Astrochemistry of protoplanetary disks: Living ALMA, preparing SKA

SKAO

C. Codella
(INAF-OA Arcetri)

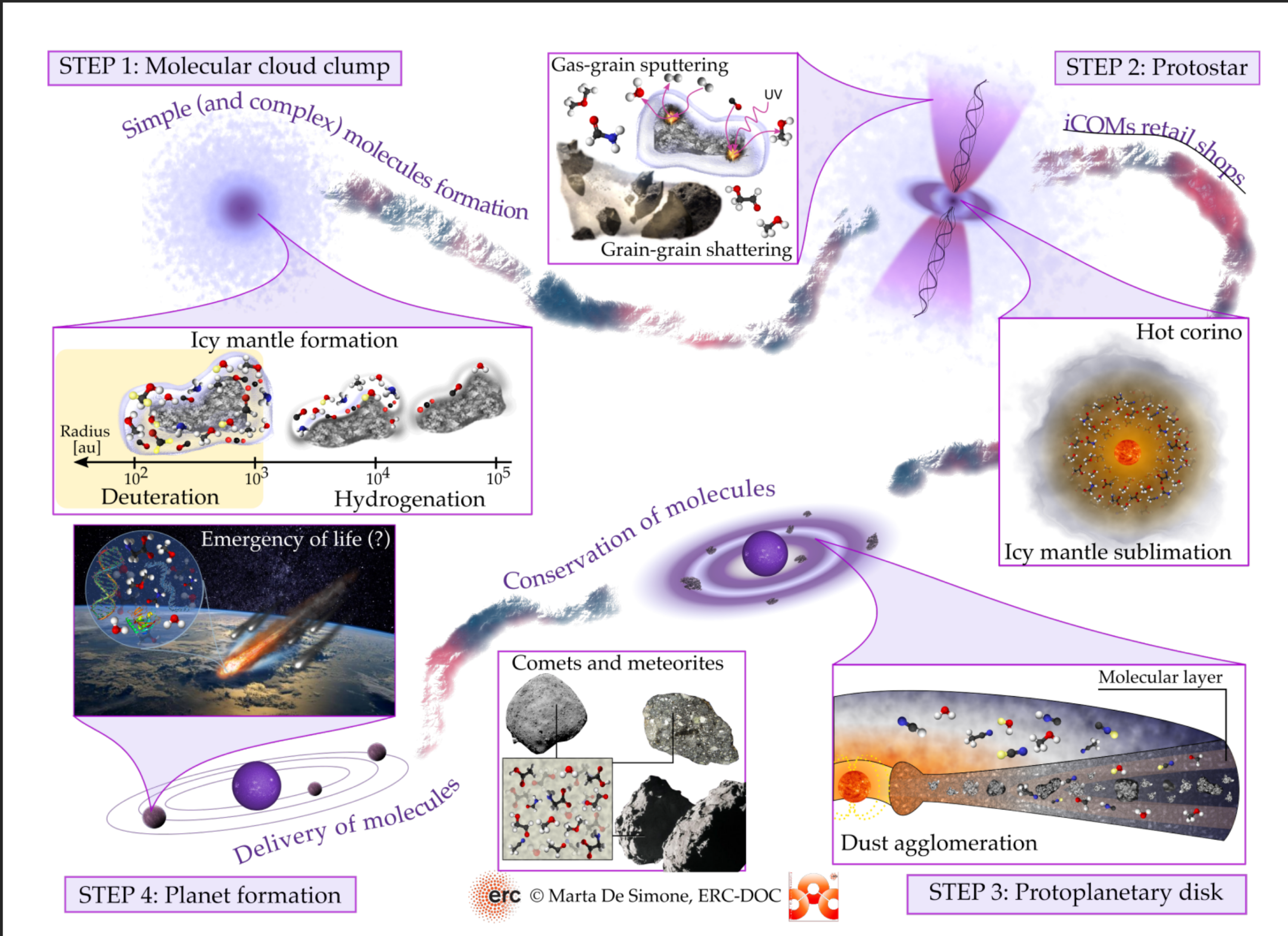
EU H2020 Innovative Training Network
Astro-Chemical Origins

Fossils

MUR

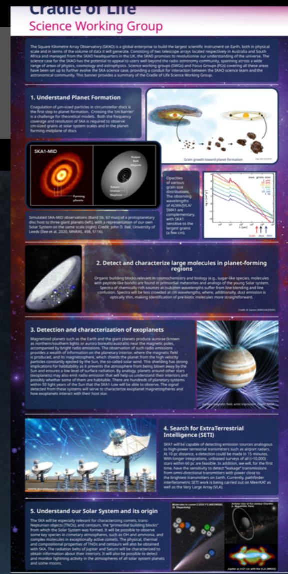
MUR

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

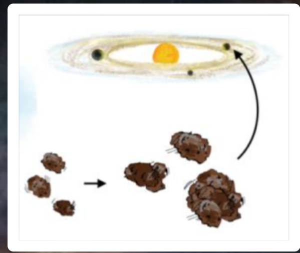


STEP 1: Molecular cloud clump
Simple (and complex) molecules formation
Gas-grain sputtering
UV
Grain-grain shattering
STEP 2: Protostar
iCOMs retail shops
Icy mantle formation
Radius [au]
10^2
10^3
10^4
10^5
Deuteration
Hydrogenation
Hot corino
Icy mantle sublimation
Emergency of life (?)
Conservation of molecules
Comets and meteorites
Molecular layer
Dust agglomeration
Delivery of molecules
STEP 4: Planet formation
© Marta De Simone, ERC-DOC
STEP 3: Protoplanetary disk

Cradle of Life: Context & Goals

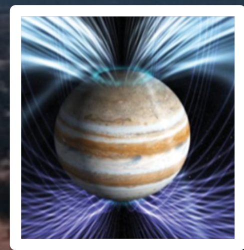


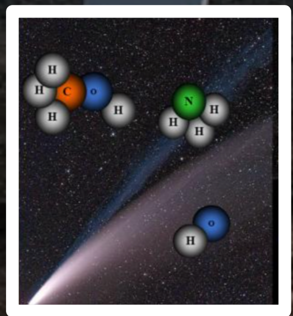
1. Understand planet formation



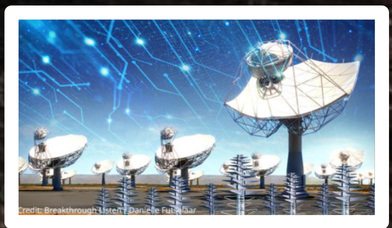
2. Detect and characterise heavy molecules in planet-forming regions

3. Detection and characterisation of exoplanets





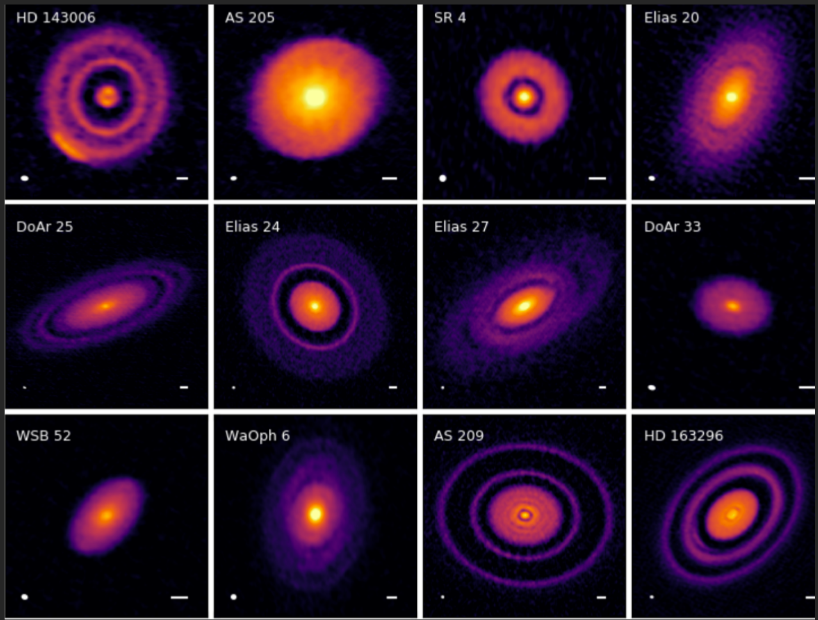
4. Understand our Solar System and its origin



