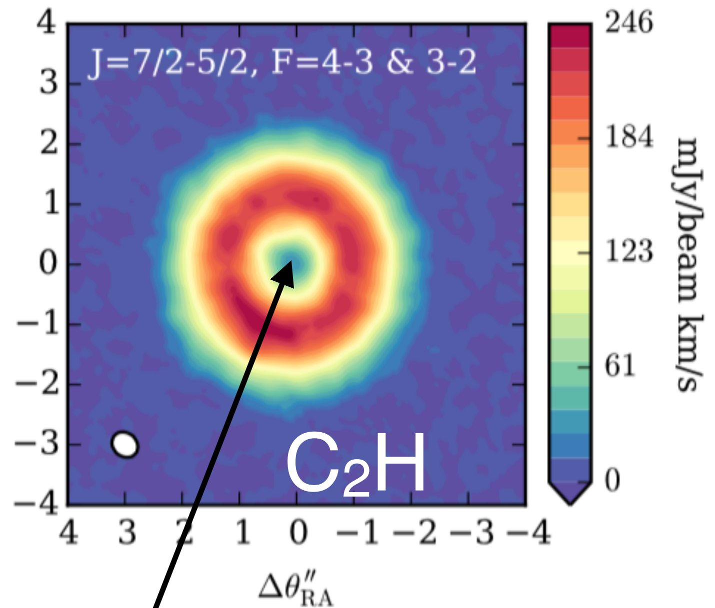
Followed **by rapid formation of carbon chains** (**C_xH_x**) or CO_2

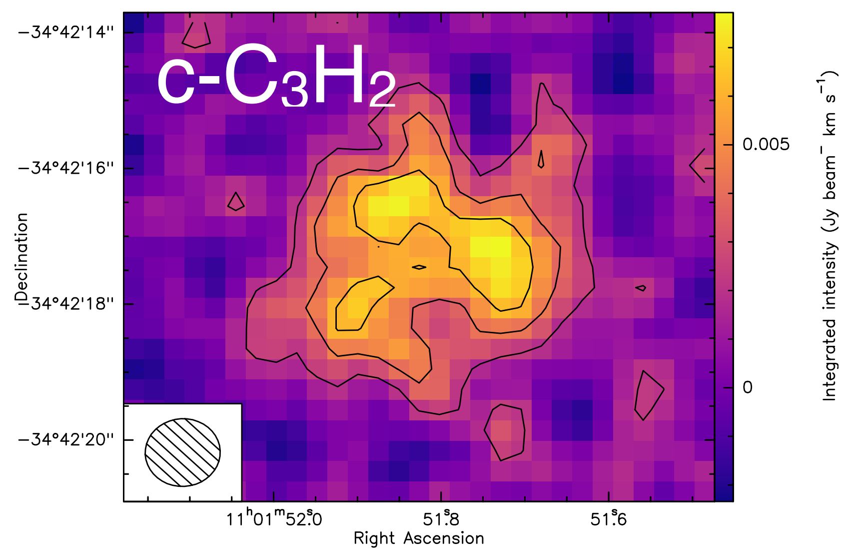
+

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

Carbon reservoir in gas?

A non solar C/O ratio observed via the emission of c-C_3H_2 and S-bearing molecules

