3. BLOOMING AND CONSERVING: THE HOT CORINOS & PROTOPLANETARY DISKS

1. Hot corinos: the retail shops
2. Molecular outflow shocks: the snapshots
3. Super-deuterated molecules
4. Complex organic molecules
5. Conservations in protoplanetary disks

NOTE: This is NOT a review
=> references illustrative and NOT exhaustive

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3.1 HOT CORINOS: THE RETAIL SHOPS

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THE COLLAPSE PHASE

ONCE THE PSC MASS OVERCOMES THE JEANS MASS, THE COLLAPSE STARS. THIS IS THE *CLASS 0* PHASE, WHEN THE LUMINOSITY IS GIVEN BY THE GRAVITATIONAL ENERGY.

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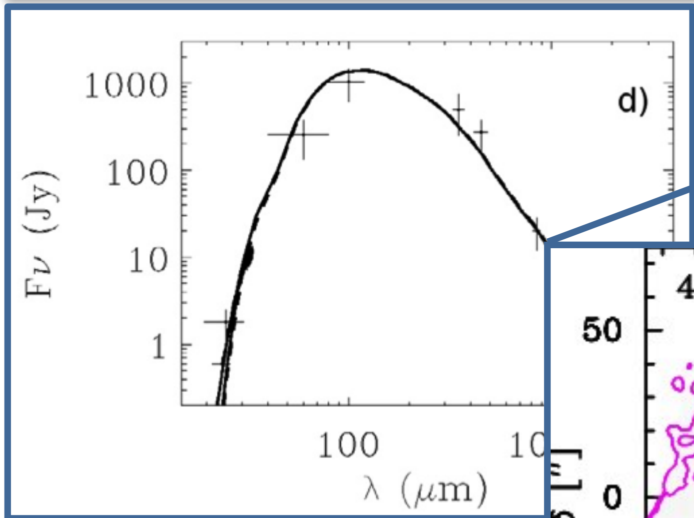
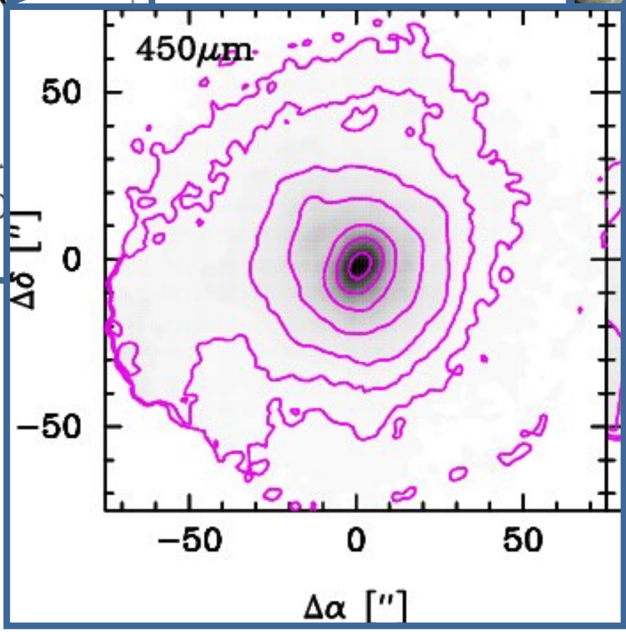
CLASS 0 SOURCES

CLASS 0 SOURCES ARE STILL BLACK SPOTS ON OPTICAL PLATES BECAUSE OF THE DUSTY ENVELOPES THAT ABSORB VISIBLE PHOTONS FROM INSIDE.



Crimier et al. 2010



BUT THEY HAVE AN INNER SOURCE OF ENERGY => THEY ARE WARMER THAN THE PSCs

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CLASS 0 PHYSICAL STRUCTURE

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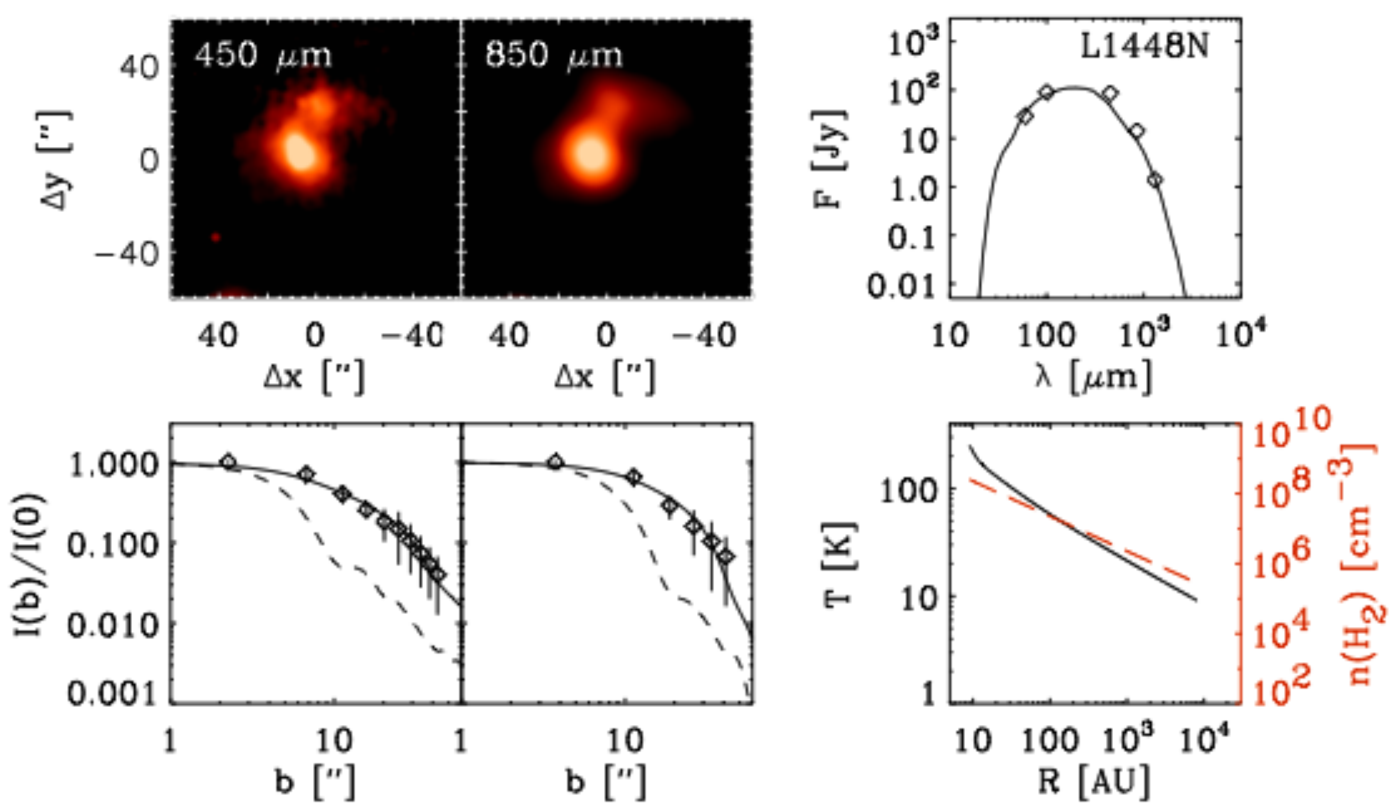


Jorgensen et al. 2002

THE DENSITY AND TEMPERATURE PROFILES ARE DERIVED BY RADIATIVE TRANSFER MODELS OF THE CONTINUUM EMISSION

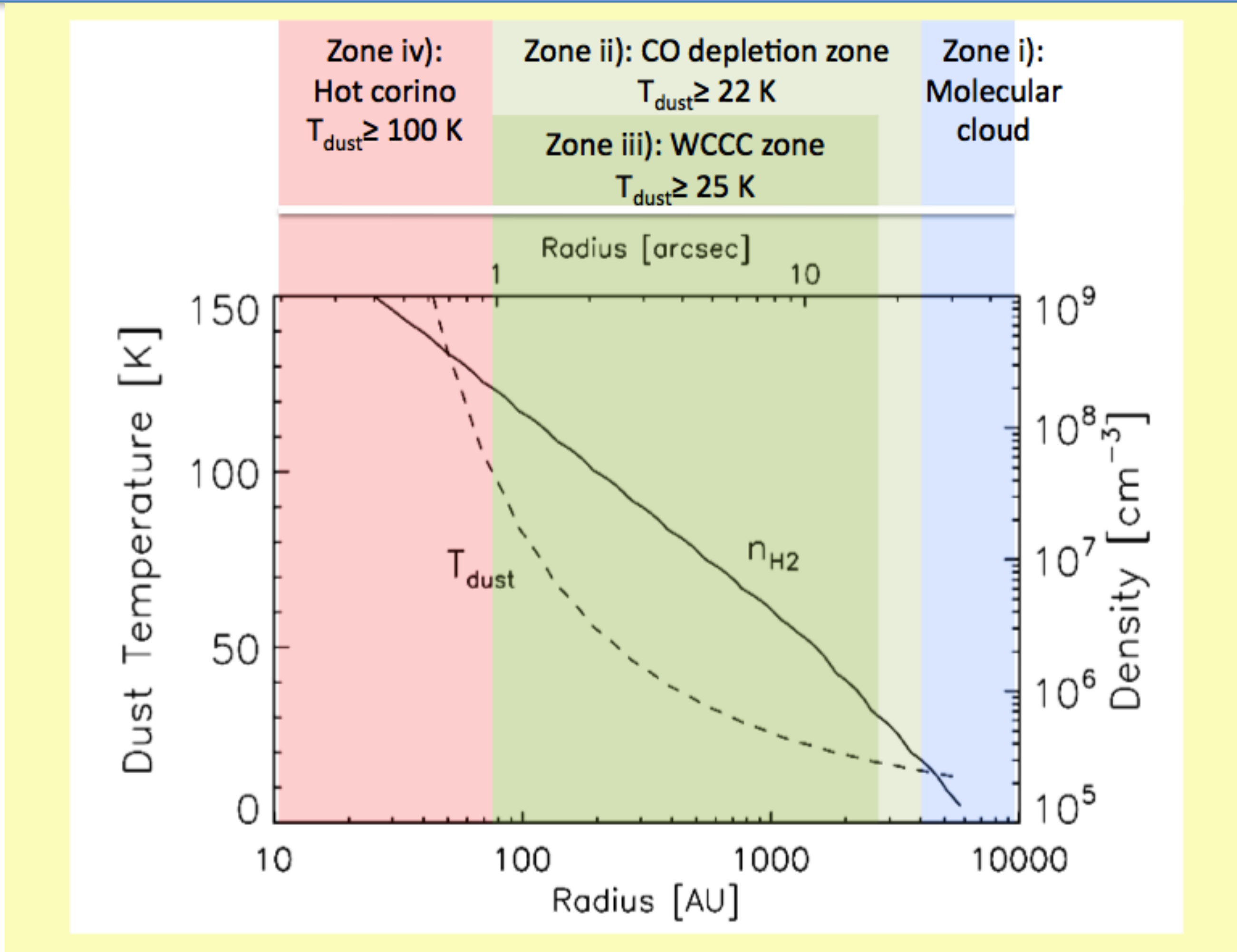
TYPICALLY, $n_{H2} \sim r^{-3/2}$

COMPATIBLE WITH FREE-FALLING ENVELOPES

CLASS 0 CHEMICAL STRUCTURE

3.Blooming & conserving

3.1 Hot corinos



Caselli & Ceccarelli 2012

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COLD OUTER ENVELOPE: SIMILAR TO PRE-STELLAR-CORES
HOT CORINO: DOMINATED BY THE SUBLIMATION OF THE GRAIN MANTLES => THE PREVIOUS OBJECT HISTORY

HOT CORINOS

3.Blooming & conserving

3.1 Hot corinos

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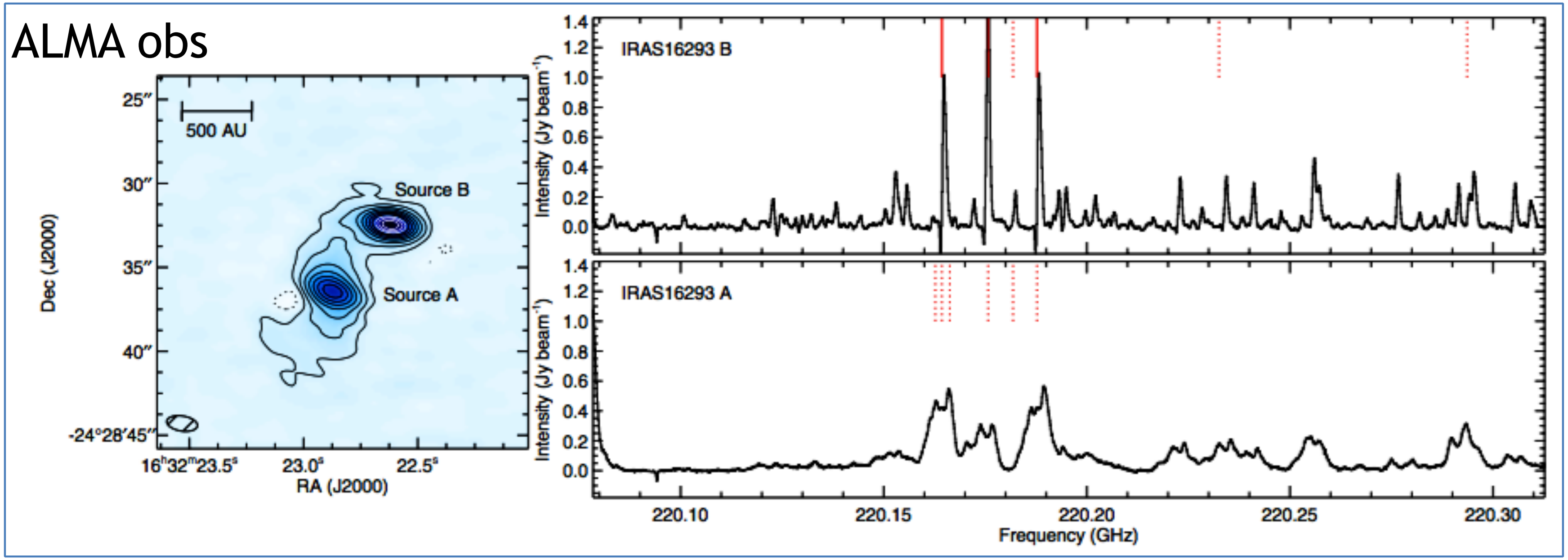
Pineda et al. 2012



COMPACT (<100AU), WARM (~100K), DENSE (>10^7cm^{-3})
→ ENRICHED OF COMPLEX ORGANIC MOLECULES
→ AND OF SUPER-DEUTERATED MOLECULES

THE HOT CORINOS ARE THE BEST MOLECULE RETAIL SHOPS

3.2 MOLECULAR OUTFLOW SHOCKS: THE SNAPSHOTS

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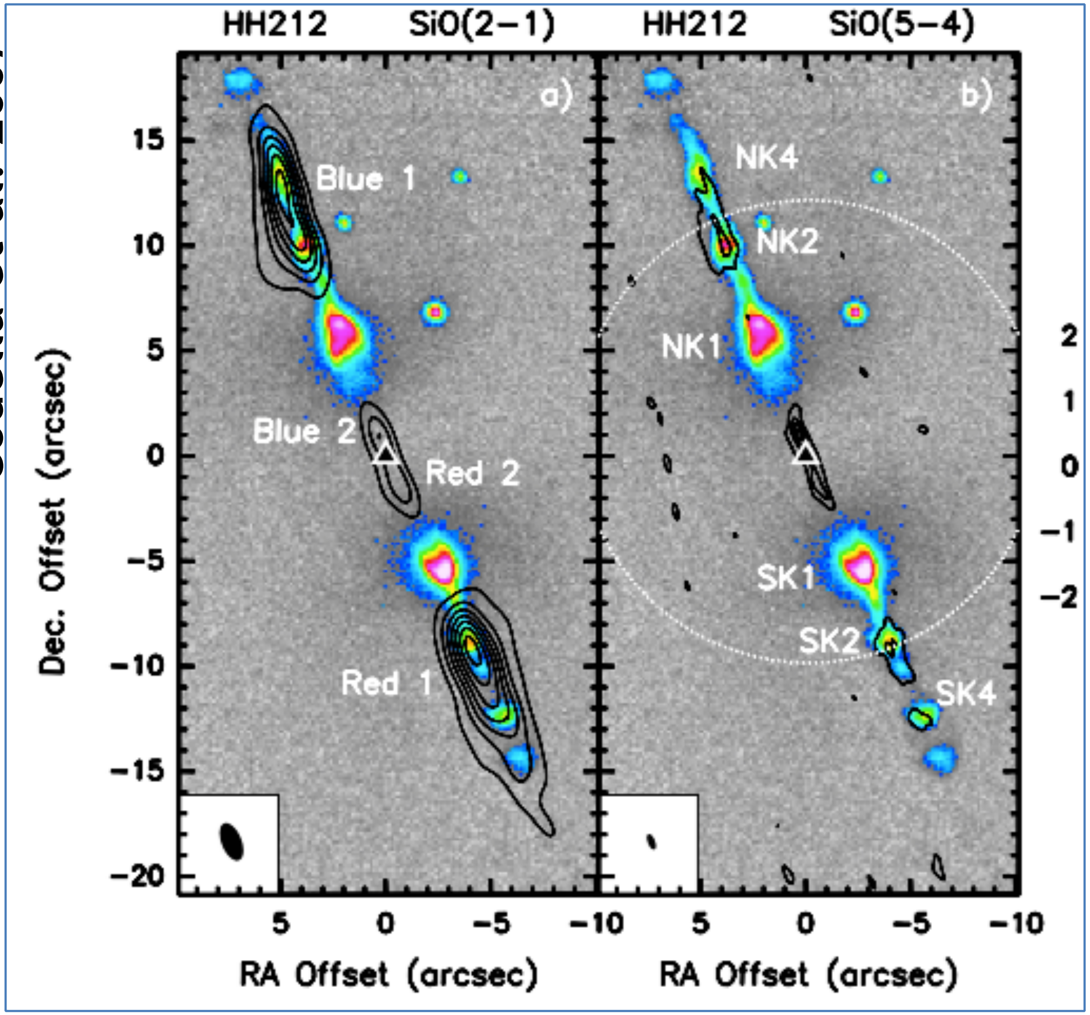
THE OUTFLOWS

