Unveiling the aromatic Galaxy with AtLAST

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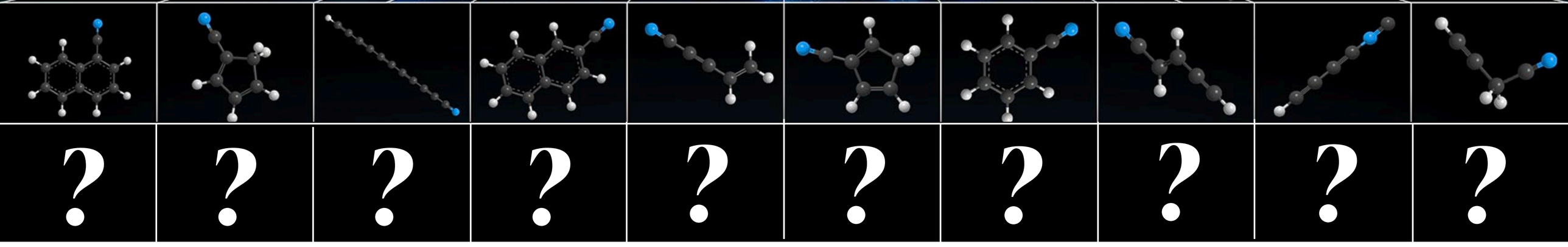

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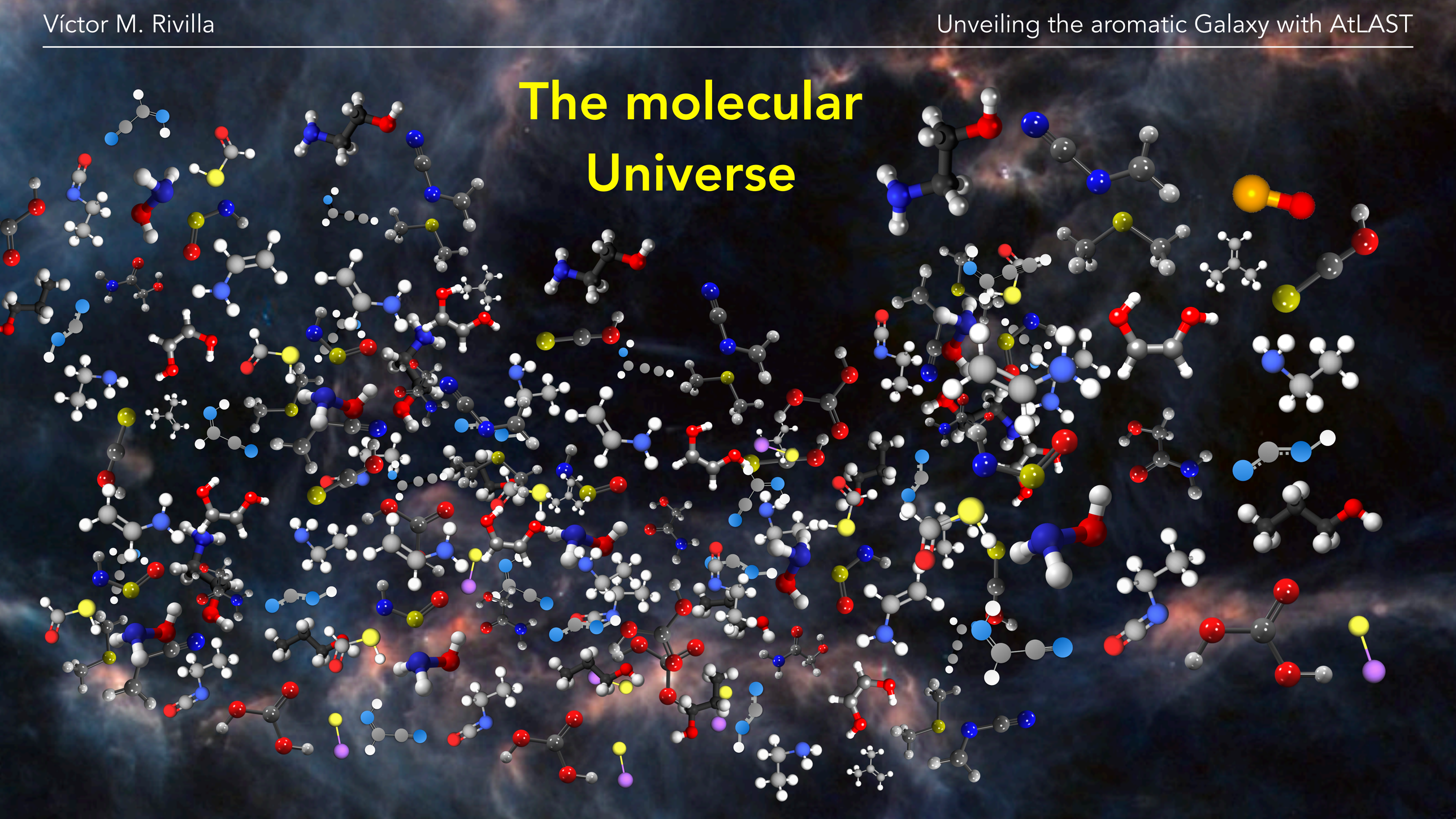
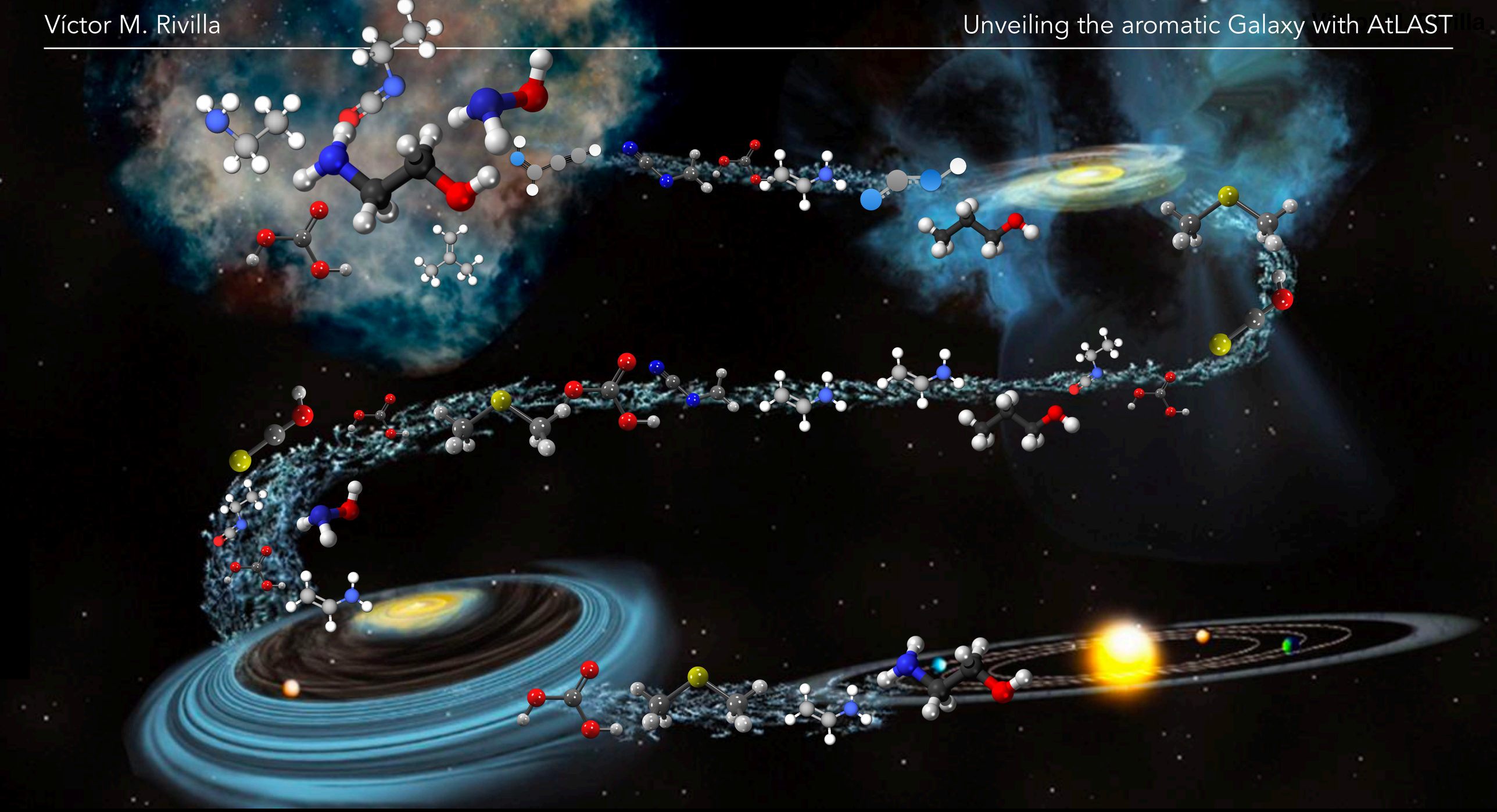
The molecular Universe

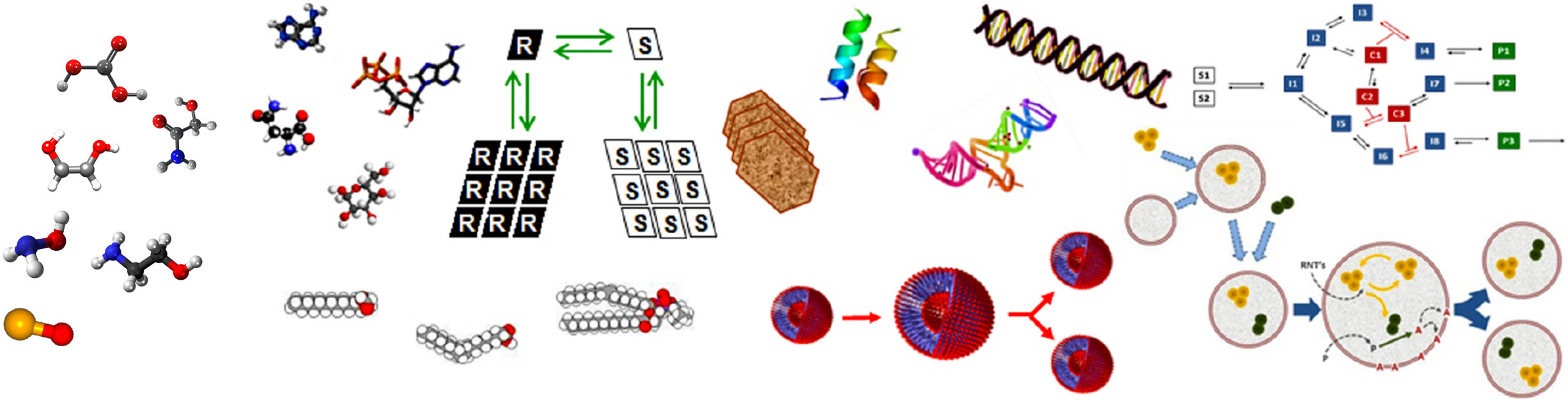




BILL SAXTON/NSF/AUI/NRAO

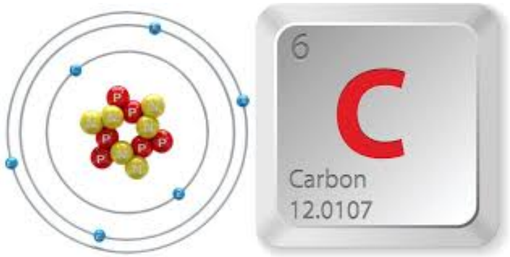
Ingredients for life

CHEMICAL COMPLEXITY



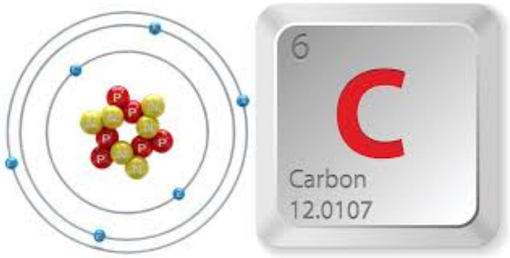
Ruiz-Mirazo et al. (2014)

The importance of Carbon



- "Chemical backbone" of life.
- C-based compounds provide an excellent balance between molecular **diversity, stability, versatility and reactivity** (Petkowski et al. 2020).

The importance of Carbon



- "Chemical backbone" of life.
- C-based compounds provide an excellent balance between molecular **diversity, stability, versatility and reactivity** (Petkowski et al. 2020).

Tetravalency

- 4 electrons in outer shell.
- 4 covalent bonds.
- Single, double and triple bonds.
- Link with H, O, N, O and P.

Bond strength

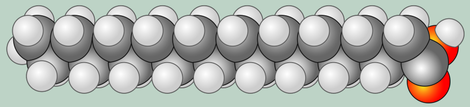
stable enough, but can be broken and rearranged

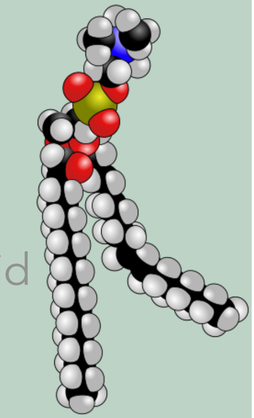
Structural versatility

- It bonds exceptionally well with itself, forming large stable structures.

Carbon chains: fatty acids in cell membranes

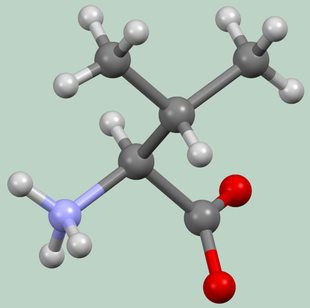
Fatty acid





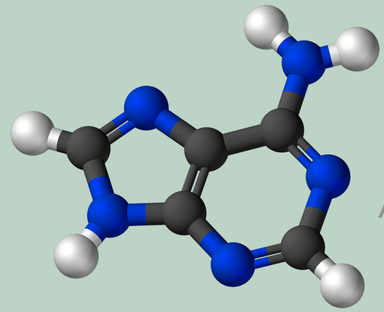
Phospholipid

Branched trees: carbohydrates or amino acids



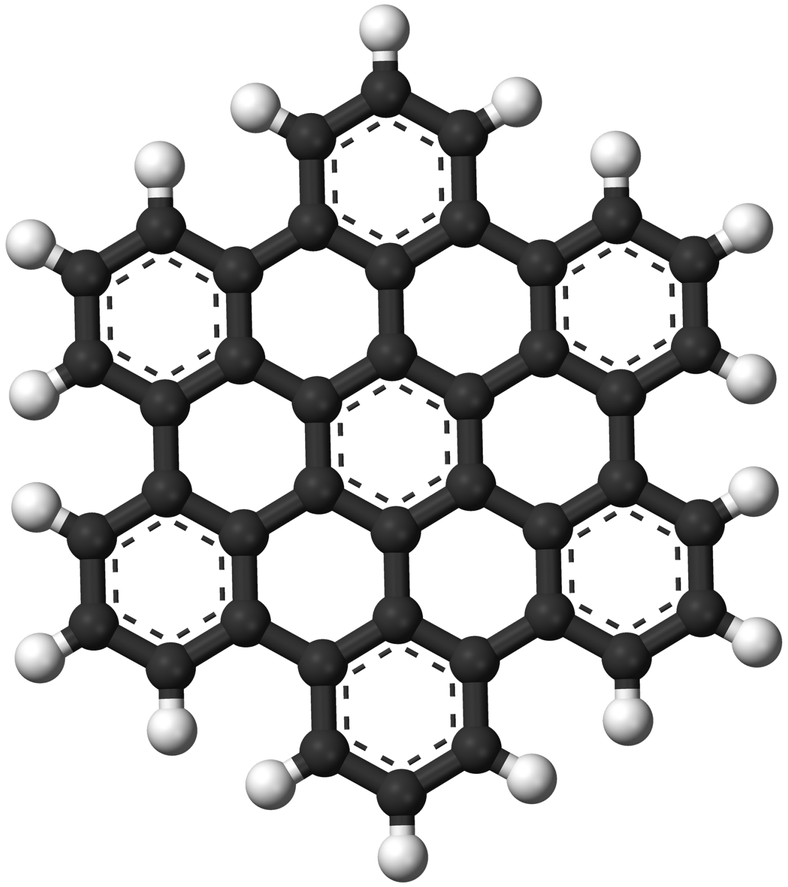
Valine (branched amino acid)

Rings: RNA and DNA



Adenine

Polycyclic aromatic hydrocarbons (PAHs)



- **CHEMICAL BUDGET:** Substantial fraction of interstellar C (**10% - 25%**) is present in the form of **Polycyclic Aromatic Hydrocarbons (PAHs)**, organic compounds made up with **benzene rings (c-C_6H_6)** (Dwek et al. 1997; Chiar et al. 2013).

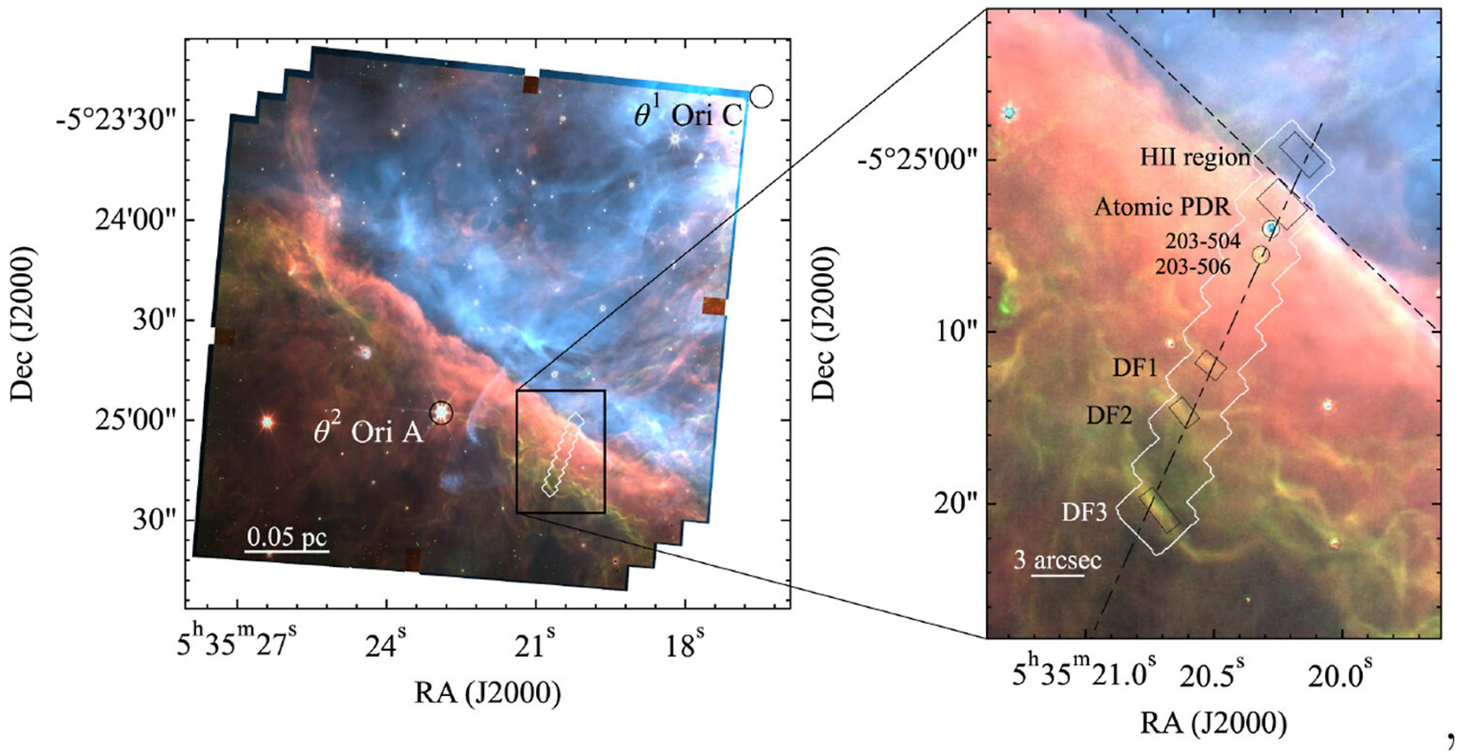
- **PHYSICAL MECHANISMS:** Control the heating of neutral gas and the charge balance of molecular clouds (Tielens 2026).

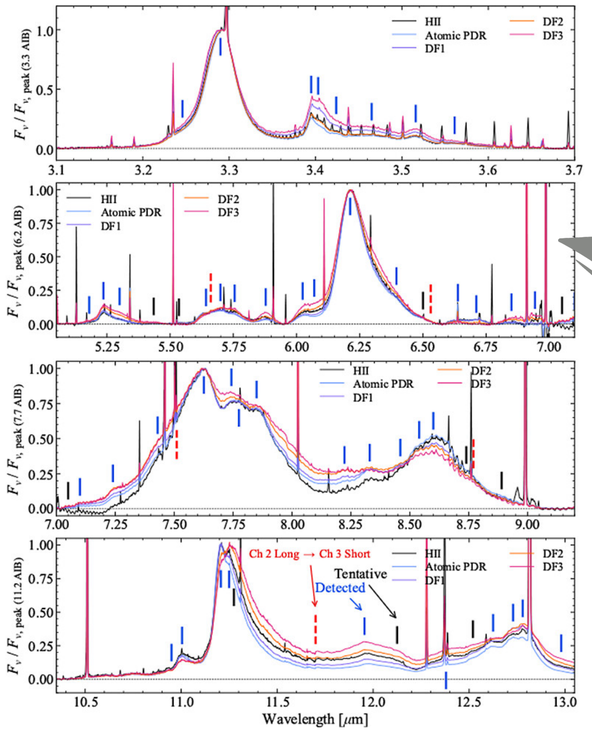
- **PREBIOTIC INTEREST:** Largest PAHs might play an important role in the growth of carbonaceous dust grains that can potentially transfer prebiotic material into new planetary systems (Piacentino et al. 2025)

PAHs in the interstellar medium

- **Emission bands at mid-infrared** wavelengths produced by vibrational modes of aromatic C–C and C–H bonds (AIB = aromatic infrared bands at 3.3, 6.2, 7.7, 8.6 and 11.3 microns).

- Plethora of different interstellar environments, including galactic and extragalactic sources (e.g., Tielens 2008; García-Bernete et al. 2022; Chown et al. 2024, 2025).