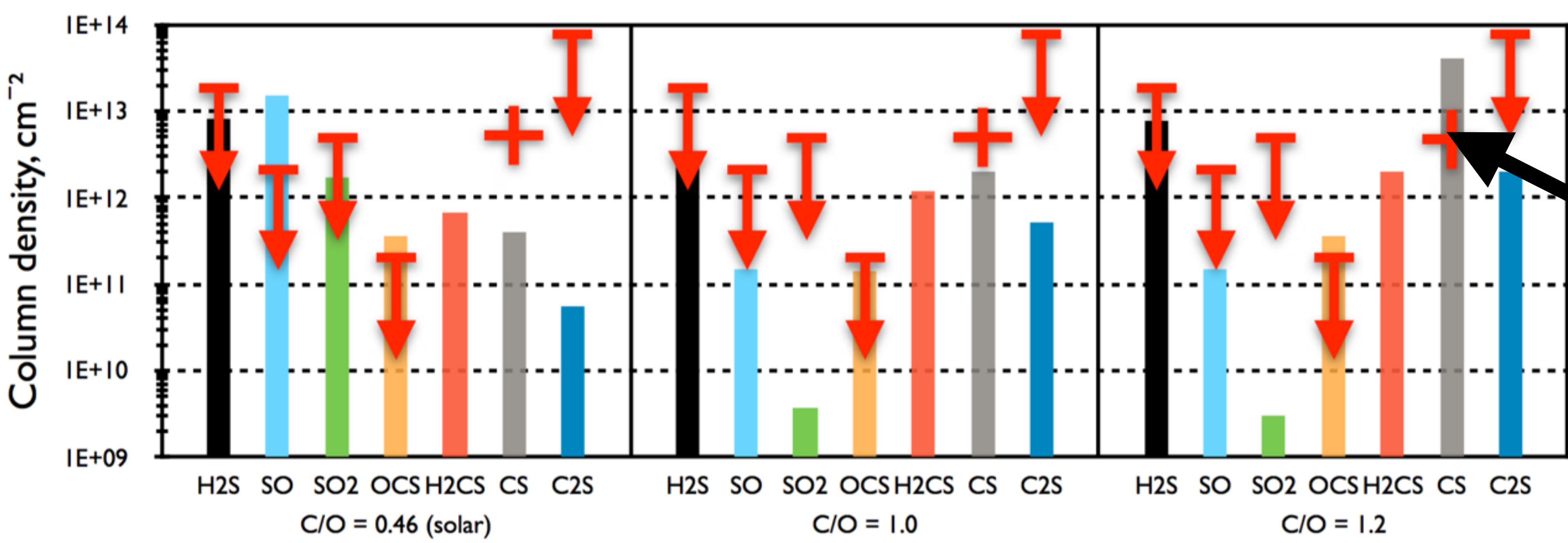


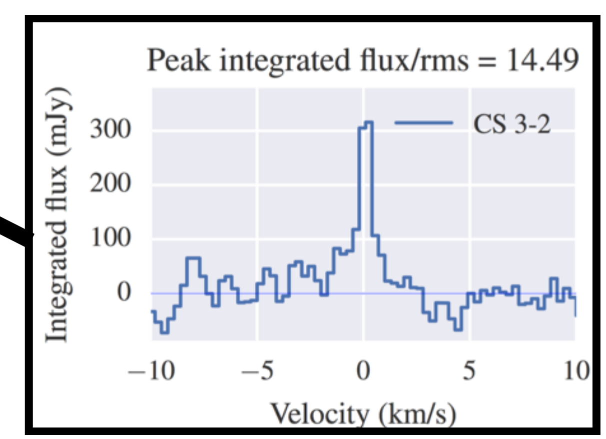


Bergin et al. (2016)
Favre, Fedele, kamp (in prep.)

C/O ≥ 1

Carbon chemistry?





Semenov, Favre, Fedele et al. (2018), A&A, in press

Oxygen chemistry?
(Bergin et al. 2016)