3.Blooming & conserving

3.2 Outflow shocks

PdBI obs

Codella et al. 2007



MATTER OUTFLOWS OCCUR SIMULTANEOUSLY WITH INFALL

THIS IS HUGELY IMPORTANT FOR DYNAMICS AND CHEMISTRY

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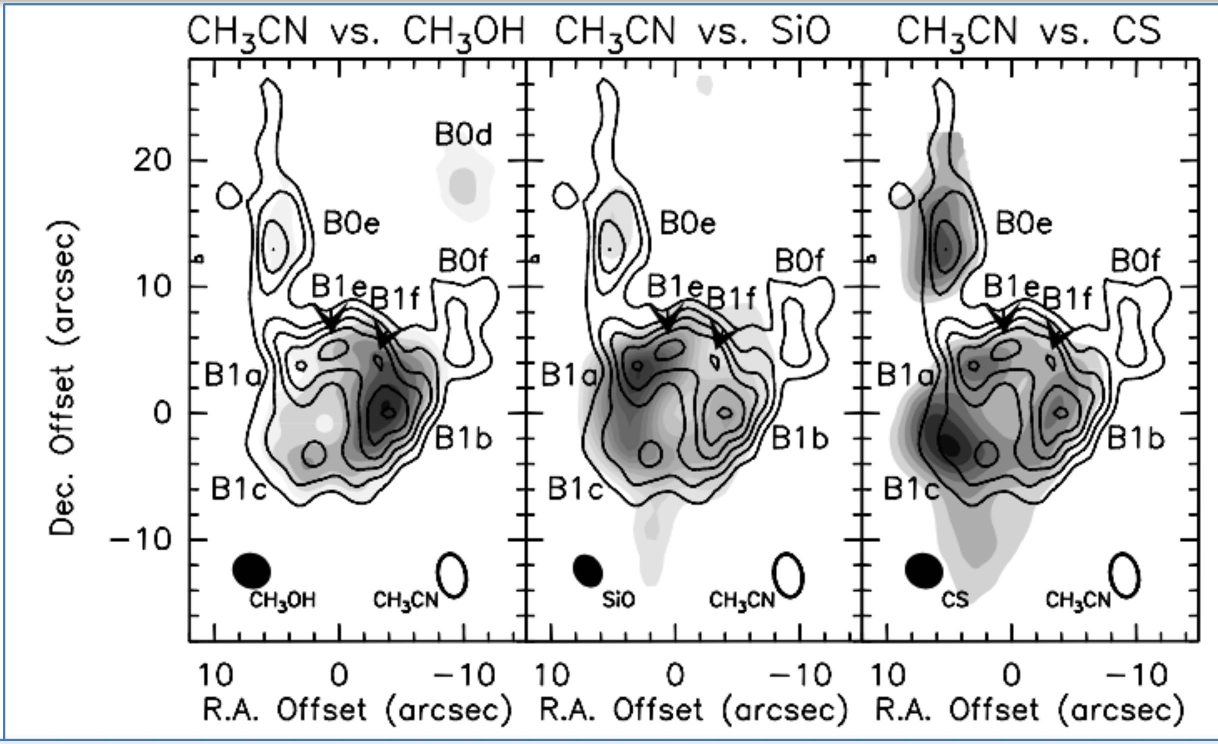
THE OUTFLOWS

PdBI obs

Codella et al. 2009



OUTFLOWS ARE INTERESTING IN THE ASTROCHEMICAL CONTEXT FOR TWO REASONS:

1) THEY CREATE SHOCKS FROM WHICH MOLECULES ON THE **GRAIN MANTLES** ARE INJECTED IN THE GAS
2) THEIR **SHORT LIFETIME**, ~10^3 yr => ONLY FAST CHEMISTRY CAN ALTER THE GAS PHASE COMPOSITION

EXTREMELY USEFUL BENCHMARKS FOR ASTROCHEMICAL MODELS

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3.3 SUPER-DEUTERATED MOLECULES

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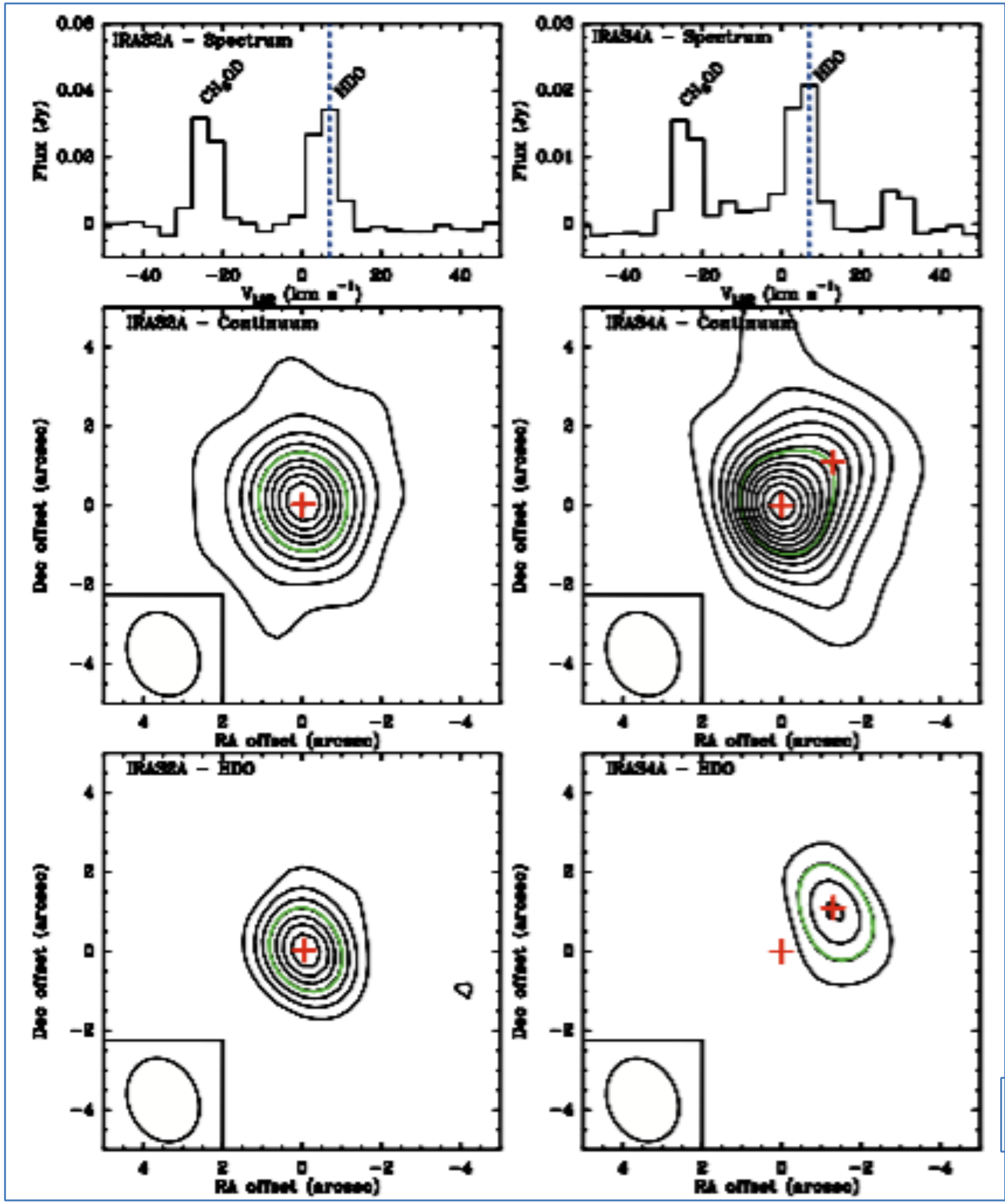
DEUTERATED WATER



IN HOT CORINOS THE GRAIN MANTLE WATER SUBLIMATE

1) ABUNDANT WATER VAPOR
2) HIGHLY DEUTERATED

PdBI

Taquet et al. 2013a

DEUTERATED WATER

3.Blooming & conserving

3.3 Super-deuterated molecules

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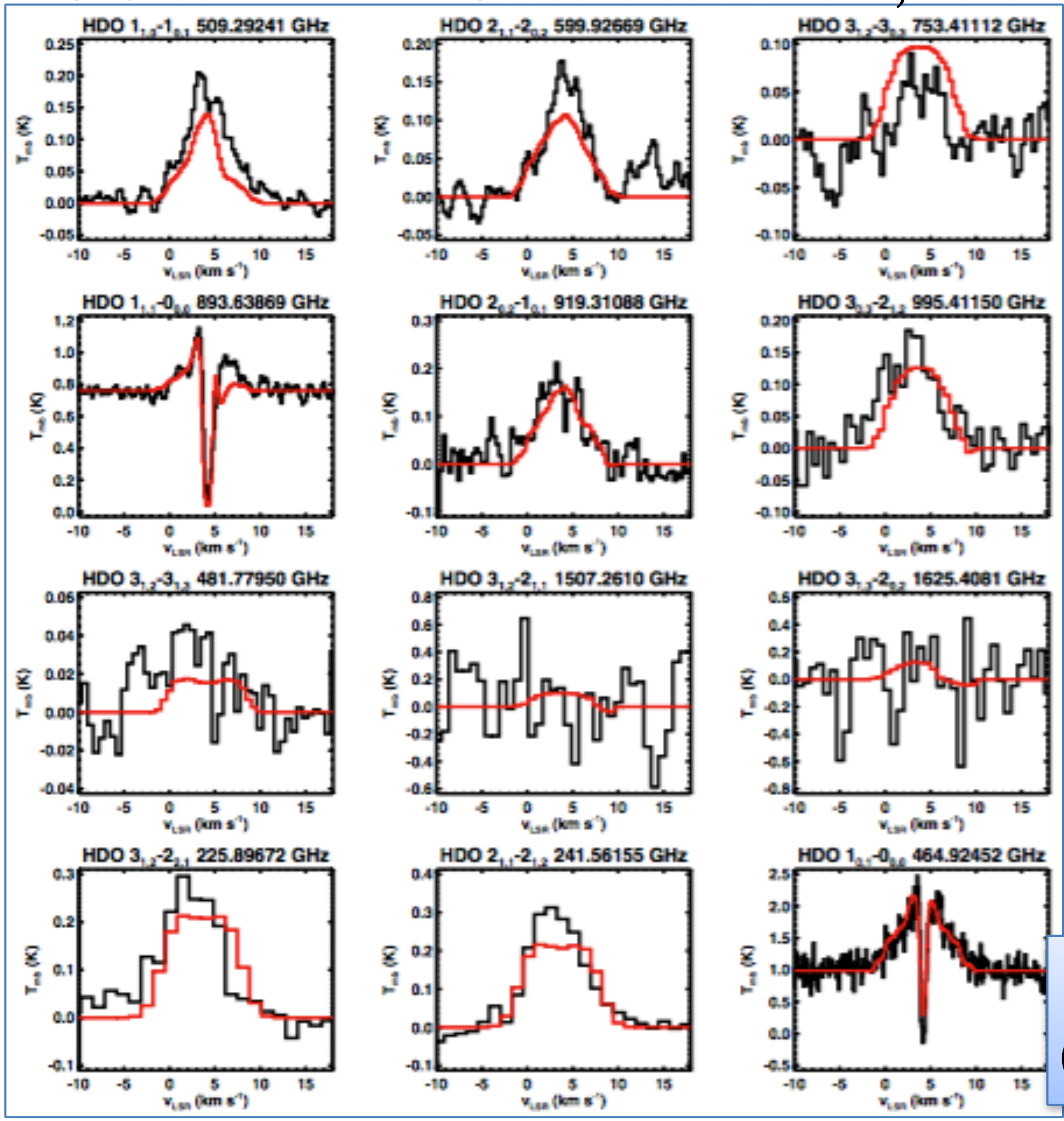
IRAS16293-2422 Coutens et al. 2012, 2013



IN HOT CORINOS THE GRAIN MANTLE WATER SUBLIMATE

1) ABUNDANT WATER VAPOR
2) HIGHLY DEUTERATED

HERSCHEL KP CHESS OBSERVATIONS

MANY LINES = LOT OF INFORMATION

DEUTERATED WATER

IRAS16293-2422 Coutens et al. 2012, 2013

	Hot corino		Outer envelope		Photodesorption layer
	Best-fit	3σ	Best-fit	3σ	$A_V \sim 1$–4 mag
HDO^a	1.8×10^{-7}	1.4–2.4×10^{-7}	8×10^{-11}	5.5–10.6×10^{-11}	~ 0.6–2.4×10^{-8}
$H_2O^{a,b}$	1×10^{-5}	4.7–40.0×10^{-6}	1.5×10^{-8}	7.0–22.5×10^{-9}	~ 1.3–5.3×10^{-7}
D_2O	7×10^{-10}	$\leq 1.3 \times 10^{-9}$	5×10^{-12}	$\leq 1.3 \times 10^{-11}$	~ 6.6–27×10^{-10}
HDO/H_2O	1.8%	0.4%–5.1%	0.5%	0.3%–1.5%	$\sim 4.8\%^c$
D_2O/HDO	0.4%	≤0.9%	6.3%	≤23%	$\sim 10.8\%^c$
D_2O/H_2O	0.007%	≤0.03%	0.03%	≤0.2%	$\sim 0.5\%^c$

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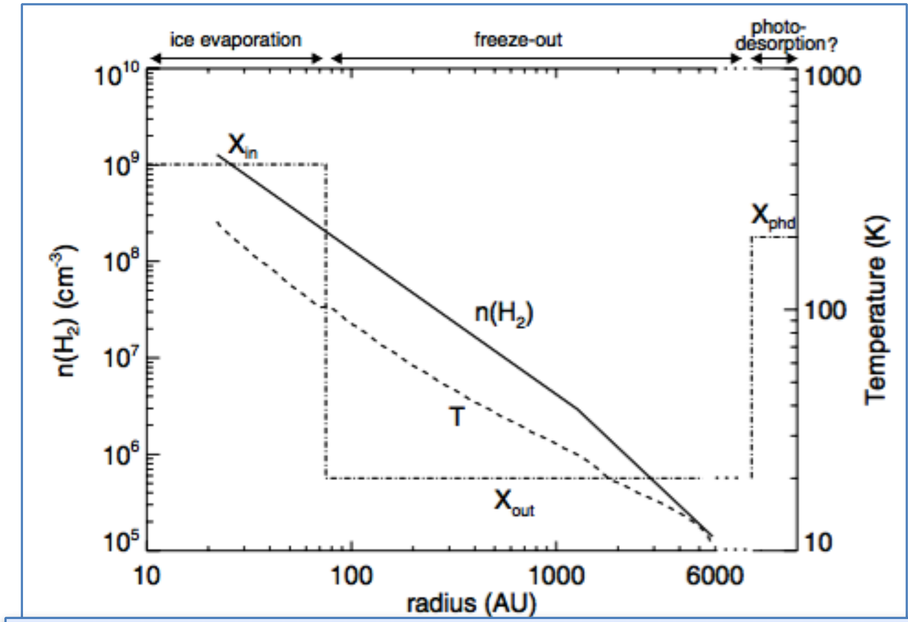