5. Search for ExtraTerrestrial Intelligence (SETI)

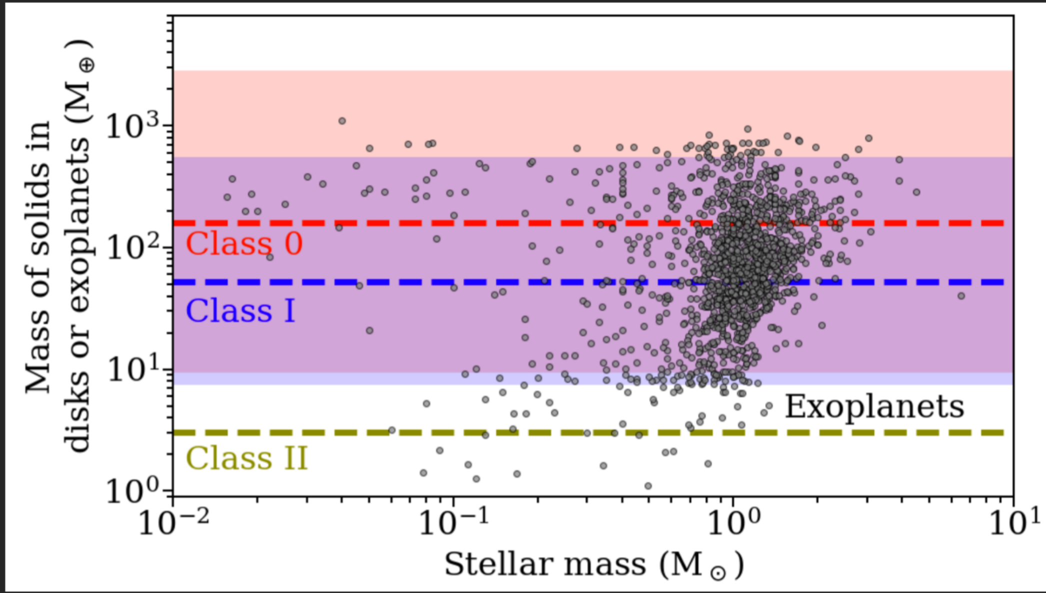
PLANET FORMATION: WHEN ?

Rings and gaps in disks of less than 0.5 Myr



Segura-Cox et al. 2020
DSHARP Andrews et al. 2018
MAPS Öberg et al. 2021

Class II disks may not be massive enough to form planets

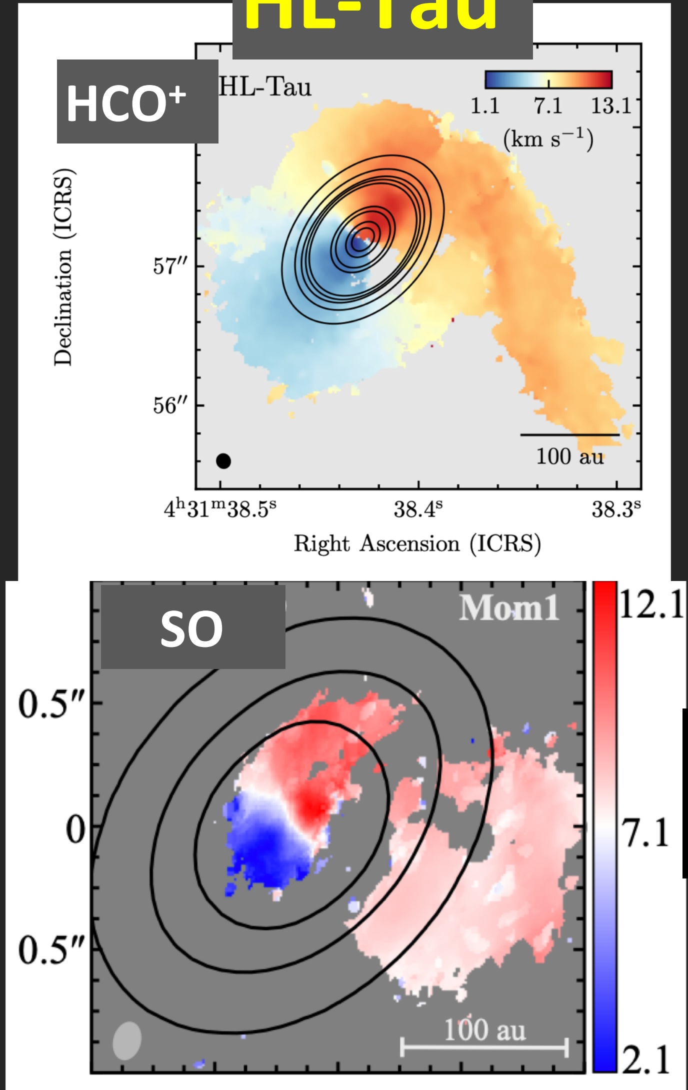


Tychoniec et al. 2020

PLANET FORMATION STARTS EARLY

ACCRETION SREAMERS !

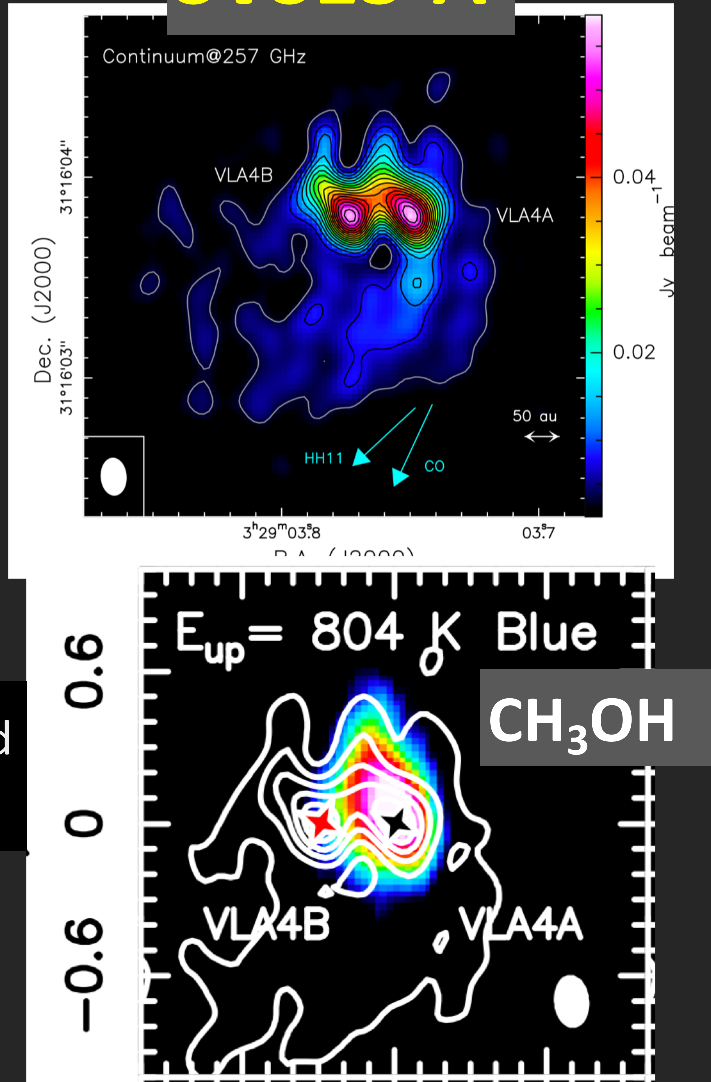
HL-Tau



Yen et al. 2019, Garufi et al. 2022, Pineda et al. 2022

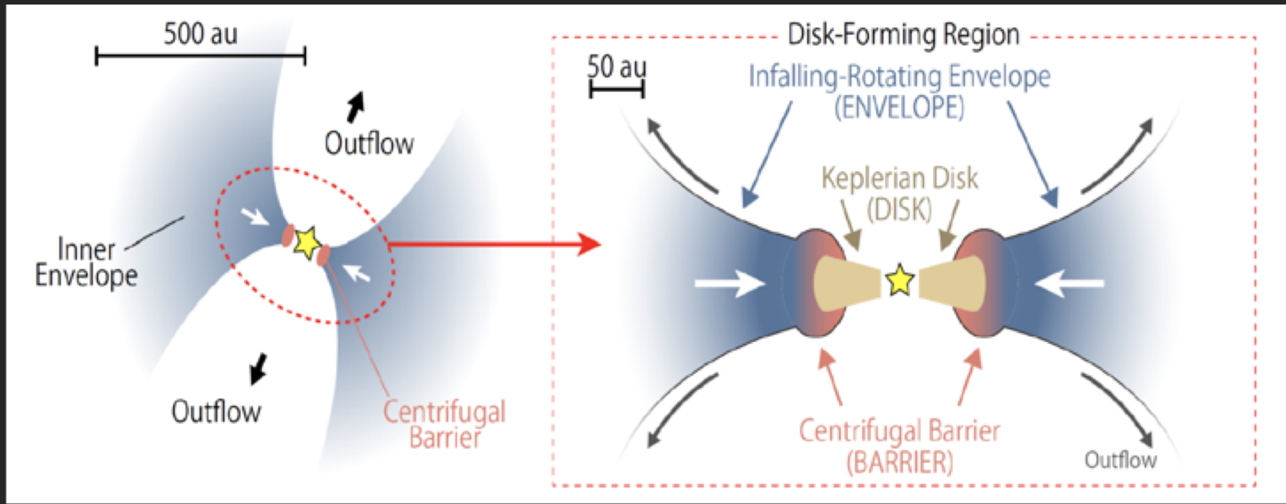
Shocks: altered chemistry….

