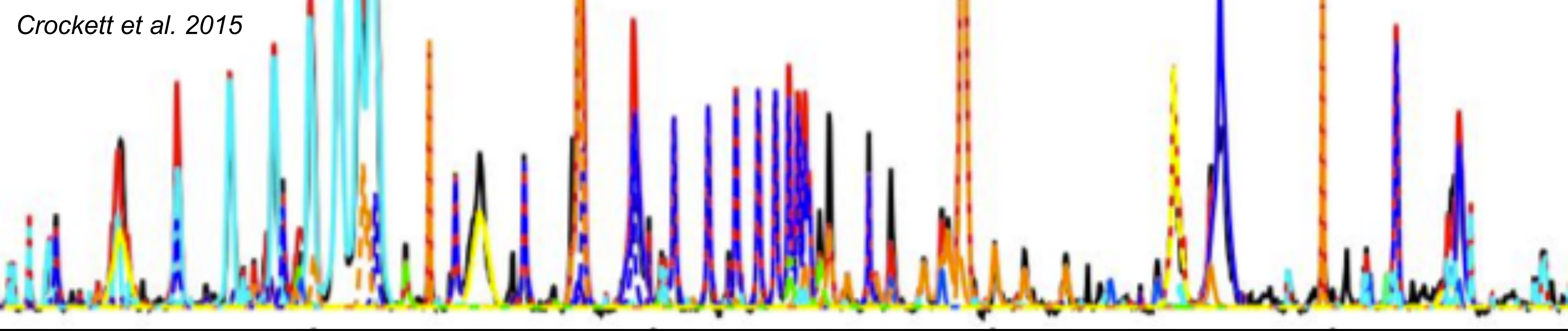
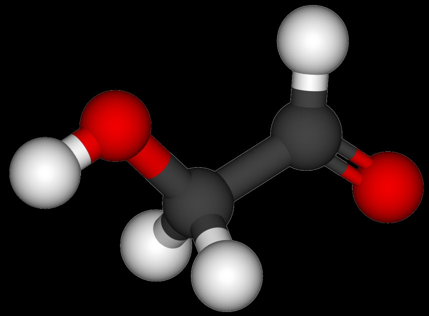
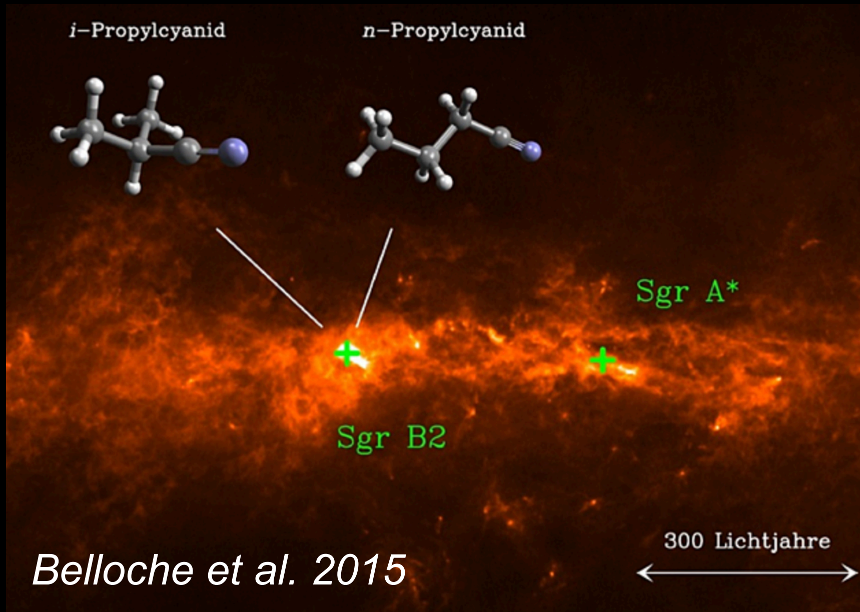


4. Complex* Organic Molecules (COMs)





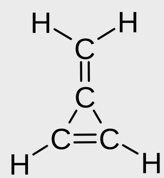
* ≥ 6 atoms in size *(Herbst & van Dishoeck 2009)*

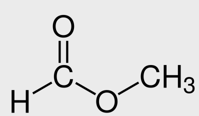
COMs start forming at the edge of the “catastrophic” CO freeze-out zone

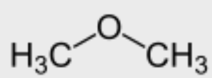
(see theory work by Vasyunin+2017)

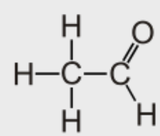
See also:

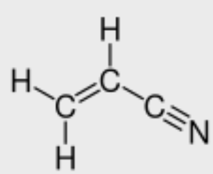
Marcelino+2007
Öberg+2010
Bacmann+2013
Bizzocchi+2014
Vastel+2014
Bacmann&Faure 2016
Jiménez-Serra+2016, 2021
Spezzano+2016, 2017, 2020
Scibelli & Shirley 2020
Ambrose+2021
Punanova+2022

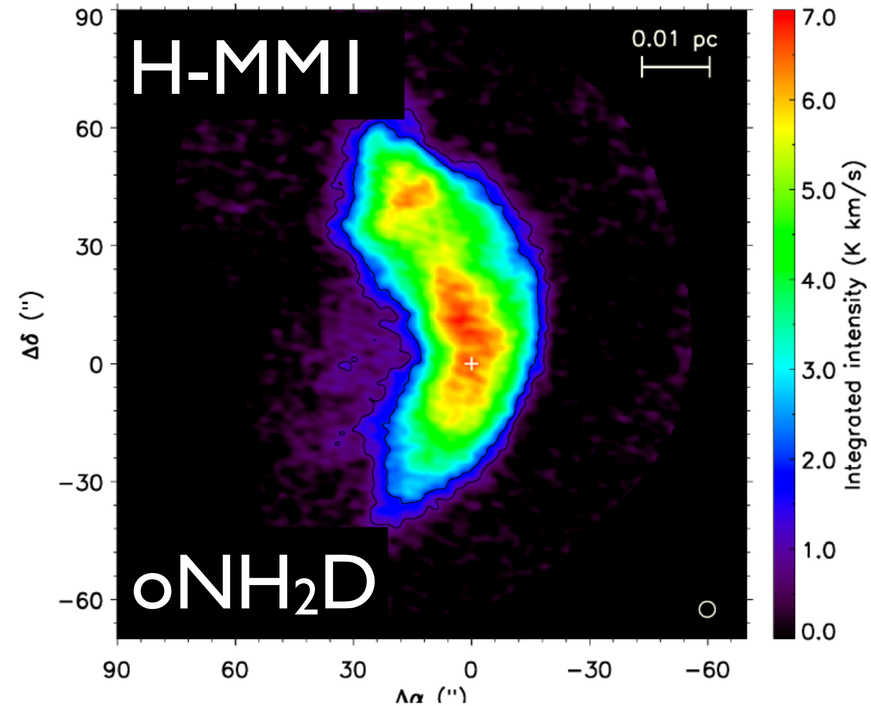


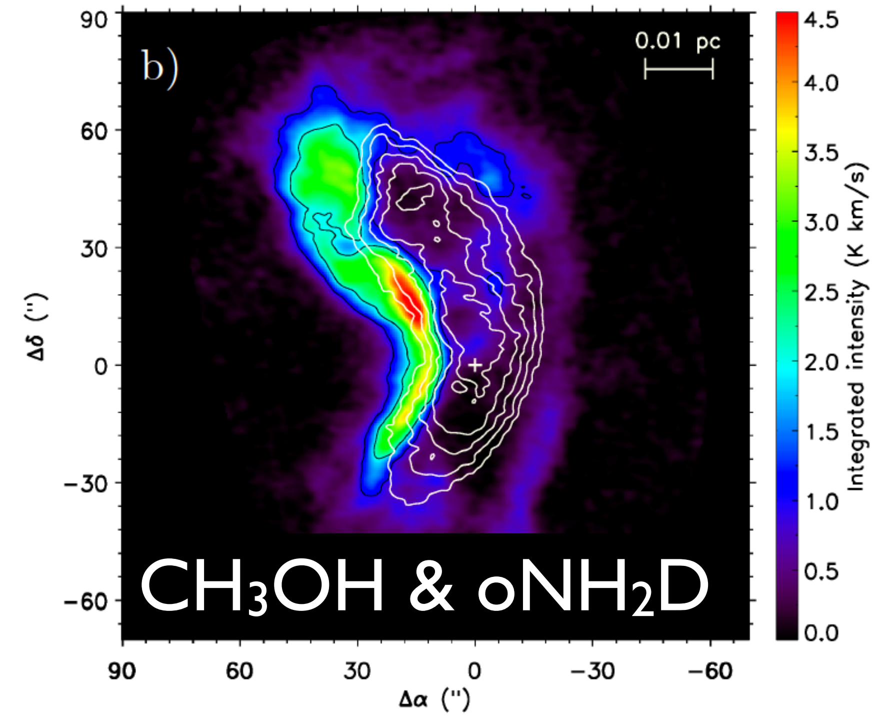








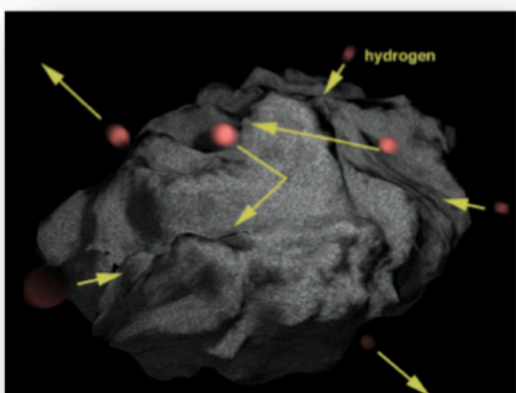


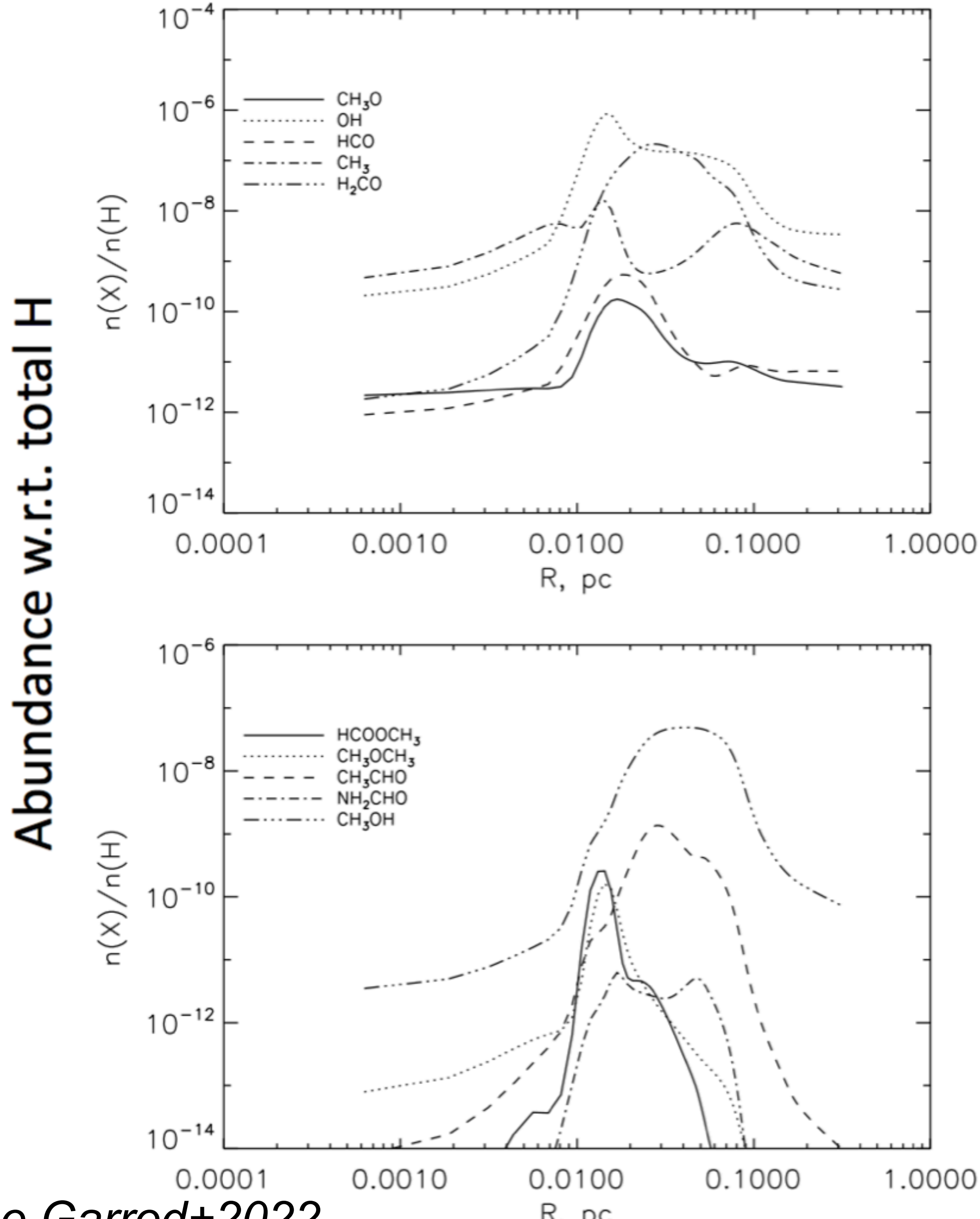


Gas + grain chemistry in L1544

- physical structure
- gas-grain chemistry
- reactive desorption
- photodesorption
- neutral-neutral reactions

