From disc chemistry to planetary atmospheres

DAVIDE FEDELE

ON BEHALF OF WG `PLANET FORMATION' @ INAF/ARCETRI

Outline

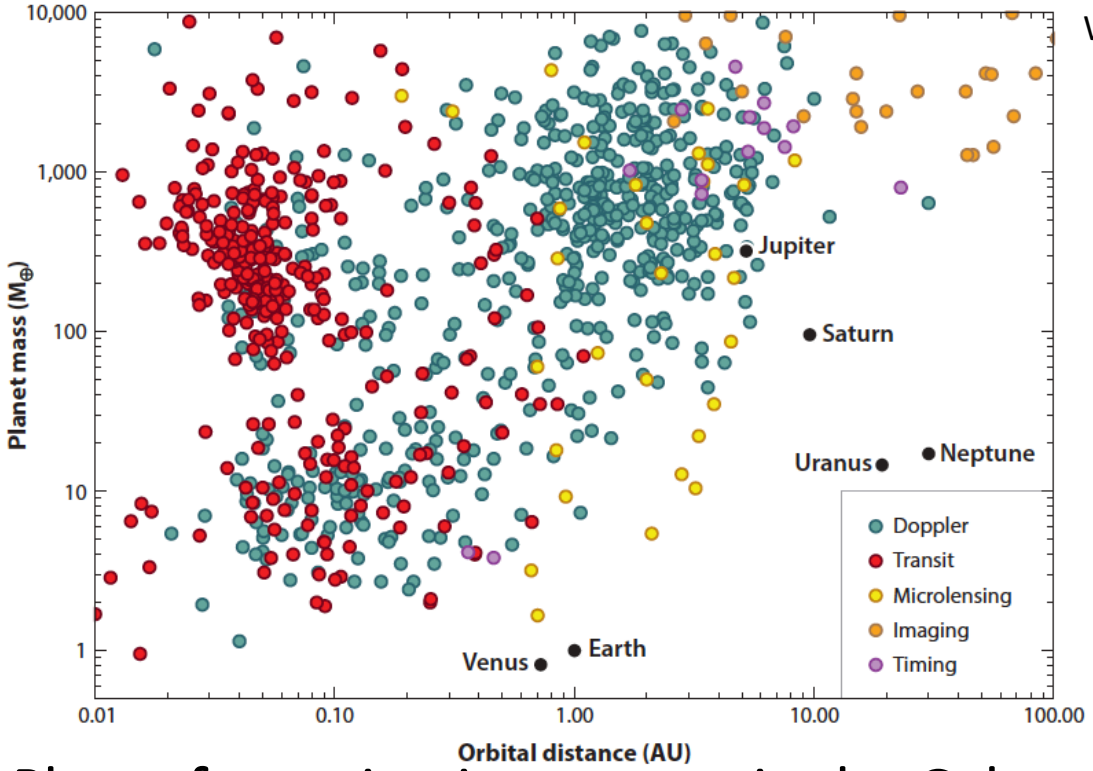
Introduction to protoplanetary discs

ALMA (initial) results on protoplanetary discs

Ariel `Planet formation' WG @ OAA

Conclusions

Planets ‘demography’



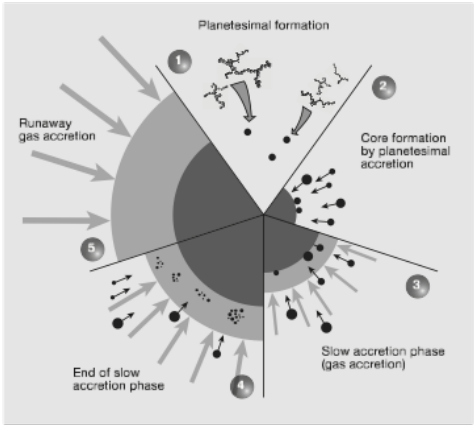
Winn & Fabrycky 2015

Planet formation is common in the Galaxy

Architecture of planetary systems is highly heterogeneous

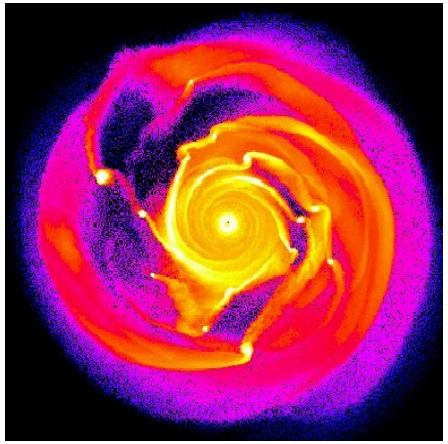
Planet formation

Core-accretion



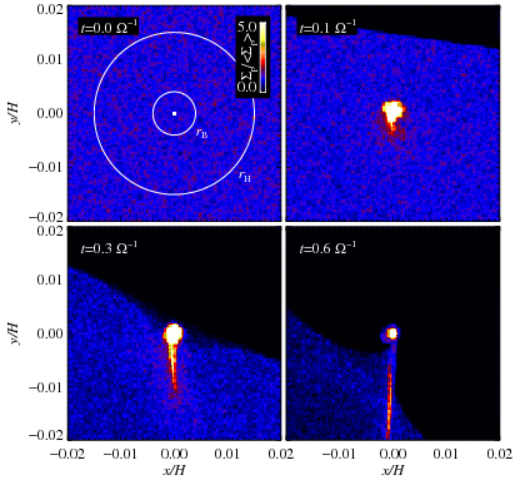
e.g., Mizuno 1980, Lissauer 1993, Pollack 1996

Gravitational instability



e.g., Adams 1989, Boss 1997, Durisen 2007

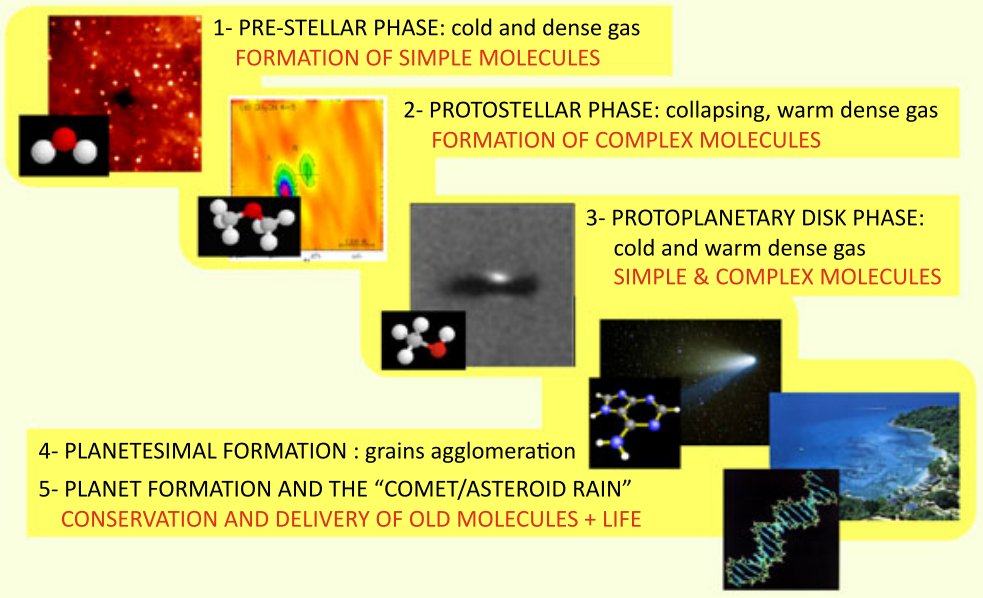
Pebble accretion



e.g., Lambrechts et al. 2014

Observations of protoplanetary discs provide the initial conditions for planet formation

