Chemical complexity in the earliest stages of star formation in the SKA era

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EU H2020 Innovative Training Network
Astro-Chemical Origins

PRIN – 2020
BEYOND-2p
Astrochemistry beyond the Second Period Elements

MUR
Fossils

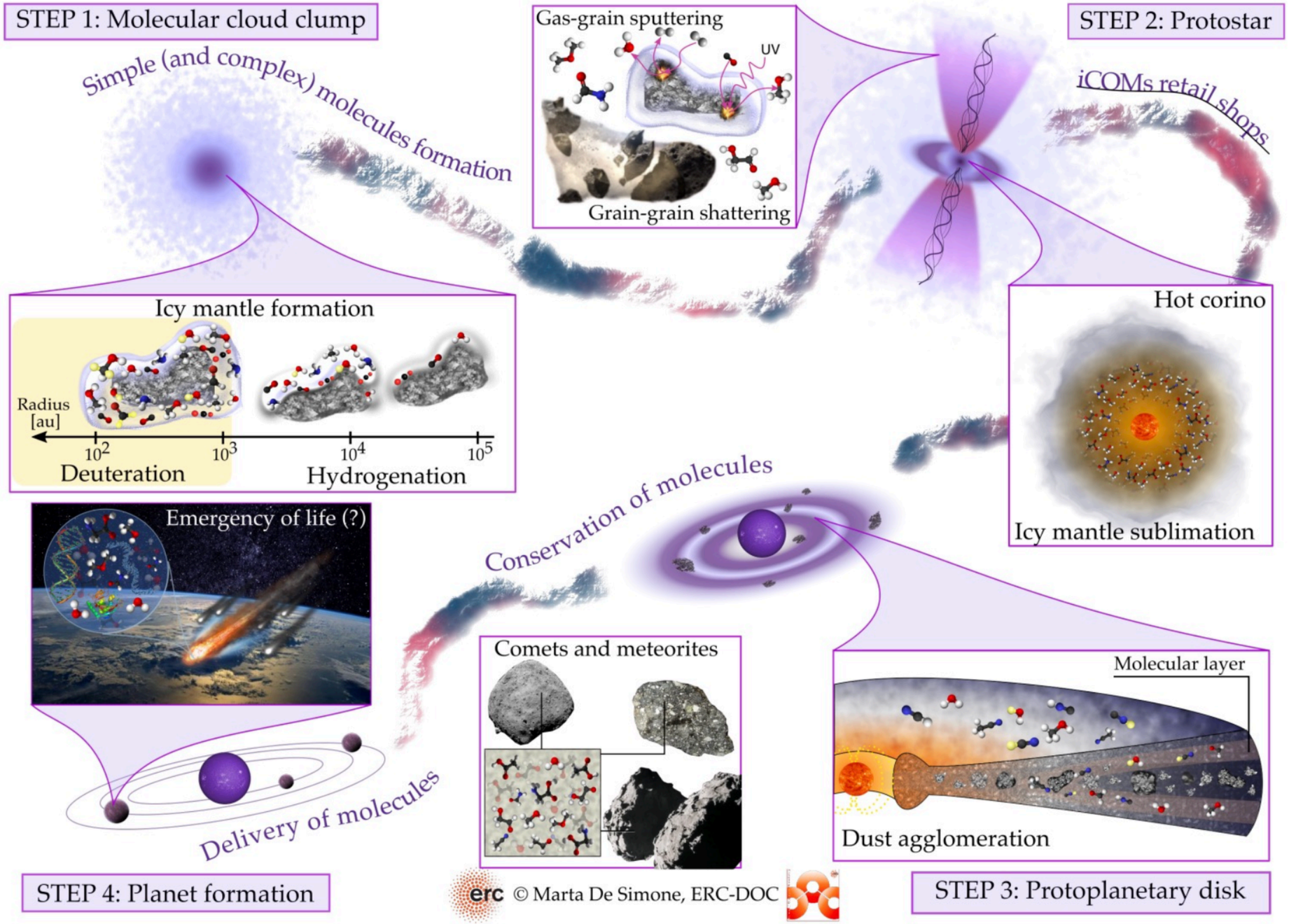
INAF
PROTOSKA

MIGLIORA

agenzia spaziale italiana

FAUST

ALMA DOT



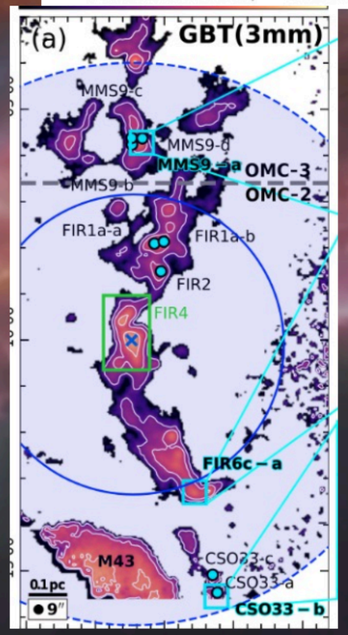
Is the chemical diversity at a molecular envelope scale also present in the inner disk system (50 au) ?

Planetary composition: disk chemical reset or inheritance ?

Chapter in **Advancing Astrophysics with the SKA – II**

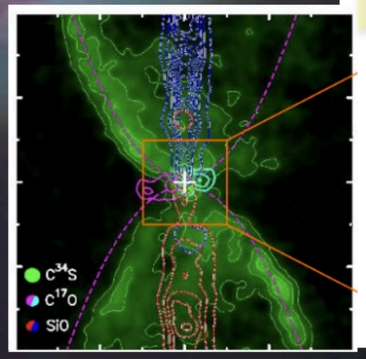
Chemical complexity in the early stages of star formation in the SKAO era

Eleonora Bianchi,[1] Mathilde Bouvier,[2] Claudio Codella,[1] Laura Colzi,[3] Audrey Coutens,[4] Marta De Simone,[5] Joan Enrique Romero,[6] Gisela Esplugues,[7] Francesco Fontani,[1,15] Antonio Garufi,[8] Lisa Giani,[1] Arshia Maria Jacob,[9,10] Izaskun Jiménez-Serra,[3] Marco Padovani,[1] Linda Podio,[1] Albert Rimola,[11] Pablo Rivière Marichalar,[7] Giovanni Sabatini,[1] Andrea Socci,[12] Riccardo Giovanni Urso,[13] Tyler Bourke,[14] Gemma Busquet,[15] Paola Caselli,[16] Cecilia Ceccarelli,[17] Tomoya Hirota,[18] John D. Ilee,[19] Valerio Lattanzi,[16] Manuela Lippi,[1] Ana López-Sepulcre,[17] Pierre Marchand,[4] Liton Majumdar,[27,28] Sabyasachi Pal,[29] Maria Elisabetta Palumbo,[13] Jaime E. Pineda,[16] Manoj Puravankara,[20] Elena Redaelli,[5] Victor M. Rivilla,[3] Basmah Riaz,[21] Álvaro Sánchez-Monge,[22] Silvia Spezzano,[16] Leonardo Testi,[23] Himanshu Tyagi,[20] Claudia Toci,[24,5] Alessio Traficante,[25] Grazia Umana,[13] Charlotte Vastel[4] and Susanne Wampfler[26]



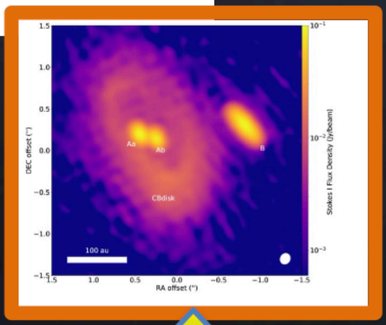
Unveiling complex chemistry in planet-forming disks with the SKAO

Linda Podio,[1] Catherine Walsh,[8] Lisa Giani,[1] Audrey Coutens,[5] Izaskun Jiménez-Serra,[10] Claudio Codella,[1] Maria Jose Maureira,[3] Marta De Simone,[6] John D. Ilee,[8] Manuela Lippi,[1] Chin-Fei Lee,[26] Romane Le Gal,[4] Mayank Narang,[12] Giovanni Sabatini,[1] Eleonora Bianchi,[1] Elenia Pacetti,[13] Danai Polychroni,[15] Bihan Banerjee,[2] Paola Caselli,[3] Cecilia Ceccarelli,[4] Amin Farhang,[7] Antonio Garufi,[23] Greta Guidi,[4] Adriano Ingallinera,[9] Pamela Klaassen,[11] Ana López-Sepulcre,[4] Liton Majumdar,[24,25] Giulia Perotti,[14] Jaime E. Pineda,[3] Daniel J. Price,[16,4] Manoj Puravankara,[17] Pablo Rivière-Marichalar,[18] Álvaro Sánchez-Monge,[19] Eugenio Schisano,[13] Leonardo Testi,[20] Claudia Toci,[21,6] Diego Turrini,[15] Alessio Traficante[13] and Yinhao Wu[22]



