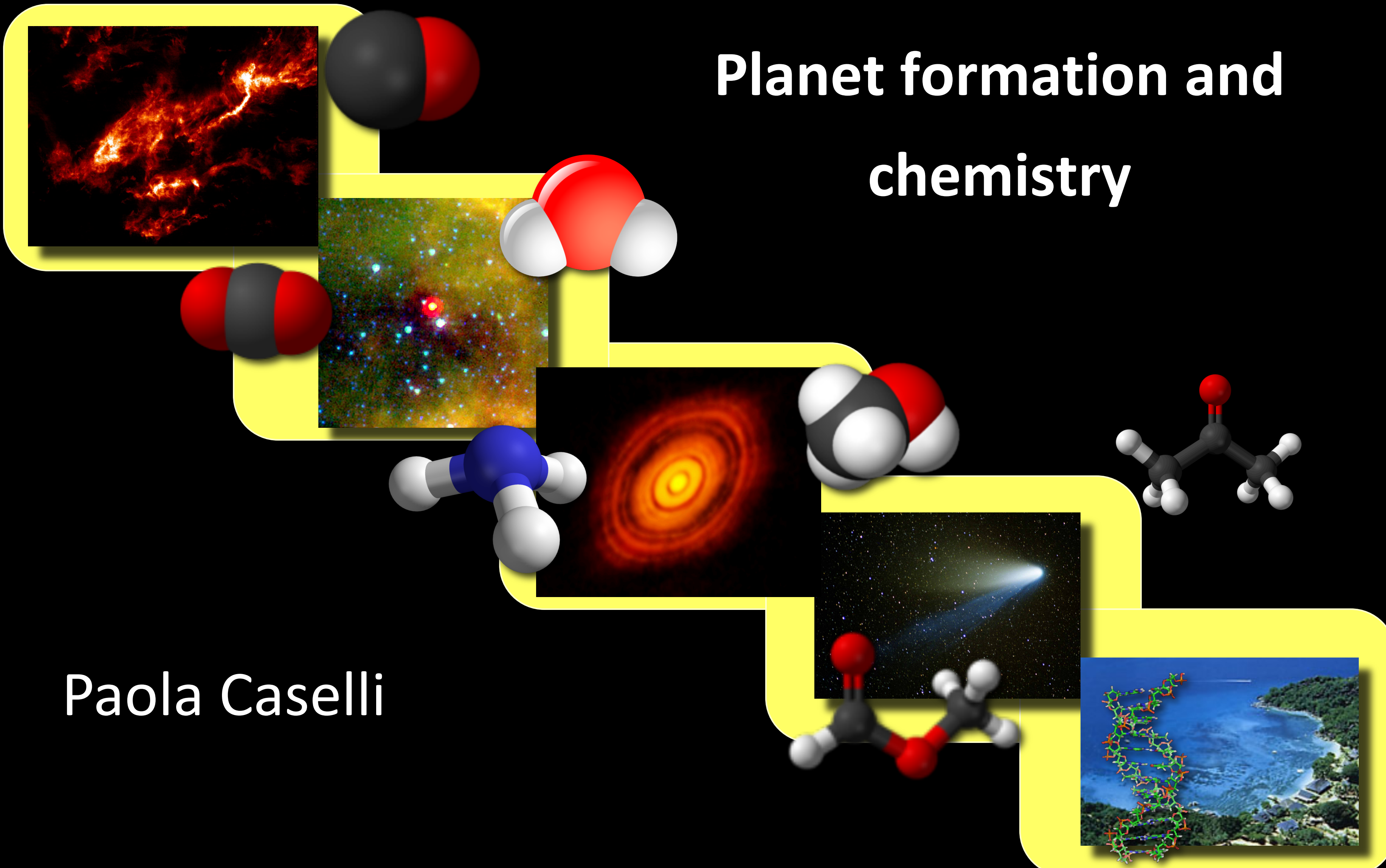
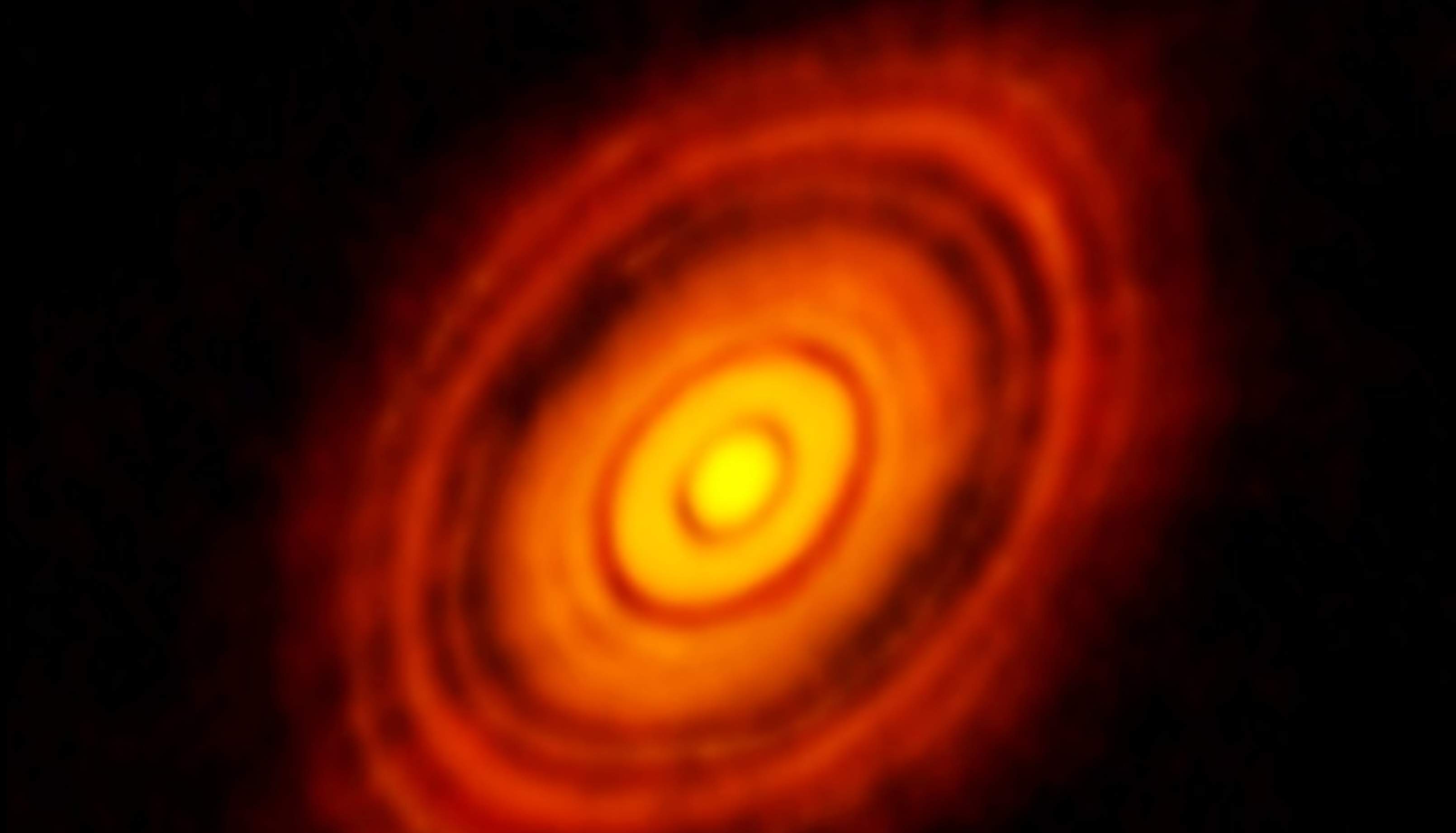
Center for Astrochemical Studies
Max-Planck-Institute for Extraterrestrial Physics

