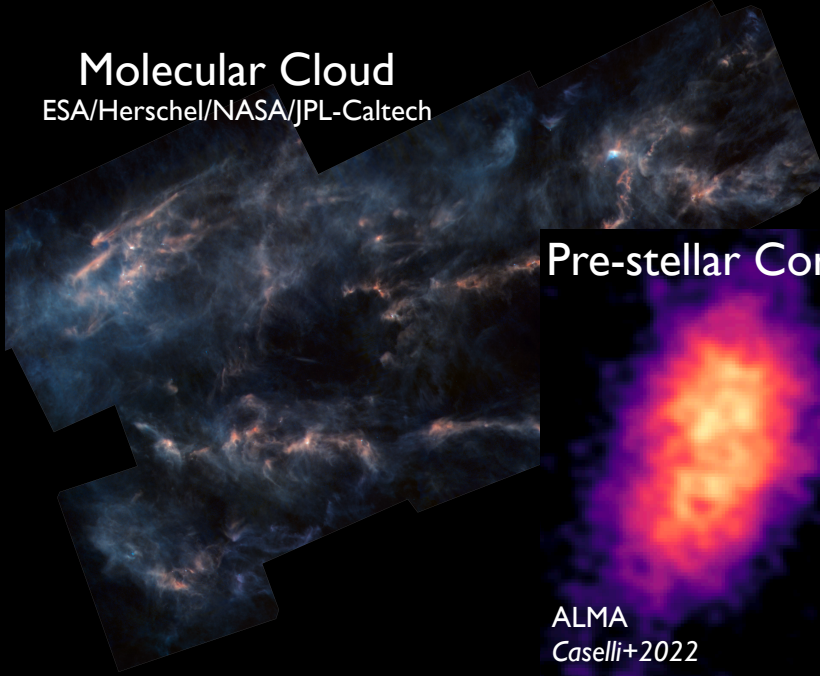
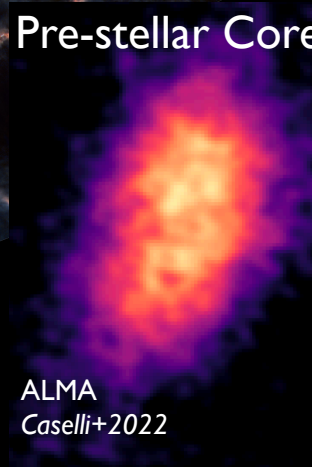


# The early stages of star formation [thanks to astrochemistry]

Molecular Cloud  
ESA/Herschel/NASA/JPL-Caltech

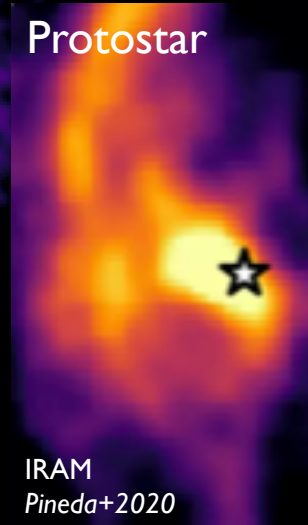


Pre-stellar Core



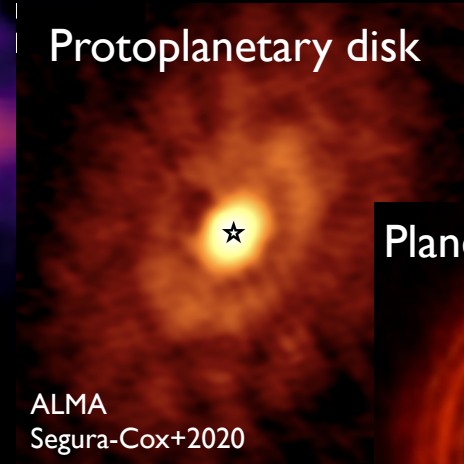
ALMA  
Caselli+2022

Protostar



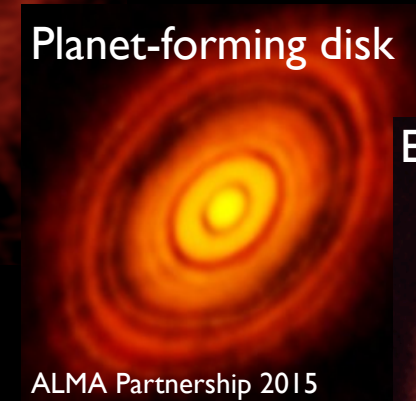
IRAM  
Pineda+2020

Protoplanetary disk



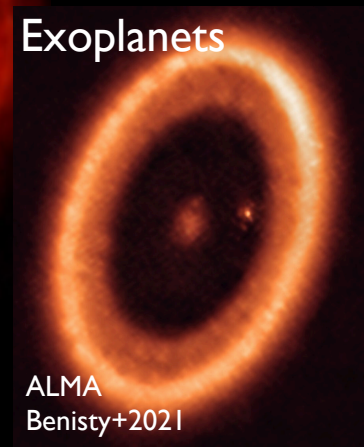
ALMA  
Segura-Cox+2020

Planet-forming disk



ALMA Partnership 2015

Exoplanets



ALMA  
Benisty+2021

**Paola Caselli**

*Center for Astrochemical Studies*

*Max Planck Institute for Extraterrestrial Physics*

*The Arcetri Star Formation Group - Vintage Edition*



# My first paper with Riccardo



## WATER MASERS ASSOCIATED WITH COMPACT MOLECULAR CLOUDS AND ULTRACOMPACT HII REGIONS: THE EXTENDED SAMPLE

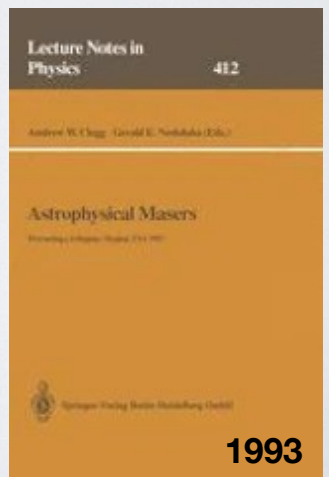
R. Cesaroni, G. Comoretto, M. Felli, F. Palla  
Osservatorio Astrofisico di Arcetri  
Largo E. Fermi 5, I-50125 Firenze, Italy

J. Brand, P. Caselli  
Istituto di Radioastronomia  
Via Irnerio 46, I-40100 Bologna, Italy

### ABSTRACT

We present the results of a survey of water maser emission at 22.2 GHz towards a selected sample of IRAS-PSC sources which are believed to be associated with very young massive stars. The sample consists of 591 sources. The observations have been carried out using the Medicina 32-m radiotelescope, operated by the Istituto di Radioastronomia - C.N.R., Bologna.

Whereas previous searches for maser emission have been directed towards known HII regions, the aim of the present survey is to identify new sources in an even earlier evolutionary phase, corresponding to the development of an ultracompact HII region. It is shown that our sample contains a significant number of sources that could be considered good candidates of massive protostellar cores still in the main accretion phase.



**CITATIONS: 1**

## The Arcetri catalogue of H<sub>2</sub>O maser sources update\*

J. Brand<sup>1,2</sup>, R. Cesaroni<sup>1</sup>, P. Caselli<sup>3</sup>, M. Catarzi<sup>4</sup>, C. Codella<sup>2,5</sup>, G. Comoretto<sup>1</sup>, G.P. Curioni<sup>1</sup>, P. Curioni<sup>1</sup>, S. Di Franco<sup>5</sup>, M. Felli<sup>1</sup>, C. Giovanardi<sup>4</sup>, L. Olmi<sup>5</sup>, F. Palagi<sup>4</sup>, F. Palla<sup>1</sup>, D. Panella<sup>1</sup>, G. Pareschi<sup>3</sup>, E. Rossi<sup>1</sup>, N. Speroni<sup>4</sup> and G. Tofani<sup>1</sup>

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Received April 13; accepted June 26, 1993

**Abstract.** — An update is presented of the Arcetri Atlas of water masers (Comoretto et al. 1990). It contains the results of observations of water masers with the Medicina 32-m antenna. The observed sources were all discovered in the period 1989-1993, and were found either directly in the course of our own programs or were taken from the literature in which case they were re-observed at Medicina. We give the observed parameters of 214 sources in tabular form, and present *all* the spectra of the 141 detections.

**Key words:** catalogs — radio lines: interstellar — radio lines: stars



Medicina 32 m

**In August 1997 we went to IRAM 30m**





$\text{CH}_3\text{CCH}$   
*propyne*



● Carbon (C)  
● Hydrogen (H)

## The structure of molecular clumps around high-mass young stellar objects<sup>\*</sup>

F. Fontani<sup>1</sup>, R. Cesaroni<sup>2</sup>, P. Caselli<sup>2</sup>, and L. Olmi<sup>3</sup>

<sup>1</sup> Dipartimento di Astronomia e Fisica dello spazio, Largo E. Fermi 2, 50125 Firenze, Italy

<sup>2</sup> INAF, Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy

<sup>3</sup> LMT/GTM Project, Dept. of Astronomy, 815J Lederle GRT Tower B, University of Massachusetts, 710 N. Pleasant st., Amherst, MA 01003, USA

Received 14 December 2001 / Accepted 12 April 2002

**Abstract.** We have used the IRAM 30-m and FCRAO 14-m telescopes to observe the molecular clumps associated with 12 ultracompact (UC) HII regions in the  $J = 6-5$ ,  $8-7$  and  $13-12$  rotational transitions of methyl-acetylene ( $\text{CH}_3\text{C}_2\text{H}$ ). Under the assumption of LTE and optically thin emission, we have derived temperature estimates ranging from 30 to 56 K. We estimate that the clumps have diameters of 0.2–1.6 pc,  $\text{H}_2$  densities of  $10^5$ – $10^6$   $\text{cm}^{-3}$ , and masses of  $10^2$ – $2 \times 10^4$   $M_\odot$ . We compare these values with those obtained by other authors from different molecular tracers and find that the  $\text{H}_2$  density and the temperature inside the clumps vary respectively like  $n_{\text{H}_2} \propto R^{-2.6}$  and  $T \propto R^{-0.5}$ , with  $R$  distance from the centre. We also find that the virial masses of the clumps are  $\sim 3$  times less than those derived from the  $\text{CH}_3\text{C}_2\text{H}$  column densities: we show that a plausible explanation is that magnetic fields play an important role to stabilise the clumps, which are on the verge of gravitational collapse. Finally, we show that the  $\text{CH}_3\text{C}_2\text{H}$  line width increases for decreasing distance from the clump centre: this effect is consistent with infall in the inner regions of the clumps. We conclude that the clumps around UC HII regions are likely to be transient ( $\sim 10^5$  yr) entities, remnants of isothermal spheres currently undergoing gravitational collapse: the high mass accretion rates ( $\sim 10^{-2}$   $M_\odot$   $\text{yr}^{-1}$ ) lead to massive star formation at the centre of such clumps.

**Key words.** stars: formation – radio lines: ISM – ISM: molecules



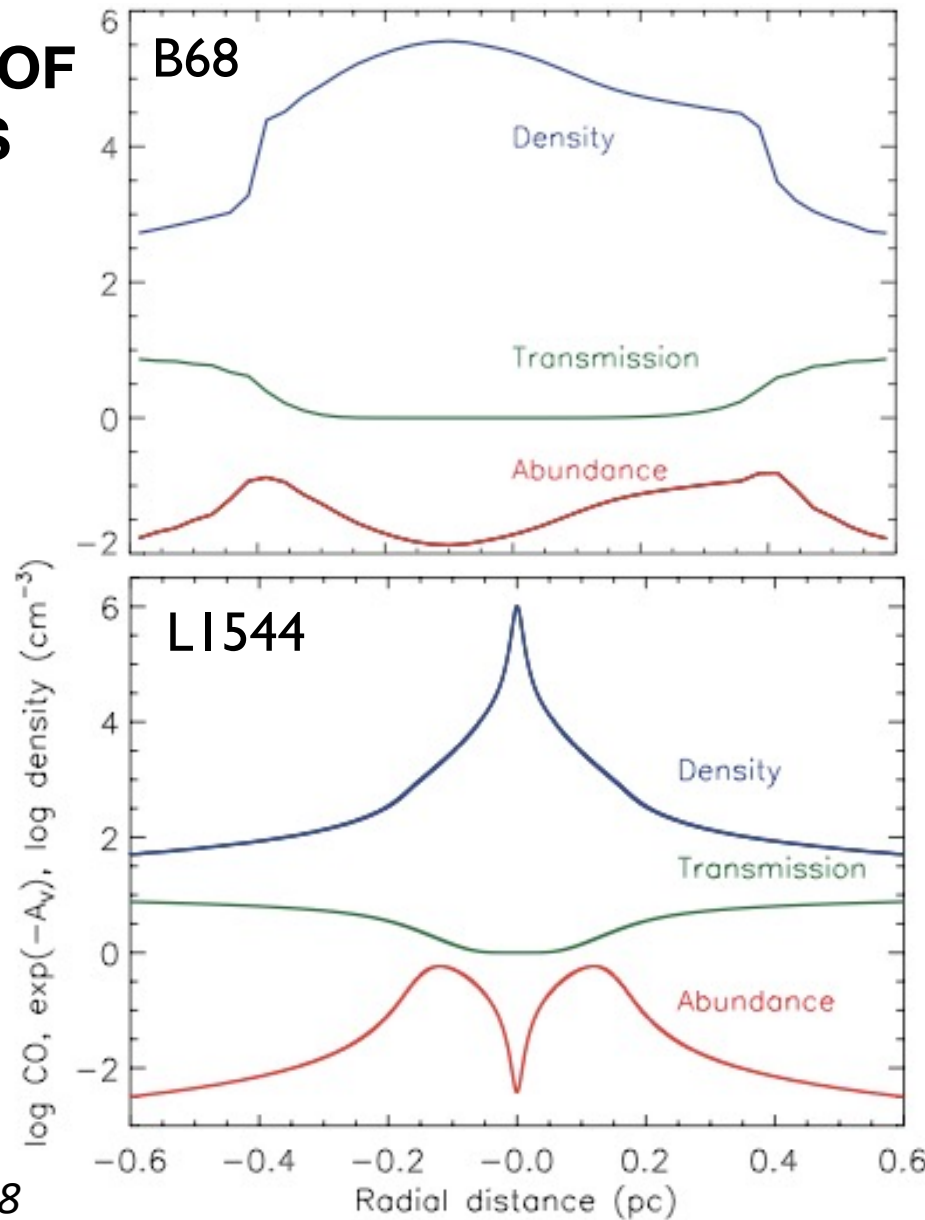


**PRE-STELLAR CORES**  
*(the stellar system cradles)*

~ 1 light year

# THE TWO CLASSES OF STARLESS CORES

Pre-stellar



Keto & Caselli 2008

**Thermally subcritical**

$$n_c \lesssim 10^5 \text{ cm}^{-3}$$

$$T_c \sim 10 \text{ K}$$

Spectral line profiles consistent with oscillations  
(Lada+2003)