Jets and outflows in young stellar objects with the SKAO

Sabatini G.,[1] Busquet G.,[2] Carrasco-González C.,[3] Rodríguez-Kamenetzky A.,[4] Codella C.,[1] Podio L.,[1] Martínez-Henares A.,[5] Girart J. M.,[6] De Simone M.,[7] Cacciapuoti L.,[8] Tychoniec L.,[9] Giani L.,[1] Puravankara M.,[10] Anglada G.,[11] Bacciotti F.,[1] Bachiller R.,[12] Bianchi E.,[1] Bourke T.,[13] Bovino S.,[14,15,1,16] Caselli P.,[17] Cavallaro F.,[18] Ceccarelli C.,[19] Diaz-Marquez E.,[2] Facchini S.,[20] Garufi A.,[21] Guidi G.,[22] Hirota T.,[23,24] Ilee J.,[25] Ingallinera A.,[18] Jiménez-Serra I.,[5] Lattanzi V.,[17] Lee C.-F.,[26] Lippi M.,[1] Lupi A.,[27] Majumdar L.,[28,29] Narang M.,[30] Osorio M.,[11] Padovani M.,[1] Pineda J.,[17] Radley I.,[22] Riaz B.,[31] Rodríguez L. F.,[3] Sánchez-Monge Á.,[32] Sanna A.,[33] Spezzano S.,[17] Testi L.,[34] Toci C.,[35,7] Traficante A.,[36] Tyagi H.[10] and Umana G. M.[18]



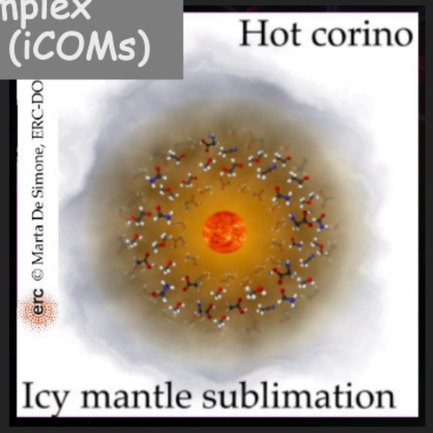
See Sabatini's talk

Prestellar & Protostars: paving the way to (pre)biotic molecules

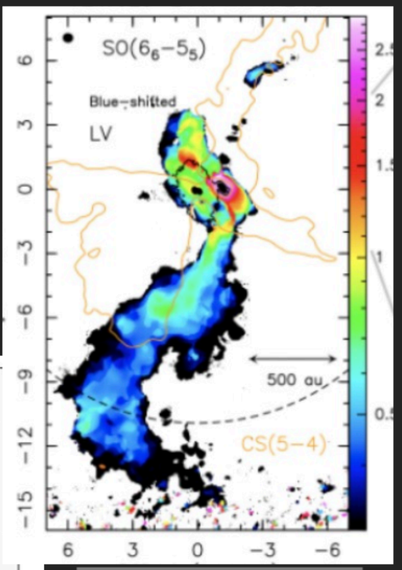
De Simone+ 2020, 2022, 2024, 2025

Name	Formula
Methanol	CH_3OH
Formic acid[b]	$HCOOH$
Acetaldehyde	CH_3CHO
Methyl formate	$HCOOCH_3$
Glycolaldehyde	$HCO(CH_2)OH$
Acetic acid	CH_3COOH
Dimethyl ether	CH_3OCH_3
Acetone	CH_3COCH_3
Ethanol	CH_3CH_2OH
Propanal	CH_3CH_2CHO
Ethylene glycol	$(CH_2OH)_2$
Methyl cyanide	CH_3CN
Ethyl cyanide	CH_3CH_2CN
Cyanoacetylene	HC_5N
Formamide	NH_2CHO

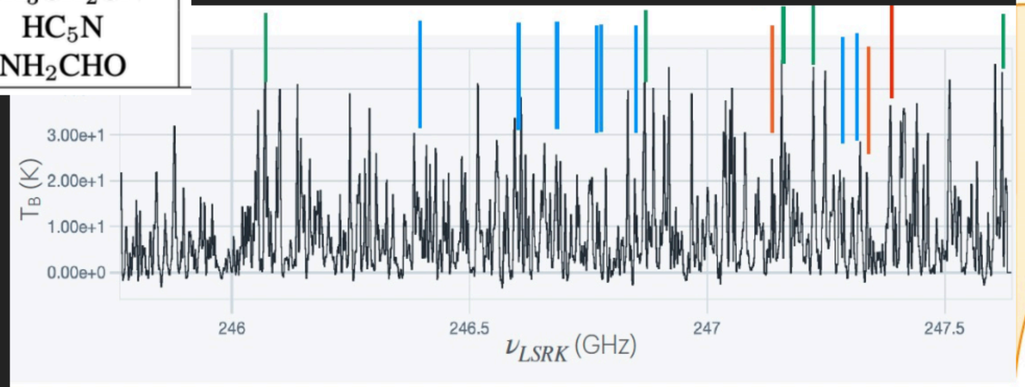
interstellar Complex Organic Molecules (iCOMs)

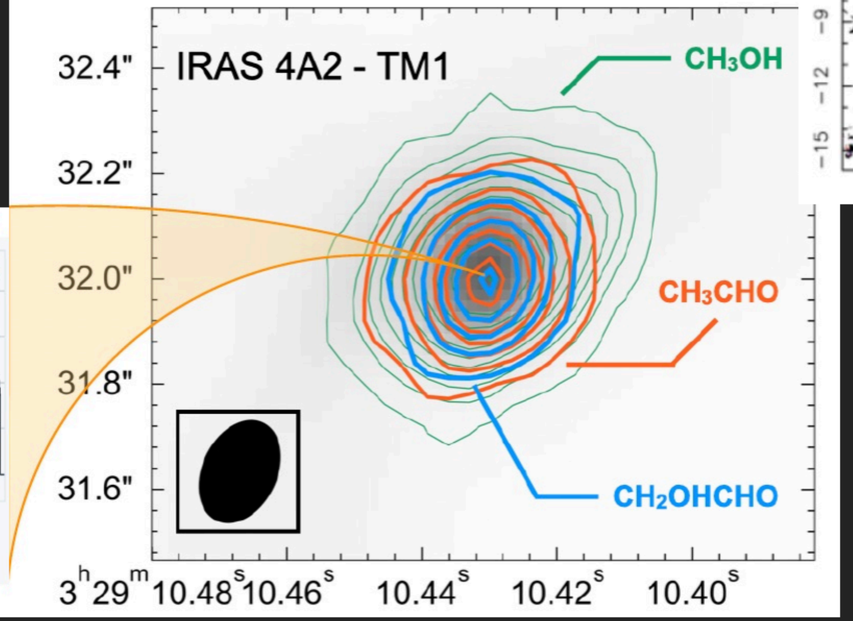


- **Methanol** trace the most extended emitting radius (40 au), followed by:
- **Methyl formate** (36 au)
- **Acetaldehyde** (28 au)
- **Ethanol** (27 au)
- **Glycolaldehyde** & **Formamide** with the most compact emission (22-23 au)