Planet formation and chemistry



Paola Caselli

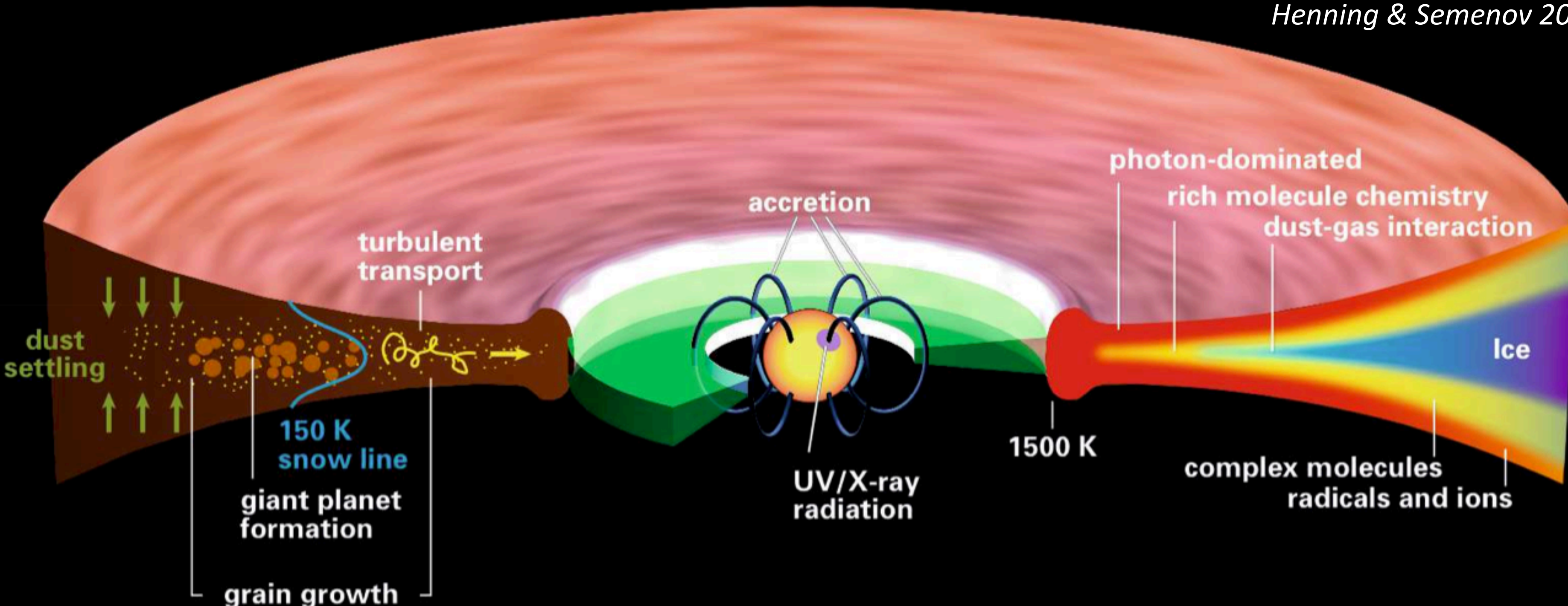
Planet-forming disks

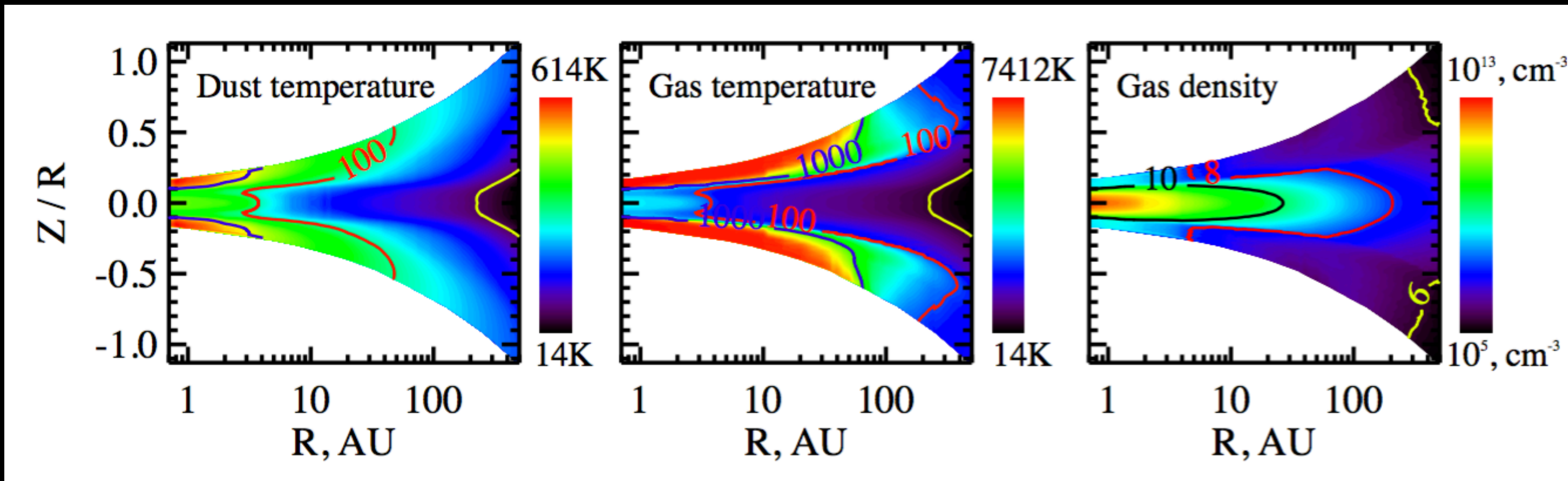


http://www.eso.org/public/news/eso1436/

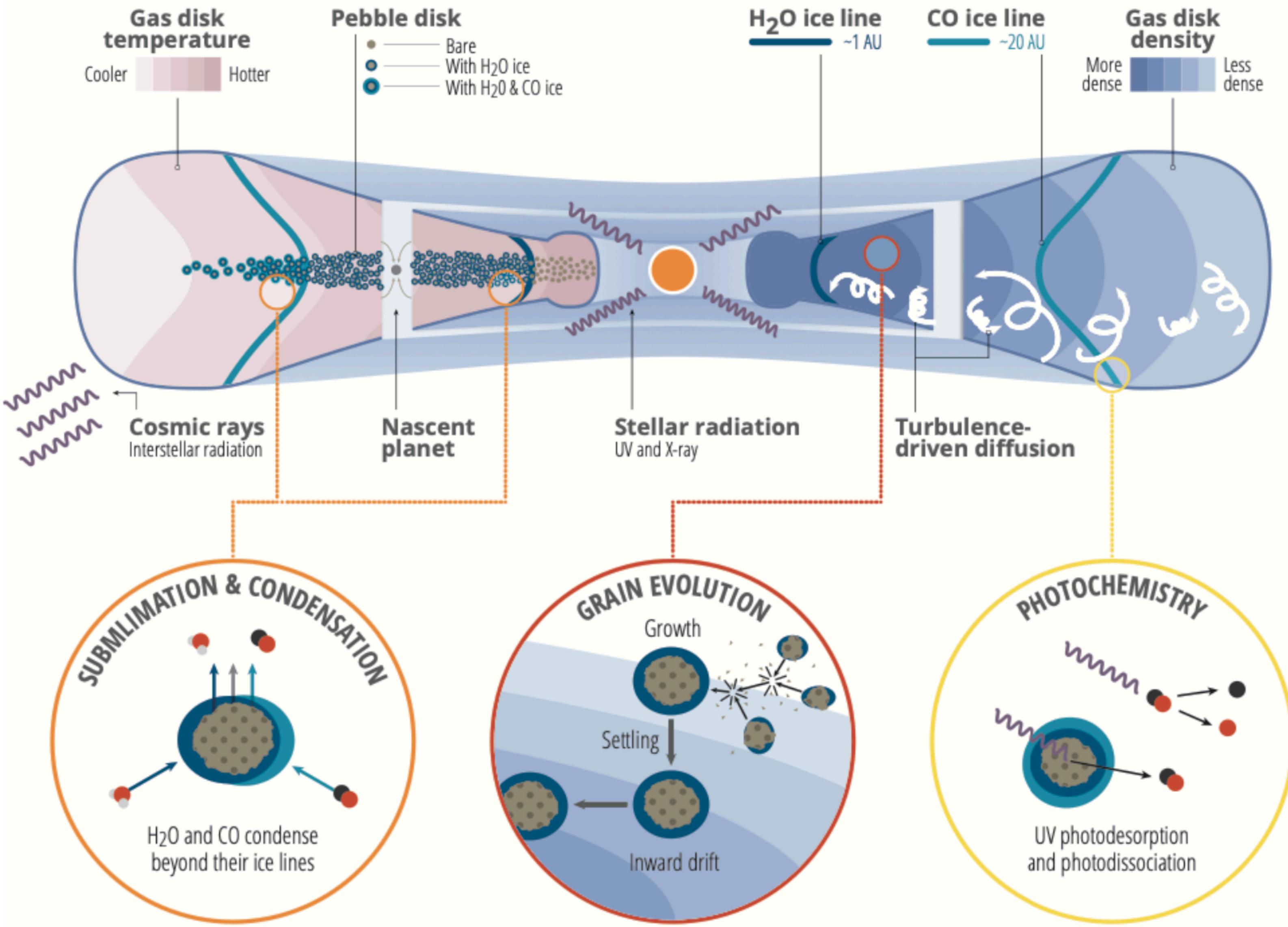
The structure of planet-forming disks

Henning & Semenov 2013

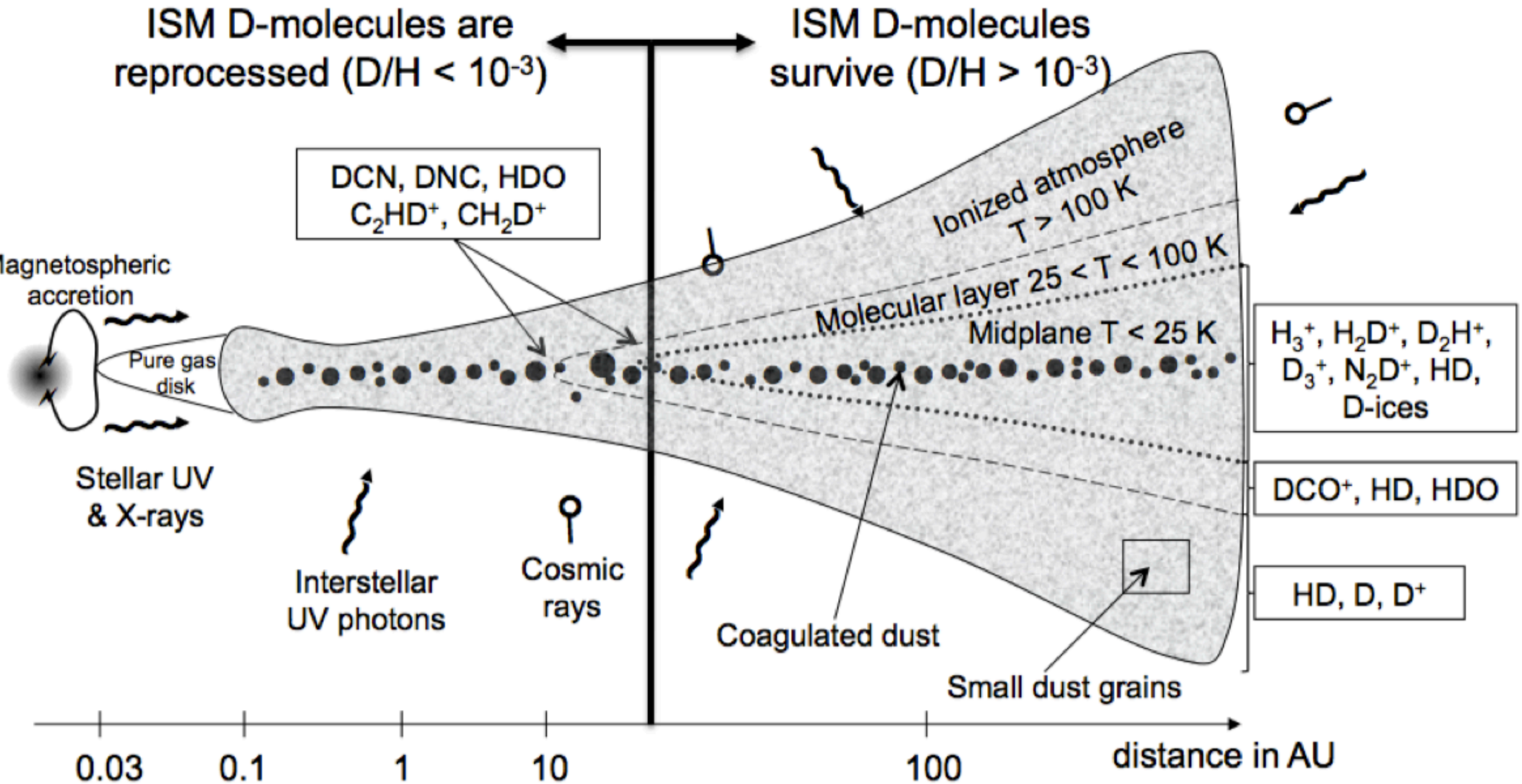




Planet-forming disks



Öberg & Bergin 2020

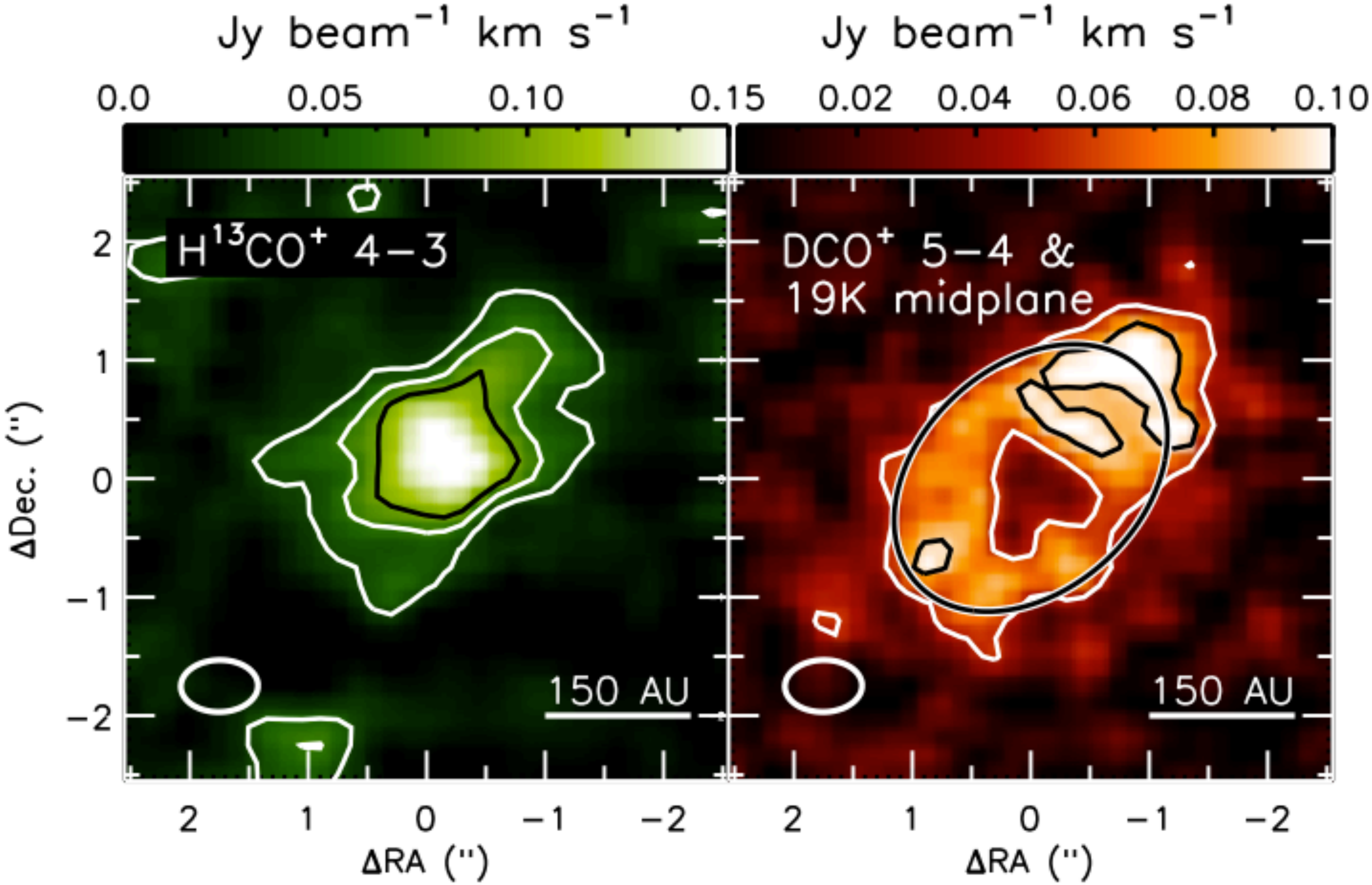


Ceccarelli+2014, PPVI [Adapted from: Bergin et al. 2007 + Caselli & Ceccarelli 2012 + Dullemond et al. 2007 + 2010 + Öberg et al. 2011 + Semenov 2011]

See also, e.g., Willacy et al. 1998, 2000; Aikawa et al. 2006; Vasyunin et al. 2008, 2011; Woitke et al. 2010; Kamp et al. 2011; Walsh et al. 2012, 2013; Albertsson et al. 2014

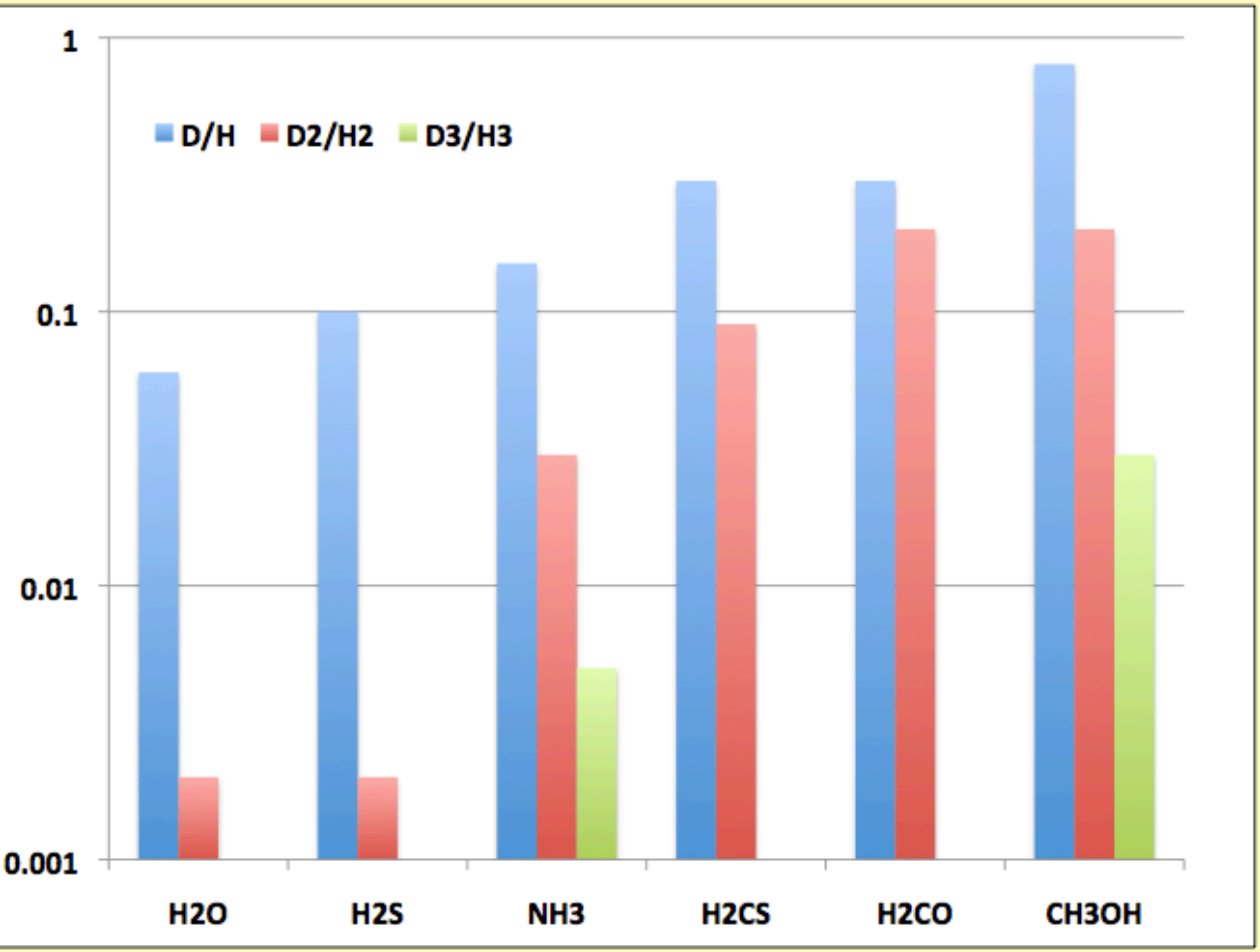
ALMA imaging of the CO snowline of HD163296