SVS13-A



Bianchi et al. 2022b, 2023

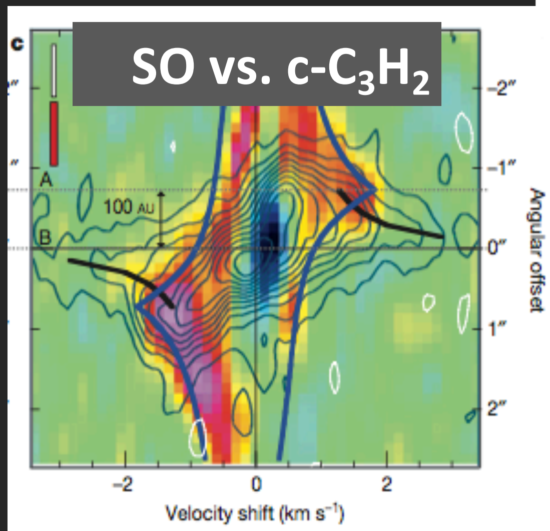
SLOW ACCRETION SHOCKS
(at the centrifugal barrier)

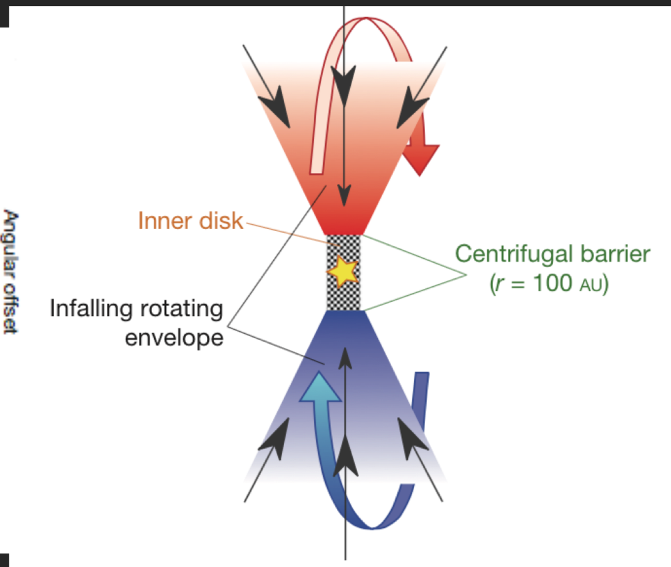


Sakai et 2014ab, Oya et al. 2017, 2019, Codella et al. 2019

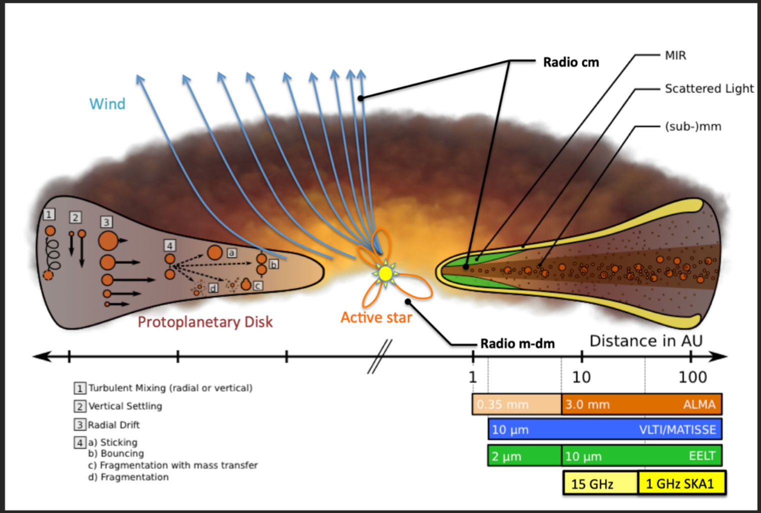
Keplerian disk-free fall envelope interface: Accretion shocks

- inner 50 au
- rotating ring V ~ R

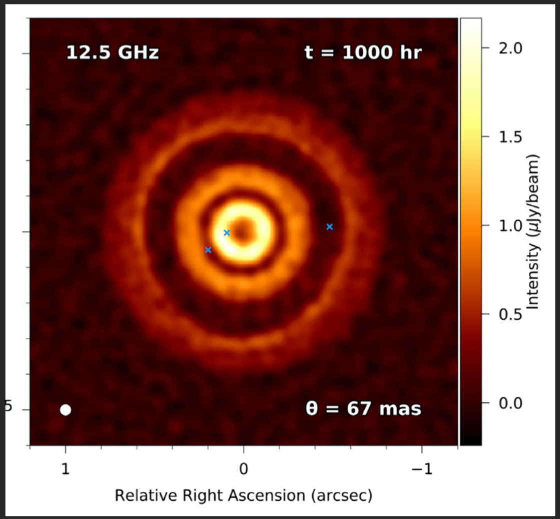


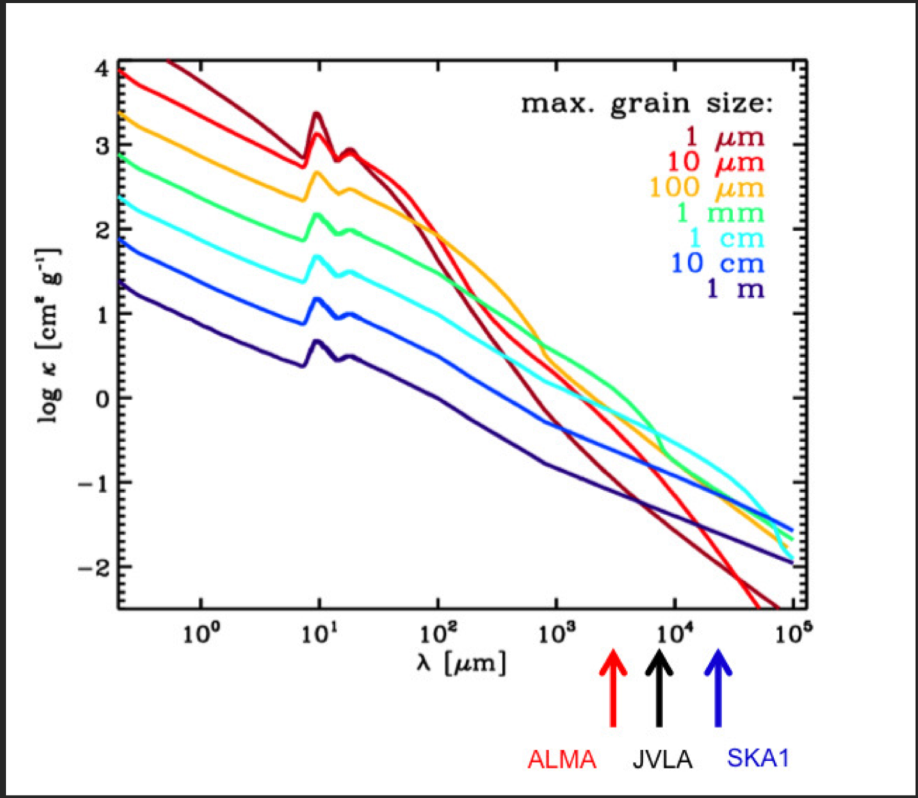


SKA covers the right wavelengths to probe cm-sized grains



Hoare+ 2015, Testi+ 2015, Coutens+2019, Ilee+ 2020





A&A 631, A58 (2019)
https://doi.org/10.1051/0004-6361/201935340

Astronomy & Astrophysics

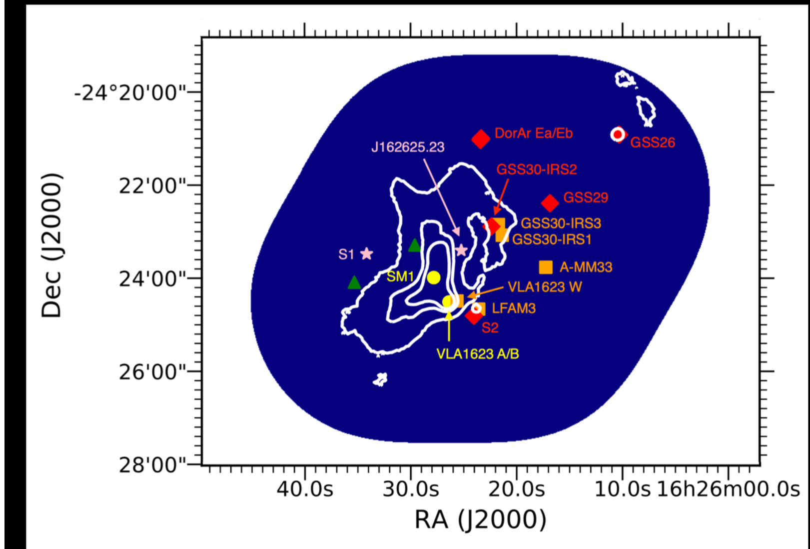
VLA cm-wave survey of young stellar objects in the Oph A cluster: constraining extreme UV- and X-ray-driven disk photoevaporation

A pathfinder for Square Kilometre Array studies★

A. Coutens[1], H. B. Liu[2], I. Jiménez-Serra[3], T. L. Bourke[4], J. Forbrich[5], M. Hoare[6], L. Loinard[7,8], L. Testi[2,9], M. Audard[10,11], P. Caselli[12], A. Chacón-Tanarro[13], C. Codella[9,14], J. Di Francesco[15,16], F. Fontani[9], M. Hogerheijde[17,18], A. Johansen[19], D. Johnstone[15,16], S. Maddison[20], O. Panić[6], L. M. Pérez[21], L. Podio[9], A. Punanova[22], J. M. C. Rawlings[23], D. Semenov[24,25], M. Tazzari[26], J. J. Tobin[27], M. H. D. van der Wiel[28], H. J. van Langevelde[29,16], W. Vlemmings[30], C. Walsh[6], and D. Wilner[31]

Coutens+2019

JVLA continuum observations at 10 GHz of Ophiuchus A, ~0.4" (~50 au).