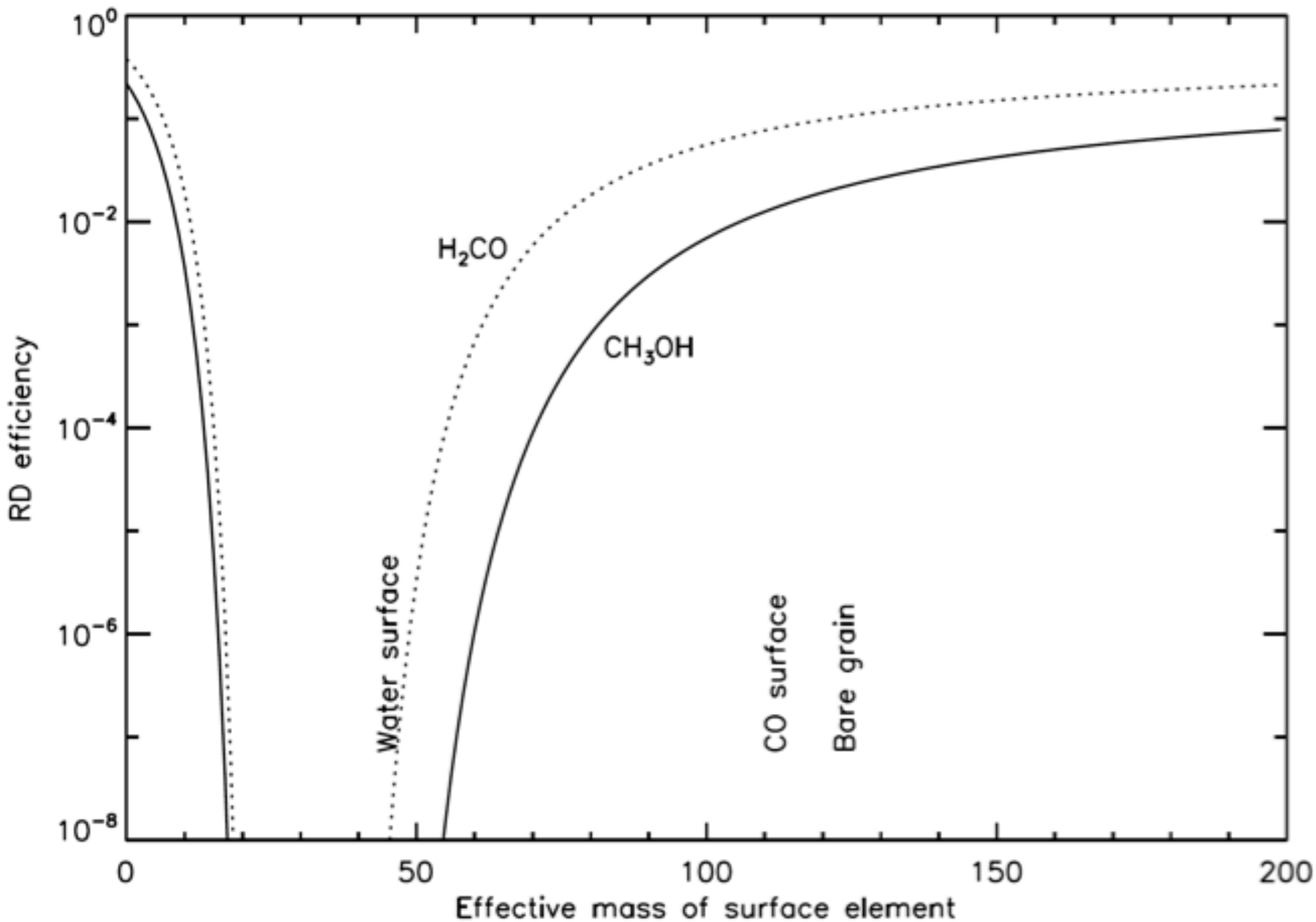
(Shannon+2008; Balucani+2015; Barone+2015; Skouteris+2017)





Vasyunin et al. 2017 *see also Garrod+2022*

Reactive desorption efficiency of CH_3OH and H_2CO in surface reactions H + HCO → H_2CO and H + H_3CO → CH_3OH, vs. the effective mass of the surface element (based on *Minissale et al. 2016)*

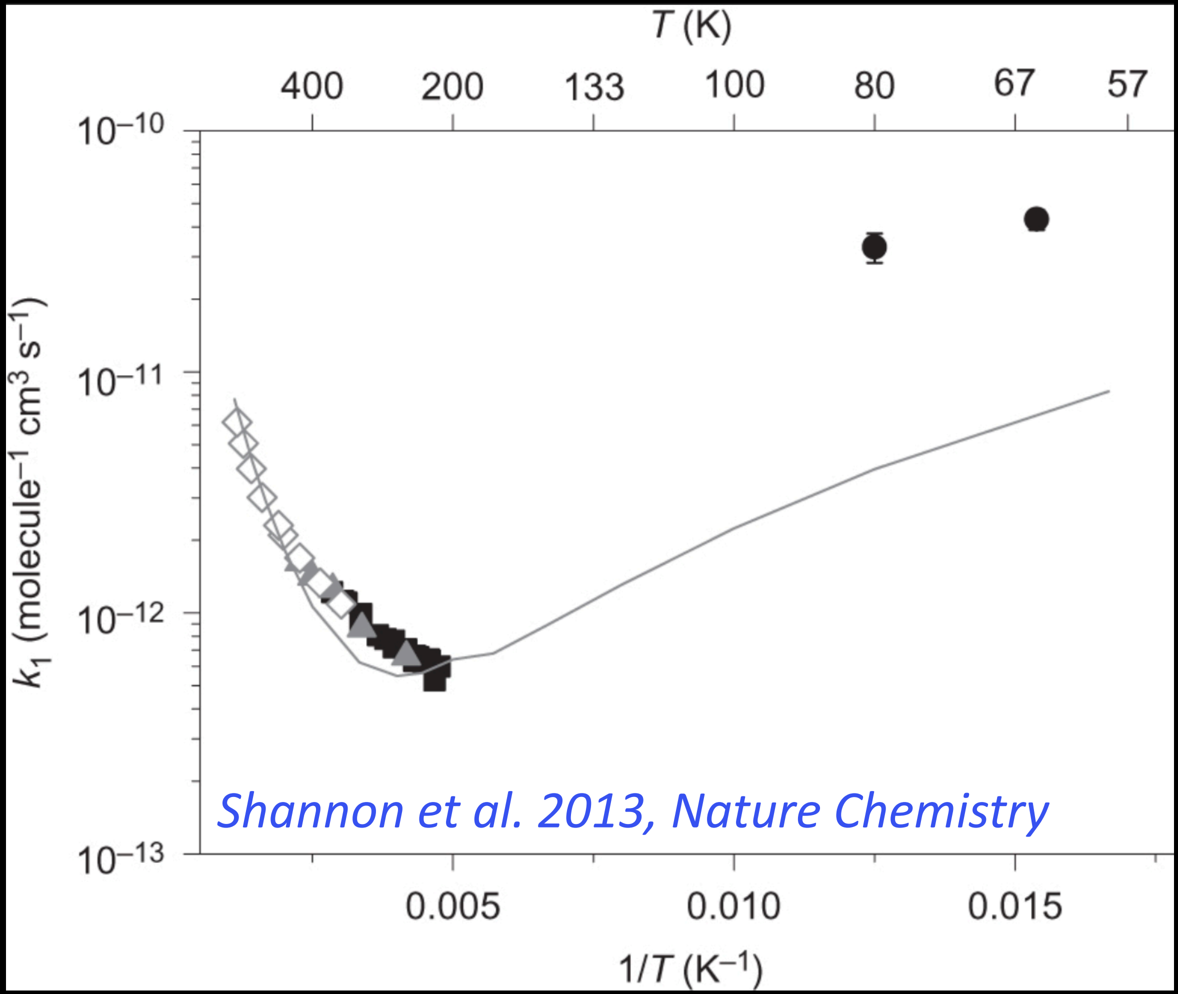


Vasyunin et al. 2017

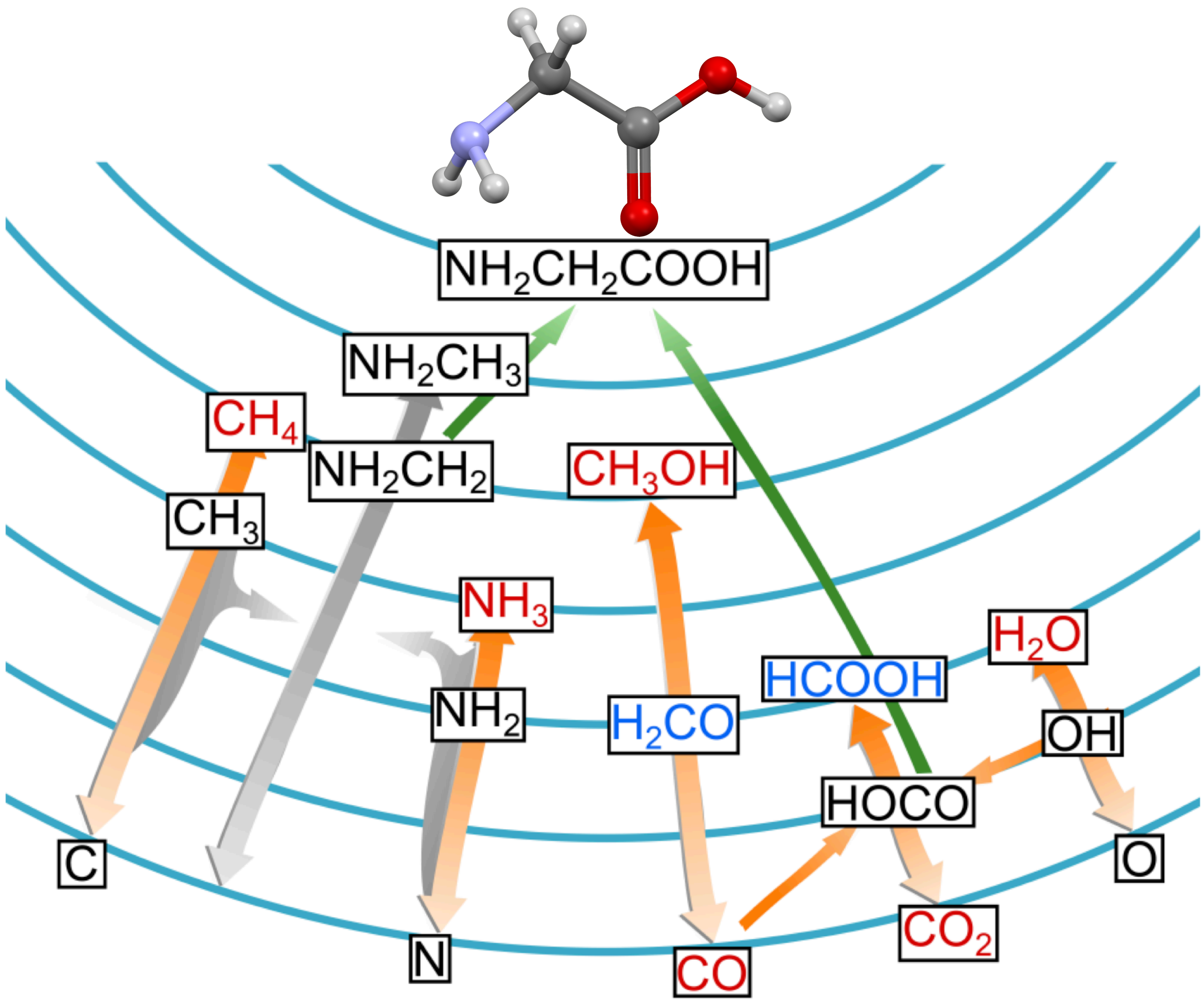
Neutral-Neutral reactions

$$OH + CH_3OH \rightarrow CH_3O + H_2O$$

Accelerated chemistry at low interstellar temperatures, facilitated by tunneling.