**Thermally supercritical**

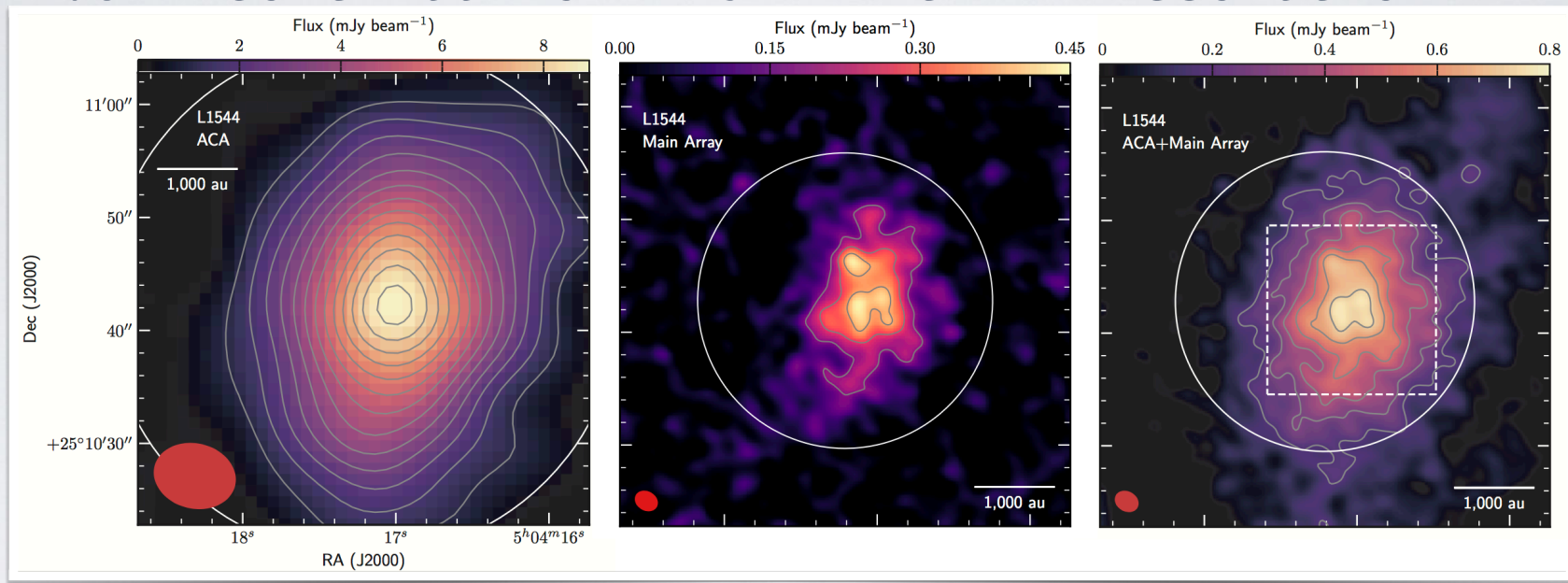
$$n_c > 10^5 \text{ cm}^{-3}$$

$$T_c \sim 6 \text{ K}$$

Spectral line profiles consistent with contraction motions  
(Tafalla+1998; Caselli+2002)

# ALMA observations of a $8 M_{\odot}$ pre-stellar core reveal a dense ( $10^6 \text{ cm}^{-3}$ ) “kernel” of $0.16 M_{\odot}$ and radius 1800 au

*1.3mm continuum of L1544 with 2" resolution*



consistent with *non-ideal MHD simulations* of a contracting pre-stellar core with peak density  $\sim 10^7 \text{ cm}^{-3}$ .

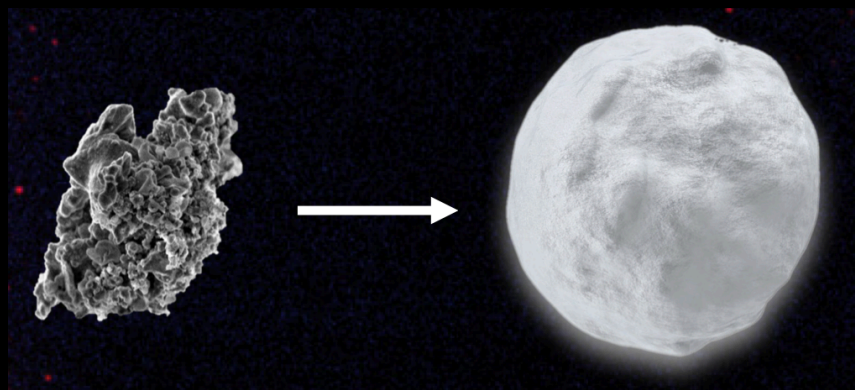
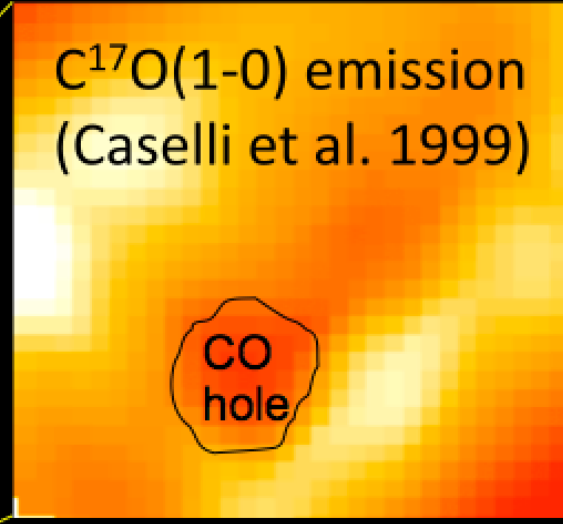
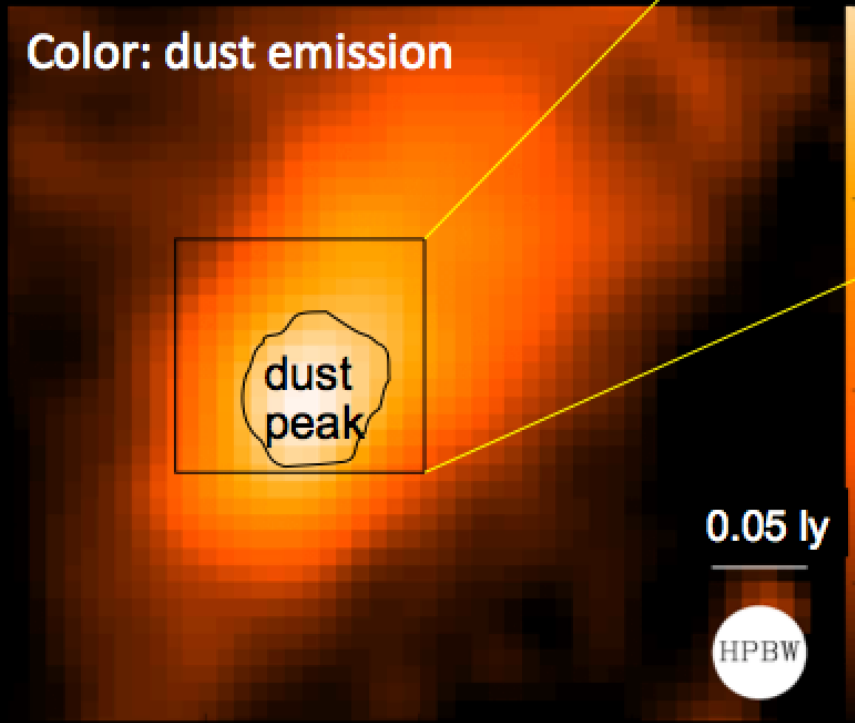
*Caselli, Pineda, Zhao+ 2019*

# In pre-stellar cores, molecules freeze out onto dust grains

“Catastrophic” CO freeze-out within the central 7000 au of pre-stellar core L1544

Central density:  
 $\geq 10^6$  H<sub>2</sub> per cc  
(Keto & Caselli 2008)

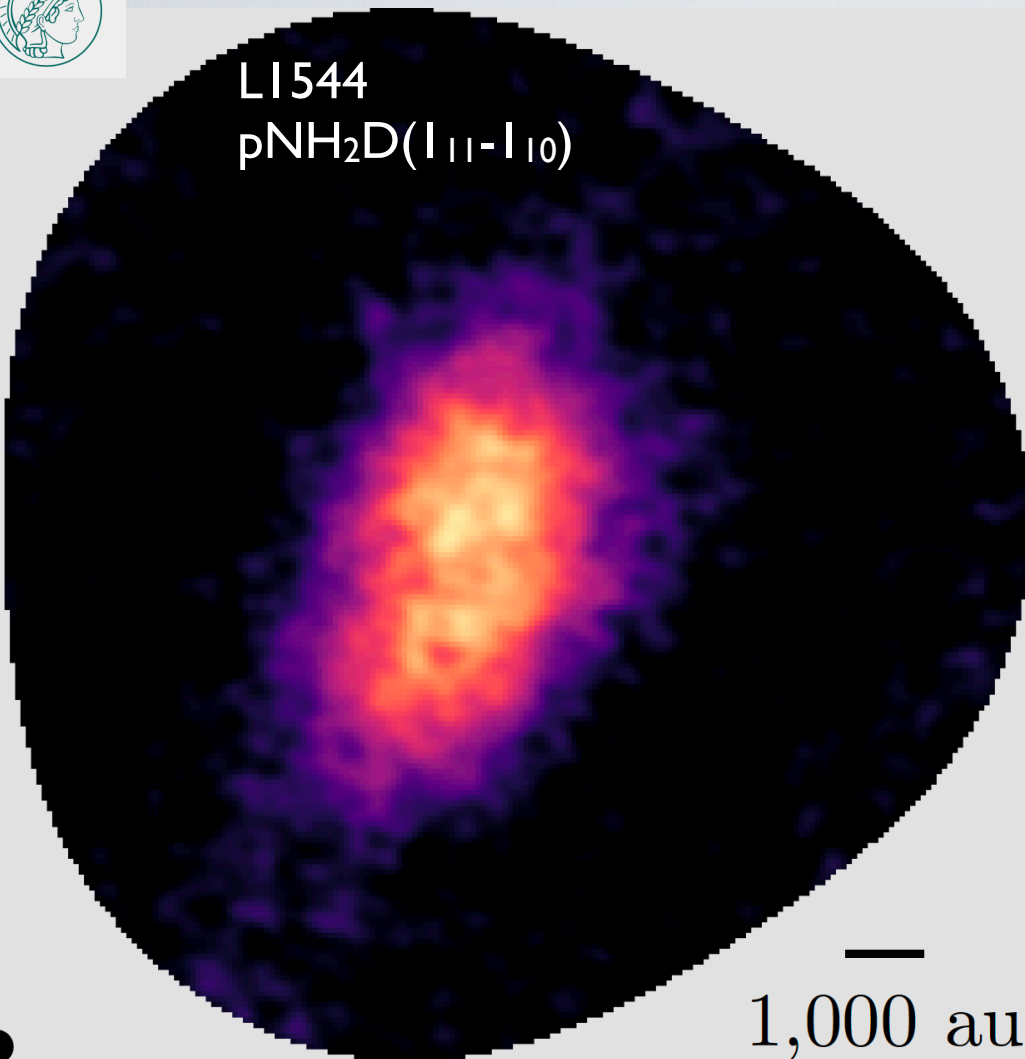
Central temperature:  
~6K  
(Crapsi+2007)



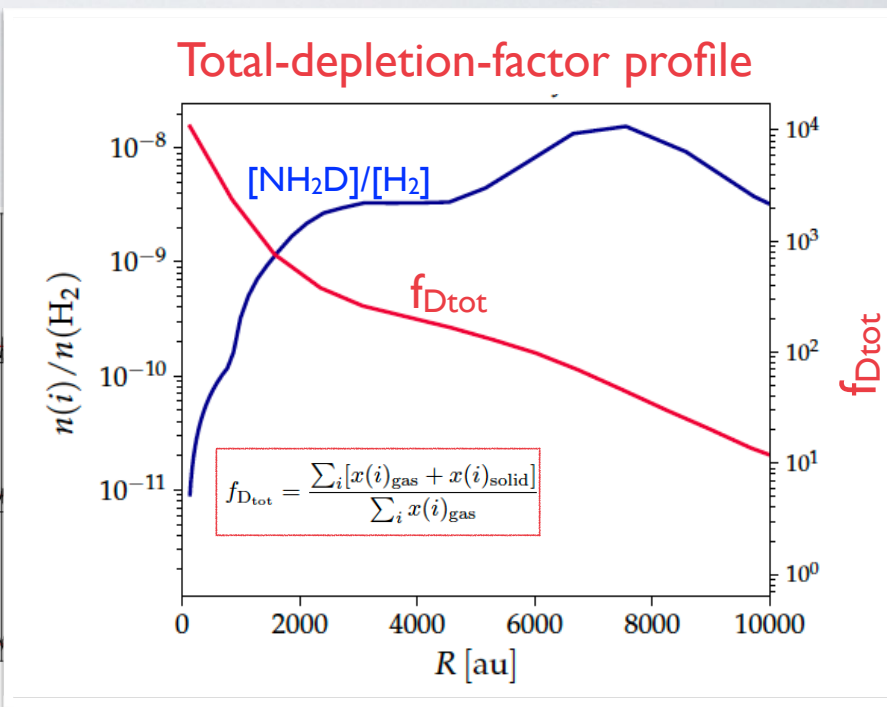
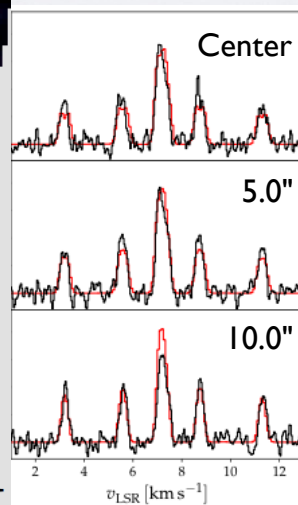
>90% of CO molecules are frozen onto dust grains