Observed field

16 Young Stellar Objects detected (from Class 0 to Class III).
Thermal emission: < 30%.
Other mechanisms needed: e.g. free-free emission from jets and/or photoevaporated disk material, or synchroton due to accelerated CRs.

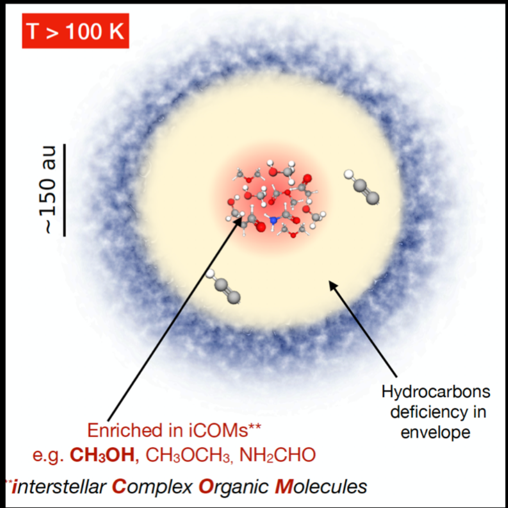
SKA performances needed to disntangle among these possibilities….

PROTOSTARS: THE RETAIL SHOPS OF ORGANICS

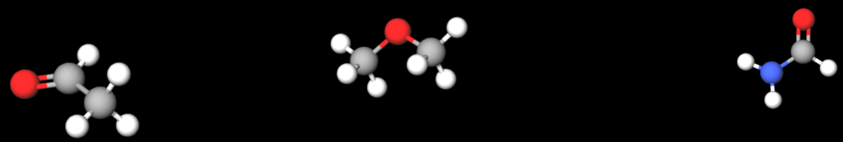
Ceccarelli et al. 2004, 2022, Sakai & Yamamoto 2013, Yoshida et al. 2019, Bouvier et al. 2020

HOT CORINOS:

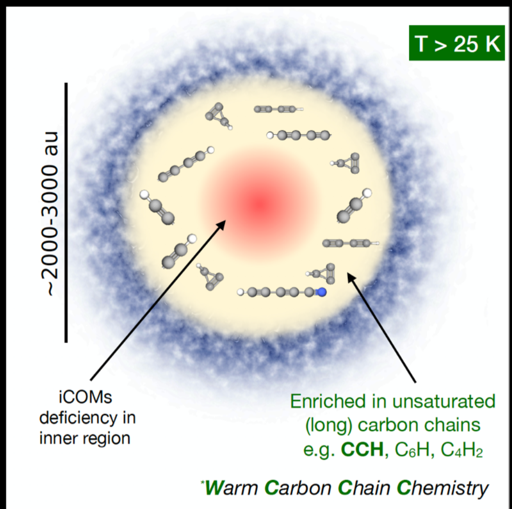
COMPACT (≲ 100 au), HOT (≳ 100K) AND DENSE (≳ $10^7 cm^{-3}$) OBJECTS ENRICHED IN iCOMs



e.g. $HCOOCH_3$, CH_3OCH_3, CH_3CH_2OH, NH_2CHO...



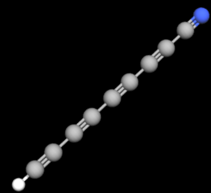
Examples: SVS13-A, IRAS4A, IRAS16293-2422..



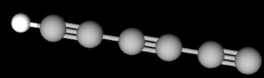
WARM CARBON CHAIN CHEMISTRY (WCCC):

ENRICHED IN C-CHAINS AND POOR OF iCOMs

Unsaturated (long) carbon chains:
e.g. C_4H_2, C_4H, C_6H, HC_7N, HC_9N...



