Lecture 11 : Protostars

NASA, ESA, CSA and STScI

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Outline

- Physical structure
- Chemical structure
- Observations of molecules in protostellar envelopes
- New era of discoveries with James Webb Space Telescope (JWST)

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- **Physical structure**
- Chemical structure
- Observations of molecules in protostellar envelopes
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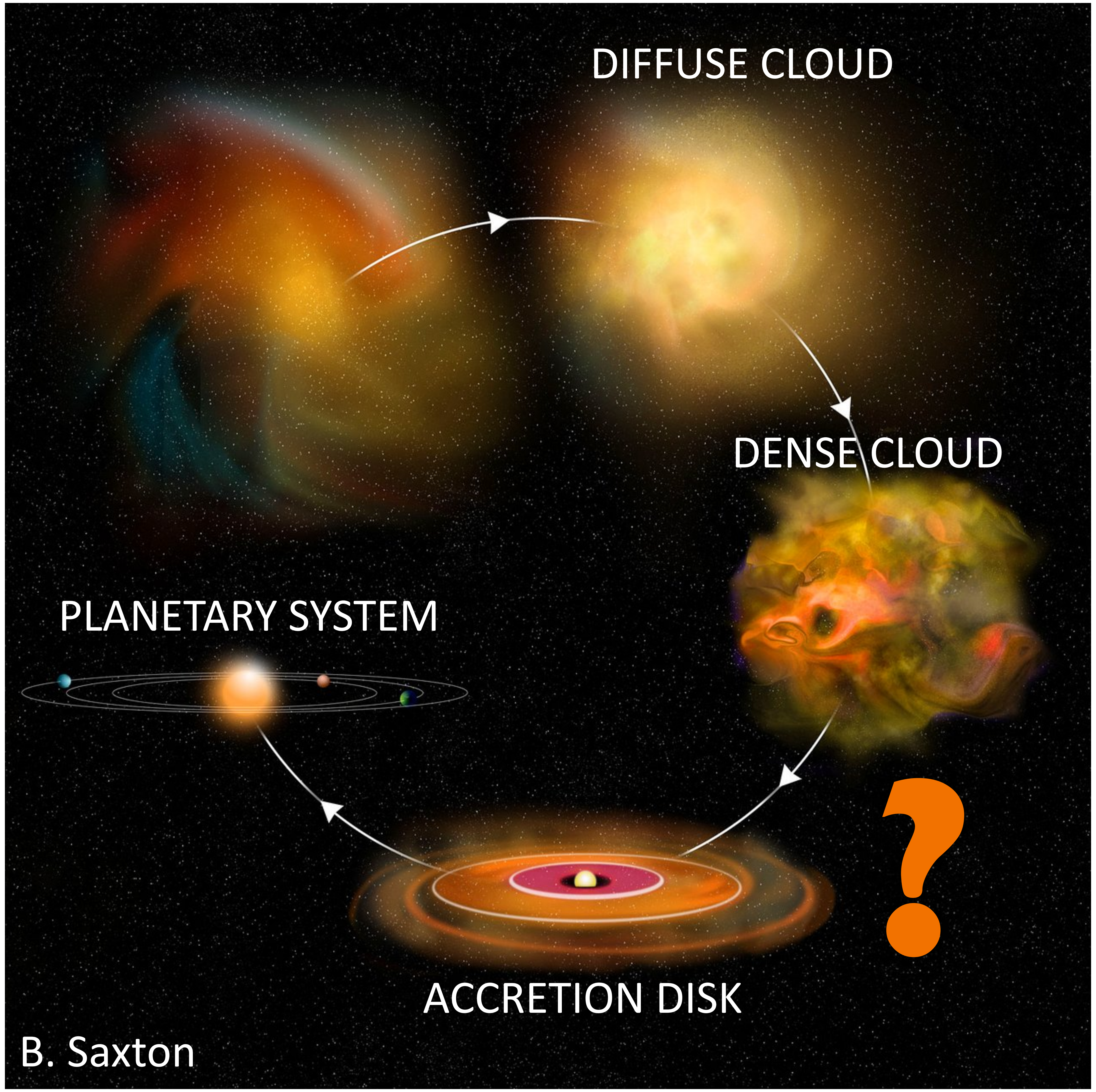
Recap...

From molecular clouds to protostars



- **Cold cores**: no star, formation of first polyatomic molecules and ices
- **Protoplanetary disks:** the star has formed, evolution of remaining gas and dust

Let us take a step back …

Classical picture of the formation of the Solar System

Molecular Cloud

$< 10^5$ years
$\sim 10^4$ au

Chameleon Molecular Cloud

JWST/NIRCam: NASA, ESA, CSA

Classical picture of the formation of the Solar System

L1527

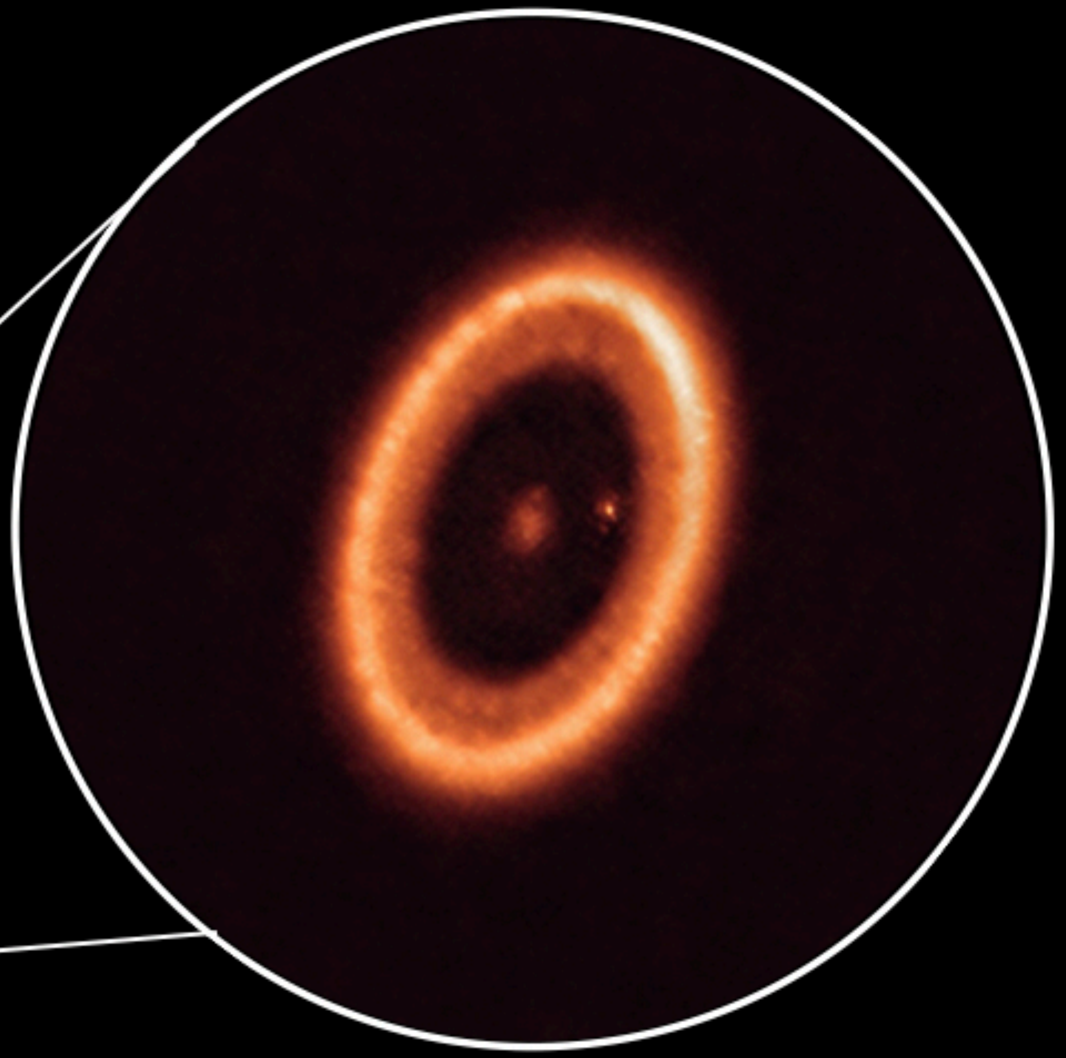
Protostar

10^5 – 5×10^5 years

~ 10^3 au

JWST/NIRCam: NASA, ESA, CSA

Classical picture of the formation of the Solar System



Protoplanetary disk

$5 \times 10^5 - 5 \times 10^6$ years

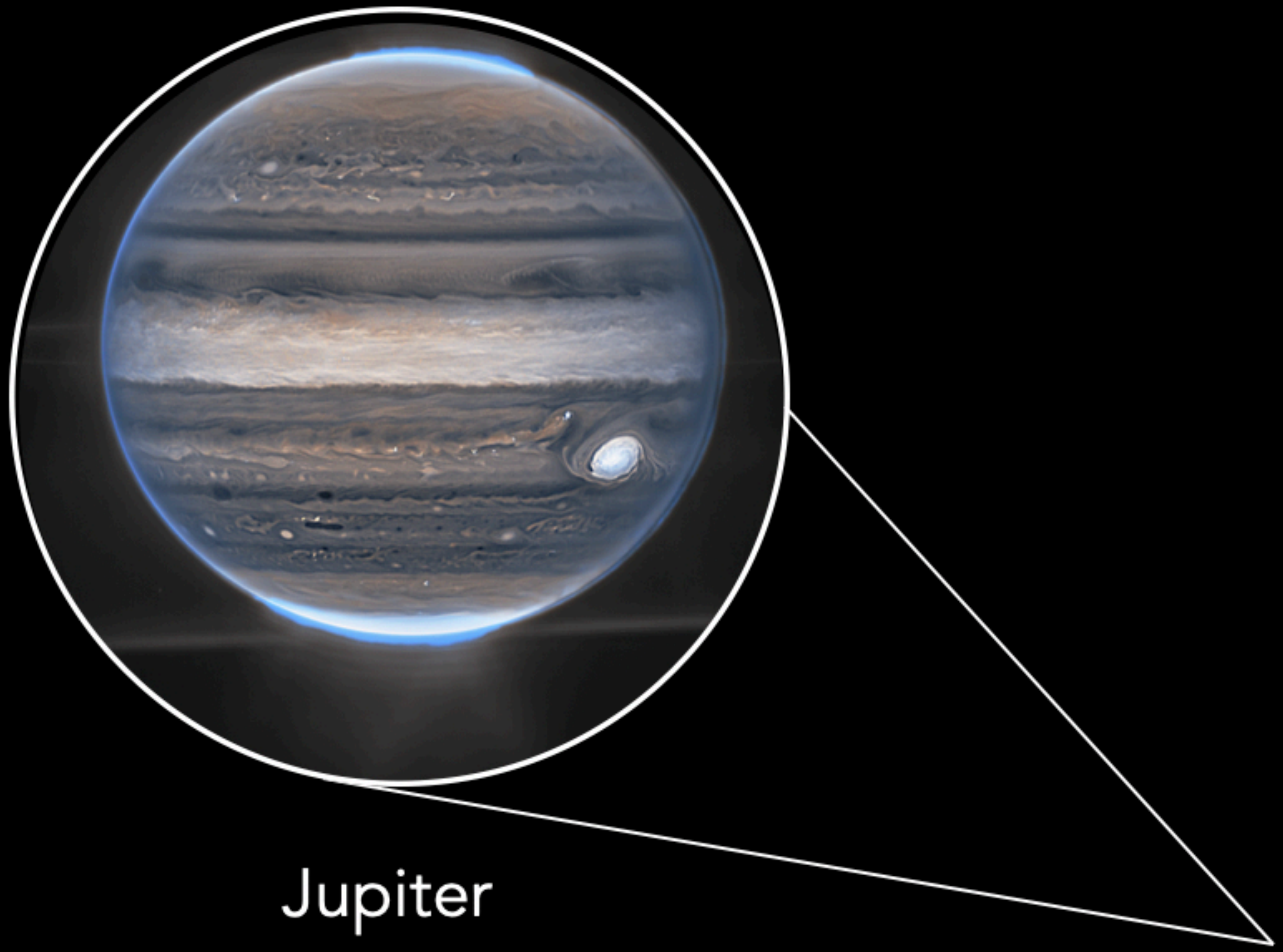
~100 au

PDS 70

Benisty et al. 2021

ALMA: ESO, AUI/NRAO, NAOJ

Classical picture of the formation of the Solar System

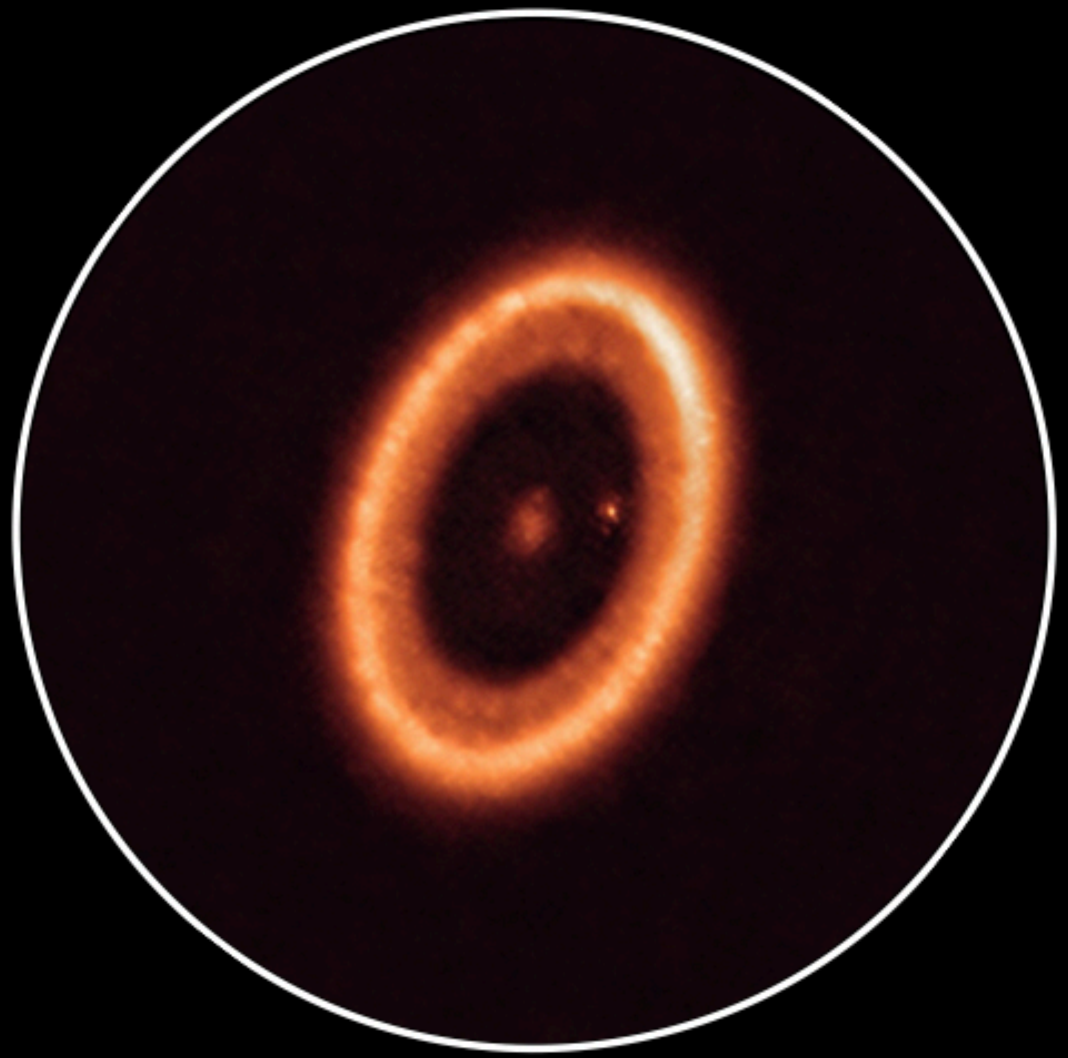


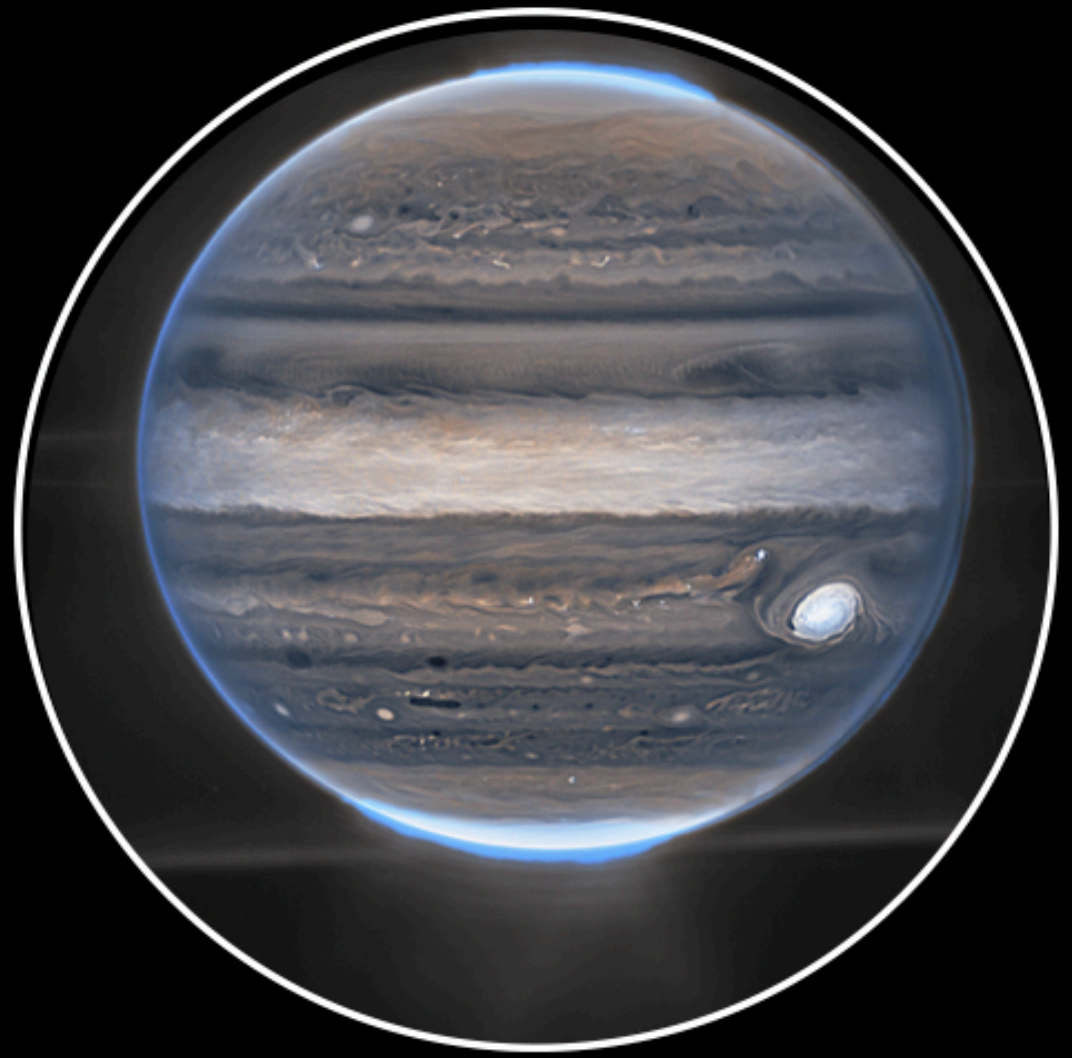
Jupiter

Planetary system

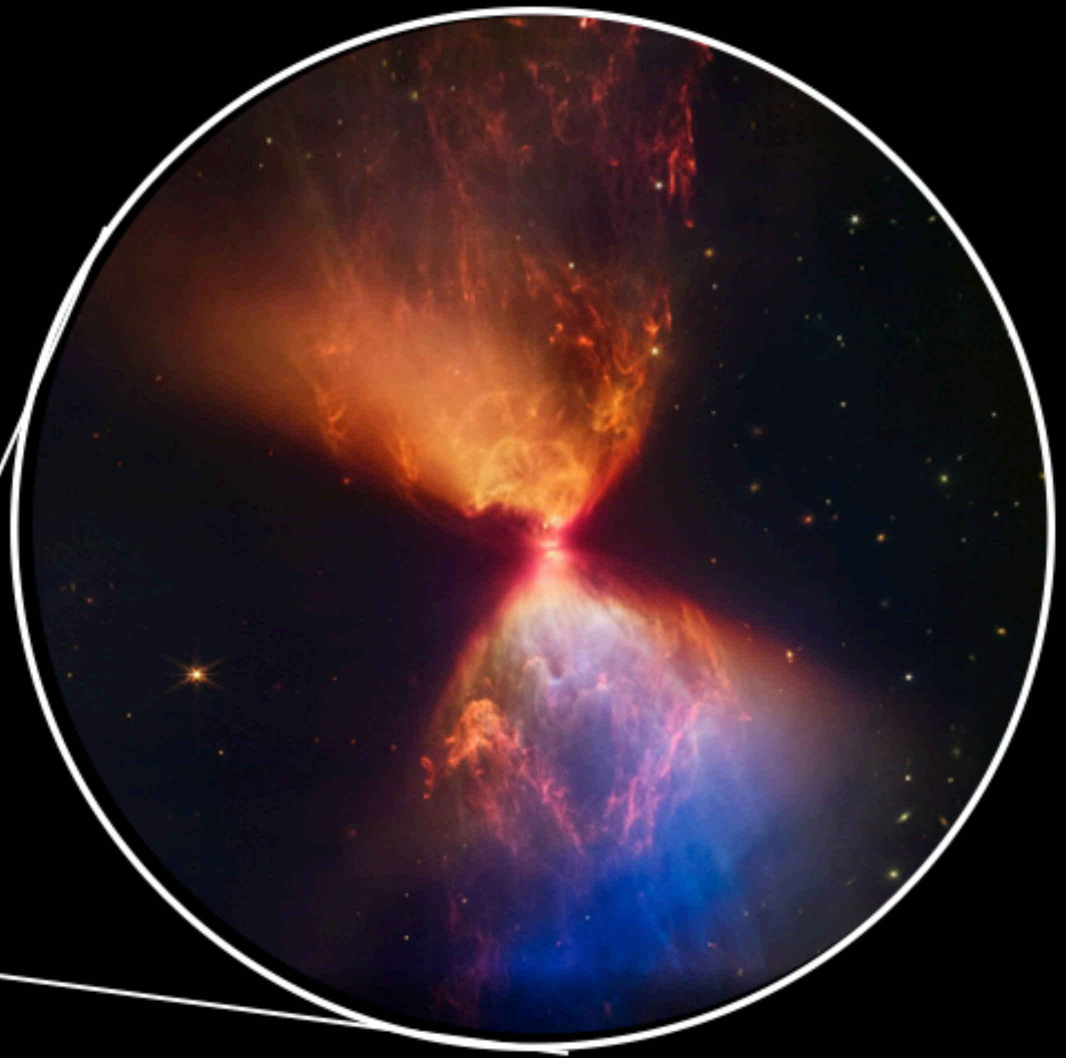
> 5 × 10^6 years
~10 au

JWST/NIRCam, NASA, ESA, CSA





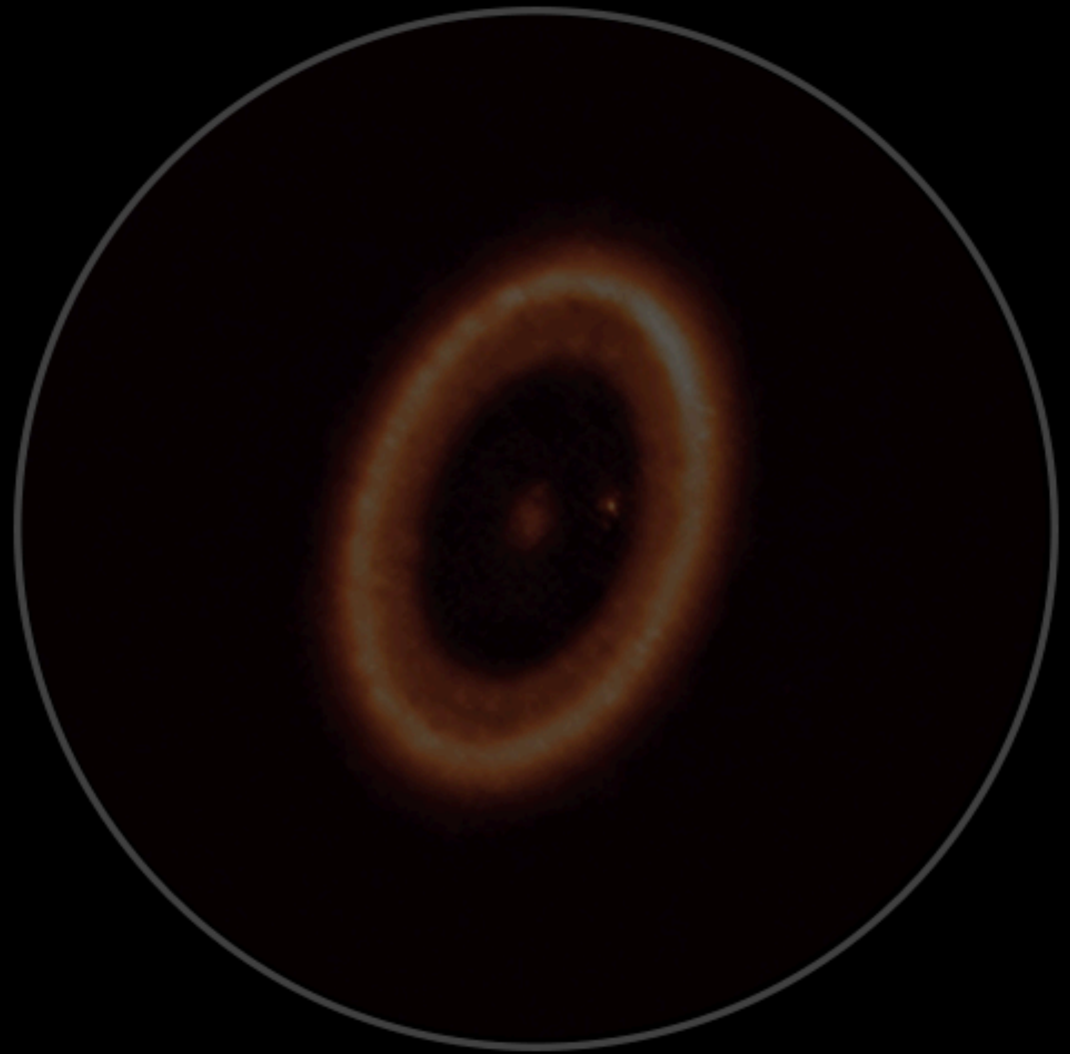
JWST/NIRCam: NASA, ESA, CSA | ALMA: ESO, AUI/NRAO, NAOJ



This lecture

Protostar

10^5 - 5 x 10^5 yrs
~ 10^3 au



JWST/NIRCam: NASA, ESA, CSA | ALMA: ESO, AUI/NRAO, NAOJ

Low-mass star-forming regions

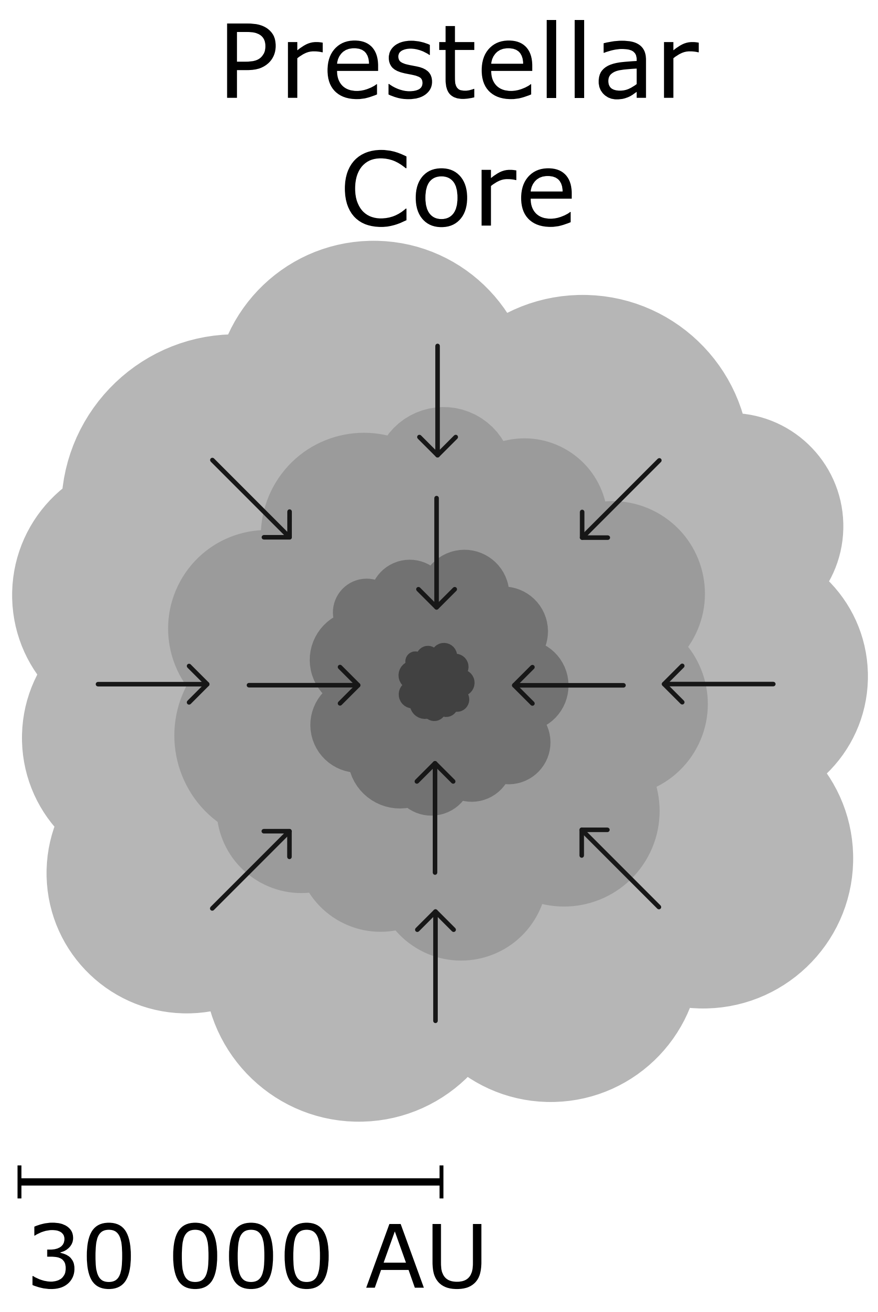
ESO

We study low-mass stars to understand how our Sun formed

- Low-mass stars = stars with masses < 2 $M_{\odot}$
- They constitute most of the total mass of our Galaxy
- Their study sheds light on the formation and evolution of our Sun and Solar System (Disk formation and evolution, planet formation)

Observational challenges: they are faint, thus far-IR and mm-/submm are favourable spectral domains to study their physical and chemical evolution

Classic picture of low-mass star formation



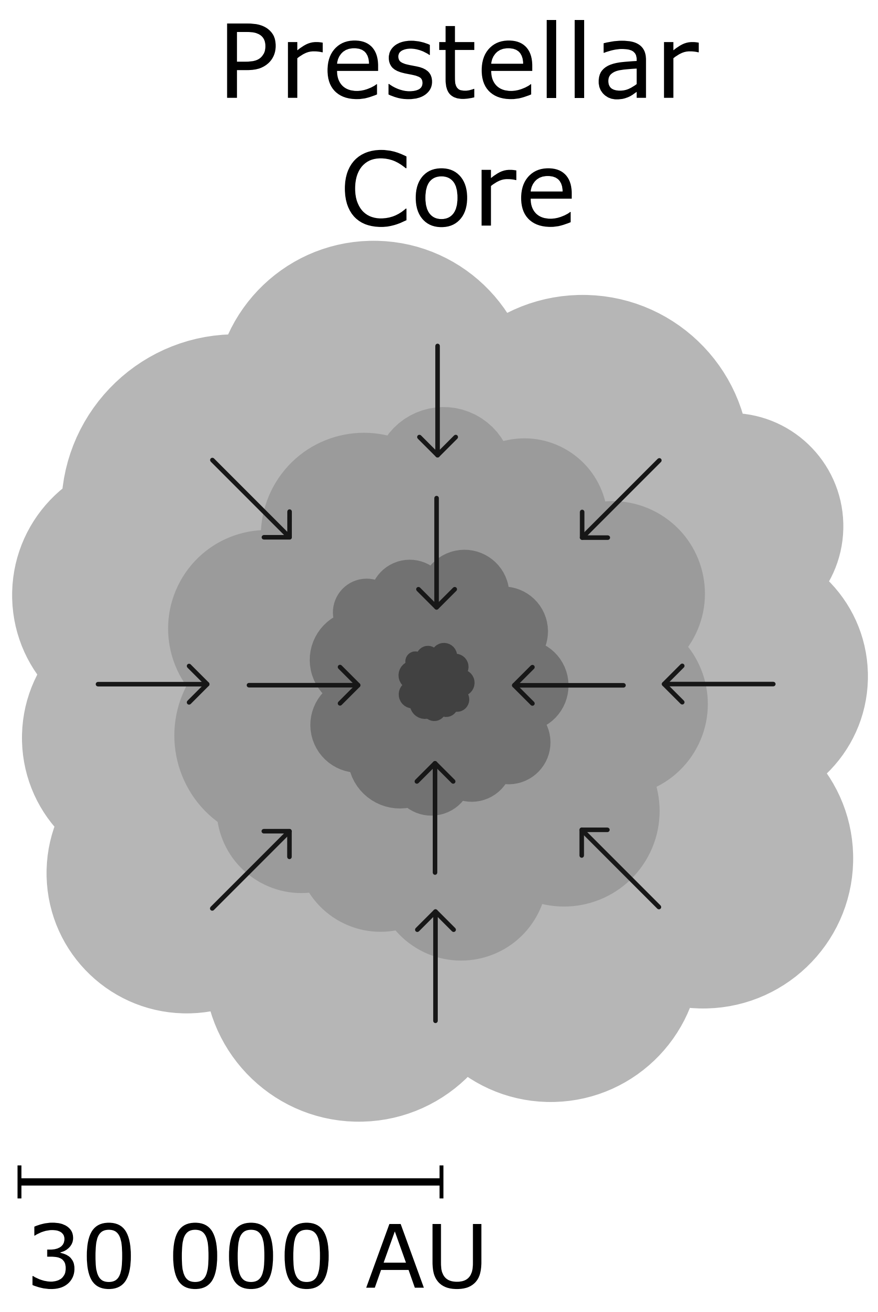
Pre-stellar cores can undergo gravitational collapse, initiating a cascade of processes leading to the formation of a star

The core is approximated as an isothermal sphere of gas with a density profile following the power-law $\rho \propto r^{-2}$

Assumption vs reality: the spherical cow

M. V. Persson

Classic picture of low-mass star formation



Pre-stellar cores can undergo gravitational collapse, initiating a cascade of processes leading to the formation of a star

The core is approximated as an isothermal sphere of gas with a density profile following the power-law $\rho \propto r^{-2}$

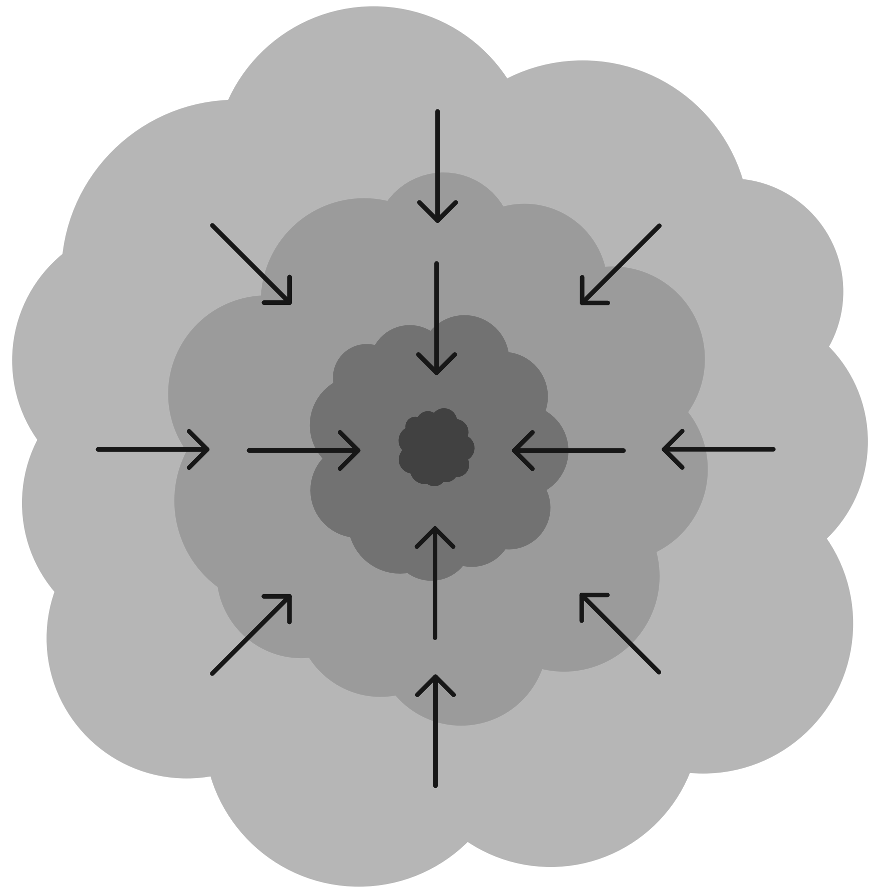
The maximum mass the core can have to be gravitationally bounded is referred to as the mass of a Bonnor-Ebert sphere:

$$M_{\mathrm{BE}} = \frac{C_{\mathrm{BE}} c_{\mathrm{s}}^4}{\sqrt{P_0 G^3}}$$

where C_{BE} is the Bonnor-Ebert constant,
c_s is the isothermal sounds speed,
P is the pressure of the gas and G is the gravitational constant

M. V. Persson

Classic picture of low-mass star formation



The maximum mass the core can have to be gravitationally bounded is referred to as the mass of a Bonnor-Ebert sphere

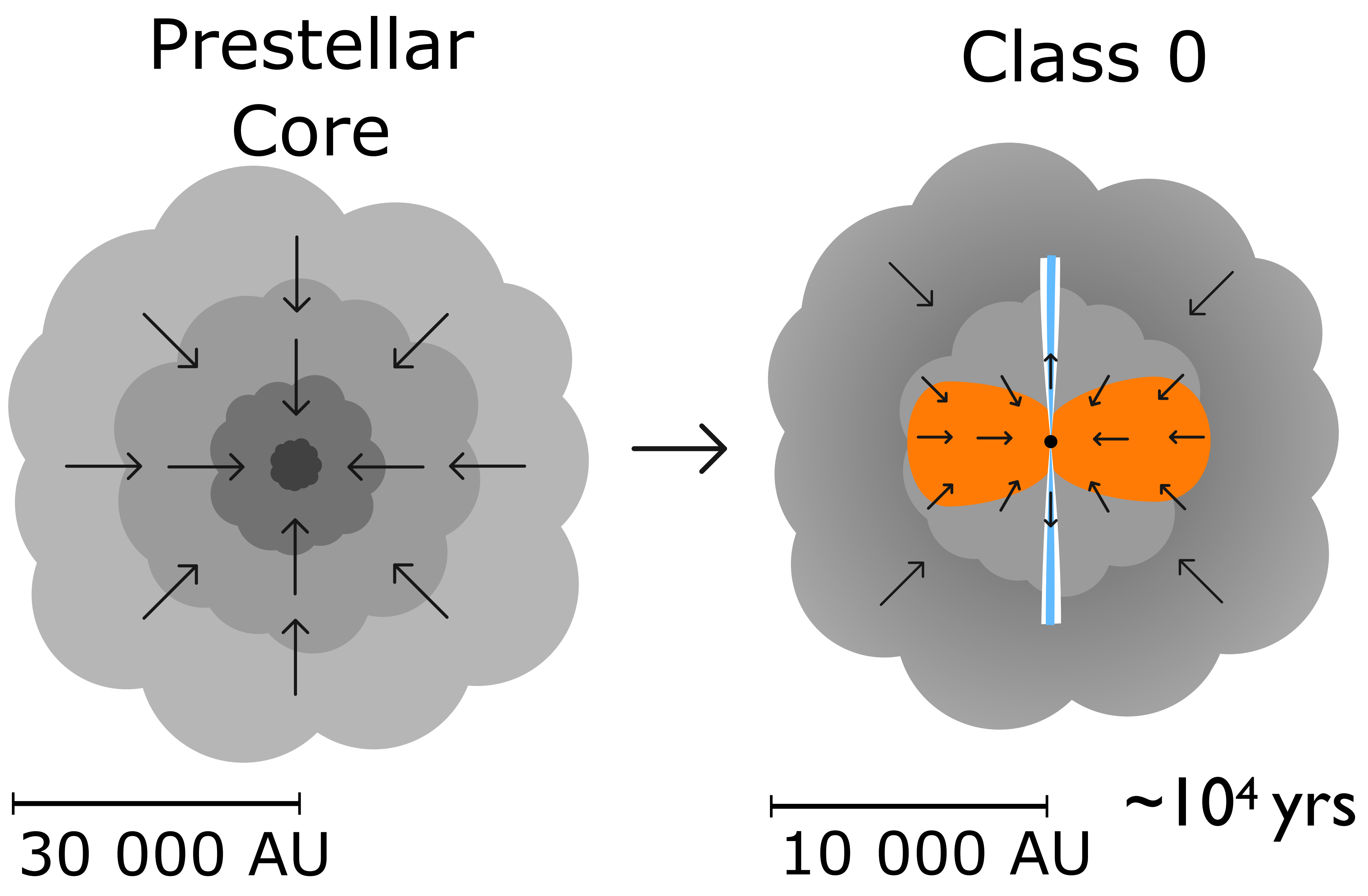
$$M_{\rm BE} = \frac{C_{\rm BE} c_{\rm s}^4}{\sqrt{P_0 G^3}}$$

When the mass of the core exceeds the critical mass of the Bonnor-Ebert sphere, the core begins to collapse in free-fall from the central regions, characterized by higher densities.