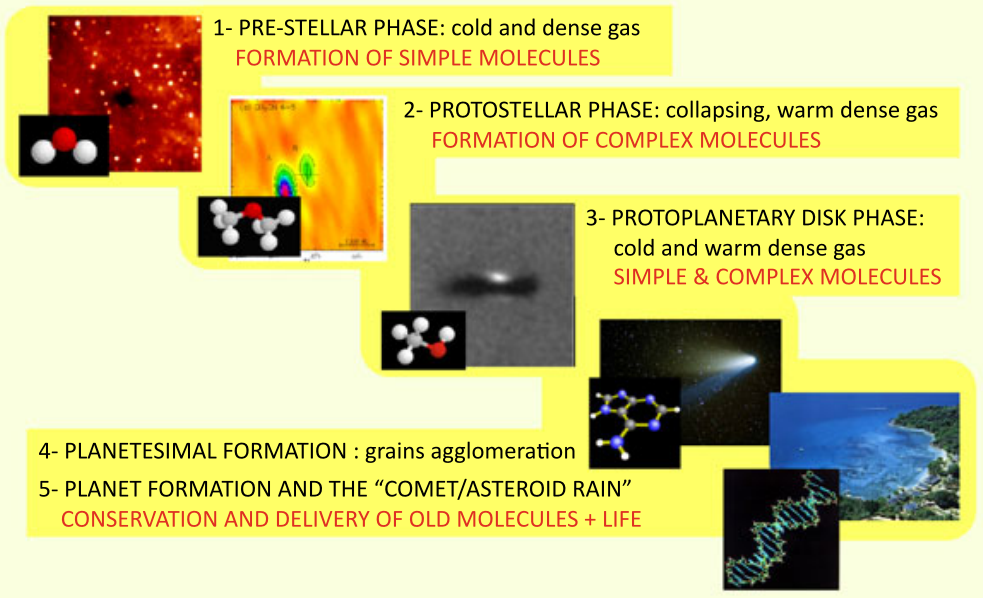
From atoms to life



Caselli & Ceccarelli 2012

Observations of protoplanetary discs to address chemical enrichment during planet formation

From atoms to life

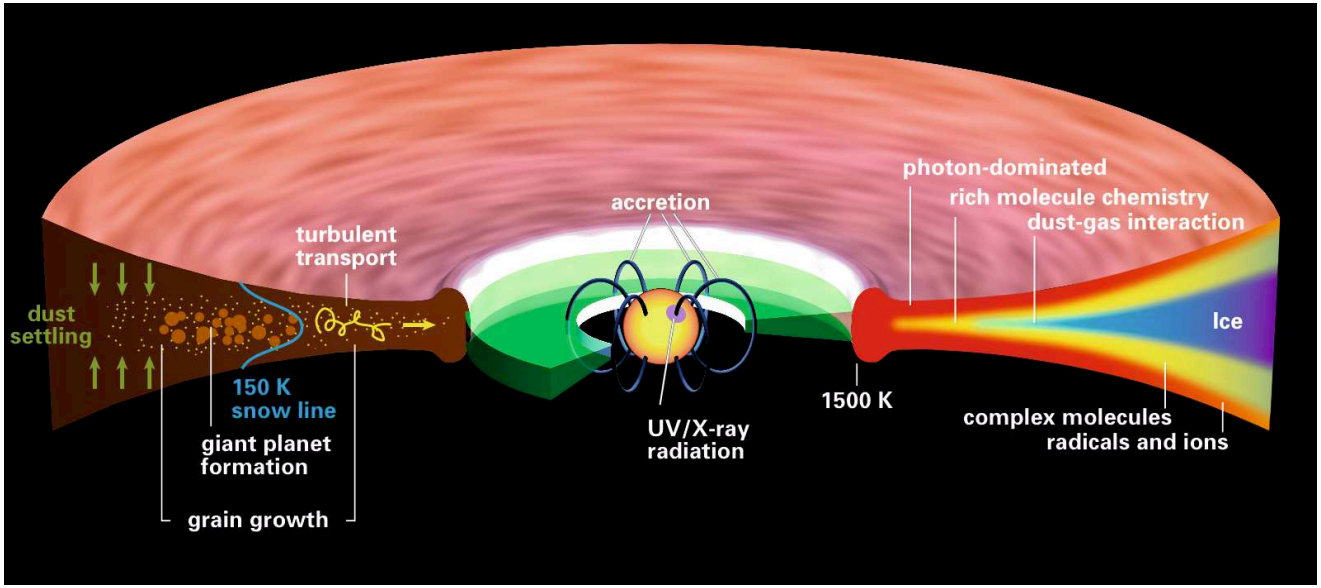


Caselli & Ceccarelli 2012

Planetary composition: disc chemical reset *vs* inheritance scenario ?

Schematic of disc interior

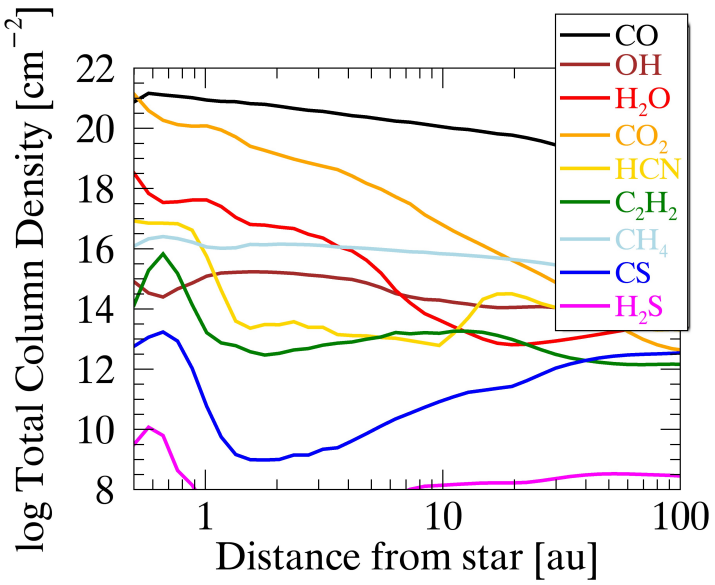
Henning & Semenov 2013



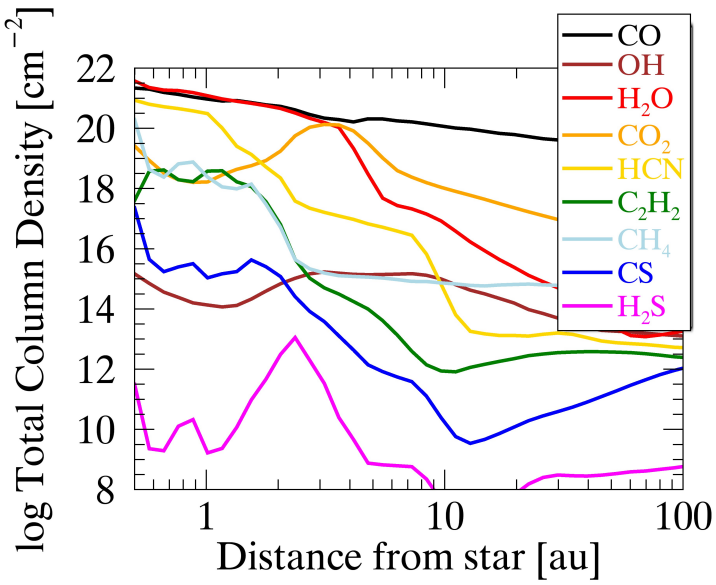
Discs are characterized by large density ($n = 10^4 – 10^{12}$ cm^{-3}) and temperature ($T = 10 – 10^4$ K) gradients

