The chemical heritage of protoplanetary disks

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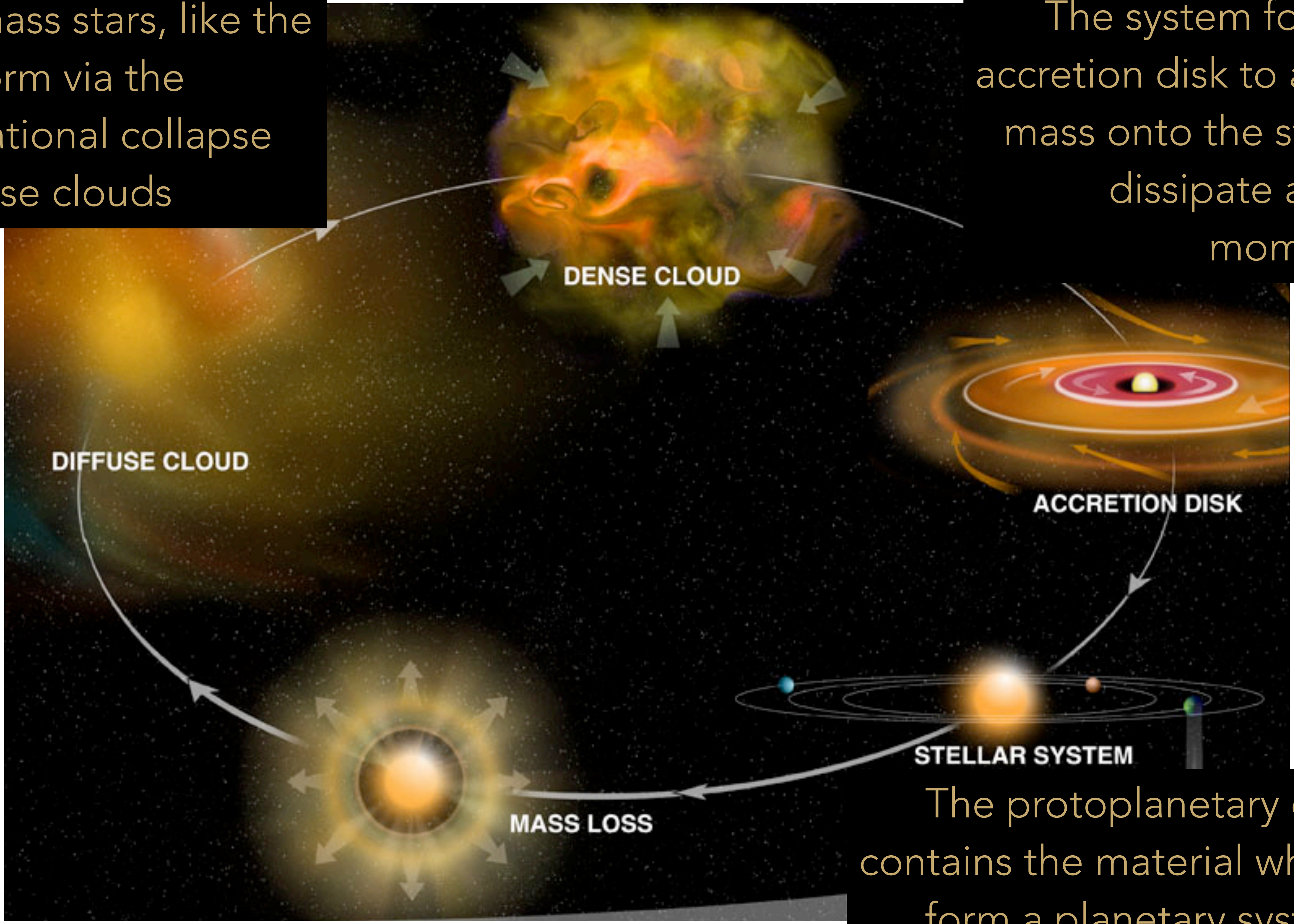
*From September 2016, Leeds University, UK

Life cycle of stars and planets

Low-mass stars, like the sun, form via the gravitational collapse of dense clouds

The system forms an accretion disk to accrete mass onto the star and dissipate angular momentum



The protoplanetary disk contains the material which will form a planetary system

Credit:Bill Saxton/NRAO

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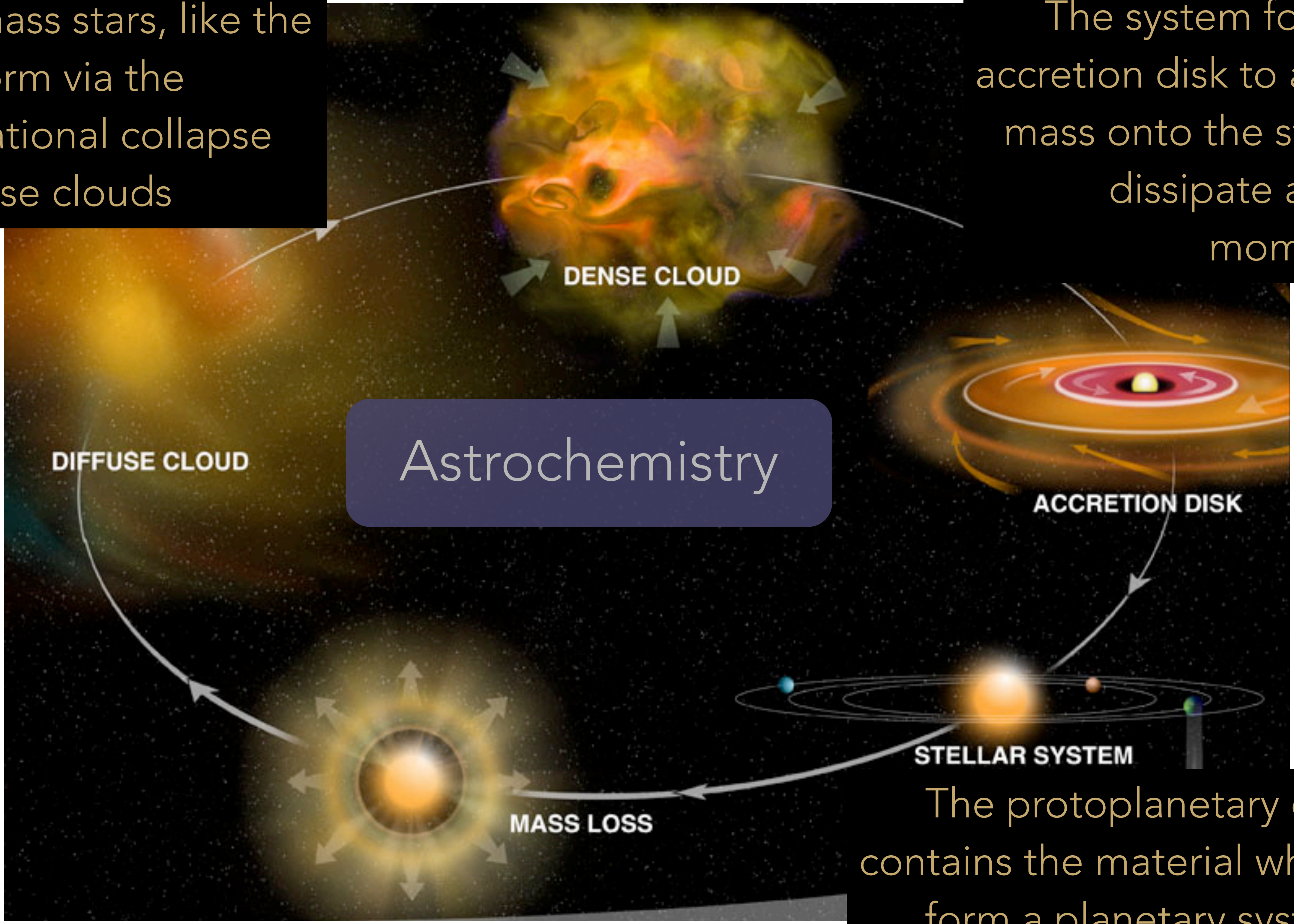
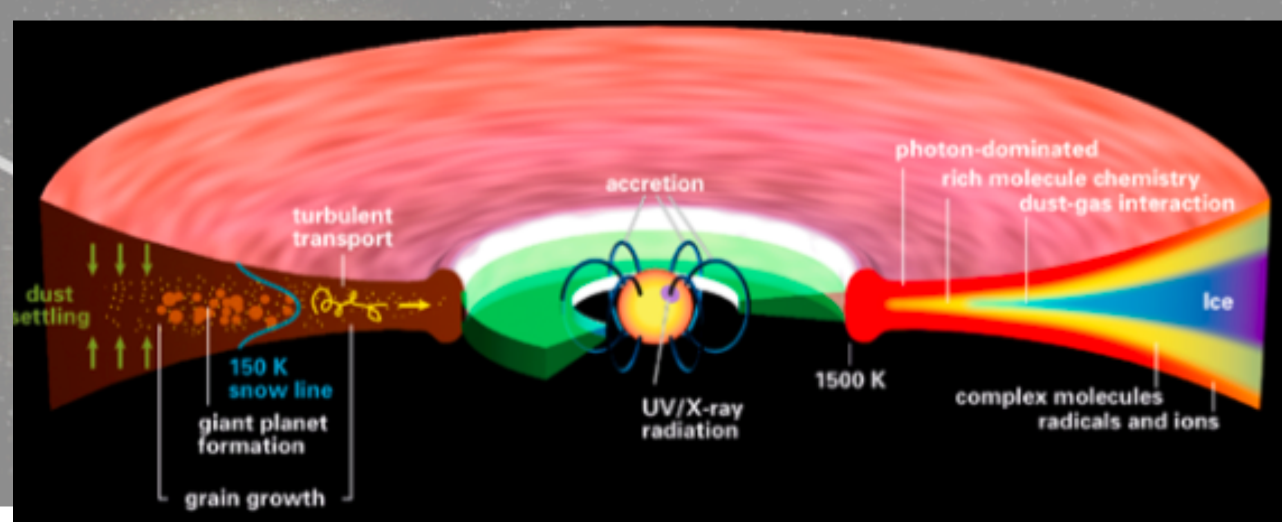


The protoplanetary disk contains the material which will form a planetary system

Credit:Bill Saxton/NRAO

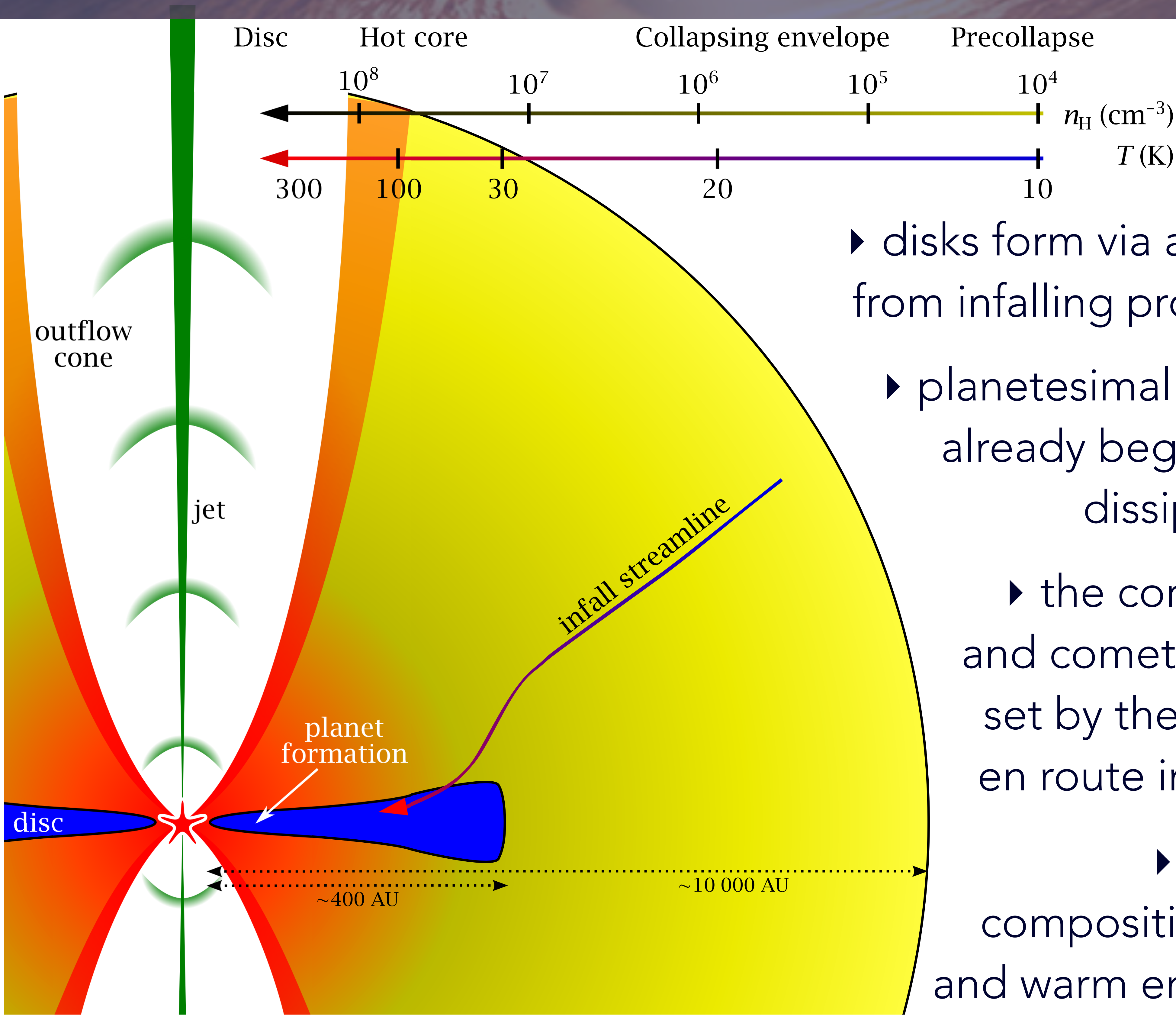
Why study protoplanetary disks?

Initial conditions of solar system formation?
How do planets form?
Is our solar system unique?
Origin of the architecture of exoplanetary systems?
Origin of complexity in solar systems?
Our origins?



Bill Saxton/NRAO; Henning, Th. & Semenov, D. 2013, Chem. Rev., 113, 9016

Formation of a protoplanetary disk

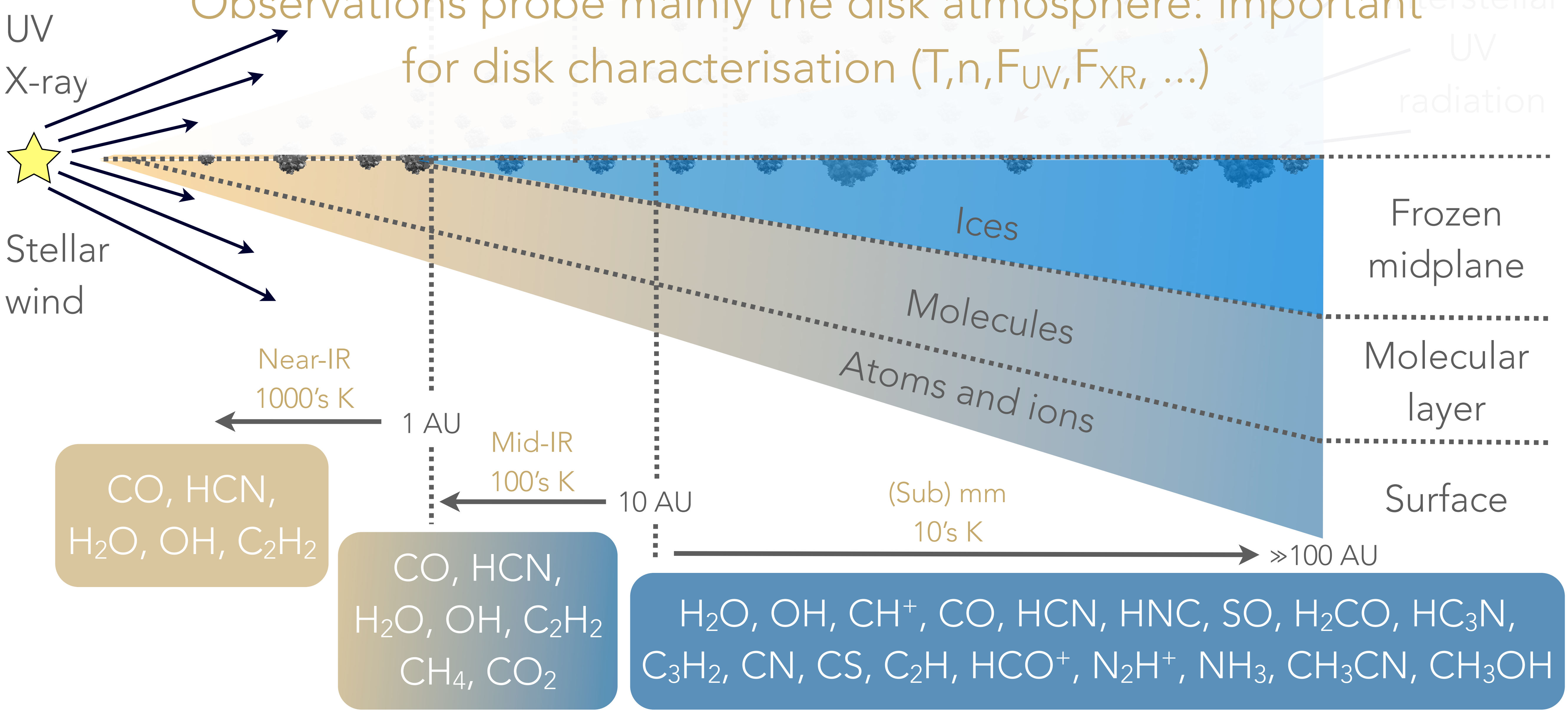


- disks form via accretion of material from infalling protostellar envelopes
- planetesimal formation has likely already begun before envelope dissipation (e.g., HL Tau)
- the composition of planet- and comet-building material is set by the physical conditions en route into the forming disk
- overlap in chemical composition between comets and warm environs of protostars

Anatomy of a protoplanetary disk

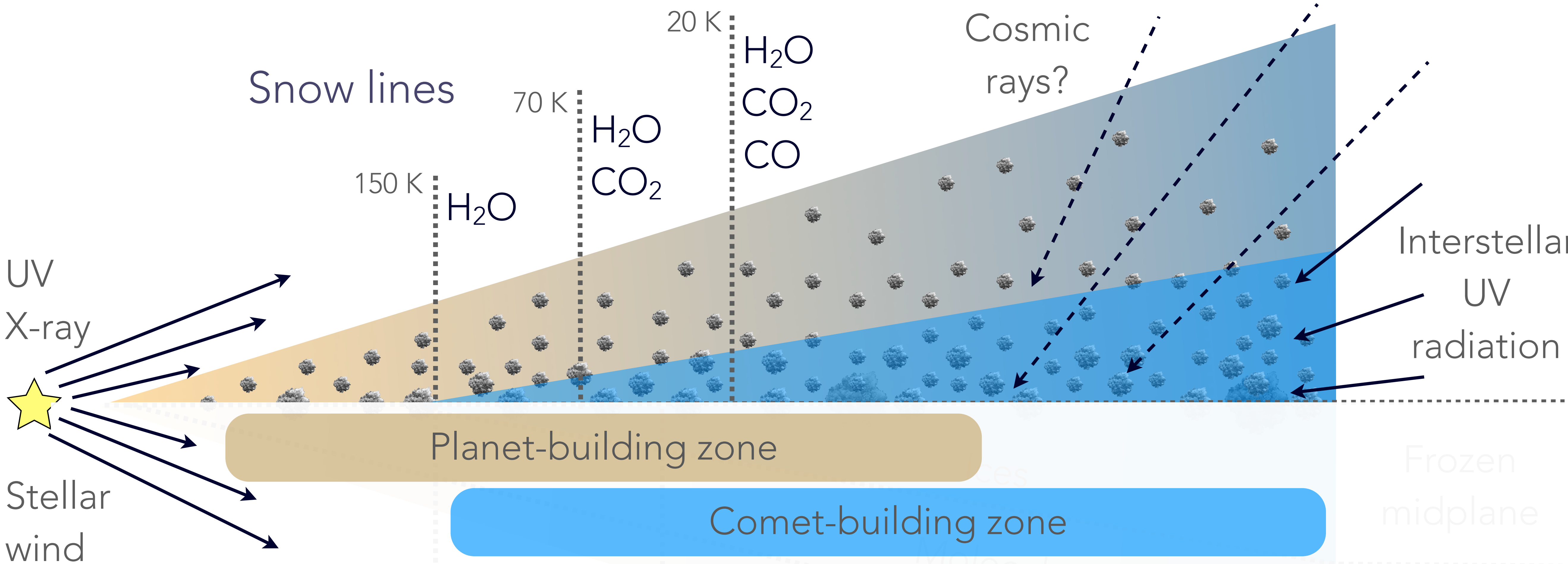
Two phases of molecules/volatiles in protoplanetary disks: gas (H_2 dominated) and ice (H_2O dominated)

Observations probe mainly the disk atmosphere: important for disk characterisation (T,n,F_{UV},F_{XR}, ...)



Pontoppidan+, Gibb+, Salyk+, van Dishoeck+, Dutrey+, Chapillon+, Qi+, Oberg+, Kastner+, Thi+, Carr+, Najita+, Hogerheijde+, Fedele+, Meeus+

Anatomy of a protoplanetary disk

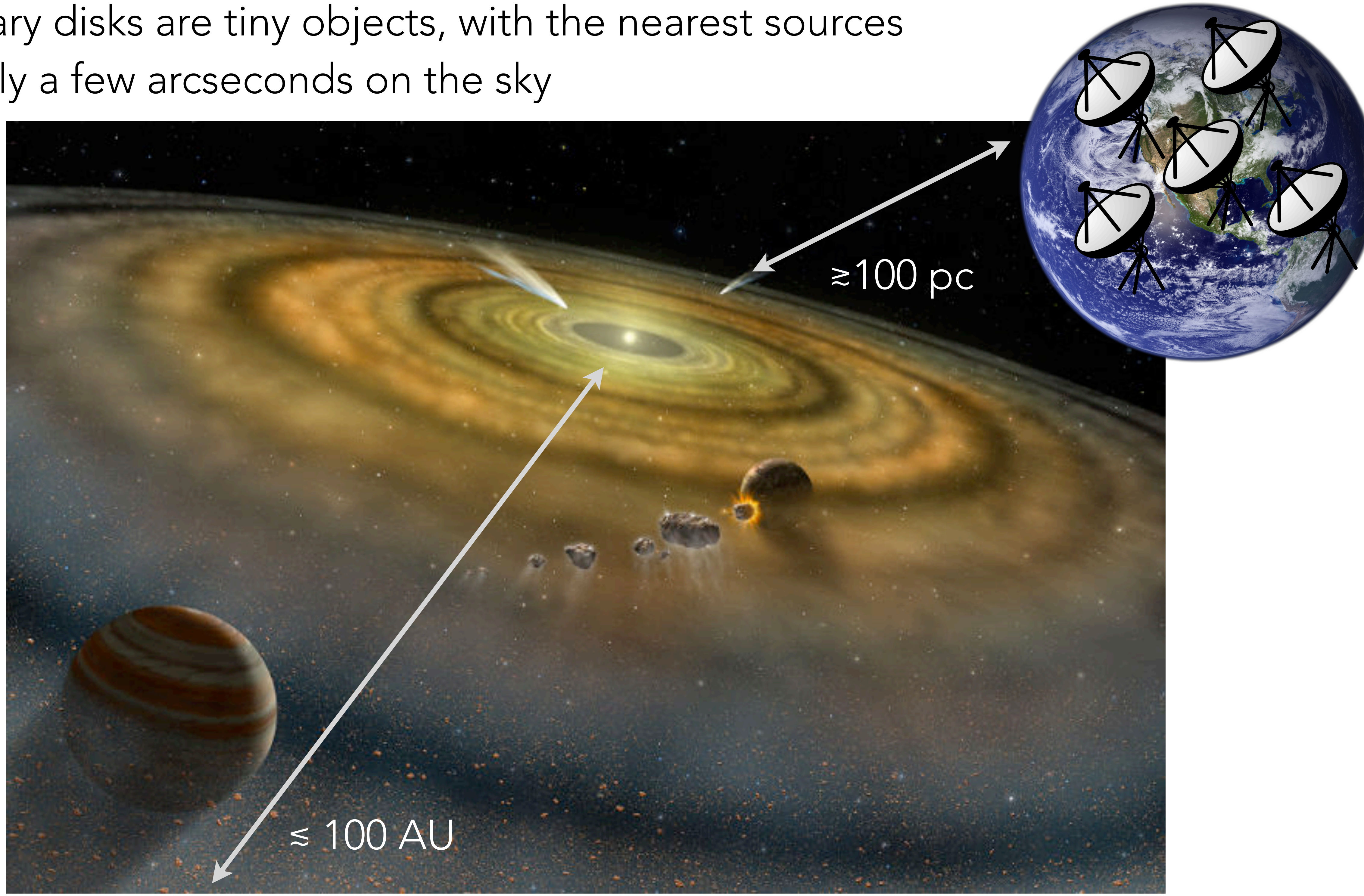


Disk midplane composition will determine the ingredients for planetesimals and comets

The relative ratios of dominant volatiles will dictate the resulting compositions of planetary atmospheres

Protoplanetary disks in the ALMA era

Protoplanetary disks are tiny objects, with the nearest sources spanning only a few arcseconds on the sky



Outer, cold regions of protoplanetary disks emit at long (~ mm) wavelengths

The Atacama Large Millimeter/Submillimeter Array

- probes the cold universe
- the ultimate astrochemical tool
- dust and molecules from 90 to 900 GHz
- 66 antennas
- baselines up to 16km
- sub-milliarcsecond resolution at highest frequencies

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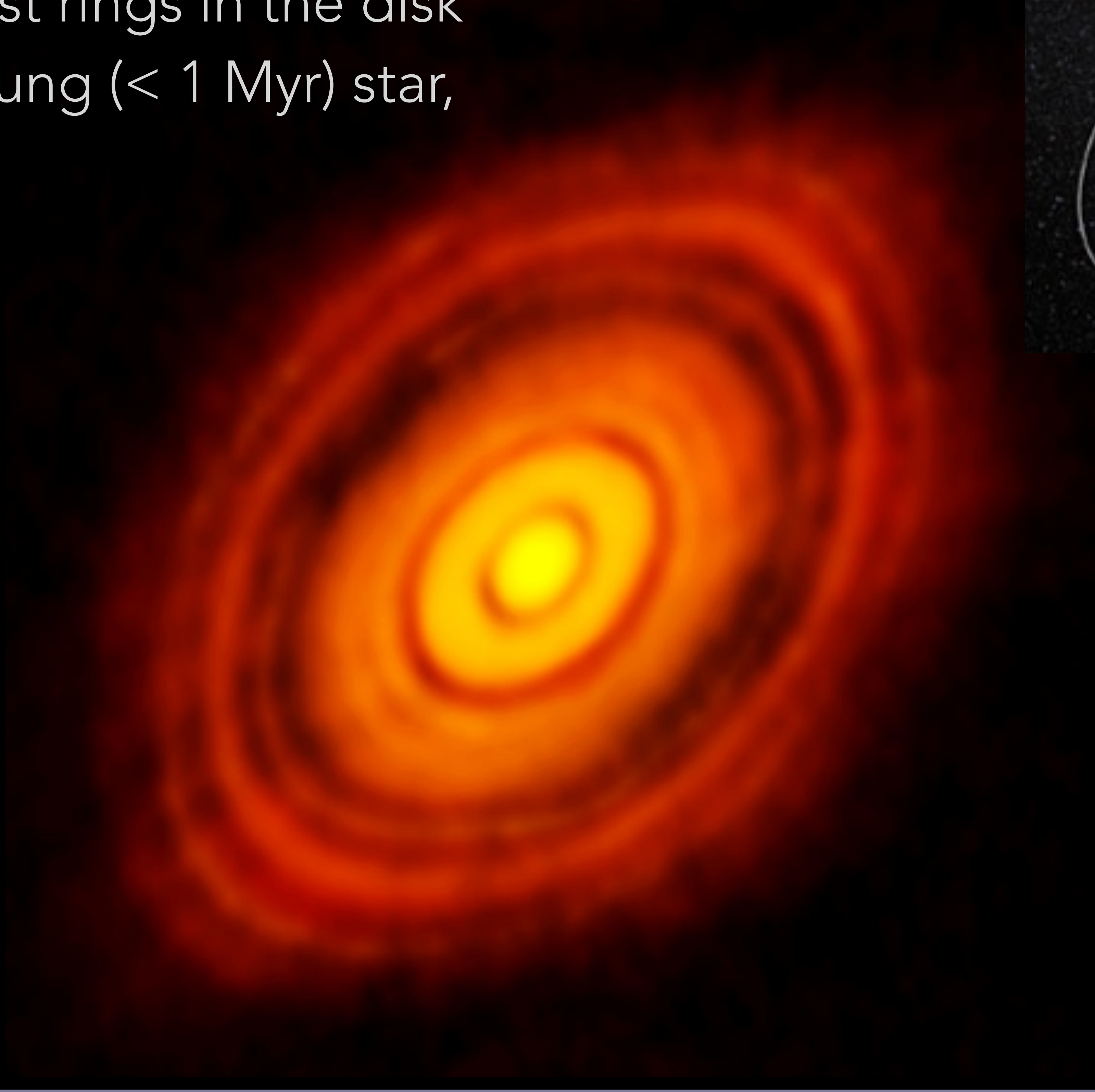
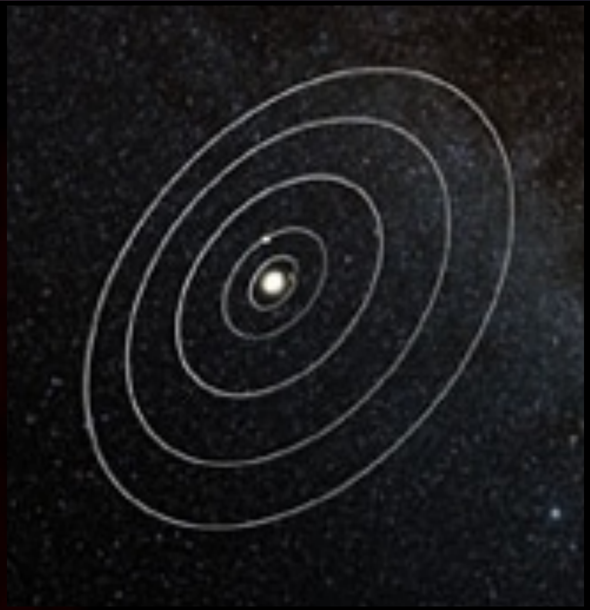
ALMA is the perfect tool for probing the planet- and comet-building reservoir in protoplanetary disks

Protoplanetary disks in the ALMA era

Concentric dust rings in the disk around the young (< 1 Myr) star, HL Tau





ALMA Partnership 2015; Zhang et al. 2015; Dipierro et al. 2015; Loren-Aguilar et al. 2015; Okuzumi et al. 2015; Jin et al. 2016

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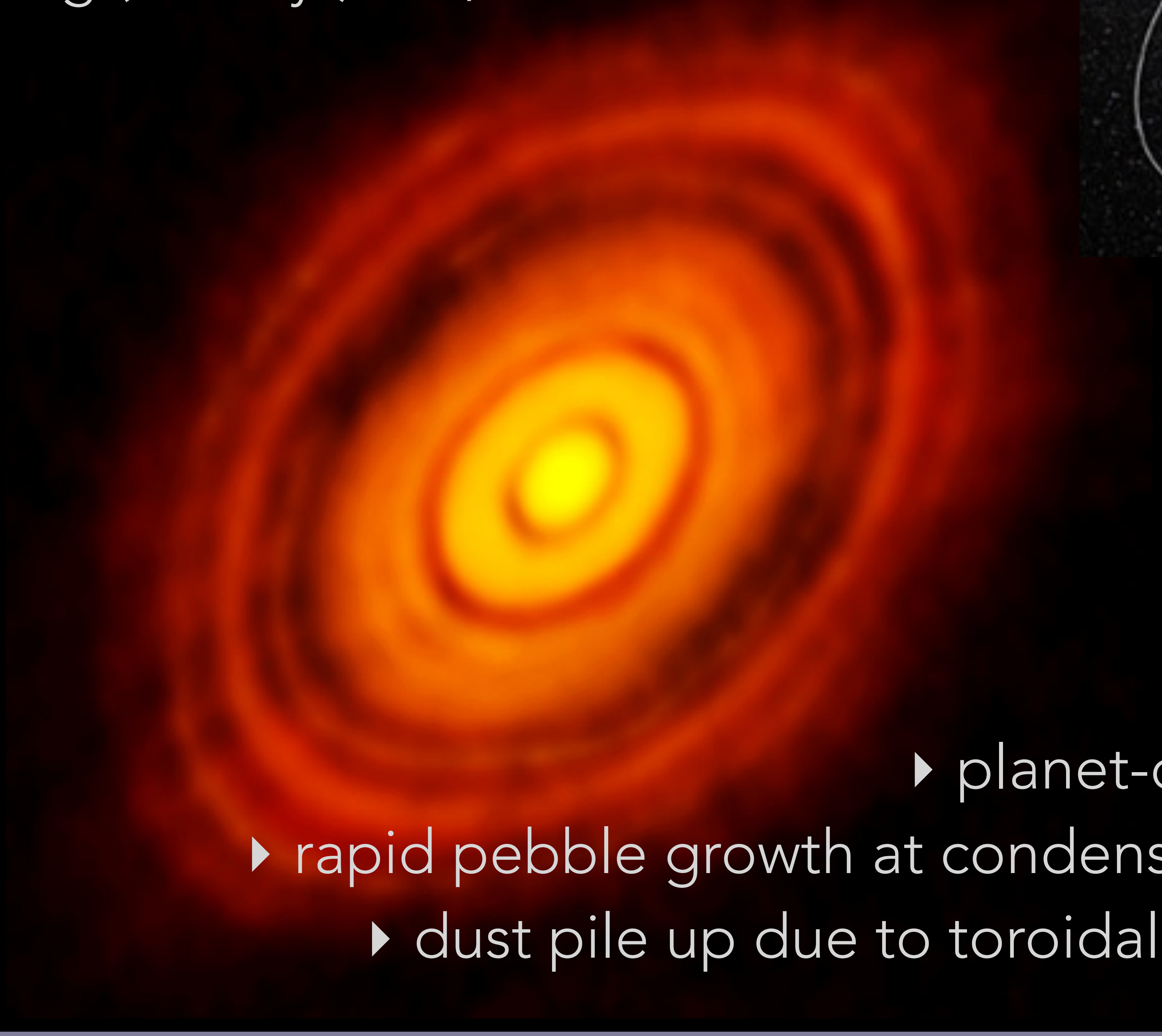
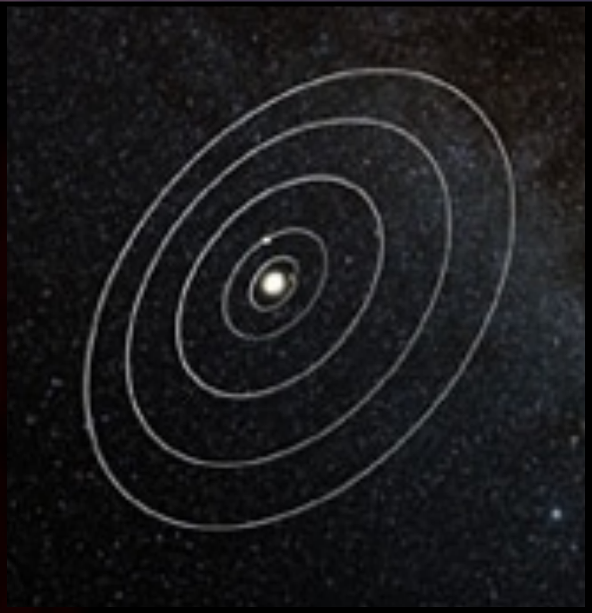
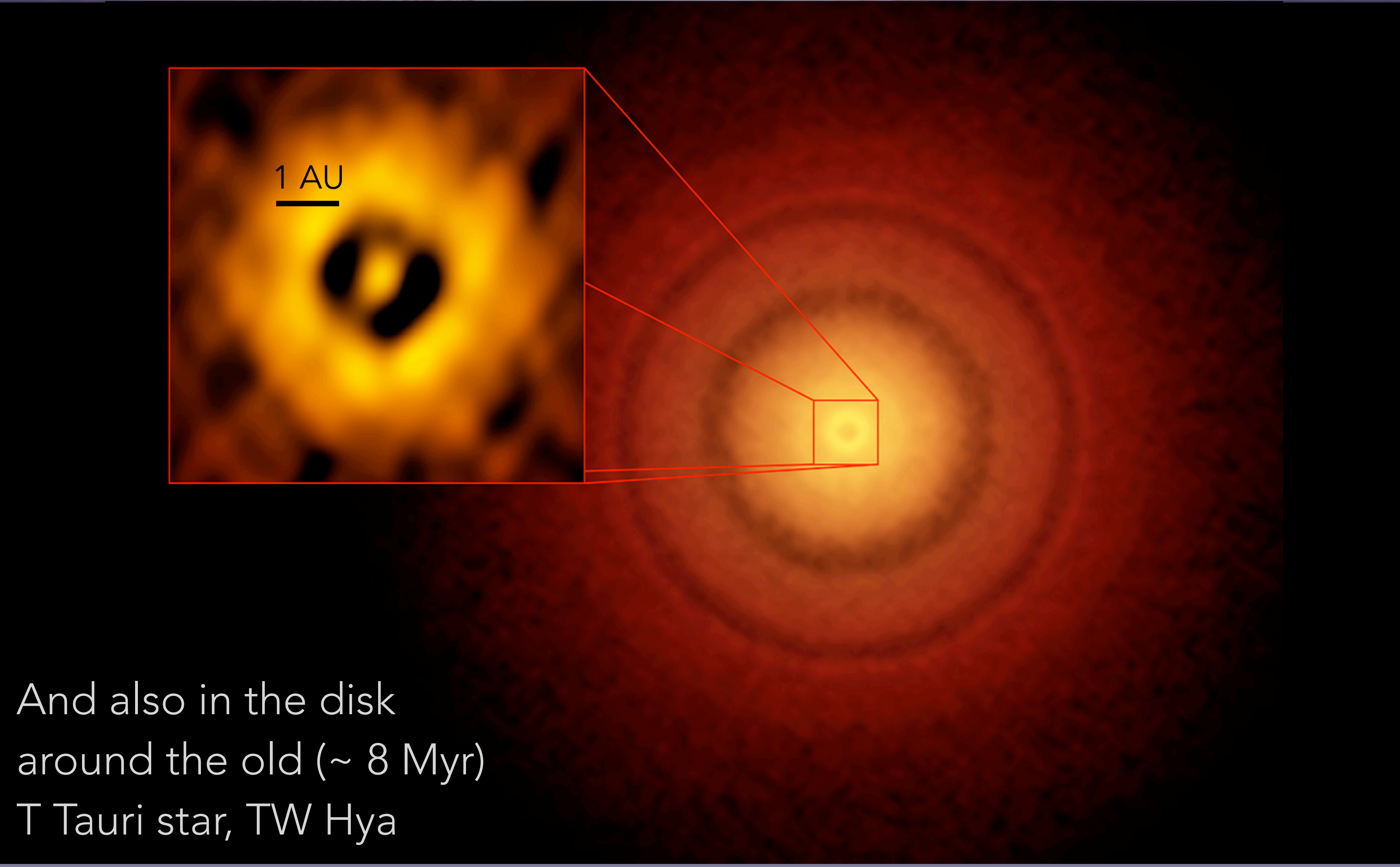




- planet-carved gaps?
- rapid pebble growth at condensation fronts?
- dust pile up due to toroidal instabilities?