Since the expansion occurs from the inner to the outer layers of the cloud core, this model is called the *inside-out* collapse.

M. V. Persson

Classic picture of low-mass star formation

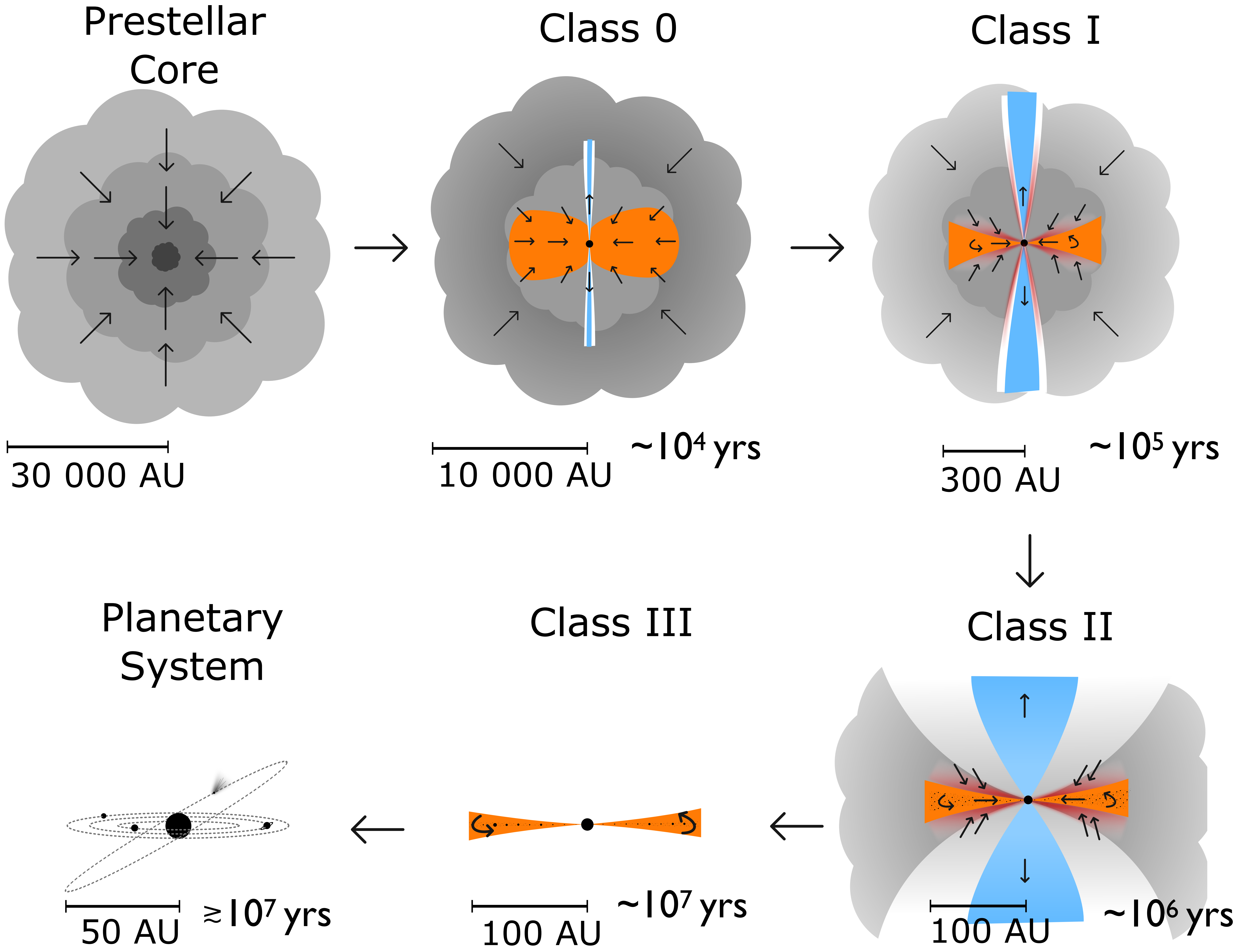


After the collapse has begun, more and more material accretes towards the center of the core.

When the material reaches densities and temperatures sufficiently high ($T \approx 10^6$ K) for deuterium fusion reactions to ignite, a protostar forms at the center.

M. V. Persson

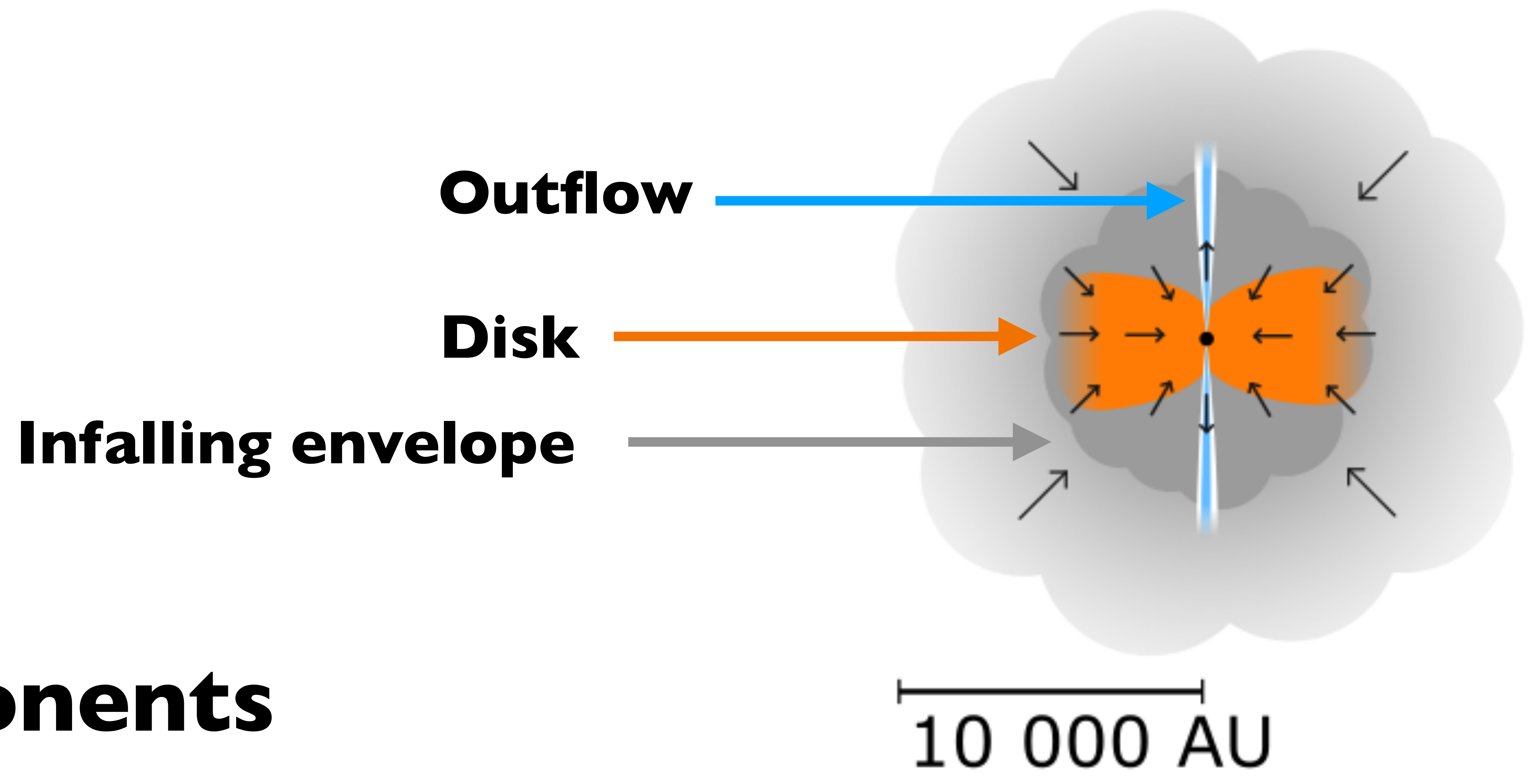
Classic picture of low-mass star formation



M. V. Persson

Protostellar phase: embedded stages

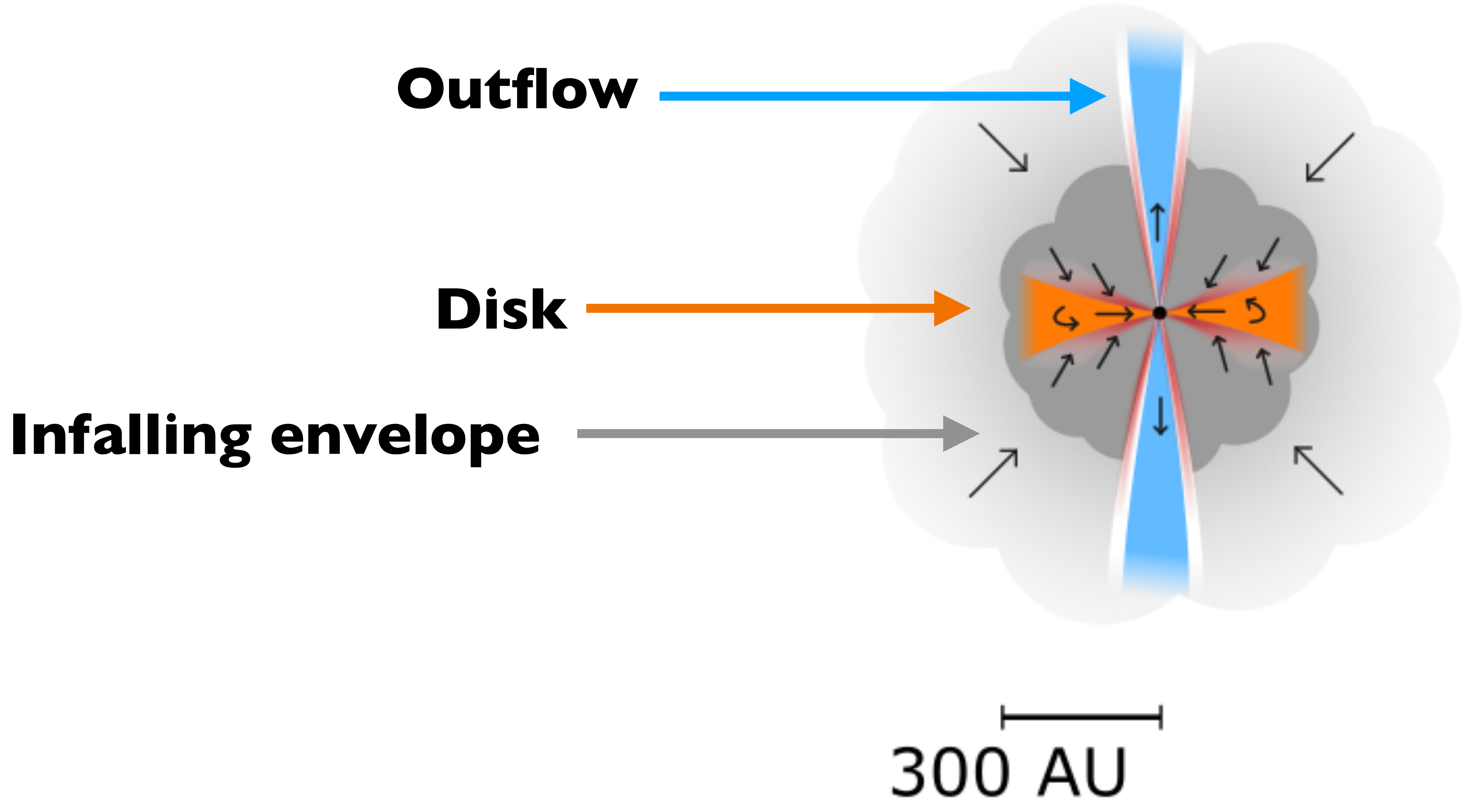
Main components



- **Class 0**

Massive protostellar envelope
Sizes: 10^4 AU
It may harbour a thick proto-disk
Estimated lifetime: 50 000 yrs
Outflows/Herbig-Haro (HH) objects

HH objects = bright clumps of gas located along outflow direction



- **Class I**

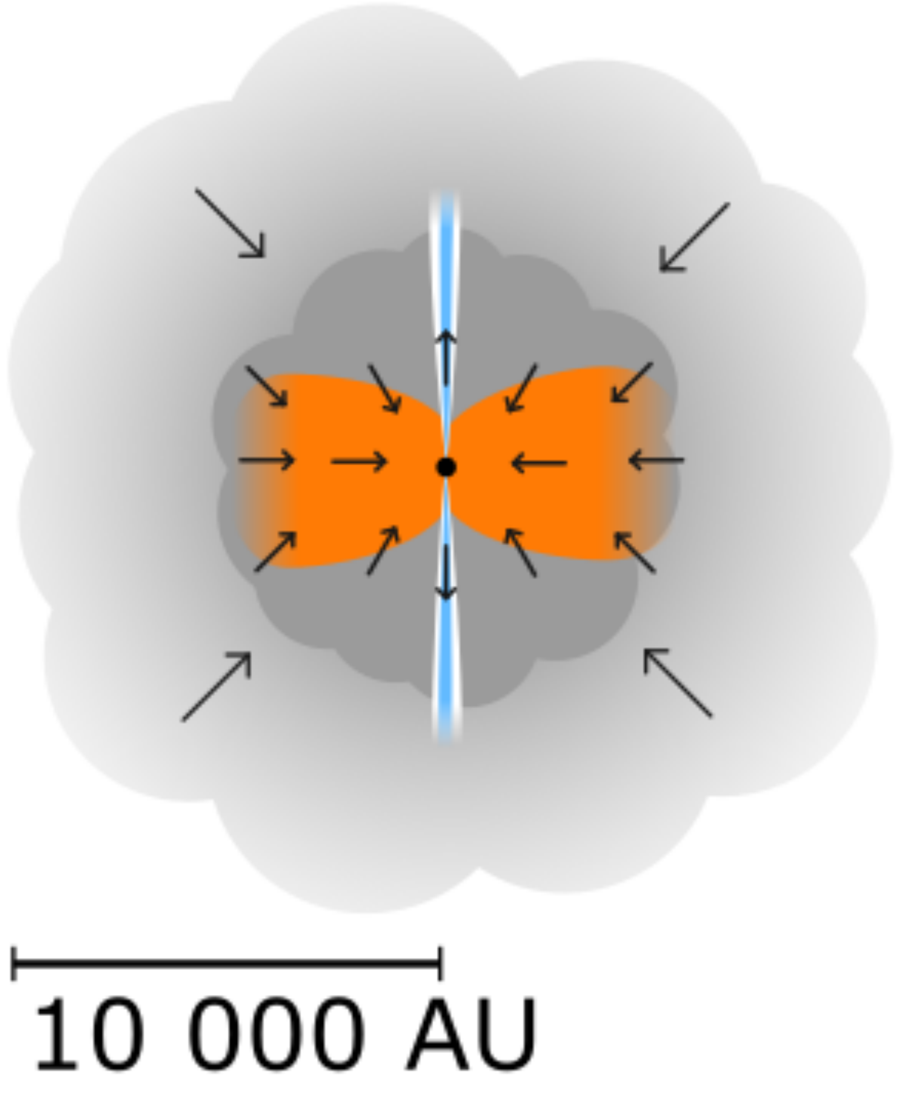
Less massive envelope w.r.t. Class 0
Presence of a disk (R disk ~ 25-500 AU)
Outflows/jets/Herbig-Haro objects
(less energetic w.r.t. Class 0)

Adapted from M. V. Persson

Protostellar phase: indicators

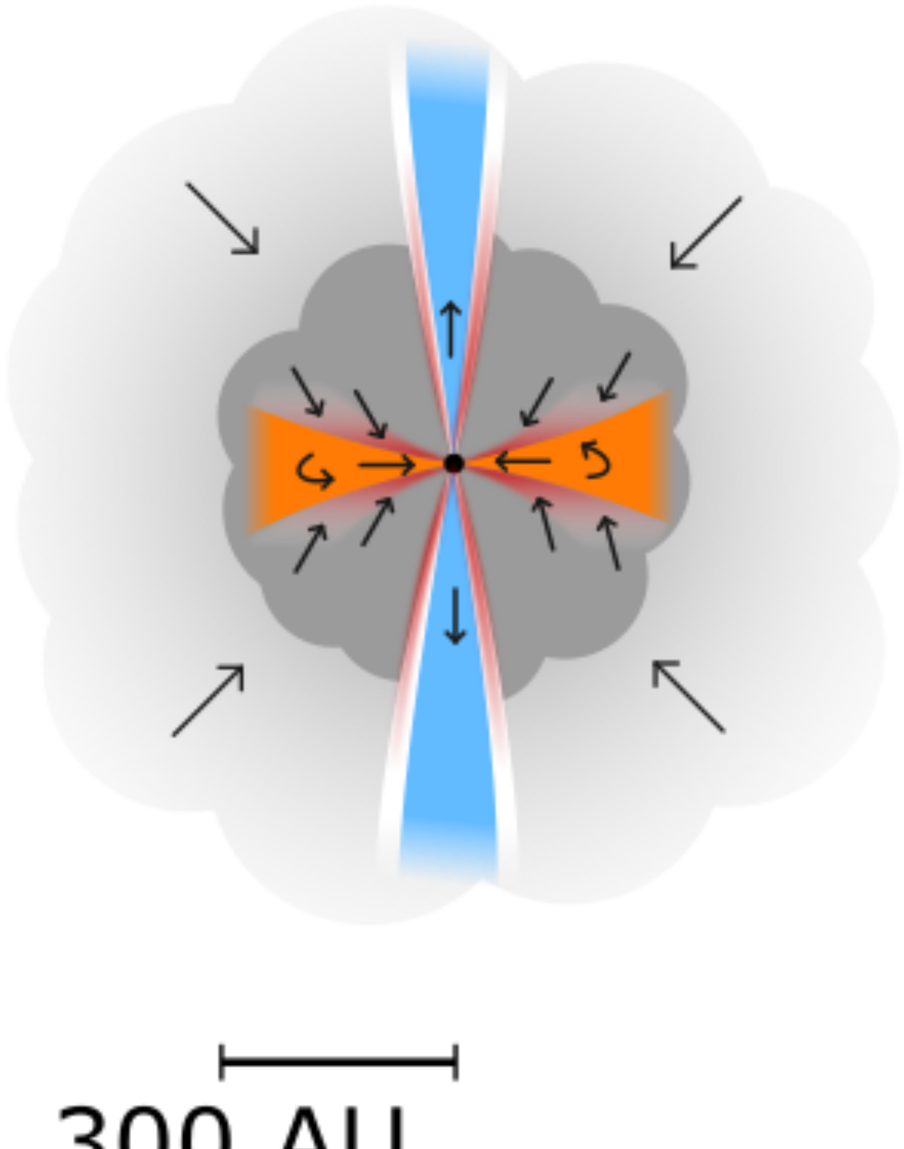
- **Infrared spectral index (α_{IR}):**

$$\frac{d \log (\lambda F_\lambda)}{d \log (\lambda)} \quad \text{where } 2.2 < \lambda < 20\ \mu m$$

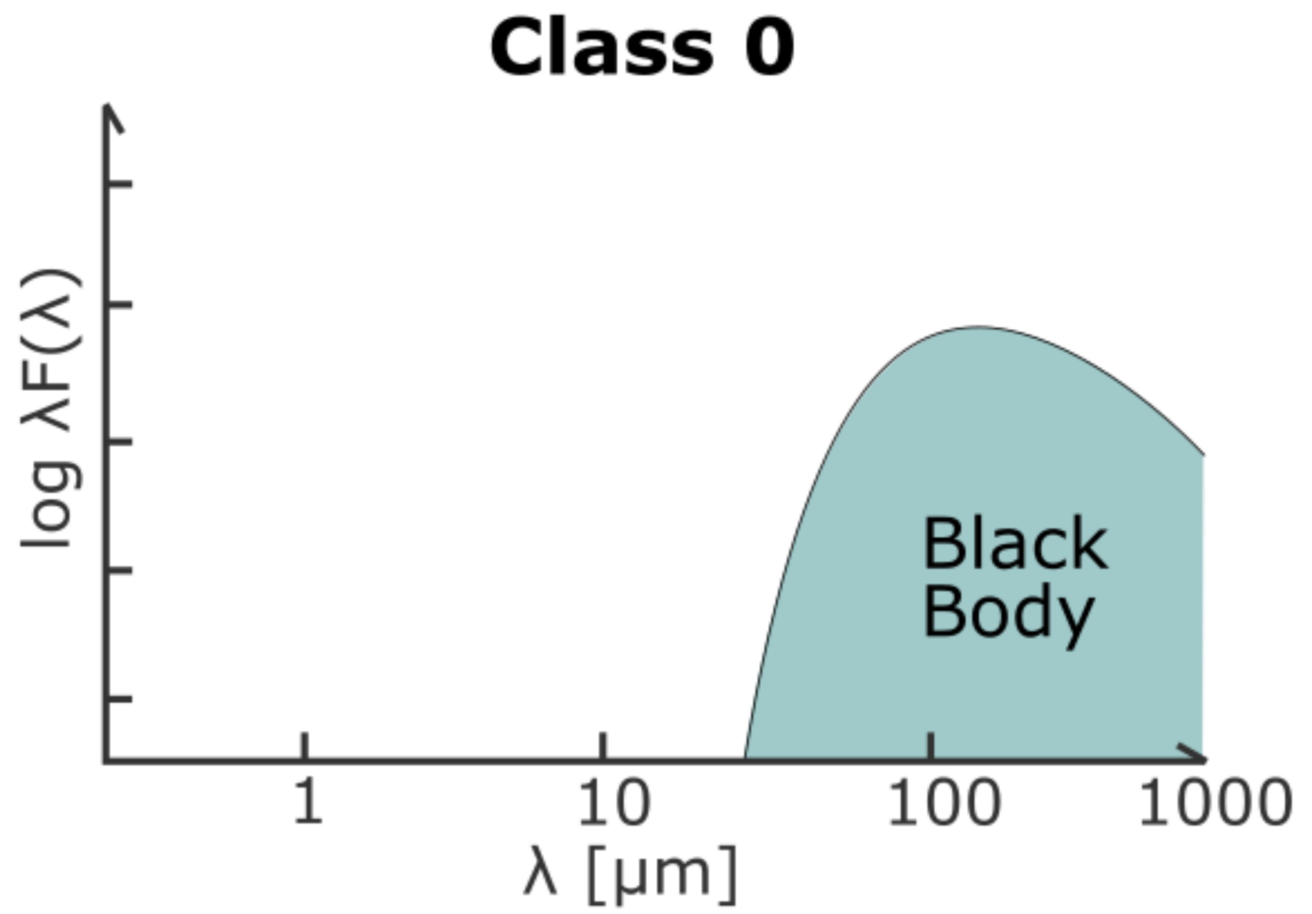


- **Bolometric temperature (T_{bol}) :**
temperature of a black body with the same mean frequency as the observed continuum spectrum

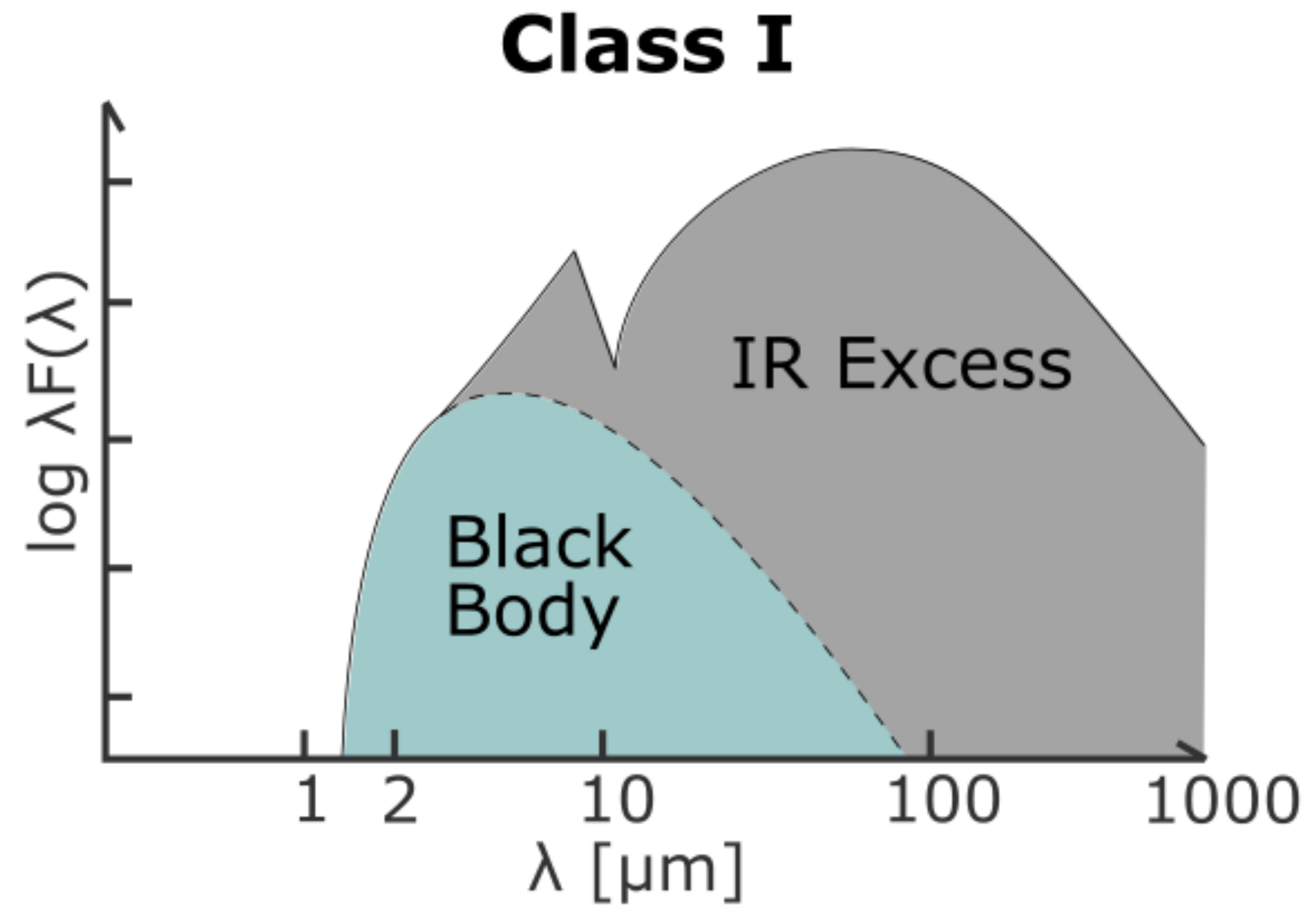
- **Ratio between L_{submm} and L_{bol} :**
introduced to discriminate between Class 0 and Class I
($\lambda_{submm} \geq 350\ \mu m$)



- **Class 0**



- **Class I**



Lada 1987, Myers and Ladd 1993, Dunham et al. 2014

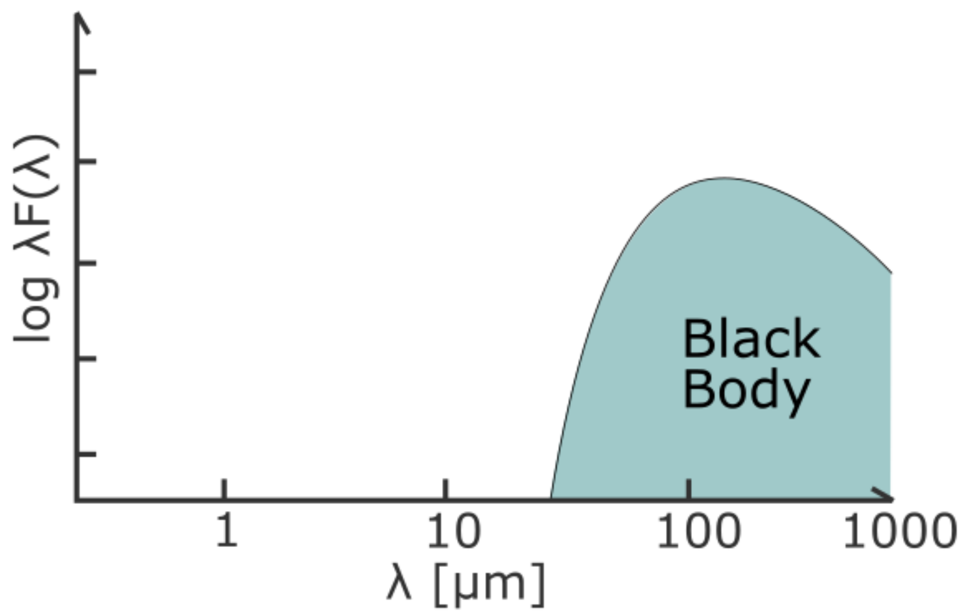
Protostellar phase:

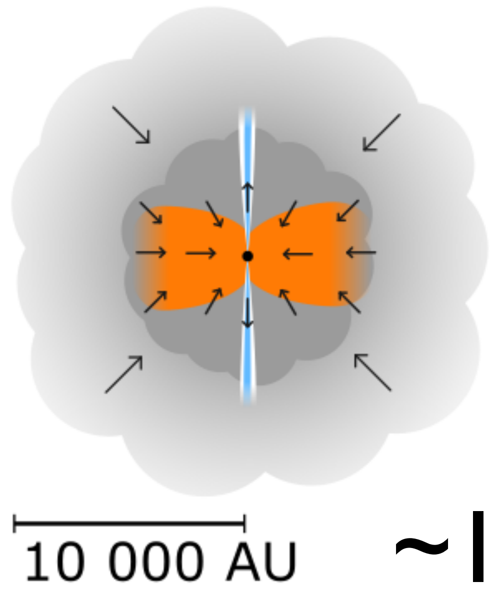
Evolutionary stages of
Young Stellar Objects (YSOs)

Spectral energy distributions (SEDs)

Class	SED slope (α_{IR})	Bolometric temperature (T_{bol})	Luminosity ratio (L_{submm}/L_{bol})
0	-	$T_{bol} \leq 70$ K	> 0.5 %
I	$\alpha_{IR} > 0.3$	70 K < $T_{bol} \leq 650$ K	< 0.5 %
II	-1.6 < α_{IR} < -0.3	650 K < $T_{bol} \leq 2800$ K	-
III	$\alpha_{IR} < -1.6$	$T_{bol} > 2800$ K	-

Class 0





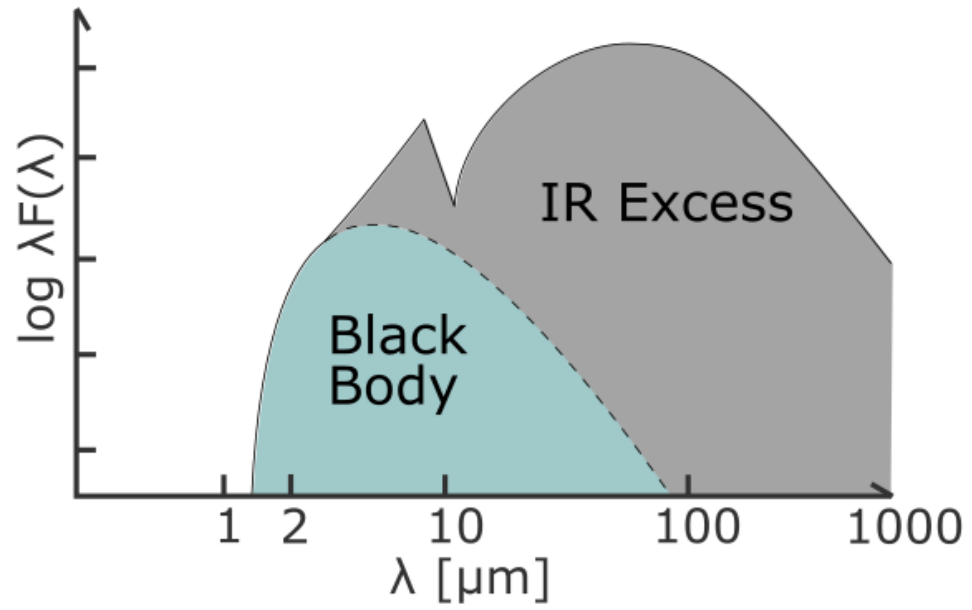
~10^4 yrs

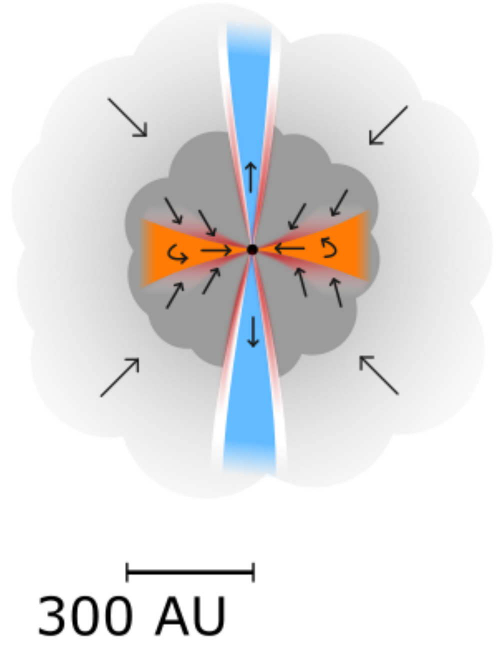
- **Young accreting protostar**

  $M_* << M_{env}$

  Lack of emission in the near-IR

Class I





~10^5 yrs

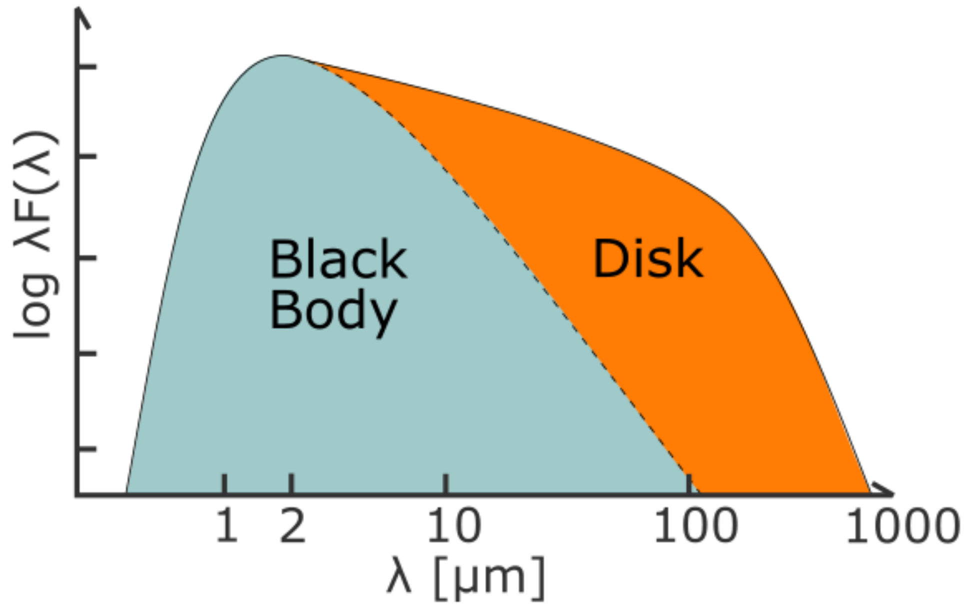
- **Evolved accreting protostar**

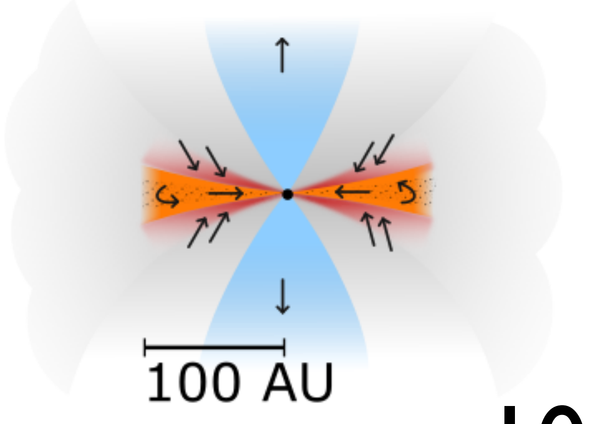
  $M_* > M_{env}$

  Emission: composite of env + disk

  9.7 μm silicate absorption band

Class II



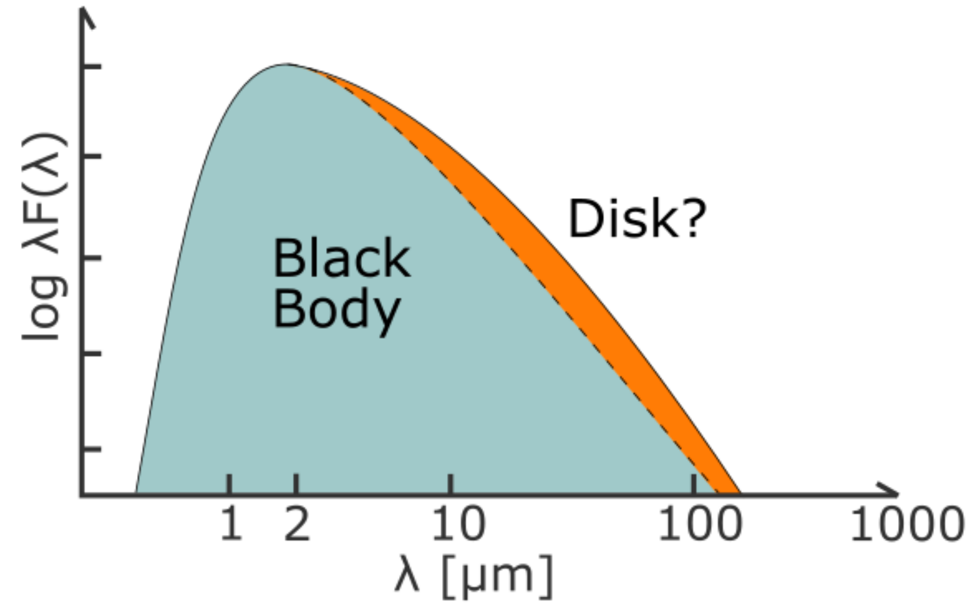


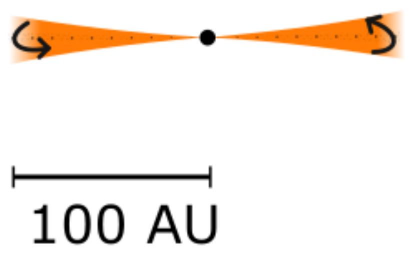
~10^6 yrs

- **Classical T Tauri star**

  $M_{disk} \sim 0.01\ M_\odot$

Class III





~10^7 yrs

- **Weak T Tauri star**

  $M_{disk} < M_{Jupiter}$

Adapted from M. Persson

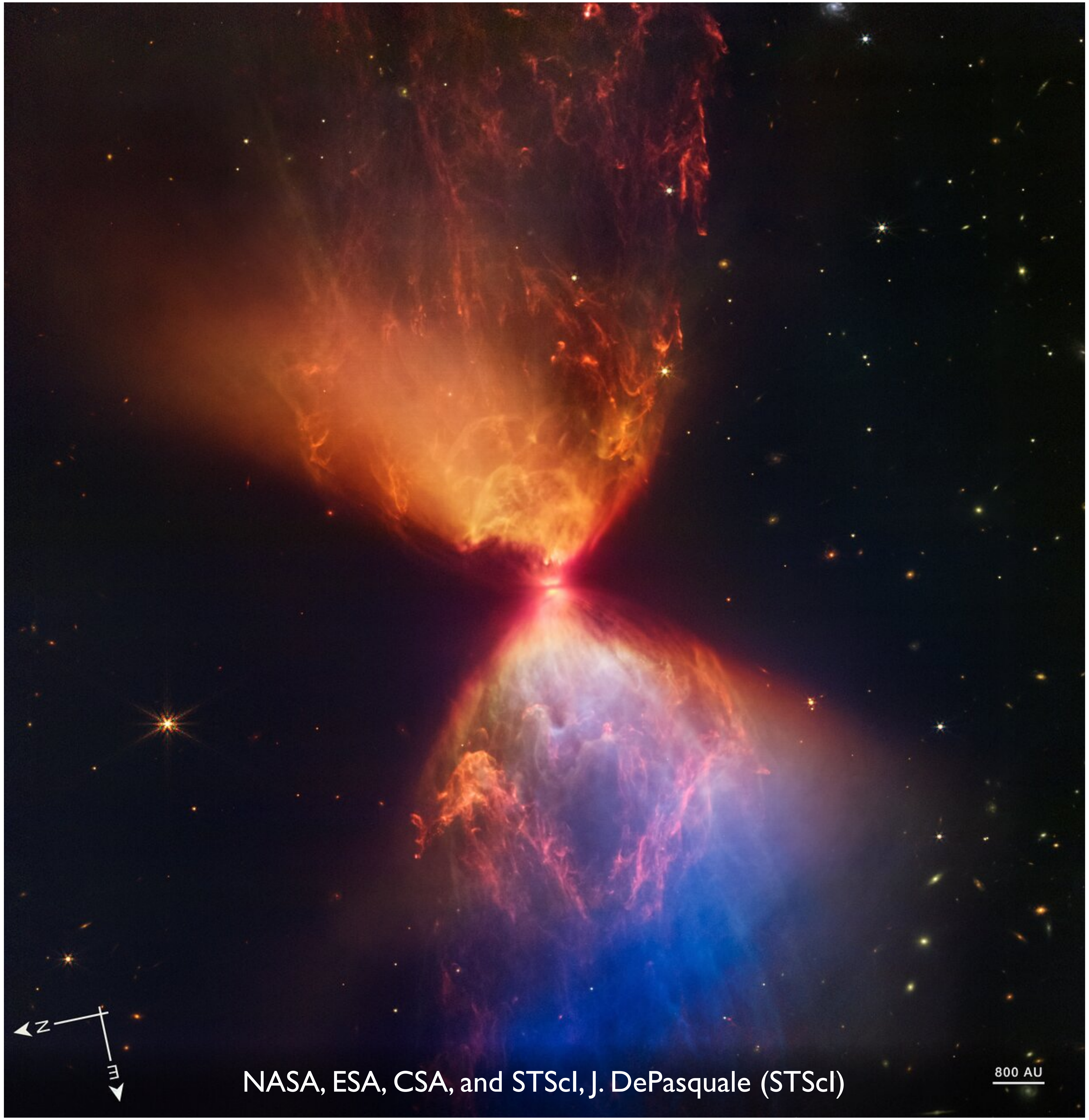
Protostellar phase:

Envelope
Disk
Outflows

Class 0/I protostar
L1527 IRS (IRAS 04365+2557)

Location: Taurus molecular cloud (d=140 pc)
i = 85°, edge-on configuration
$L_{bol} = 2.0\ L_{\odot}$
T_{bol} = 44 K

JWST NIRCam



Diversity of protostellar systems

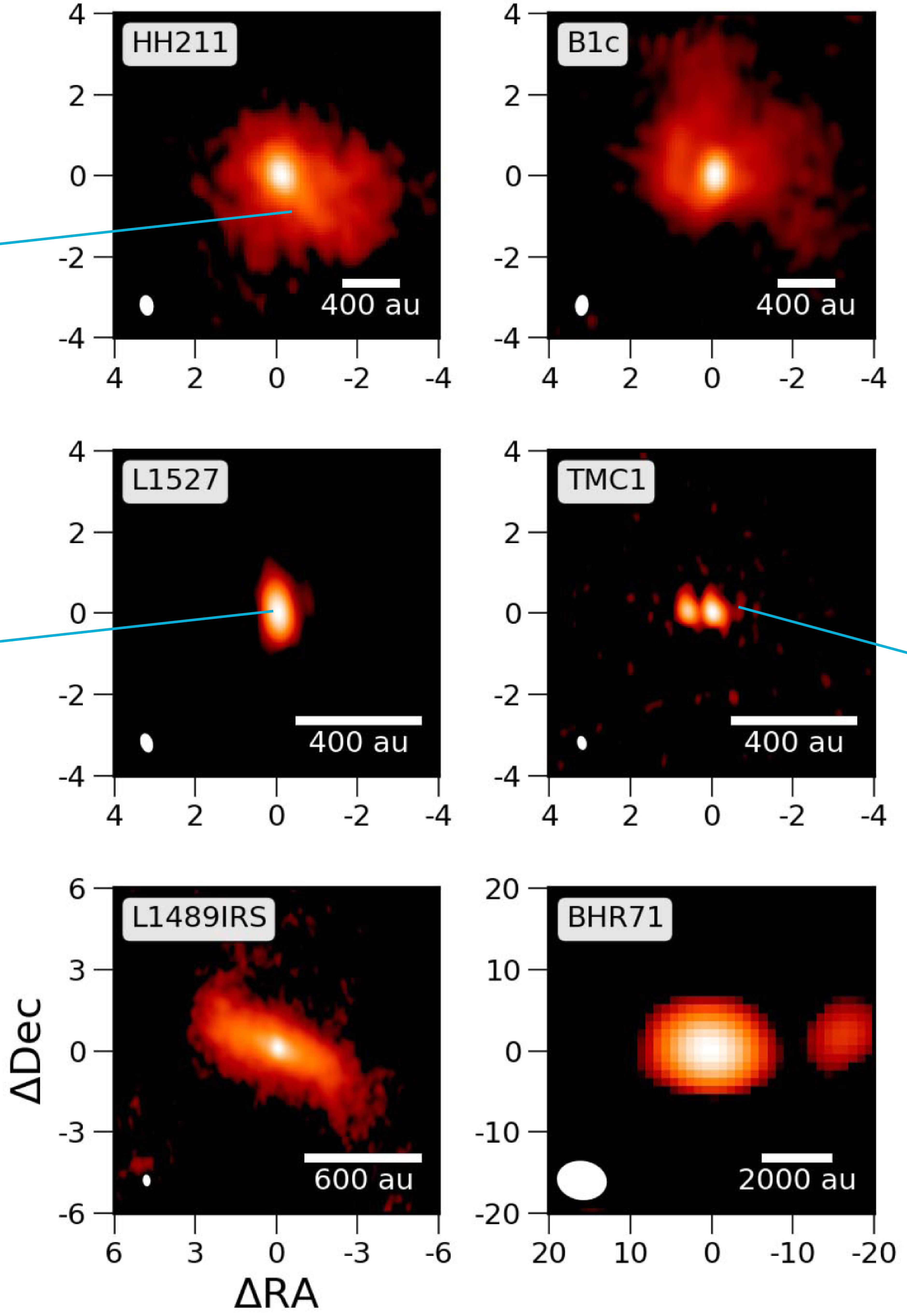
Multiplicity
They tend to form in clusters

Diverse morphology
(extended and compact sources)

Different configurations
(face-on, edge-on, misaligned disks)

Extended

Compact



Binary

Tychoniec et al. 2021

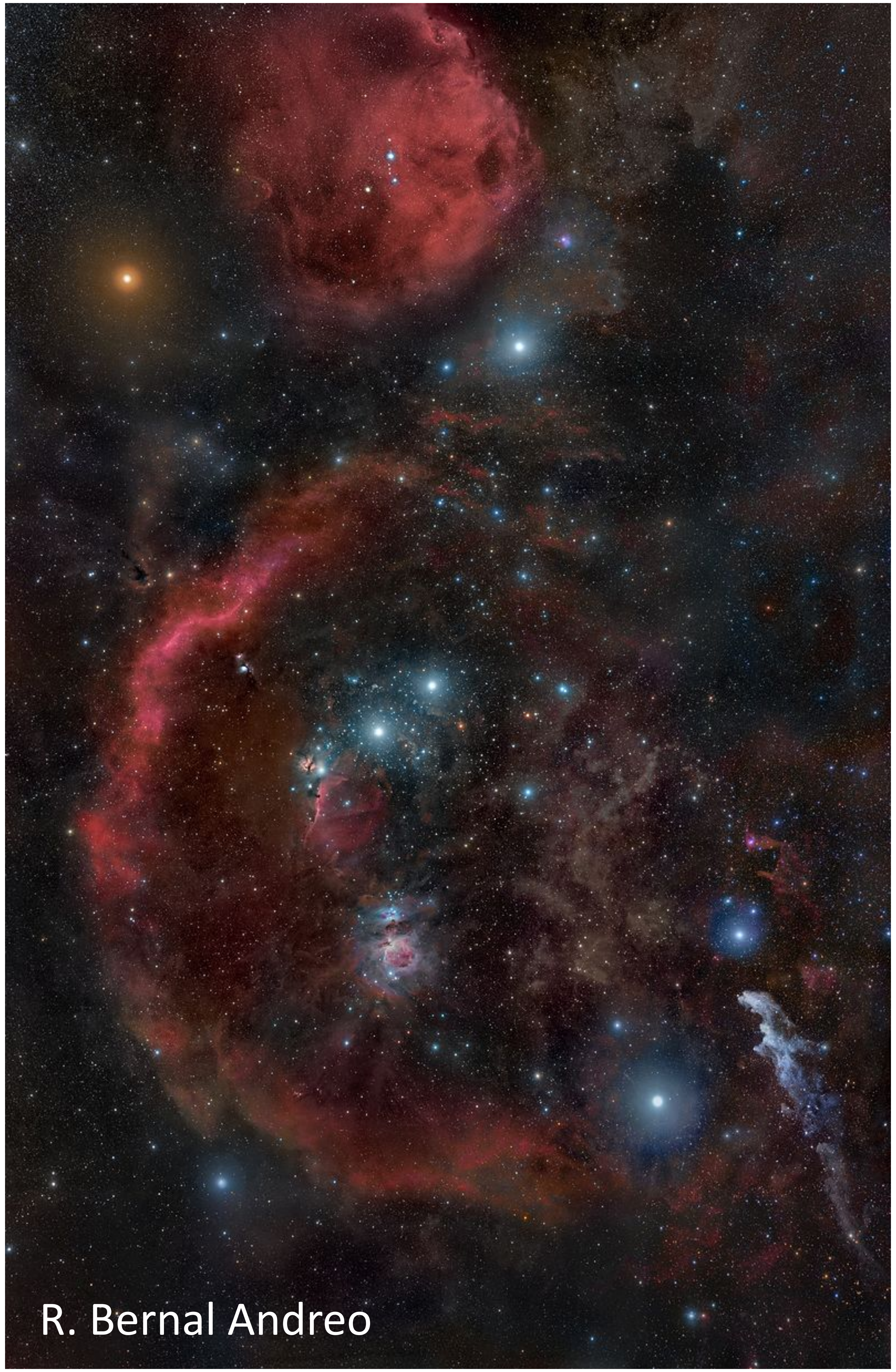
High-mass star-forming region

NASA, ESA, CSA and STScI


NASA, ESA, CSA, and STScI, J. DePasquale (STScI)

Why are high-mass stars important ?

- High-mass stars = stars with masses > 8 $M_\odot$
- Few compared to low-mass stars but much more luminous
- They tend to form in clusters and associations
- Their "feedback" shape the interstellar medium
  (radiation, outflows, winds, supernovae)
- They regulate galaxy evolution (heavy metal production, star bursts)
- They trigger the formation of low-mass stars



Why high-mass star formation is not well constrained ?

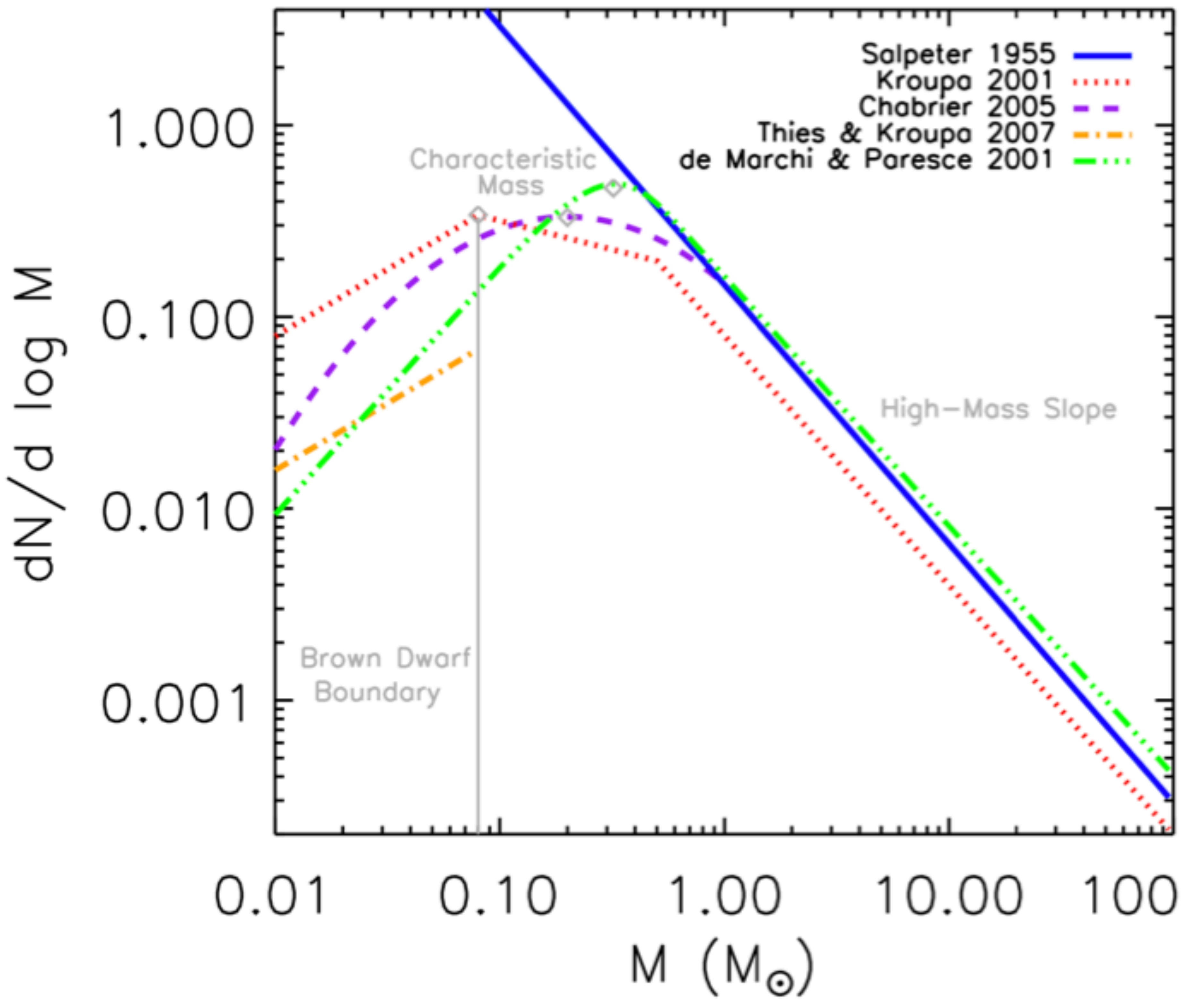
- Few compared to low-mass stars

[There are ~100 1.0 $M_\odot$ star for each 30 $M_\odot$ star and 1$M_\odot$ stars live 1000 times longer]

- Short lives

- Not observable in the pre-main sequence phase

- They tend to form in clusters



All of the above makes it extreme challenging to observe high-mass star formation

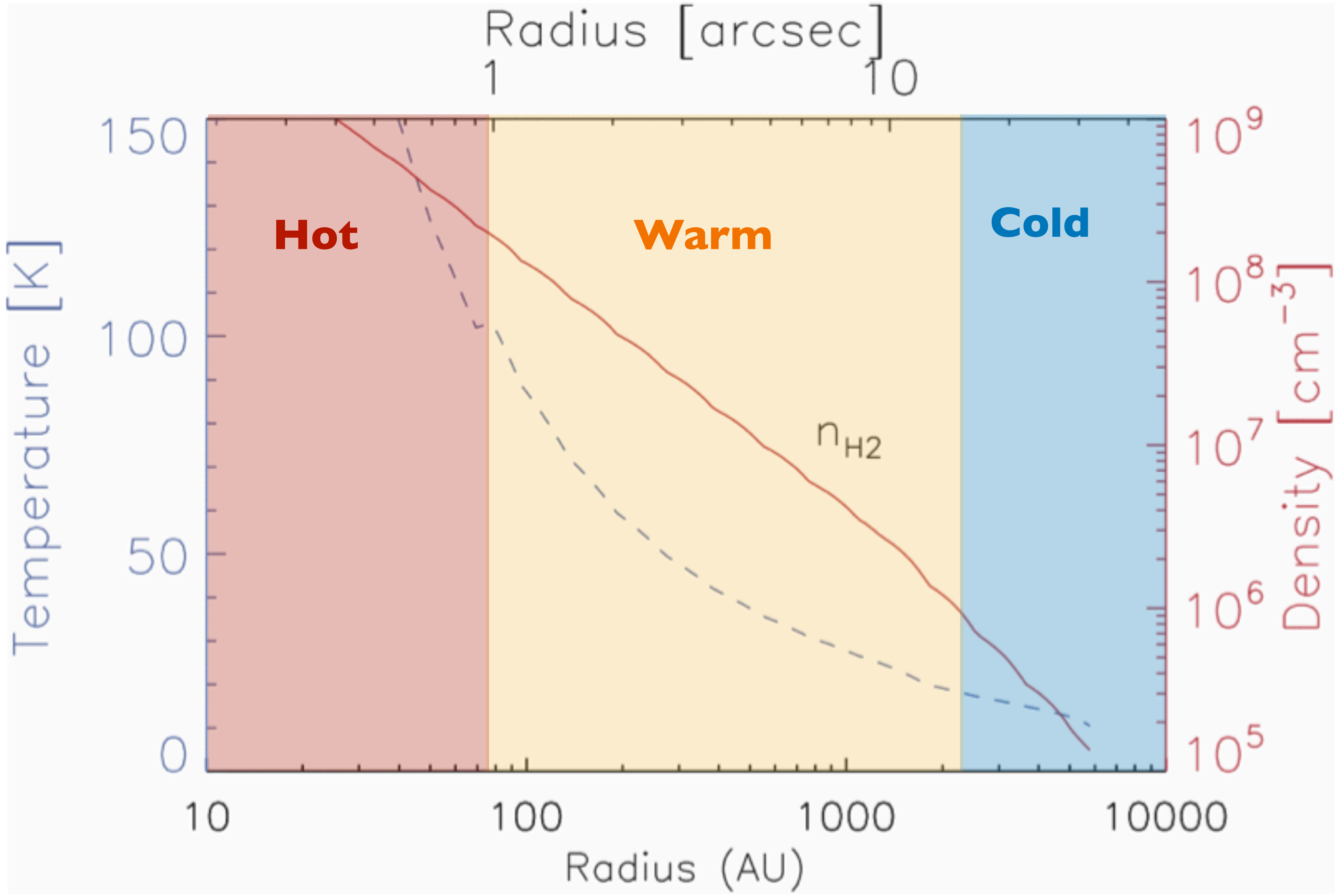
Offner et al. 2014

Outline

- Physical structure
- **Chemical structure**
- Observations of molecules in protostellar envelopes
- New era of discoveries with JWST

Physical and chemical structure of a typical Solar-type Class 0/I protostar

It can be roughly divided into three zones, which are defined by the status of the grain icy mantles formed during the pre-stellar phase.

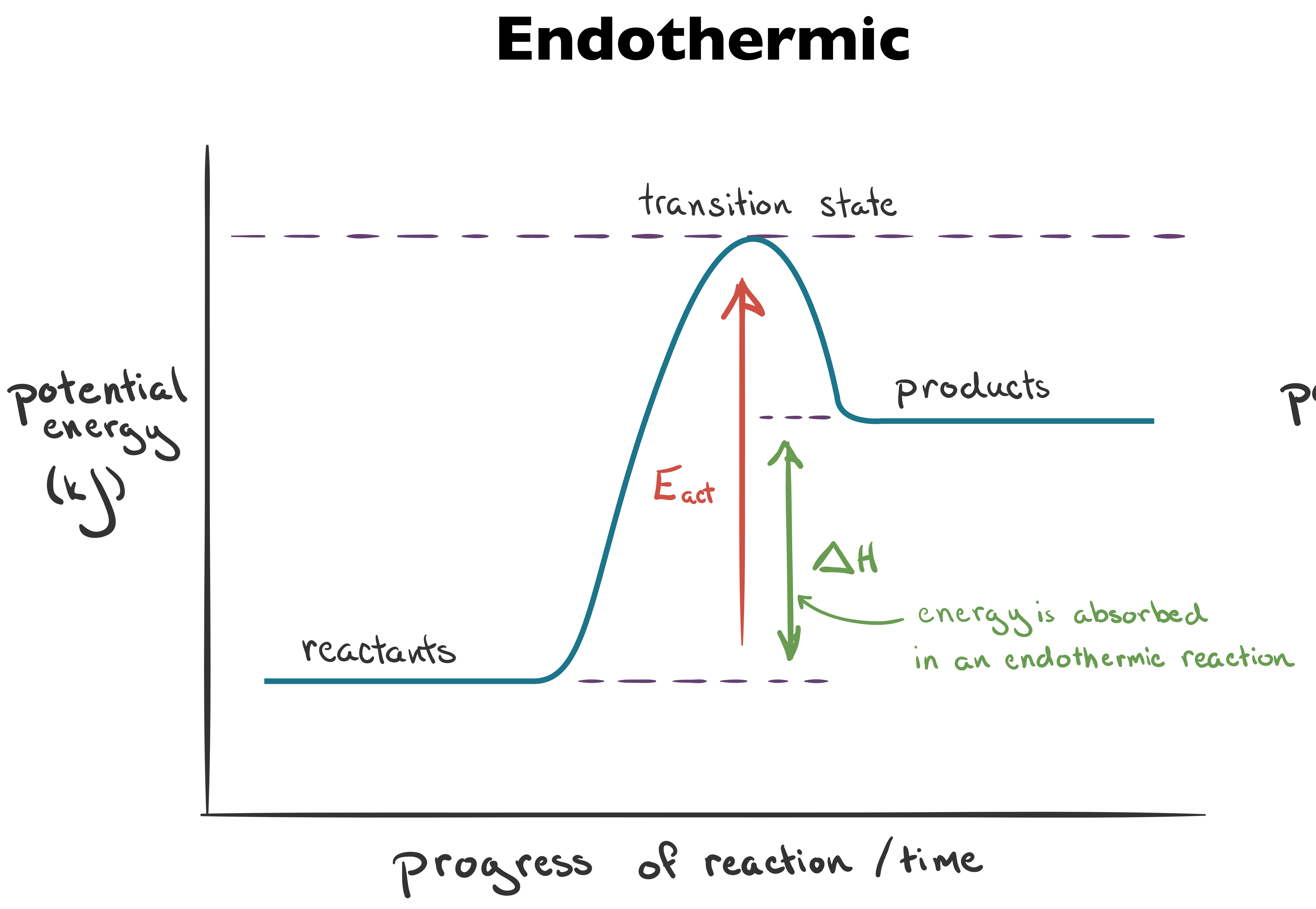


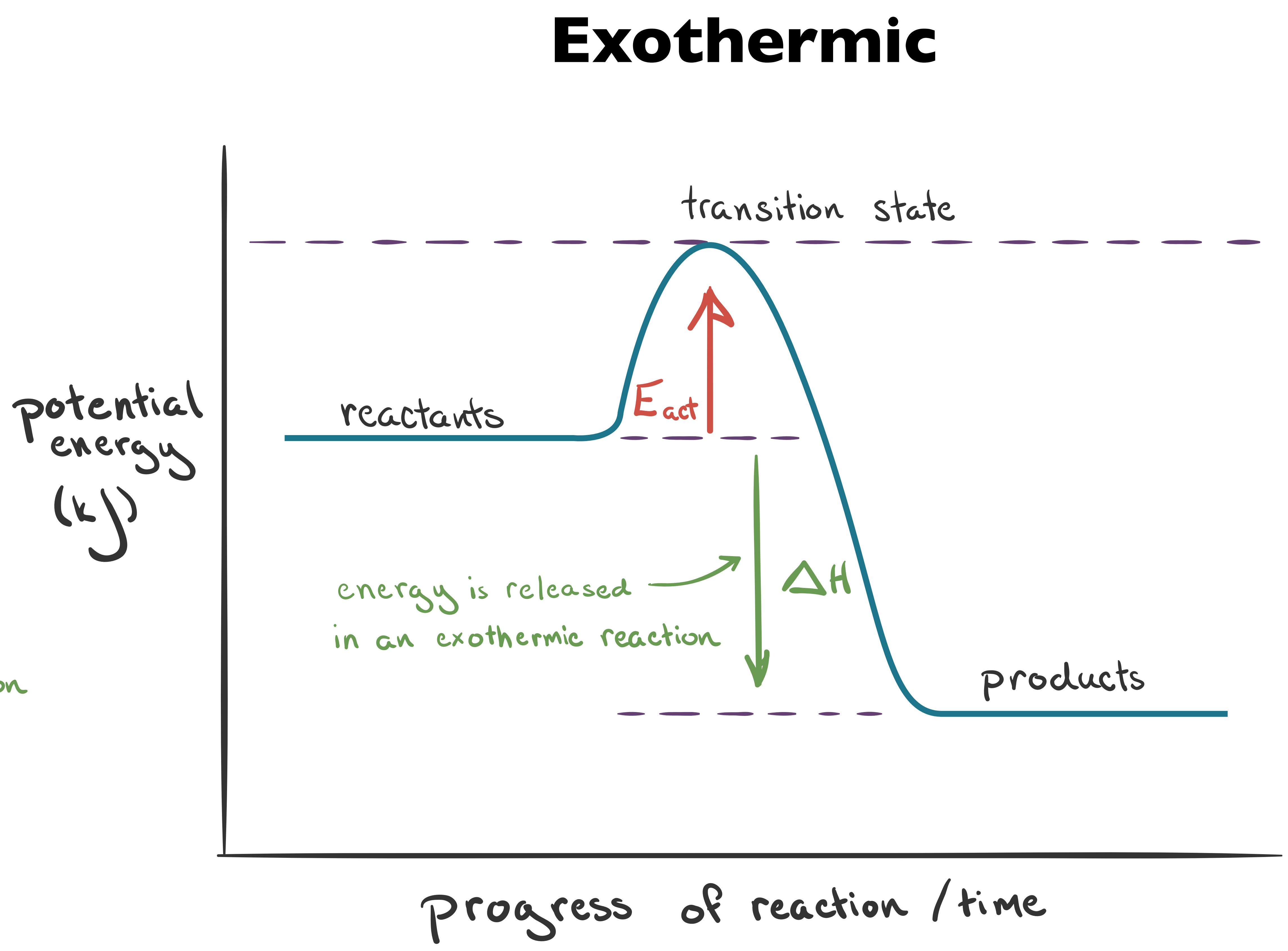
Cold envelope: the dust temperature (T_{dust}) is lower than the sublimation of CO-rich ices (~ 22 K);

Warm envelope: it is the intermediate, lukewarm envelope region.

Hot envelope (or hot-corino) : T_{dust} is higher than the sublimation temperature of H_2O-rich ices (~100 K);

Recap: Endothermic vs exothermic reactions

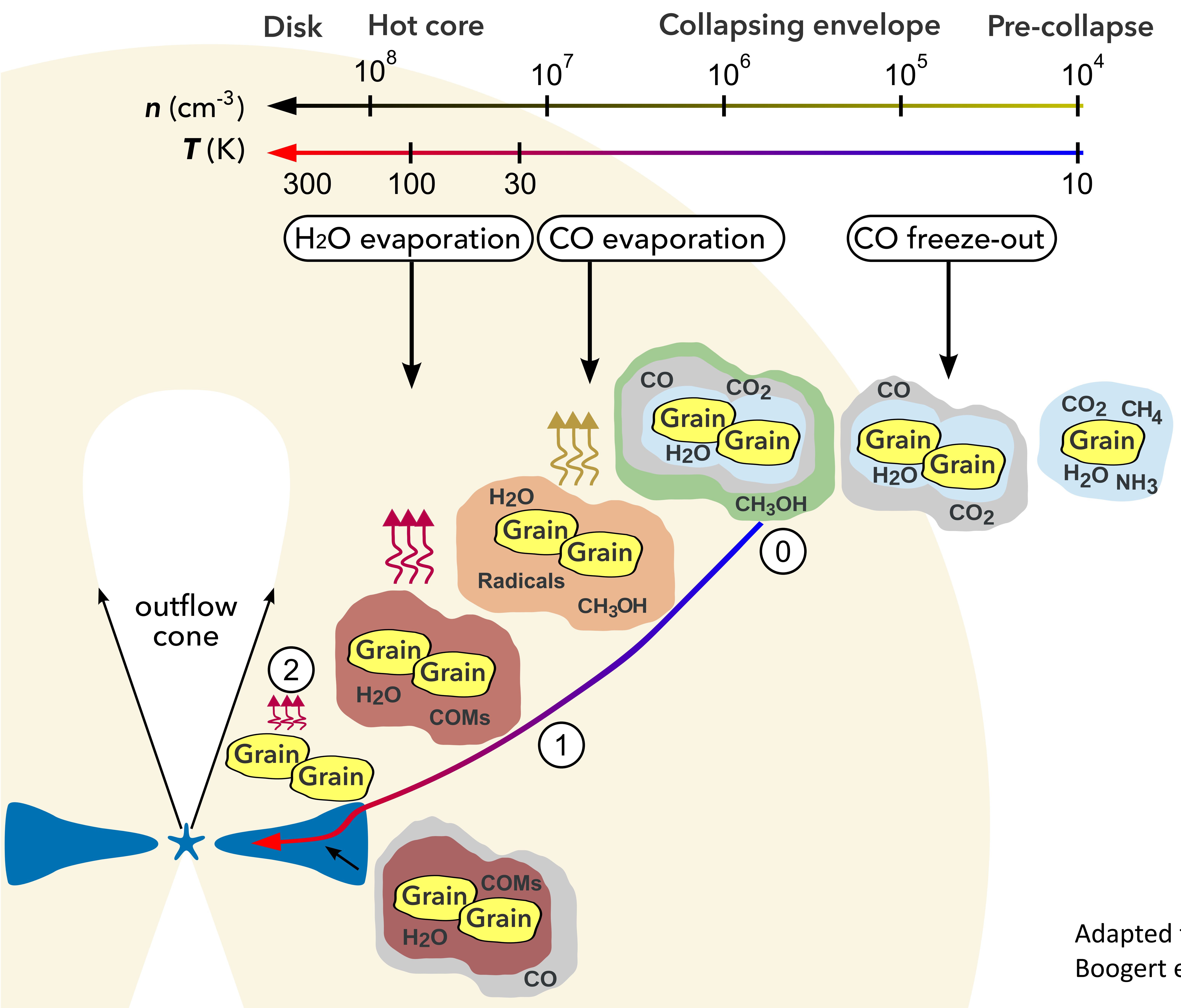




Cold envelope & Warm envelope

Hot envelope (or hot-corino)

Chemical evolution during low-mass star formation



Adapted from Herbst & van Dishoeck 2009, Boogert et al. 2015

Chemical evolution during low-mass star formation

Cold envelope (*T* <22 K, *n* ~10^4 cm^{-3})

- **0th-generation molecules**
  e.g., H_2O, CO_2, CH_3OH, CH_3CH_2OH

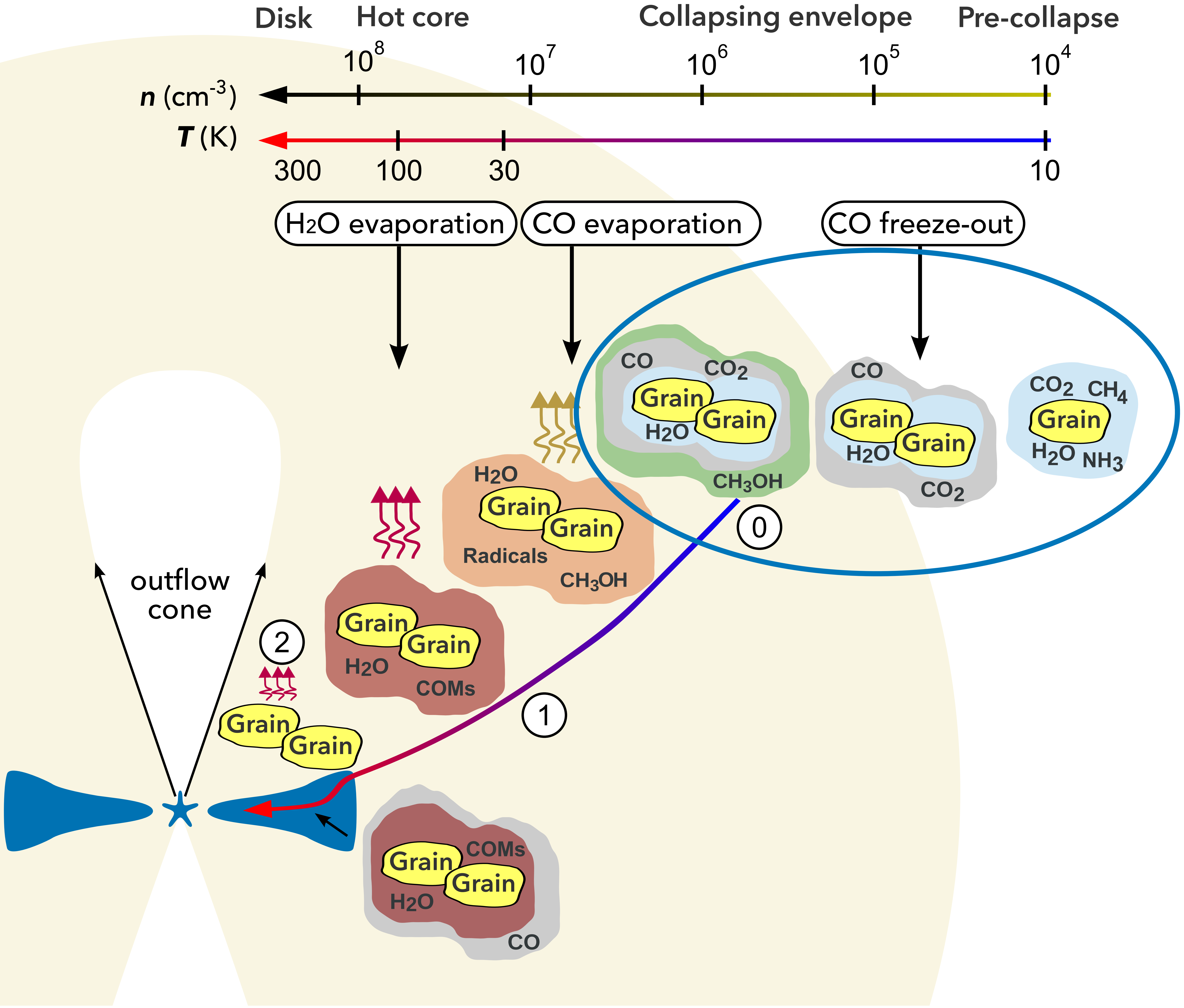
Chemical processes:

Exothermic reactions

Built up of ice layers: e.g., CO freeze-out

Atom addition/abstraction of accreted species

Non-thermal desorption



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Chemical evolution during low-mass star formation

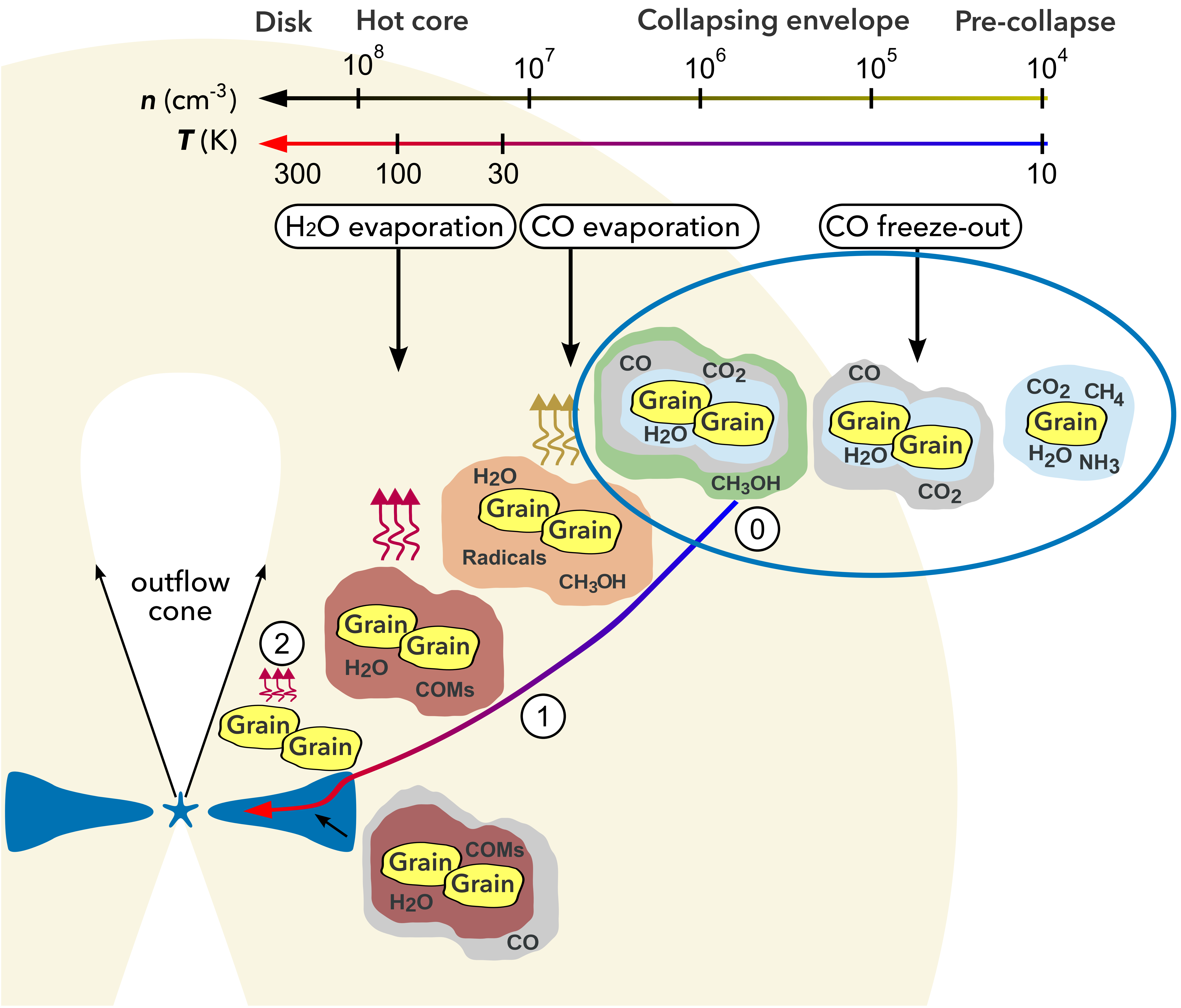
Cold envelope (*T* <22 K, *n* ~10^4 cm^{-3})

- **0^{th}-generation molecules**
  e.g., H_2O, CO_2, CH_3OH, CH_3CH_2OH

CO freeze-out

Highly dependent on T, *n*, and Av

- 'Heavy freeze-out' at $A_v > 6$ mag
- 'Catastrophic freeze-out' at $A_v > 9$ mag



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Chemical evolution during low-mass star formation