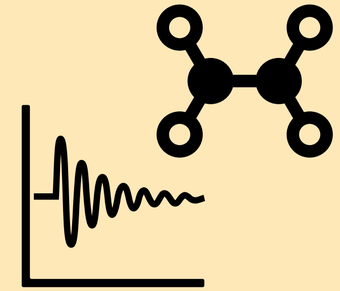


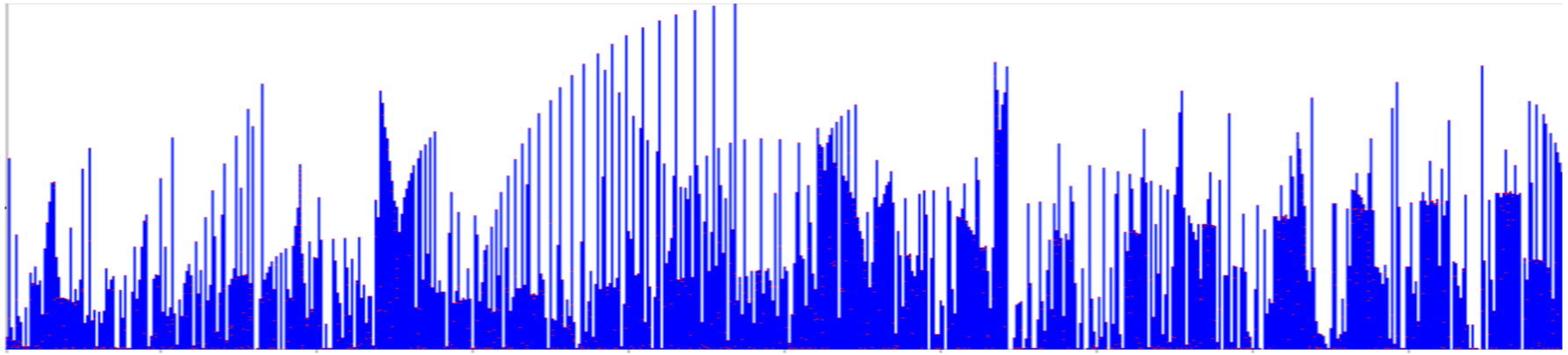
JWST spectra

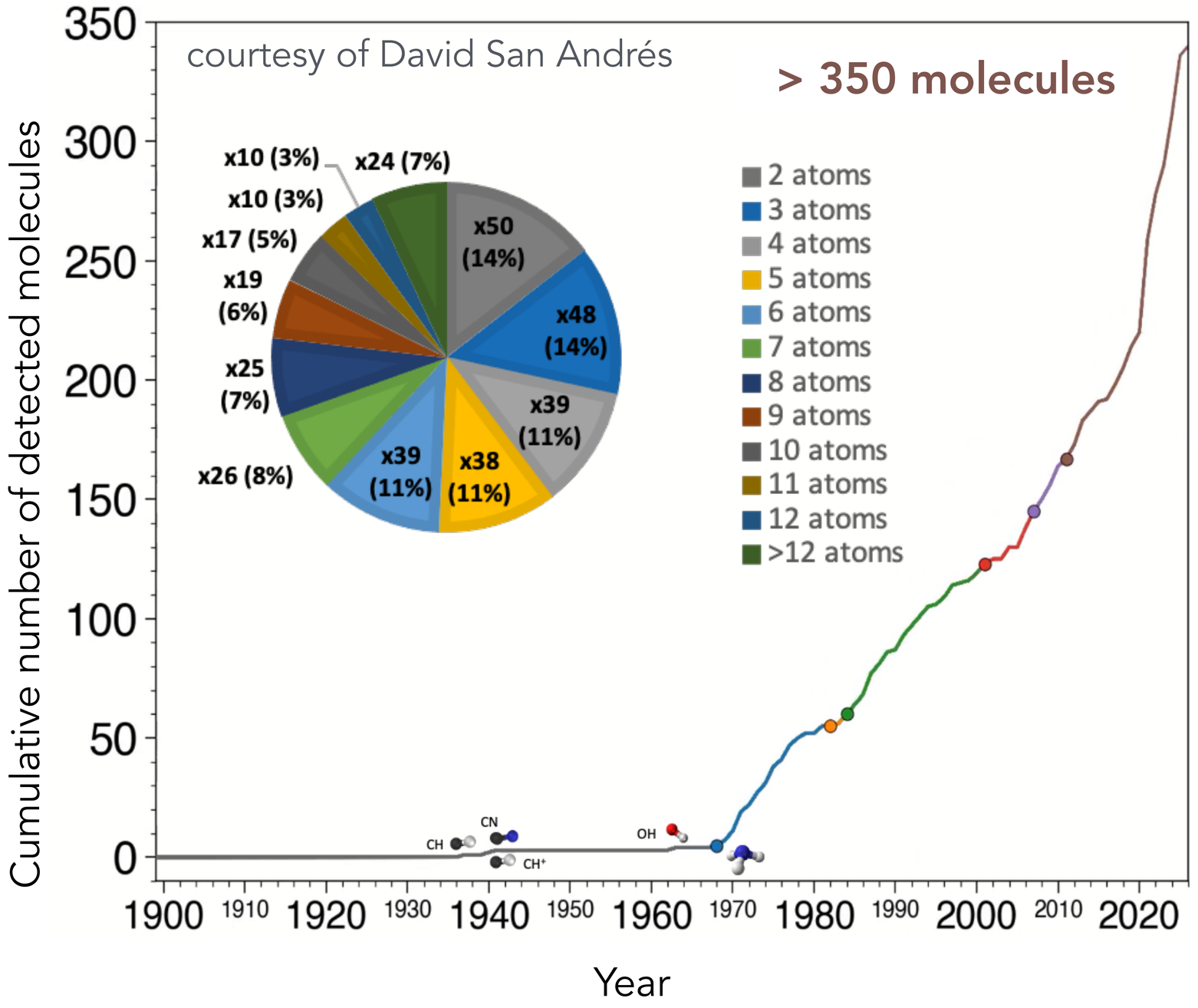
Chown et al. (2024), Tielens 2026

Rotational spectroscopy

MOLECULAR SPECTROSCOPY IN THE LAB







ALMA interferometer

Yebes 40m radiotelescope

GBT 100m radiotelescope

IRAM 30m radiotelescope

Nobeyama 45m radiotelescope

NRAO 36ft radiotelescope

Carbon is ubiquitous in the interstellar medium

CHEMICAL COMPLEXITY

2 Atoms		3 Atoms		4 Atoms		5 Atoms		6 Atoms	7 Atoms
CH	NH	H_2O	MgCN	NH_3	SiC_3	HC_3N	C_4H^-	CH_3OH	CH_3CHO
CN	SiN	HCO^+	H_3^+	H_2CO	CH_3	HCOOH	CNCHO	CH_3CN	CH_3CCH
CH^+	SO^+	HCN	SiCN	HNCO	C_3N^-	CH_2NH	HNCNH	NH_2CHO	CH_3NH_2
OH	CO^+	OCS	AlNC	H_2CS	PH_3	NH_2CN	CH_3O	CH_3SH	CH_2CHCN
CO	HF	HNC	SiNC	C_2H_2	HCNO	H_2CCO	NH_3D^+	C_2H_4	HC_5N
H_2	N_2	H_2S	HCP	C_3N	HOCN	C_4H	H_2NCO^+	C_5H	C_6H
SiO	CF^+	N_2H^+	CCP	HNCS	HSCN	SiH_4	$NCCNH^+$	CH_3NC	c-C_2H_4O
CS	PO	C_2H	AlOH	$HOCO^+$	HOOH	c-C_3H_2	CH_3Cl	HC_2CHO	CH_2CHOH
SO	O_2	SO_2	H_2O^+	C_3O	l-C_3H^+	CH_2CN	MgC_3N	H_2C_4	C_6H^-
SiS	AlO	HCO	H_2Cl^+	l-C_3H	HMgNC	C_5	HC_3O^+	C_5S	CH_3NCO
NS	CN^-	HNO	KCN	$HCNH^+$	HCCO	SiC_4	NH_2OH	HC_3NH^+	HC_5O
C_2	OH^+	HCS^+	FeCN	H_3O^+	CNCN	H_2CCC	HC_3S^+	C_5N	$HOCH_2CN$
NO	SH^+	HOC^+	HO_2	C_3S	HONO	CH_4	H_2CCS	HC_4H	HC_4NC
HCl	HCl^+	SiC_2	TiO_2	c-C_3H	MgCCH	HCCNC	C_4S	HC_4N	HC_3HNH
NaCl	SH	C_2S	CCN	HC_2N	HCCS	HNCCC	CHOSH	c-H_2C_3O	c-C_3HCCH
AlCl	TiO	C_3	SiCSi	H_2CN		H_2COH^+		CH_2CNH	
KCl	ArH^+	CO_2	S_2H					C_5N^-	
AlF	NS^+	CH_2	HCS					HNCHCN	
PN	HeH^+	C_2O	HSC					SiH_3CN	
SiC	VO	MgNC	NCO					MgC_4H	
CP		NH_2	CaNC					CH_3CO^+	
		NaCN	NCS					H_2CCCS	
		N_2O						CH_2CCH	

8 Atoms	9 Atoms	10 Atoms	11 Atoms	12 Atoms	13 Atoms	PAHs	Fullerenes
$HCOOCH_3$	CH_3OCH_3	CH_3COCH_3	HC_9N	C_6H_6	C_6H_5CN	1-$C_{10}H_7CN$	C_{60}
CH_3C_3N	CH_3CH_2OH	$HOCH_2CH_2OH$	CH_3C_6H	n-C_3H_7CN	$HC_{11}N$	2-$C_{10}H_7CN$	C_{60}^+
C_7H	CH_3CH_2CN	CH_3CH_2CHO	C_2H_5OCHO	i-C_3H_7CN		C_9H_8	C_{70}
CH_3COOH	HC_7N	CH_3C_5N	CH_3COOCH_3	1-C_5H_5CN			
H_2C_6	CH_3C_4H	CH_3CHCH_2O	CH_3COCH_2OH	2-C_5H_5CN			
CH_2OHCHO	C_8H	CH_3OCH_2OH	C_5H_6				
HC_6H	CH_3CONH_2						
CH_2CHCHO	C_8H^-						
CH_2CCHCN	CH_2CHCH_3						
NH_2CH_2CN	CH_3CH_2SH						
CH_3CHNH	HC_7O						
CH_3SiH_3	CH_3NHCHO						
NH_2CONH_2	$H_2CCCHCCH$						
$HCCCH_2CN$	$HCCCHCHCN$						
CH_2CHCCH	H_2CCHC_3N						

McGuire et al. (2022)

> 90% of interstellar molecules contain C

100% of those with >6 atoms (complex organic molecules, COMs)

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CH^+	SO^+	HCN	SiCN	HNCO	C_3N^-	CH_2NH	HNCNH	NH_2CHO	CH_3NH_2
OH	CO^+	OCS	AlNC	H_2CS	PH_3	NH_2CN	CH_3O	CH_3SH	CH_2CHCN
CO	HF	HNC	SiNC	C_2H_2	HCNO	H_2CCO	NH_3D^+	C_2H_4	HC_5N
H_2	N_2	H_2S	HCP	C_3N	HOCN	C_4H	H_2NCO^+	C_5H	C_6H
SiO	CF^+	N_2H^+	CCP	HNCS	HSCN	SiH_4	$NCCNH^+$	CH_3NC	c-C_2H_4O
CS	PO	C_2H	AlOH	$HOCO^+$	HOOH	c-C_3H_2	CH_3Cl	HC_2CHO	CH_2CHOH
SO	O_2	SO_2	H_2O^+	C_3O	l-C_3H^+	CH_2CN	MgC_3N	H_2C_4	C_6H^-
SiS	AlO	HCO	H_2Cl^+	l-C_3H	HMgNC	C_5	HC_3O^+	C_5S	CH_3NCO
NS	CN^-	HNO	KCN	$HCNH^+$	HCCO	SiC_4	NH_2OH	HC_3NH^+	HC_5O
C_2	OH^+	HCS^+	FeCN	H_3O^+	CNCN	H_2CCC	HC_3S^+	C_5N	$HOCH_2CN$
NO	SH^+	HOC^+	HO_2	C_3S	HONO	CH_4	H_2CCS	HC_4H	HC_4NC
HCl	HCl^+	SiC_2	TiO_2	c-C_3H	MgCCH	HCCNC	C_4S	HC_4N	HC_3HNH
NaCl	SH	C_2S	CCN	HC_2N	HCCS	HNCCC	CHOSH	c-H_2C_3O	c-C_3HCCH
AlCl	TiO	C_3	SiCSi	H_2CN		H_2COH^+		CH_2CNH	
KCl	ArH^+	CO_2	S_2H					C_5N^-	
AlF	NS^+	CH_2	HCS					HNCHCN	
PN	HeH^+	C_2O	HSC					SiH_3CN	
SiC	VO	MgNC	NCO					MgC_4H	
CP		NH_2	CaNC					CH_3CO^+	
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C_7H	CH_3CH_2CN	CH_3CH_2CHO	C_2H_5OCHO	i-C_3H_7CN		C_9H_8	C_{70}
CH_3COOH	HC_7N	CH_3C_5N	CH_3COOCH_3	1-C_5H_5CN			
H_2C_6	CH_3C_4H	CH_3CHCH_2O	CH_3COCH_2OH	2-C_5H_5CN			
CH_2OHCHO	C_8H	CH_3OCH_2OH	C_5H_6				
HC_6H	CH_3CONH_2						
CH_2CHCHO	C_8H^-						
CH_2CCHCN	CH_2CHCH_3						
NH_2CH_2CN	CH_3CH_2SH						
CH_3CHNH	HC_7O						
CH_3SiH_3	CH_3NHCHO						
NH_2CONH_2	$H_2CCCHCCH$						
$HCCCH_2CN$	HCCCHCHCN						
CH_2CHCCH	H_2CCHC_3N						

McGuire et al. (2022)

Aromatic rings?

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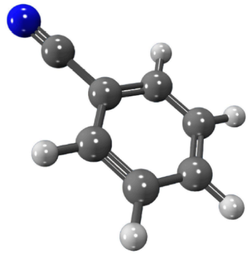
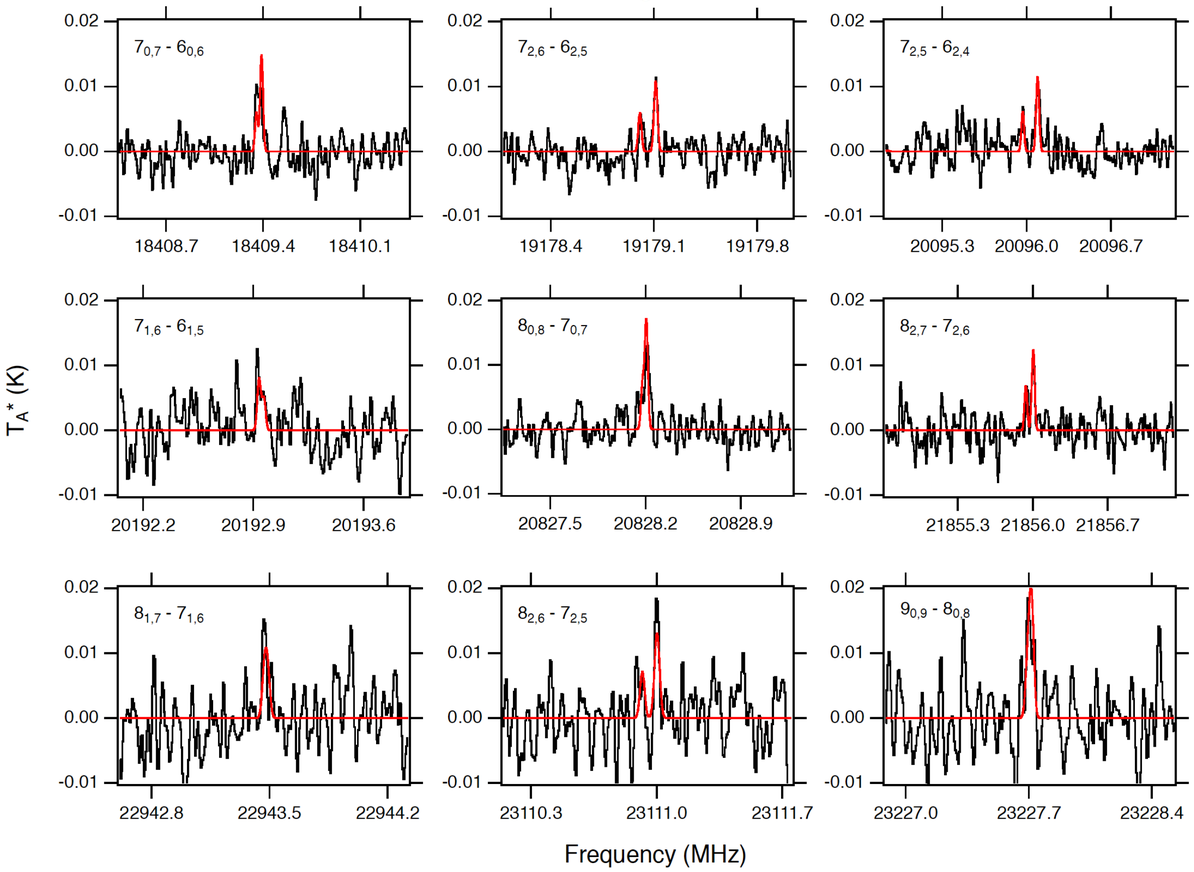
100% of those with >6 atoms (complex organic molecules, COMs)

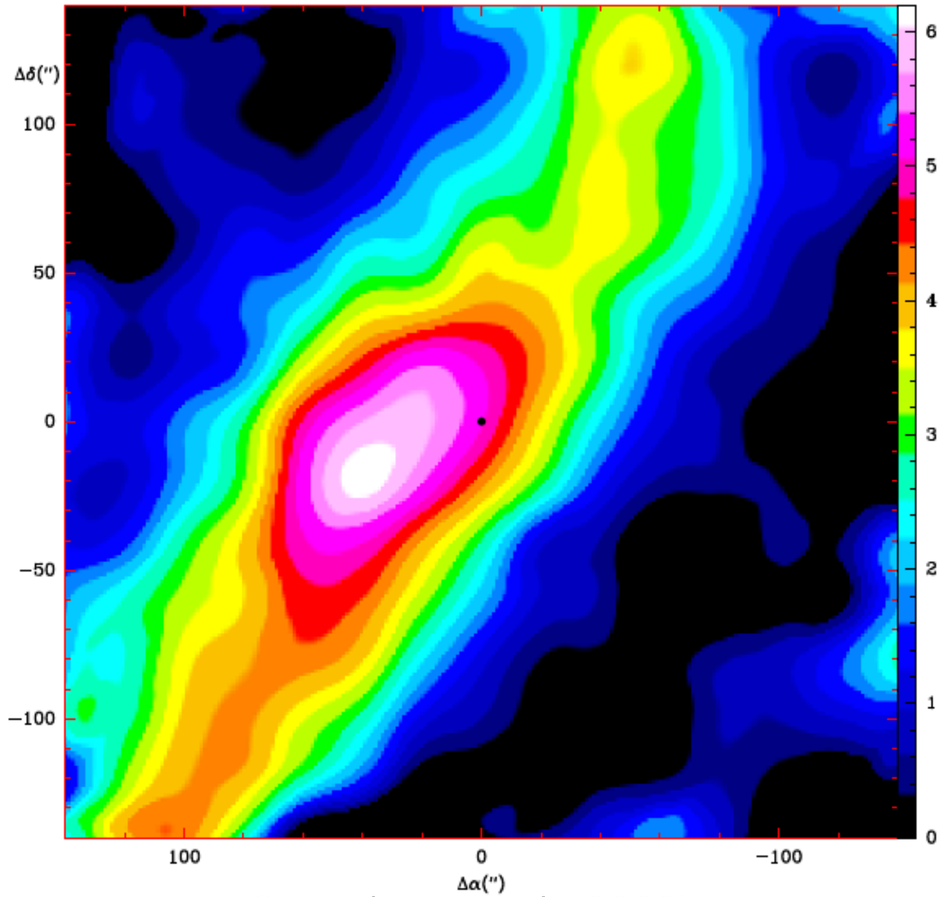
Aromatic rings in the cold molecular cloud TMC-1



$c\text{-}C_6H_5CN$ Benzonitrile



McGuire et al. (2018)



Cernicharo et al. (2023)

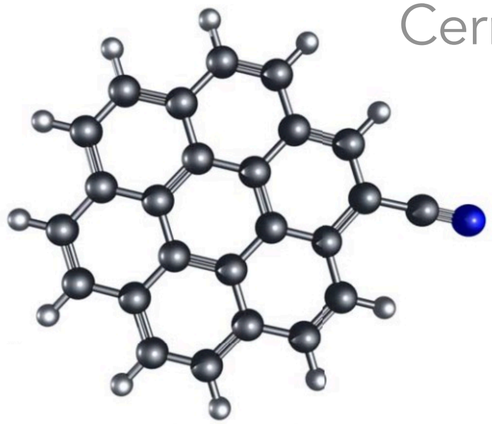
TMC-1

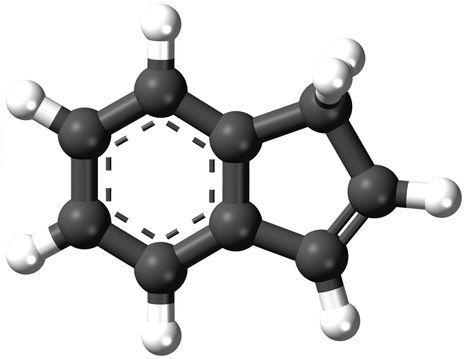
> 20 molecules composed by 6- and 5-,membered rings, from 1 to 7 rings

GOTHAM
McGuire et al.

GOTHAM

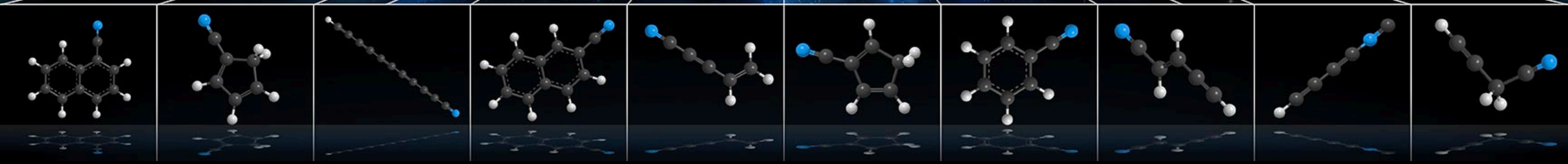
Cernicharo et al. (2021)





Wenzel et al. (2025)

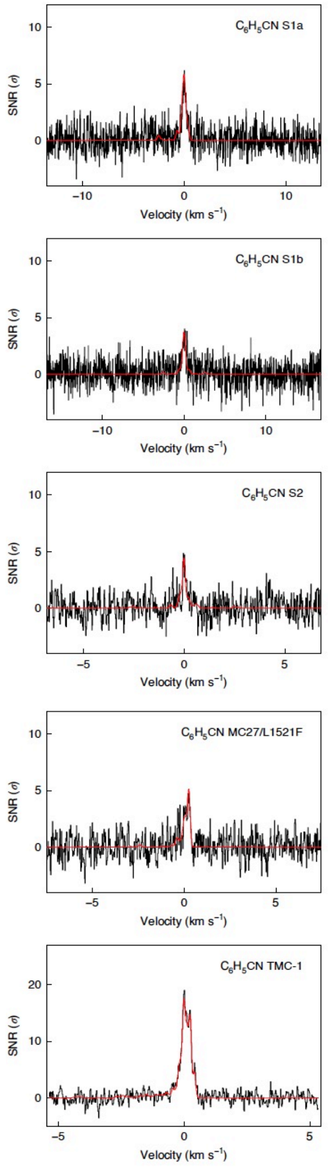
QUIJOTE
Cernicharo et al.

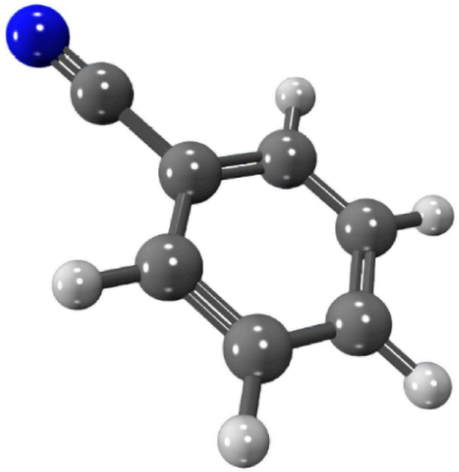


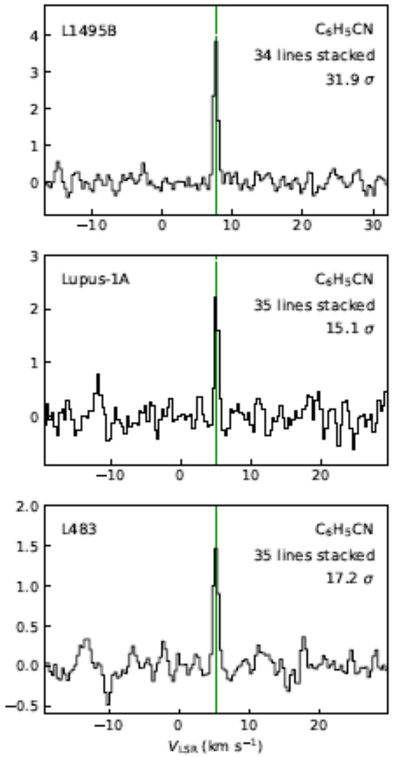
Is TMC-1 unique?

Benzonitrile also detected in similar cold Galactic clouds in the solar vicinity

Burkhardt et al. (2021)







Agúndez et al. (2023)

Very weak lines! Stacking technique was needed

Formation of PAHs

Bottom-up

larger PAHs might be formed ***in situ*** in molecular clouds by the combination of **smaller species** (Doddipatla et al. 2021; Kaiser & Hansen 2021; Cernicharo et al. 2022, 2023; Reizer et al. 2022; García de la Concepción et al. 2023; Yang et al. 2024; Castiñeira Reis et al. 2024; Mallo et al. 2025).

Top-down

simple PAHs would be the result of **destruction of dust carbonaceous grains** by collisions or interstellar shocks (Jones et al. 1996; Scott et al. 1997; Merino et al. 2014), and/or **fragmentation of large PAHs formed in the hot circumstellar medium** (CSM) around evolved stars (e.g. Zhao et al. 2019).