ALMA Partnership 2015; Zhang et al. 2015; Dipierro et al. 2015; Loren-Aguilar et al. 2015; Okuzumi et al. 2015; Jin et al. 2016

Protoplanetary disks in the ALMA era

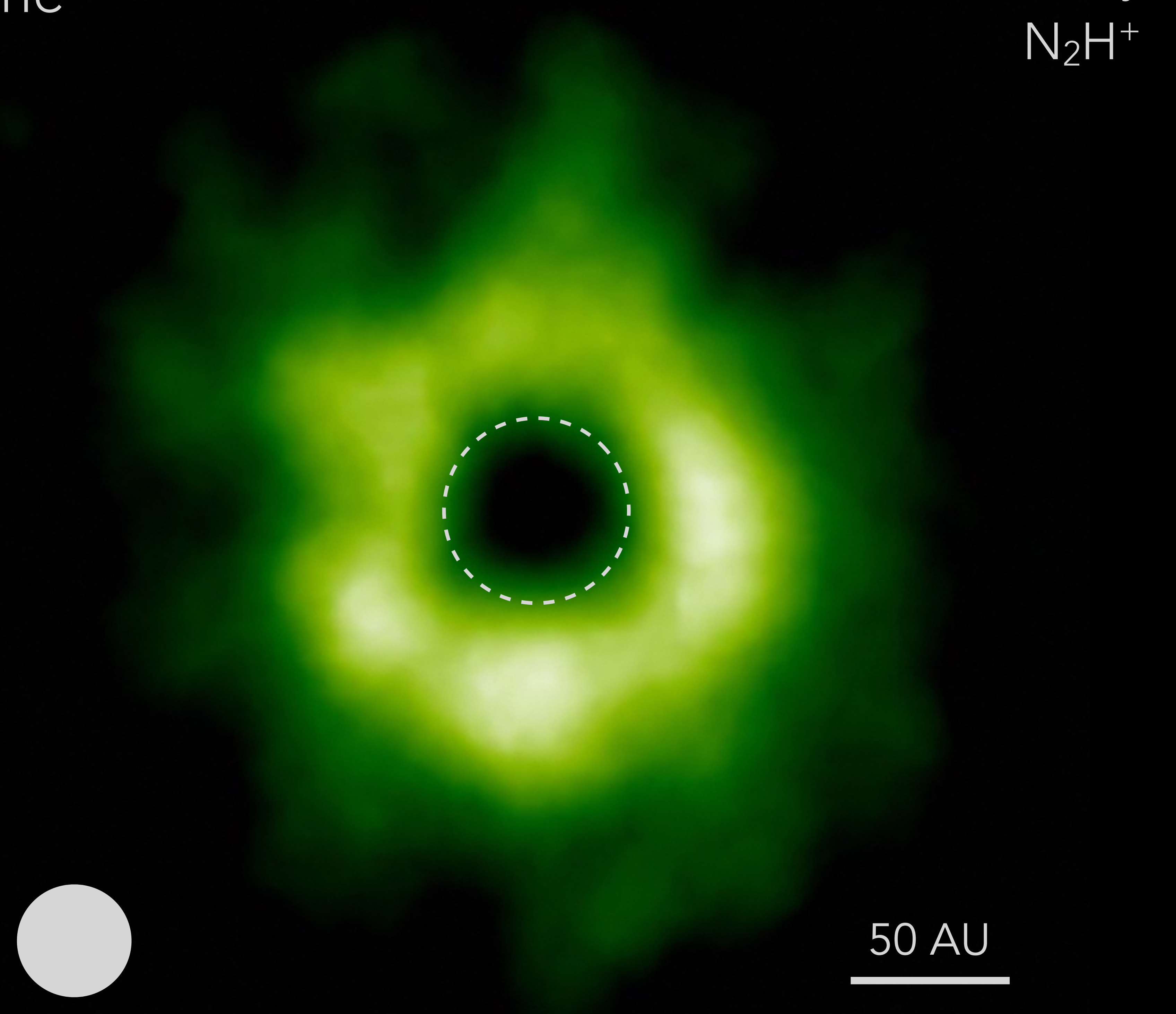


And also in the disk around the old (~ 8 Myr) T Tauri star, TW Hya

Andrews, S. M., et al, 2016, ApJ, 820, L40

Protoplanetary disks in the ALMA era

Molecular rings tracing the CO snow line



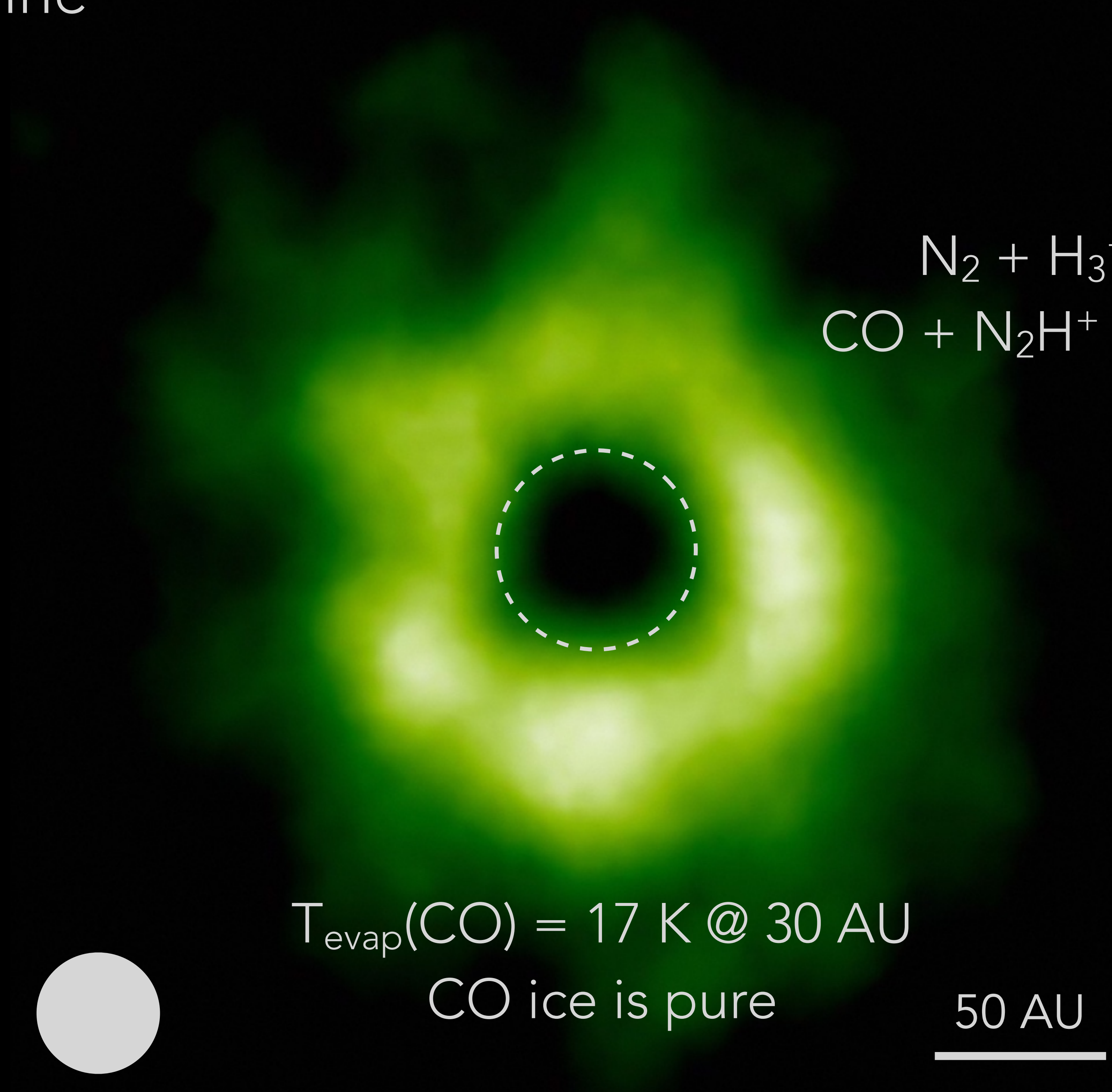
Qi, C., et al. 2013, Science, 341, 630; van 't Hoff, M., et al. 2016, A&A, in preparation

Protoplanetary disks in the ALMA era

Molecular rings tracing
the CO snow line

TW Hya
N_2H^+

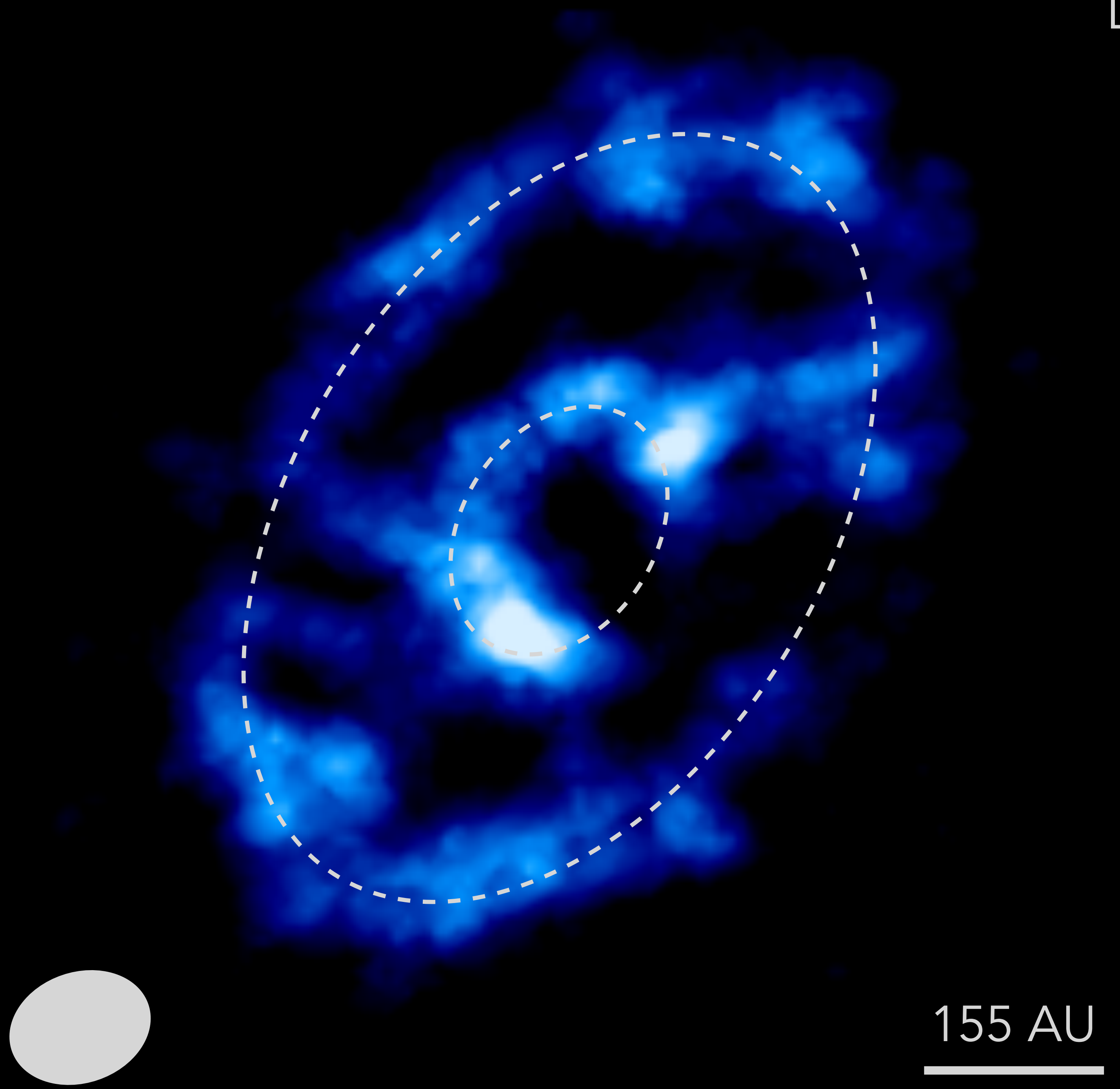
$N_2 + H_3^+ \rightarrow N_2H^+ + H_2$
$CO + N_2H^+ \rightarrow HCO^+ + N_2$



$T_{evap}(CO)$ = 17 K @ 30 AU
CO ice is pure

Protoplanetary disks in the ALMA era

Tracing multiple CO snow lines

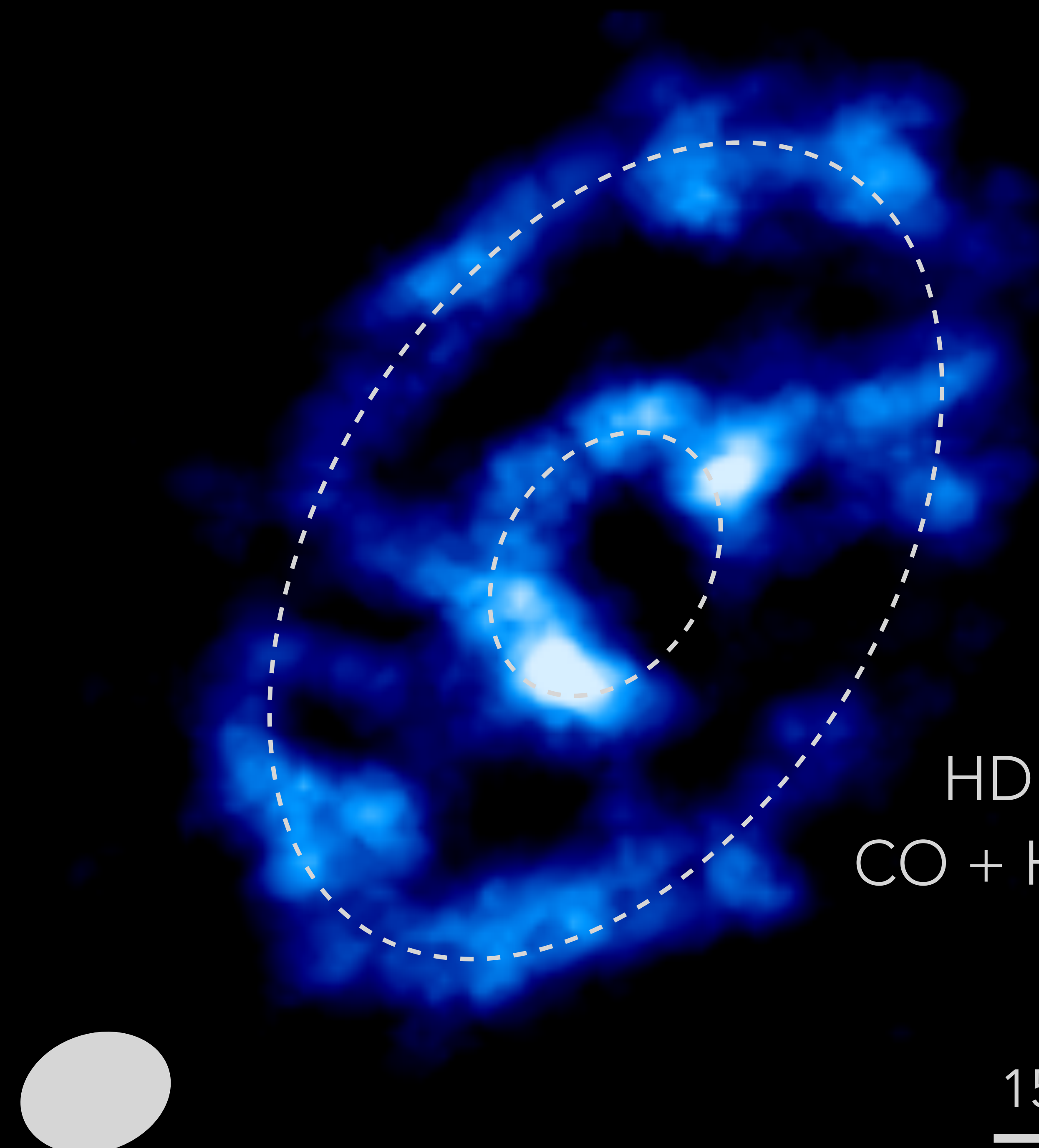


Öberg, K. I., et al. 2015, ApJ, 810, 112

Protoplanetary disks in the ALMA era

Tracing multiple CO snow lines

IM Lup
DCO^+



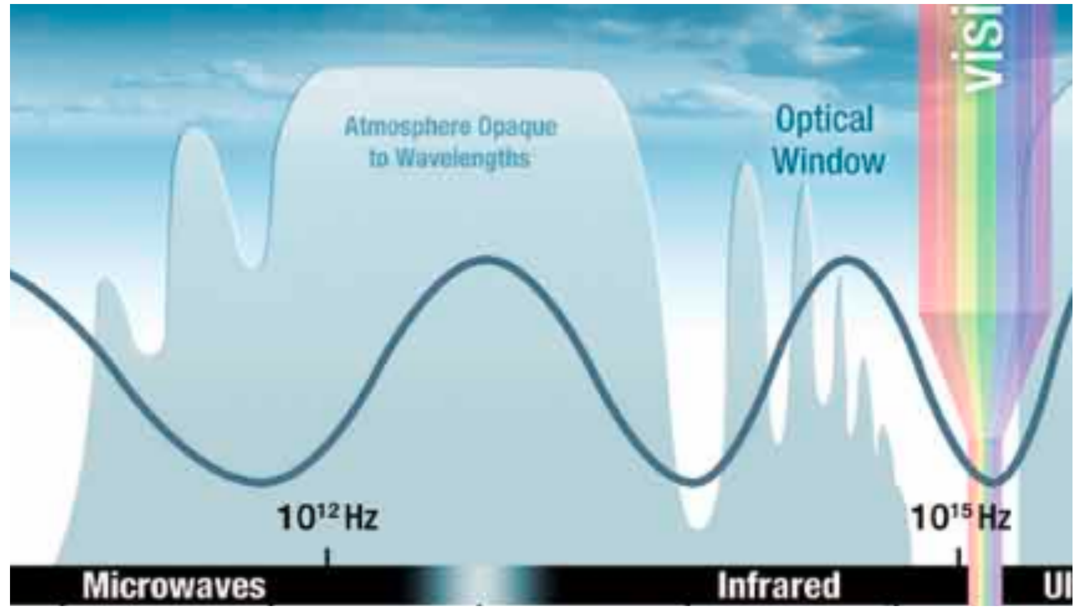
$HD + H_3^+ \rightarrow H_2D^+ + H_2$

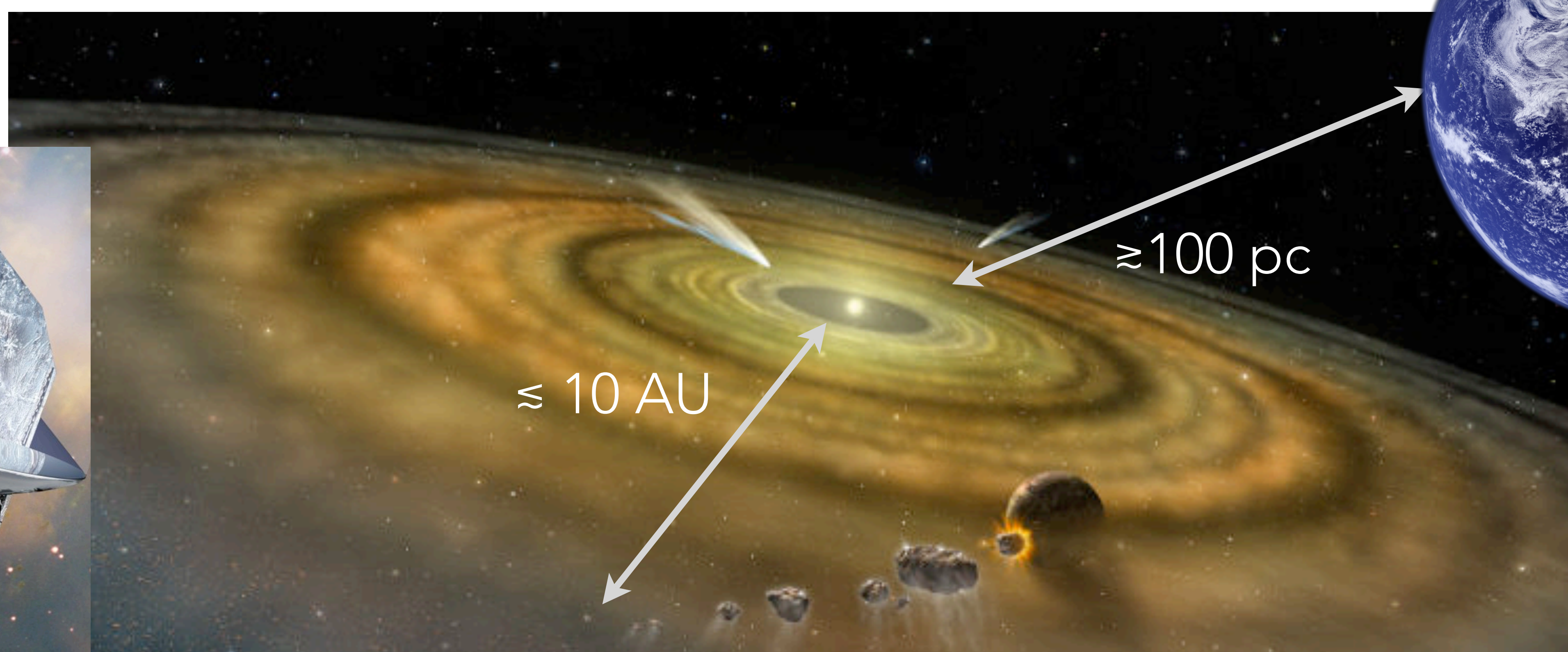
$CO + H_2D^+ \rightarrow DCO^+ + N_2$

155 AU

Öberg, K. I., et al. 2015, ApJ, 810, 112

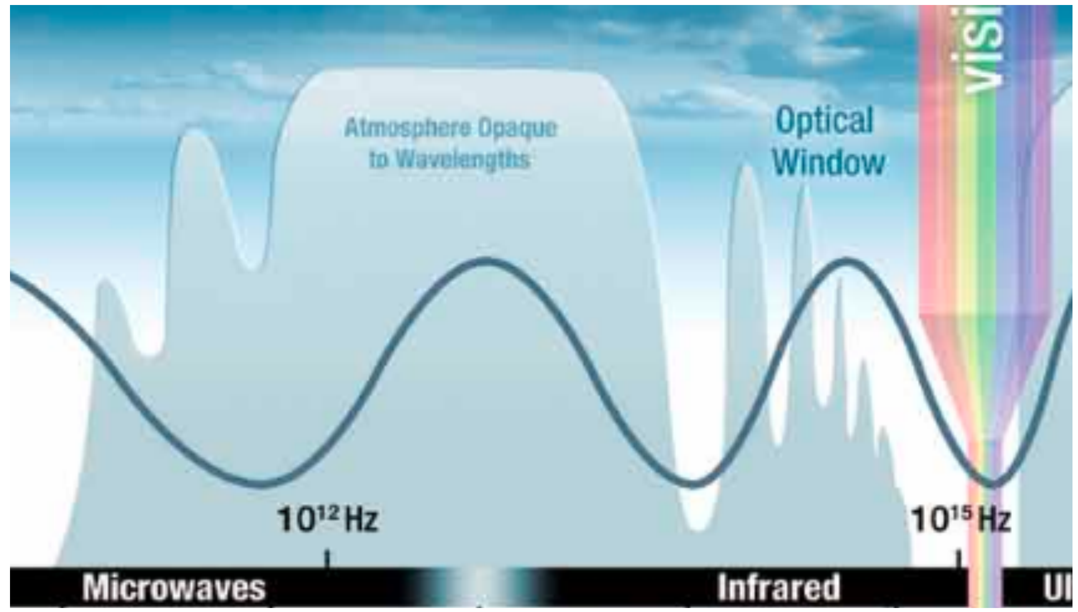
Simple volatiles in protoplanetary disks

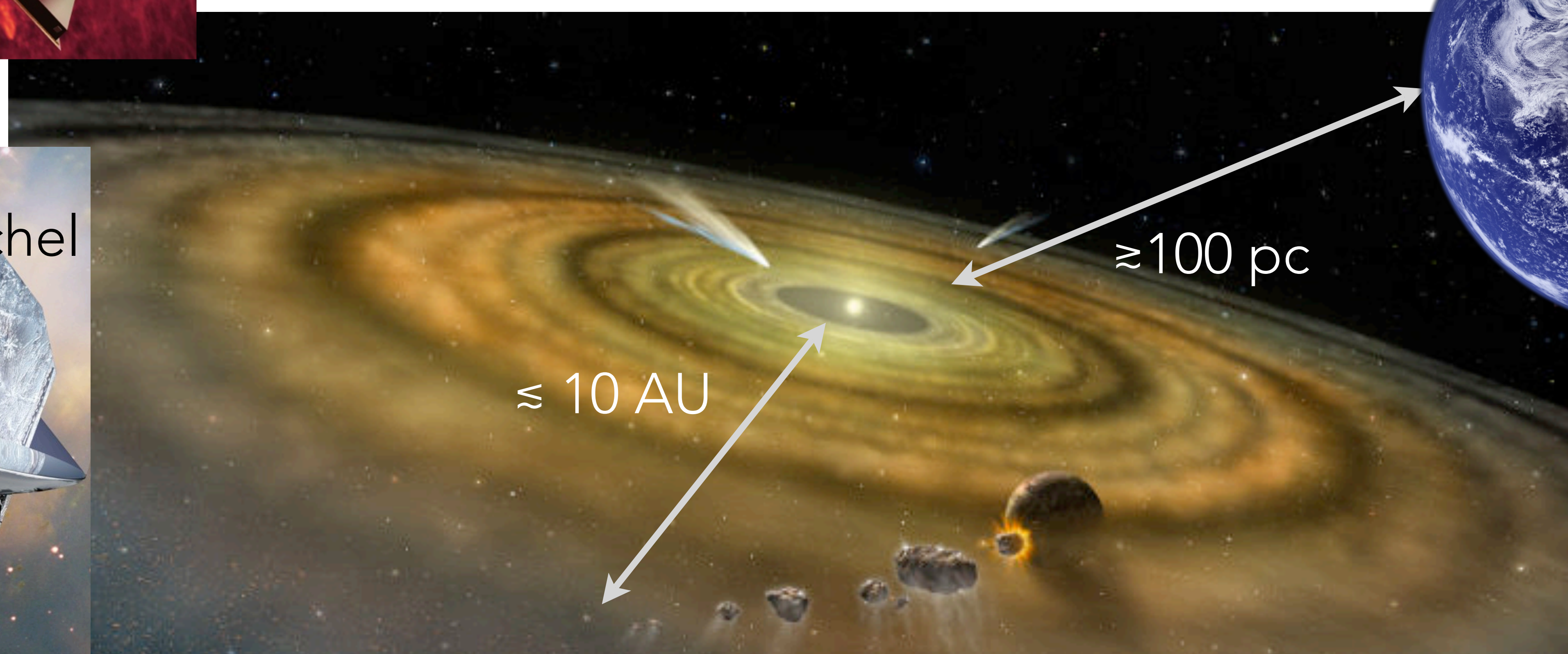




Inner, warm regions of protoplanetary disks emit
at infrared (~ a few - 100's μm) wavelengths

Simple volatiles in protoplanetary disks



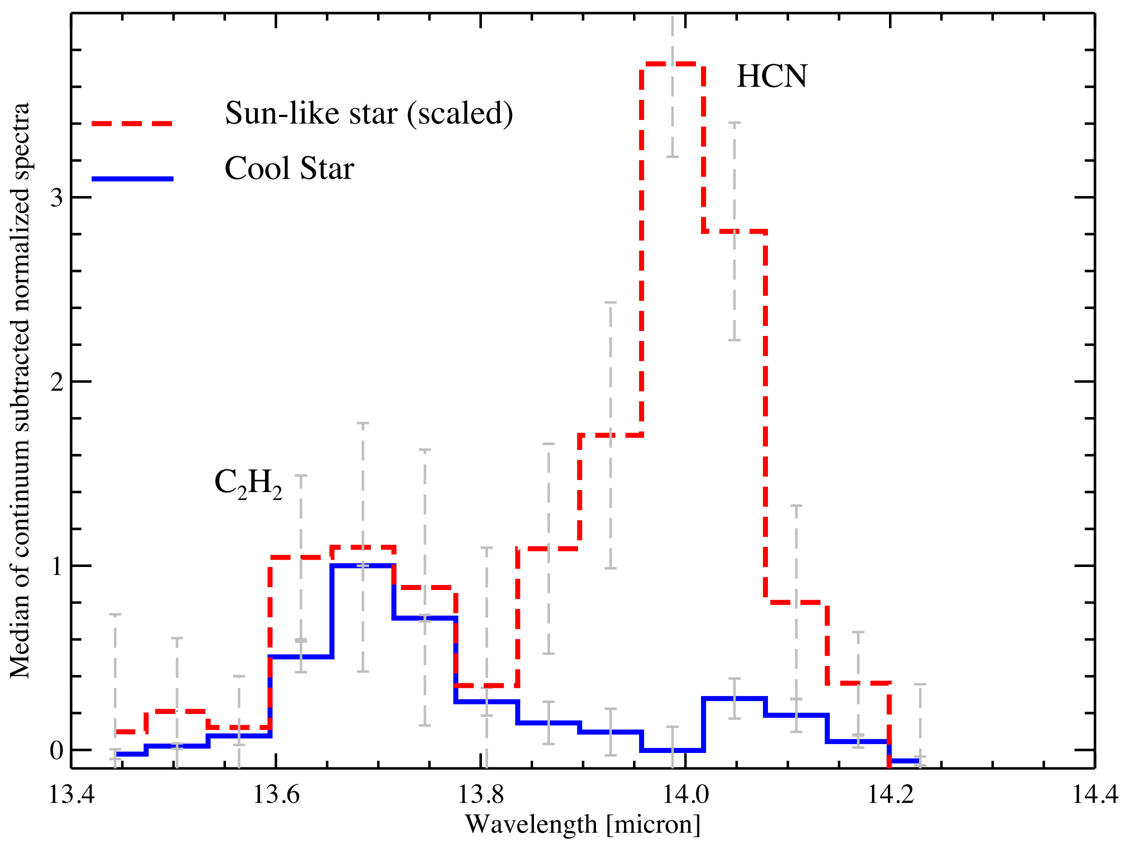


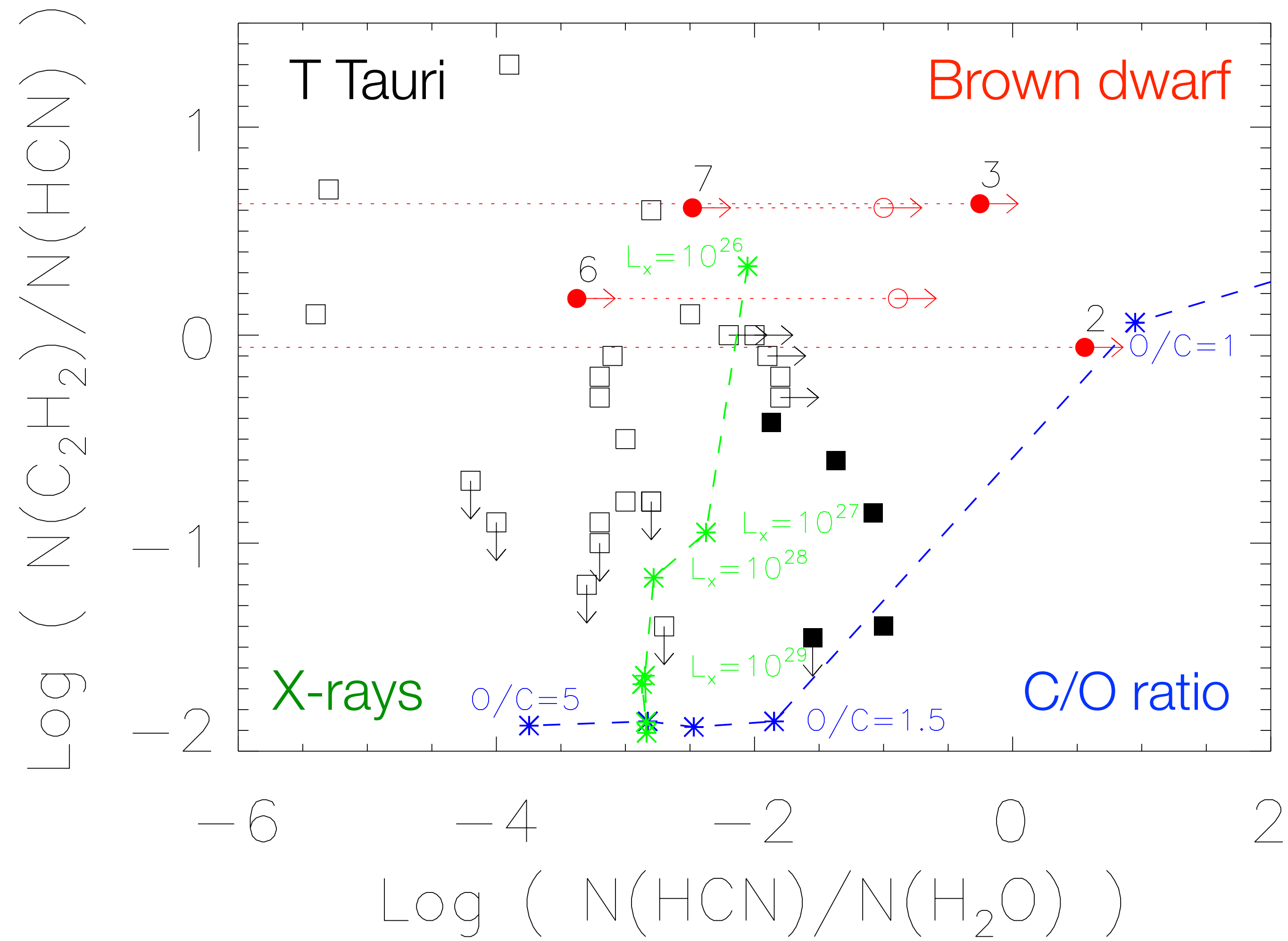
Inner, warm regions of protoplanetary disks emit
at infrared (~ a few - 100's μm) wavelengths

Zooming into the planet-forming region

The resulting composition of the atmospheres of forming planets will depend upon the relative accretion rates of dominant ice/gas components in the disk:

H_2O, CO, CO_2, CH_4, N_2, NH_3, … , CH_3OH, HCN, O_2, C_2H_2, …

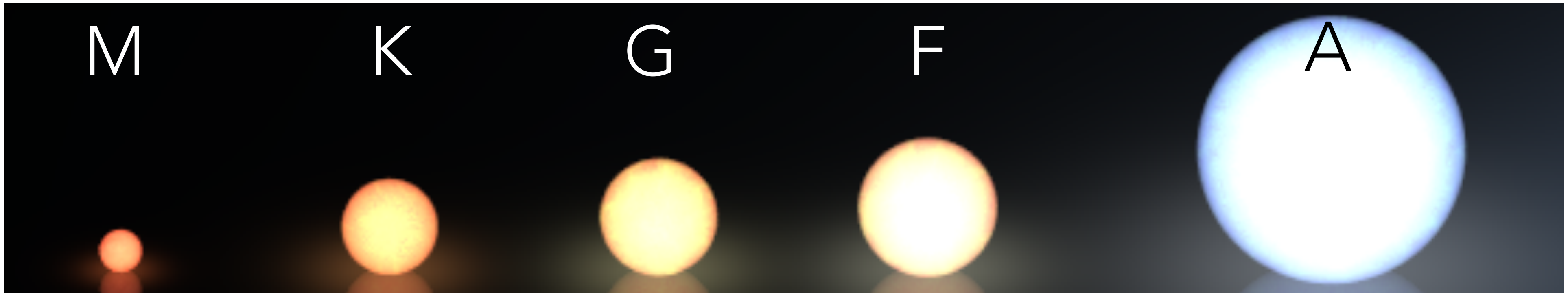




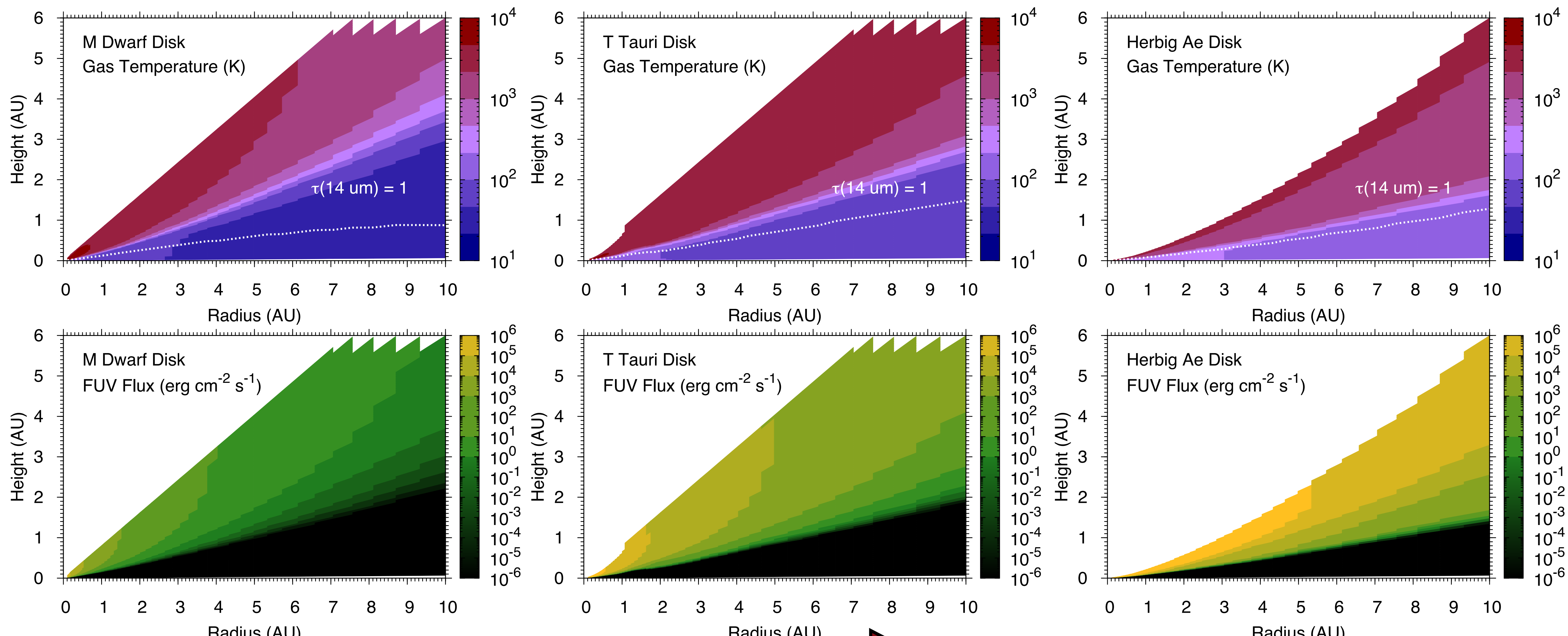
Are disks around cooler stars are (i) more carbon rich and (ii) more molecule rich, than those around hotter stars?

