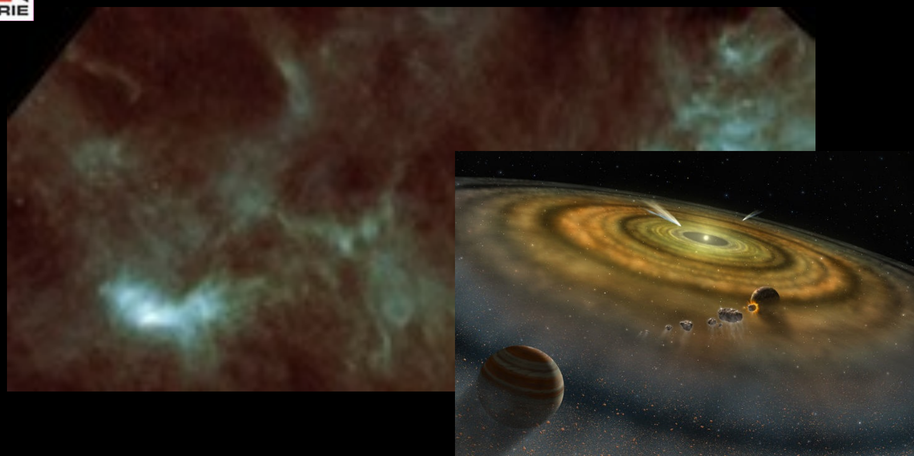
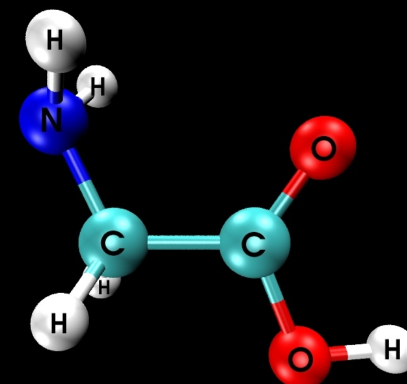
DISK CHEMISTRY with ALMA





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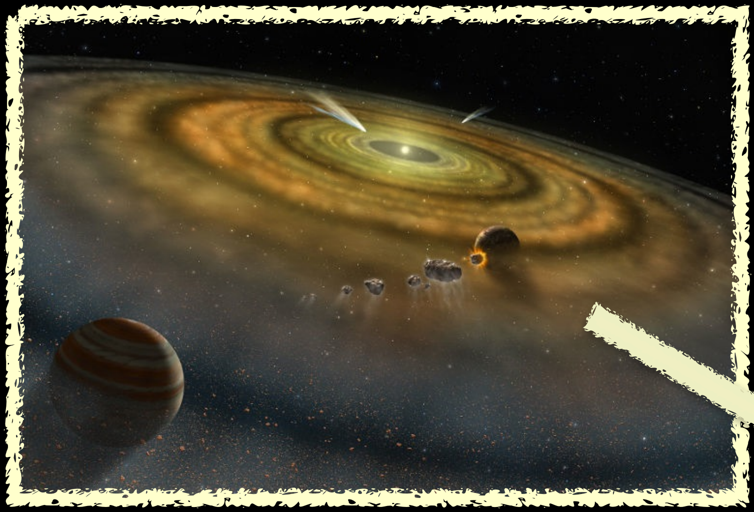
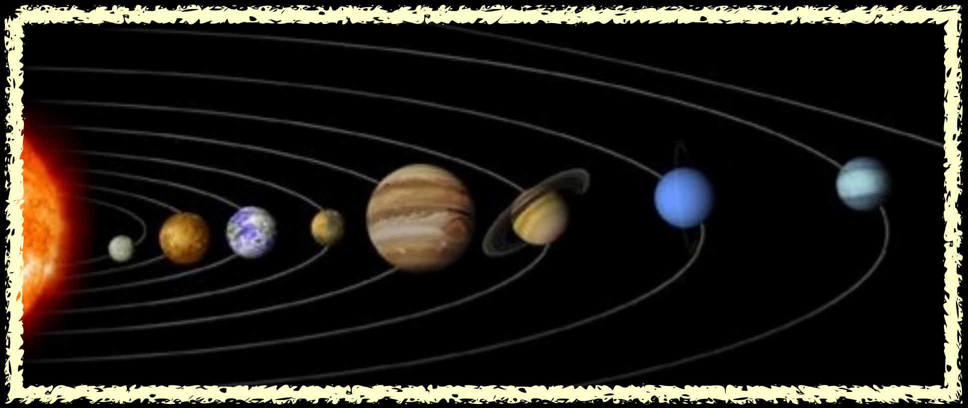
WHY DISKS ?

disks are the birthplace of planets

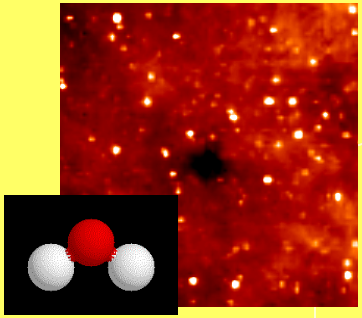




WHY CHEMISTRY ?