L1544  
 $p\text{NH}_2\text{D}(1_{11}-1_{10})$



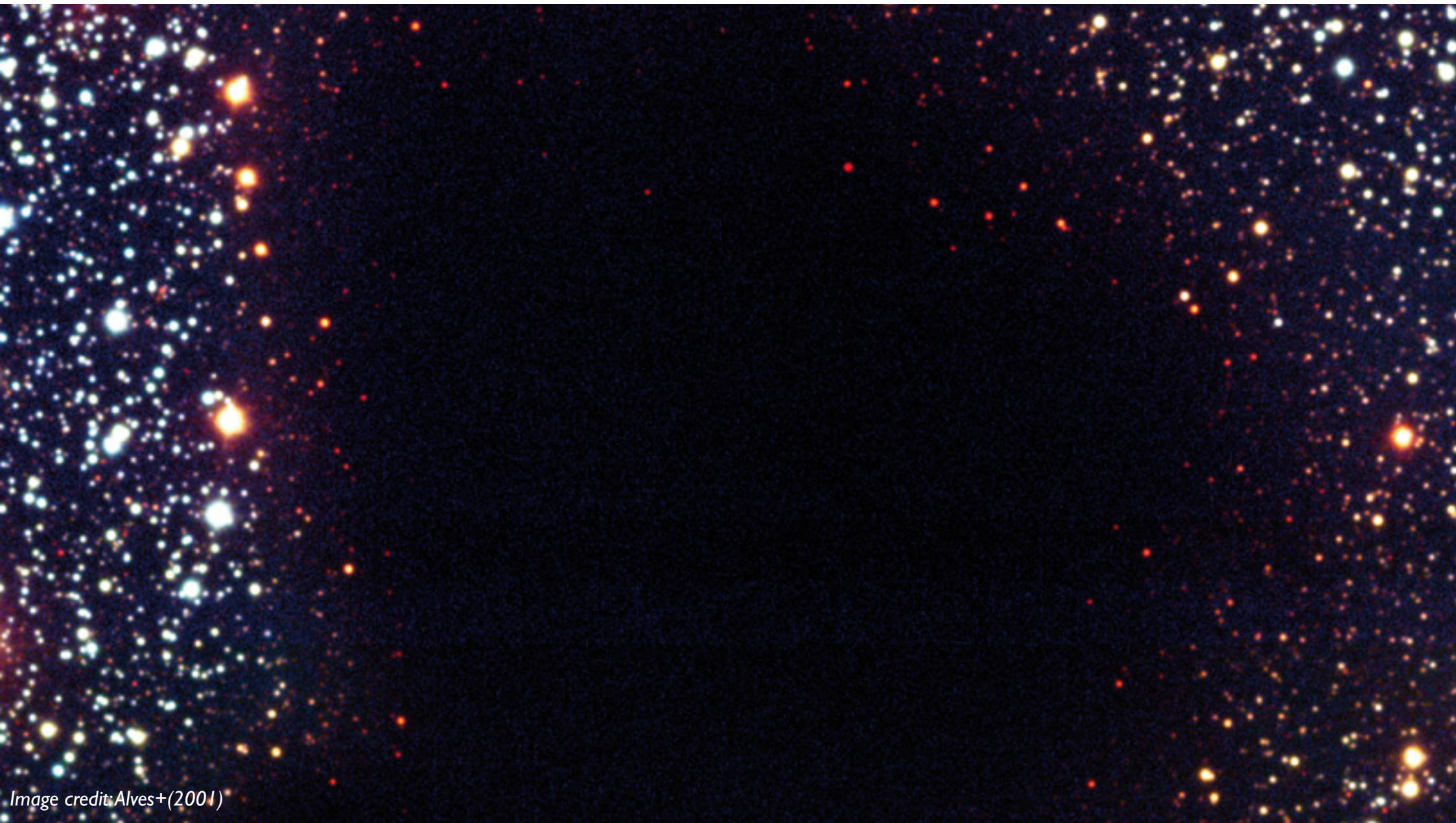
In the central 2000 au, 99.99% of all species heavier than He are frozen onto dust grains



Caselli, Pineda, Sipilä+2022 (see also Pineda+2022)



ALMA



*Image credit: Alves+(2001)*

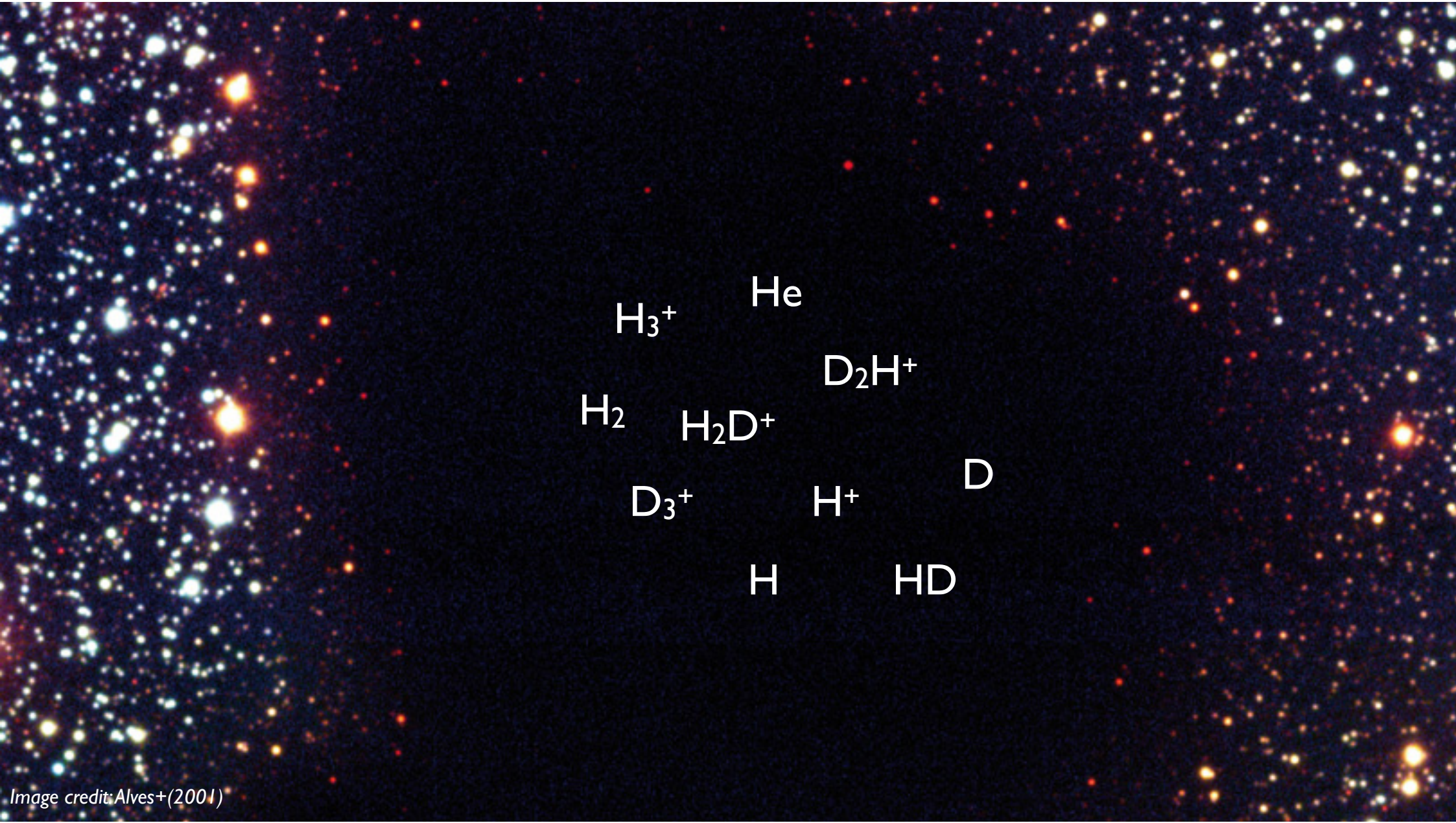
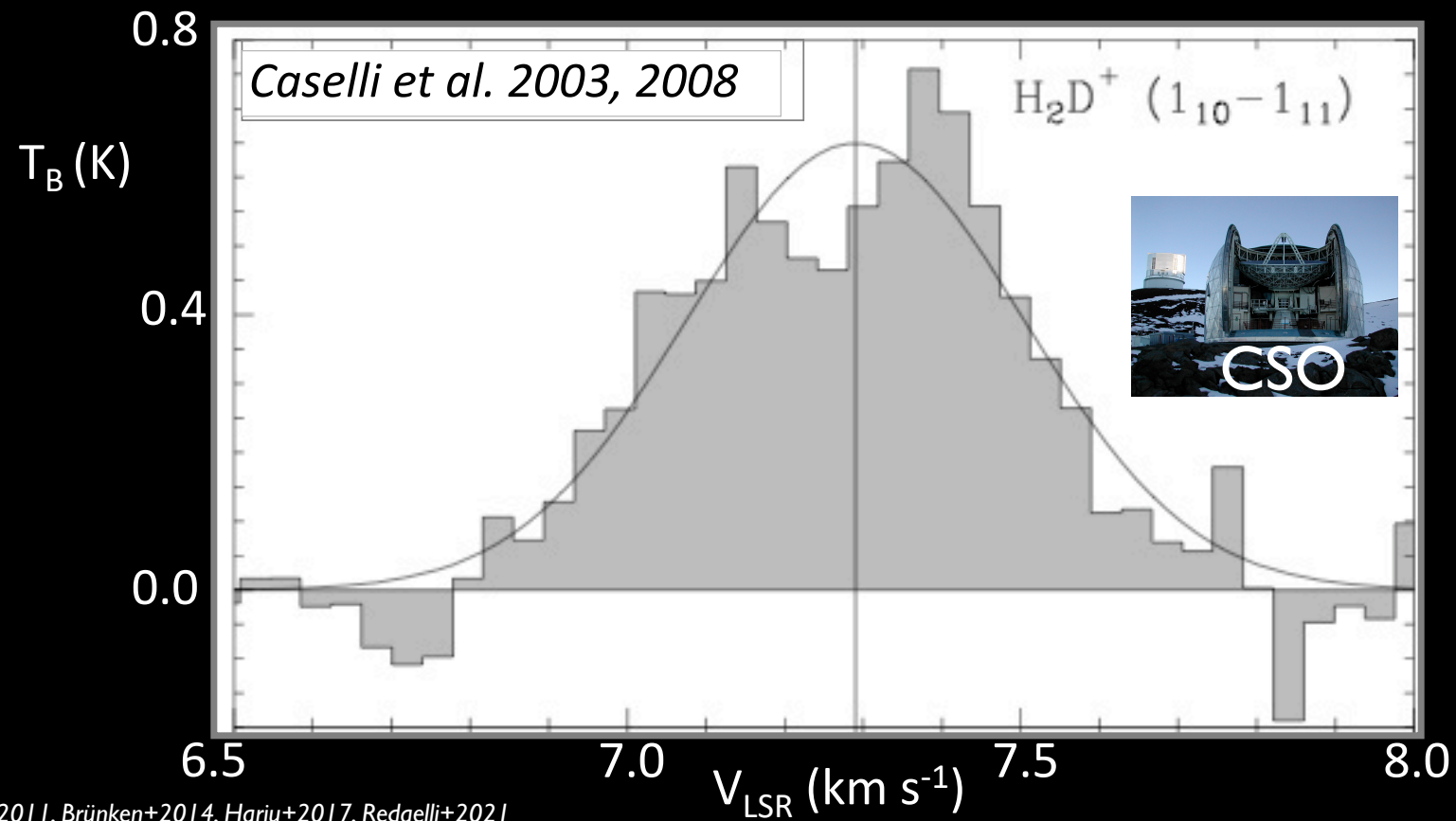


Image credit: Alves+(2001)

# Surprisingly strong ortho- $\text{H}_2\text{D}^+$ in pre-stellar cores

- Led to strong revision of astrochemical models (e.g. Roberts et al. 2003)
- Triggered new laboratory work (e.g. Hugo et al. 2009)