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To distinguish between them, it is crucial to **detect aromatic species across a broad range of interstellar environments** spanning diverse physical conditions, which imprint distinct signatures on the aromatic chemistry

COLD GALACTIC DISK CLOUDS

“gentle” environment

- Tkin ~10 K
- Solar vicinity d < 500 pc
- Quiescent: narrow line widths of 0.5-1 km s^{-1}
- No presence of shocks
- Low cosmic-ray ionisation rate of ~10^{-17} s^{-1}

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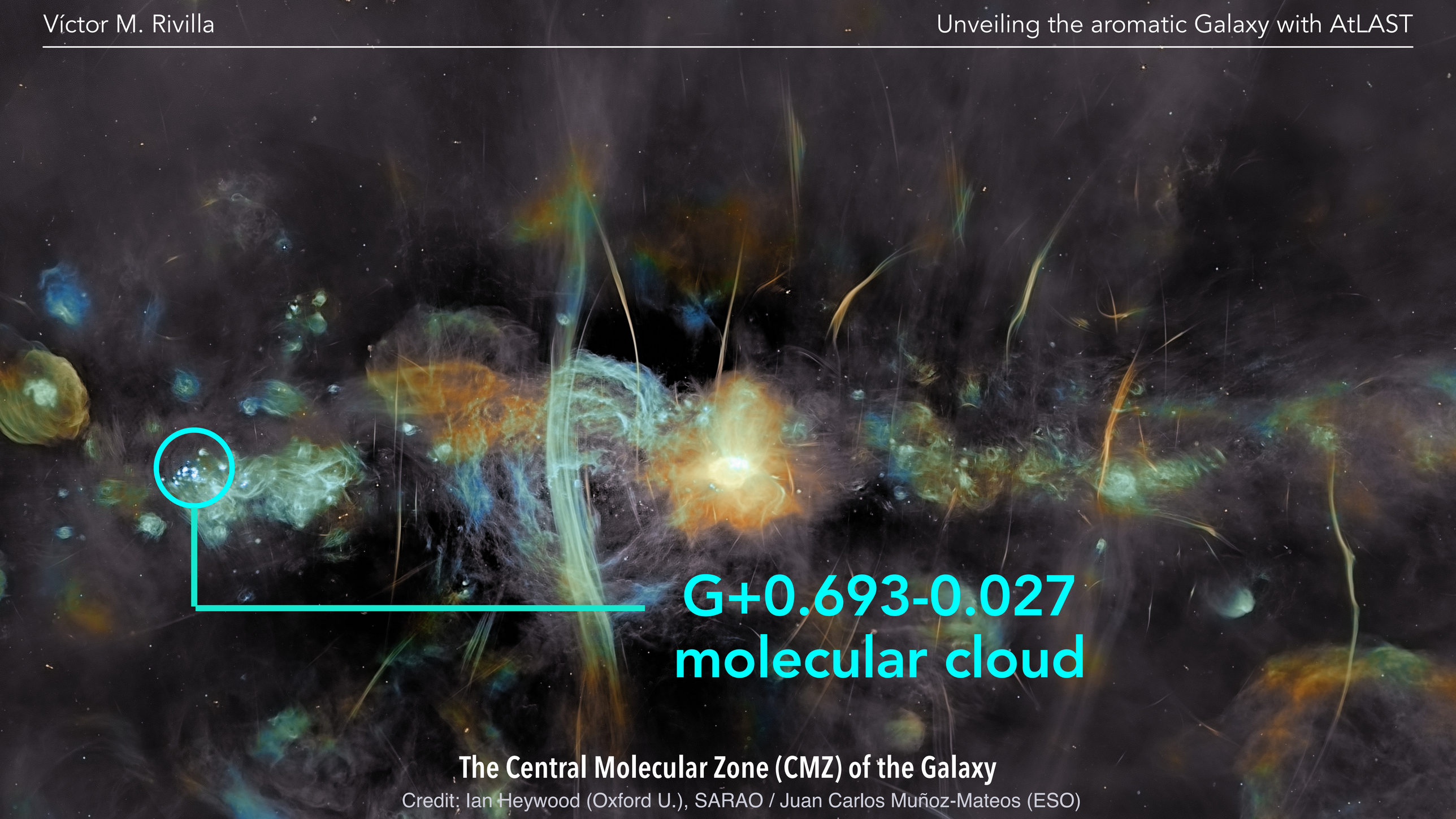
GALACTIC CENTER CLOUDS

"harsh" environment

- Tkin ~100 K
- Galactic Center: d ~ 8 kpc
- Turbulent: line widths of 15-20 km s^{-1}
- Large-scale low-velocity shocks
- Enhance cosmic-ray ionisation rate of ~10^{-15} s^{-1}

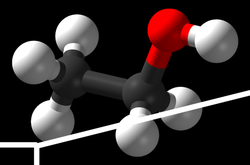


The Central Molecular Zone (CMZ) of the Galaxy

Credit: Ian Heywood (Oxford U.), SARAO / Juan Carlos Muñoz-Mateos (ESO)

The G+0.693-0.027 molecular cloud

Ethanol
(CH_3CH_2OH)



G+0.693-0.027

SgrB2 N

SgrB2 M

ALMA 3mm
continuum
Ginsburg et al. (2016)

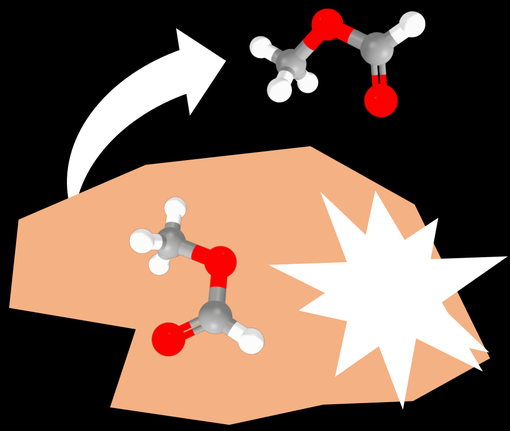
SiO(3-2)

G+0.693

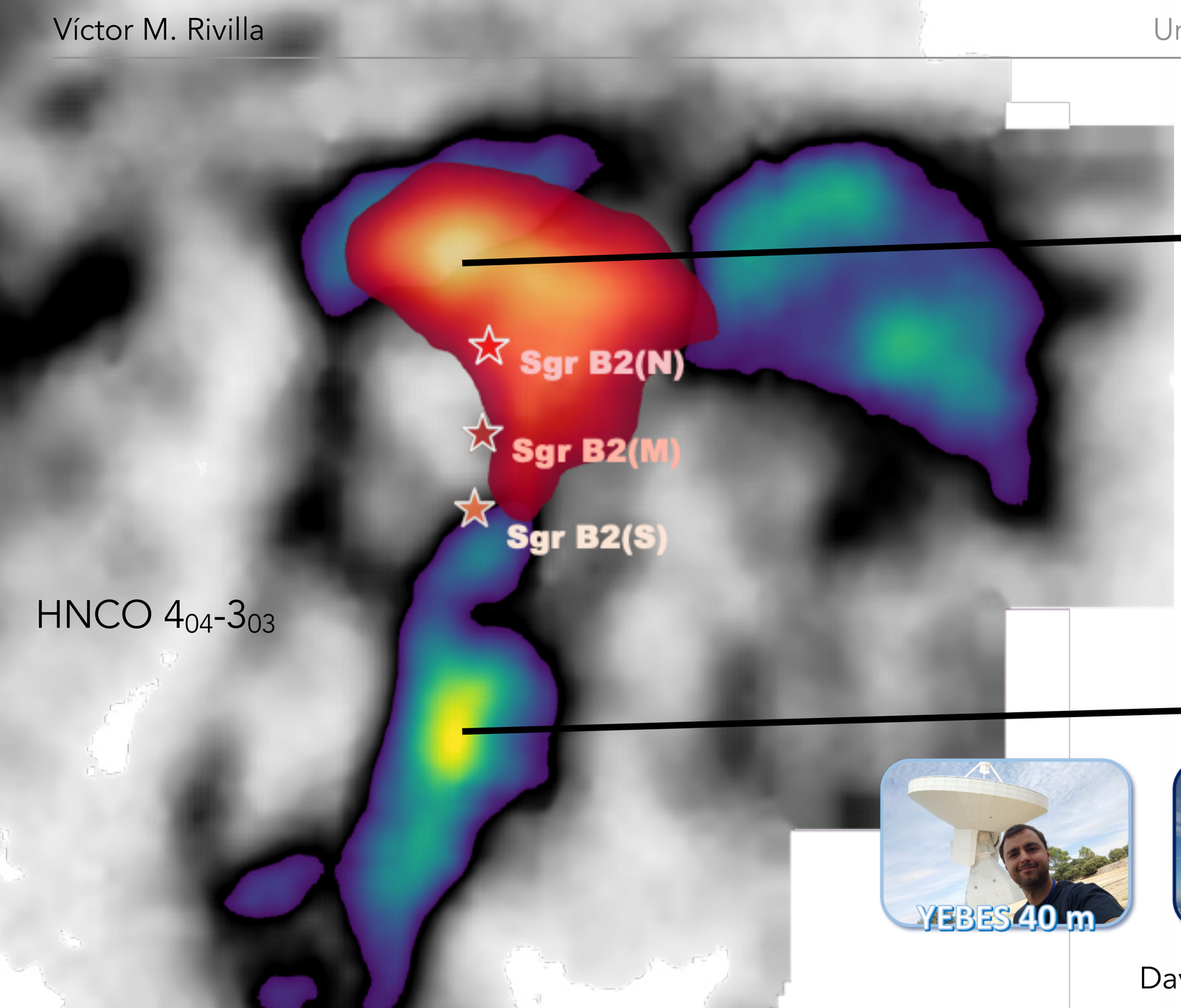
SgrB2 N

SMA+APEX
Zeng et al. (2020)

SHOCKS



RICH MOLECULAR COMPLEXITY

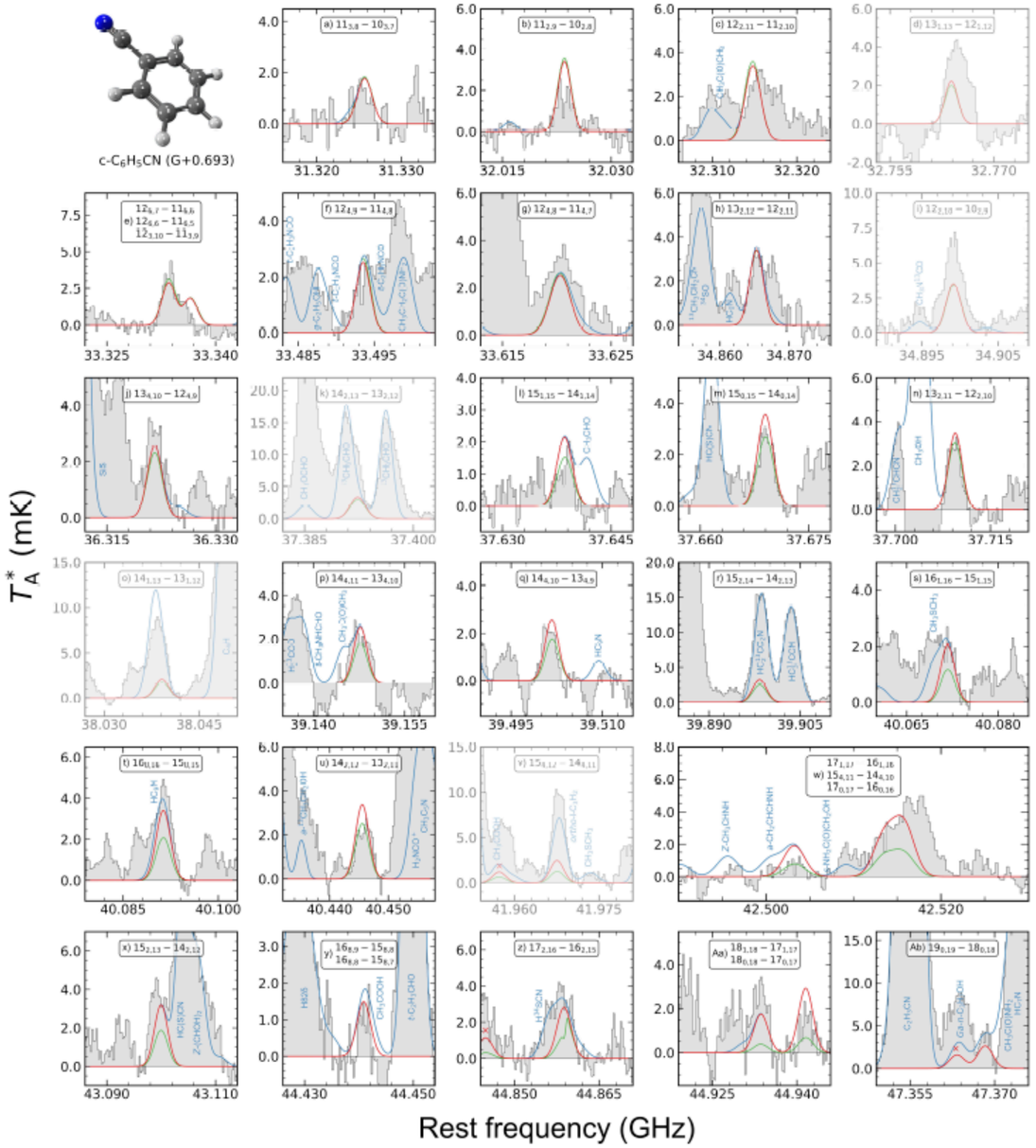


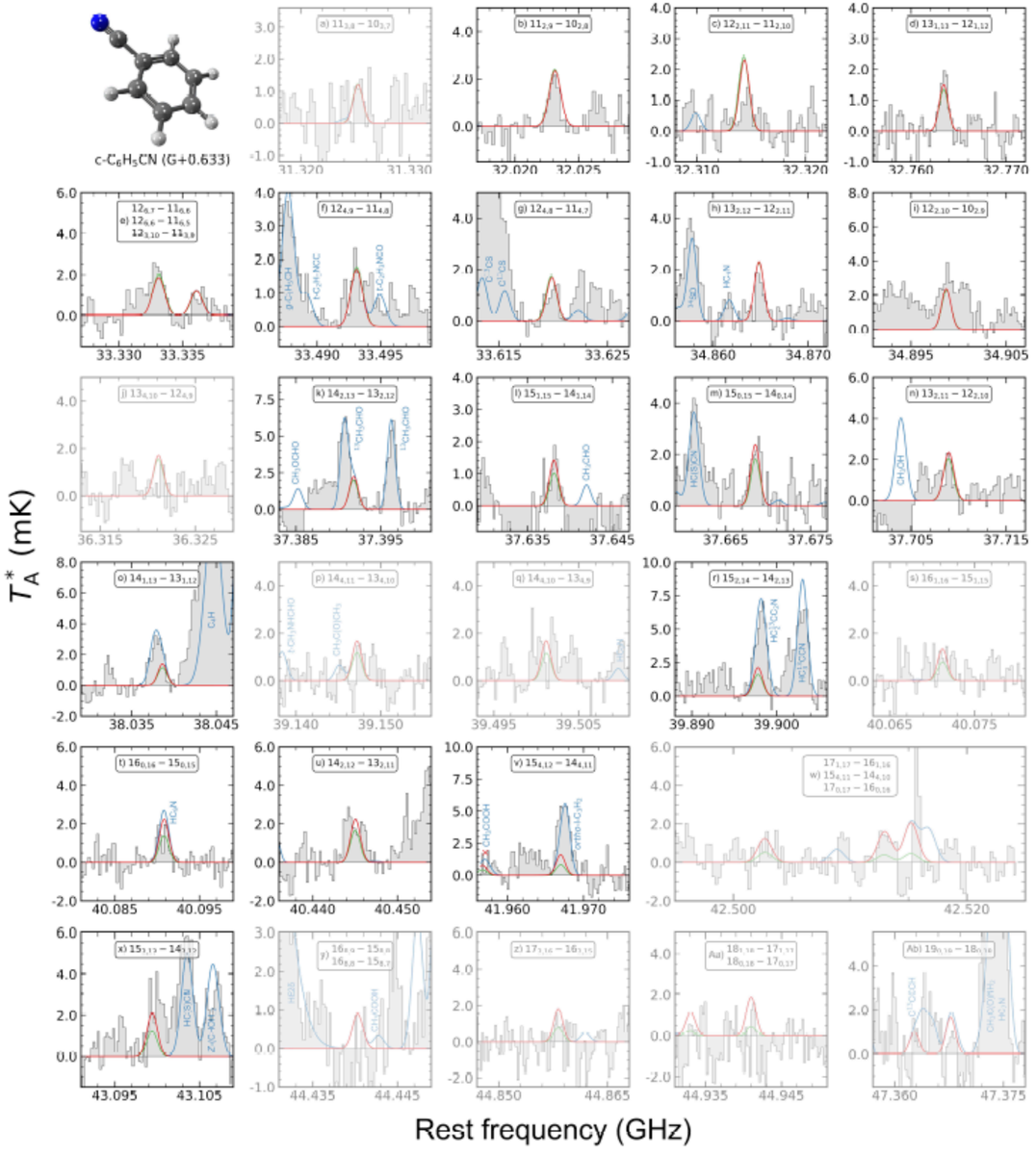
G+0.693-0.027

G+0.693-0.004

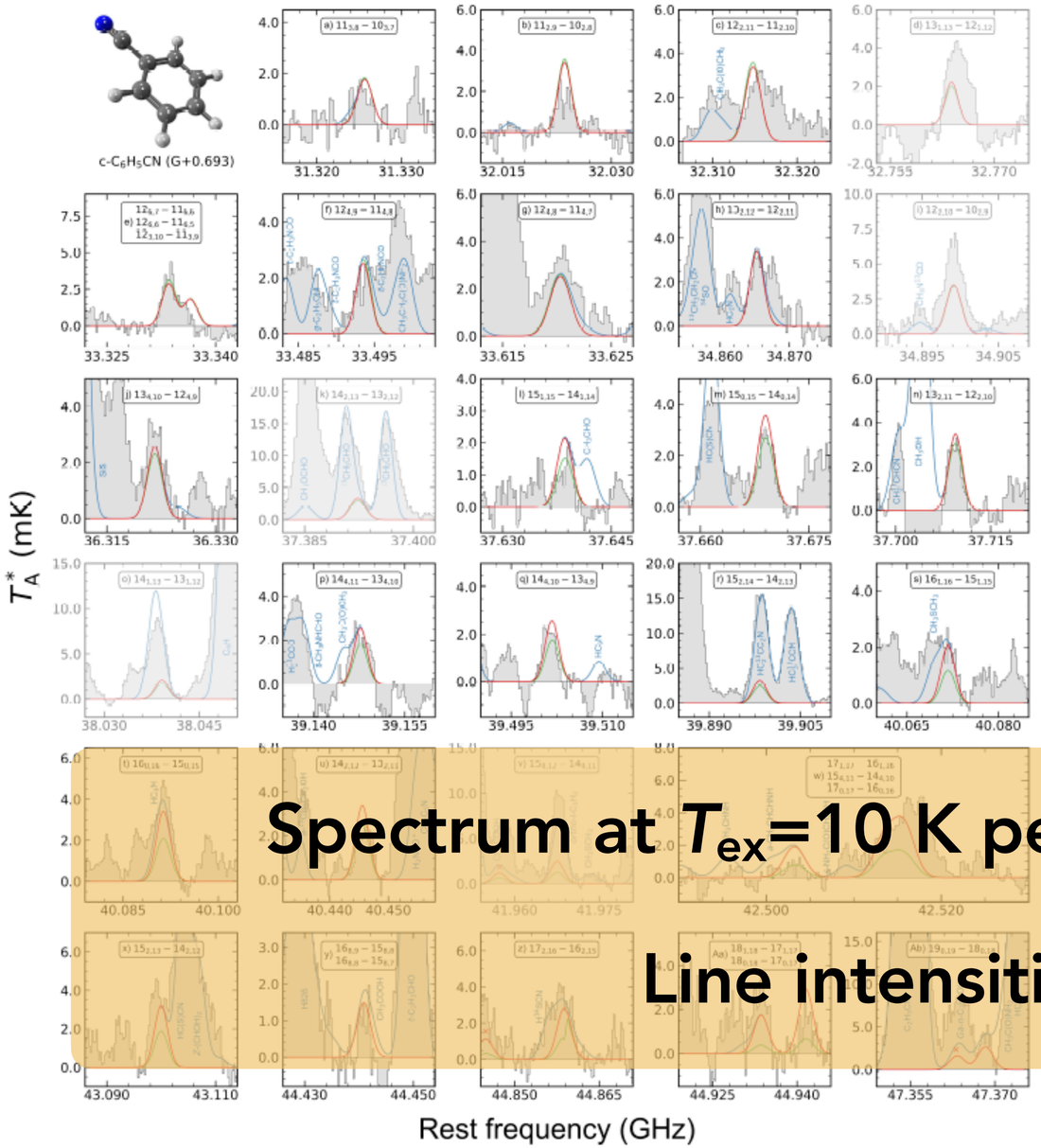
David San Andrés Phd thesis

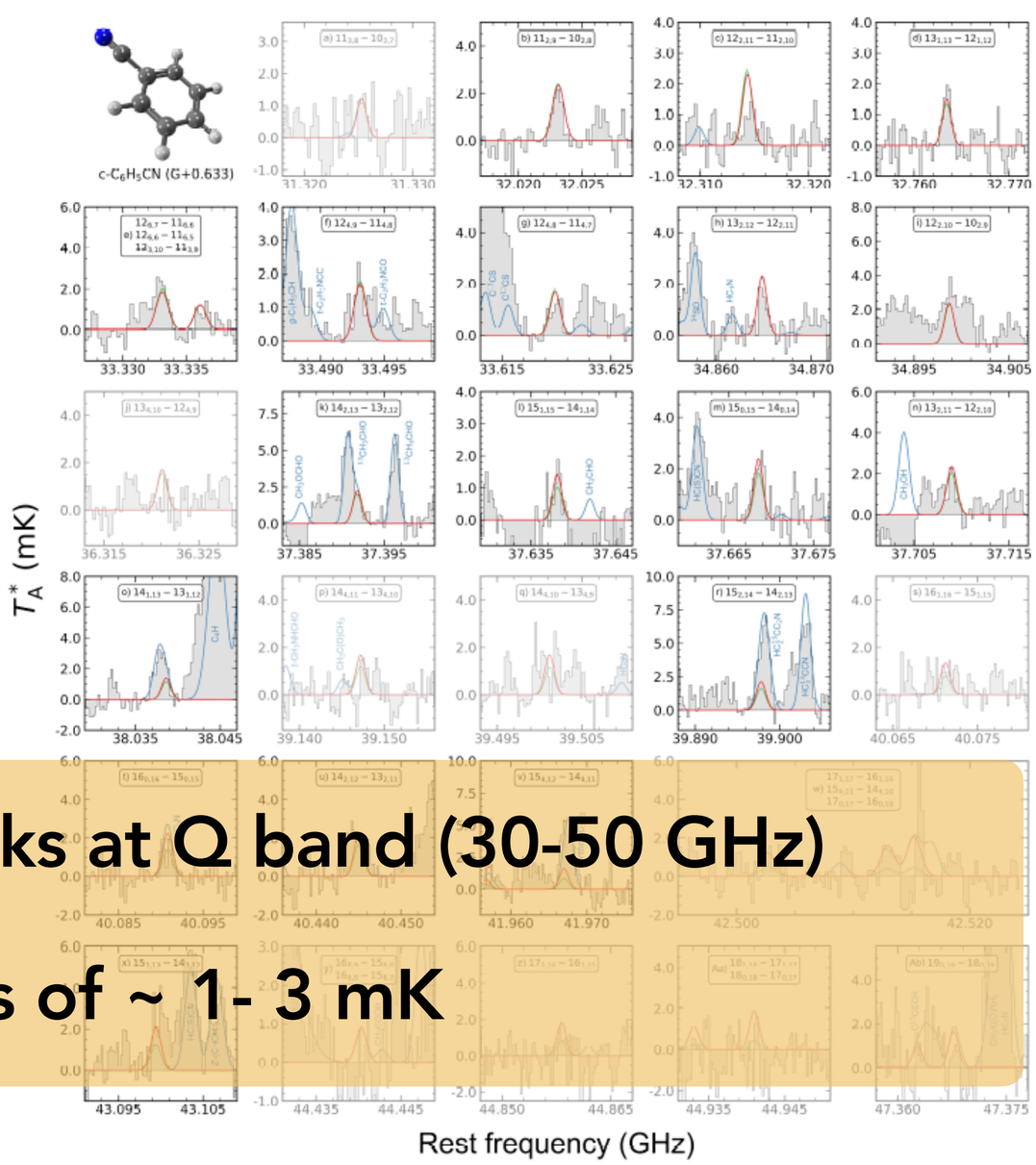
G+0.693-0.027 Rivilla et al. (2026) G+0.693-0.004