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

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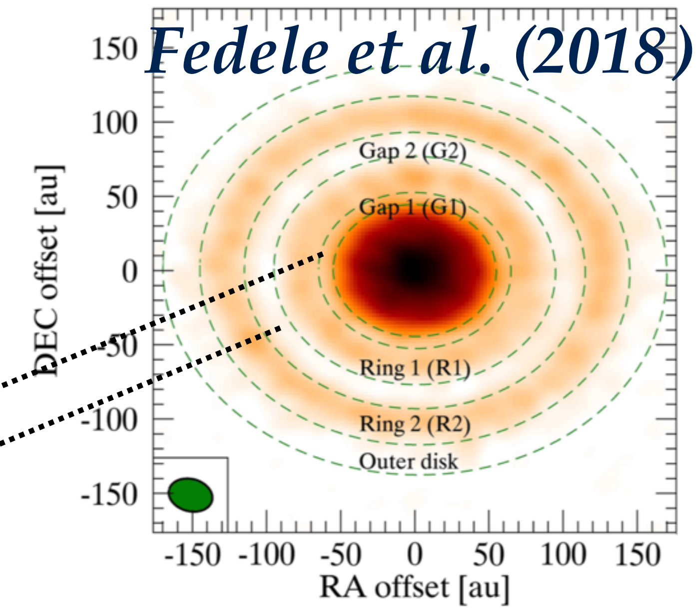
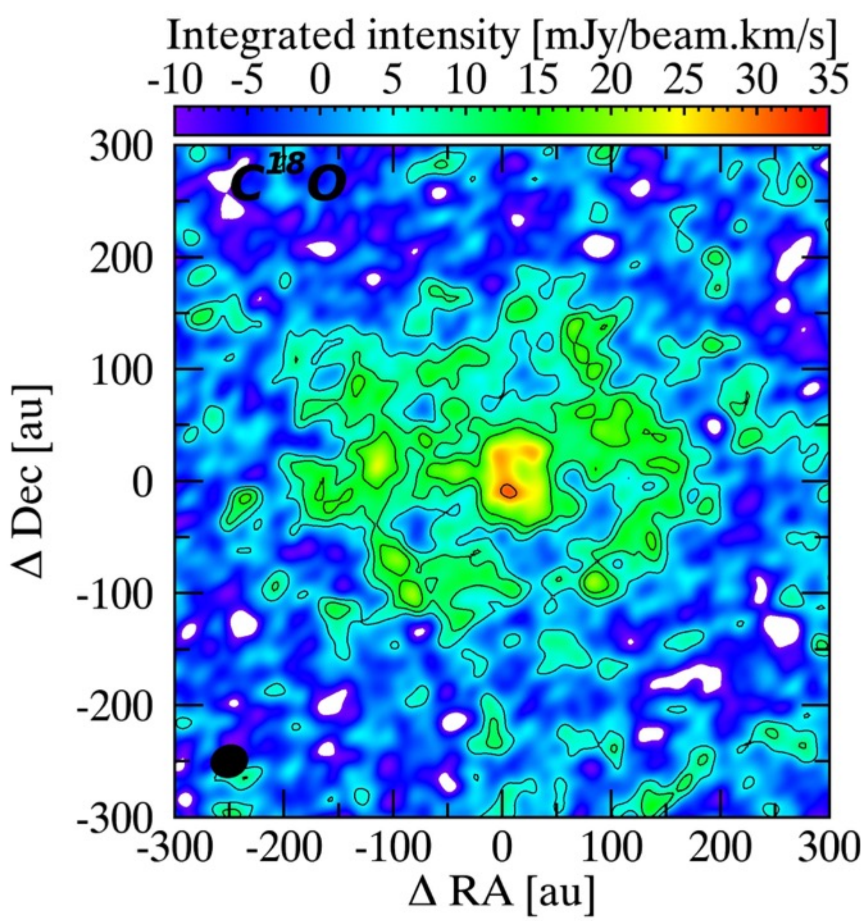
Planet(s) formation seen in both gas and dust

