Chemical map of the Solar System analogues in the embedded stage:

ALMA paves the way for JWST

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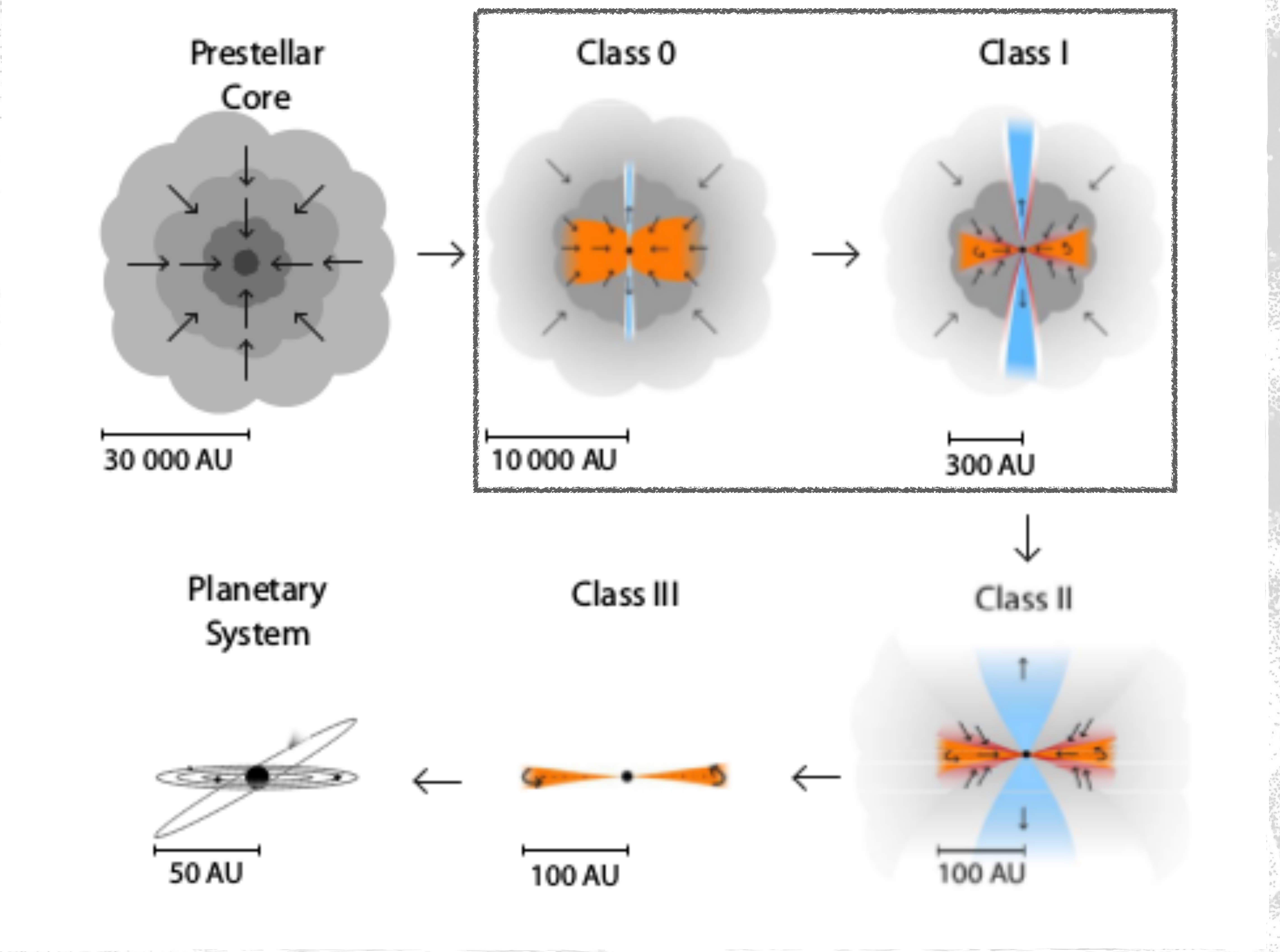
Artwork: Marta Tychoniec
@ambrozona

Formation of Solar System analogues

Lada & Wiliking 1984, Andre+1993

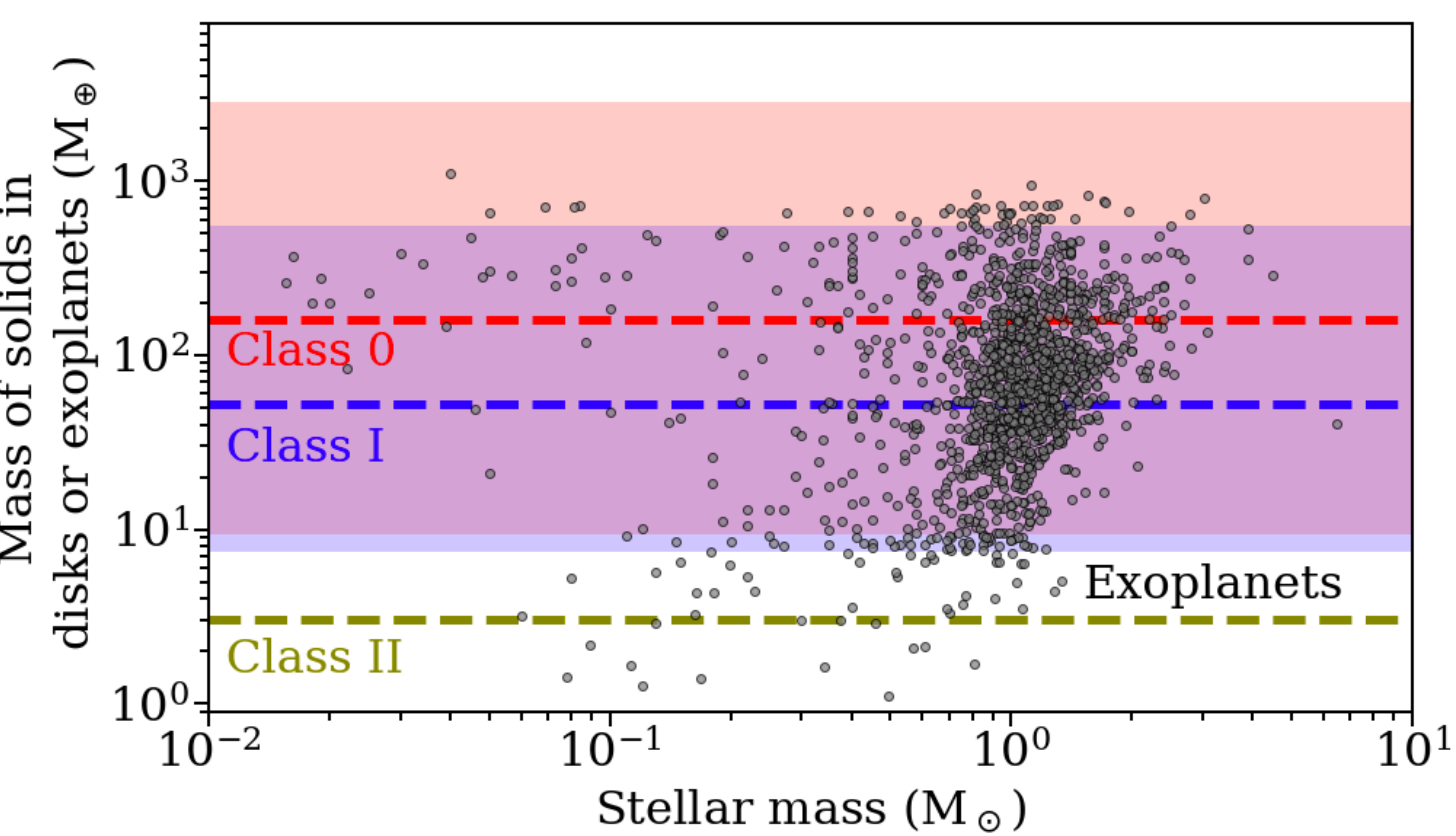
- **Embedded phase**: first 0.5 Myr after the collapse of the natal prestellar core
- This is where the action happens: most powerful outflows and bulk of the mass is accreted
- To understand how Sun and planets are formed we need to focus on this stage