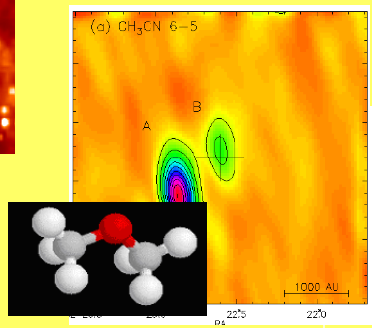
from atoms and simple molecules to LIFE

Caselli & Ceccarelli 2012



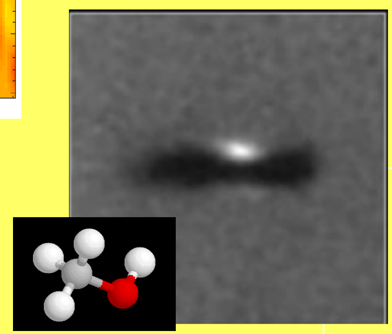
1- PRE-STELLAR PHASE: cold and dense gas
FORMATION OF SIMPLE MOLECULES

10^4 yr



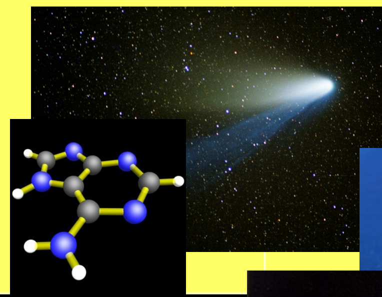
2- PROTOSTELLAR PHASE: collapsing, warm dense gas
FORMATION OF COMPLEX MOLECULES

10^4-10^5 yr

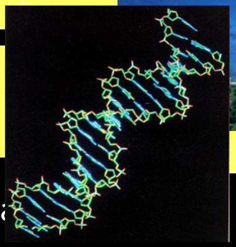


3- PROTOPLANETARY DISK PHASE:
cold and warm dense gas
SIMPLE & COMPLEX MOLECULES

10^6 yr



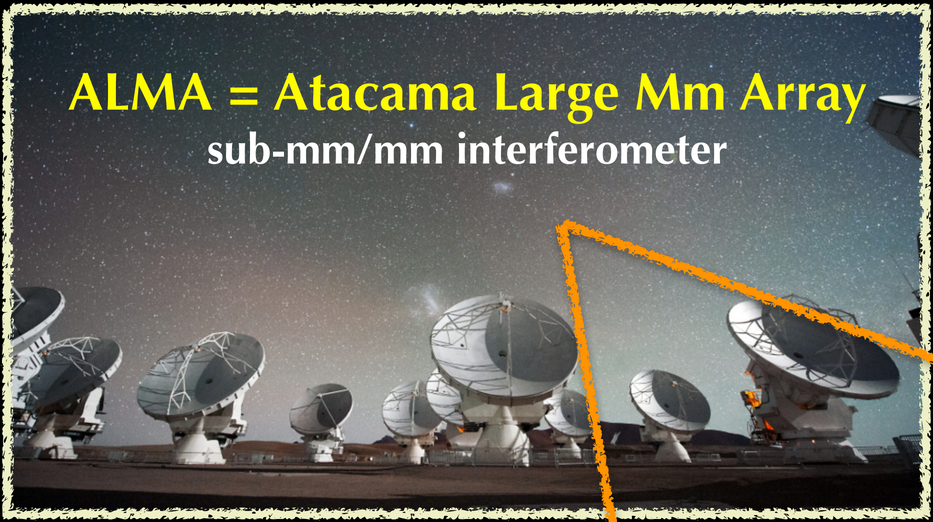
4- PLANETESIMALS FORMATION : grains agglomeration



5- PLANETS FORMATION AND THE “COMETS/ASTEROIDES RAIN”
CONSERVATION AND DELIVERY OF OLD MOLECULES + LIFE

WHY ALMA ?

high sensitivity & resolution to observe molecules in disks

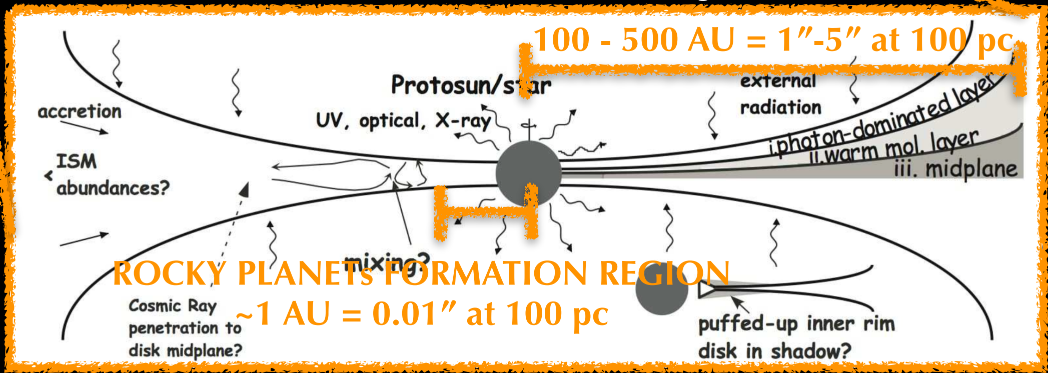


array of 66 antennas in Atacama, Chile:
50 12-m + 12 7-m (ACA) + 4 12-m (TP)

ν = **80 - 950 GHz** (band 3-10)
λ = 3 - 0.3mm

B_{max} = **16 Km —> 6 - 40mas**

Bergin et al. 2007



Atoms & molecules in disks

surface layers —> molecules destroyed due to photodissociation by UV

outer disk/mid-plane (T <100 K) —> molecules freeze out onto dust grains
H_2O & COMs are efficiently produced by surface grain chemistry: $X_{\#} \sim 10^{-6} - 10^{-4}$
BUT only a few percent released in gas-phase by non-thermal processes: $X_{gas} \sim 10^{-11} - 10^{-7}$

Modica & Palumbo 2010
Hogerheijde et al. 2011
Kamp et al. 2013
Podio et al. 2013
Walsh et al. 2014

The chemical composition of disks is hidden in ices !!!