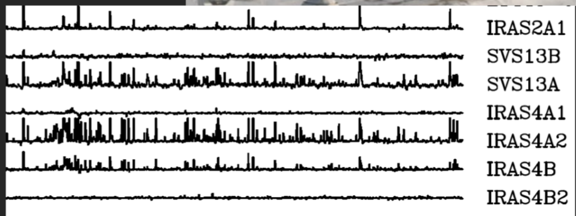
Examples: L1527



iCOMs MINES

IRAM NOEMA LP

CALYPSO

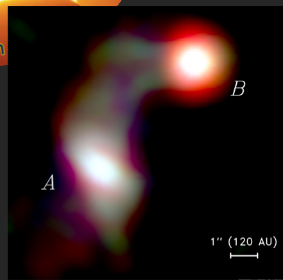


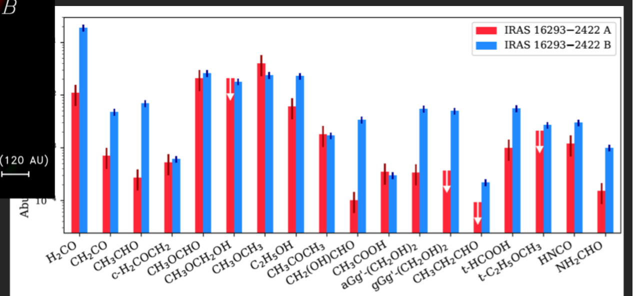
Belloche et al. 2020

PEACHES & ORANGES

Yang et al. 2021, Bouvier et al. 2022

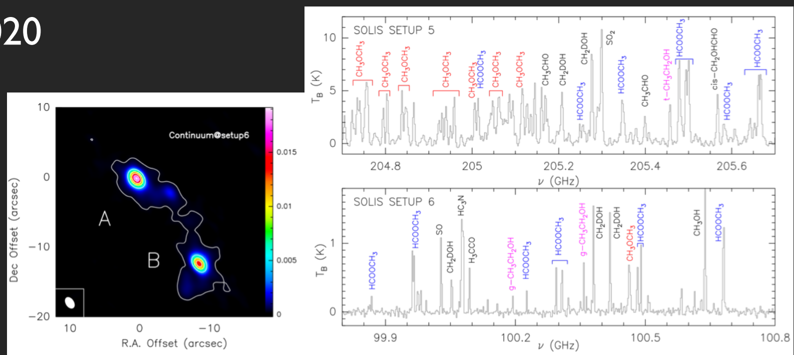
PILS





Jørgensen et al. 2016; Manigand et al. 2020

SOLIS

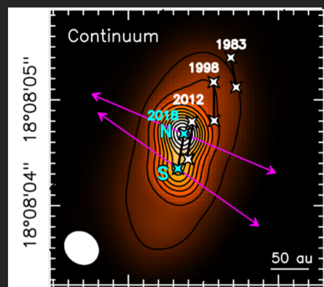


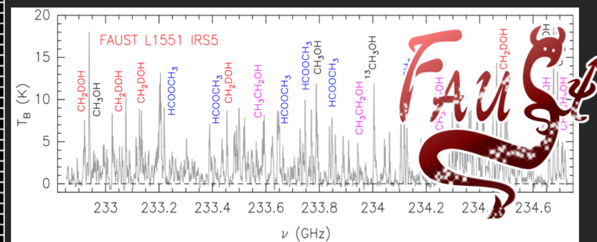
Ceccarelli et al. 2017

ASAI

Lefloch et al. 2018

~40 hot corino
3 WCCC
2 hybrids



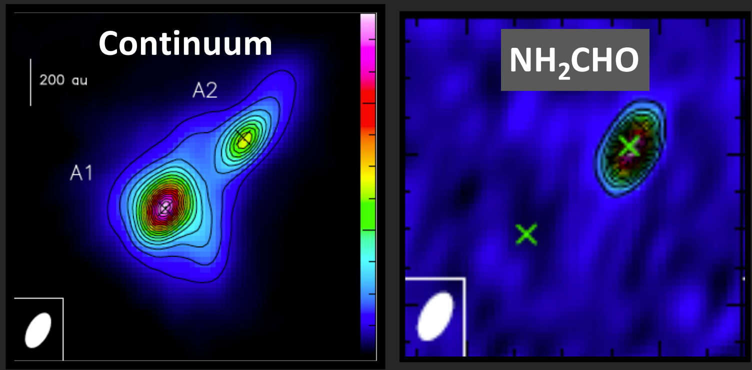


ALMA LP FAUST

Bianchi et al. 2020, Codella et al. 2021

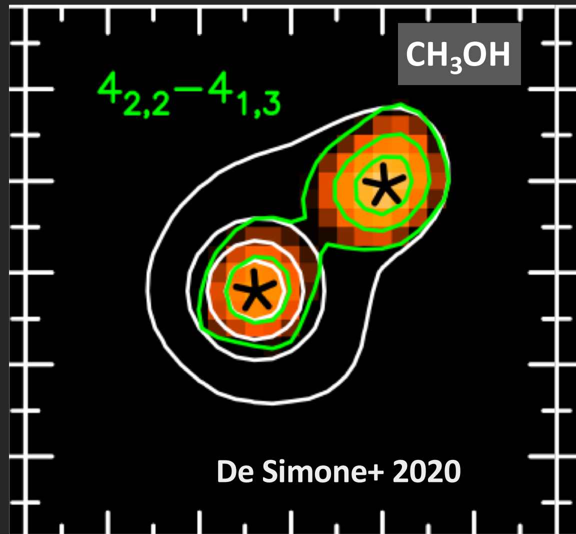
HOT-CORINOS AT cm-WAVELENGTH

Marta De Simone
ESO Fellow



López-Sepulcre+ 2017

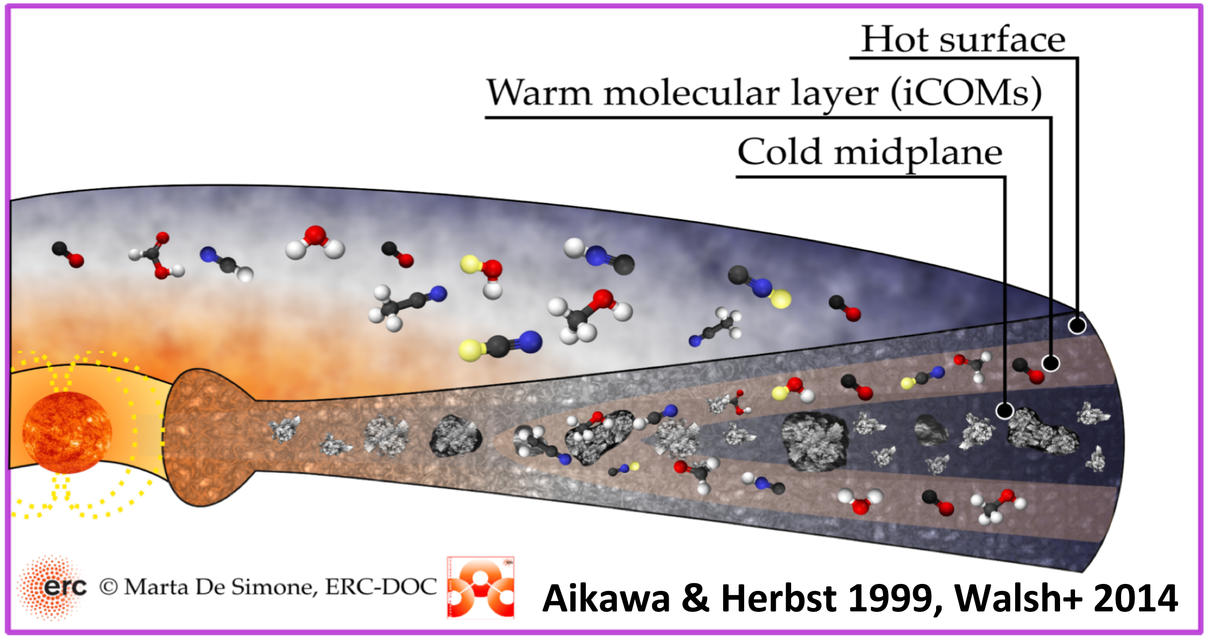
With ALMA:
Hot corino in one of the two components



With VLA:
Both IRAS4A1 and IRAS 4A2 have a hot corino !

iCOMs abundances at mm-wavelengths can be underestimated: road to cm-interferometry

PROTOPLANETARY DISKS

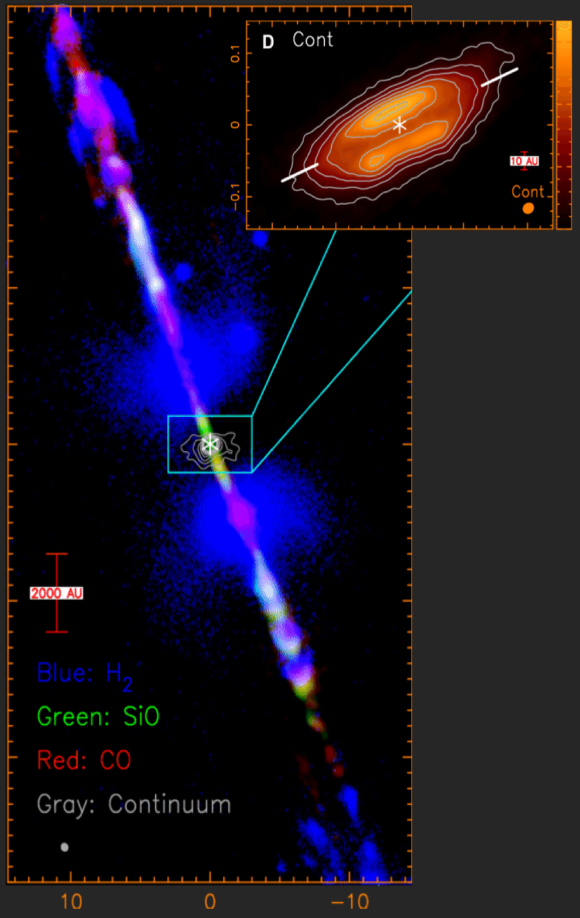


1. Hot Surface layer, dominated by UV. PDR-like chemistry

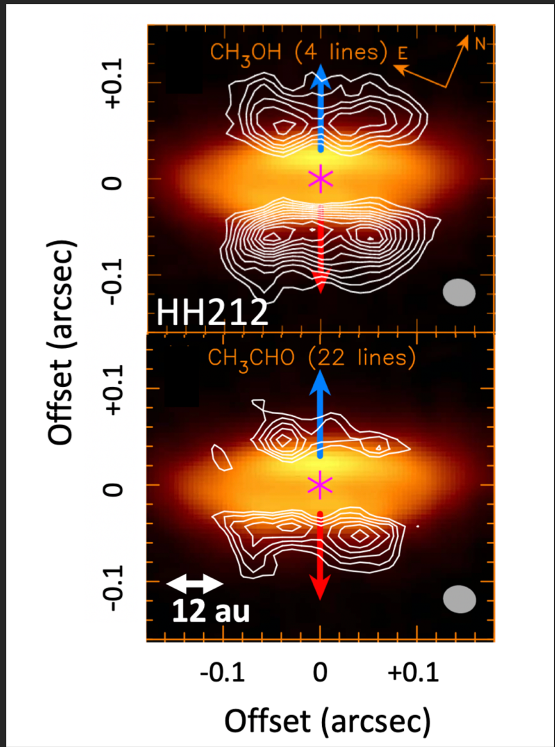
2. Warm molecular layer. Dust warm enough to observe iCOMS

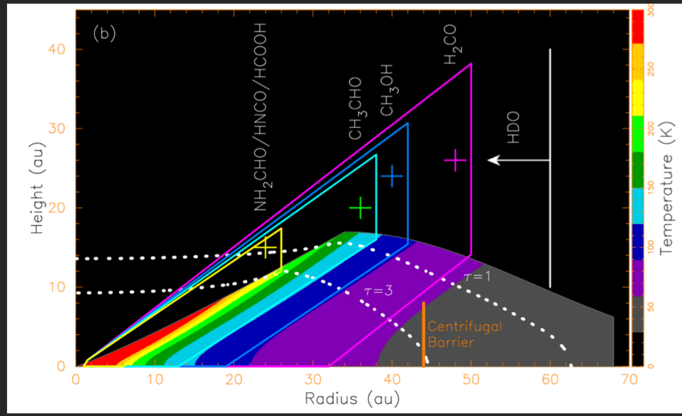
3. Cold (outer) midplane. Freeze-out molecules.