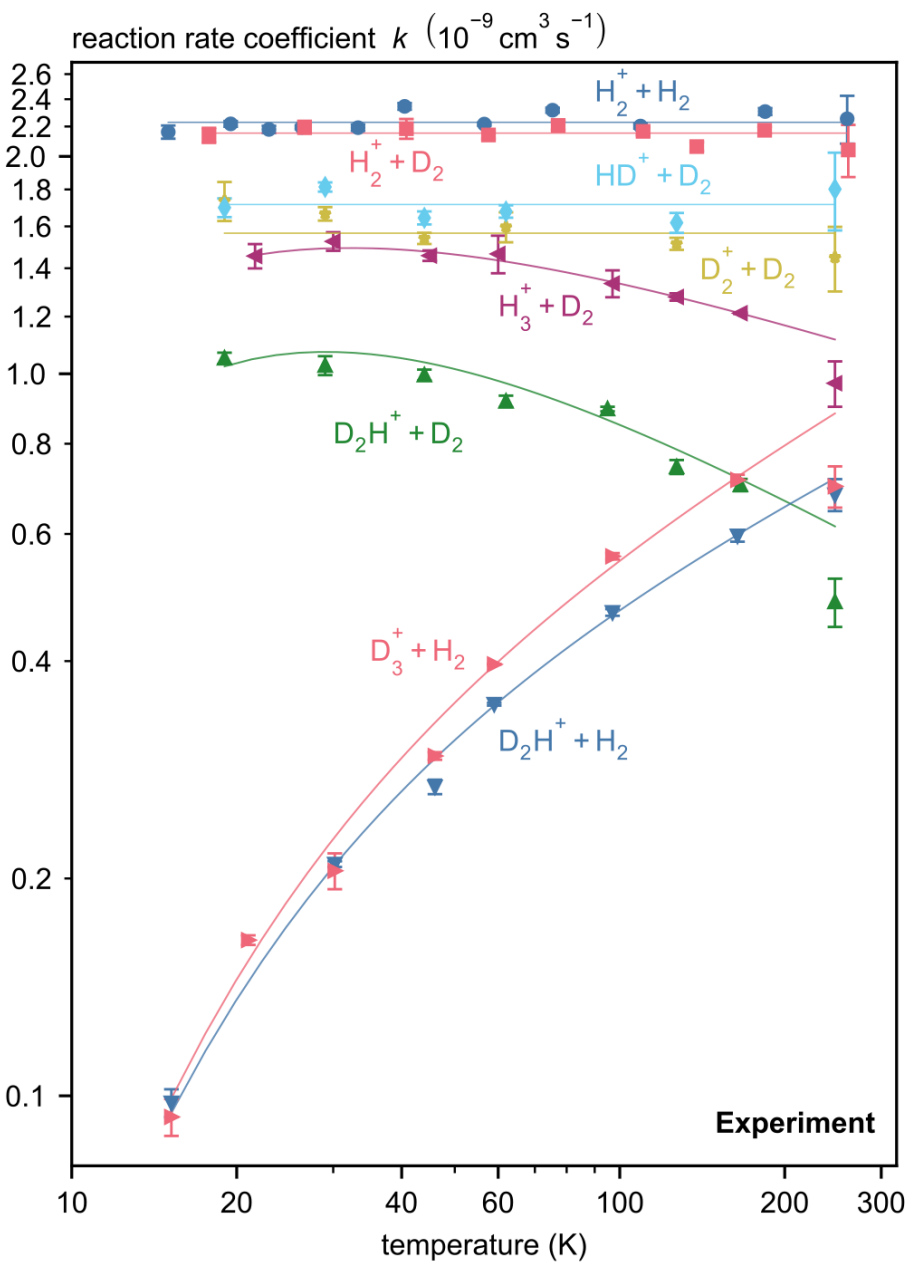
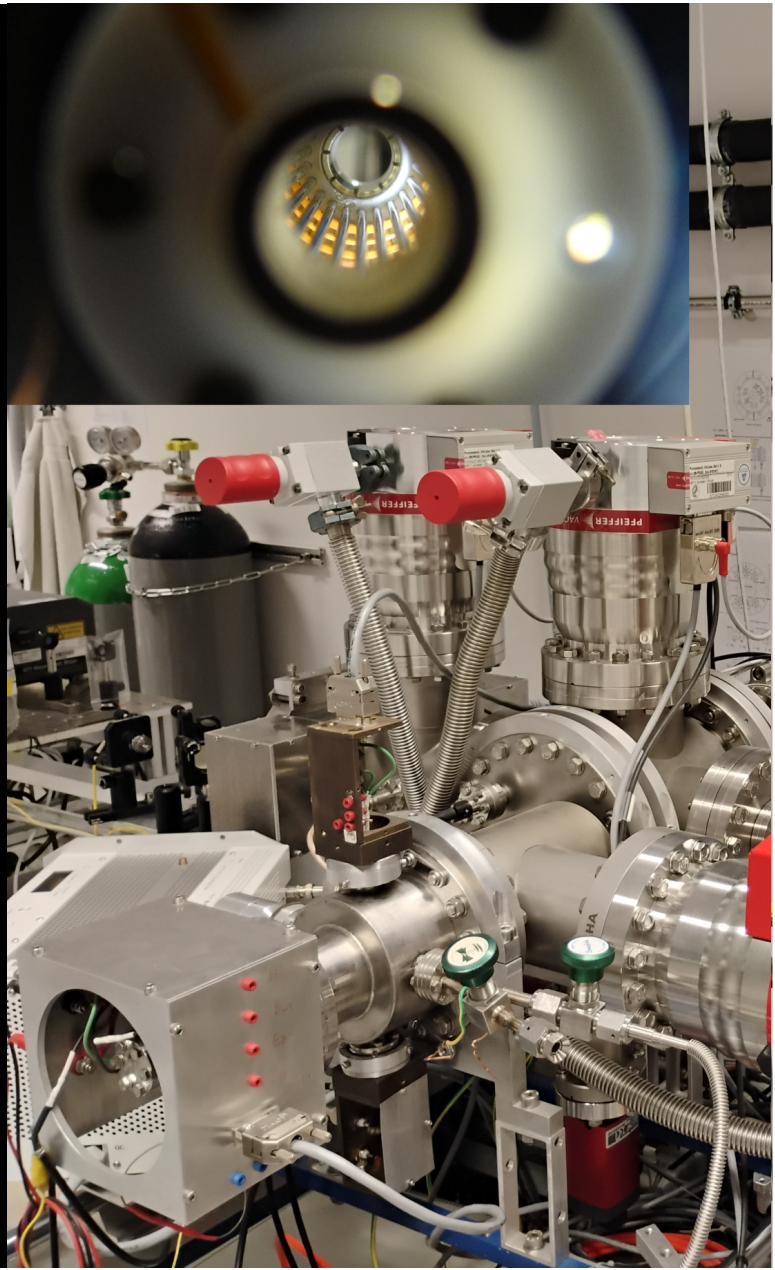


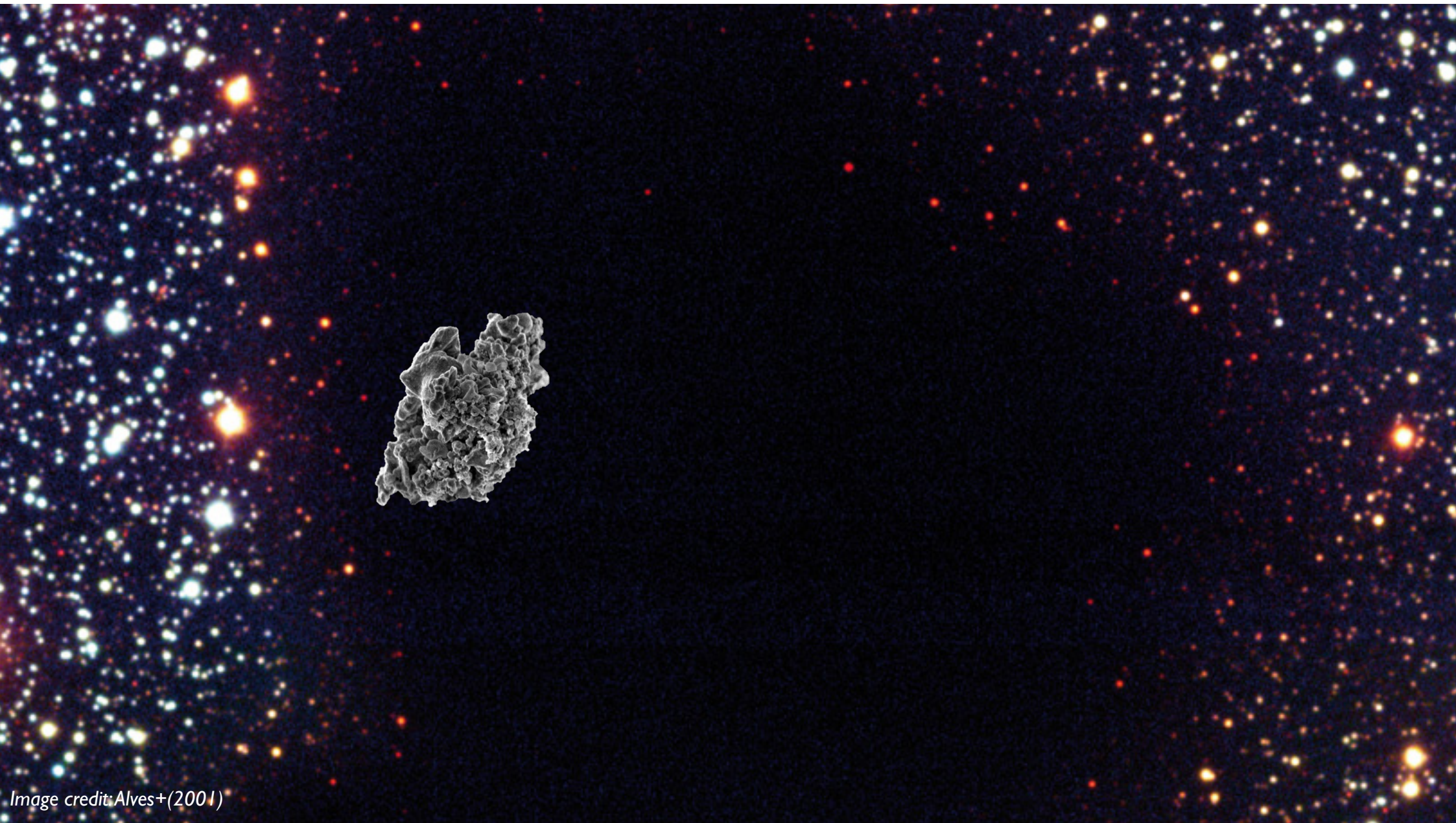
See also Vastel+2004, Parise+2011, Brünken+2014, Harju+2017, Redaelli+2021

# Rate coefficient measurements of light ion-molecule reactive systems with the cryogenic 22-pole radio frequency ion trap in our laboratories

[Rates are needed for our astrochemical models]

*Jiménez-Redondo, Sipilä, Jusko & Caselli 2024*





*Image credit: Alves+(2001)*

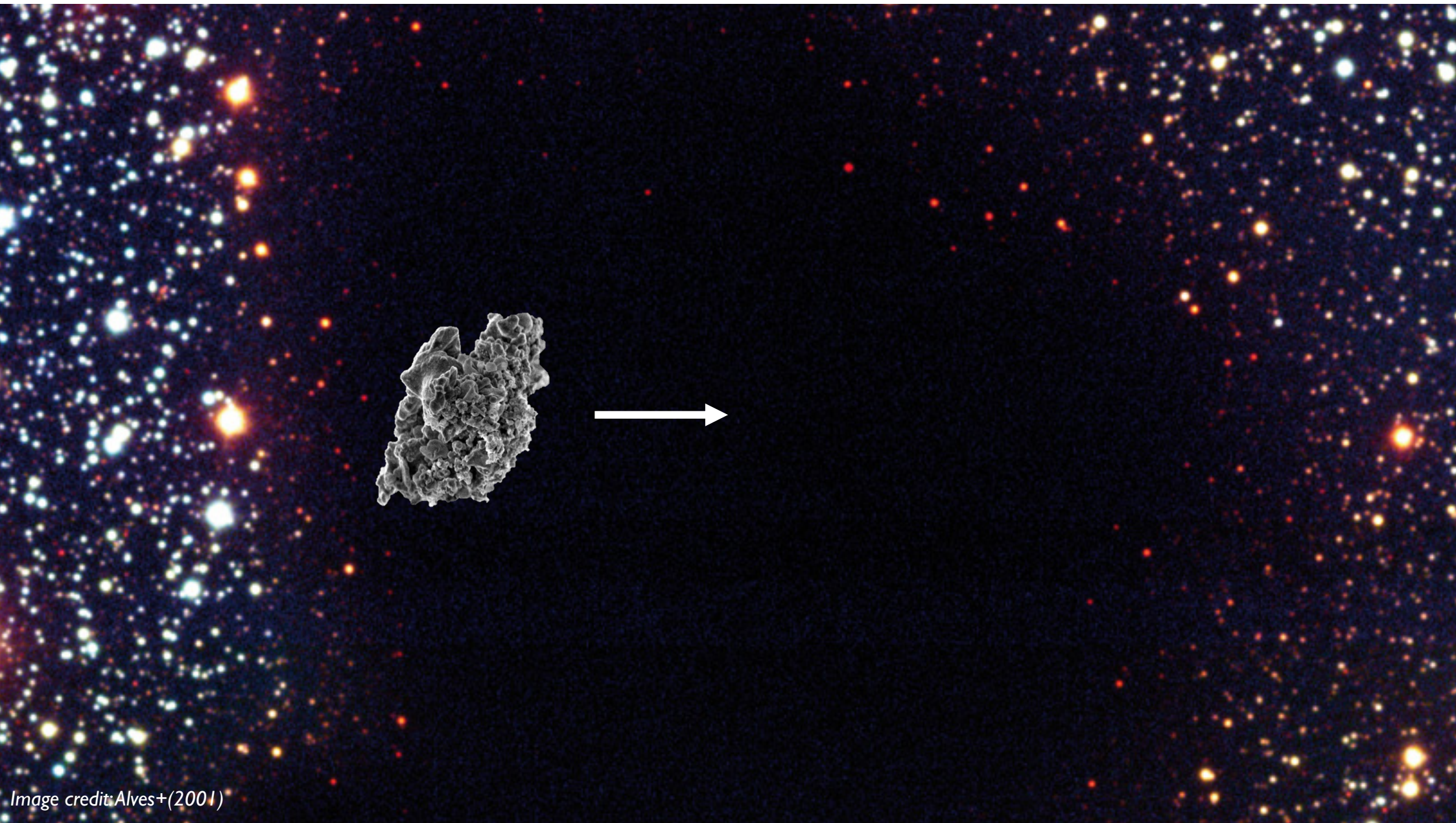


Image credit: Alves+(2001)