1) ABUNDANT WATER VAPOR
2) HIGHLY DEUTERATED

HERSCHEL KP CHESS OBSERVATIONS

MANY LINES = LOT OF INFORMATION

DEUTERATED METHANOL IN HOT CORINOS

3.Blooming & conserving

3.3 Super-deuterated molecules

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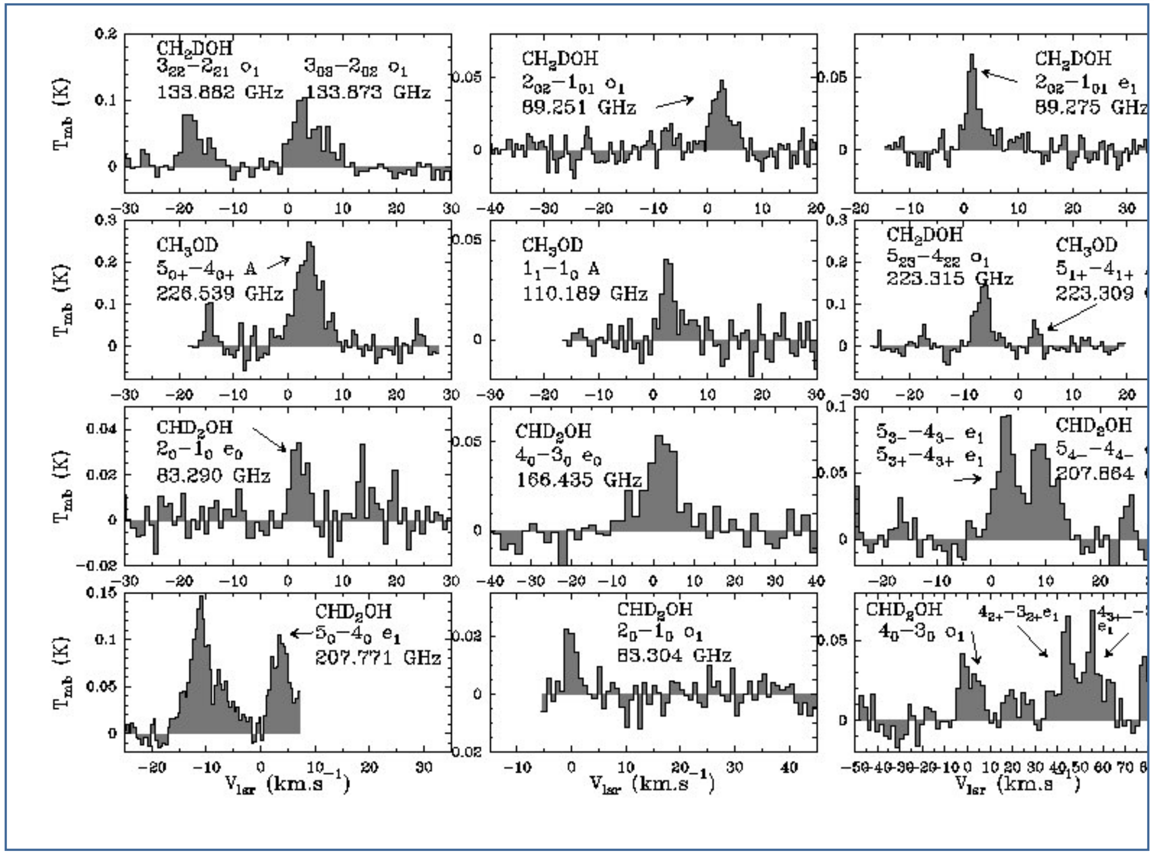


Parise et al. 2002,2004

CH_2DOH/CH_3OH~30%

CHD_2OH/CH_3OH~ 10%

CD_3OH/CH_3OH~ 3%

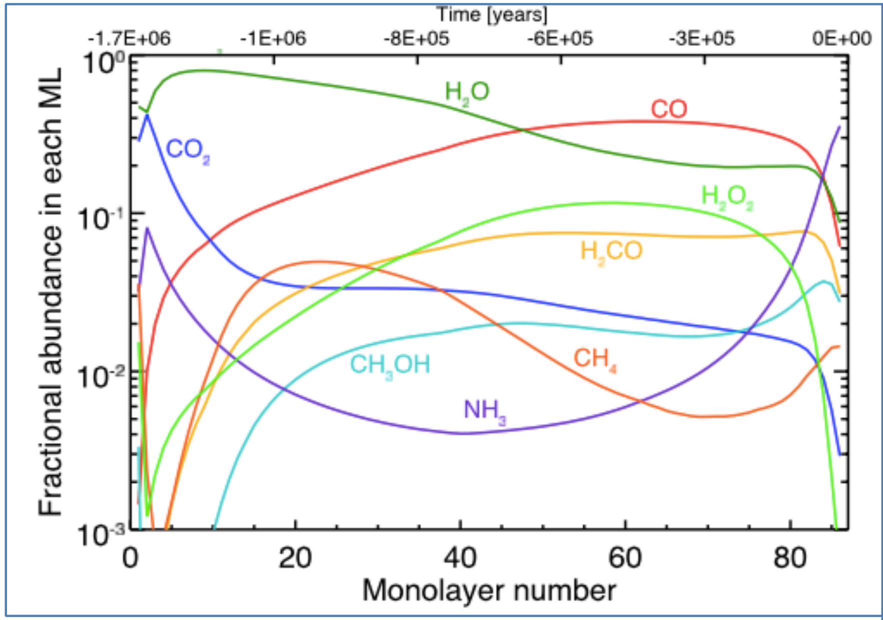
IN HOT CORINOS THE GRAIN MANTLE WATER SUBLIMATE

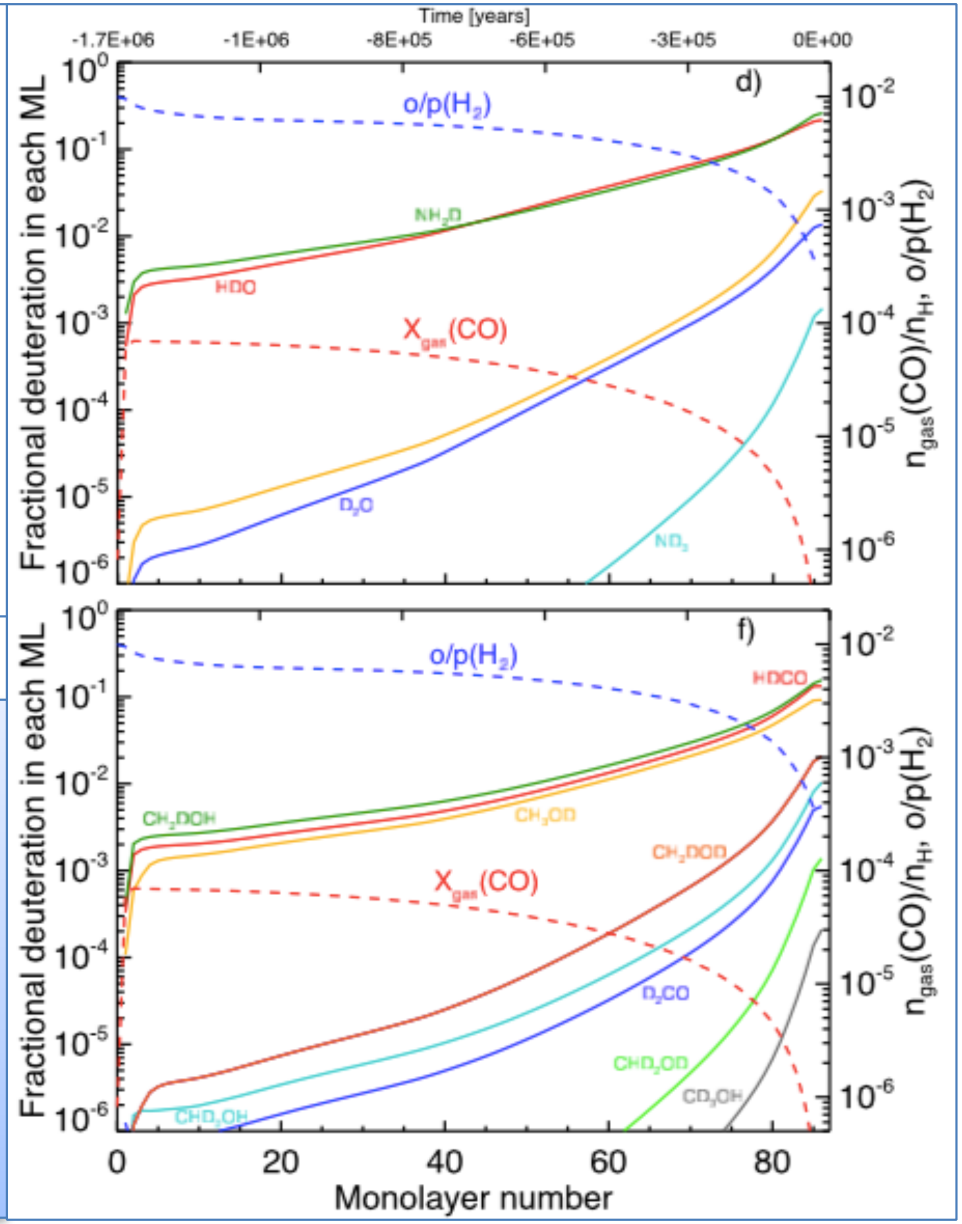
1) ABUNDANT METHANOL
2) HIGHLY DEUTERATED

THE HIGH DEUTERATION IN WARM GAS MUST HAVE BEEN **INHERITED FROM THE PSC PHASE**

MODELS OF MOLECULAR DEUTERATION

Taquet et al. 2014



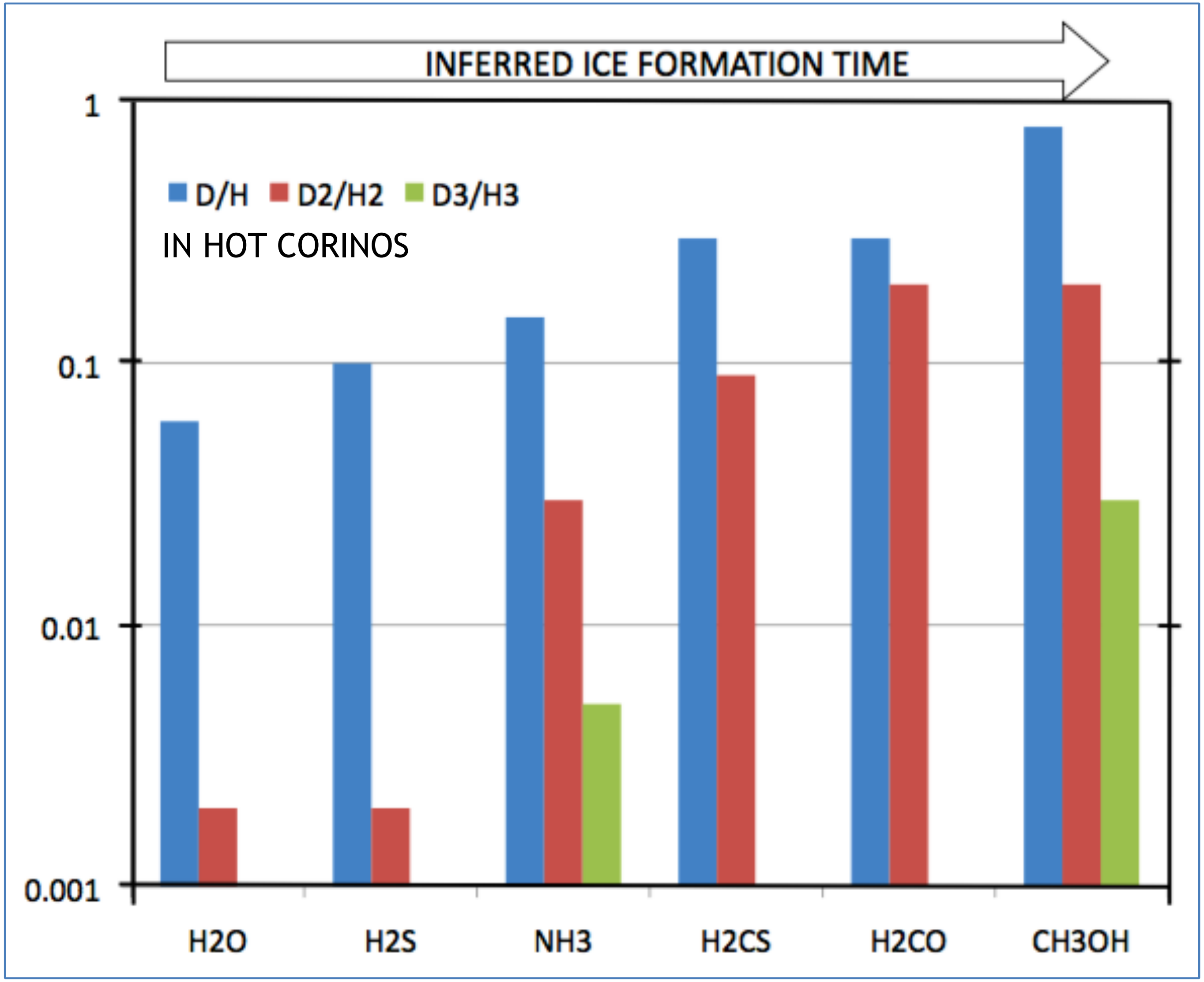


THE LEVEL OF DEUTERATION DEPENDS ON WHEN THE MANTLE MOLECULE WAS FORMED => ITS PAST HISTORY

H_2O —> H_2CO —> CH_3OH

CHEMICAL COMPOSITION = LOT OF INFORMATION = LOT OF PATIENCE

DEUTERATED MOLECULES



Ceccarelli et al. 2014, PP6

THE LEVEL OF DEUTERATION IN HOT CORINOS GIVE US THE SEQUENCE OF THE MANTLE FORMATION

=> ITS PAST HISTORY

DEUTERATED MOLECULES IN OUTFLOWS

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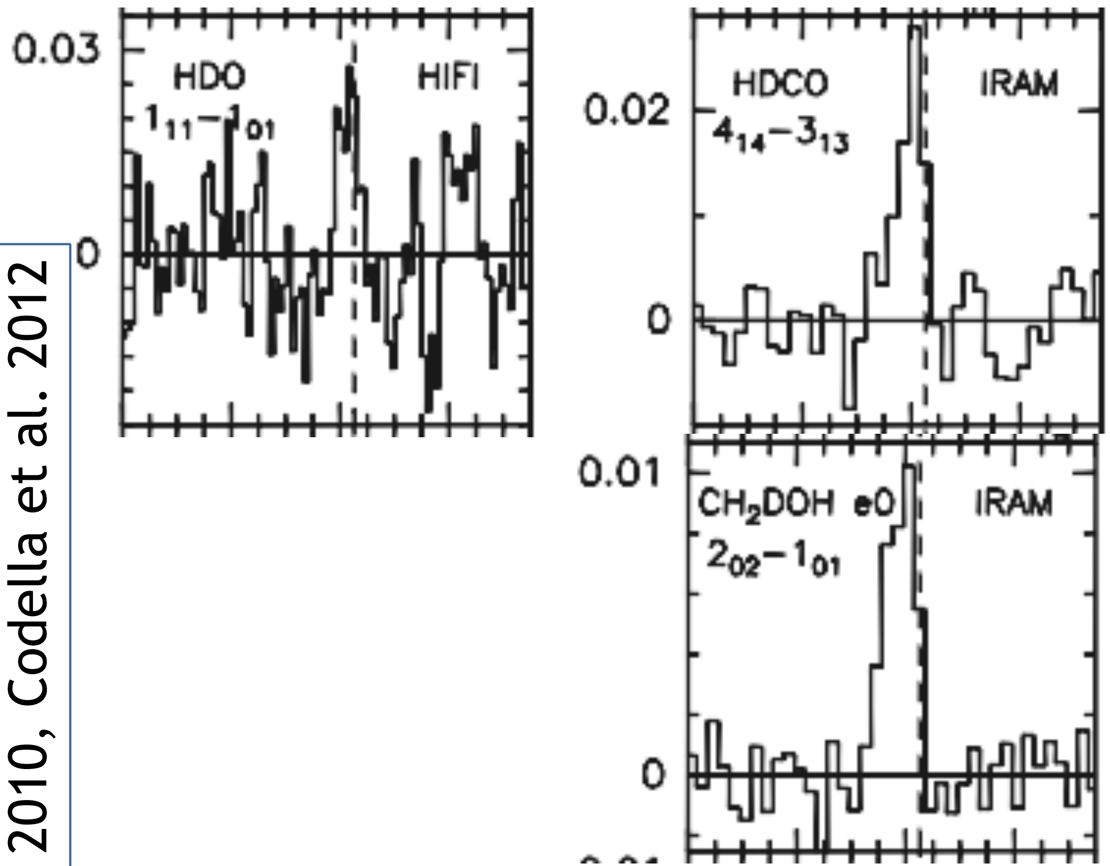
Lelfoch et al. 2010, Codella et al. 2012