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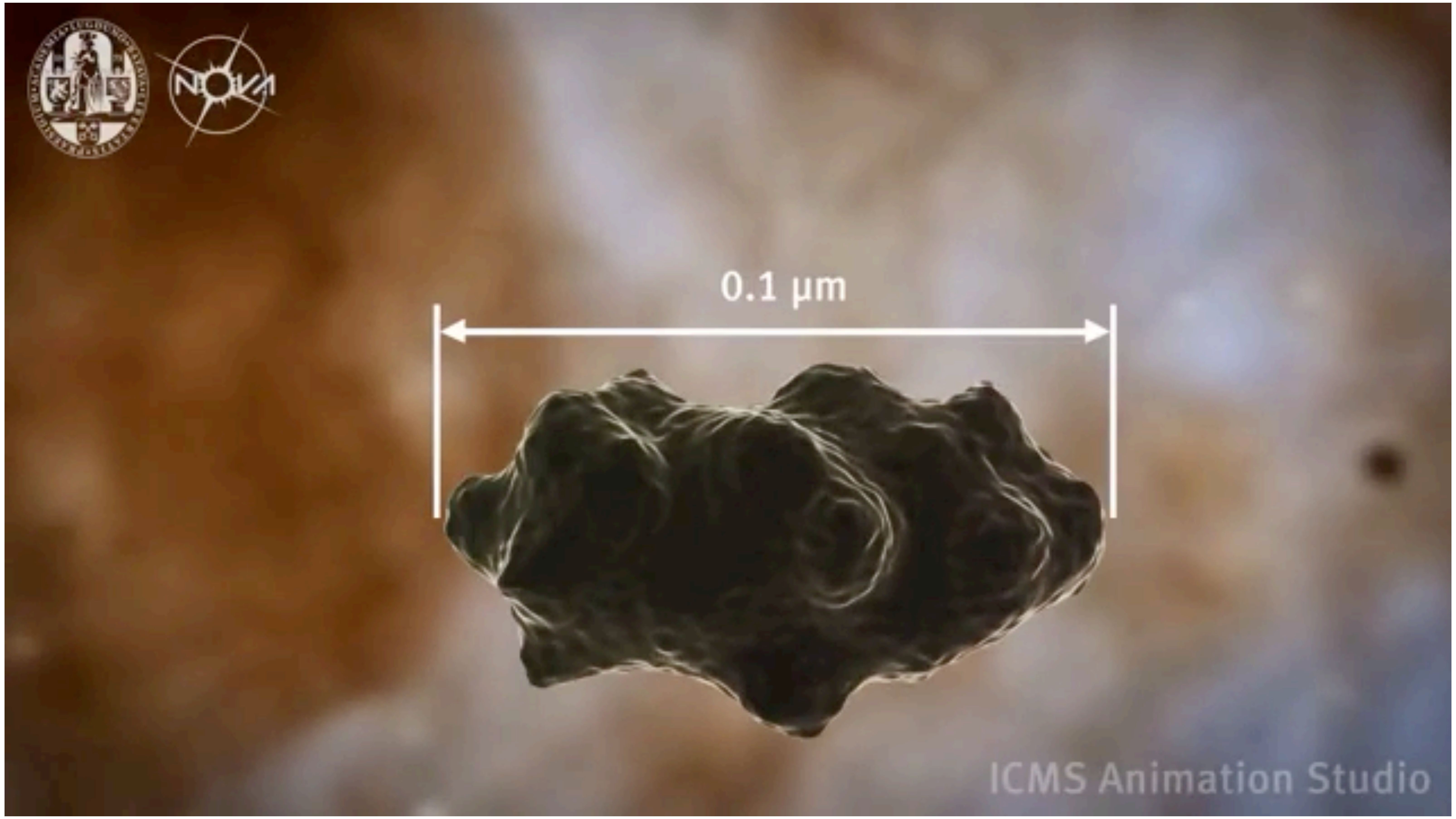


ICMS animation studio, Lamberts, van Dishoeck

Chemical evolution during low-mass star formation

Warm envelope
(T =20-100 K, *n* ~10^6 cm^{-3})

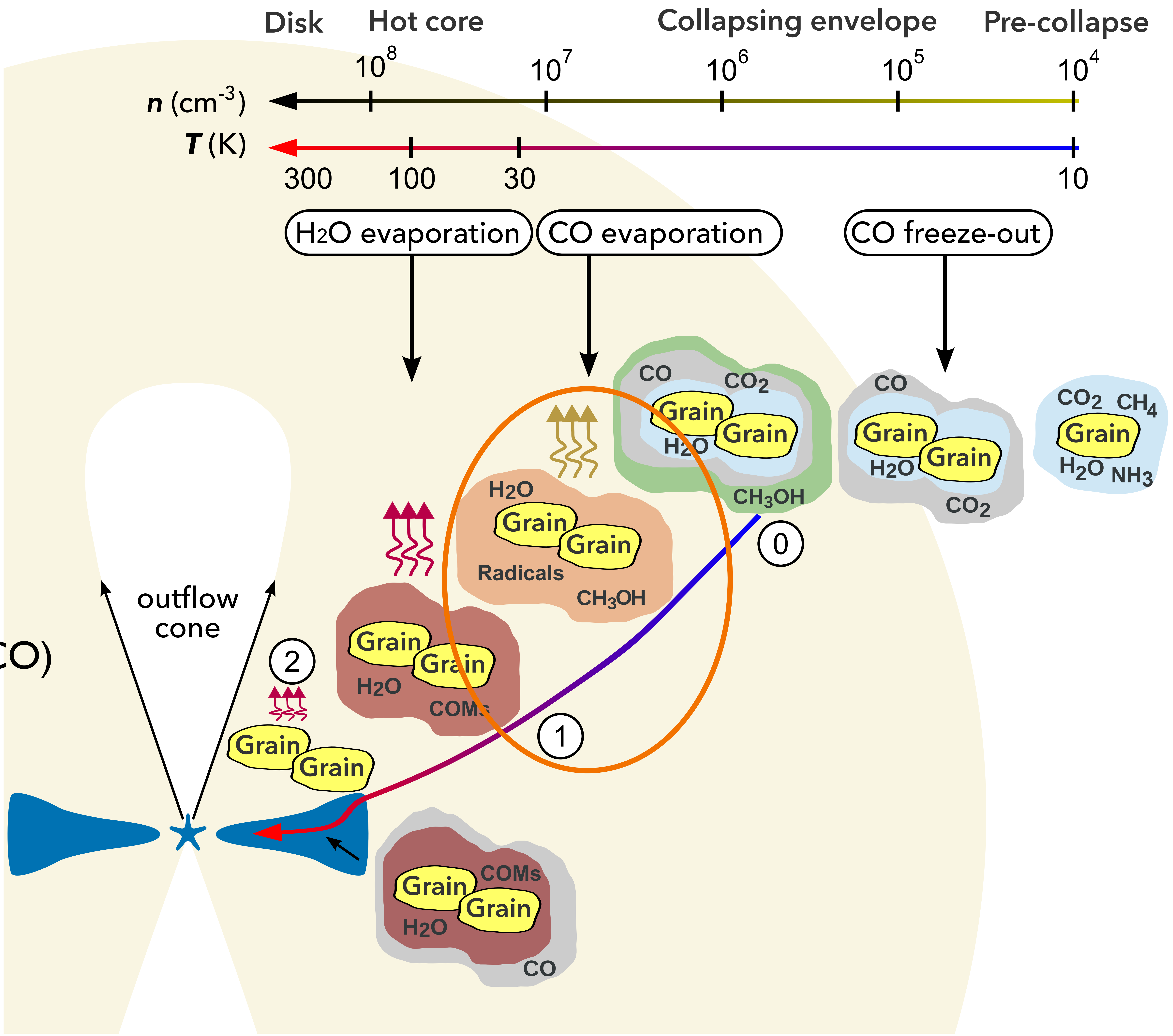
- **1^{st}-generation molecules**
  e.g, saturated species such as HCOOH, CH_3CH_2OH

Chemical processes:

Thermal desorption of volatile species (e.g., CO)

Photochemistry: radical production

Surface reactions: radical-radical addition



Adapted from Herbst & van Dishoeck 2009, Boogert et al. 2015

Chemical evolution during low-mass star formation

Hot-corino (T > 100 K, *n* ~10^8 cm^{-3})

Hot corino: innermost envelope region (R < 200 AU)

- **2nd-generation molecules**
  e.g, NH_2CHO, $HOCH_2CH_2OH$, COMs

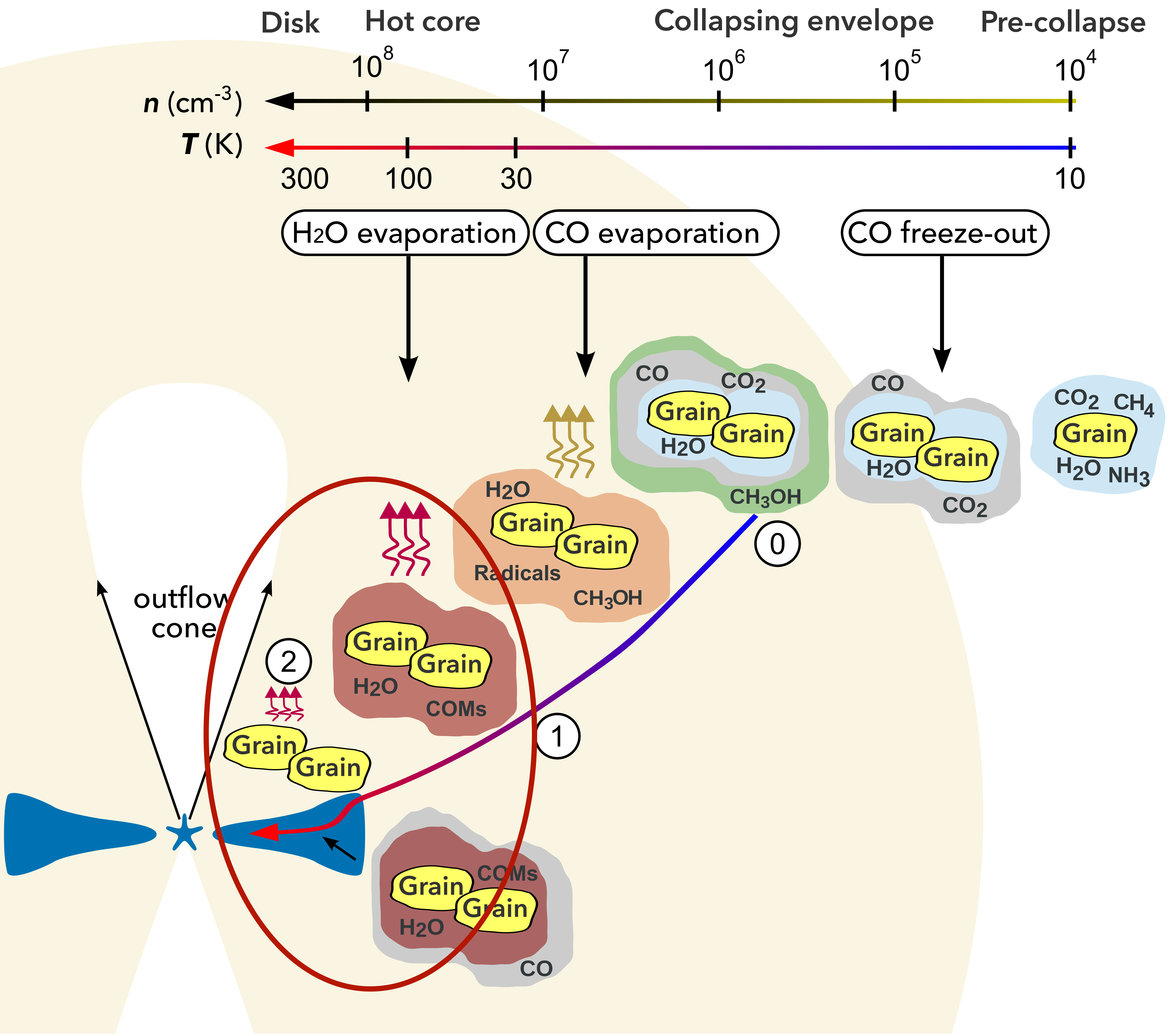
Chemical processes:

Gas-phase dominated chemistry: endothermic reactions possible !

Thermal desorption

Ion-molecule and neutral-neutral reactions

Photodissociation



Adapted from Herbst & van Dishoeck 2009, Boogert et al. 2015

Chemical evolution during low-mass star formation

Hot-corino phase (T > 100 K, *n* ~10^8 cm^{-3})

Hot corino: innermost envelope region (R < 200 AU)

Complex Organic Molecules (COMs) = molecules with at least 6 atoms
COMs are also referred to as interstellar COMs (iCOMs)

- **2nd-generation molecules**
  e.g, NH_2CHO, $HOCH_2CH_2OH$, COMs

ICMS animation studio, Lamberts, van Dishoeck

Recap

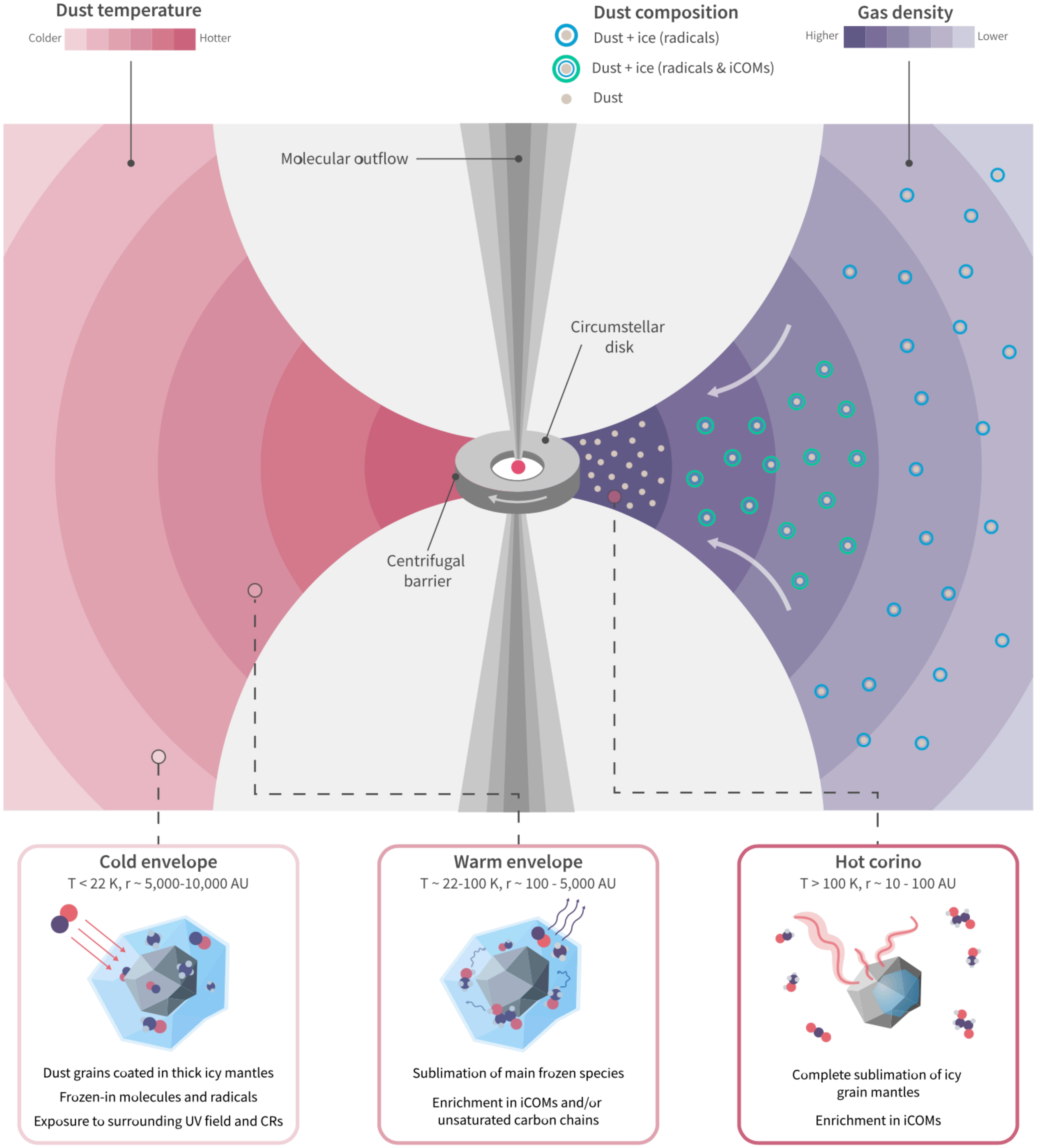
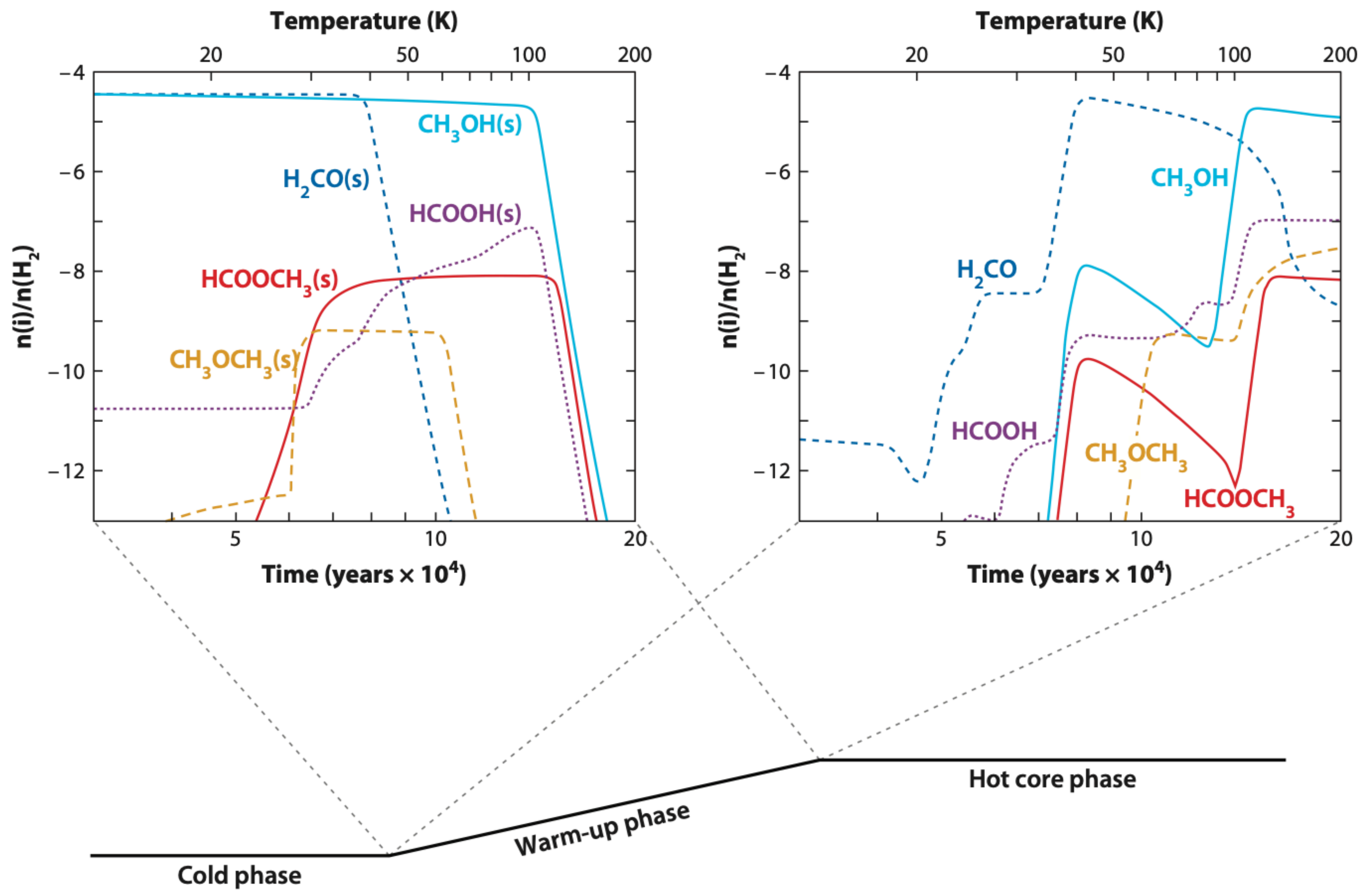


Image credit: Houge, A.

Astrochemical modelling

Categories of models



- Hot-corino phase model:

  only 2nd generation molecules are considered

- Cold and hot-corino phase model:

  only 0th and 2nd generation molecules are considered

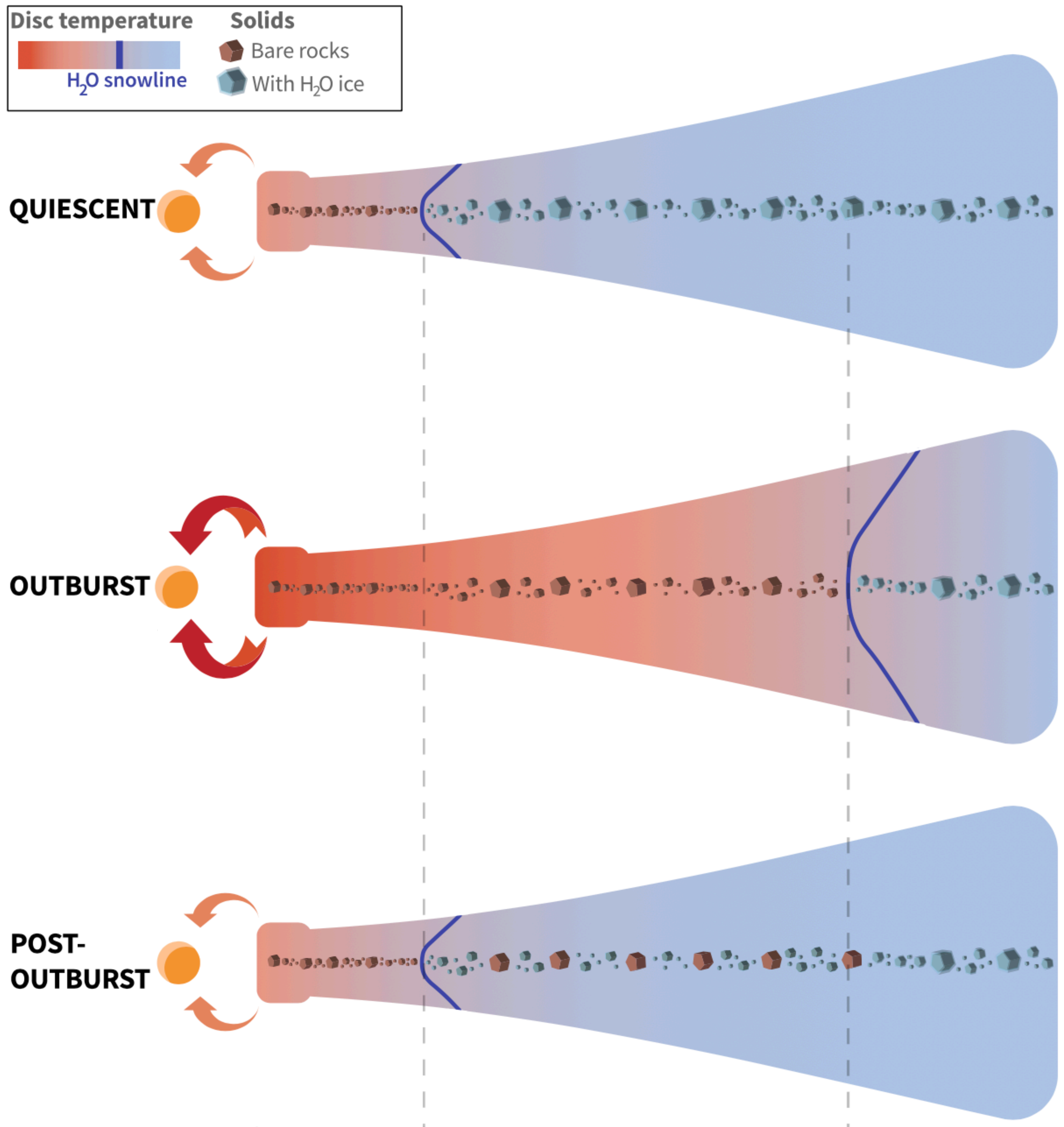
- Cold and warm-up phase model:

  only 0th and 1st generation molecules are considered

- All-phase model

Garrod & Herbst 2006

Changes in chemical signatures of protostellar envelopes during accretion bursts



Water snowline = location at which the temperature is ~150 K and water ice sublimates.

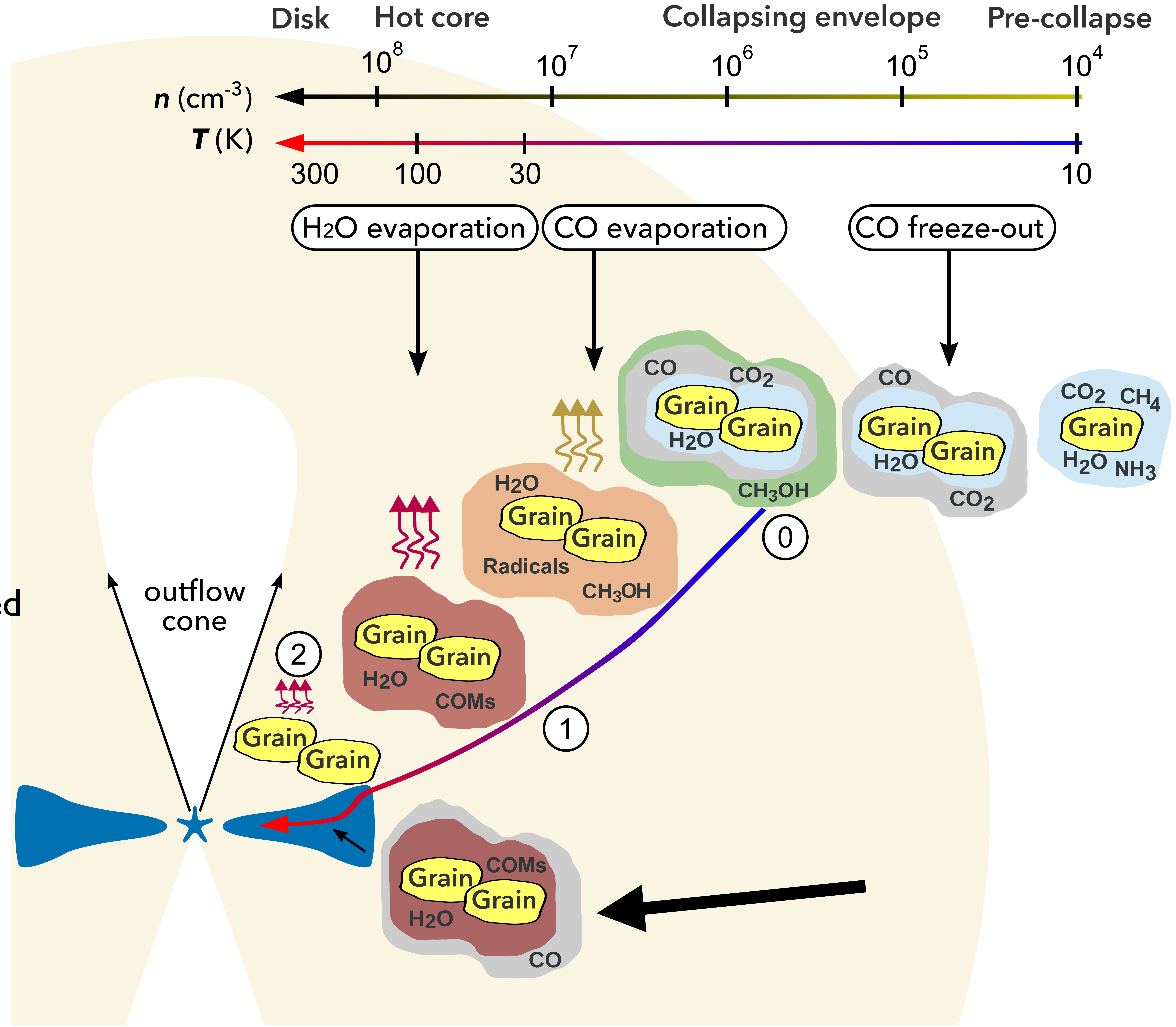
During the burst the luminosity
(and temperature) of the protostar increases
the water snowline is shifted to larger radii where
the sublimation of water ice occurs instantaneously.

Image credit: Houge, A.

Inheritance of (pre-) protostellar material vs reset

A fraction of molecules in the hot-corino is inevitably photodissociated however…

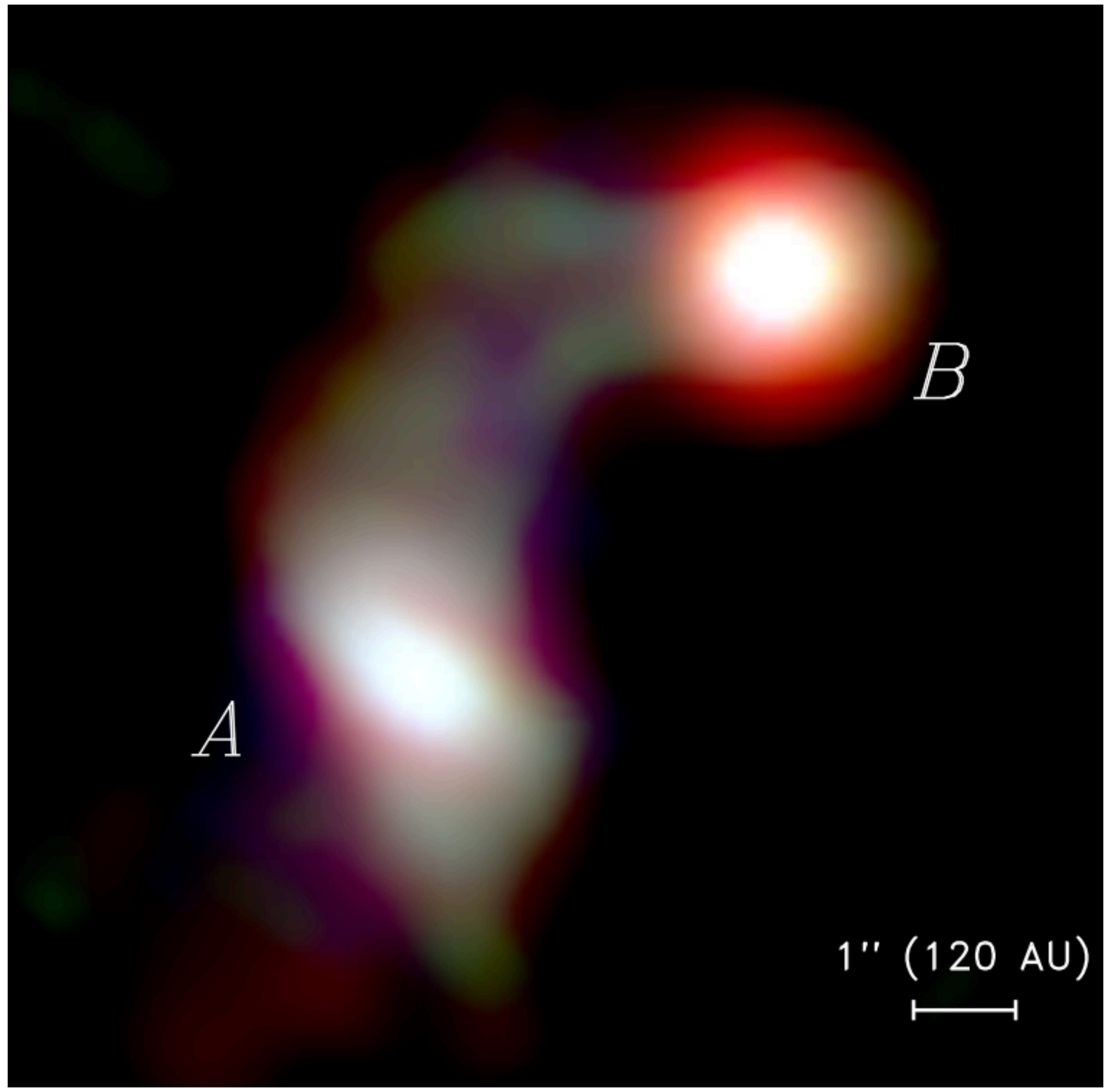
the cold envelope material may be incorporated into the disk mid-plane and thus be *inherited* to the planet and comet forming zones.



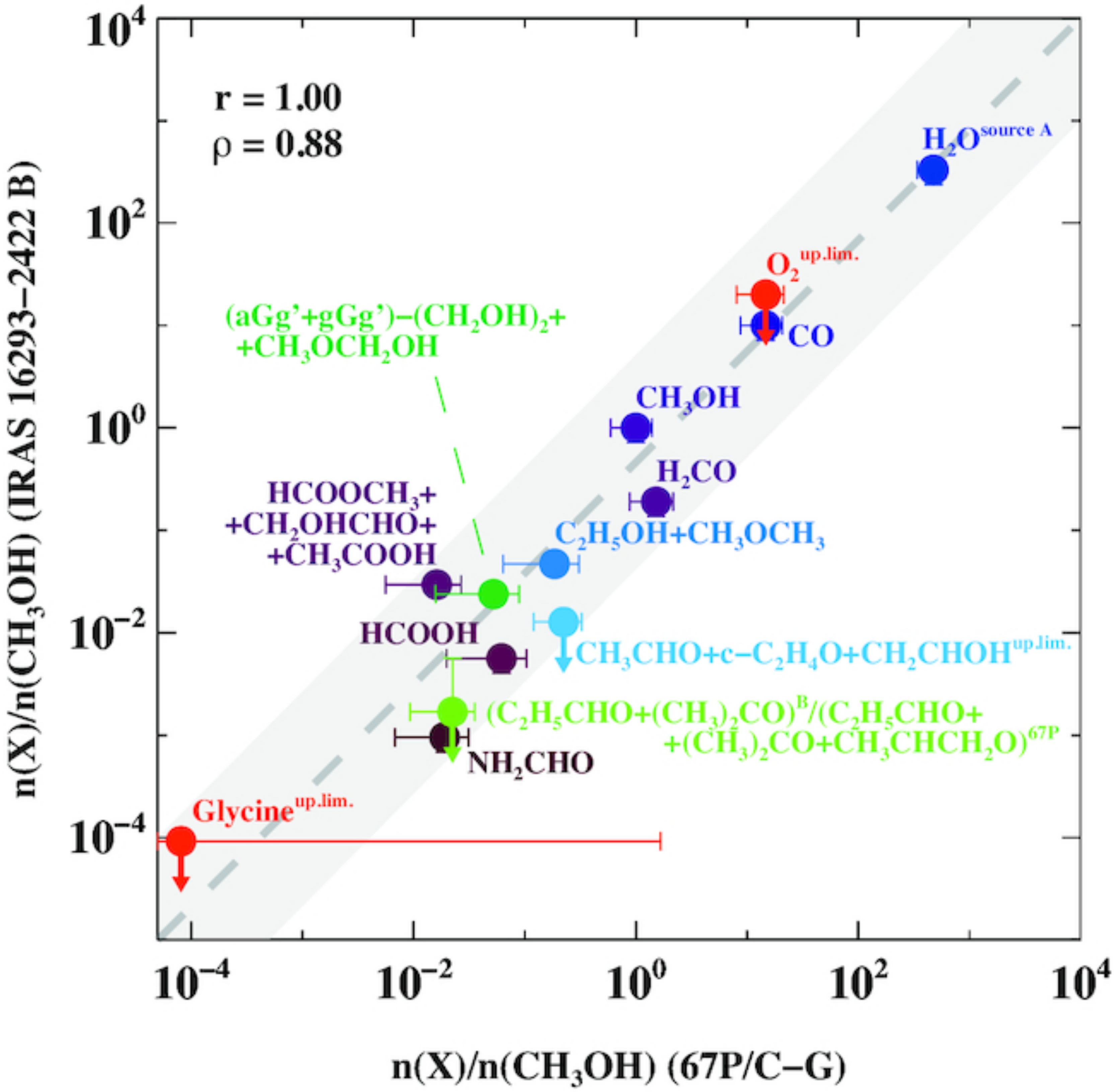
Adapted from Herbst & van Dishoeck 2009,
Boogert et al. 2015

Evidence of inheritance of protostellar material ?