Codella+ 2024

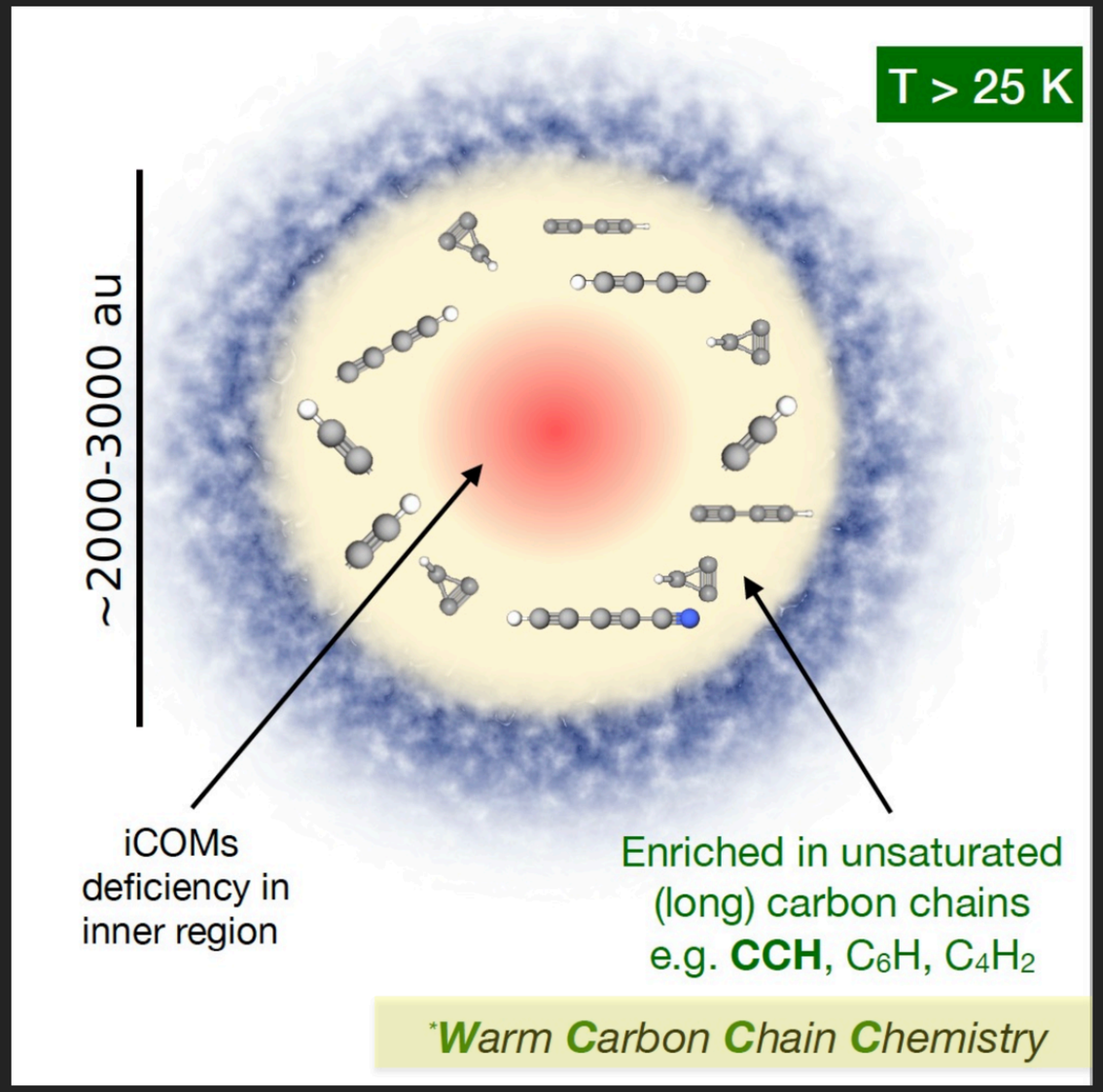




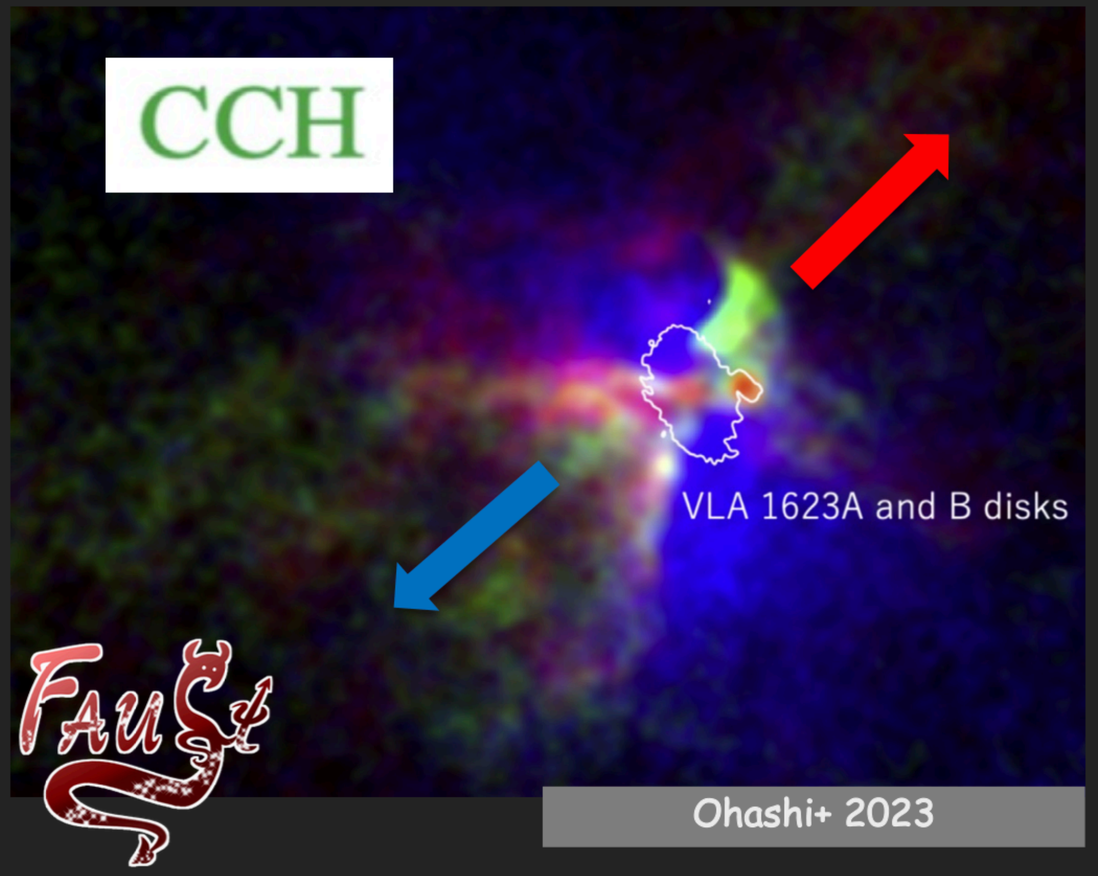
iCOMs extend out to different spatial scales.....