Mathews+2013



$DCO^+/HCO^+ \sim 0.3$; DCO^+ in a 110-160 AU ring (T = 19-21 K)

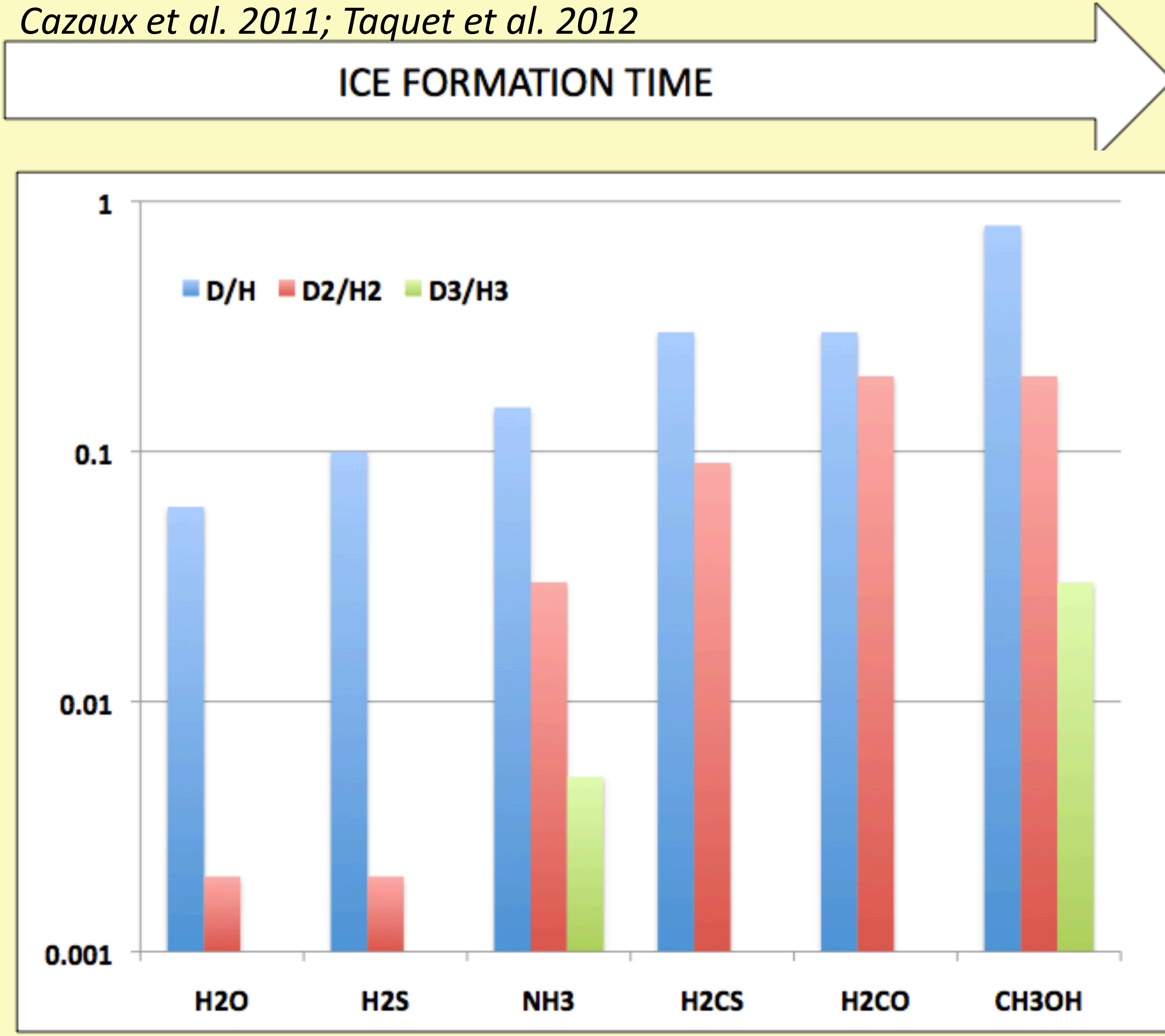
The youngest protostars show very large deuterations, especially of organic molecules



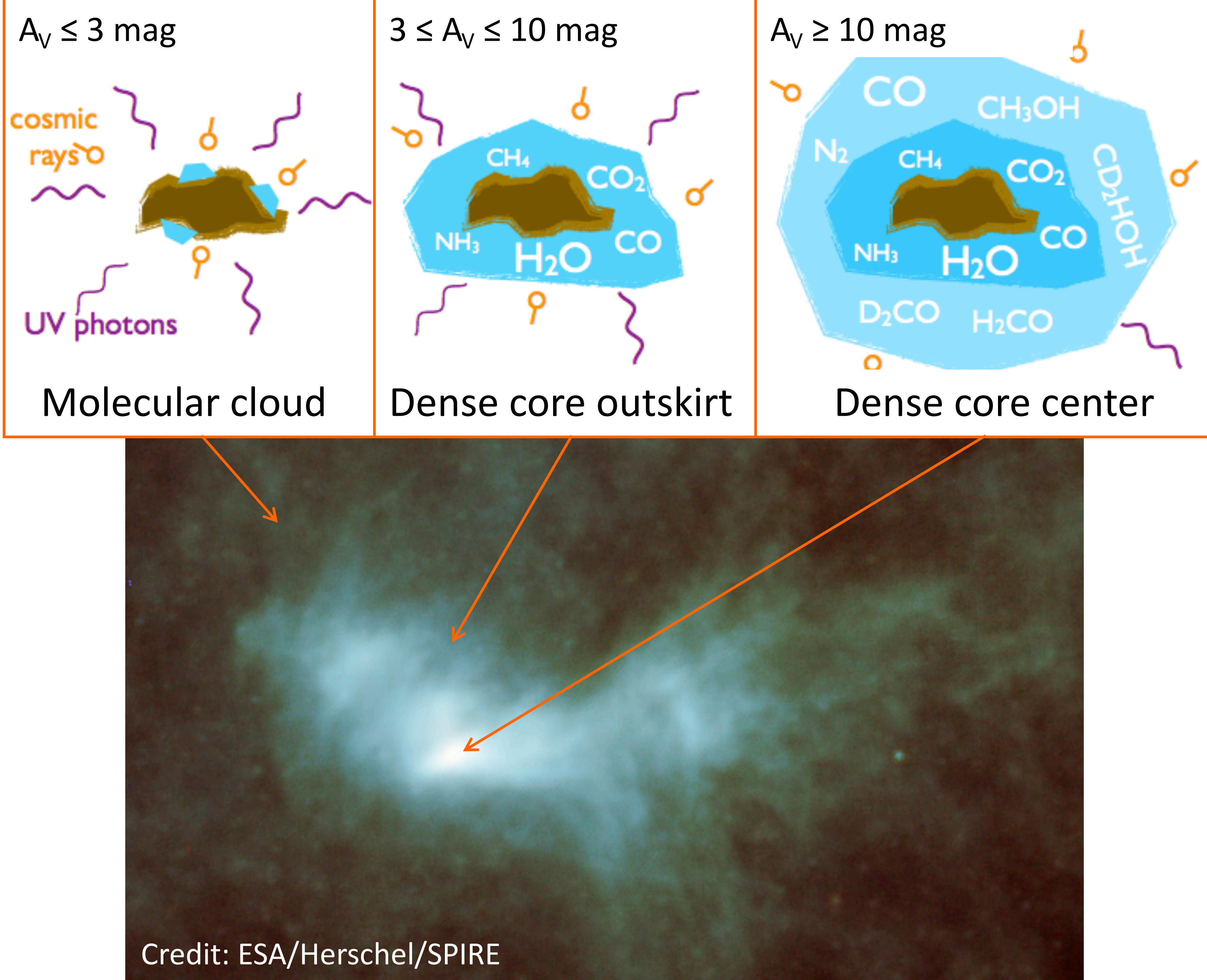
Caselli & Ceccarelli 2012 A&ARv

H_2O:
Coutens+ 2012,2013
Persson et al. 2012
Taquet+ 2012,2013
Butner et al. 2007
Vastel et al. 2010
H_2S:
Vastel et al. 2003
NH_3:
Loinard et al. 2001
van der Tak et al. 2002
H_2CS:
Marcelino et al. 2005
H_2CO:
Ceccarelli et al. 1998
Parise et al. 2006
CH_3OH:
Parise et al. 2002
Parise et al. 2004
Parise et al. 2006

Cazaux et al. 2011; Taquet et al. 2012

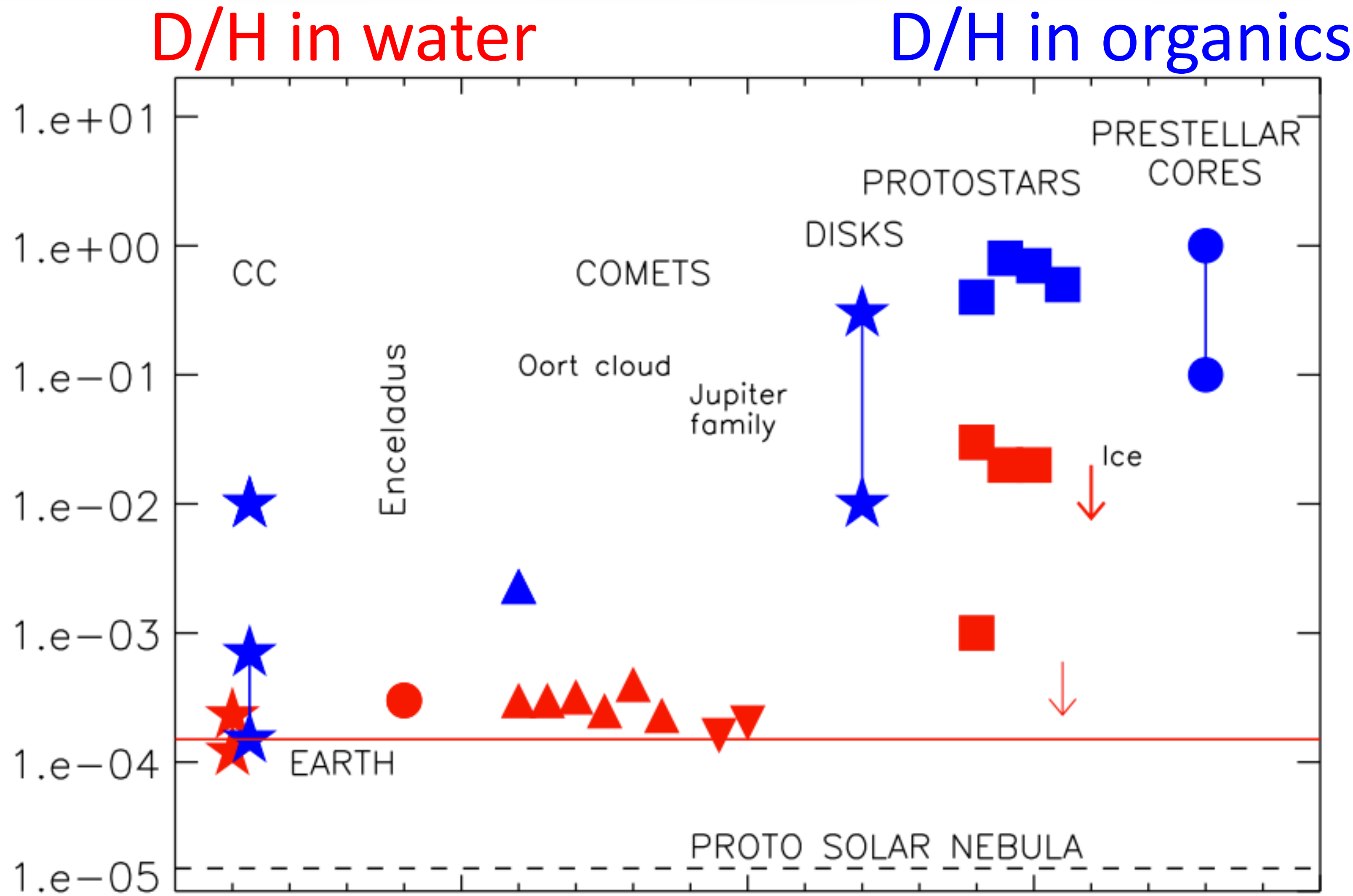


Caselli & Ceccarelli 2012 A&ARv



$A_V \leq 3$ mag
cosmic rays
UV photons
Molecular cloud
$3 \leq A_V \leq 10$ mag
CH_4
CO_2
NH_3
H_2O
CO
Dense core outskirt
$A_V \geq 10$ mag
CO
CH_3OH
N_2
CH_4
CO_2
CD_2HOH
NH_3
H_2O
CO
D_2CO
H_2CO
Dense core center
Credit: ESA/Herschel/SPIRE