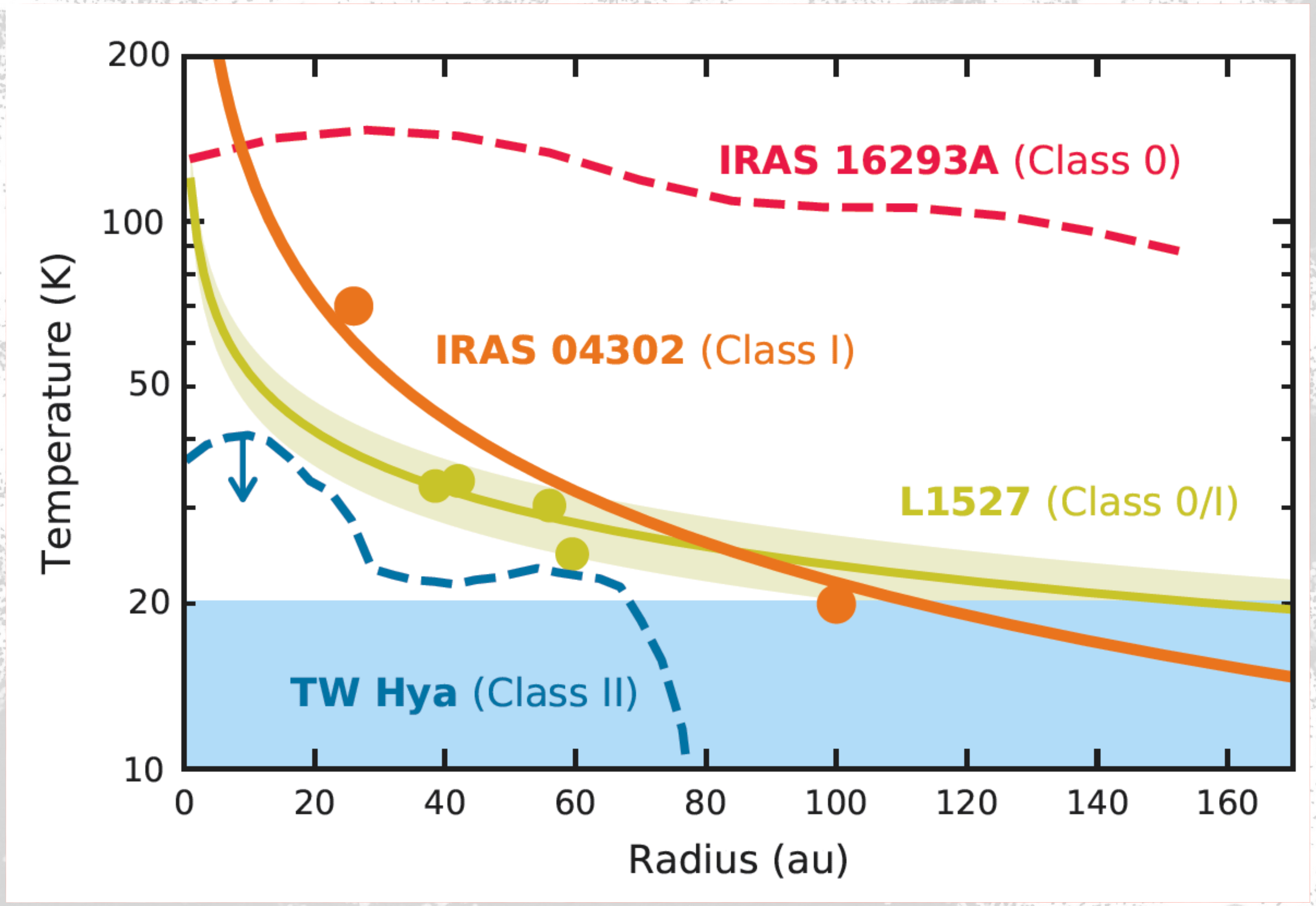


Credit: M. Persson

Importance of the embedded stage

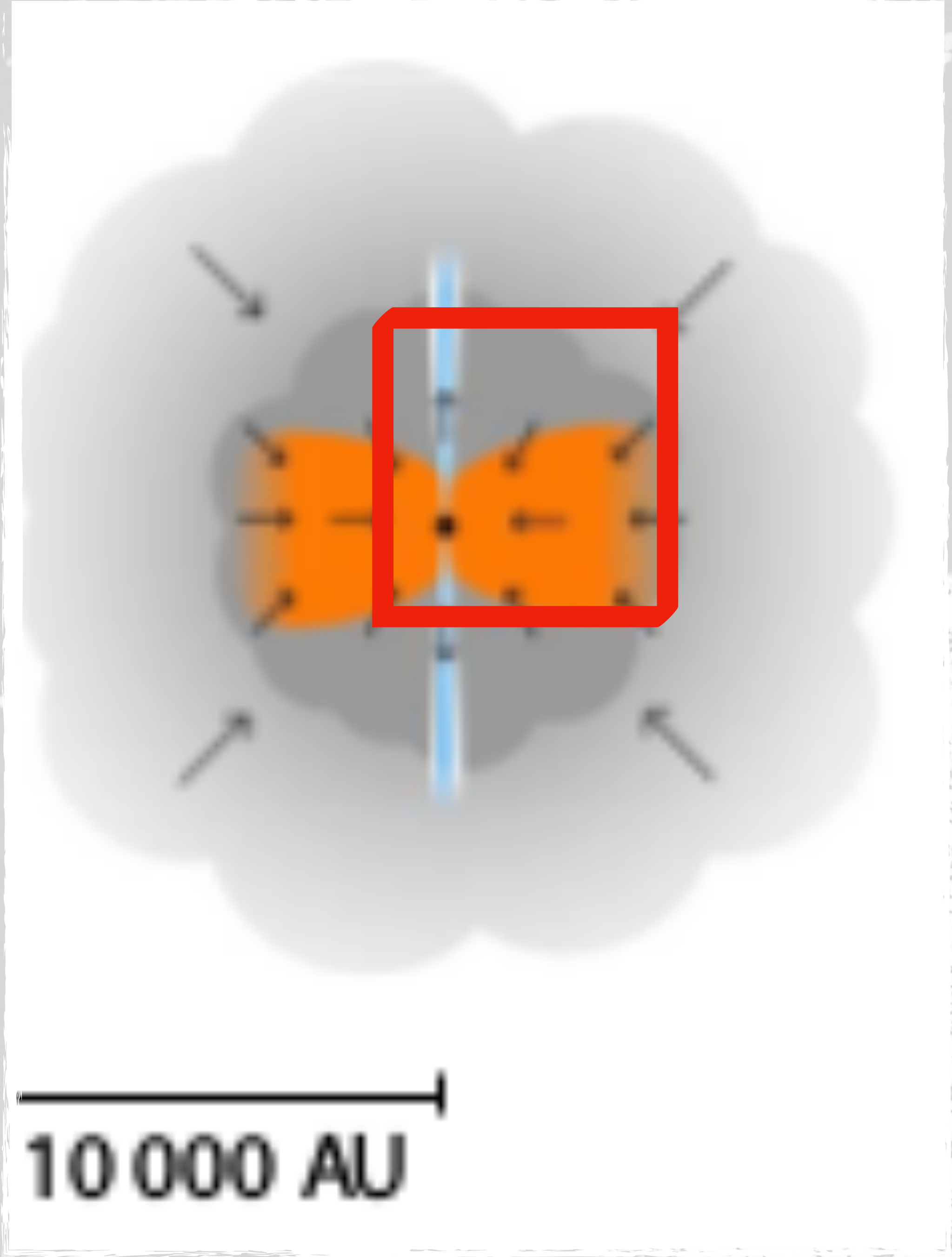
Tychoniec+2020, van 't Hoff+2020

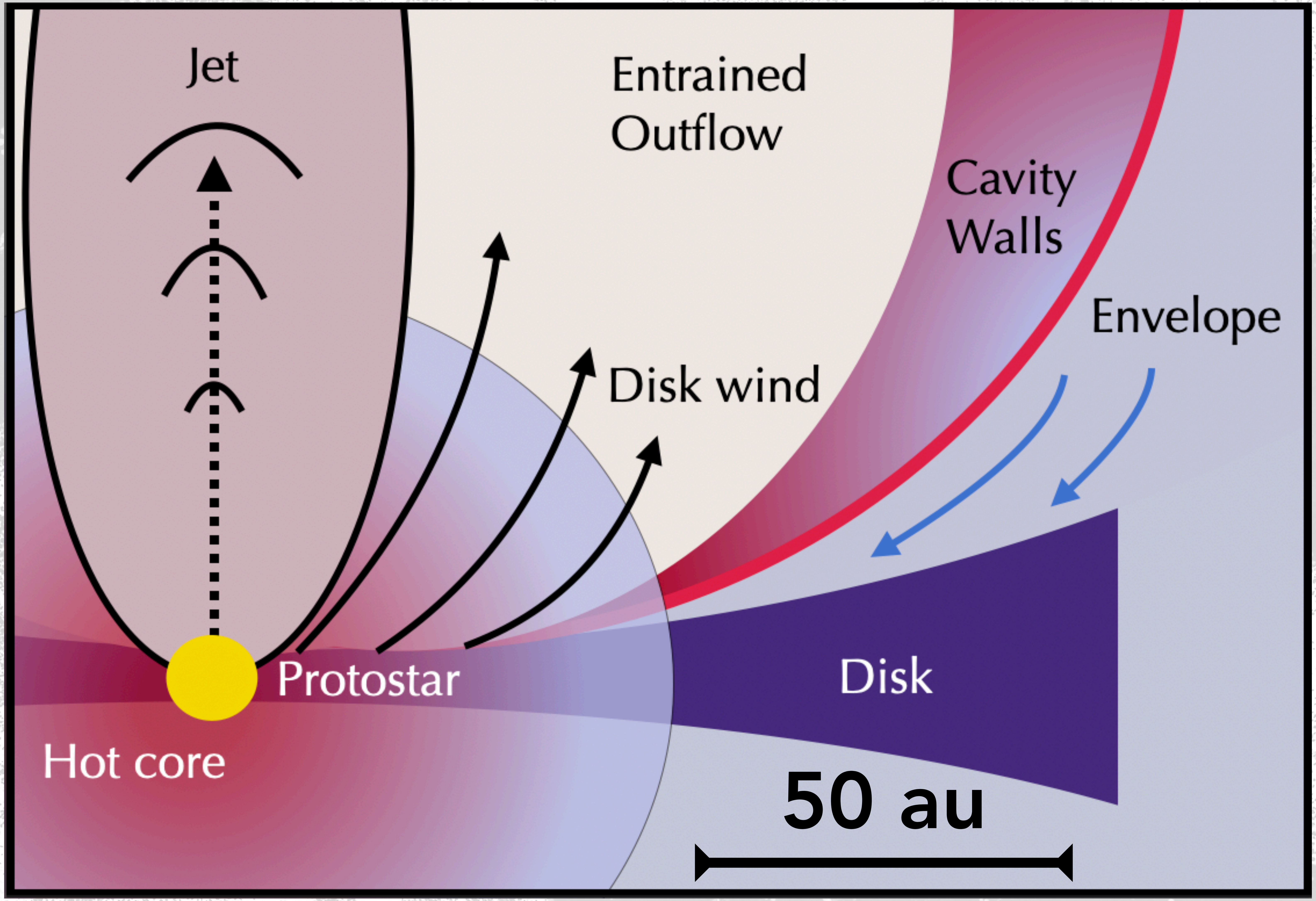




Planet formation likely starts in the embedded phase

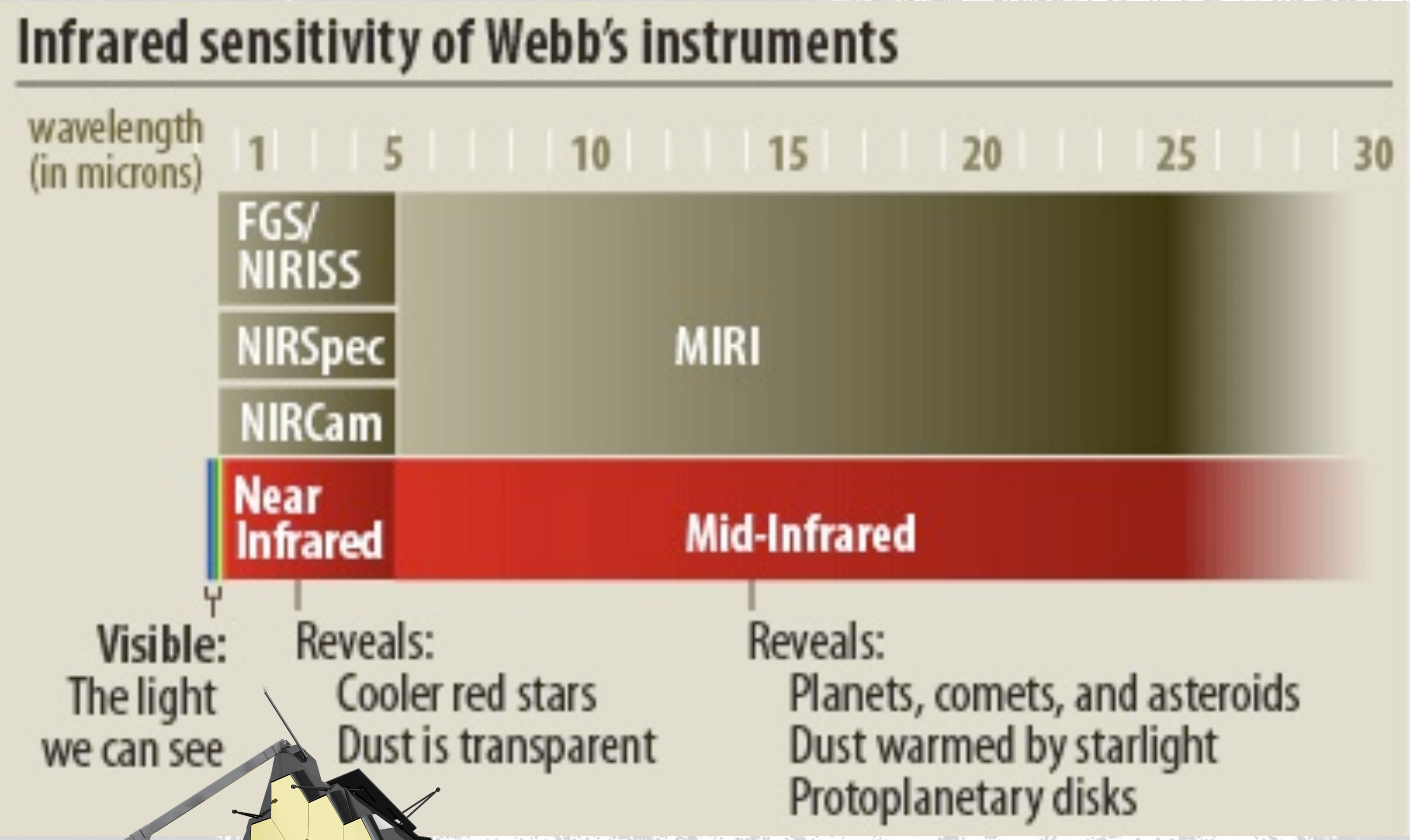
Deconstructing the protostellar system

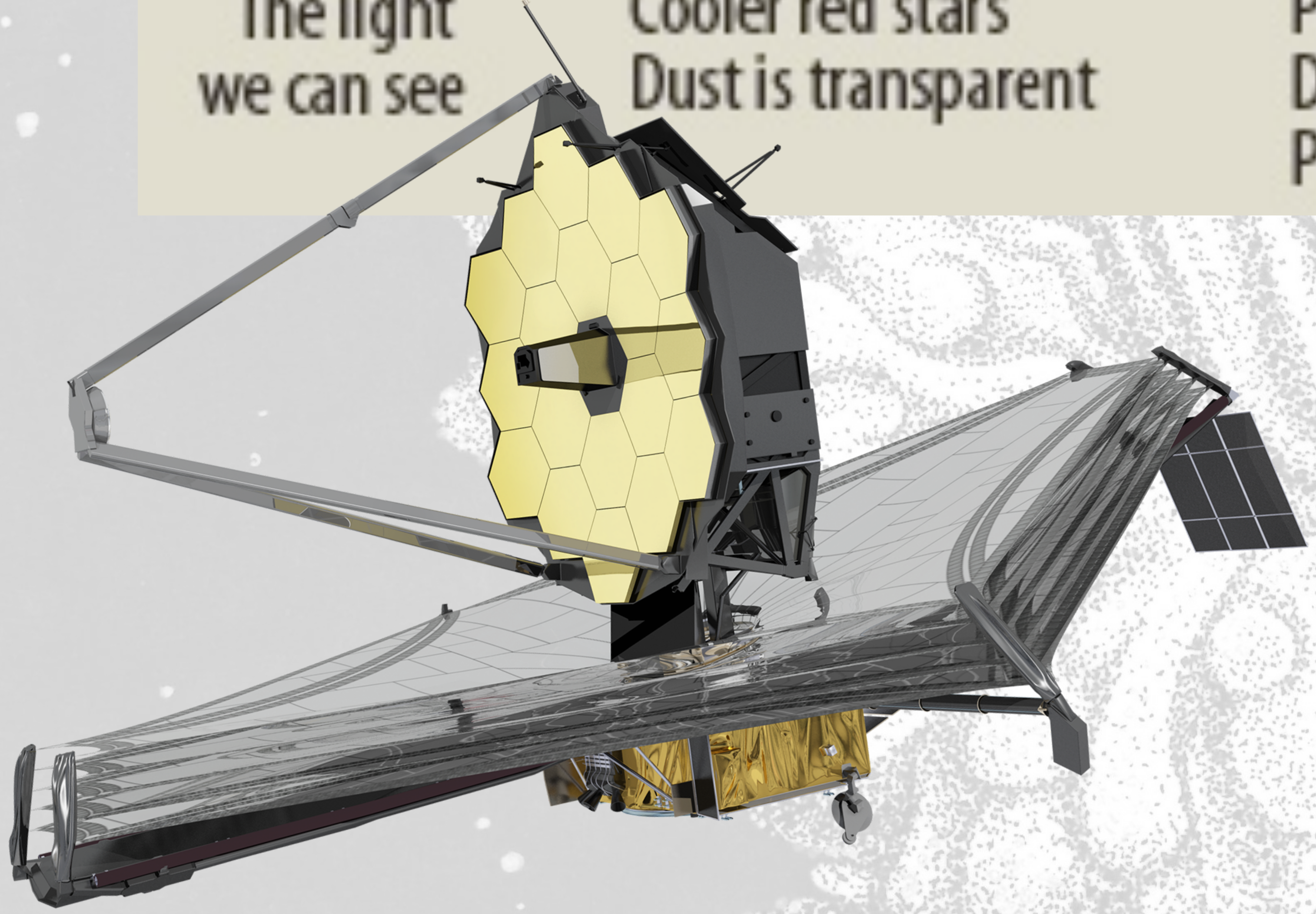


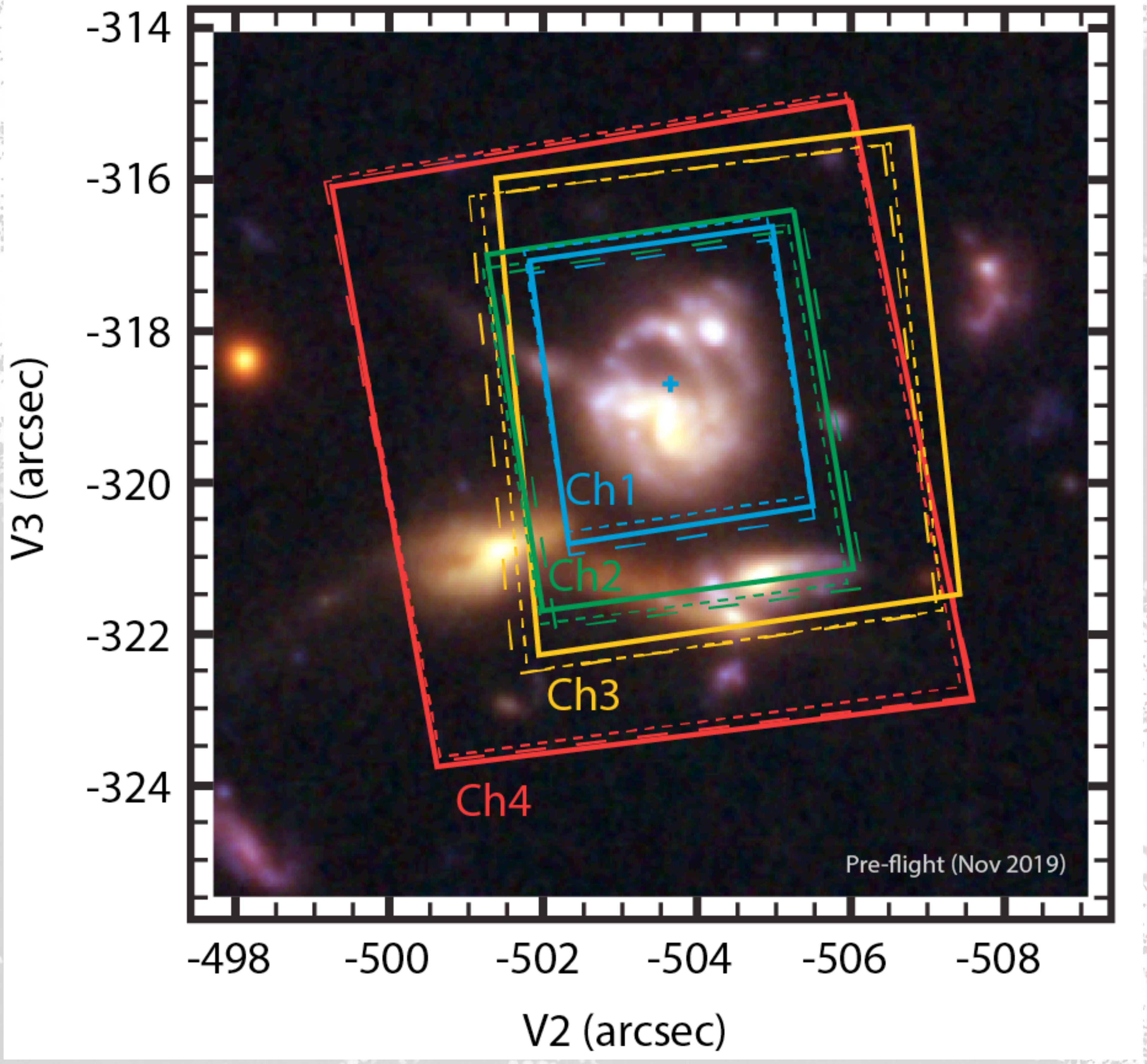


JWST-MIRI: breakthrough in mid-IR spatial resolution

Rieke+2015, Wright+2015, Wells+2015

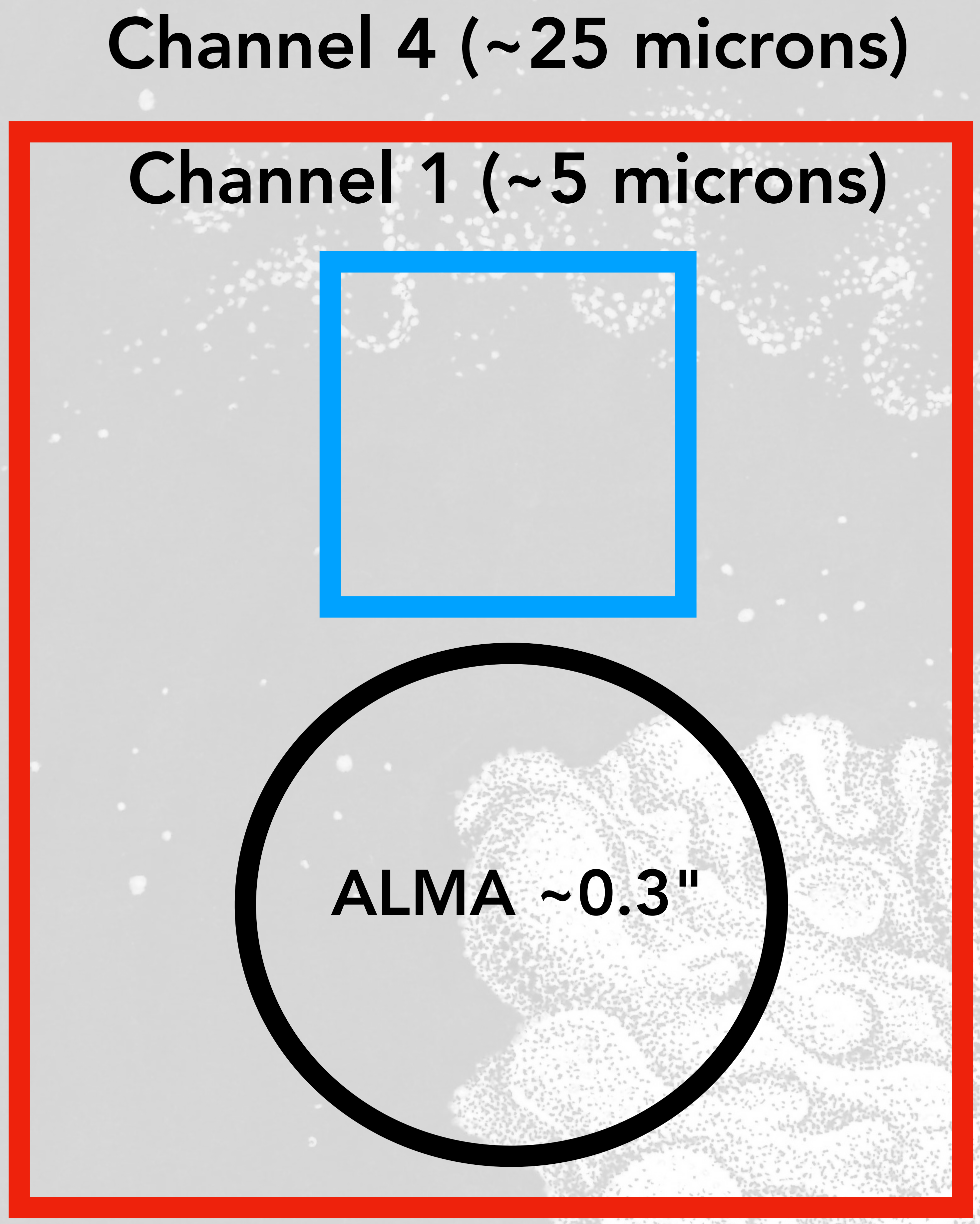


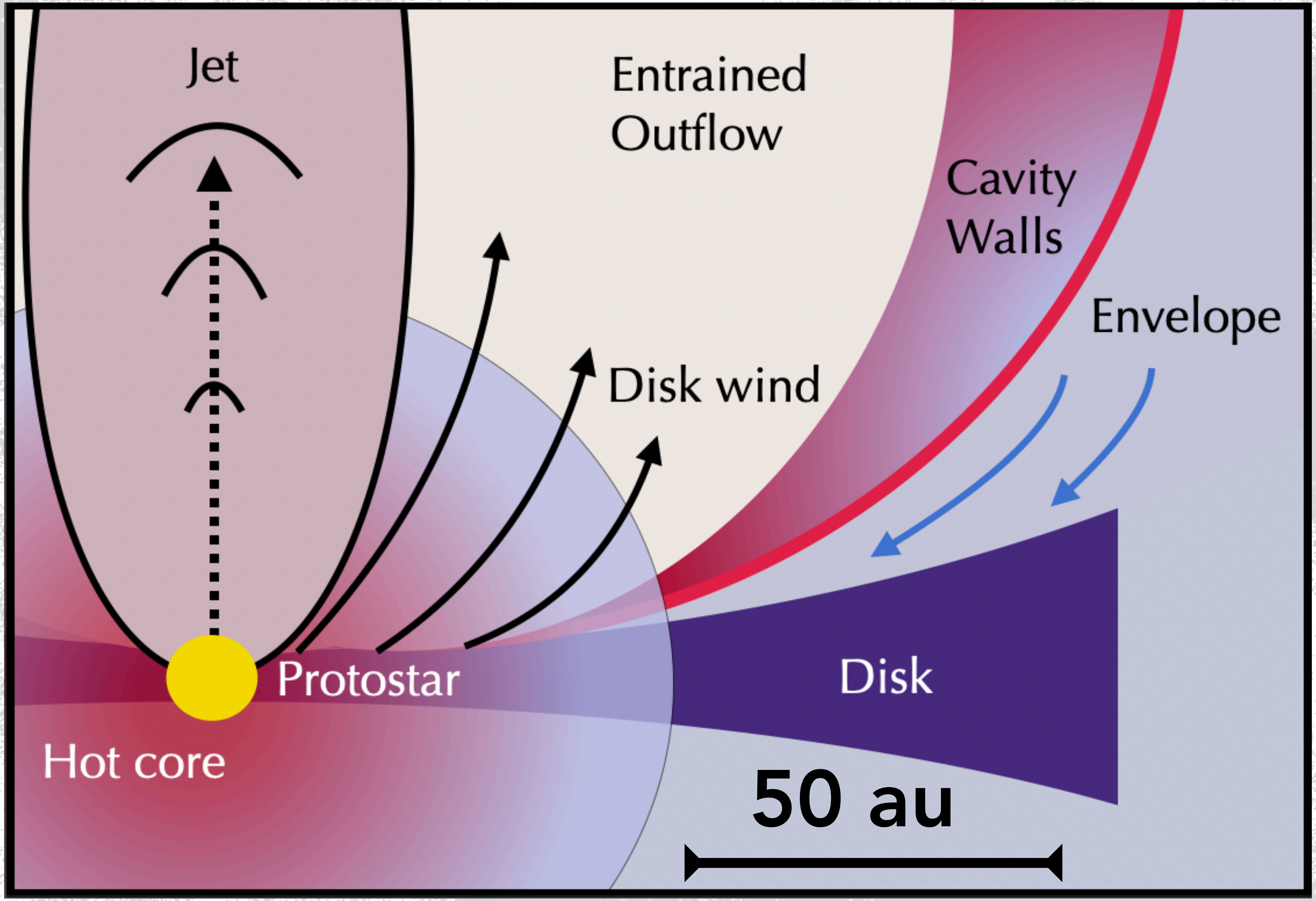




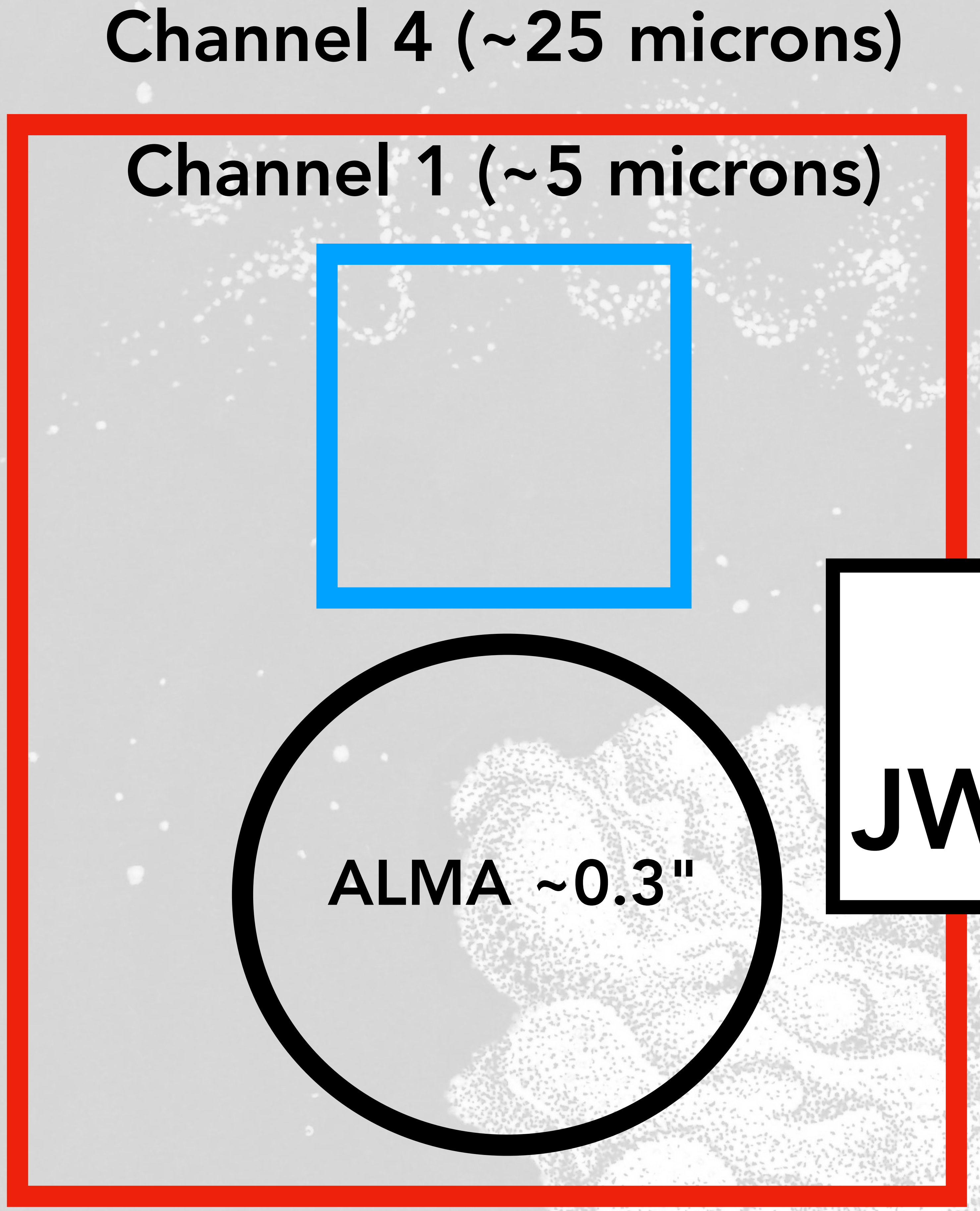
https://jwst-docs.stsci.edu/ nasa.gov

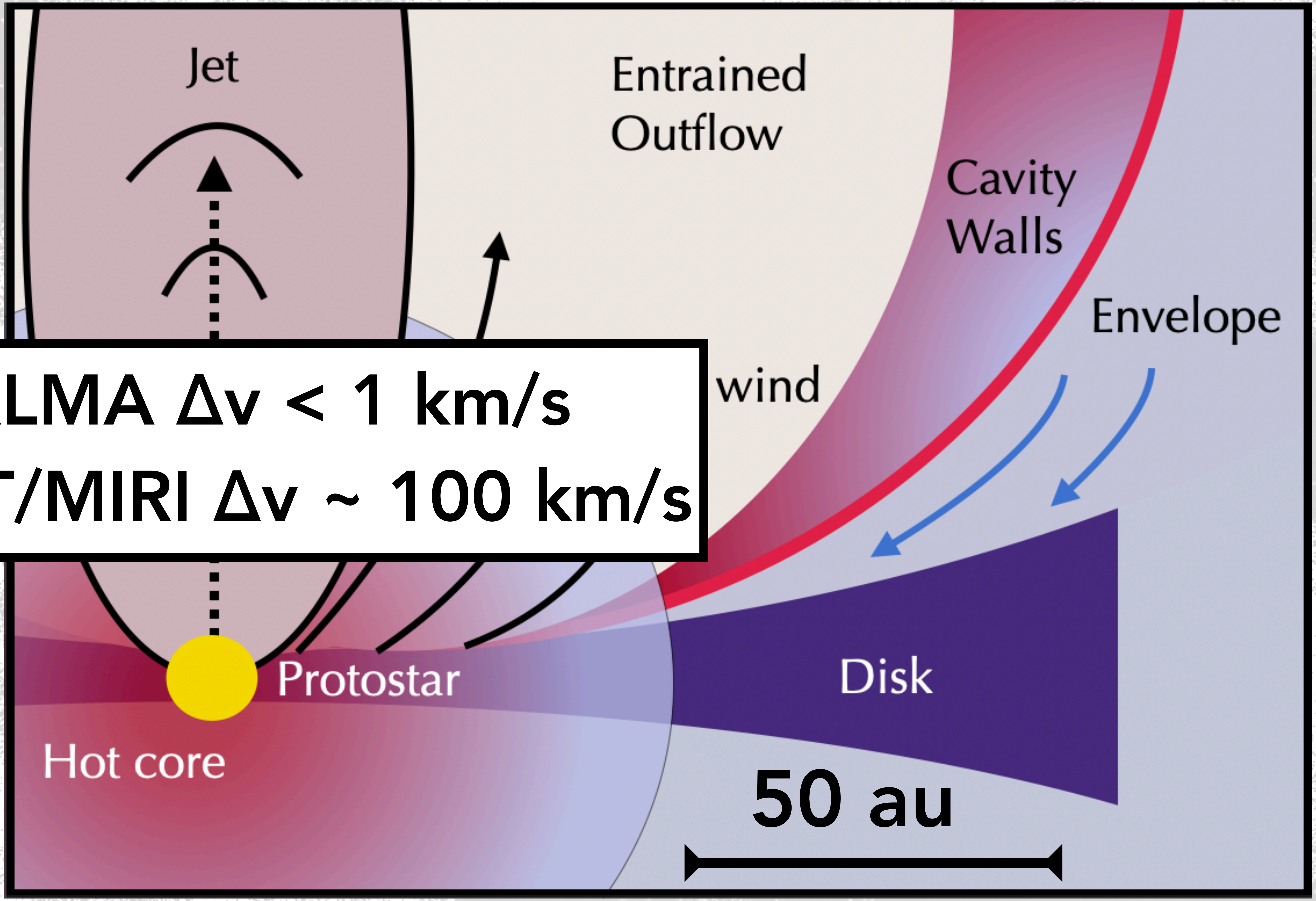
JWST-MIRI: breakthrough in mid-IR spatial resolution





JWST-MIRI and ALMA synergy





ALMA Δv < 1 km/s

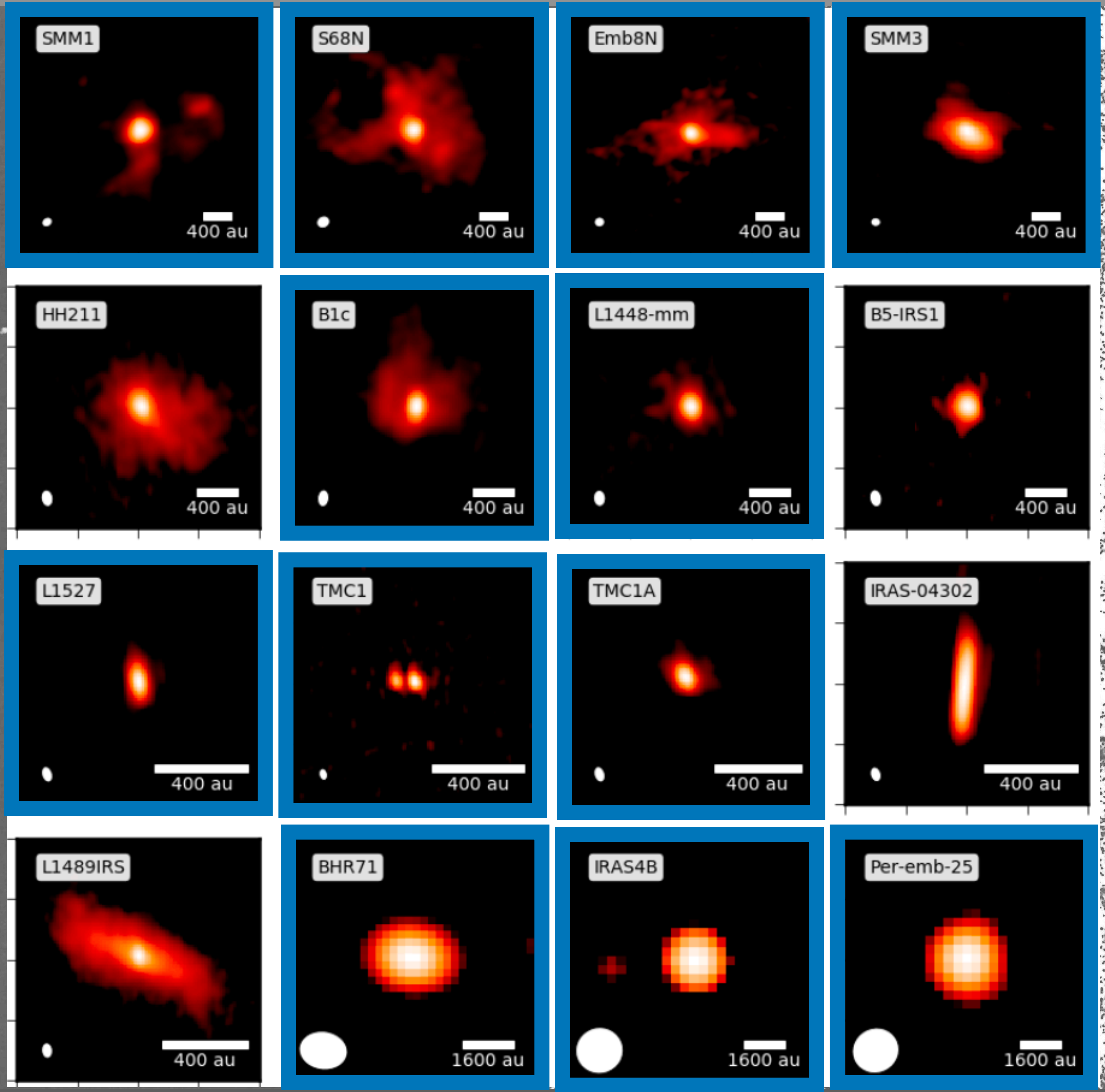
JWST/MIRI Δv ~ 100 km/s

Goal:

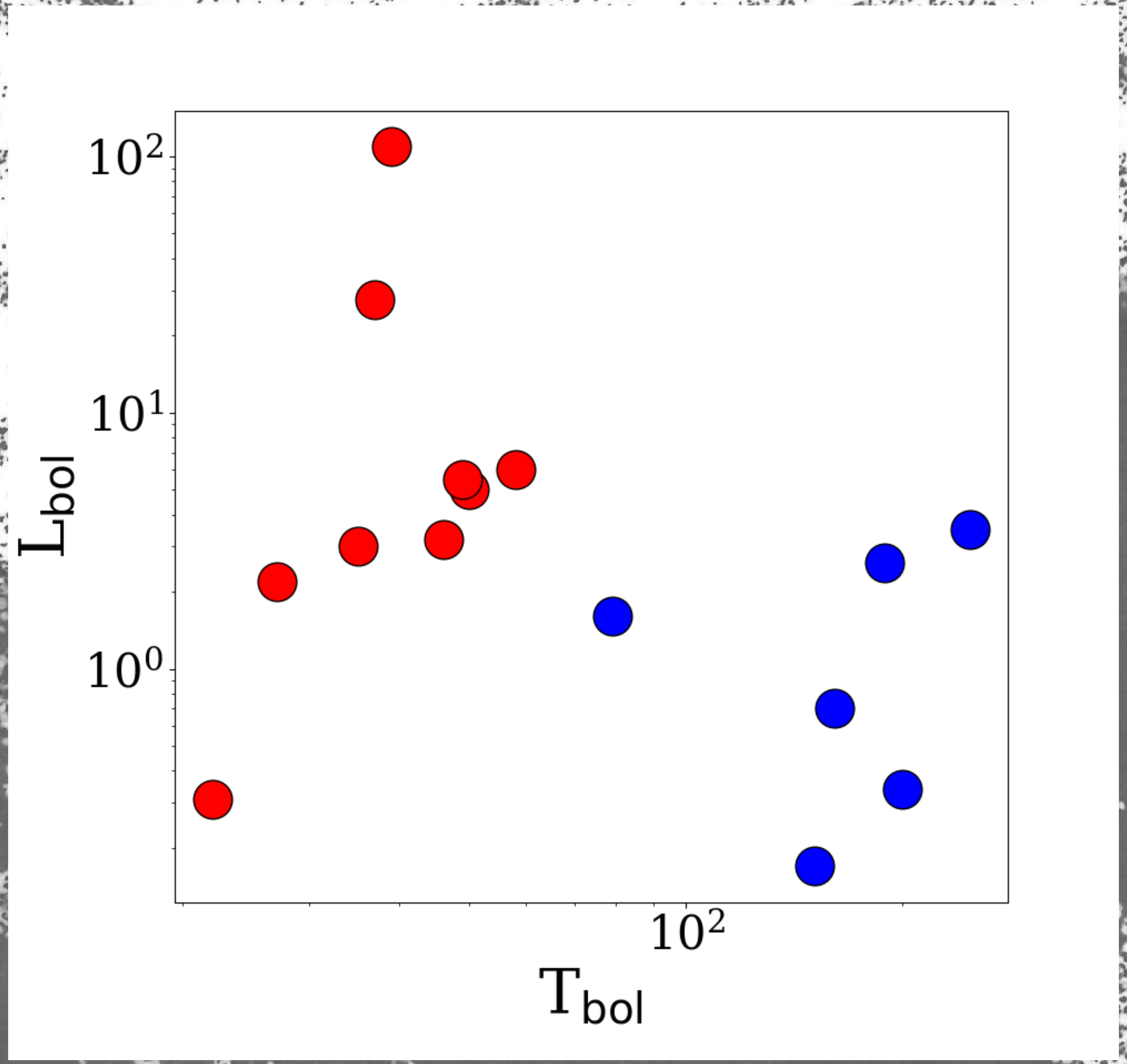
Use observations of chemical tracers to map the kinematics and physics of the protostellar systems