G+0.693-0.027 Rivilla et al. (2026) G+0.693-0.004

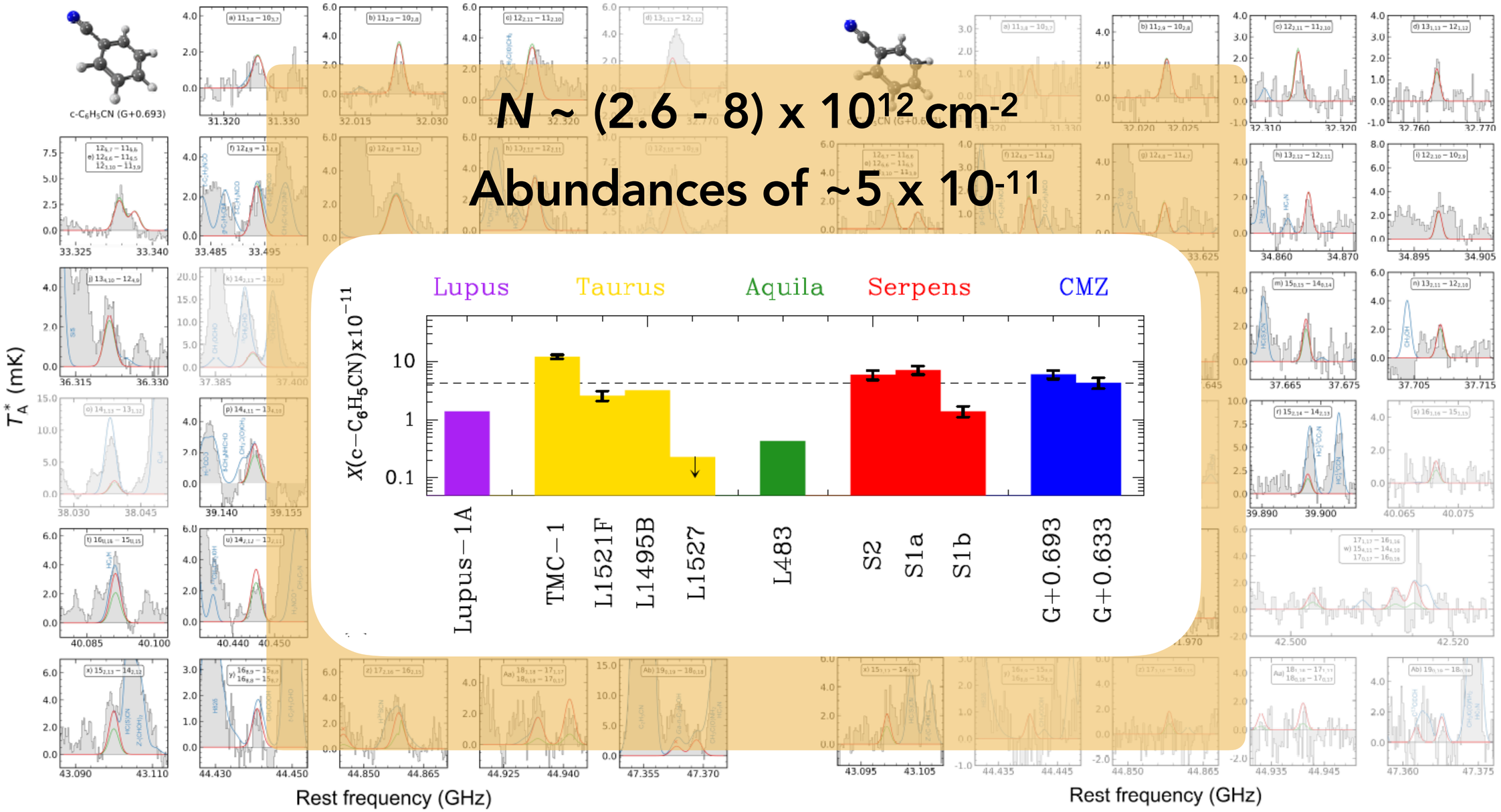




Spectrum at T_{ex}=10 K peaks at Q band (30-50 GHz)

Line intensities of ~ 1- 3 mK

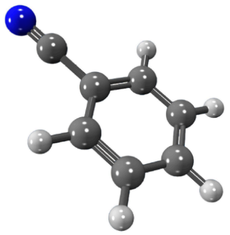
G+0.693-0.027 Rivilla et al. (2026) G+0.693-0.004

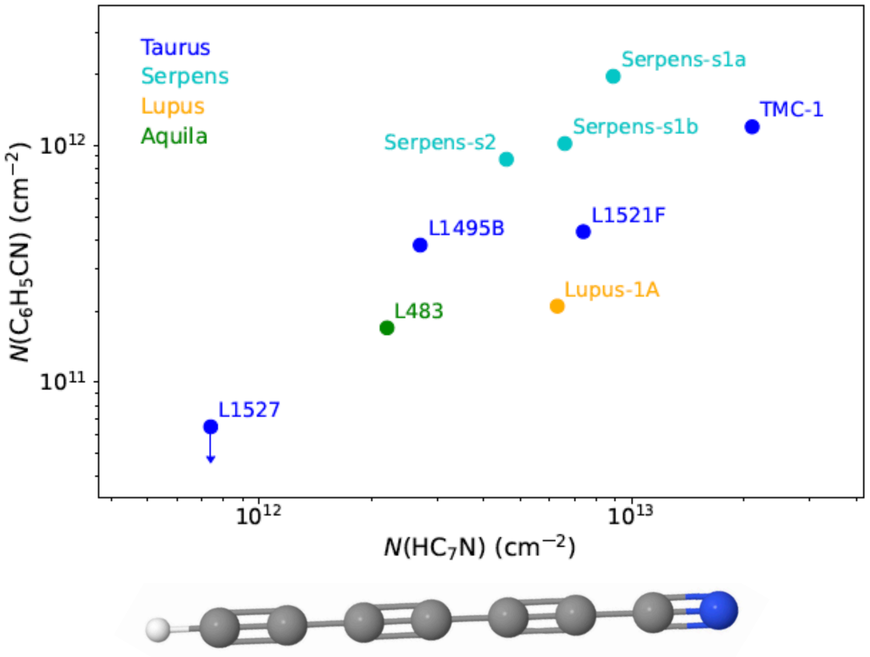


Preference of aromatic chemistry in the Galactic Center

Agúndez et al. (2023)

Burkhardt et al. (2023)





Preference of aromatic chemistry in the Galactic Center

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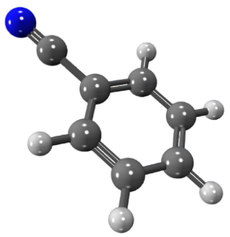
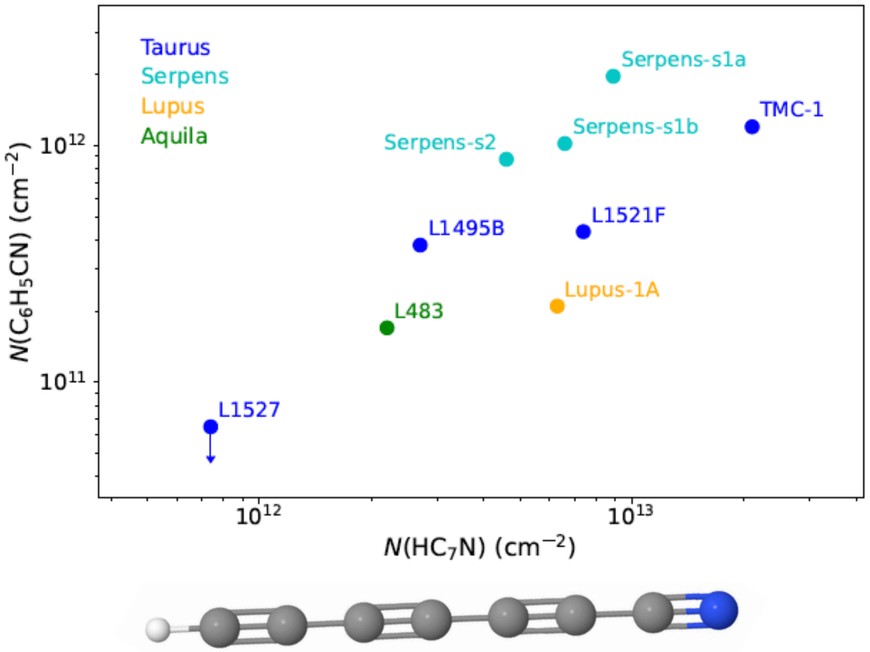
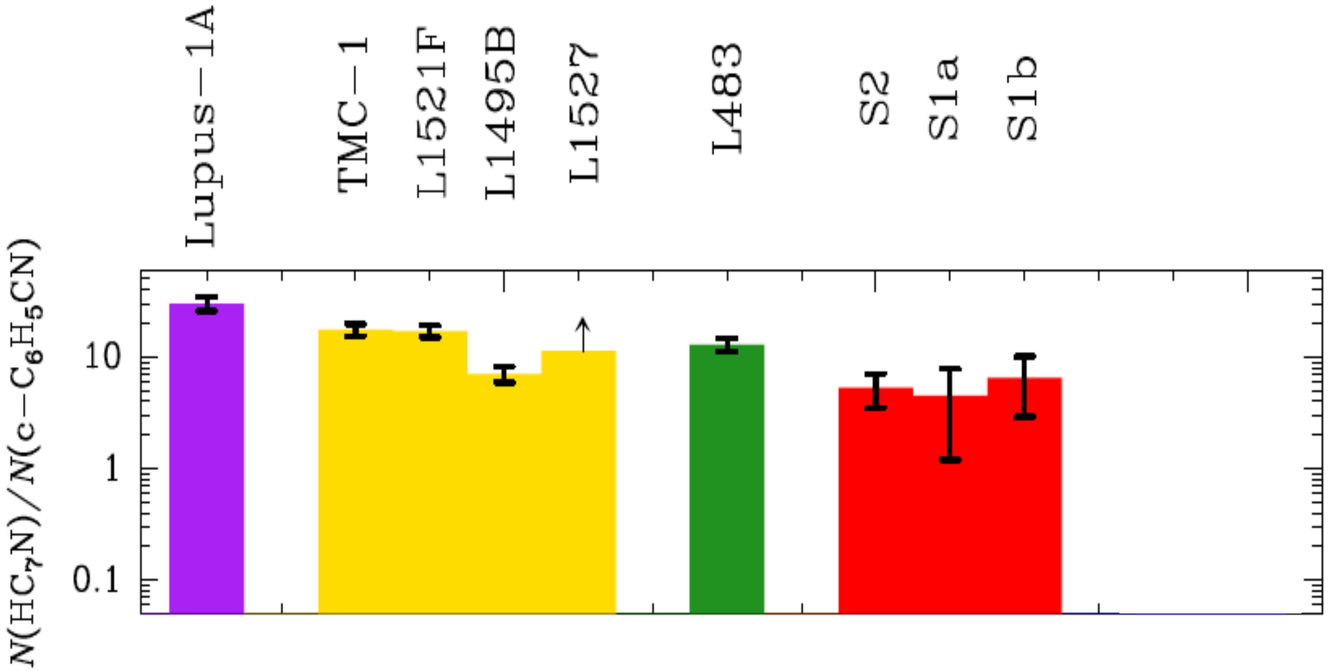




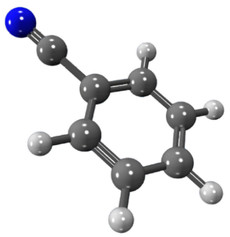
Rivilla et al. (2026)

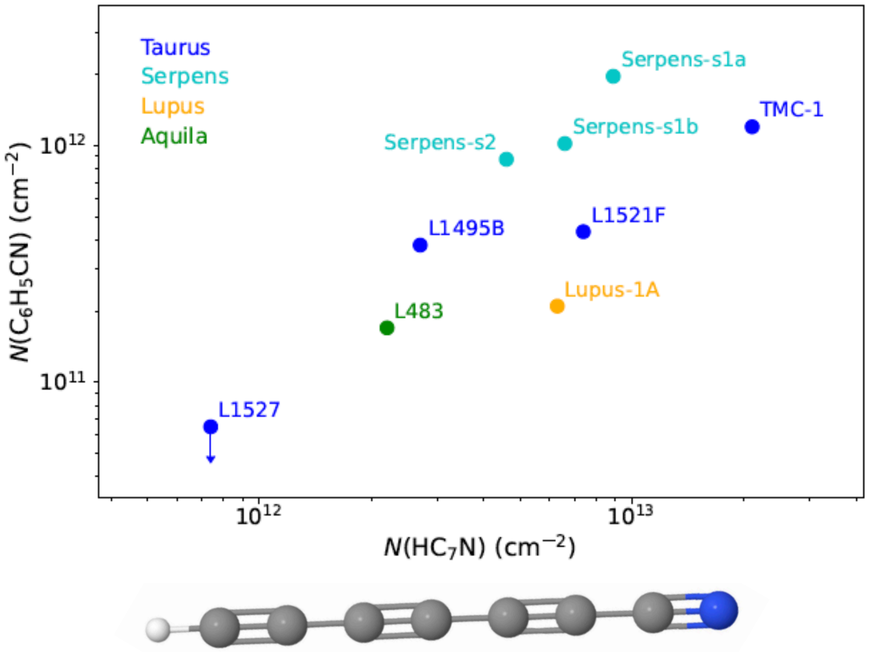
$N(HC_7N)$ / $N(c\text{-}C_6H_5CN)$



Preference of aromatic chemistry in the Galactic Center

Agúndez et al. (2023)
Burkhardt et al. (2023)





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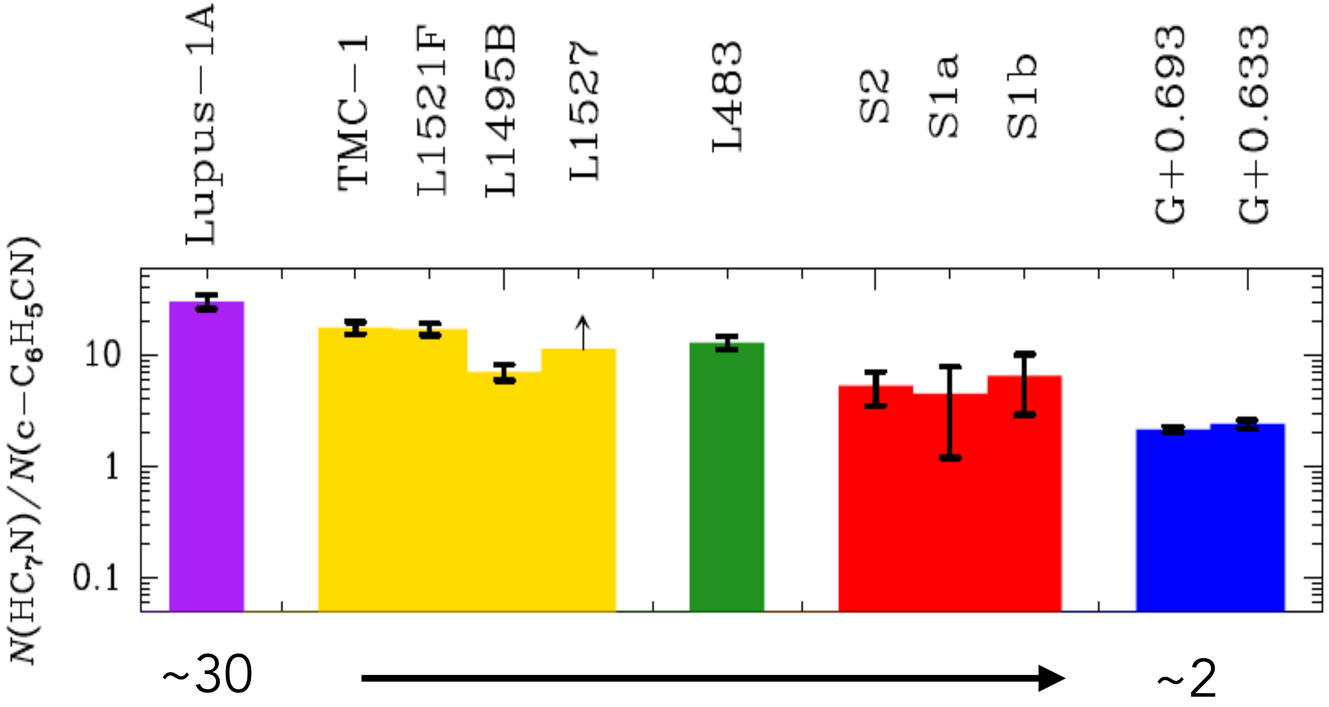

Preference of aromatic chemistry in the Galactic Center

Agúndez et al. (2023)
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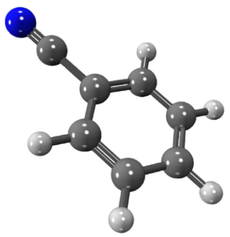

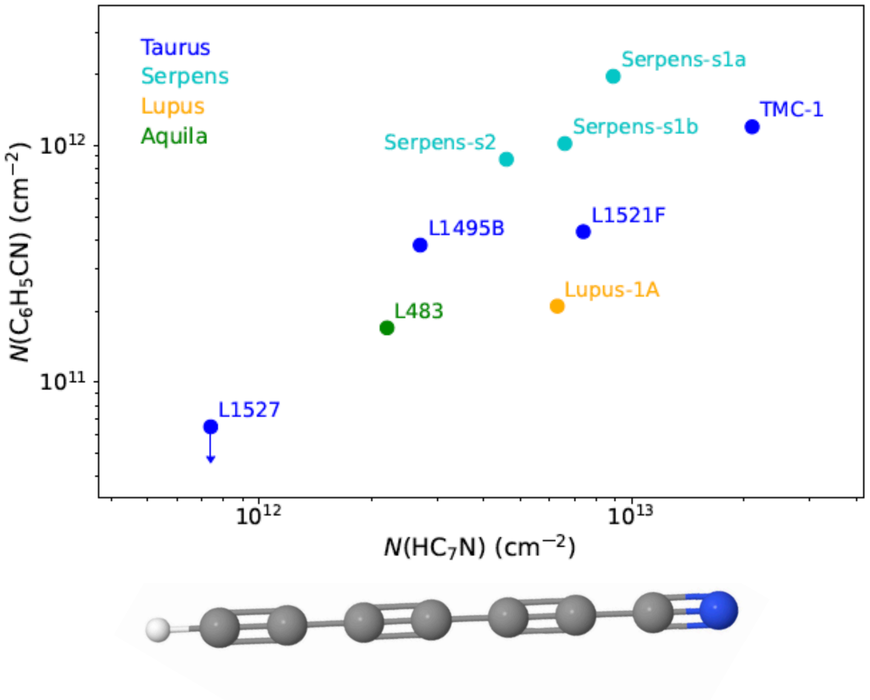

Rivilla et al. (2026)

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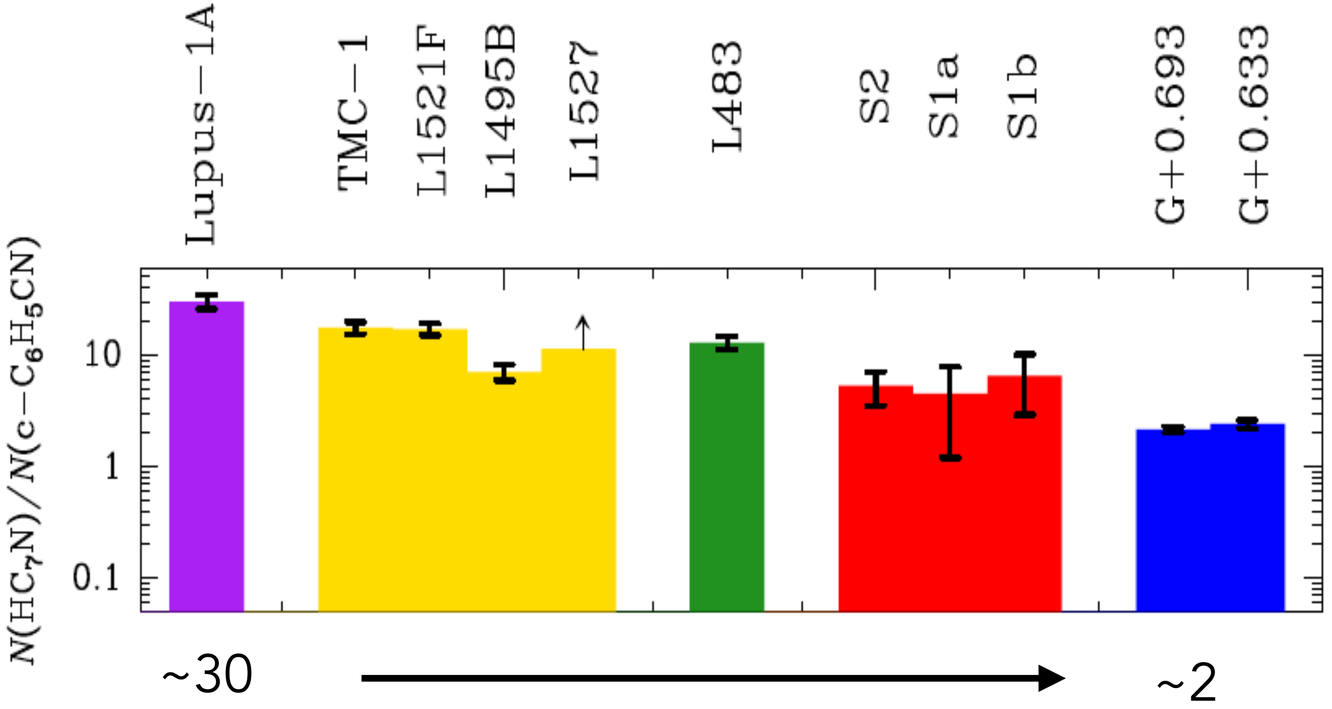
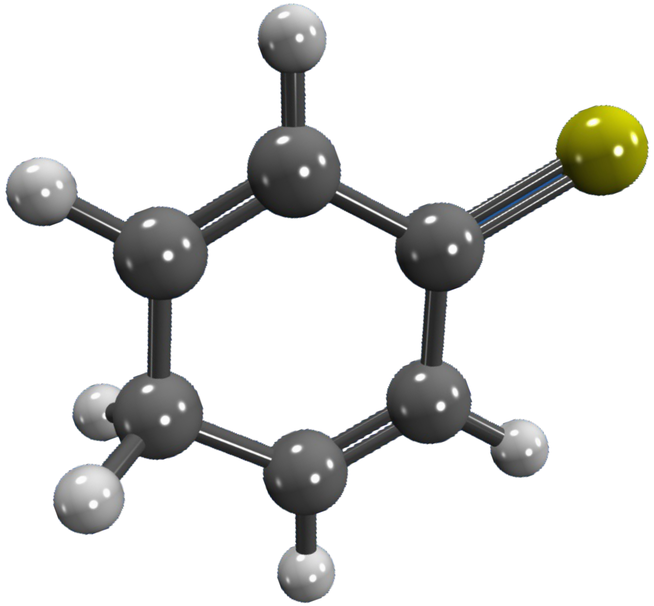
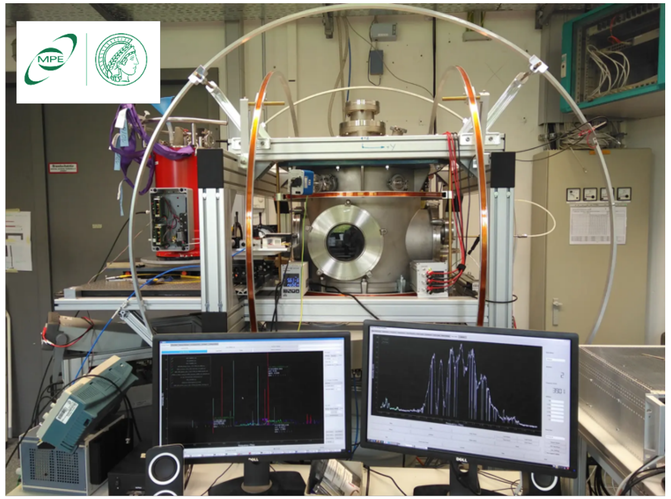


- **Aromatic vs. C-chain chemistry dependence on environmental conditions.**
- **Preference of aromatic in the Galactic Center over linear C chains.**

Other C-rings?