Formation of glycine in a water-rich ice at low T

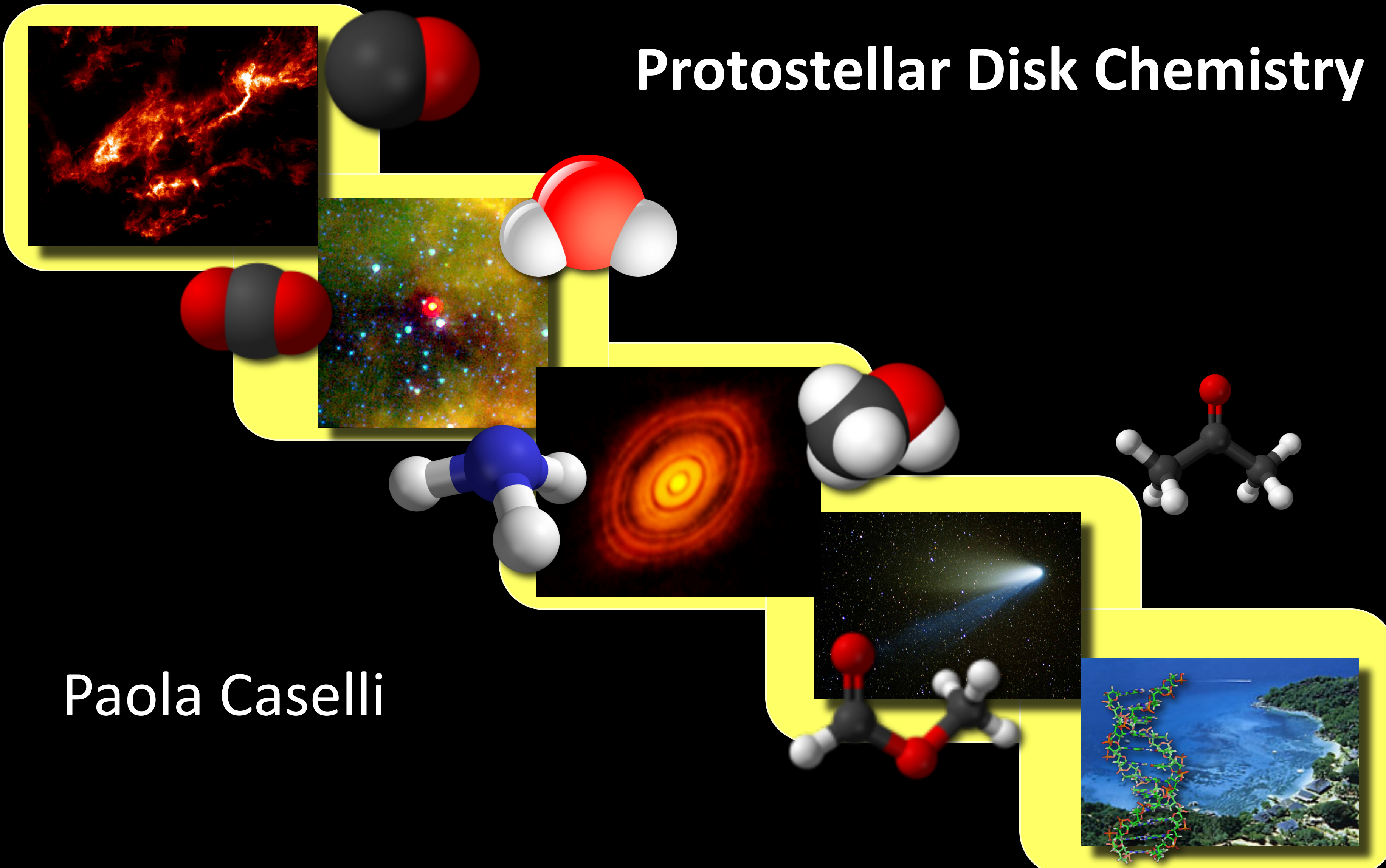


Laboratory experiment: *Ioppolo+2021, Nature Astronomy*

see also Krasnokutski+2022, Nature Astronomy

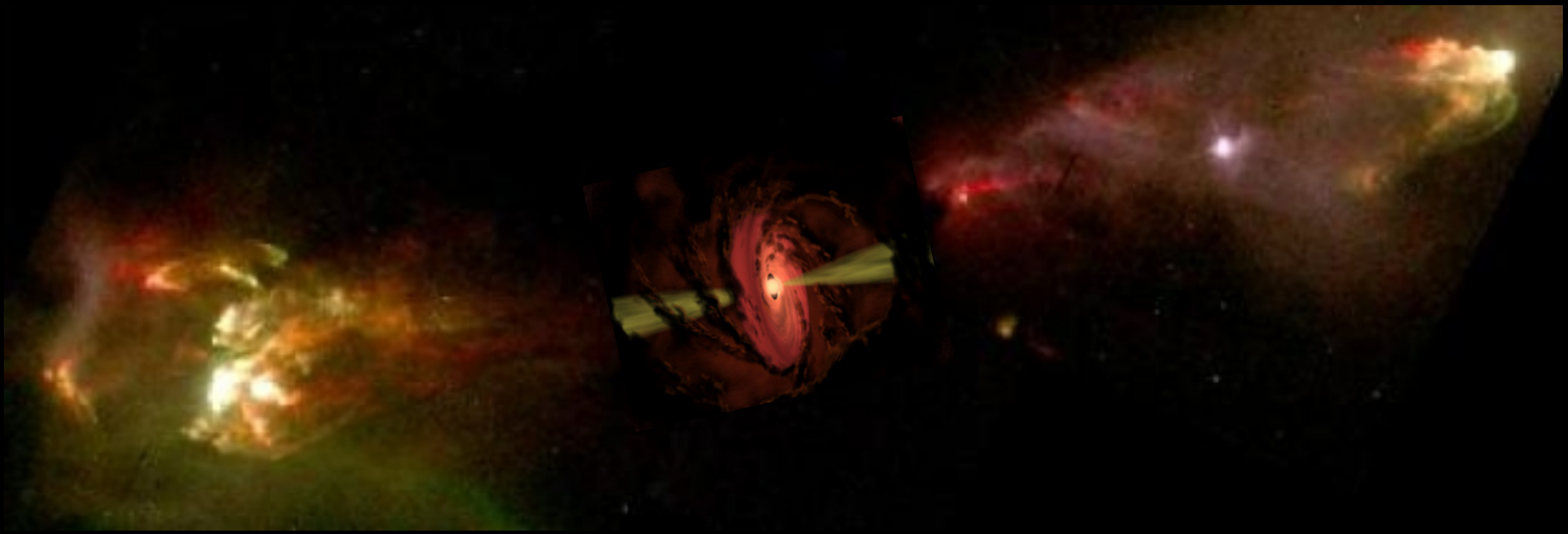
Center for Astrochemical Studies
Max-Planck-Institute for Extraterrestrial Physics

Protostellar Disk Chemistry



Paola Caselli

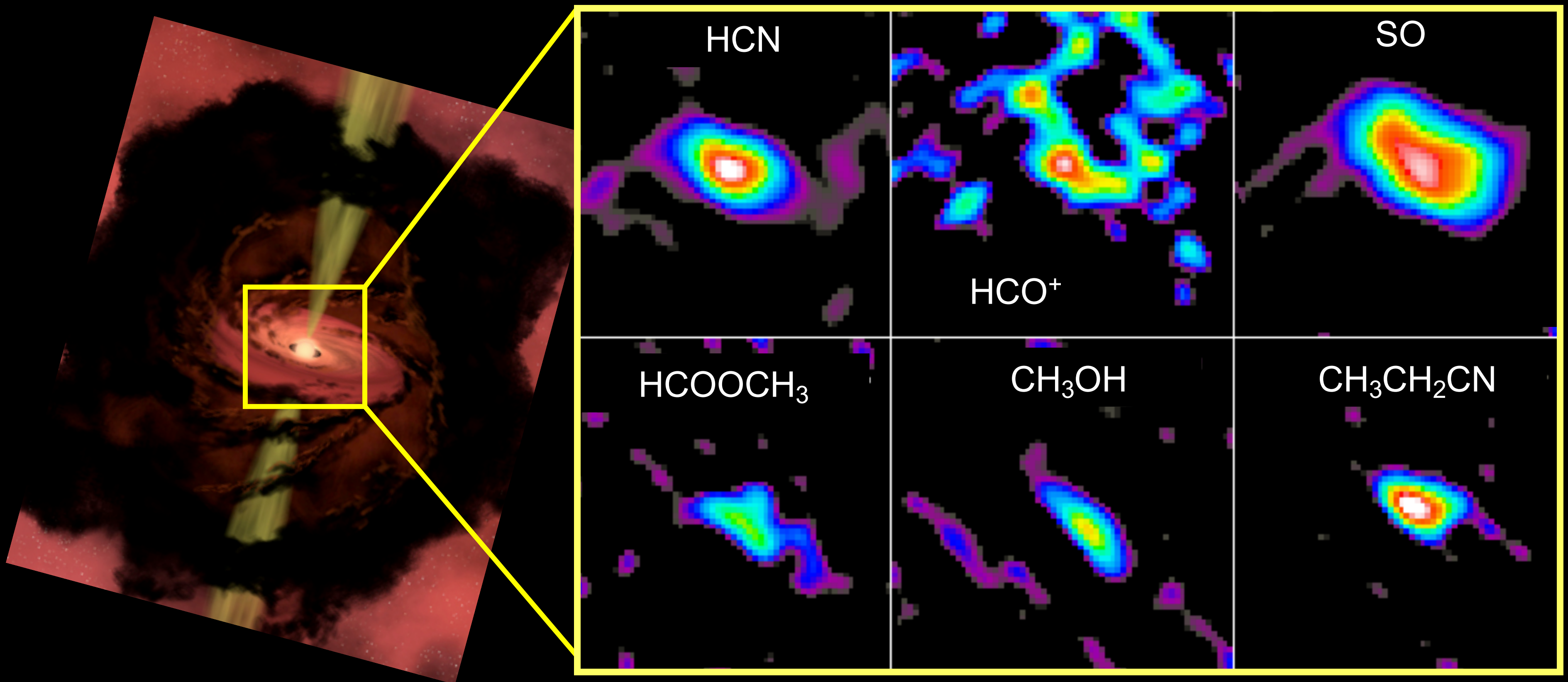
Protostellar disks



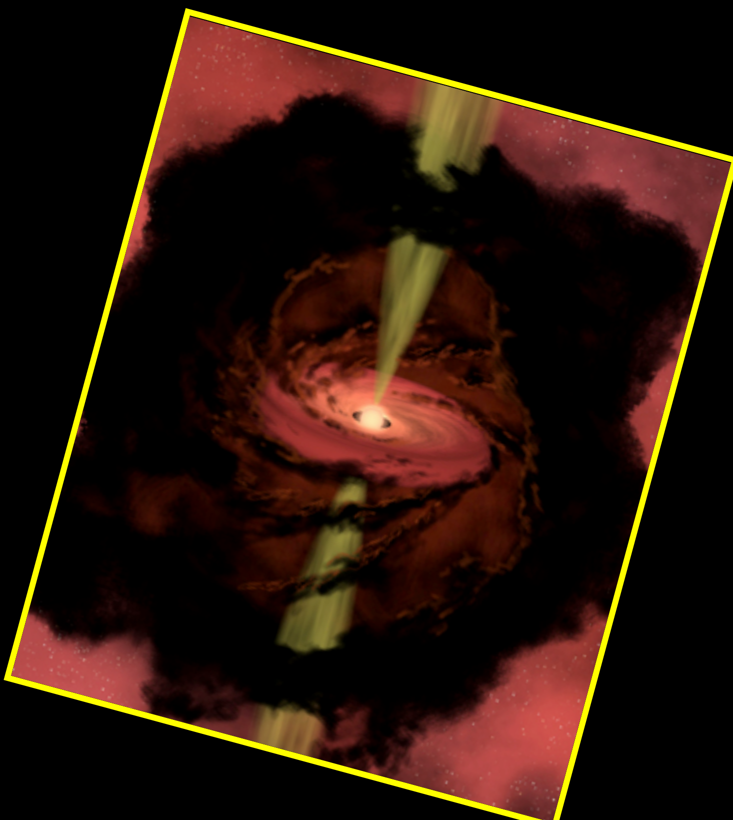
Hubble/WFPC2 – http://hubblesite.org/gallery/album/entire/pr1995024c/web/npp/16/

Complex organic molecules in hot cores and hot corinos

(e.g. Wright et al. 1996; Cazaux et al. 2003; Bottinelli et al. 2004, 2008; Kuan et al. 2004, Ceccarelli+2022, PPVII)



Large abundances of multiply deuterated species are found in protostellar envelopes (Ceccarelli+1998; Parise+2002, 2004, 2006; van der Tak+2002; Vastel+2003; Manigand+2021)