ALMA survey of 16 Class 0/I protostars

Tychoniec+2021



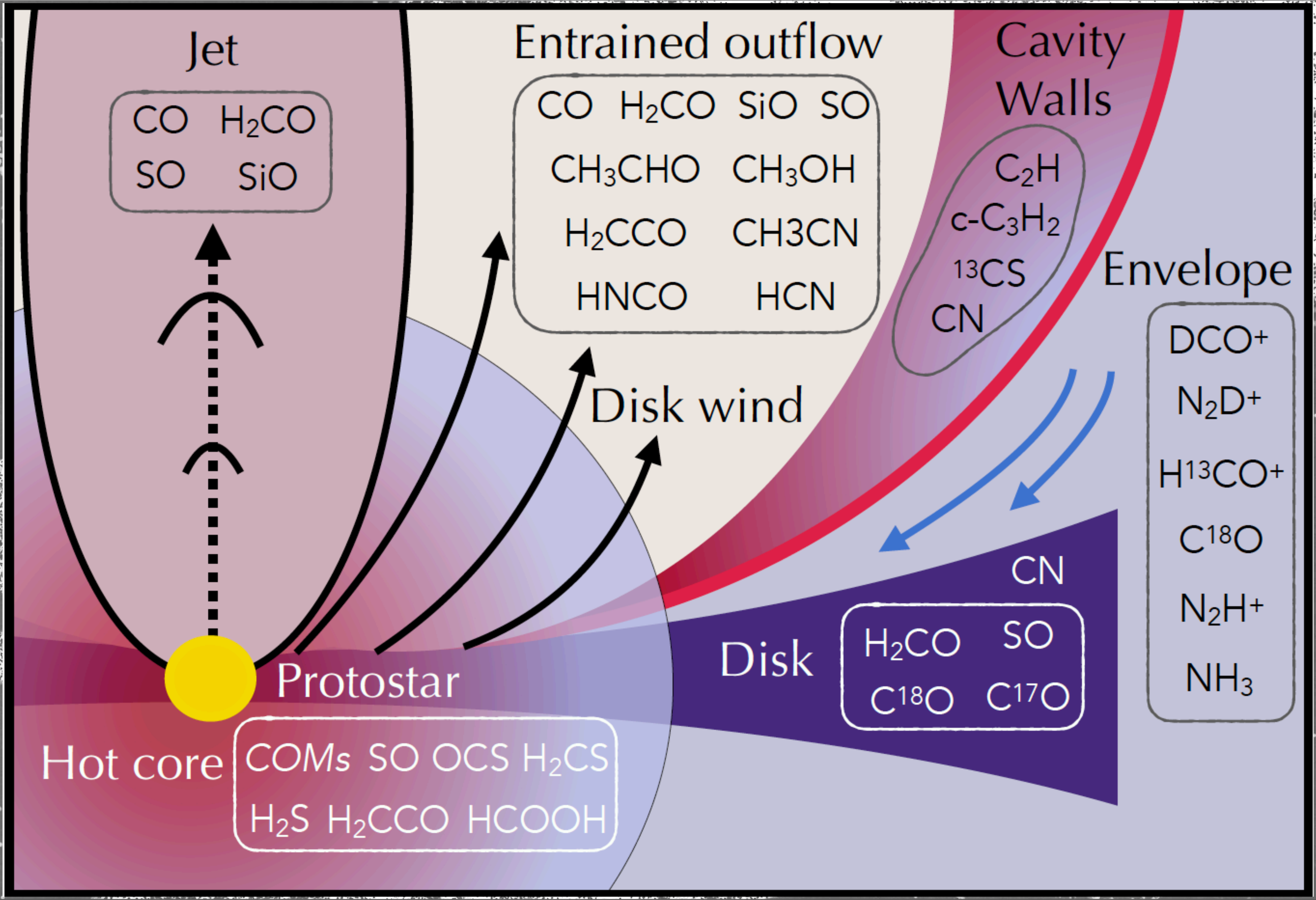
13 selected for JWST GTO



ALMA Band 3, Band 5, Band 6 at 0.4" - 6" resolution

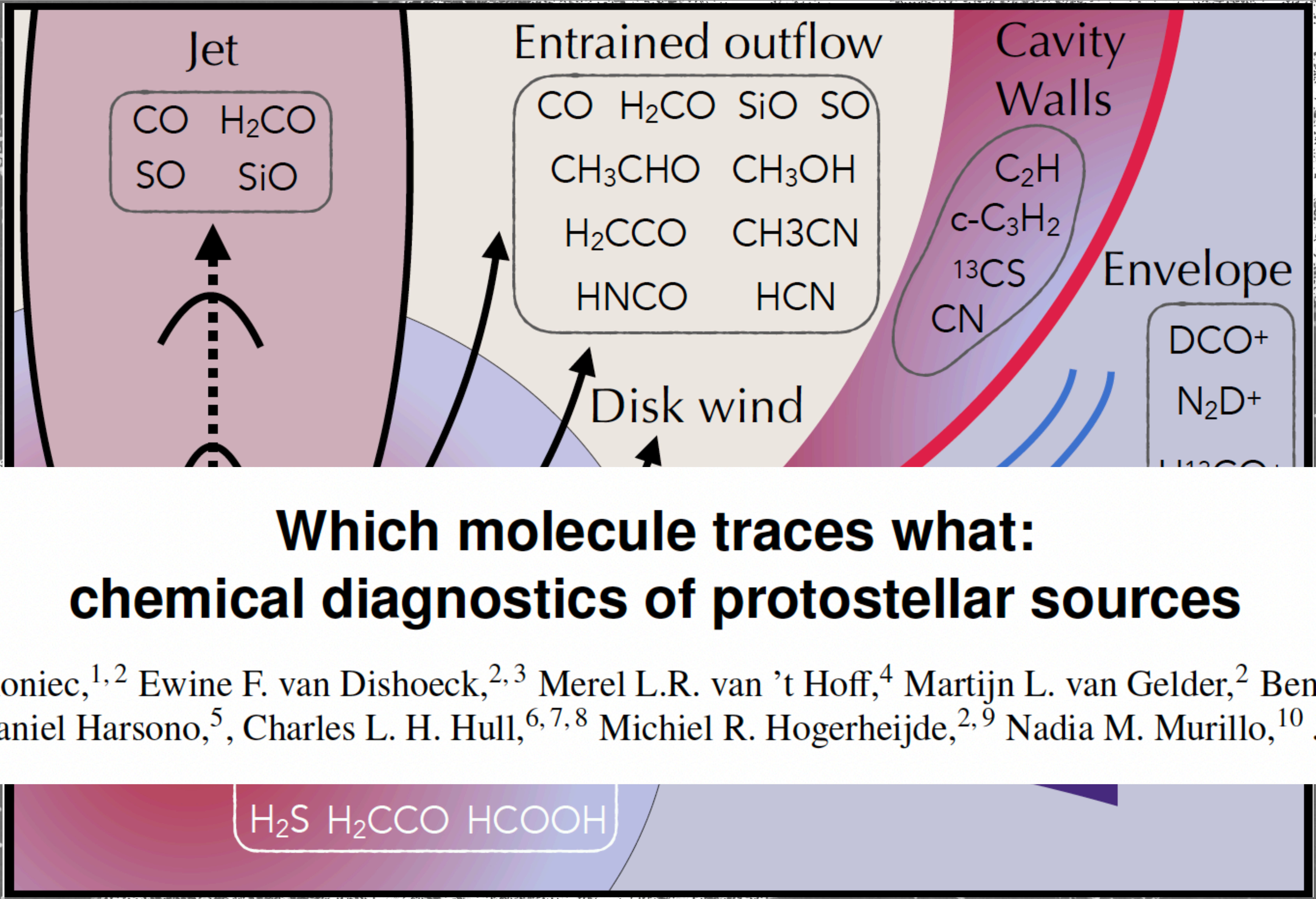
Chemical tracers of physical components

Tychoniec+2021



Chemical tracers of physical components

Tychoniec+2021

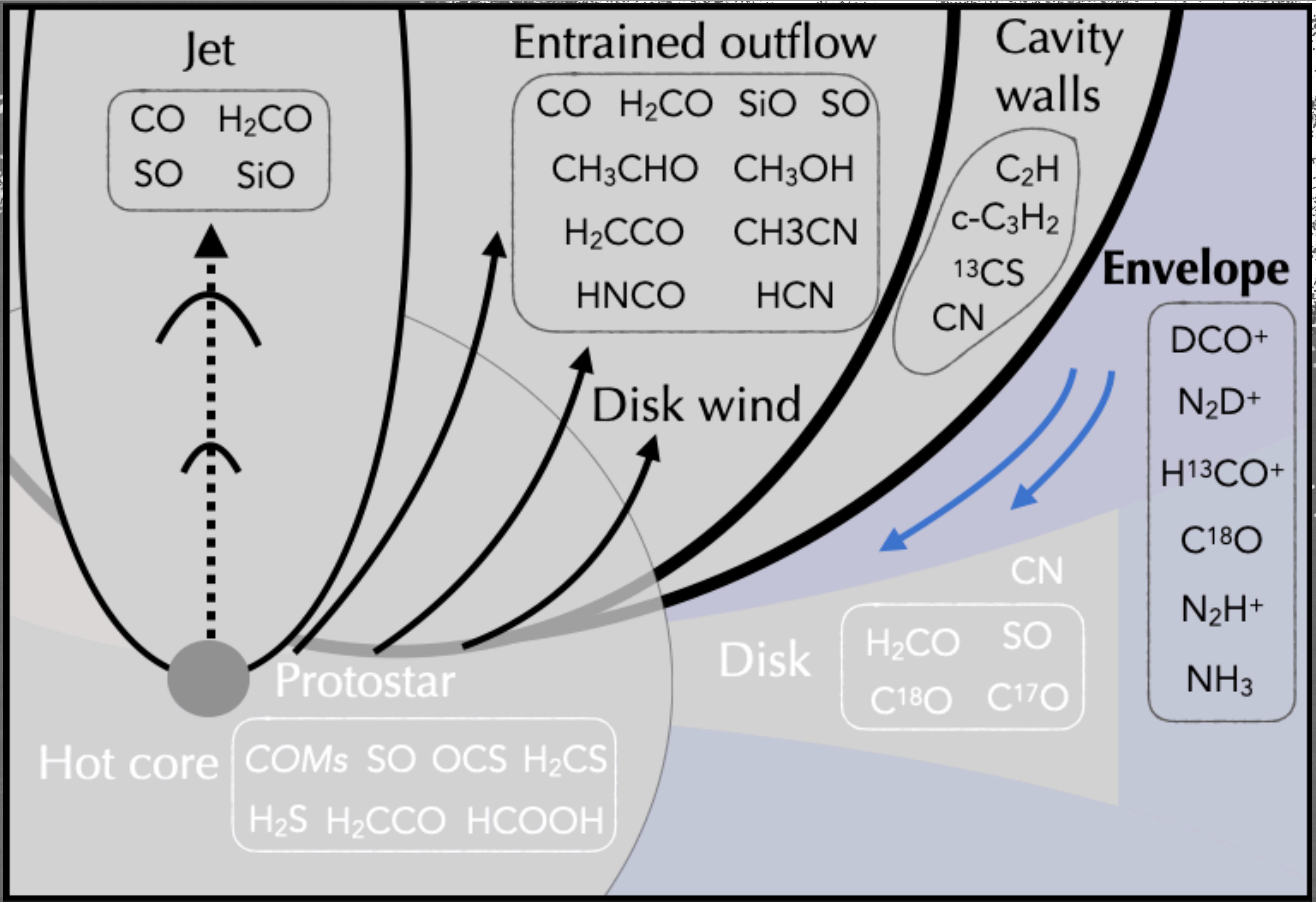


Which molecule traces what: chemical diagnostics of protostellar sources

Łukasz Tychoniec,[1,2] Ewine F. van Dishoeck,[2,3] Merel L.R. van 't Hoff,[4] Martijn L. van Gelder,[2] Benoit Tabone,[2] Yuan Chen,[2] Daniel Harsono,[5], Charles L. H. Hull,[6,7,8] Michiel R. Hogerheijde,[2,9] Nadia M. Murillo,[10] John J. Tobin[11]