Zooming into the planet-forming region

Cool
3000 K
Weak FUV



Hot
10,000 K
Strong FUV



Increasing gas temperature

Increasing FUV flux

Walsh, C., et al. 2015, A&A, 582, A88

Zooming into the planet-forming region

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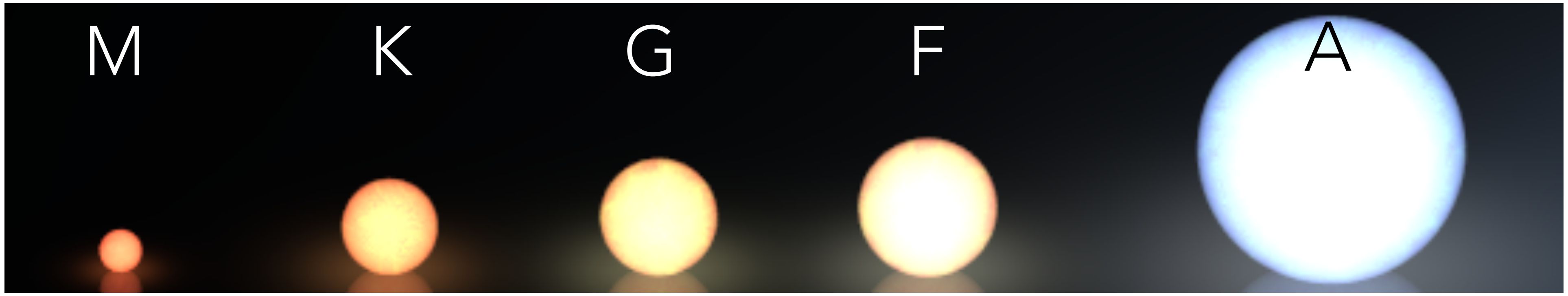

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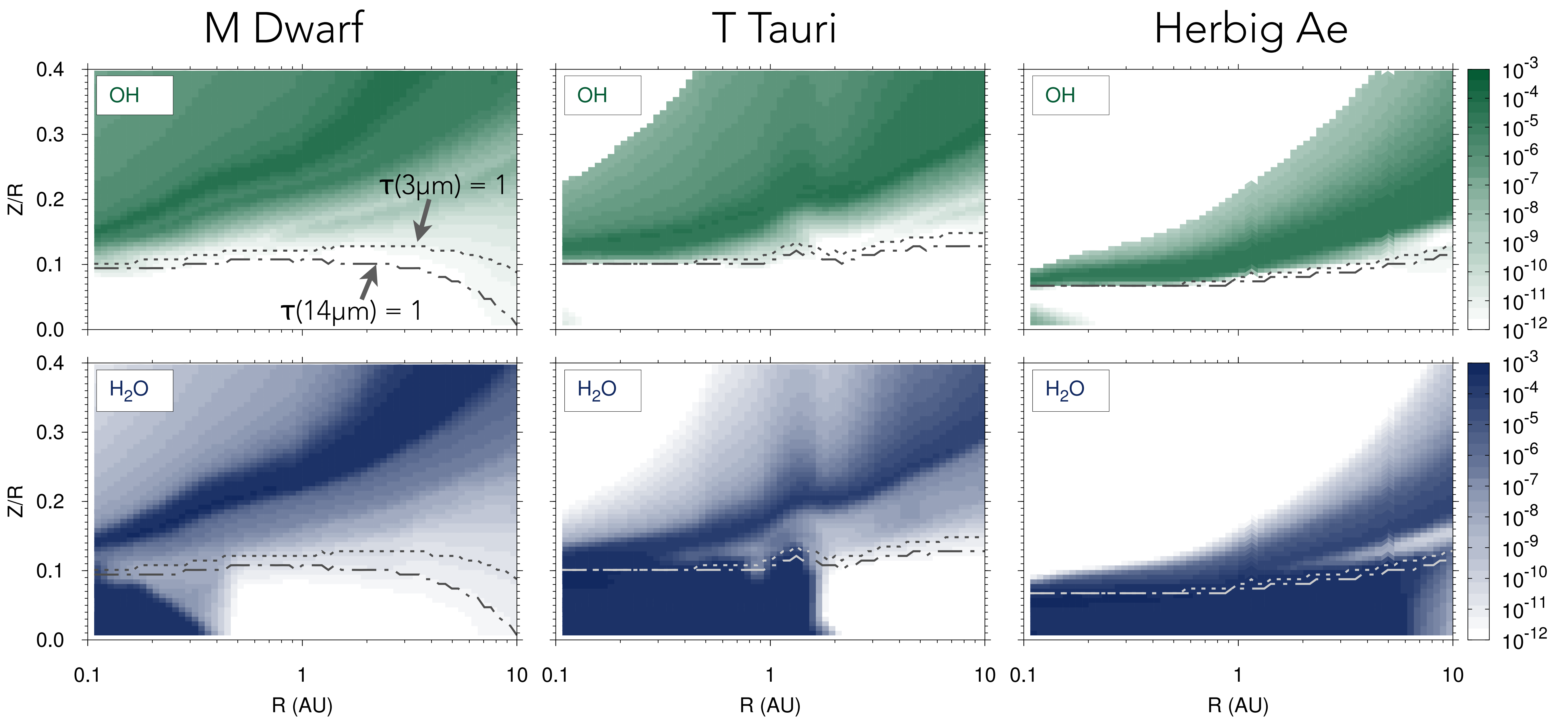

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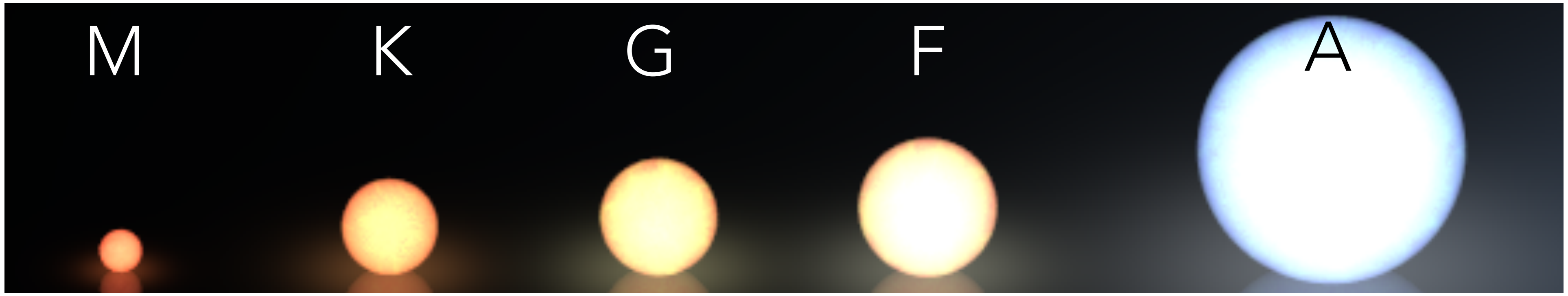

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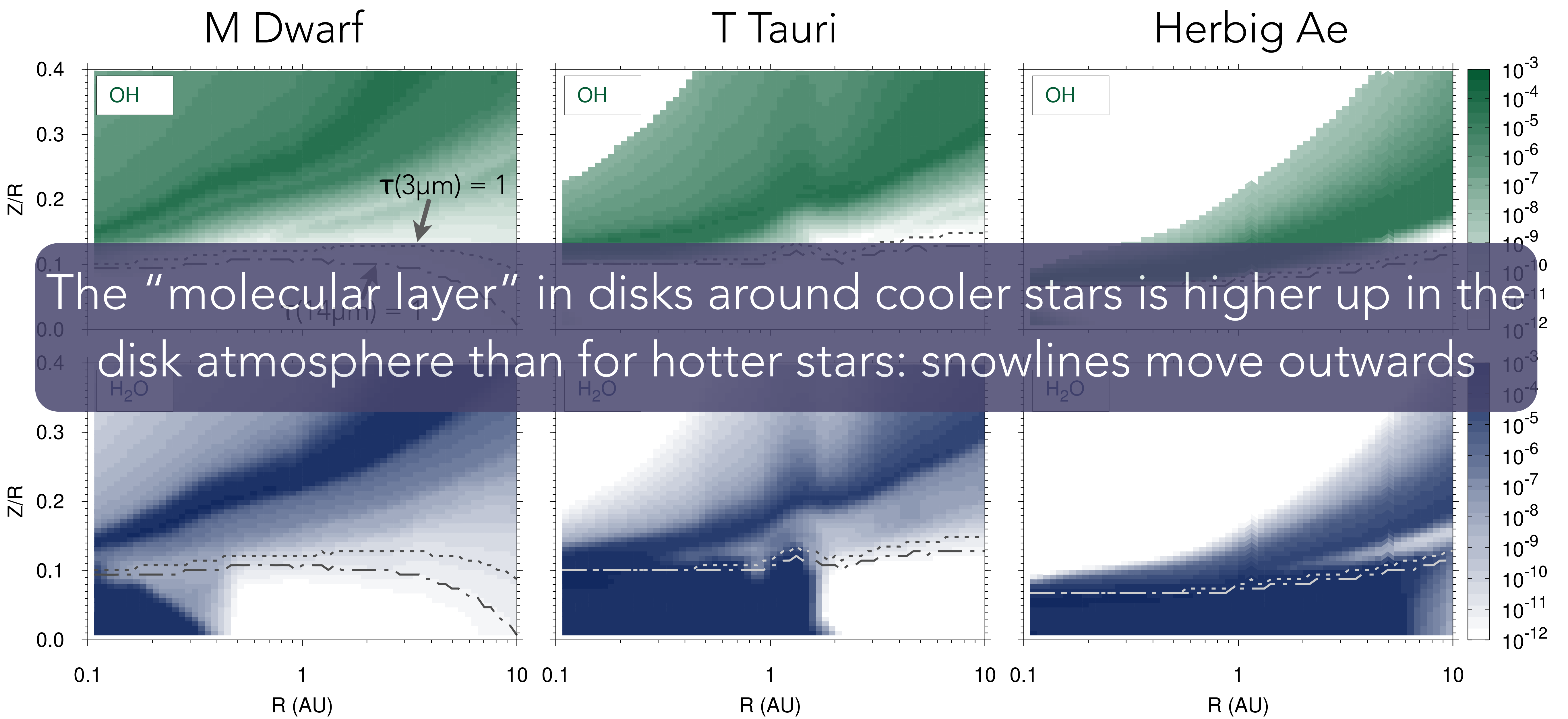

The "molecular layer" in disks around cooler stars is higher up in the disk atmosphere than for hotter stars: snowlines move outwards

Walsh, C., et al. 2015, A&A, 582, A88

Zooming into the planet-forming region

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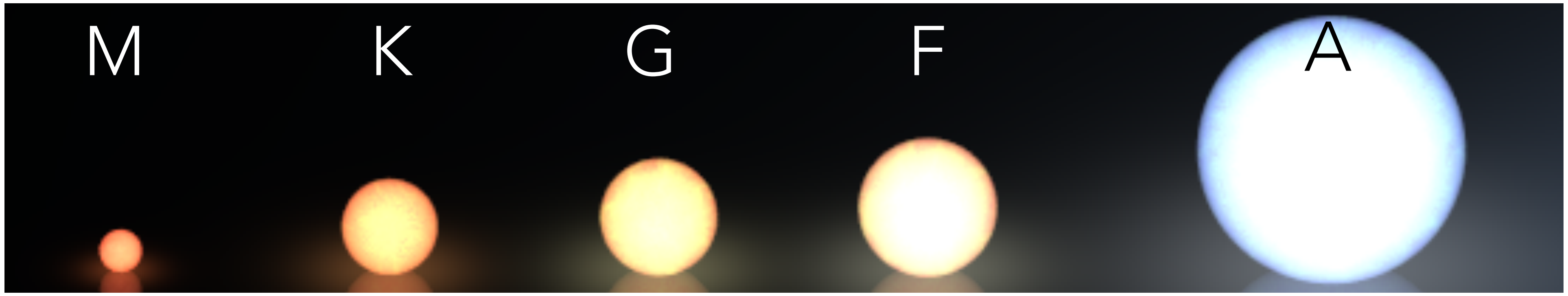

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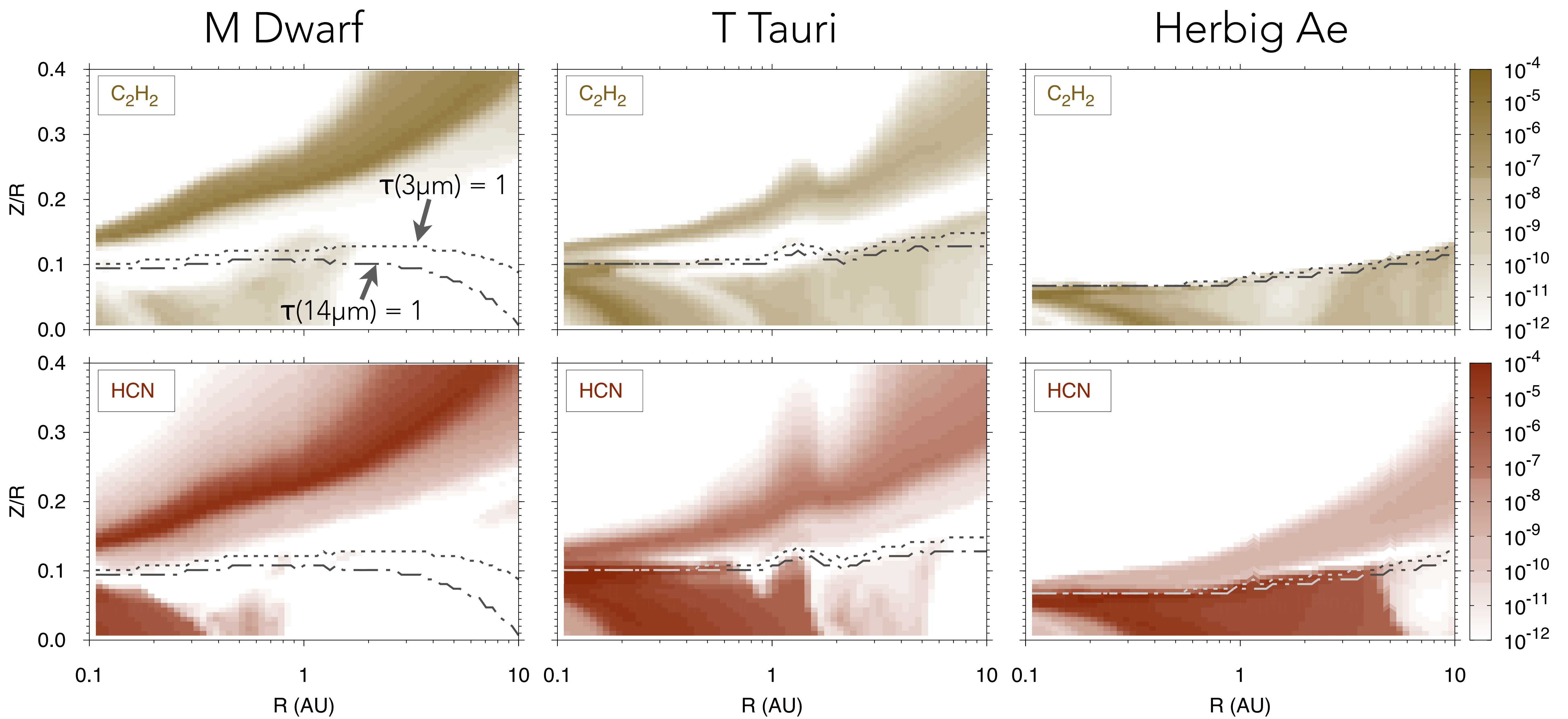

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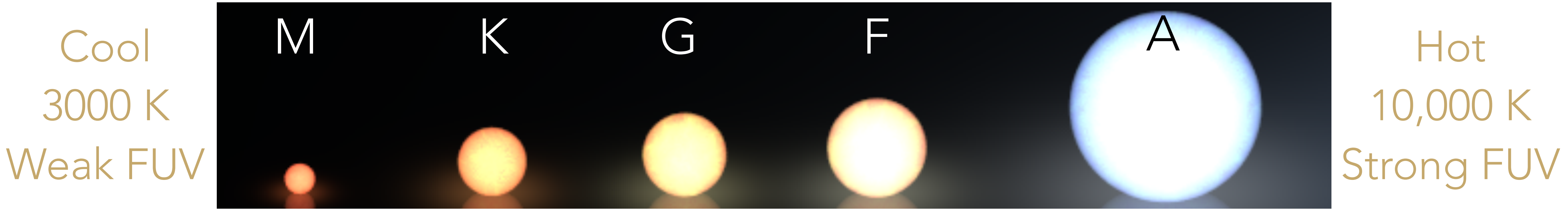
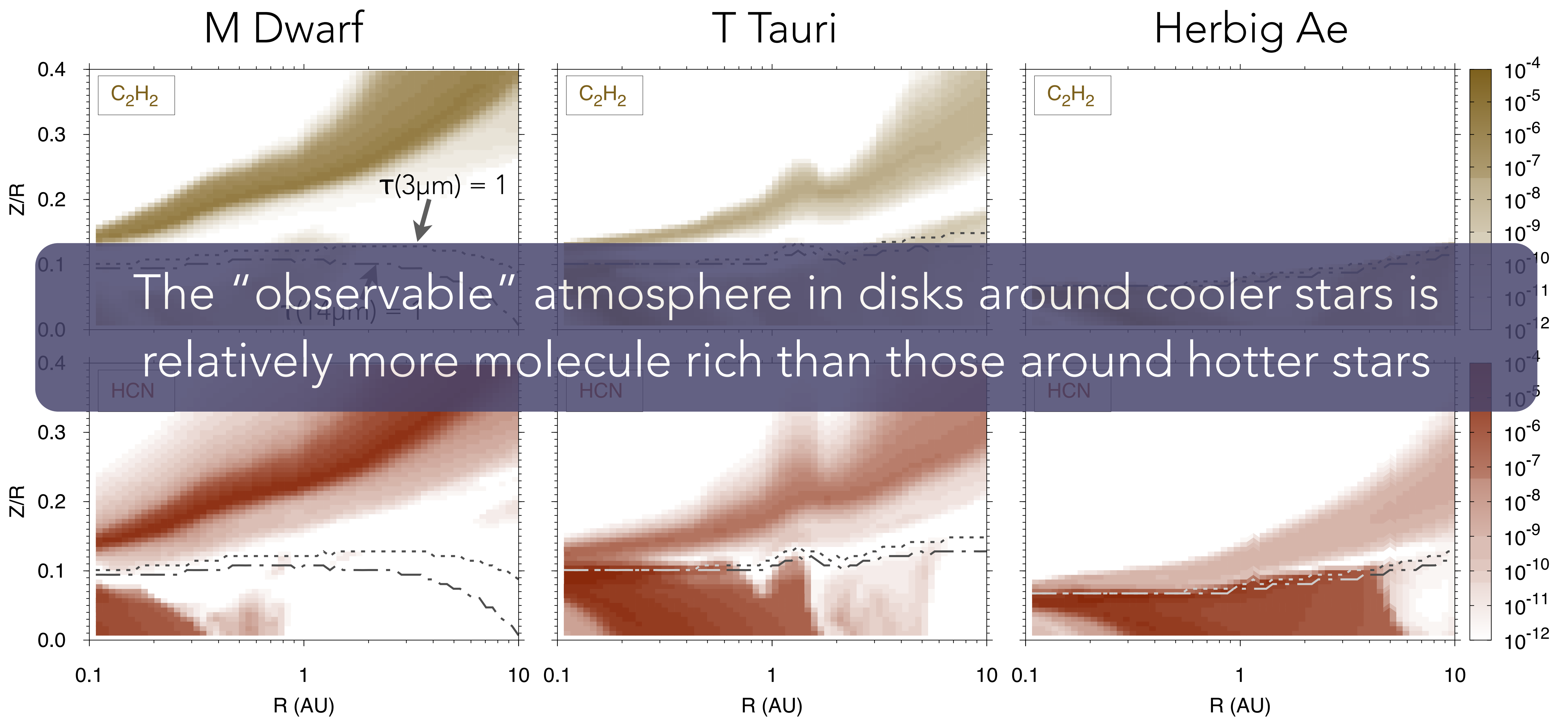


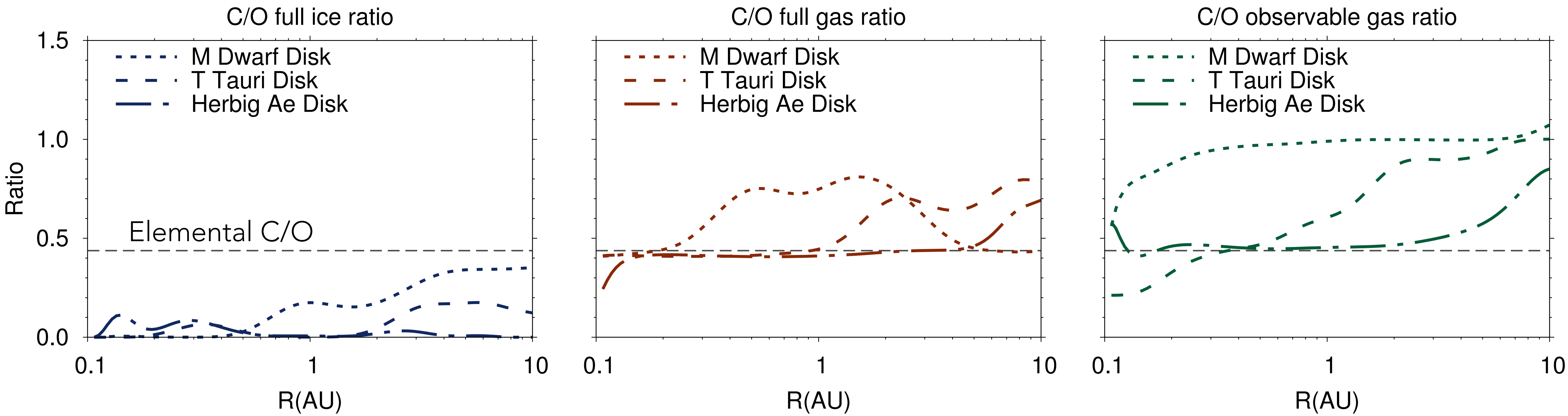


The "observable" atmosphere in disks around cooler stars is relatively more molecule rich than those around hotter stars

Walsh, C., et al. 2015, A&A, 582, A88

Tracing the composition of the planet-forming region?

Does the disk atmosphere composition represent that in the disk midplane where planets and planetesimals are forming?



Ice is generally oxygen rich: dominated by H_2O

Gas is generally carbon rich: C/O decreases from M Dwarf to Herbig Ae

Gas appears more carbon rich when summing over observable tracers only

Observable tracers: H_2O, OH, CO, CO_2, CH_4, C_2H_2, ...

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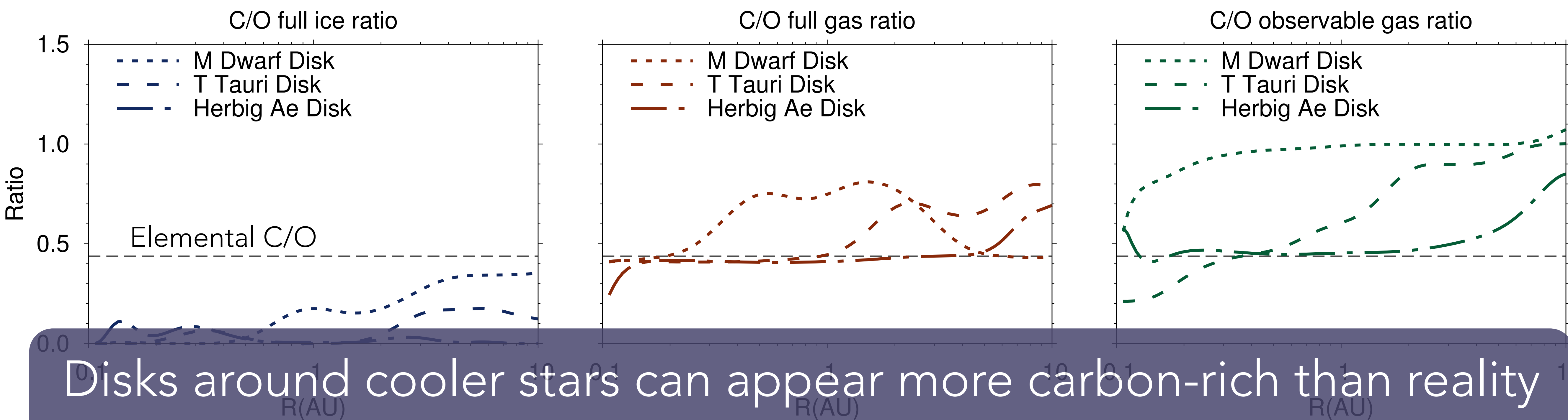

Disks around cooler stars can appear more carbon-rich than reality due to the neglect of O_2 as an oxygen reservoir

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Gas appears more carbon rich when summing over observable tracers only

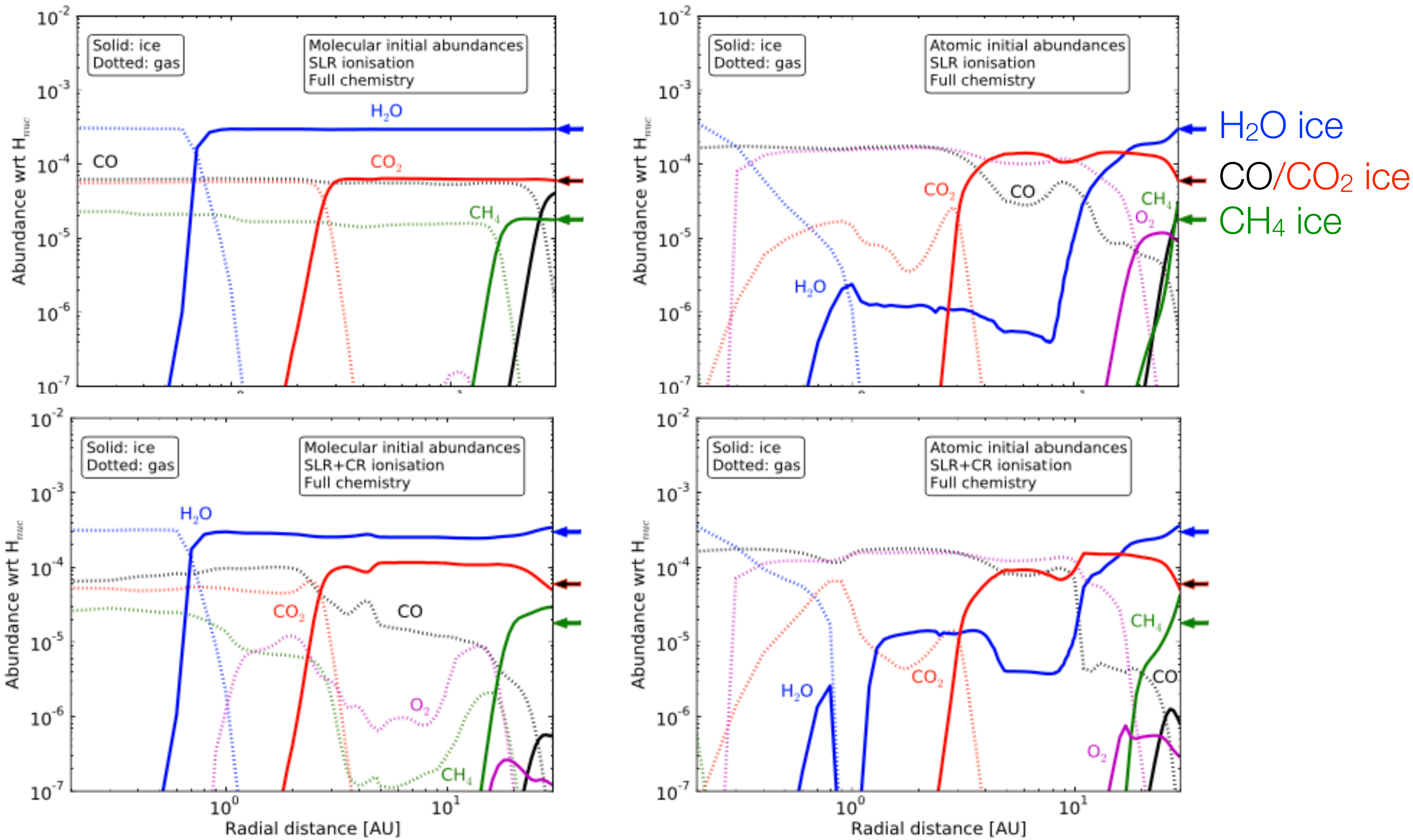
Observable tracers: H_2O, OH, CO, CO_2, CH_4, C_2H_2, ...

Interstellar inheritance versus chemical reset

How important is kinetic chemistry in determining the relative abundances of dominant volatiles in protoplanetary disk midplanes?

Inheritance versus reset

High versus low ionisation



Eistrup, C., Walsh, C., & van Dishoeck, E. F. 2016, A&A, under review

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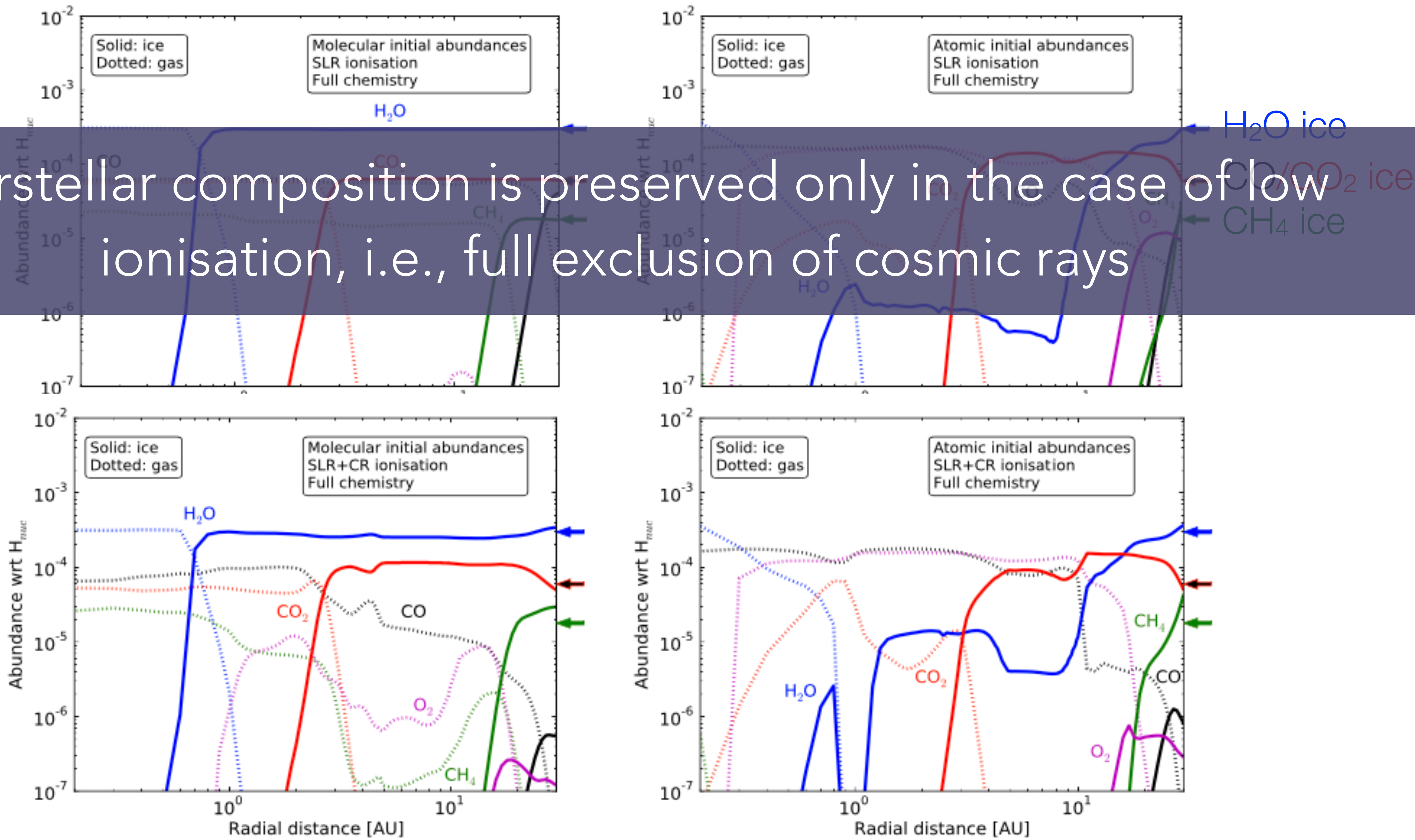

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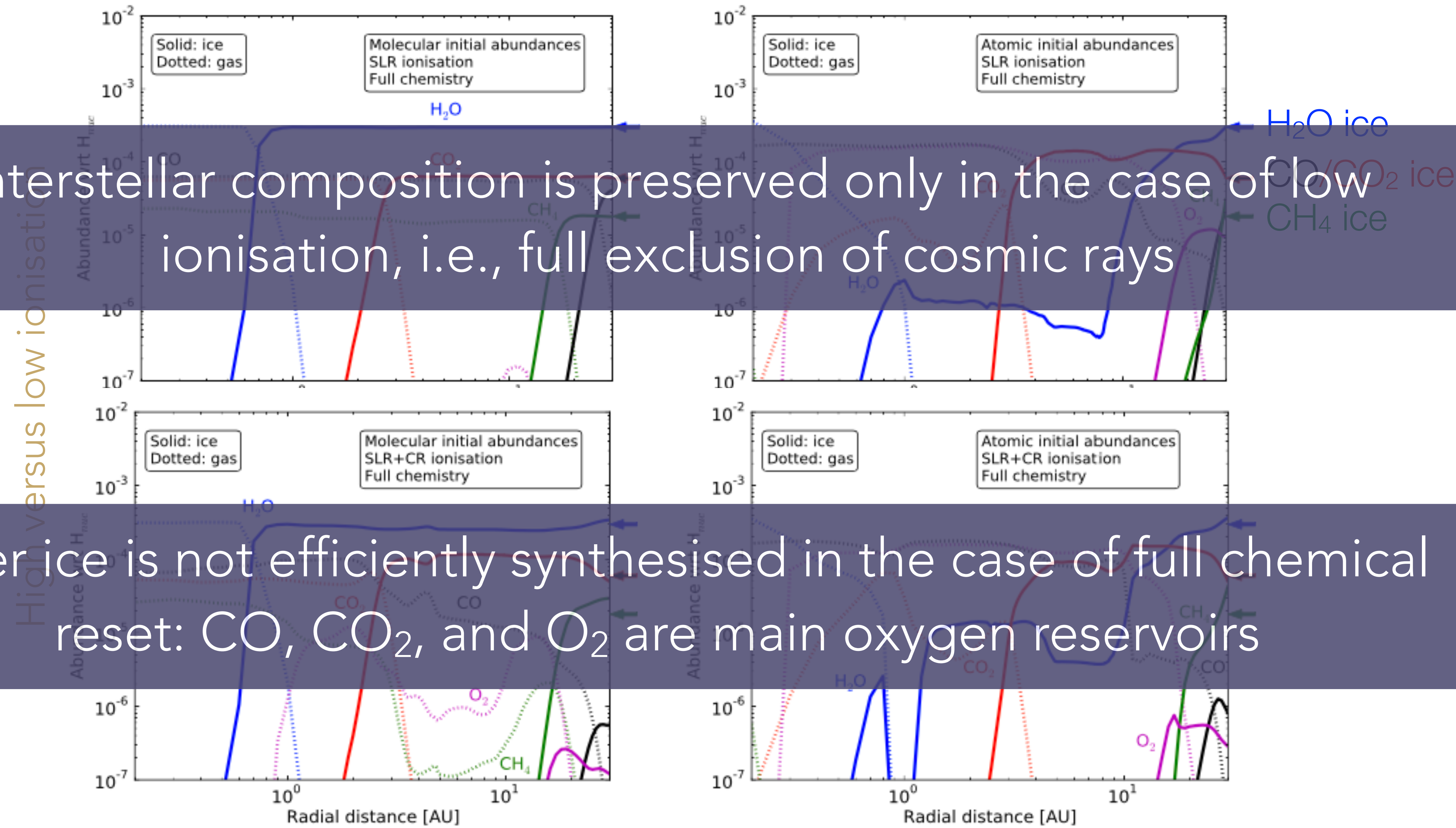

Interstellar composition is preserved only in the case of low ionisation, i.e., full exclusion of cosmic rays

Water ice is not efficiently synthesised in the case of full chemical reset: CO, CO_2, and O_2 are main oxygen reservoirs

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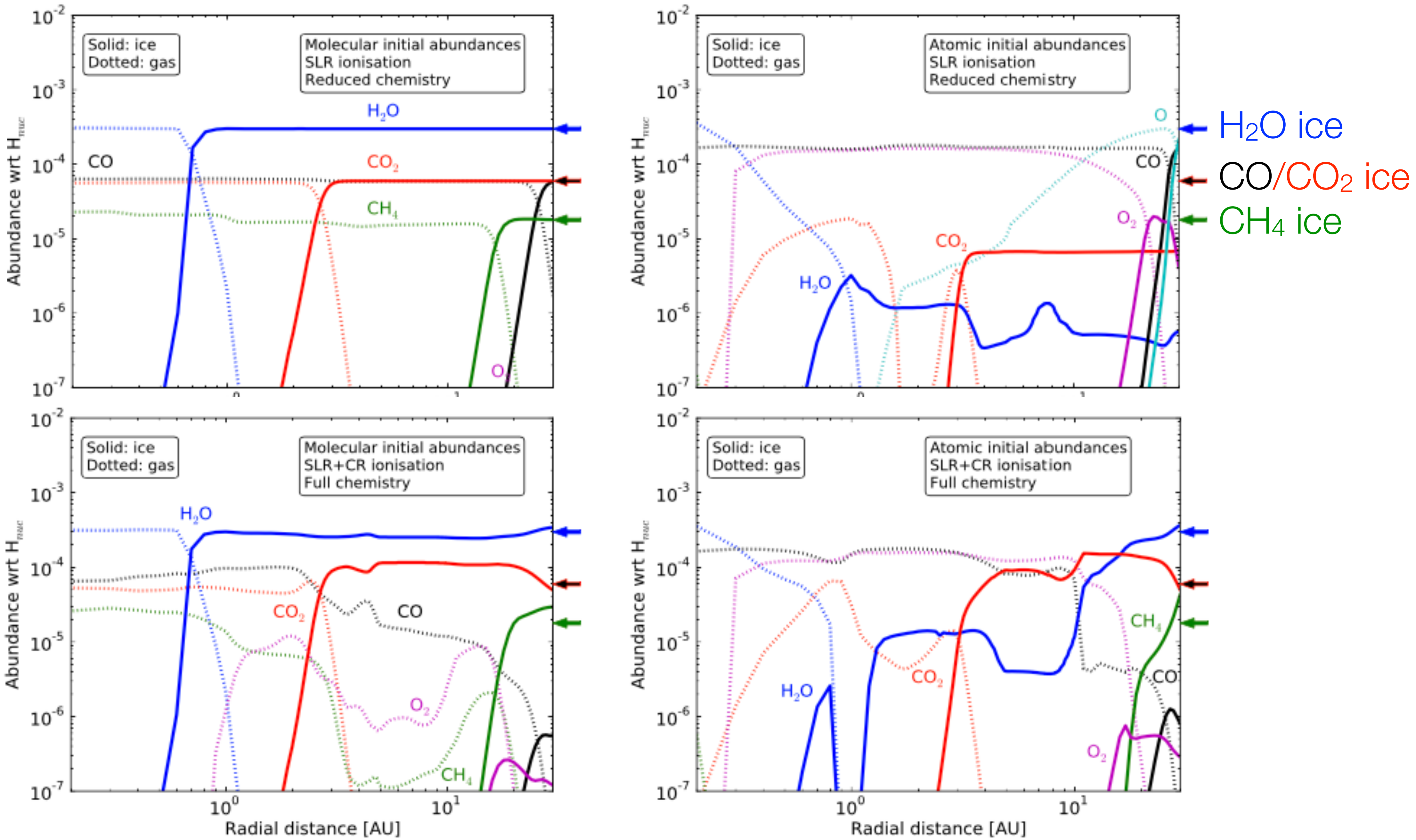
How important is ice processing in determining the relative abundances of dominant volatiles in protoplanetary disk midplanes?