Similar abundances of CHO-bearing molecules towards protostellar systems and comets



Jørgensen et al. 2016



Drozdovskaya et al. 2019

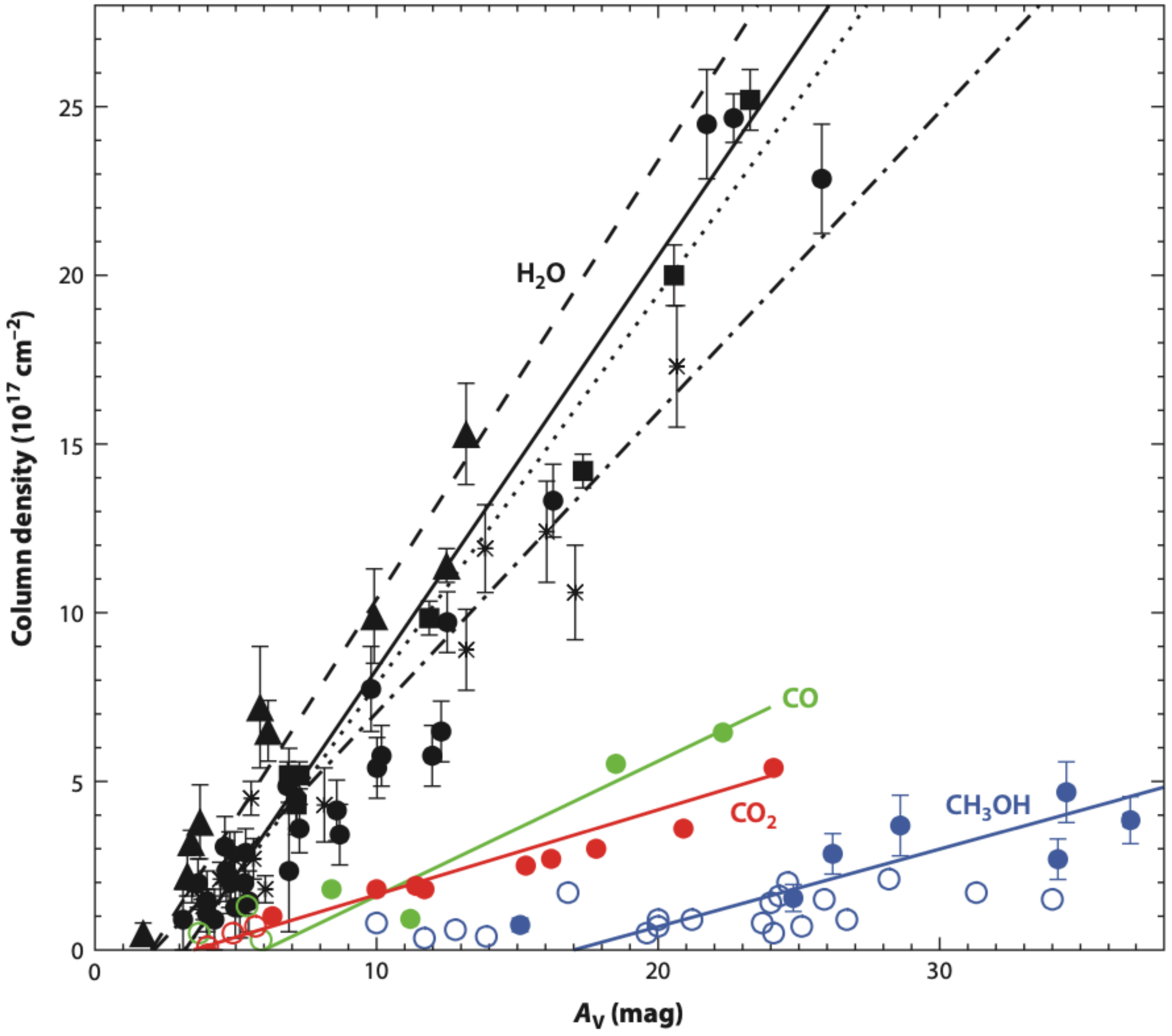
ESA / Rosetta / MPS for OSIRIS Team

However, the organic matter found in meteorites (i.e., carbonaceous chondrites) has a more complex chemical structure (Alexander et al. 2017)

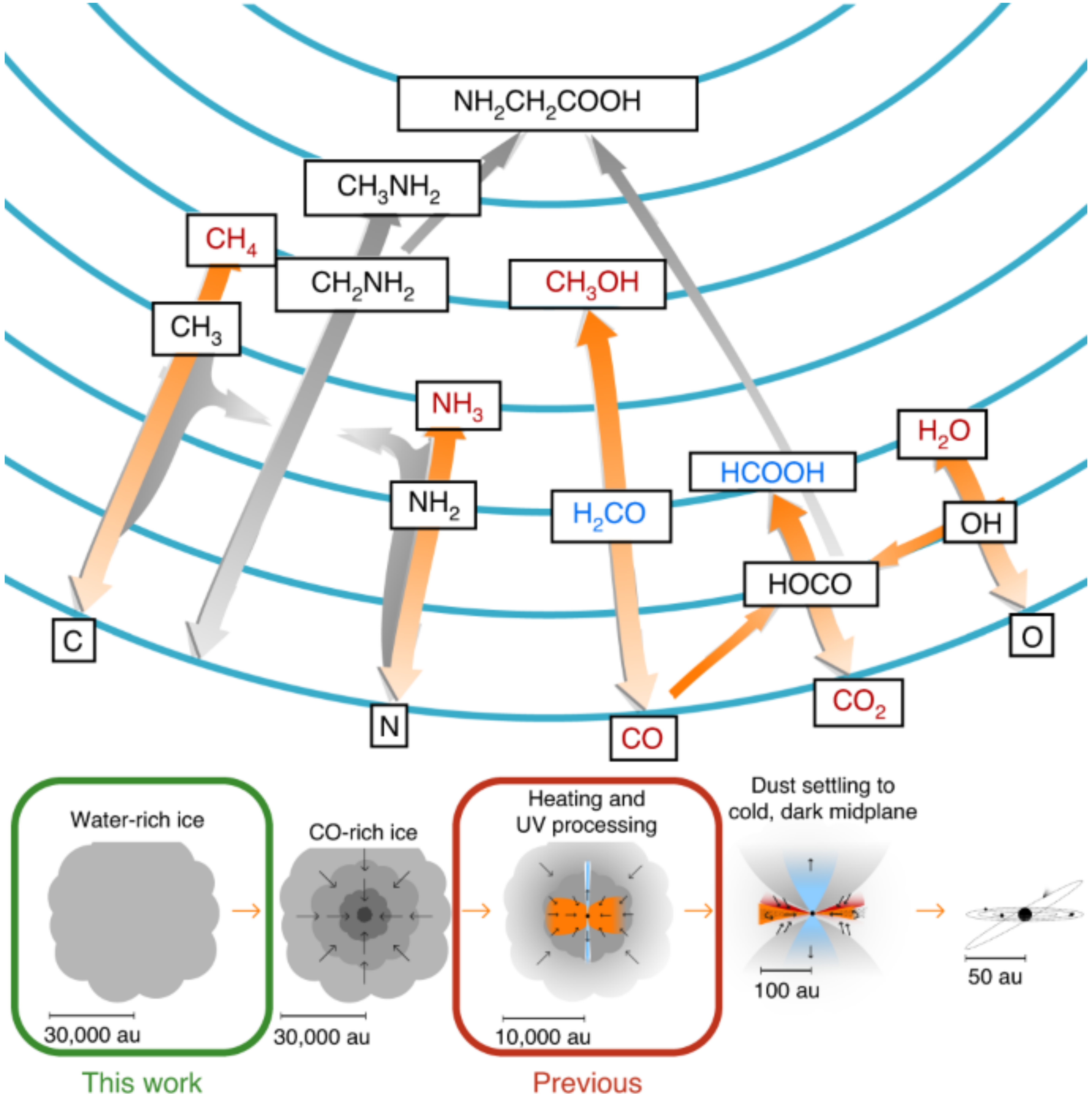
Complex organics may form already during the cold phase

Formation of simplest amino acid (glycine) in the laboratory under cold phase conditions (non-energetic mechanism)

Ice growth as function of visual extinction (A_V)



Boogert et al. 2015



Ioppolo et al. 2021

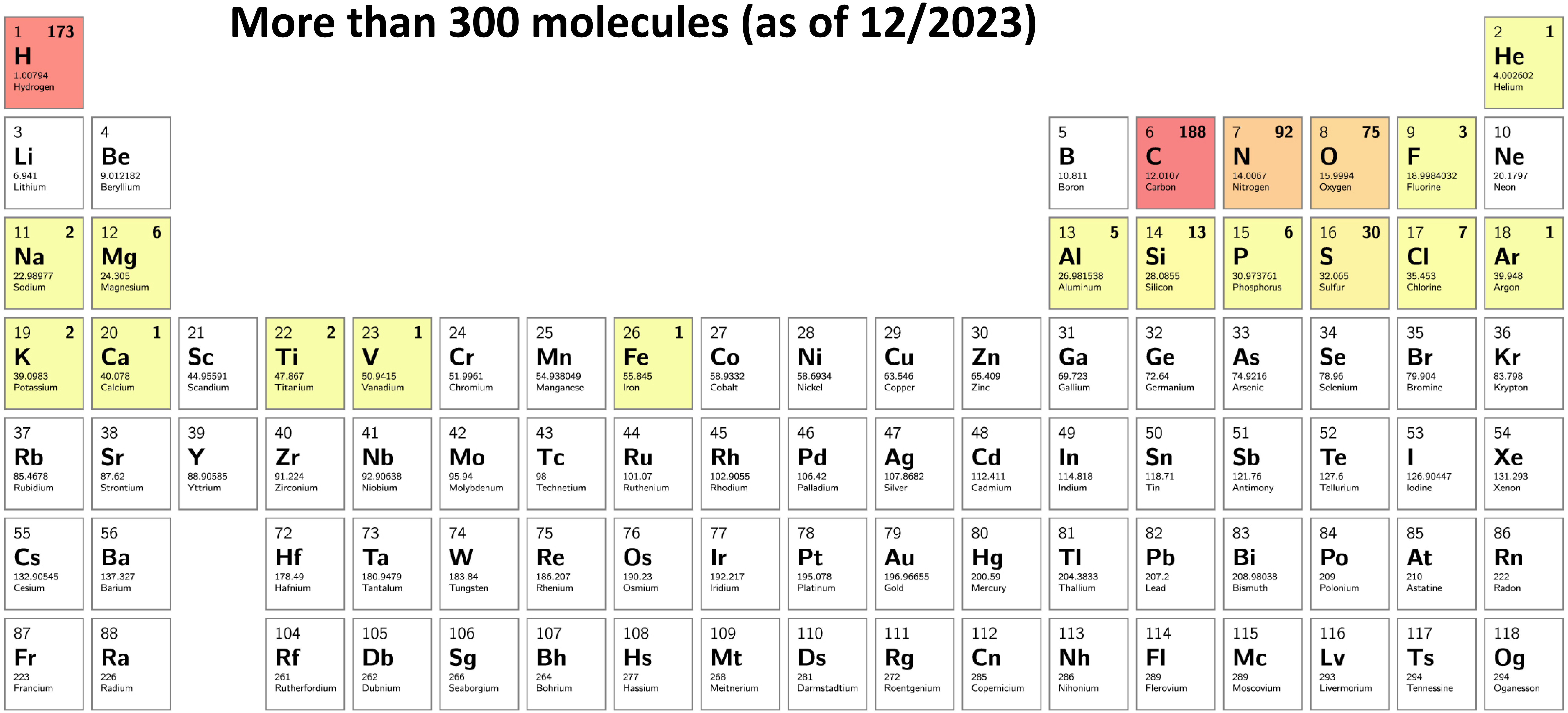
Outline

- Physical structure
- Chemical structure
- **Observations of molecules in protostellar envelopes**
- New era of discoveries with James Webb Space Telescope (JWST)

Detected molecules* in space

*[Interstellar and circumstellar]

More than 300 molecules (as of 12/2023)



A large fraction of molecules were detected in hot cores/corinos

https://cdms.astro.uni-koeln.de/classic/molecules

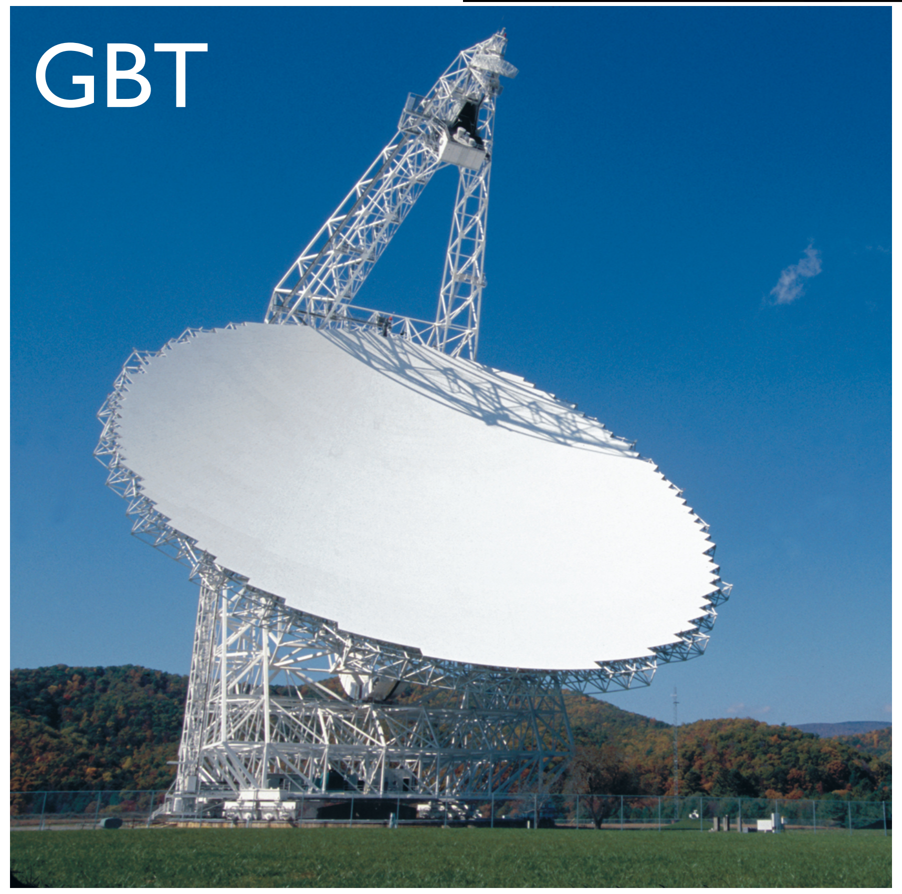
McGuire 2021

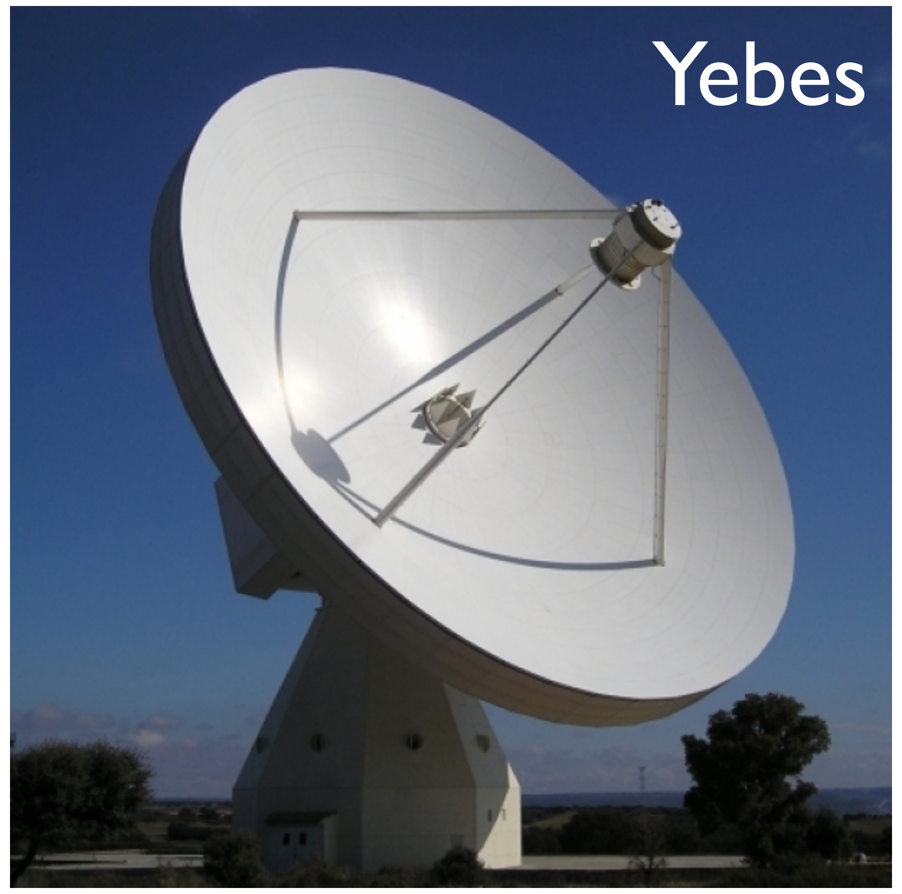
Detected molecules* in space

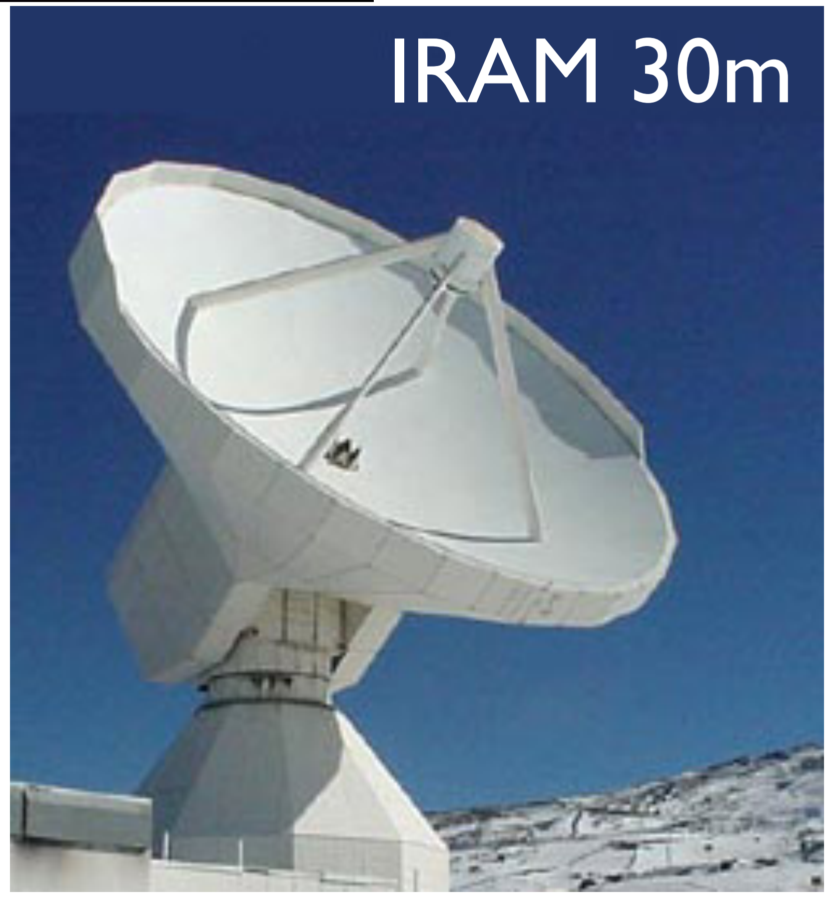
300+ molecules (as of 12/2023)

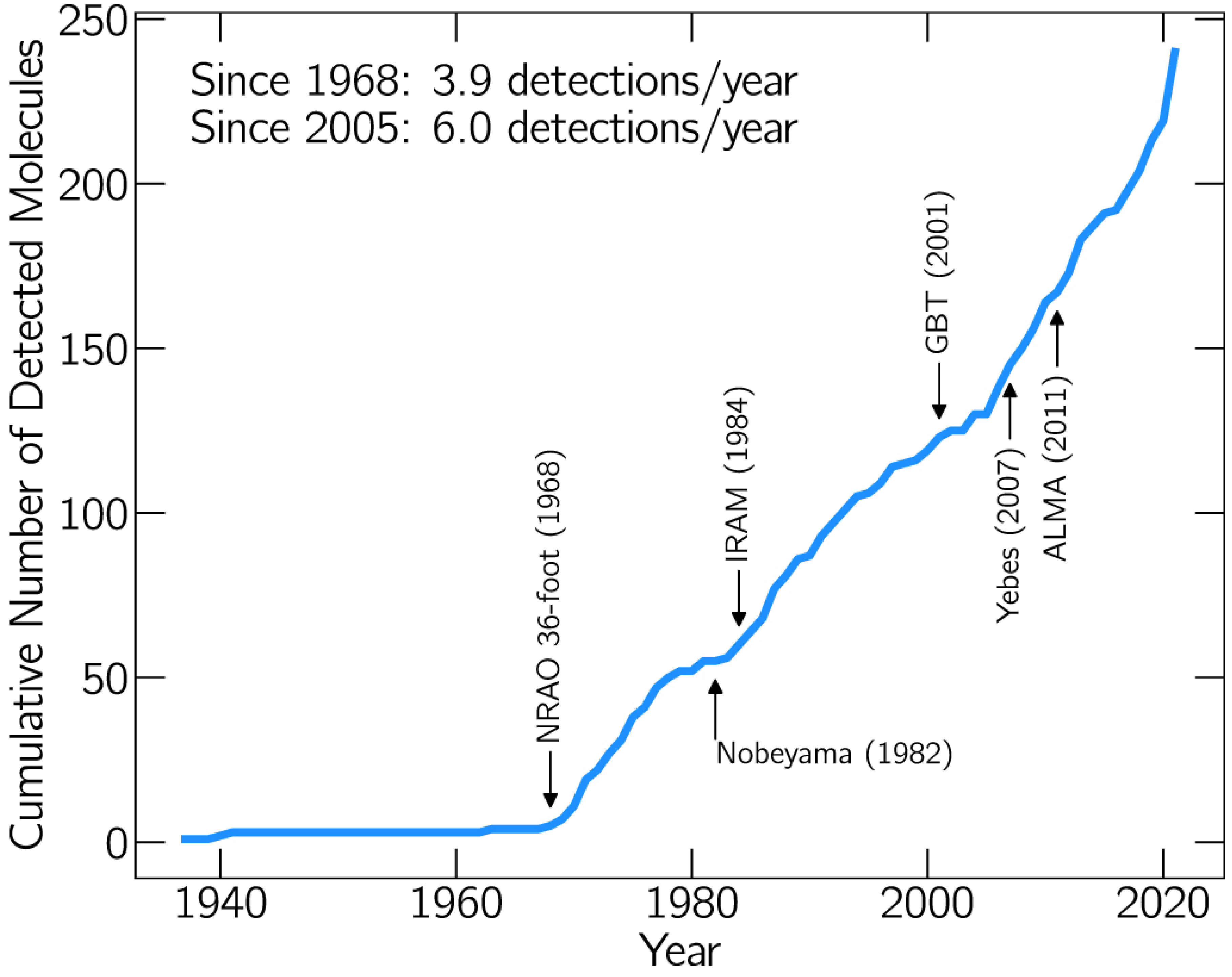
*[Interstellar and circumstellar]

Atacama Large Millimeter/submillimeter Array (ALMA)







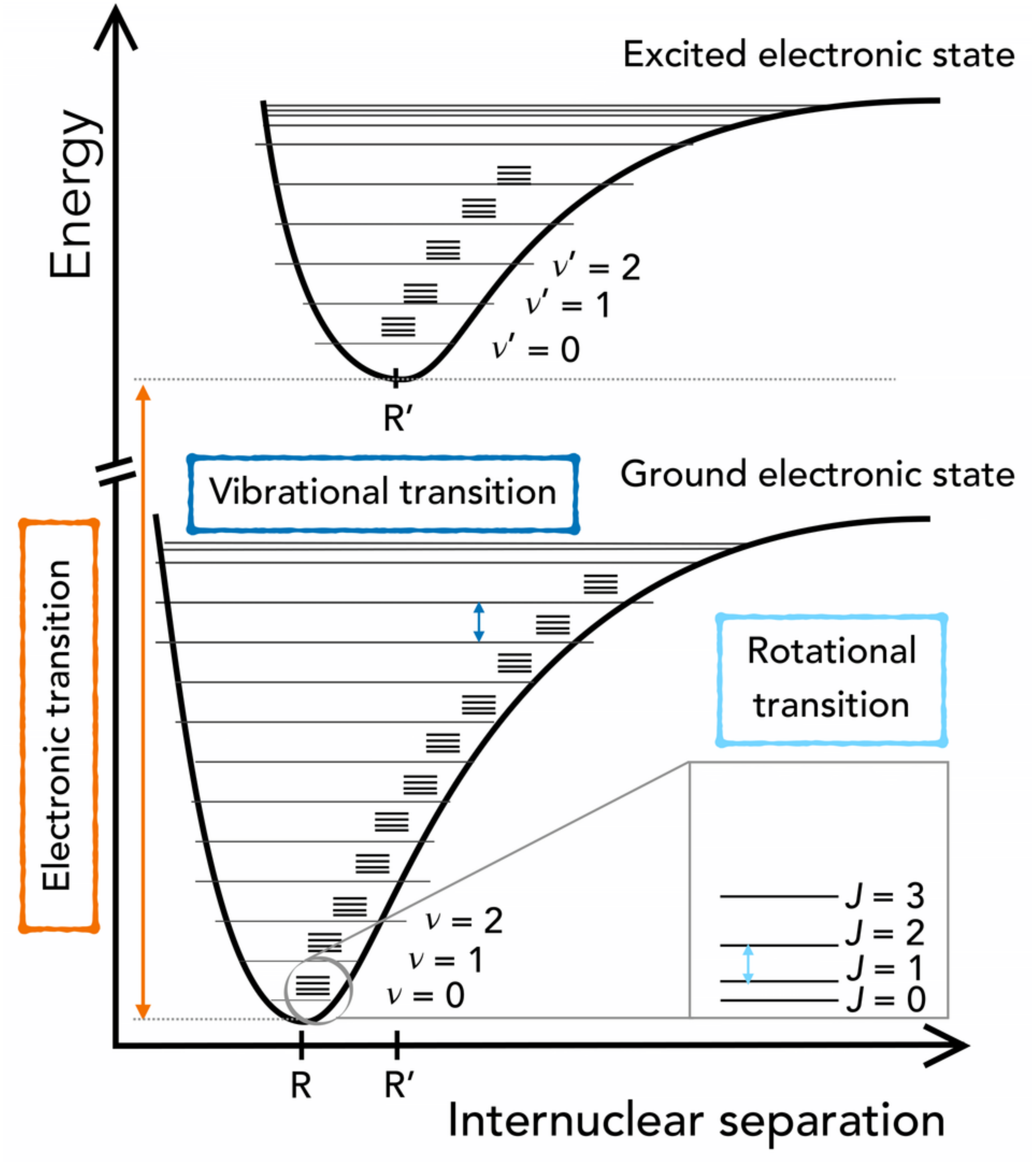


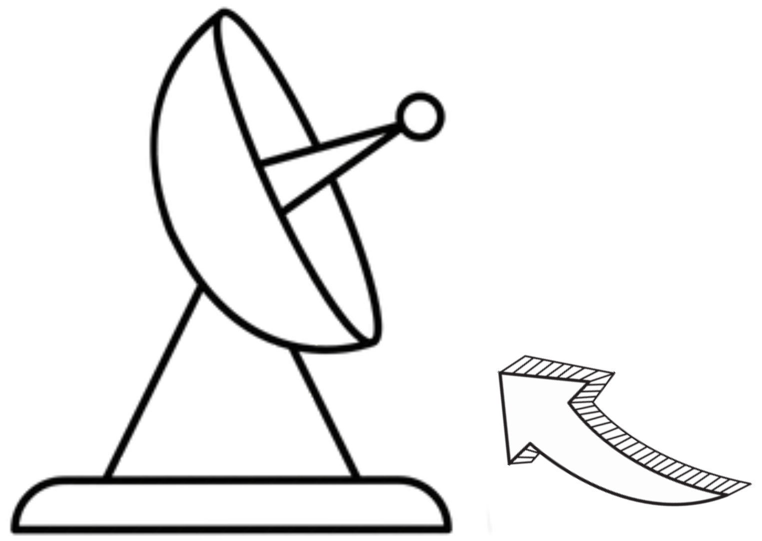
https://cdms.astro.uni-koeln.de/classic/molecules

McGuire 2021

Observing solid-state (ice) and gas-phase molecules

Gas-phase molecules are studied in emission

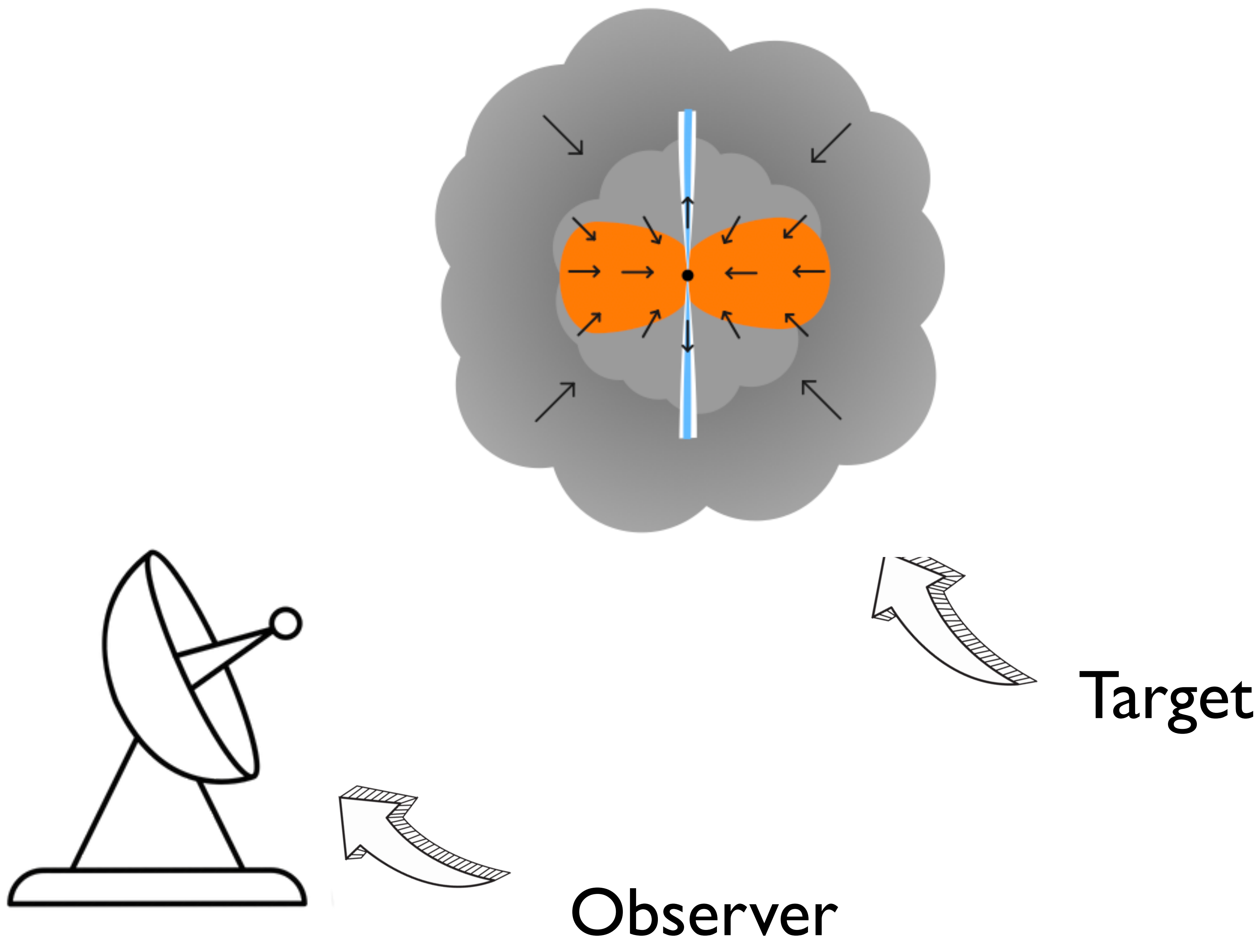


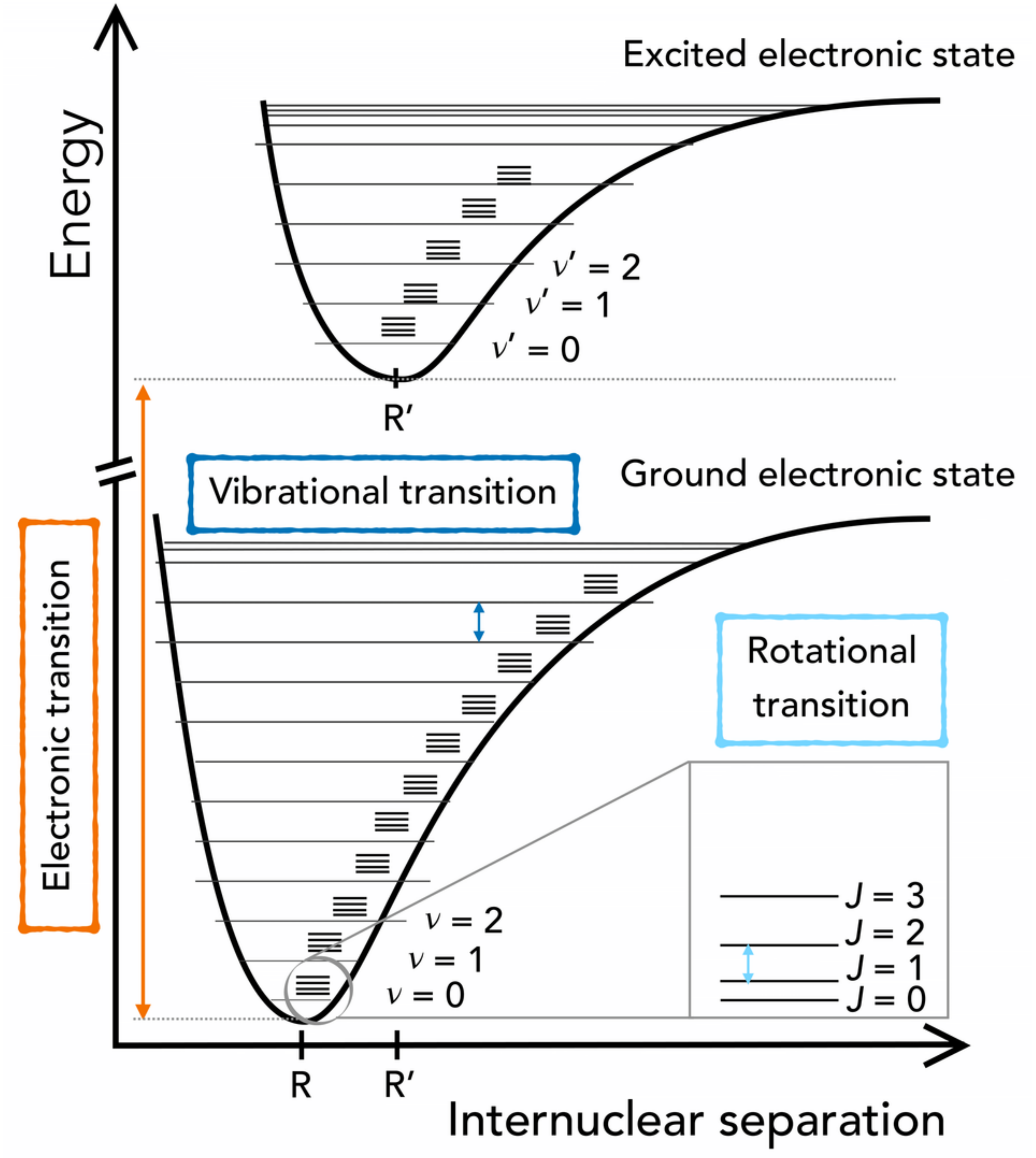


Observer

Observing solid-state (ice) and gas-phase molecules

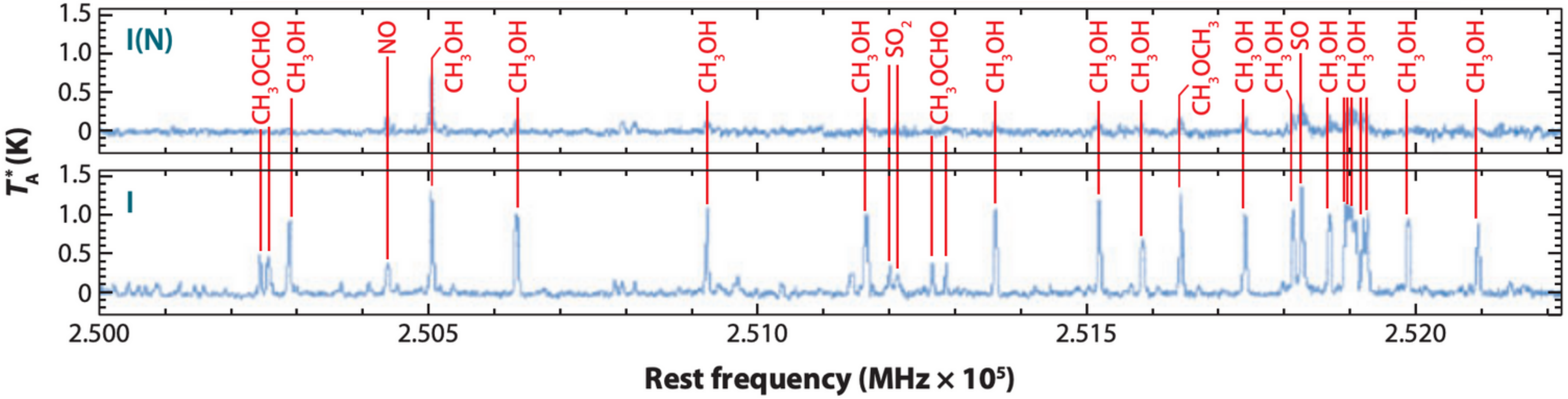
Gas-phase molecules are studied in emission