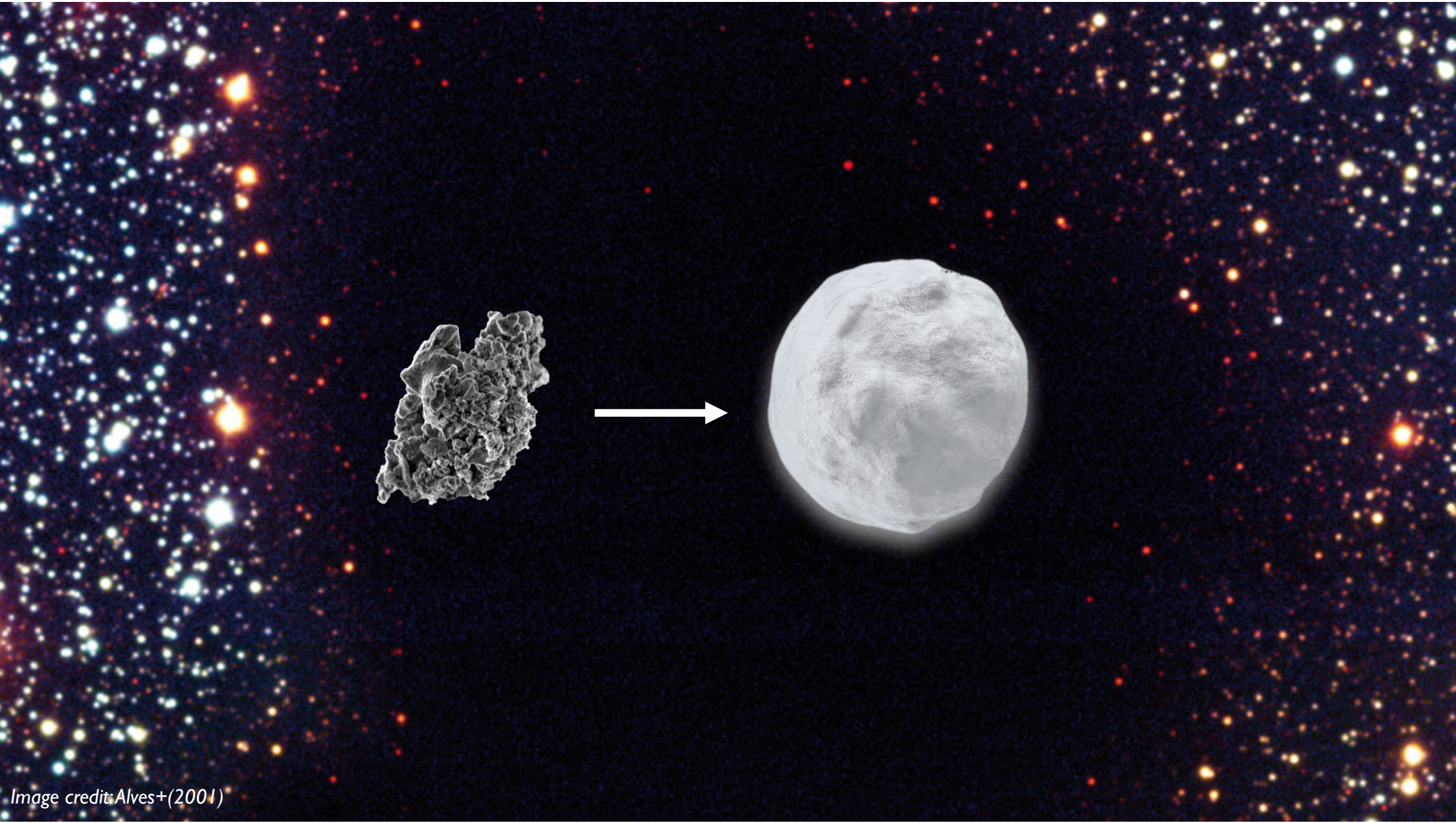


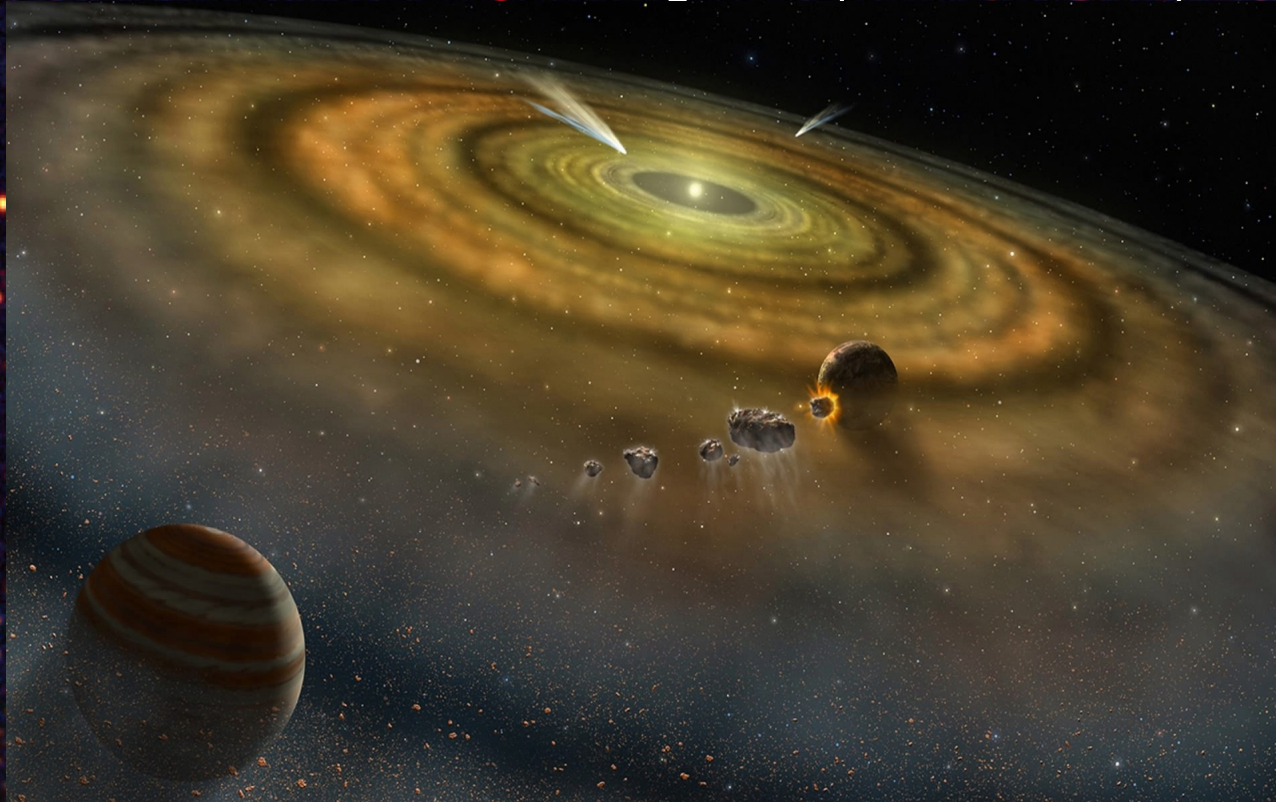
Image credit: Alves+(2001)

Just before stellar birth, in the central 2000 au of pre-stellar cores, almost all (99.99%) species heavier than He are frozen onto dust grains (Caselli+2022).



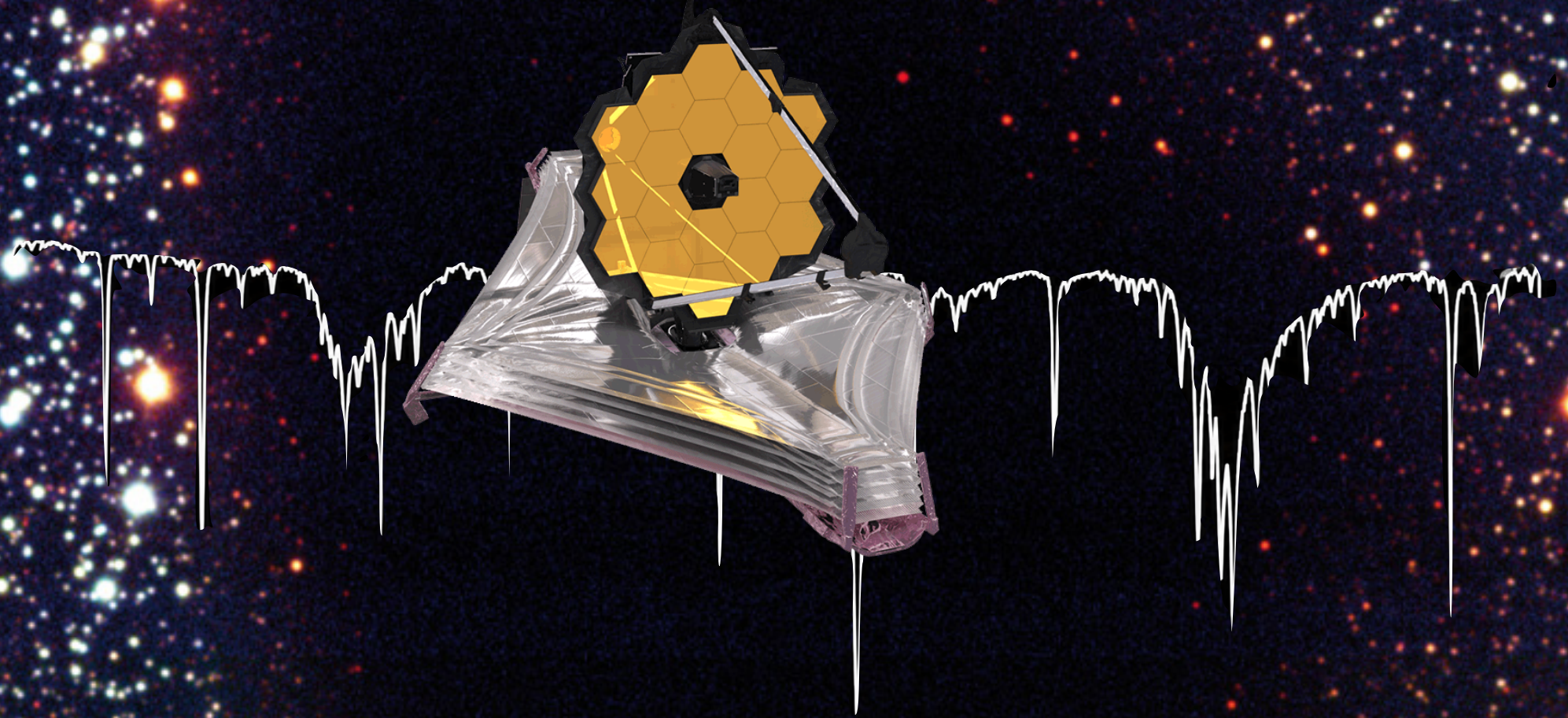
Dust grains are covered with thick icy mantles, storing molecules for the next stages of planet formation.

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Dust grains are covered with thick icy mantles, storing molecules for the next stages of planet formation.

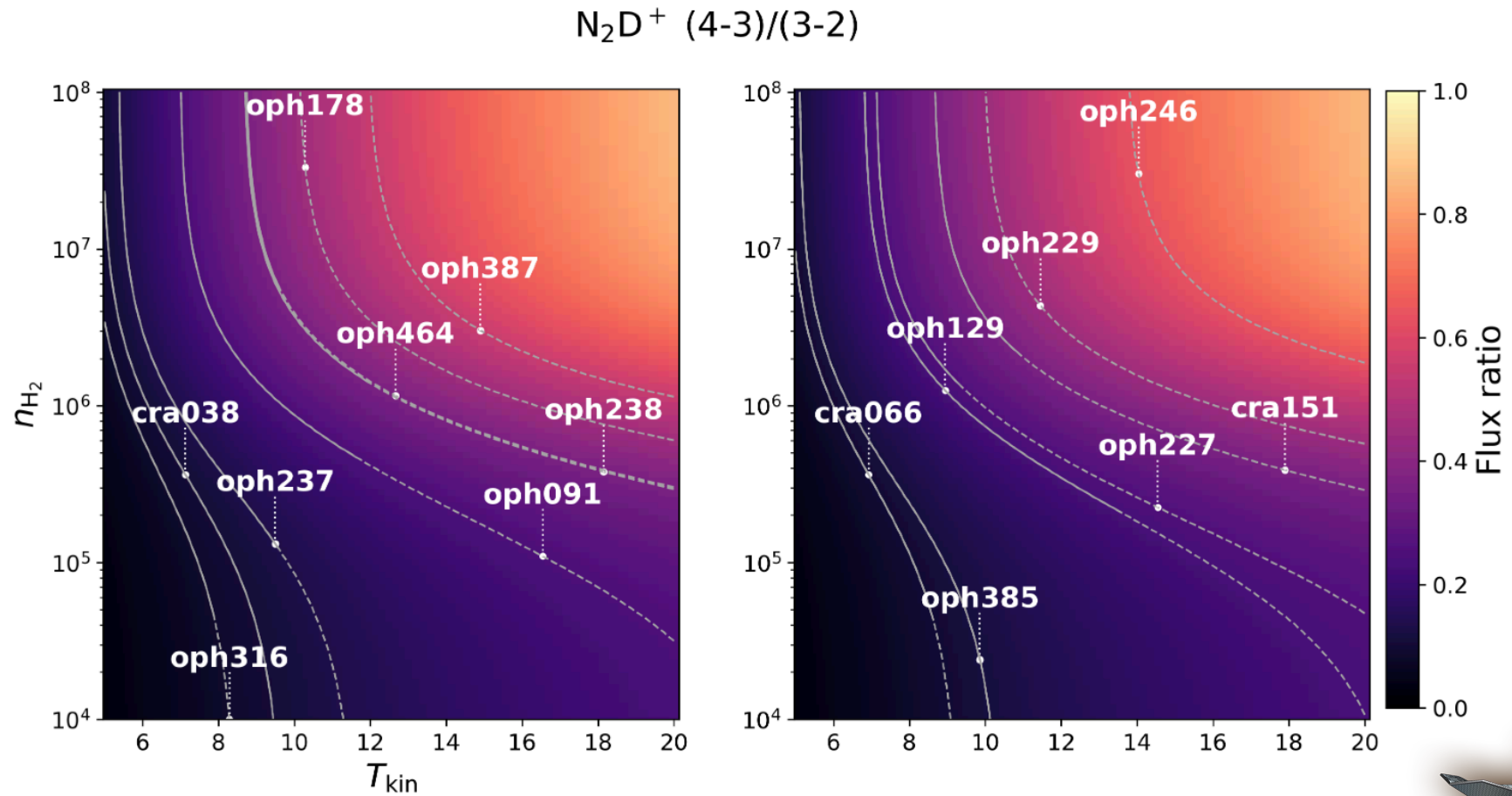
**New JWST data coming up soon !!**



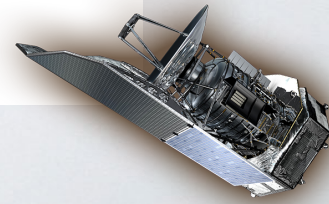
*PI: Izaskun Jiménez-Serra*

*Image credit: Alves+(2001)*

# New (rare!) pre-stellar cores have been identified with APEX and Herschel, and are currently being studied with ALMA



*Caselli+2025, Redaelli+2025, Spezzano+2025, Giers+, in prep.*





# Complex organic molecules (COMs) form at the edge of the catastrophic CO freeze-out zone

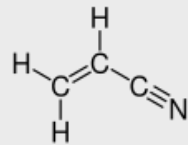
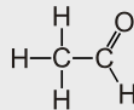
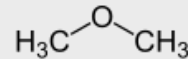
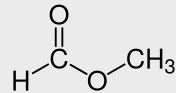
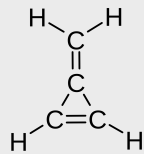
(see astrochemical models by *Vasyunin+2017*)

See also:

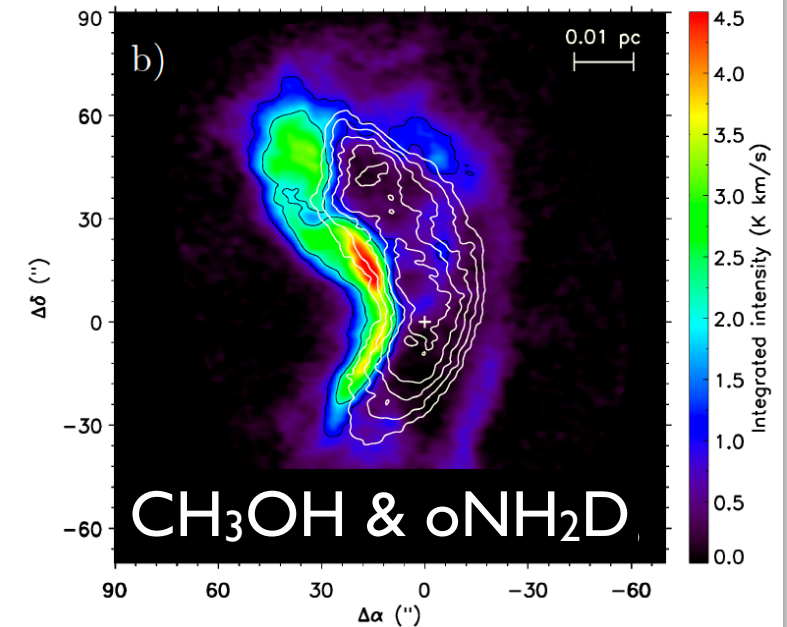
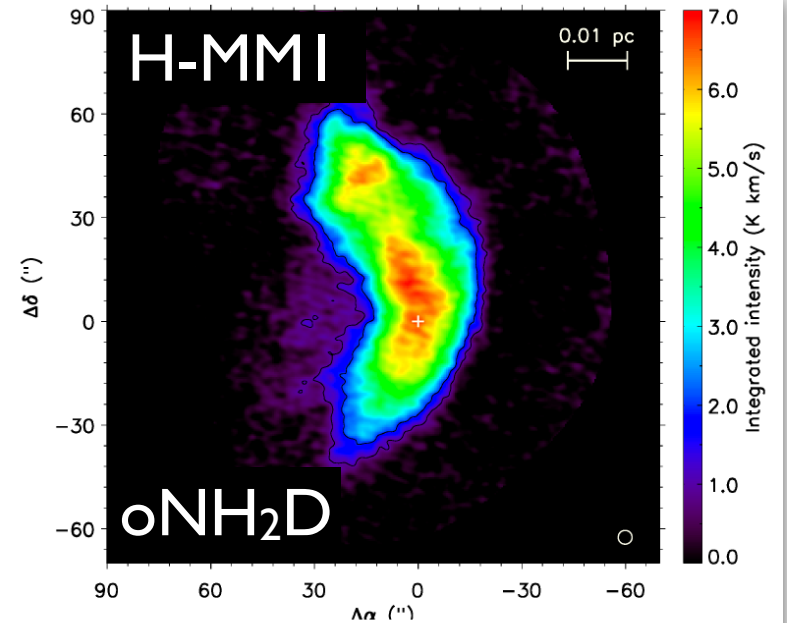
- Marcelino+2007*
- Öberg+2010*
- Bacmann+2013*
- Bizzocchi+2014*
- Vastel+2014*
- Bacmann&Faure 2016*
- Jiménez-Serra+2016, 2021*
- Spezzano+2016, 2017, 2020*
- Scibelli & Shirley 2020, Scibelli+2024*
- Ambrose+2021*
- Punanova+2022, 2025*
- Remijan+2025*
- Lin+2026*



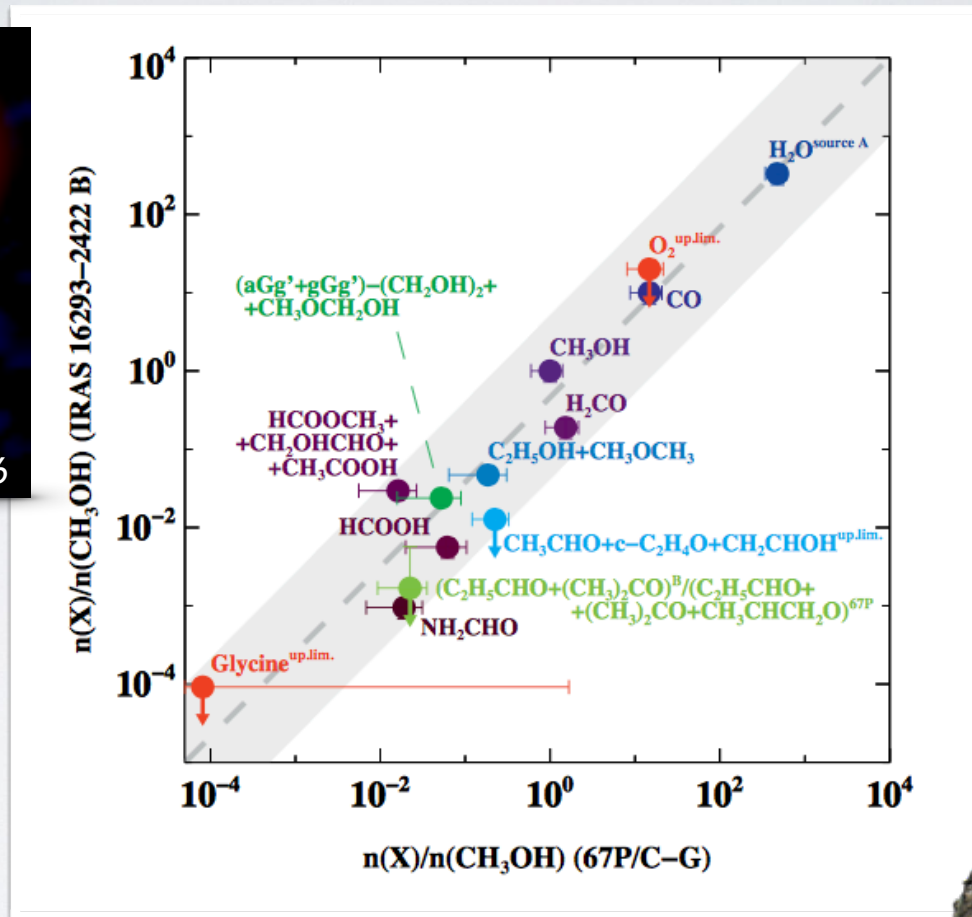
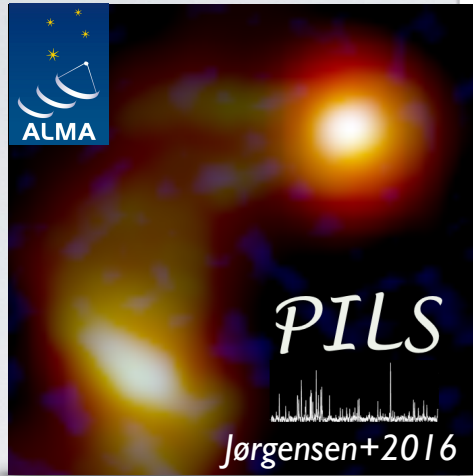
*Harju+2020*



***Ceccarelli+2023, PPVII***



# Similar complex organic abundances in comets and star-forming regions suggest pre-stellar core inheritance

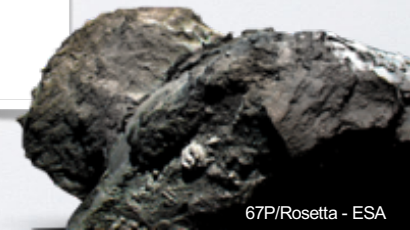


“The volatile composition of cometesimals and planetesimals is partially inherited from the pre- and protostellar phases of evolution.”

-Drozdovskaya+2019

Drozdovskaya+2019, 2021, 2022

















see also Biver+2015, Rivilla+2020, Ceccarelli+2023, Rocha+2024, Scibelli+2025

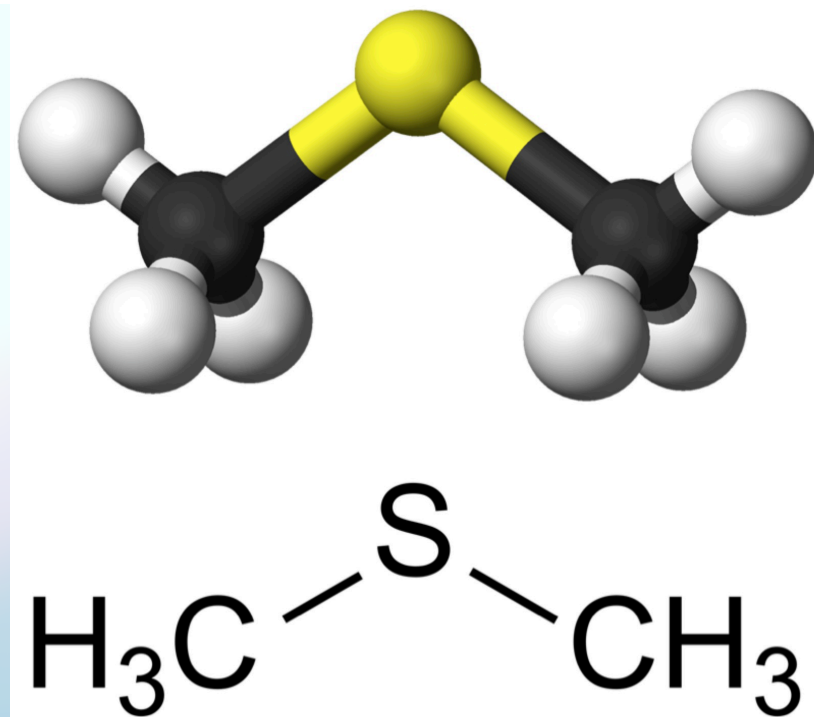


67P/Rosetta - ESA



# On the Abiotic Origin of Dimethyl Sulfide: Discovery of Dimethyl Sulfide in the Interstellar Medium

Miguel Sanz-Novo<sup>1</sup> , Víctor M. Rivilla<sup>1</sup> , Christian P. Endres<sup>2</sup> , Valerio Lattanzi<sup>2</sup>, Izaskun Jiménez-Serra<sup>1</sup> , Laura Colzi<sup>1</sup> ,  
Shaoshan Zeng<sup>3</sup> , Andrés Megías<sup>1</sup> , Álvaro López-Gallifa<sup>1</sup> , Antonio Martínez-Henares<sup>1</sup> , David San Andrés<sup>1</sup> ,  
Belén Tercero<sup>4</sup> , Pablo de Vicente<sup>5</sup> , Sergio Martín<sup>6,7</sup> , Miguel A. Requena-Torres<sup>8</sup> , Paola Caselli<sup>2</sup> , and  
Jesús Martín-Pintado<sup>1</sup> 



**OPEN ACCESS**



# On the Abiotic Origin of Dimethyl Sulfide: Discovery of Dimethyl Sulfide in the Interstellar Medium

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**DMS/CH<sub>3</sub>OH ~ 10<sup>-3</sup>**

in the GC cloud G+0.693-0.027

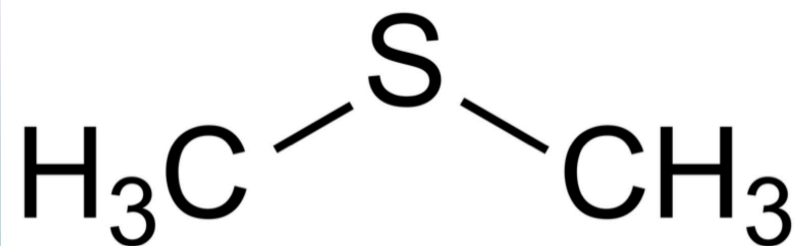
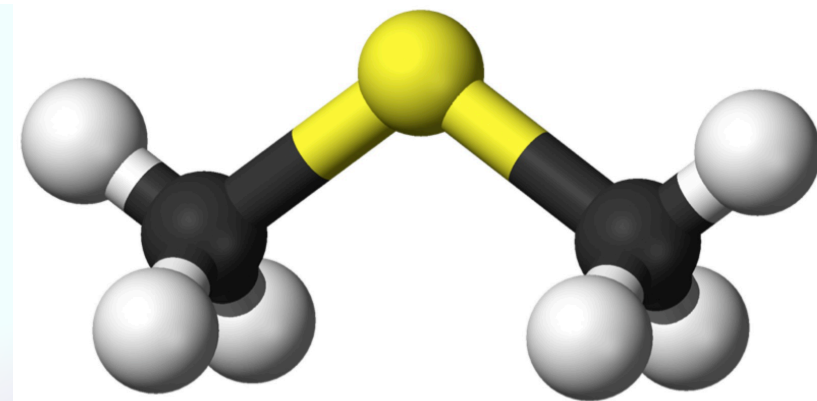


(NASA/JPL-Caltech/S. Stolovy, Spitzer Science Center/Caltech)