Inheritance versus reset

Full versus reduced chemistry



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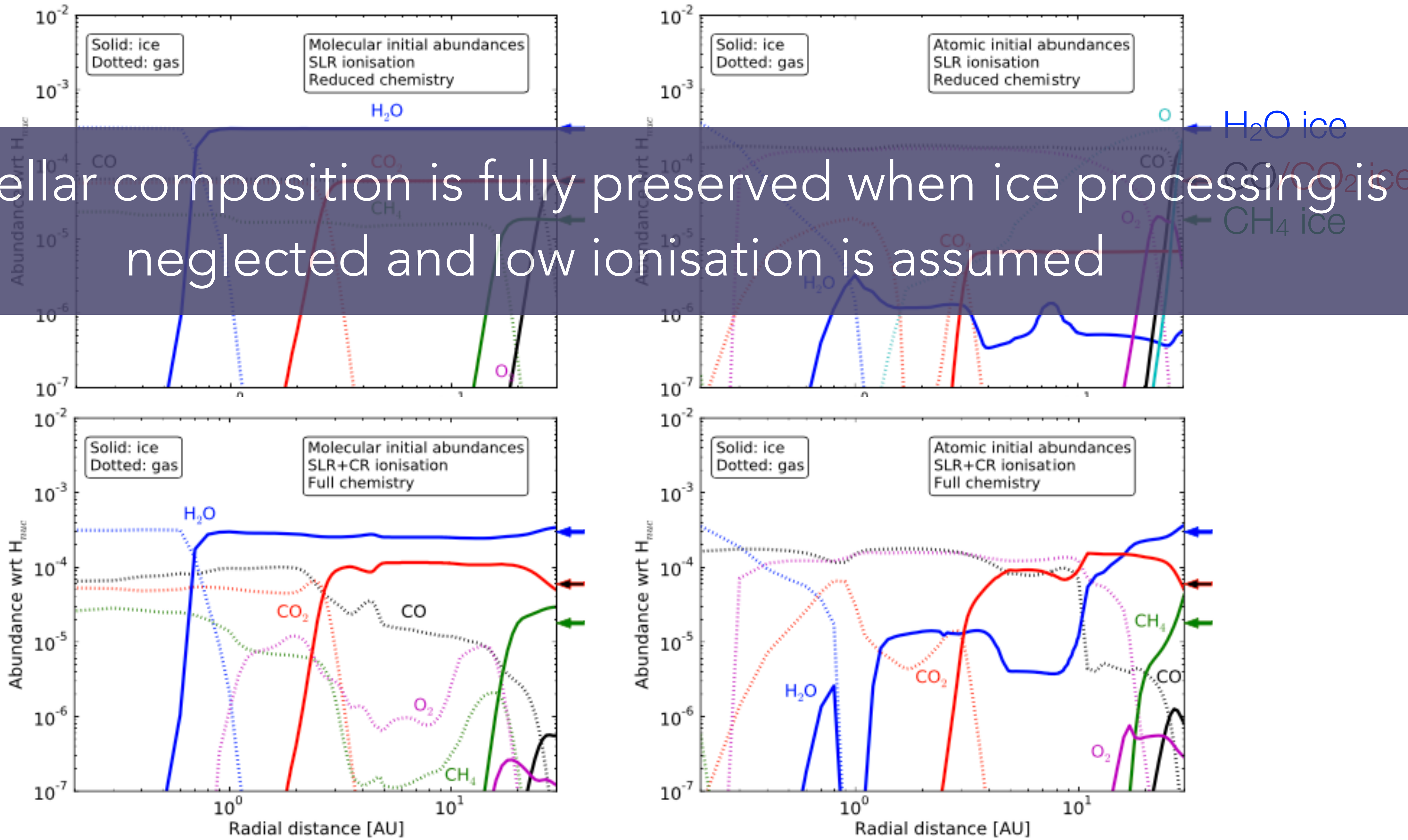

Interstellar composition is fully preserved when ice processing is neglected and low ionisation is assumed

Eistrup, C., Walsh, C., & van Dishoeck, E. F. 2016, A&A, under review

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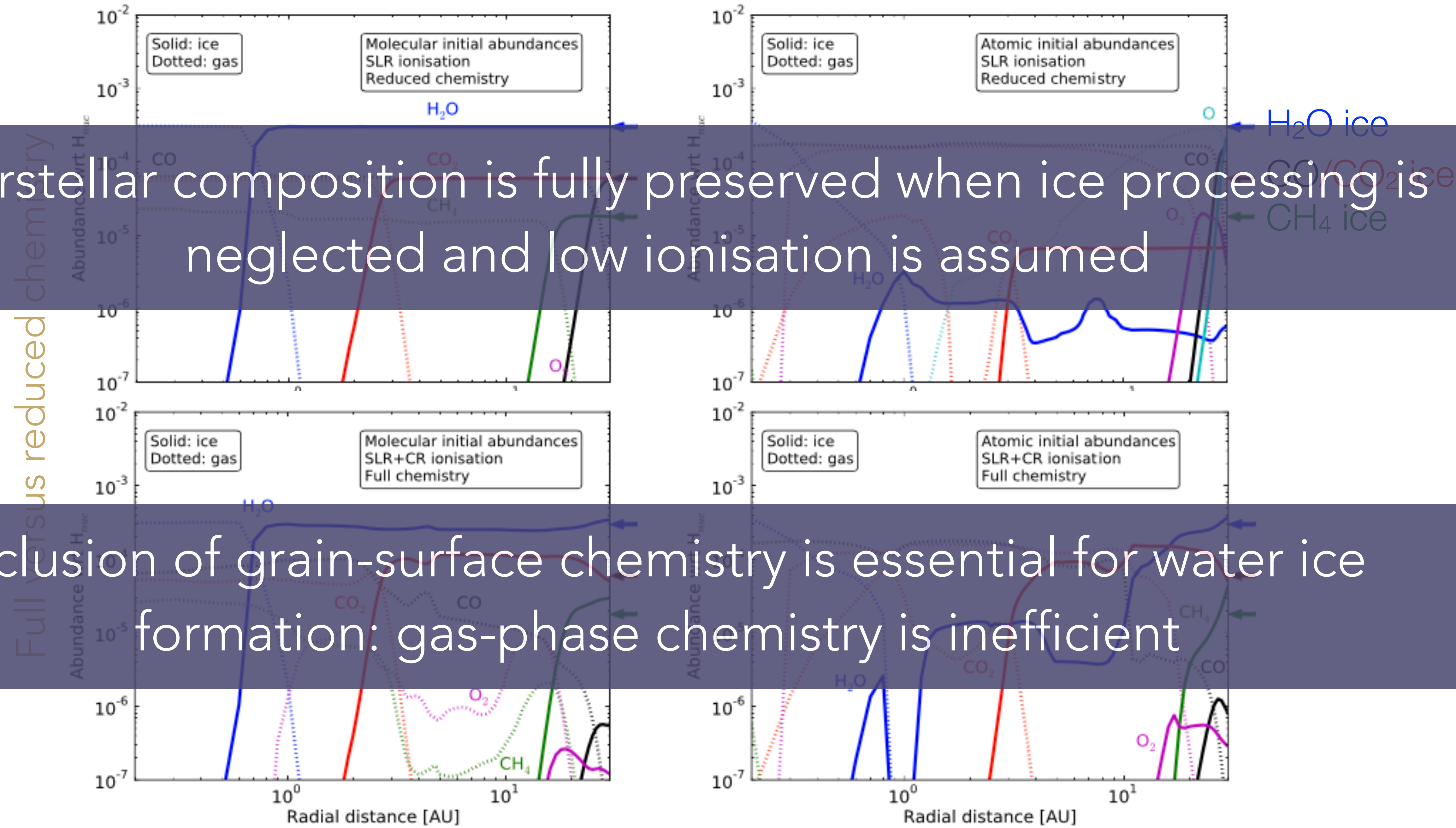


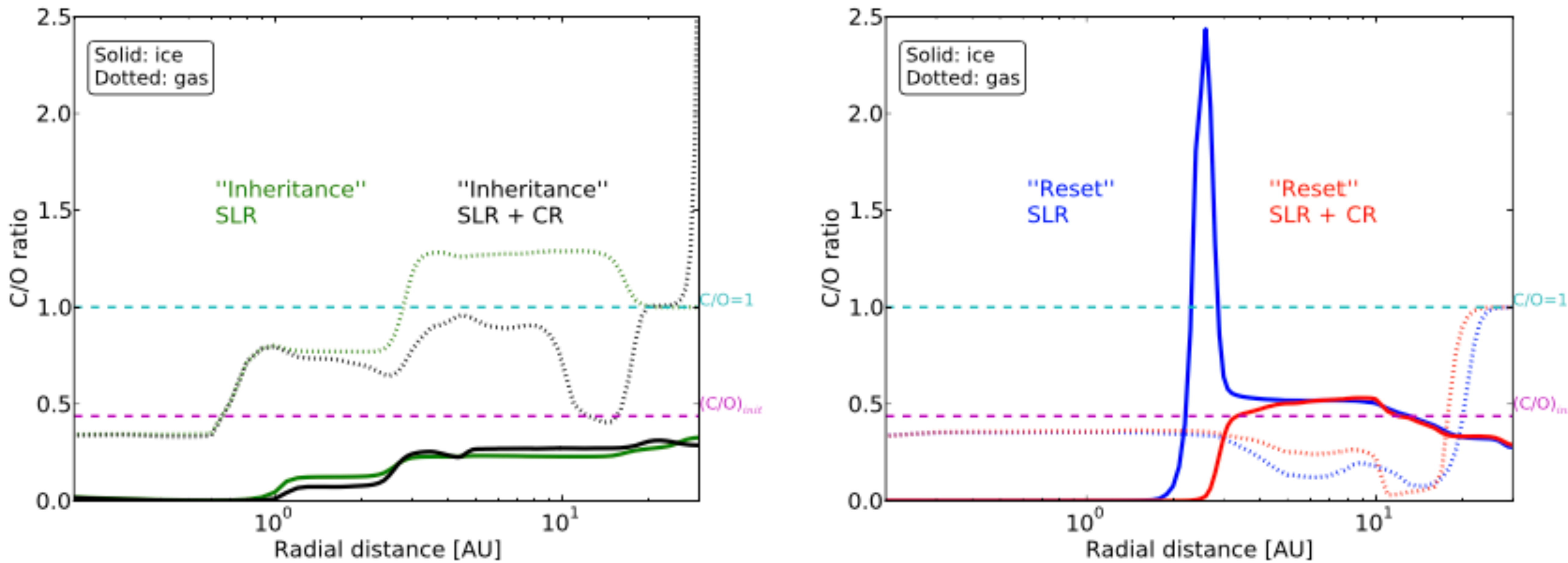
Interstellar composition is fully preserved when ice processing is neglected and low ionisation is assumed

Inclusion of grain-surface chemistry is essential for water ice formation: gas-phase chemistry is inefficient

Eistrup, C., Walsh, C., & van Dishoeck, E. F. 2016, A&A, under review

Interstellar inheritance versus chemical reset

How do the different scenarios affect the C/O ratio of planet-building material?



Ionisation: C/O gas-phase ratio is generally decreased (< 1)

Inheritance: C/O ratio follows snowlines, gas is more C rich than ice

Reset: C/O ratios of gas and ice are switched, ice is more C rich than gas

Interstellar inheritance versus chemical reset

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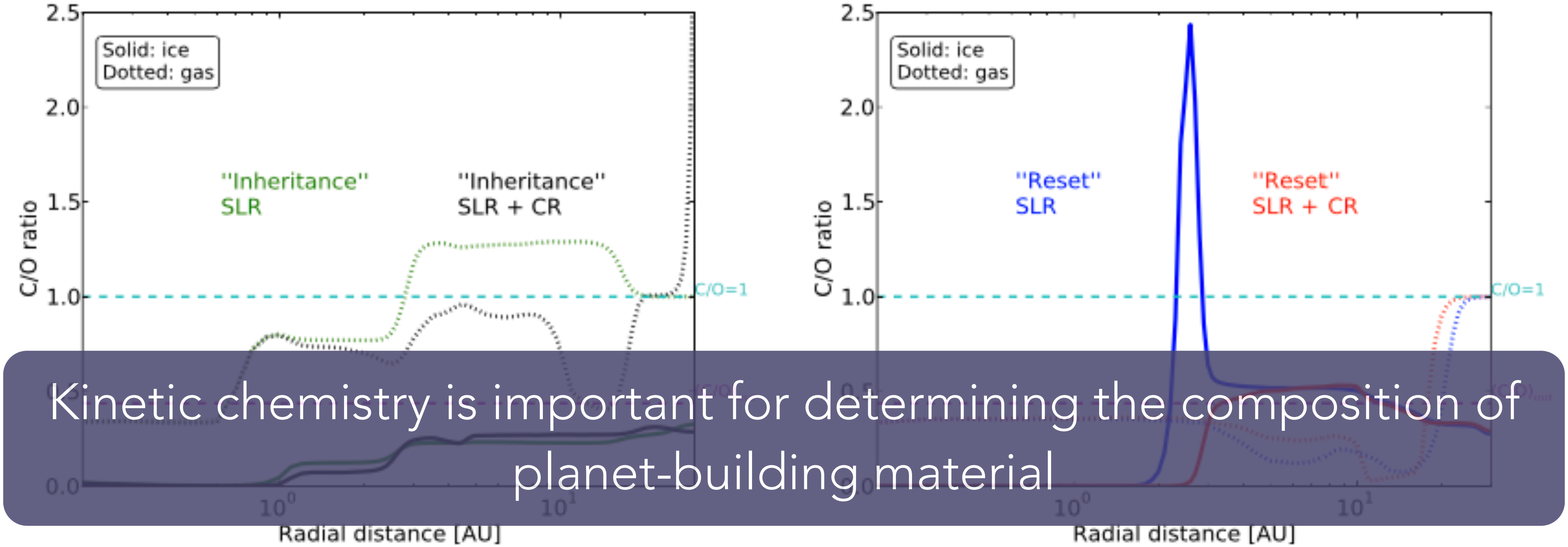

Kinetic chemistry is important for determining the composition of planet-building material

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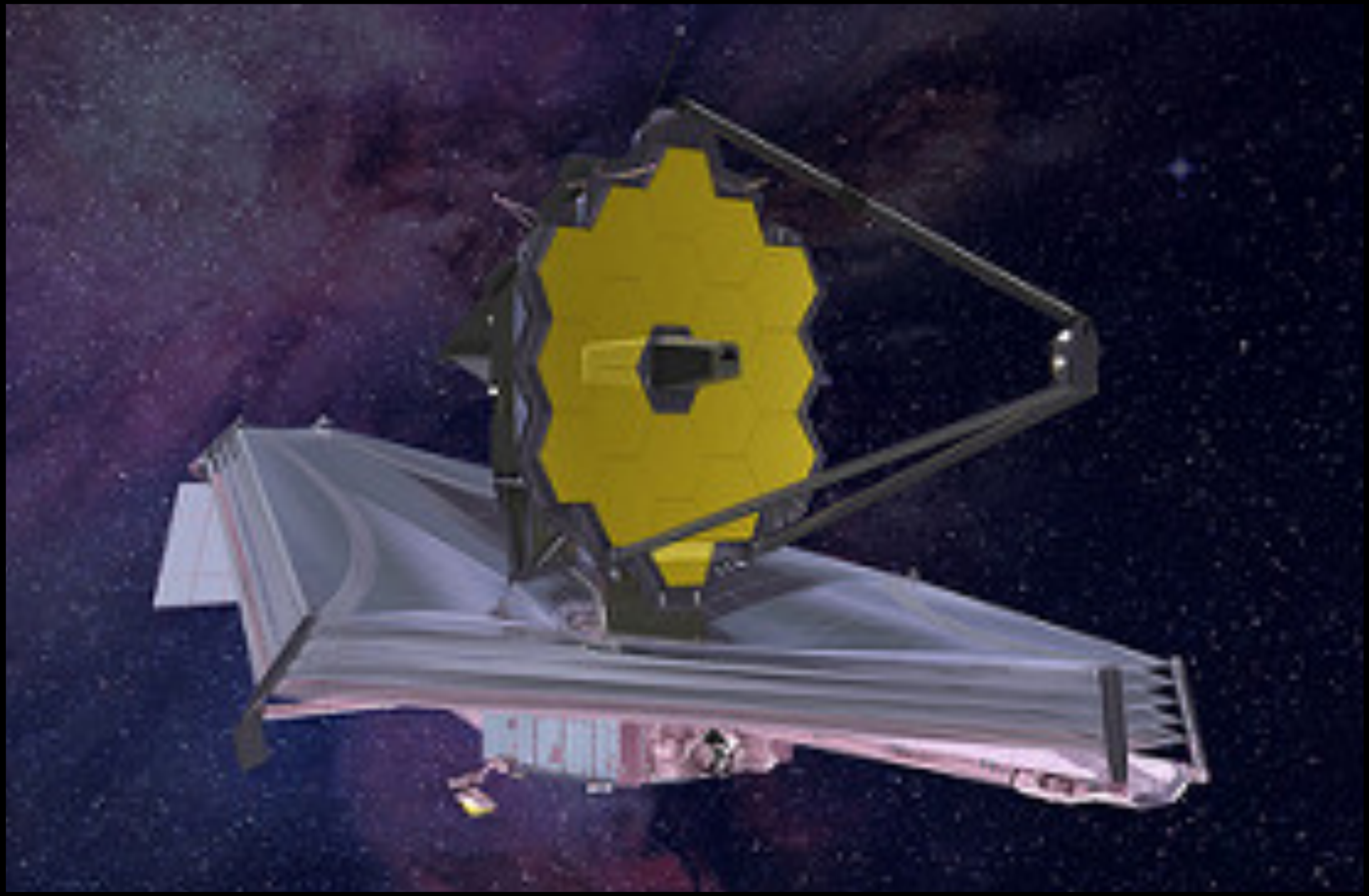
Inheritance: C/O ratio follows snowlines, gas is more C rich than ice

Reset: C/O ratios of gas and ice are switched, ice is more C rich than gas

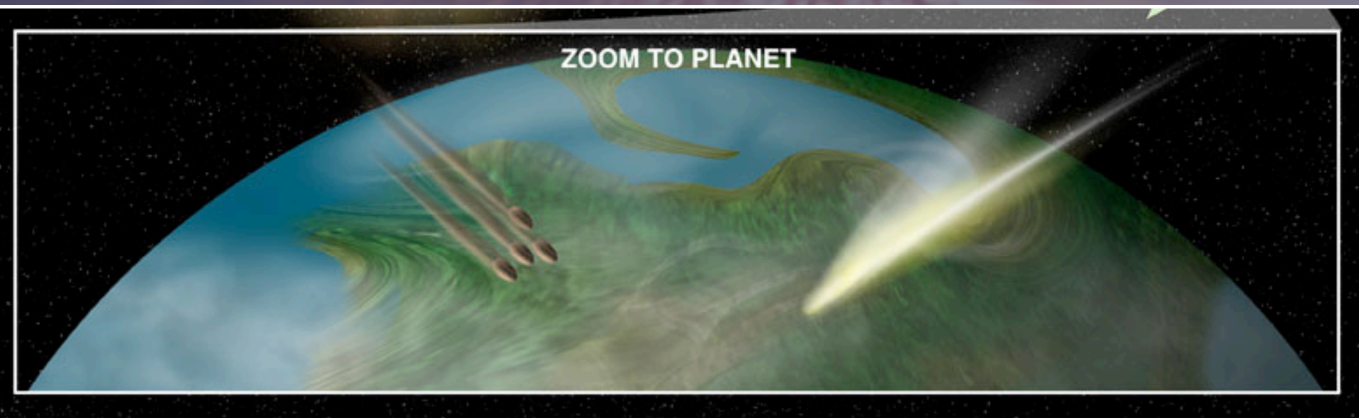
Future observations of planet-building material

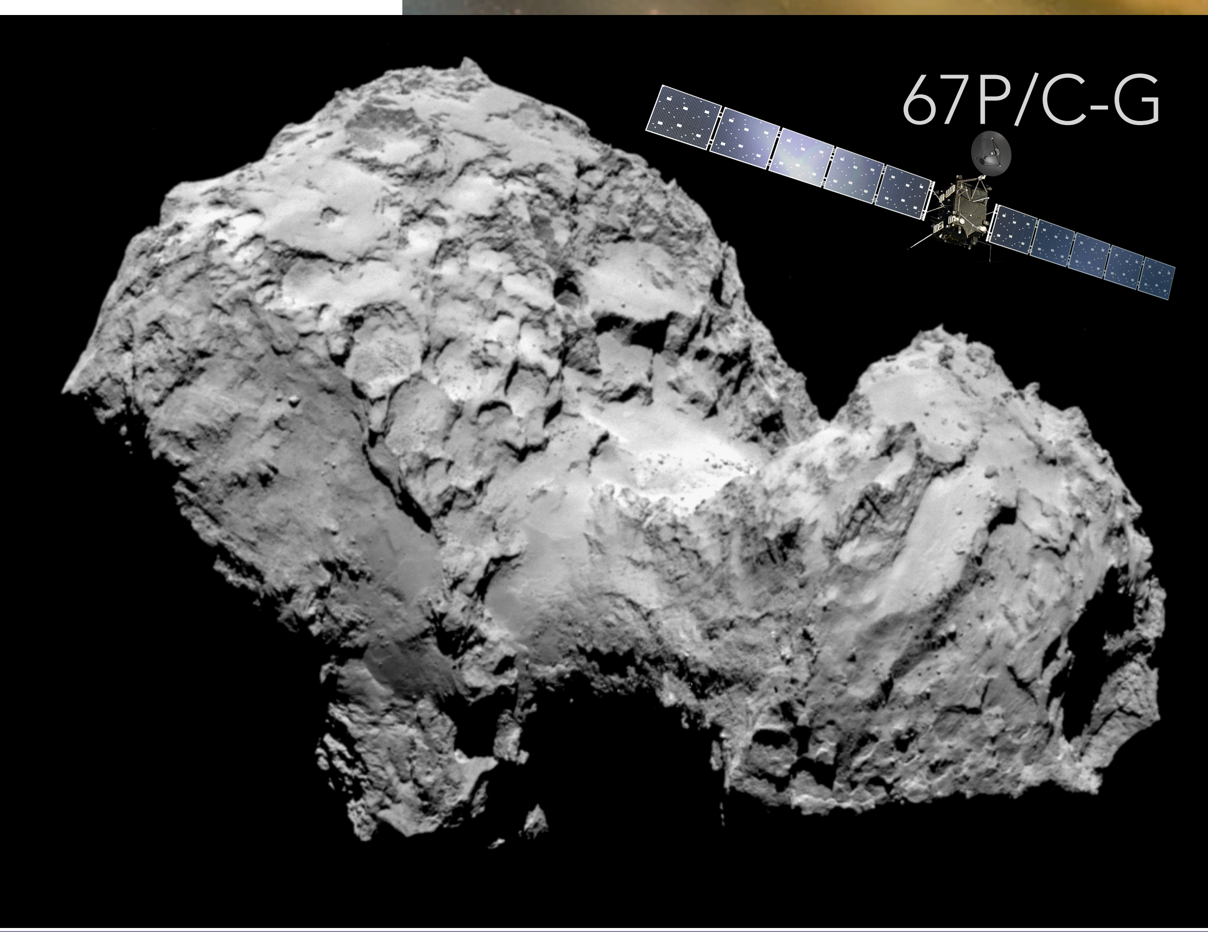
James Webb Space Telescope: October 2018



- probes the "warm" universe
- dust and molecules from 0.6 to 28.5 μm
- 6.5 meter primary mirror
- 0.1 arcsecond resolution

Comets: a unique view into the disk midplane





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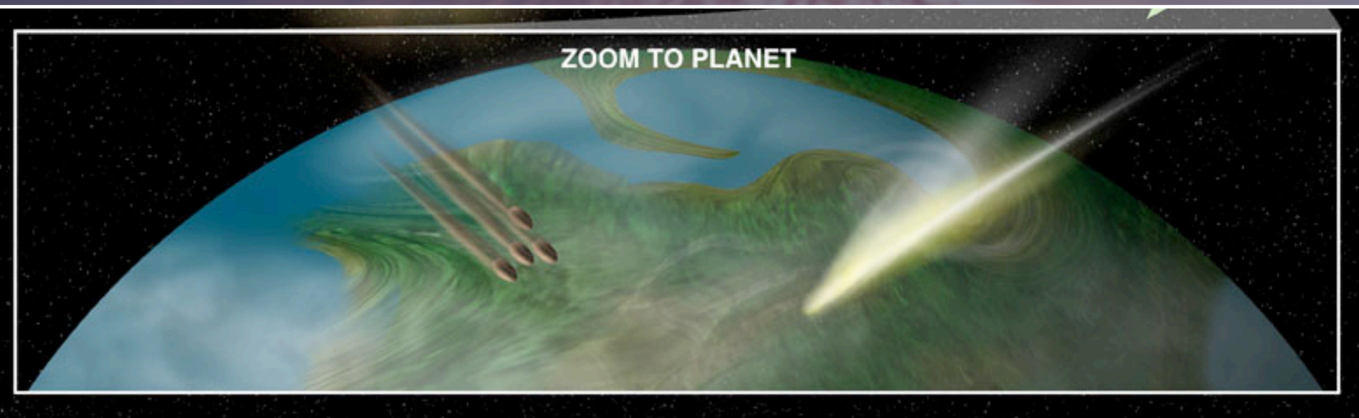
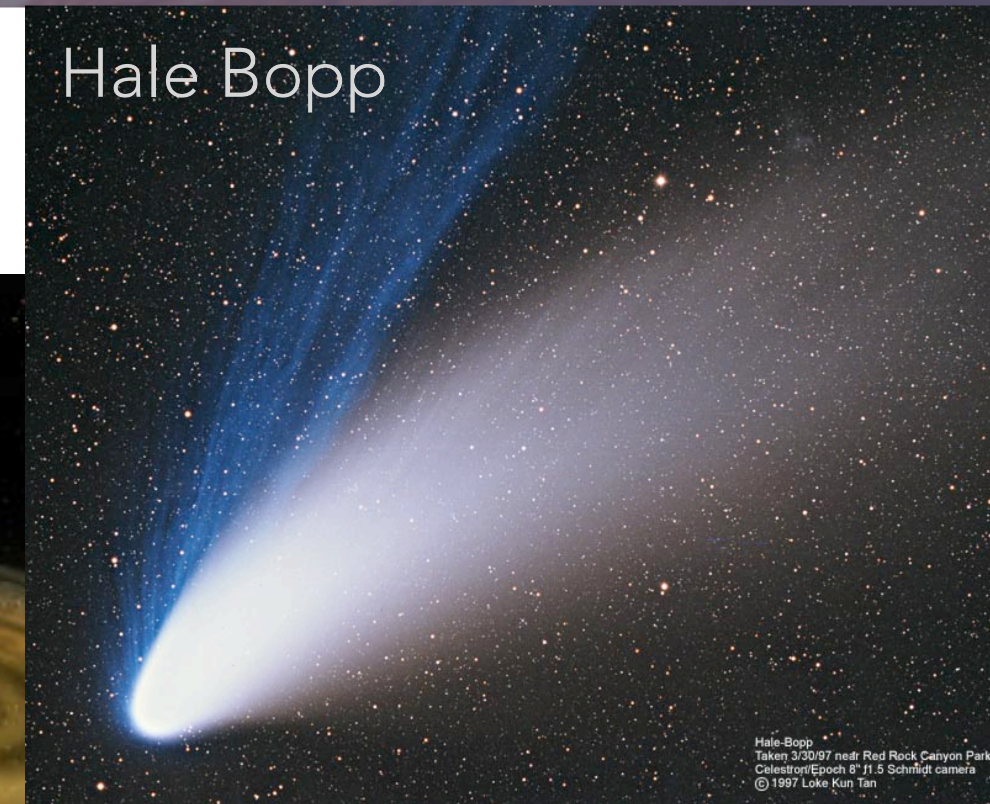
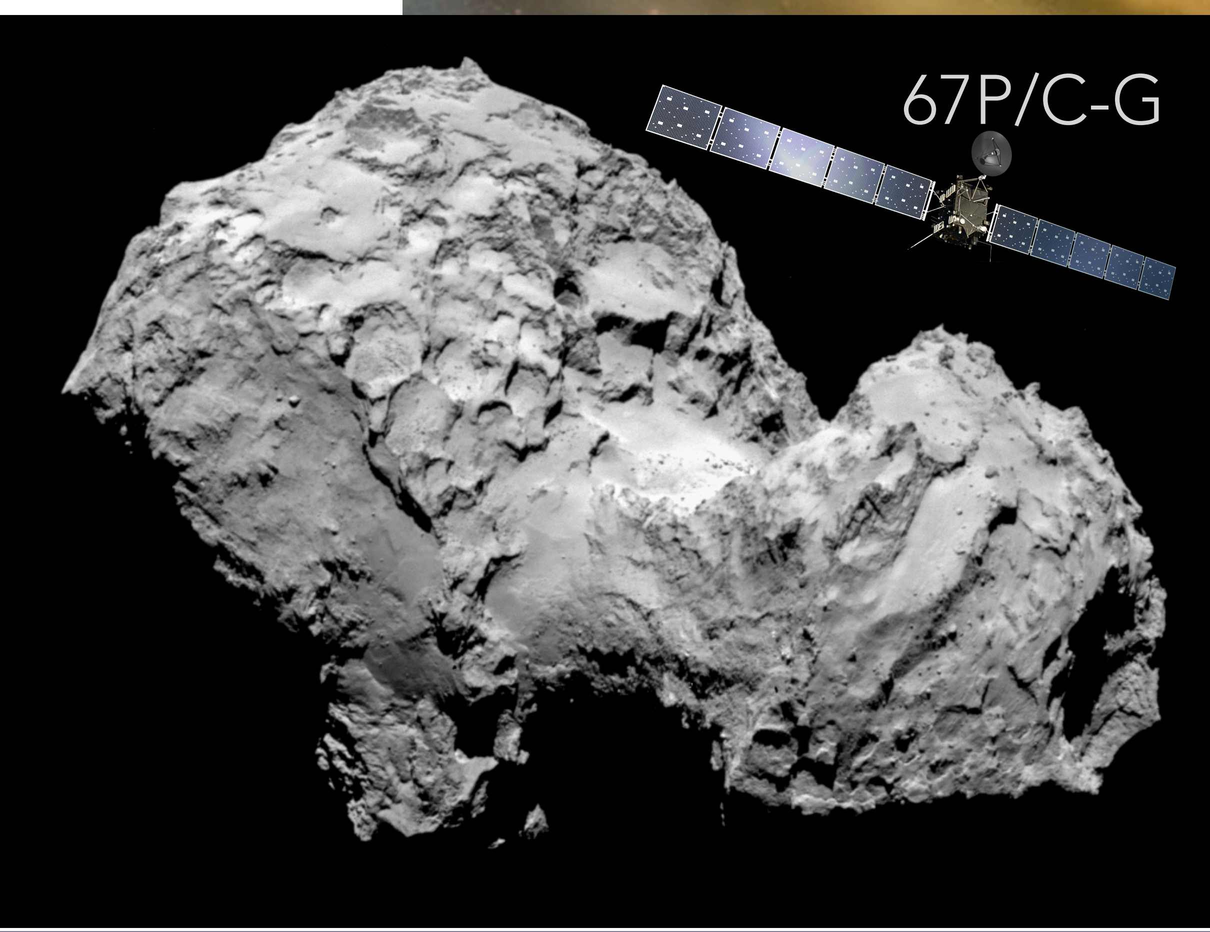
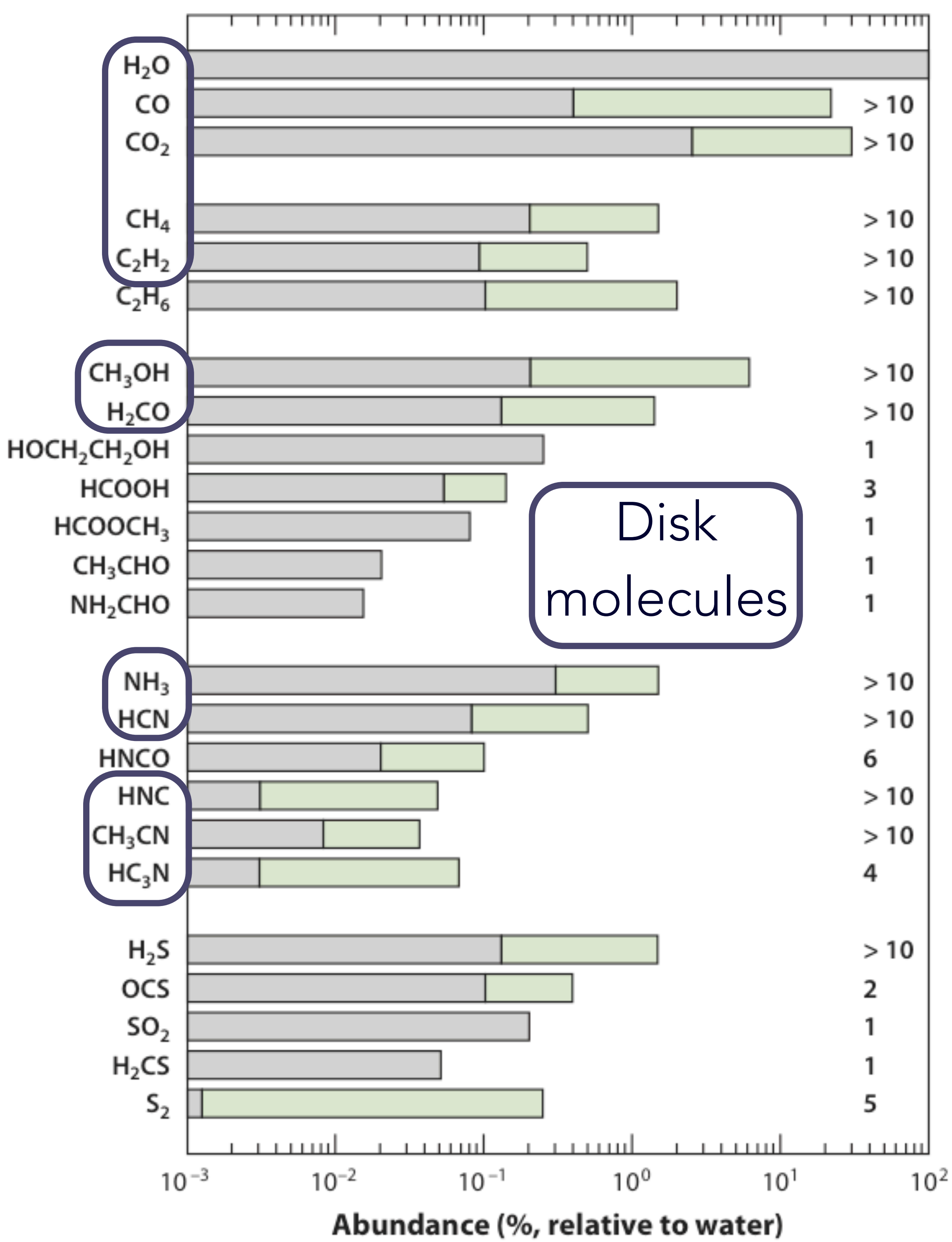


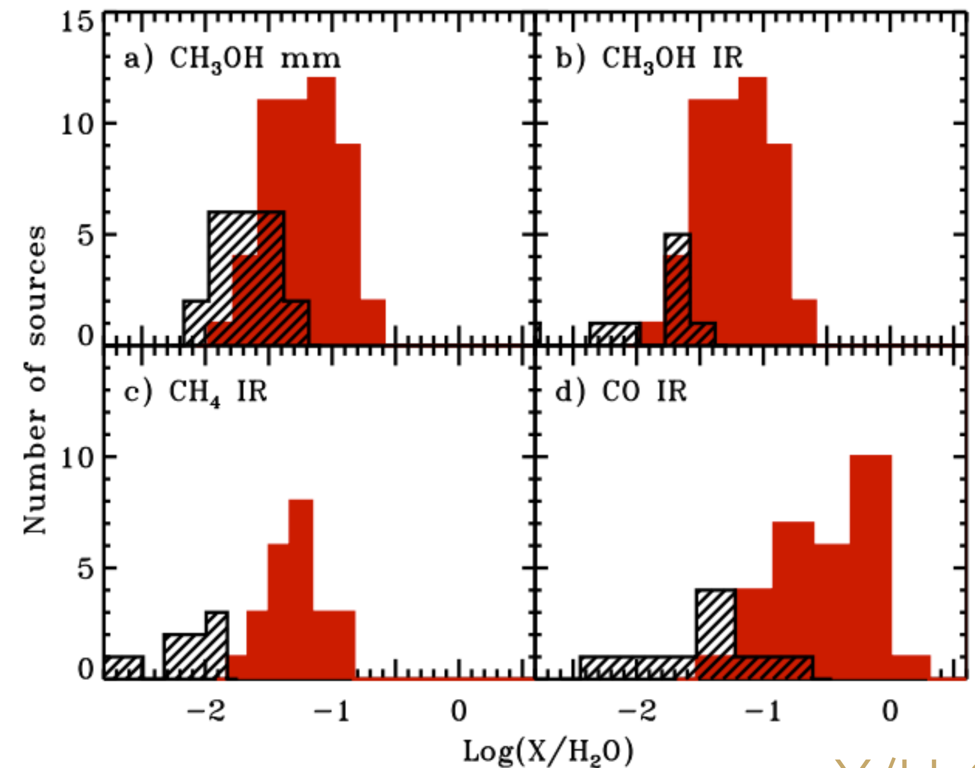




Inheritance?
Disk origin?
In-situ?
Delivery?