INTO THE DEEP INNER 50 au OF A SUN-LIKE PROTOSTELLAR DISK



Lee+ 2017abc, 2019, 2021
Codella+ 2019, 2021





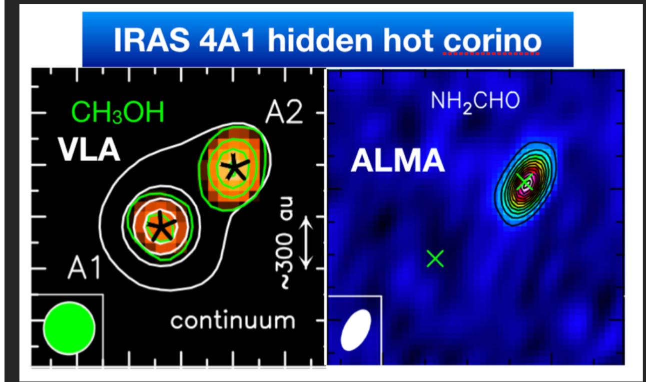
Binding energies and sublimation temperatures from Ferrero et al. 2020

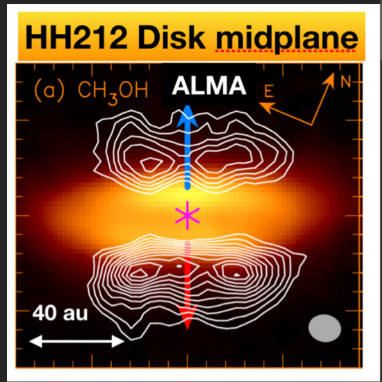
Chemistry gives information on the physical structure

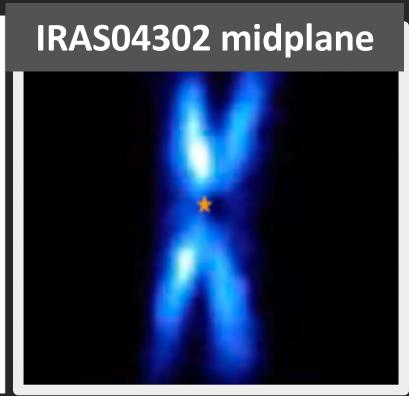
Observations give insights on the formation/destruction routes

MOVING TO LOWER FREQUENCIES…..

Dust opacity problem in the (sub-) mm

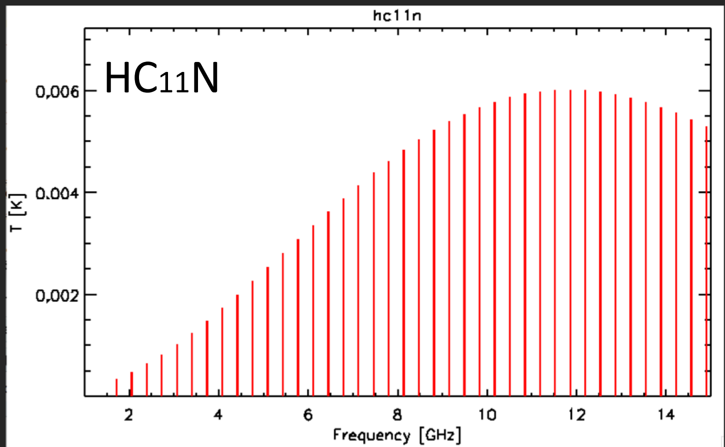


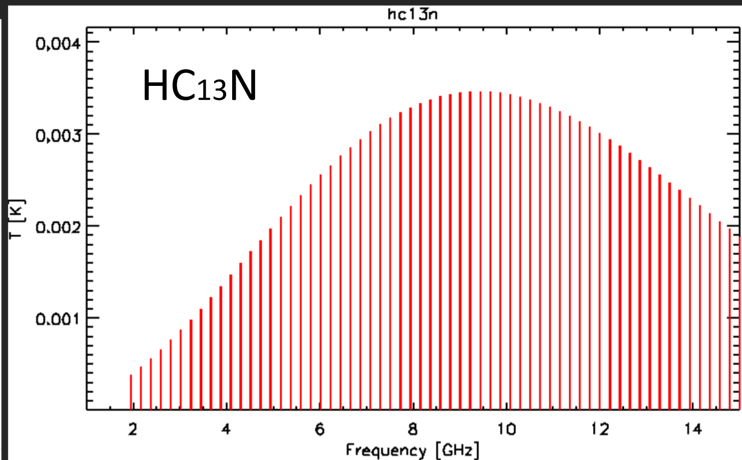




Dust opacity can totally hamper observations of molecules near the disk mid plane, this problem is less critical at radio wavelengths

e.g. De Simone et al. 2020, Codella et al. 2019, Lee et al. 2019, 2022 ALMA DOT disks: Podio et al. 2022a,b,





Increasing complexity

Large molecules peak at lower frequencies

THE CARBON RUSH.....

GOBIERNO DE ESPAÑA
MINISTERIO DE TRANSPORTES, MOVILIDAD Y AGENDA URBANA

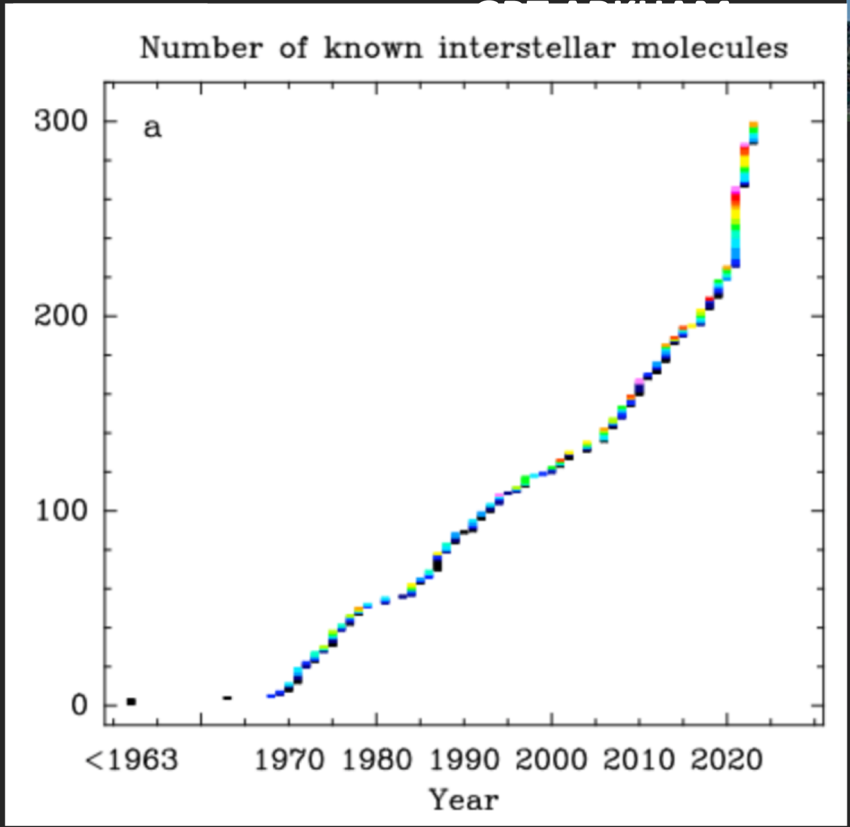
YEBES 40m
QUIJOTE:
Cernicharo et al. 2021

GREEN BANK OBSERVATORY

GBT GOTHAM:
McGuire et al. 2020
GBT ARKHAM:
Burkhardt et al. 2021

THE CARBON RUSH.....

GBT GOTHAM:
McGuire et al. 2020



YEBES 40m
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Cernicharo et al. 2021

THE CARBON RUSH.....

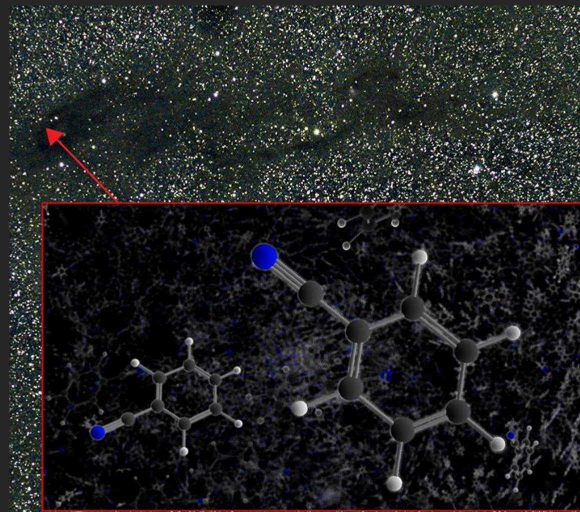
GOBIERNO DE ESPAÑA MINISTERIO DE TRANSPORTES, MOVILIDAD Y AGENDA URBANA

GREEN BANK OBSERVATORY

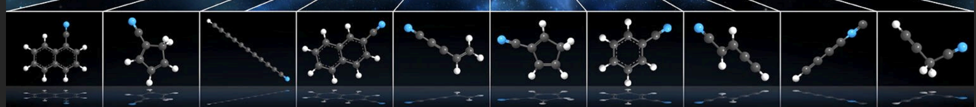
GBT GOTHAM:
McGuire et al. 2020
GBT ARKHAM:
Burkhardt et al. 2021

YEBES 40m
QUIJOTE:
Cernicharo et al. 2021

$c\text{-}C_5H_4CCH_2$
$HCCCH_2$
C_6H_5CN
$c\text{-}C_6H_4$
$c\text{-}C_9H_8$



Aromatic chemistry detected in prestellar cores.
Abundances underpredicted.
What about protostellar regions?