IN OUTFLOW SHOCKS THE GRAIN MANTLES ARE SPUTTERED

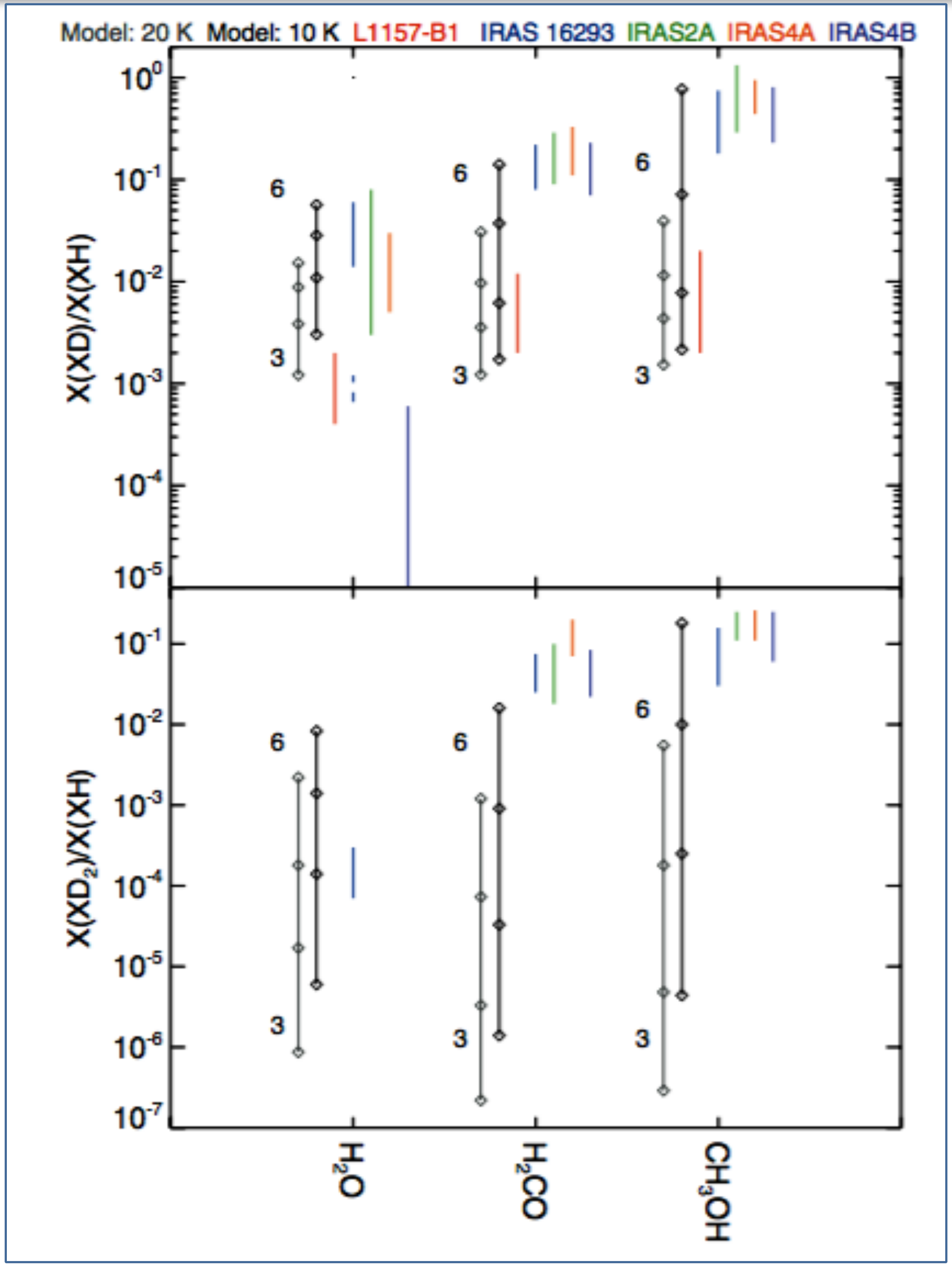
SINGLE-DISH AVERAGE

CH_2DOH/CH_3OH~1%
$HDCO/H_2CO$~0.7 %
HDO/H_2O~0.1%

1) ABUNDANT WATER & Co.
2) HIGH, BUT LESS DEUTERATED MOLECULES

THE HIGH DEUTERATION IN WARM GAS MUST HAVE BEEN **INHERITED FROM THE PSC PHASE**

DEUTERATION & HISTORY



Codella et al. 2012, Taquet et al. 2013

COMPARISON OBSERVATIONS MODEL PREDICTIONS

ICES IN THE L1557-B1 SHOCK FORMED AT A DENSITY SMALLER THAN THAT OF THE FOUR HOT CORINOS (IRAS16293, IRAS2A, IRAS4A AND IRAS4B) SO FAR STUDIED

CHEMICAL COMPOSITION = LOT OF INFORMATION = LOT OF PATIENCE

DEUTERATED MOLECULES IN OUTFLOWS

3.Blooming & conserving

3.3 Super-deuterated molecules

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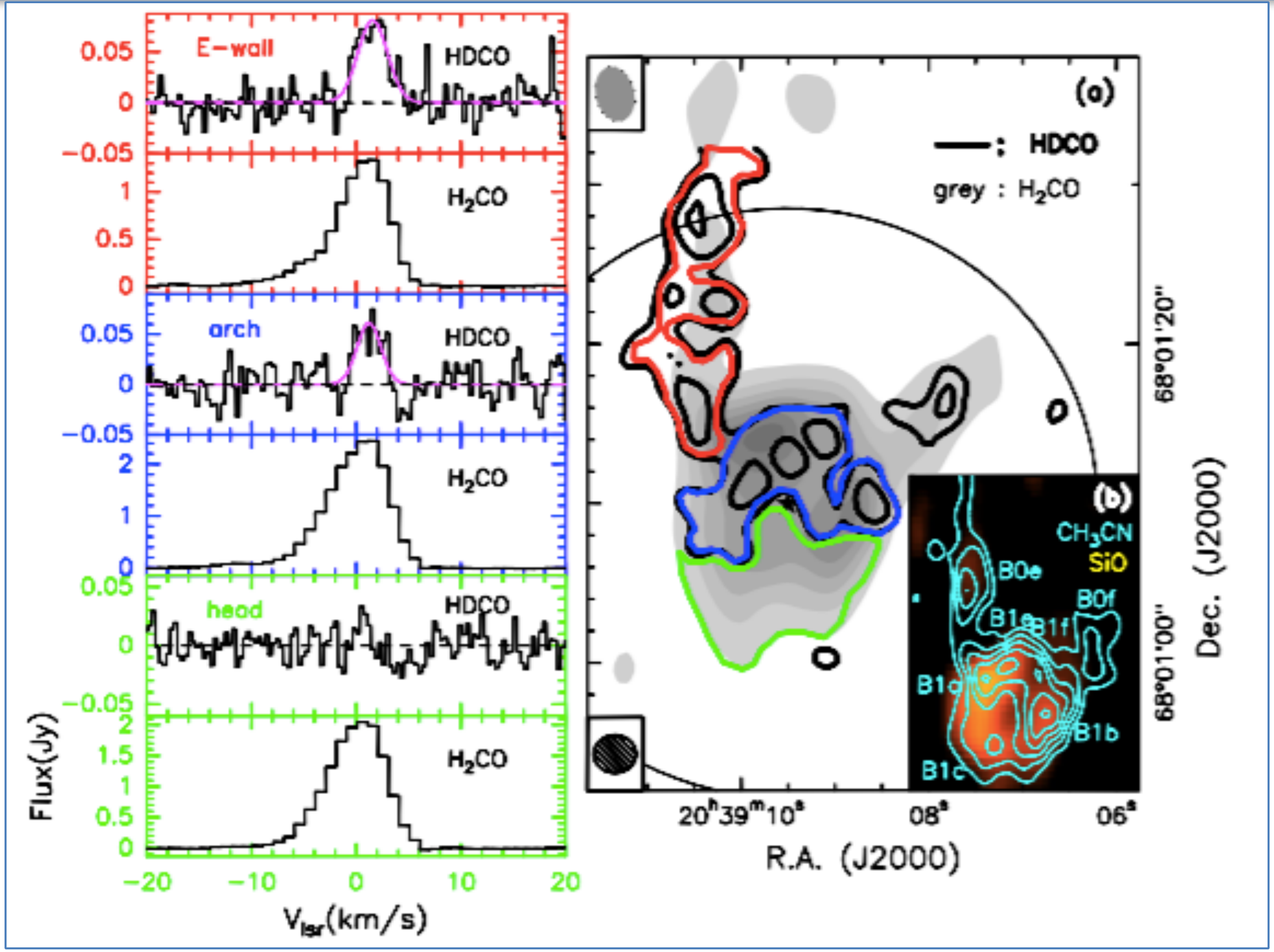

Fontani et al. 2015

INTERFEROMETRIC OBS => $HDCO/H_2CO$~10% **IN THE ICES** (higher wrt the single-dish averaged value)

CHEMICAL COMPOSITION = LOT OF INFORMATION = LOT OF PATIENCE

DEUTERATION & HISTORY

AT PRESENT, WE HAVE ONLY A HANDFUL OF SOURCES WITH THESE OBSERVATIONS
BUT VERY SOON ALMA AND NOEMA WILL PROVIDE US WITH A MUCH LARGER SAMPLE

=> WE WILL THEN BE ABLE TO ESTABLISH AN EXACT MAP OF THE CONDITIONS AT THE BEGINNING OF THE COLLAPSE
=> LONG TERM, WE WILL BE LIKELY BE ABLE TO LINK IT TO THE SOLAR SYSTEM START

CHEMICAL COMPOSITION
LOT OF INFORMATION
LOT OF PATIENCE

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3.4 ORGANIC MOLECULES IN HOT CORINOS

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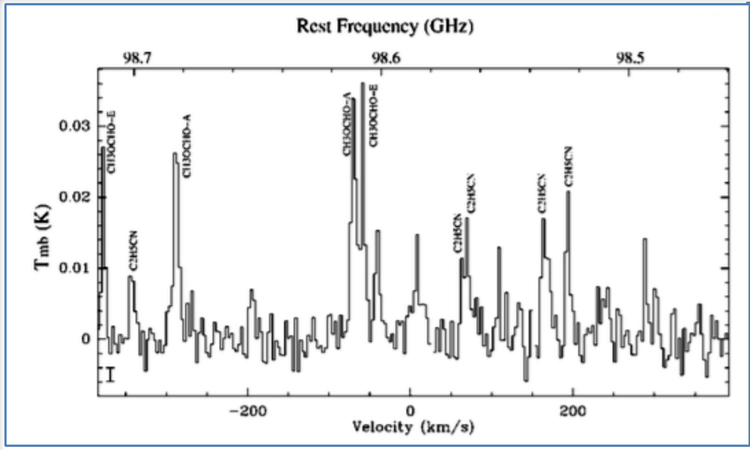
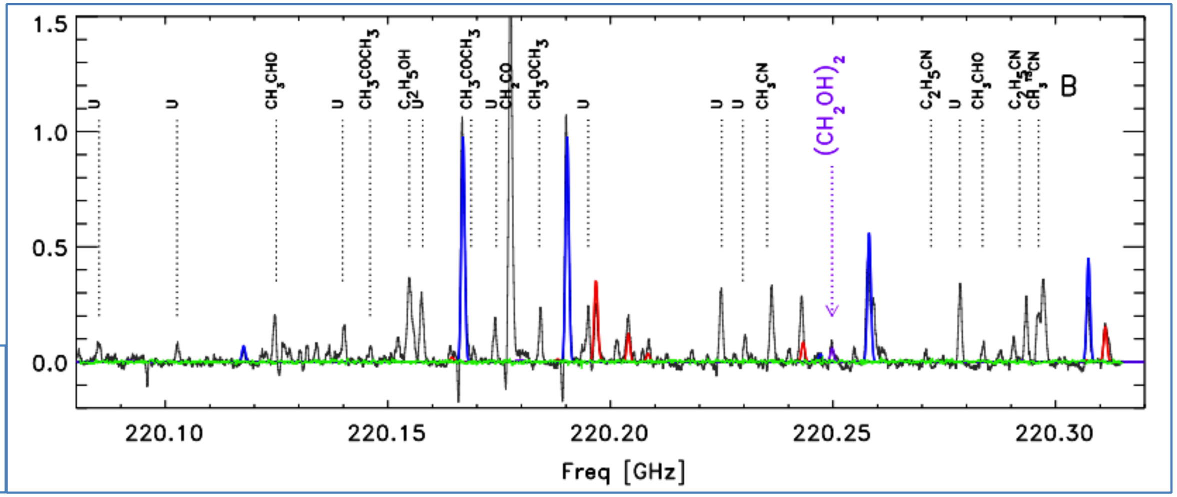
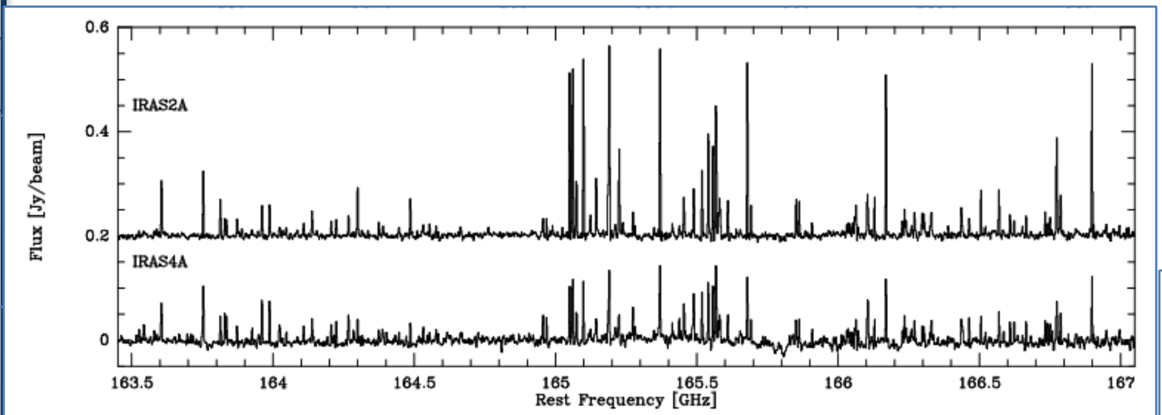
RETAIL SHOPS OF COMs



Cazaux et al. 2003:
single-dish IRAM30m



Jorgensen et al. 2012:
interferometer ALMA



Taquet et al. 2015:
interferometer PdBI

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RETAIL SHOPS OF COMs

3.Blooming & conserving

3.4 COMs

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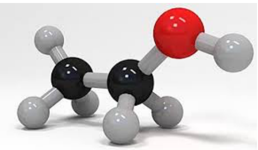
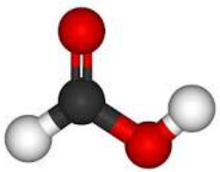
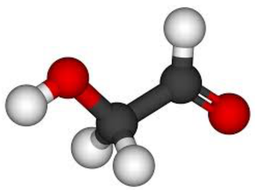
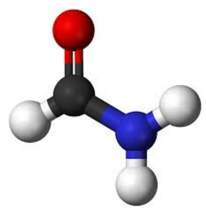
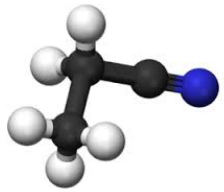
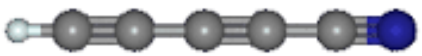
MOST MOLECULES WITH >5 ATOMS DETECTED IN THE ISM ARE NOW ALSO DETECTED IN THE HOT CORINOS



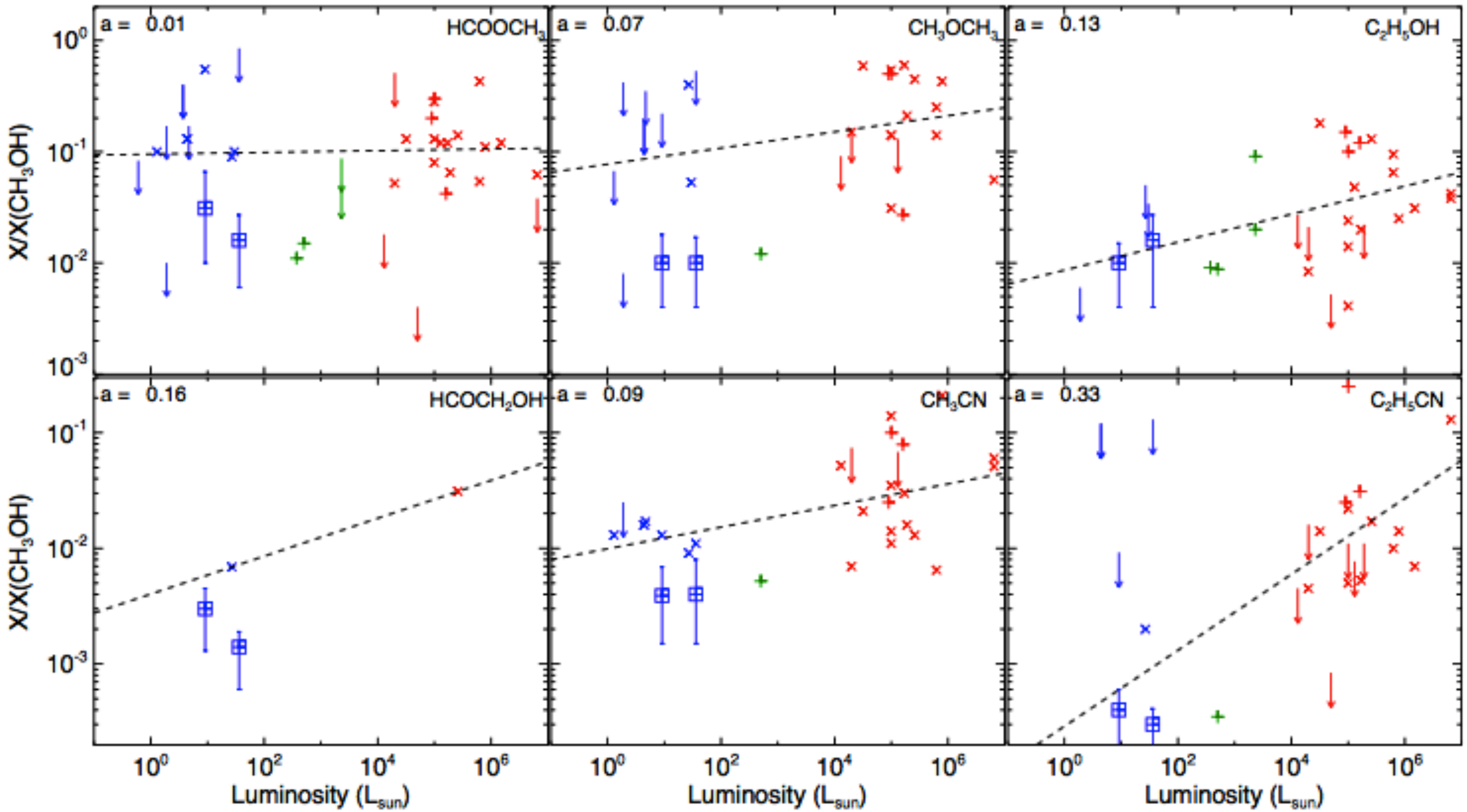


6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	>12 atoms
C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	c-C_6H_6 *	$HC_{11}N$
l-H_2C_4	CH_2CHCN	$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	n-C_3H_7CN	C_{60} *
C_2H_4*	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	i-C_3H_7CN 2014	C_{70} *
CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO	$CH_3OC(O)CH_3$		
CH_3NC	CH_3CHO	C_6H_2	HC_7N				
CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H				
CH_3SH	c-C_2H_4O	l-HC_6H *	$CH_3C(O)NH_2$				
HC_3NH^+	H_2CCHOH	CH_2CHCHO (?)	C_8H^-				
HC_2CHO	C_6H^-	CH_2CCHCN	C_3H_6				
NH_2CHO		H_2NCH_2CN	CH_3CH_2SH (?)				
C_5N		CH_3CHNH					
l-HC_4H *							
l-HC_4N							
c-H_2C_3O							
H_2CCNH (?)							
C_5N^-							
$HNCHCN$							