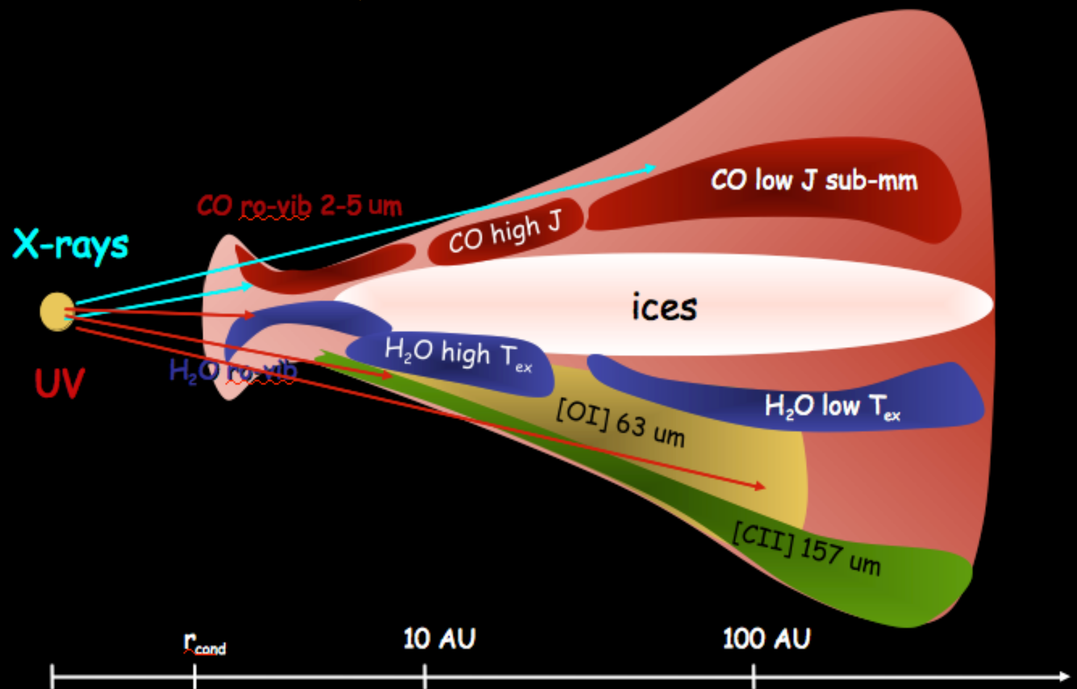
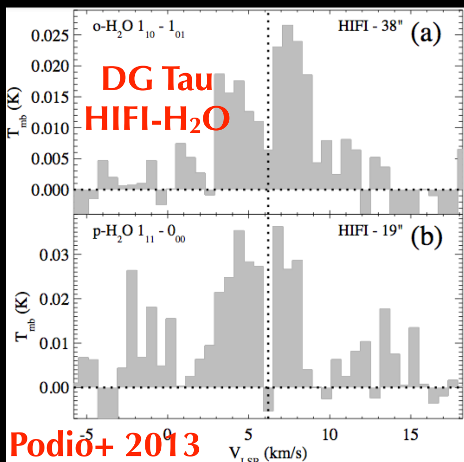


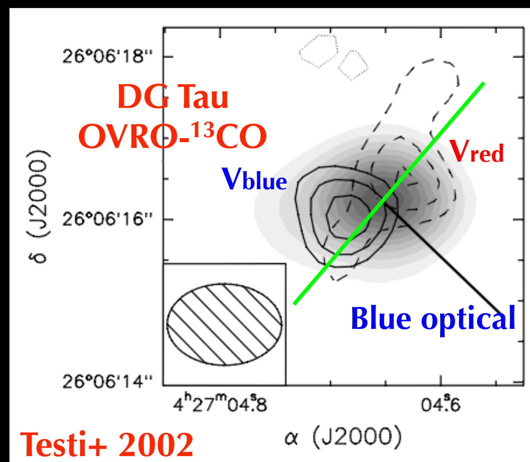
Figure by I. Kamp
based on
Kamp & Dullemond 2004
Dullemond et al. 2007
Bergin et al. 2007

Only a few molecules observed in disks … (CO, HCO+, CS, CN, HCN, …)

Dutrey et al. 1997, 2007, Chapillon et al. 2011, 2012, Guillotteau et al. 2013, Thi et al. 2004, Oberg et al. 2009, 2010, 2012, Qi et al., ….

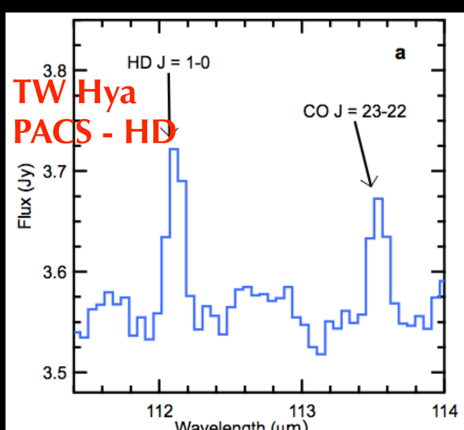
… some recent detections with Herschel !!





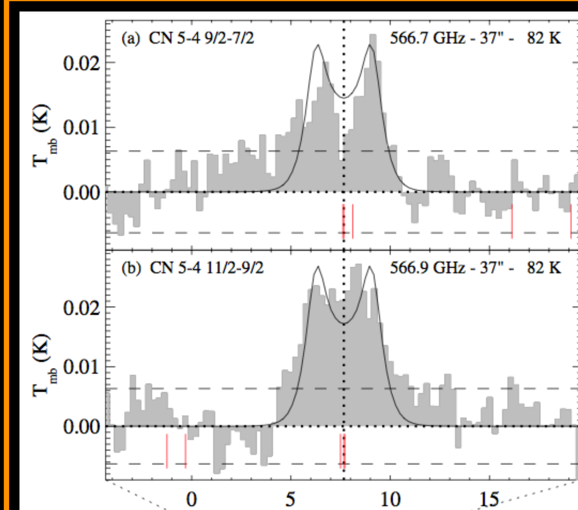
H_2O ices in protoplanetary disk
—> H_2O delivery on Earth by comets/asteroids ?