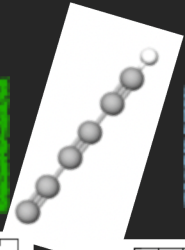
McGuire et al. 2018, Burkhardt et al. 2021, Agúndez et al. 2023, Fuentetaja et al. 2023, Cernicharo et al. 2021a, 2021b, 2022, 2023.....

Heavy C-species in prestellar cores and protostellar envelopes

Bianchi+ 2023a,c

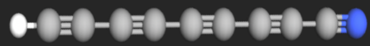
SKA Band 5 frequencies; Ku + X bands

C_4H

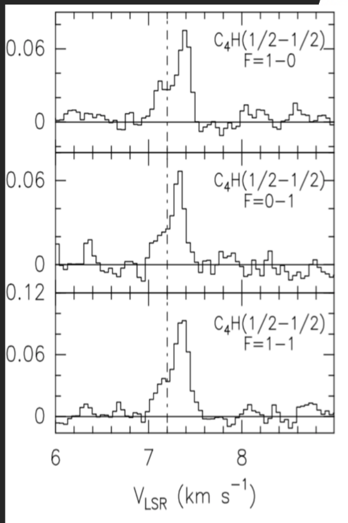


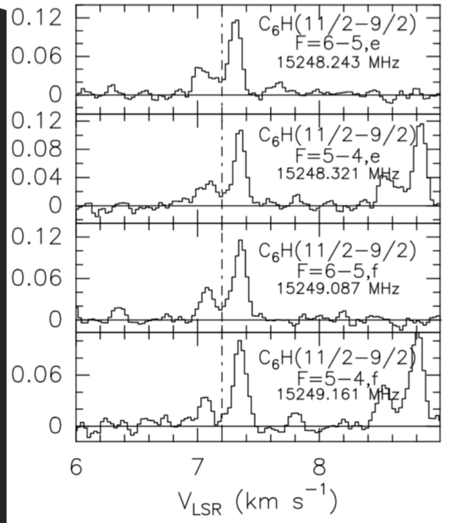
C_6H

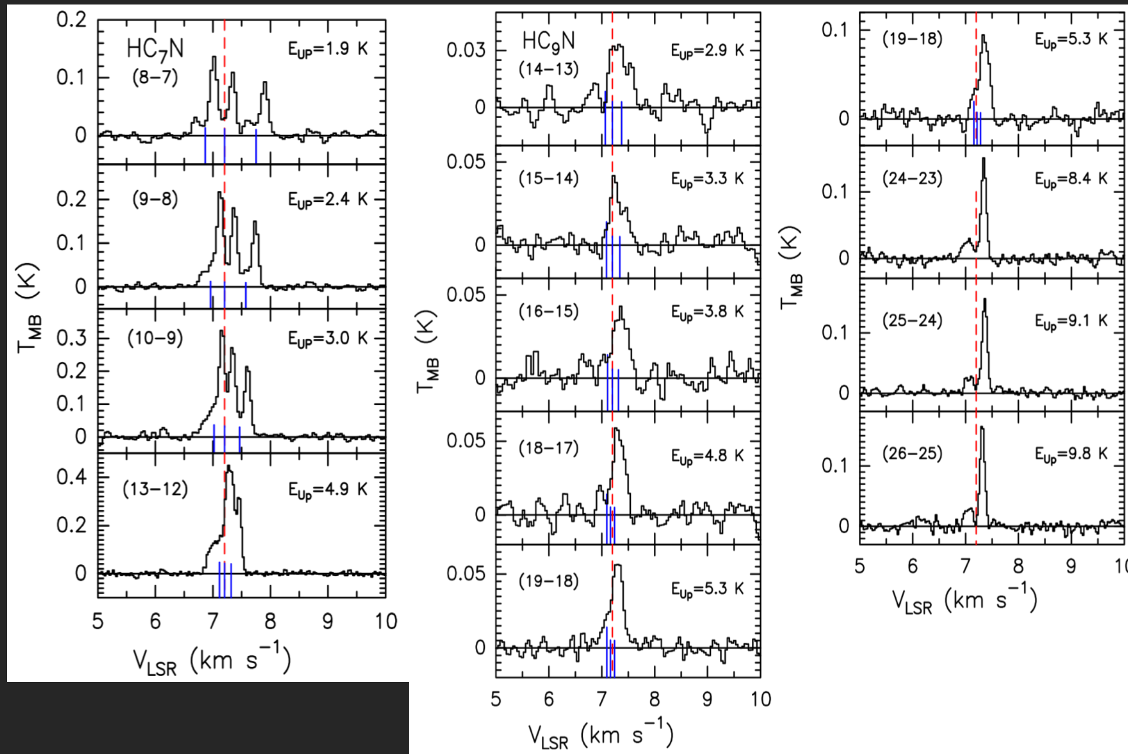
HC_7N



HC_9N







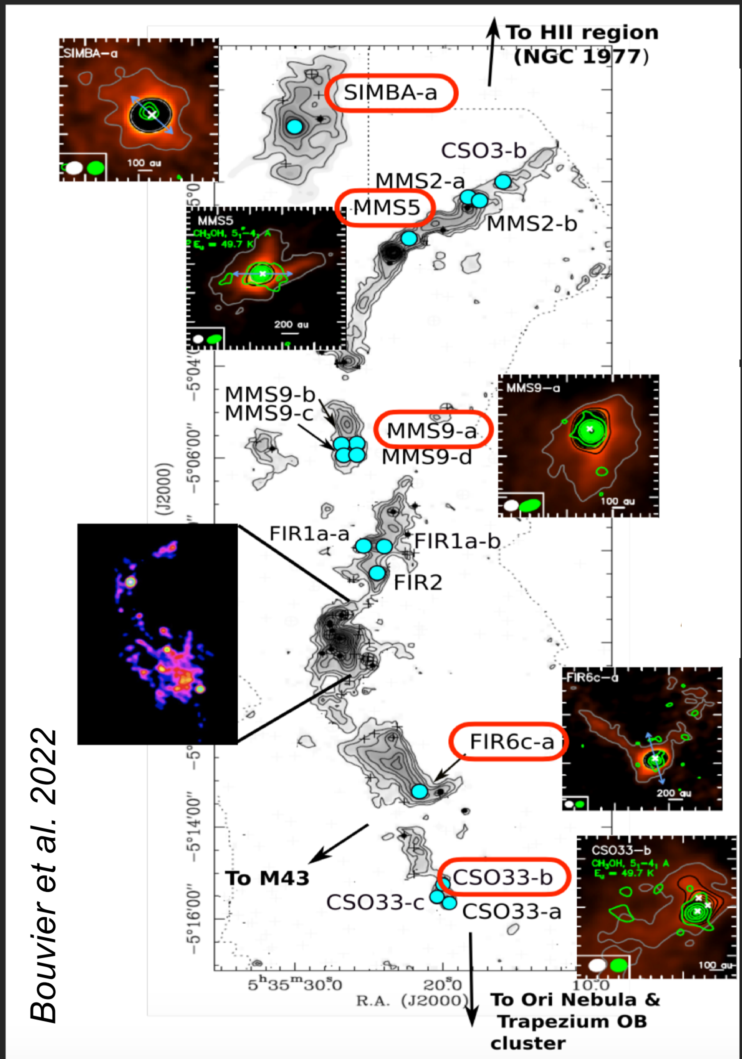
- L1544: The emission is dominant in the outer layers of the prestellar core

- IRAS 16293-2422: On 1000 au scales, protostellar envelopes look C-poor….