Protostellar envelope

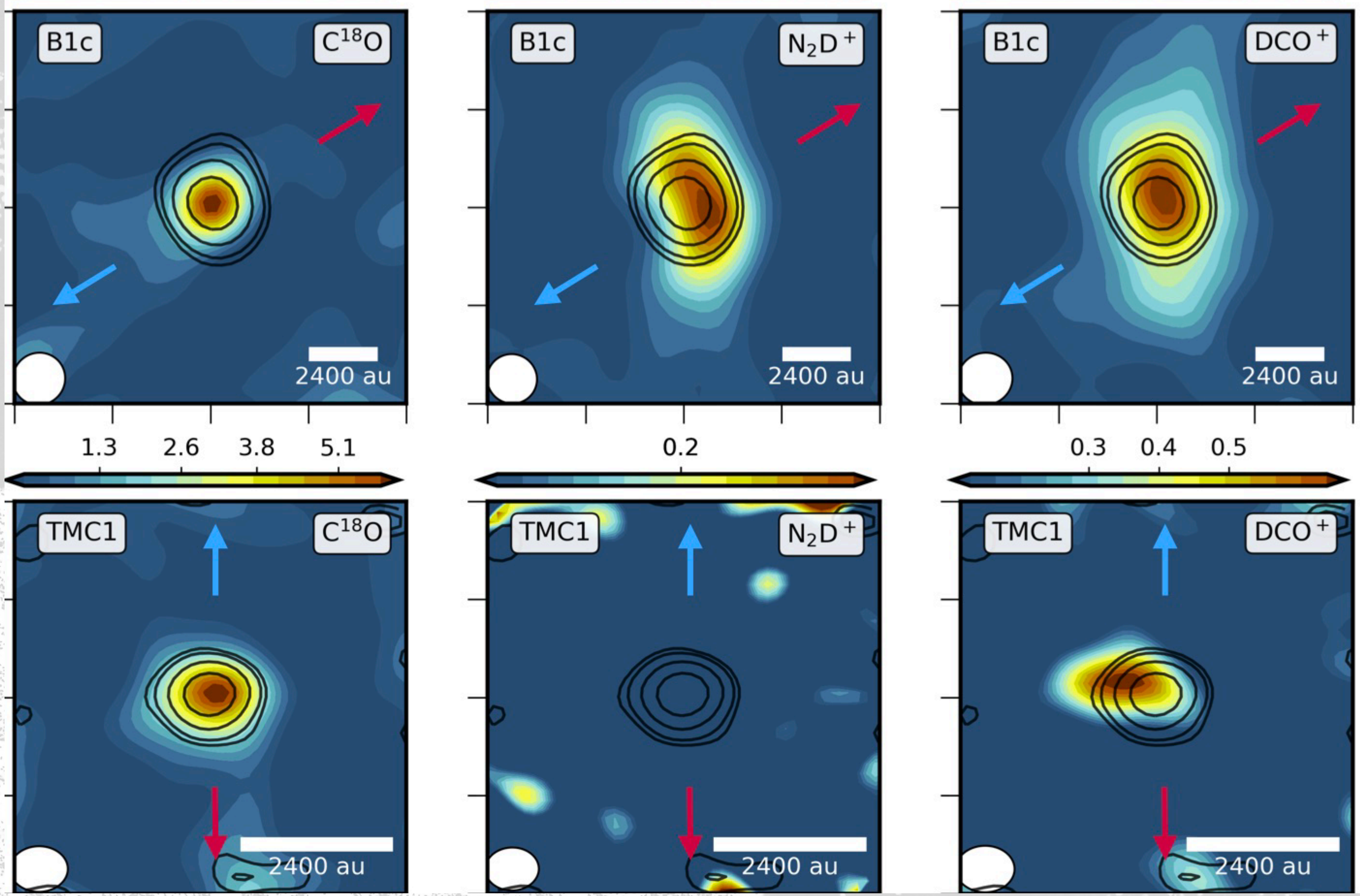
Tychoniec+2021



Protostellar envelope

Class 0

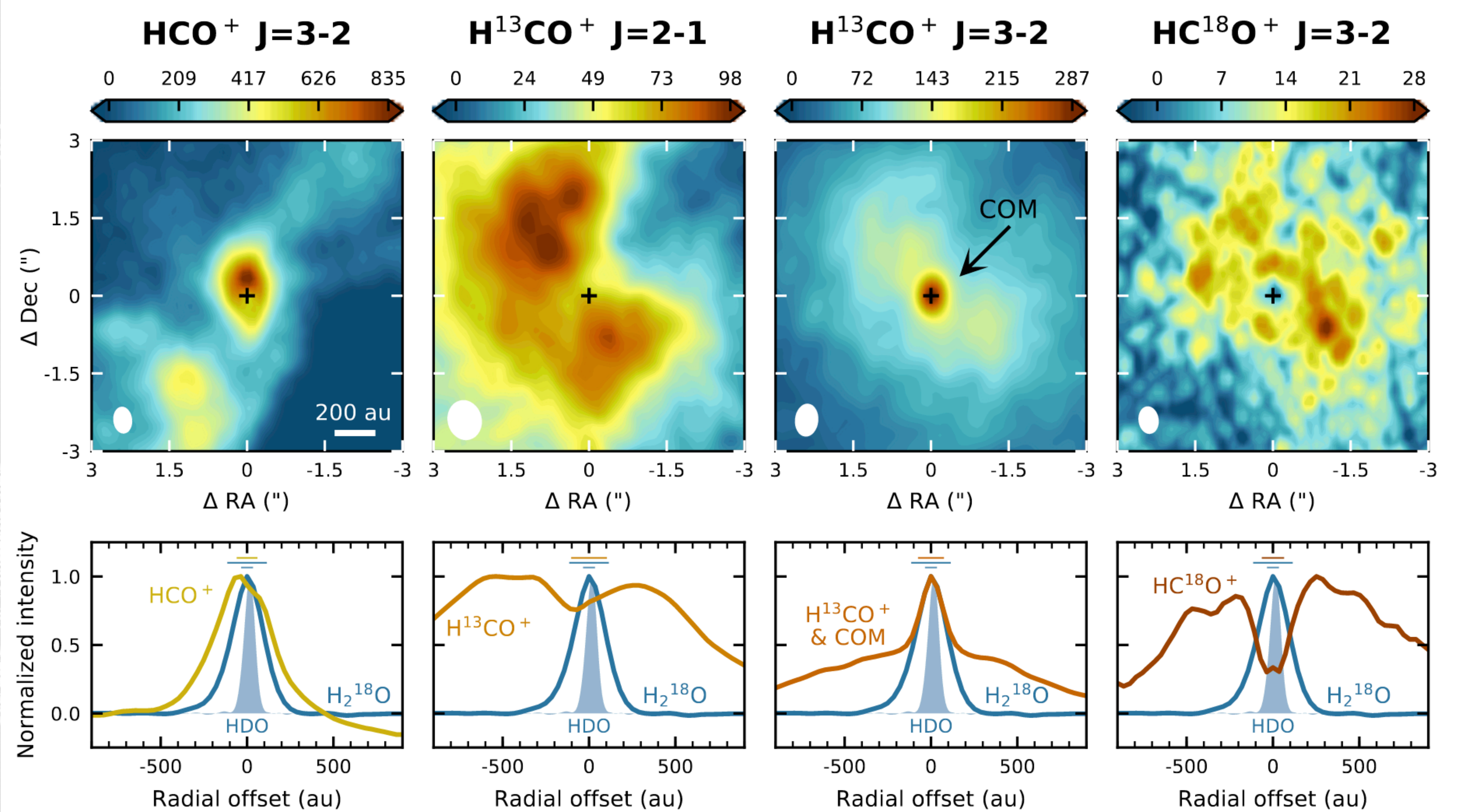
Class I



CO chemistry and mass density regulates the molecular emission

Envelope and disk on small scales

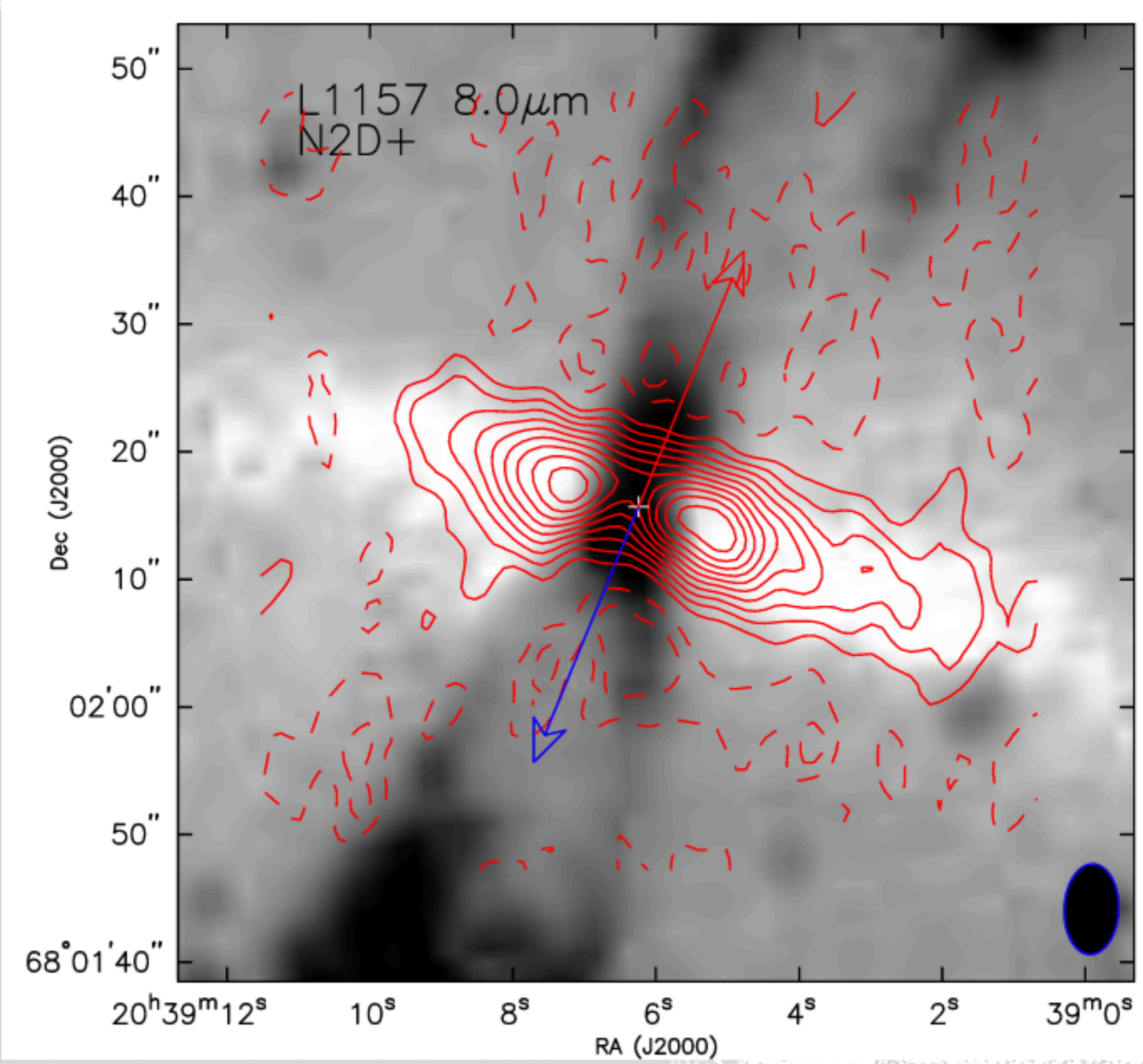
van 't Hoff+2021

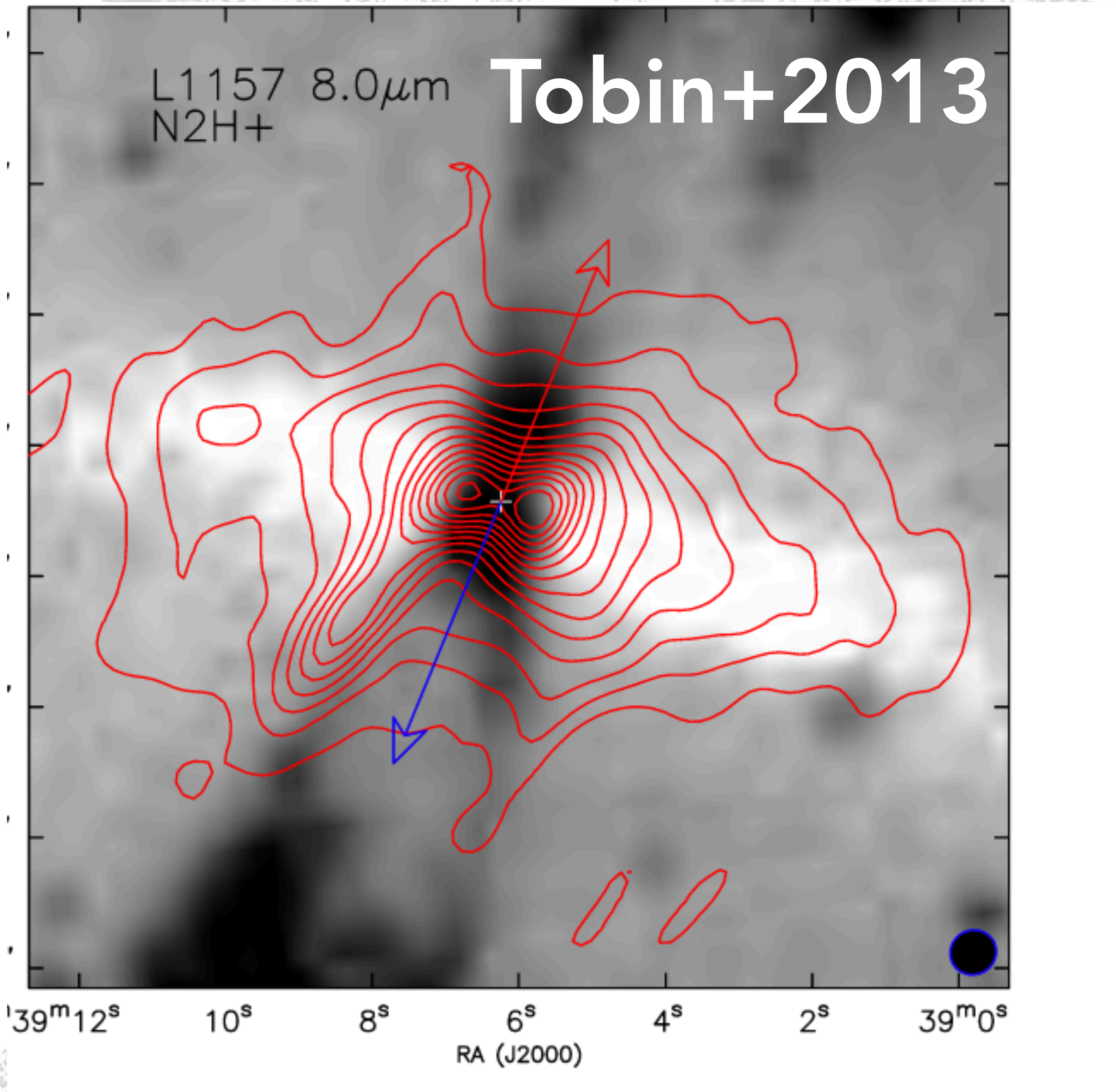


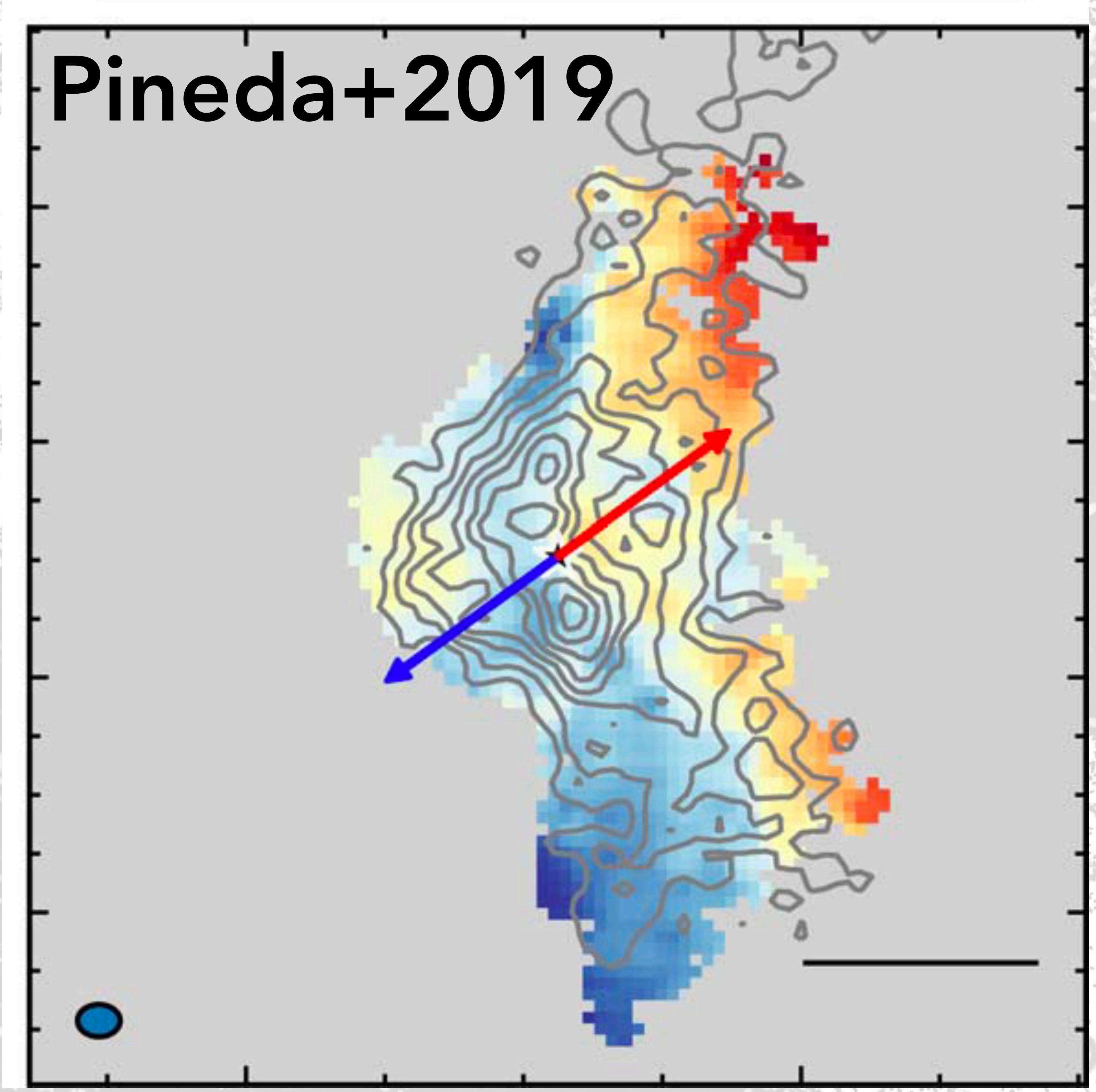
$H^{13}CO^+$ tracing the water ice line

Protostellar envelope

N_2D^+ N_2H^+ NH_3



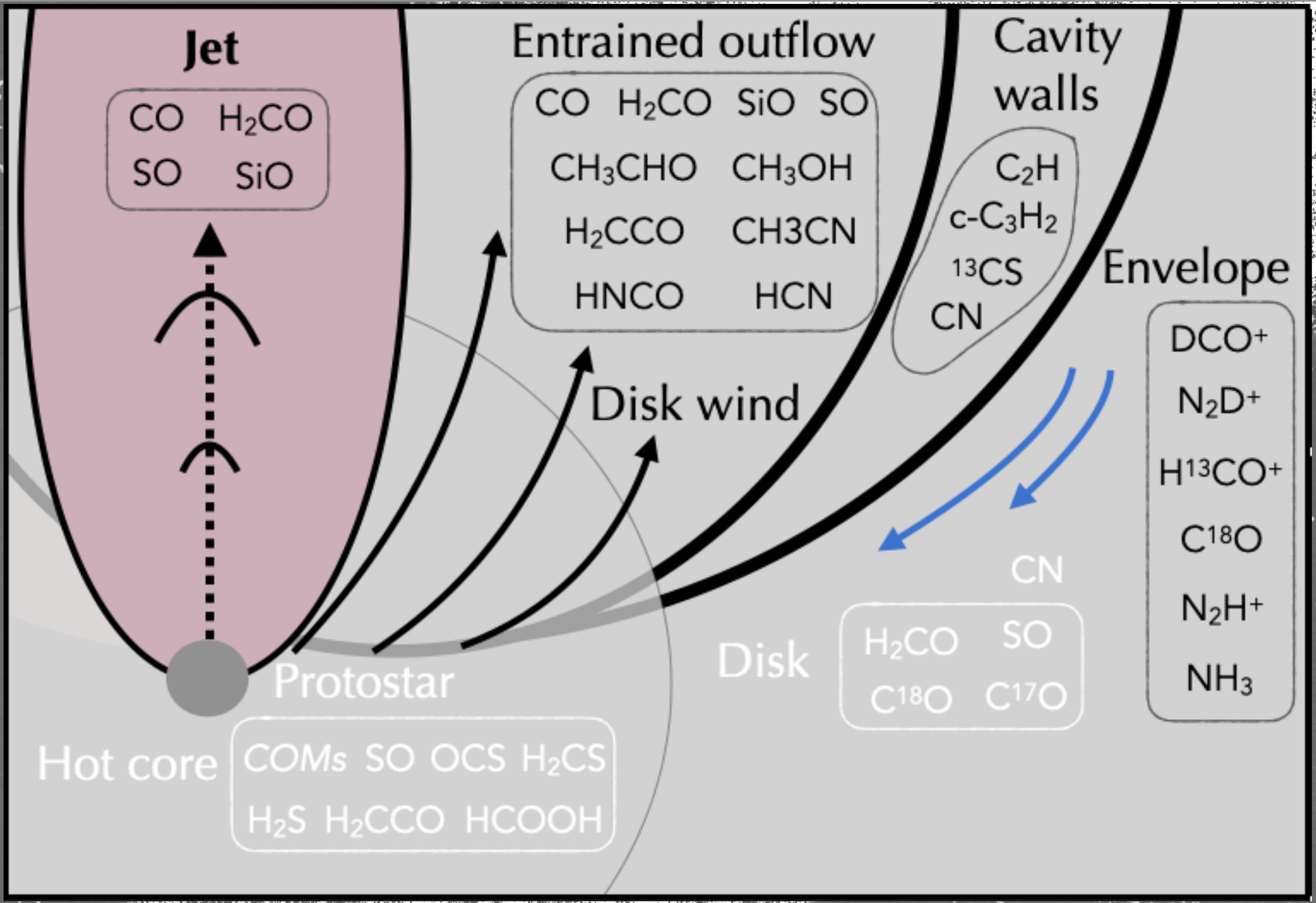




Nitrogen-bearing species as relevant tracers of kinematics

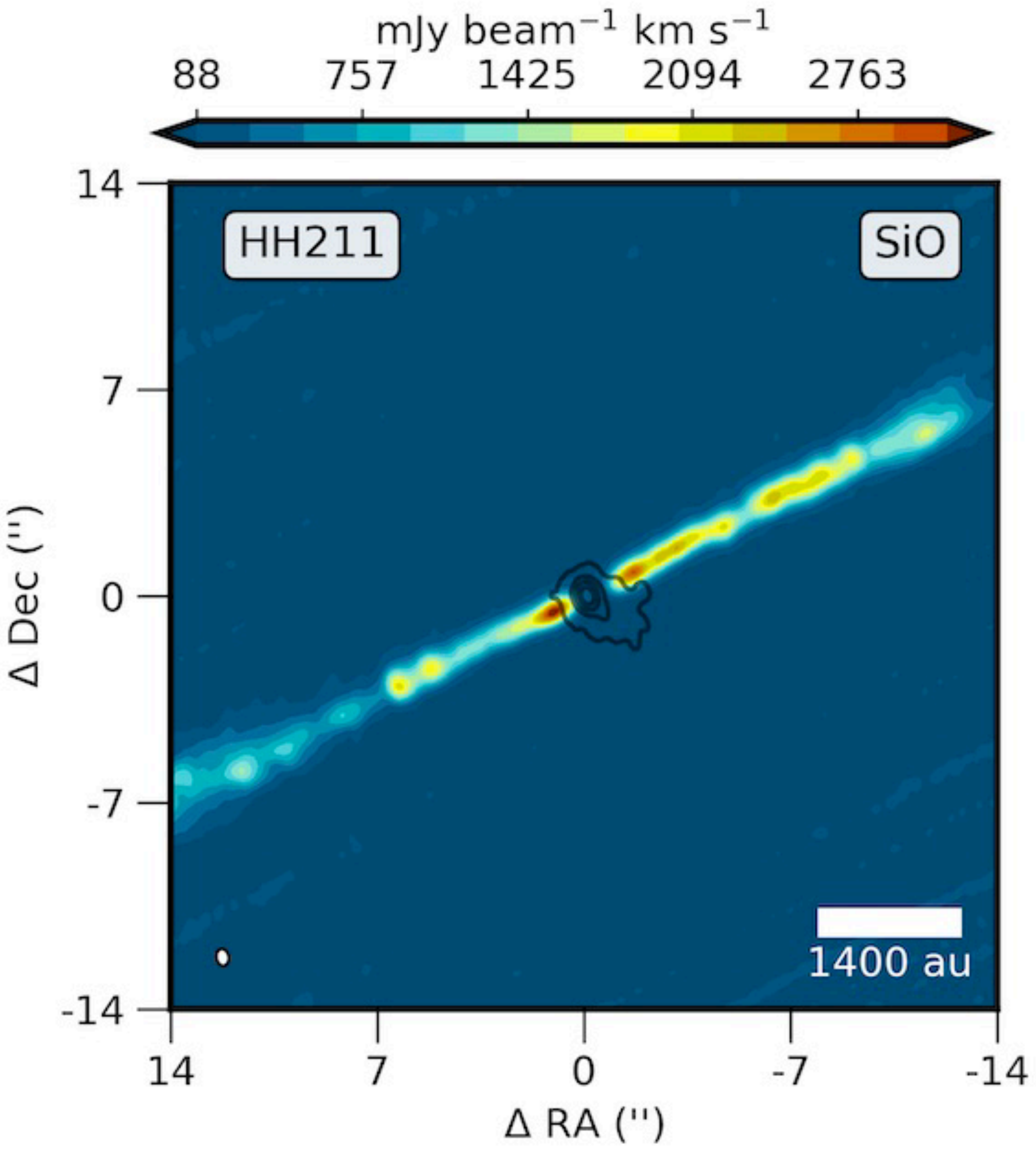
Protostellar jets

Tychoniec+2021



Protostellar jets

Tychoniec+2021

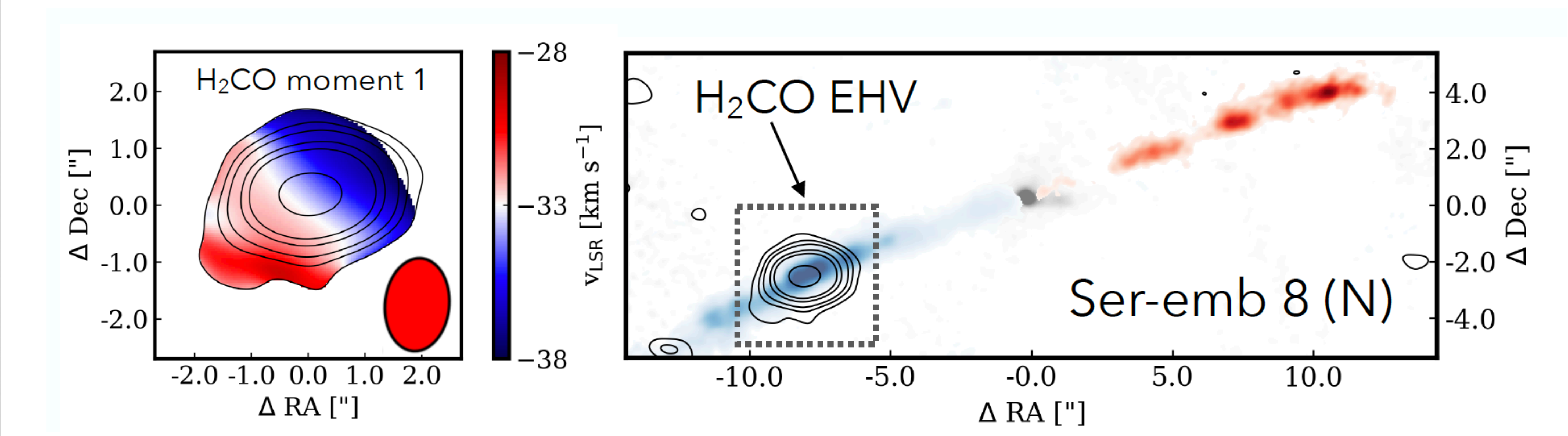


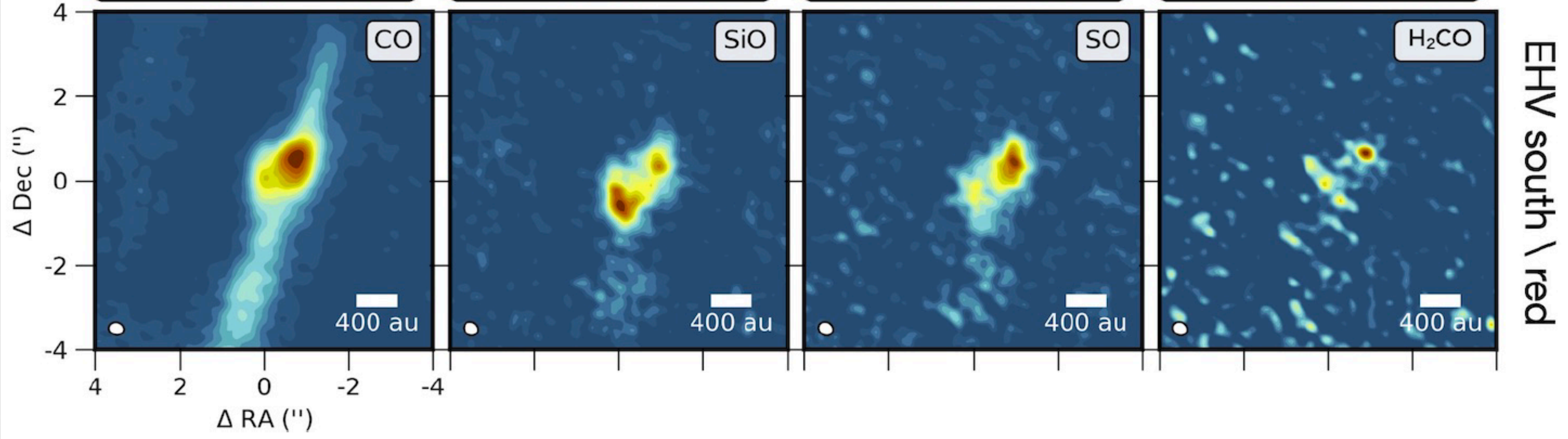
SiO - the classical shock tracer: grain disruption

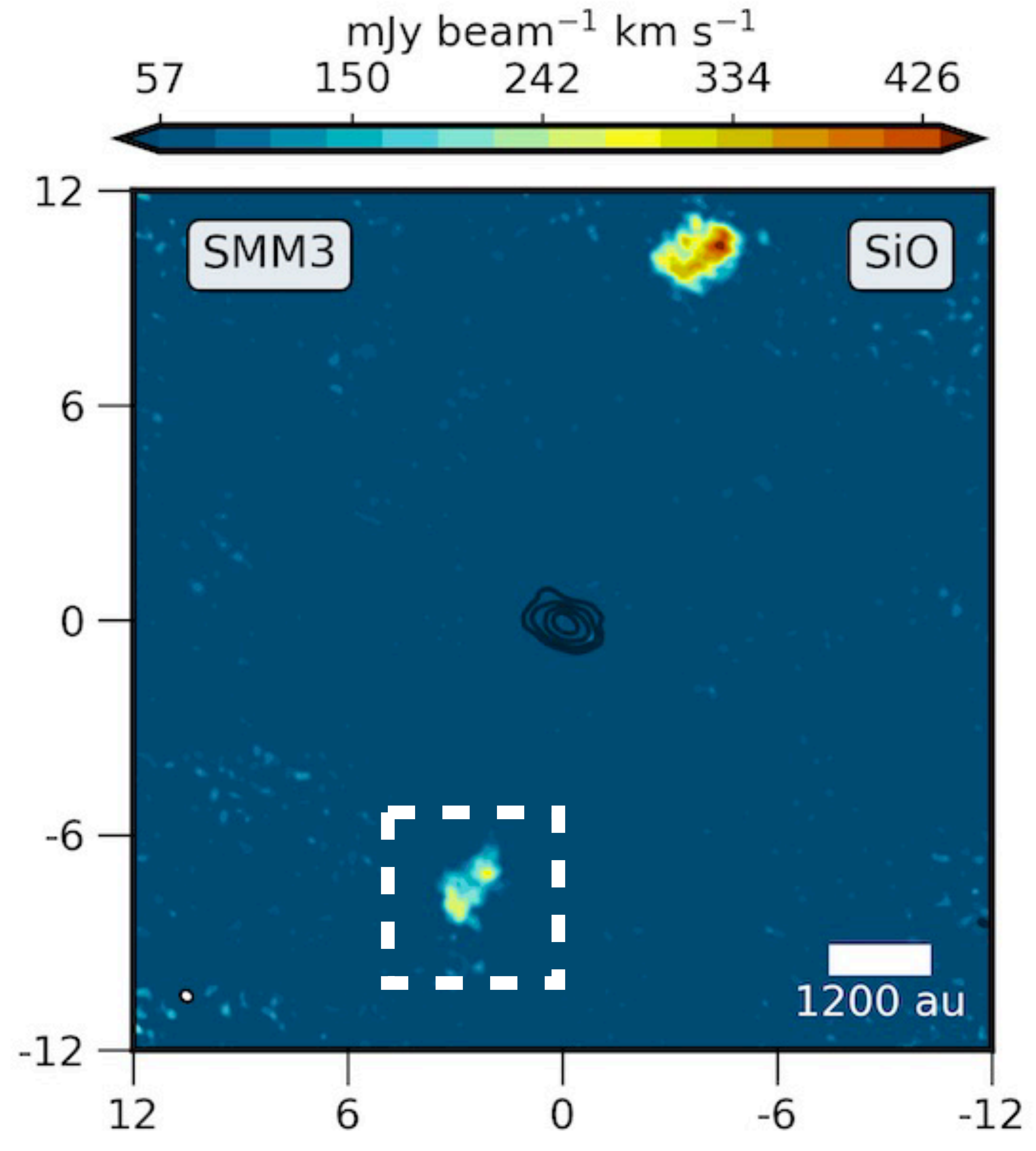
Protostellar jets

Talk: A. Schutzer

Tychoniec+2019, 2021



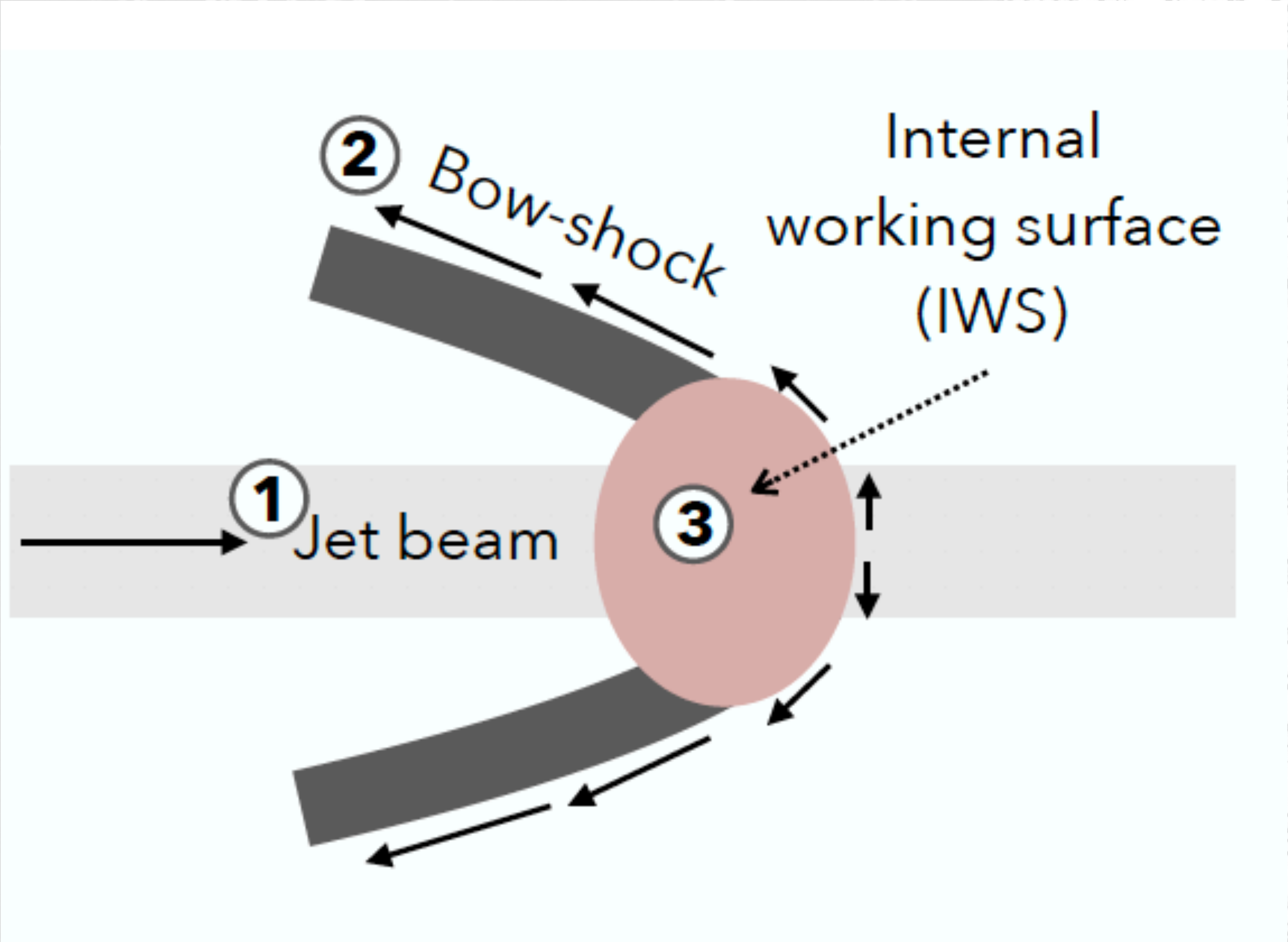




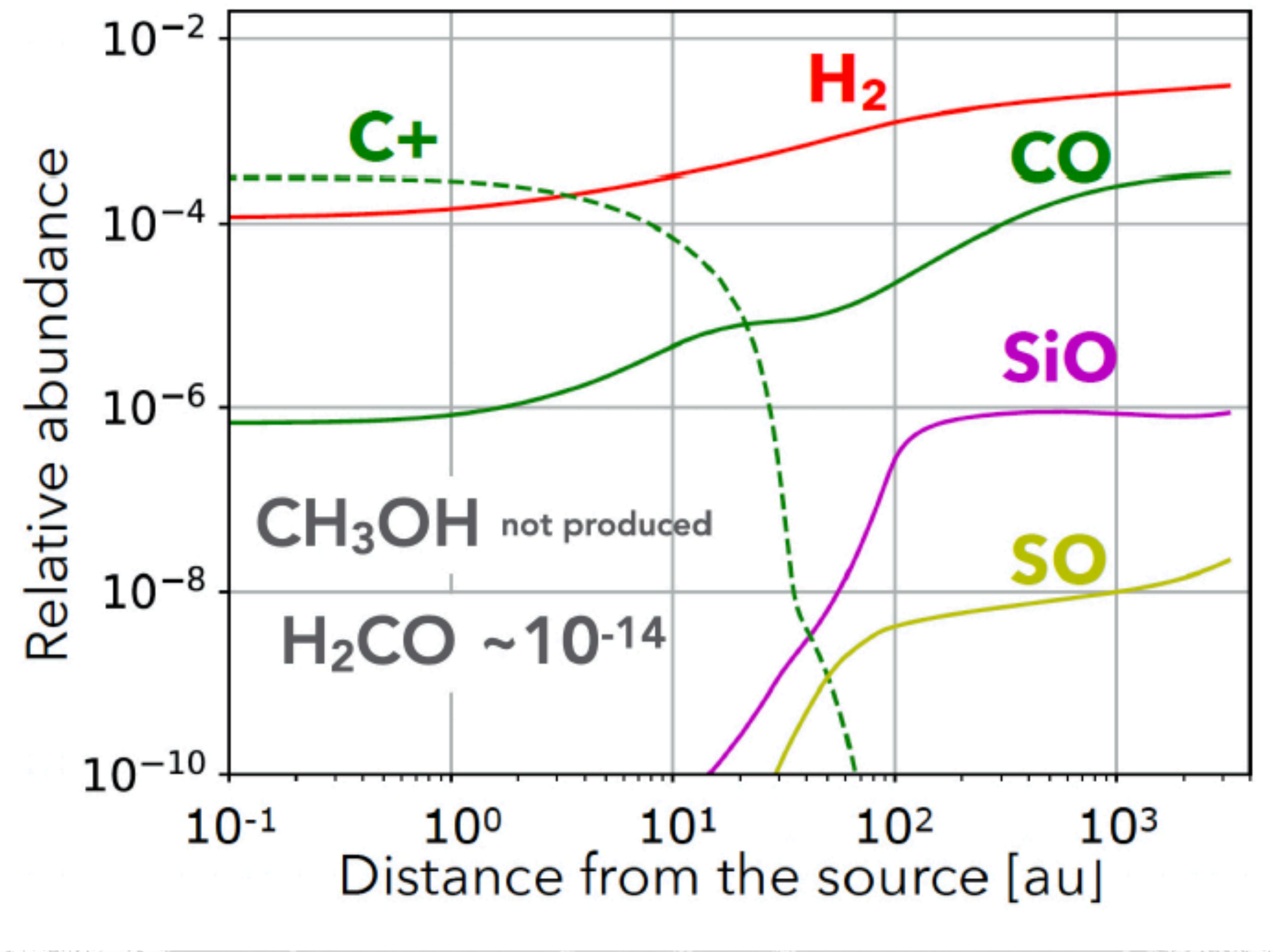
Oxygen-bearing molecules abundant in the jet

Molecule formation in the jet

Tabone+2020



Tabone+2020

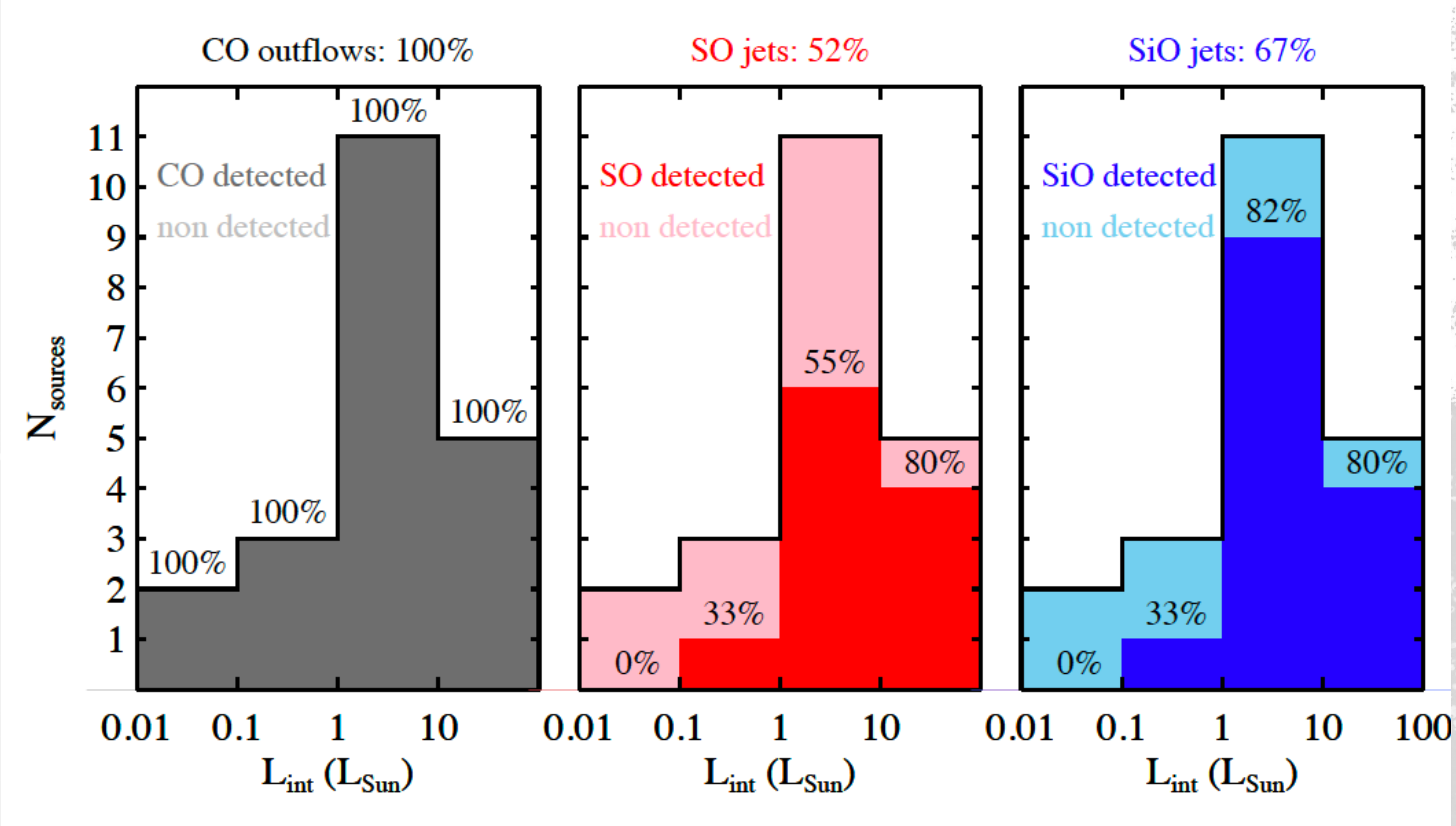


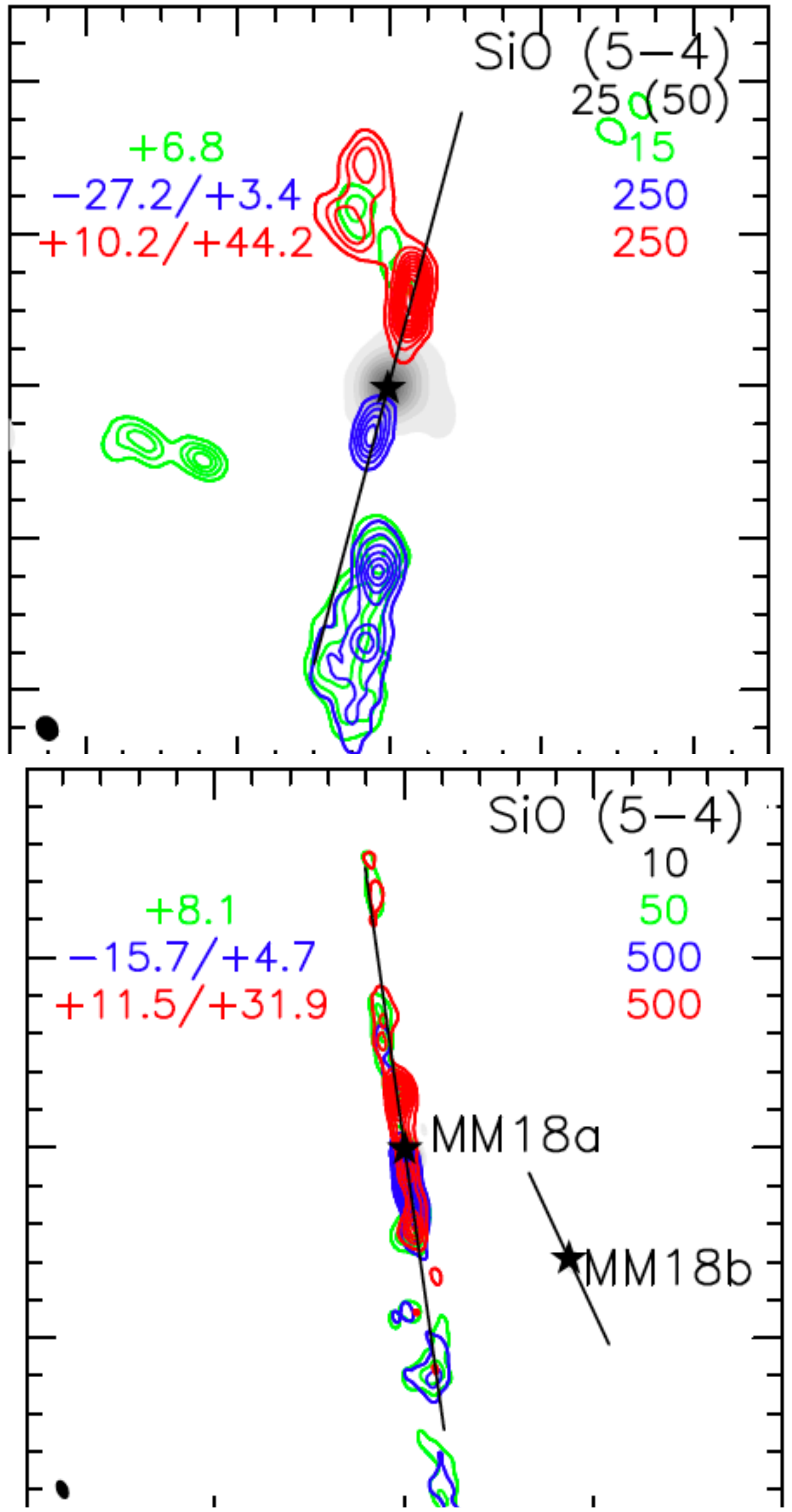
Molecules can be efficiently formed even in dust-poor gas

Molecular jets abundant in low-mass protostars?