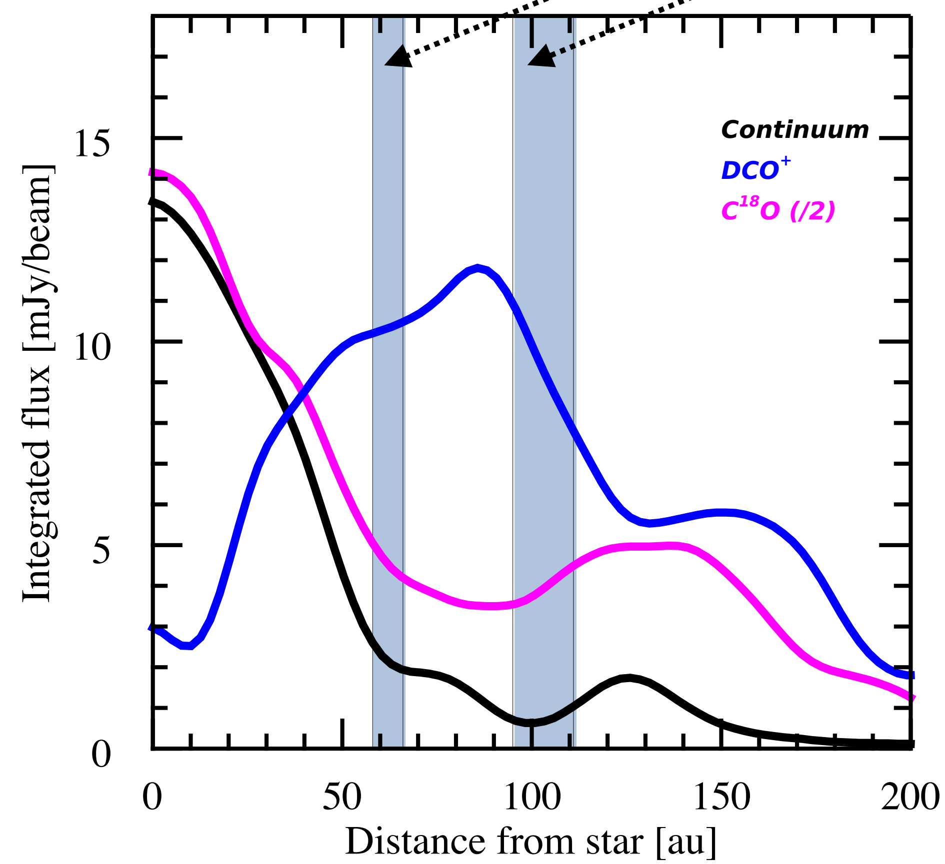
Talk by D. Fedele

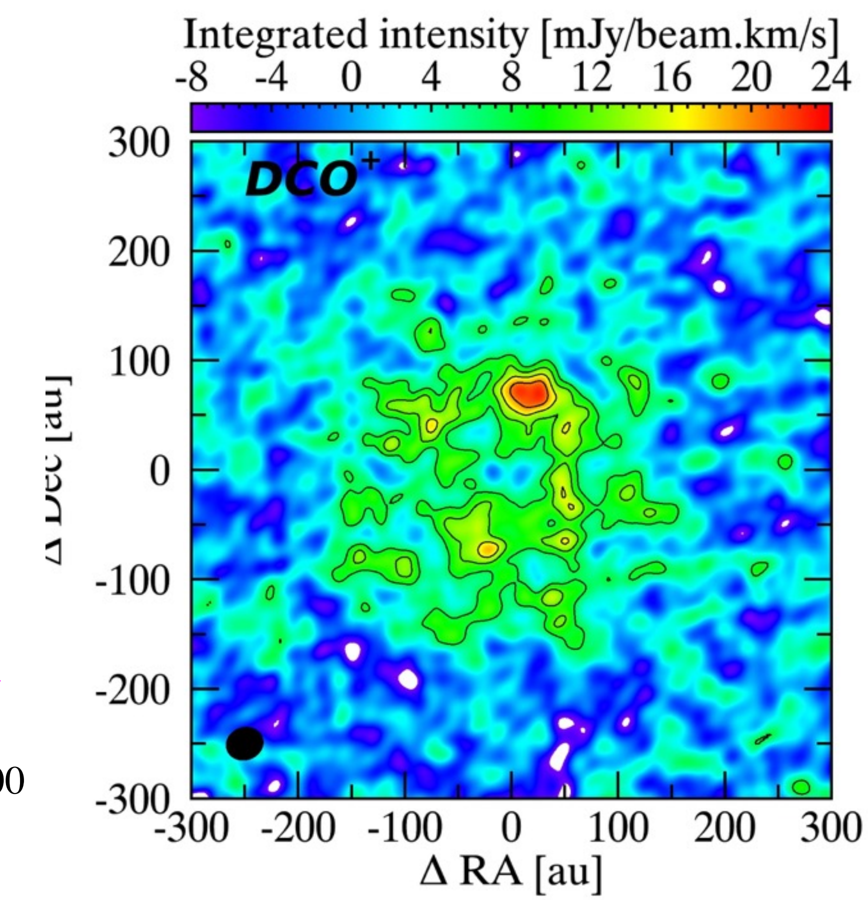
dust gaps

Fedele et al. (2018)









Favre et al. (in prep.)

see also Isella et al. (2016), Teague et al. (2018), Muro-Arena et al. (2018)

One should be able to observe the molecular content in these objects that is directly inherited by the forming planets (and small bodies)

Summary

Complex molecules (N- and O-bearing)
are present towards proto-planetary disks

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

- ISM inheritance?

- Reprocessed?

ALMA

(resolution and sensitivity)

key interferometer for astrochemical studies

But still it will be difficult to detect larger species

« For your attention
I thank you »