D2CO/H2CO = 0.1

CHD2OH/CH3OH = 0.02

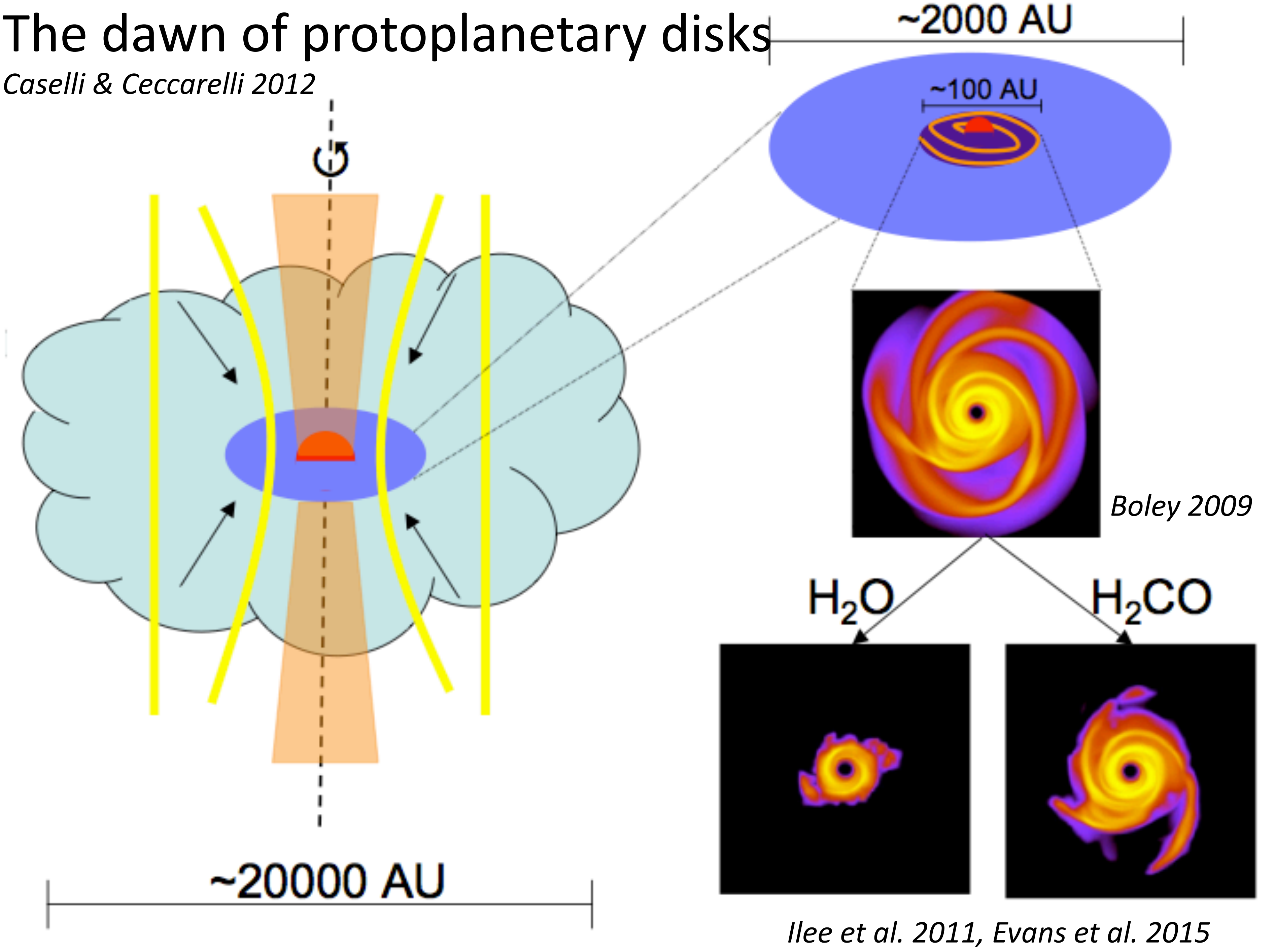
D2S/H2S = 0.02

ND3/NH3 = 0.001

CD3OH/CH3OH = 0.02

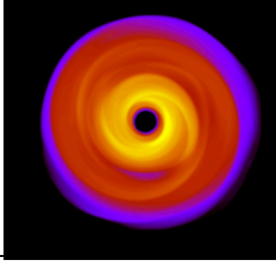
The dawn of protoplanetary disks

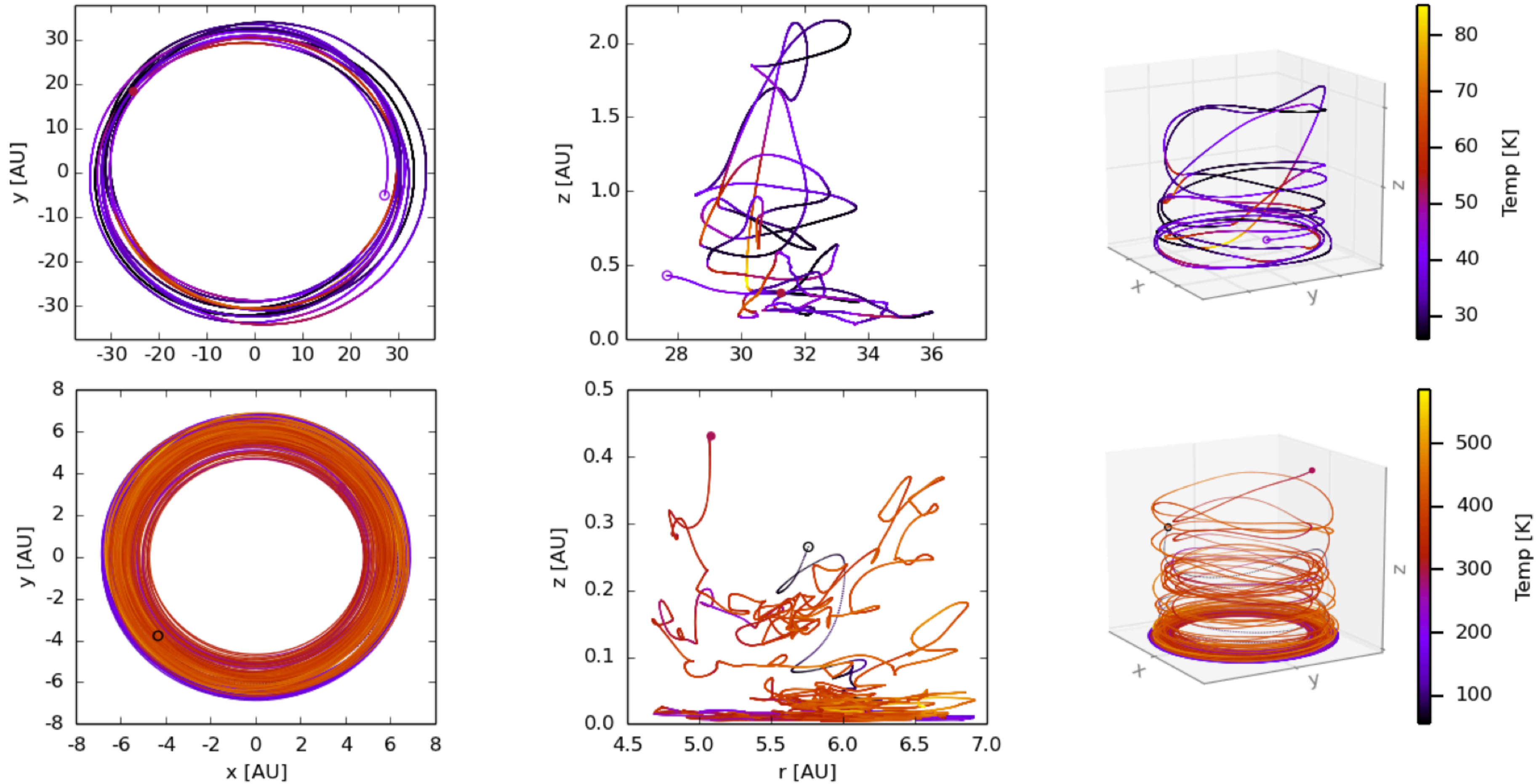
Caselli & Ceccarelli 2012



Proto-Solar young disks:

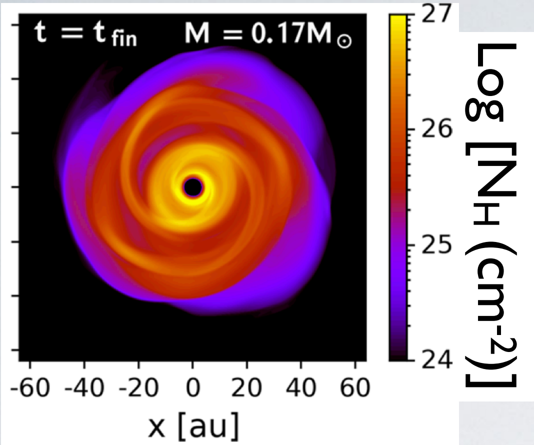
complex orbits and temperature excursions

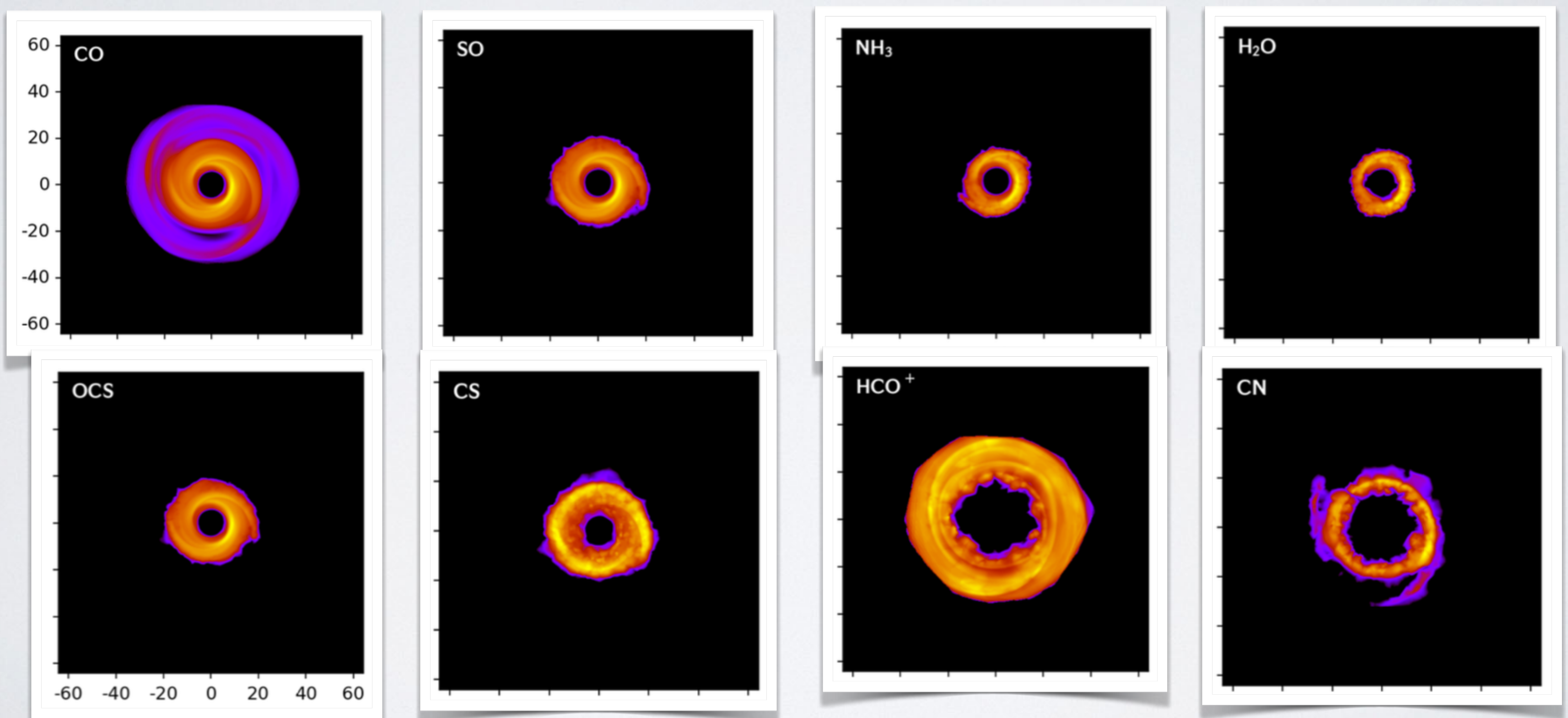




Evans et al. 2015

Chemical inventory in a gravitationally unstable (proto-Solar) young disk



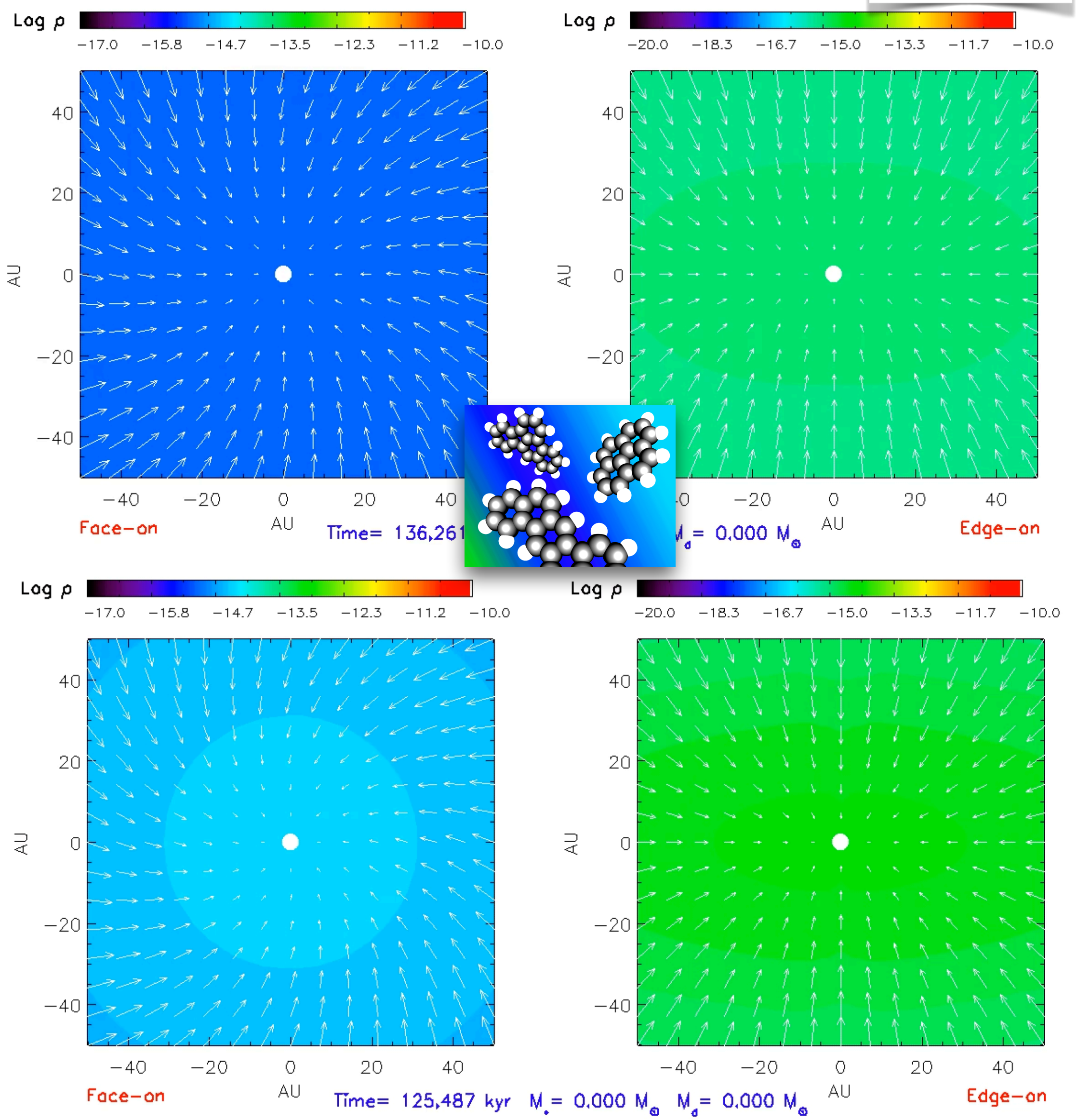


Evans, Ilee et al. 2015

Protostellar disk formation enabled by removal of very small dust grains (VSGs)

VSGs (10-100 Å) are well coupled with the magnetic field B; they "drag" B-flux, causing rotation to slow down during contraction.

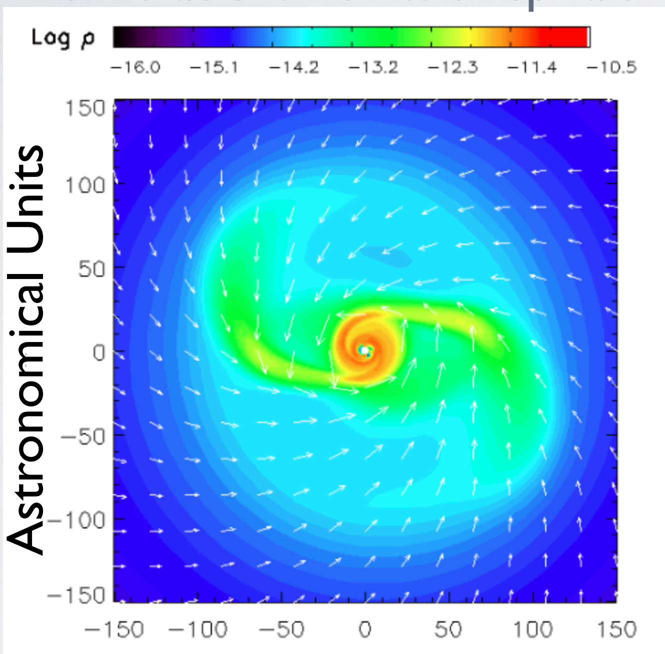
Removal of VSGs (via adsorption onto larger dust particles) reduces magnetic flux in the inner region, enabling disk to form.