Podio+2021

NOEMA study, Podio+2021

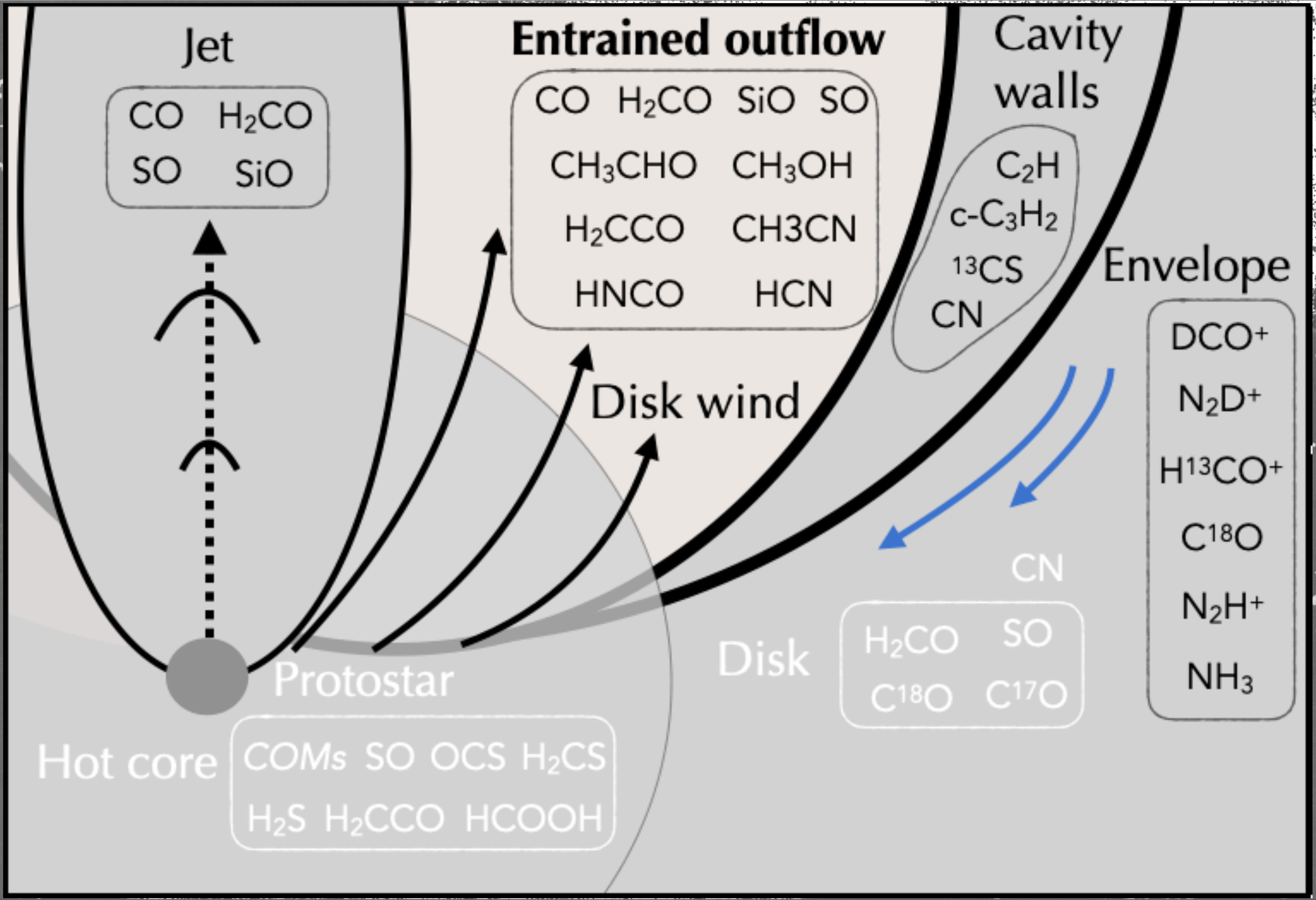




Possibility of chemical information on the inner regions

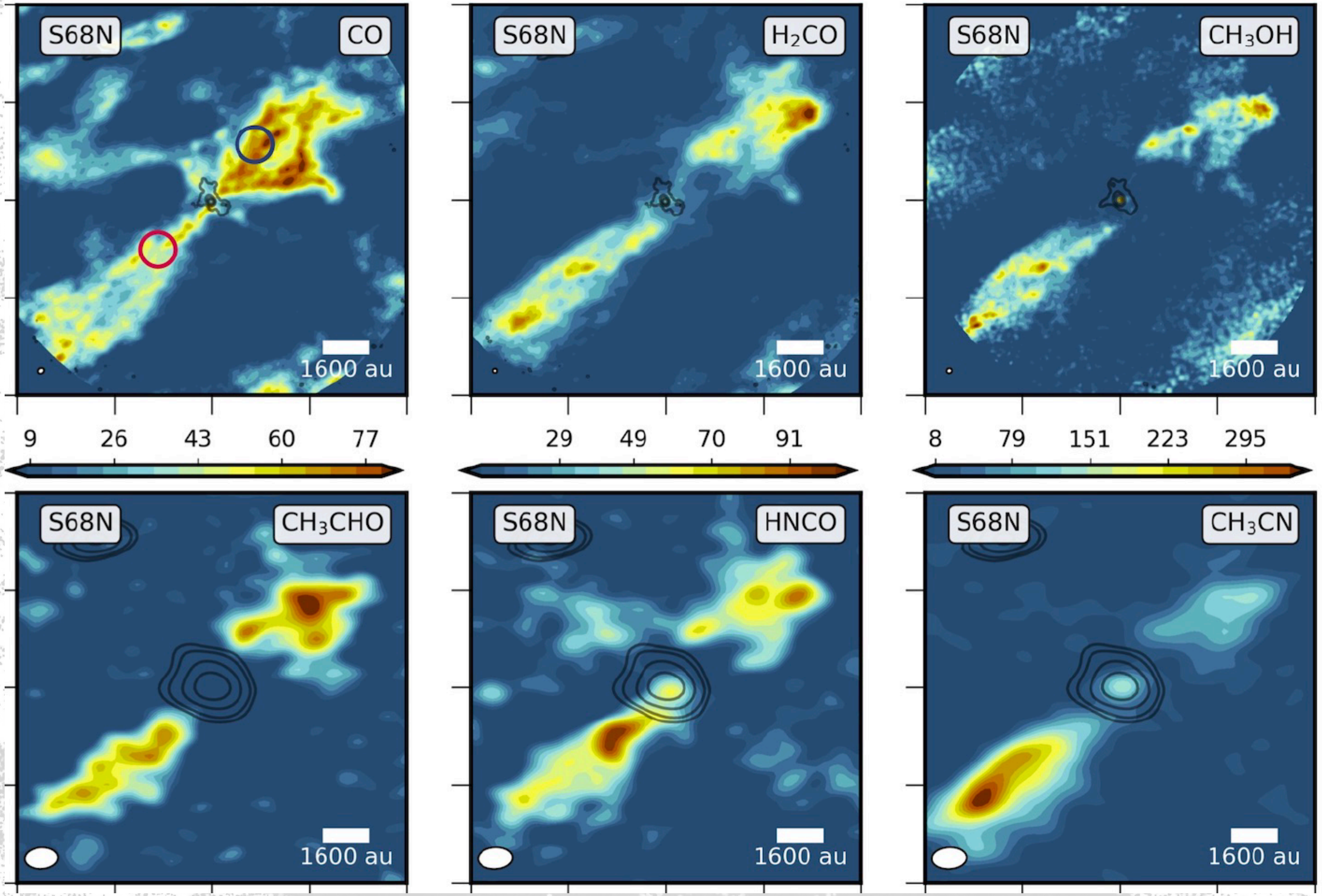
Entrained outflow

Tychoniec+2021



Entrained outflow

Tychoniec+2021



- **Entrained outflow** represents the envelope material carried with launched jet
- Complex species typically produced on the ices sputtered by shock

Apart from usual tracers - interesting chemical richness

Complex organics in the outflow

Van Gelder+2020, Nazari+2021

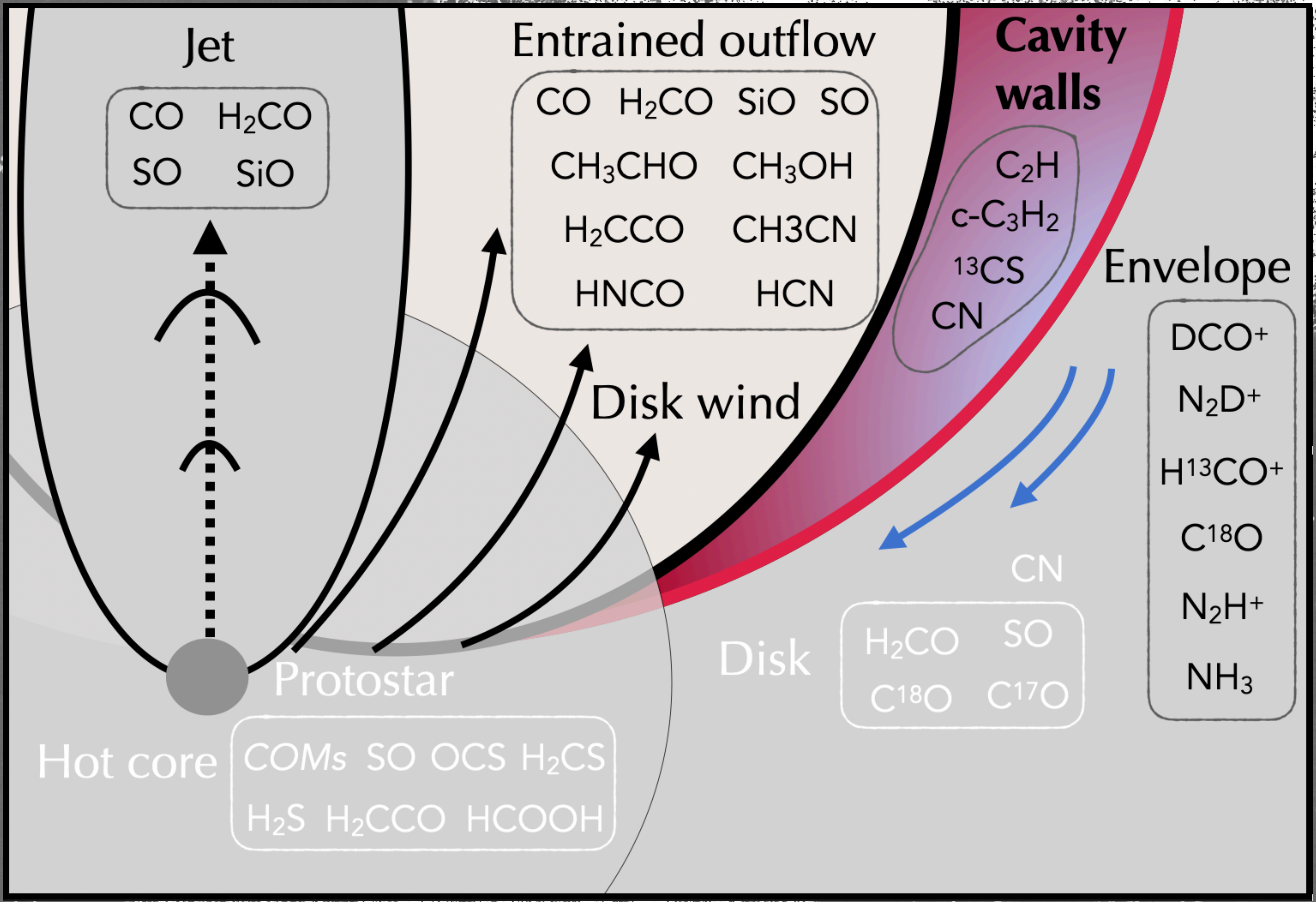
Gas-phase formation?

Entrained outflow

De Simone+2020,Tychoniec+2021

Cavity walls

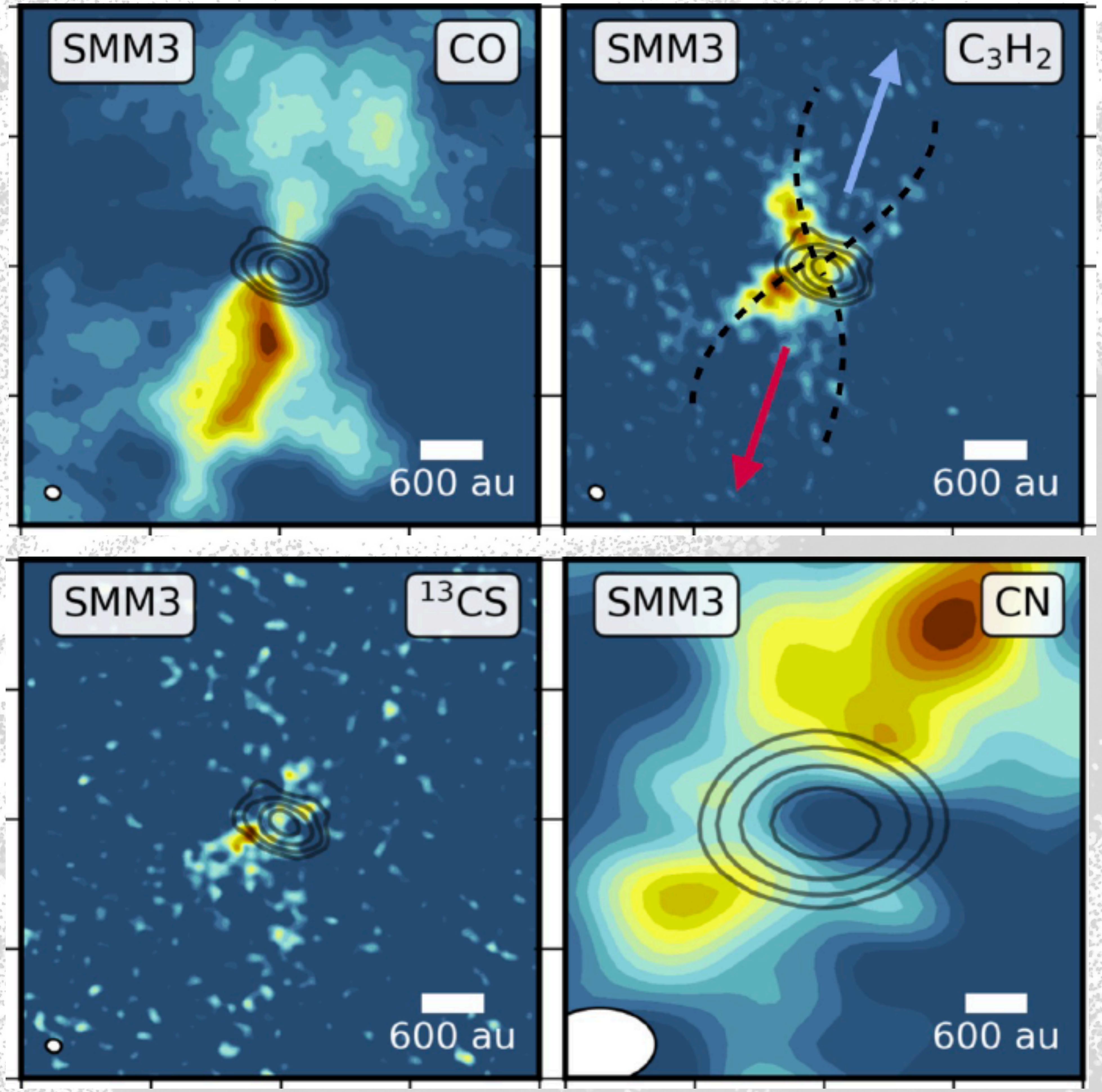
Tychoniec+2021



Cavity walls

Tychoniec+2021

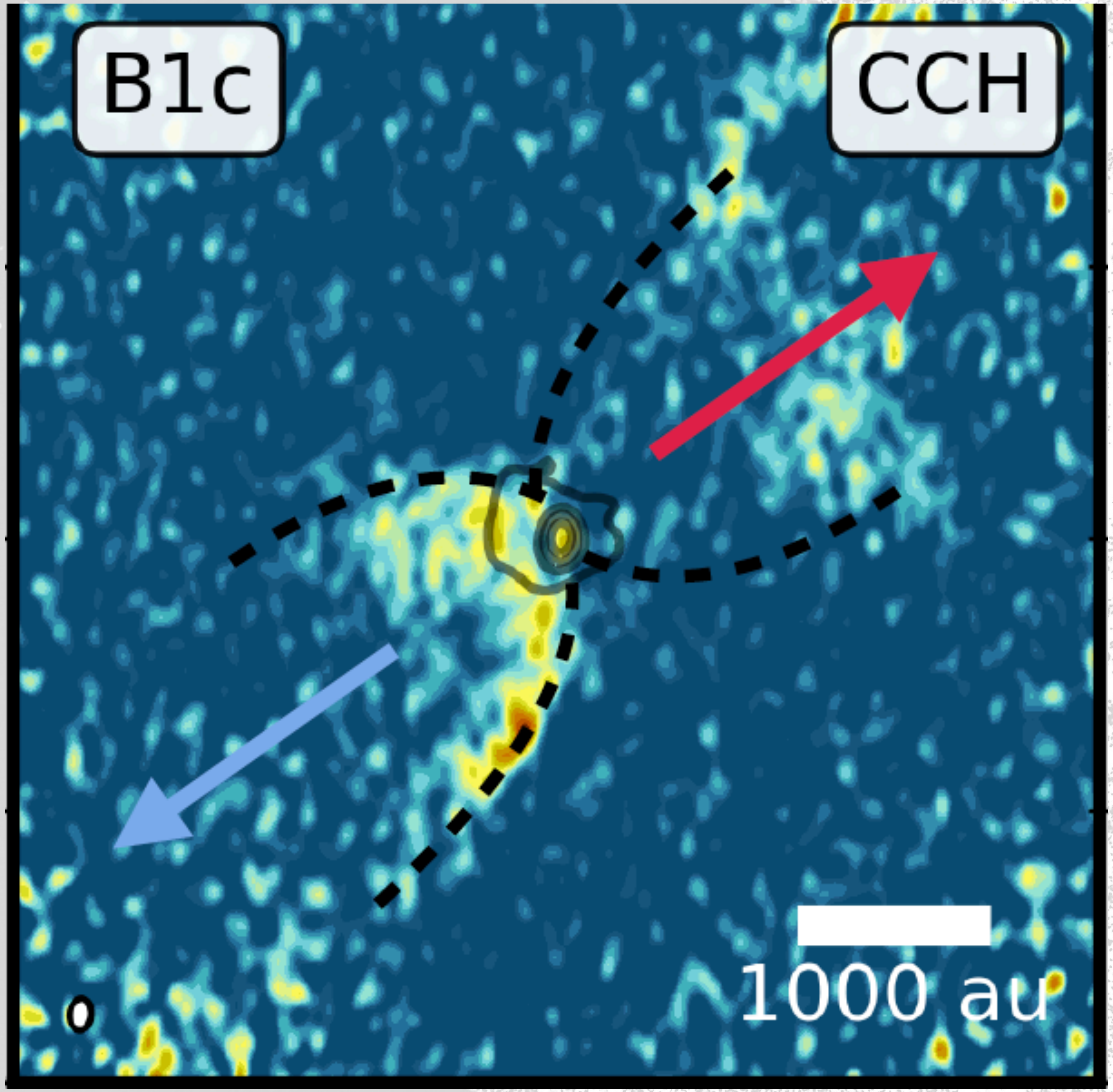
- Environment where UV radiation propagates easily
- Molecular composition comparable with PDRs

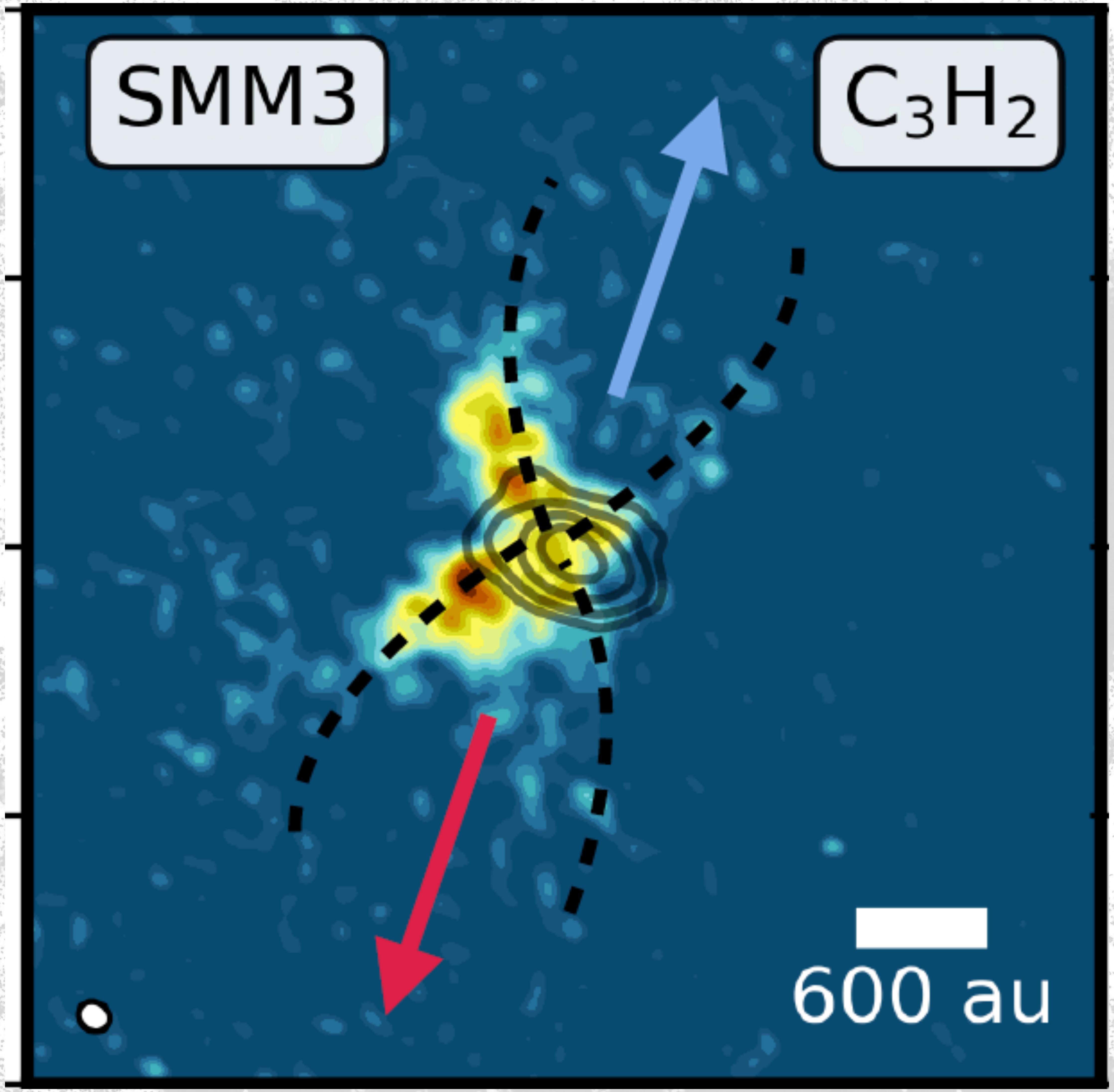


Simple hydrocarbons and dense gas tracers

UV radiation exposed at the cavity walls

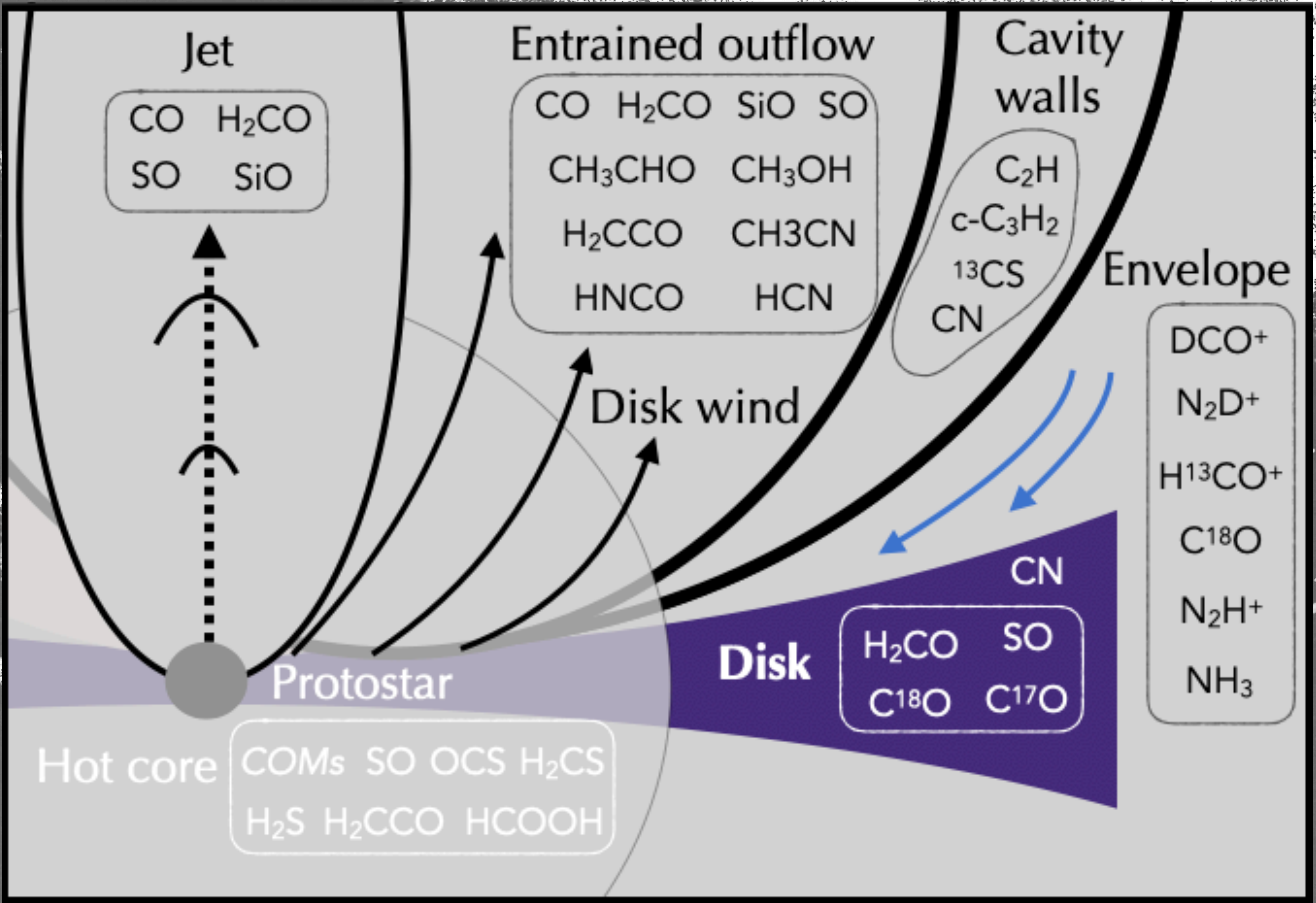
Tychoniec+2021





Embedded disk

Tychoniec+2021

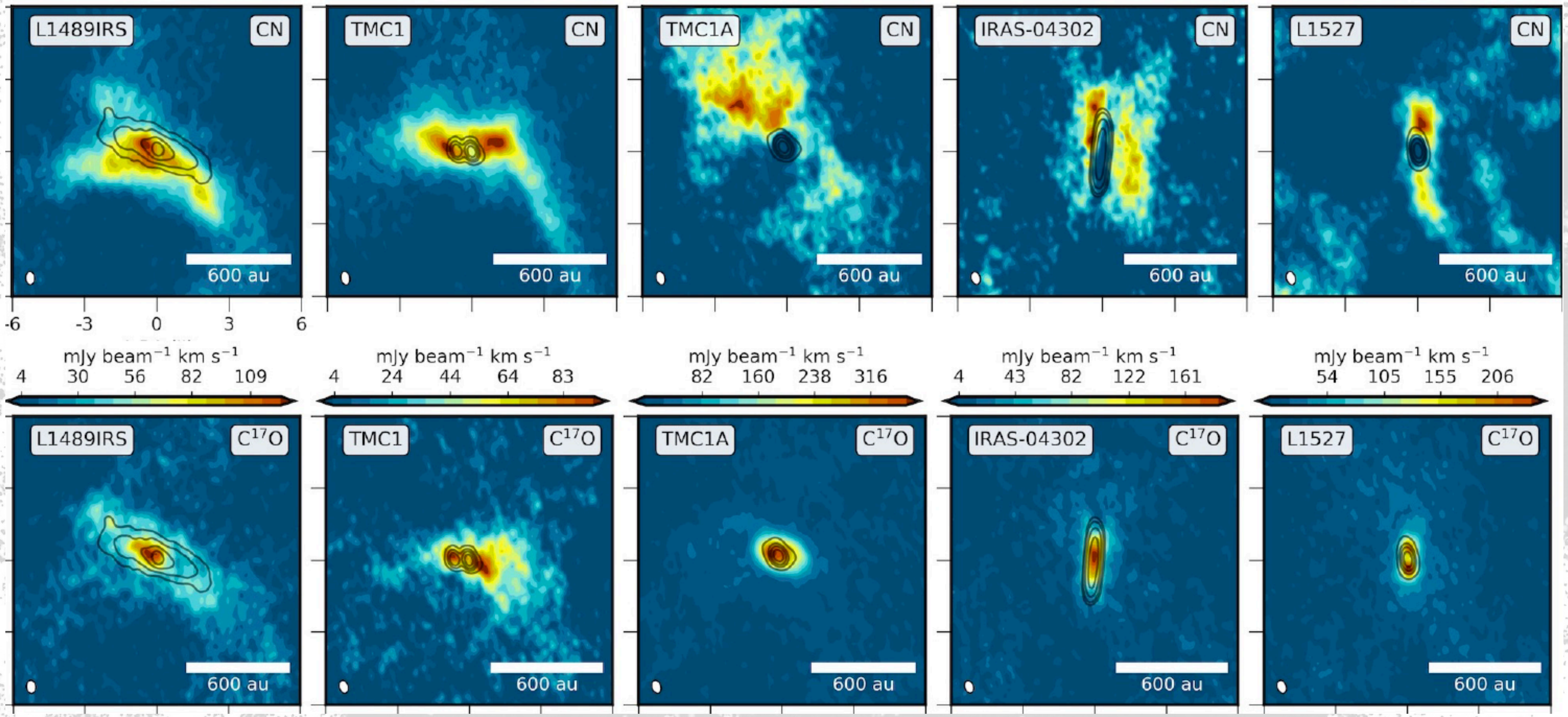


Embedded disk

Tychoniec+2021

- **Class 0** disks are typically too compact for our resolution
- Large surveys at high-resolution incoming