Detection of a S-bearing C-ring: 2,5-cyclohexadien-1-thione (2,5-CT)





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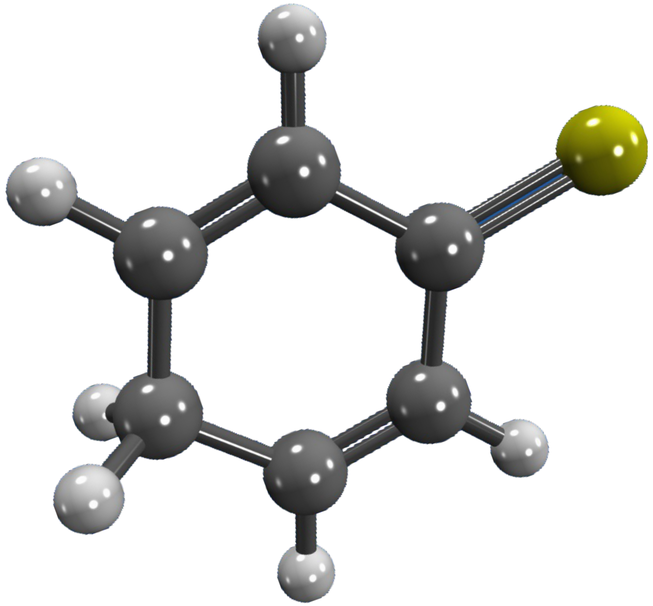
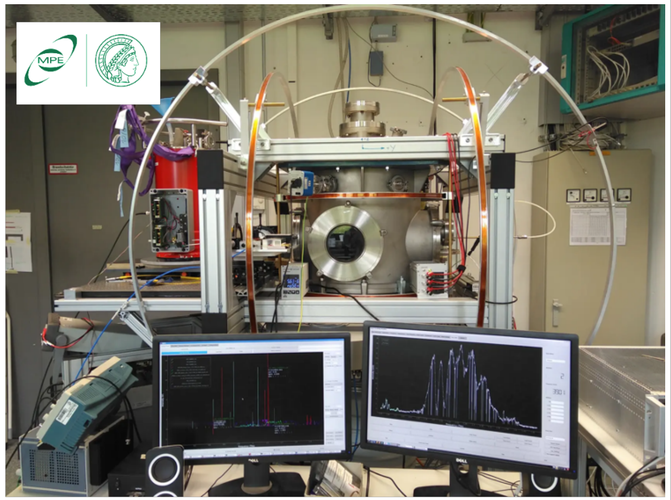
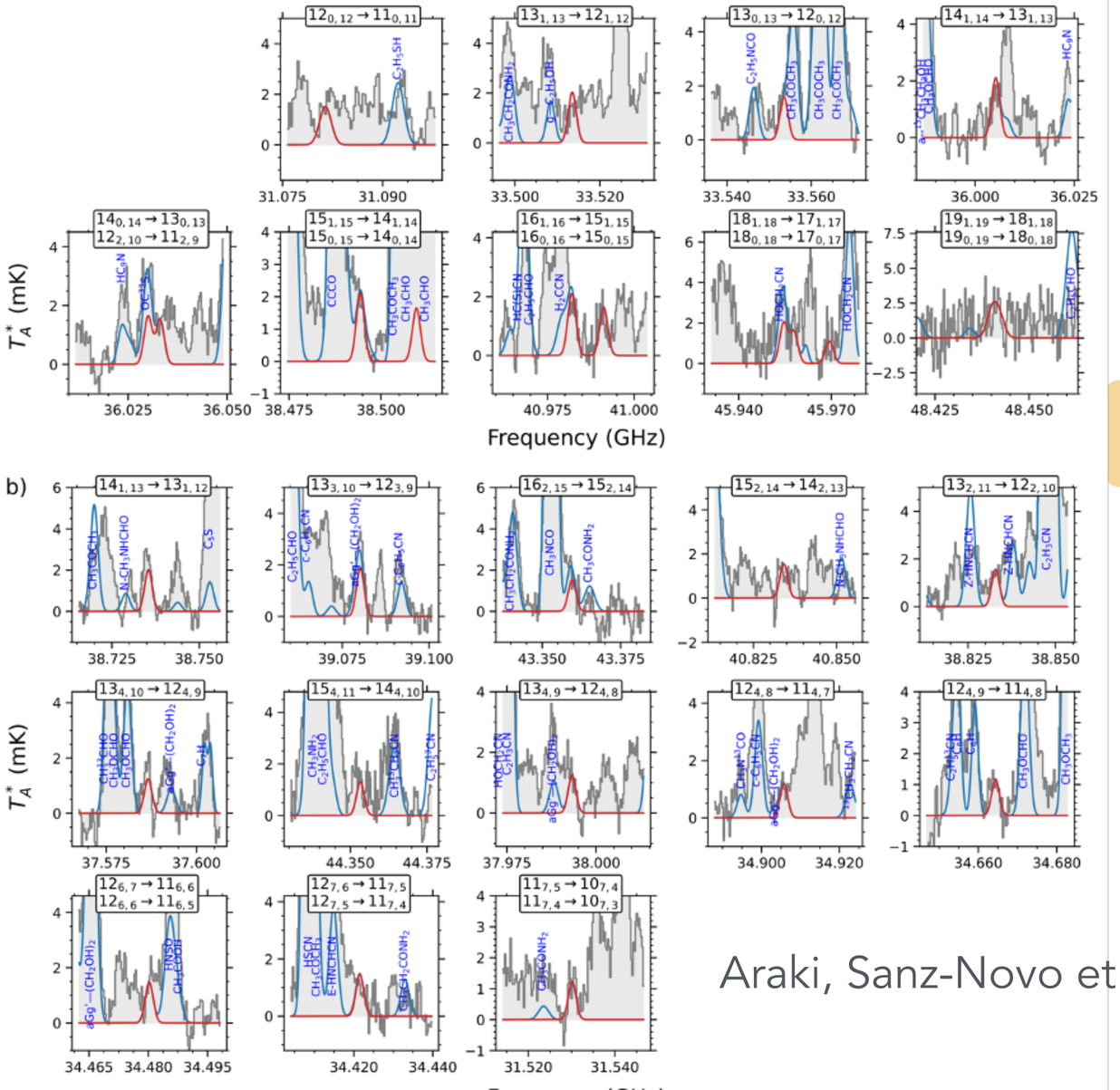






G+0.693-0.027

c-C_6H_5CN/2,5-CT = 1.2±0.1

Araki, Sanz-Novo et al. (2026), Nat. Astro.

Rings in the Galactic Center

2,5-cyclohexadien-1-thione (c-C_6H_6S)

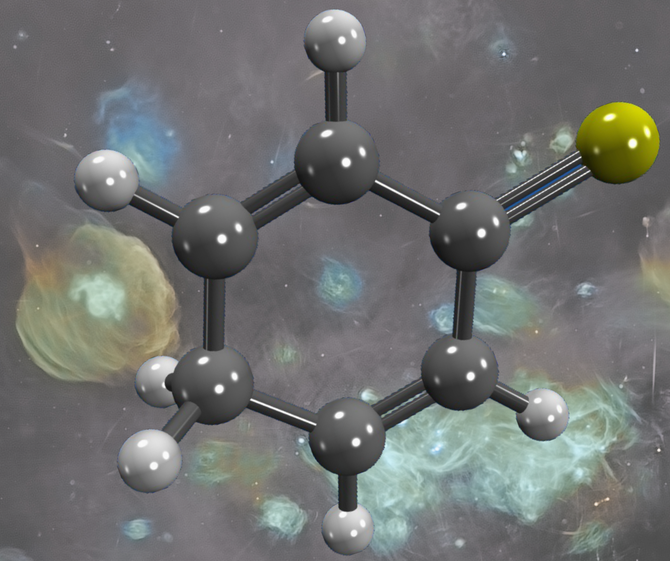
Araki, Sanz-Novo et al. (2026), Nat. Astro.

First detection in the ISM

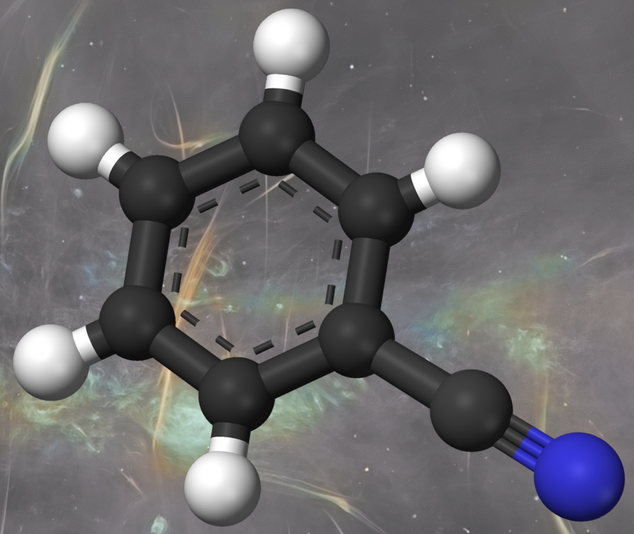
Benzonitrile (c-C_6H_5CN)

Rivilla et al. (2026)

First detection(s) beyond dark clouds

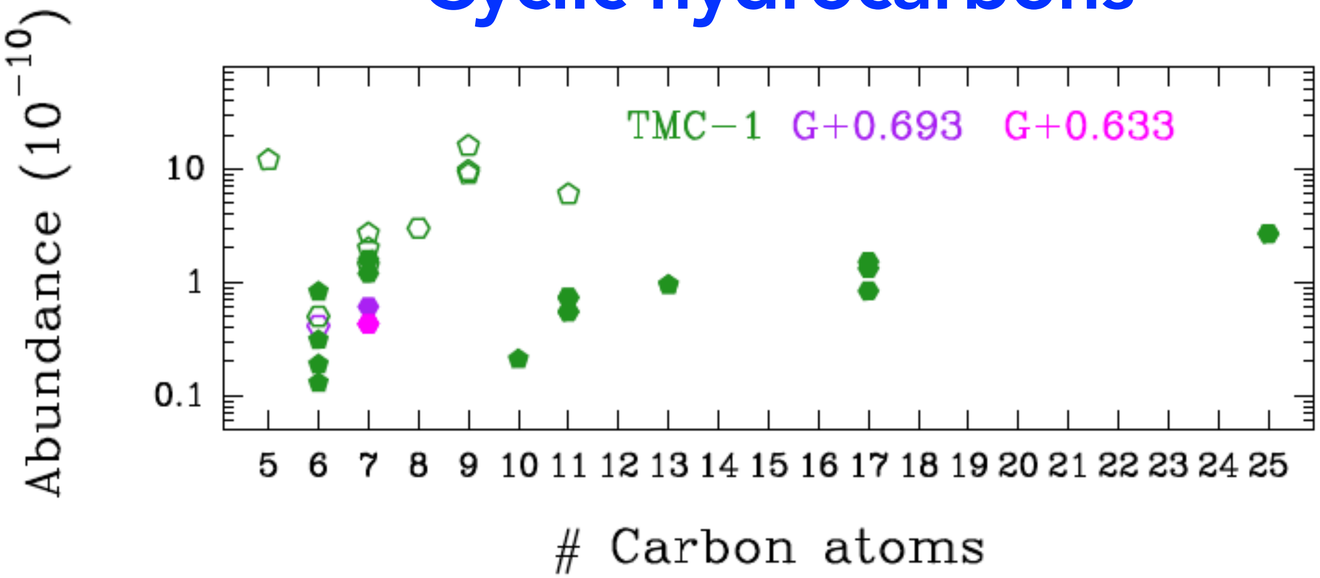


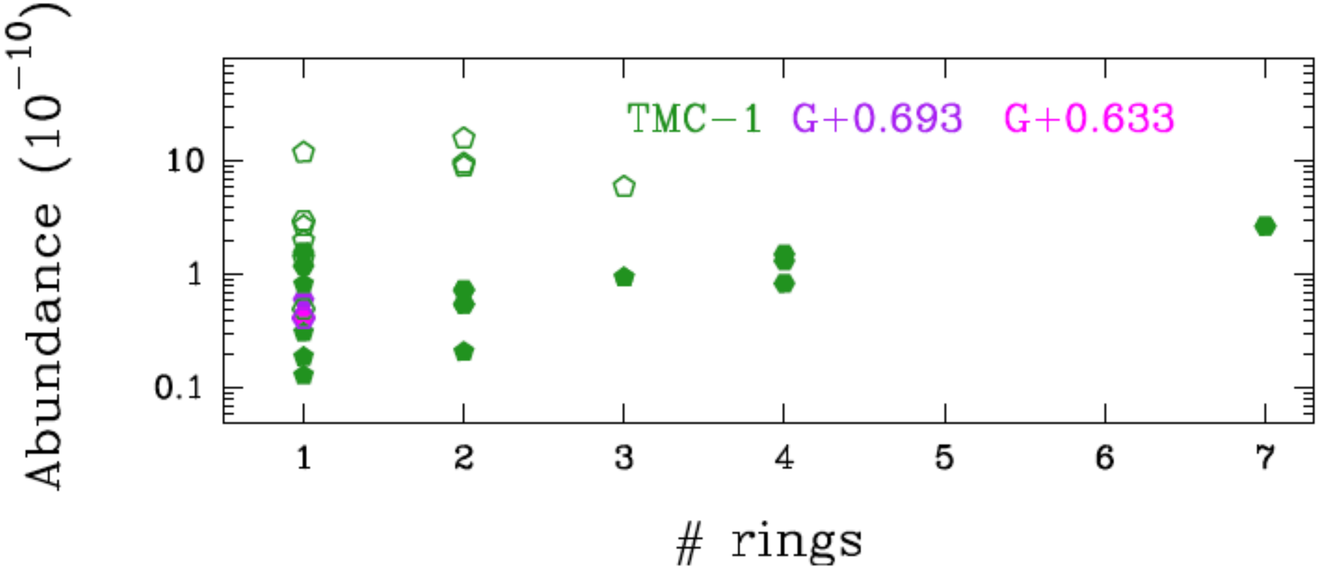
Aromatic species can survive under hard conditions



Wenzel et al. (2024, 2025), Rivilla et al. (2026)

Cyclic hydrocarbons





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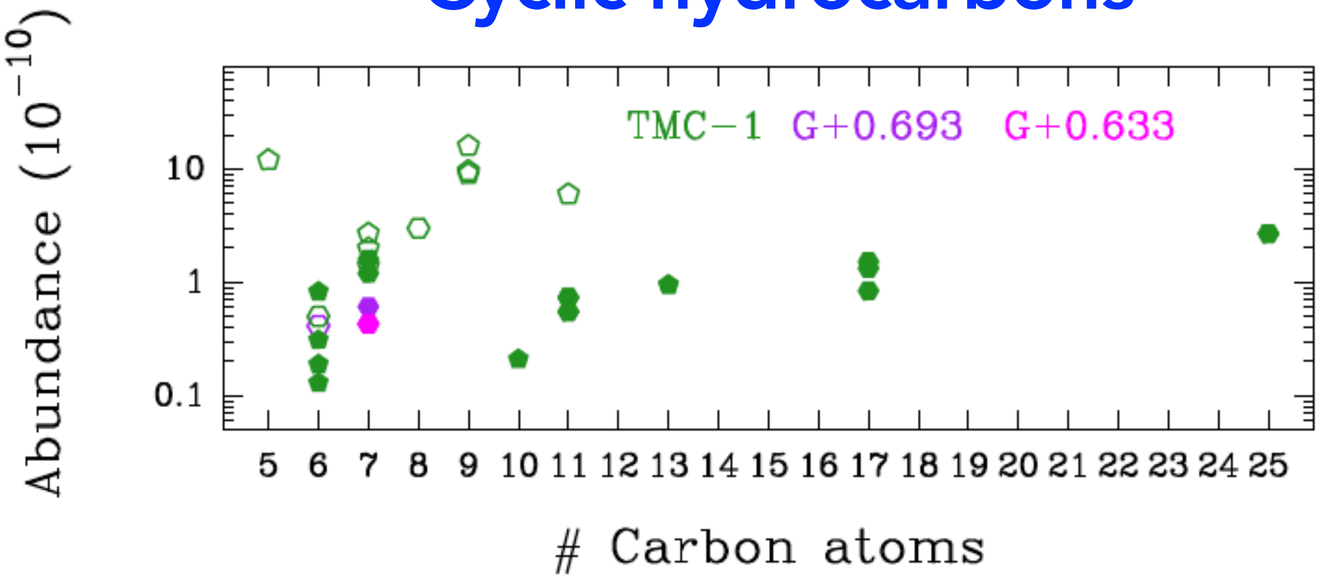
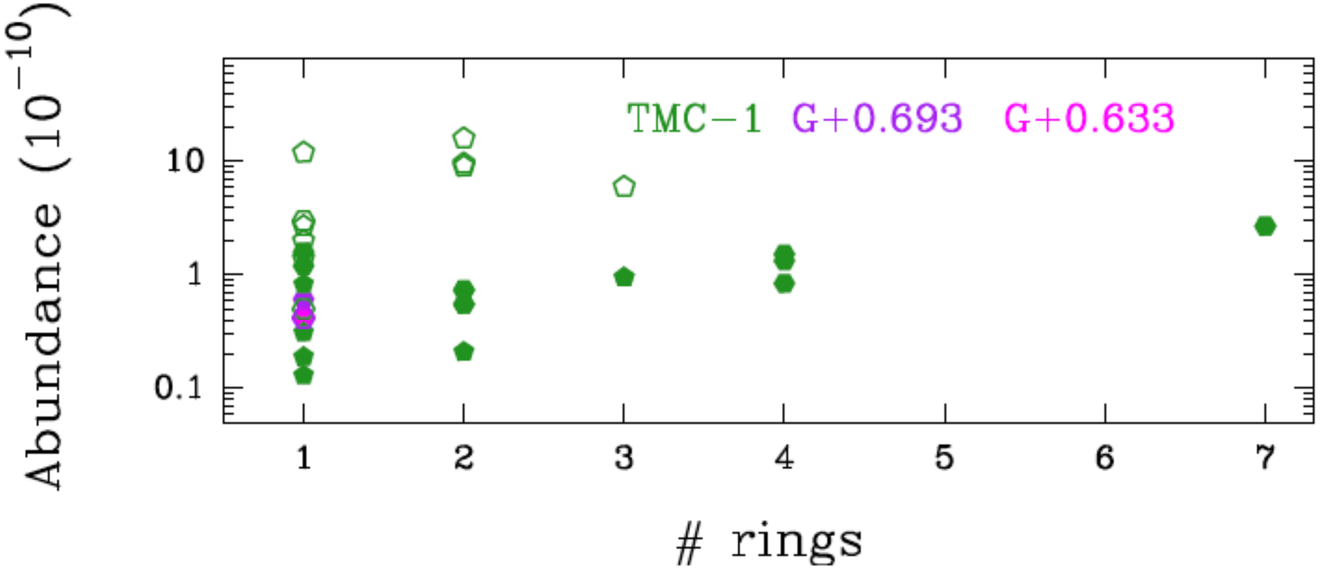
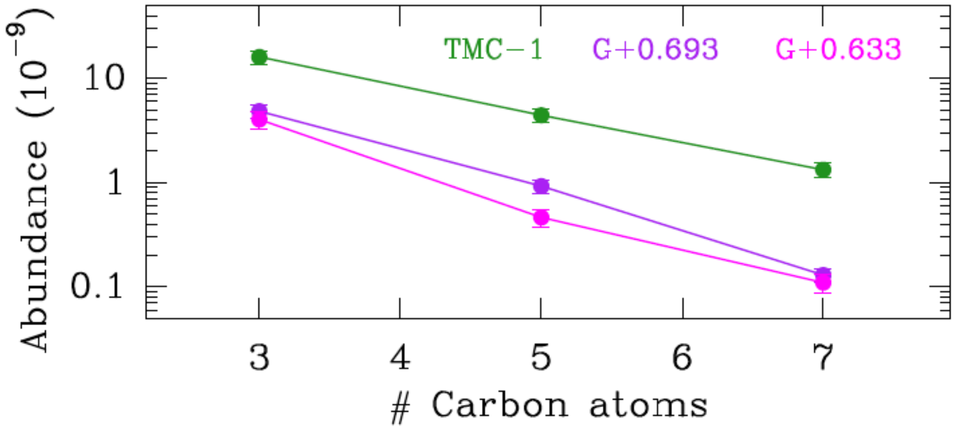


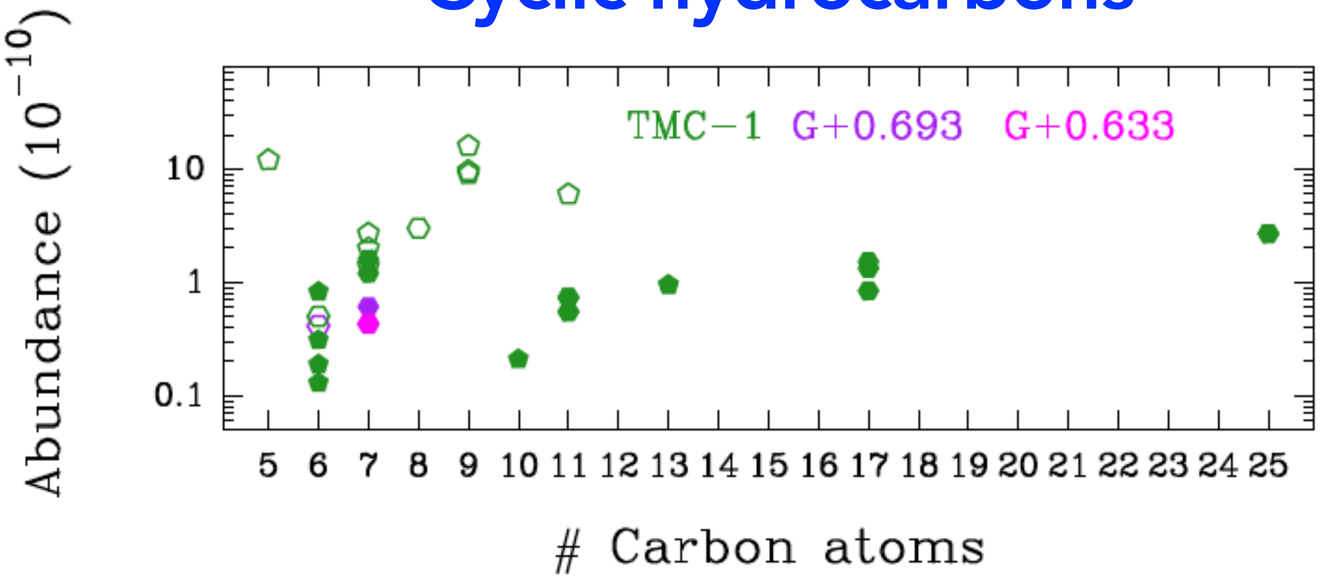


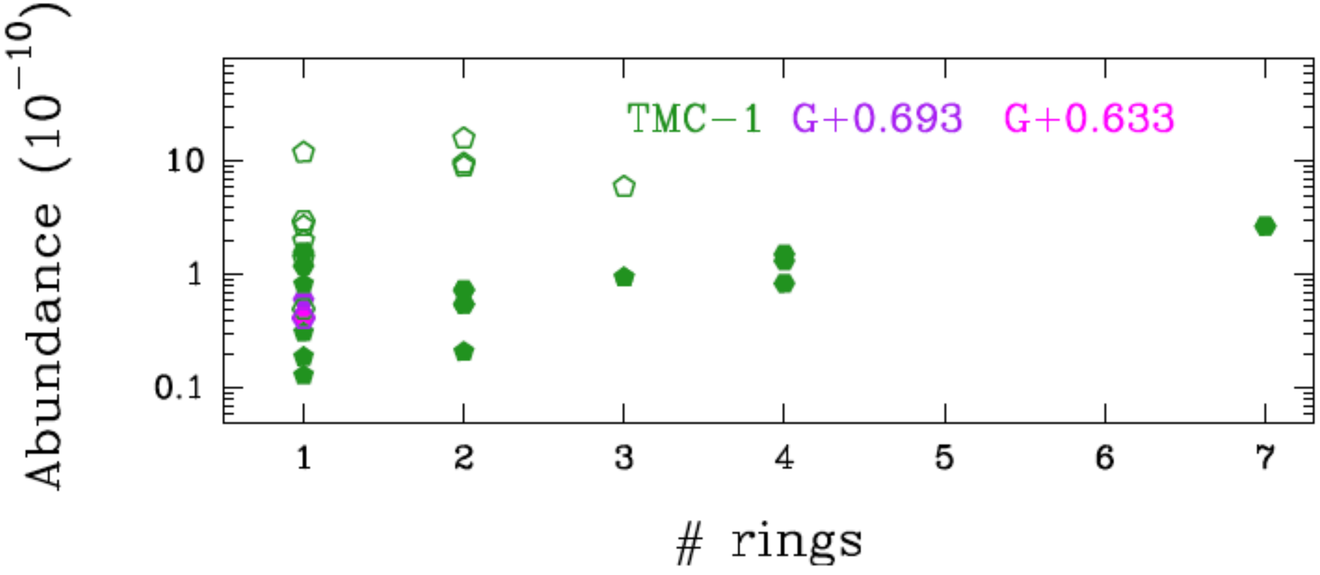
Cyanopolyynes HC_nN



Wenzel et al. (2024, 2025), Rivilla et al. (2026)