Hogerheijde et al. 2011 (TW Hya, HD 100546)
Podio et al. 2013 (DG Tau)



HD probe the disk gas-mass
—> M_{disk} > 0.05 $M_\odot$ > MMSN
—> the disk can form a planetary system like our solar system !

Bergin et al. 2013



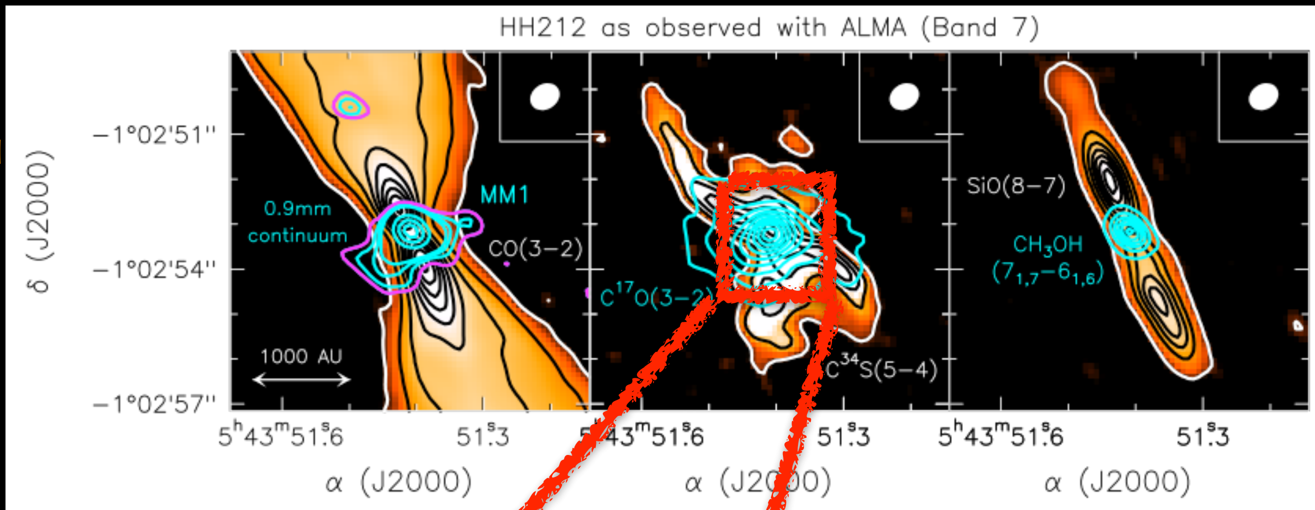
CN can probe the disk in embedded Class I sources !
(CO lines are affected by jet/outflow/envelope)

Podio et al. 2014a

DISKS around Sun-like protostar with ALMA

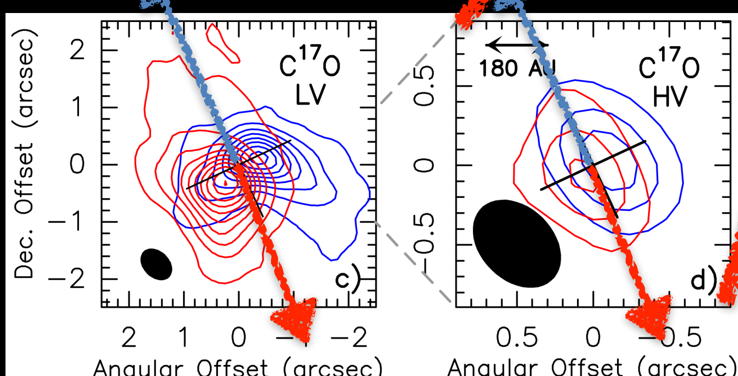
HH 212: Class 0 low-mass protostar (d = 450 pc)

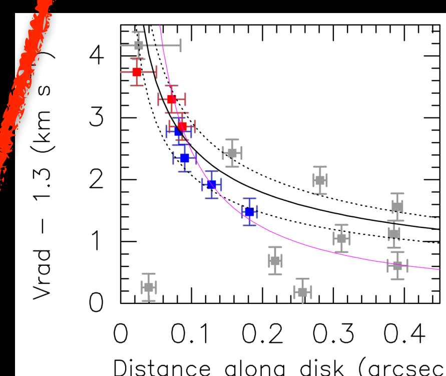
previously observed with PdBI & SMA
Codella+ 2007
Cabrit+ 2007, 2012
Lee+ 2006, 2007, 2008



ALMA obs:
Lee et al. 2014
Codella et al. 2014b
Podio et al. 2015

All the ingredients of the Sun-like star formation recipe imaged in a single shot !