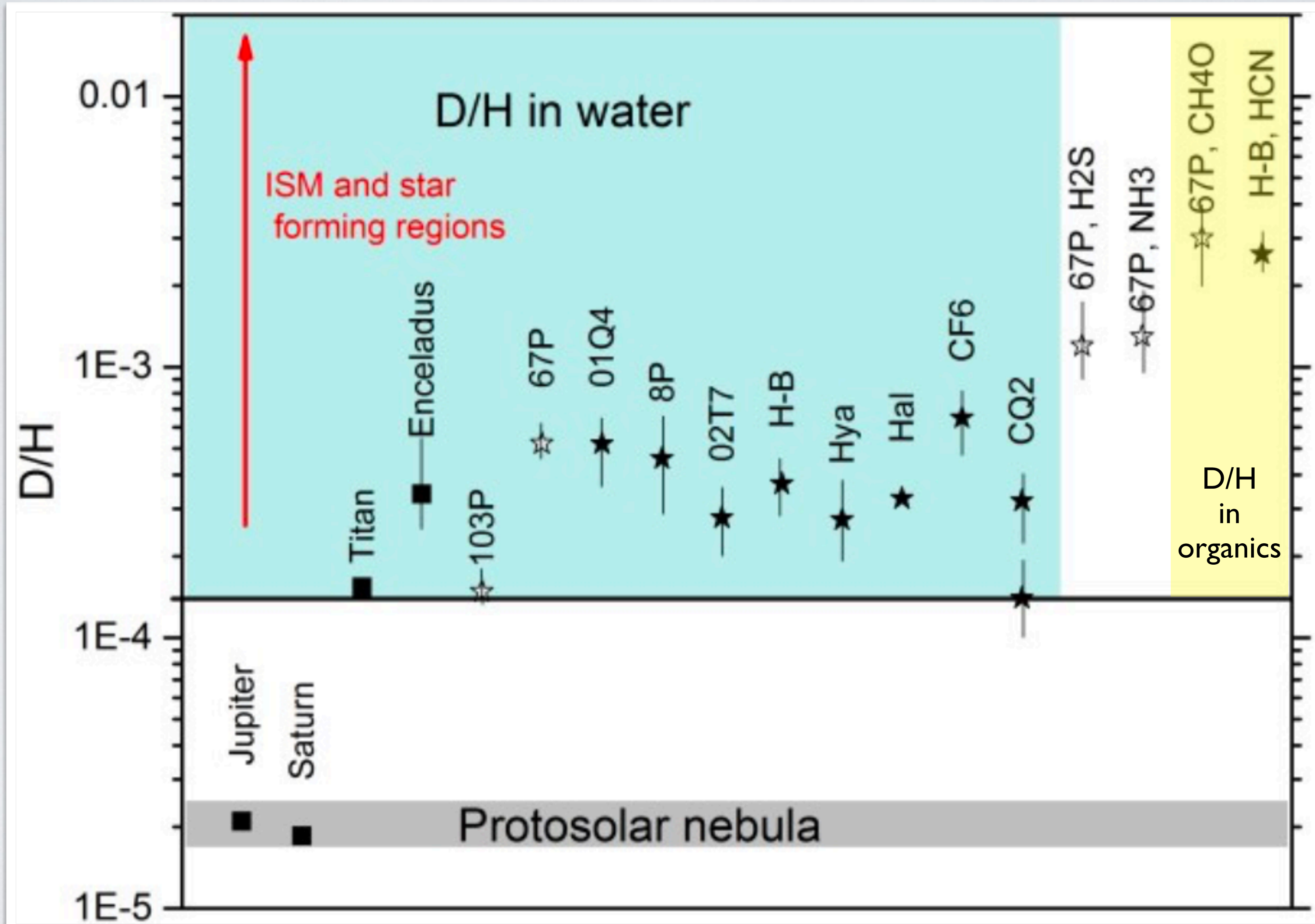
D/H in organics overall larger than in water



Ceccarelli, Caselli, Bocklelèe-Morvan, Mousis, Pizzarello, Robert, Semenov 2014, PPVI

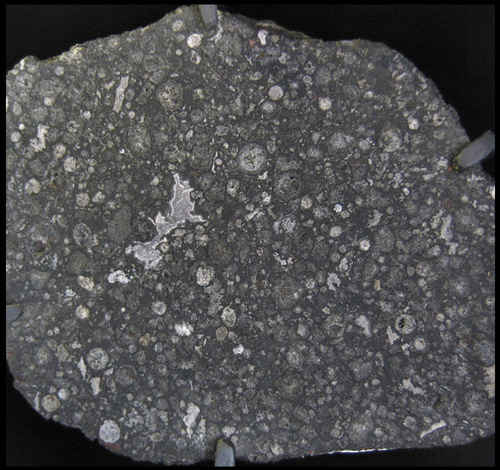
See also: Nomura, Furuya, Cordiner, Charnley, Alexander, Nixon, Guzman, Yurimoto, Tsukagoshi, Iino 2022, PPVII

Comets also show significantly larger D-fractions in organic molecules than in water

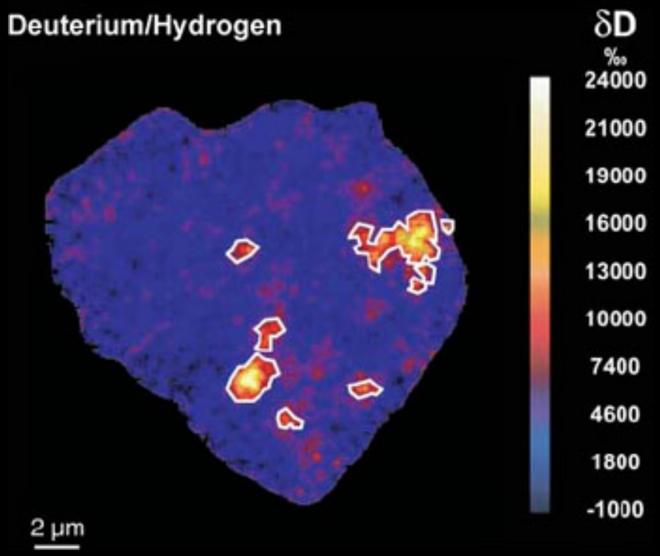


Altwegg, Balsiger & Fuselier 2019, ARA&A; Drozdovskaya+2021

D/H in carbonaceous chondrites and IDPs



Hydrated silicates and hydrous carbon: D/H ~ 1.2-2.2×10^{-4} (Robert 2003), similar to terrestrial oceans.



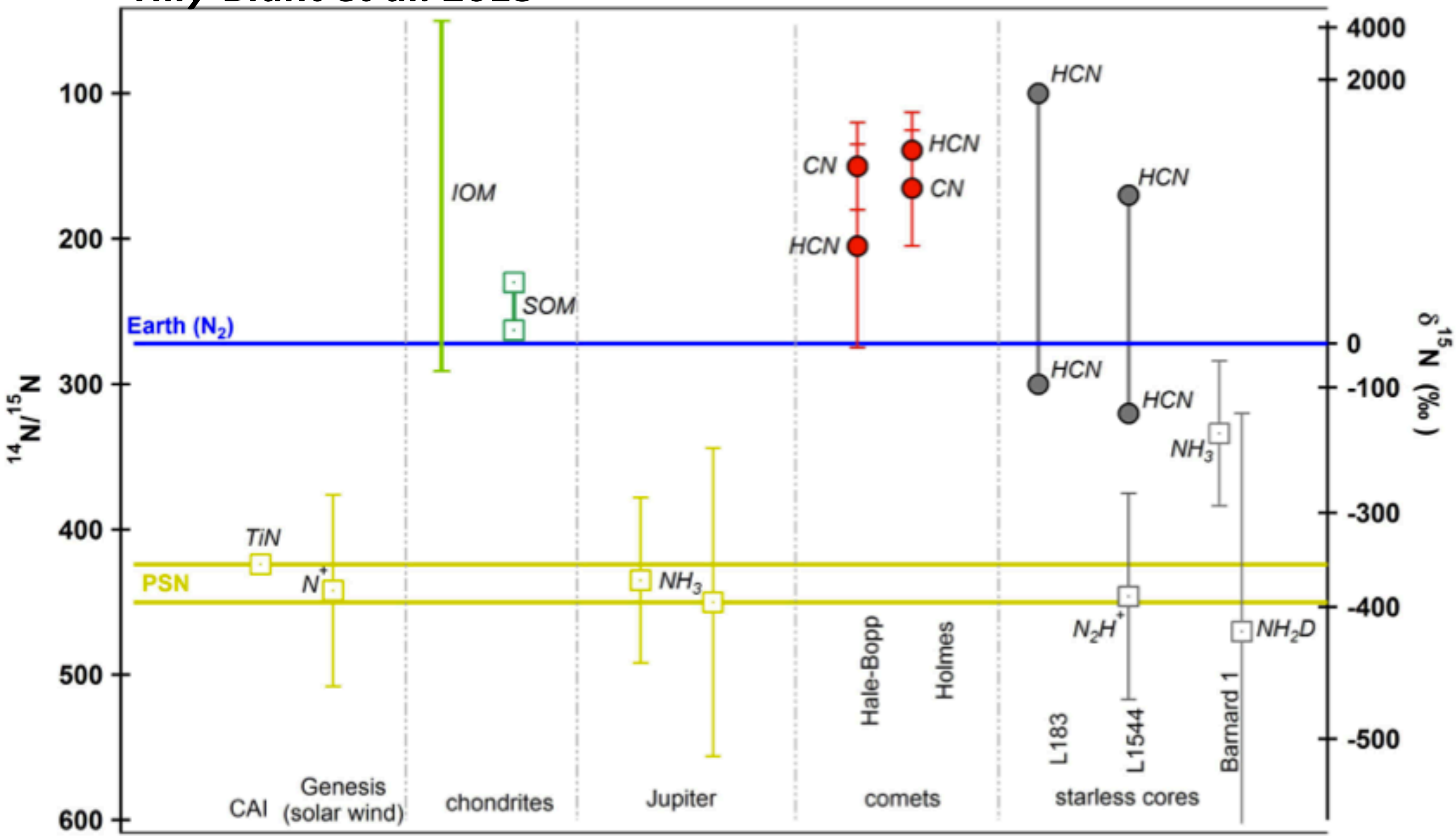
Micrometer-sized "hot spots" in organic matter within chondrites and IDPs: D/H up to 0.01 (e.g. Alexander et al. 2007; Remusat et al. 2009).

http://www.psrd.hawaii.edu/May06meteoriteOrganics.html

^{15}N fractionation

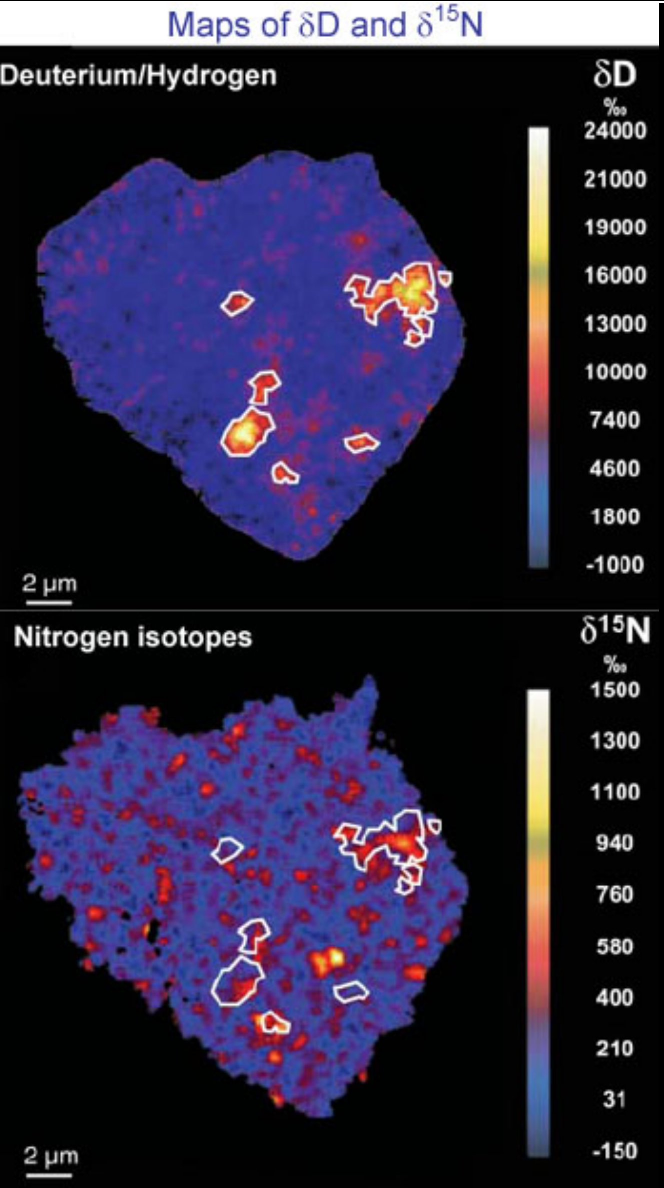
Differential ^{15}N enhancement between nitrile- and amine-bearing interstellar molecules. No correlation with D-frac.

Hily-Blant et al. 2013



*See also: Wampfler+2014 for **protostars** (HCN/HC^{15}N~150-400),*
*Guzmán+2017 for **planet-forming disks** (HCN/HC^{15}N~80-160)*

^{15}N excess in primitive SS material



(From Busemann *et al.*, 2006, *Science*, v. 312, p. 728.)

Large ^{15}N excess is found in primitive material (meteorites, IDPs, cometary dust particles returned by *Stardust*): e.g. $^{14}N/^{15}N$ ~ 65 found in the "hot spots" of the meteorite Bells (*Buseman et al. 2006*).

D-enriched spots do not always coincide with ^{15}N-enriched ones *(e.g. Buseman et al. 2010; Robert et al. 2006)*.