Frediani+ 2025

ALMA is missing one key ingredient: heavy C-chains and rings



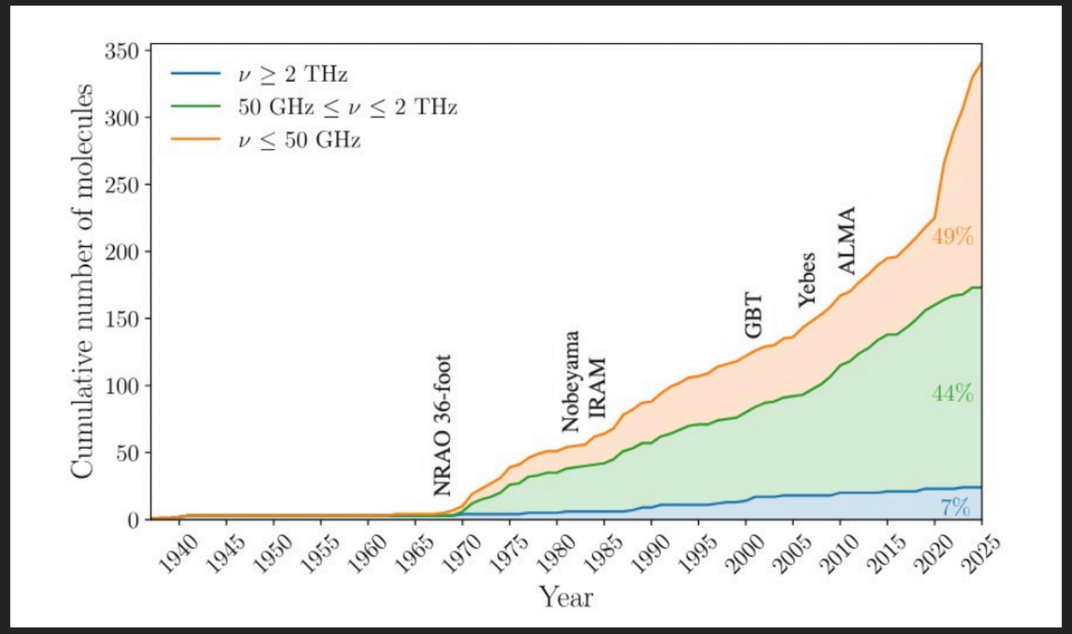
ALMA main WCCC tracer: CCH, c-C_2H3



THE CARBON RUSH…

GBT 100-m GOTHAM:
McGuire et al. 2020

YEBES 40m QUIJOTE & SANCHO:
Cernicharo et al. 2021



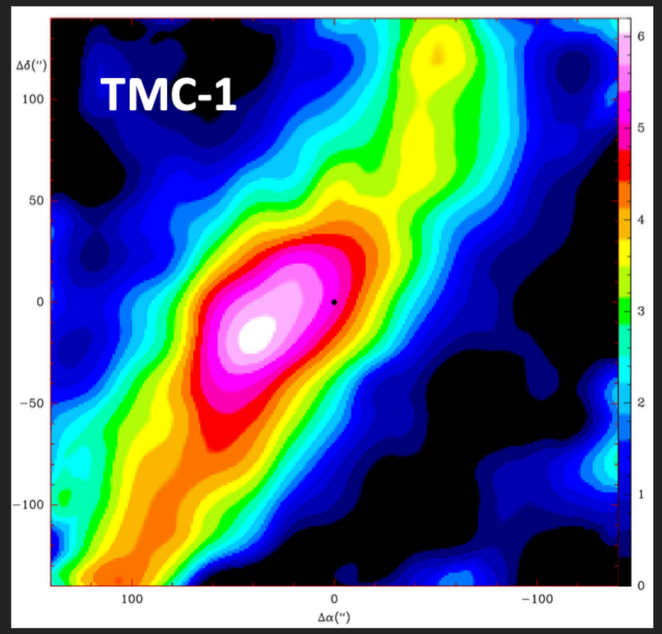
Bianchi et al. 2025

C_2H_5OH
CH_3COCH_3
C_2H_5CHO
CH_3CHCO

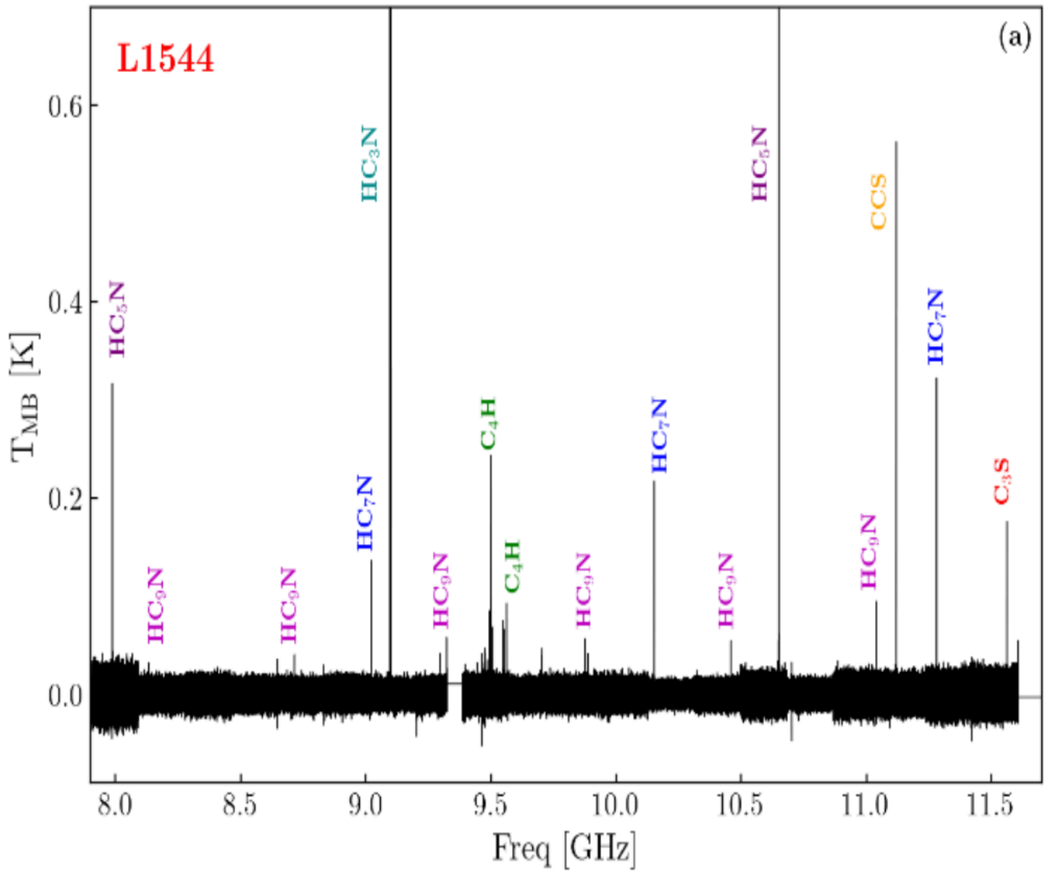
$c\text{-}C_5H_4CCH_2$
$HCCCH_2$
$c\text{-}C_6H_4$
$c\text{-}C_9H_8$

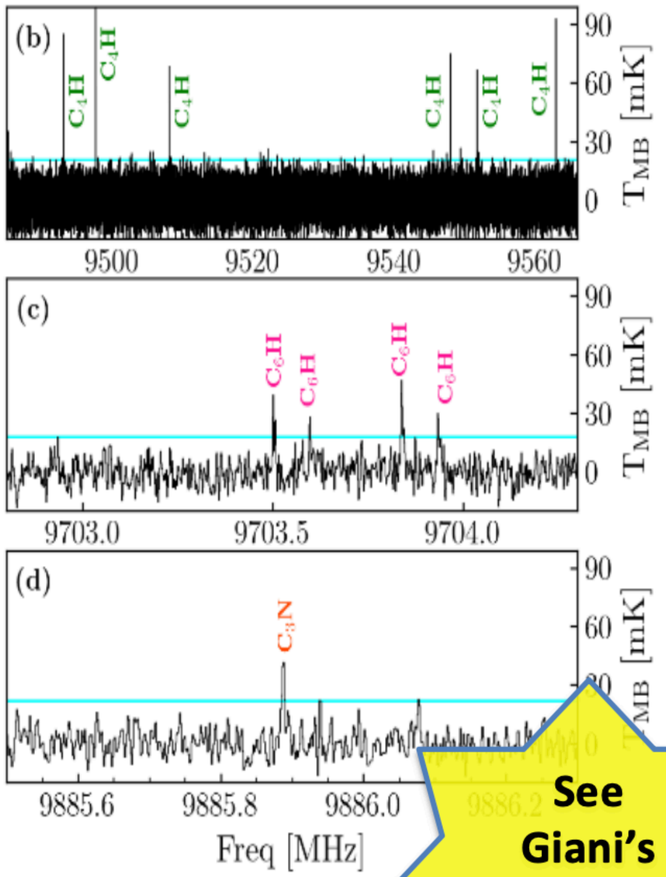
McGuire et al. 2018, Burkhardt et al. 2021, Agúndez et al. 2023, Cernicharo et al. 2021a, 2021b, 2022…..

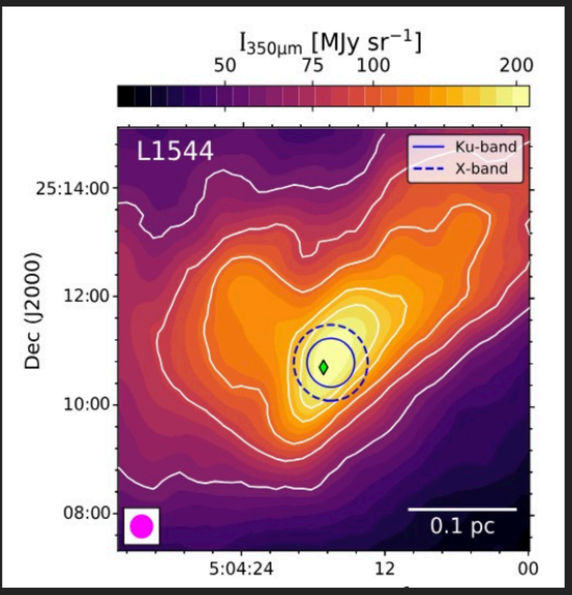
C_6H_5CN benzonitrile



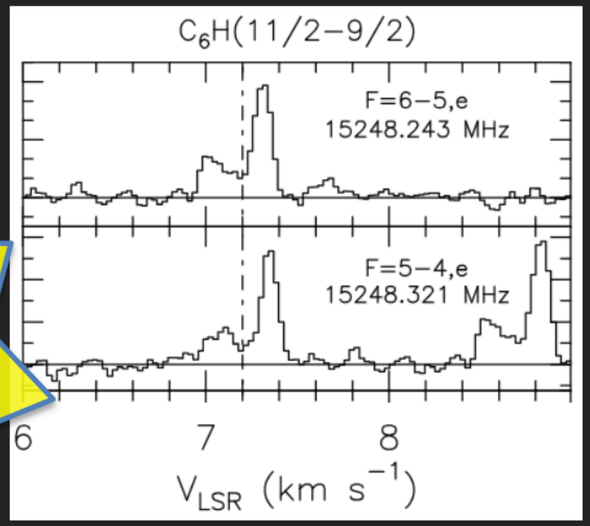
L1544 PRESTELLAR CORE AT SKA FREQUENCIES (GBT-100m)