Disc chemistry

Mstar = 0.5 Msun



Mstar = 2.5 Msun

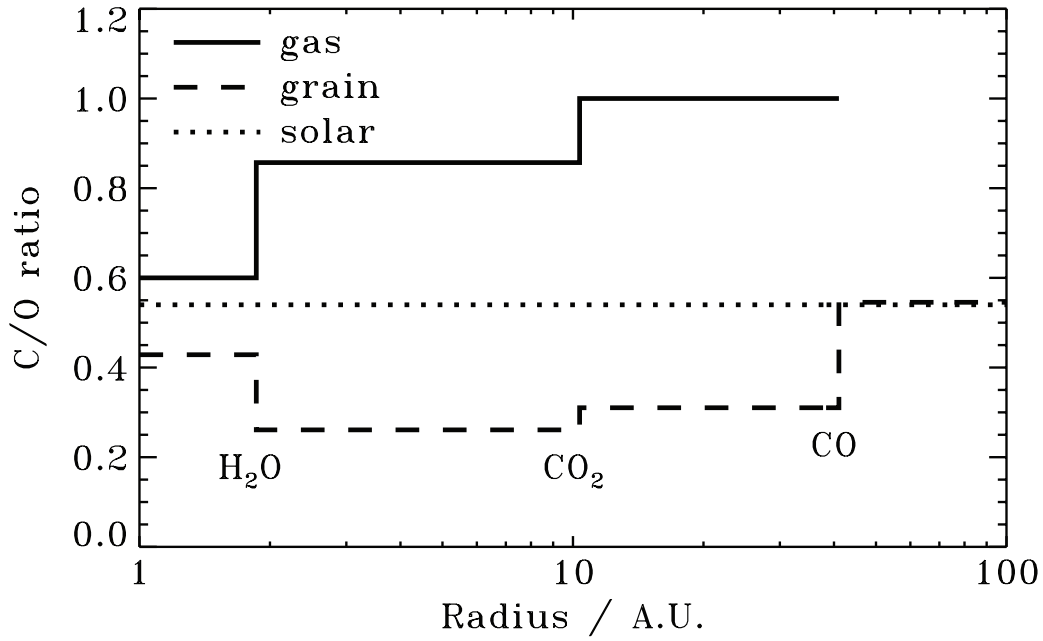


Agundez et al. 2018
Walsh et al. 2015

Discs are chemically active

Spatial distribution of volatiles

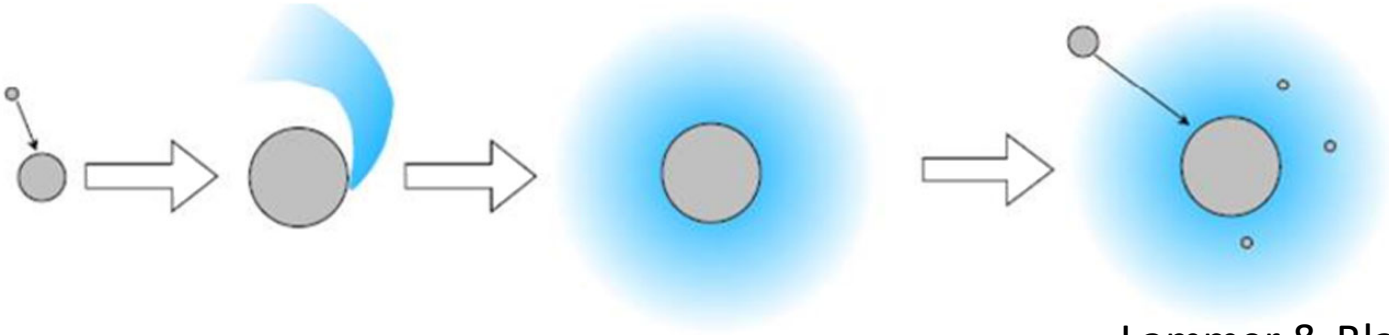
Oberg et al. 2011



The sequence of *icelines* induces radial stratification of C, N & O

Origin of planetary atmospheres

Schematic of core accretion



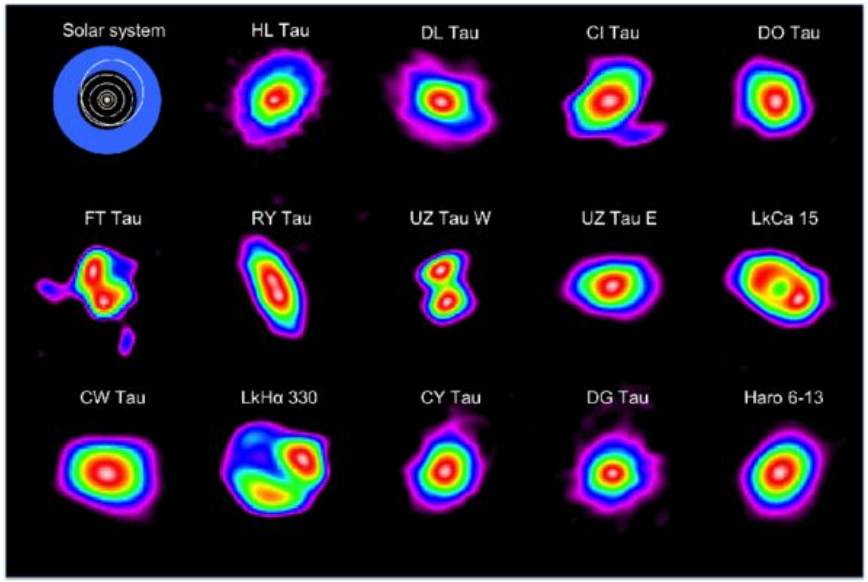
Lammer & Blanc 2018

Atmosphere of giant planets reflects disc chemical composition
→ Where and how planets form