Class I

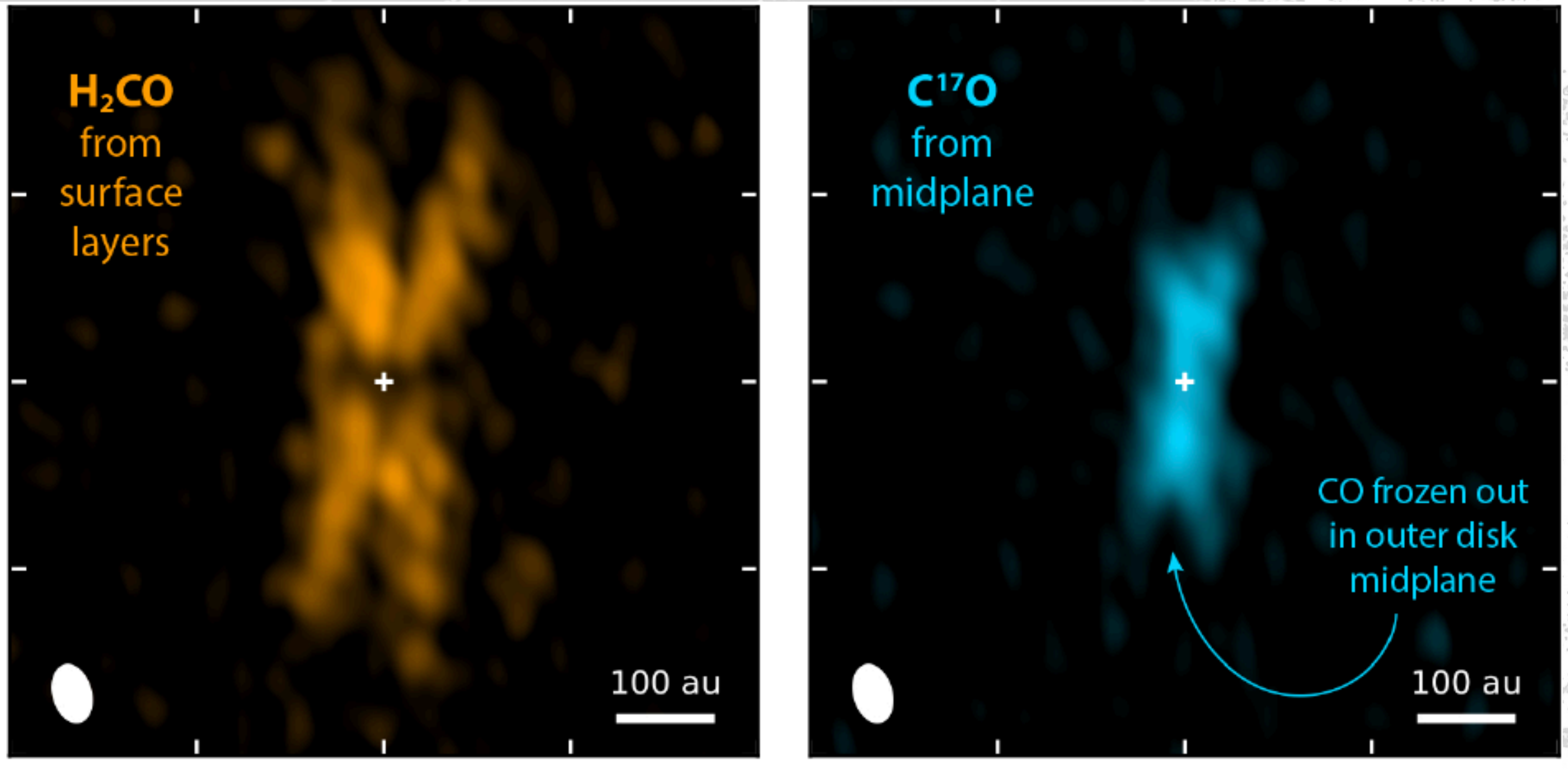


Dense gas tracers at the midplane, CN tracing upper layers

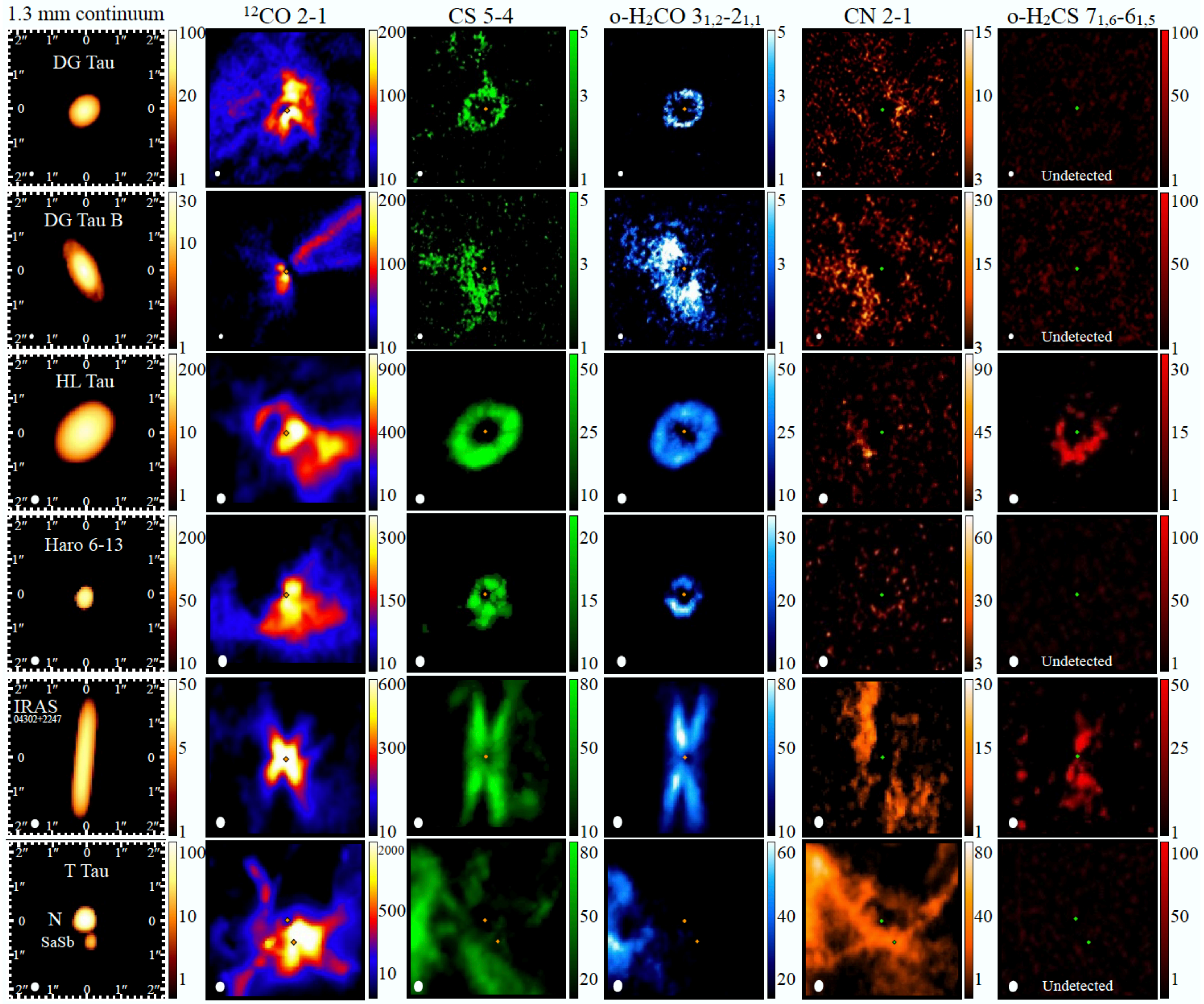
Embedded disk

Garufi+2021

ALMA-DOT, Garufi+2021



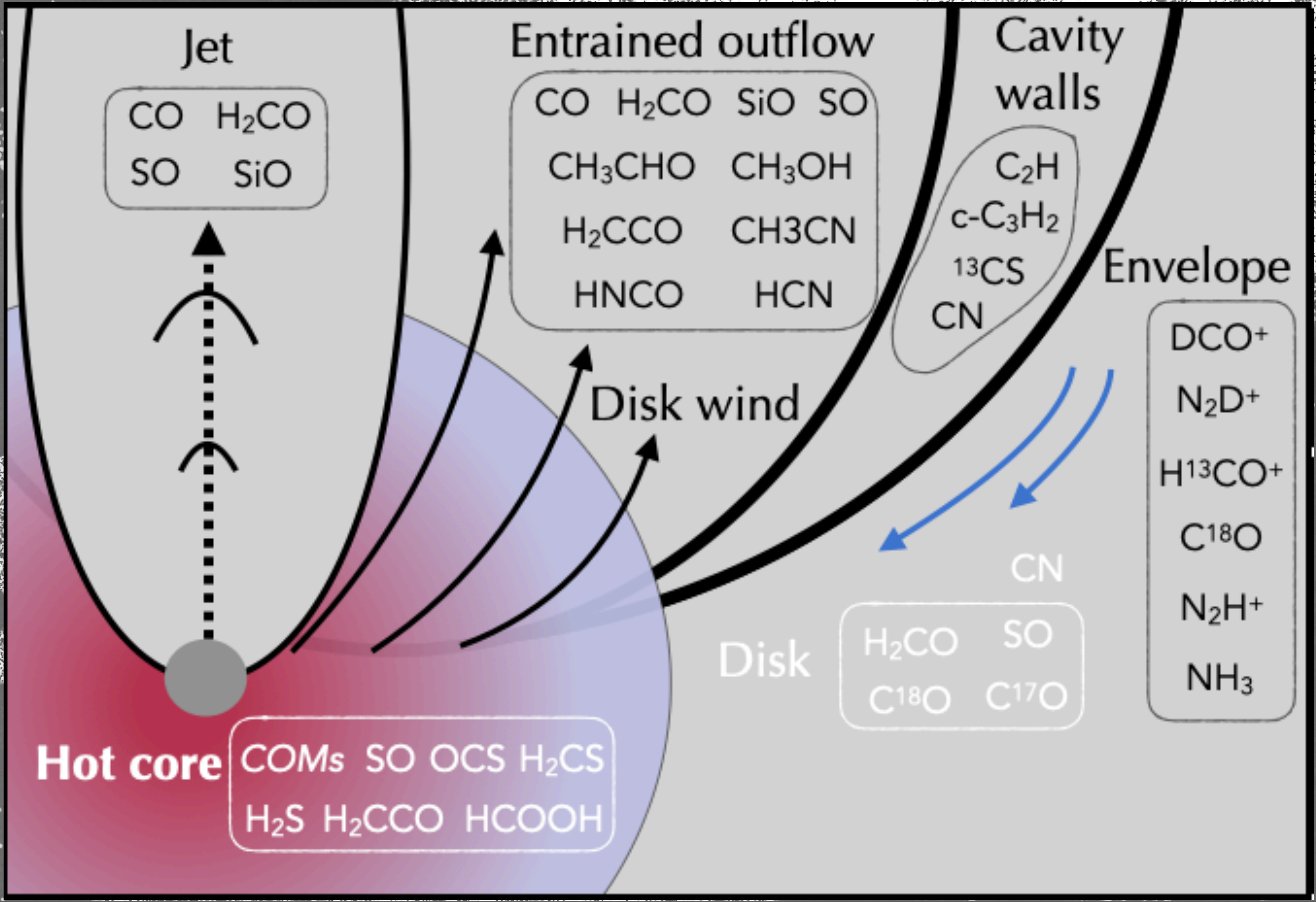
van 't Hoff+2020



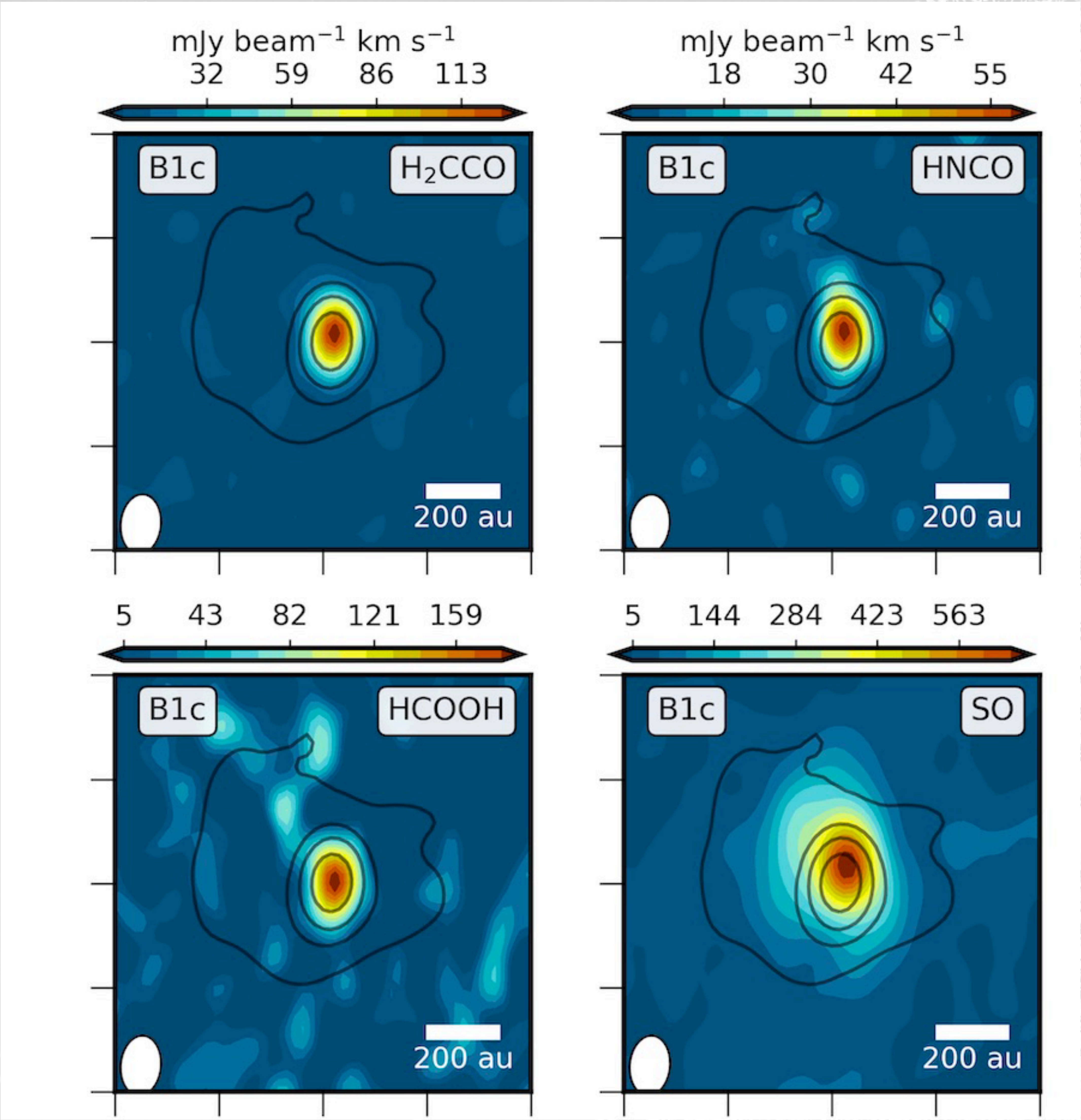
Chemistry can be used to probe disk temperature structure

Warm inner envelope / hot core

Tychoniec+2021

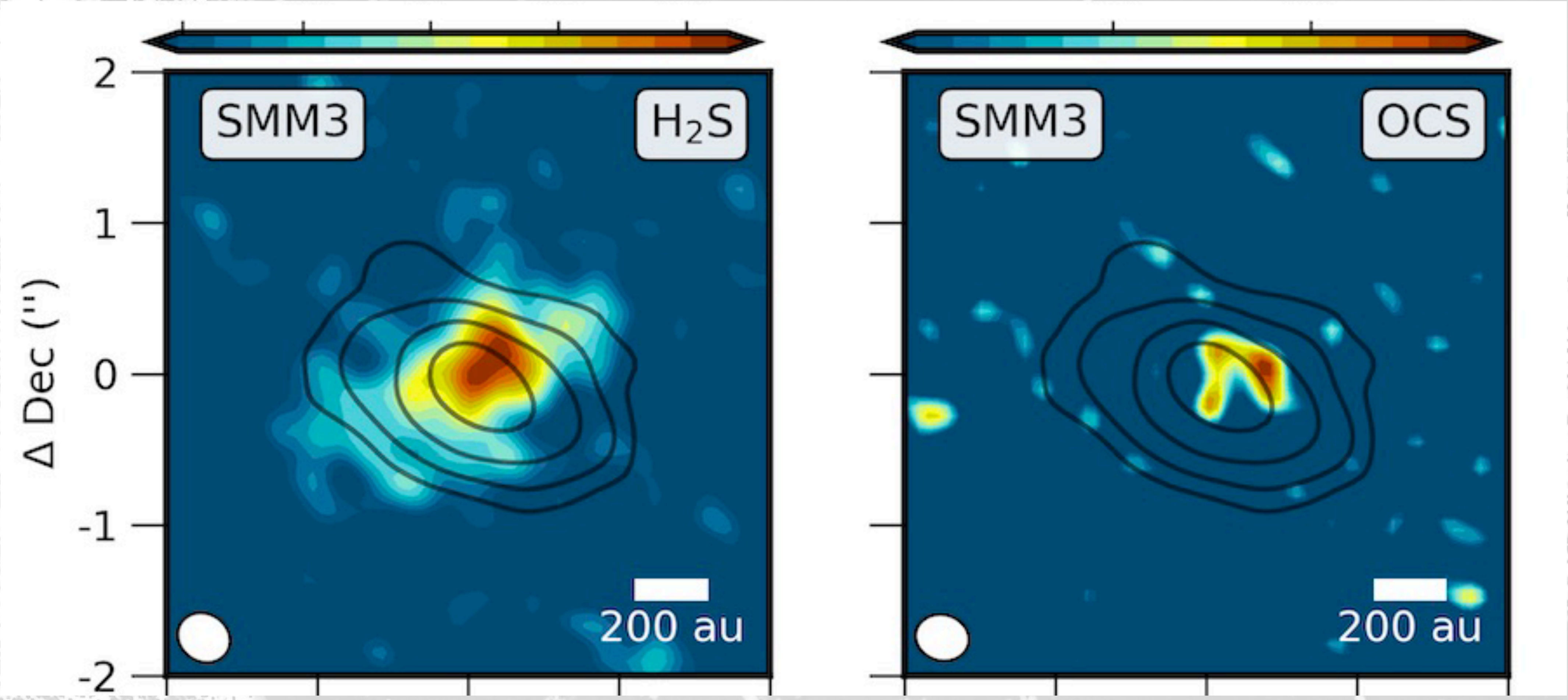


Warm inner envelope



Warm regions > 100 K, abundant in ice-grain products

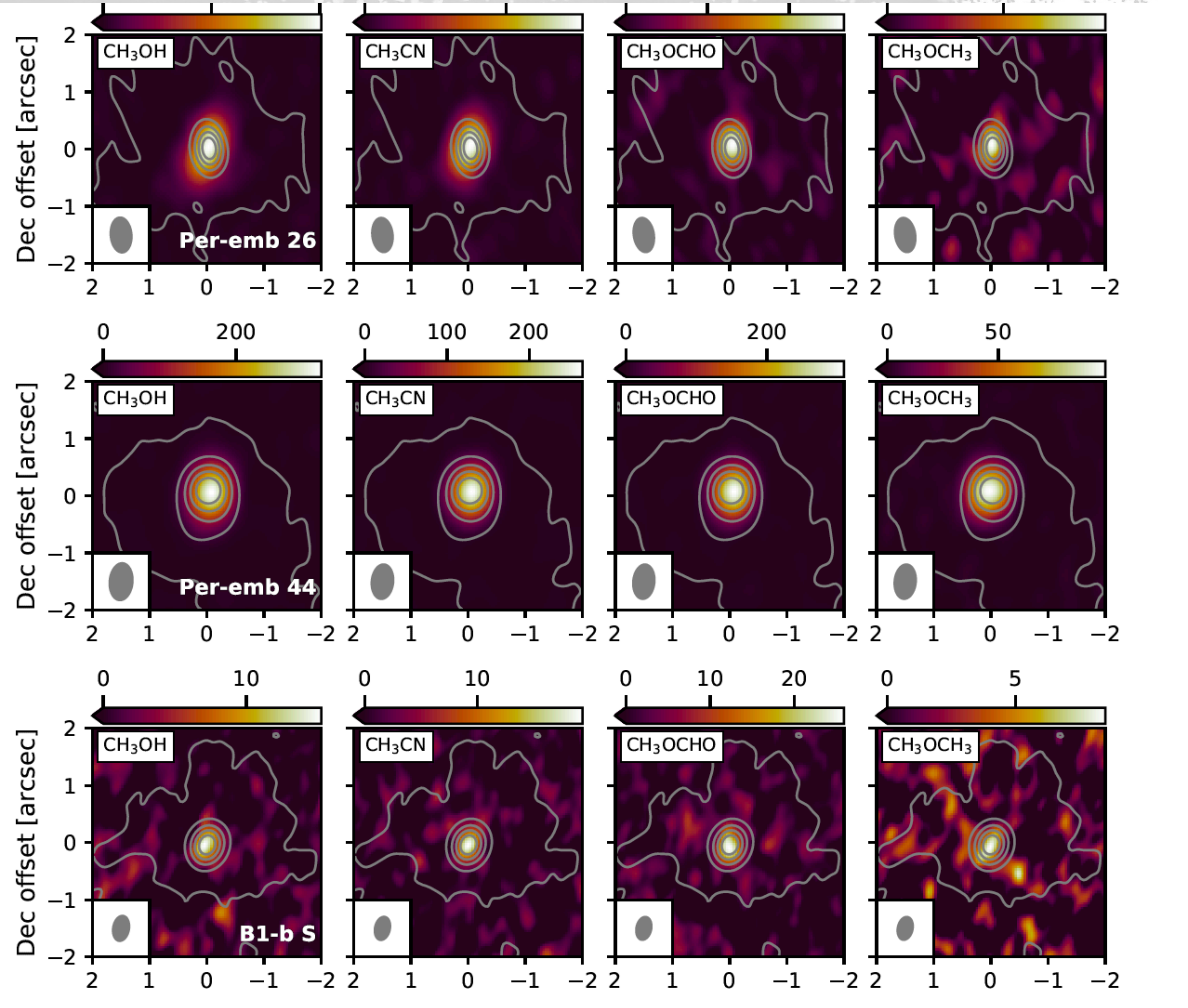
Sulphur-bearing species: alternative hot core tracers?