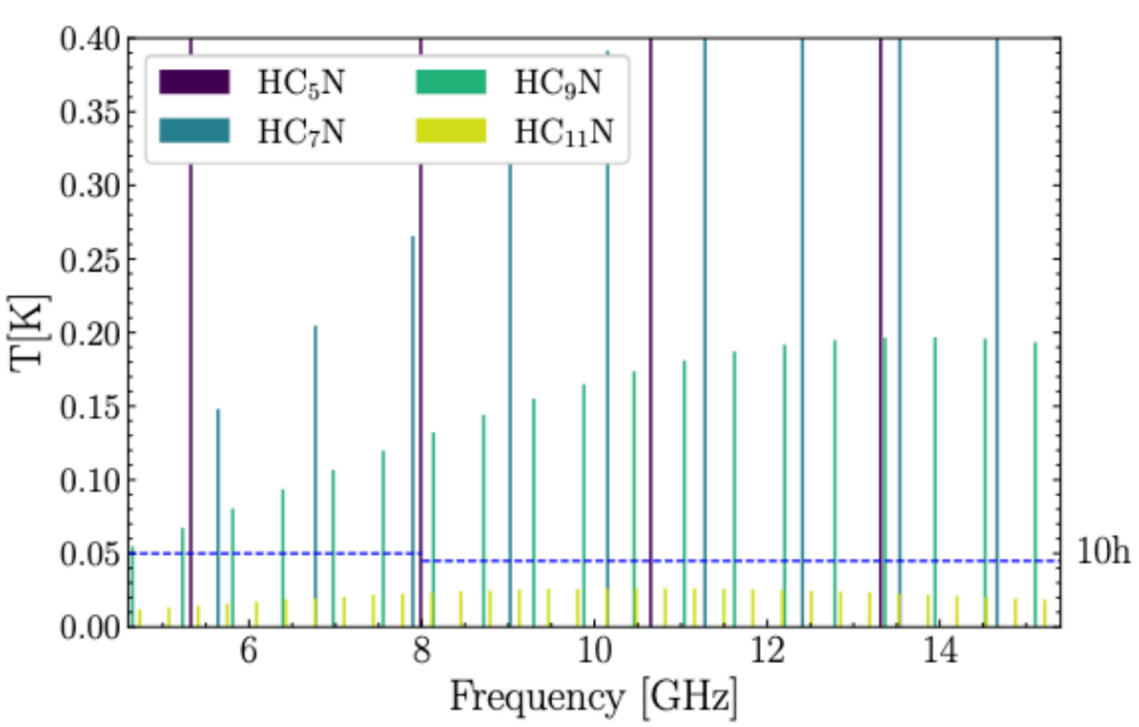
Up to HC_7N up to C_6H

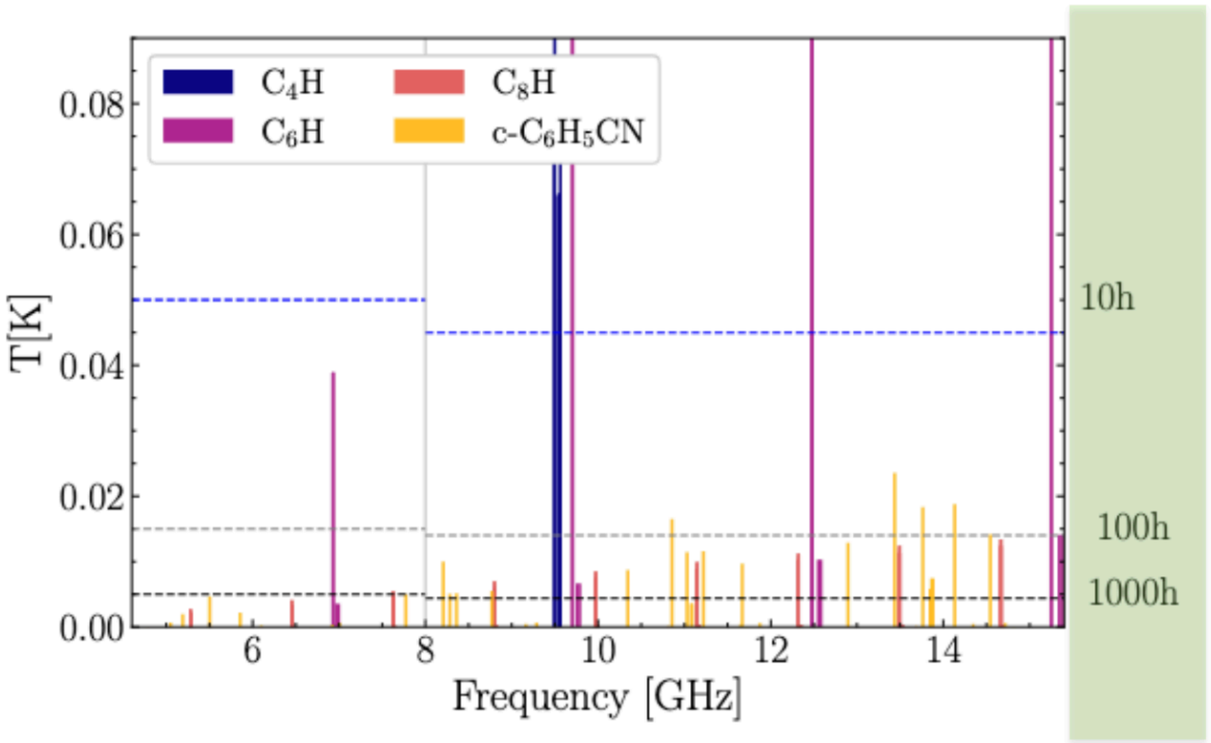


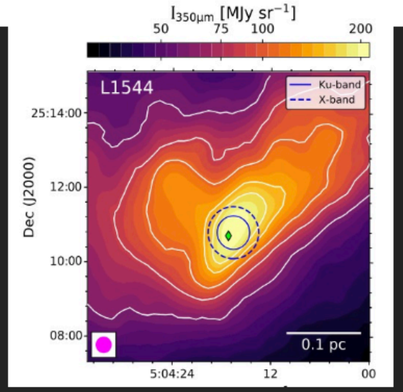
See Giani's flash talk

Bianchi+ 2023, Giani+ 2025

SKAO (INTEGRATION) TIME







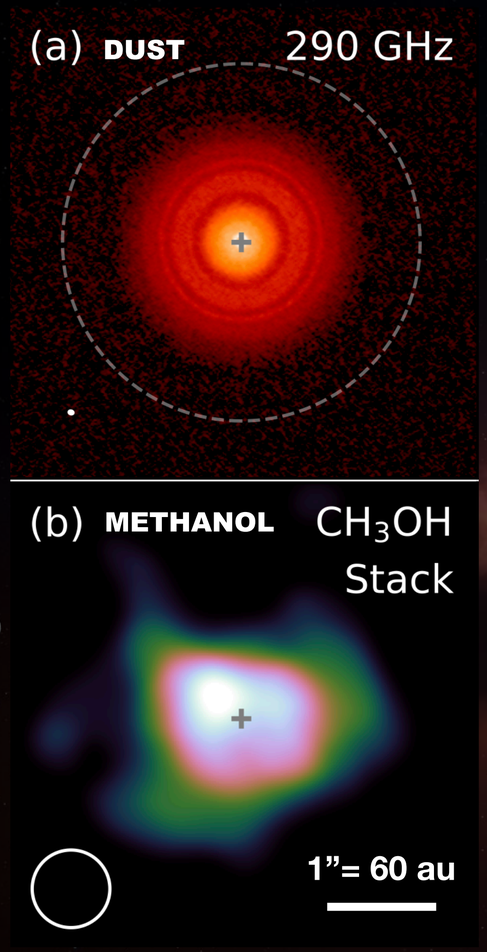
From Bianchi+ 2025, Advancing Astrophysics with the SKA II

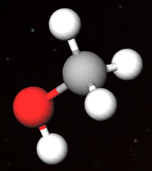
SKAO sensitivity calculator:
SKA-Mid AA4,
extended emission, 3.36 kHz
spectral resolution

Unveiling complex chemistry in planet-forming disks with the SKAO

ALMA observations of TW Hya DISK (d=60 pc)

Ilee et al. 2025





Protoplanetary disks are the birthplace of planets

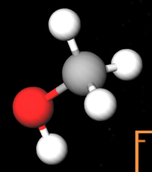
Characterising their chemistry is crucial
to determine what chemical complexity is inherited by the forming planets

Draft contribution to **Advancing Astrophysics: Preparing for Science with the SKAO**

Unveiling complex chemistry in planet-forming disks with the SKAO

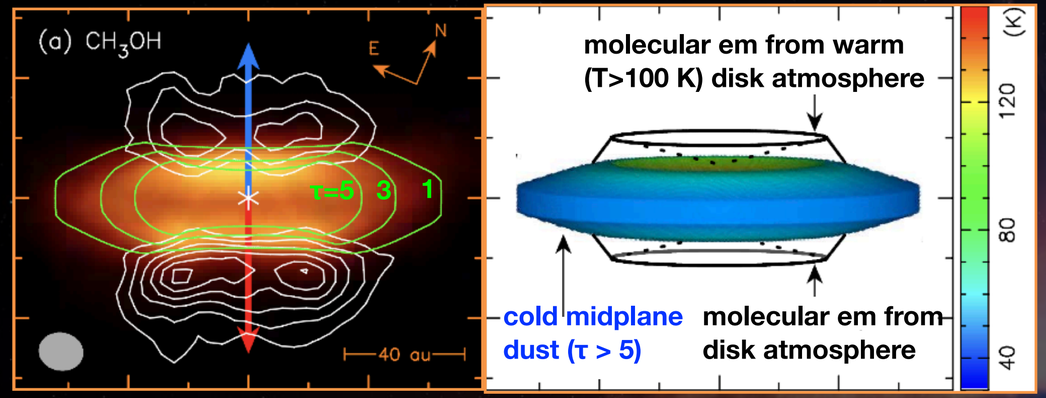
The limits of ALMA in studying disk chemistry

the planet formation region is obscured by optically thick dust at mm wavelengths