position vs velocity: 90 AU disk rotating around a 0.3±0.1 M_{sun}

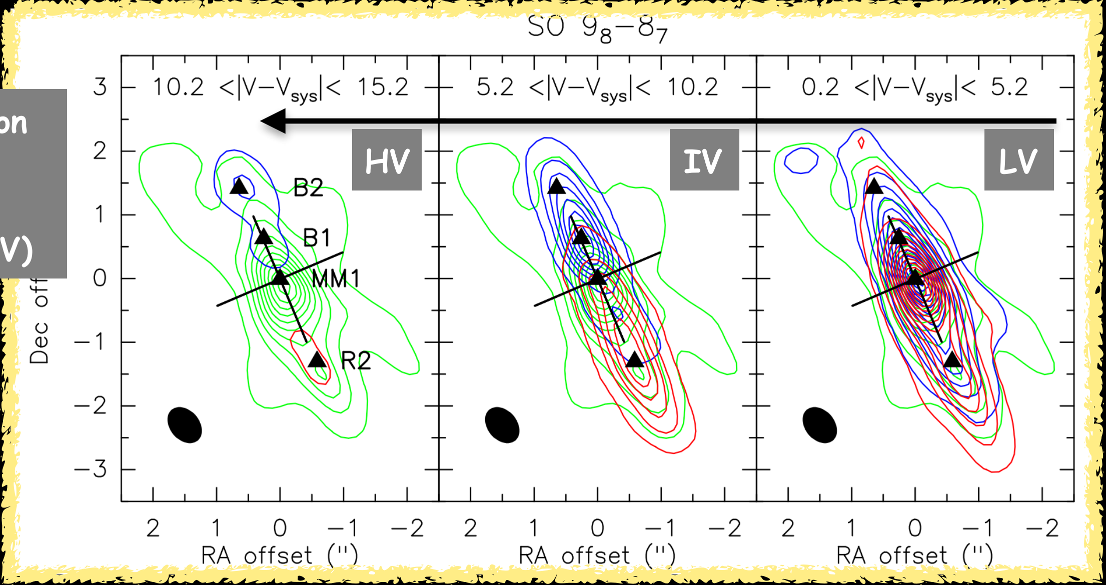
Codella et al. 2014b

see also Lee et al. 2014 disk seen in HCO^+ 4-3

HH 212 - SO obs: the JET & the DISK

SO 9_8 - 8_7: the molecular JET !

increasing collimation going from Low Velocity (LV) to High Velocity (HV)



Podio et al 2015

V_{jet} = 100-200 km/s, R_{jet} ~ 90 AU

n_{jet} ~ 10^5 — 10^6 cm^{-3}

$\dot{M}_{jet} \geq 0.2\text{-}2\ 10^{-6}\ M_{sun}/yr$

jet efficiency = $\dot{M}_{jet} / \dot{M}_{infall} \geq 0.03\text{-}0.3$!

SO is a probe of the collimated molecular jet !
(as other well-known jet tracers, e.g. SiO)

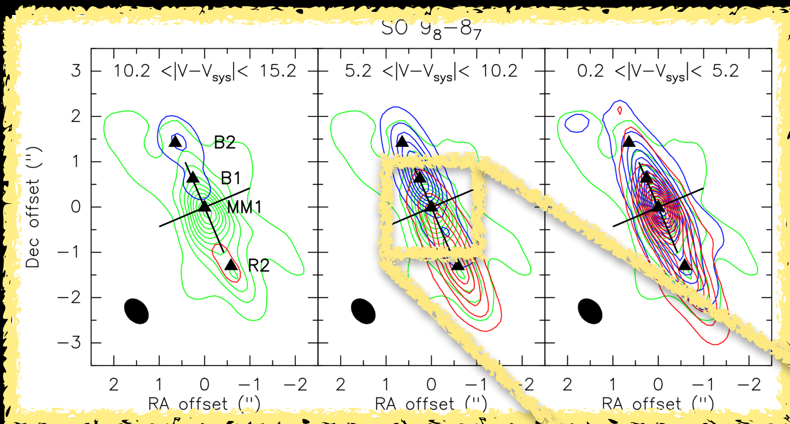
more on jet chemistry by G. Santangelo !

SO + SO_2 —> allow to study the jet chemistry in shocks !

HH 212 - SO obs: the JET & the DISK

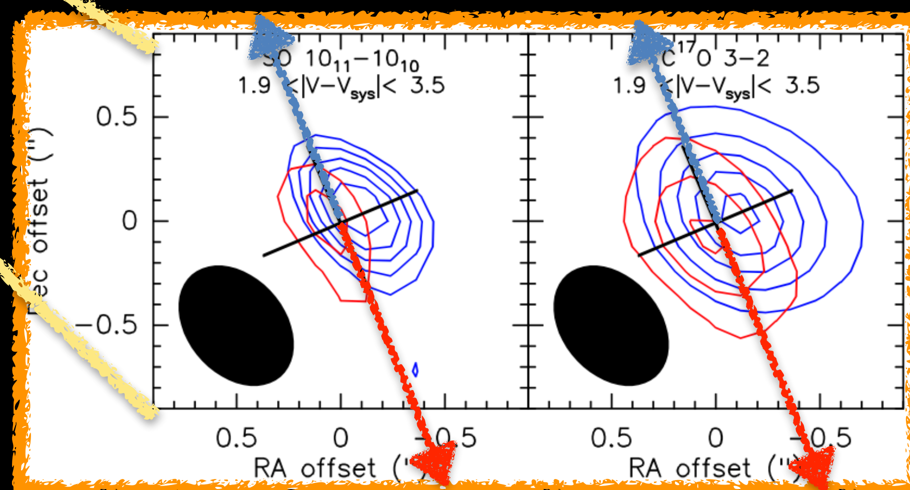
Podio et al 2015

The molecular JET !



$SO\ 9_8 - 8_7$ — $E_{up} \sim 79$ K
—> outflow + jet emission !

The compact rotating DISK !