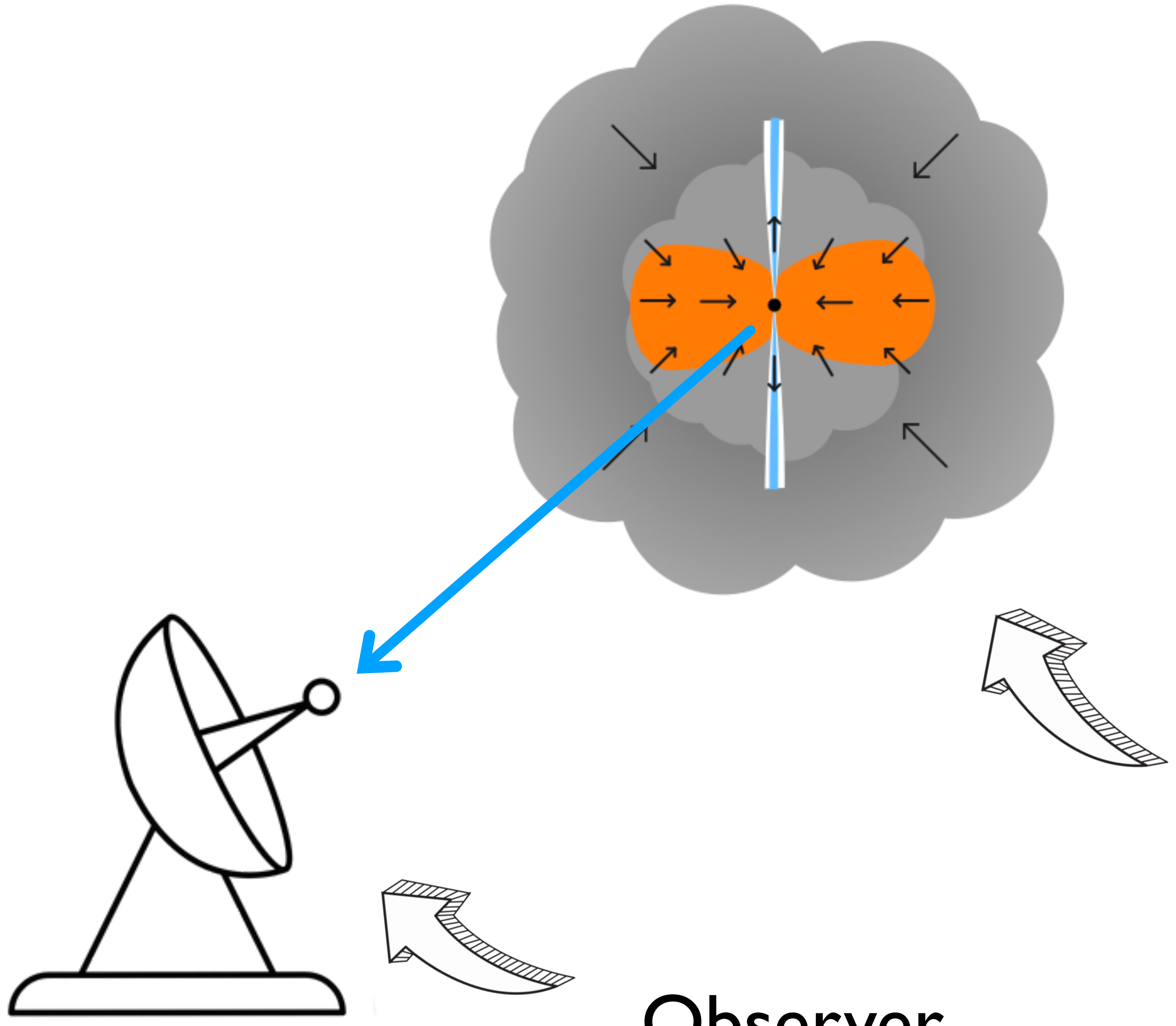


Observing solid-state (ice) and gas-phase molecules

Rotational spectroscopy



Rotational transitions corresponding to gas-phase species



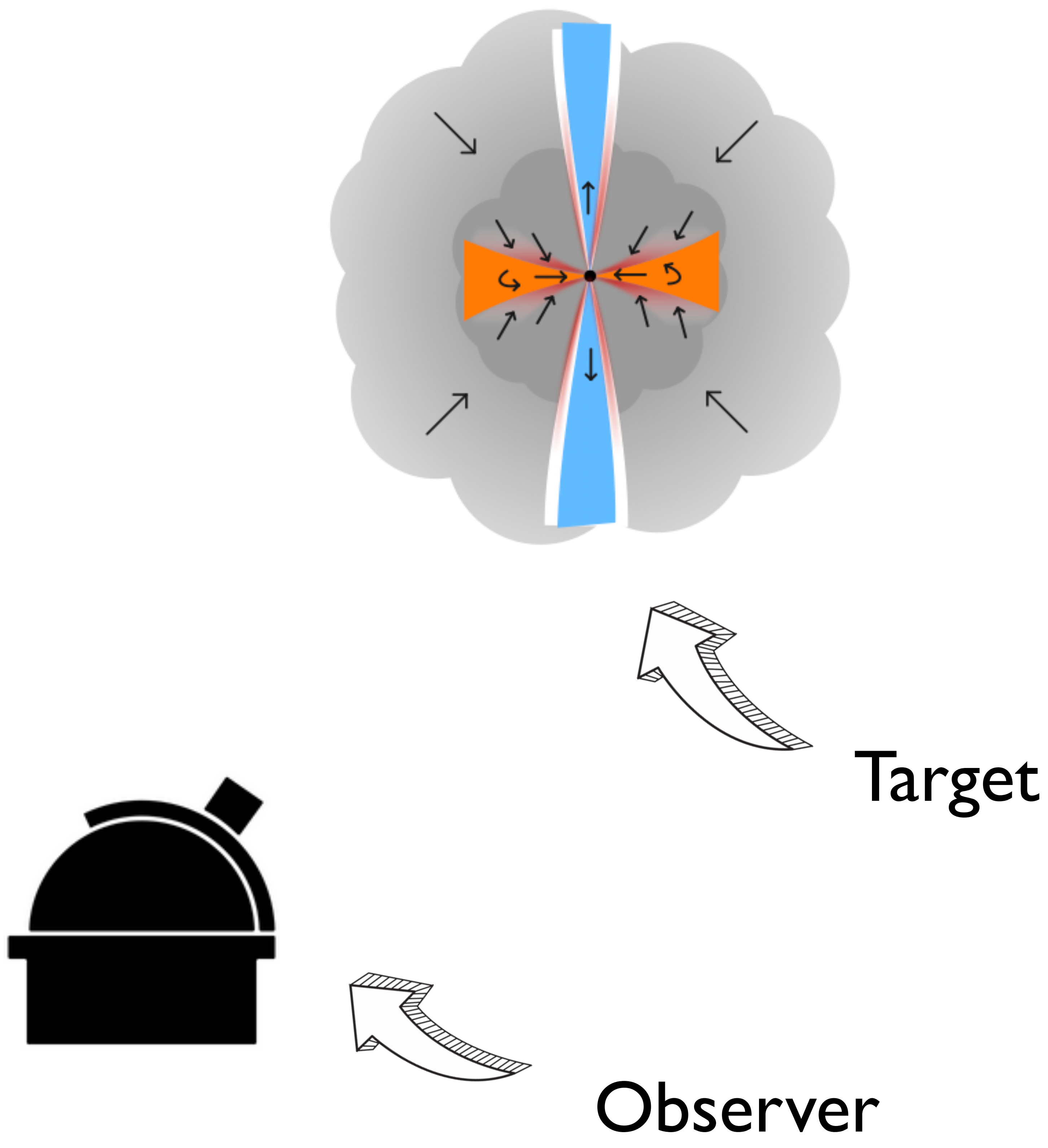
Target

Observer

Herbst & van Dishoeck 2009

Observing solid-state (ice) and gas-phase molecules

Solid-state (ice) molecules in the ice mantles are studied in absorption

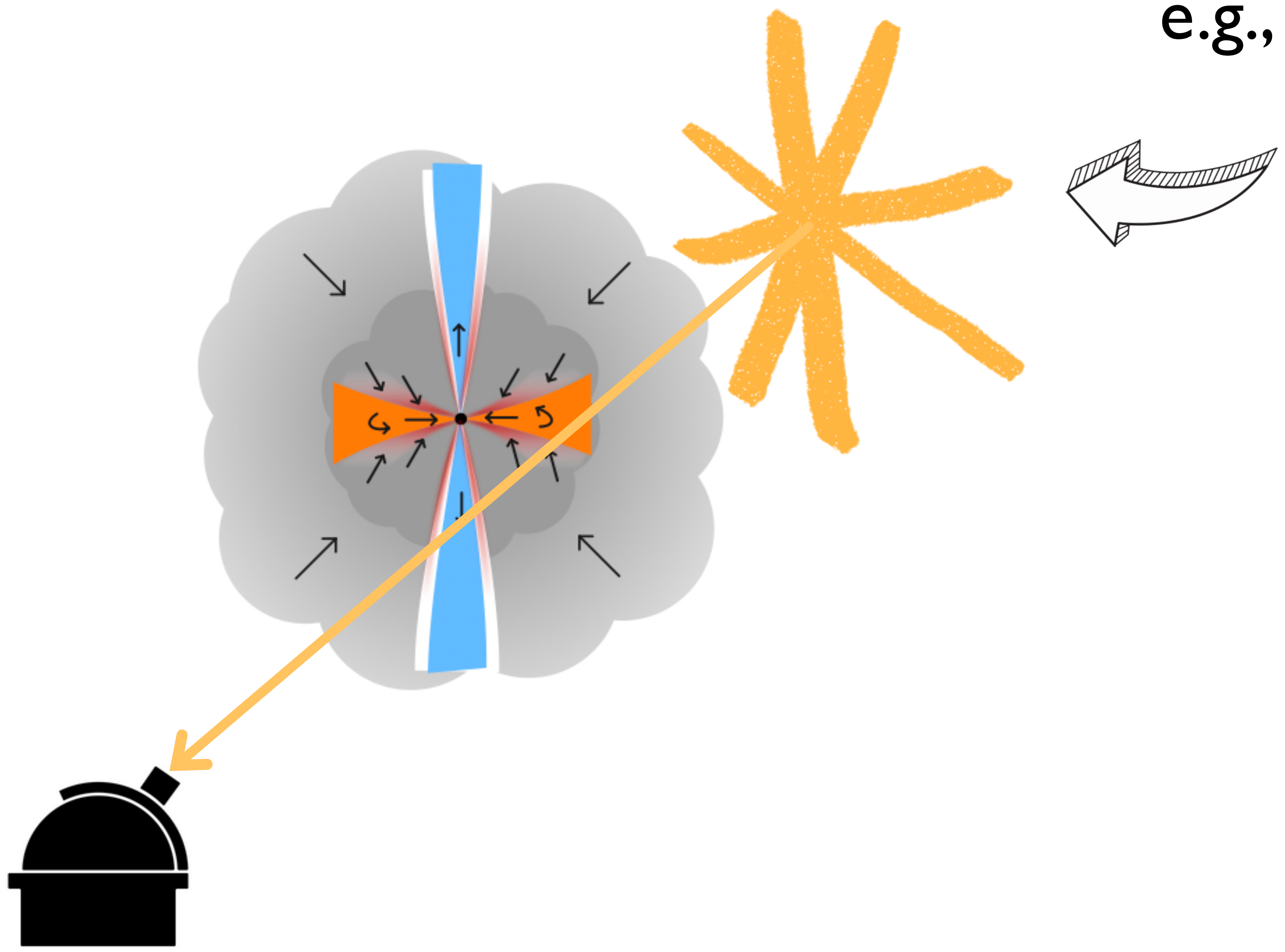


Boogert, Gerakines, Whittet 2015

Observing solid-state (ice) and gas-phase molecules

Solid-state (ice) molecules in the ice mantles are studied in absorption

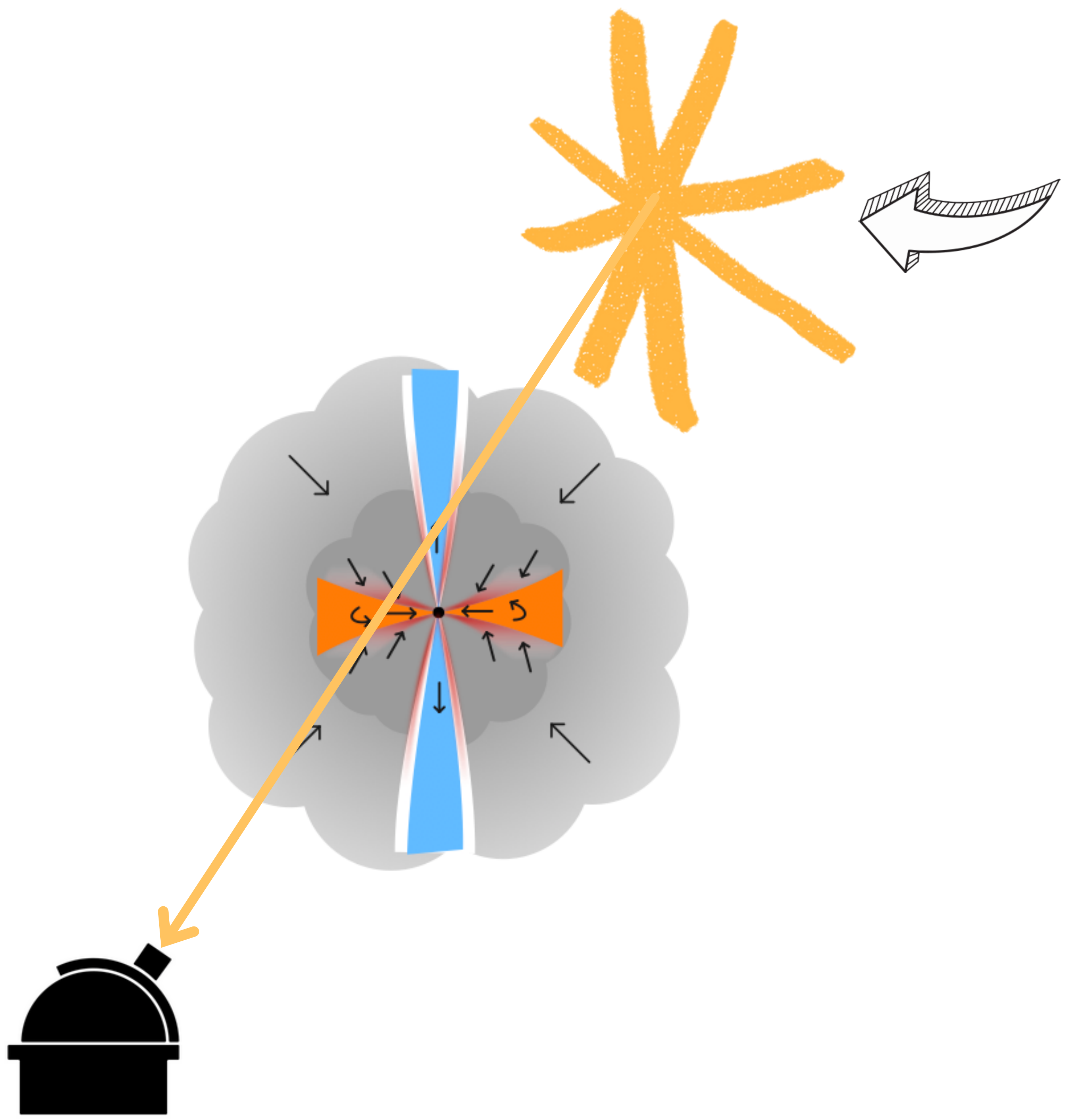
Background star
e.g., bright IR giant, YSOs



Presence of background stars required to study the composition of the ice mantles

Observing solid-state (ice) and gas-phase molecules

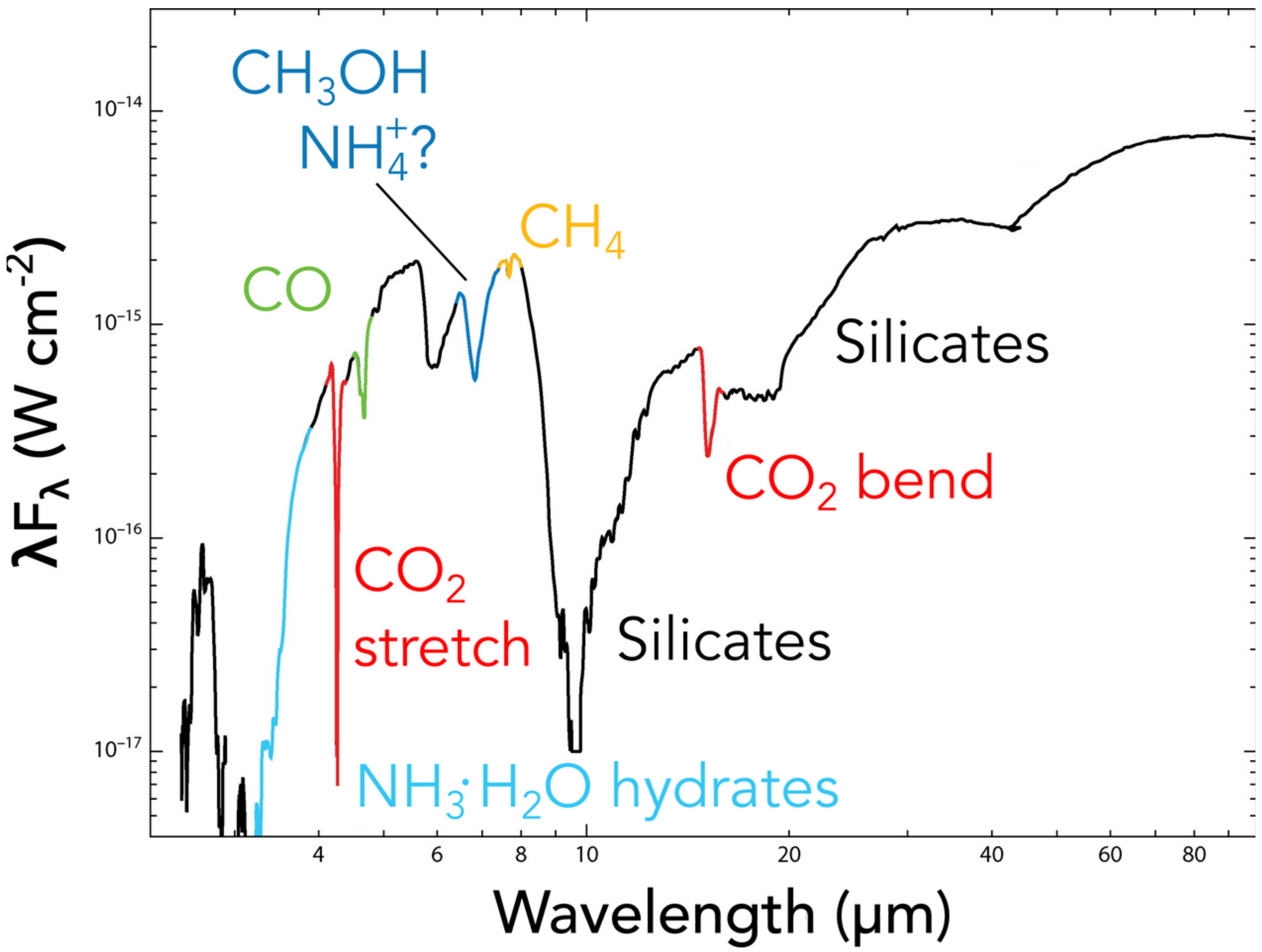
Absorption bands : vibrational modes of the functional groups



Background star

e.g., bright IR giant, YSOs

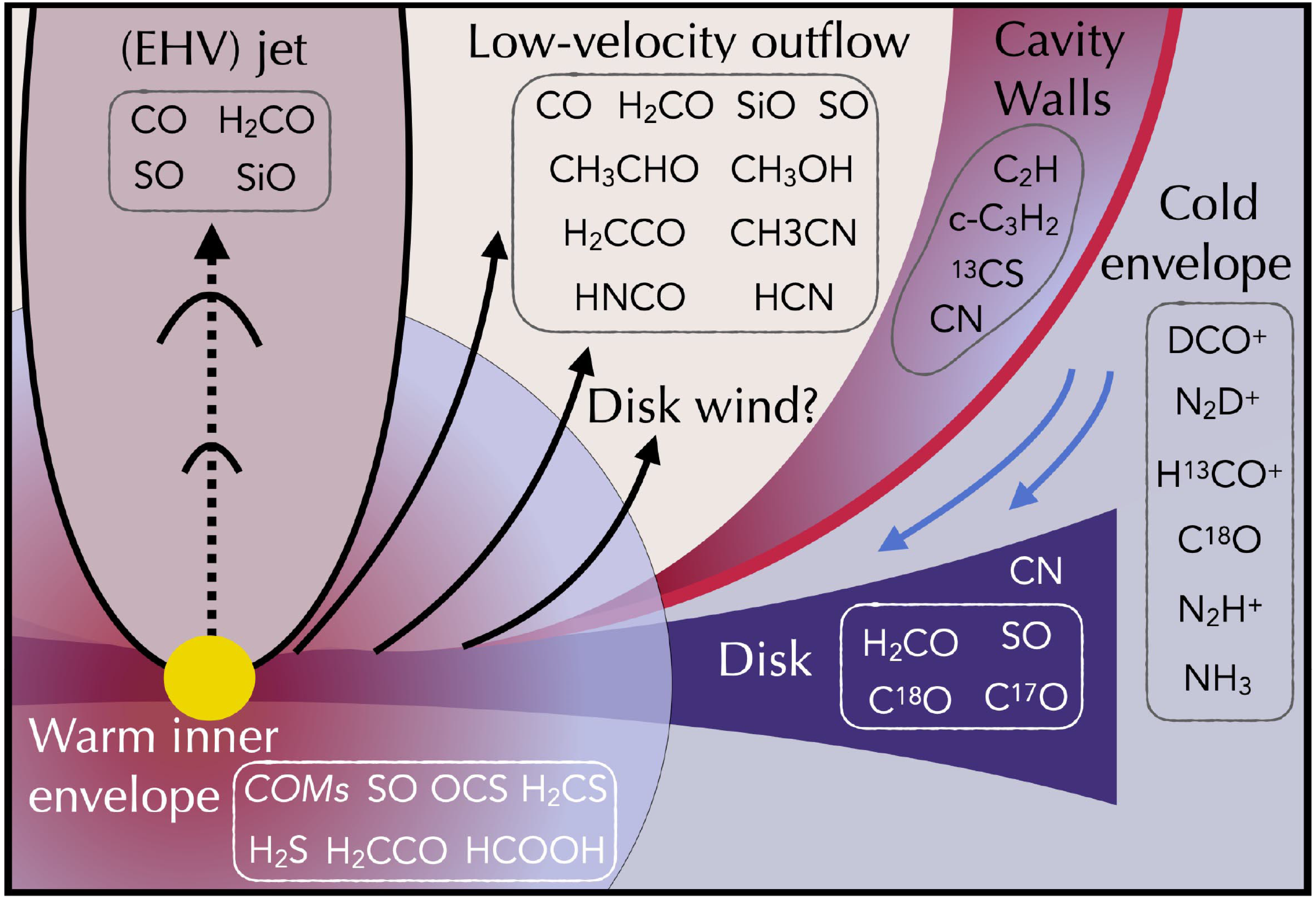
Vibrational spectroscopy



Boogert et al. 2015

Which molecule traces what ?

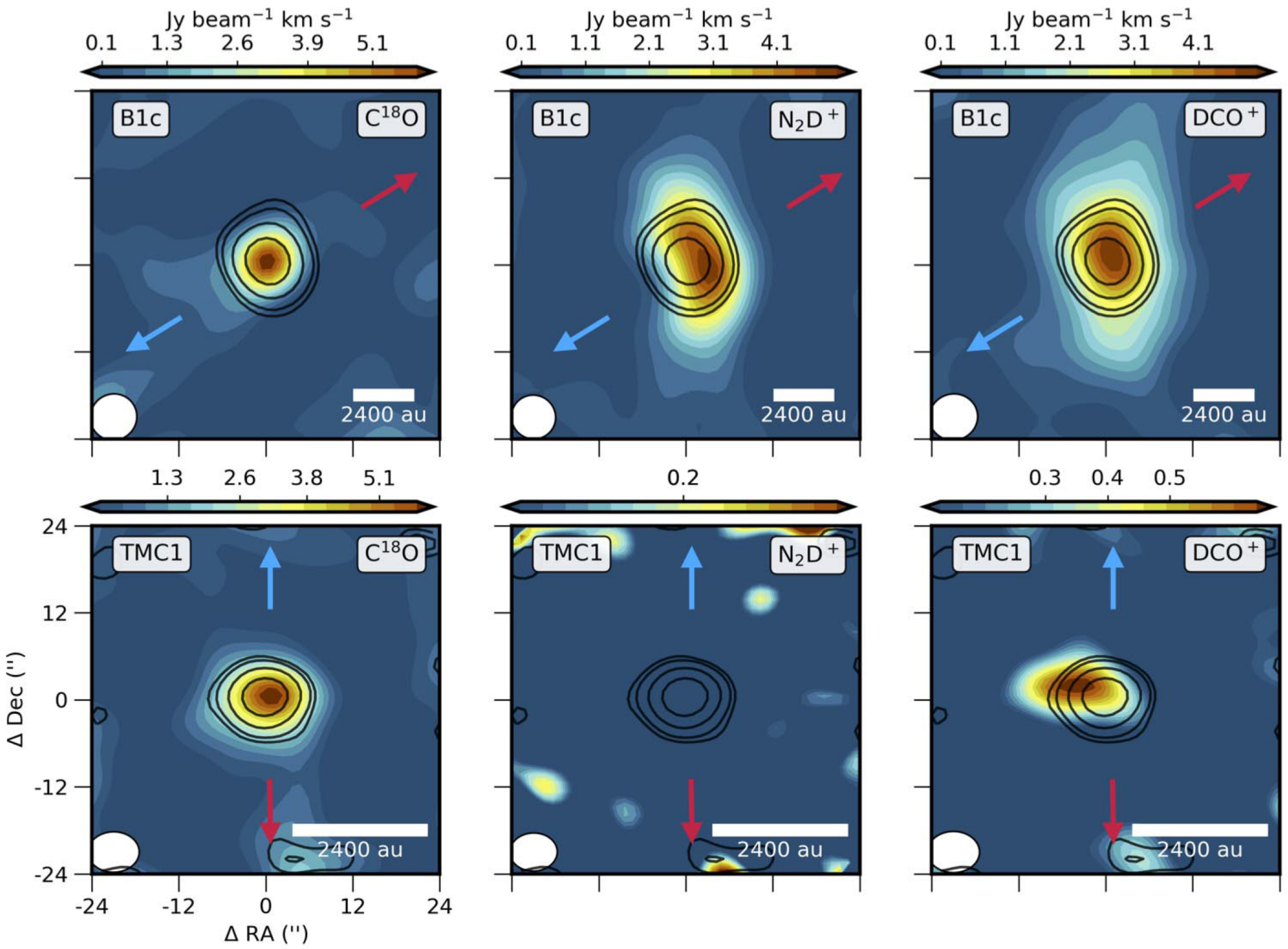
Chemical diagnostics of protostellar sources



Tychoniec et al. 2021

Which molecule traces what ?

Chemical diagnostics of protostellar sources



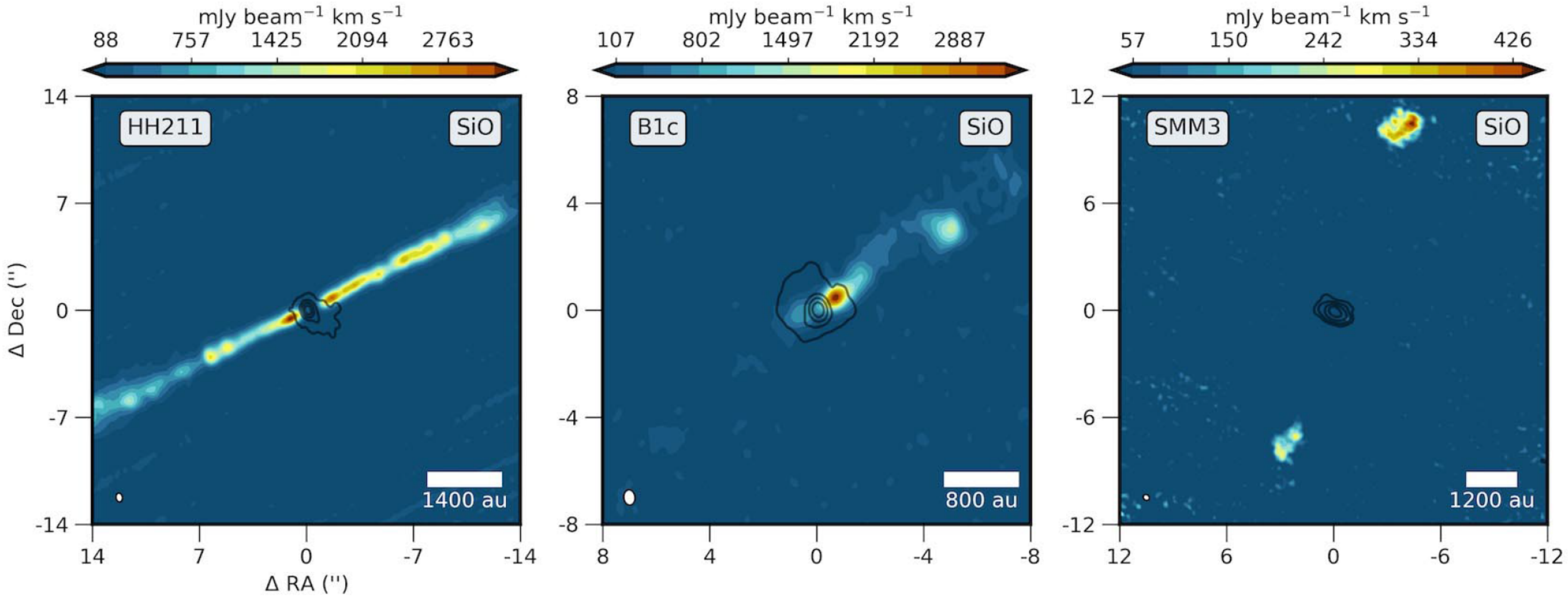
Envelope tracers

e.g., $C^{18}O$, N_2D^+, DCO^+

Extended emission tracing low excitation temperatures

Jet tracer e.g., SiO

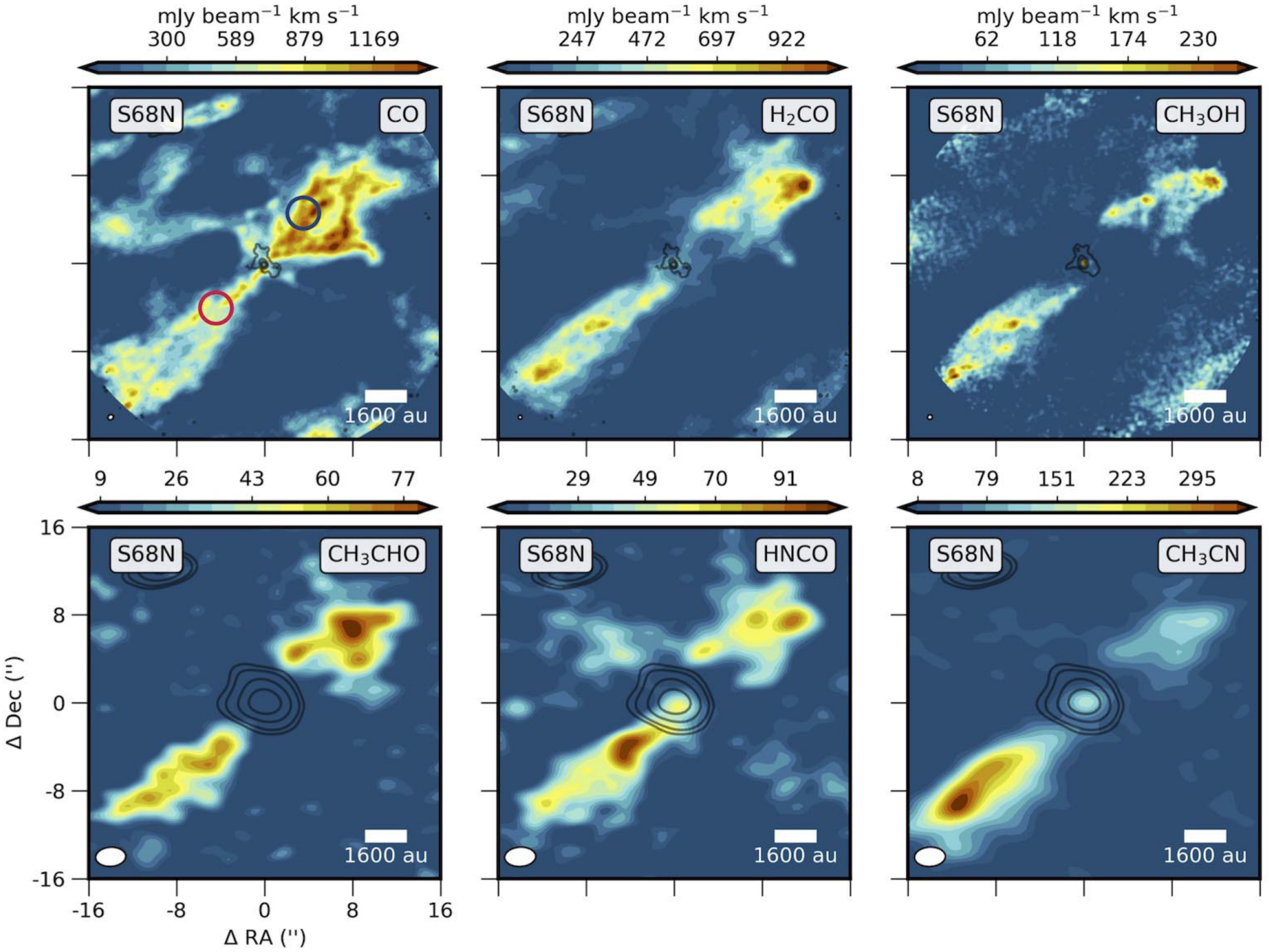
Evidence of blue and red-shifted emission, molecular bullets



Tychoniec et al. 2021

Which molecule traces what ?

Chemical diagnostics of protostellar sources



sputtering is the process in which solid-state molecules on the surface of dust grains are knocked free by high-speed atomic particles in jets, shocks.

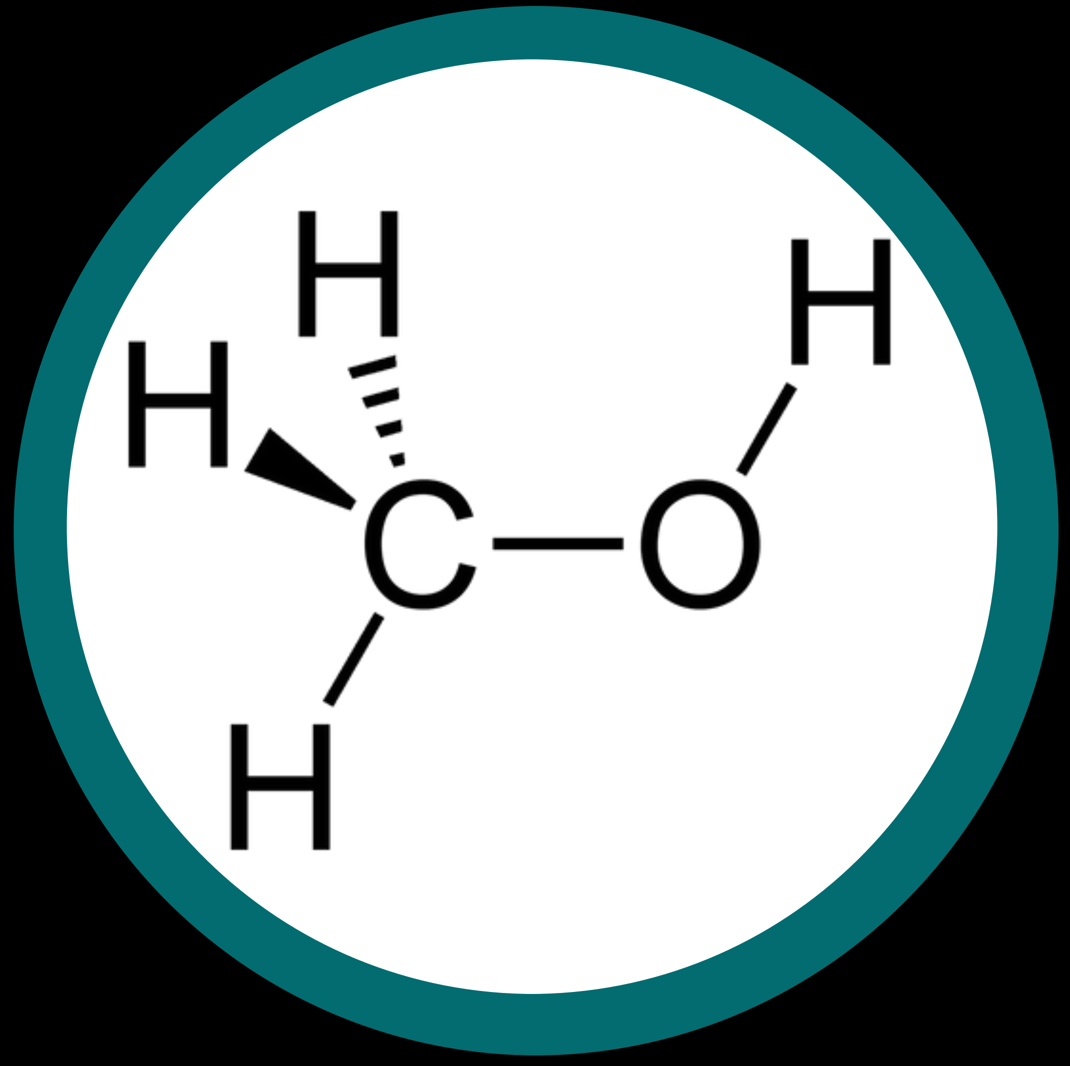
Ice mantle tracers

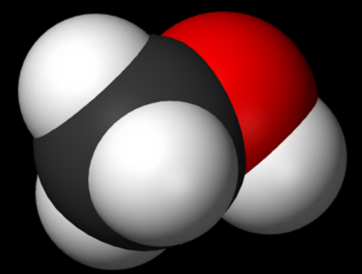
e.g., CH_3OH, HNCO, CH_3CN

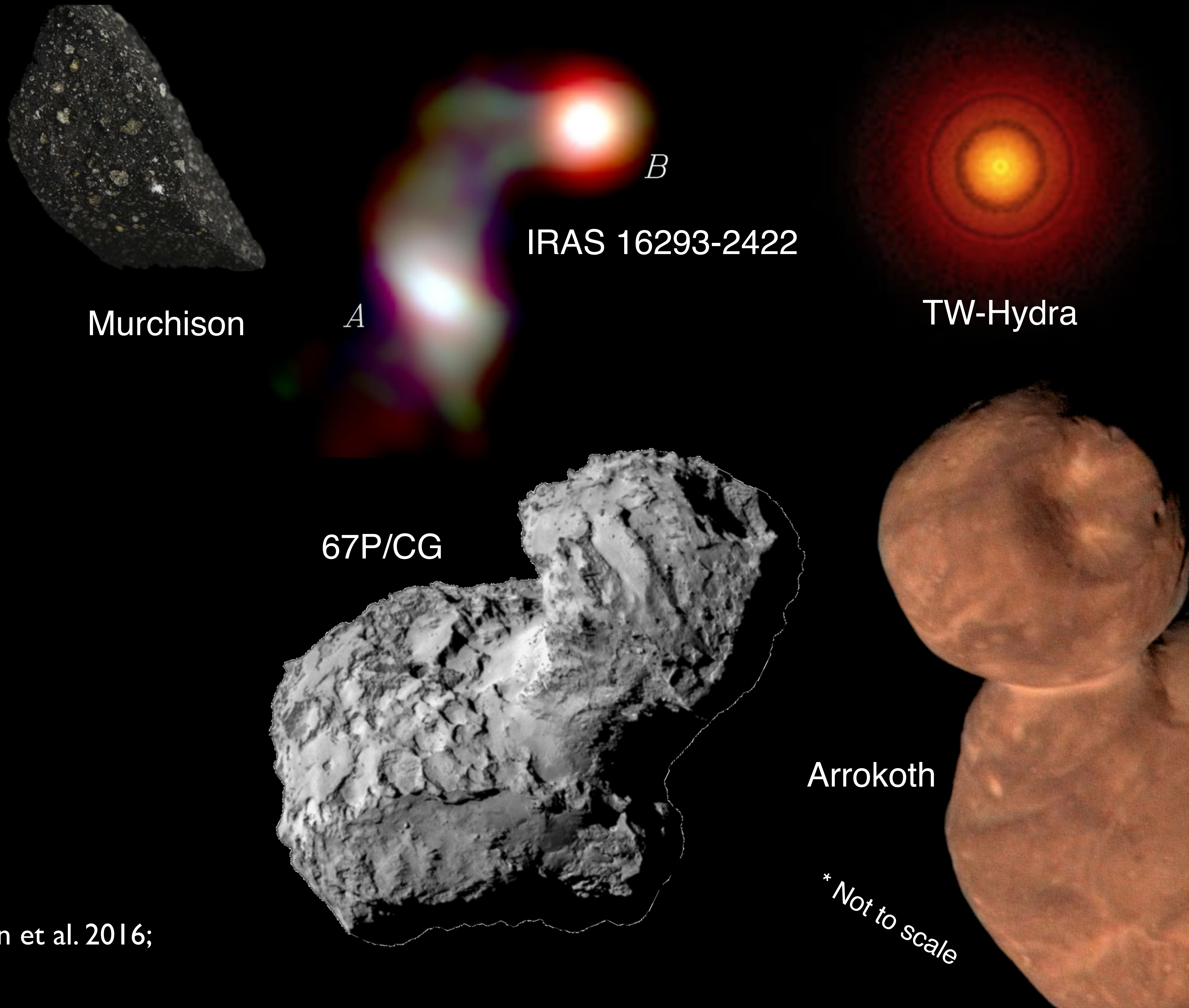
Molecules that form most efficiently on ices, but are abundant in the gas phase - desorbed during sputtering events in shocks and jets.