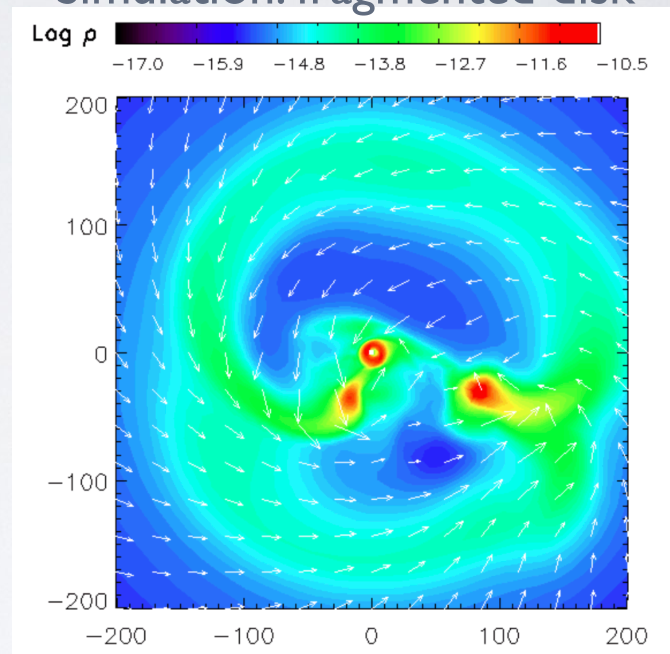
Zhao+2016, 2018, 2020; Silsbee+2020

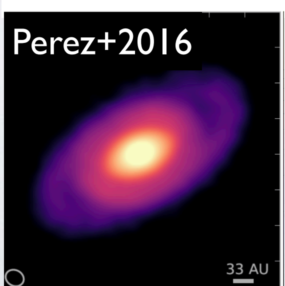
Zhao+2018: good agreement with high resolution observations of young disks !

Simulation: disk with spirals

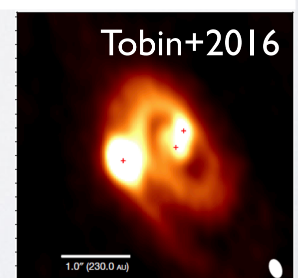


Simulation: fragmented disk

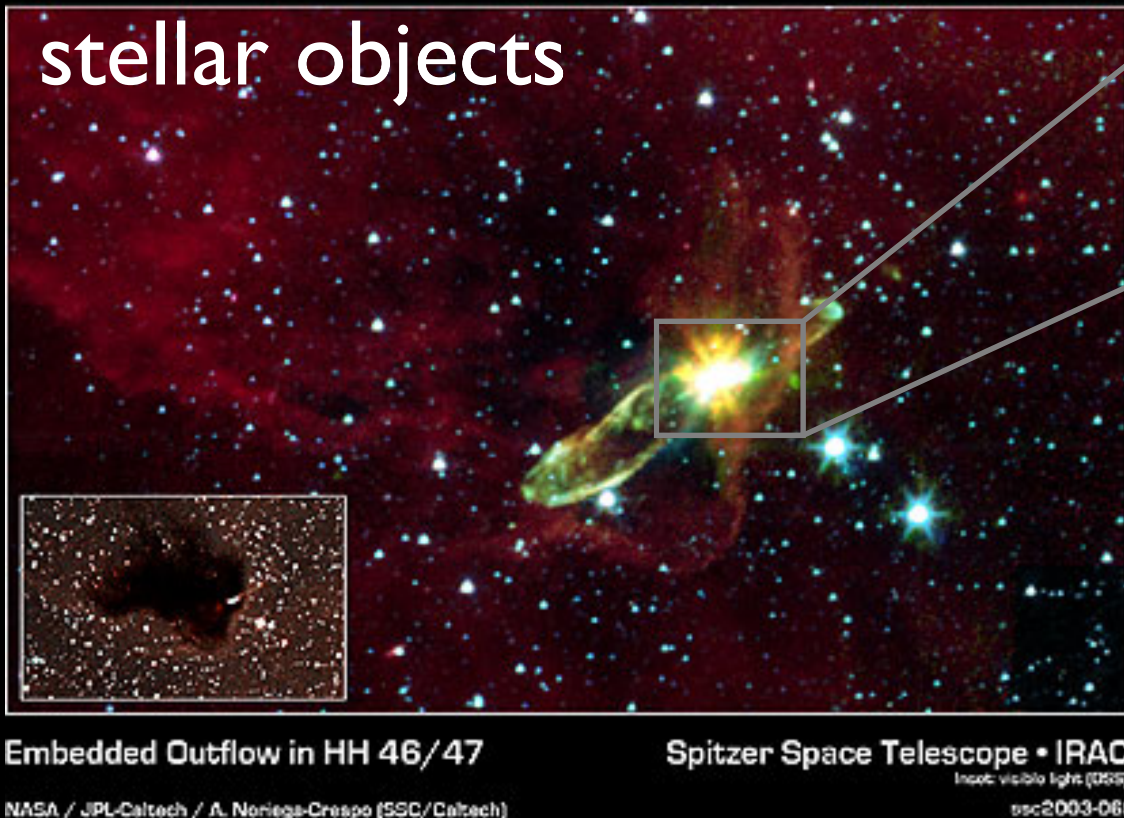


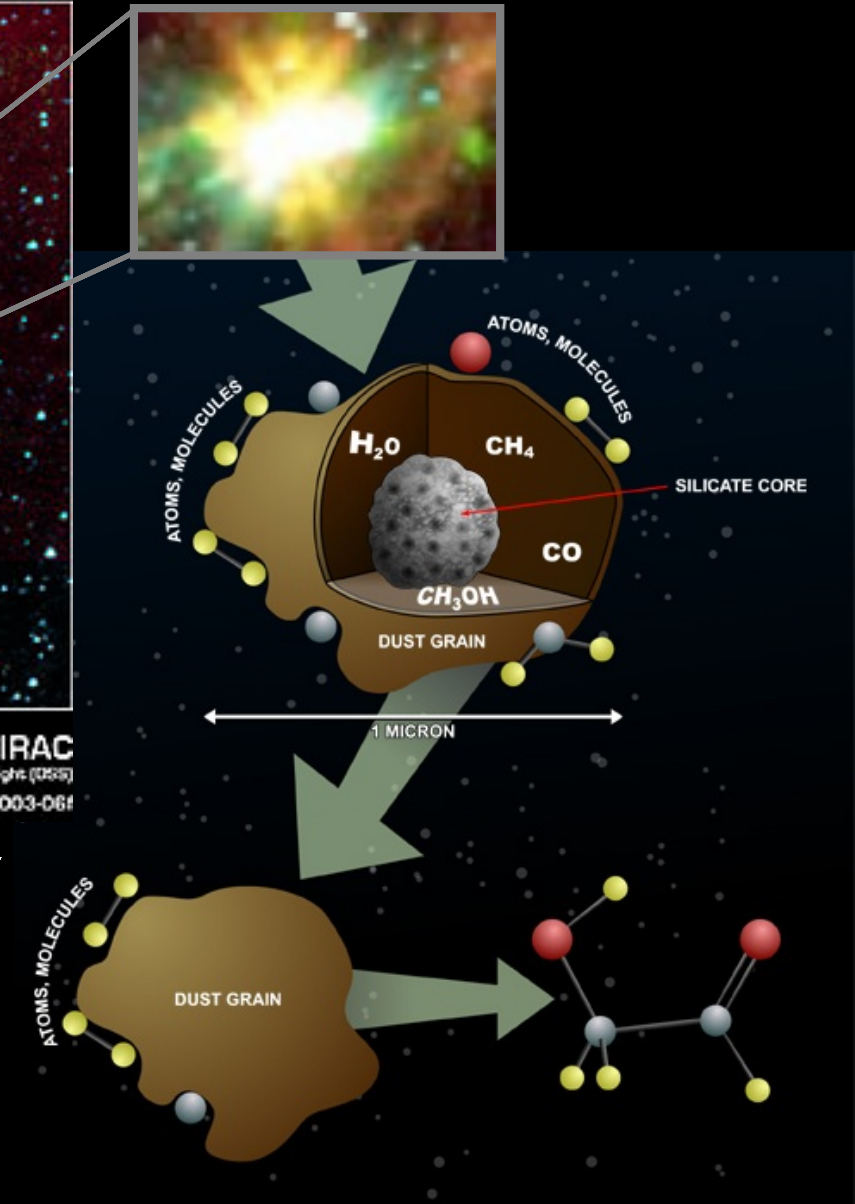


Observations



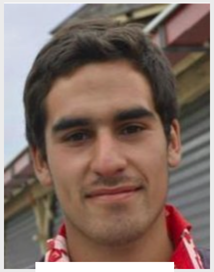
Icy species can return in gas phase nearby young stellar objects

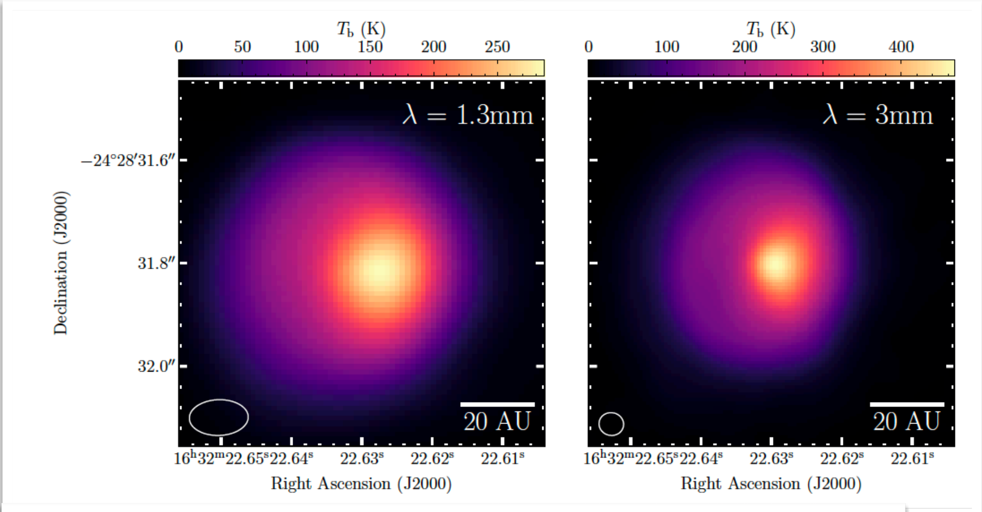




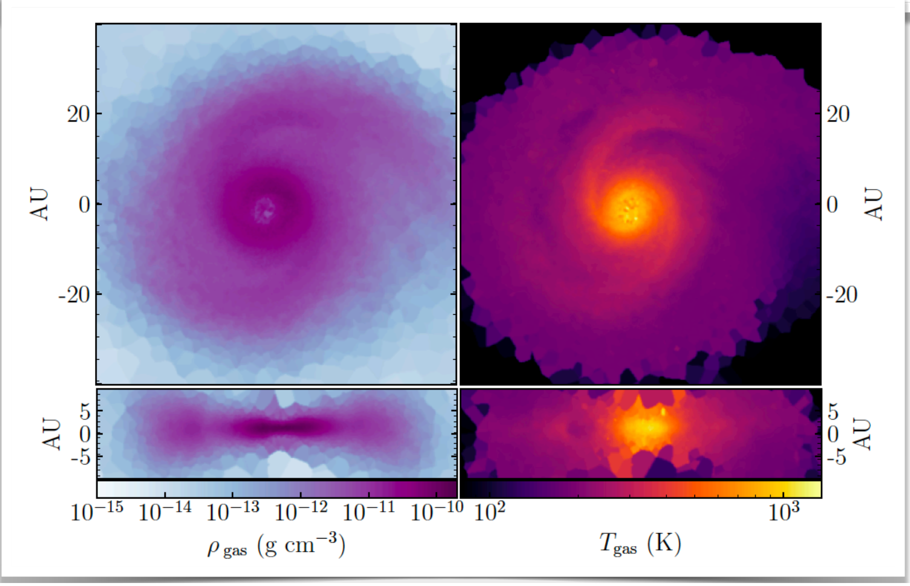
- Dust heating + energetic particles nearby protostars (icy mantle processing and evaporation; e.g. Viti+2004, Garrod+2008)
- Dust (icy mantles and cores) sputtering + vaporisation along outflows (e.g. Caselli+1997, Jiménez-Serra+2008)

Protostellar disks can be hot and gravitationally unstable





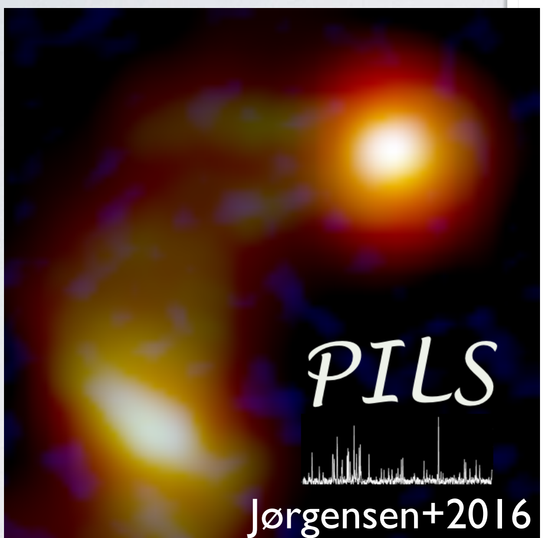
IRAS16293B ALMA observations: high brightness temperatures with T_b(3mm) > T_b(1mm), indicative of hot mid-plane.