Differences are found between functional groups in "hot spots": ^{15}N fractionation larger in –CN than in $–NH_2$ and –NH functional groups *(van Kooten et al. 2017).*

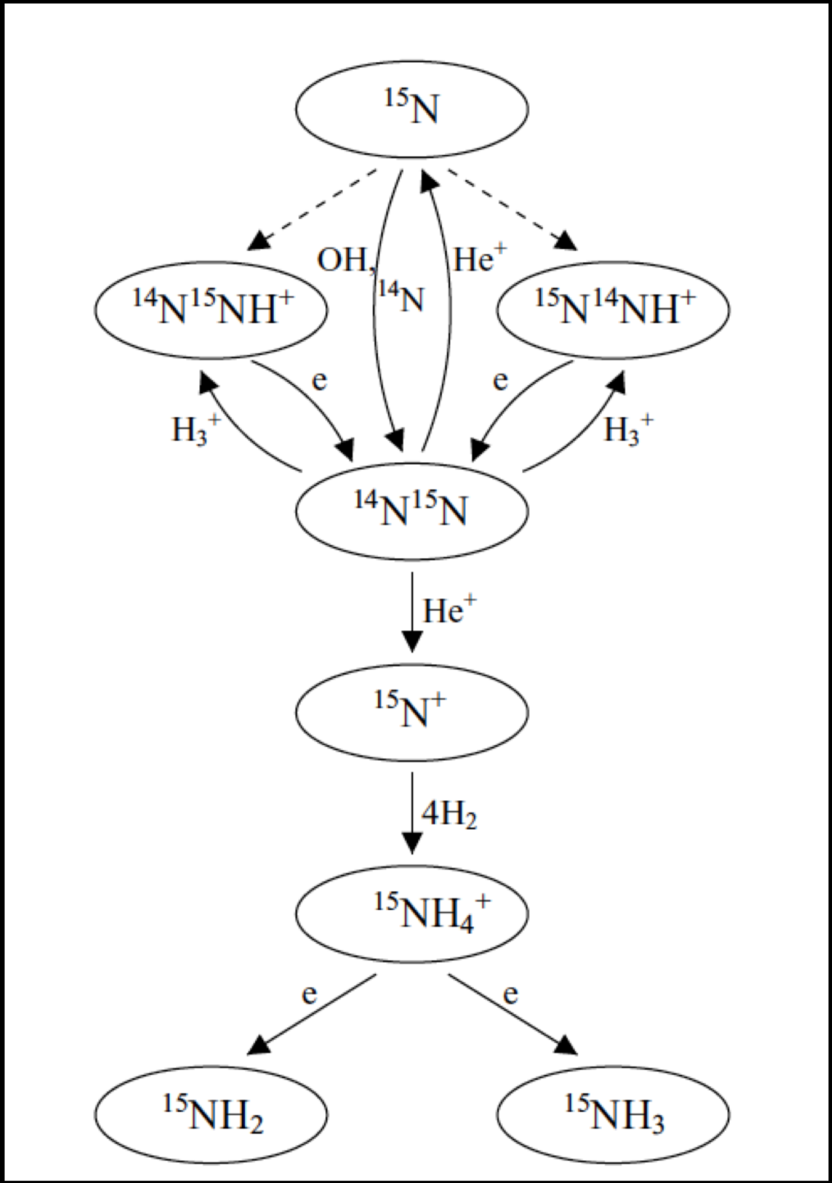
^{15}N-fractionation: the **old** picture

The key fractionation reactions are (Rodgers & Charnley 2008a,b; Terzieva & Herbst 2000):

$$^{15}N + {}^{14}N_2H^+ \rightleftharpoons {}^{14}N + {}^{15}N^{14}NH^+ + \Delta E_1$$

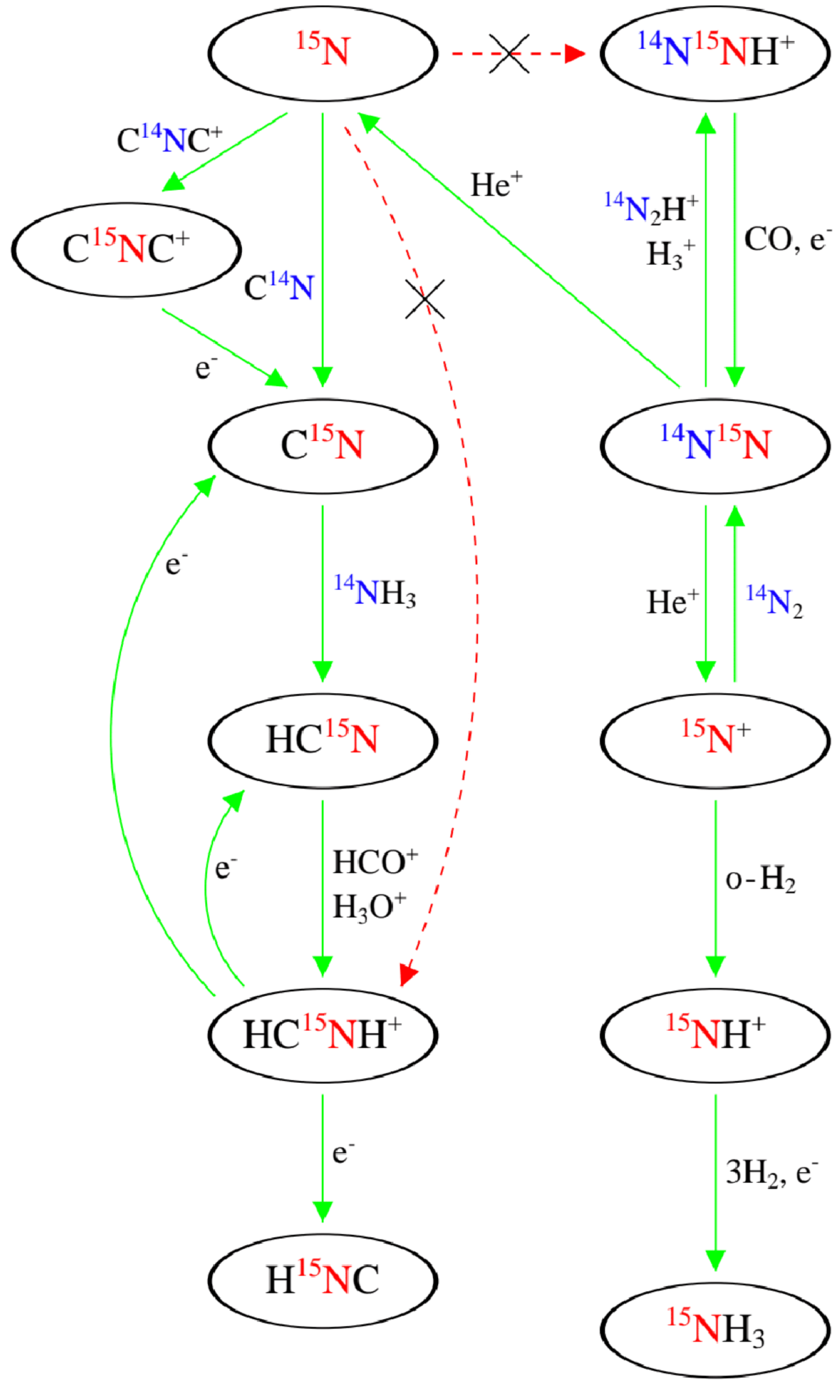
$$^{15}N + {}^{14}N_2H^+ \rightleftharpoons {}^{14}N + {}^{14}N^{15}NH^+ + \Delta E_2$$

At low temperatures, they drive ^{15}N into molecular nitrogen upon dissociative recombination (Molek et al. 2007).



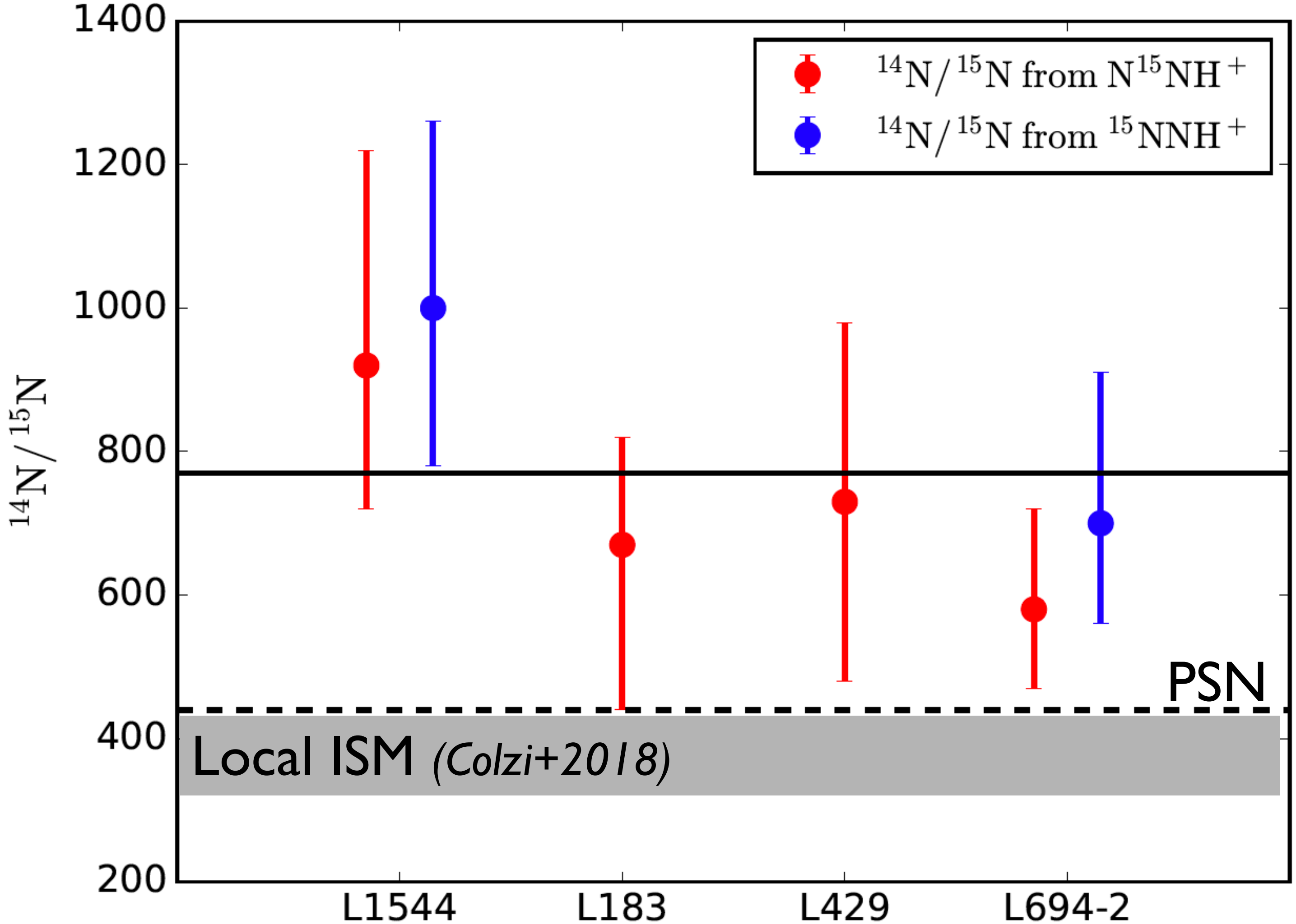
^{15}N fractionation models have been challenged by Roueff et al. (2015), who performed quantum chemistry calculations and found energy barriers for important reactions (marked by “X“ in figure).

→ *no significant ^{15}N enhancement predicted for HCN and HNC and still problems with N_2H^+ .*



From Wirström & Charnley 2017

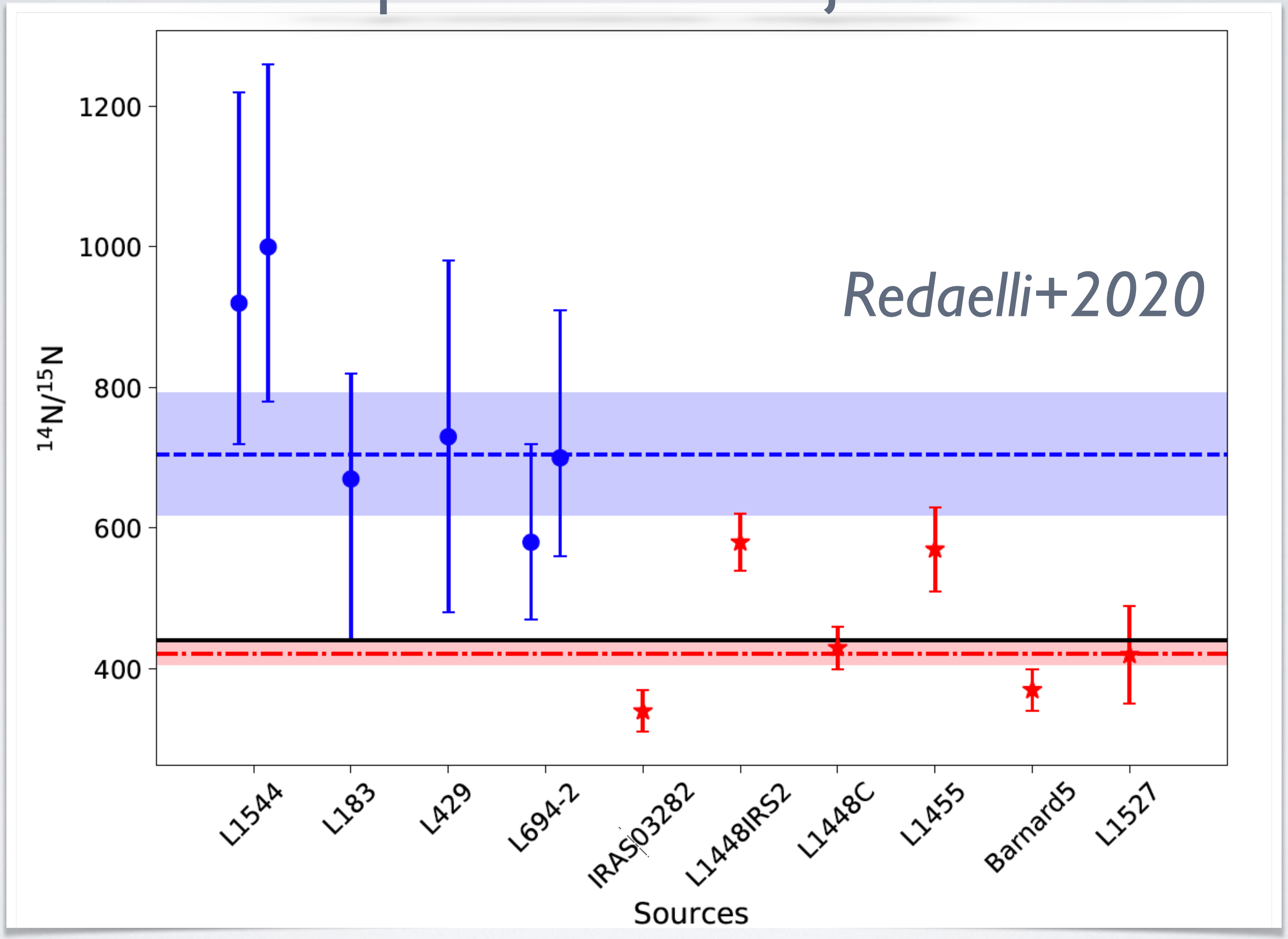
^{15}N-antifractionation in N_2H^+ within pre-stellar cores is still a puzzle