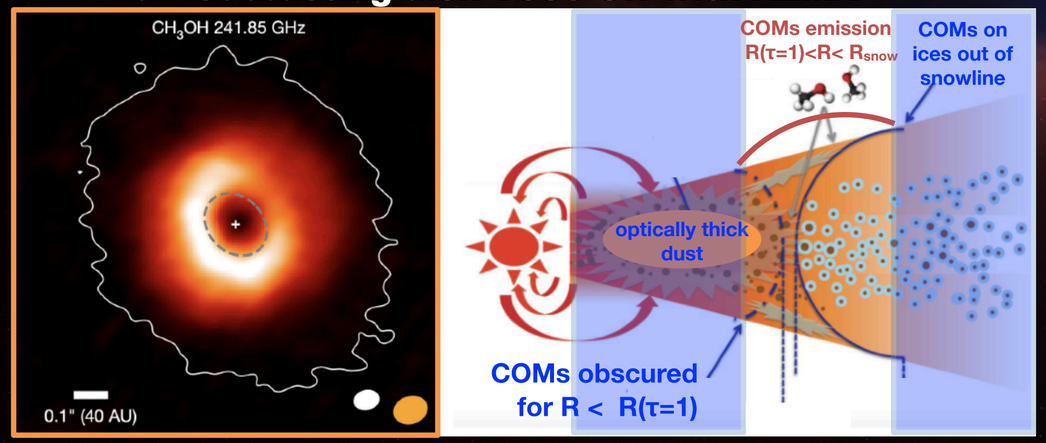
Protostellar disk HH 212 with ALMA

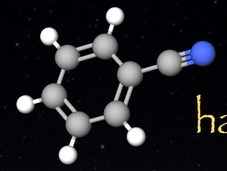
Lee et al. 2022



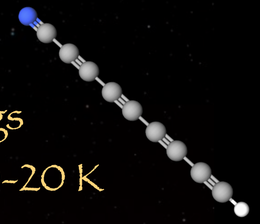
Outbusting disk V883 Ori with ALMA

Tobin et al. 2023

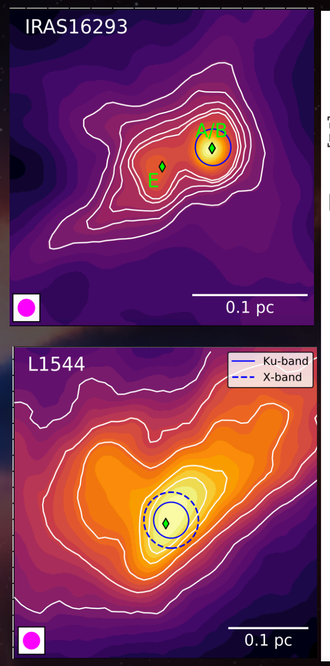


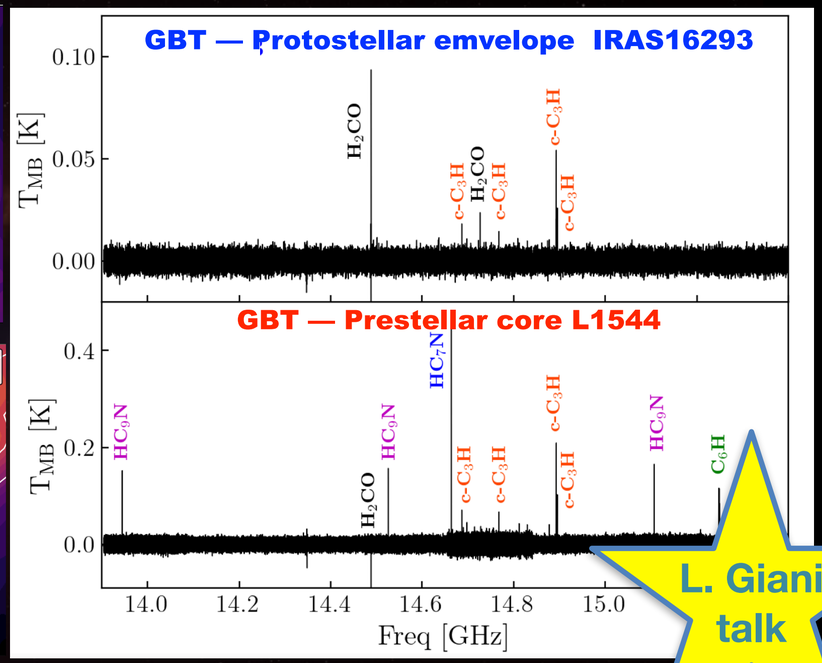


complex C-bearing chains and rings have their peak emission in the cm at 10-20 K



Bianchi et al. 2023, Giani et al. 2025





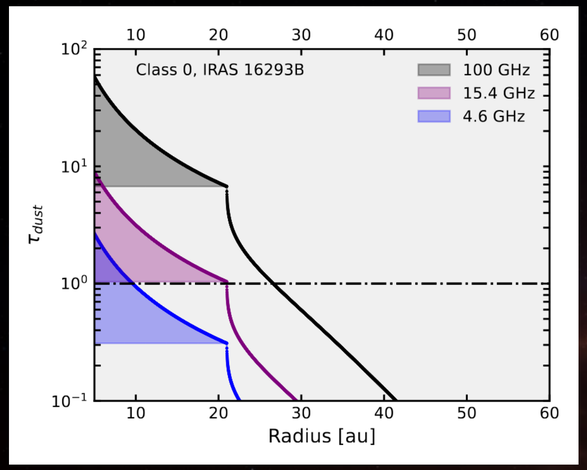
L. Giani talk

Large beam of single-dish antennas (60-80"" with GBT) prevents detection of complex C-species in compact sources such as disks (100 au scales)

Unveiling complex chemistry in planet-forming disks with the SKAO

The need for disk observations @cm with the SKAO

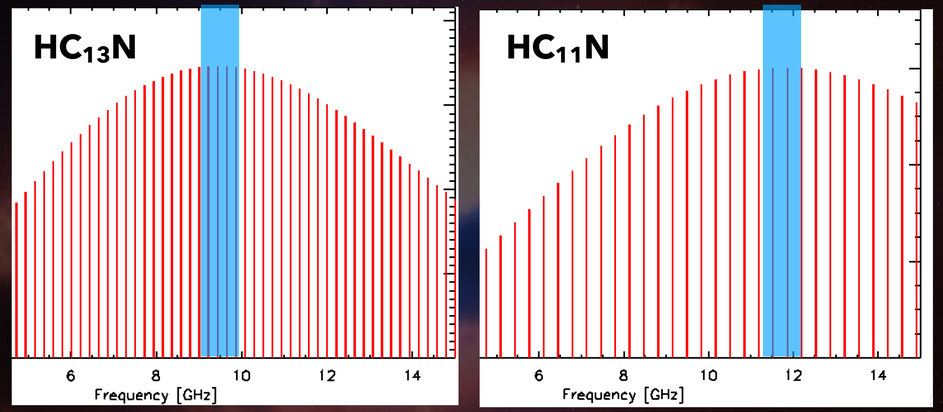
Dust opacity sharply decreases at cm



Maureira et al. 2025
De Simone et al. 2020

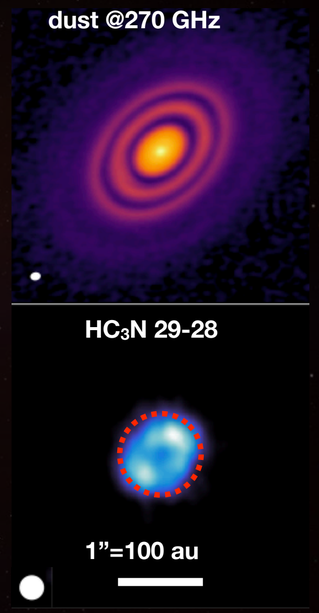
emission from complex C-species
at low T peak at cm

Increasing complexity



LTE @T=10 K

disks are compact (< 1”-2”)