Cyclic hydrocarbons





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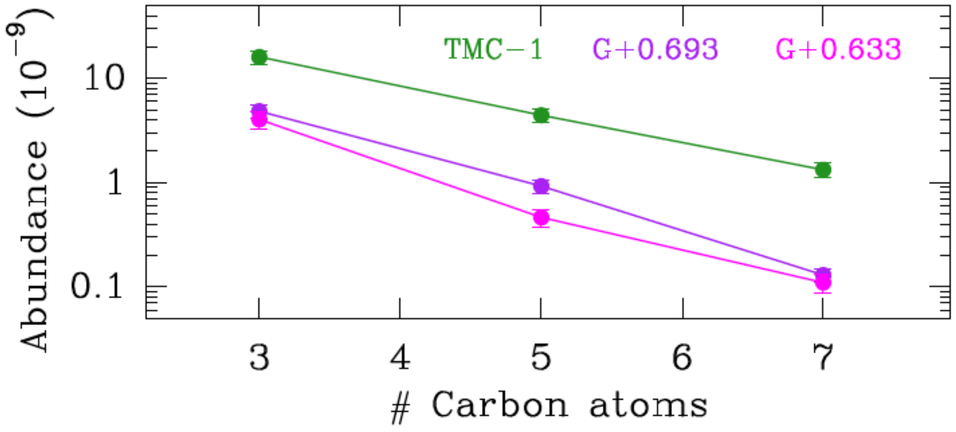
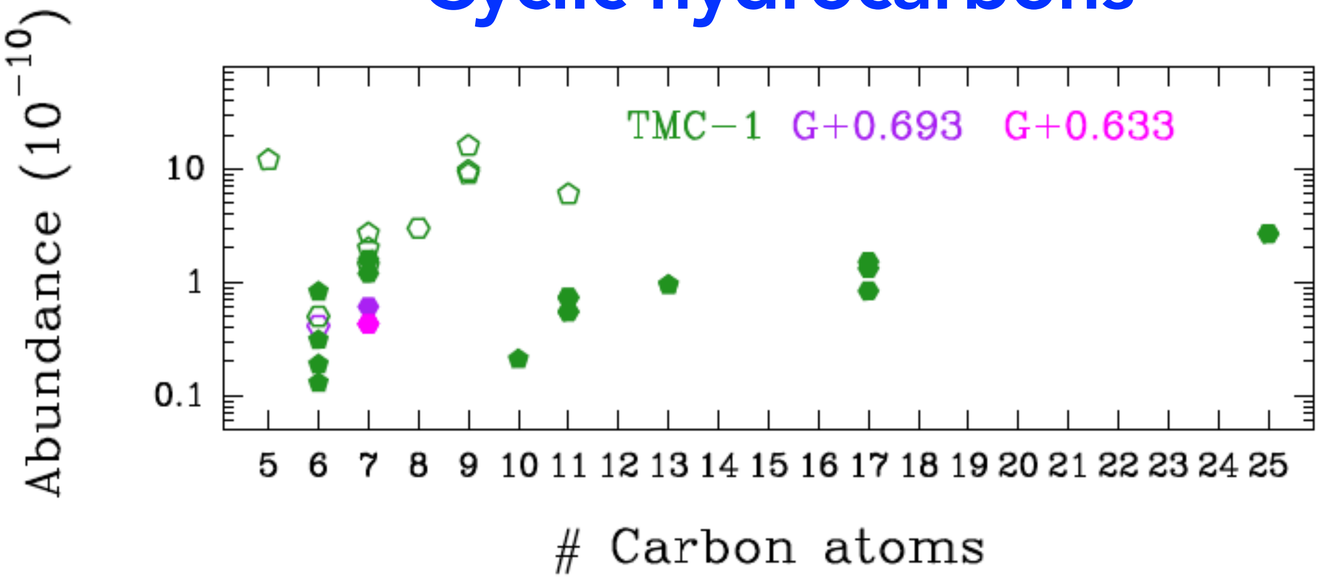
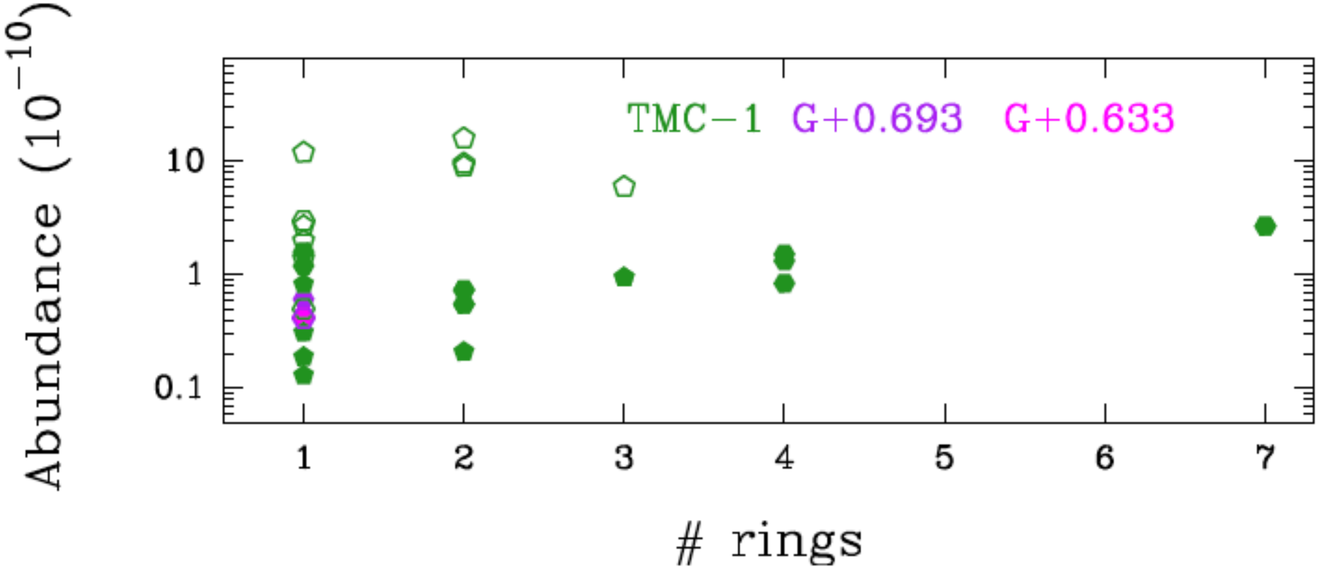


Top-down formation

Wenzel et al. (2024, 2025), Rivilla et al. (2026)

Cyclic hydrocarbons





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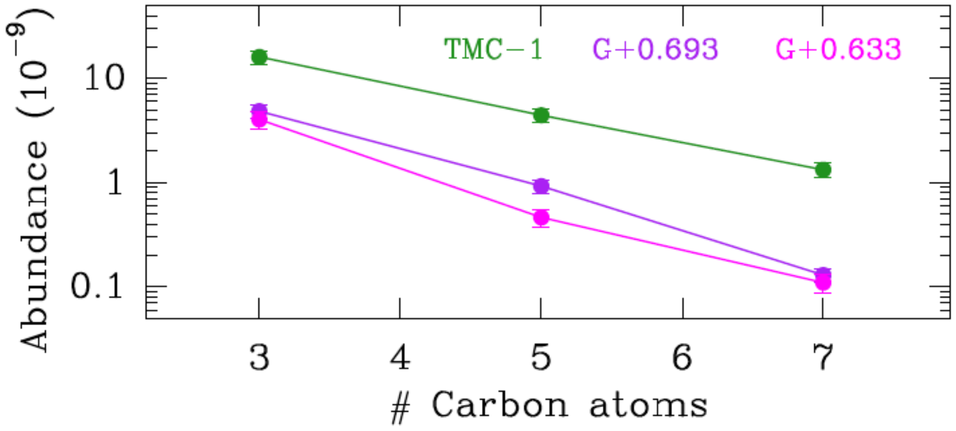


Top-down formation

PAHs can account for a significant fraction of the total C interstellar budget

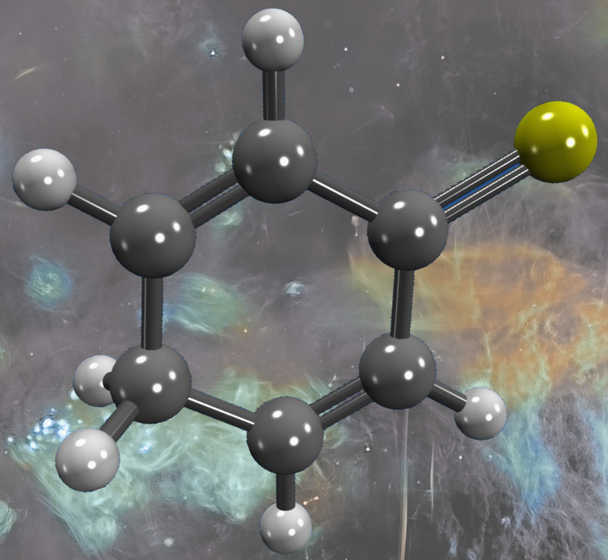
More *complex** rings?

Rings in the Galactic Center

2,5-cyclohexadien-1-thione (c-C_6H_6S)

Araki, Sanz-Novo et al. (2026), Nat. Astro.

First detection in the ISM



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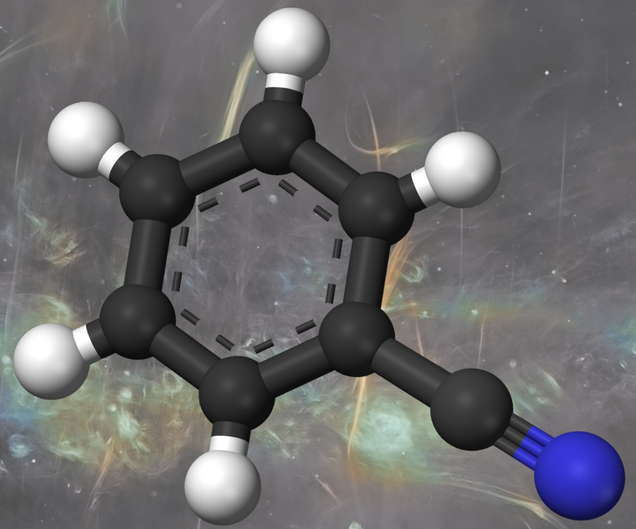
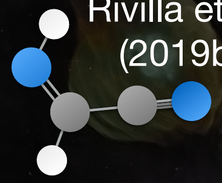


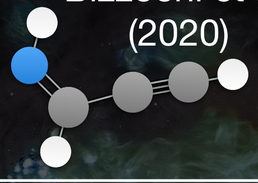
New interstellar species discovered by our group including species with the 6 key chemical elements for life:

(H, C, O, N, S y P) + Si + Mg + Na

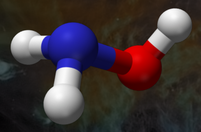
Z-cyanomethanimine
Rivilla et al. (2019b)



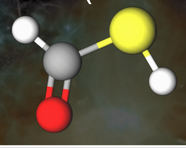
Propargylimine
Bizzochi et al. (2020)



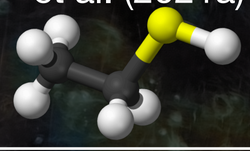
Hydroxylamine
Rivilla et al. (2020c)



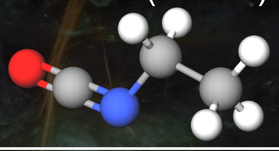
Thioformic acid
Rodríguez-Almeida et al. (2021a)



Ethyl mercaptan
Rodríguez-Almeida et al. (2021a)

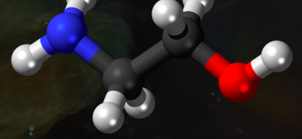


Ethyl isocyanate
Rodríguez-Almeida et al. (2021b)

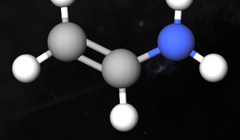


Cyanomidyl
Rivilla et al. (2021b)

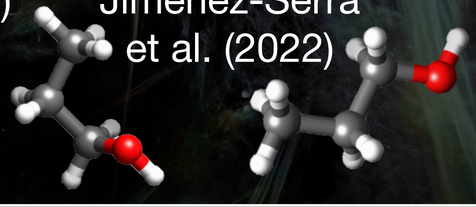
Ethanolamine
Rivilla et al. (2021a)



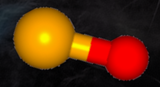
Vinyl amine
Zeng et al. (2021)



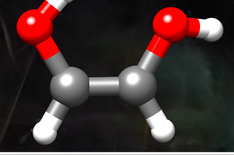
n-propanol
Jiménez-Serra et al. (2022)



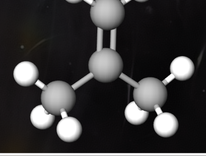
Phosphorus oxide cation
Rivilla et al. (2022b)



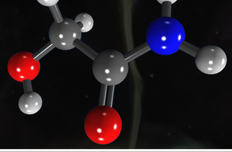
Z-1,2-ethenediol
Rivilla et al. (2022a)



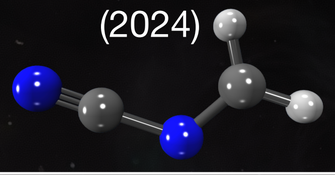
Isobutene
Fatima et al. (2023)



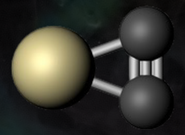
Glycolamide
Rivilla et al. (2023)



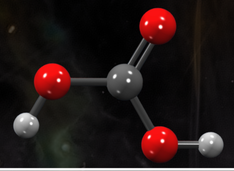
N-cyanomethanimine
San Andrés et al. (2024)



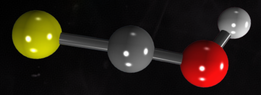
Silacyclopropynylidene
Massalkhi el al. (2023)



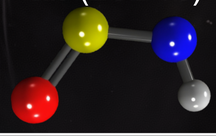
Carbonic acid
Sanz-Novo et al. (2023)



Protonated carbonyl sulphide
Sanz-Novo et al. (2024a)



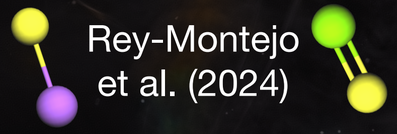
Thionylimide
Sanz-Novo et al. (2024b)



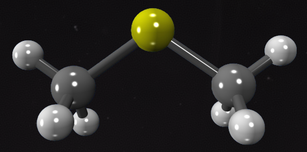
Magnesium sulfide

Sodium sulfide

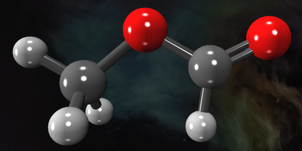
Rey-Montejo et al. (2024)



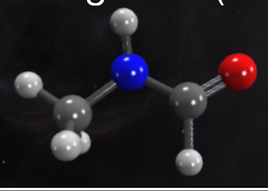
Dimethyl sulfide
Sanz-Novo et al. (2025a)



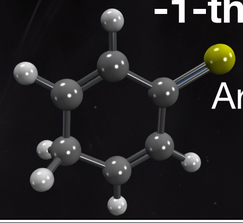
Trans methyl formate
Sanz-Novo et al. (2025b)



Cis N-methyl formamide
Zeng et al. (2025)

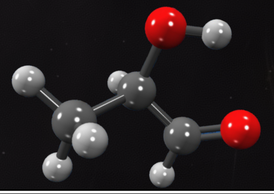


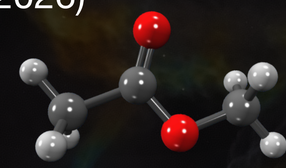
2,5-cyclohexadien -1-thione
Araki et al. (2026)



Lactaldehyde

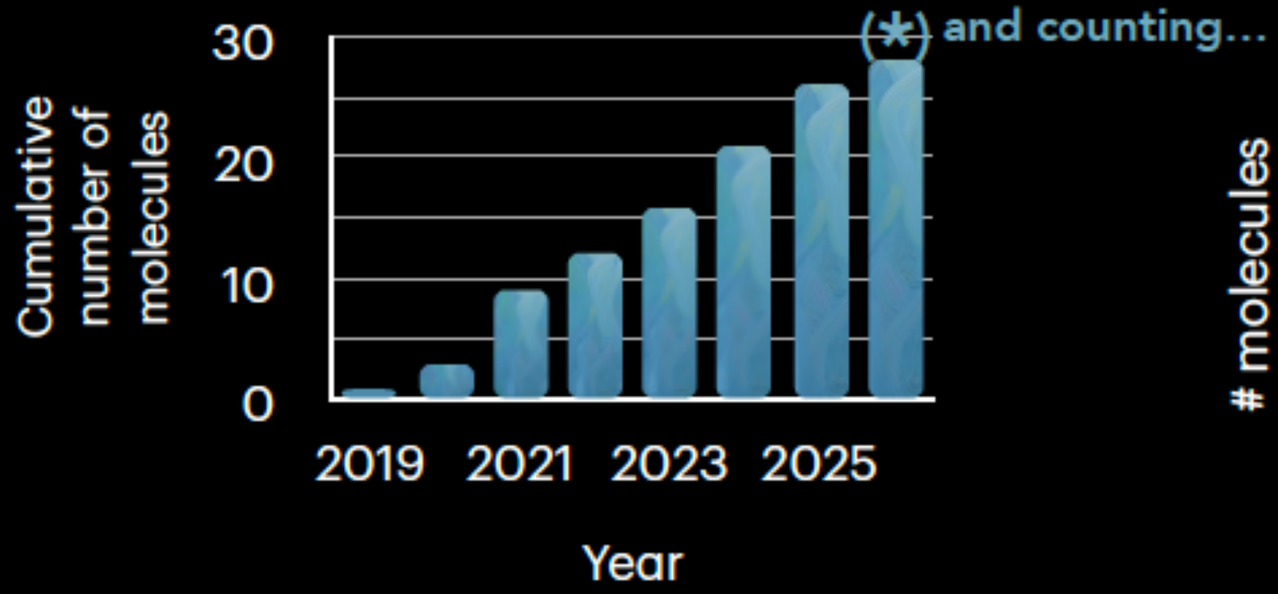
Methoxacetaldehyde
Sanz-Novo et al. (2026)

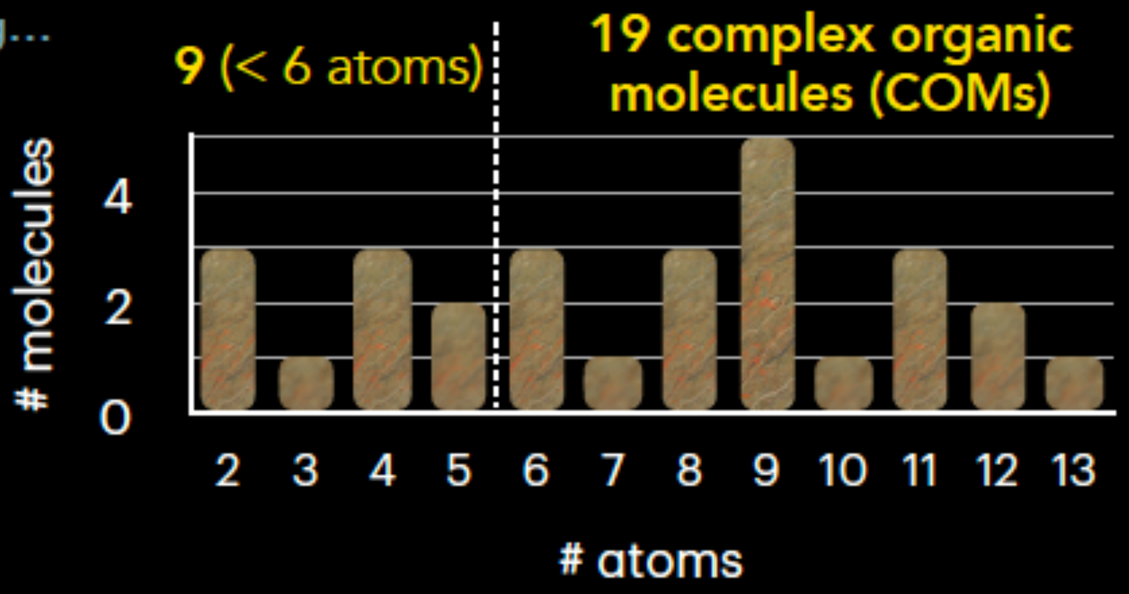




28 new interstellar species discovered towards the G+0.693-0.027 molecular cloud, including species with the 6 key chemical elements for life:

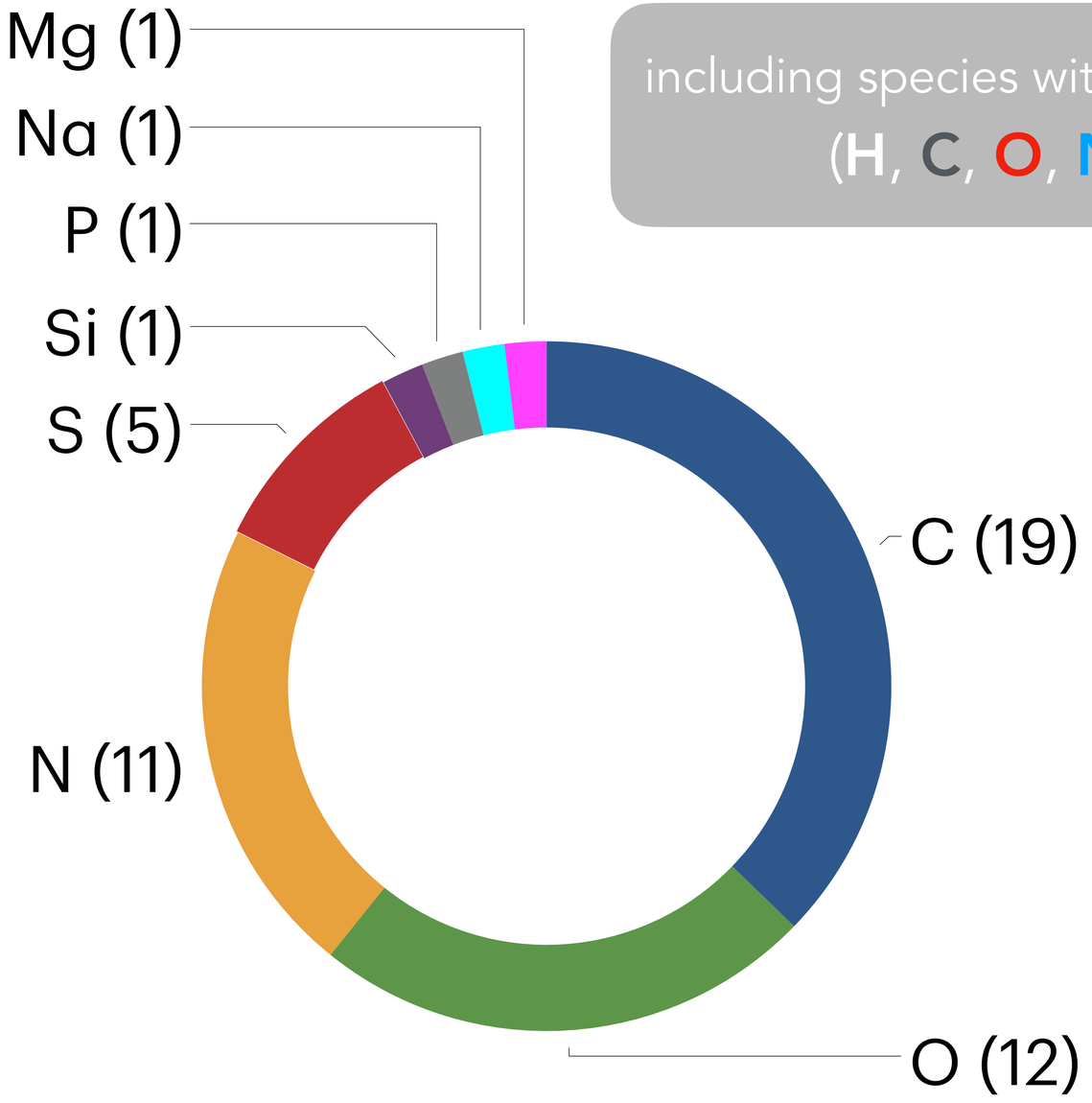
(H, C, O, N, S y P) + Si + Mg + Na

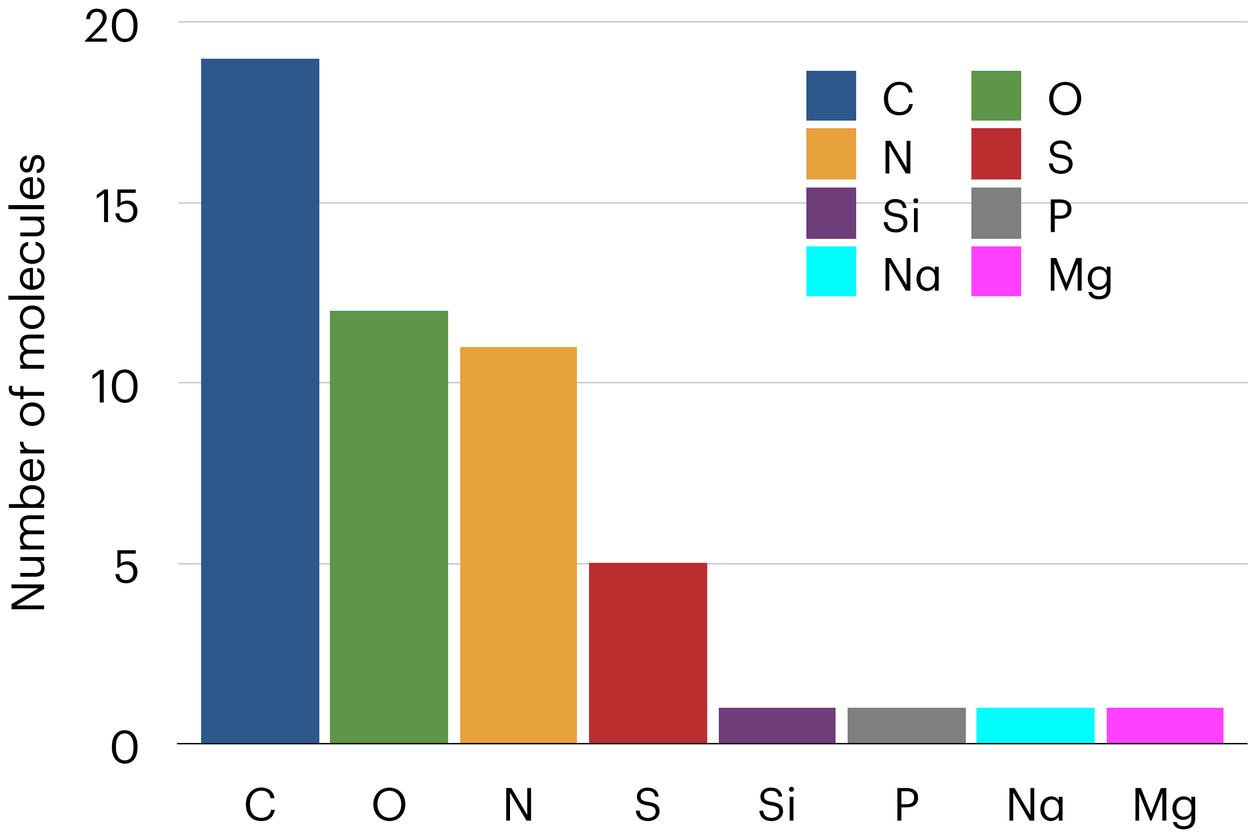




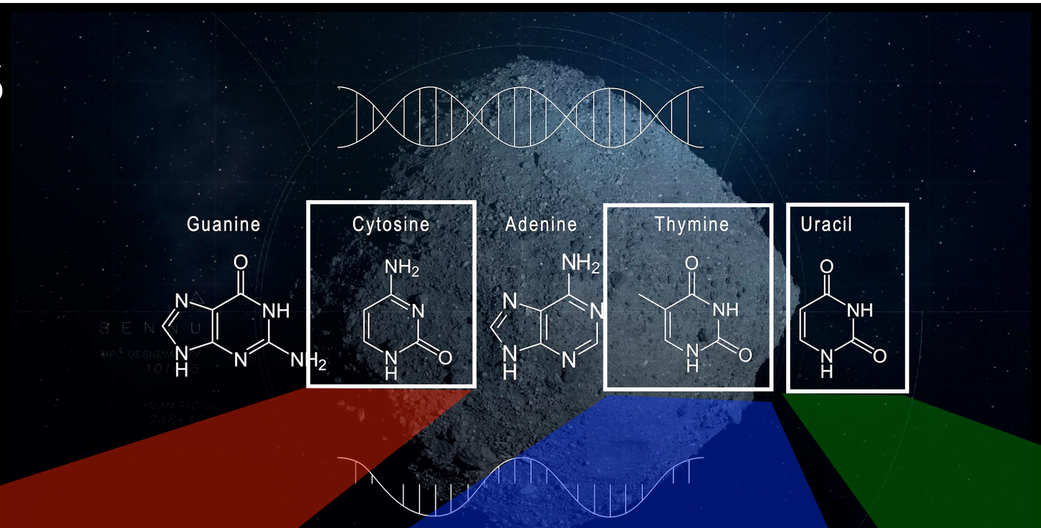
New detections in G+0.693

including species with the 6 key chemical elements for life:
(H, C, O, N, S y P) + Si + Mg + Na



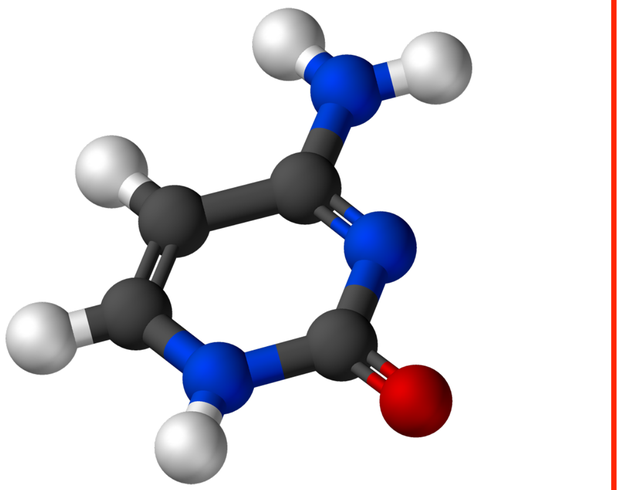


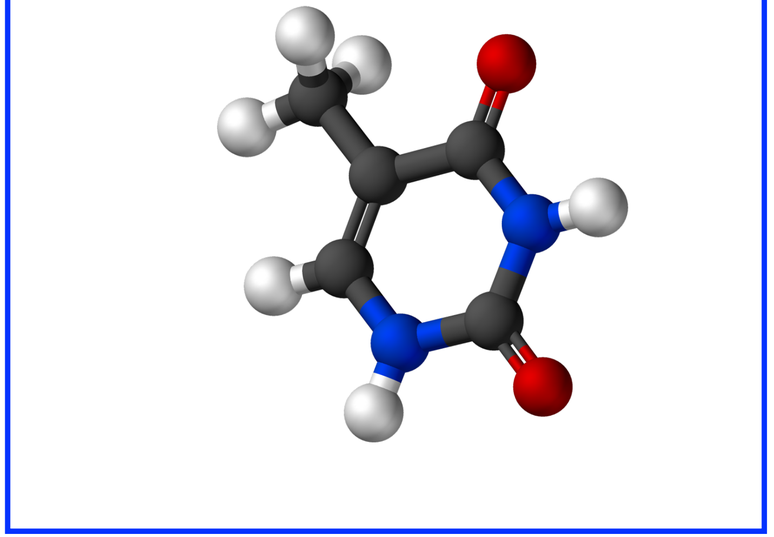
Heterocyclic rings

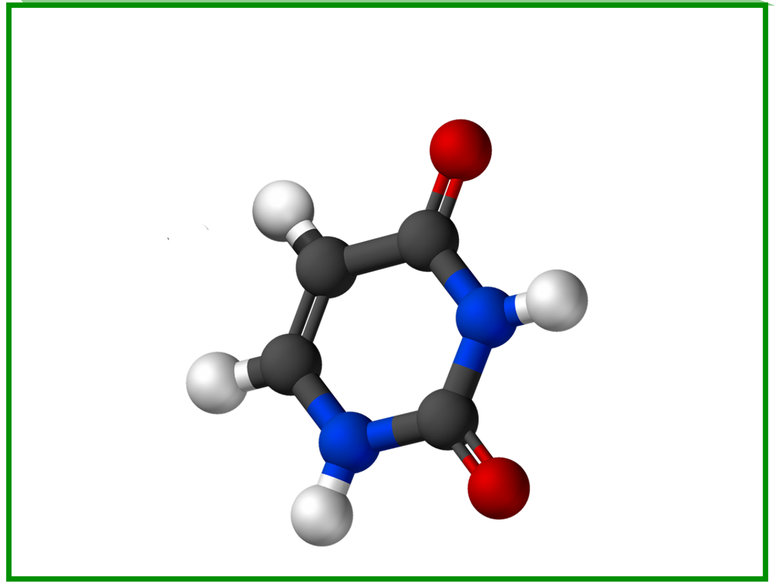


Bennu asteroid

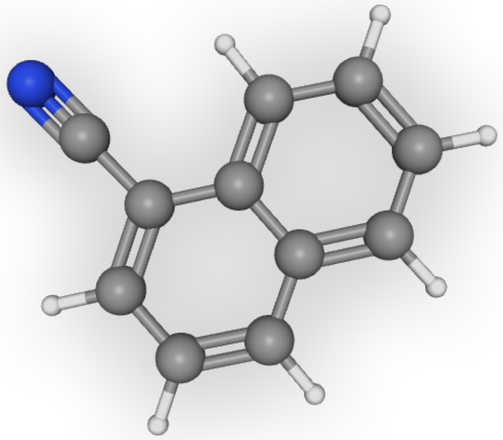
Glavin et al. (2025)

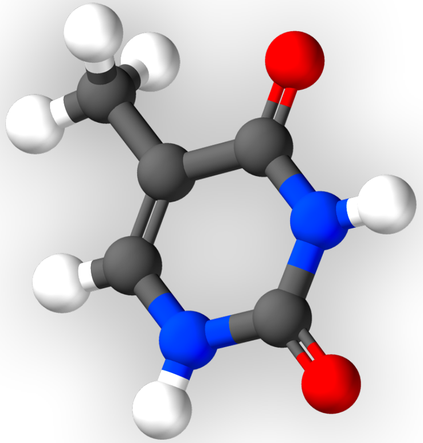


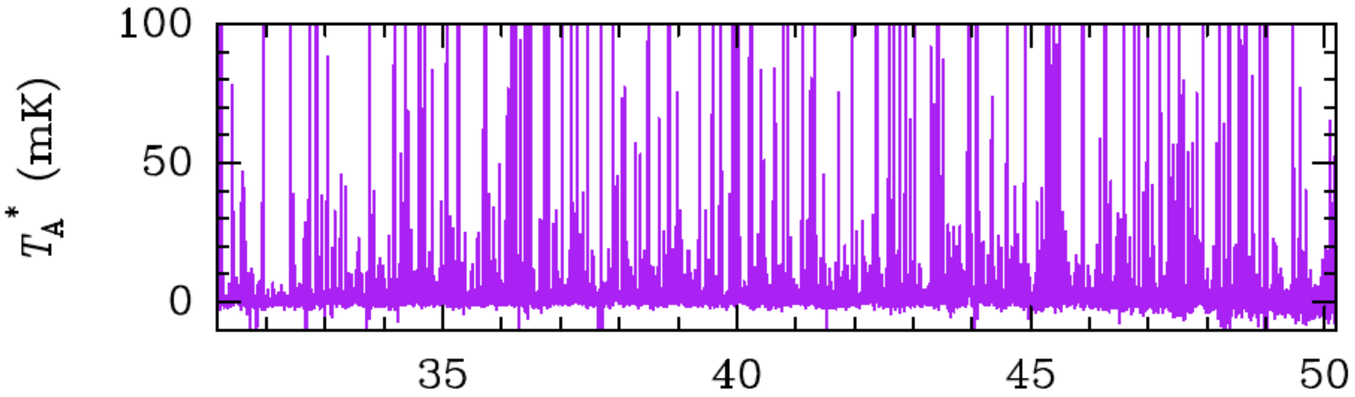




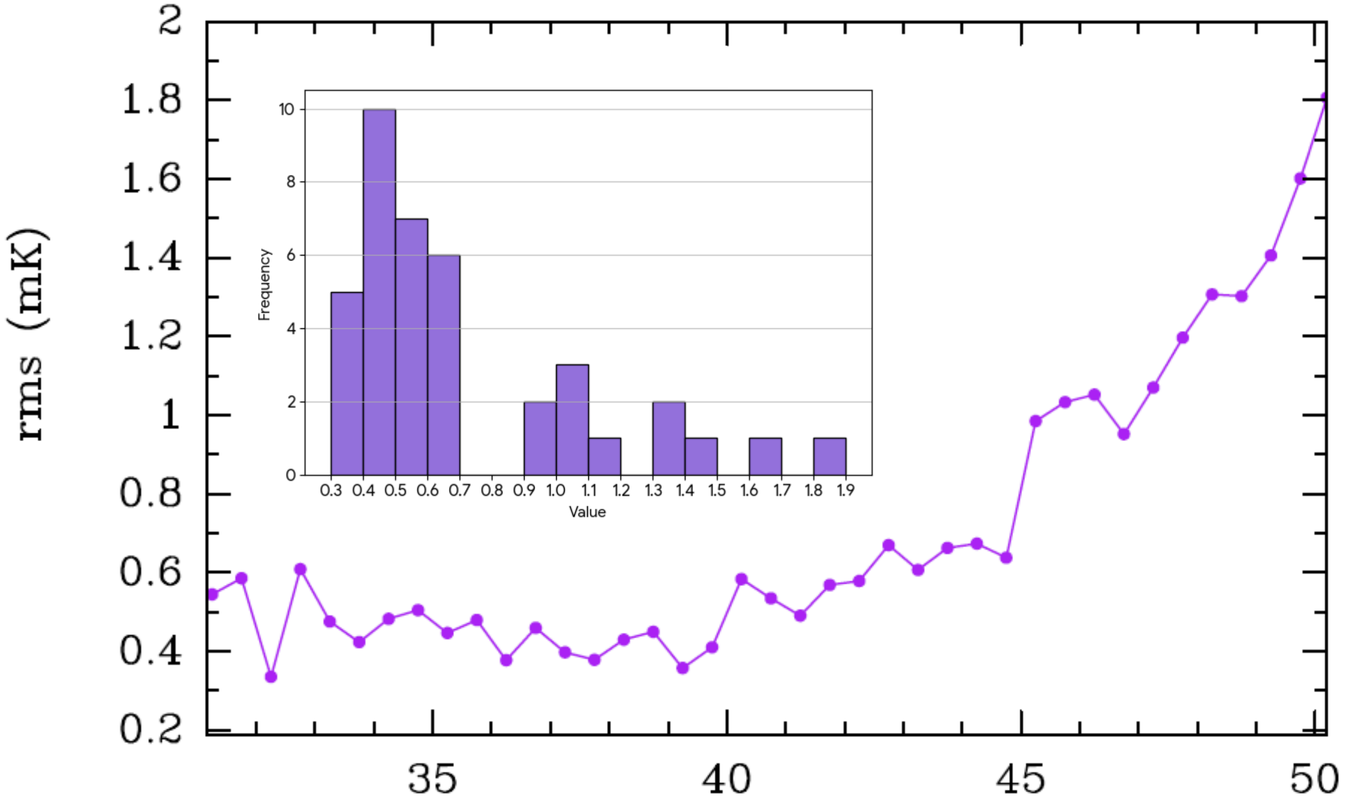
How to unveil these new rings?