in comet 67P

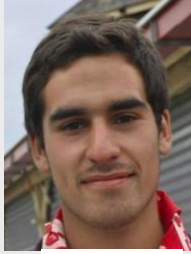


ESA/Rosetta/NAVCAM

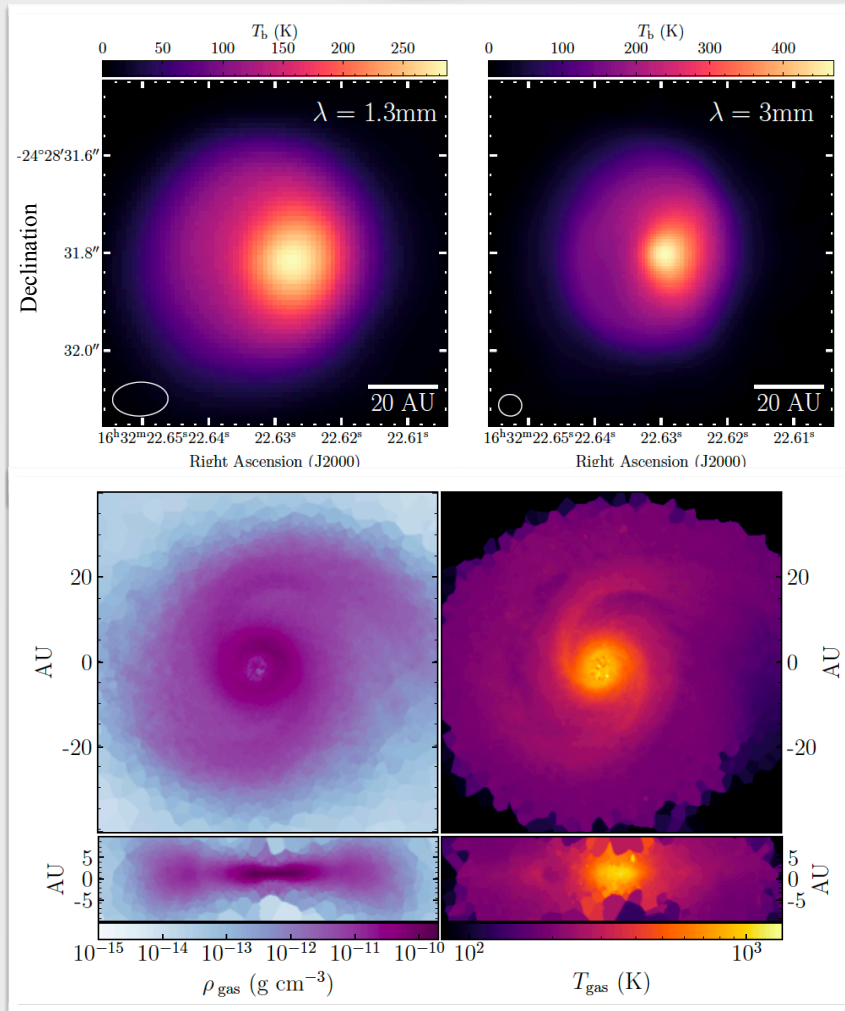




# Protostellar disks can be hot and gravitationally unstable



Joaquin Zamponi

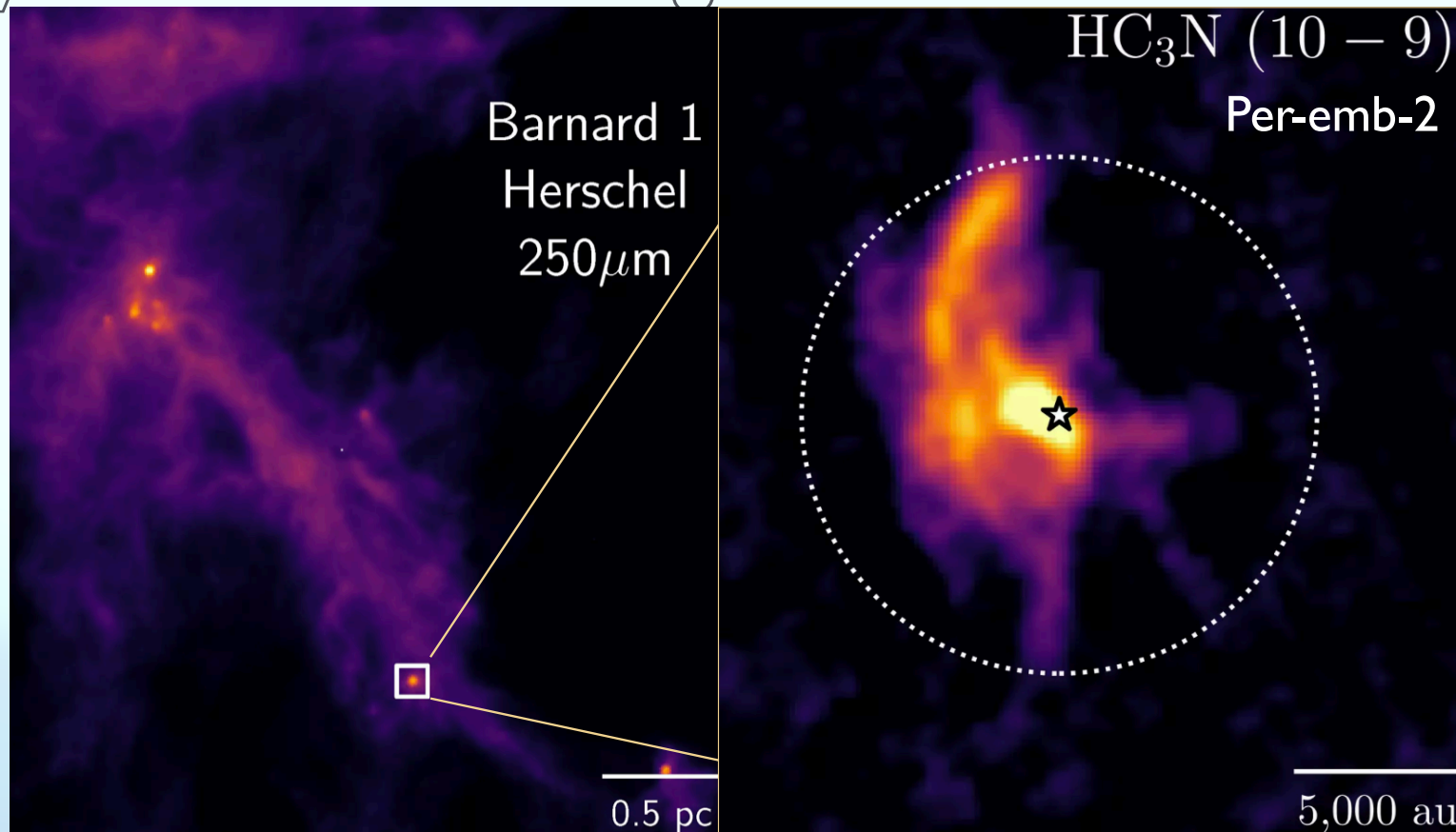


IRAS 16293B ALMA observations: high brightness temperatures with  $T_b(3\text{mm}) > T_b(1\text{mm})$ , indicative of hot mid-plane.

Simulations of a gravitationally unstable disk reproduce ALMA observations. The high temperatures allow the evaporation of icy mantles and the processing of dust.

Zamponi, Maureira, Liu+2021  
(see also van't Hoff+2020 ; Nazari+2023)

Young protostars are fed  
by the surrounding cloud via streamers



IRAM-NOEMA

*Pineda, Segura-Cox, Caselli+2020, Nature Astronomy*

(See also *Valdivia-Mena+2022, 2024; Hsieh+2023, Flores+2023; Gieser+2024; Codella+2024; Taniguchi+2024...*)

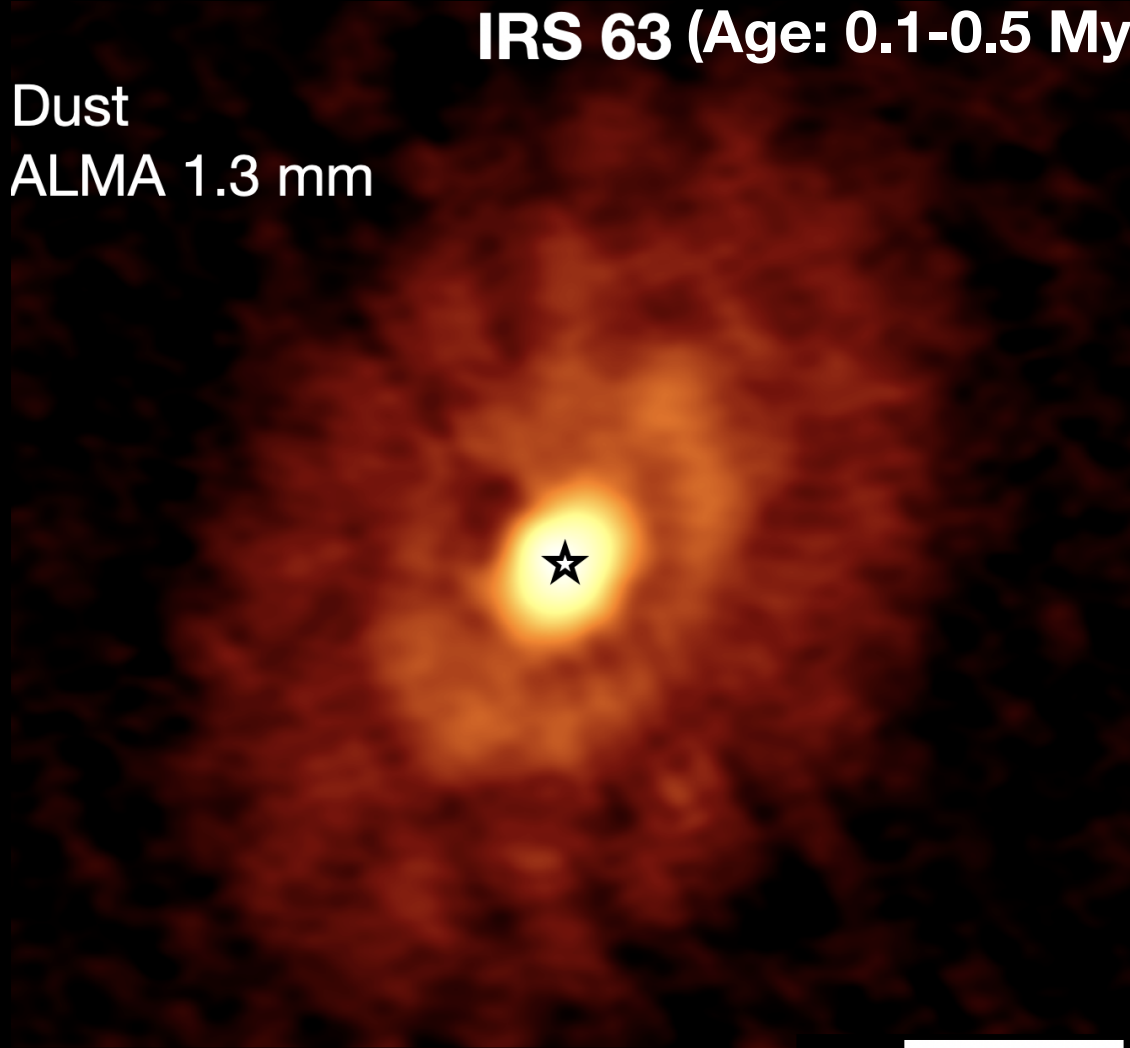


# Planet formation starts early!



**IRS 63 (Age: 0.1-0.5 Myr)**

Dust  
ALMA 1.3 mm



**30 au = Neptune's Orbit**

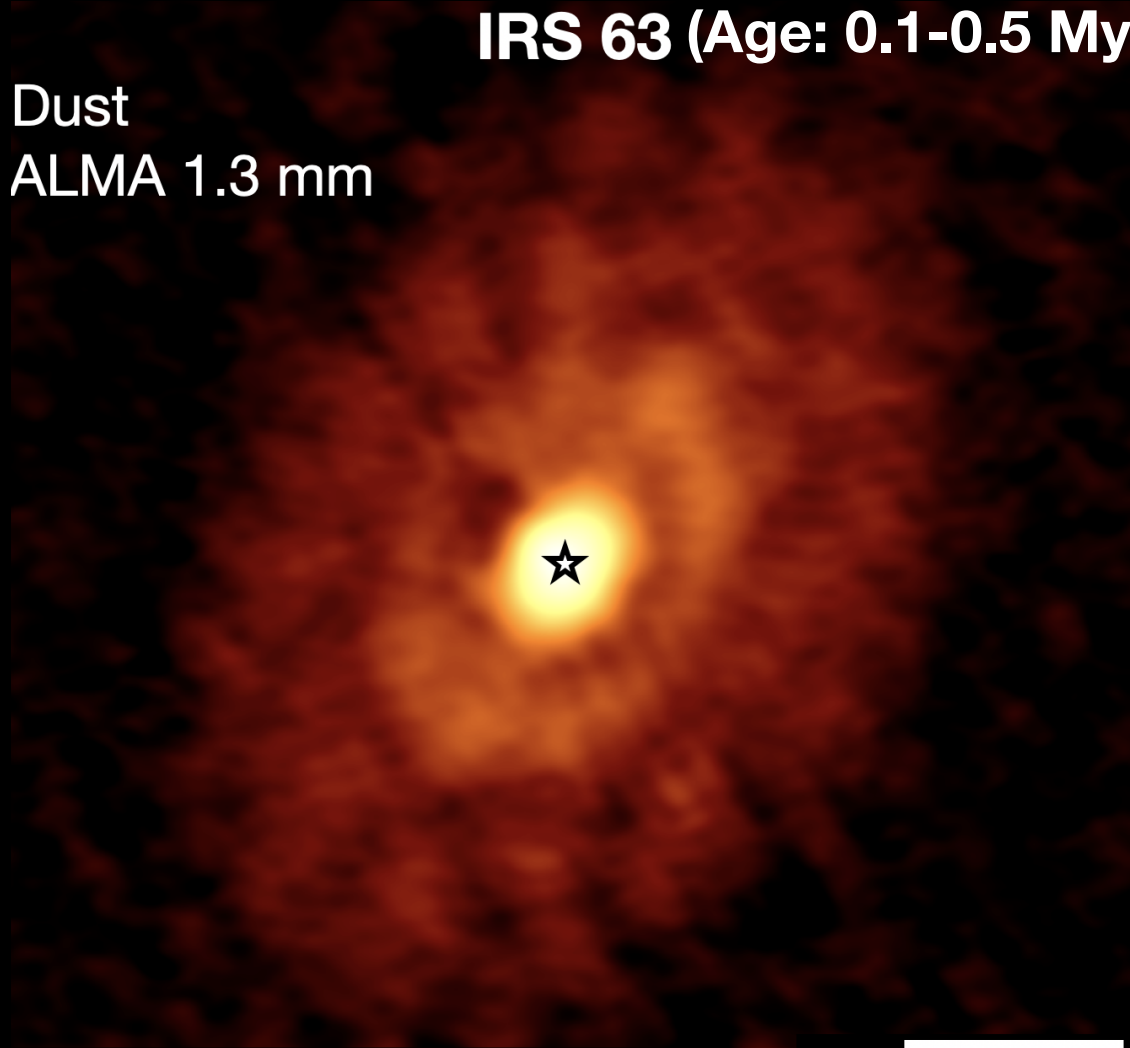
**30 au**

# Planet formation starts early!



**IRS 63 (Age: 0.1-0.5 Myr)**

Dust  
ALMA 1.3 mm



**30 au = Neptune's Orbit**

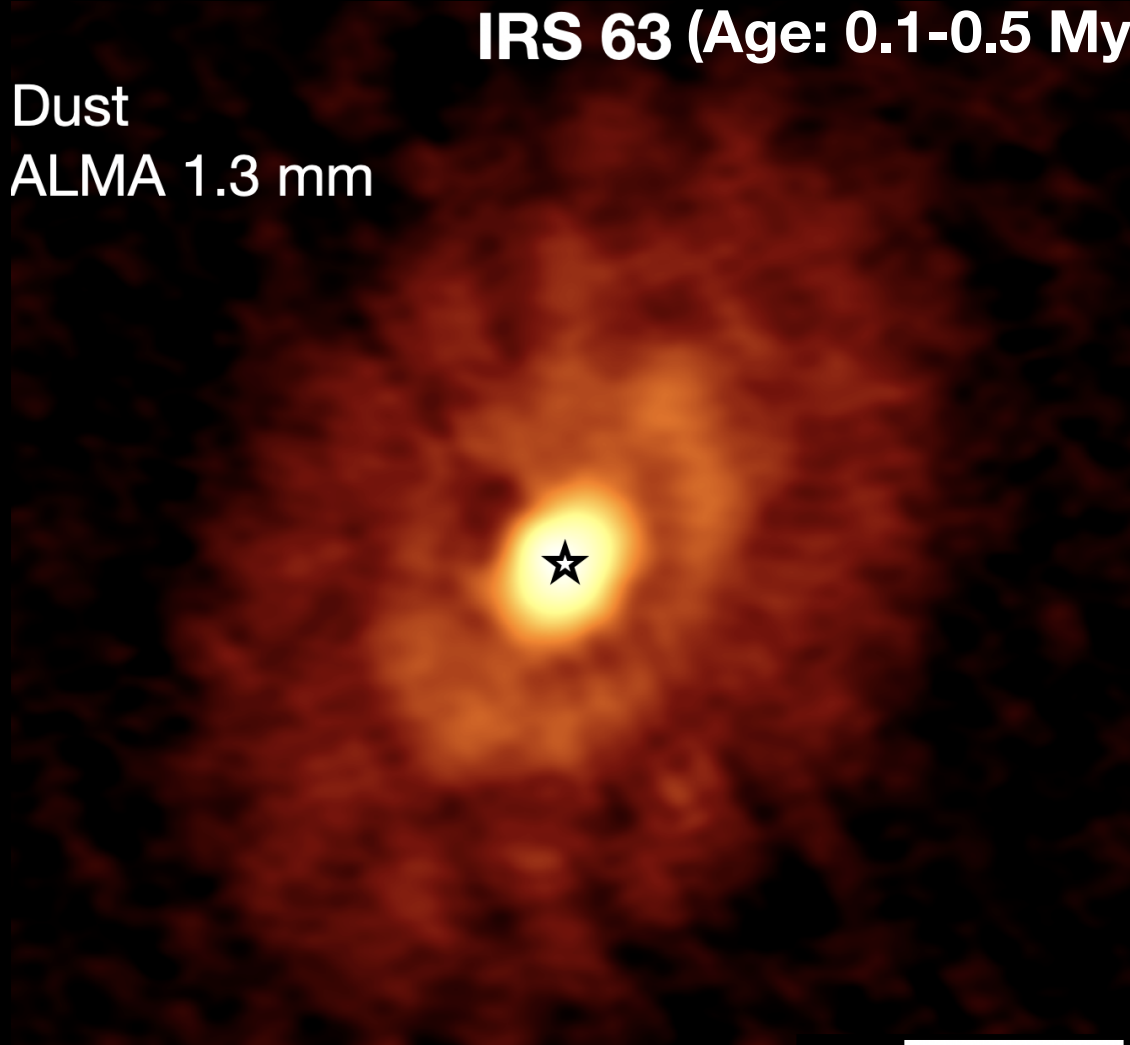
**30 au**

# Planet formation starts early!

**IRS 63 (Age: 0.1-0.5 Myr)**

Dust  
ALMA 1.3 mm

Due to disk  
instabilities triggered  
by streamers (?)