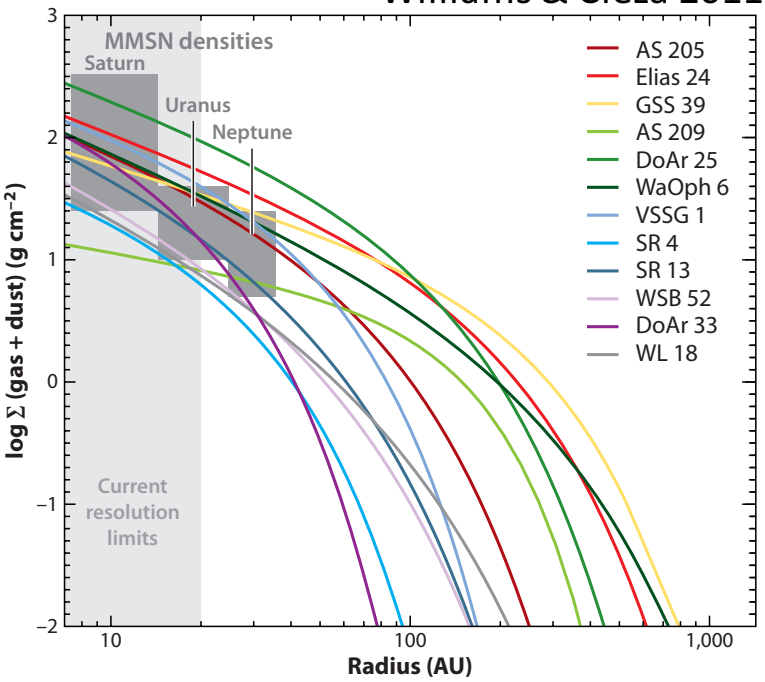
ALMA results

DISC SURFACE DENSITY

Disc surface density

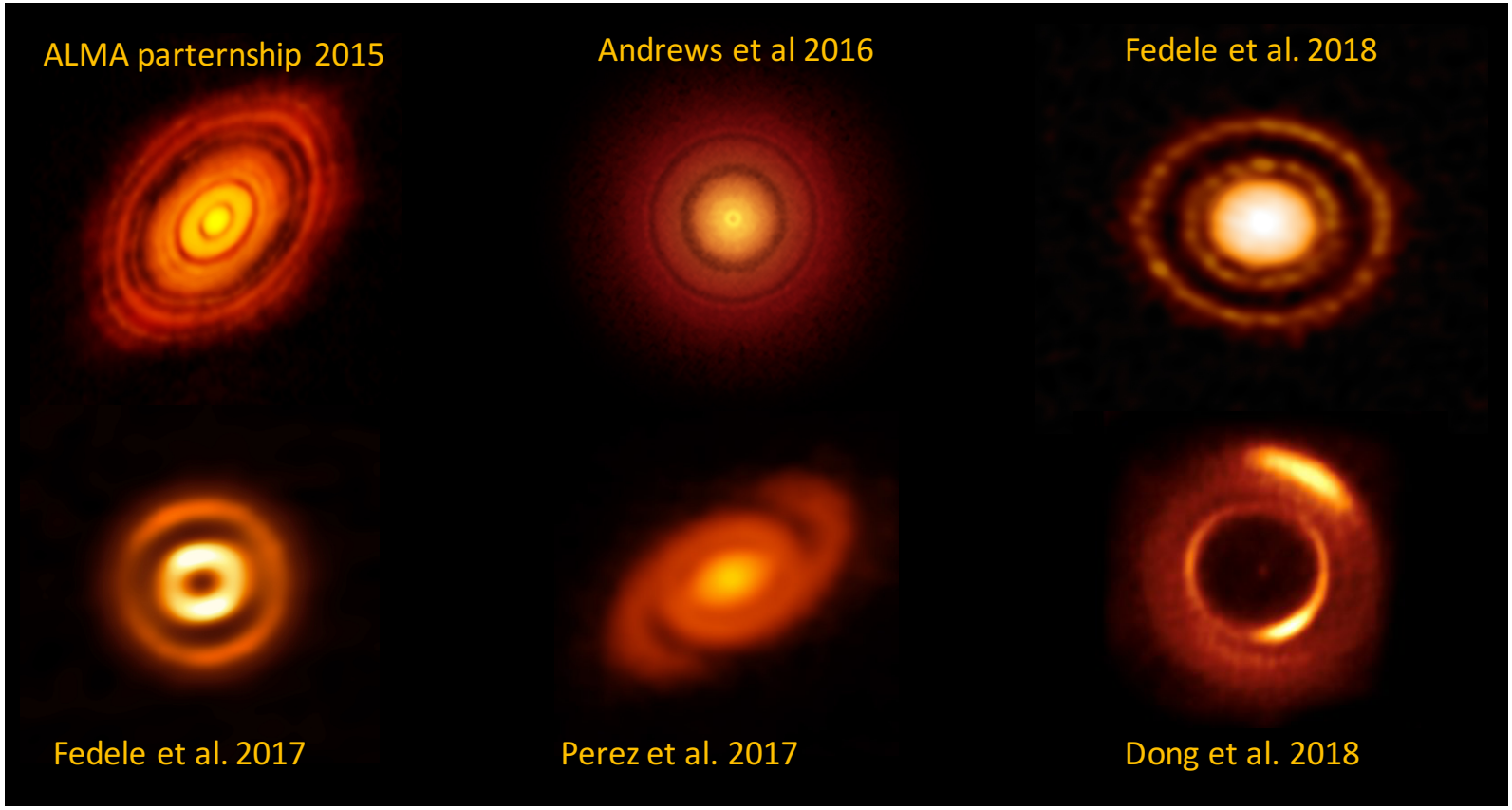


Williams & Cieza 2011



Before ALMA: smooth surface density structure.
Some disks with large cavity

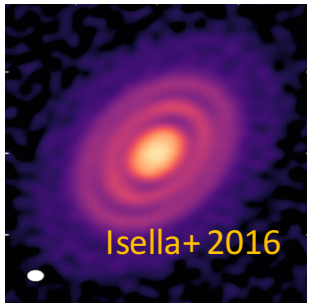
ALMA discography



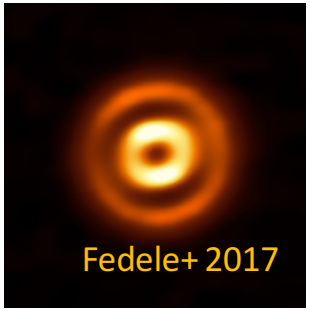
ALMA reveals the existence of gaps and rings & azimuthally asymmetric structure