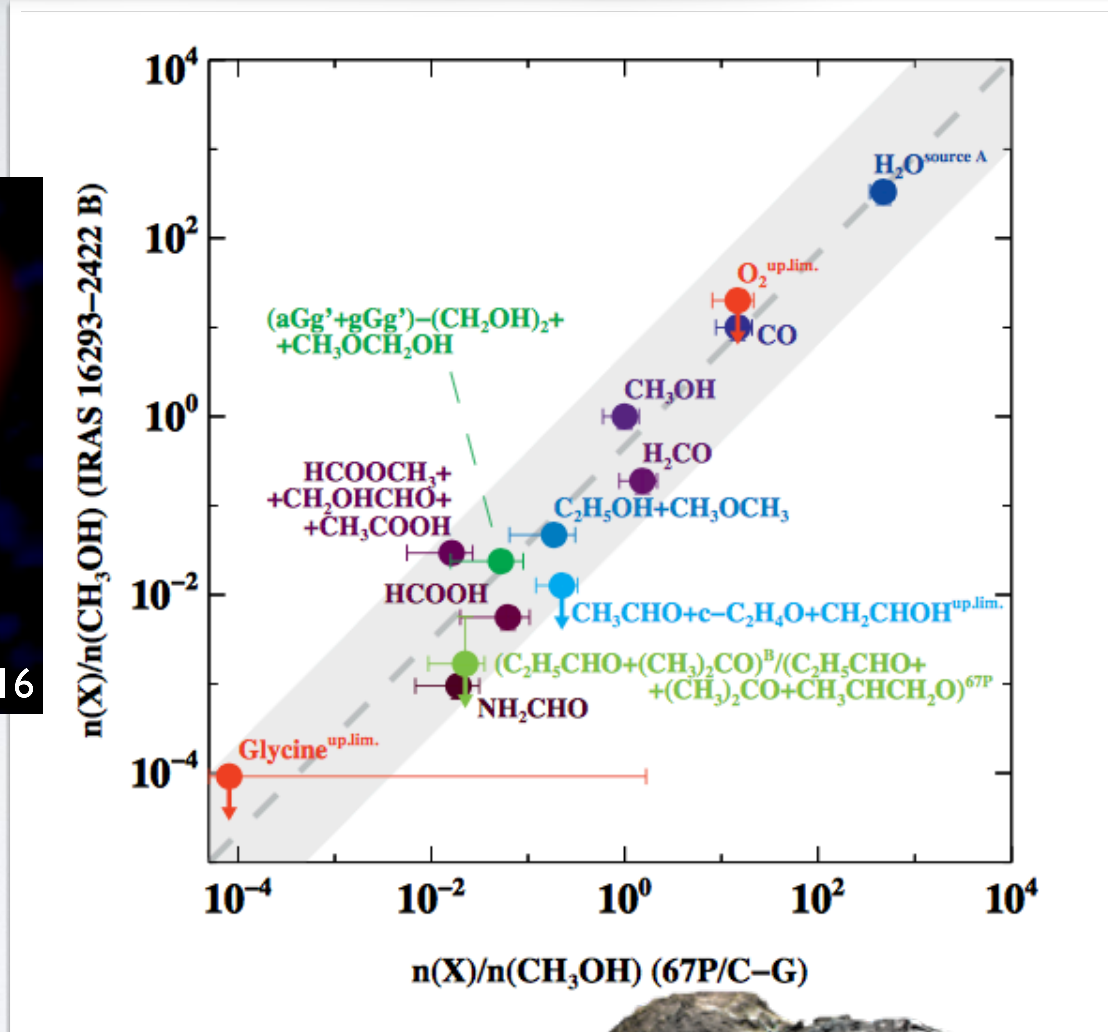


Simulations of a gravitationally unstable disk reproducing ALMA observations: all icy mantles should evaporate + dust processing.

Zamponi, Maureira, Zhao+2021

Similar COM abundances in comets and star forming regions

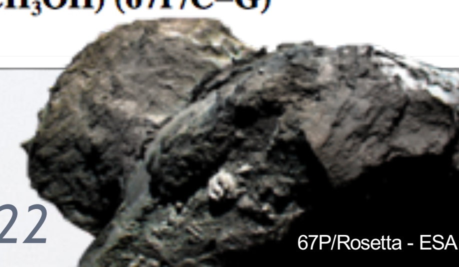




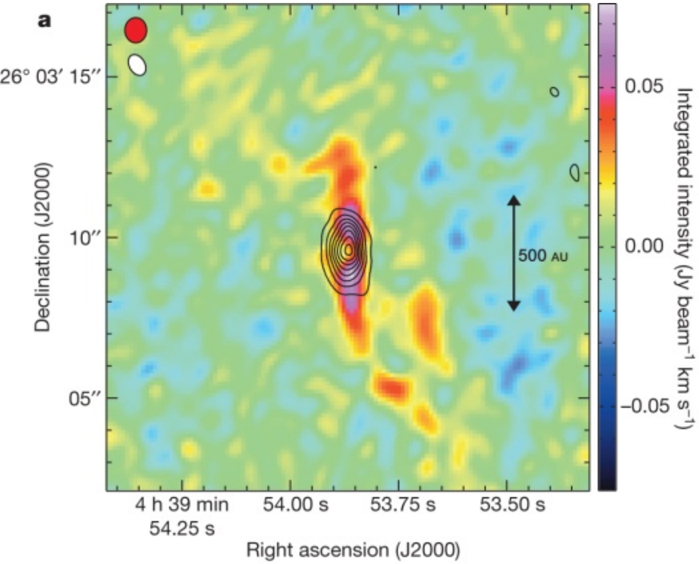
"The volatile composition of cometesimals and planetesimals is partially inherited from the pre- and protostellar phases of evolution."

Drozdovskaya+2019

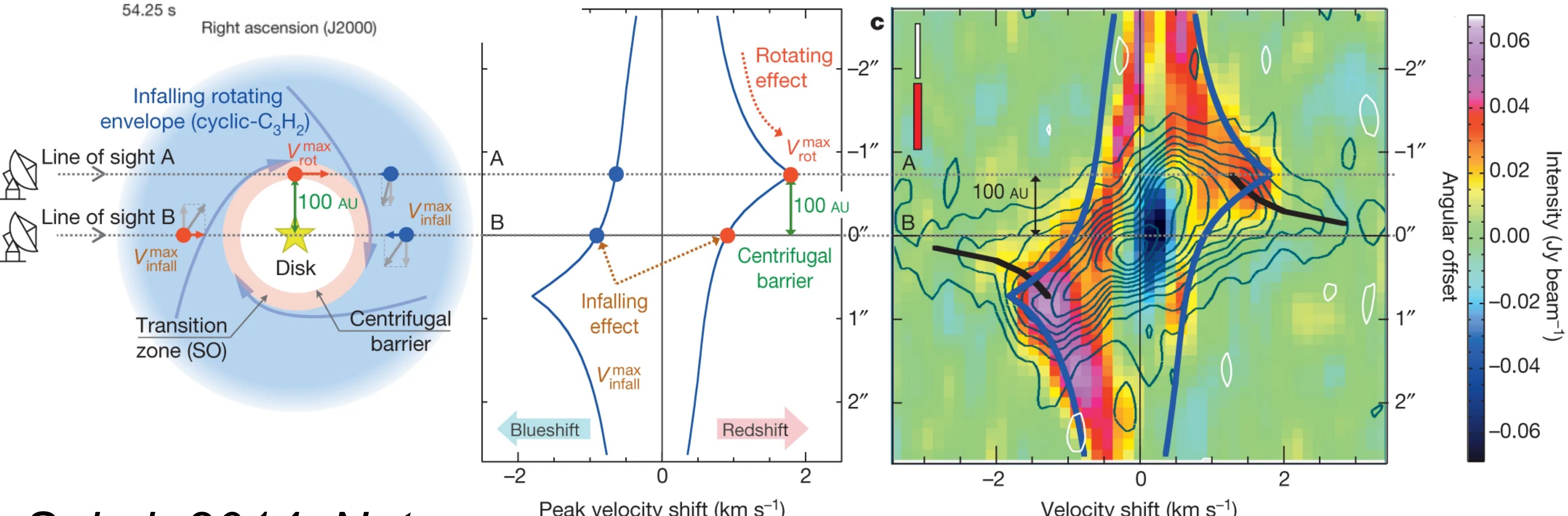
See also Biver+2015, Rivilla+2020, Drozdovskaya+2022



The chemical composition of infalling envelope material changes when reaching the protoplanetary disk

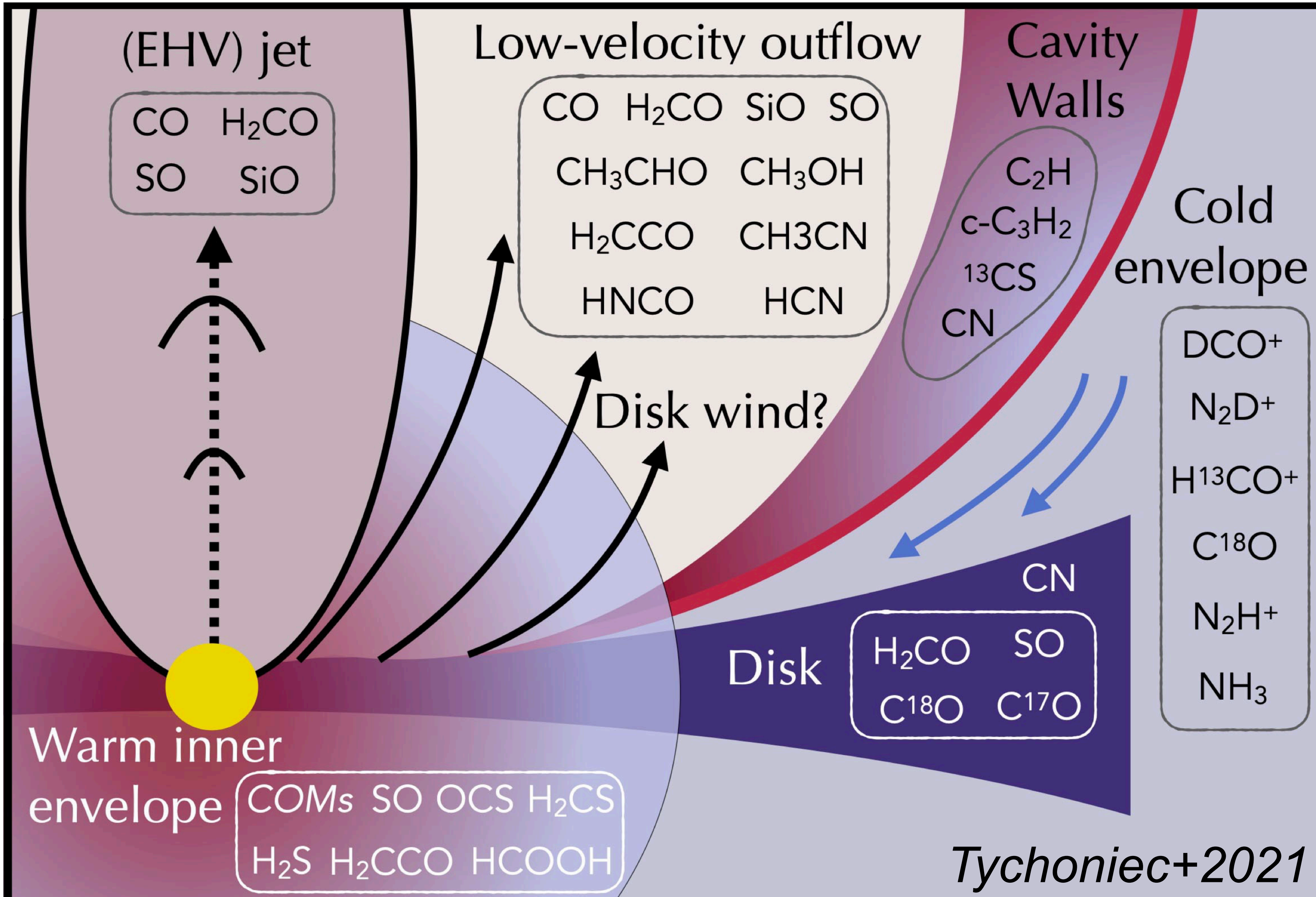


SO is tracing the centrifugal barrier
C_3H_2 is tracing the infalling envelope

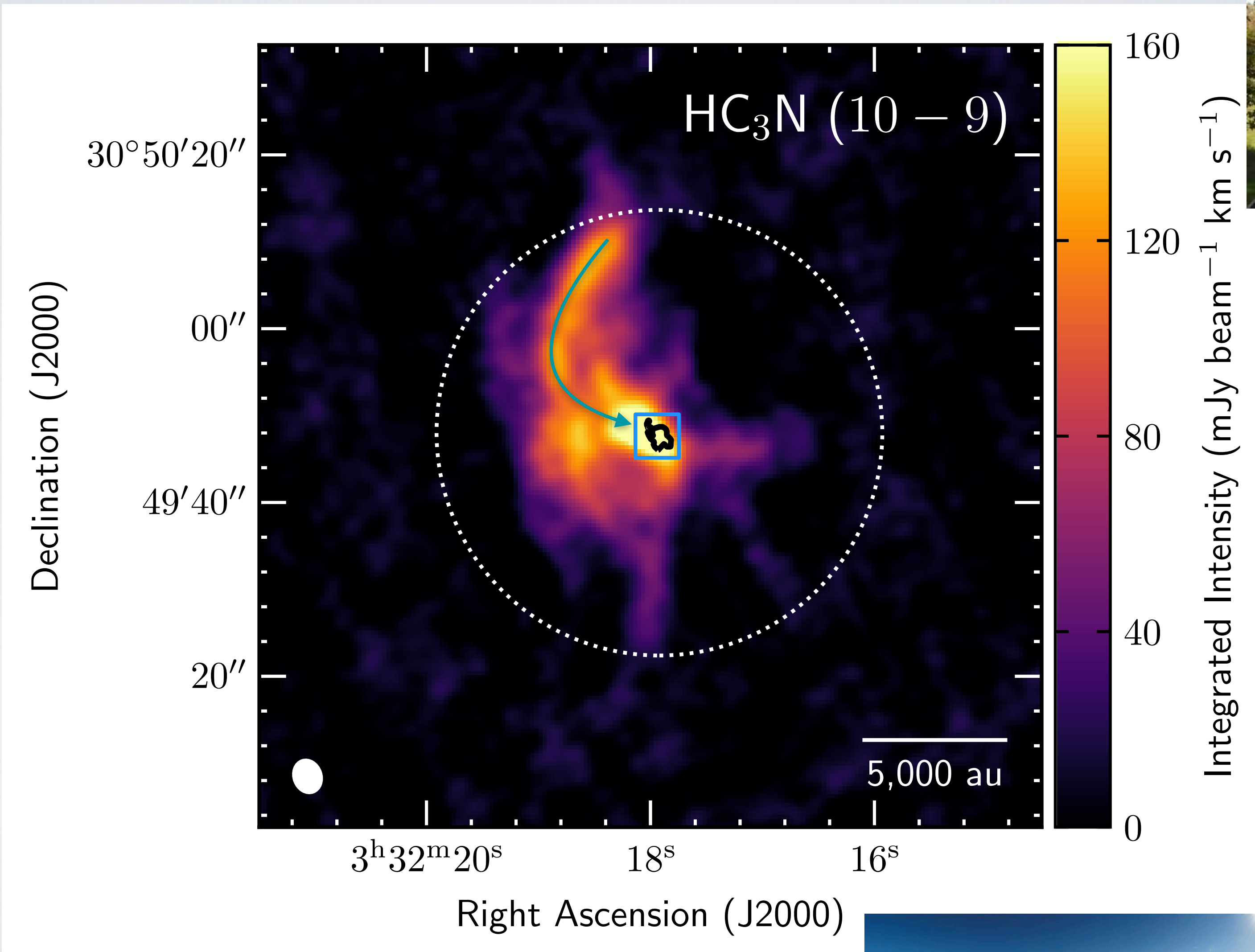


Sakai+2014, Nature

Which molecule traces what



Protostars accrete chemically young material directly from the surrounding cloud through streamers