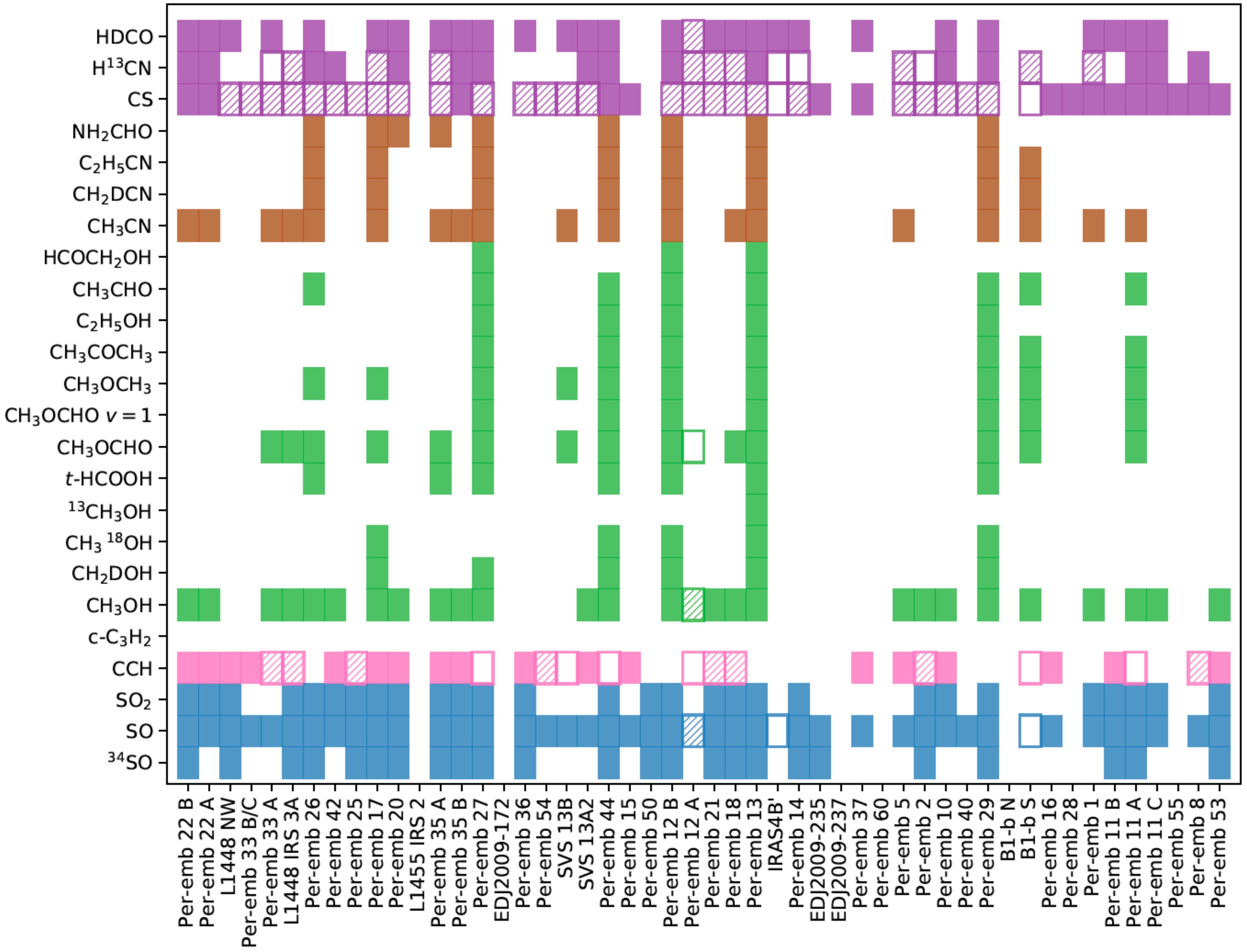


Complex organics are frequent around protostars

Yang+2021

Statistical grasp on chemistry in the first stages of star formation

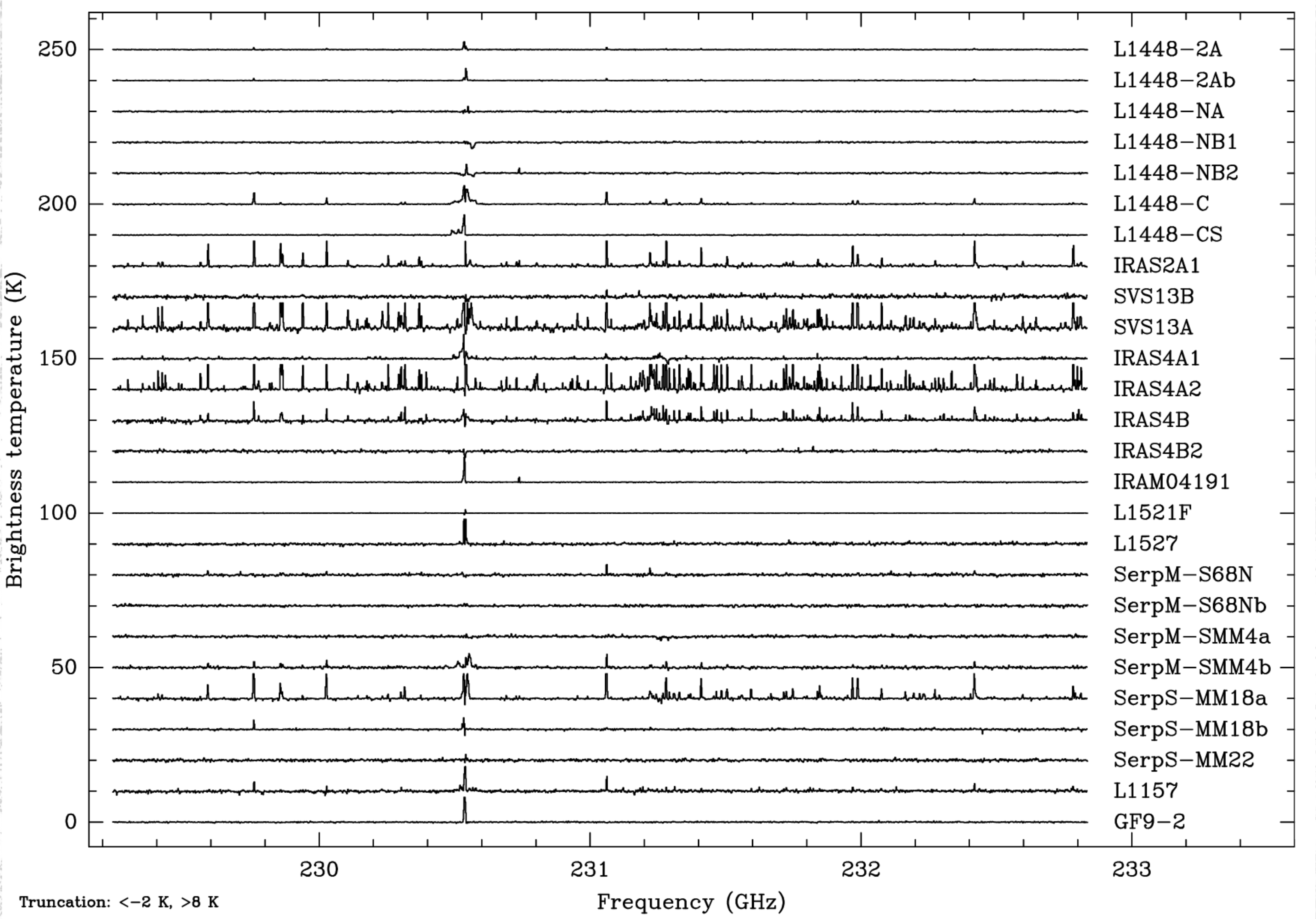




Complex organics are frequent around protostars

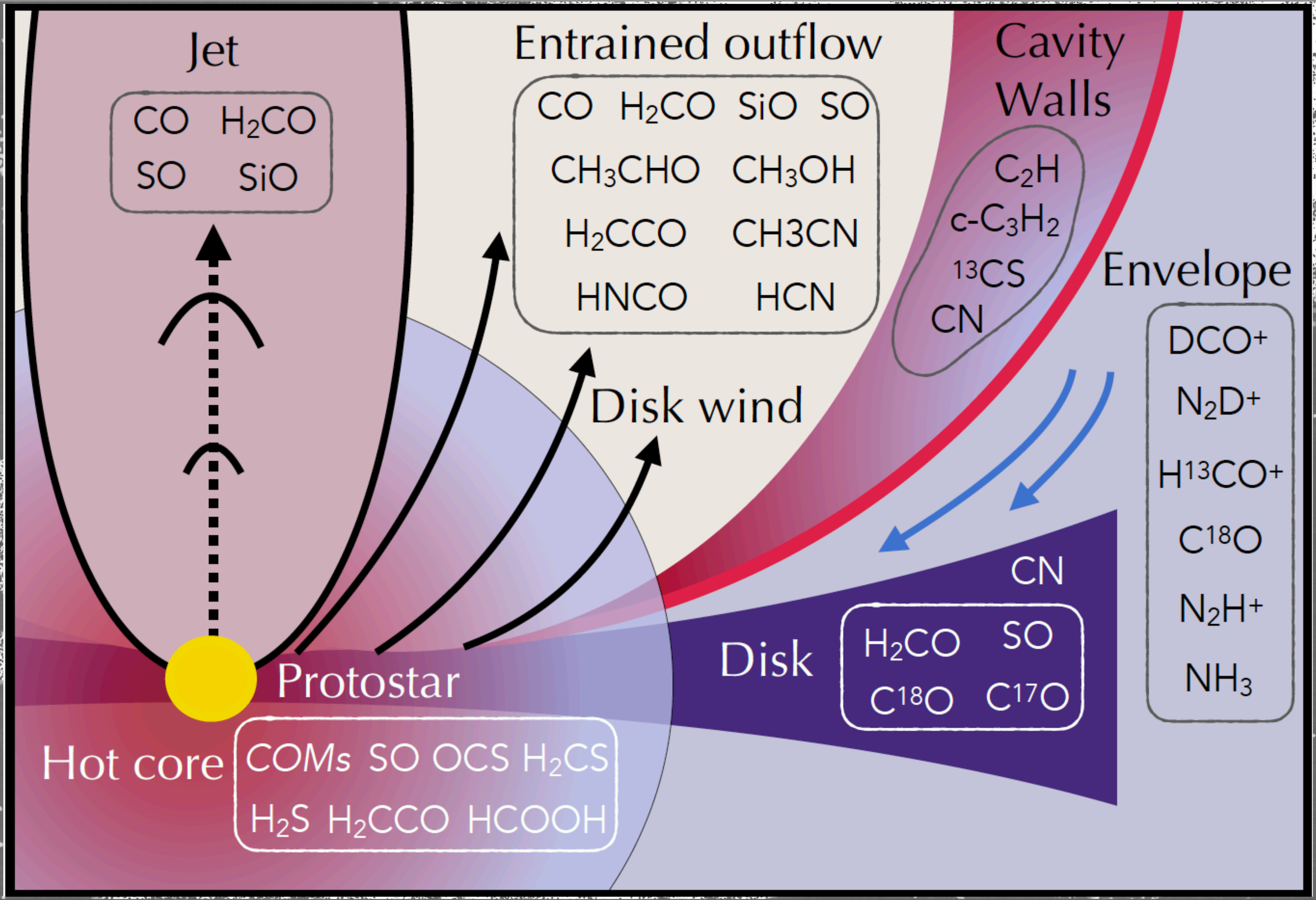
Belloche+2020

- **NOEMA** with broader bandwidth receiver can deliver more instantaneous detections
- Sensitivity is needed for detection of faint species



Chemical tracers of physical components

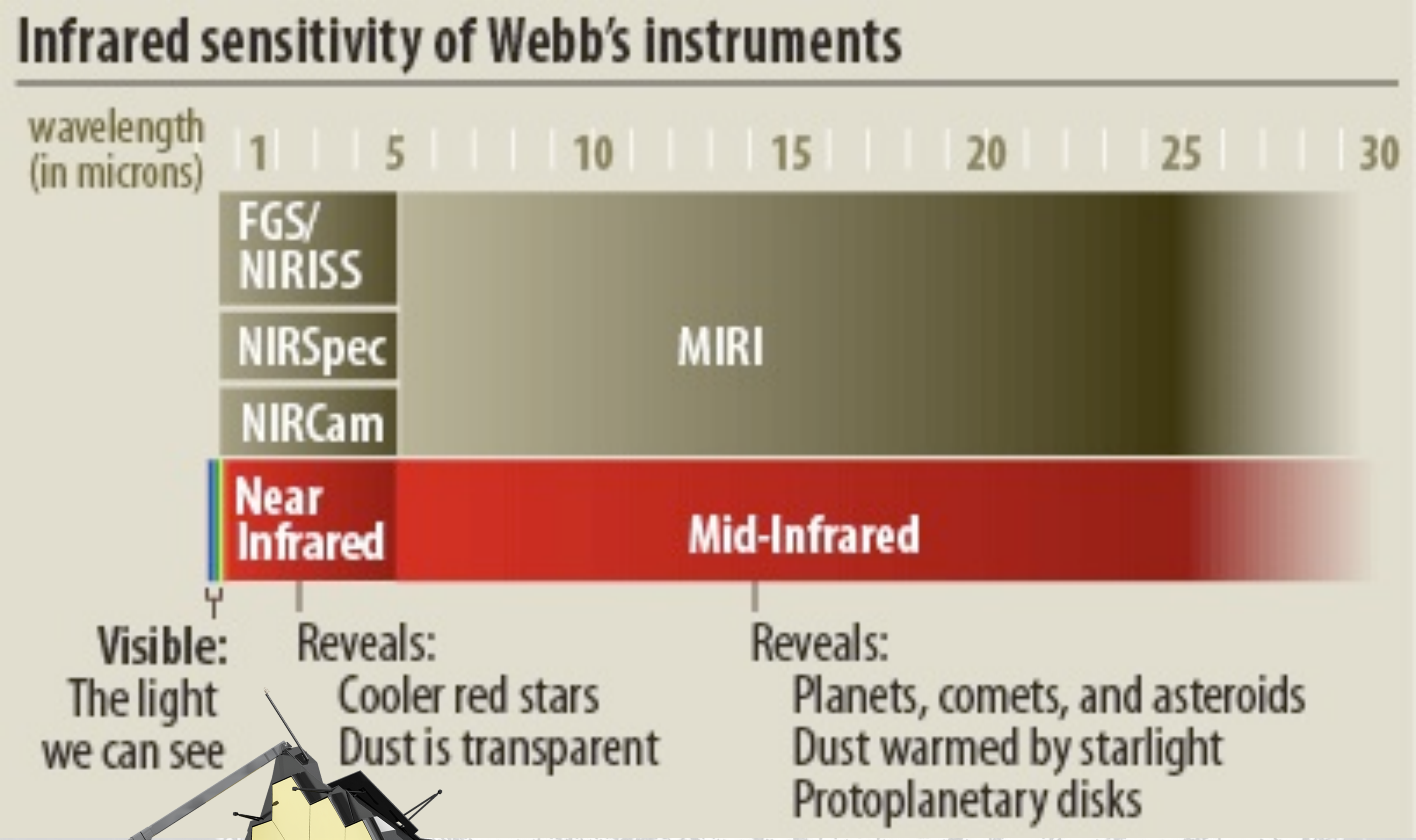
Tycheniec+2021

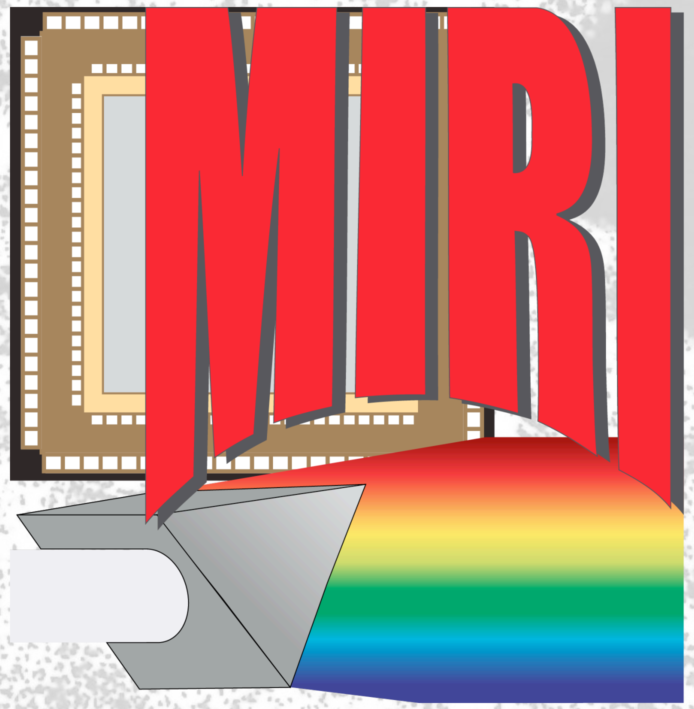


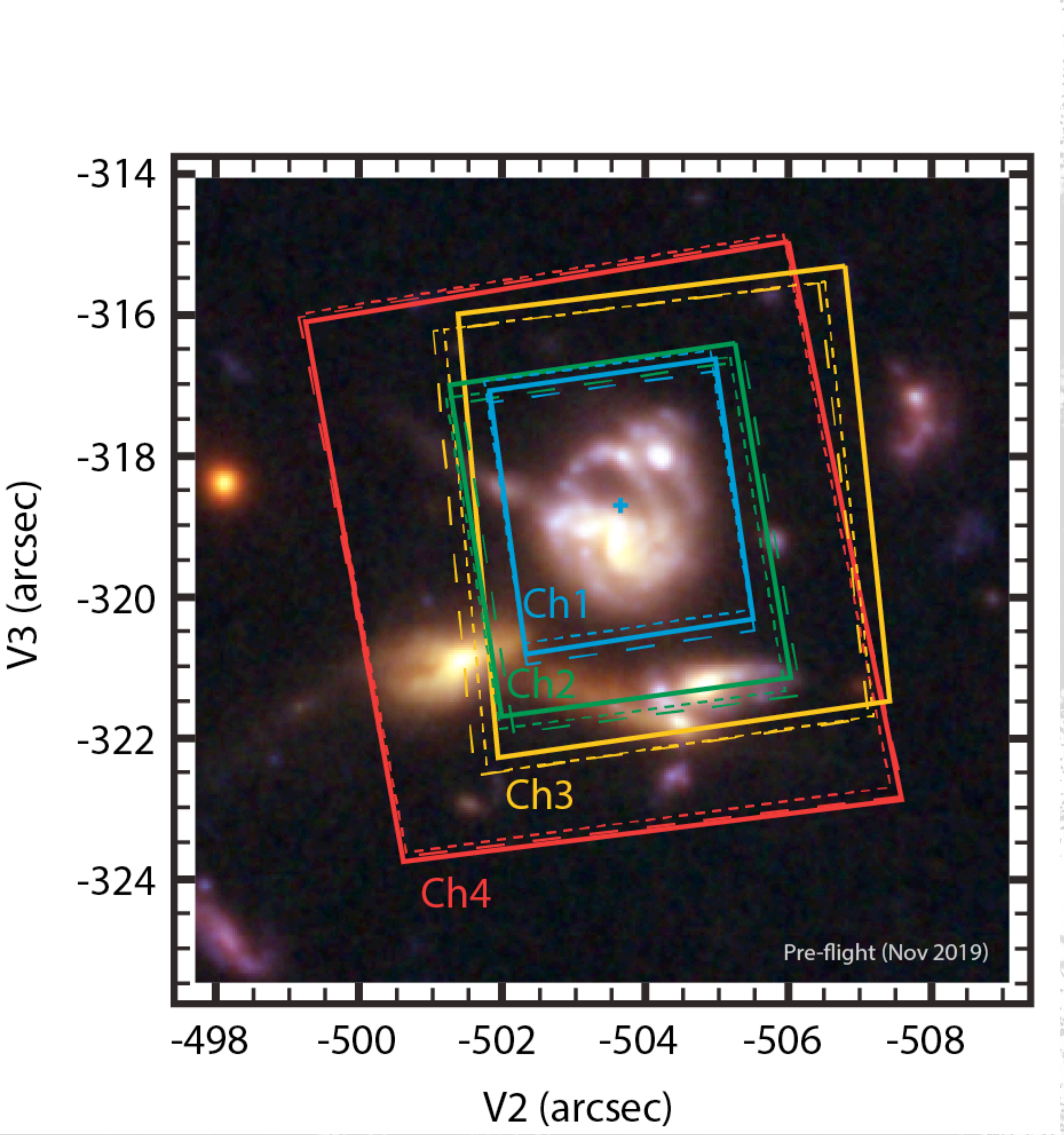
Chemical map for JWST

JWST-MIRI: breakthrough in mid-IR spatial resolution

Rieke+2015, Wright+2015, Wells+2015







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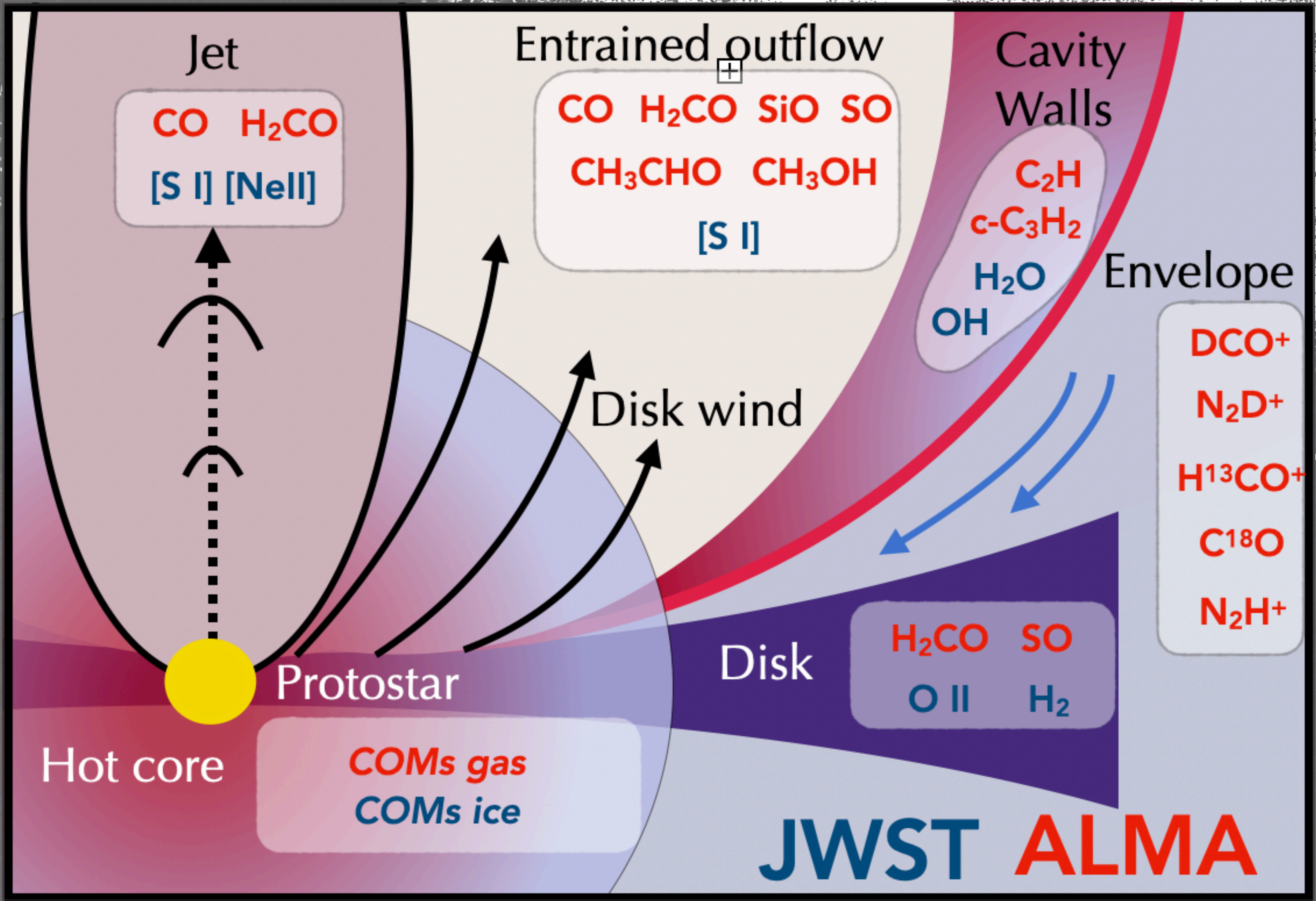
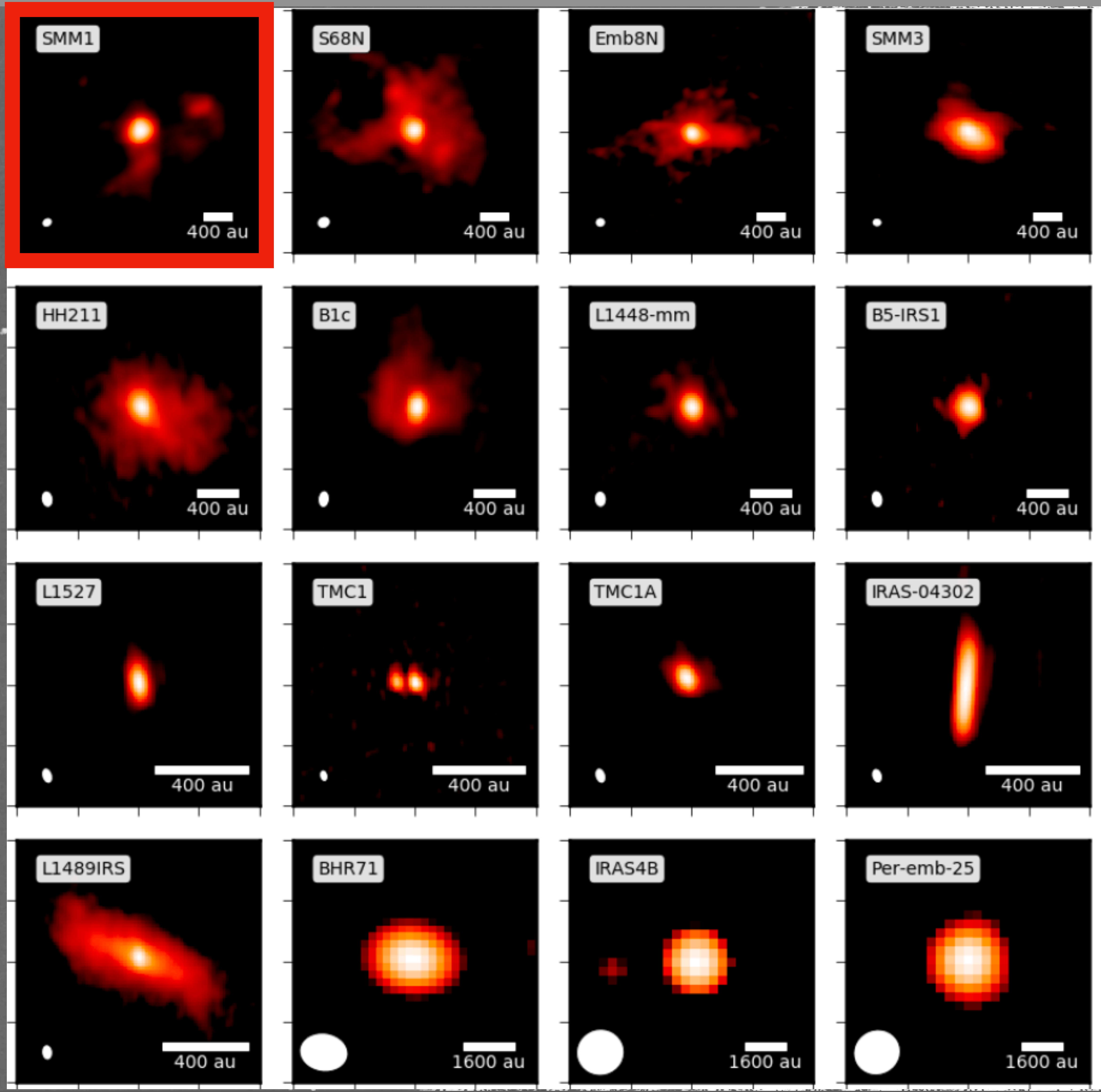
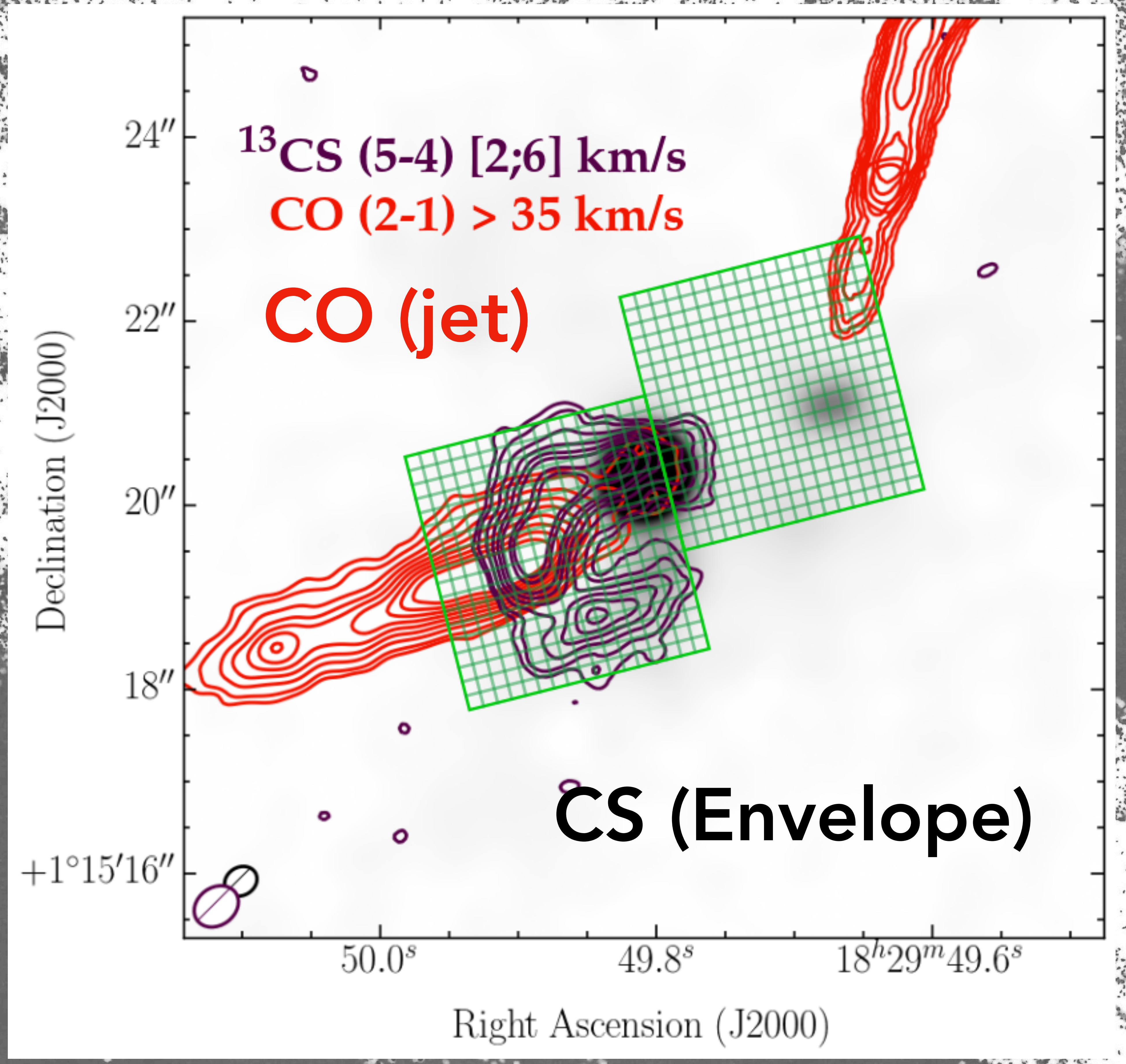
ALMA and JWST are complementary