Tychoniec et al. 2021

Methanol (CH_3OH)







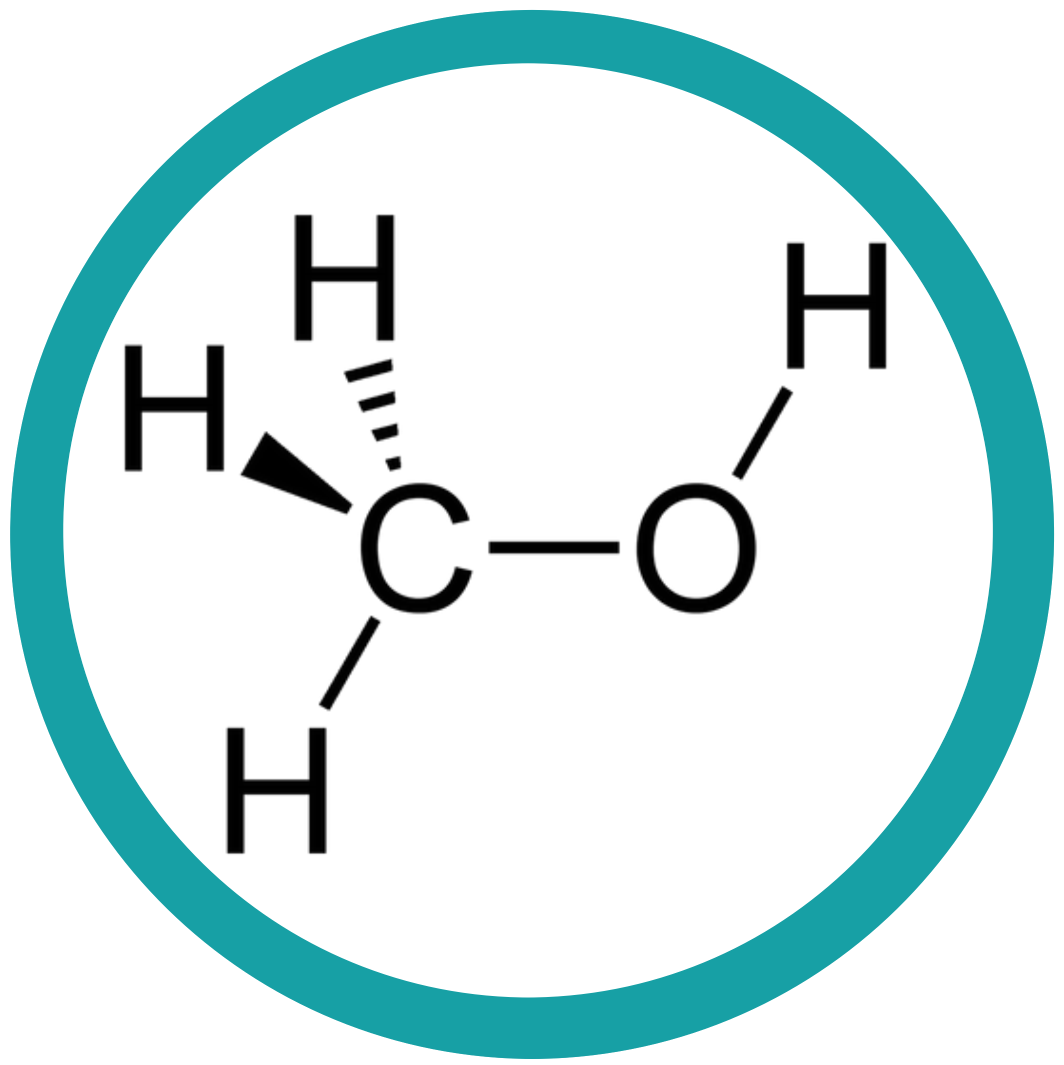
e.g., Hoban et al. 1993; Walsh et al. 2015; Jørgensen et al. 2016; Rubin et al. 2019; Grundy et al. 2020

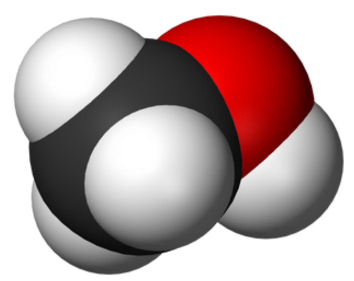
Methanol (CH_3OH) Gateway species for the formation of complex organics

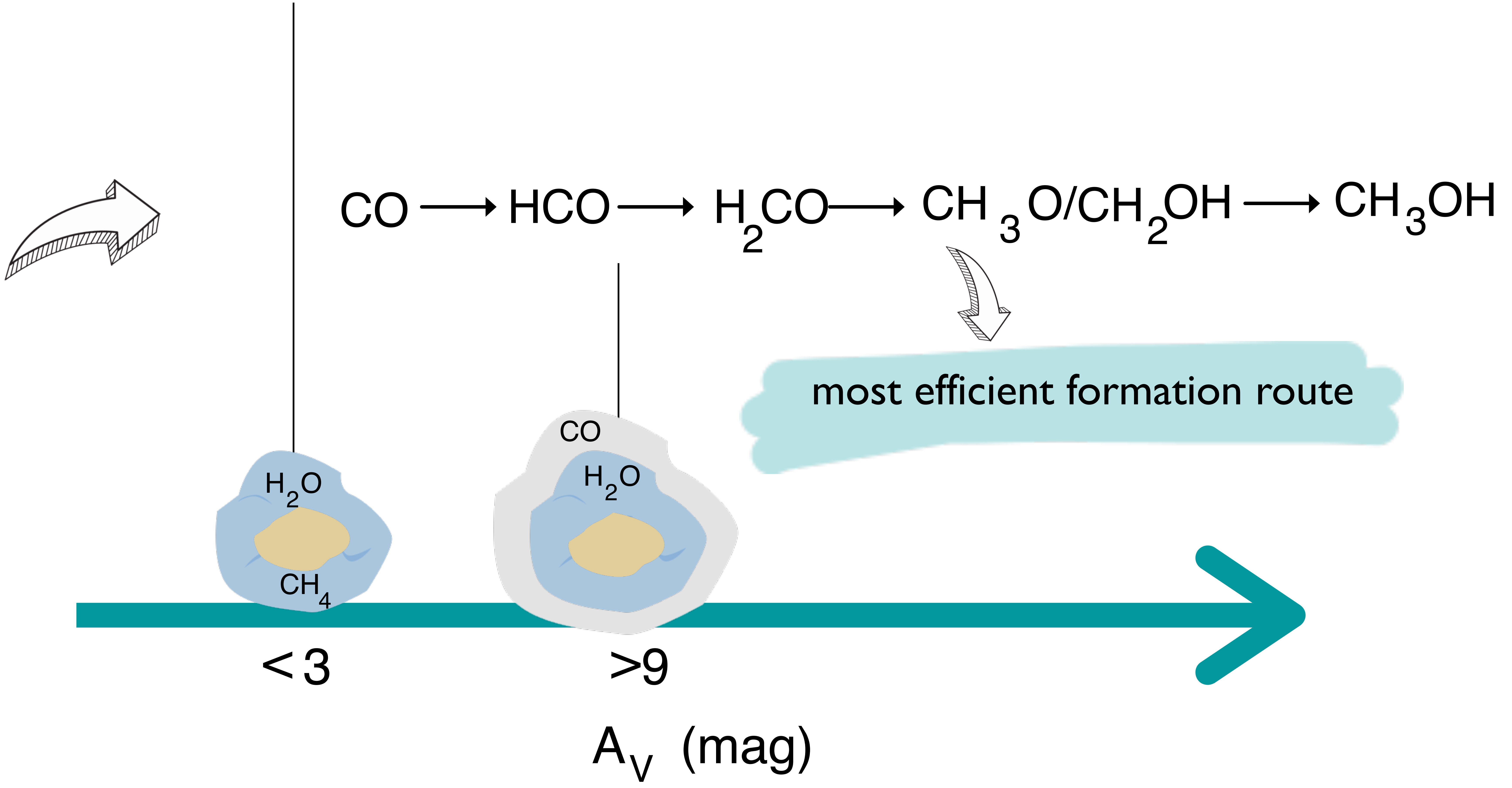
Ice mantle tracer

$$CH_4 + OH \longrightarrow CH_3 + H_2O$$

$$CH_3 + OH \longrightarrow CH_3OH$$





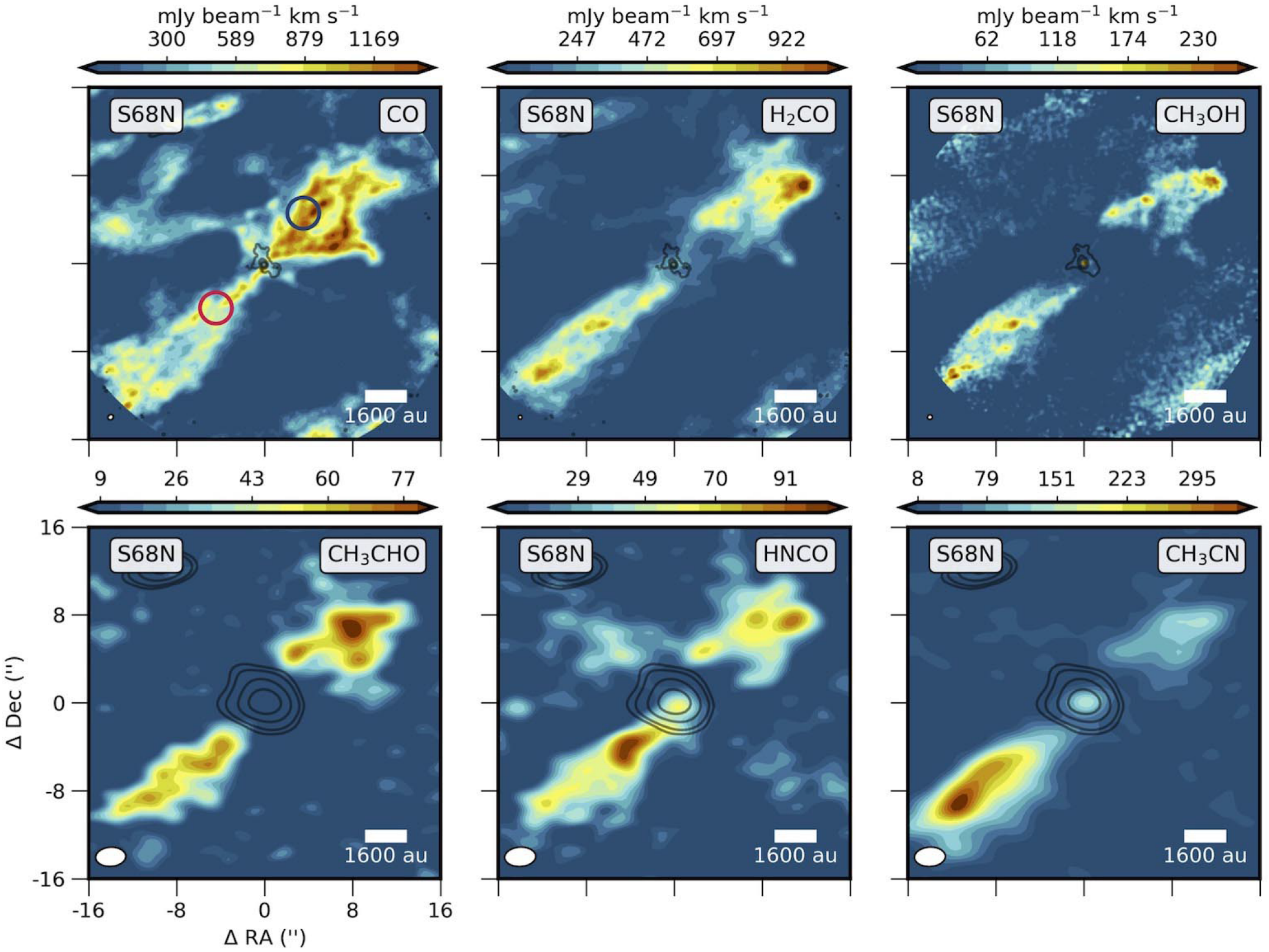


It forms most efficiently on the dust grains but it is abundantly detected in the gas

e.g., Watanabe & Kouchi 2002; Fuchs et al. 2009

Which molecule traces what ?

Chemical diagnostics of protostellar sources



sputtering is the process in which solid-state molecules on the surface of dust grains are knocked free by high-speed atomic particles in jets, shocks.

Observations of gas-phase methanol enable to indirectly study the abundance of methanol ice

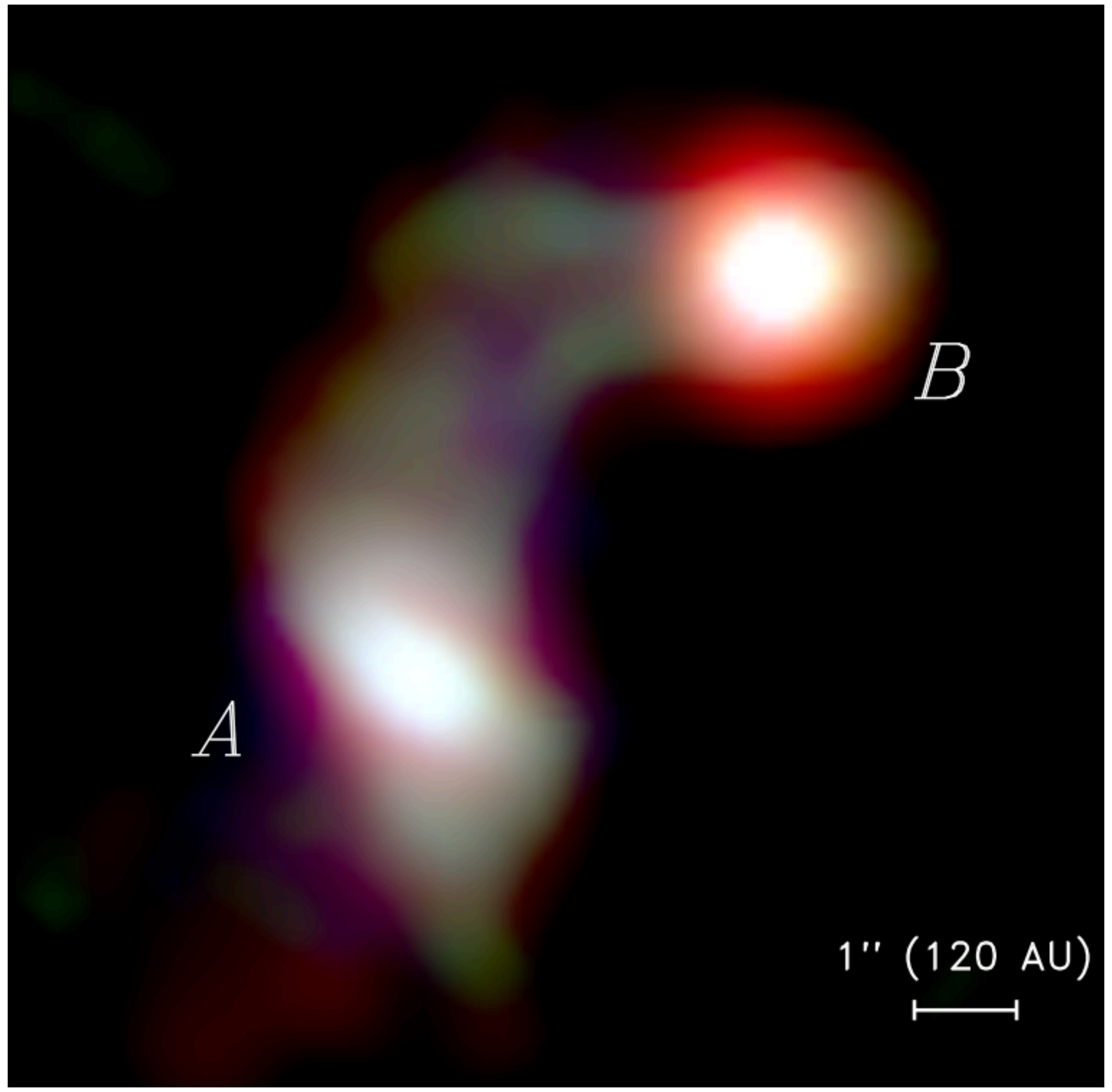
Ice mantle tracers

e.g., CH_3OH, HNCO, CH_3CN

Molecules that form most efficiently on ices, but are abundant in the gas phase - desorbed during sputtering events in shocks and jets.

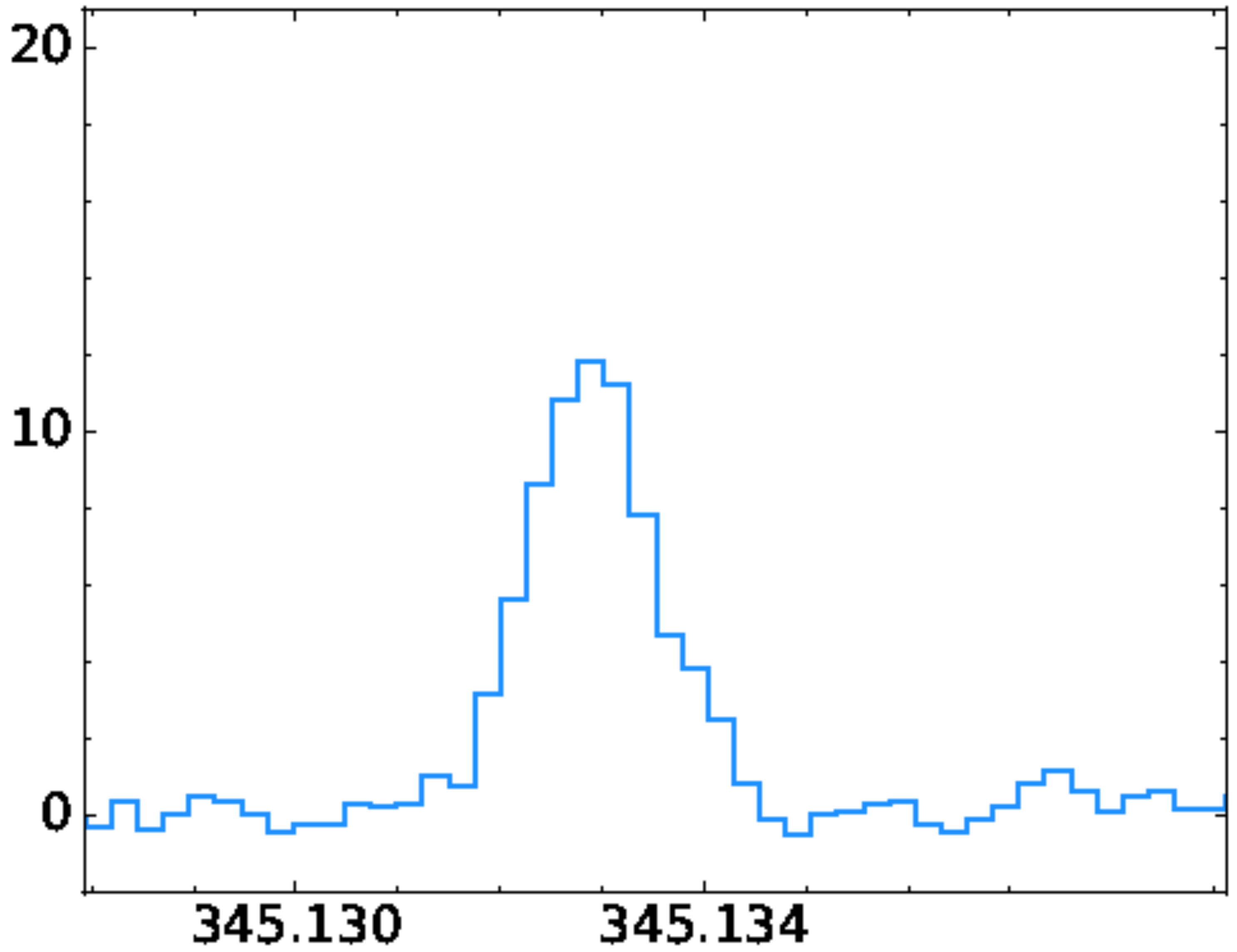
Tychoniec et al. 2021

Protostellar systems: IRAS 16293-2422



Jørgensen and the PILS team 2016

Class 0 protostar
Binary system located in rho Ophiuchi (d=140 pc)
Separation between protostar A and B: 700 AU
$L_{bol} = 32\ L_{\odot}$
$M_{env} = 3\ M_{\odot}$
Envelope size = 3000 AU
Hot corino



PILS: Protostellar Interferometric Line Survey (329-363 GHz) using ALMA

Spectral resolution of 0.2 km/s

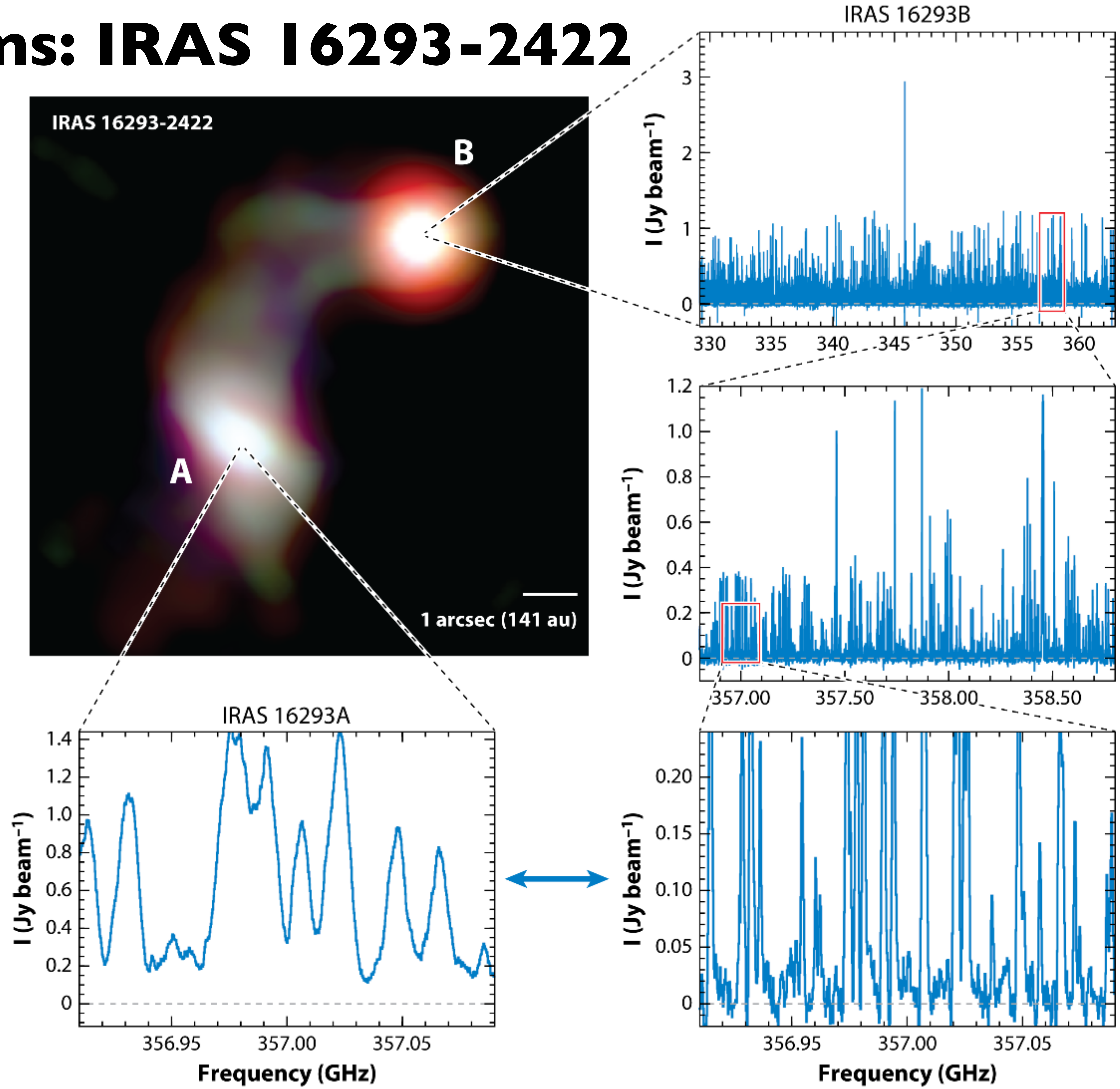
Imaging at 0.5´´ angular resolution (60 AU)

Protostellar systems: IRAS 16293-2422

Example of spectra from the ALMA/PILS Survey

Most chemically-rich
Class 0 protostar observed

Several first detections
(e.g., sugar,
doubly deuterated species)

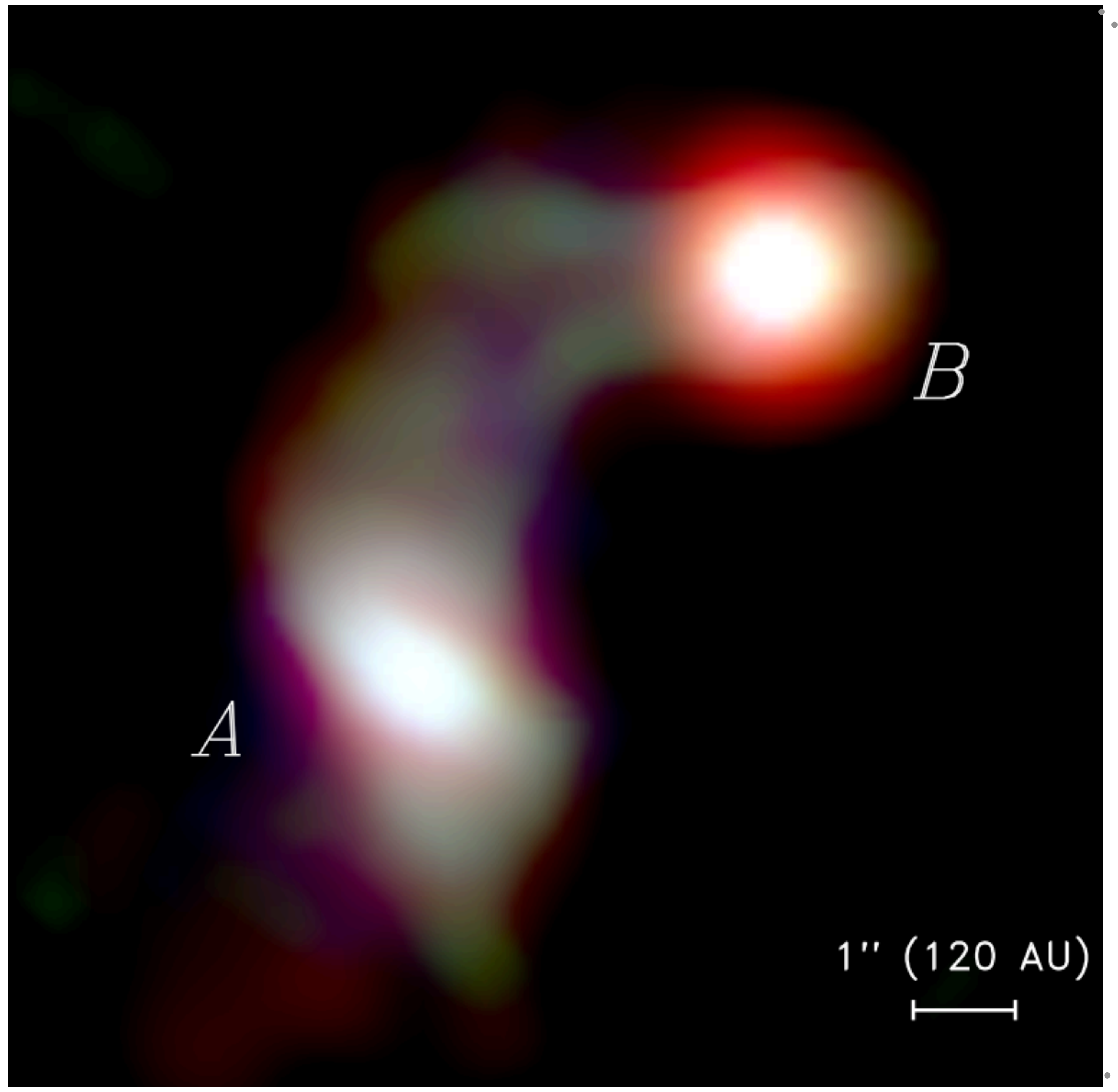


Jørgensen and the PILS team 2016

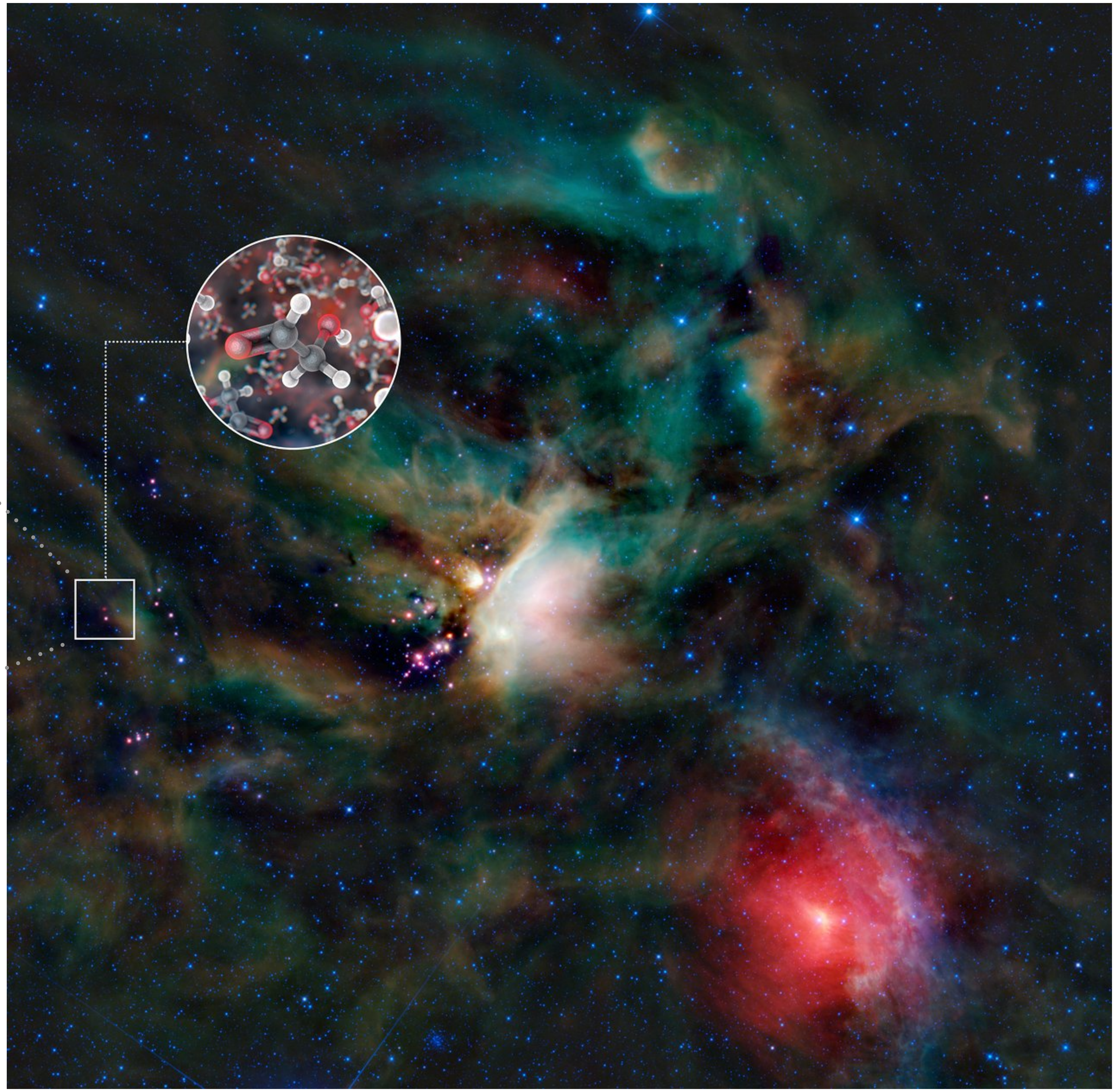
Protostellar systems: IRAS 16293-2422

First detection of a sugar in space: glycolaldehyde ($C_2H_4O_2$)

Formose reaction leading to ribose (building block of RNA)



Jørgensen and the PILS team 2016



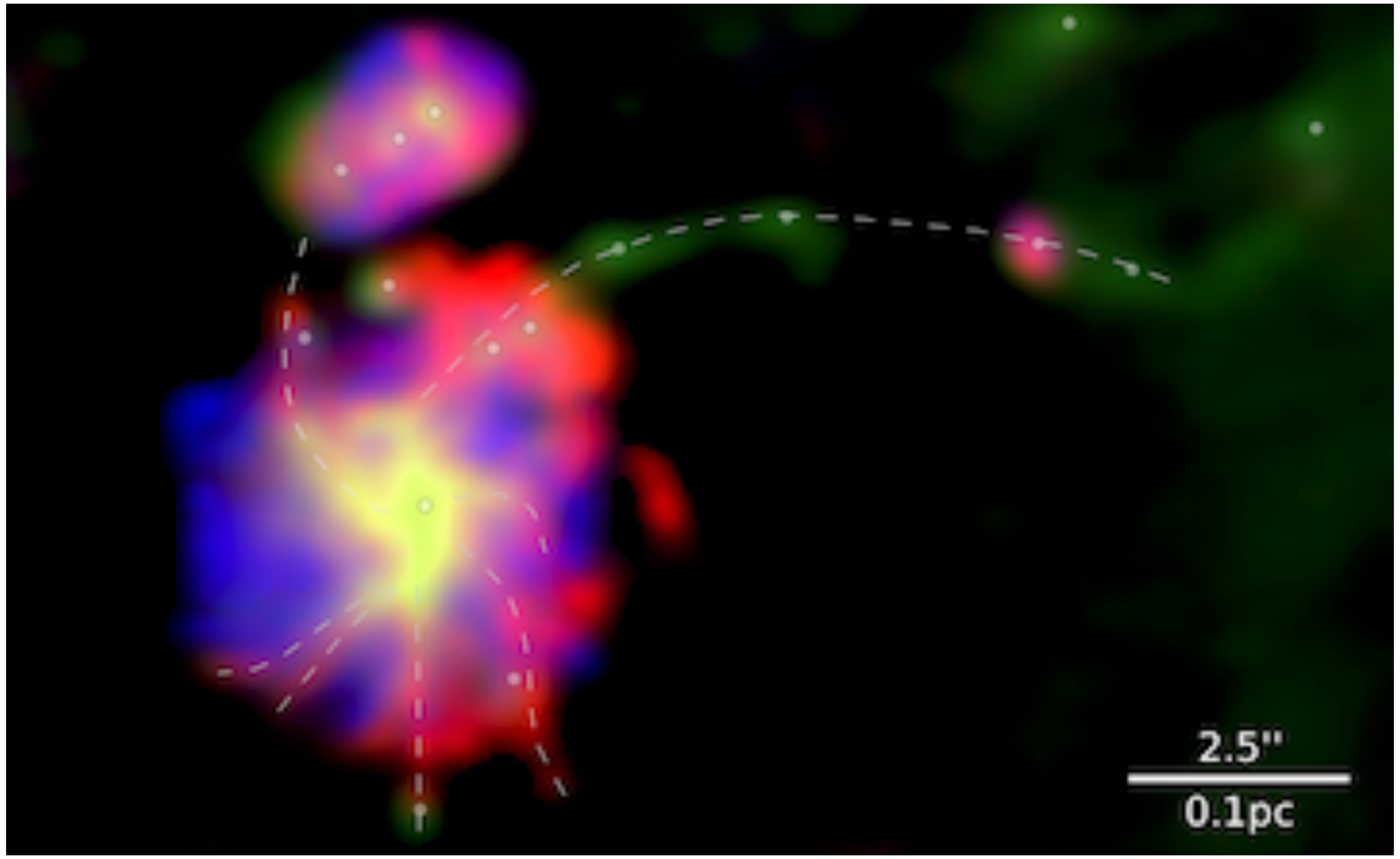
Jørgensen et al. 2012

Observational evidence for hot cores: Sgr B2 (N)

Sagittarius B2: one of the most prominent regions forming high-mass stars in our Galaxy $M \sim 10^7 M_\odot$

Location = ~100 pc from the central supermassive black hole Sgr A* (d=8.34 kpc)
Sgr B2 N(orth) contains two hot cores Sgr B2 (N1) and Sgr B2 (N2)
Hot core separation = 0.2 pc

EMOCA: Exploring molecular complexity with ALMA
(84-114 GHz)
Imaging at 1.8´´ angular resolution



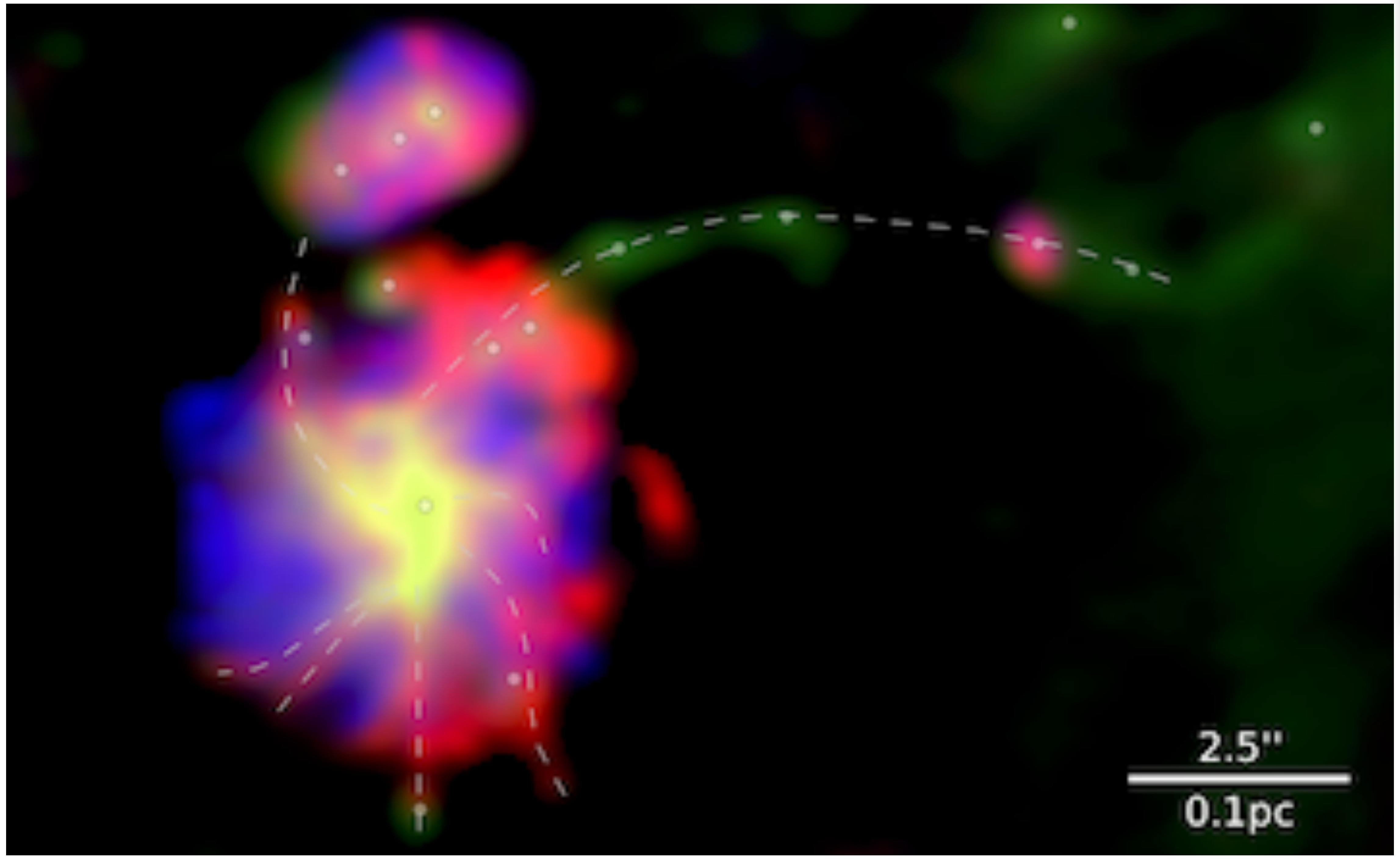
A. Schwörer et al. 2019

Observational evidence for hot cores: Sgr B2

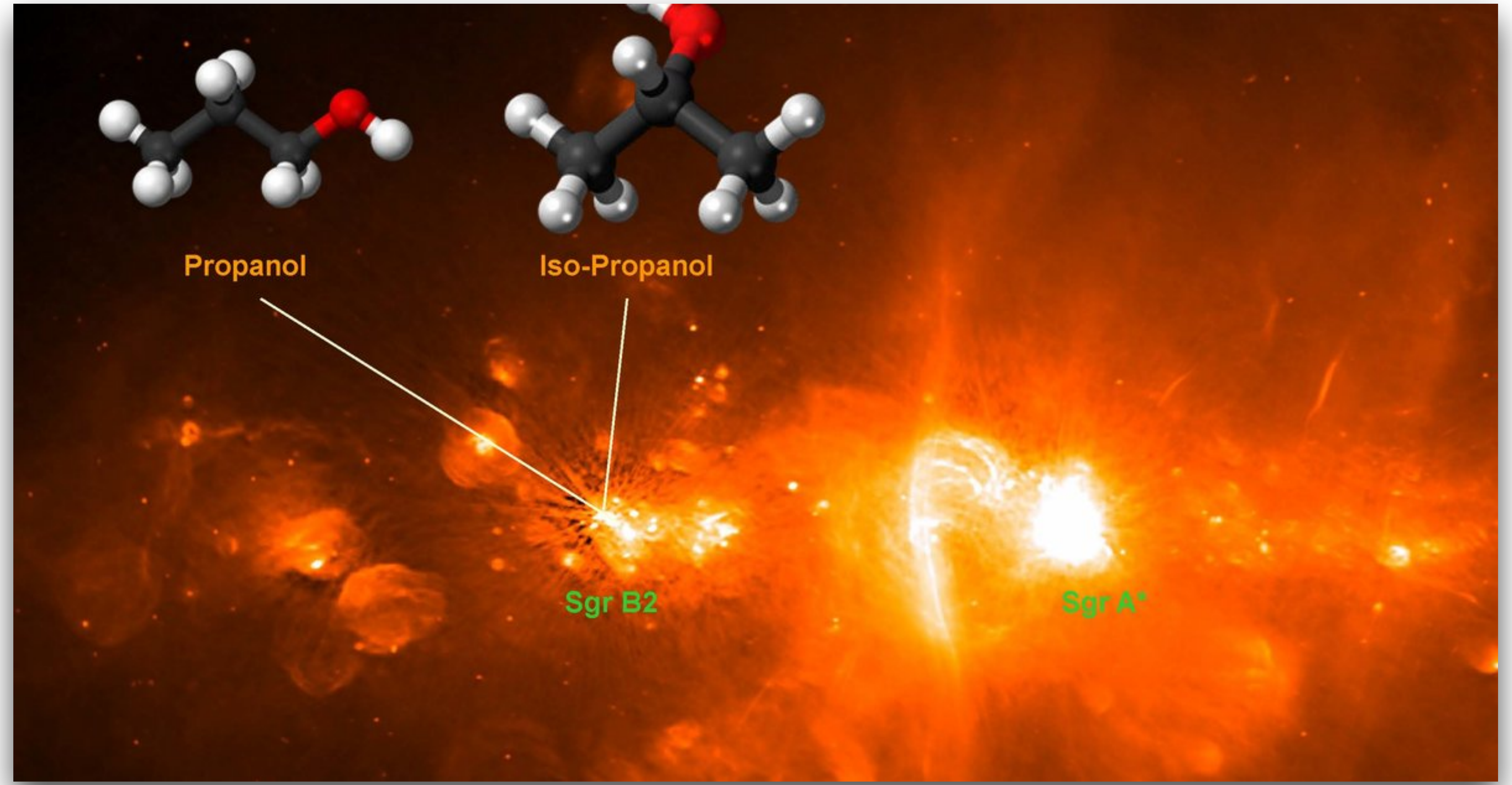
Chemical complexity: alcohols, iso-propyl cyanide, N-methylformamide, urea