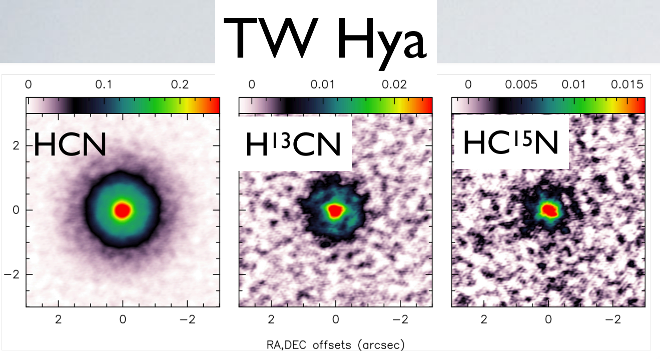
***Redaelli+2018**, Bizzocchi+2013*

(see also Furuya & Aikawa 2018, Hily-Blant+2019, Loison+2019)

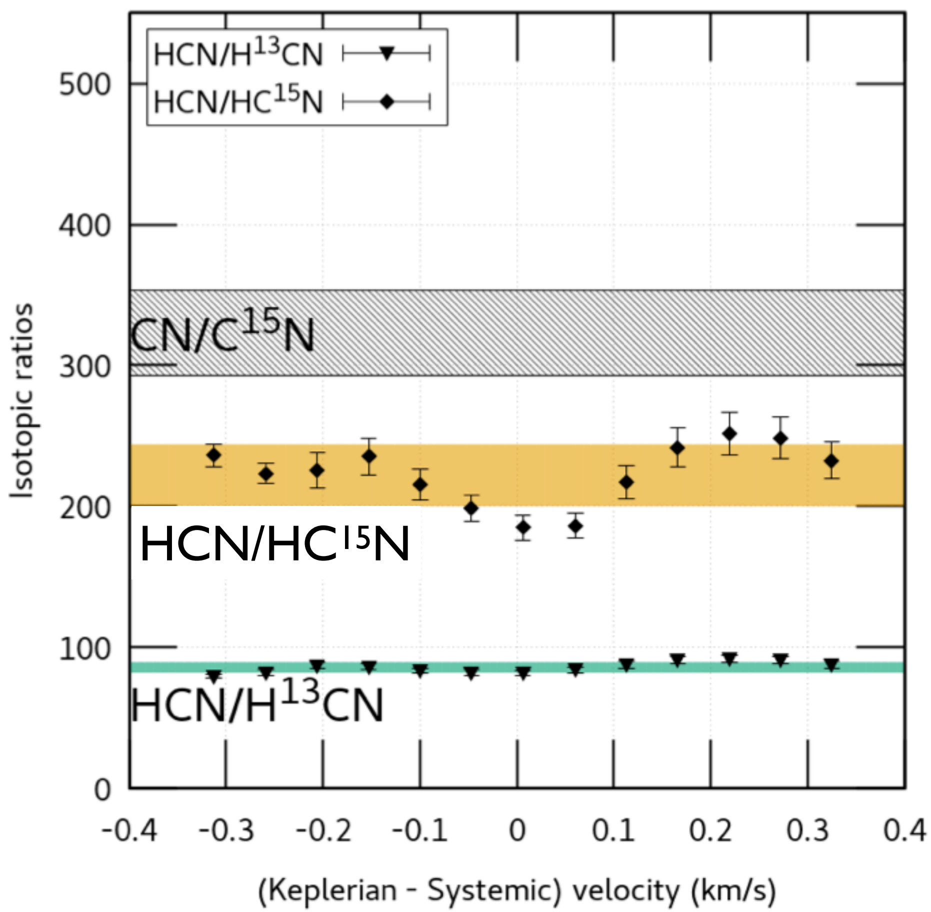
^{15}N-antifractionation in N_2H^+ drops in protostellar objects

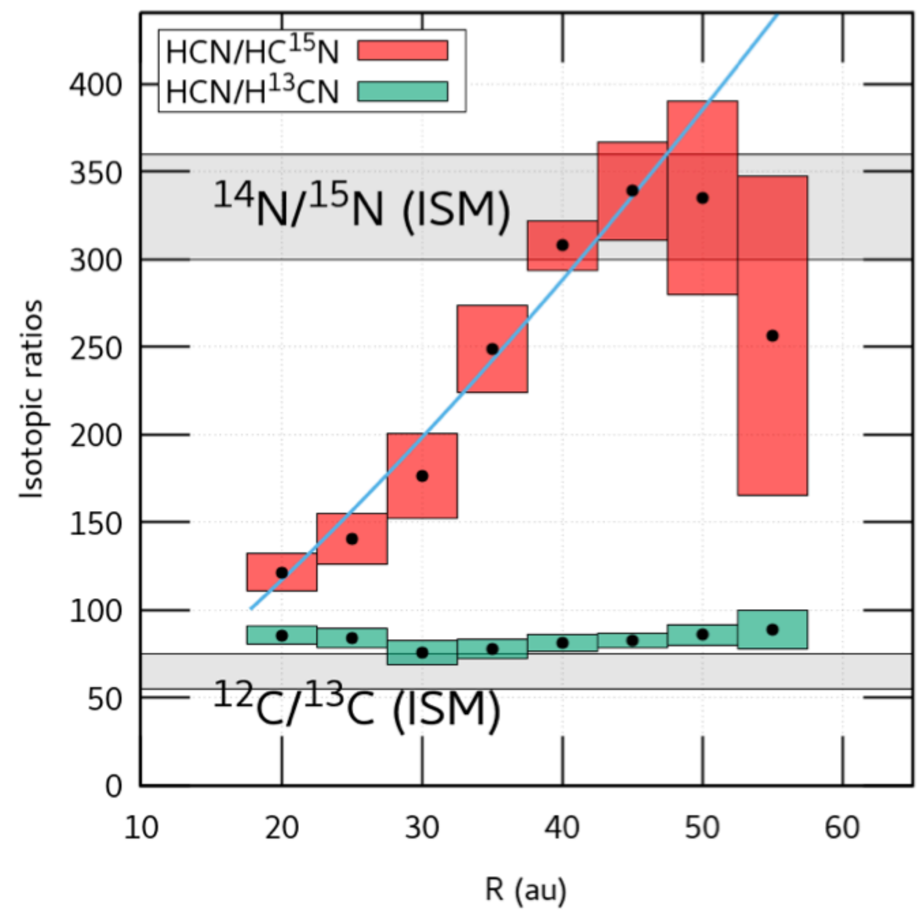


Agreement with Loison+2019 theory (faster dissociative recombination for ^{15}N N_2H^+ isotopologues — but why??)



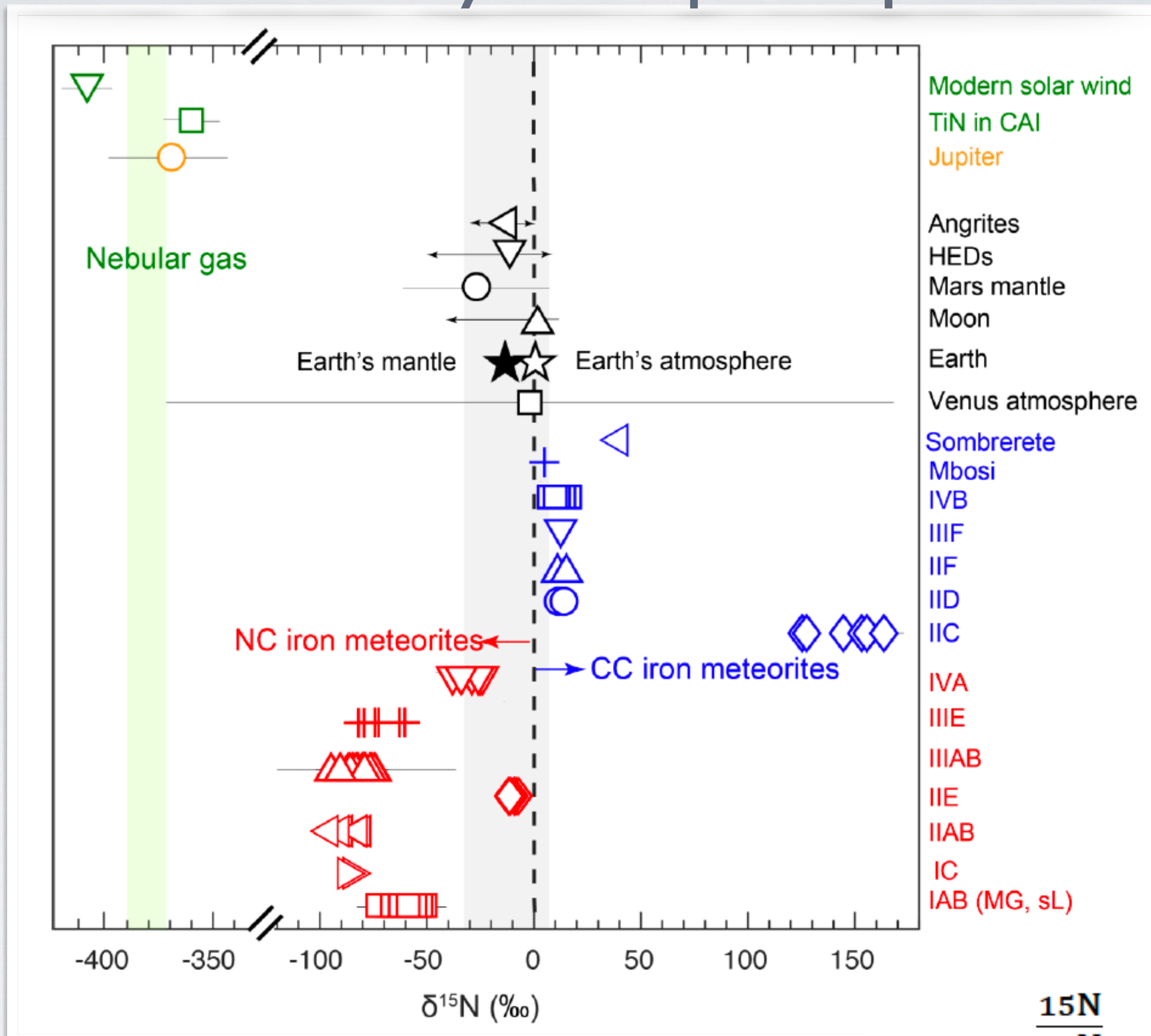
Multiple nitrogen reservoirs in a protoplanetary disk and evidence of selective photodissociation of N_2





Hily-Blant+2019 (see also Hily-Blant+2017, Visser+2018)

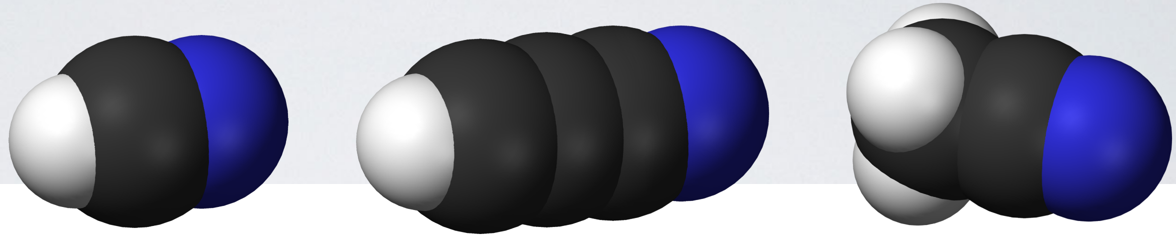
A very early origin of isotopically distinct nitrogen in inner Solar System protoplanets