Surface density with ALMA

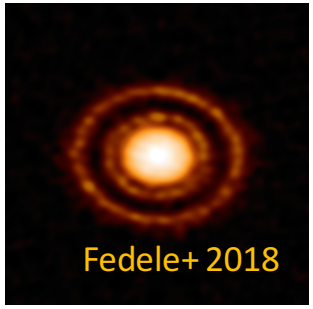
HD 163296, 2.5 M_{Sun}

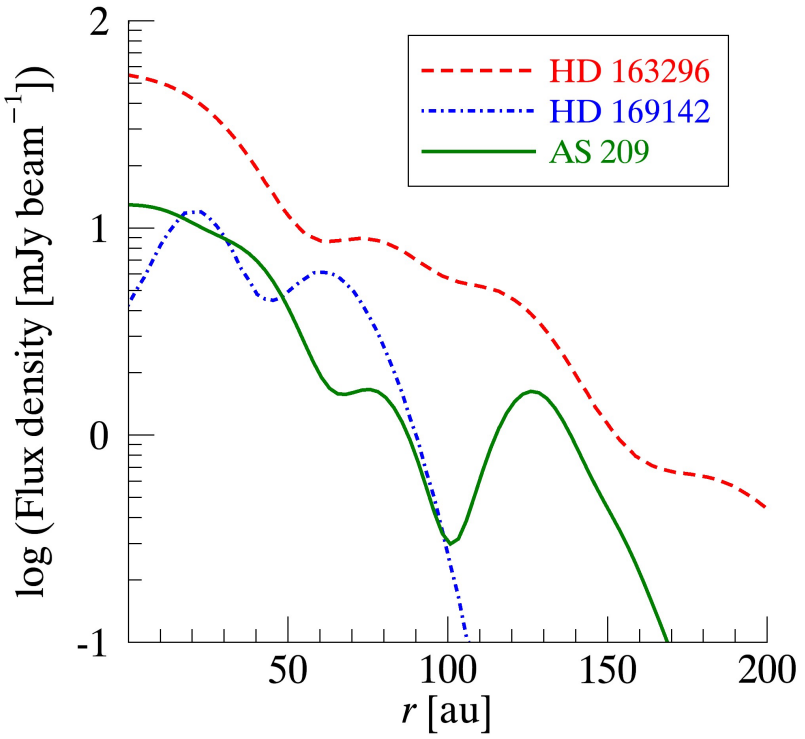


HD 169142, 1.7 M_{Sun}



AS 209, 0.5 M_{Sun}





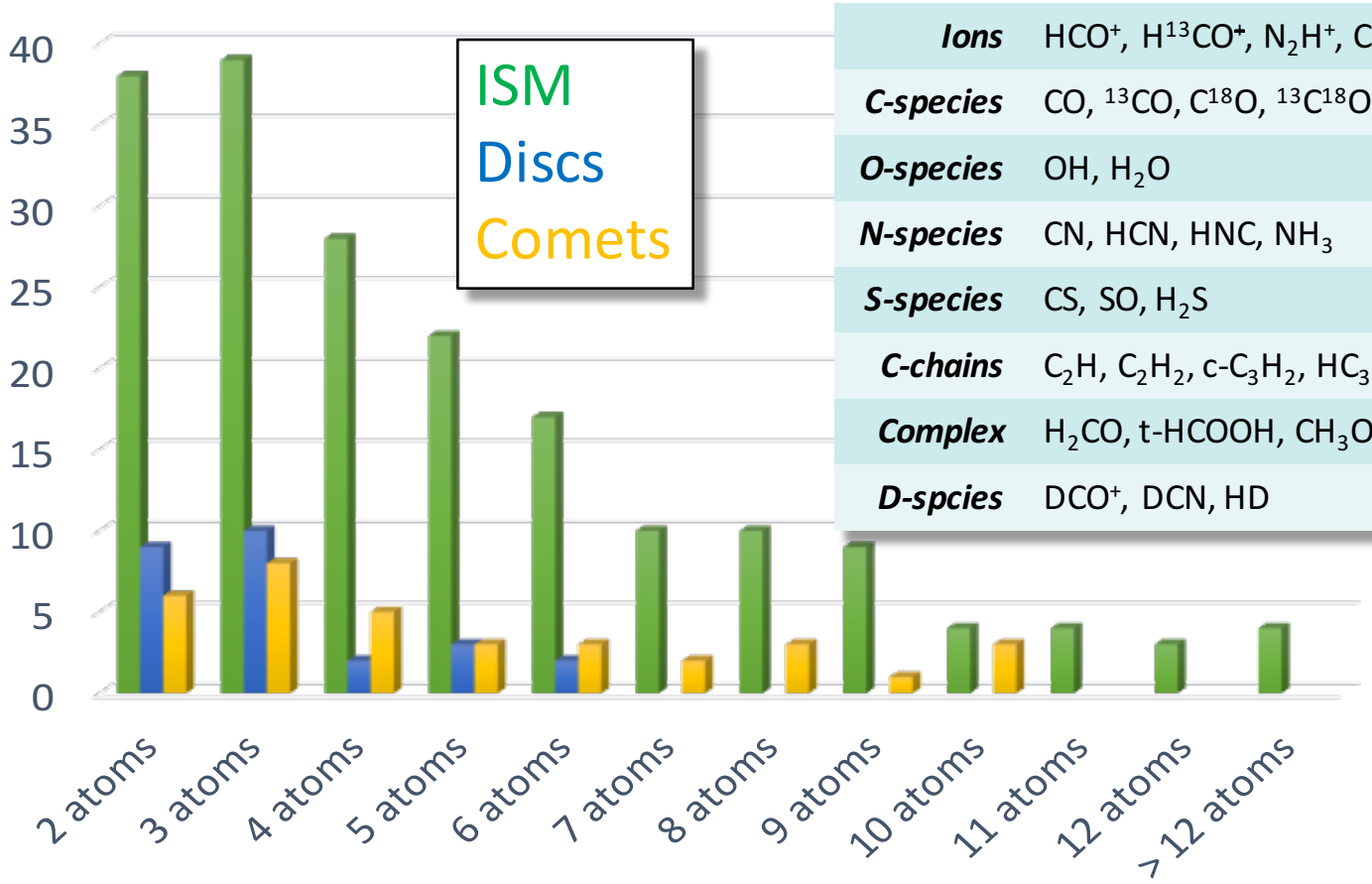
Some discs are consistent with the presence of multiple (young) planets

Planet formation must begin on short timescale (< 1 Myr)

ALMA results

DISK CHEMISTRY

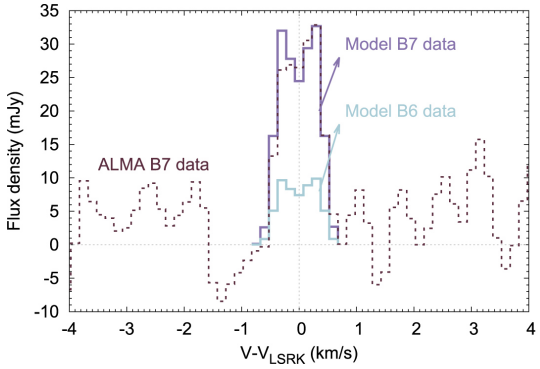
Discs molecular inventory

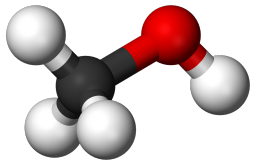


Ions	HCO^+, $H^{13}CO^+$, N_2H^+, CH^+
C-species	CO, ^{13}CO, $C^{18}O$, $^{13}C^{18}O$, CO_2
O-species	OH, H_2O
N-species	CN, HCN, HNC, NH_3
S-species	CS, SO, H_2S
C-chains	C_2H, C_2H_2, c-C_3H_2, HC_3N
Complex	H_2CO, t-HCOOH, CH_3OH, CH_3CN
D-spcies	DCO^+, DCN, HD

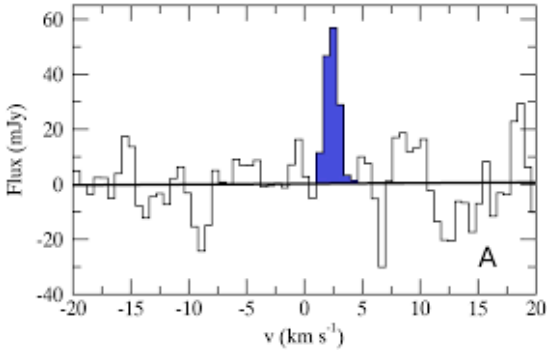
Complex molecules in discs

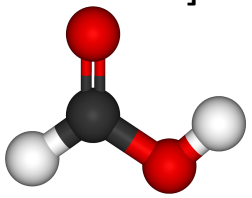
Methanol [Walsh et al. 2016]