Comets: an alternative view into the disk midplane





$X/H_2O \approx (0.1 - 1.8)$ %

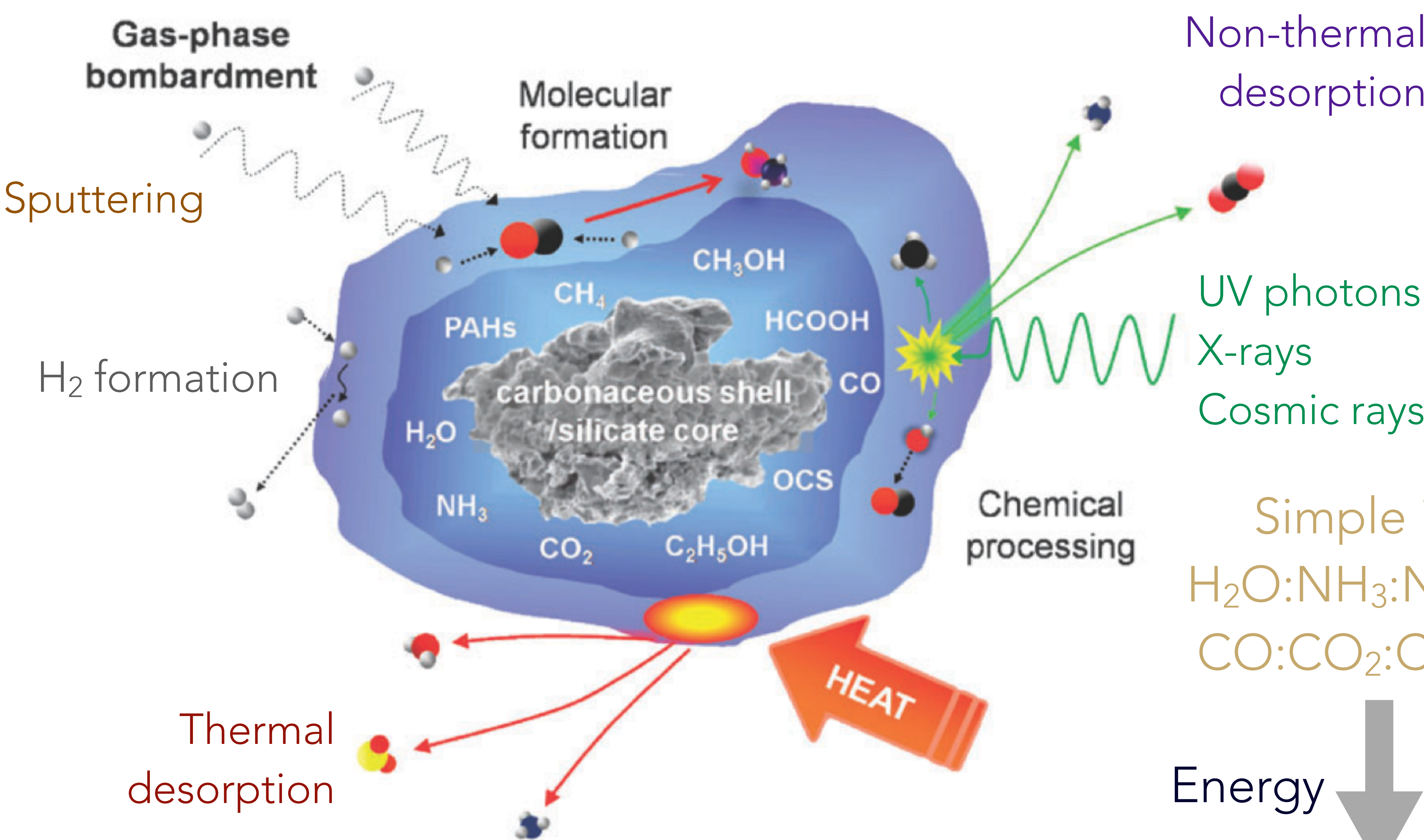
COSAC

Name	Formula	Molar mass (u)	MS fraction	Relative to water
Water	H_2O	18	80.92	100
Methane	CH_4	16	0.70	0.5
Methanenitrile (hydrogen cyanide)	HCN	27	1.06	0.9
Carbon monoxide	CO	28	1.09	1.2
Methylamine	CH_3NH_2	31	1.19	0.6
Ethanenitrile (acetonitrile)	CH_3CN	41	0.55	0.3
Isocyanic acid	HNCO	43	0.47	0.3
Ethanal (acetaldehyde)	CH_3CHO	44	1.01	0.5
Methanamide (formamide)	$HCONH_2$	45	3.73	1.8
Ethylamine	$C_2H_5NH_2$	45	0.72	0.3
Isocyanomethane (methyl isocyanate)	CH_3NCO	57	3.13	1.3
Propanone (acetone)	CH_3COCH_3	58	1.02	0.3
Propanal (propionaldehyde)	C_2H_5CHO	58	0.44	0.1
Ethanamide (acetamide)	CH_3CONH_2	59	2.20	0.7
2-Hydroxyethanal (glycolaldehyde)	CH_2OHCHO	60	0.98	0.4
1,2-Ethanediol (ethylene glycol)	$CH_2(OH)CH_2(OH)$	62	0.79	0.2

Mumma, M. & Charnley, S. 2011, ARAA, 49, 471; Öberg, K. I., et al. 2011, ApJ, 740, 109; Goesmann et al. 2015, Science, 349, 689

How do complex organic molecules form?

On and within icy dust mantles: gas-phase formation of saturated molecules is inefficient under interstellar/circumstellar conditions



Simple ices

$H_2O:NH_3:N_2:CH_4:$

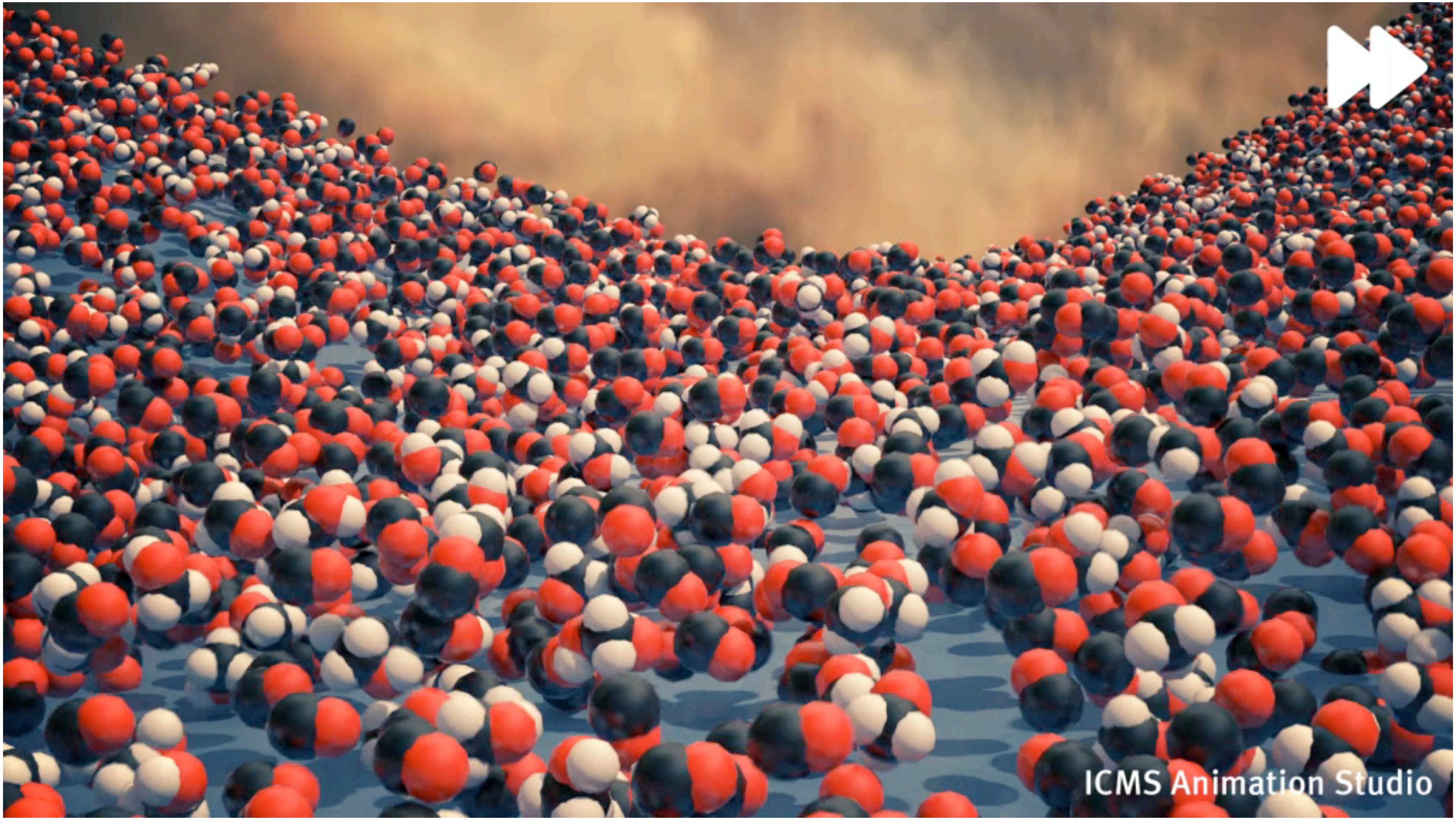
$CO:CO_2:CH_3OH$

Energy Heat

Complex molecules

How do complex molecules form?

How do complex molecules form?



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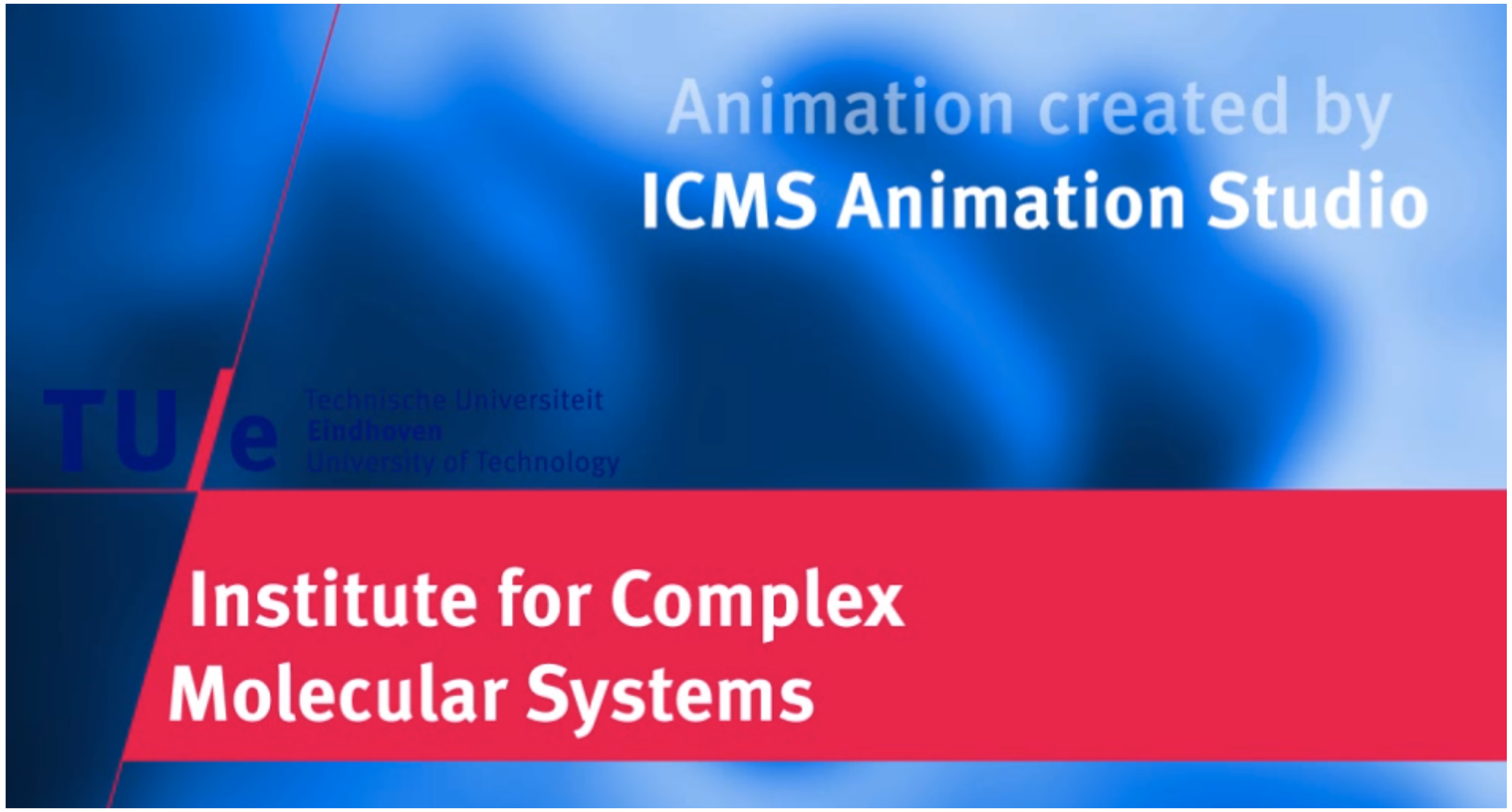


Animation based on

A.G.G.M. Tielens & S. Charnley **1997**, *Orig. Life Evol. Biosphere*, vol. 27, p. 23

R.T. Garrod & E. Herbst **2006**, *Astron. Astrophys.*, vol. 457, p. 927

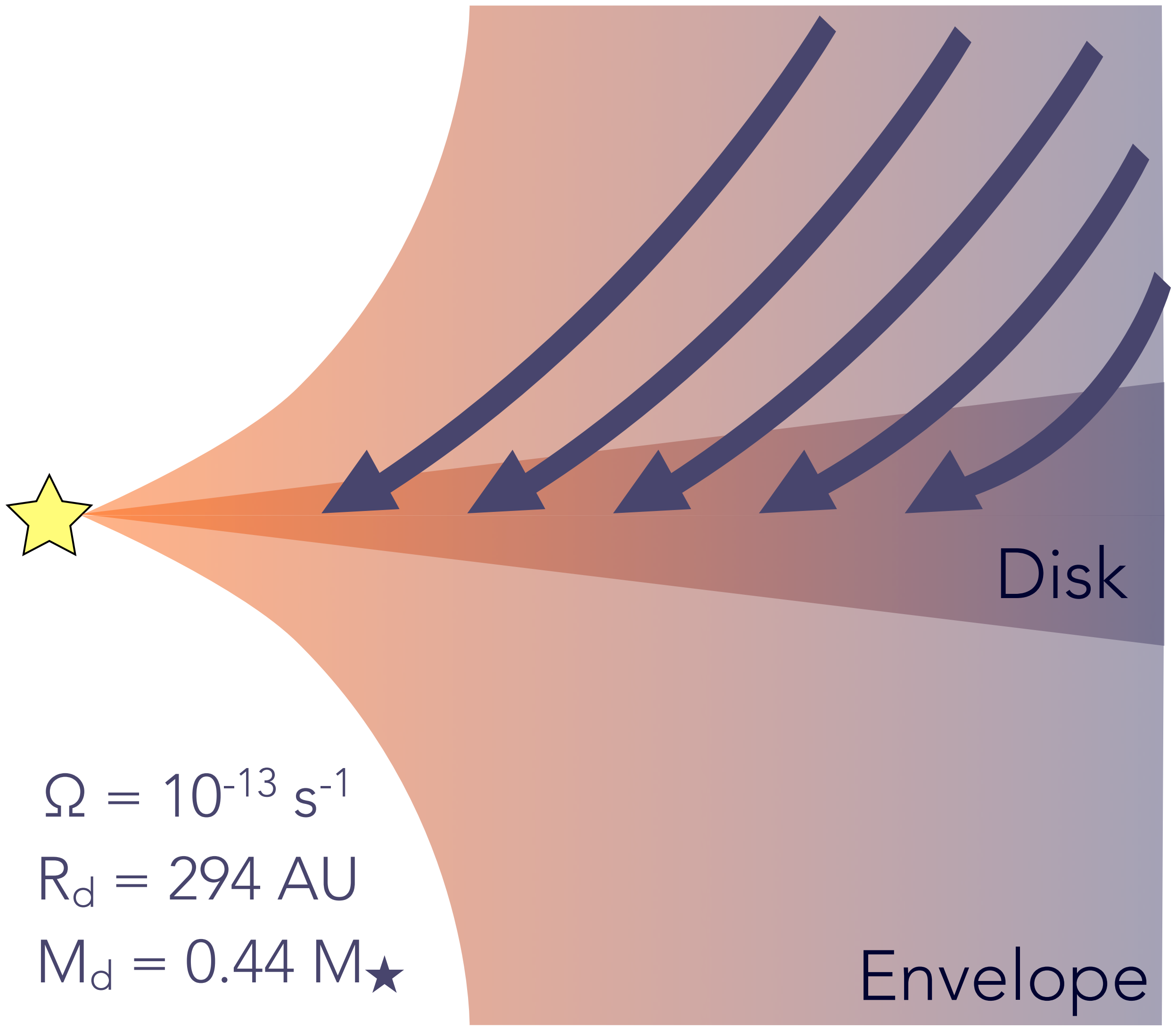
G. Fuchs et al. **2009**, *Astron. Astrophys.*, vol. 505, p. 629

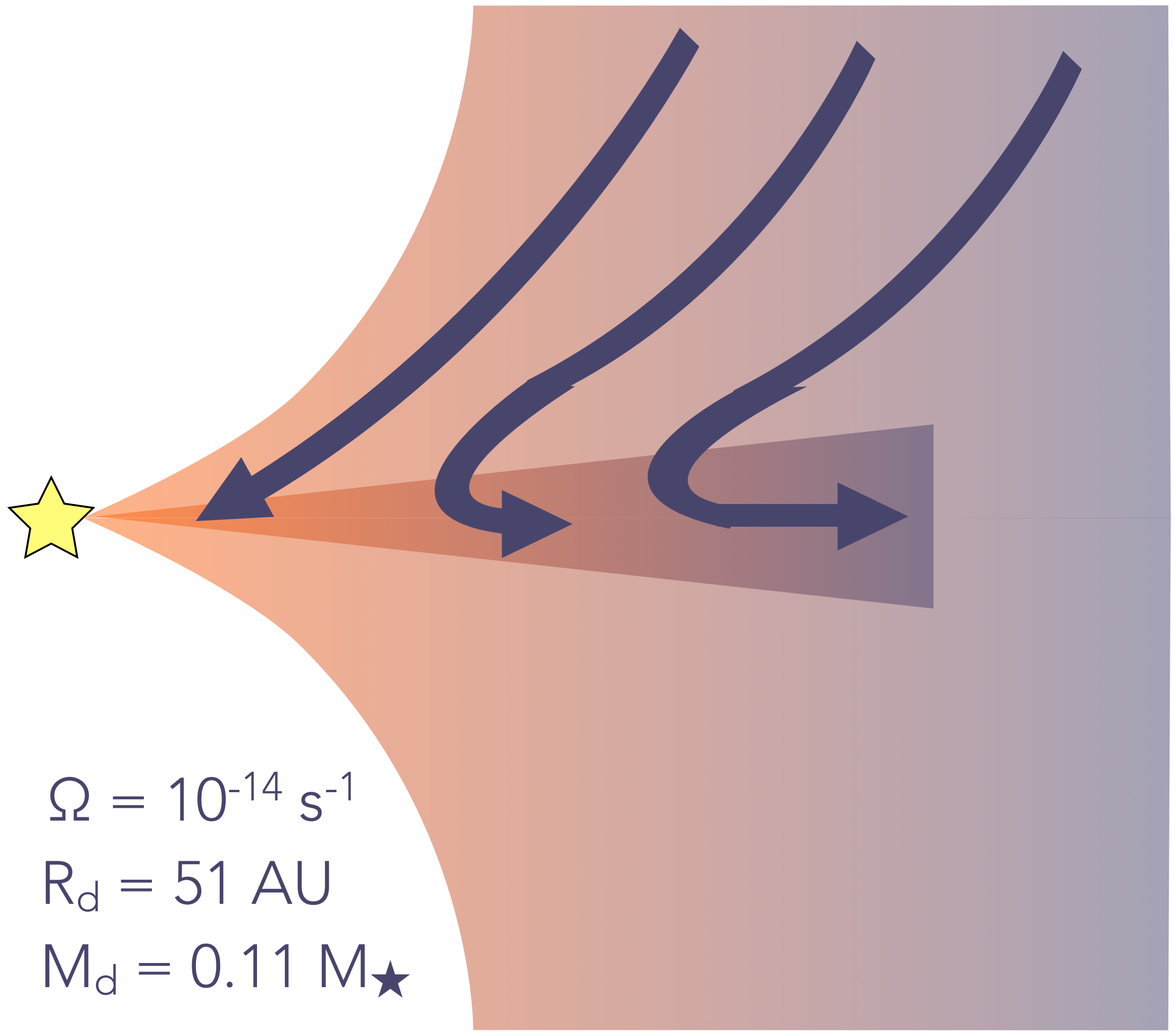
K. Öberg et al. **2009**, *Astron. Astrophys.*, vol. 504, p. 891

G. Fedoseev et al. **2015**, *Mon. Not. Roy. Astron. Soc.*, vol. 448, p. 1288

Inheritance from interstellar/protostellar material?

Two disk formation scenarios: infall versus spreading

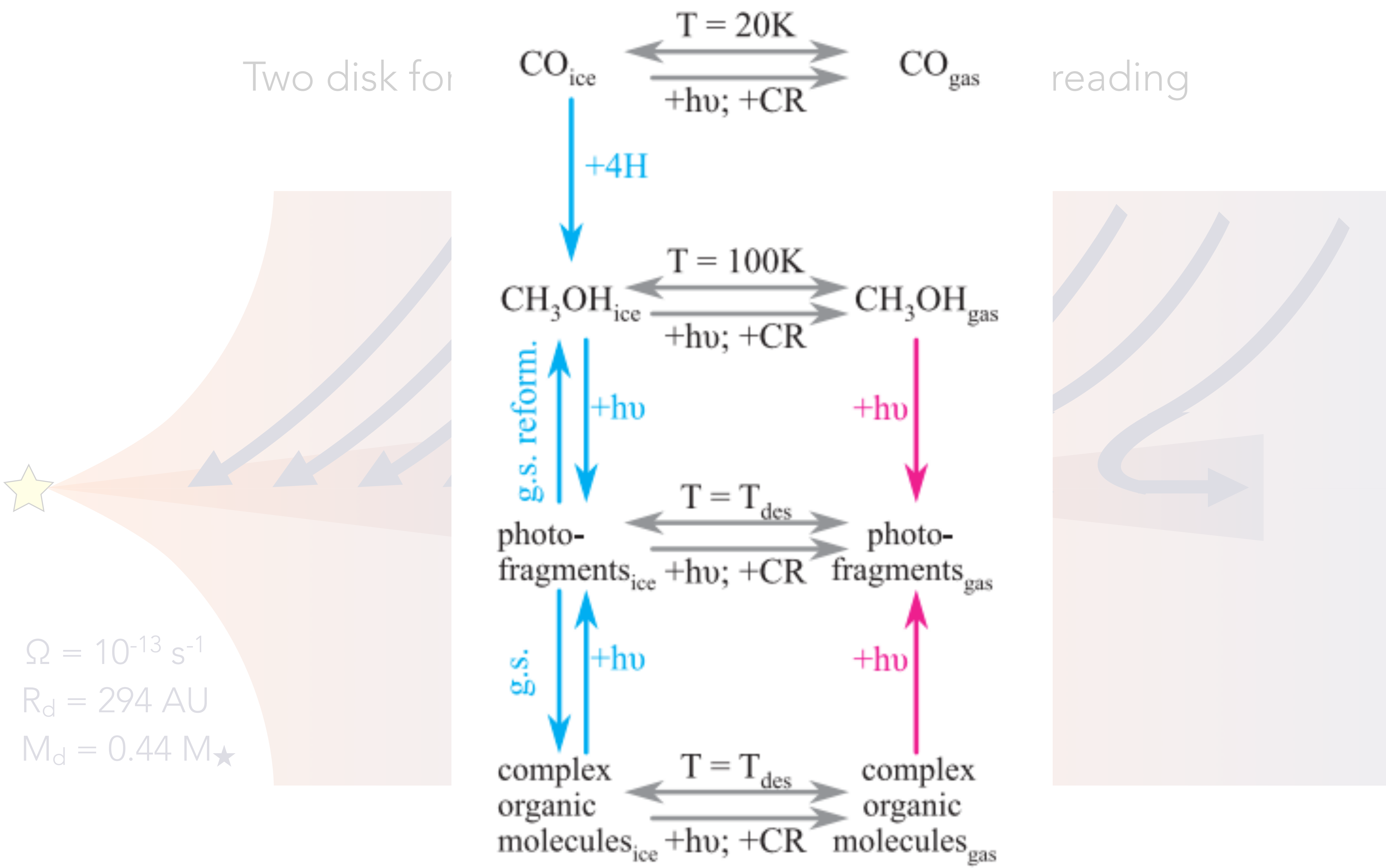




Visser, R., et al. 2009, A&A, 495, 881; Drozdovskaya, M., et al. 2014, MNRAS, 445, 913; Drozdovskaya, M. R., et al. 2016, MNRAS, under review

Inheritance from interstellar/protostellar material?

Two disk for reading



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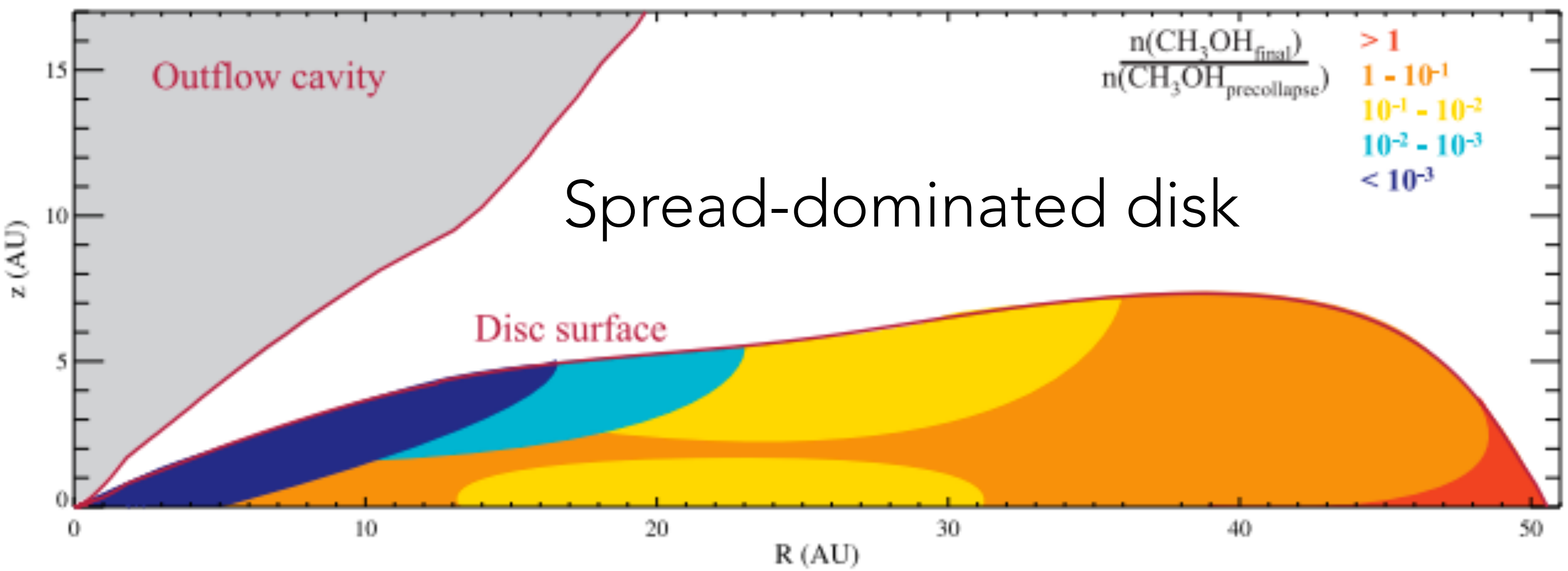
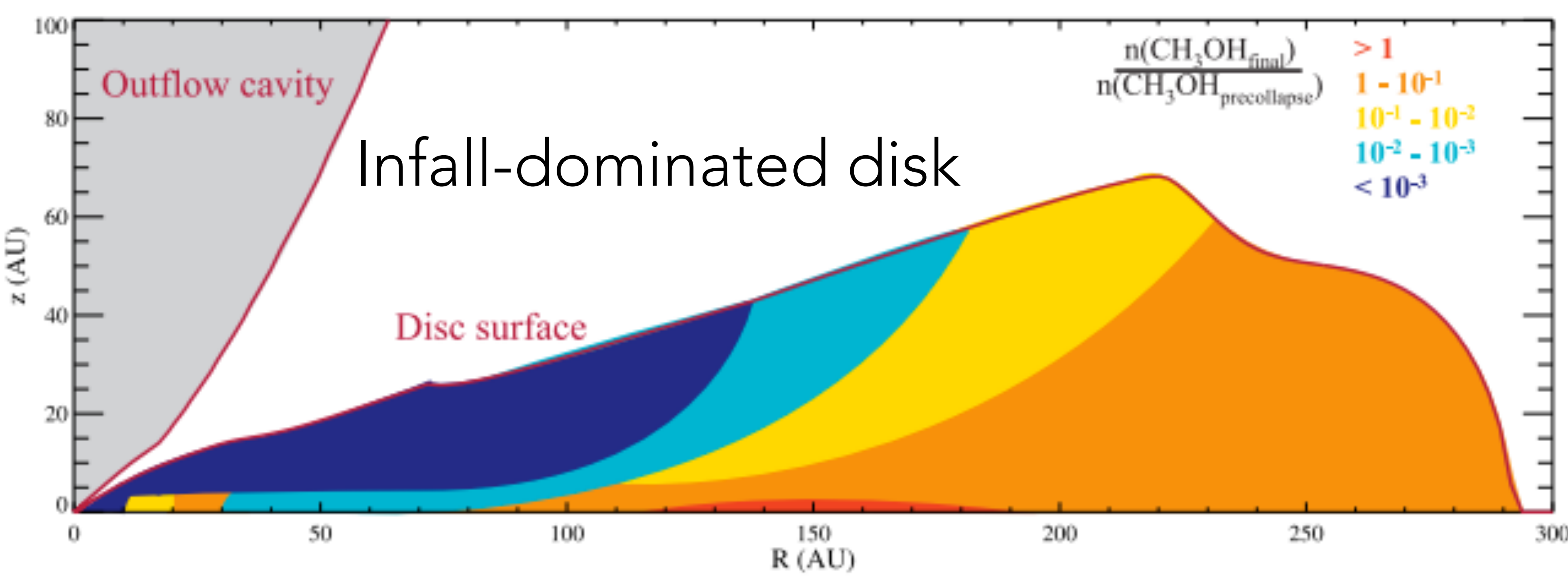
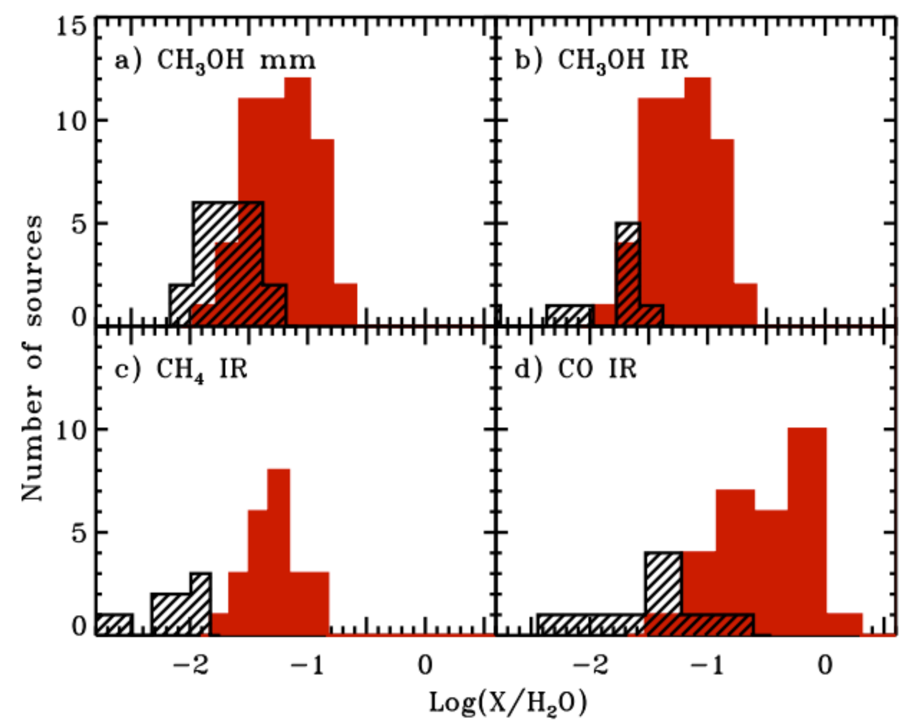
Inheritance from interstellar/protostellar material?

Methanol ice abundance relative to initial/prestellar abundance





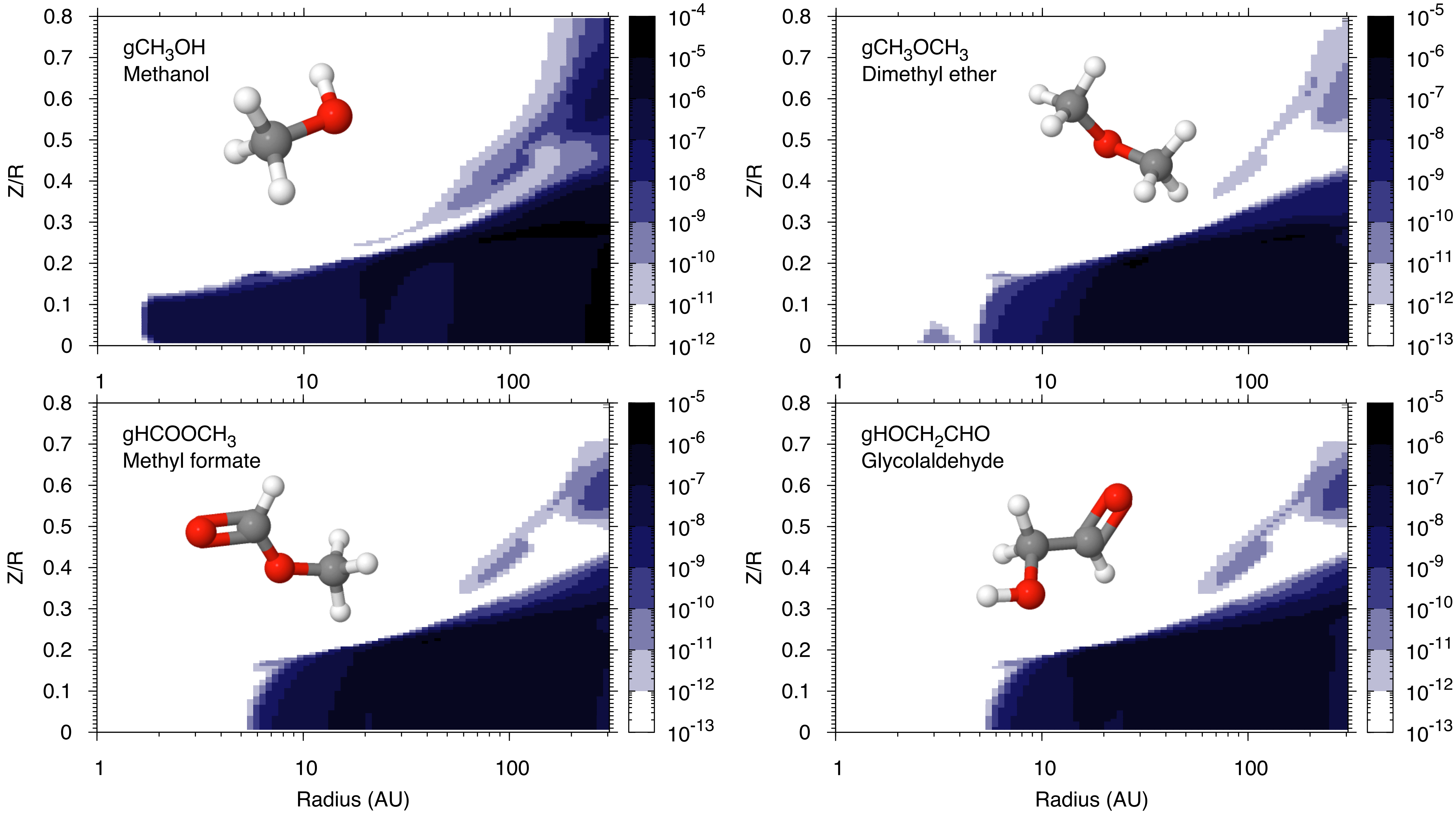
Low-mass protostars



Comets

Can chemical complexity have a disk origin?