RETAIL SHOPS OF COMs

A SUBSTANTIAL FRACTION OF C IS TRAPPED IN COMs (and NOT in refractory components)



Taquet et al. 2015

3.Blooming & conserving

3.4 COMs

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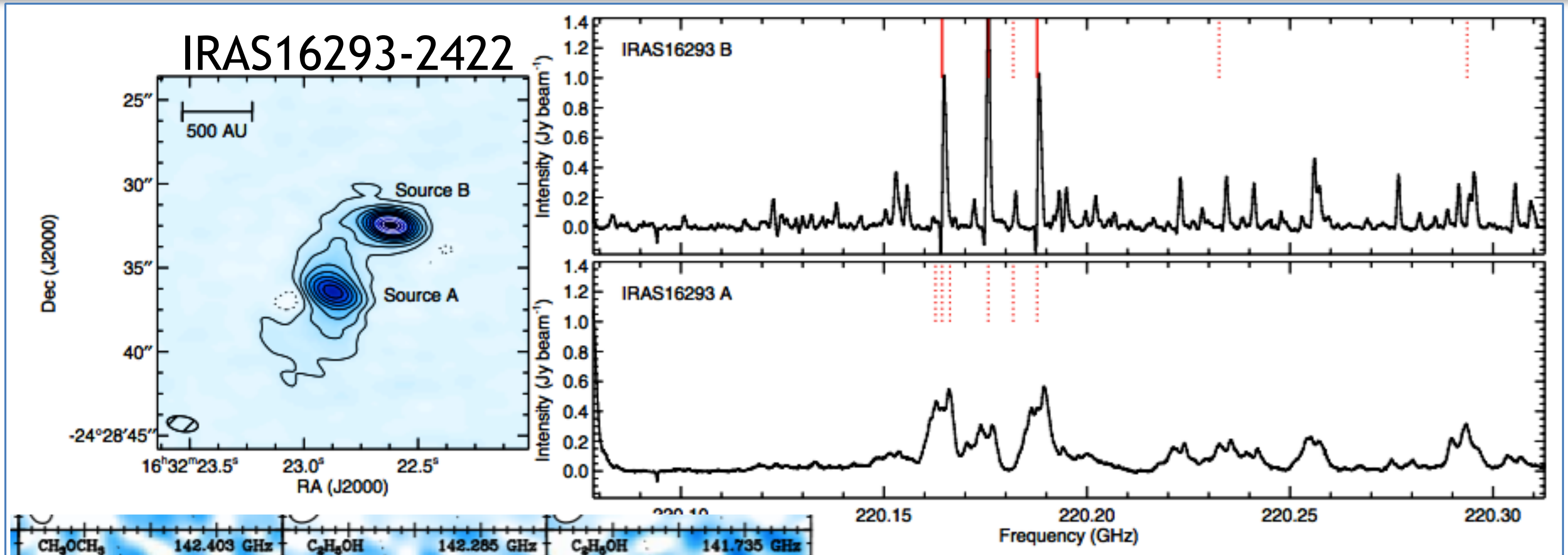
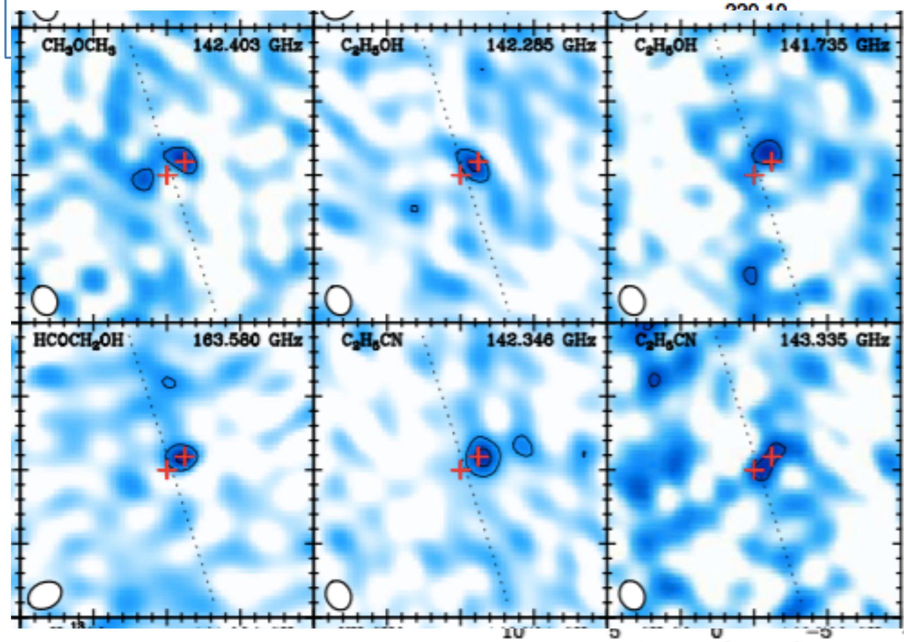
RETAIL SHOPS OF COMs

OBJECTS IN BINARY SYSTEMS SEEM TO HAVE A DIFFERENT CHEMICAL COMPOSITION=> COMs

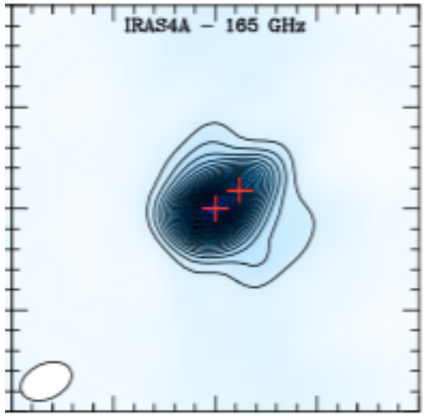
Pineda et al. 2012

IRAS16293-2422





NGC1333-IRAS4A



Taquet et al. 2015

3.Blooming & conserving

3.4 COMs

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HOW ARE COMs FORMED?

PROBLEM: THE GROWTH OF LARGE MOLECULES REQUIRES REACTIONS WITH ACTIVATION BARRIERS

GAS PHASE

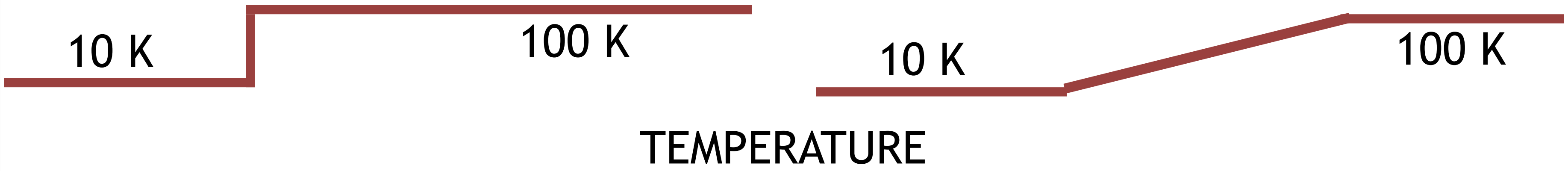
reactions in the gas phase, often started by the injection of hydrogenated molecules formed on the grain surfaces

Step 1	Step 2	Step 3
H_2CO CH_3OH NH_3	ice sublimation	$HCOCH_2OH$ CH_3OCH_3 NH_2CHO

GRAIN SURFACES

reactions on the grain surfaces between radicals during the warm-up of the dust; radicals are formed in the cold phase

Step 1	Step 2	Step 3
H_2CO CH_3OH NH_3	$HCOCH_2OH$ CH_3OCH_3 NH_2CHO	ice sublimation



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HOW ARE COMs FORMED?

PROBLEM: THE GROWTH OF LARGE MOLECULES REQUIRES REACTIONS WITH ACTIVATION BARRIERS

GAS PHASE

reactions in the gas often started by the hydrogenated molec on the grain surface

GRAIN SURFACES

grain surfaces s during the dust; radicals e cold phase

Step 1
H_2CO

Step 2
ice

ep 2
CH_2OH

Step 3
ice

OPEN DEBATE

CHEMICAL COMPOSITION
LOT OF INFORMATION
LOT OF PATIENCE

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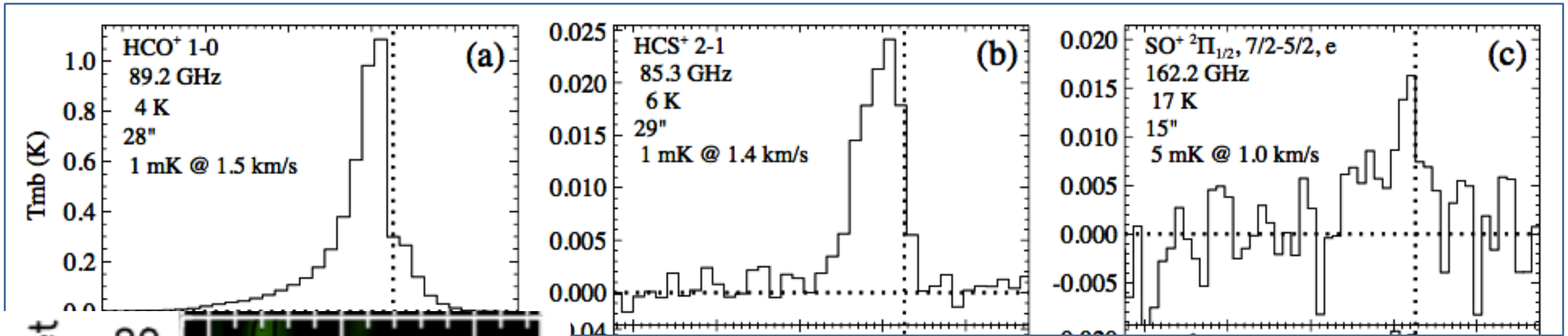
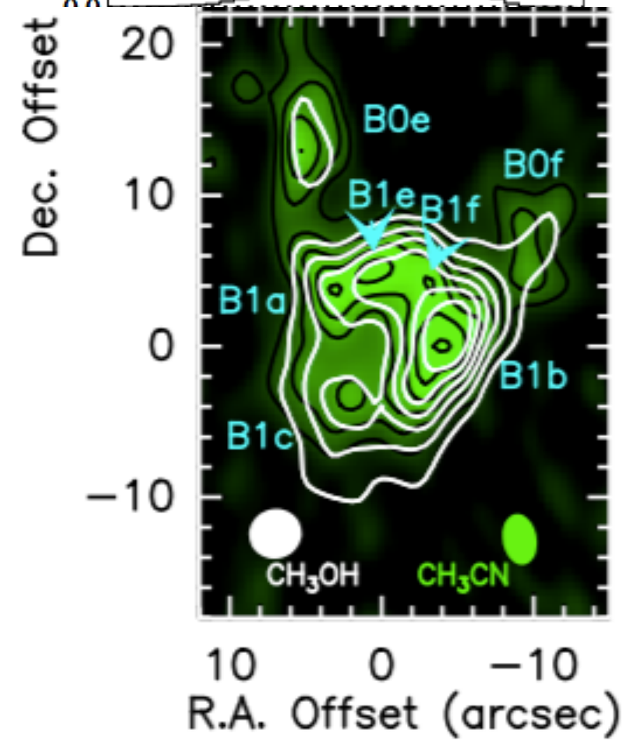
RETAIL SHOPS OF COMs

KEY INFORMATION FROM OUTFLOW SHOCKS: example of ions from CHESS and ASAI obs

Podio et al. 2014





Species	Cmp	T_{kin} K	n_{H_2} cm^{-3}	$N_{species}$ cm^{-2}	$X = N_{species}/N_{H_2}$
CO[a]	g_1	210	$\geq 10^6$	$9\ 10^{15}$	10^{-4}
	g_2	60–80	$\geq 10^5$	$9\ 10^{16}$	10^{-4}
	g_3	20	$\geq 10^5$	$1\ 10^{17}$	10^{-4}
HCO^+	g_1	210[b]	10^6-10^{7b}	1–$3\ 10^{12}$	1–$3\ 10^{-8}$
	g_2	60	10^5	$6\ 10^{12}$	$7\ 10^{-9}$
N_2H^{+c}	g_2/g_3	20–70[c]	-	0.4–$8\ 10^{12}$	0.4–$8\ 10^{-9}$
$HOCO^+$	g_2/g_3	35	10^4	$1\ 10^{12}$	$1\ 10^{-9}$
SO^{+d}	g_2/g_3	25[d]	-	$7\ 10^{11}$	$8\ 10^{-10}$
HCS^+	g_2	80	$8\ 10^5$	$6\ 10^{11}$	$7\ 10^{-10}$
	g_3	20[e]	10^{5e}	$3\ 10^{11}$	$3\ 10^{-10}$

3.Blooming & conserving

3.4 COMs

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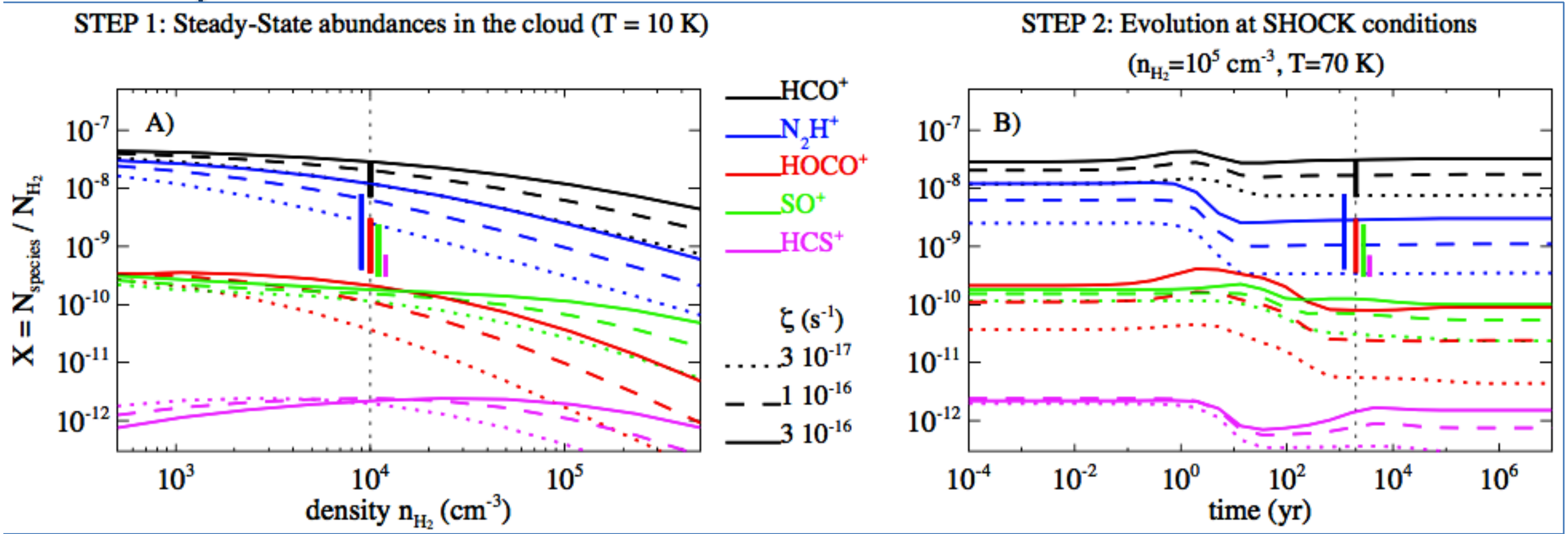
RETAIL SHOPS OF COMs