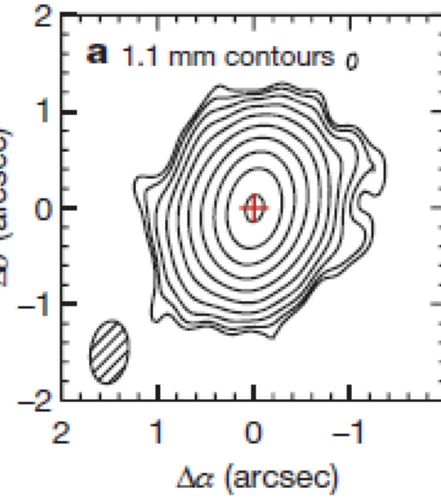


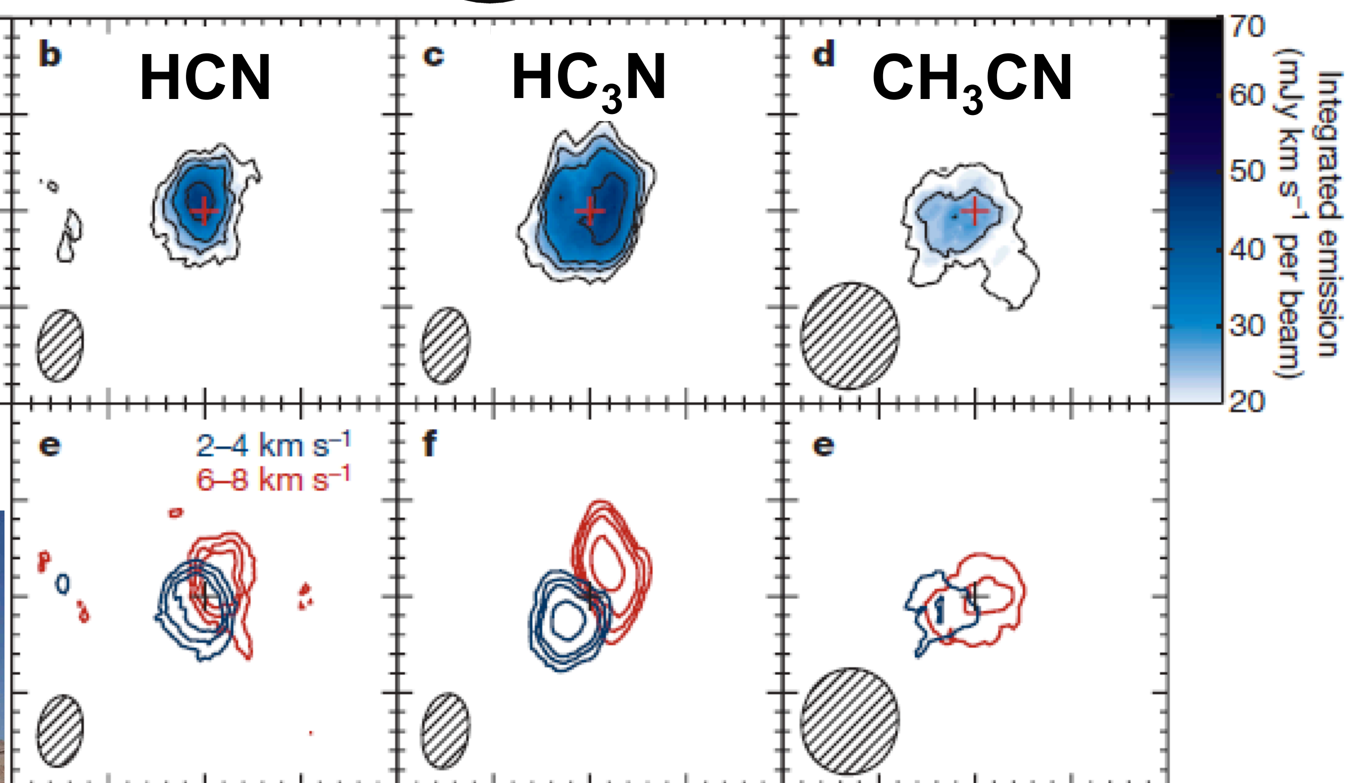
Grewal, Dasgupta, Marty 2021, Nature Astronomy

$$\delta^{15}N = \left[\frac{\frac{15N}{14N}_{sample}}{\frac{15N}{14N}_{atm}} - 1 \right] \times 1000$$

Complex cyanides and the comet-like composition of a protoplanetary disk

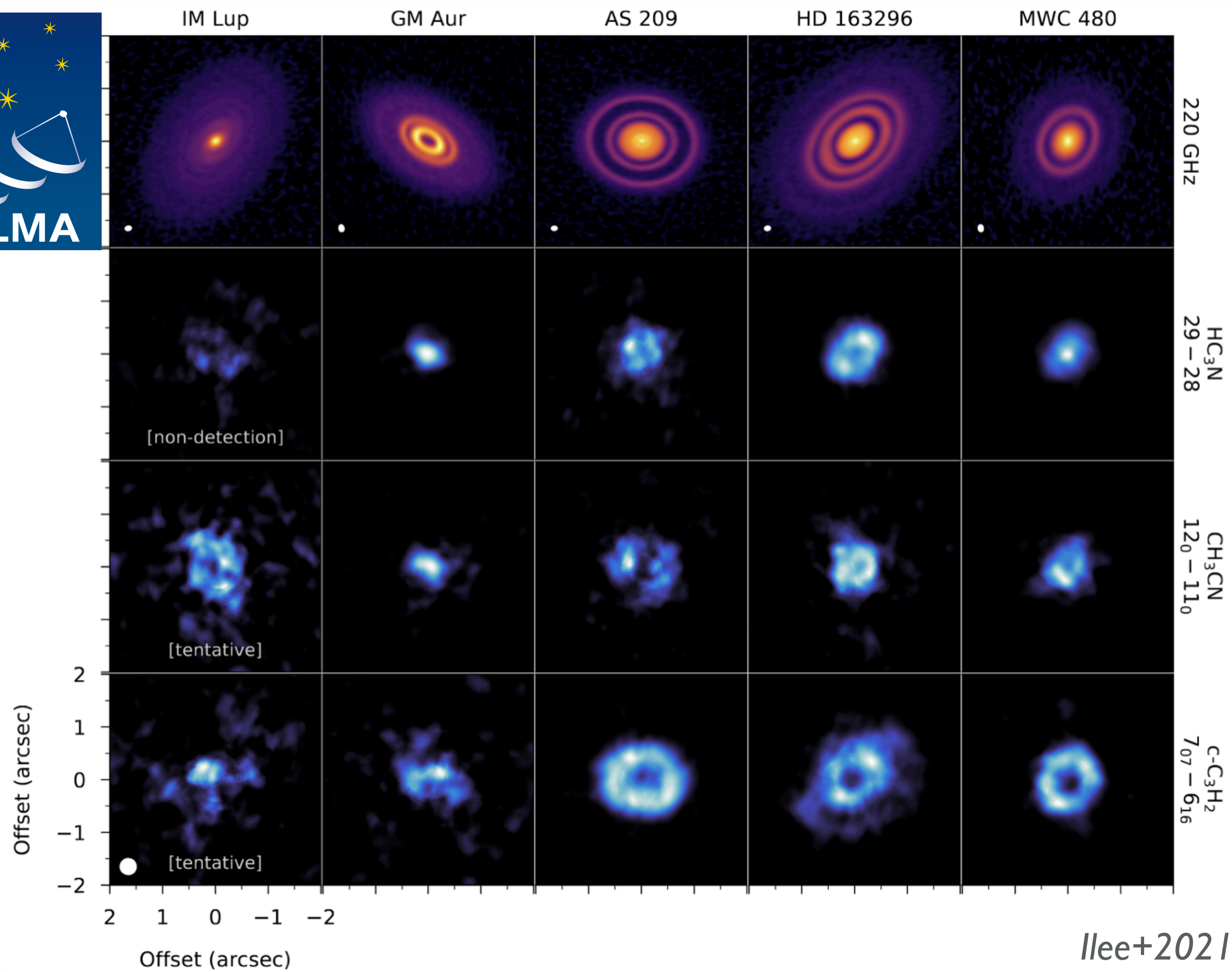






see also Walsh+2016, Favre+2018, Loomis+2018, Booth+2021, Ilee+2021, Brunken+2022

More evolved (Class II) disks and their chemical structure

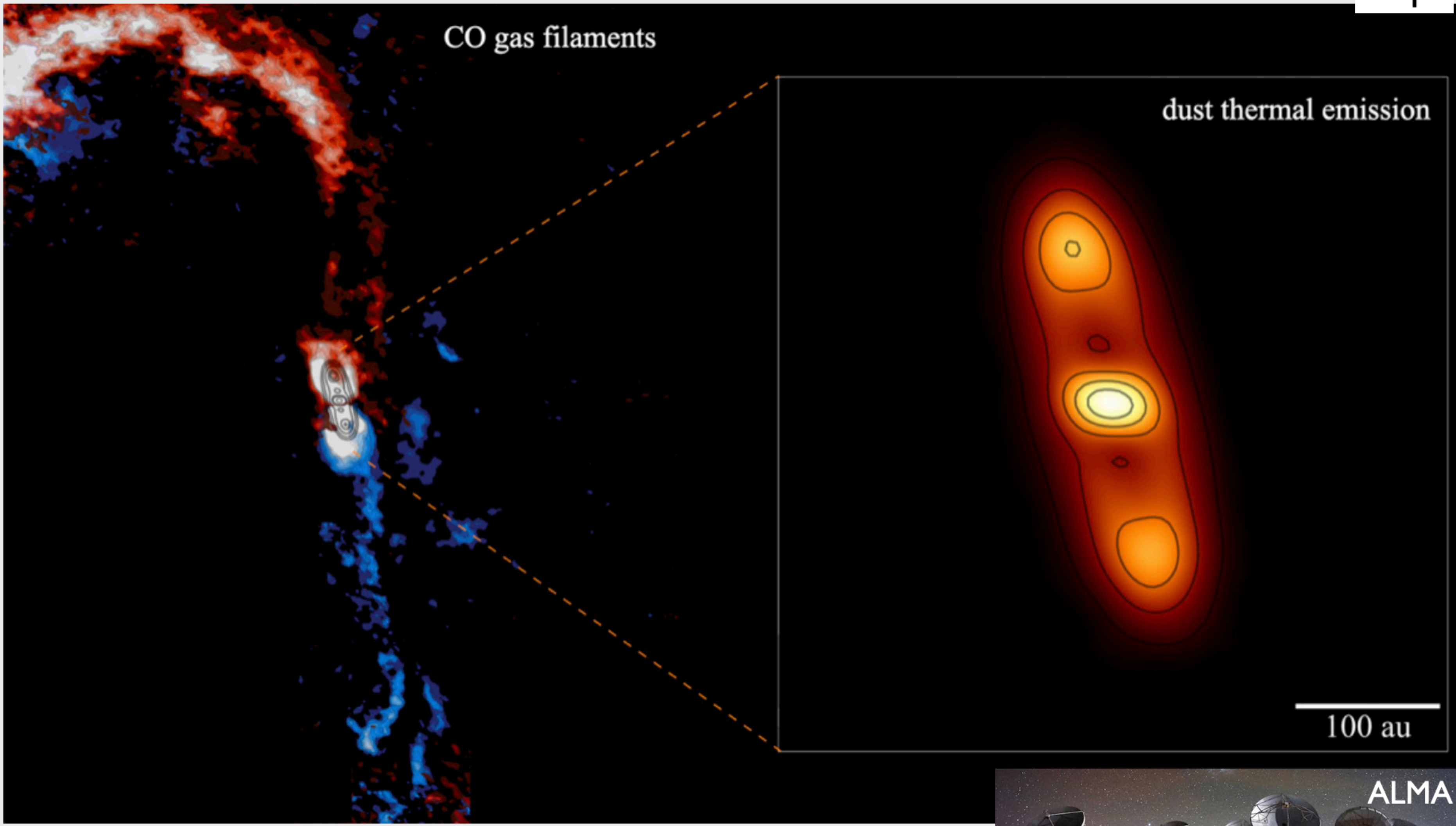


Ilee+2021

(The Molecules with ALMA at Planet-Forming Scales, MAPS; *Öberg+2021*)

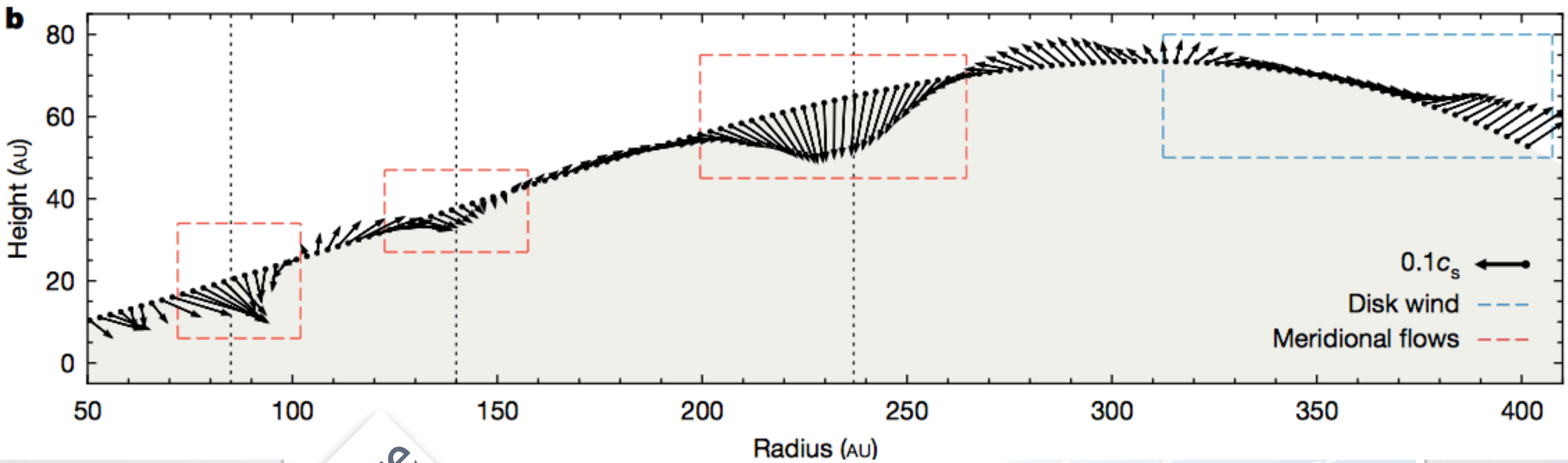
Also more evolved planet-forming disks are fed by streamers