ALMA observations of HD 163296 d=100 pc

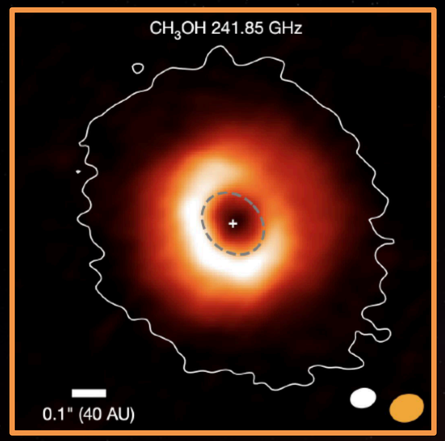
Ilee et al. 2021

High angular res (<1”-2”) and sensitivity (< 1 K/beam) at cm is required to explore
the chemistry of the cold (20 K), dusty (τ>1 @mm), compact (<200au) midplane of planet-forming disks

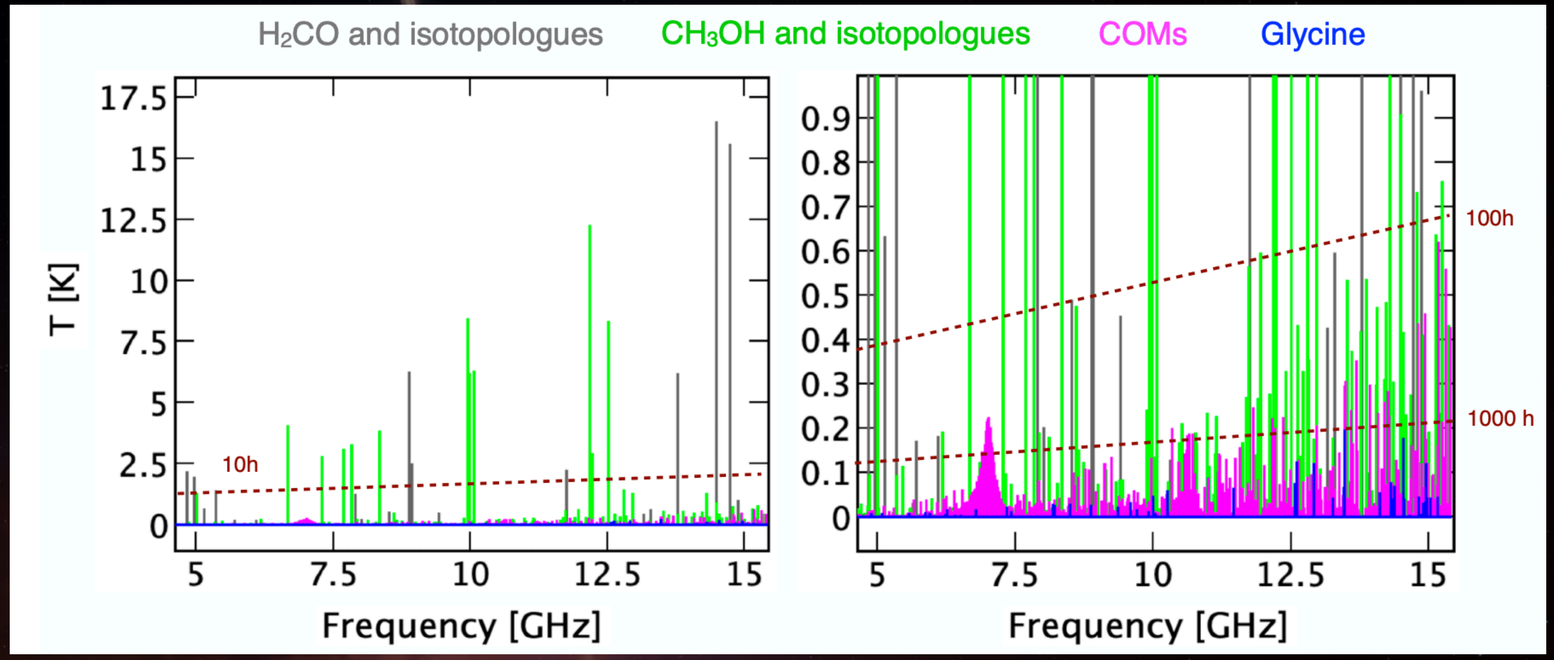
SKAO: a new window on disk chemistry

iCOMs emission from outbursting disks with SKA-Mid Band5, AA4, beam: 1”-2”

Outbusting disk V883 Ori



Tobin et al. 2023

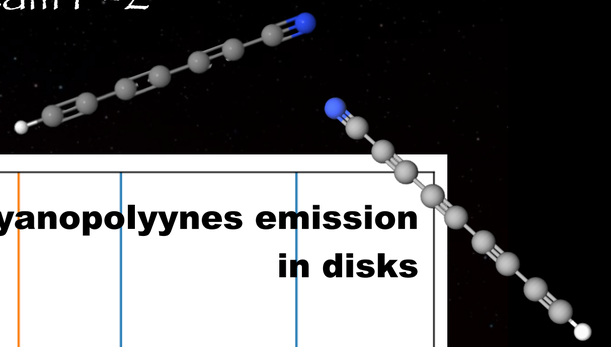


Predicted spectra for an outbursting disk with a 0.5’’ diameter, assuming LTE at T=100 K, column densities as inferred for V883 Ori (Fadul et al. 2025).

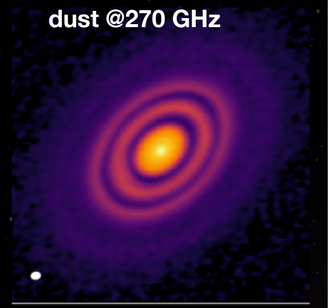
from AASKA II, Podio et al. 2025

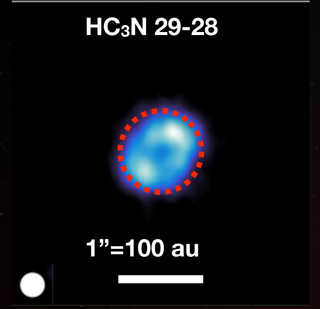
SKAO: a new window on disk chemistry

Cyanopolyynes emission (up to HC_9N) with SKA-Mid Band5, AA4, beam 1”-2”
assuming disk inheritance from prestellar cores