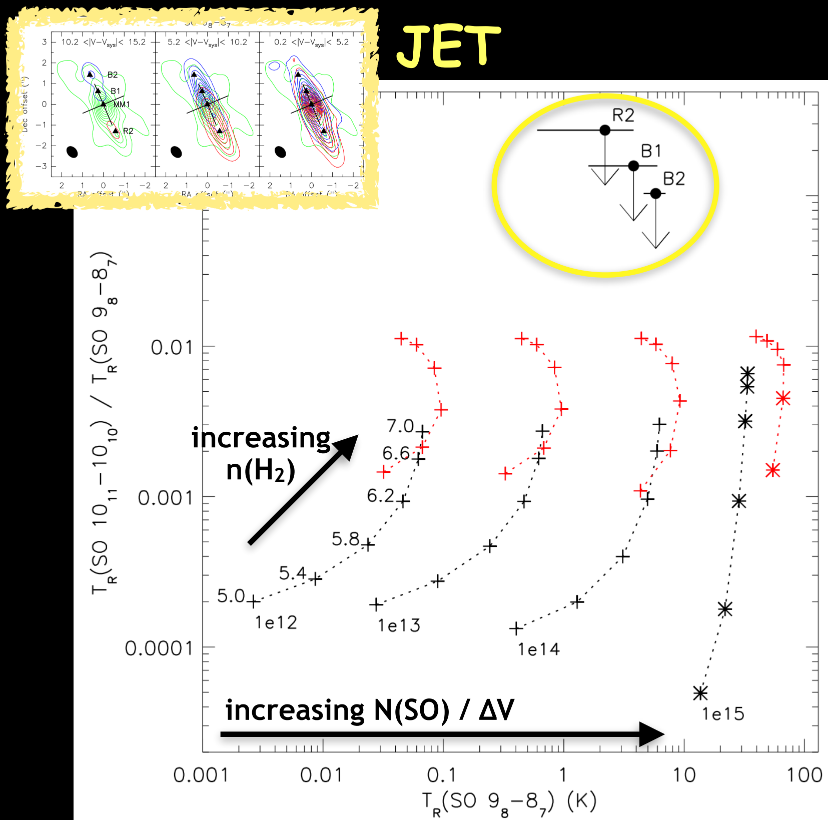
$SO\ 10_{11} - 10_{10}$ — $E_{up} \sim 143$ K
—> compact disk emission !

SO chemistry in the JET & in the DISK !

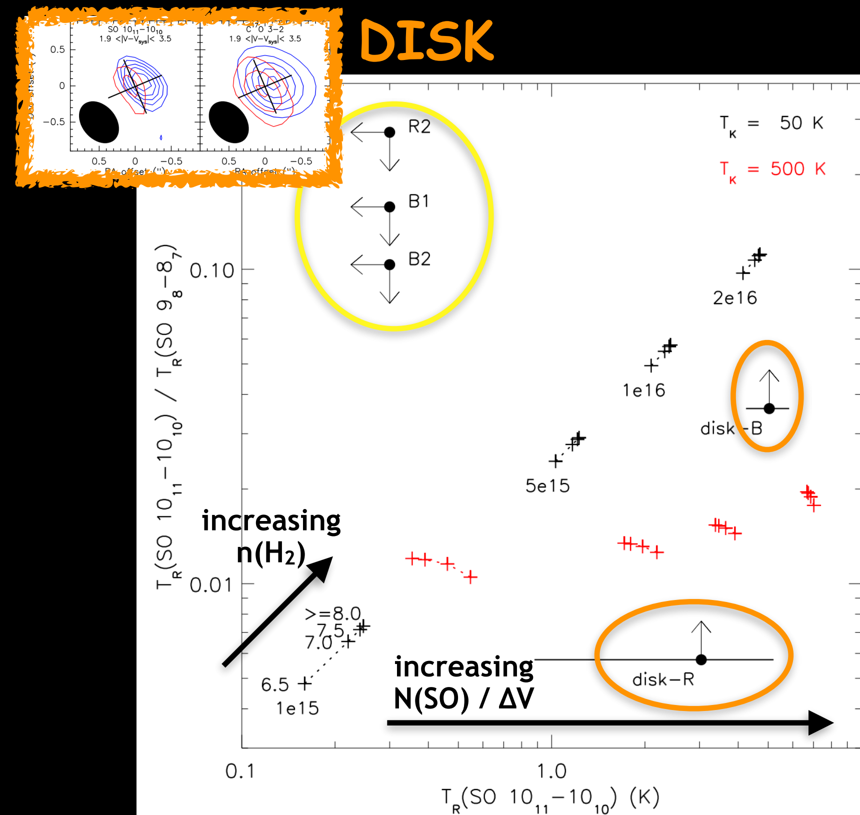
Podio et al 2015

SO observed emission
vs predictions from NLTE radiative transfer code RADEX

JET



DISK



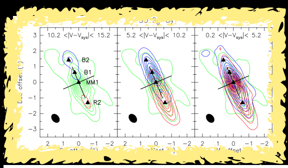
$N(SO) / \Delta V \sim 10^{14}$ cm^{-2} (km/s)$^{-1}$
—> both SO lines optically thin
$n(H_2) \sim 10^5 - 10^7$ cm^{-3}

$N(SO) / \Delta V \sim 10^{16}$ cm^{-2} (km/s)$^{-1}$
—> SO 10_{11}-10_{10} thin, SO 9_8-8_7 thick
$n(H_2) \geq 10^7$ cm^{-3} —> LTE emission !

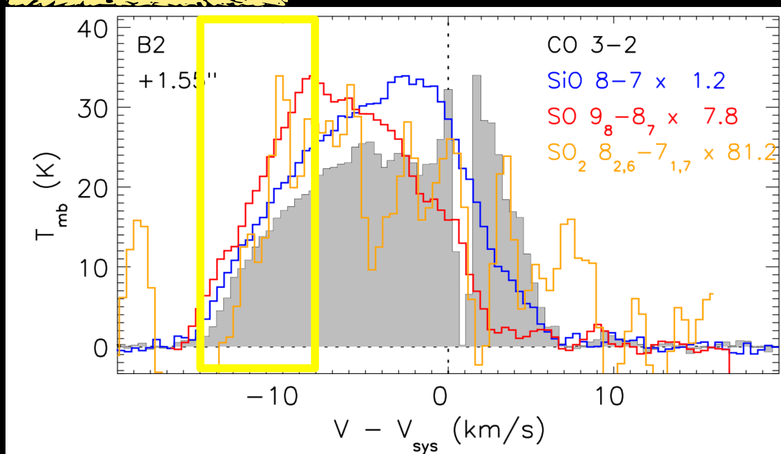
SO abundance in the JET & in the DISK !