KEY INFORMATION FROM OUTFLOW SHOCKS: example of ions from CHESS and ASAI obs

Podio et al. 2014



TIMESCALE MATTERS

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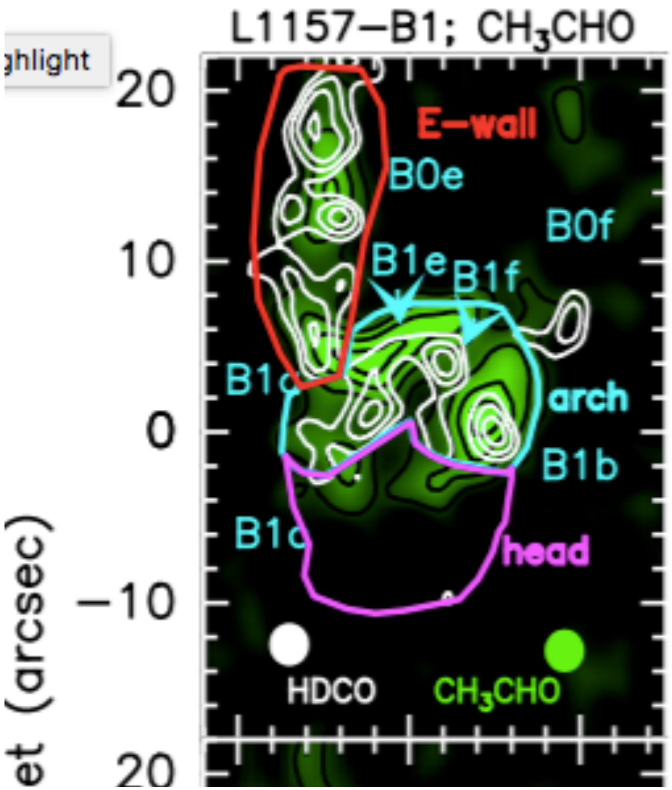
RETAIL SHOPS OF COMs

KEY INFORMATION FROM OUTFLOW SHOCKS: example of acetaldehyde (PdBI obs)

Codella et al. 2015

3.Blooming & conserving

3.4 COMs



THE MEASURED ABUNDANCE OF ACETALDEHYDE, ~2x10^{-8}, CAN BE A GAS PHASE PRODUCT, IF ~0.1% OF CARBON IS IN HYDROCARBONS

TIMESCALE MATTERS

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COMs FORMATION: WHAT IS AT STAKE

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CHEMICAL COMPOSITION
LOT OF INFORMATION
LOT OF PATIENCE

HOW DO COMs FORM?
=> OUT-OF-EQUILIBRIUM CHEMISTRY

WHAT INFORMATION CAN THEY PROVIDE TO US?
=> DENSITY, TEMPERATURE, ENVIRONMENT (PHOTONS & PARTICLES), HISTORY, AGE of THE VARIOUS OBJECTS…
=> THE PHYSICS-CHEMISTRY IN EXTREME CONDITIONS

COMPLEXITY = INFORMATION
KNOWLEDGE = PREDICTIVE POWER

COMs FORMATION: NOEMA LP SOLIS

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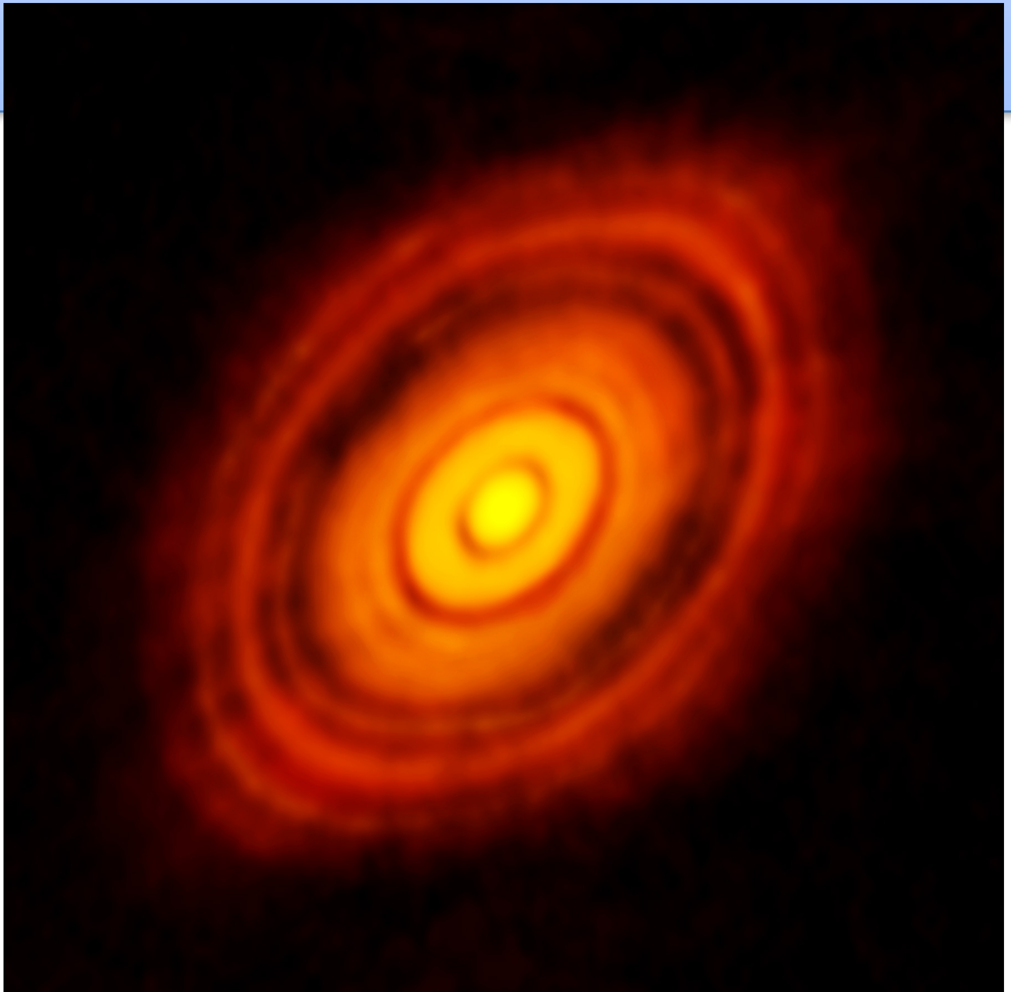
SOLIS
(Seeds Of Life In Space)
PIs: C.Ceccarelli & P.Caselli
380hr AT IRAM/NOEMA

GOALS
UNDERSTAND COMs CHEMISTRY

METHOD
SYSTEMATIC OBSERVATIONS OF 5 COMs IN DIFFERENT SOURCES REPRESENTATIVES OF SUN-LIKE STAR FORMATION

COMPLEXITY = INFORMATION
KNOWLEDGE = PREDICTIVE POWER

3.5 CONSERVATION IN PROTOPLANETARY DISKS



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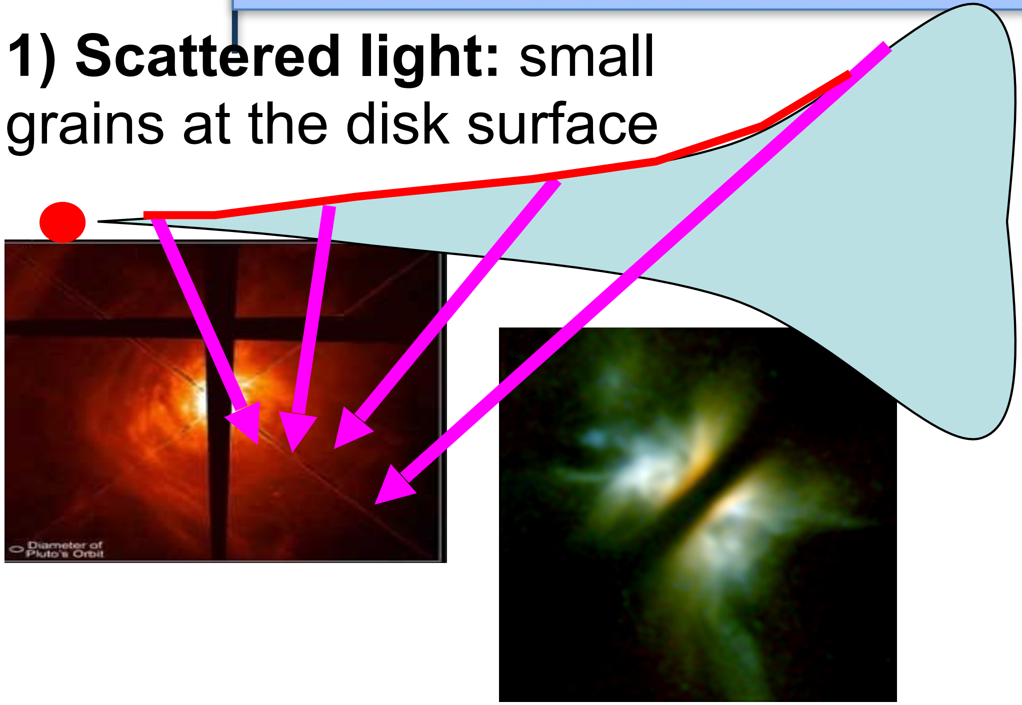
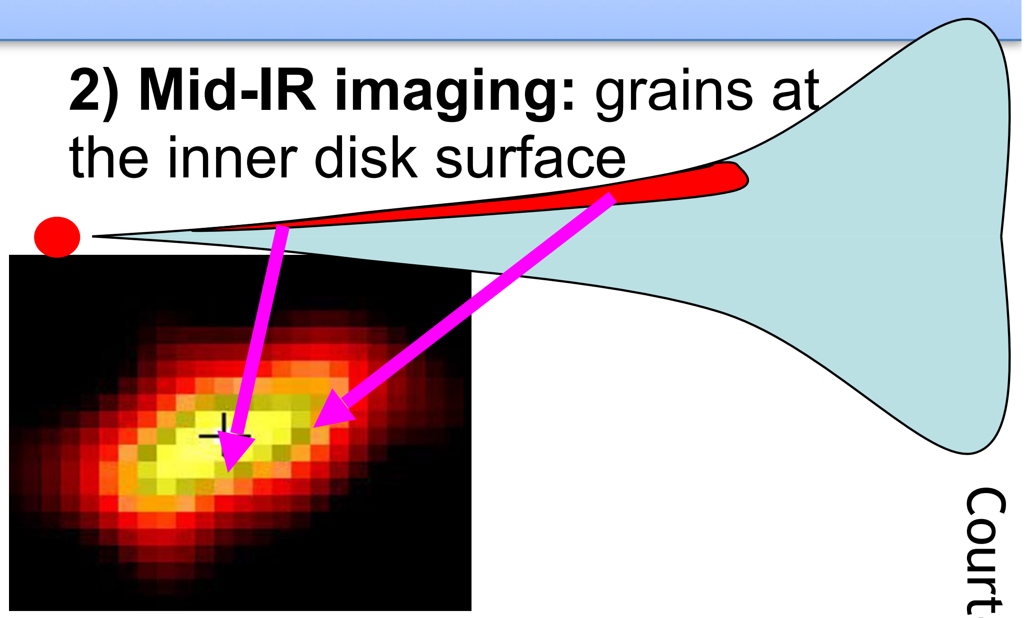
OBSERVATIONS OF DISKS

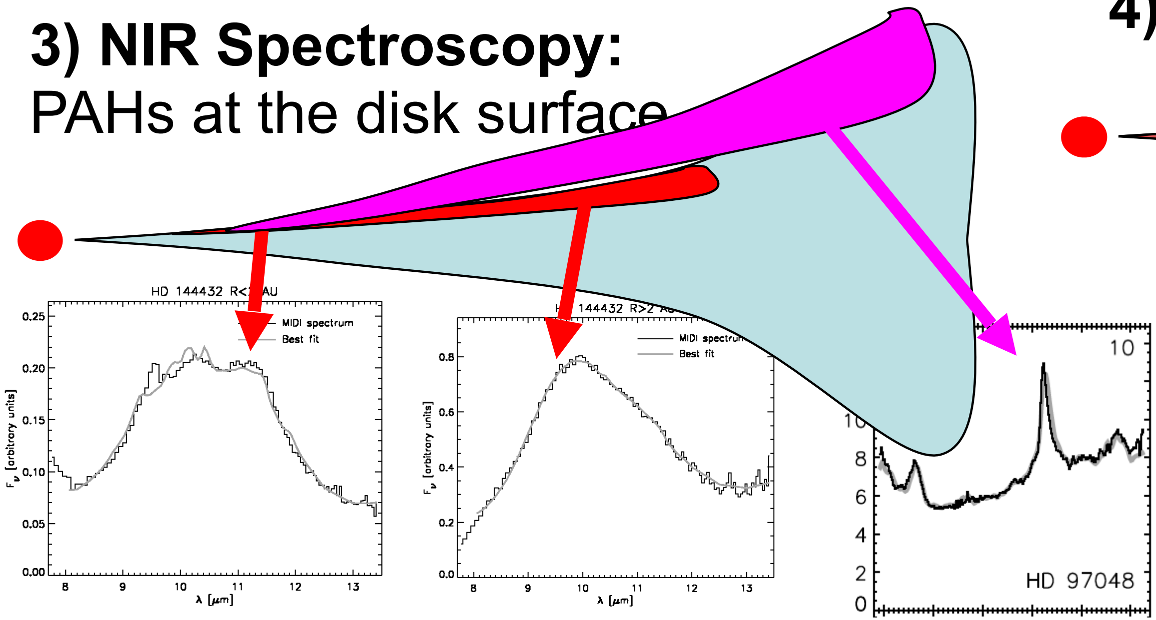
1) Scattered light: small grains at the disk surface



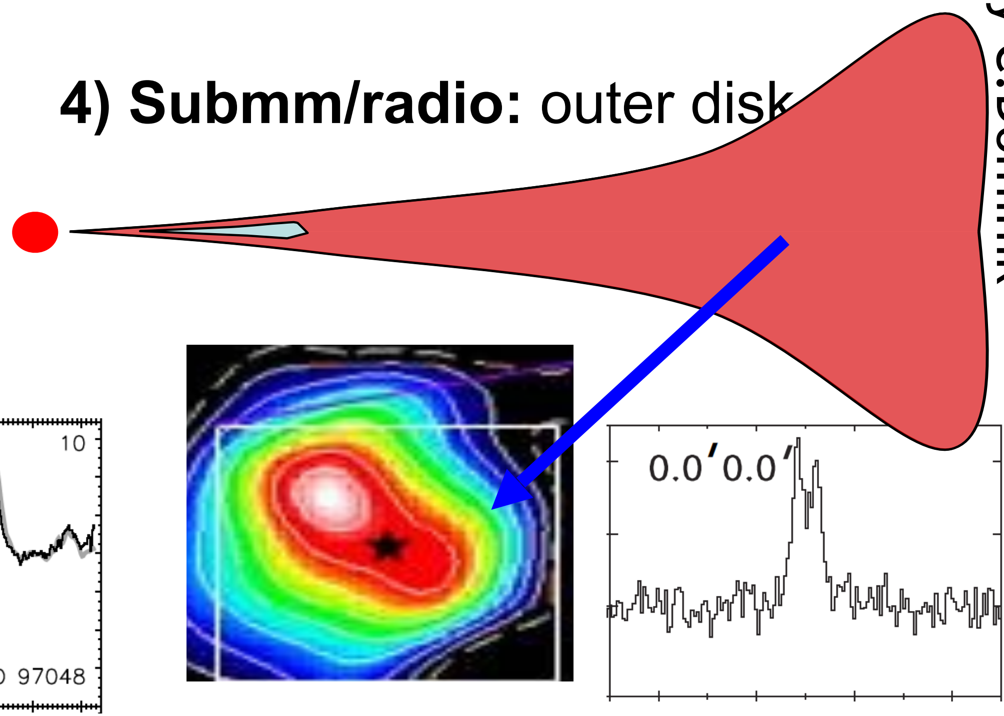
2) Mid-IR imaging: grains at the inner disk surface