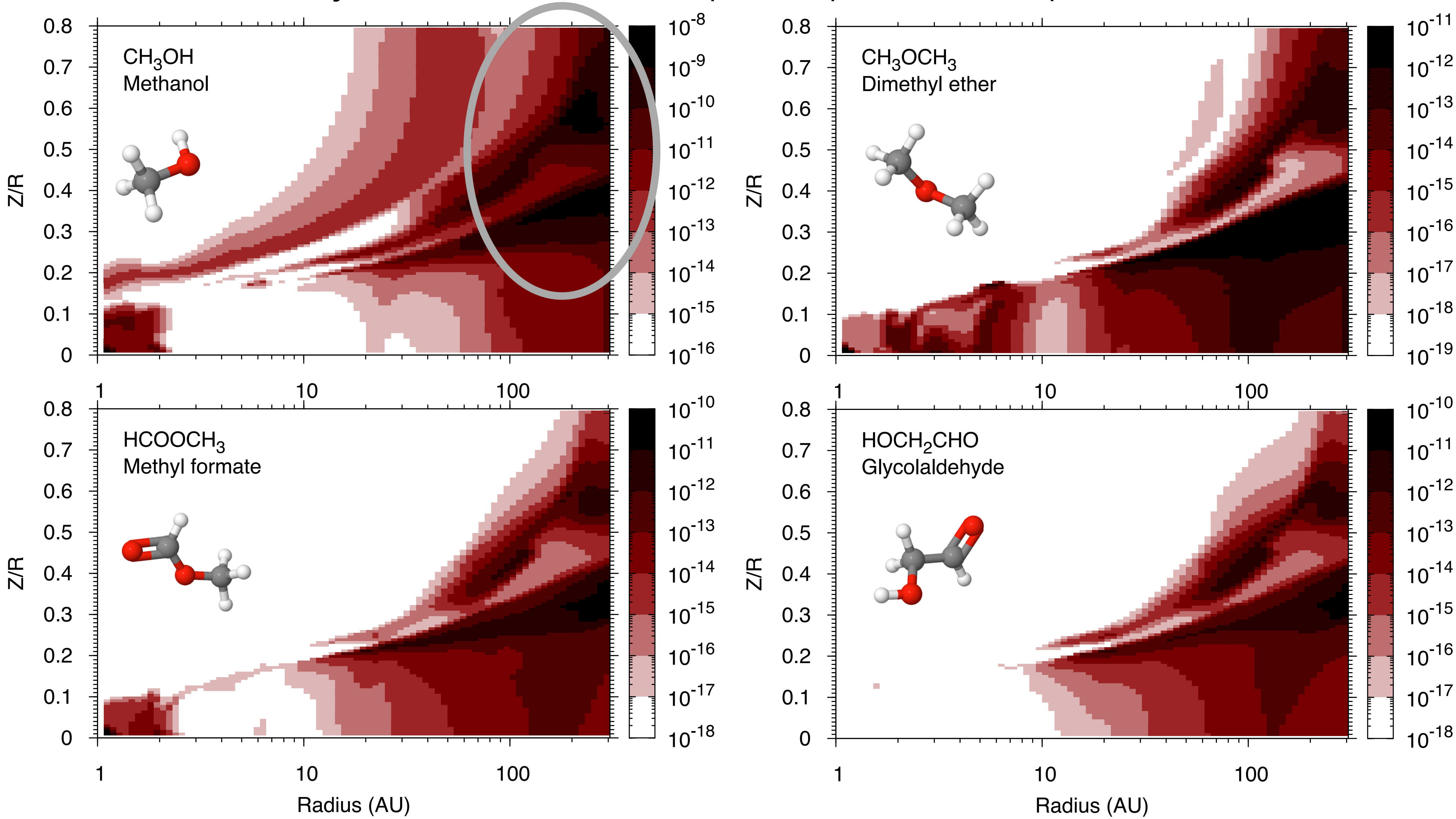
Complex molecule ices can form efficiently from simple ices in the cold outer disk midplane



Walsh, C., et al. 2014, A&A, 563, A33; Walsh, C., et al. 2014, Faraday Disk. 168, 389

Are complex molecules observable in disks?

Gas-phase complex molecules are released into the disk atmosphere by non-thermal desorption (photodesorption)



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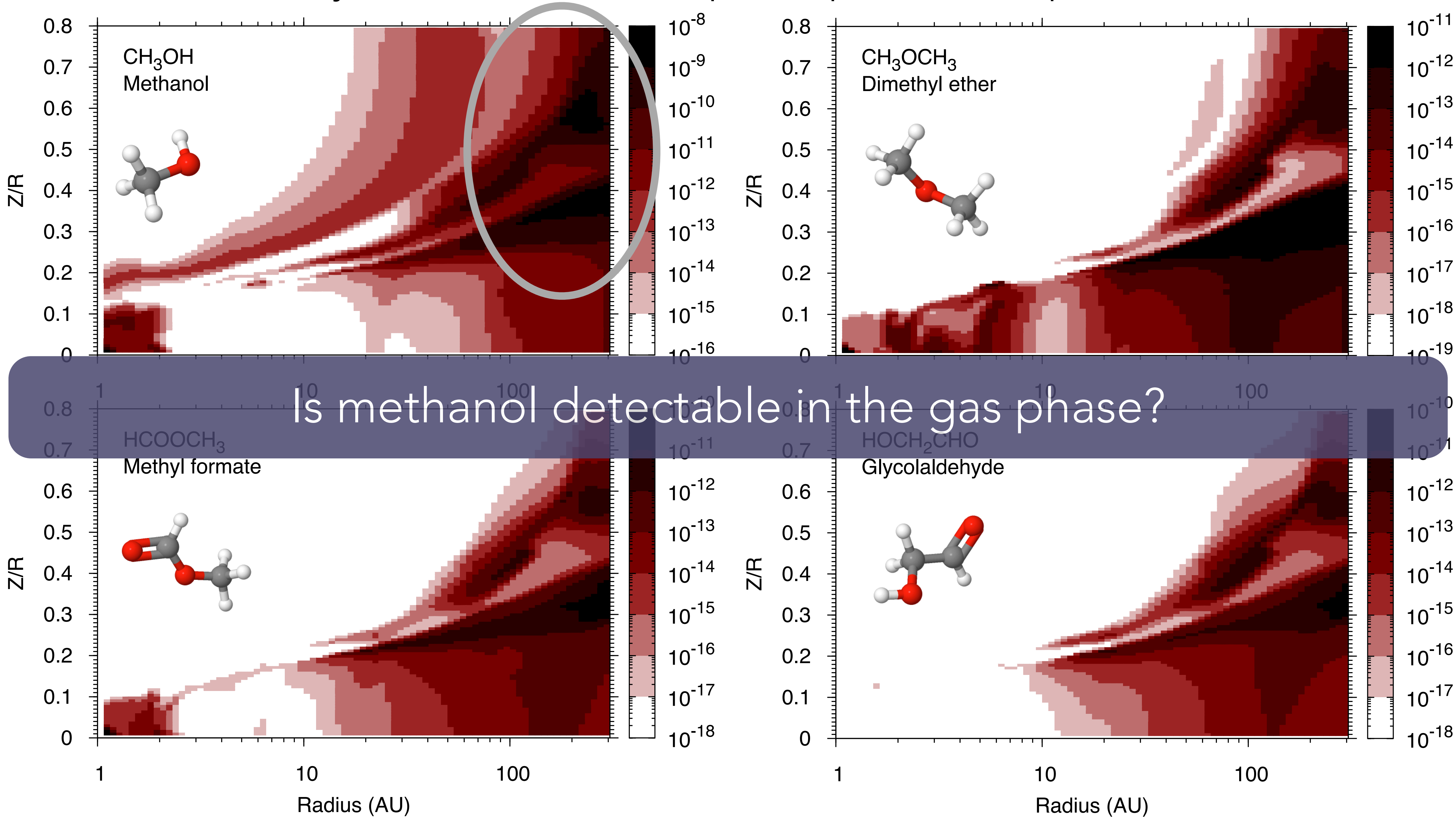
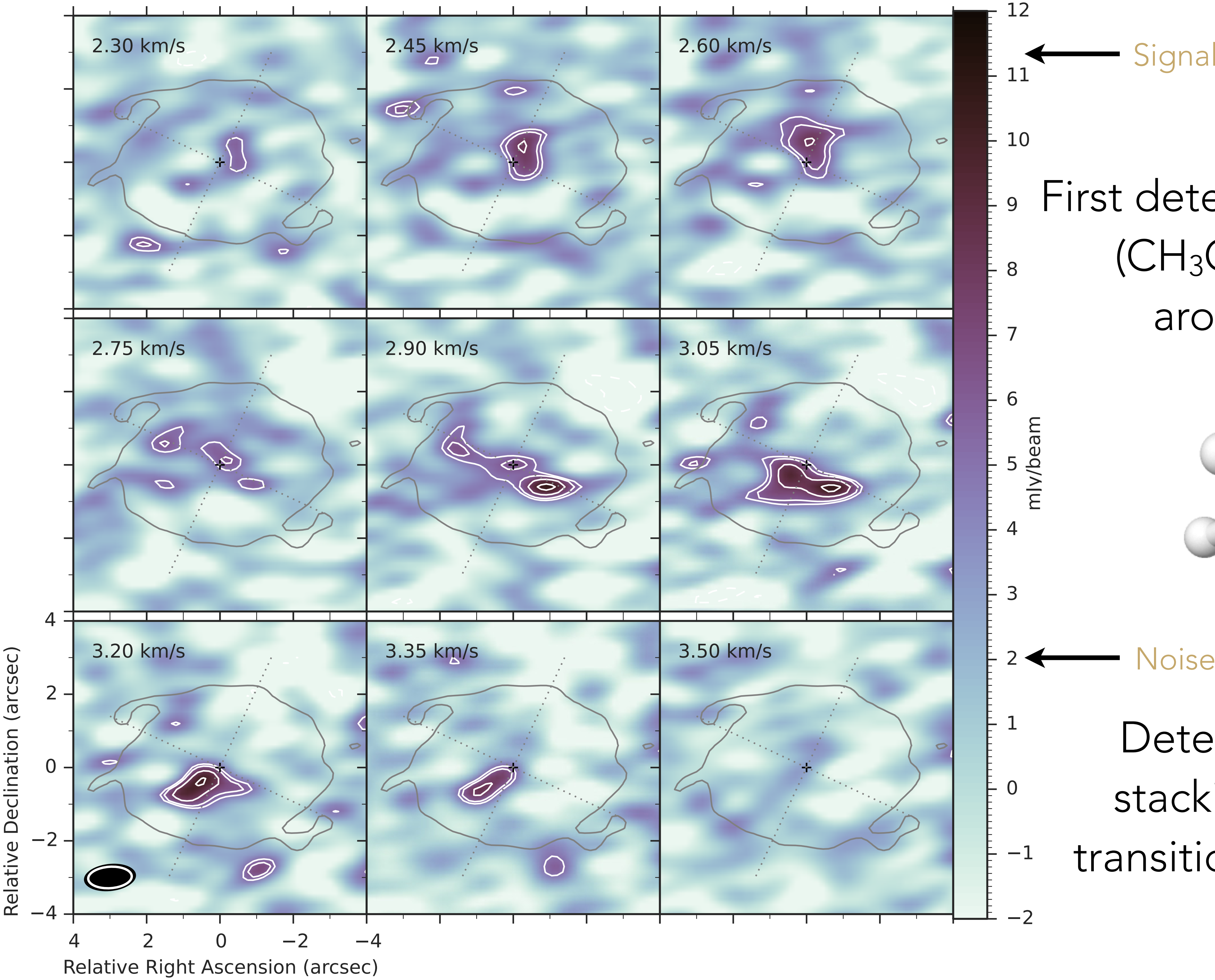


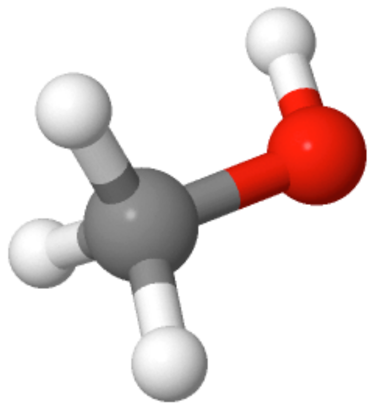
Is methanol detectable in the gas phase?

Walsh, C., et al. 2014, A&A, 563, A33; Walsh, C., et al. 2014, Faraday Disk. 168, 389

Yes it is - but it needs ALMA!



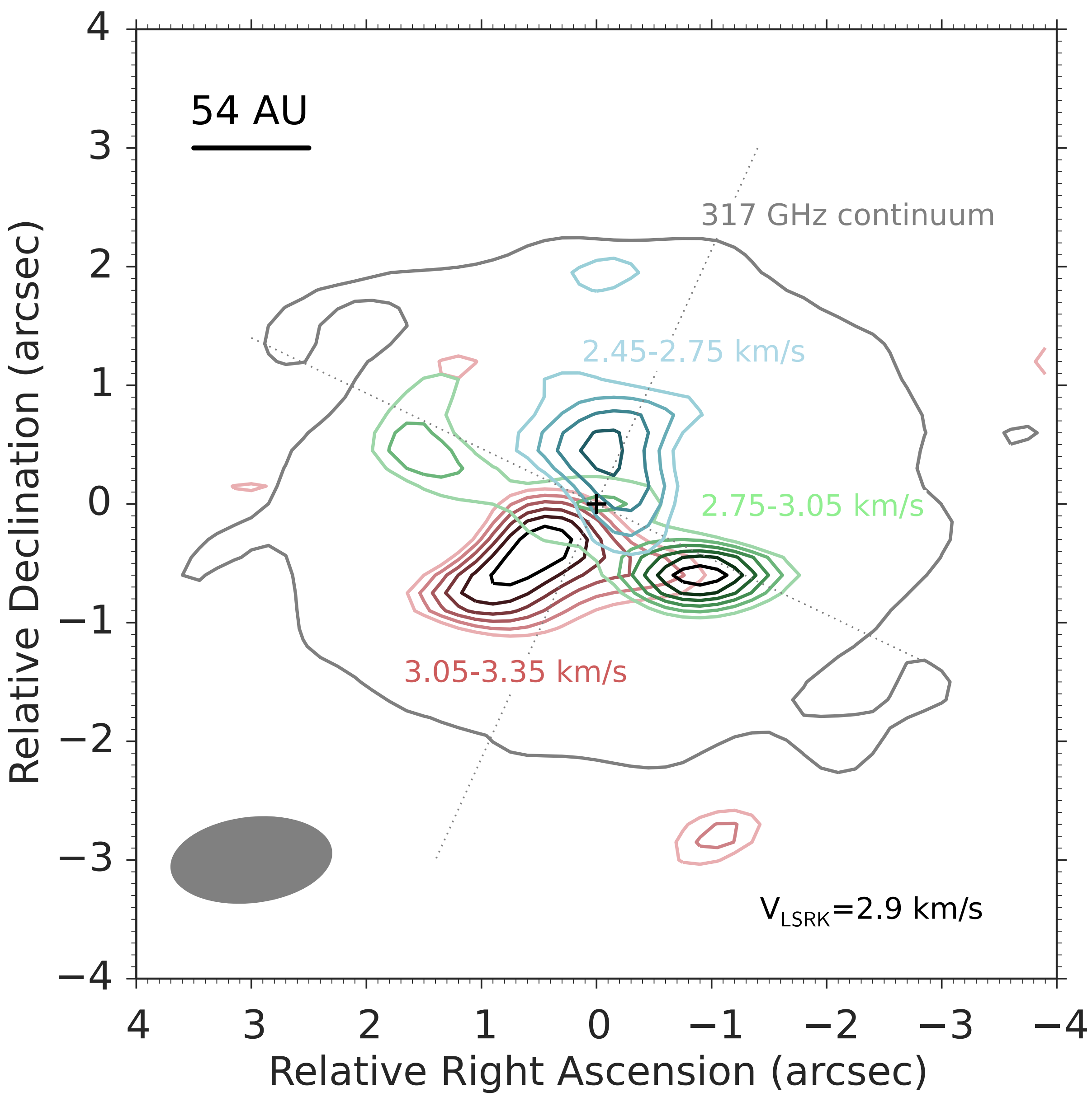
First detection of methanol (CH_3OH) in the disk around TW Hya

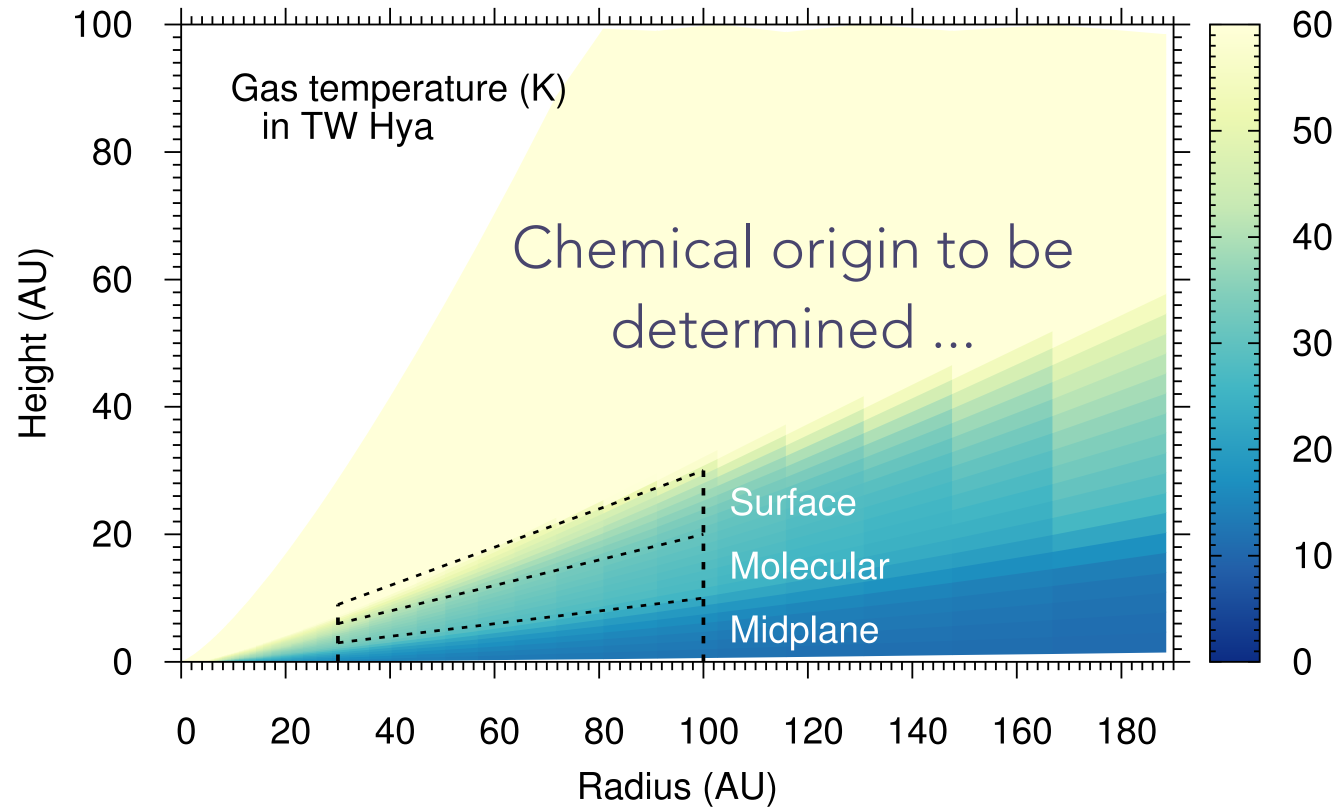


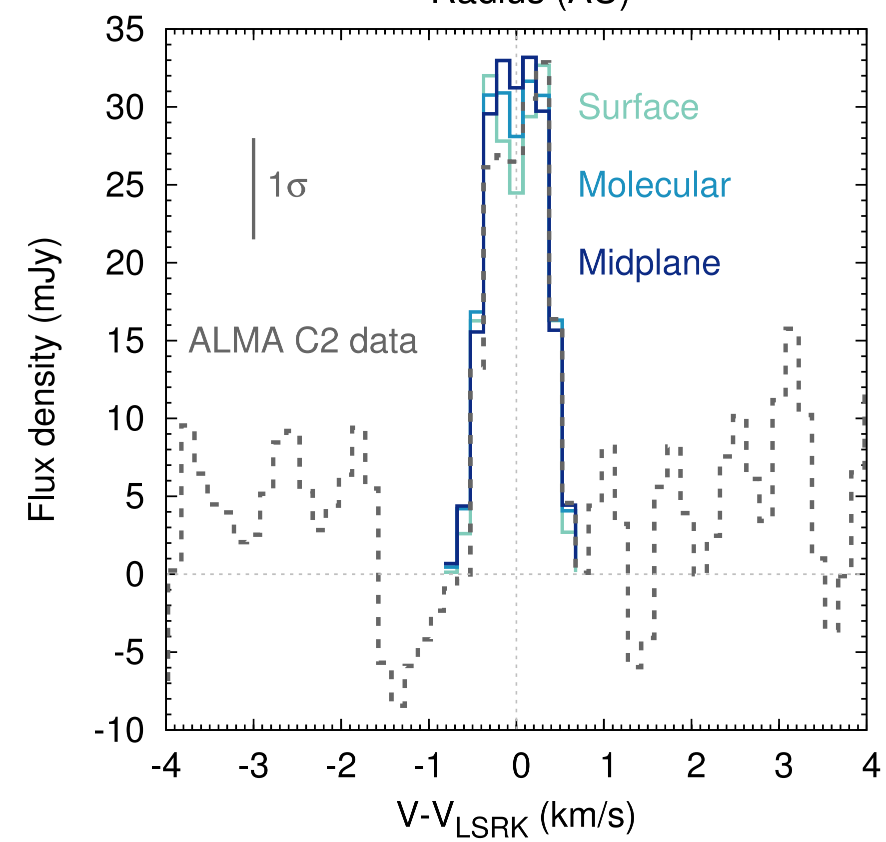
Detection required stacking of multiple transitions in uv domain

Walsh, C. et al. 2016, ApJL, 823, L10

Gas-phase methanol in TW Hya





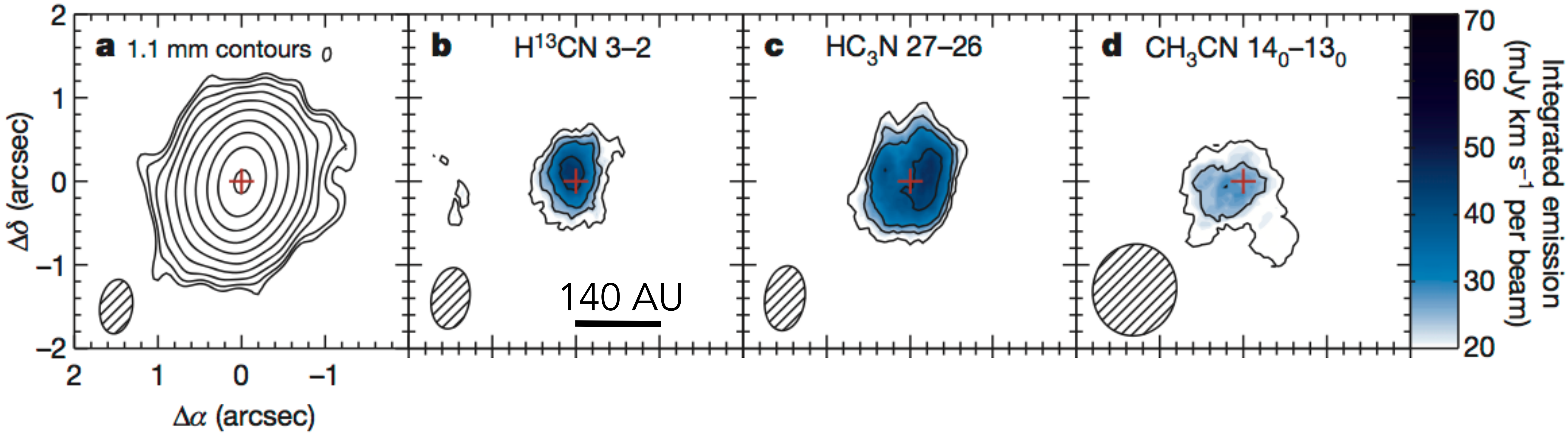


Radial location loosely constrained:
30 - 100 AU
Vertical location unconstrained

Gas-phase methyl cyanide in MWC 480

First detection of methyl cyanide (acetonitrile) in the disk around MWC 480

MWC 480 is a Herbig Ae star: $T_{eff} \approx 8{,}000$ K



Emission is compact and central - tracing sublimation of the ice reservoir?

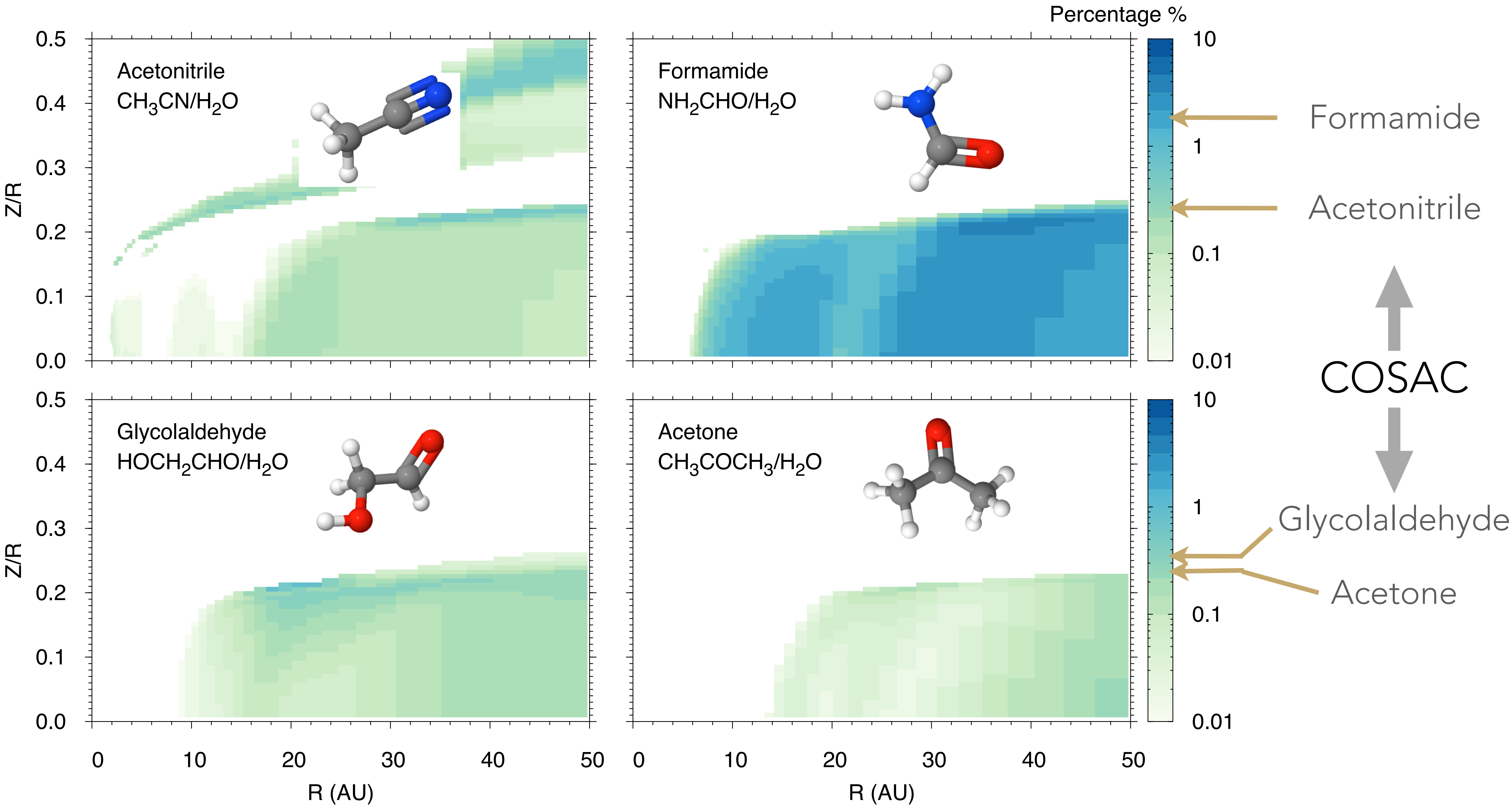
CH_3CN/HCN ratio (≈5 - 20 %) similar to that seen in comet comae (≈10 %)

Also similar to that seen on surface (≈30 %) and in coma (≈3 - 7 %) of 67P/C-G

Öberg, K. I., et al. 2015, Nature, 520, 198; Mumma, M. & Charnley, S. 2011, ARAA, 49, 471, Le Roy, L. et al. 2015, A&A, 583, A1

Can chemical complexity have a disk origin?

What does the disk model predict for the icy sub-surface complex molecules observed with COSAC?



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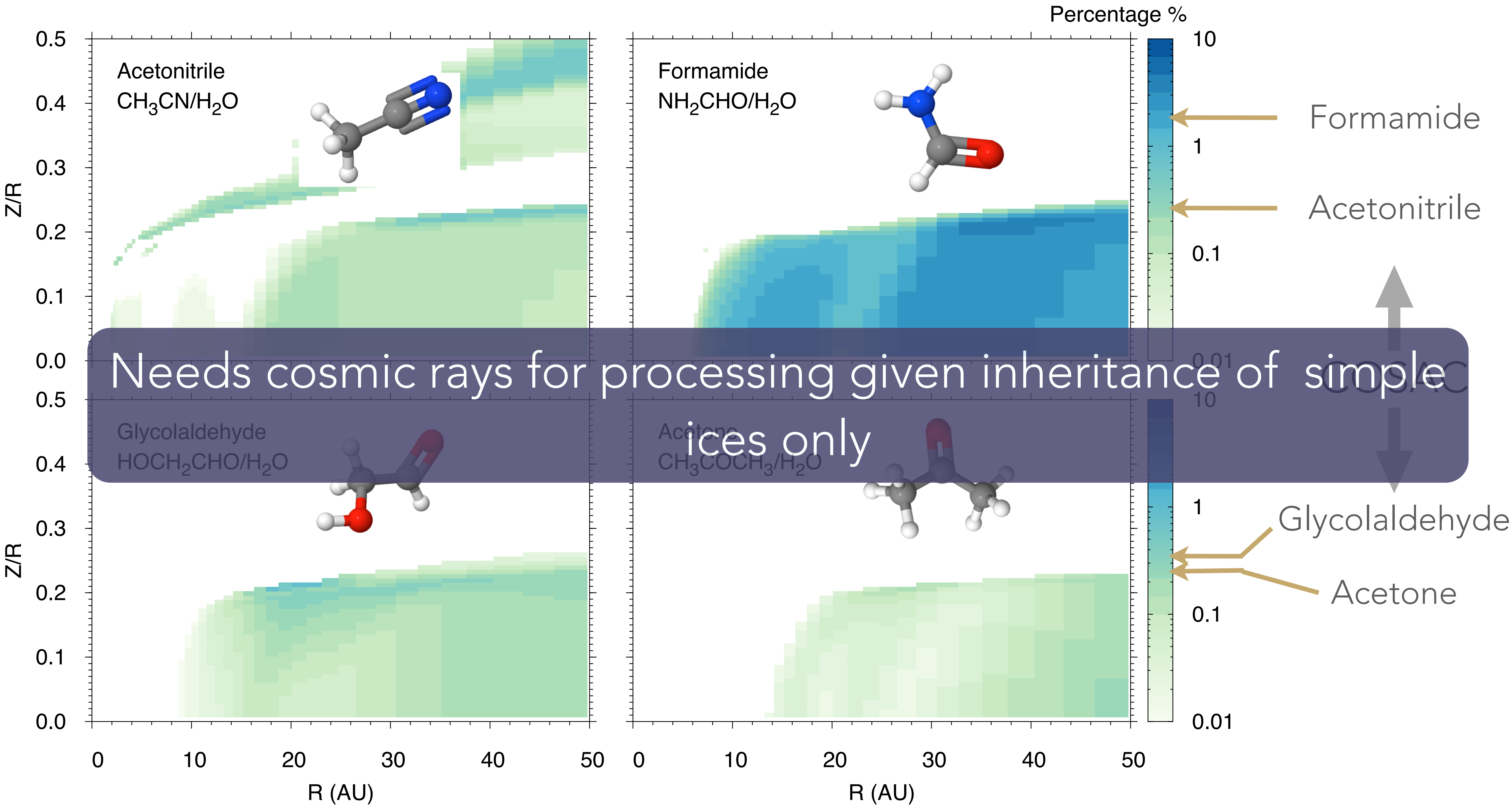
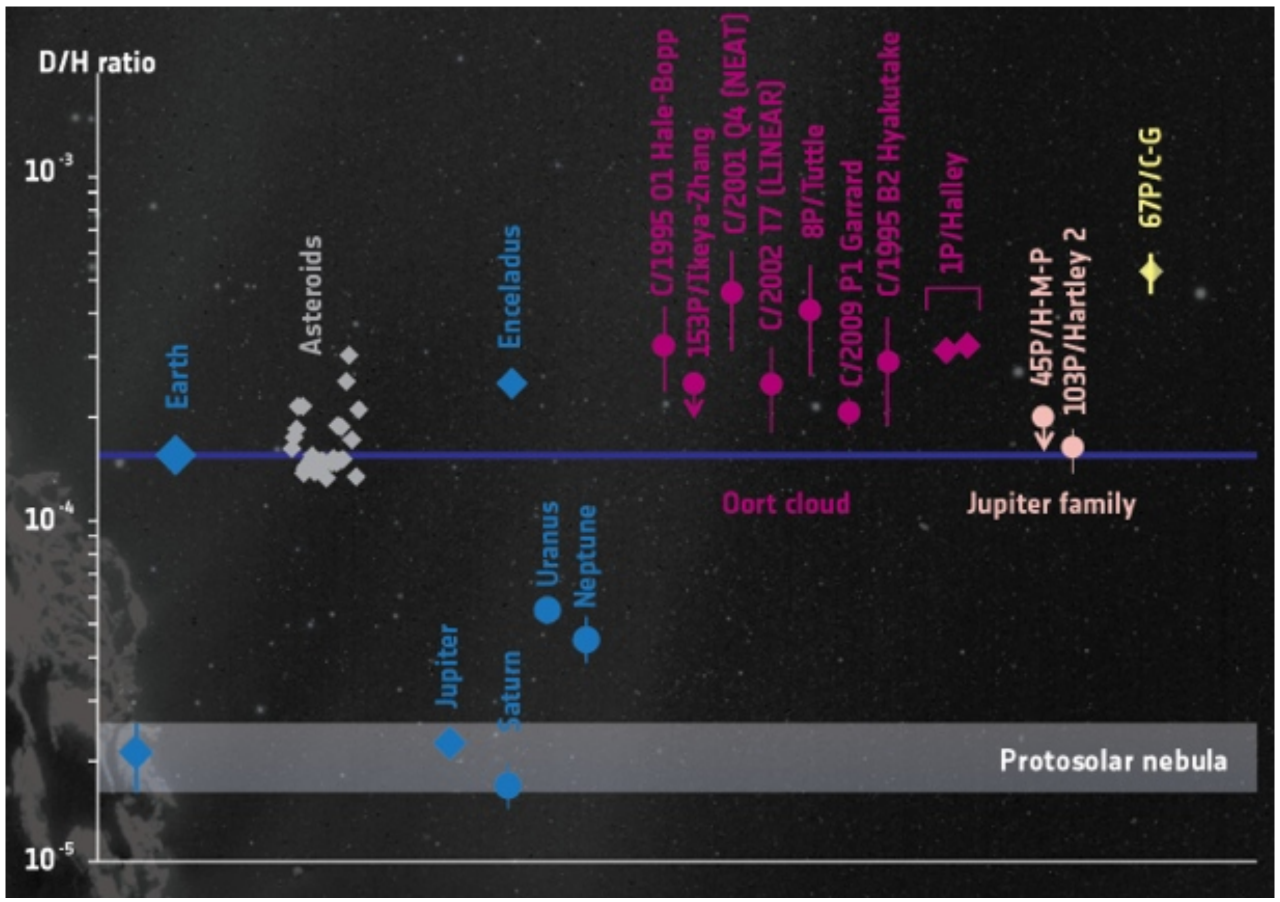
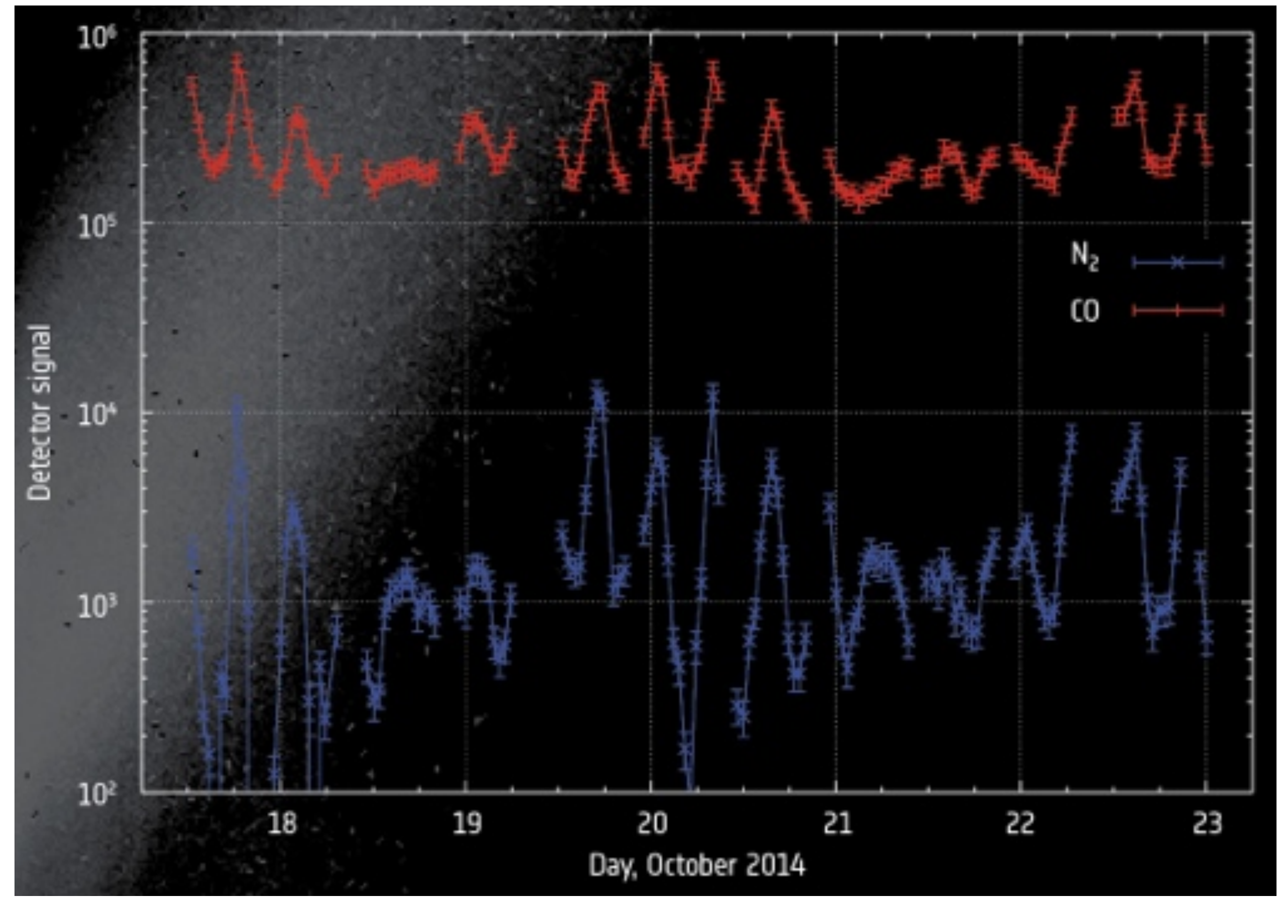