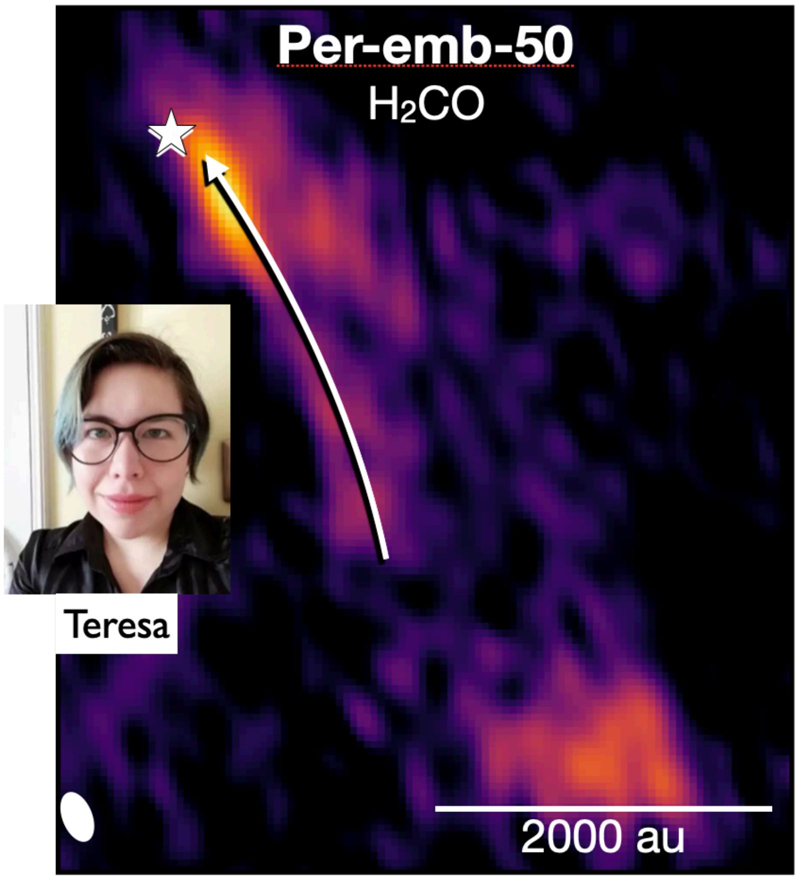


Pineda+2020, Nature Astronomy

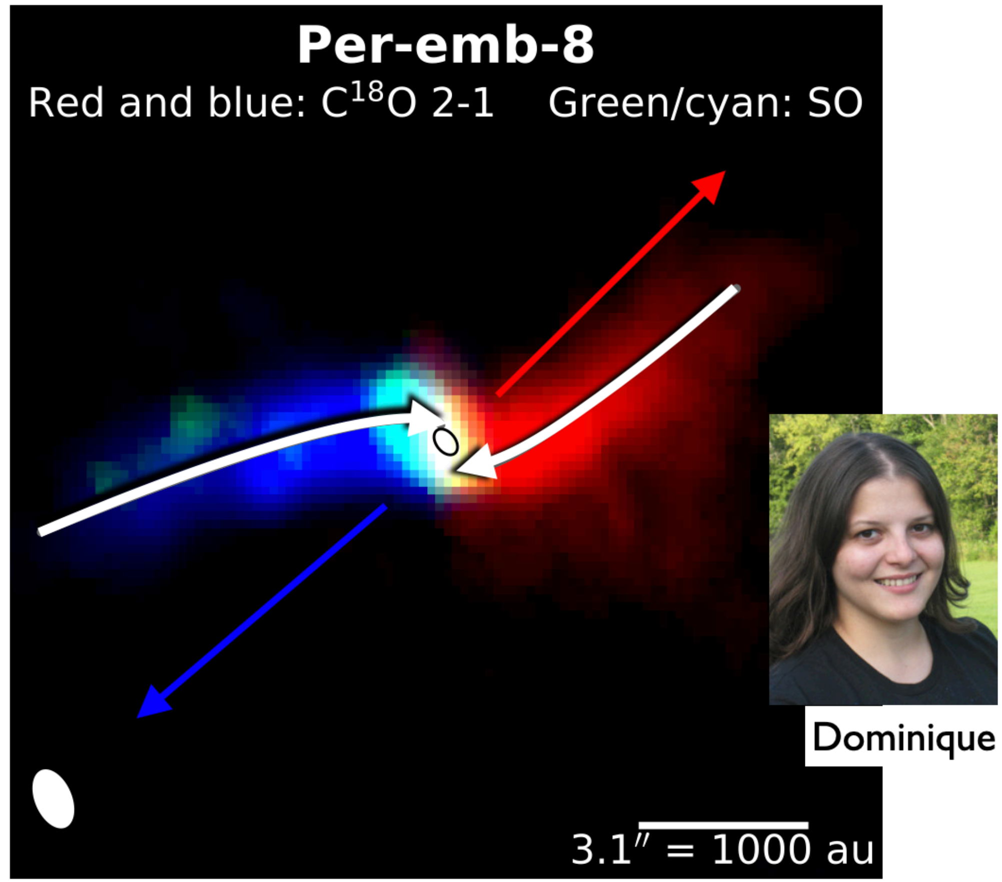
Streamers with NOEMA

Covers 32 Class 0/I and 8 Class II
520 hours observed over 4 years

PIs: Caselli & Henning



Valdivia-Mena+2022

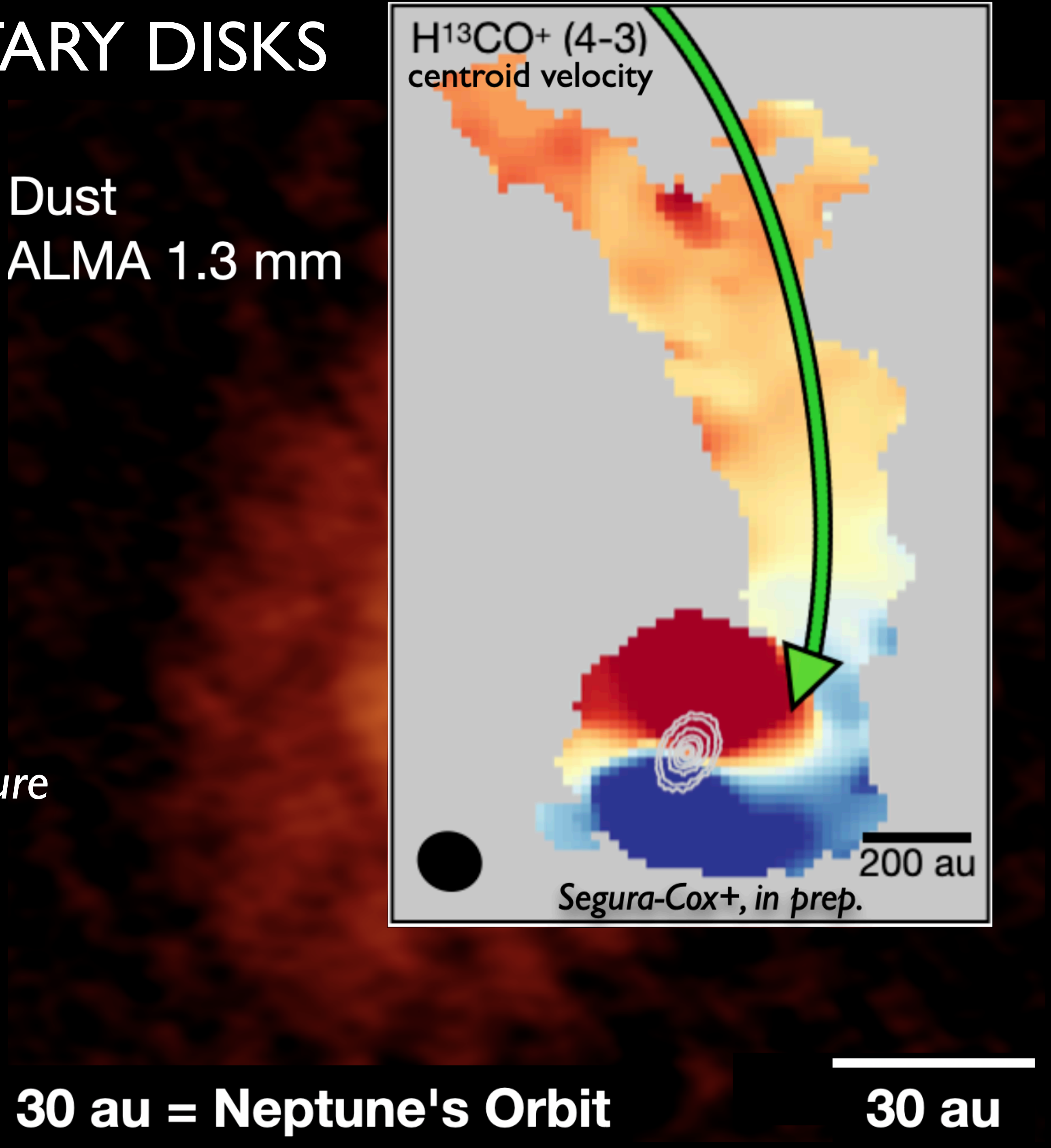


Segura-Cox et al., in prep.

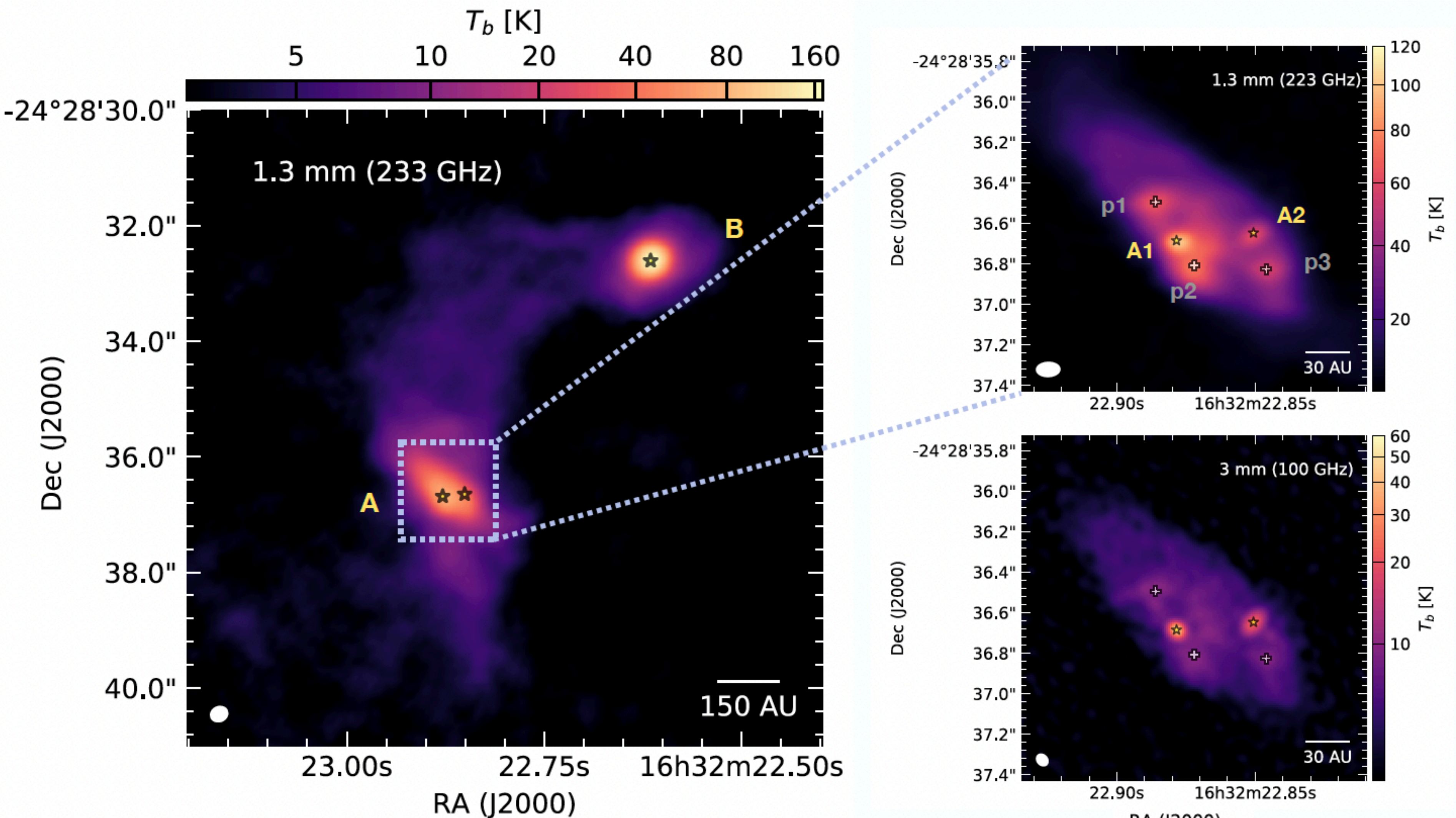
PROTOPLANETARY DISKS

Planet formation starts early!