3) NIR Spectroscopy: PAHs at the disk surface

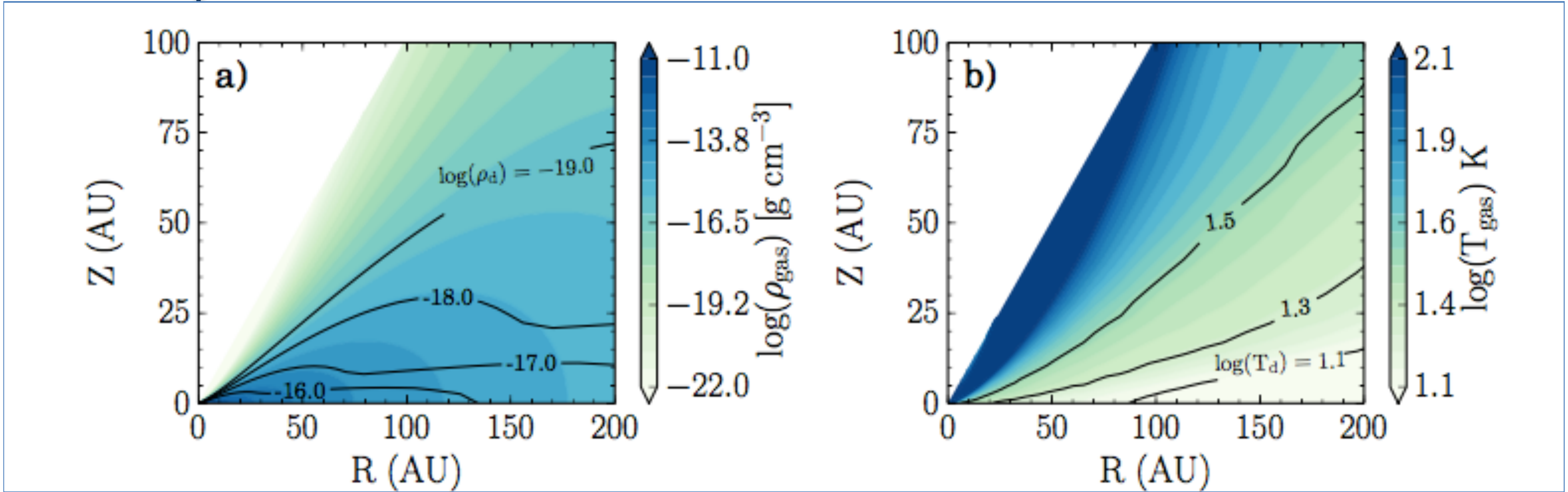


4) Submm/radio: outer disk



Courtesy C.Dominik

DISK PHYSICAL STRUCTURE



Cleeves et al. 2015

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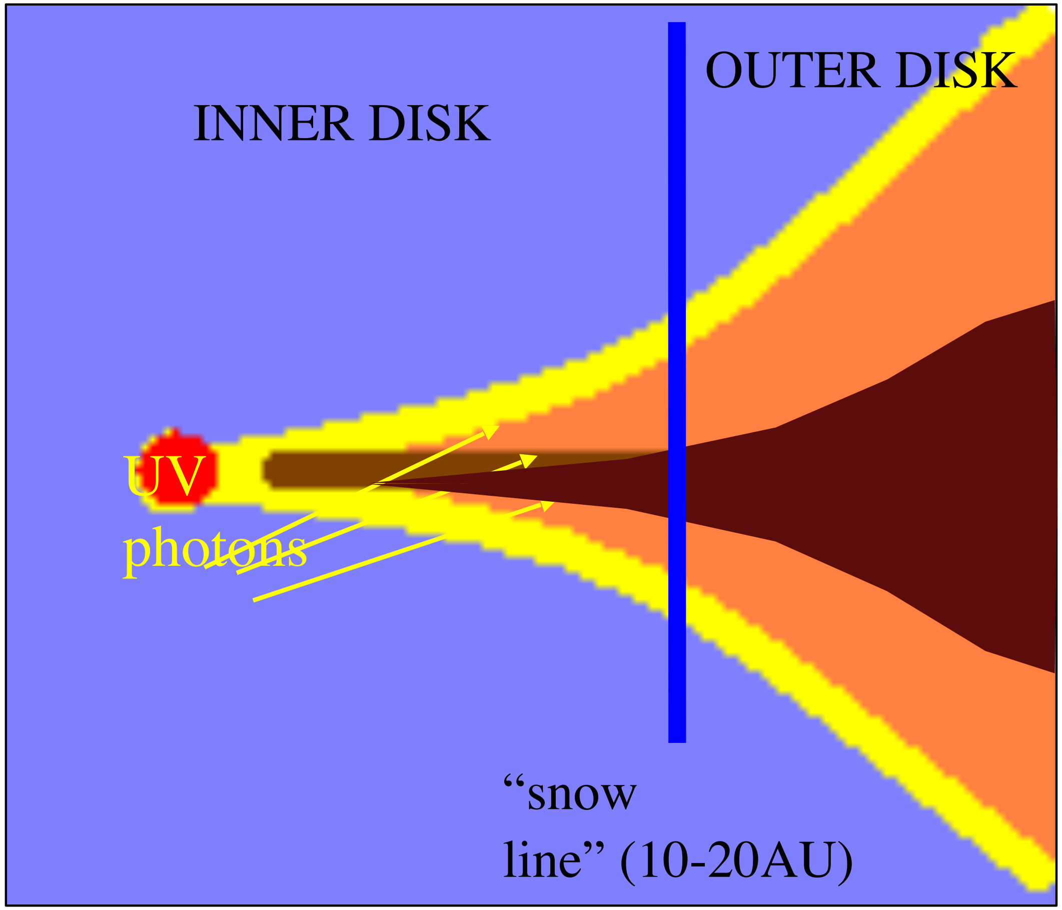
COLD MIDPLANE: SIMILAR TO PRE-STELLAR-CORES
INWARD REGIONS: SIMILAR TO HOT CORINOS
ATMOSPHERE: SIMILAR TO PHOTO-DISSOCIATION REGIONS

DISK CHEMICAL STRUCTURE

3.Blooming & conserving

3.5 Disks



COLD MIDPLANE: SIMILAR TO PRE-STELLAR-CORES
INWARD REGIONS: SIMILAR TO HOT CORINOS
ATMOSPHERE: SIMILAR TO PHOTO-DISSOCIATION REGIONS

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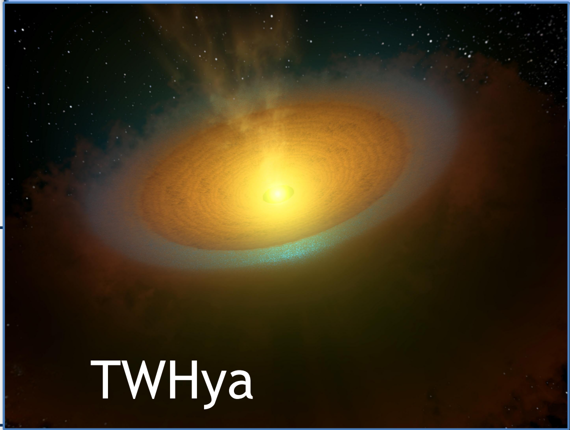
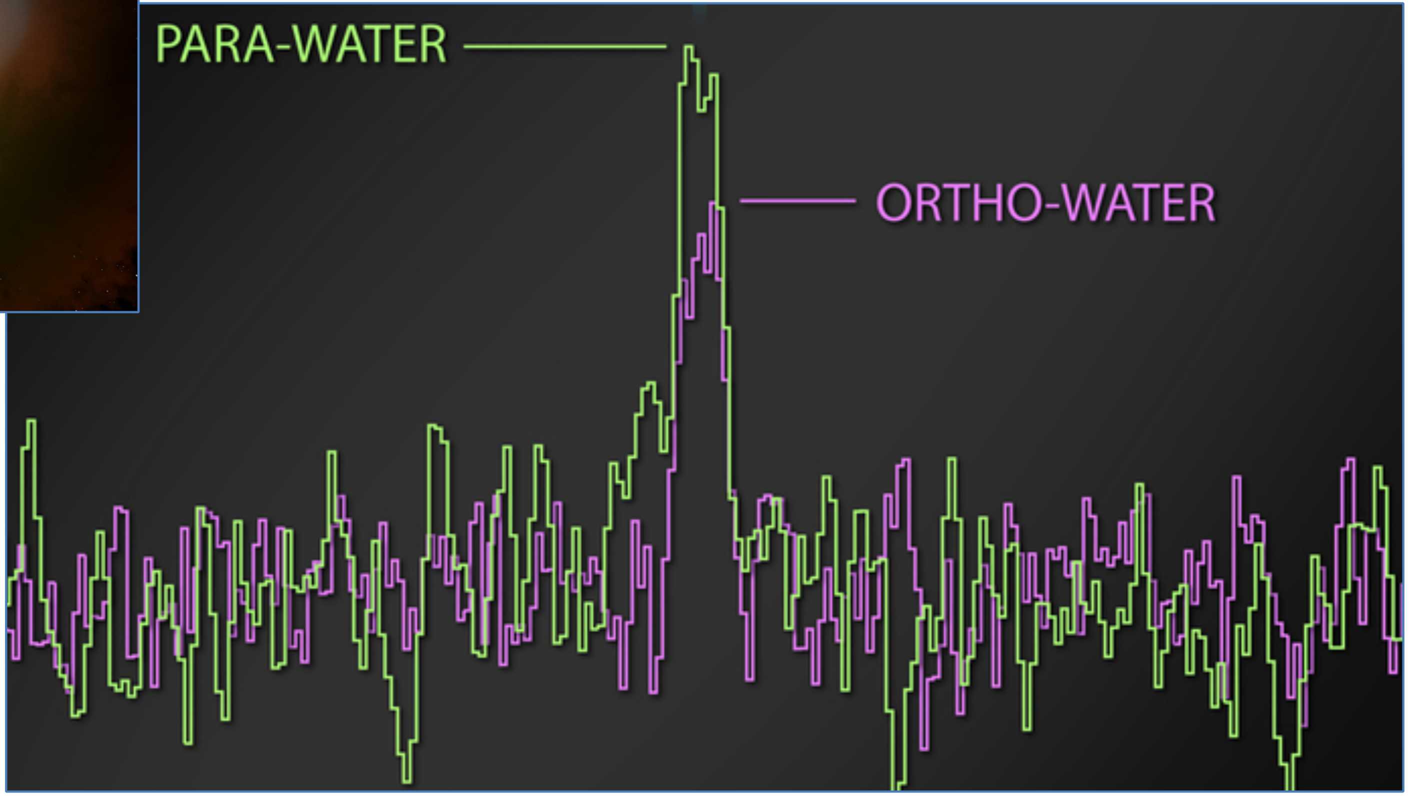
WATER IN DISKS



HERSCHEL OBSERVATIONS Hogerheijde et al. 2011



3.Blooming & conserving

3.5 Disks

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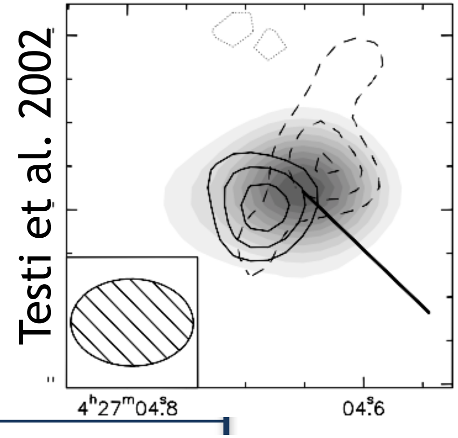
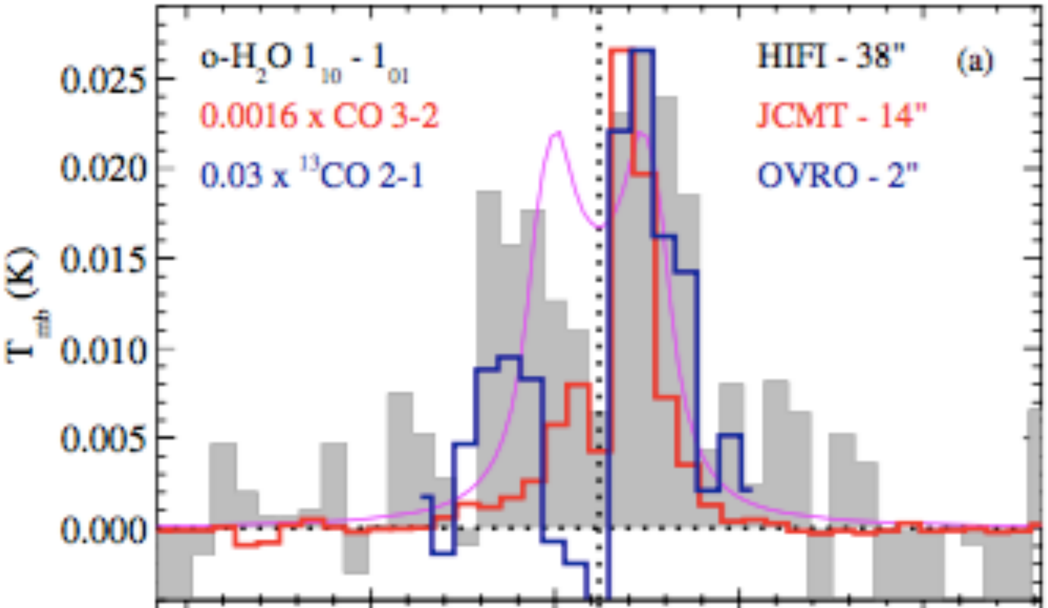
ENOUGH TO FILL THOUSANDS OF EARTH OCEANS

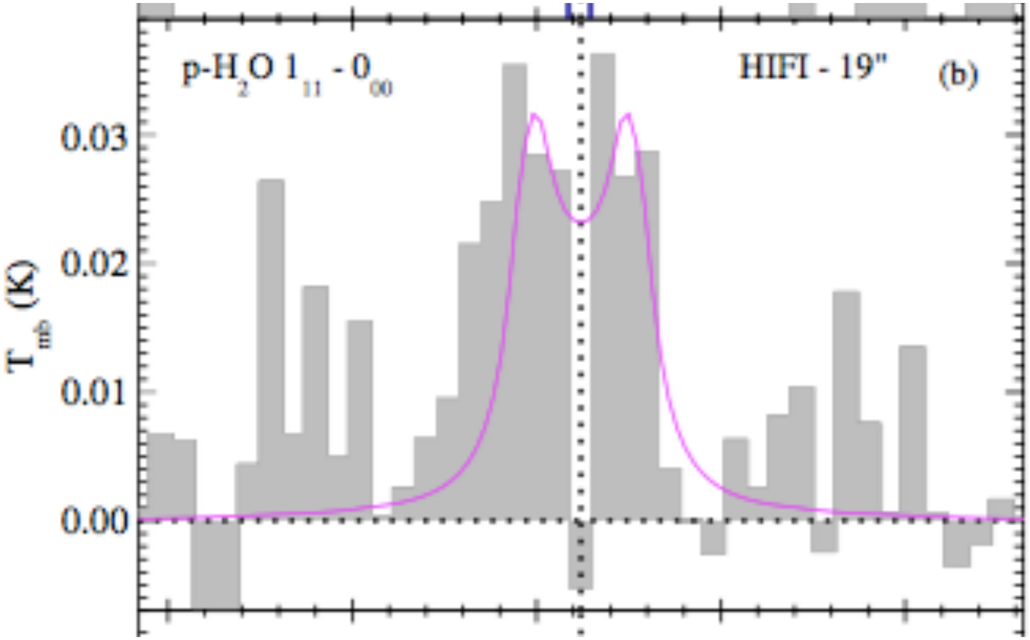
WATER IN THE **OUTER DISK** IS MOSTLY **FROZEN** ONTO THE GRAIN MANTLES

WATER IN DISKS



DG Tau HERSCHEL OBSERVATIONS Podio et al. 2013





ENOUGH TO FILL THOUSANDS OF EARTH OCEANS

WATER IN THE **OUTER DISK** IS MOSTLY **FROZEN** ONTO THE GRAIN MANTLES

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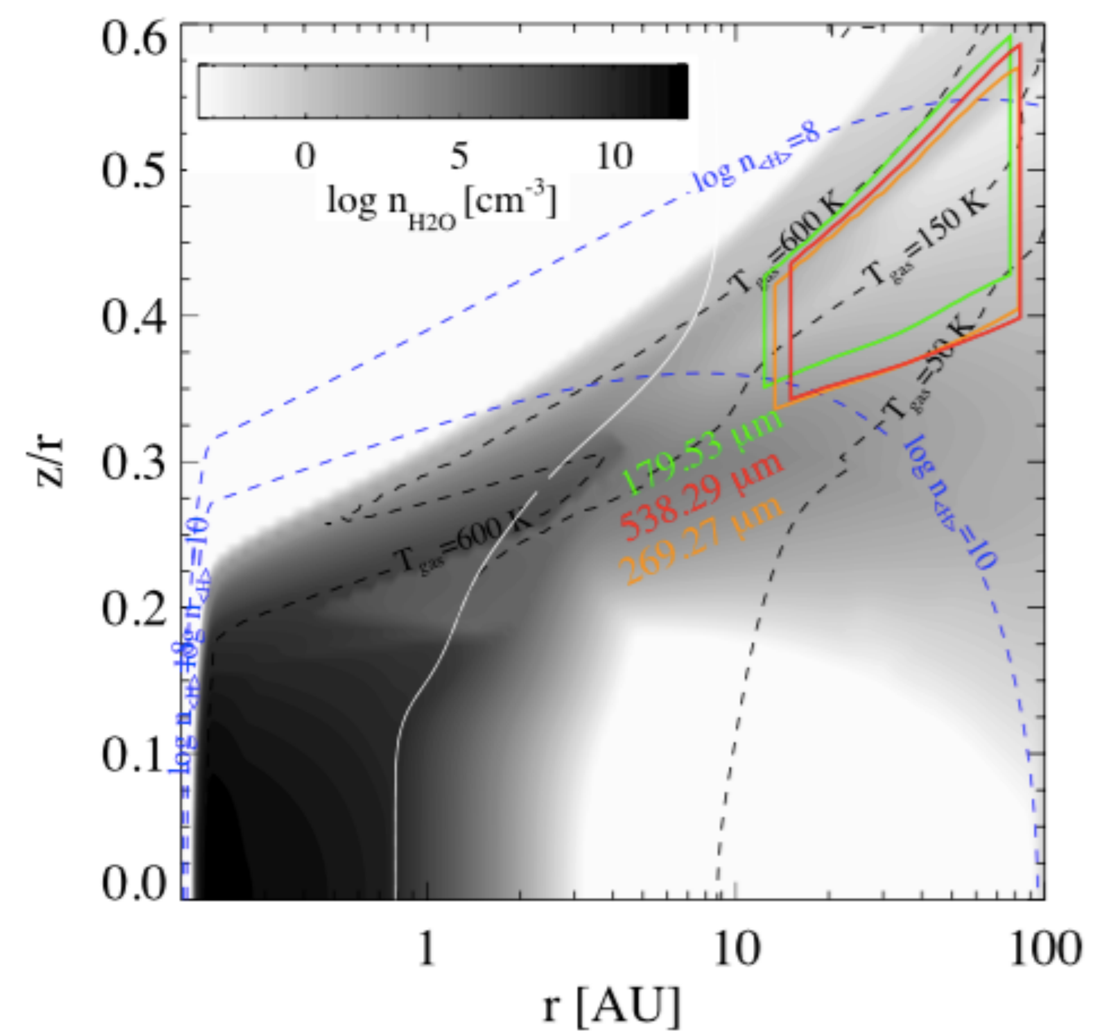
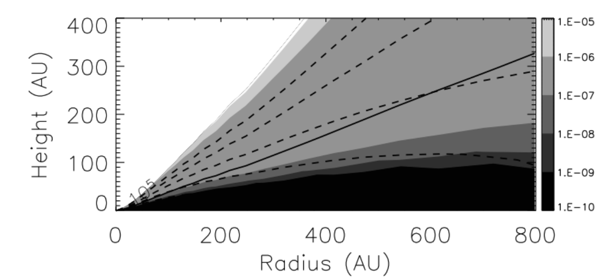
WATER IN DISKS