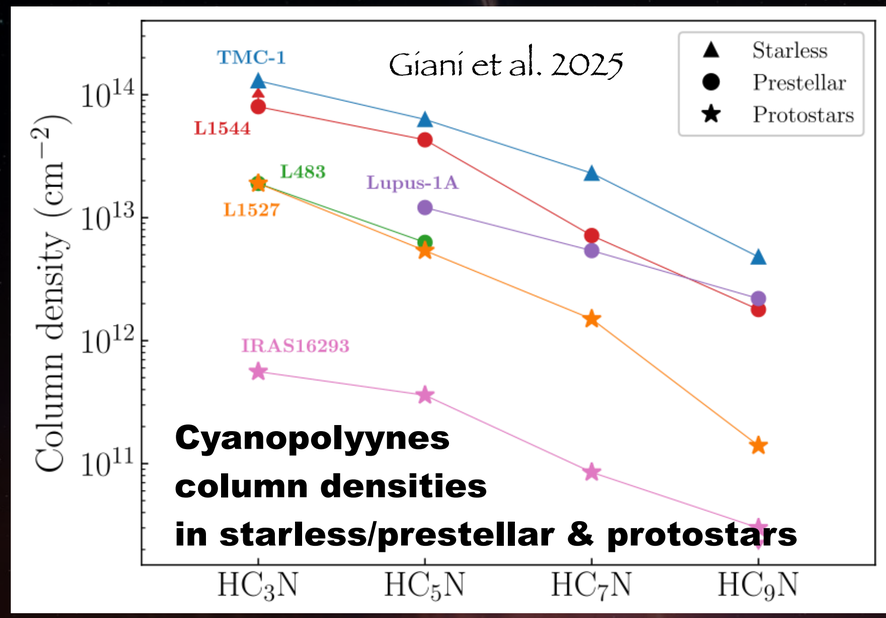


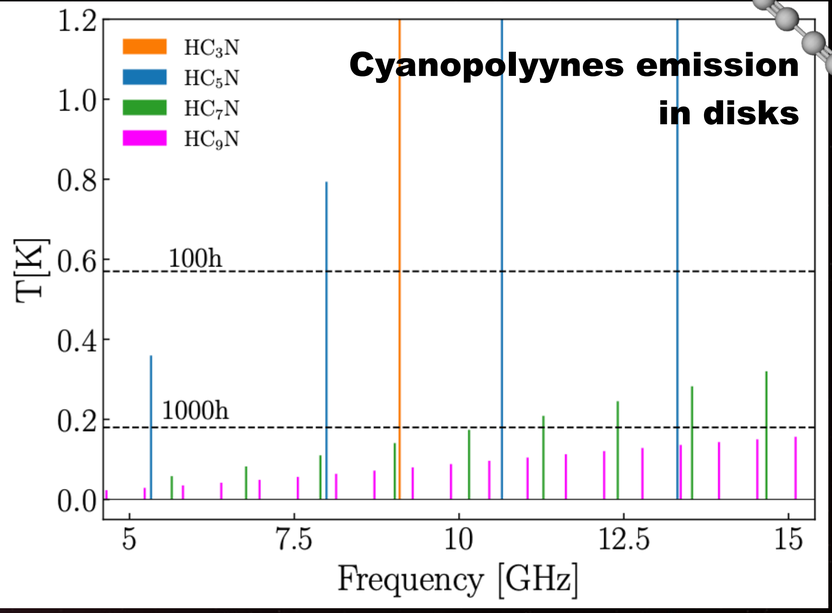
ALMA observations of HD 163296 d=100 pc





Ilee et al. 2021



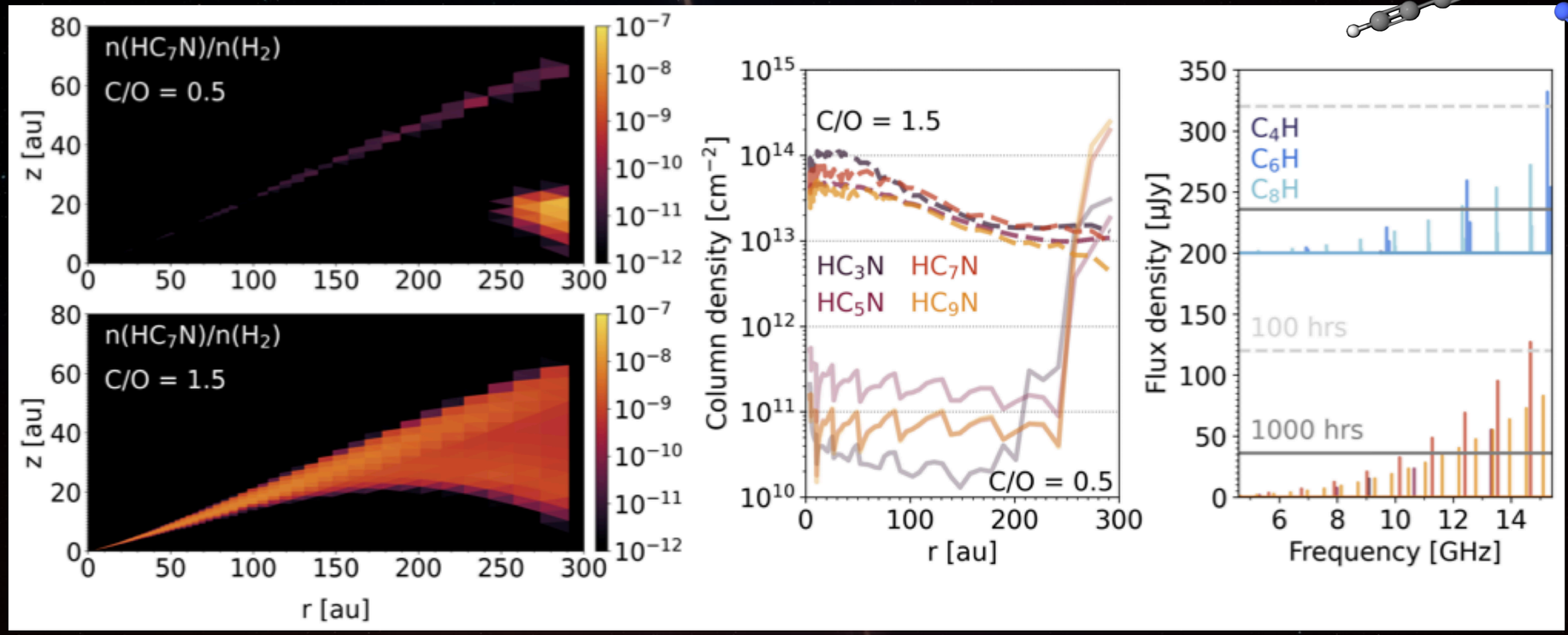


Predicted spectrum assuming LTE at T=20 K, column density of HC_3N = 2e14 cm-2 and abundance ratios as observed in starless/prestellar cores and protostars

from AASKA II, Podio et al. 2025

SKAO: a new window on disk chemistry

Cyanopolyynes (up to HC_9N) and polyynyl radical (up to C_8H) emission from carbon rich disks with SKA-Mid Band5, AA4, beam 1”-2”



based on the gas-grain model by Walsh et al. (2015) and Ilee et al. (2025) for a T Tauri disk

from AASKA II, Podio et al. 2025

The chemical evolution along star and planet formation with the SKAO

Astrochemistry / Disk

Chemical complexity in the early stages of star formation in the SKA era
Eleonora Bianchi et al.

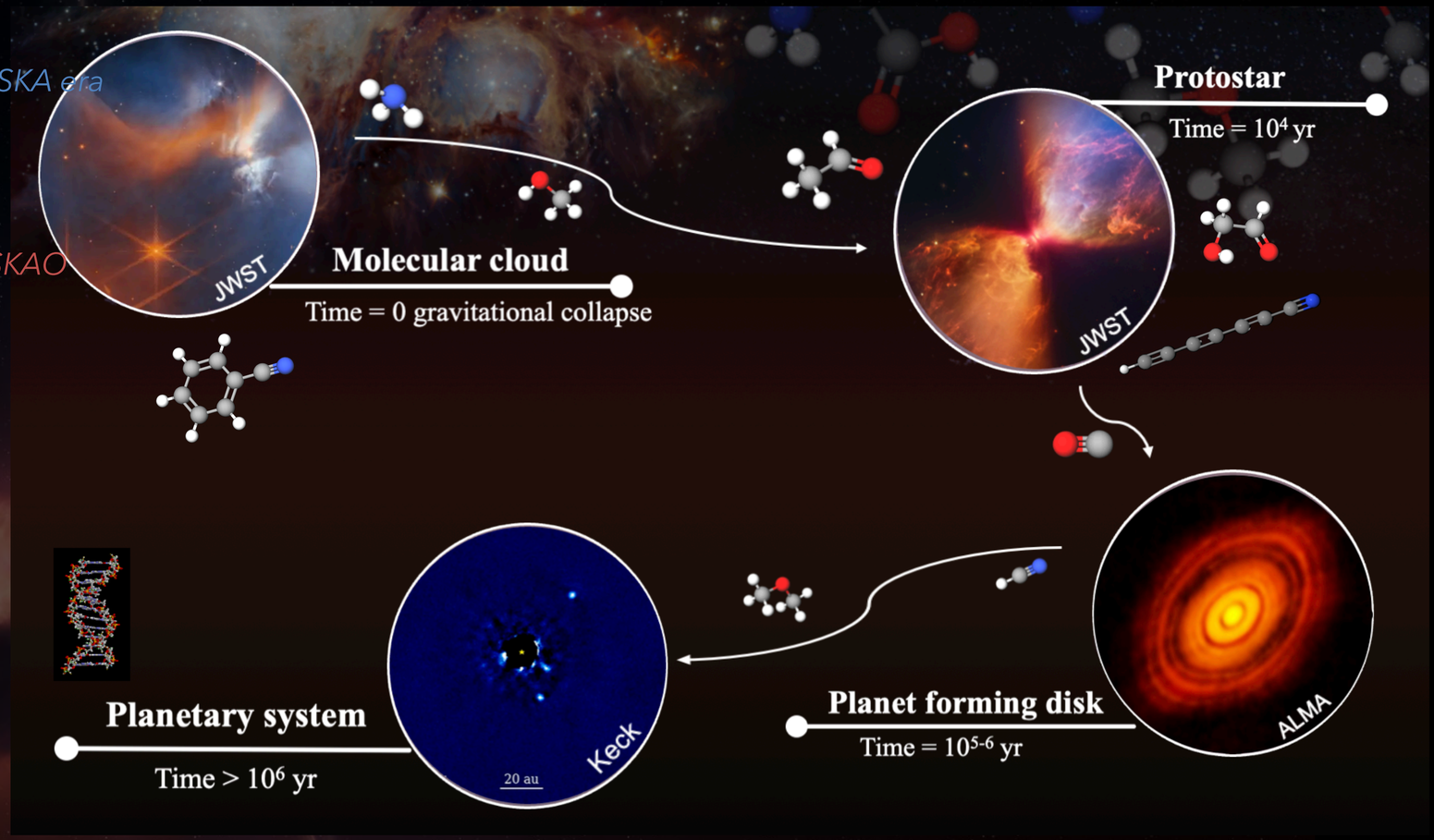
Jets and outflows in young stellar objects with the SKAO
Giovanni Sabatini et al.

Unveiling Complex Chemistry in Planet-forming Disks with the SKAO
Linda Podio et al.

Demographics of planet-forming disks with the SKAO
Antonio Garufi et al.

Substructures in planet-forming disks
Yinhao Wu et al.

Ionised gas emission in protoplanetary disks with the SKAO
Greta Guidi et al.



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