SKA1 Scientific Use Case

SKA unveiling heavy carbon chains chemistry (< 200 au)

SKA1-MID
PI: Bianchi, E. & The Cradle of Life WG



Bouvier et al. 2022

ALMA → JVLA → SKA

Target: Orion Molecular Cloud 2, the closest analogue to our Sun's birth environment

SKA MID Band 5 ~ 1000 hr

9.0-11.5 GHz + 13.0-15.5 GHZ

spectral resolution ~ 1.9 km/s

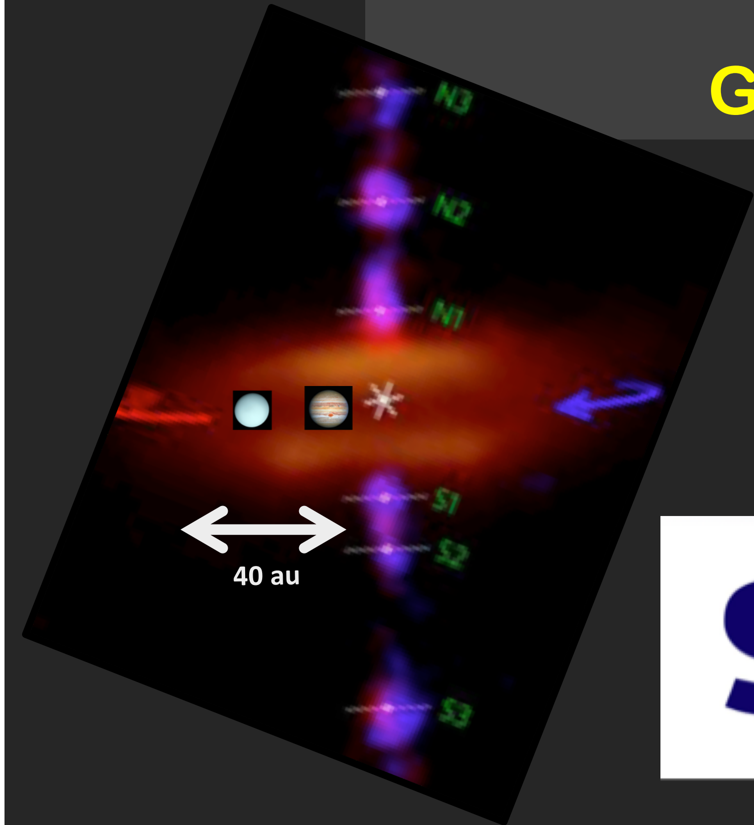
+

4 narrow zoom windows

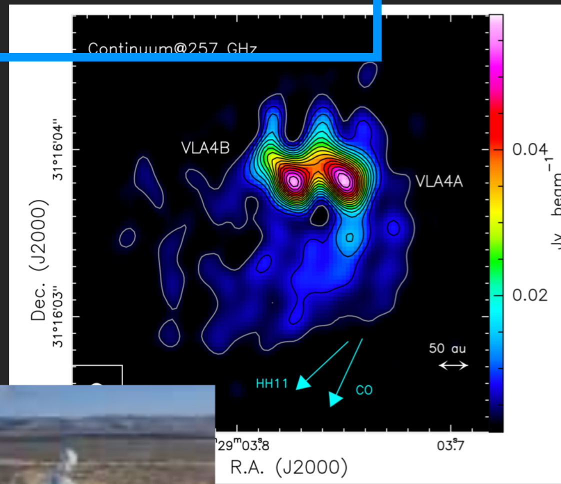
on selected lines

angular resolution <0.5" (< 200 au)

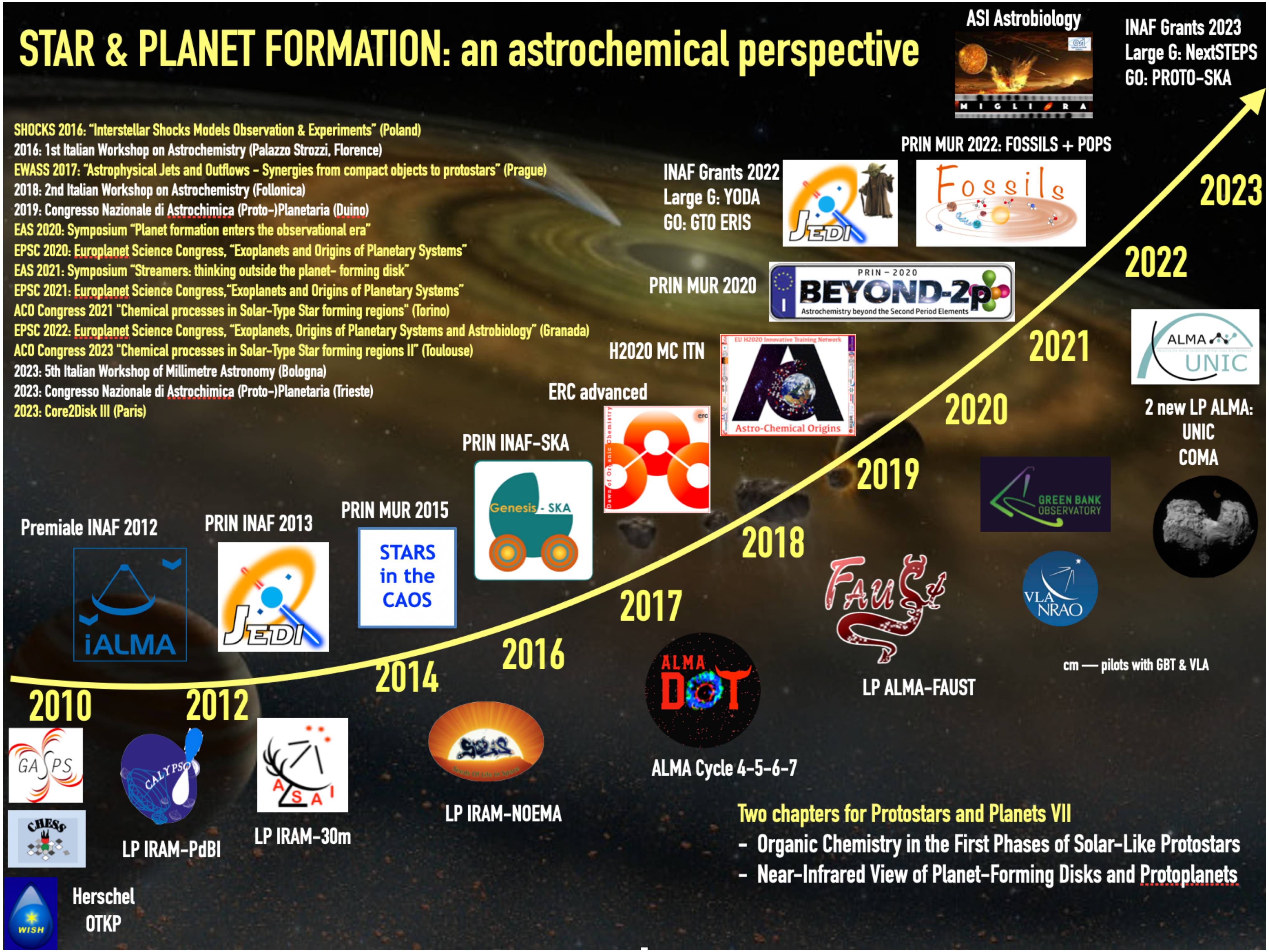
Wrapping up……
Goal: Cradle of Planets



Band 1 35-50 GHz now!
Band 2 67-116 GHz future..



We need pictures &
Statistics of protostars:
Ages: 10^4-10^5 yr
Spatial scales: from 10^3 au down to fews au
Molecular tracers: cm-sized dust, iCOMs & heavy C-chains


STAR & PLANET FORMATION: an astrochemical perspective
ASI Astrobiology
INAF Grants 2023
Large G: NextSTEPS
GO: PROTO-SKA
SHOCKS 2016: "Interstellar Shocks Models Observation & Experiments" (Poland)
2016: 1st Italian Workshop on Astrochemistry (Palazzo Strozzi, Florence)
EWASS 2017: "Astrophysical Jets and Outflows – Synergies from compact objects to protostars" (Prague)
2018: 2nd Italian Workshop on Astrochemistry (Follonica)
2019: Congresso Nazionale di Astrochimica (Proto-)Planetaria (Duino)
EAS 2020: Symposium "Planet formation enters the observational era"
EPSC 2020: Europlanet Science Congress, "Exoplanets and Origins of Planetary Systems"
EAS 2021: Symposium "Streamers: thinking outside the planet- forming disk"
EPSC 2021: Europlanet Science Congress,"Exoplanets and Origins of Planetary Systems"
ACO Congress 2021 "Chemical processes in Solar-Type Star forming regions" (Torino)
EPSC 2022: Europlanet Science Congress, "Exoplanets, Origins of Planetary Systems and Astrobiology" (Granada)
ACO Congress 2023 "Chemical processes in Solar-Type Star forming regions II" (Toulouse)
2023: 5th Italian Workshop of Millimetre Astronomy (Bologna)
2023: Congresso Nazionale di Astrochimica (Proto-)Planetaria (Trieste)
2023: Core2Disk III (Paris)
PRIN MUR 2022: FOSSILS + POPS
Fossils
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Astrochemistry beyond the Second Period Elements
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PRIN INAF 2013
PRIN MUR 2015
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ASAI
SOLIS
ALMA Cycle 4-5-6-7
CHESS
LP IRAM-PdBI
LP IRAM-30m
LP IRAM-NOEMA
Two chapters for Protostars and Planets VII
- Organic Chemistry in the First Phases of Solar-Like Protostars
- Near-Infrared View of Planet-Forming Disks and Protoplanets
WISH
Herschel
OTKP