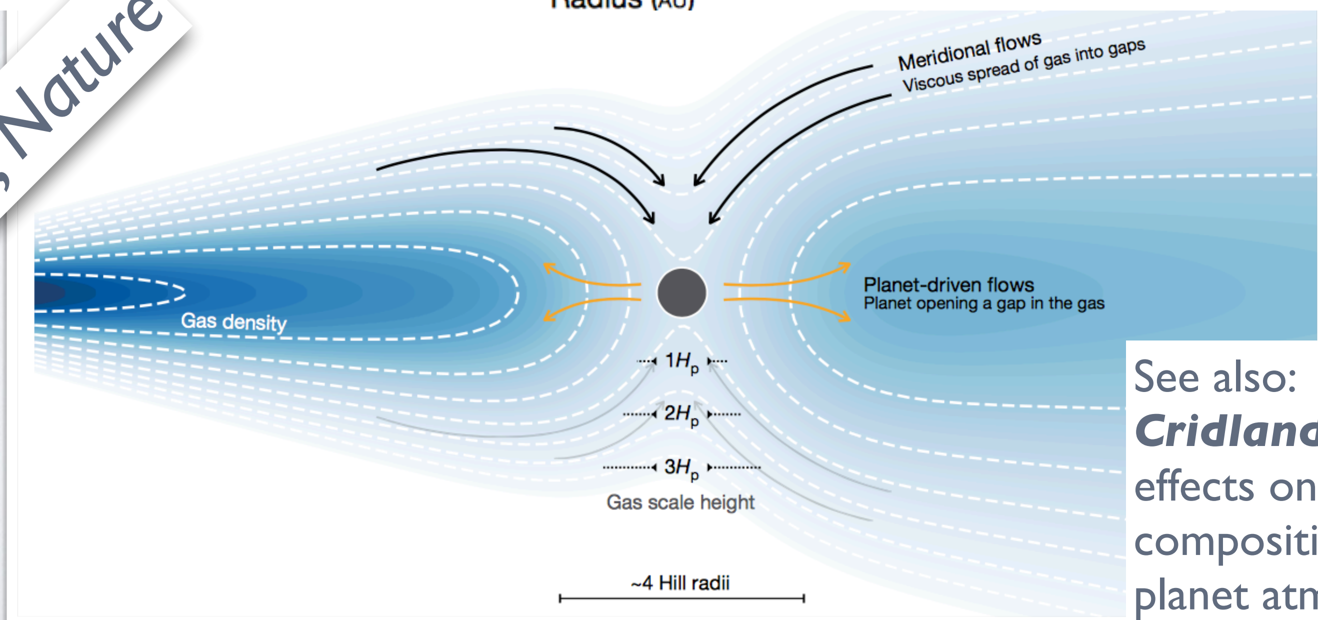
Felipe



Alves+2020 (see also Ginski+2021, Garufi+2021)

Meridional flows in disks can feed planet atmospheres of volatile-rich material

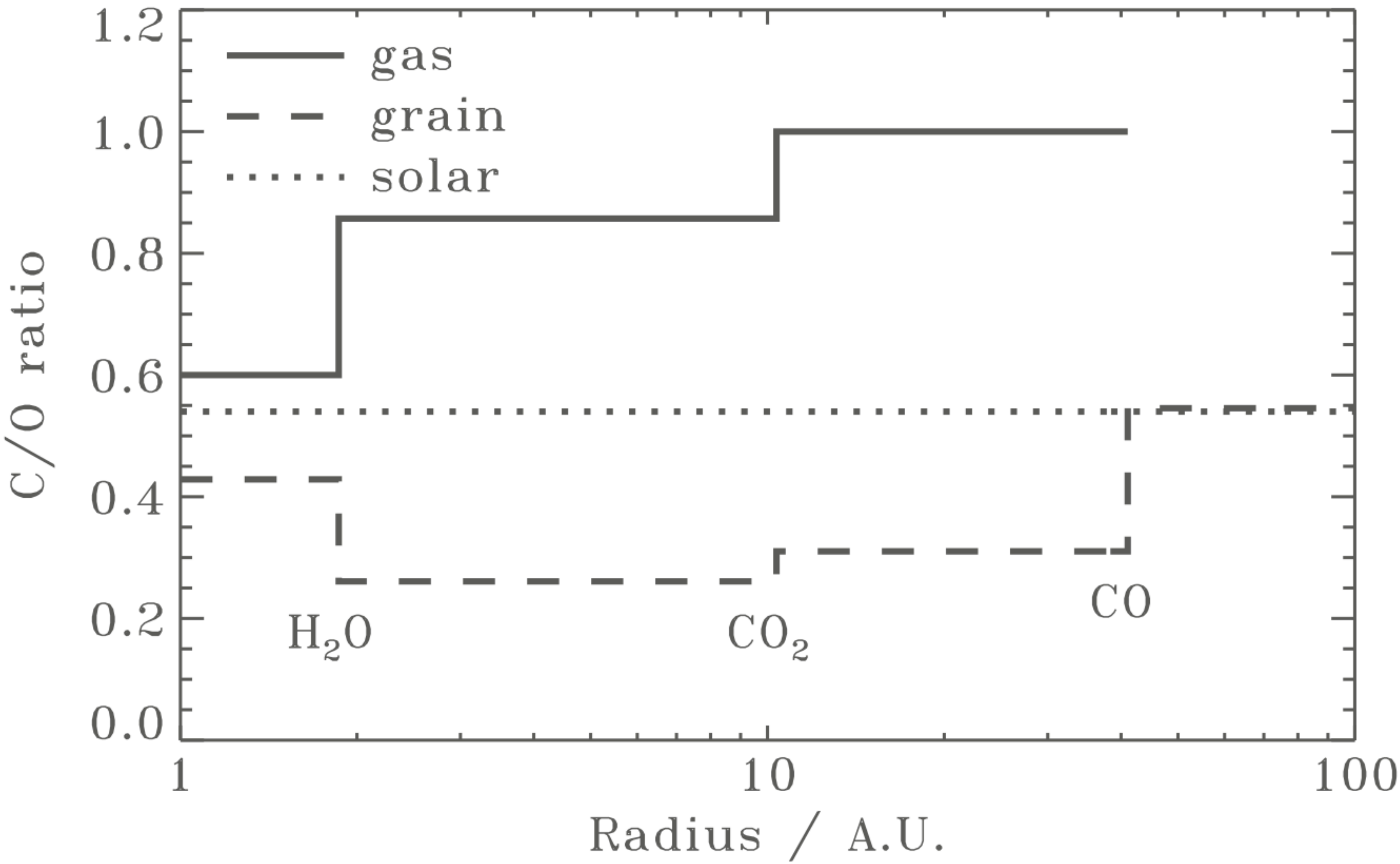




Teague+2019, Nature

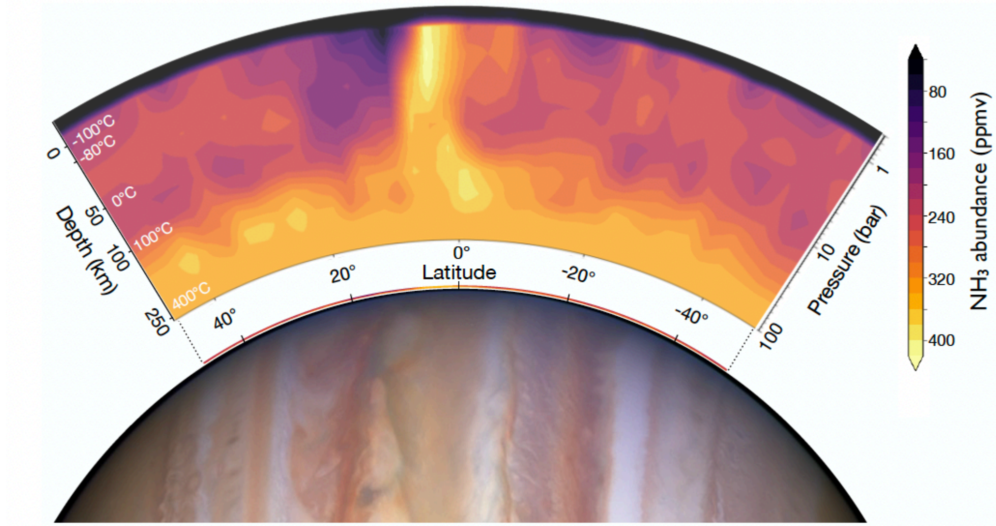
See also: ***Cridland+2020*** for effects on chemical composition of planet atmosphere.

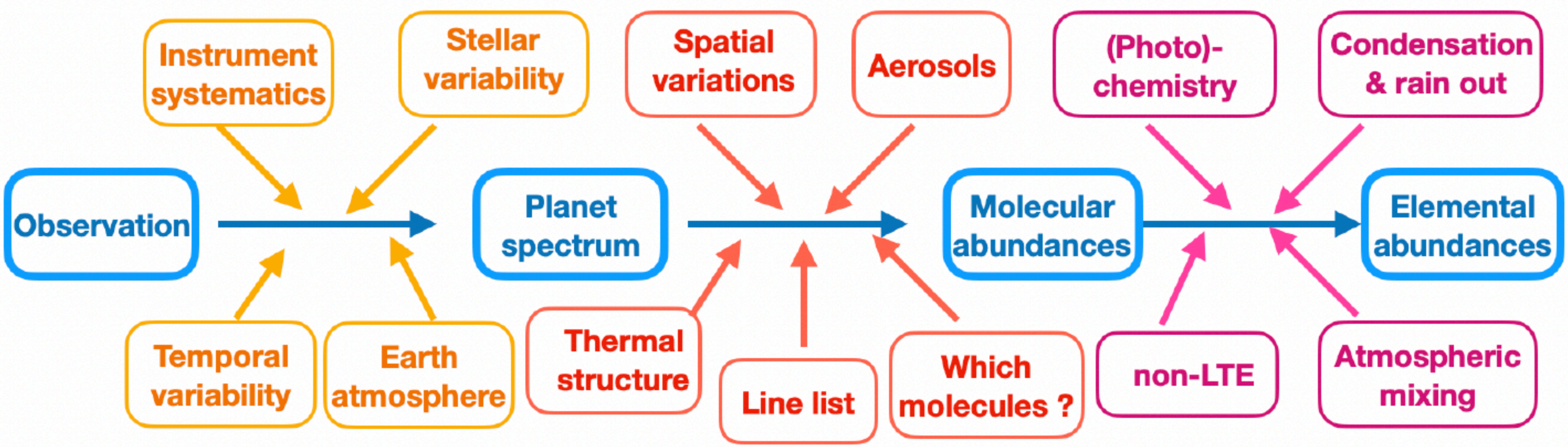
The effect of snowlines on C/O planetary atmospheres



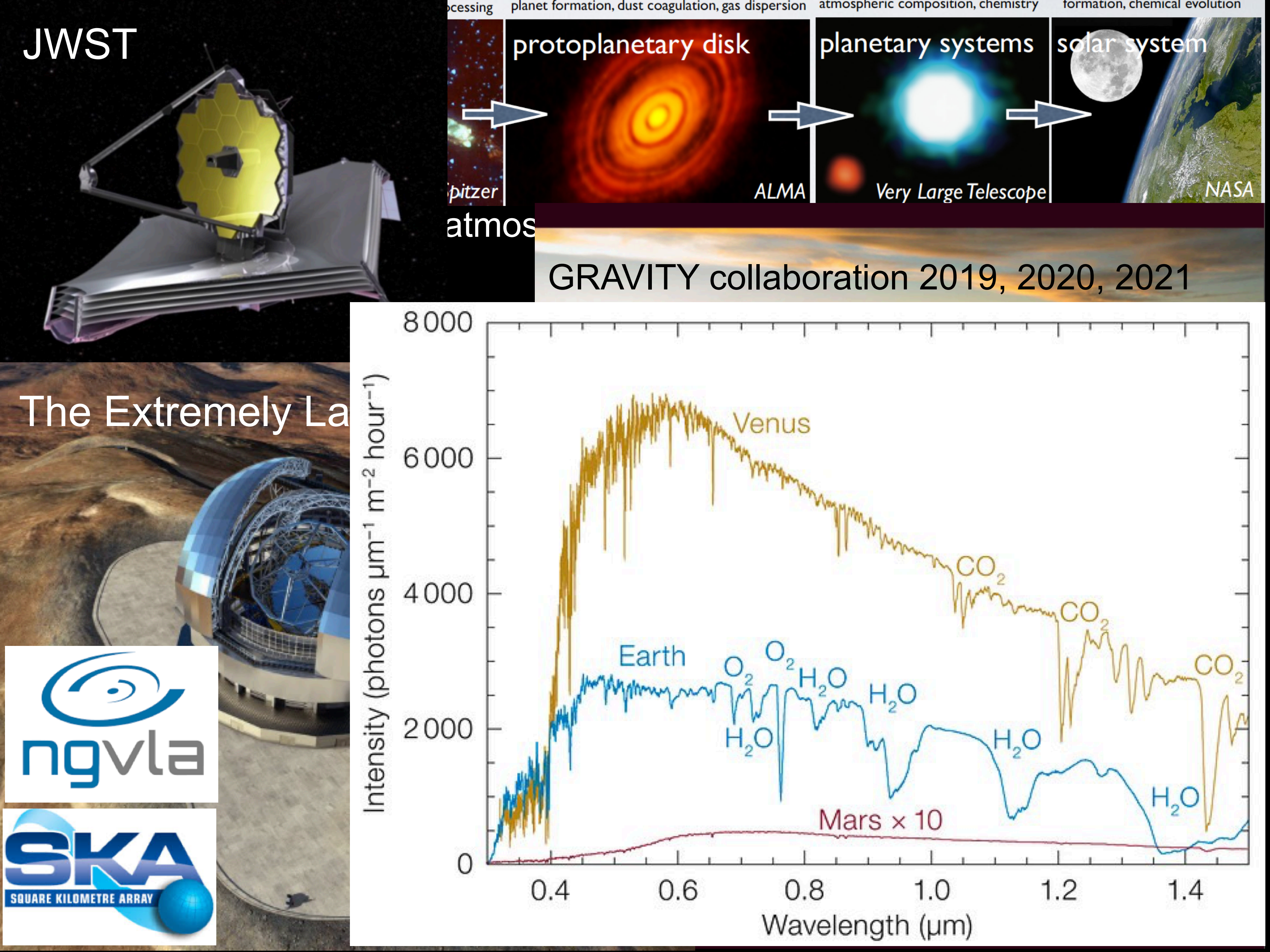
Öberg, Murray-Clay & Bergin 2011 (see also Piso+2015)

The challenge to go from an exoplanet observation to an atmospheric elemental abundance measurement





Guillot, Fletcher, Helled, Ikoma, Line, Parmentier 2022, PPVII


JWST
cessing
planet formation, dust coagulation, gas dispersion
atmospheric composition, chemistry
formation, chemical evolution
protoplanetary disk
planetary systems
solar system
pitzer
ALMA
Very Large Telescope
NASA
atmos
GRAVITY collaboration 2019, 2020, 2021
The Extremely La
ngvla
SKA
SQUARE KILOMETRE ARRAY
Intensity (photons μm⁻¹ m⁻² hour⁻¹)
8000
6000
4000
2000
0
0.4
0.6
0.8
1.0
1.2
1.4
Wavelength (μm)
Venus
CO2
CO2
CO2
Earth
O2
O2
H2O
H2O
H2O
H2O
H2O
Mars × 10