Podio et al. 2013

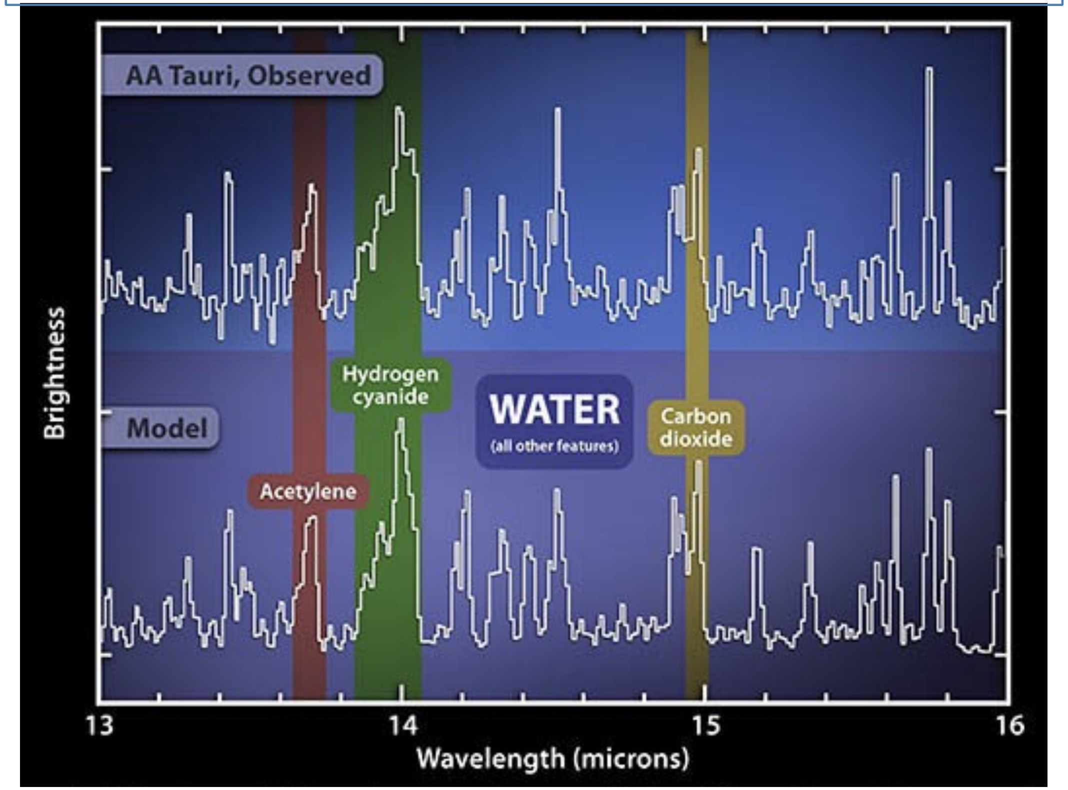


Ceccarelli & Dominik 2005

VAPOR WATER MAINLY IN A LAYER ABOVE THE MIDPLANE, UV-PHOTO-DESORBED

WATER IN DISKS

SPITZER OBSERVATIONS: Carr & Najita 2008



ENOUGH TO FILL THOUSANDS OF EARTH OCEANS

WATER IN THE INNER DISK IS GASEOUS

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ORGANICS IN DISKS

3.Blooming & conserving

3.5 Disks

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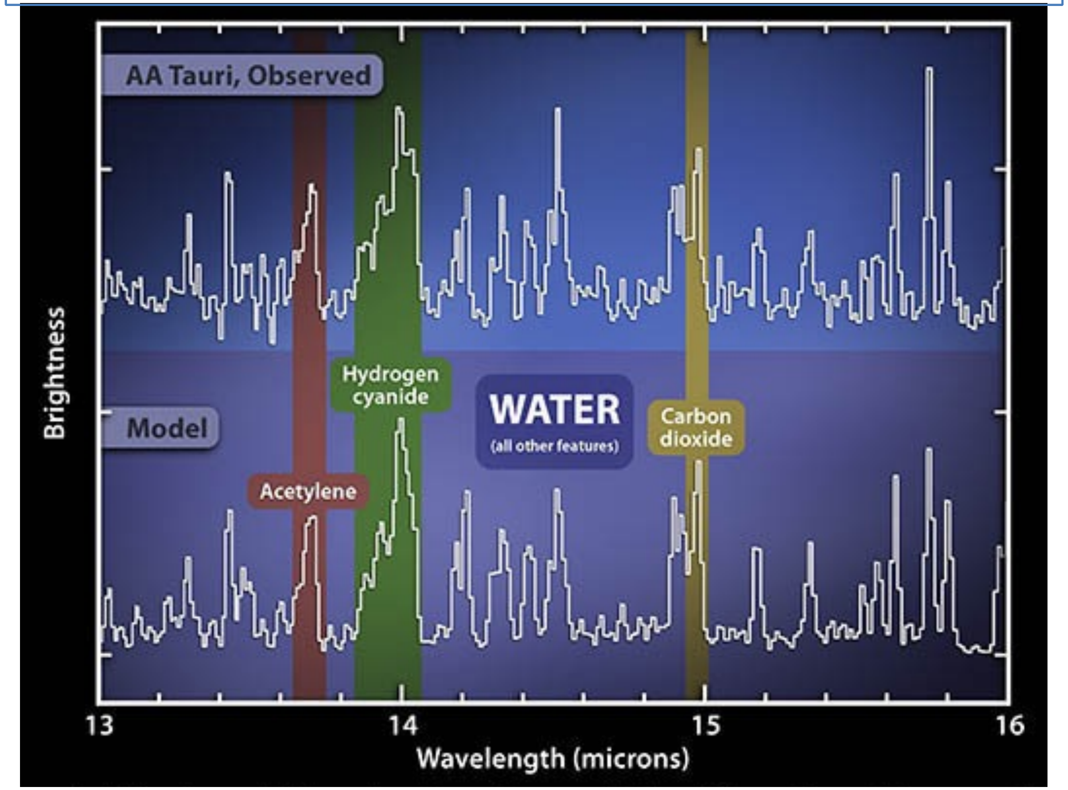
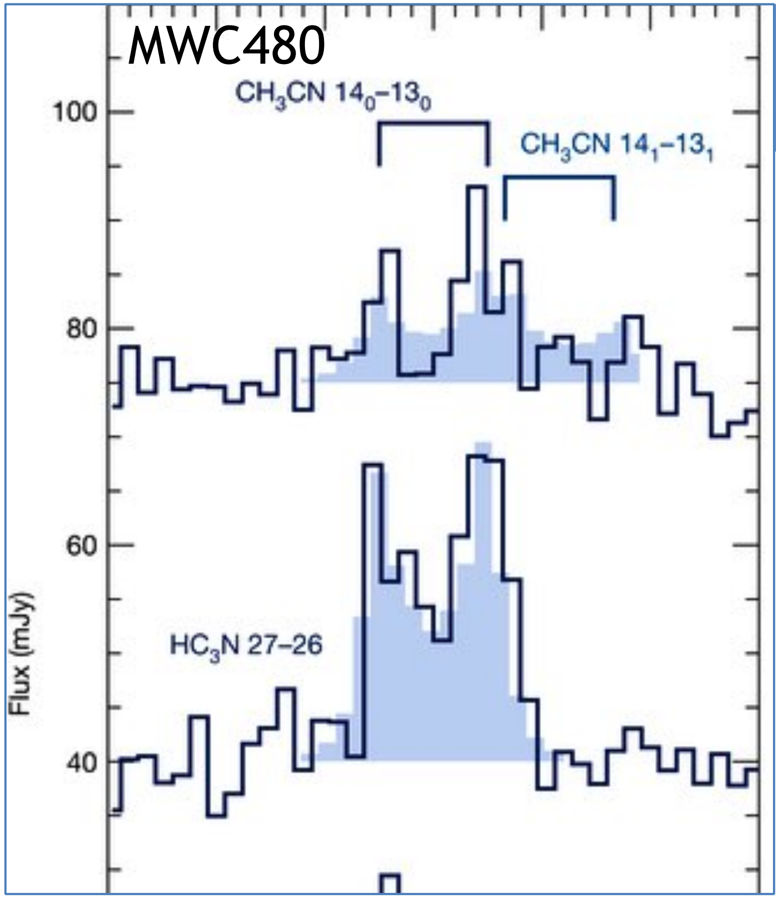
SPITZER OBSERVATIONS: Carr & Najita 2008



A LARGE FRACTION OF CARBON, >10%, IN SMALL ORGANIC MOLECULES

GASEOUS ORGANICS IN THE INNER DISK

ORGANICS IN DISKS



ALMA OBSERVATIONS:
Oberg et al. 2015

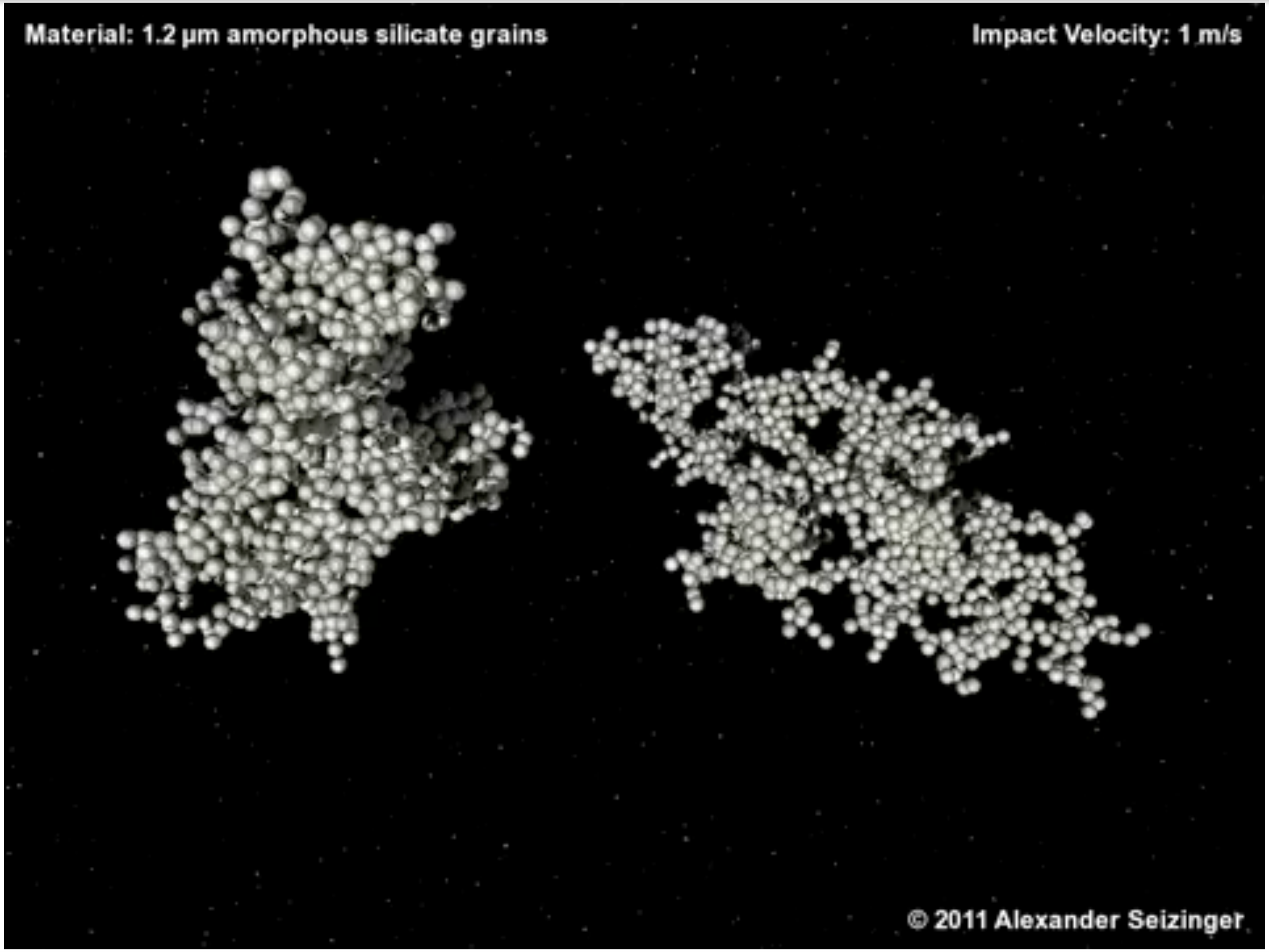
MODEL PREDICTS A KEY ROLE OF THE ICE UV-PHOTO-DESORPTION

FIRST DETECTION BY ALMA

GASEOUS METHYL CYANIDE (CH_3CN) IN THE **OUTER DISK** FROZEN MOLECULES

C.Ceccarelli

DUST COAGULATION



Courtesy C.Dominik

DURING THE PHASE OF GRAIN COAGULATION AND GROWTH SOME OF THE MOLECULES FROZEN ON THE GRAIN MANTLES WILL BE TRAPPED INSIDE: **CONSERVATION PROCESS STARTS**

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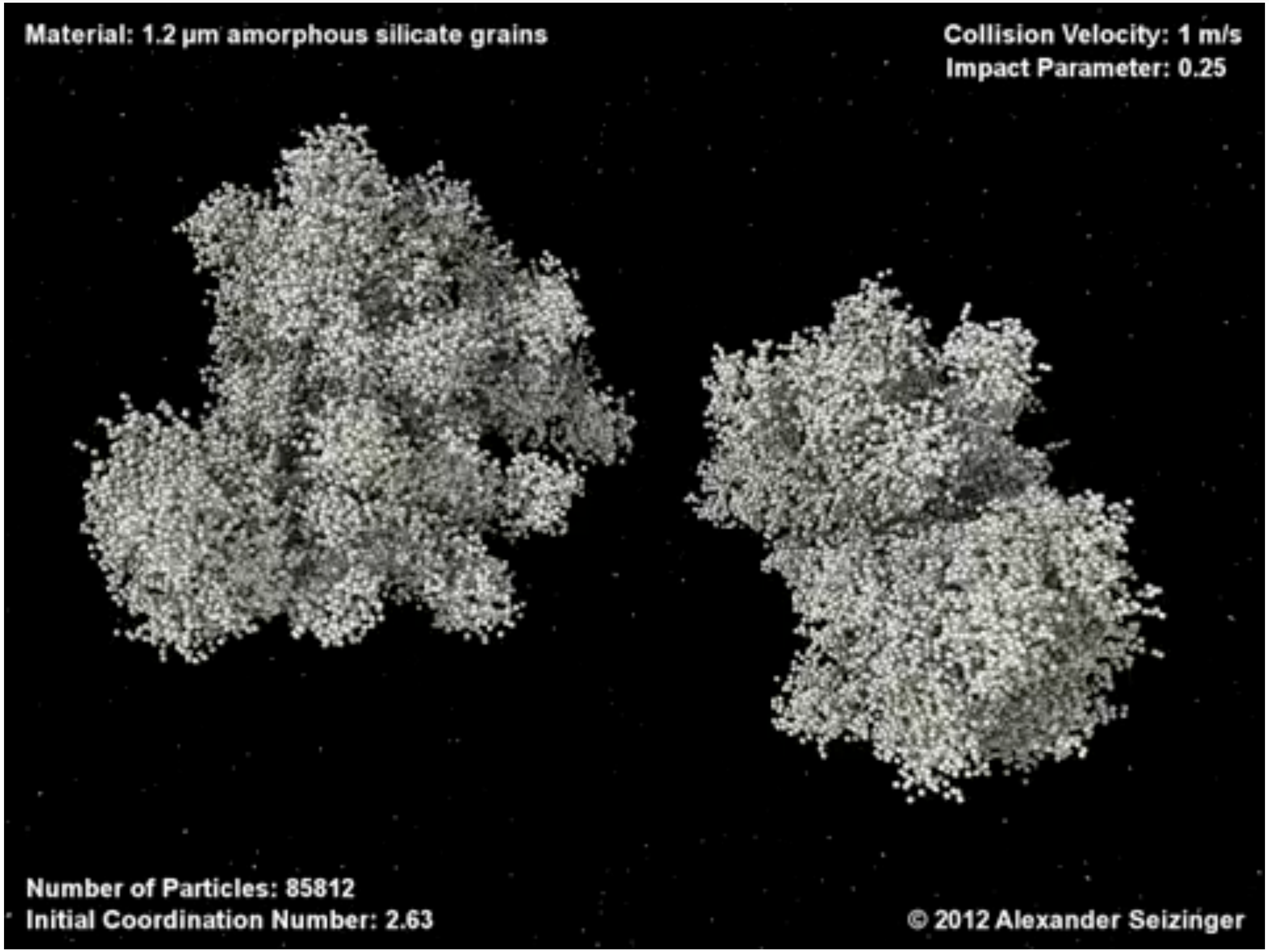
DUST COAGULATION



Courtesy C.Dominik

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