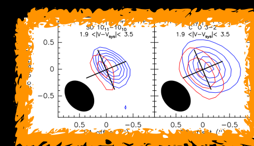
Podio et al 2015

Estimates of SO abundances
by comparing SO & CO column densities
(we assume LTE-optically thin emission)

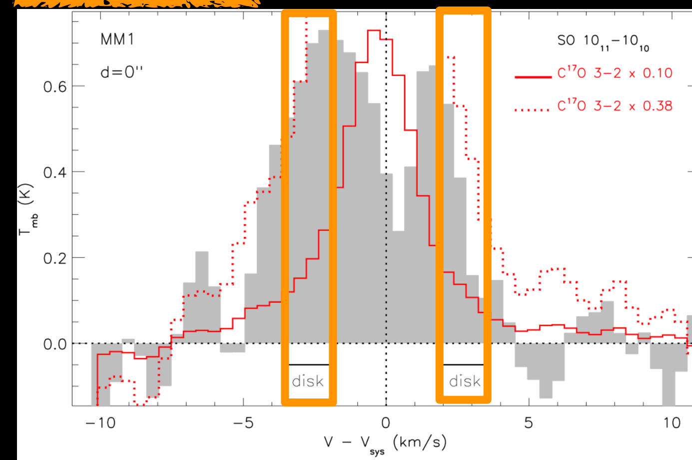


JET - HV





DISK



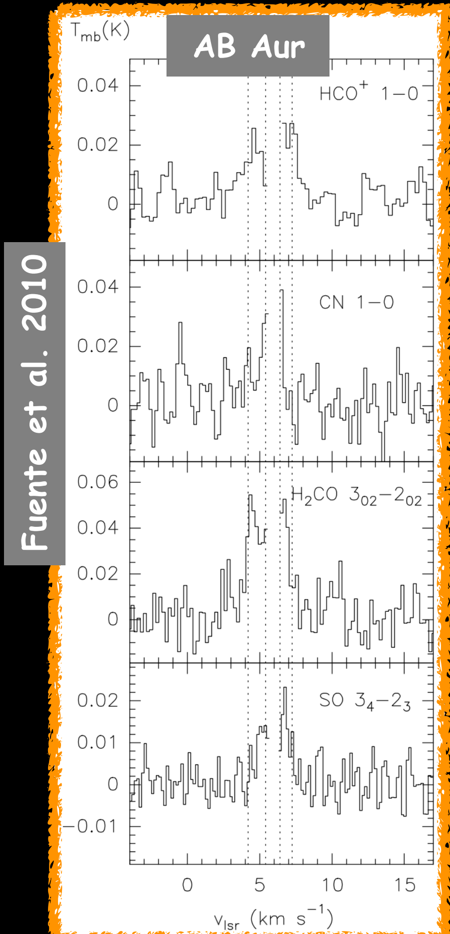
X(SO) ~ 10^{-7} - 10^{-6}
—> similar to other Class 0 outflows/jets
(Bachiller+ 97, Tafalla+ 10, Lee+ 10, Santangelo+ 15)

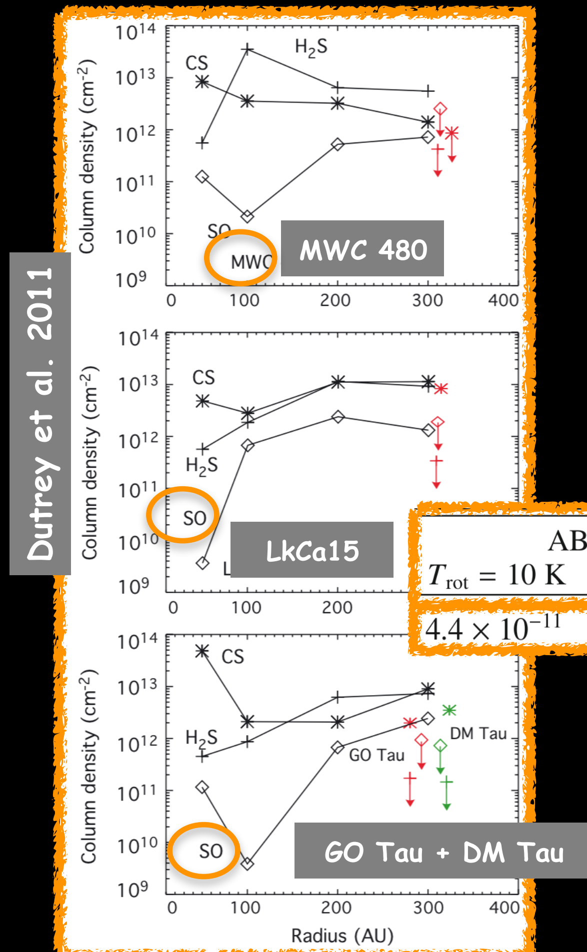
SO ORIGIN: shocks with grain mantles release
(Pineau des Forets+ 1993, Flower+ 2003)
or turbulent outflow-cloud interface (Viti+ 2002)

X(SO) ~ 10^{-8} - 10^{-7}
much higher than in Class II disks !!

SO abundance in Class II disks

In passive Class II disks
$N(SO) \lesssim 10^{12}$ cm^{-2}, $X(SO) \lesssim 10^{-11}$





- SO detected in AB Aur (Fuente et al. 2010)

- upper limits for MWC 480, LkCa 15, GO Tau, DM Tau (Dutrey et al. 2011)

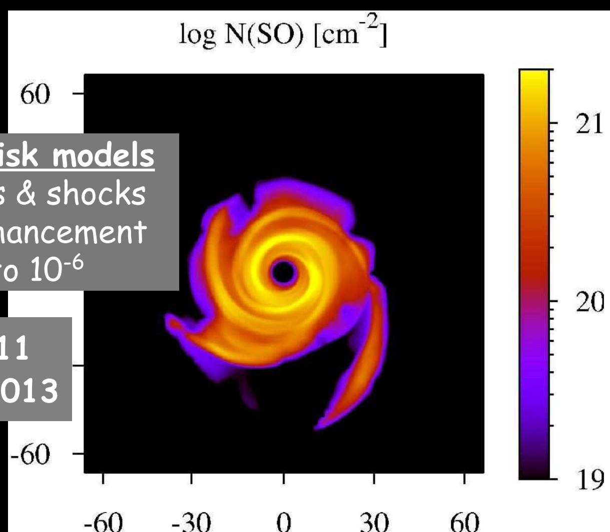
AB Aur		DM Tau	LkCa15	TW Hya
T_{rot} = 10 K	T_{rot} = 20 K			
4.4×10^{-11}	4.6×10^{-11}	$<3.0 \times 10^{-11}$	$<2.0 \times 10^{-11}$	$<4.1 \times 10^{-11}$

SO abundance in Class 0 disks ?