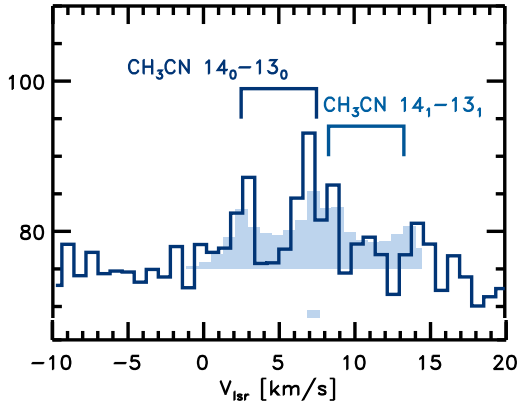


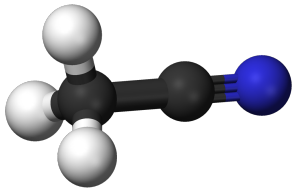
Formic acid [Favre, Fedele et al. 2018]





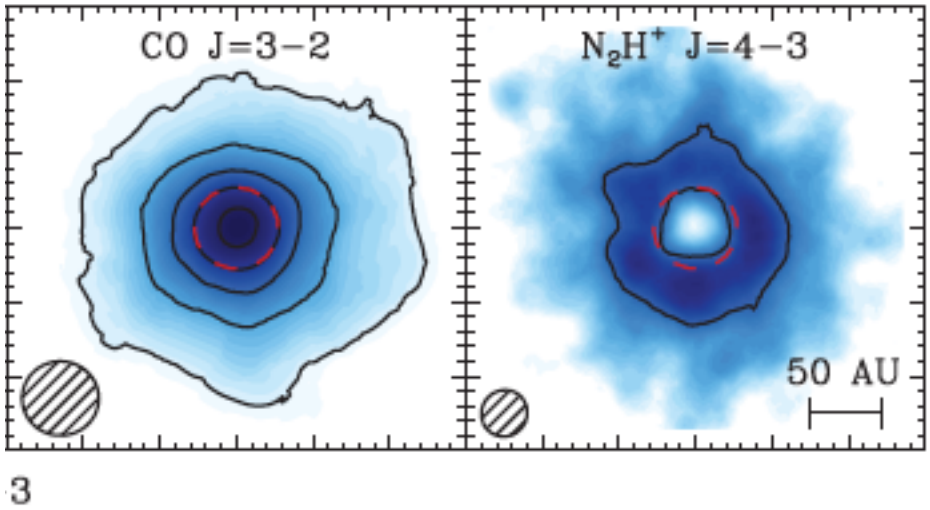
Methyl cyanide [Oberg et al. 2015]

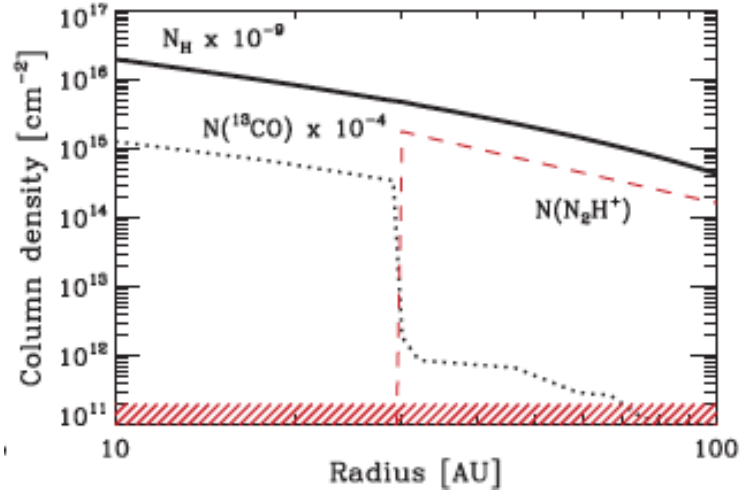




Imaging the CO *iceline*

Qi+ 2013

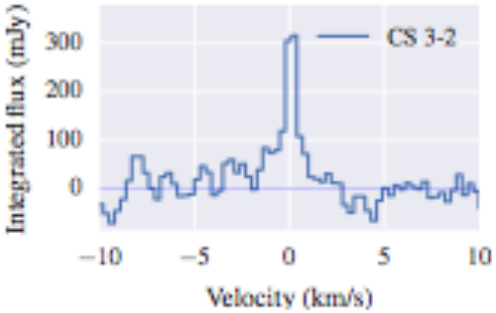


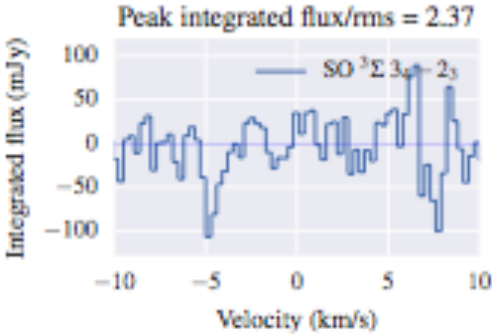


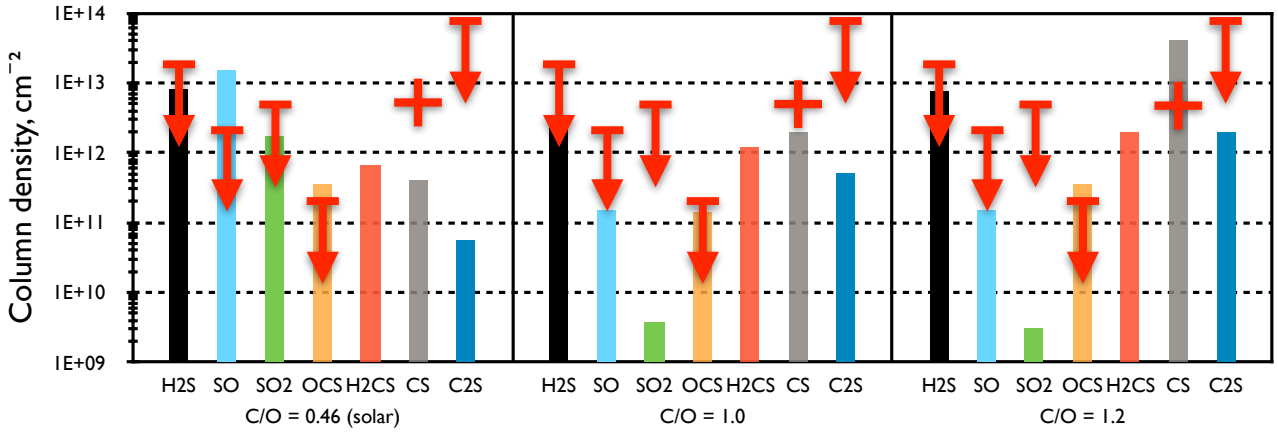
CO *iceline* measured in TW Hya using CO-N_2H^+ anti correlation