JWST GTO targets

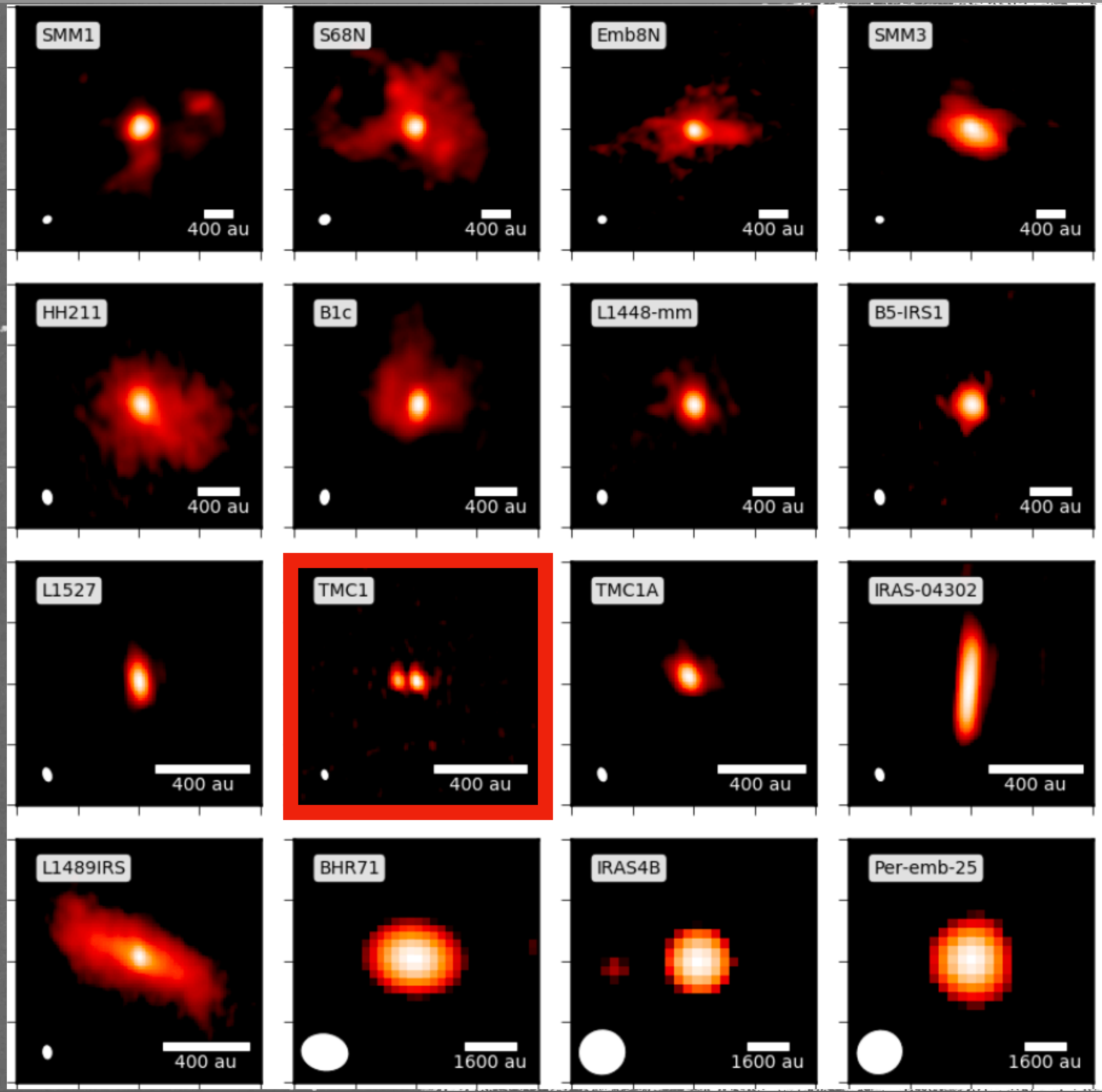
Tychoniec+2021

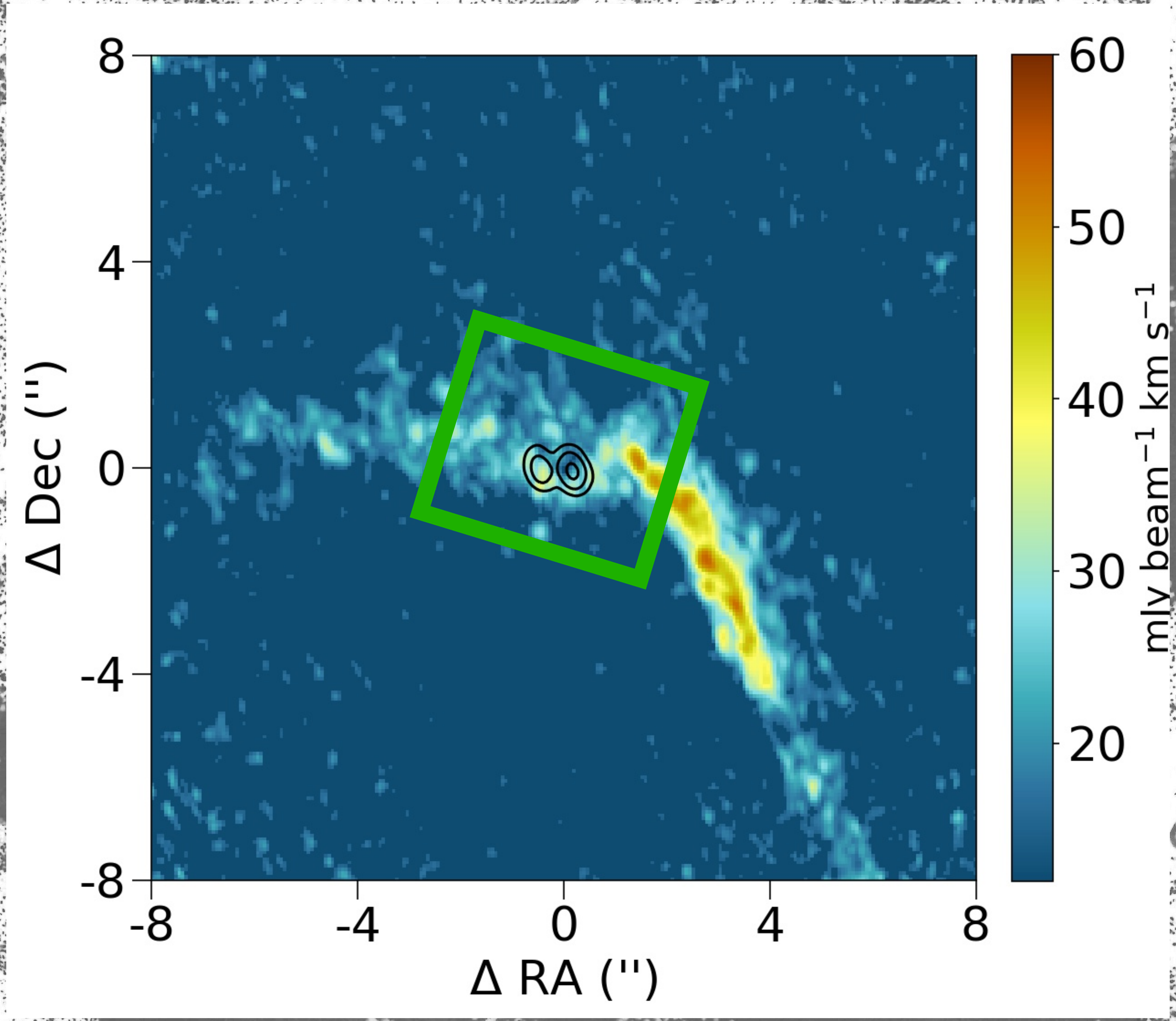




JWST GTO targets

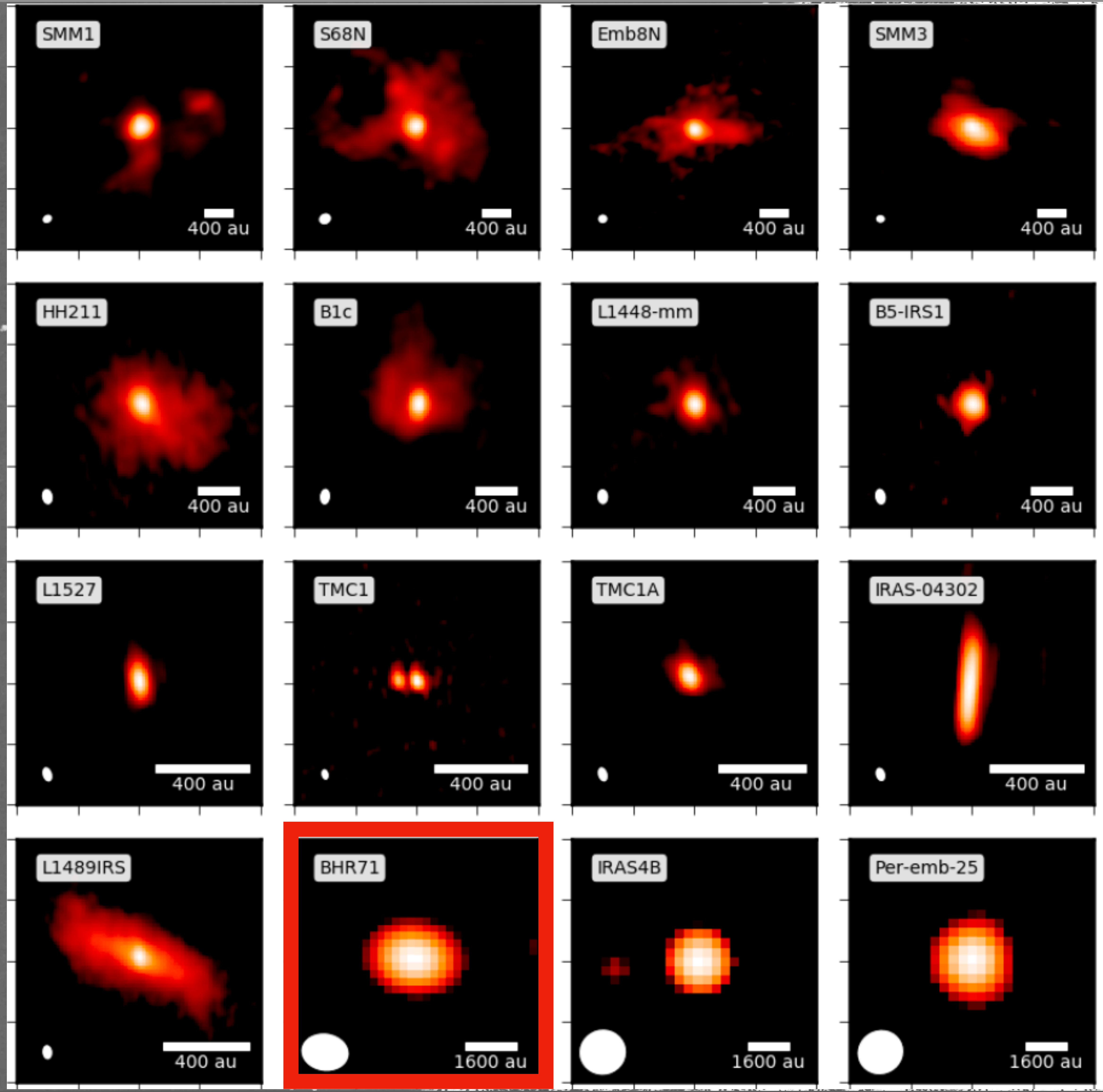
Tychoniec+2021

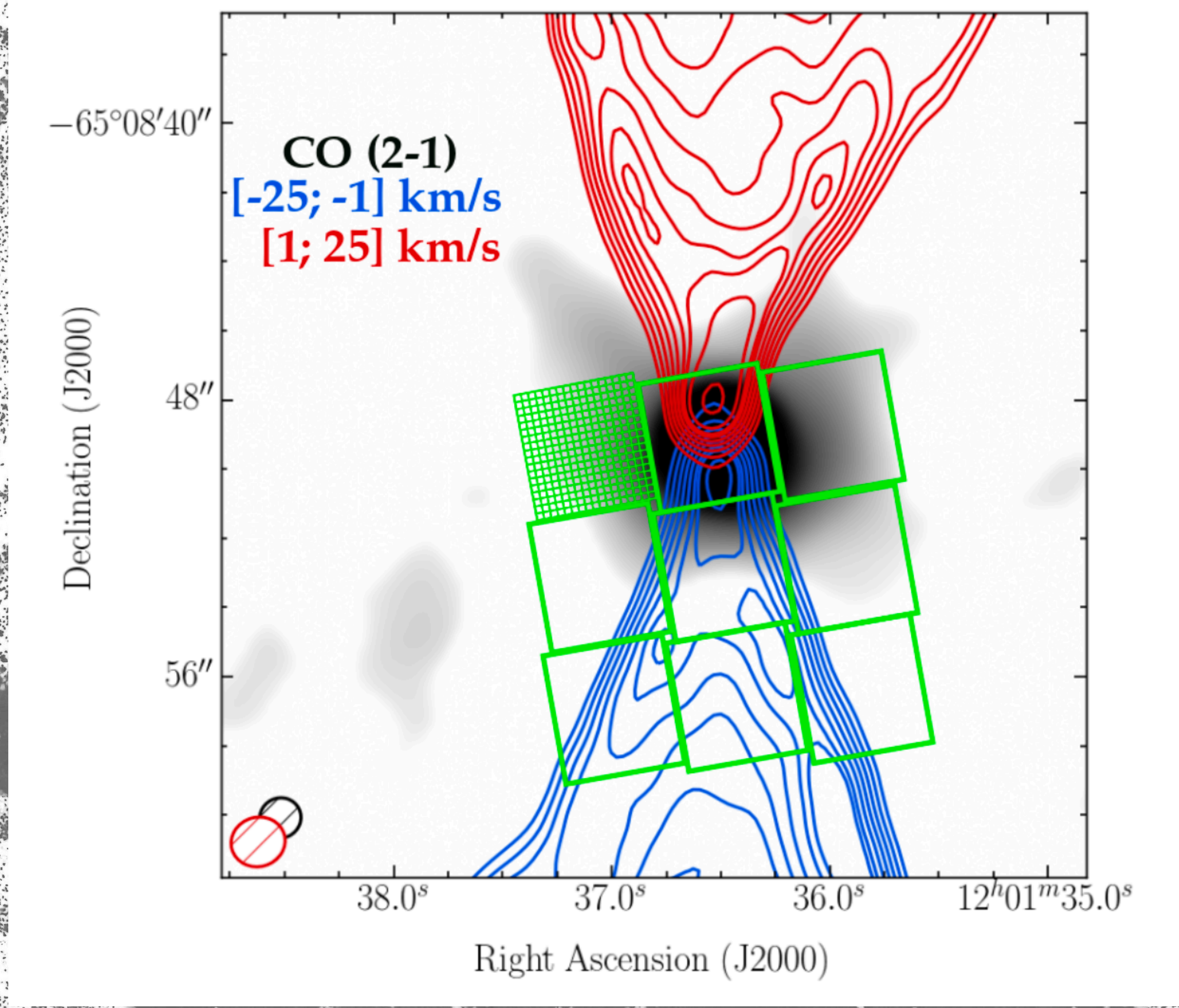




JWST GTO targets

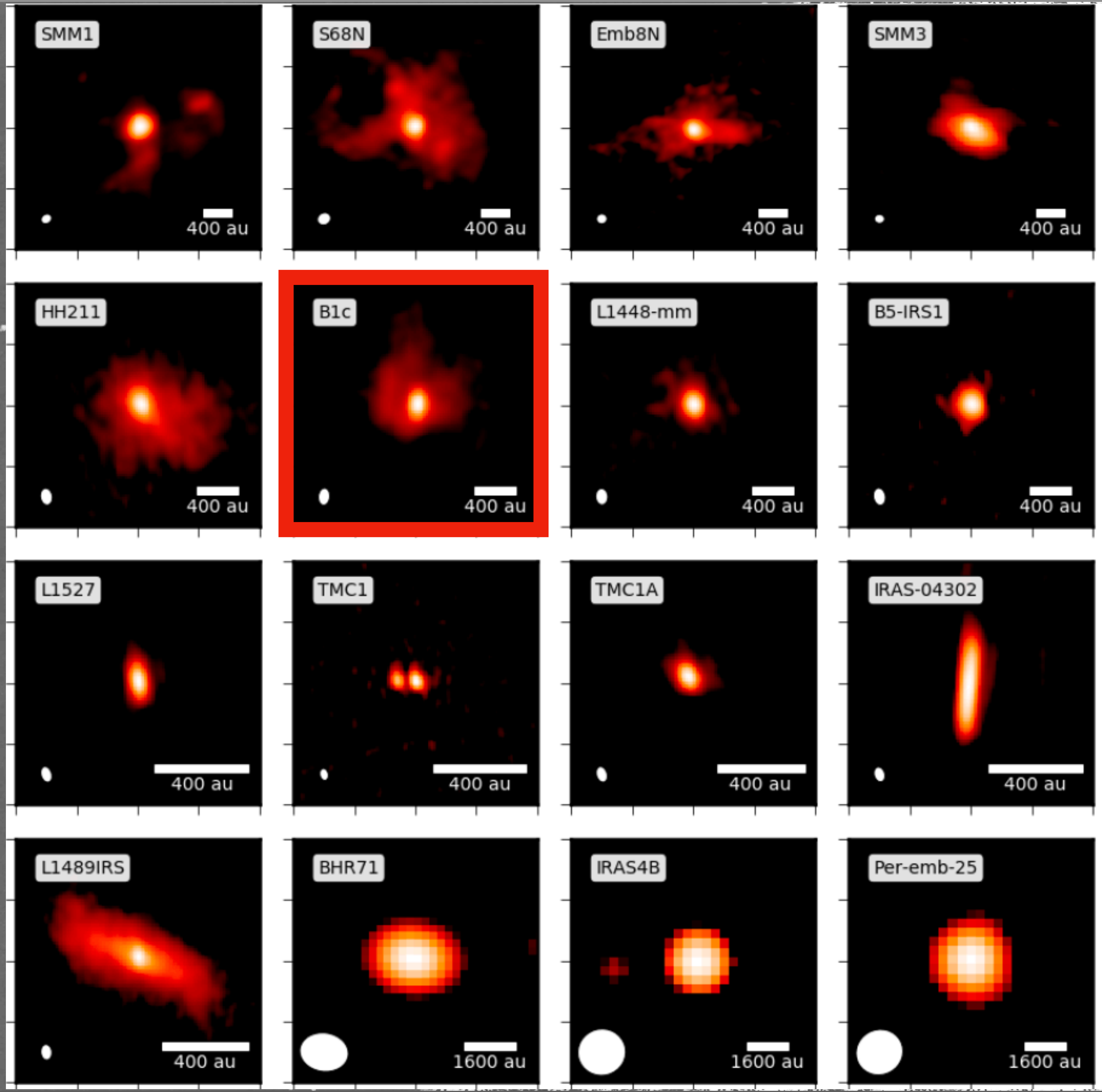
Tychoniec+2021

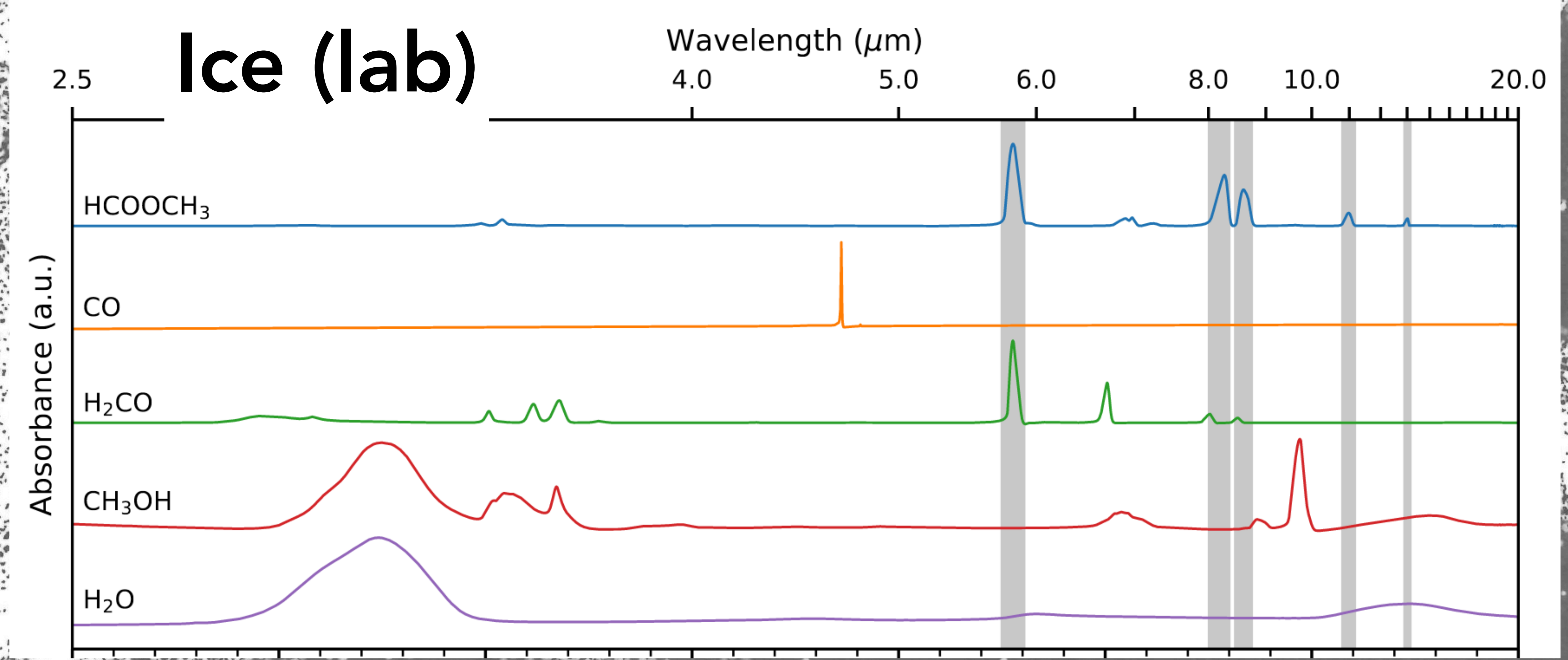


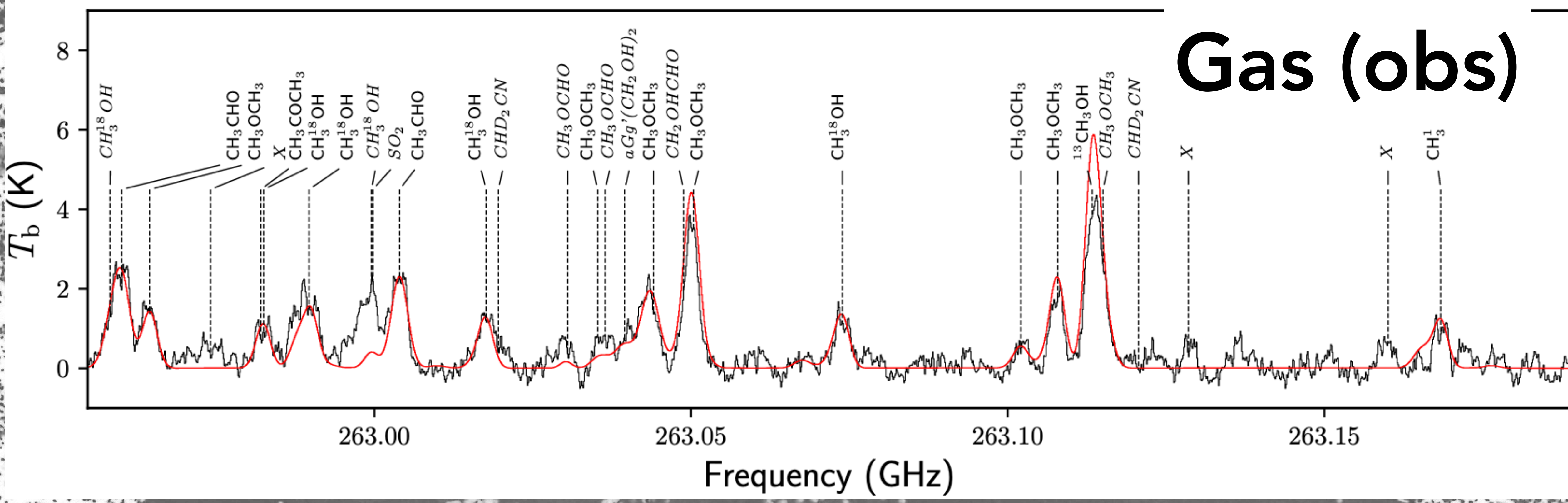


JWST GTO targets

Terrwischa van Scheltinga+2021, van Gelder+2020, Nazari+2021

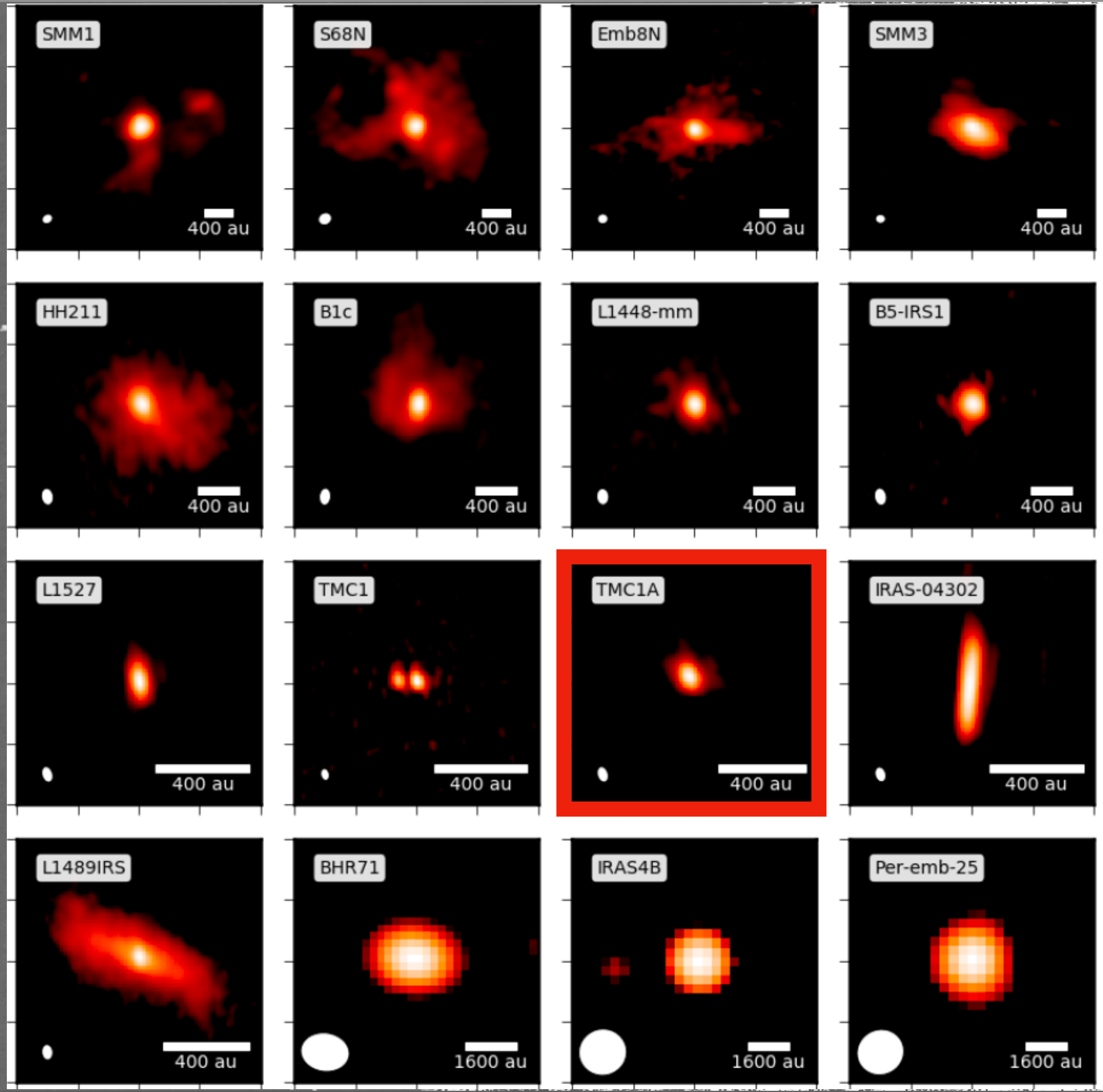


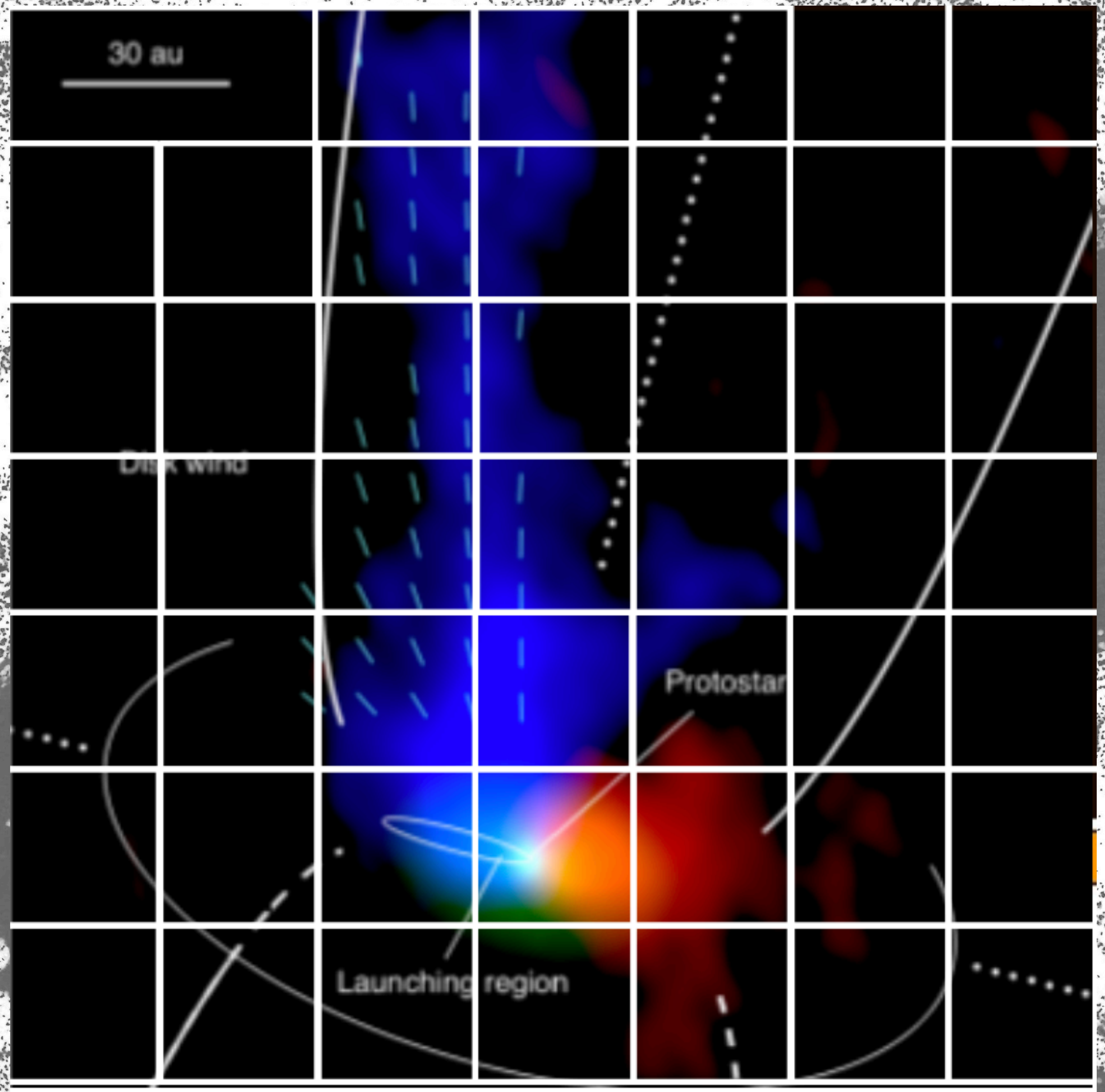




JWST GTO targets

Bjerkeli+2016





Conclusions

JWST and ALMA will deliver powerful synergy

Protostellar jets chemistry promise insight into innermost regions of the disk

Comparisons between chemical complexity in the outflow and inner envelope informs about formation routes of COMs