Podio et al 2015

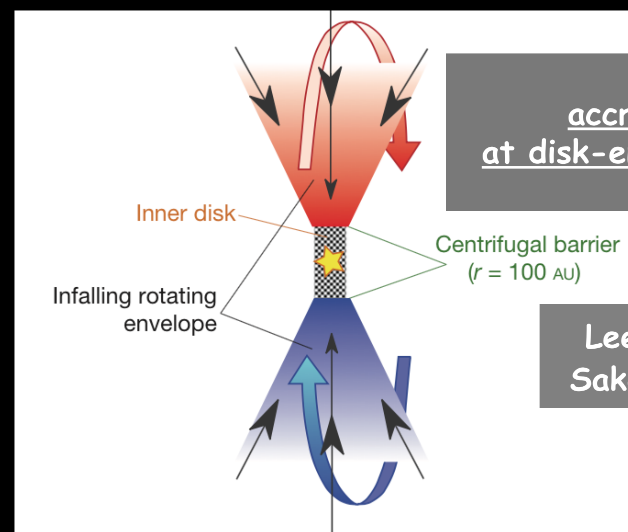
Class II disks (passively heated)
N(SO) ≤ 10^{12} cm^{-2}, X(SO) ~ 10^{-11}

Class 0 disk (HH 212)
N(SO) ~ 10^{16} cm^{-2}, X(SO) ~ 10^{-8}-10^{-7}



self-gravitating disk models
GI —> spiral waves & shocks
—> temp & abu enhancement
—> X(SO) up to 10^{-6}

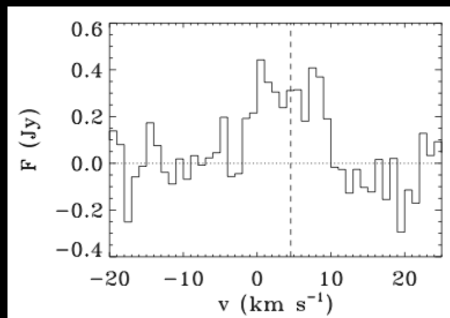
Ilee et al. 2011
Douglas et al. 2013

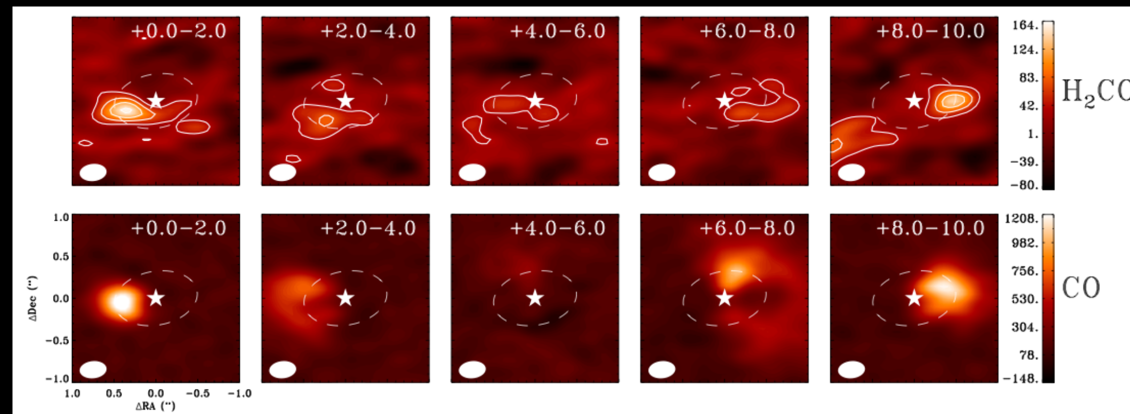


accretion shock
at disk-envelope interface

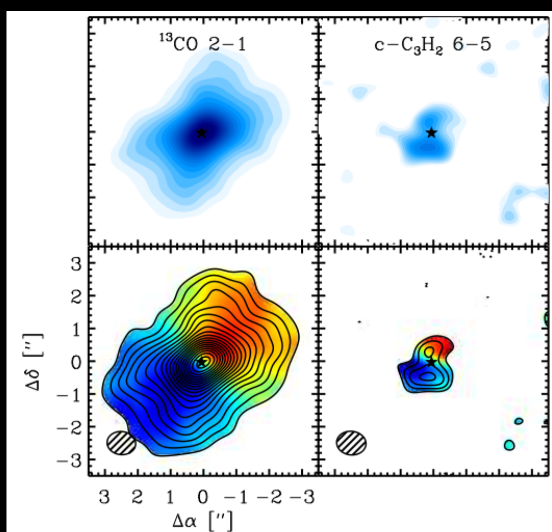
Lee et al. 2014
Sakai et al. 2014

first detections of COMs in disks with ALMA !





H_2CO in Oph IRS 48: ALMA resolved map
$CH_3OH/H_2CO < 0.3$
—> H_2CO partially formed in gas-phase
Van der Marel et al. 2014



c-C_3H_2 in HD 163296:
ALMA resolved map
—> ring=30-165 AU
Qi et al. 2013

ALMA is ideal to study the disk chemistry !