Needs cosmic rays for processing given inheritance of simple ices only

67P/C-G with Rosetta/ROSINA

Rosetta Orbiter Spectrometer for Ion and Neutral Analysis





$HDO/H_2O \approx (5.3 \pm 0.7)\times10^{-4}$

3 times higher than terrestrial value

$N_2/CO \approx (5.7 \pm 0.7)\times10^{-3}$

25 times lower than protostellar value

Altwegg, K. et al. 2015, Science, 347, 387; Rubin, M. et al. 2015, Science, 348, 232

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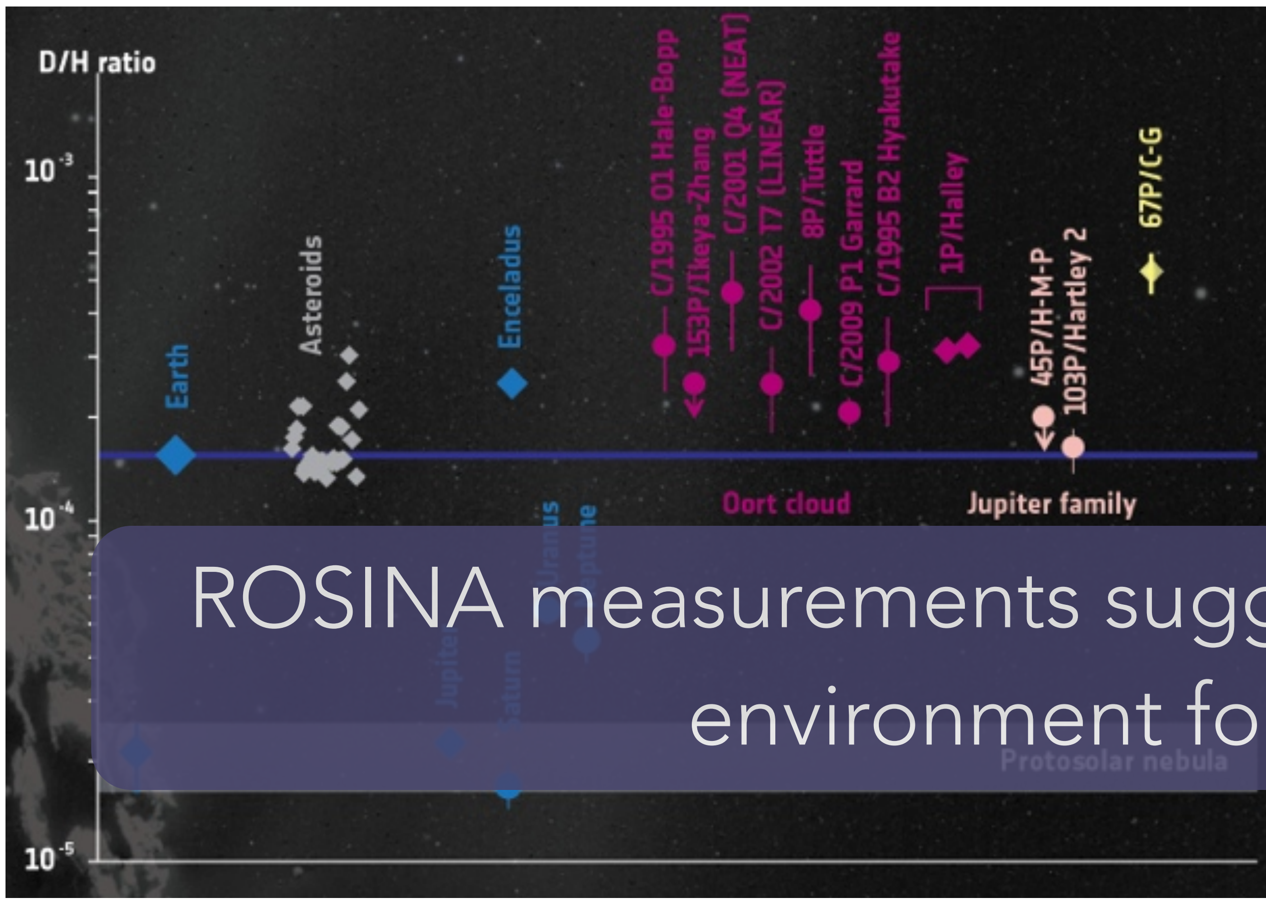

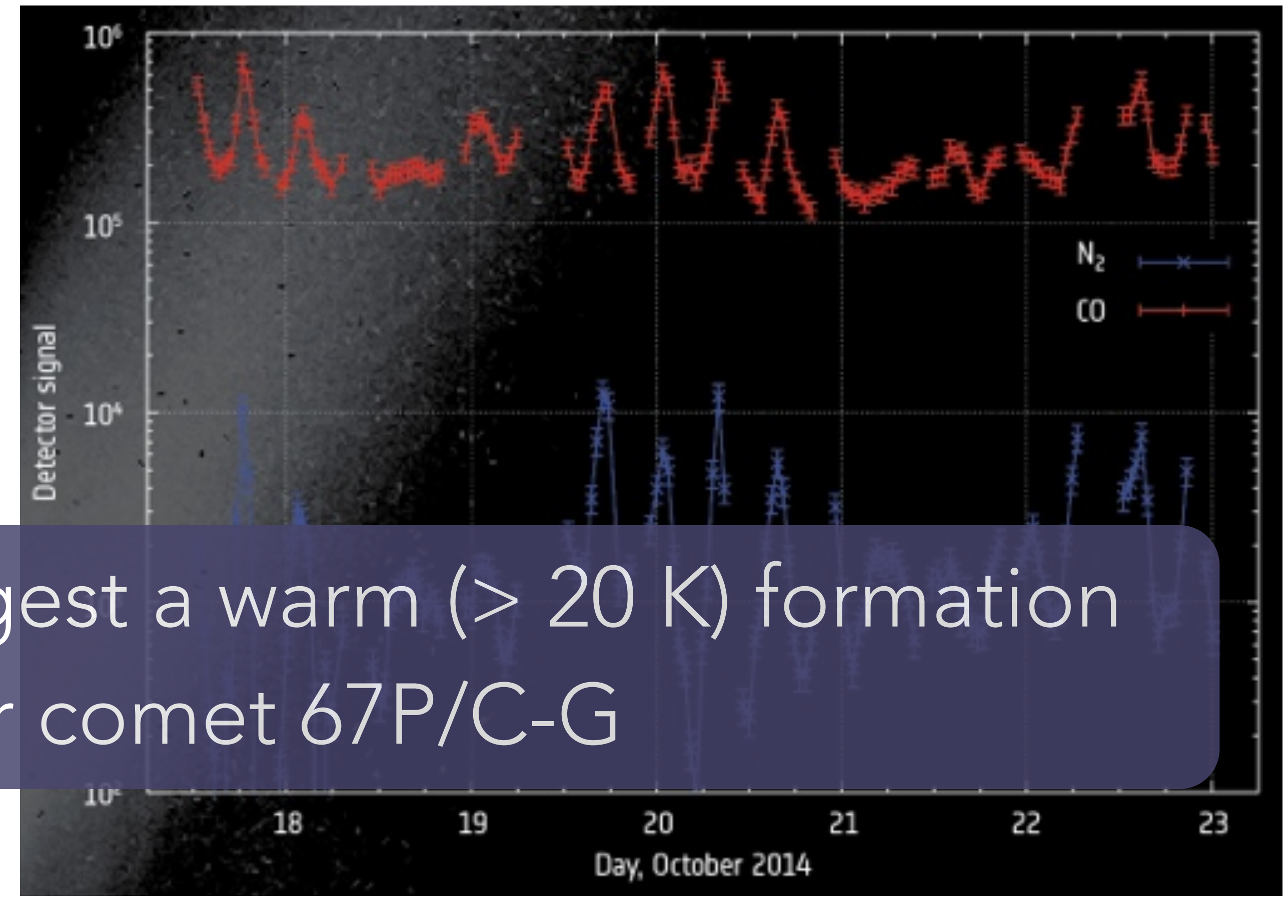

ROSINA measurements suggest a warm (> 20 K) formation environment for comet 67P/C-G

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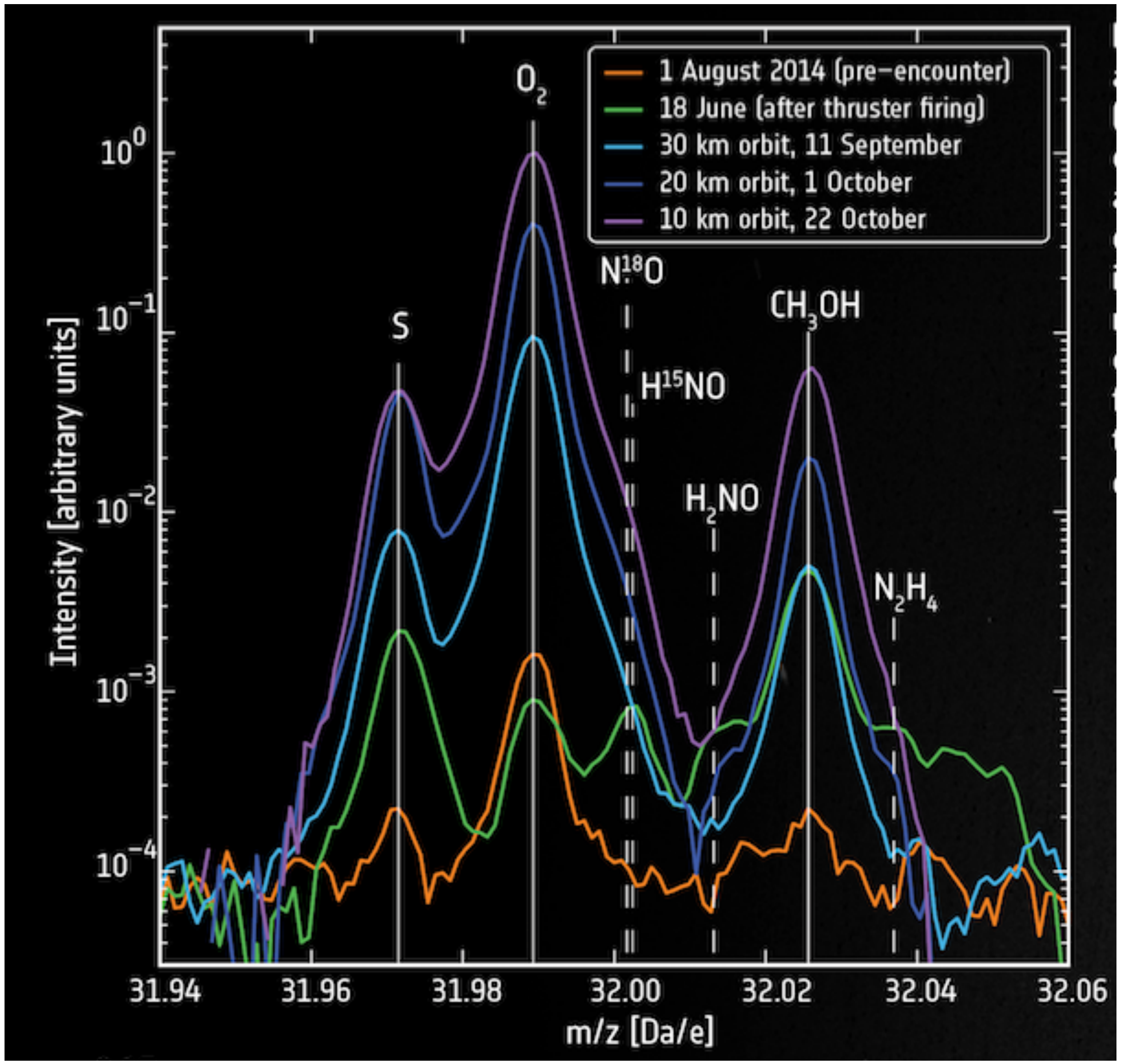
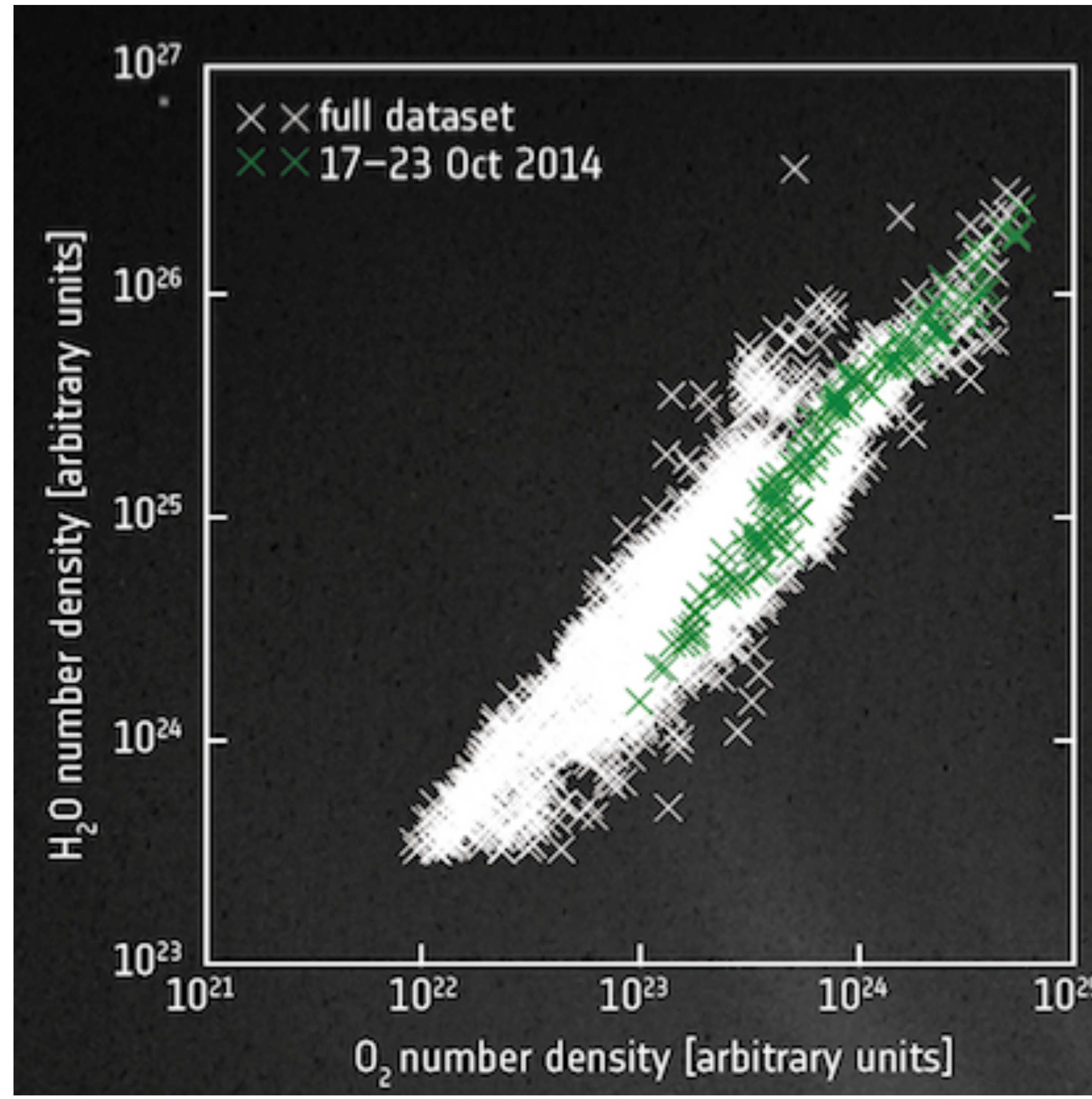
67P/C-G with Rosetta/ROSINA

First detection of molecular oxygen in a comet ($O_2/H_2O \approx 4\%$)!





Very strongly associated with water: not with other molecules with a similar volatility which show seasonal variations

Bieler, A. et al. 2015, Nature, 526, 678; Rubin, M. et al. 2016, ApJL, 815, L11

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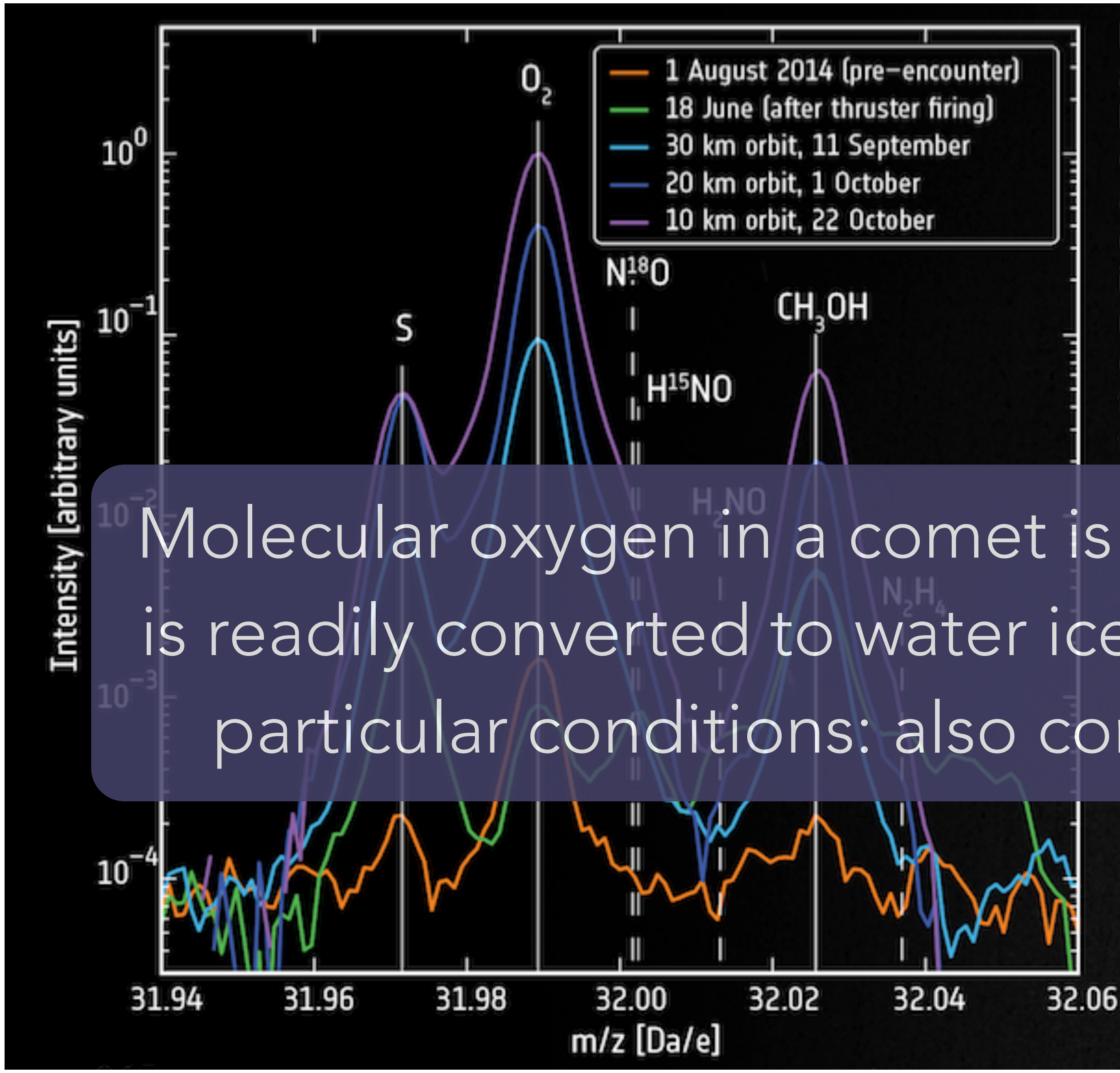
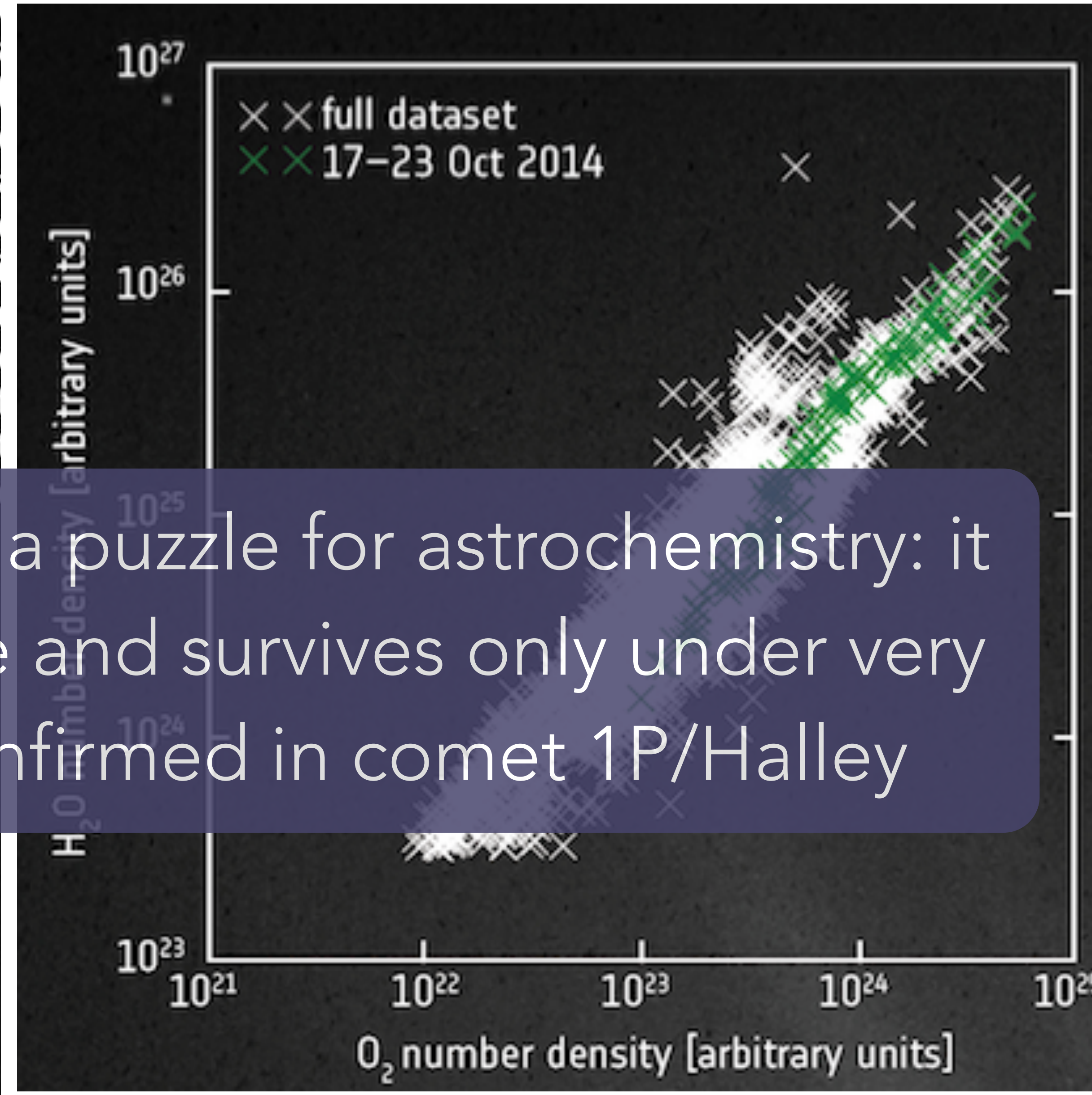


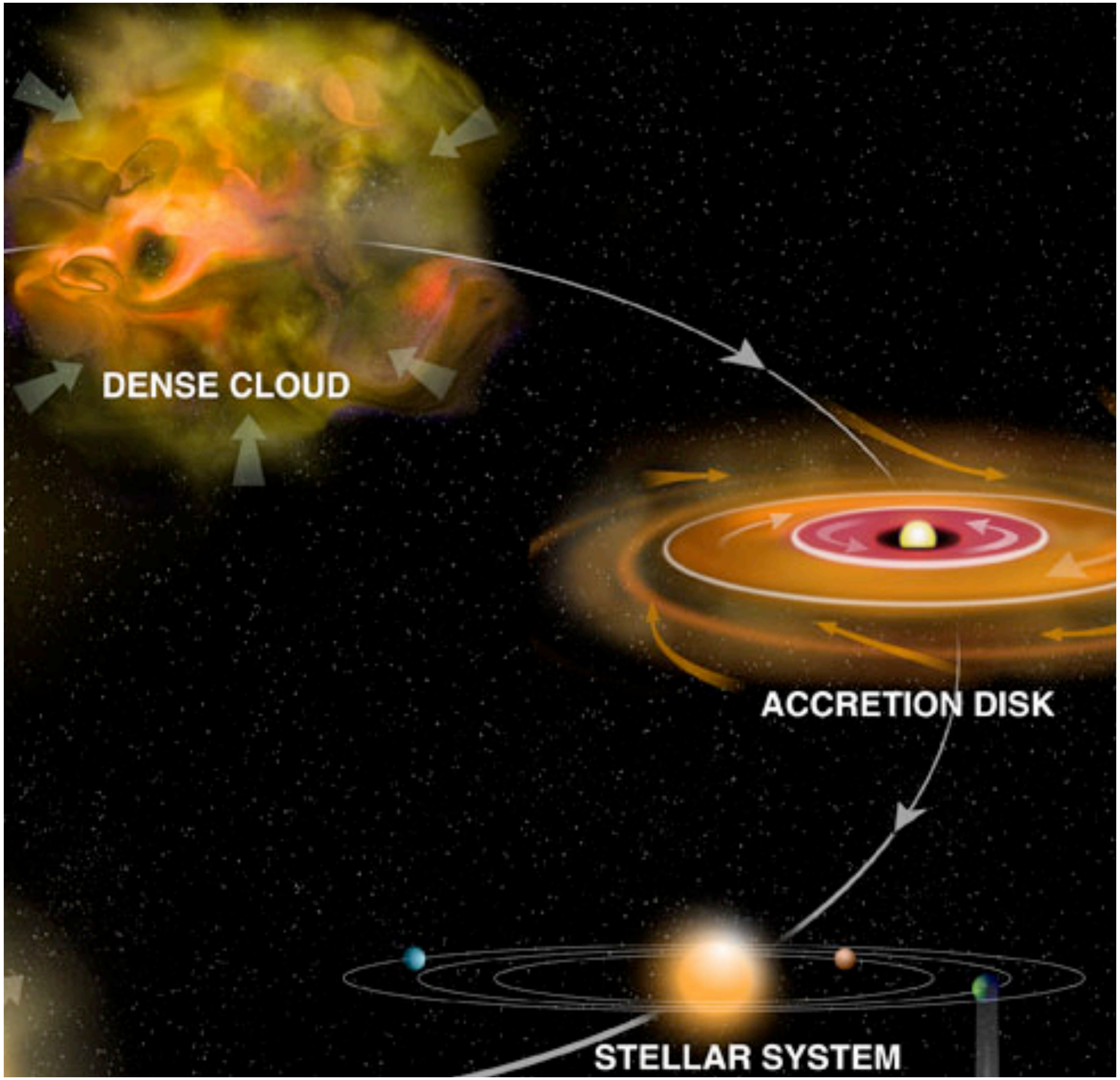


Molecular oxygen in a comet is a puzzle for astrochemistry: it is readily converted to water ice and survives only under very particular conditions: also confirmed in comet 1P/Halley

Very strongly associated with water: not with other molecules with a similar volatility which show seasonal variations

Bieler, A. et al. 2015, Nature, 526, 678; Rubin, M. et al. 2016, ApJL, 815, L11

On the origin of O_2 in 67P/C-G



Cloud origin: natal molecular cloud was in a warm (~ 20 K) and dense environment, externally irradiated by solar siblings?

Disk origin: processing of porous water-rich ice at warm temperatures or trapping of gas-phase O_2?

Comet origin: processing during storage phase? 67P has lost its outer layers during previous visits to the inner solar system

Taquet, V., Walsh, C., Furuya, K., & van Dishoeck, E. F. 2016, ApJ, in preparation; Eistrup, C., Walsh, C., & van Dishoeck, E. F. 2016, A&A, submitted

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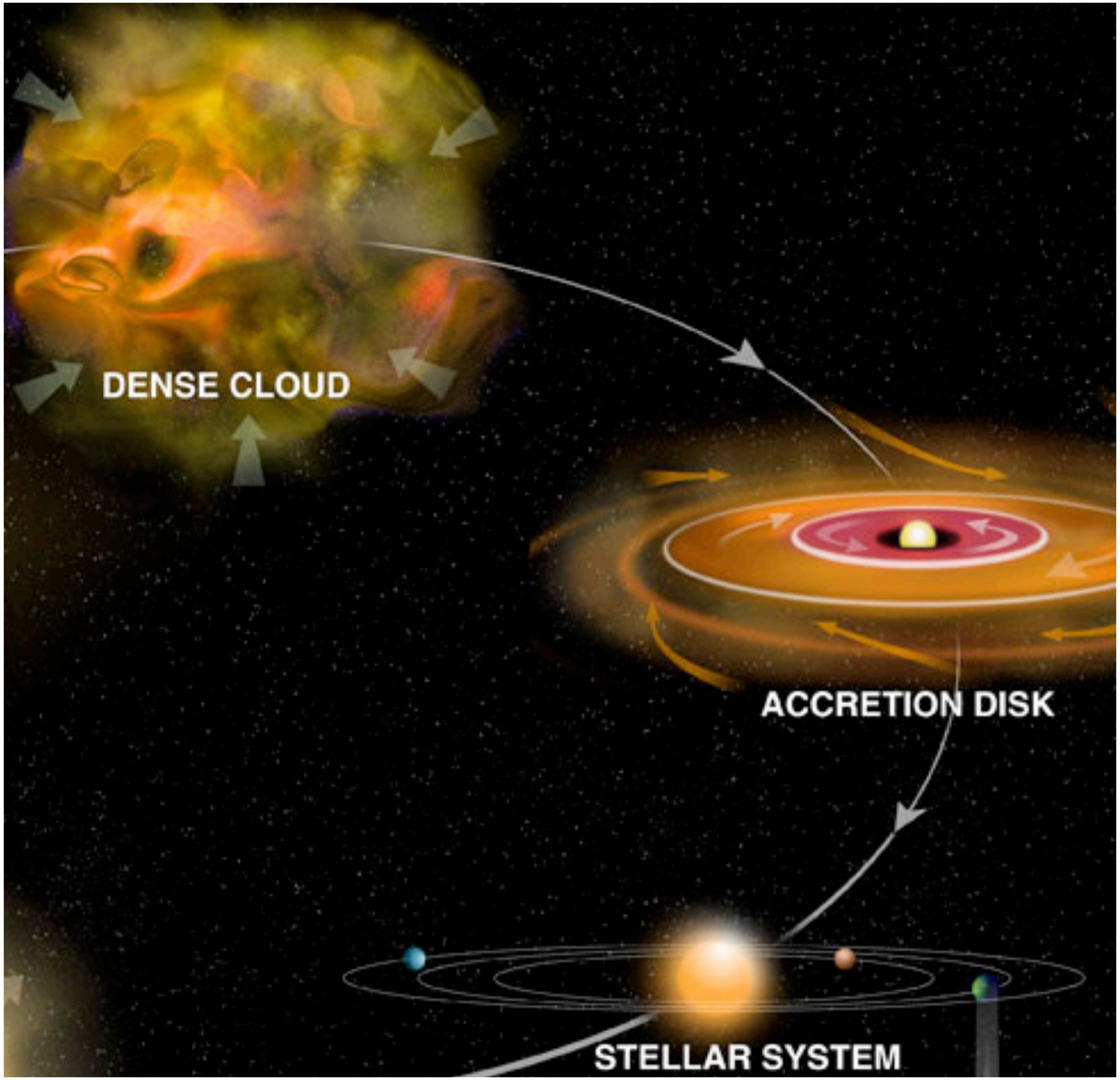

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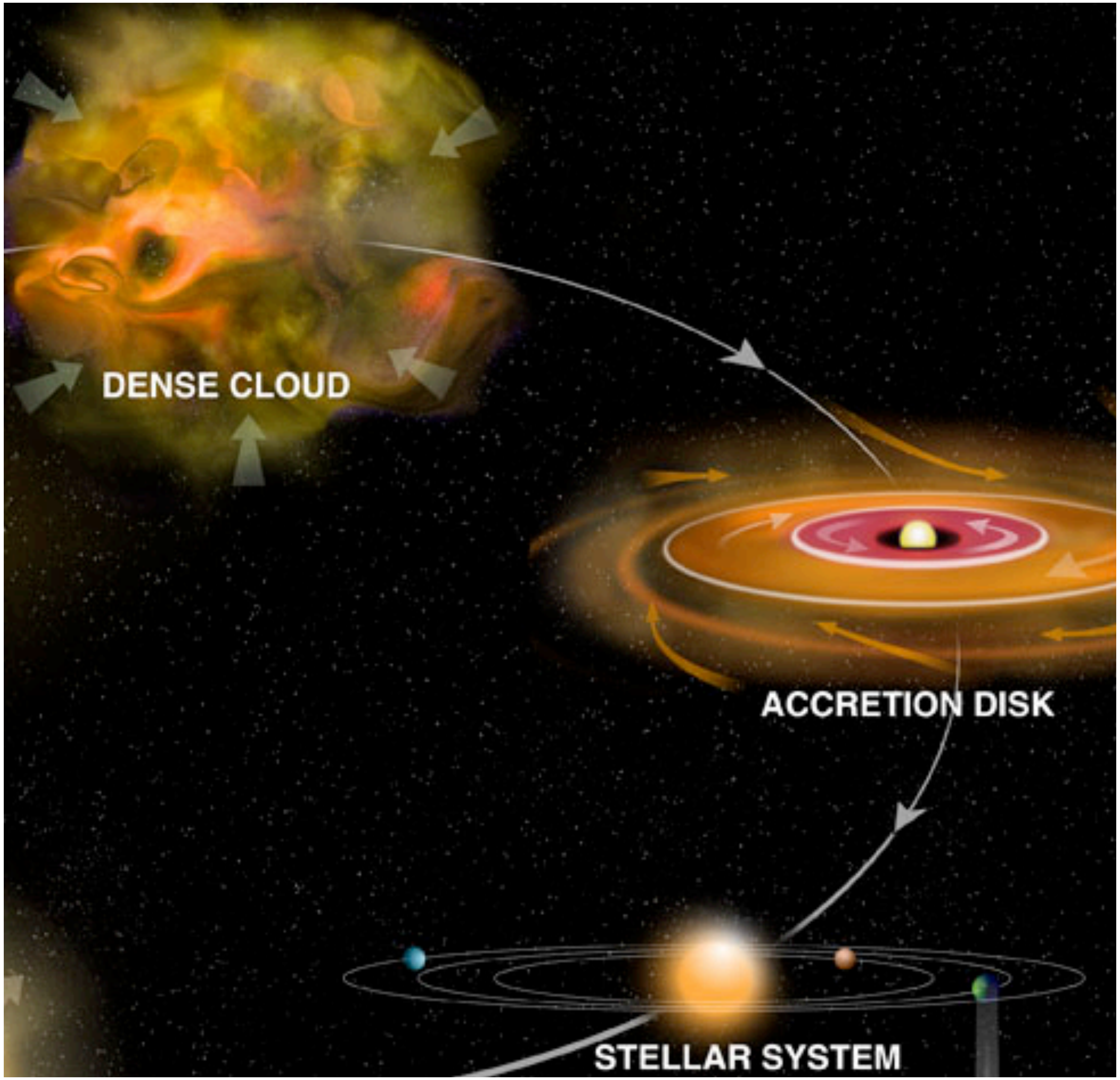