Non-Solar C/O in DM Tau

Semenov, Favre, Fedele et al. 2018



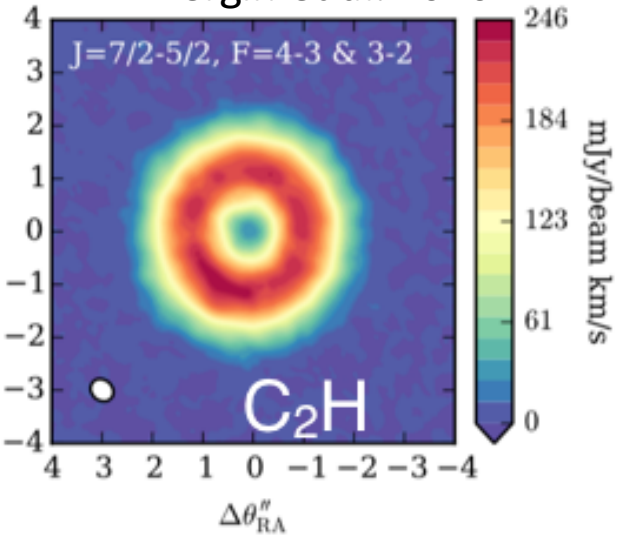




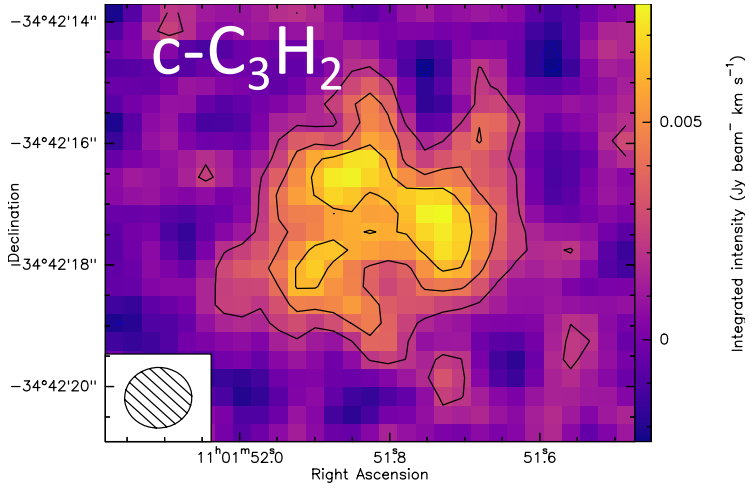
The ratio of CS/SO implies a C/O > 1

Radial gradient of C/O in TW Hya

Bergin et al. 2016



Favre, Fedele in prep



The ring-like structure of C_2H & c-C_3H_2 implies a C/O increasing with distance from star

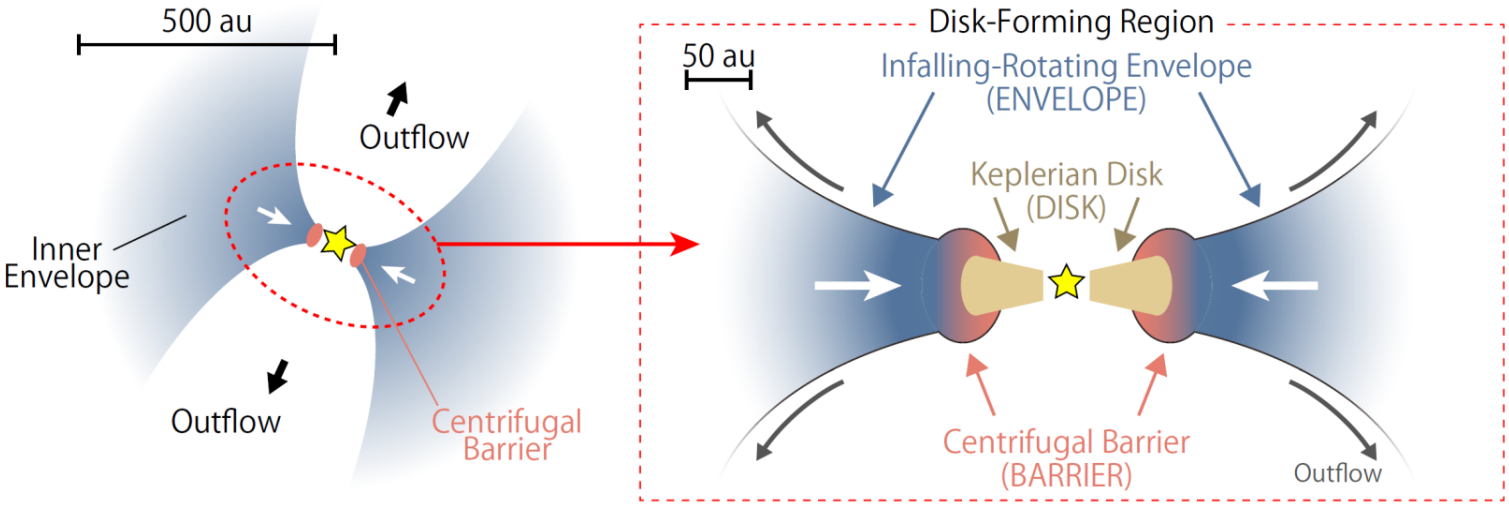
WG Planet formation @ OAA

OAA Planet formation activities

1. Protoplanetary discs: multi-wavelength studies (IR, mm)
2. Astrochemistry: origin of complex molecules
3. Astrobiology lab

FAUST, ALMA LP on astrochemistry of low-mass protostars

PI: S. Yamamoto (Un. Tokyo), C. Ceccarelli, C. Chandler, C. Codella (Arcetri), N. Sakai

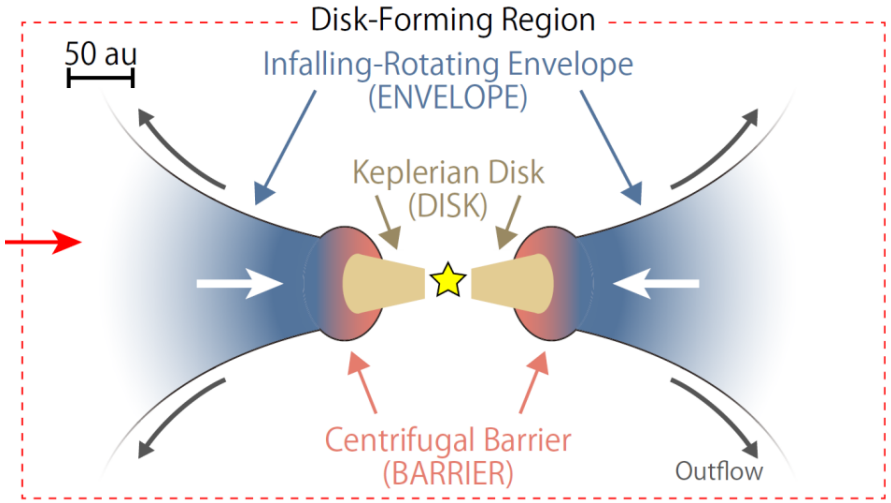


Assess chemical complexity during protostellar phase

Origin of complex (pre-biotic) molecules: heritage or reset

FAUST, ALMA LP on astrochemistry of low-mass protostars

Targets
L1527
IRAS 15398-3359
CB68
L1551 IRS5
L483
Elias 29
VLA 1623A
GSS30 (LFAM1)
RCrA IRS7B
NGC1333 IRAS4C
BHB07-11 (B59)
IRS63
NGC1333 IRAS4A