Segura-Cox+2020, Nature

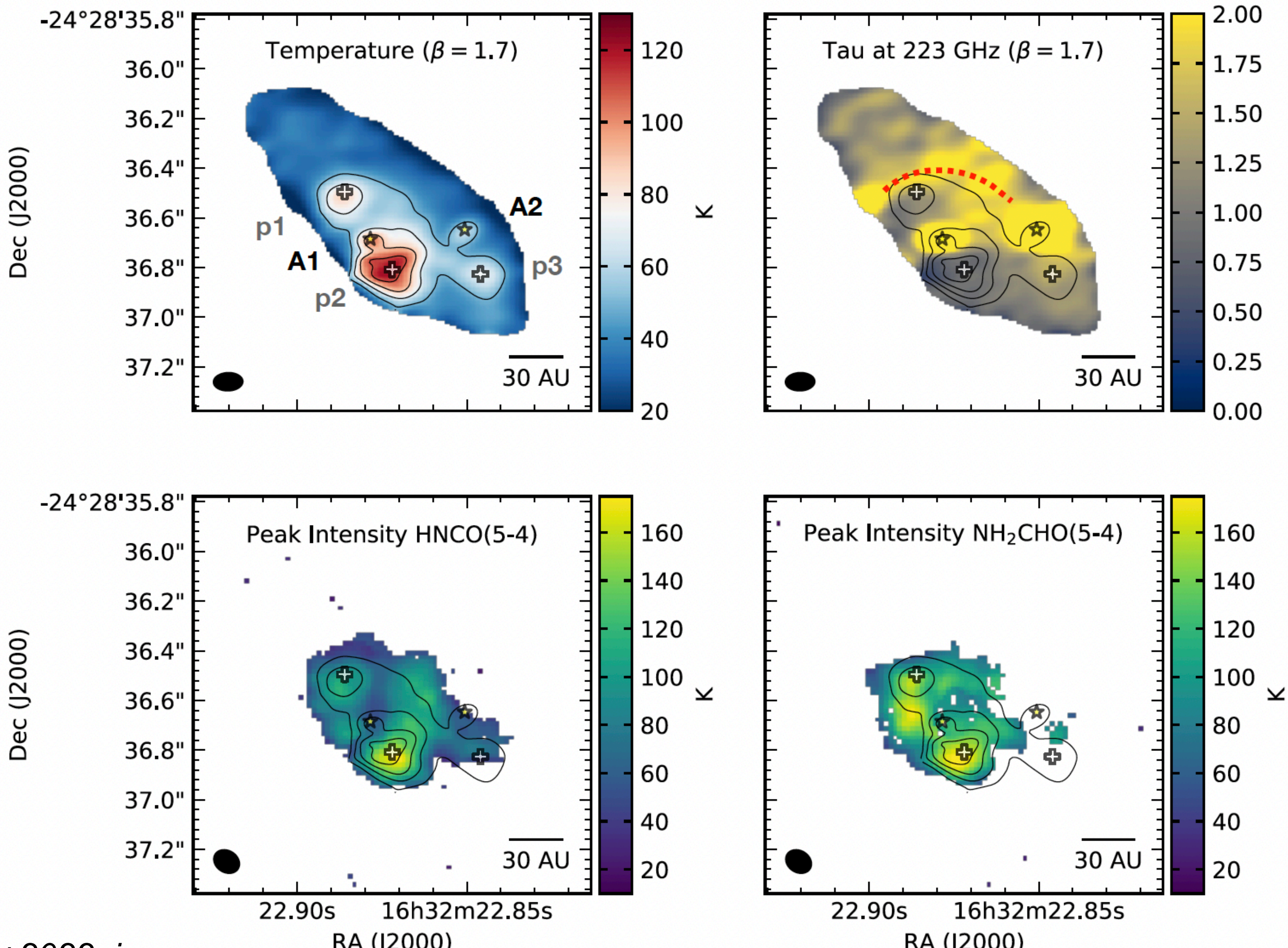


Dust hot spots at 10 au scale around the Class 0 binary IRAS 16293-2422A: evidence of shock heating



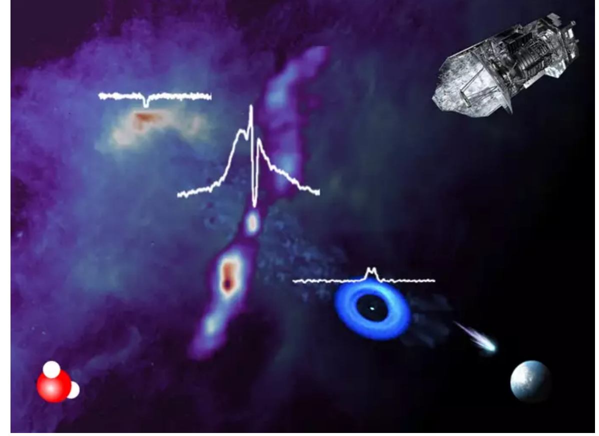
Maureira+2022, in press

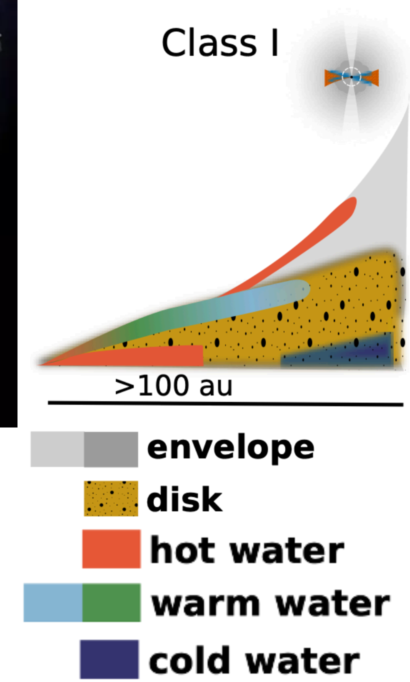
Organic molecules trace the dust hot spots

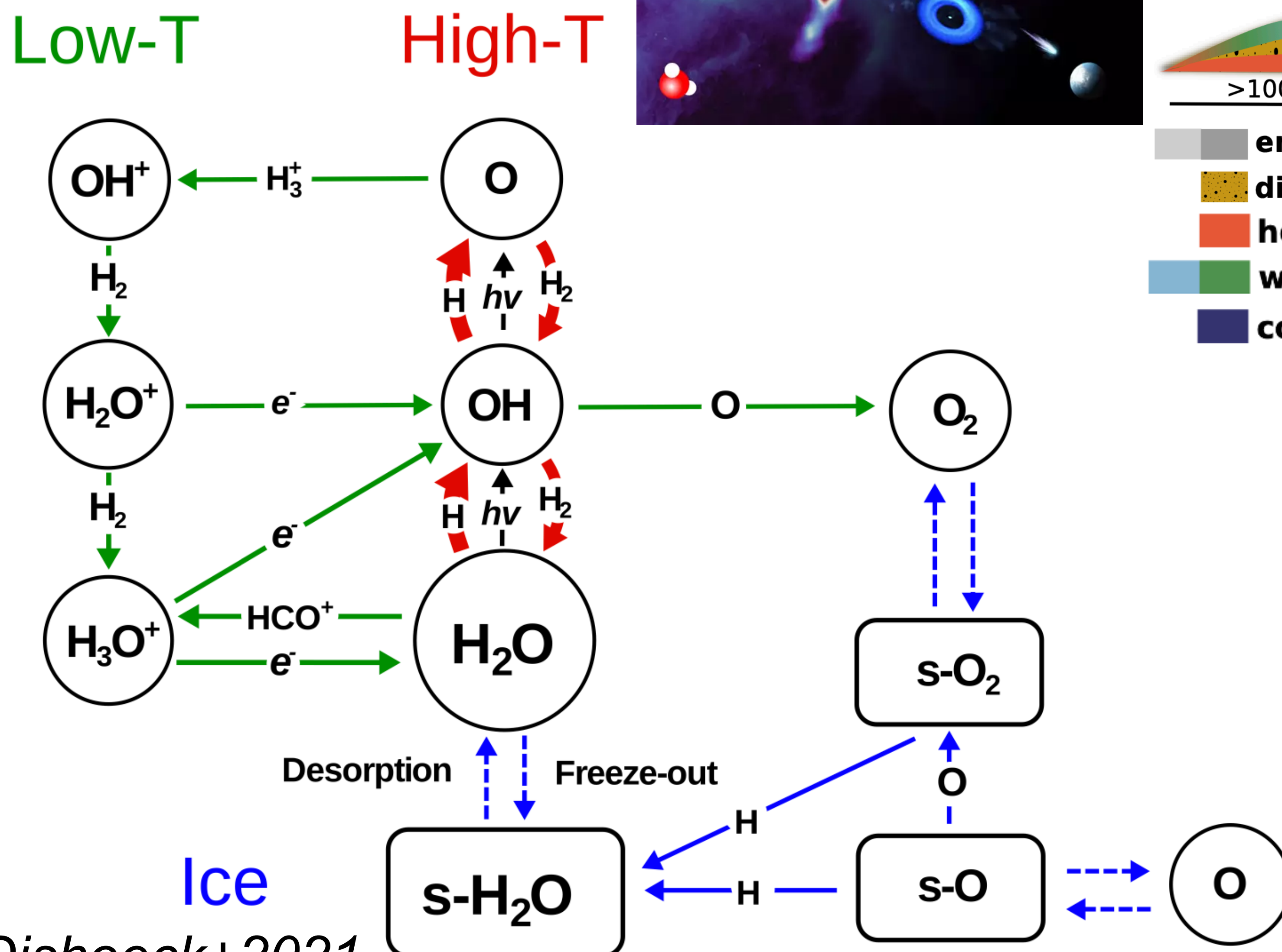


Maureira+2022, in press

Water in star-forming regions with *Herschel*

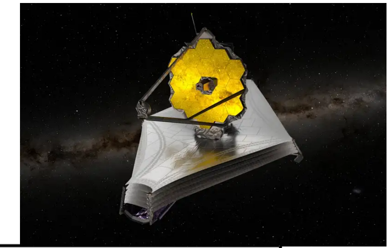


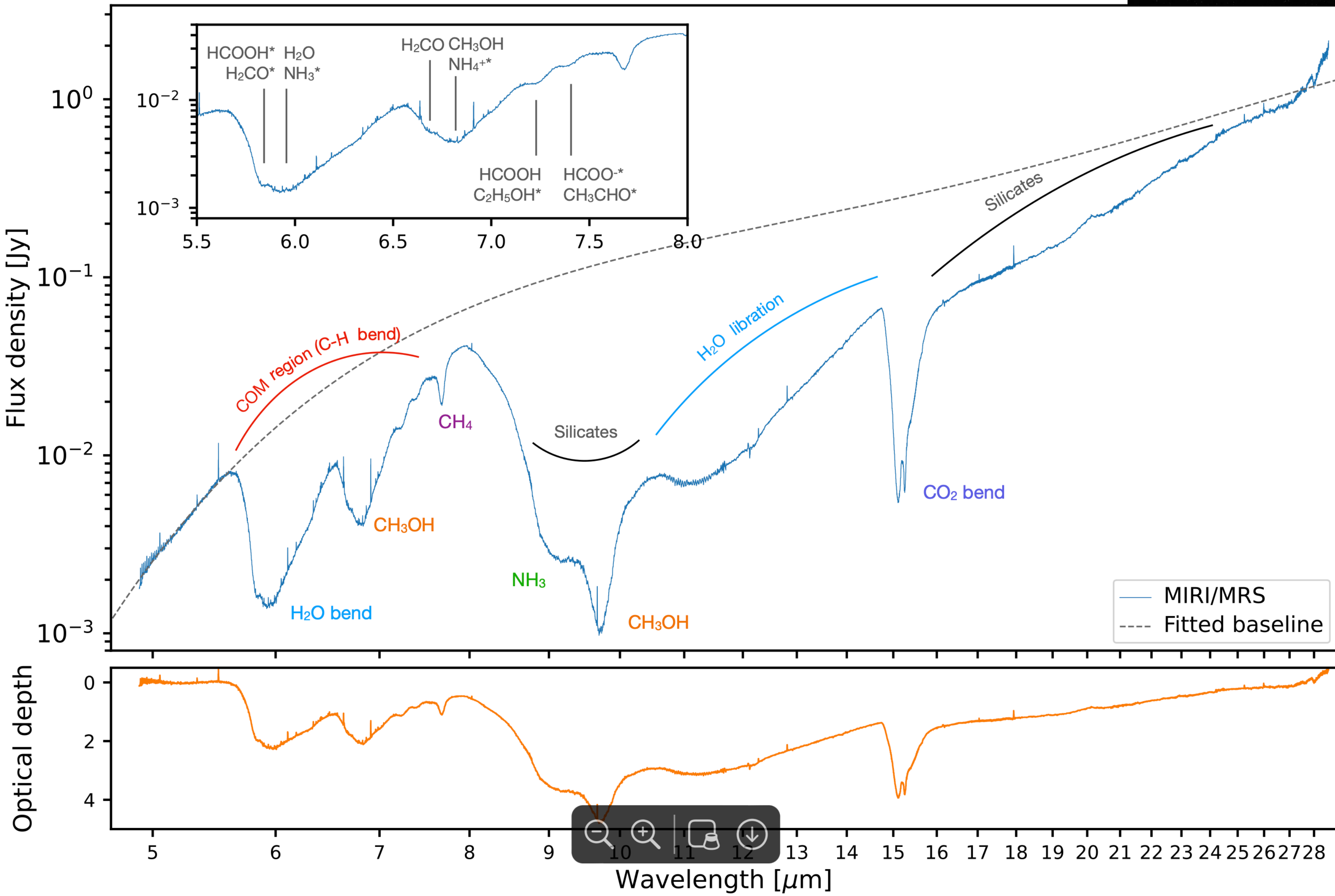




van Dishoeck+2021

Ice features towards a Class 0 protostar with **JWST**





Yang+2022