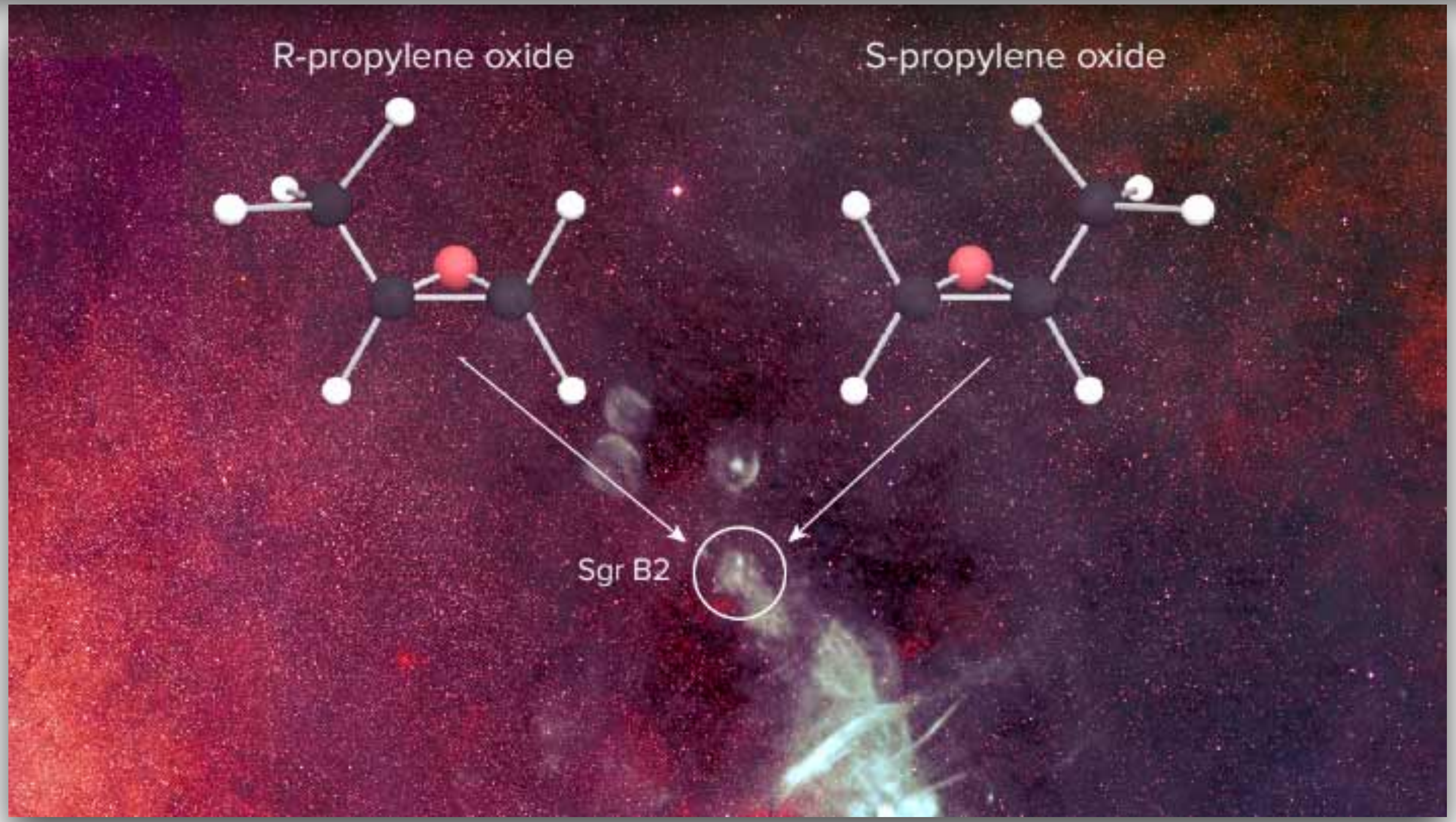
Bruntaler et al. 2021

First chiral molecule detected in space: propylene oxide



A. Schwörer et al. 2019

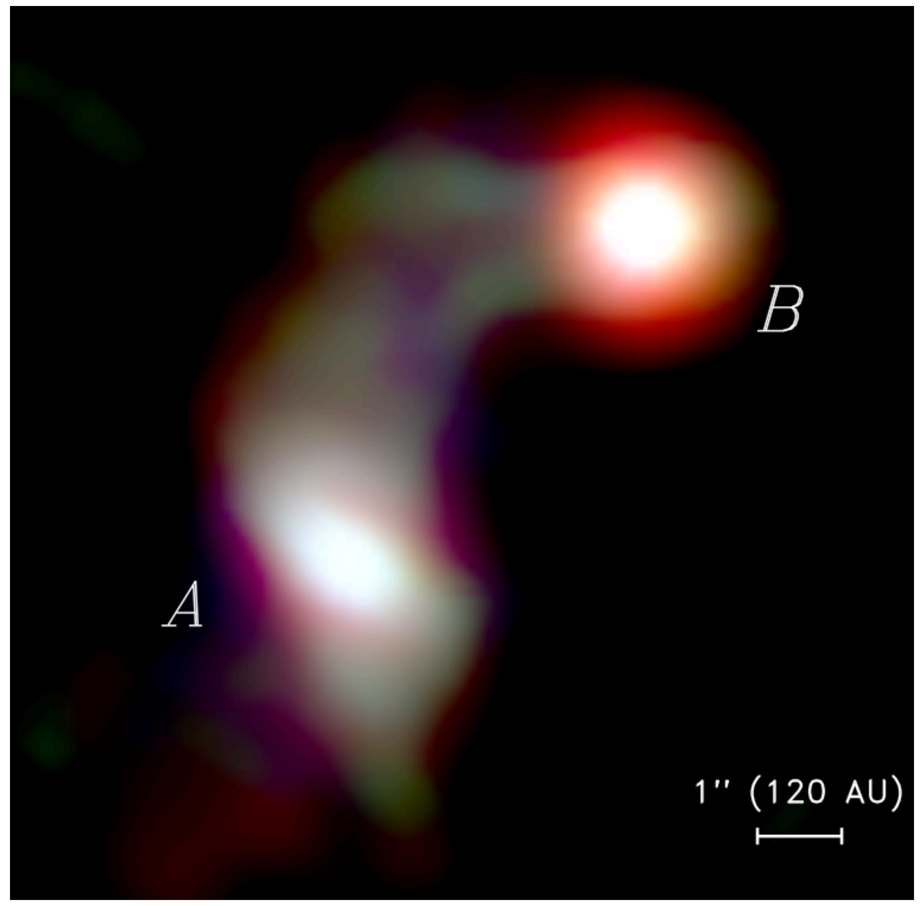


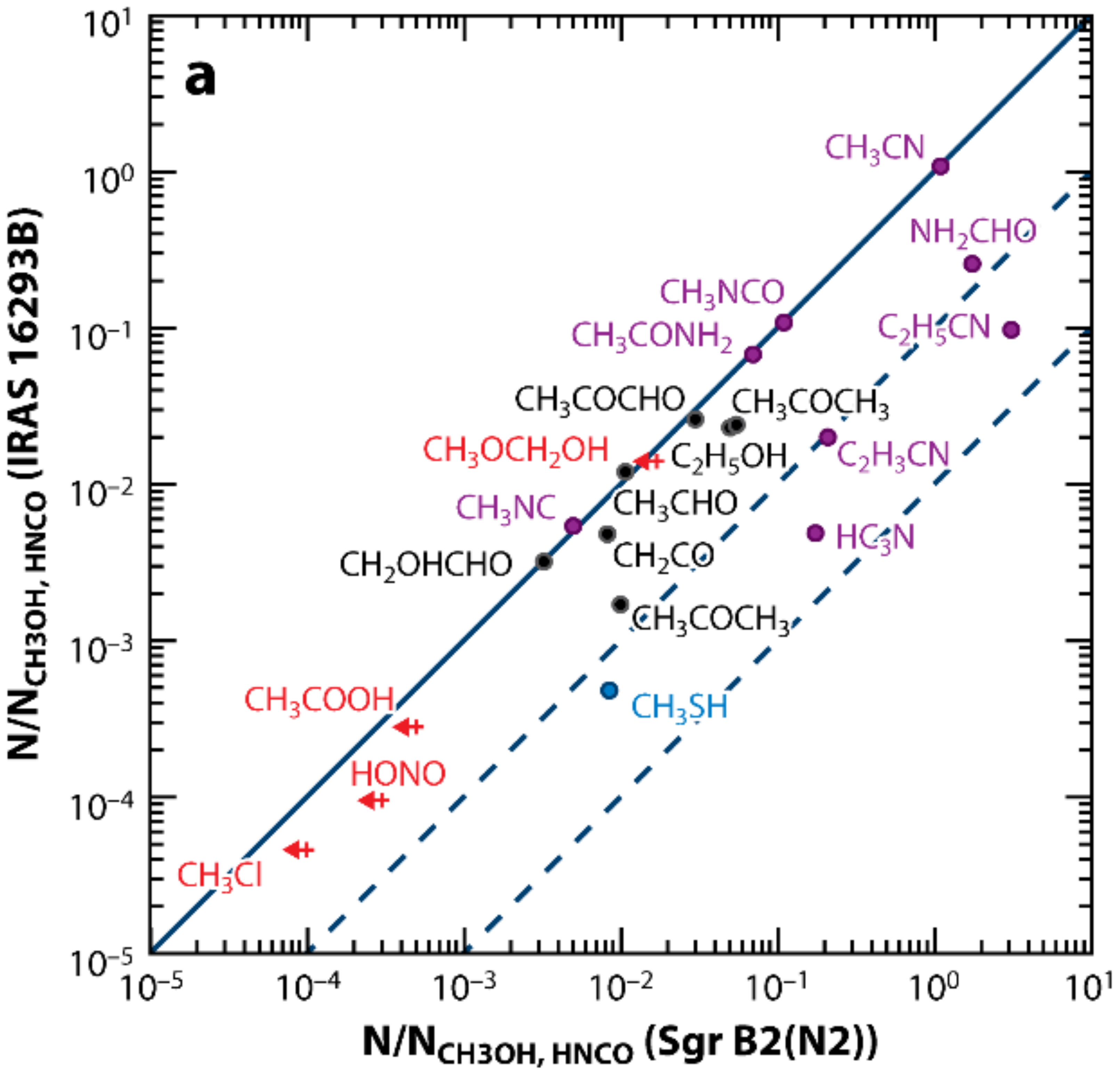


B. Saxton/NRAO

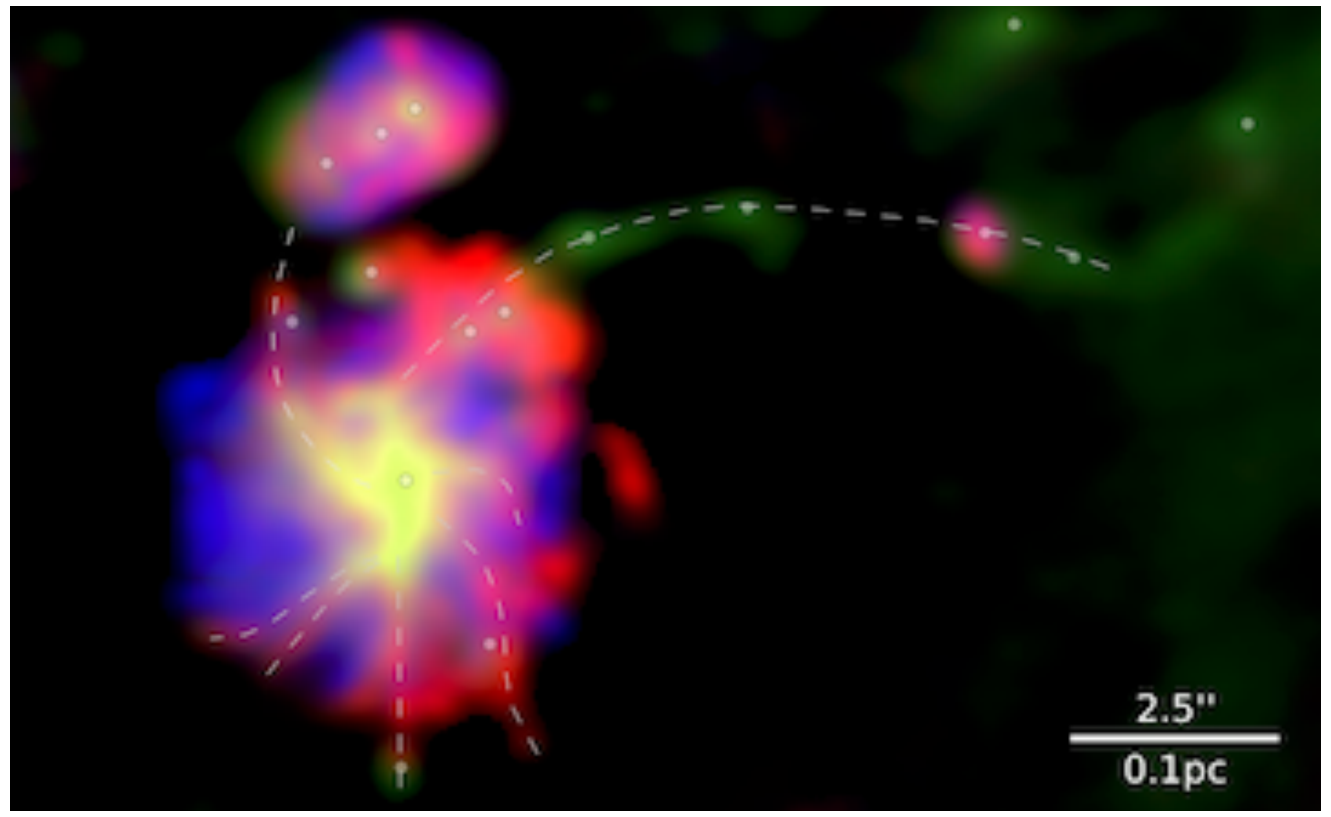
Chemical abundances in high-, low-mass protostars are similar

IRAS 16293-2422





Sgr B2 (N2)



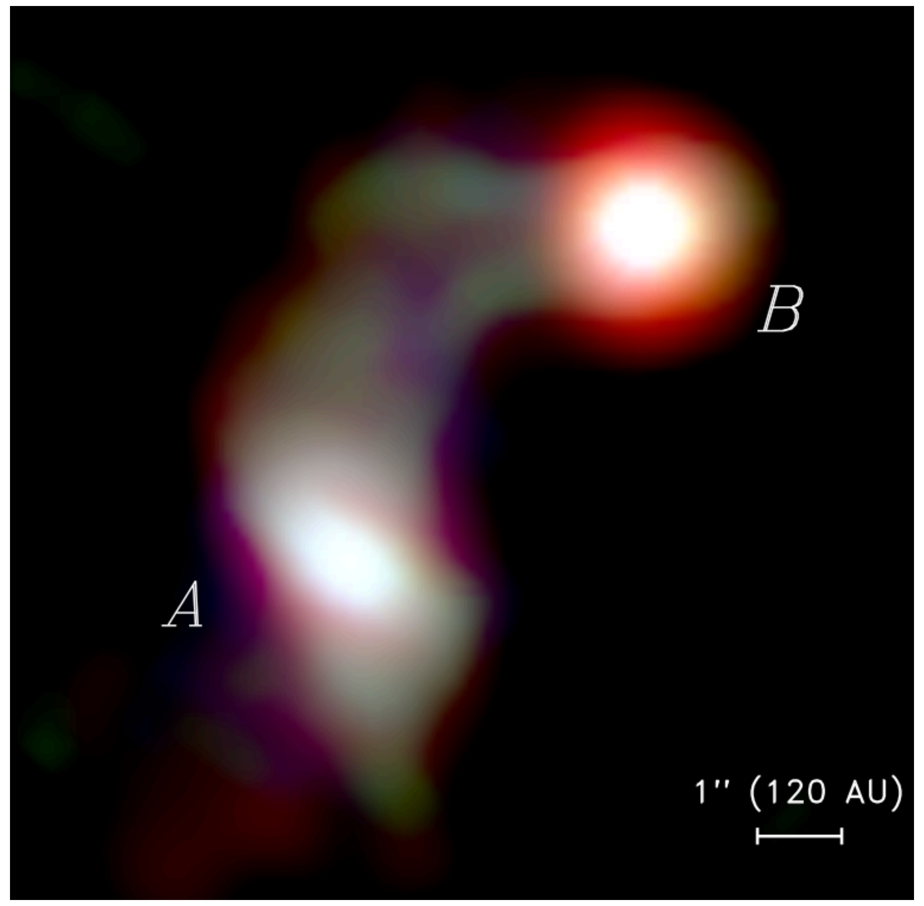
Abundances measured toward different star-forming environments
(high-mass versus low-mass, Galactic center versus Galactic disk) are in good agreement.

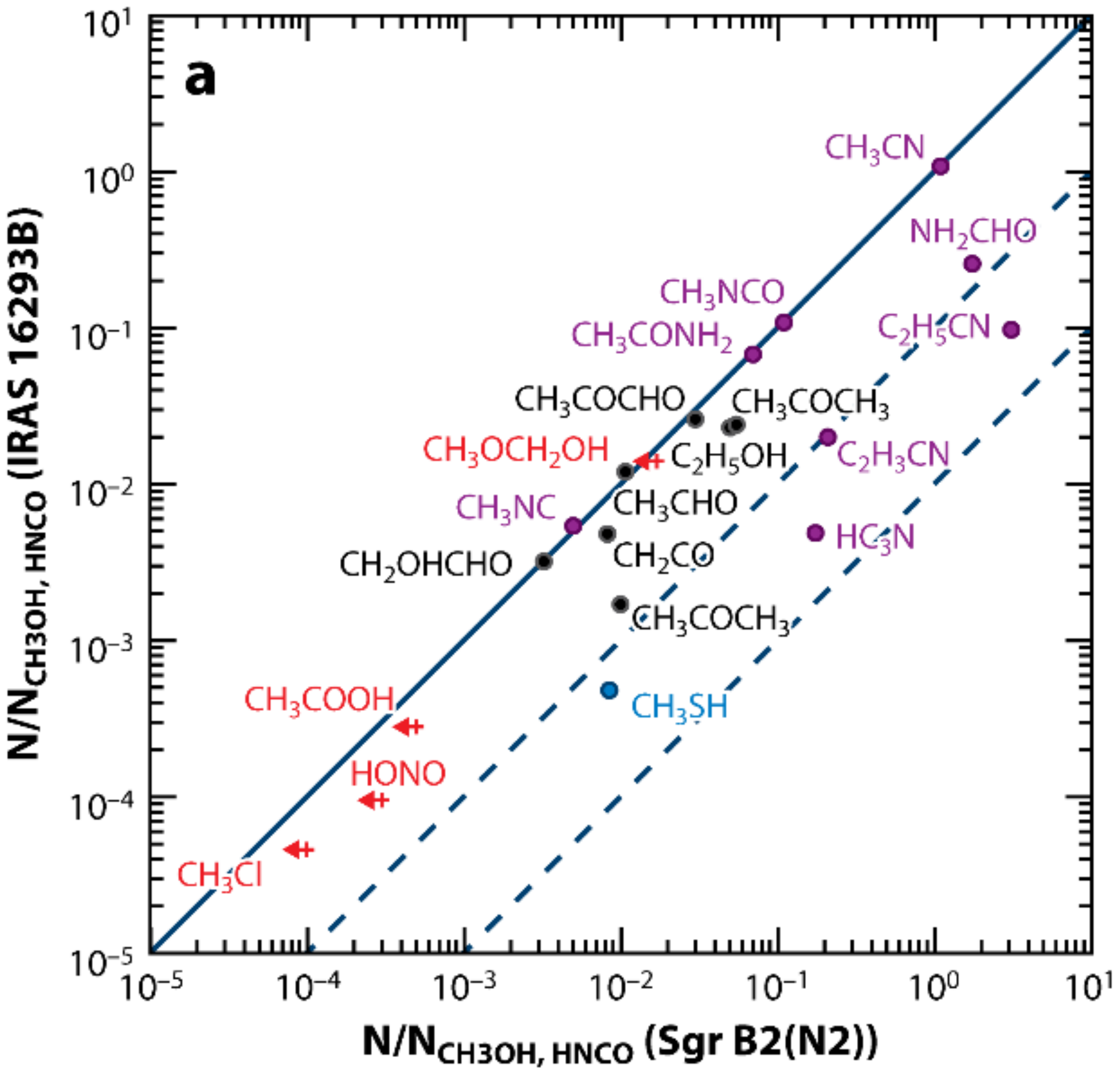
This indicates that the chemistry is relatively independent of variations in their physical conditions

Jørgensen et al. 2020

Chemical abundances in high-, low-mass protostars are similar

IRAS 16293-2422





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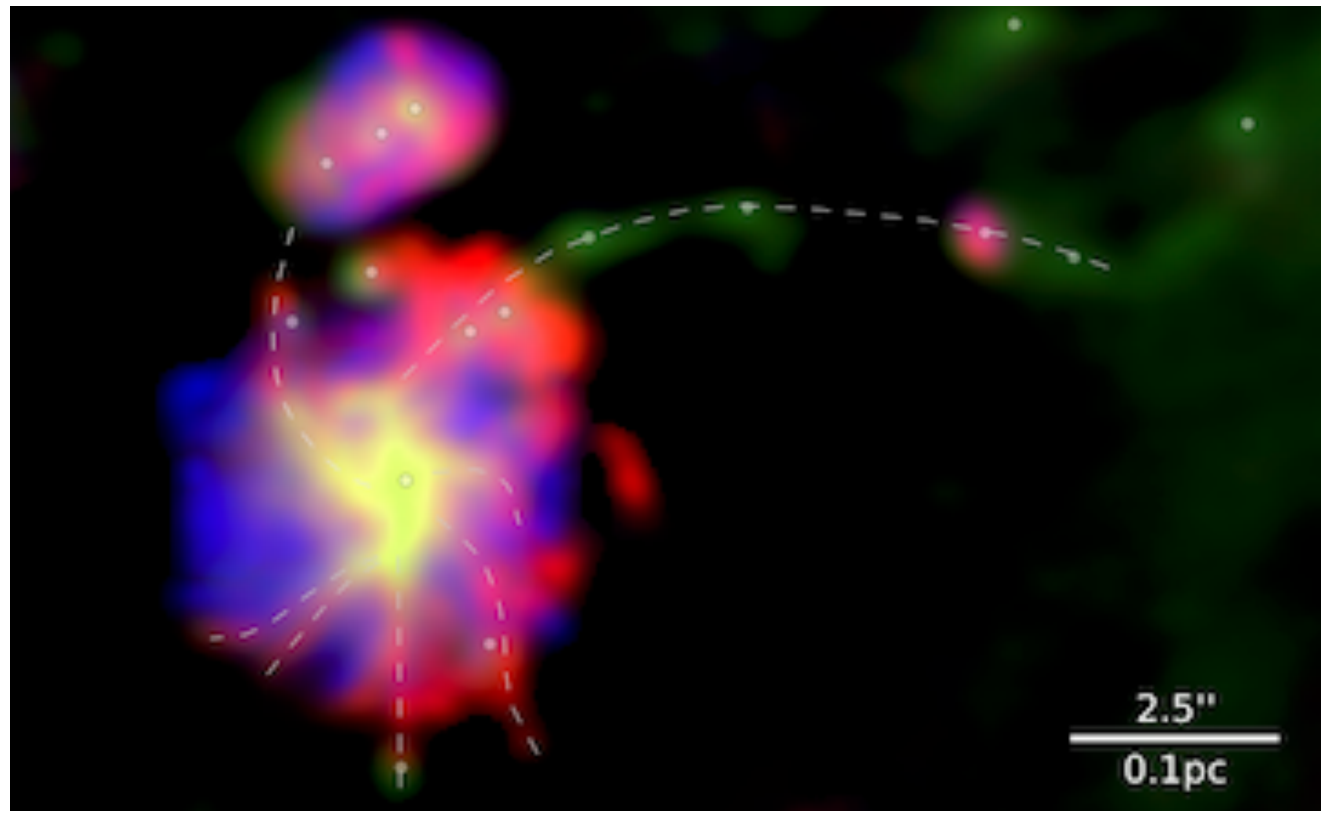

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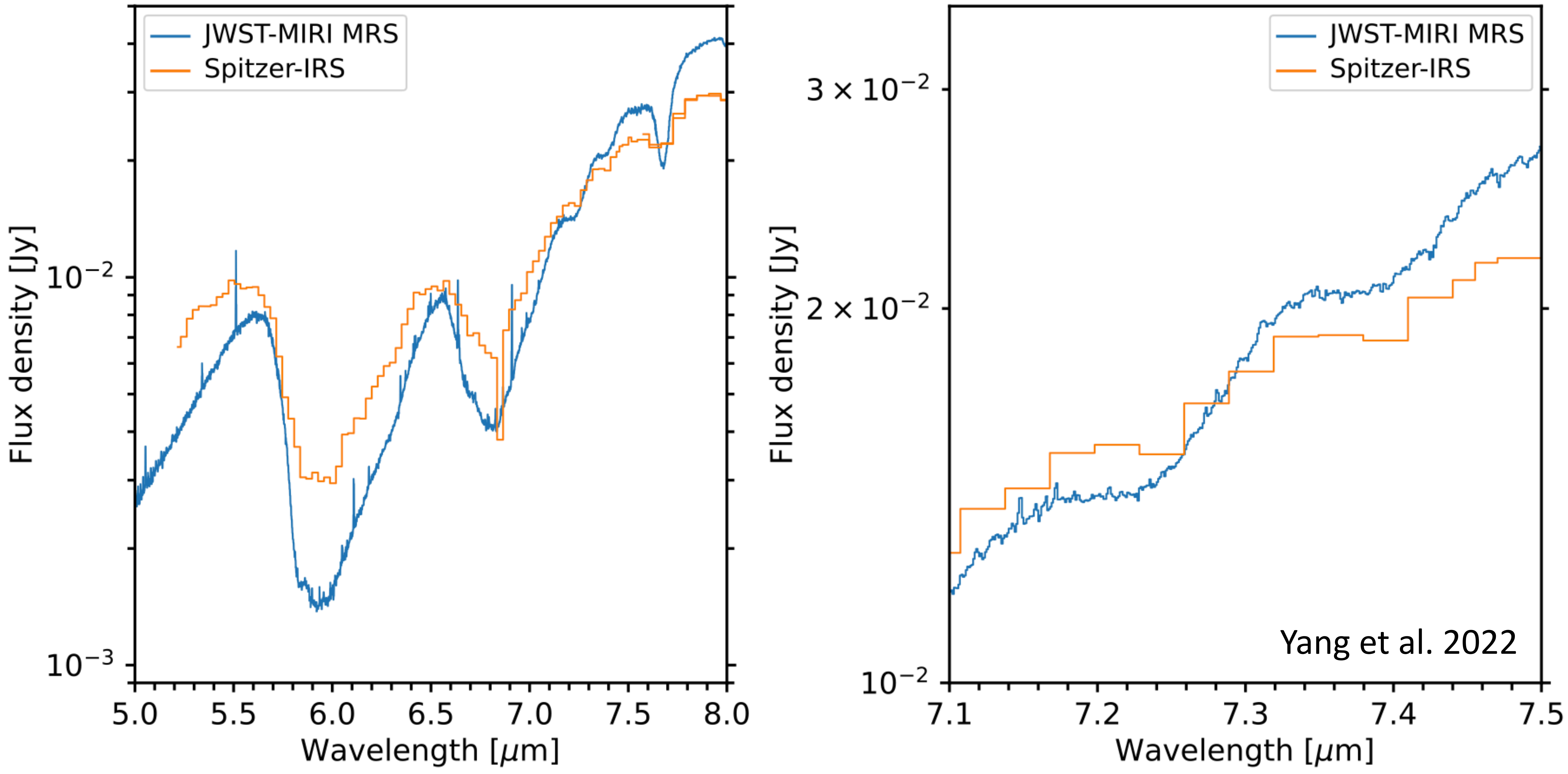
Jørgensen et al. 2020

Outline

- Physical structure
- Chemical structure
- Observations of molecules in protostellar envelopes
- **New era of discoveries with JWST**

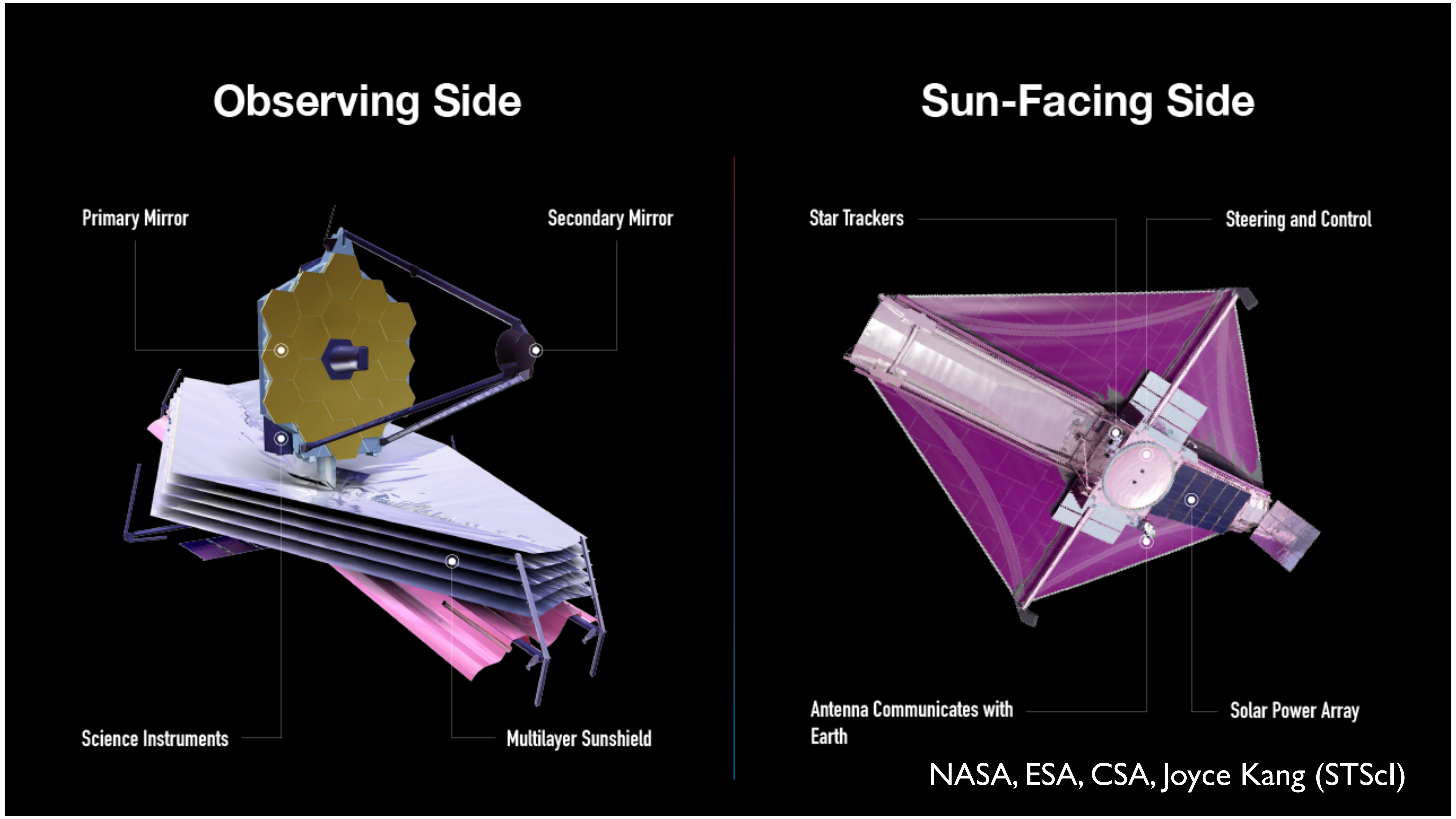
Pre-JWST times

Spitzer Space Telescope: long bandwidth but low spectral resolving power $R = \frac{\lambda}{\Delta\lambda}$

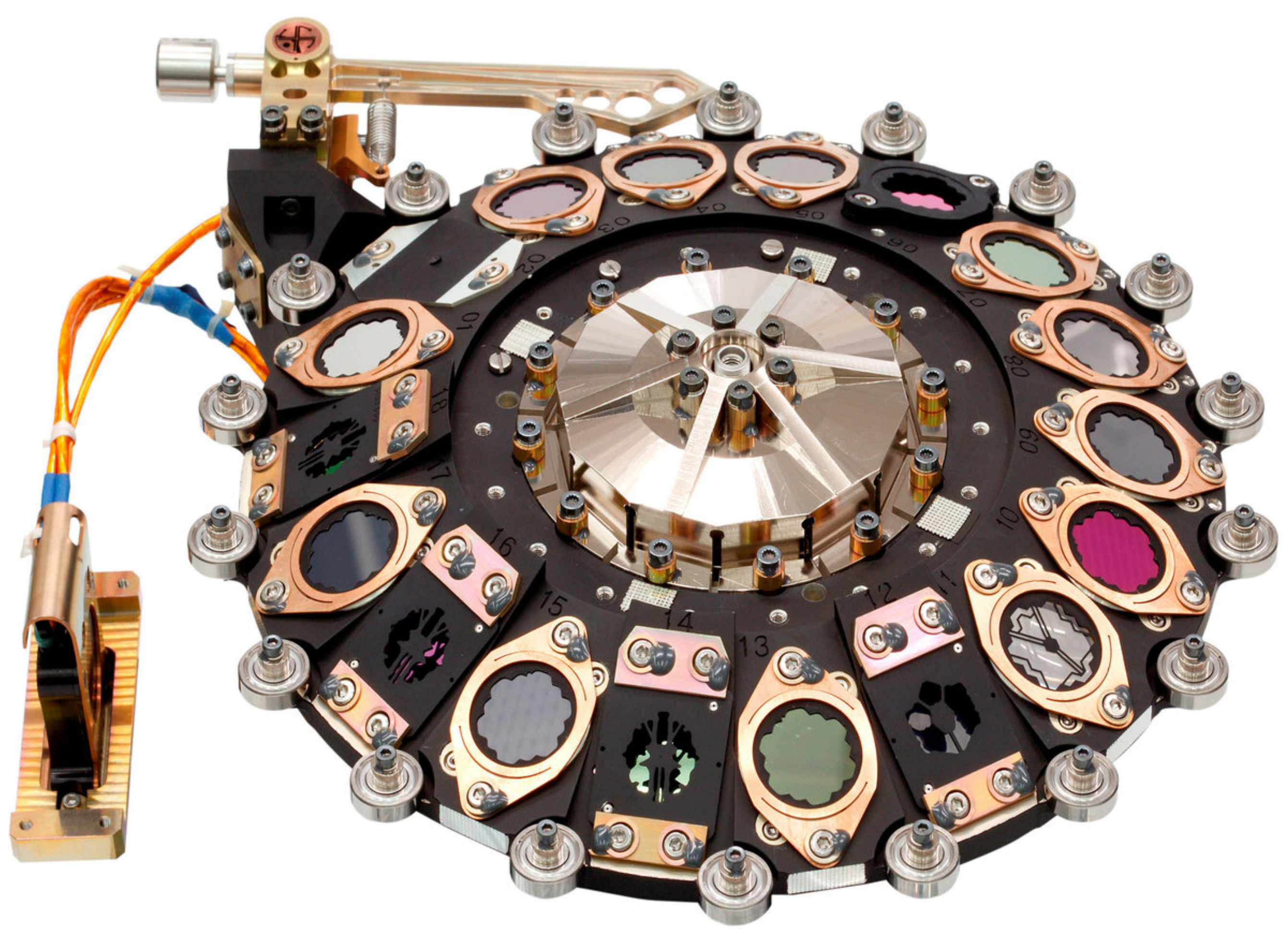


With Spitzer it was often challenging to detect molecules in the solid-state due to low signal-to-noise ratio.

James Webb Space Telescope (JWST)



Diameter = 6.5 m
Halo orbit around L_2 point
Operation temperature = 50 K (-223°C)
Wavelength coverage = 0.6 - 28 μm
Instruments: NIRCam, FGS-NIRISS, NIRSpec, MIRI
Mission duration: 10 yrs (planned), 20 yrs (expected)

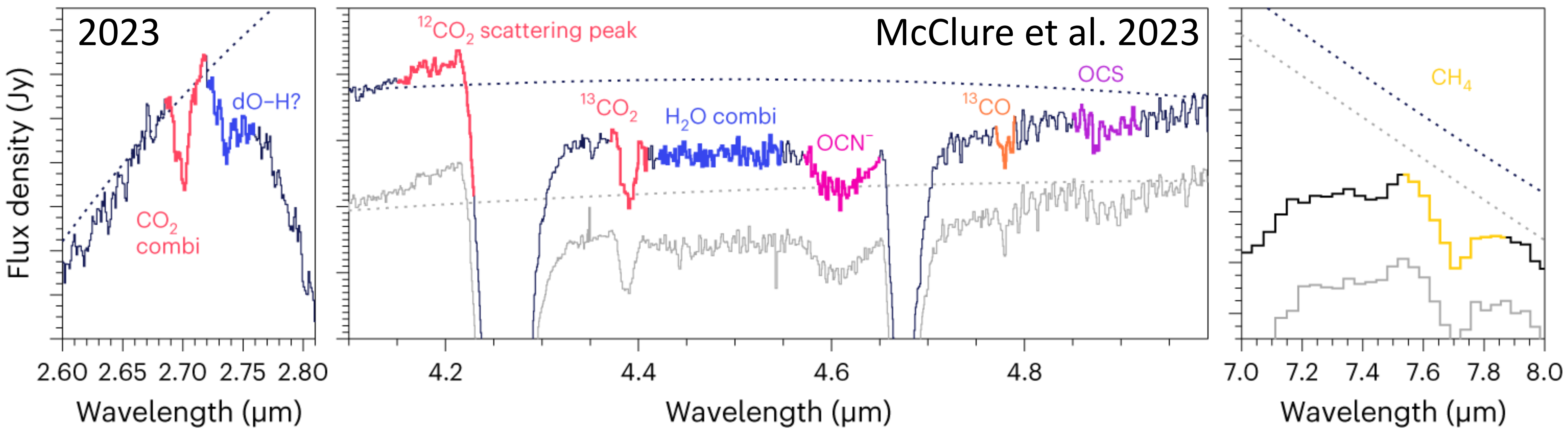


MIRI filter wheel developed at MPIA

JWST ERS Ice Age

JWST ERS Ice Age

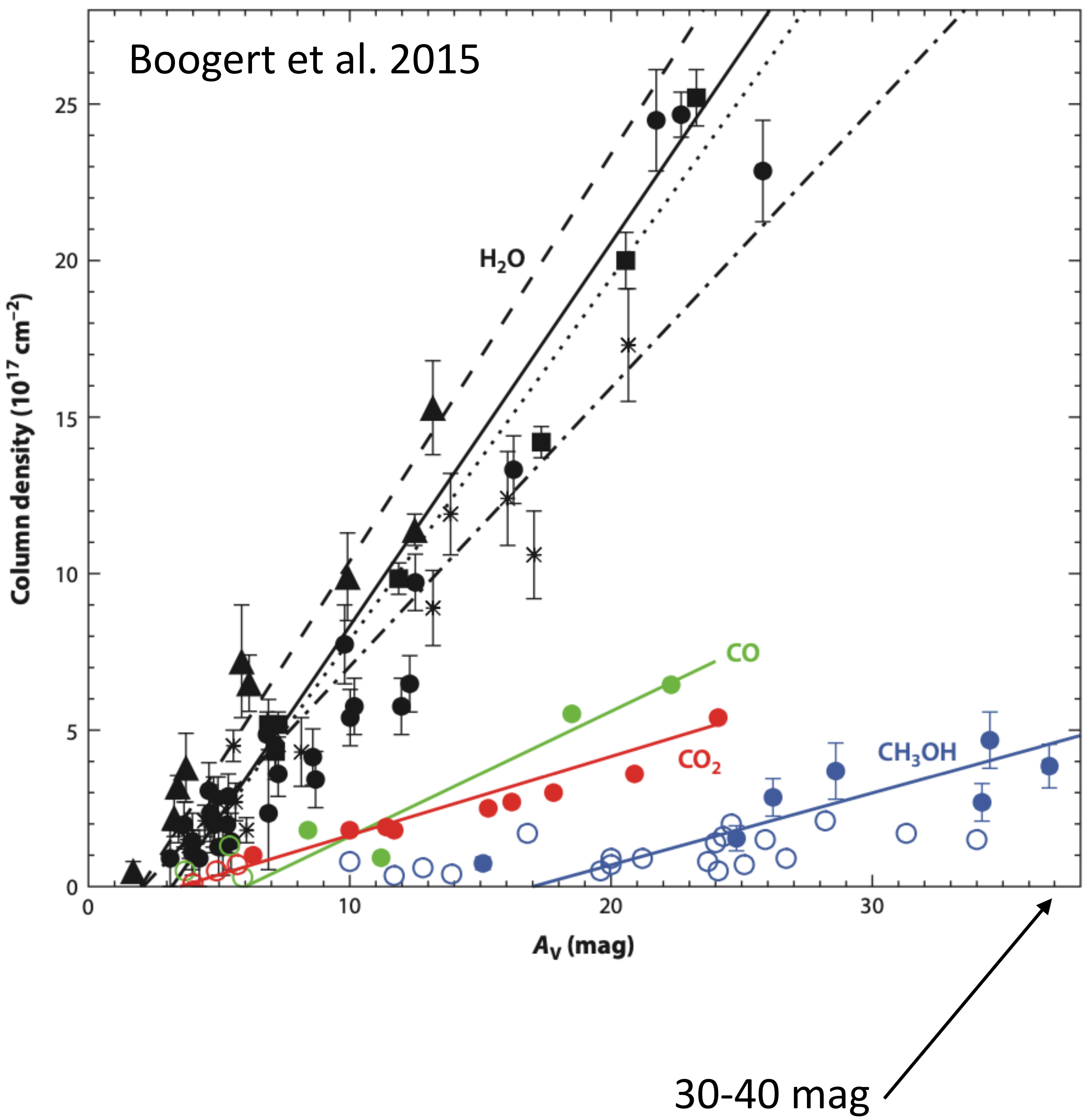
The study of interstellar ices at high visual extinction ($A_V > 60$ mag)



The sensitivity of JWST enables the identification of weaker ice species e.g., OCN^-, OCS, ^{13}CO, $^{13}CO_2$

It is also possible to understand what is the composition of the ice at visual extinction > 60 mag. Before JWST we mostly explored the parameter space up to 40 magnitudes.

Ice formation and growth as function of visual extinction (A_V)



Summary

- The study of the physical and chemical evolution of protostars gives constraints on our Solar System formation
- Low-mass protostars tend to form in clusters and they are classified based on three indicators
- High-mass star formation is challenging to constrain
- Protostellar envelopes are chemically rich regions (hot cores/hot-corinos)
- Unbiased line surveys are useful to understand chemical and physical processes during star formation

Giulia Perotti: perotti@mpia.de

Useful resources

- Boogert, Gerakines and Whittet 2015, ARA&A
- Ceccarelli et al. 2022, PPVII Chapter
- Dunham et al. 2014, PPV Chapter
- Herbst & van Dishoeck 2009, ARA&A
- Jørgensen, Belloche and Garrod 2020, ARA&A