Envelope
CS, c-C_3H_2

Centrifugal barrier
SO, SiO, CH_3OH

Disc
H_2CO, $C^{18}O$, HC_3N

Ionization
$H^{13}CO^+$, DCO^+, N_2H^+

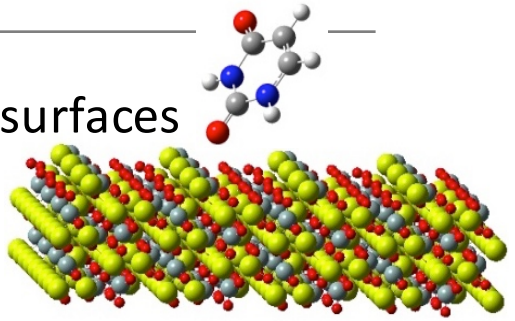
Complex
CH_3OH, NH_2CHO, CH_3CHO, CH_3OCH_3, $HCOOCH_3$

Deutaration
c-C_3HD, N_2D^+, HDCO, D_2CO, CH_2DOH

Dust continuum

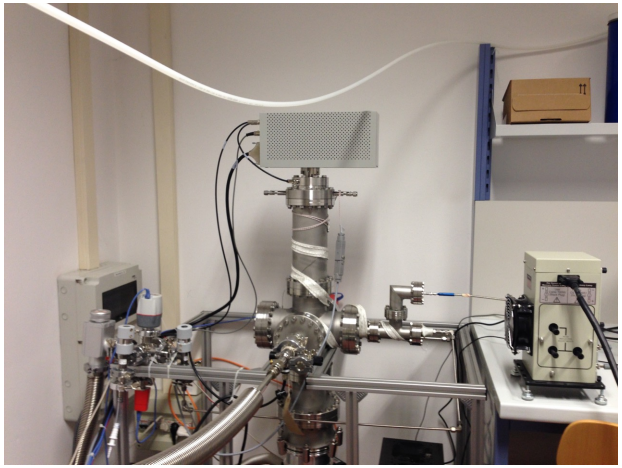
Astrobiology lab – J. Brucato

- Low temperature interactions of molecules with mineral surfaces
- UV irradiation of solid phase
- Photo-desorption and Thermal-desorption



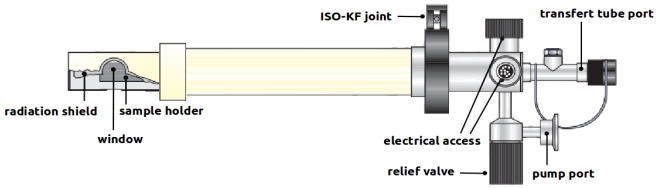
Mass spectrometer

Mass range 1-300 amu



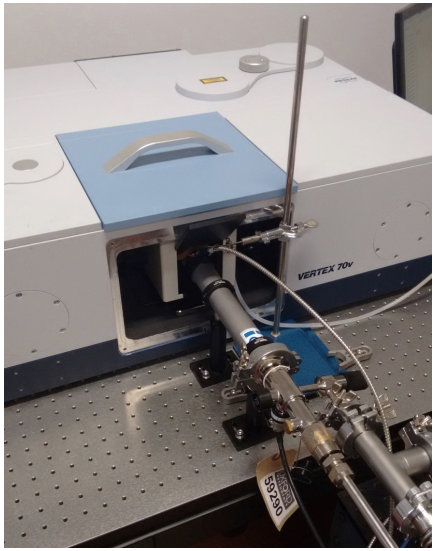
Cryostat

temperature range: 4-500 K



Spectrometer

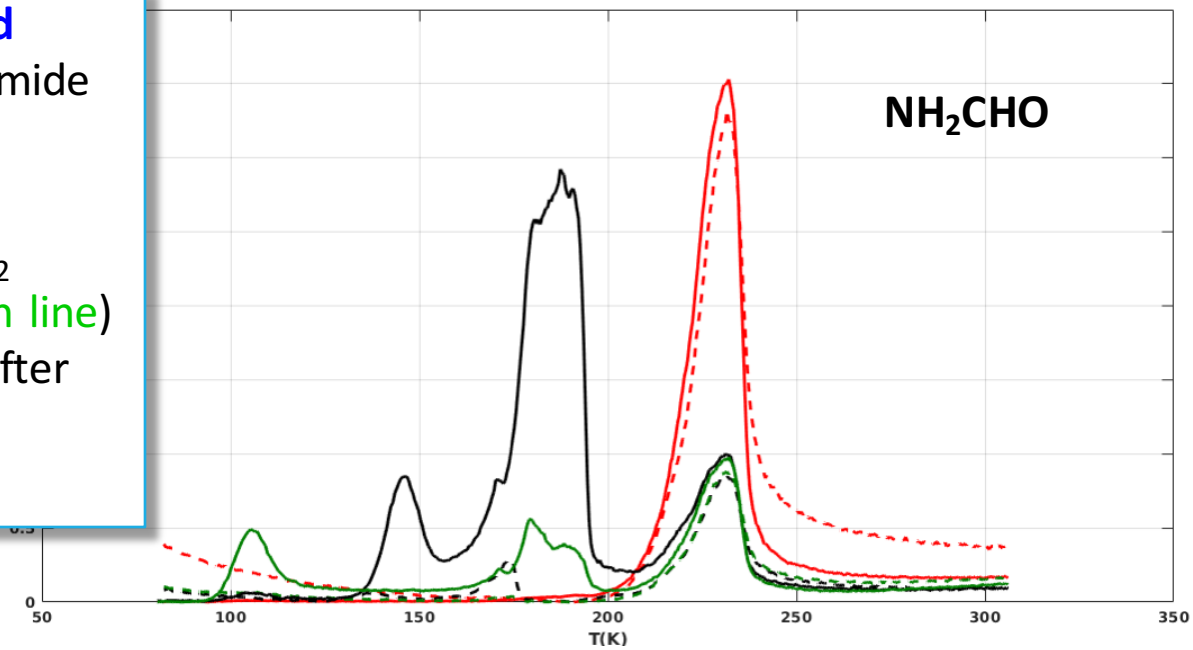
range 0.5-50 microns



Astrobiology lab: example

Temperature Programmed Desorption of pure Formamide and after UV irradiation

Formamide (red line), NH_2 (black line), CH_2NO (green line) before (dashed line) and after (continous line) 5h of UV irradiation



Pure Formamide after UV irradiation fragmented into NH_2, HCO and CH_2NO. These fragments are more volatile and desorbed HCO, NH_2 at 184 K and CH_2NO at 182 K, and Formamide at ~220 K.

Concluding remarks

ALMA studies of discs provide the initial conditions (physical structure and chemical composition) to origin of planets and atmospheres

ARIEL atmospheric composition of giant planets contain imprints of the original disc composition

Statistical comparison will help us to distinguish between *in situ* formation *vs* migration