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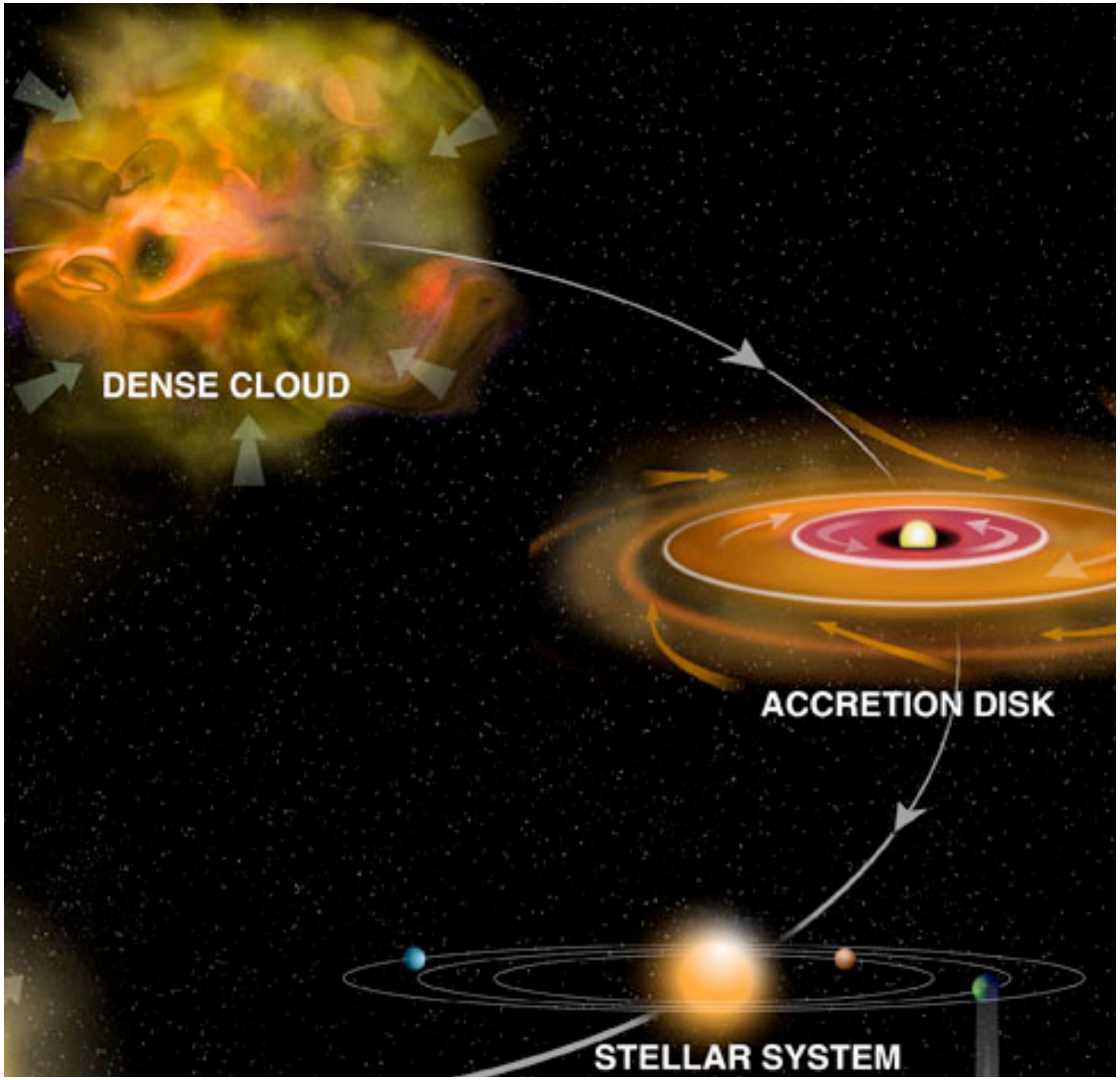

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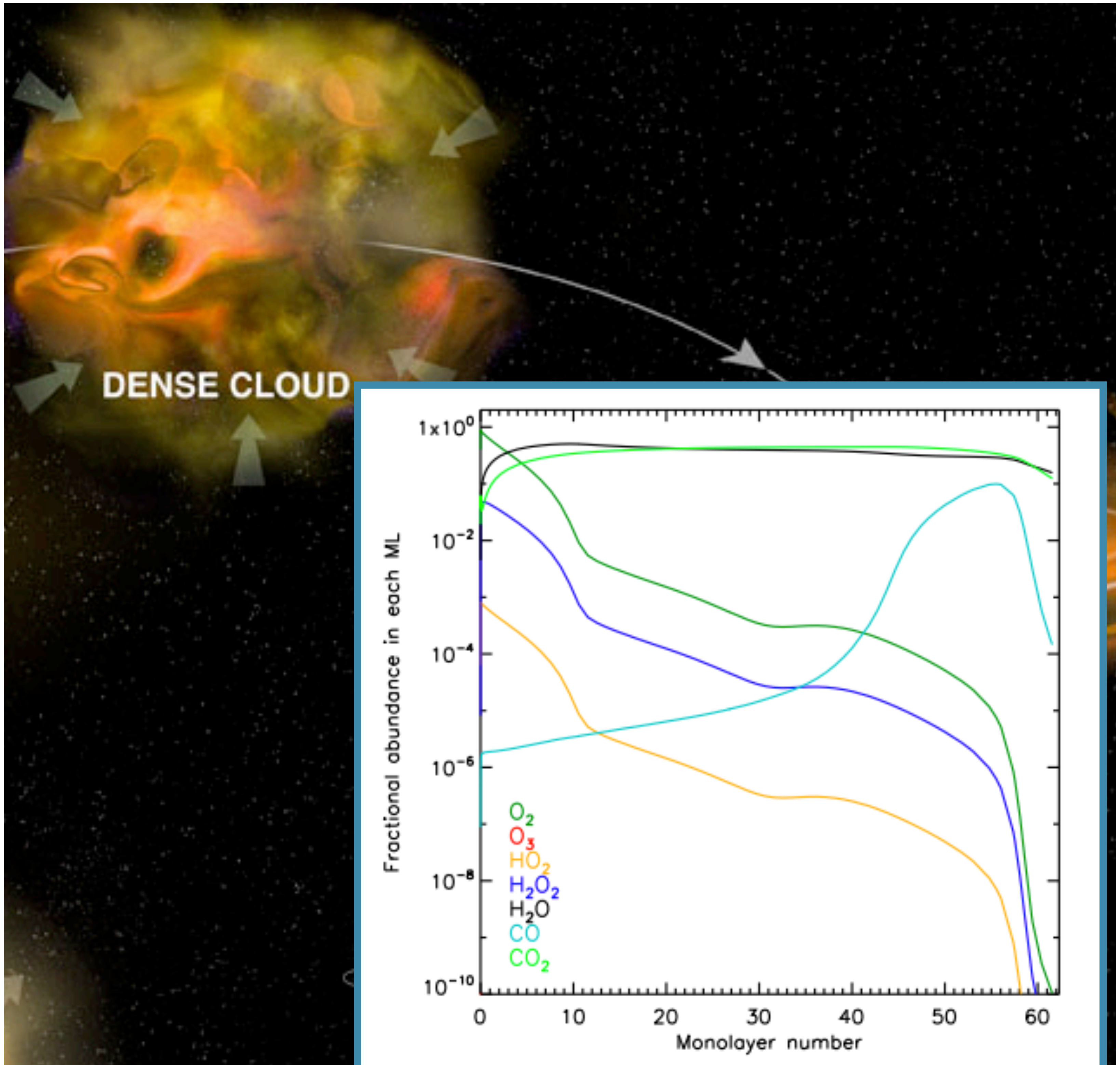

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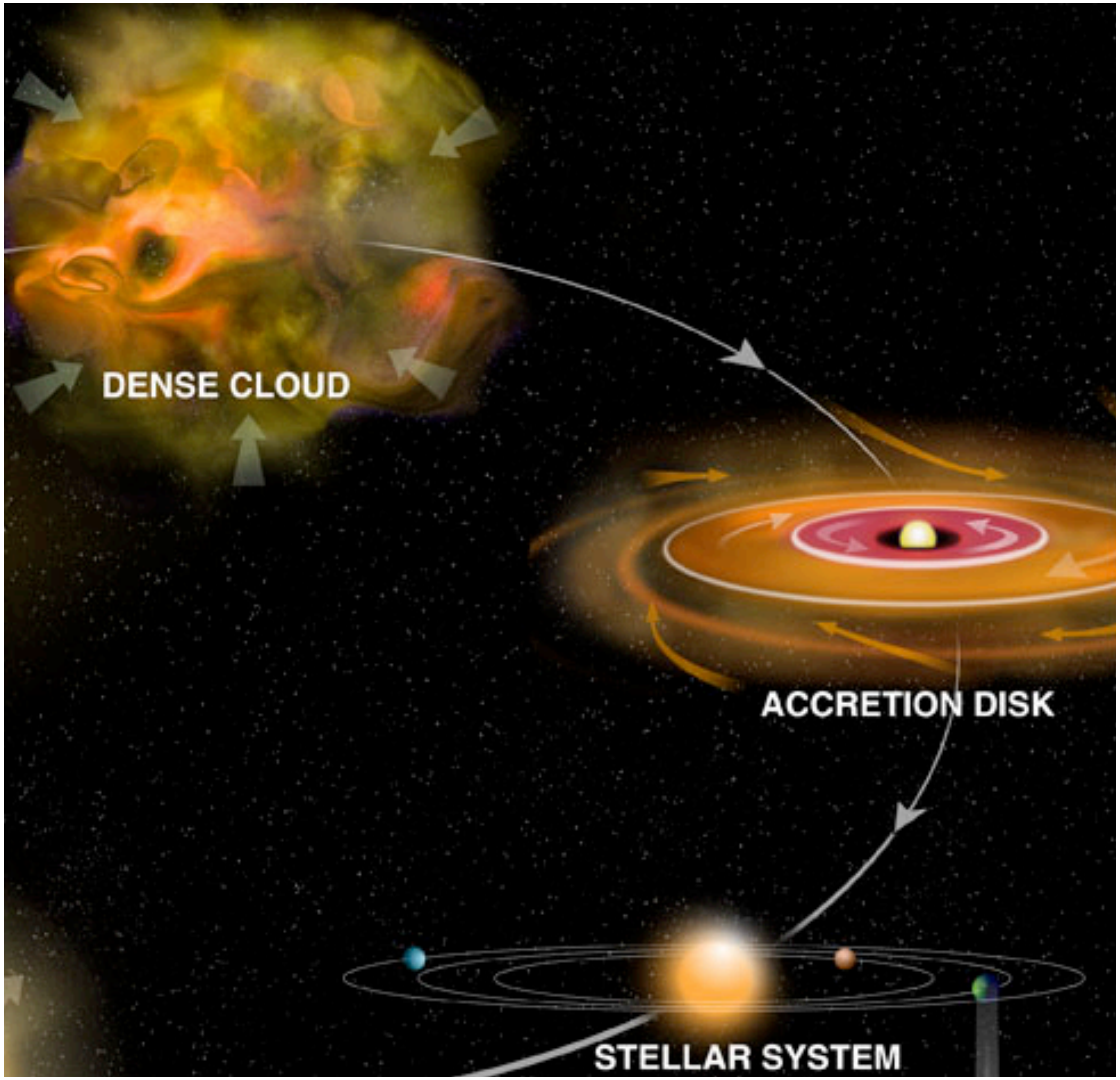

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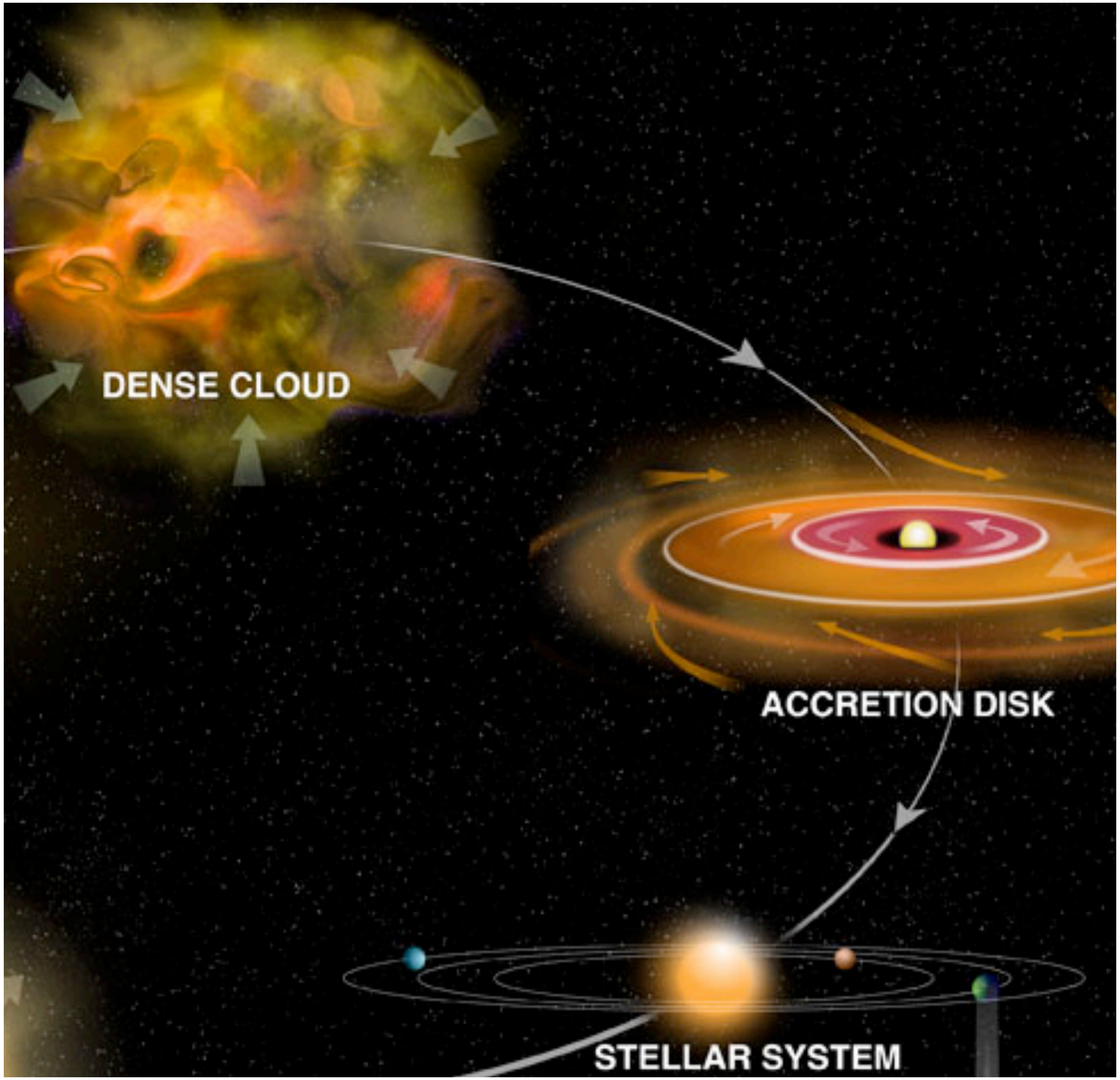

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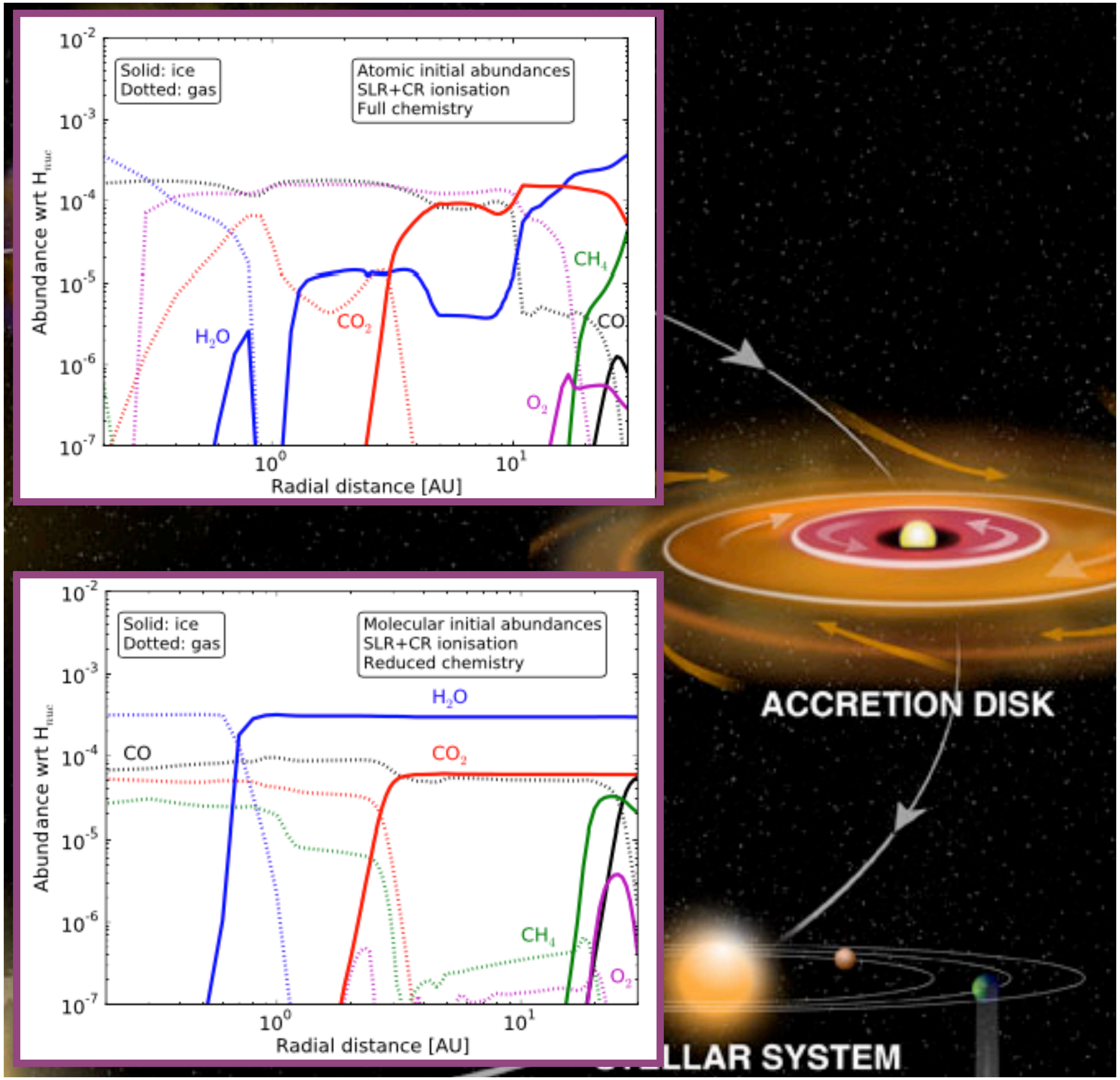

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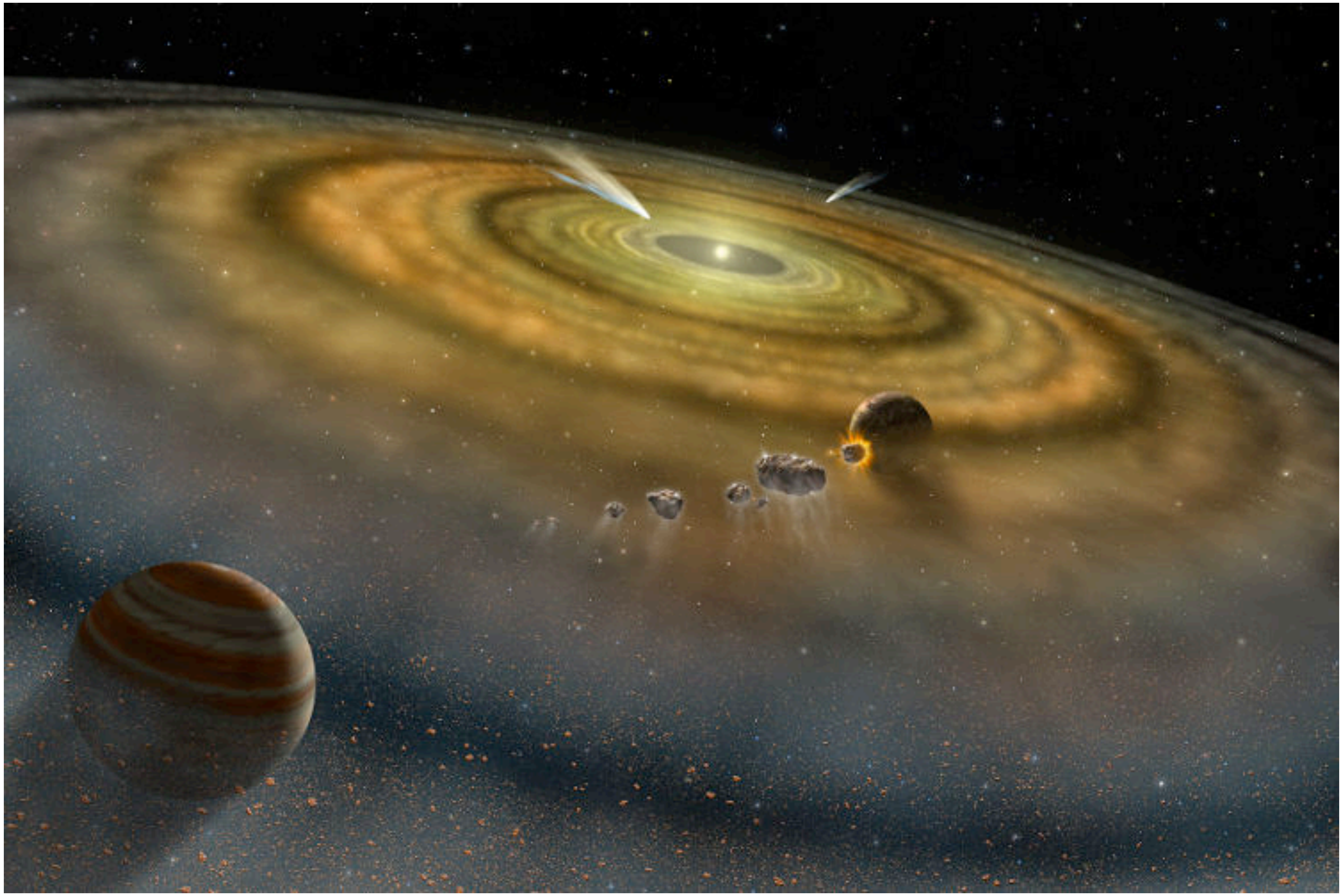
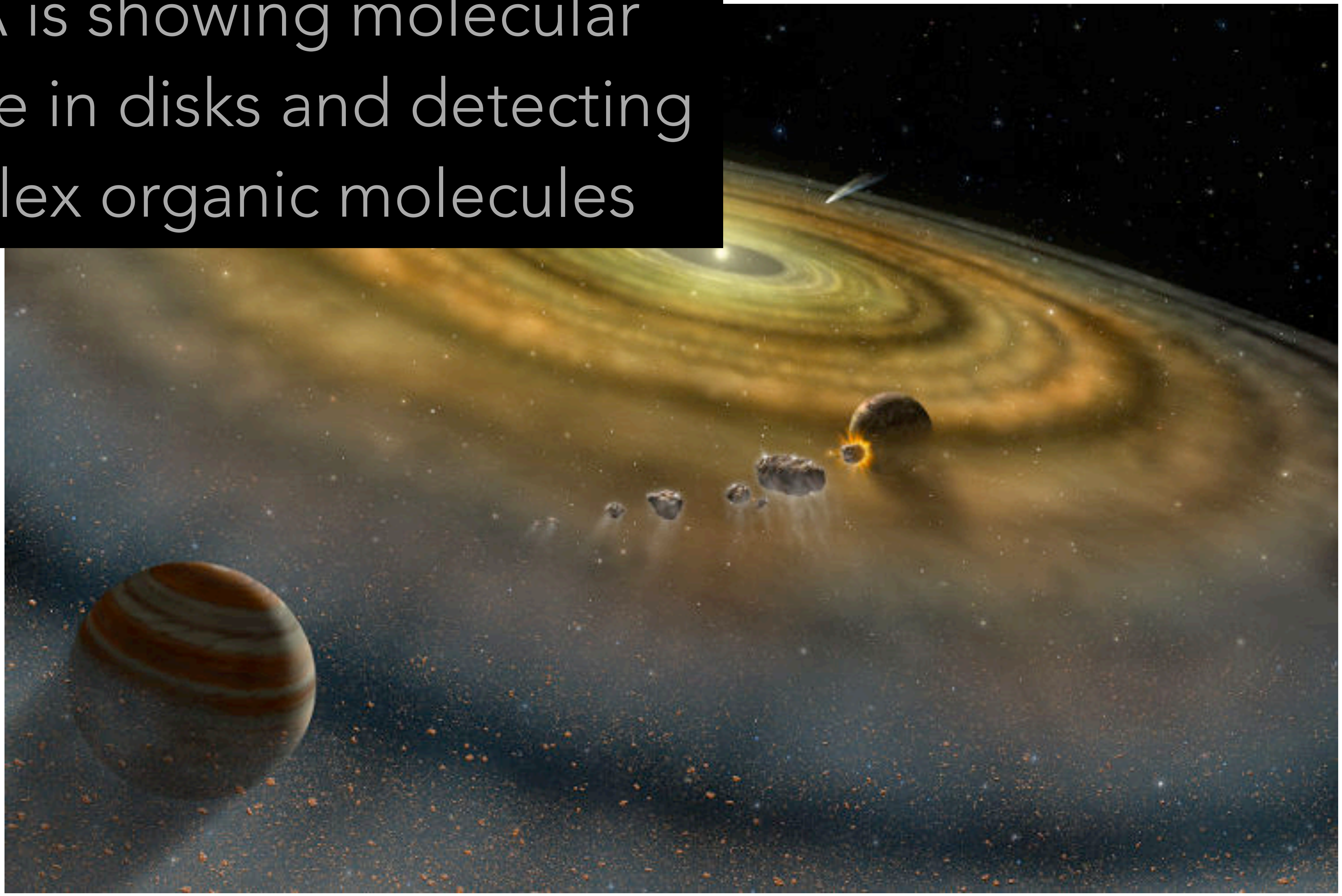
Take-home messages



Take-home messages

ALMA is showing molecular structure in disks and detecting complex organic molecules



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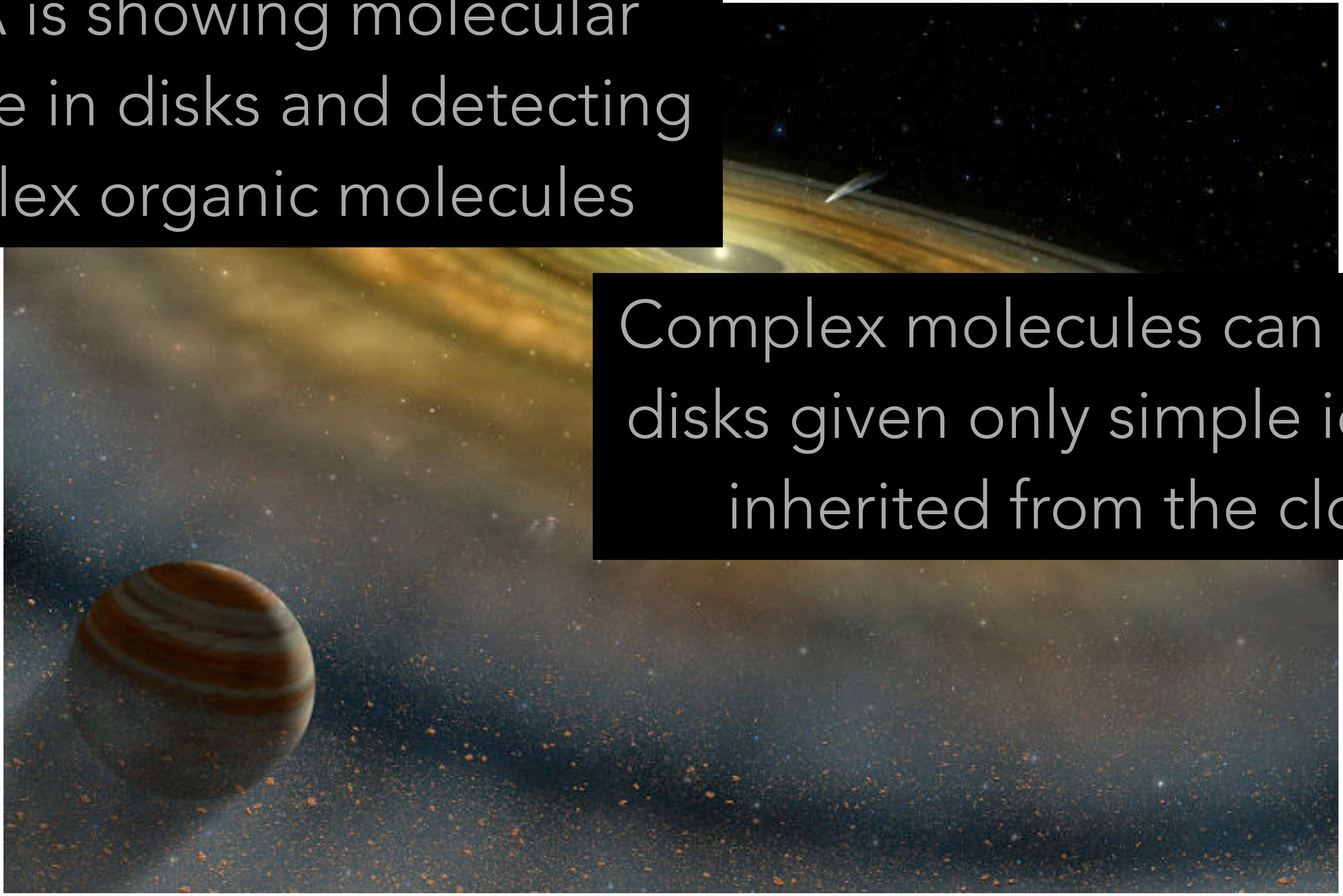
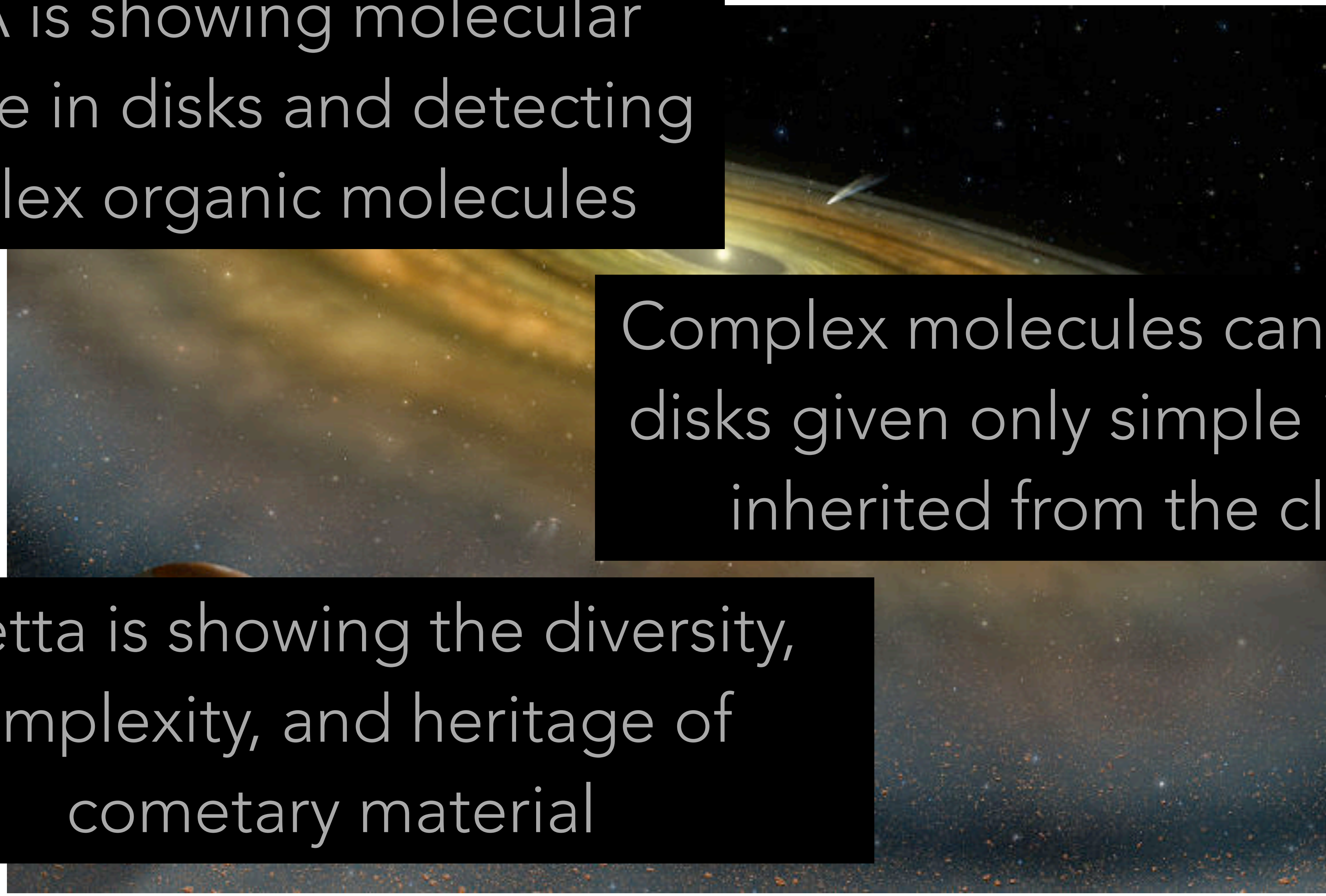


Complex molecules can form in disks given only simple ices are inherited from the cloud

Take-home messages



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Rosetta is showing the diversity, complexity, and heritage of cometary material

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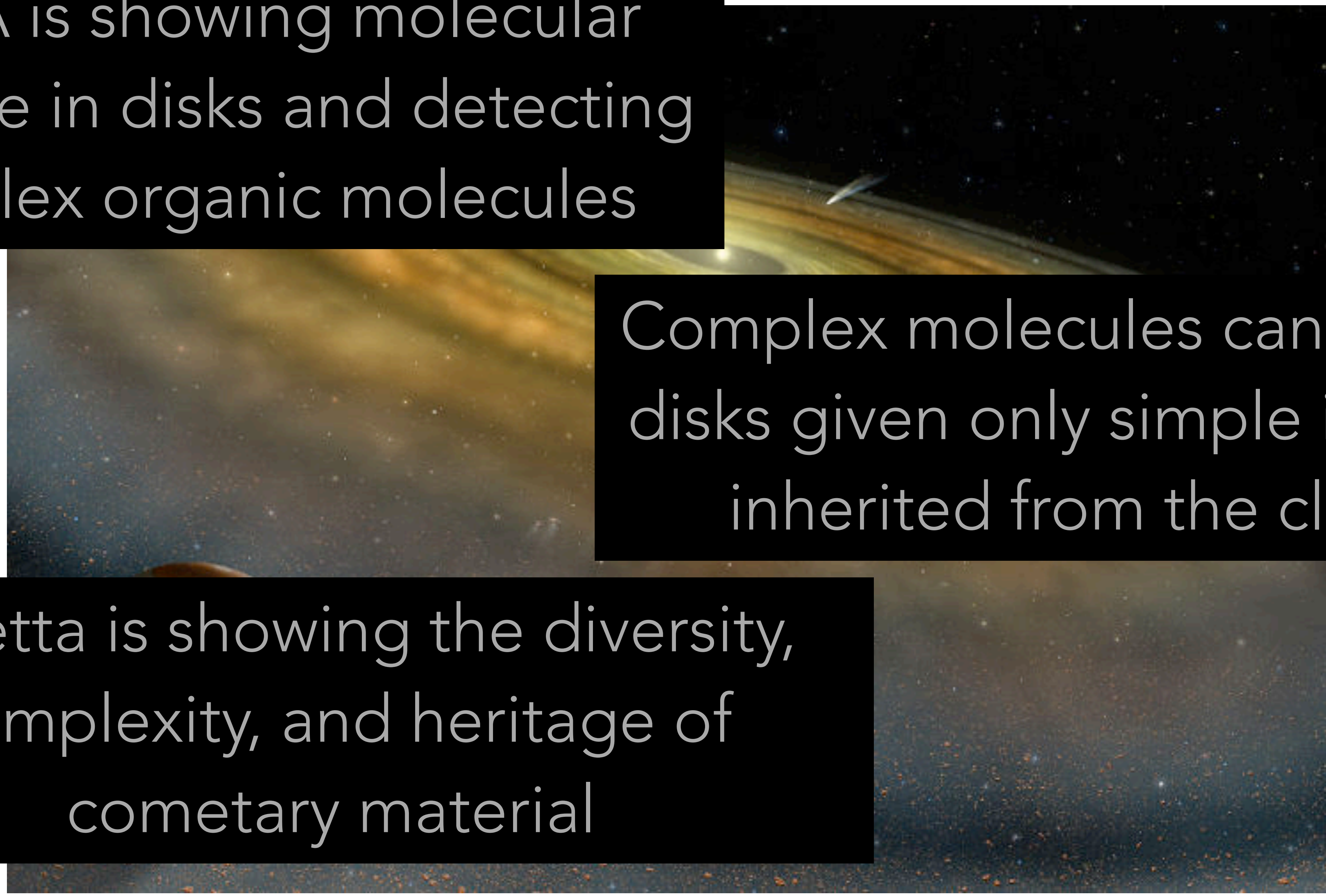

ALMA is showing molecular structure in disks and detecting complex organic molecules

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Rosetta is showing the diversity, complexity, and heritage of cometary material

Stay tuned for many more results from ALMA and Rosetta

Many thanks to …

Netherlands Organisation for Scientific Research (NWO), E. F. van Dishoeck, T. J. Millar, E. Herbst, S. Widicus Weaver, H. Nomura, Y. Aikawa, P. Pinilla, A. Juhász, M. Hogerheijde, W. R. F. Dent, …, and past and current members of the Leiden molecular astrophysics group.

NWO
Netherlands Organisation for Scientific Research

Sterrewacht Leiden