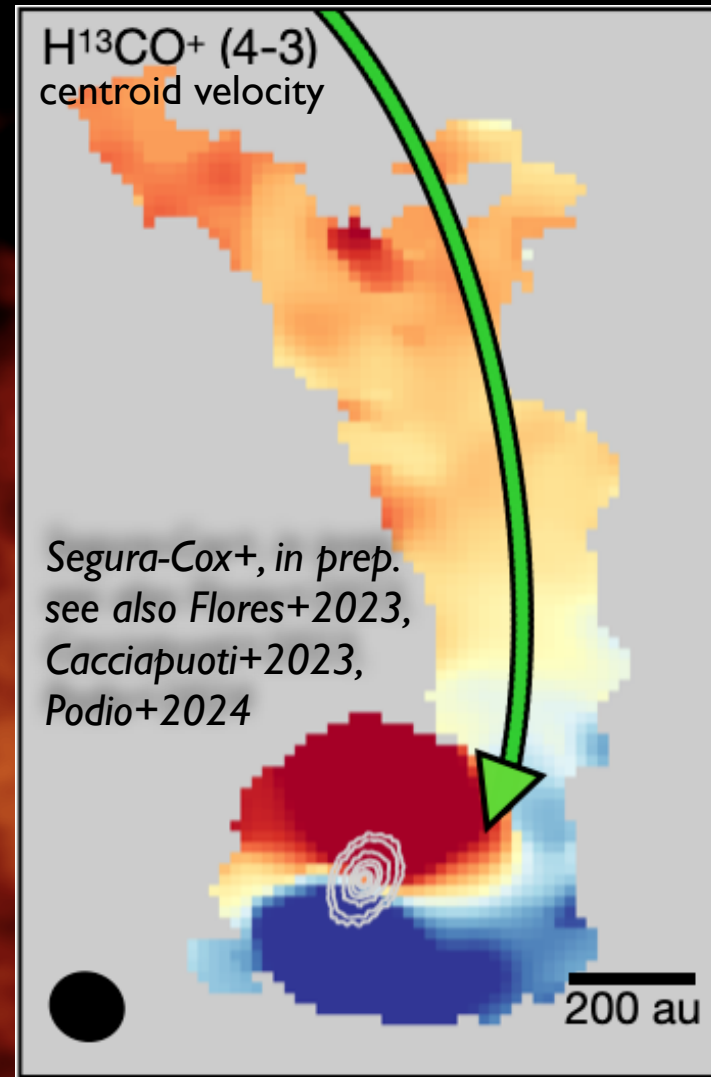
**30 au = Neptune's Orbit**

**30 au**

# Planet formation starts early!

Dust  
ALMA 1.3 mm

Due to disk  
instabilities triggered  
by streamers (?)



Segura-Cox+2020, Nature

30 au = Neptune's Orbit

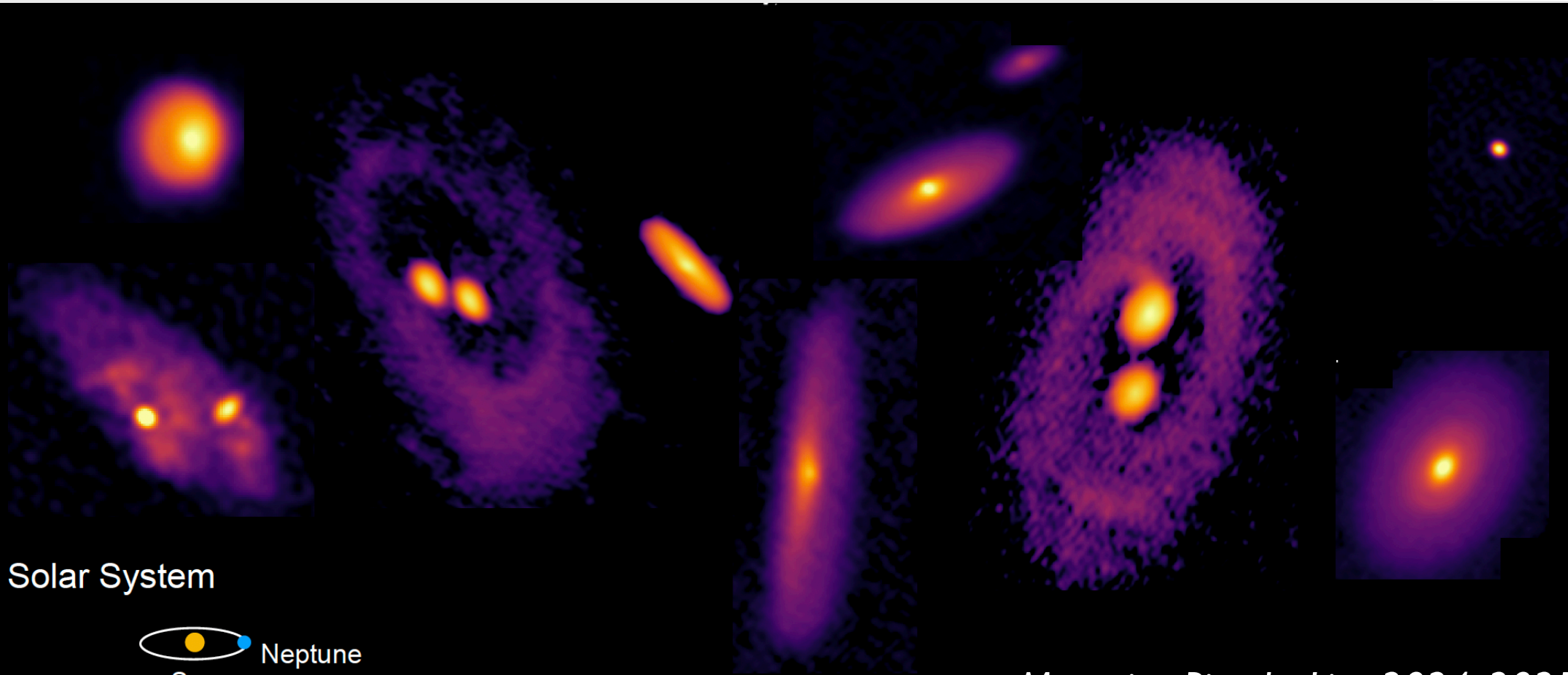
30 au



# Every protostellar disk tells a different story when viewed with ALMA at high resolution ( $\sim 7.5$ au)



María José Maureira



Solar System

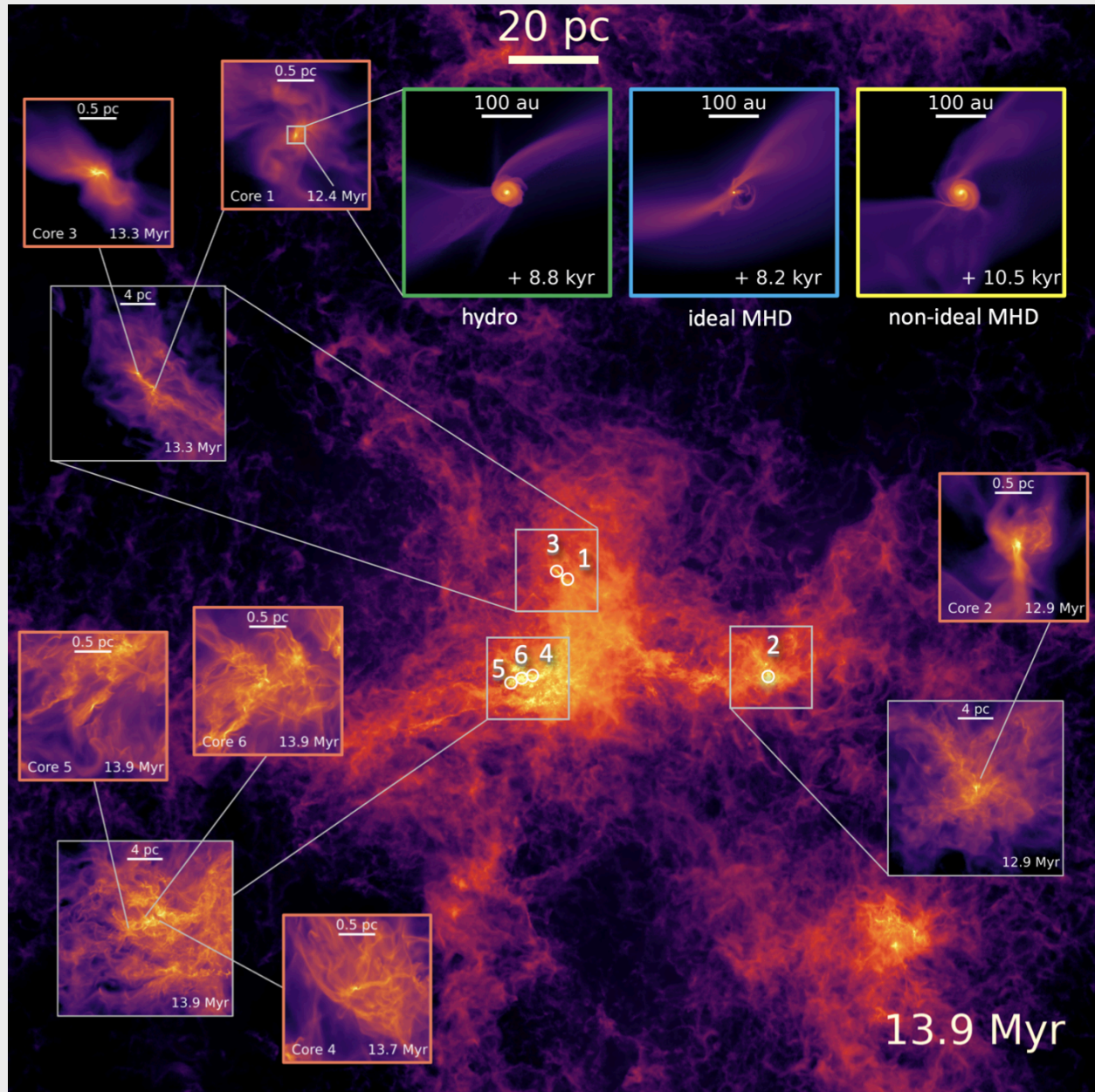


*Maureira, Pineda, Liu+2024, 2025*



# Protoplanetary disks in their natural habitat

Following the formation of pre-stellar cores, stars and disks via simulations of supernova-driven turbulent ISM



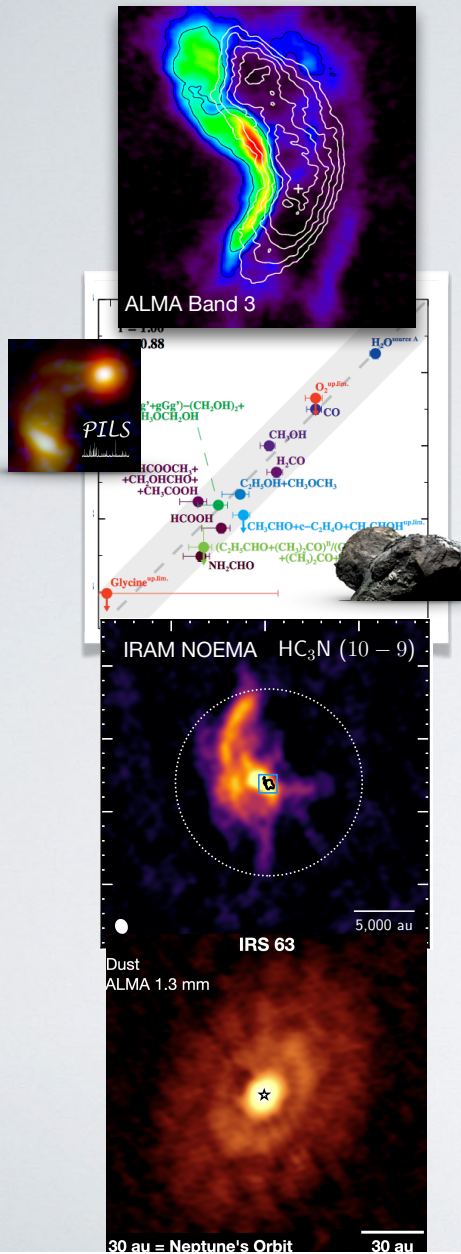
Mayer, Naab, Caselli, Ivlev, Grassi+2025

- **Pre-stellar cores:**  $n_c \geq 10^6 \text{ cm}^{-3}$ ,  $T_c = 6\text{-}7 \text{ K}$ , almost complete freeze-out (>99%), D-fraction (>20%) and COMs → *First steps toward pre-biotic chemistry.*

- **Similar COM fractional abundances** in comets and star-forming regions → *Storage of pre-stellar ice.*

- **Large-scale flows** bring cloud/core material on disk → *Important for disk dynamical and chemical evolution.*

- **Planet formation starts early**, and chemical complexity builds: tracking gas *and* dust evolution (*grain growth + chemistry/ mineralogy*) is key to understanding planets and life's first steps.



MANY  
CONGRATULATIONS,  
DEAR RICCARDO!

After a lifetime of precision  
astrophysics and precise lunch  
times, it's finally time to relax...

...at exactly the same  
time every day