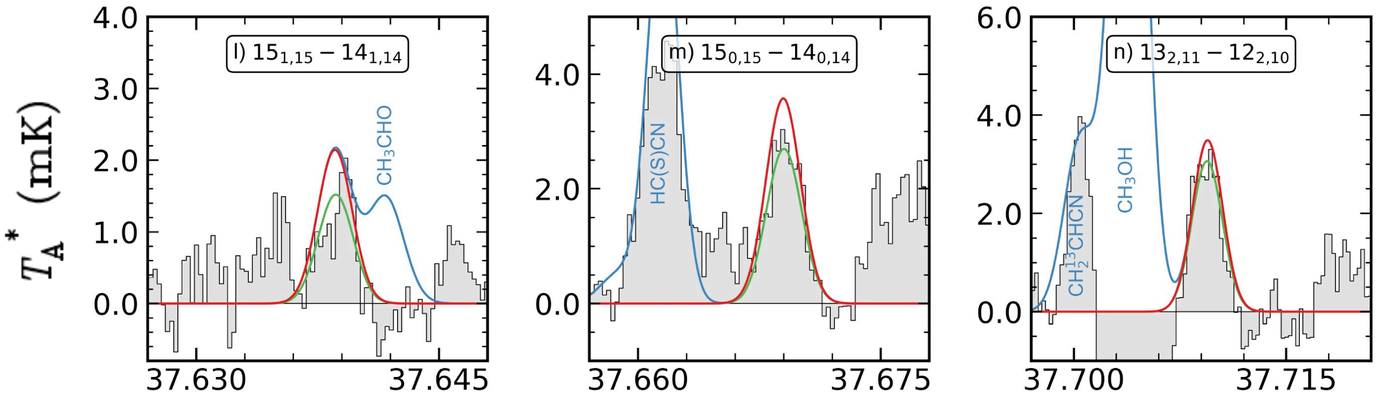




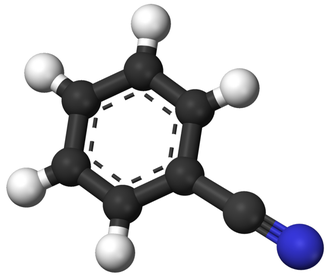


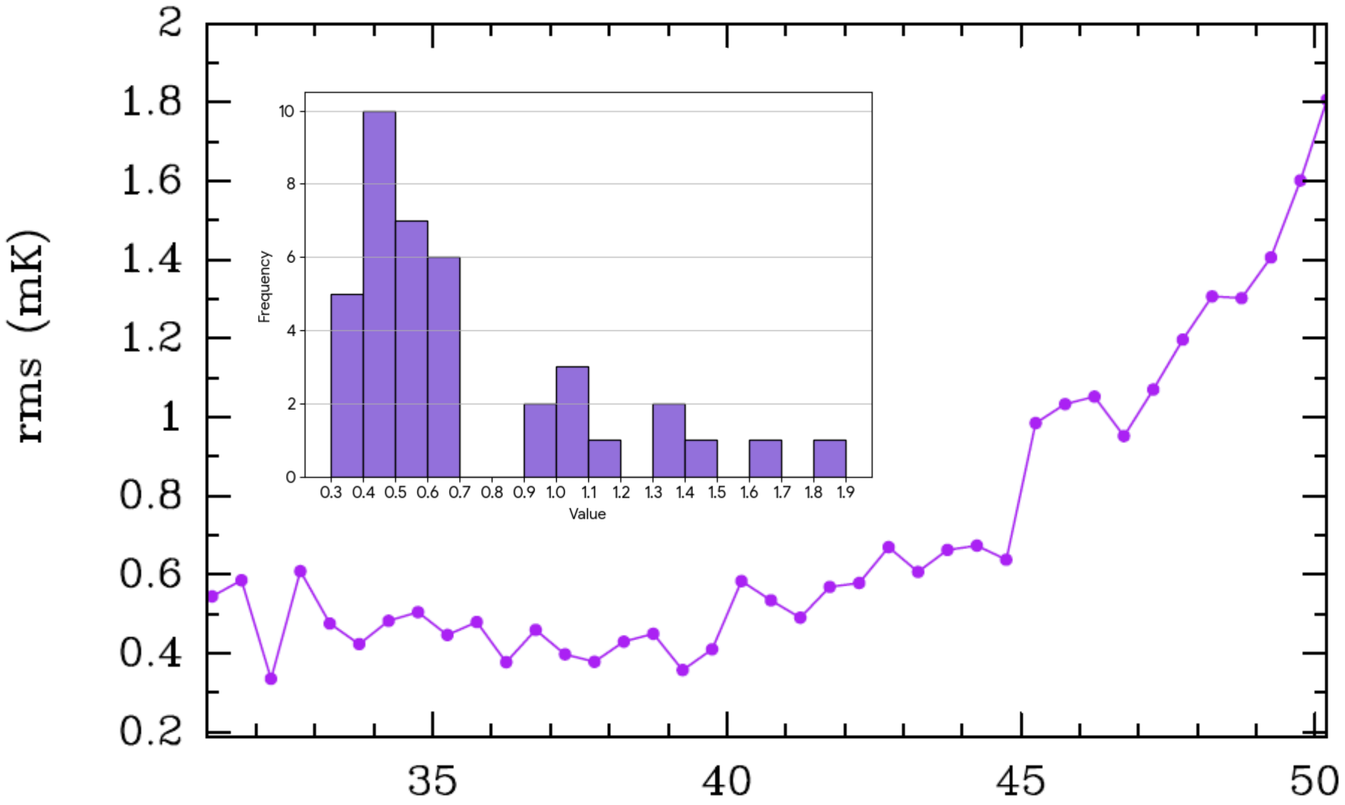
G+0.693-0.027
Yebes Q-band survey

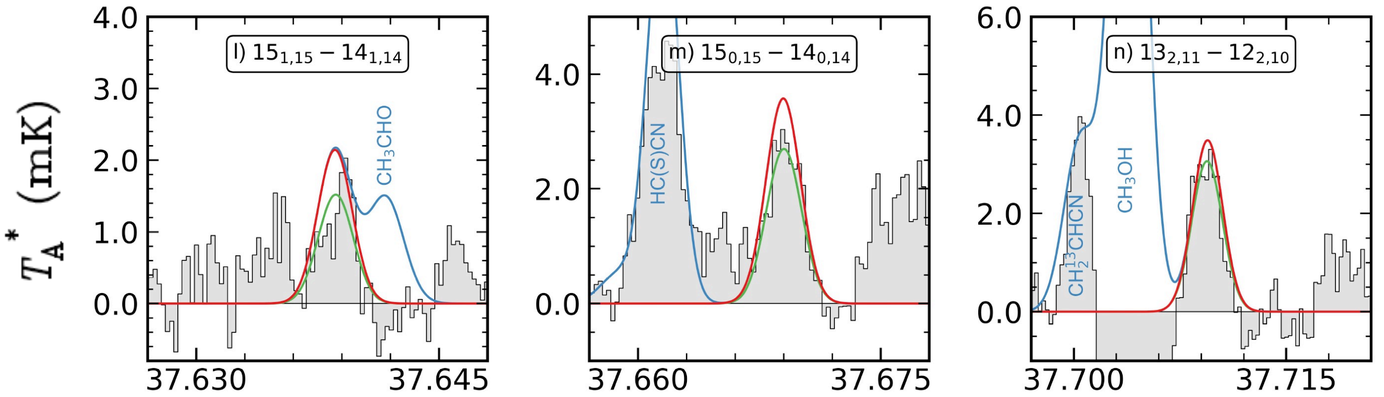




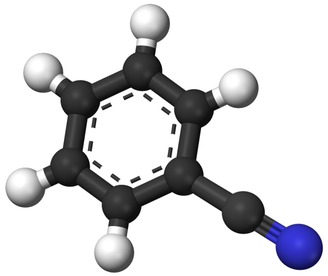
G+0.693-0.027
Yebes Q-band survey

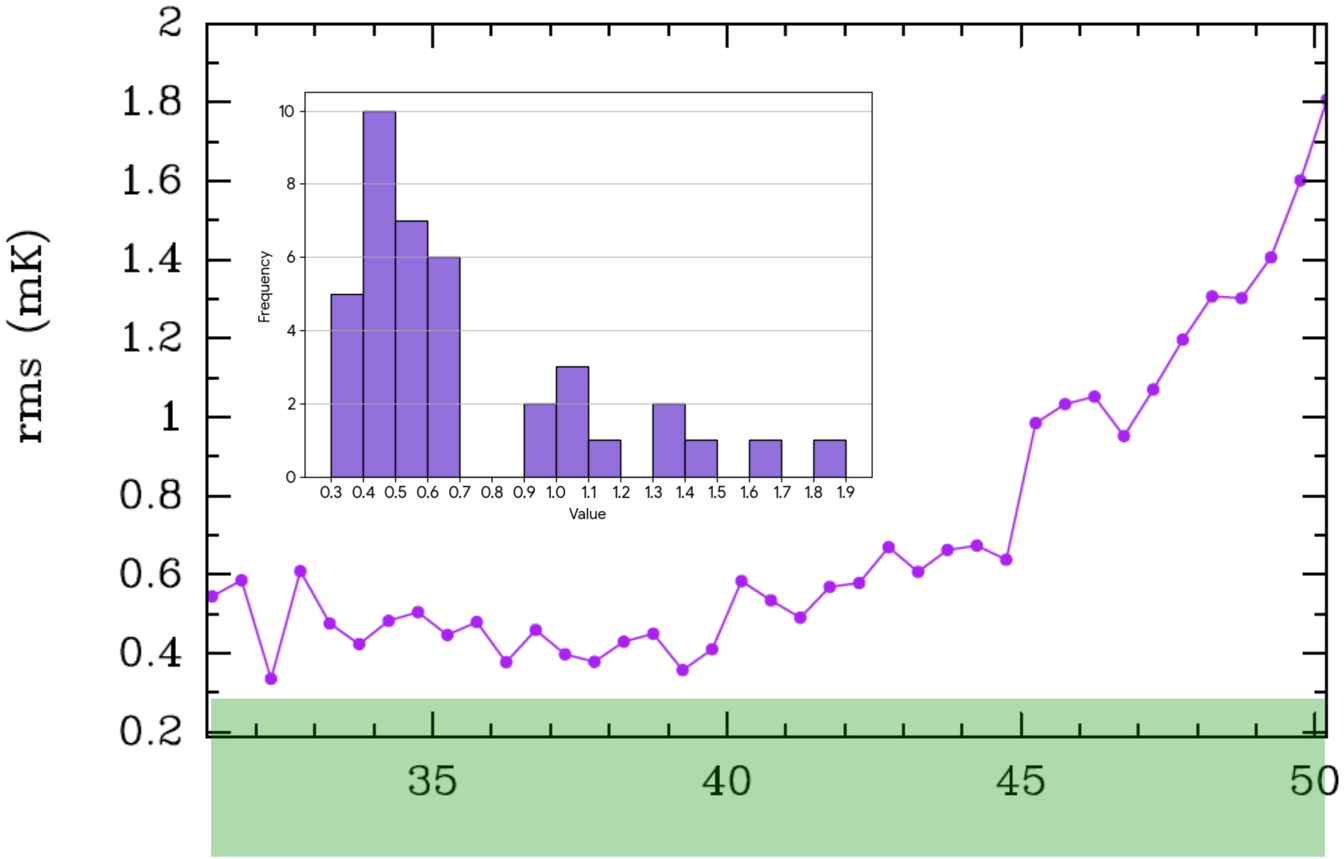






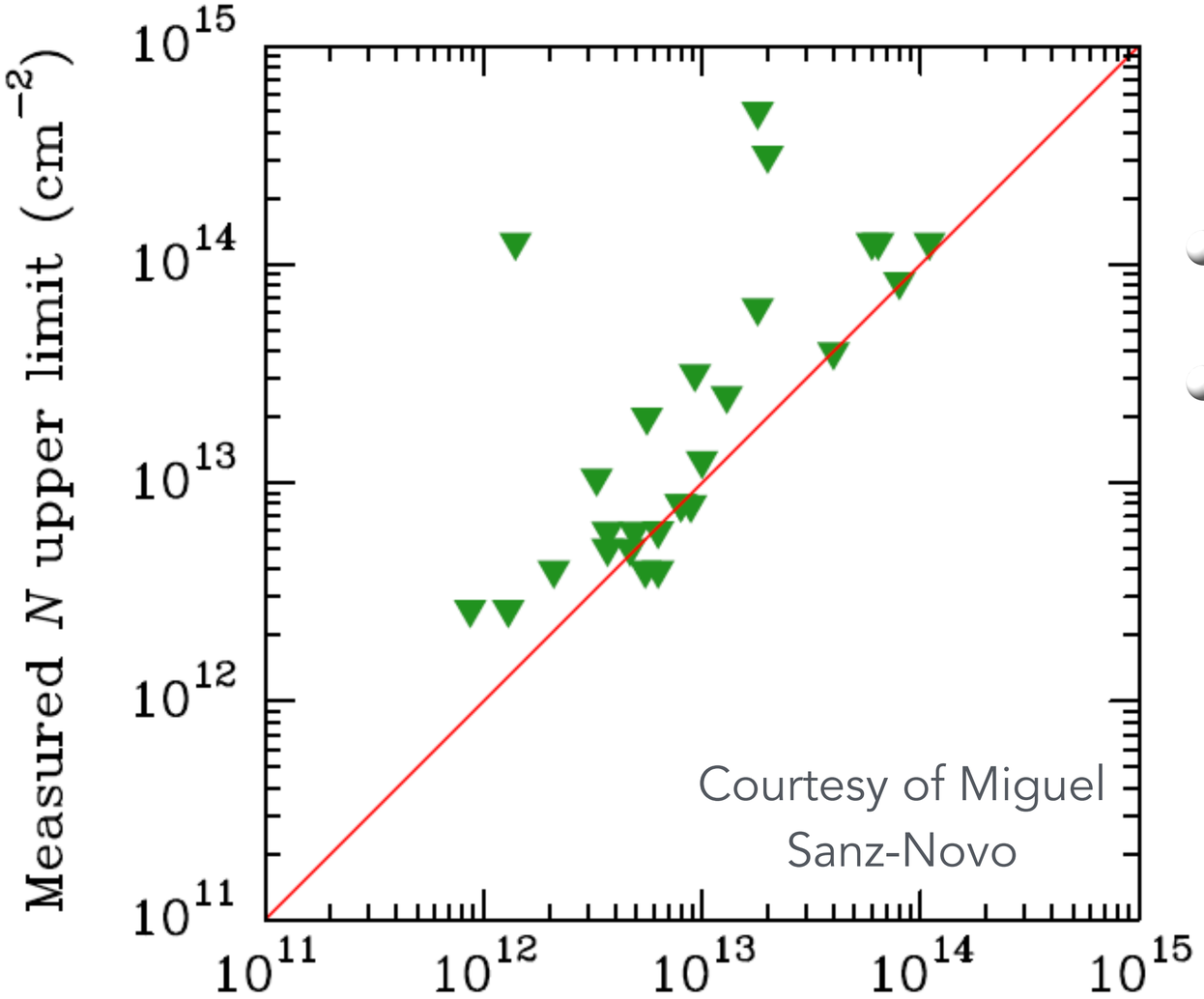
G+0.693-0.027
Yebes Q-band survey

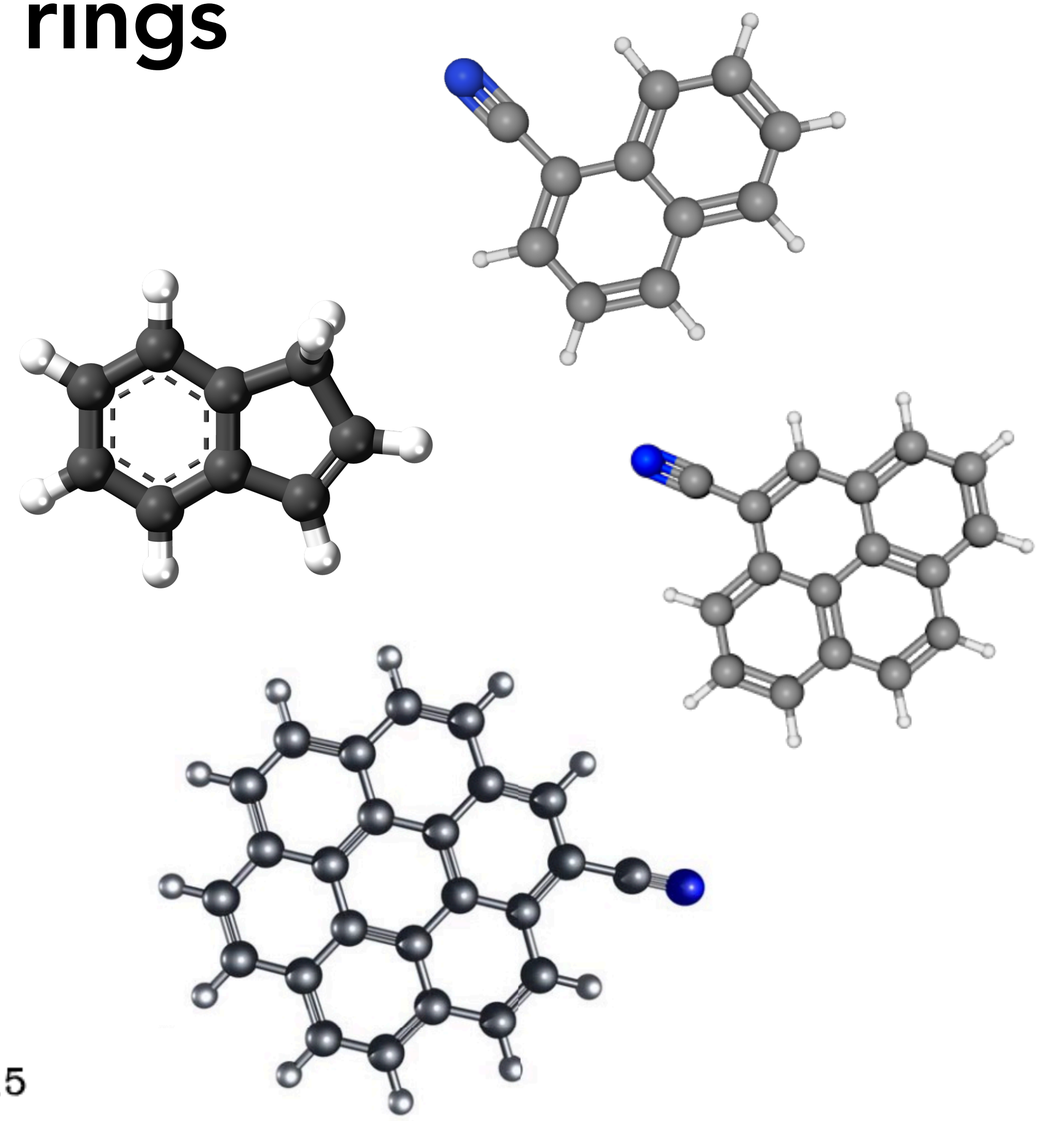




< 0.3 mK

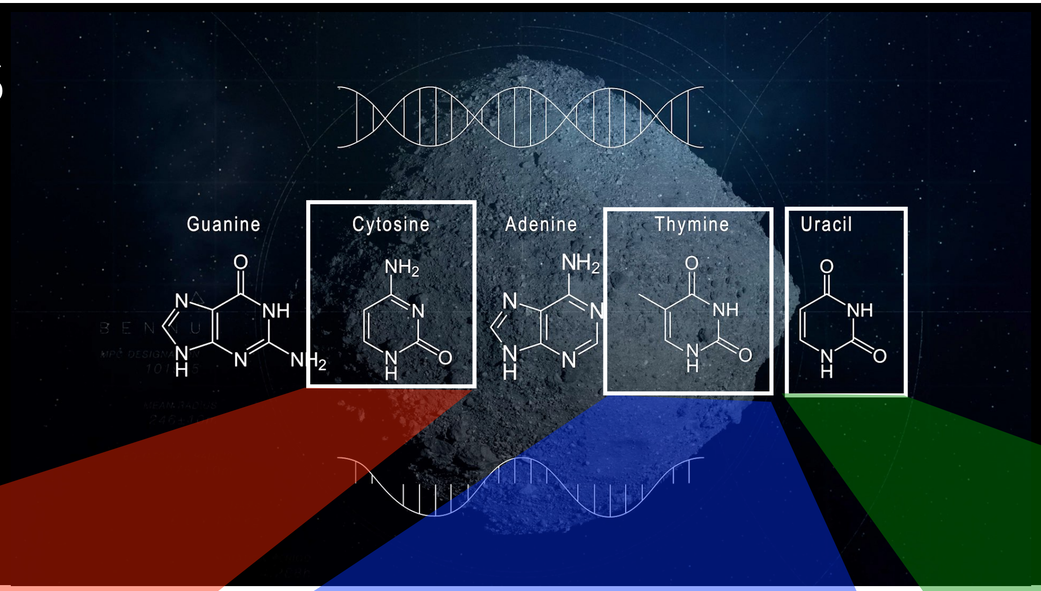
Carbon-based rings





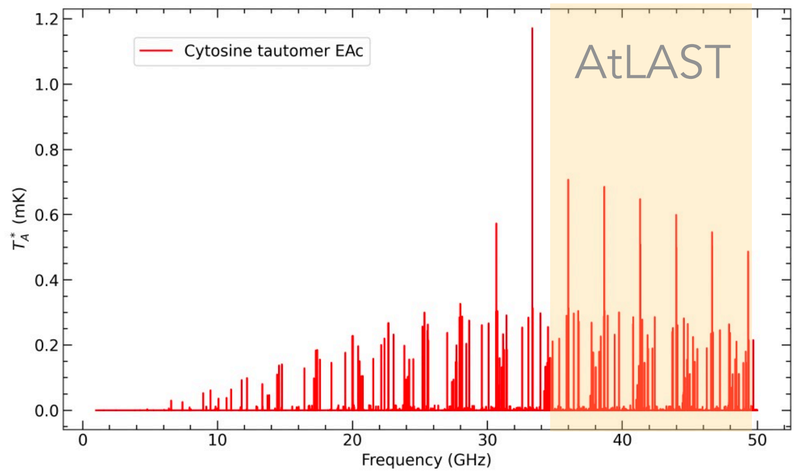
(assuming the same $N_i/N_{benzonitrile}$ than in TMC-1)

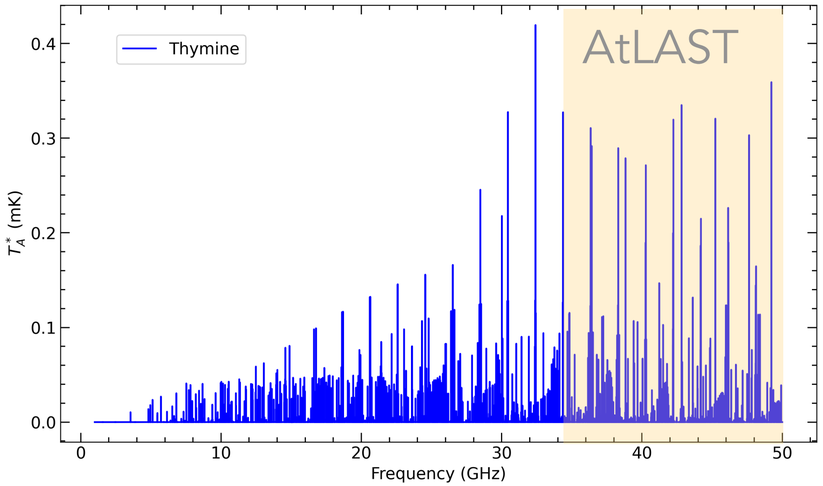
Heterocyclic rings

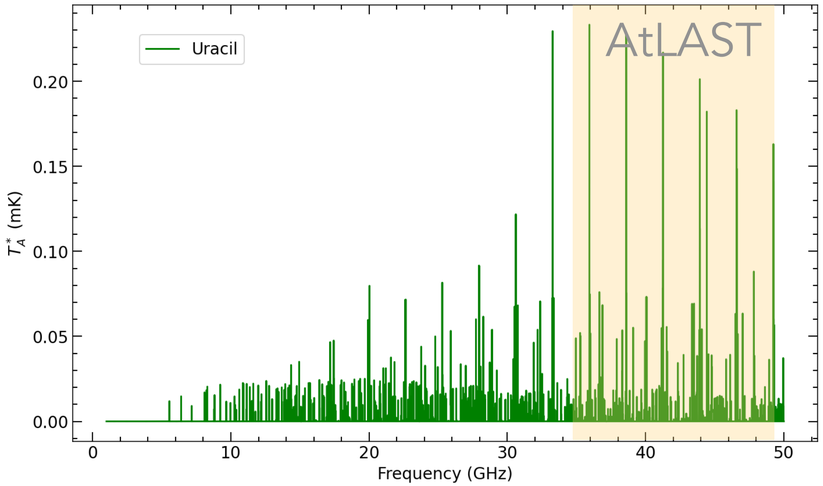


Bennu asteroid

Glavin et al. (2025)





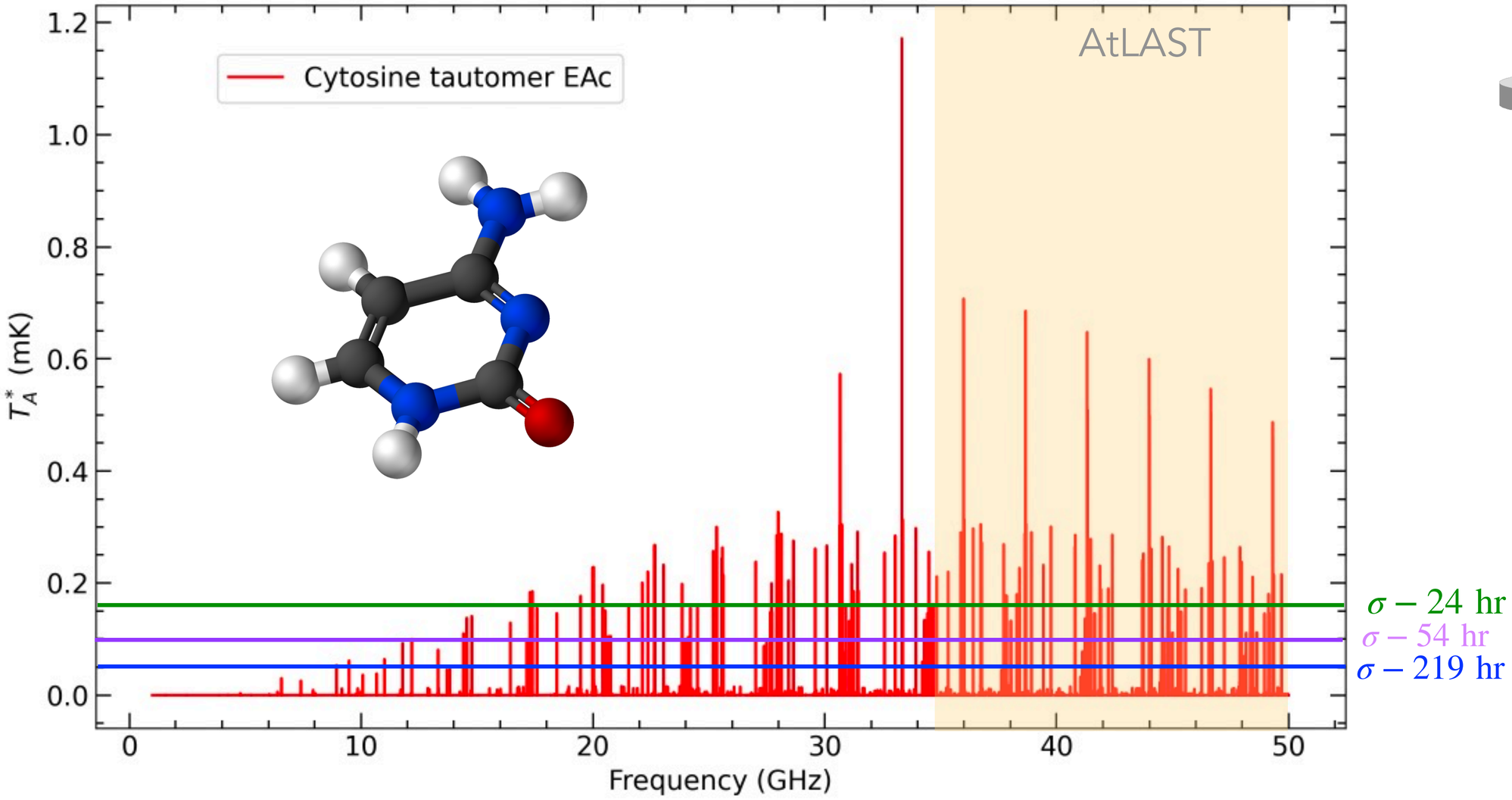


LTE simulations @ 10 K

(Courtesy of Miguel Sanz-Novo)

$N = 10^{12}\ cm^{-2};\ X = 7.5 \times 10^{-12};\ FWHM = 20$ km s^{-1}

($\nu = 40$ GHz; 60°)



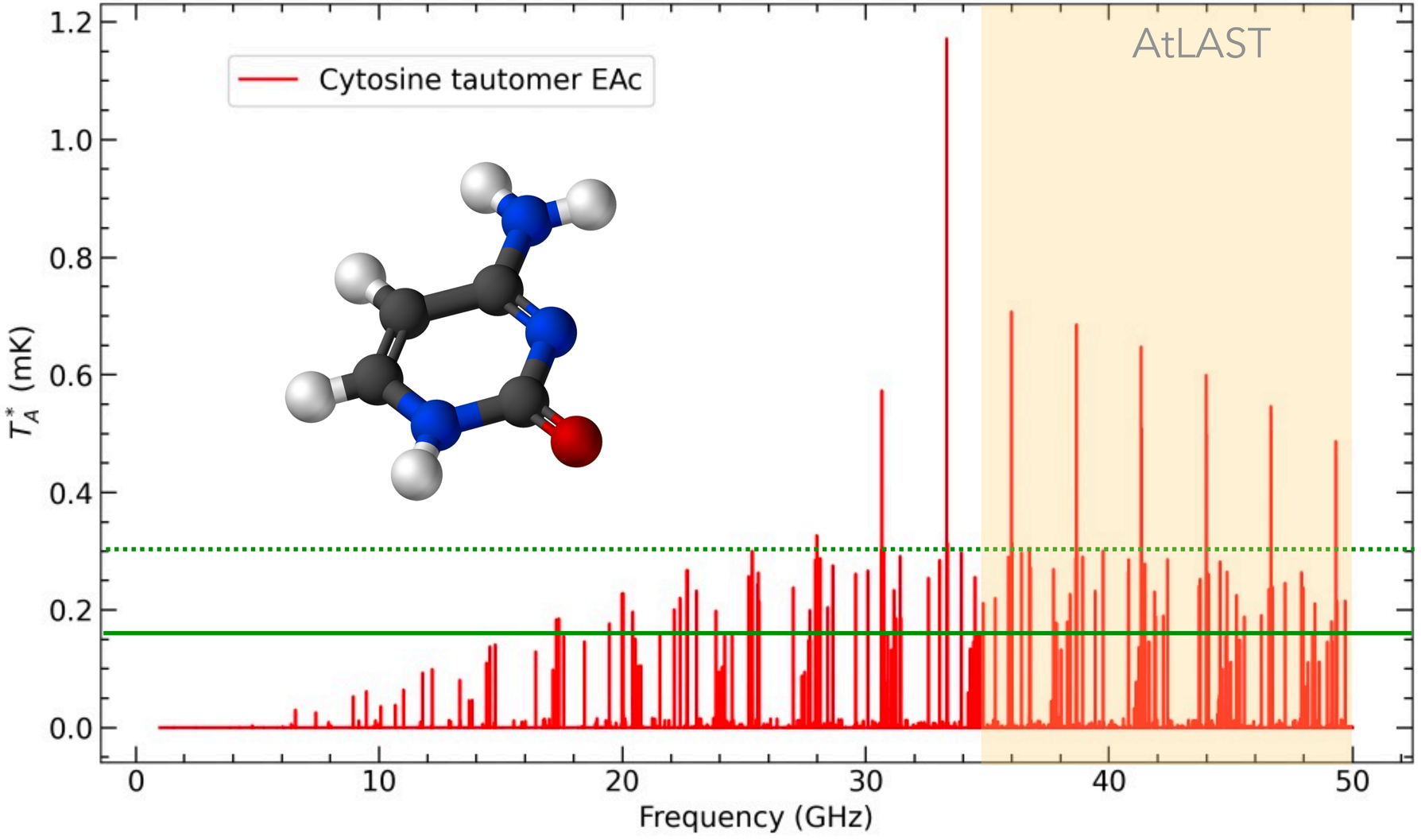
$\sigma - 24$ hr

$\sigma - 54$ hr

$\sigma - 219$ hr

$N = 10^{12}\ cm^{-2};\ X = 7.5 \times 10^{-12};\ FWHM = 20$ km s^{-1}

($\nu = 40$ GHz; 60°)

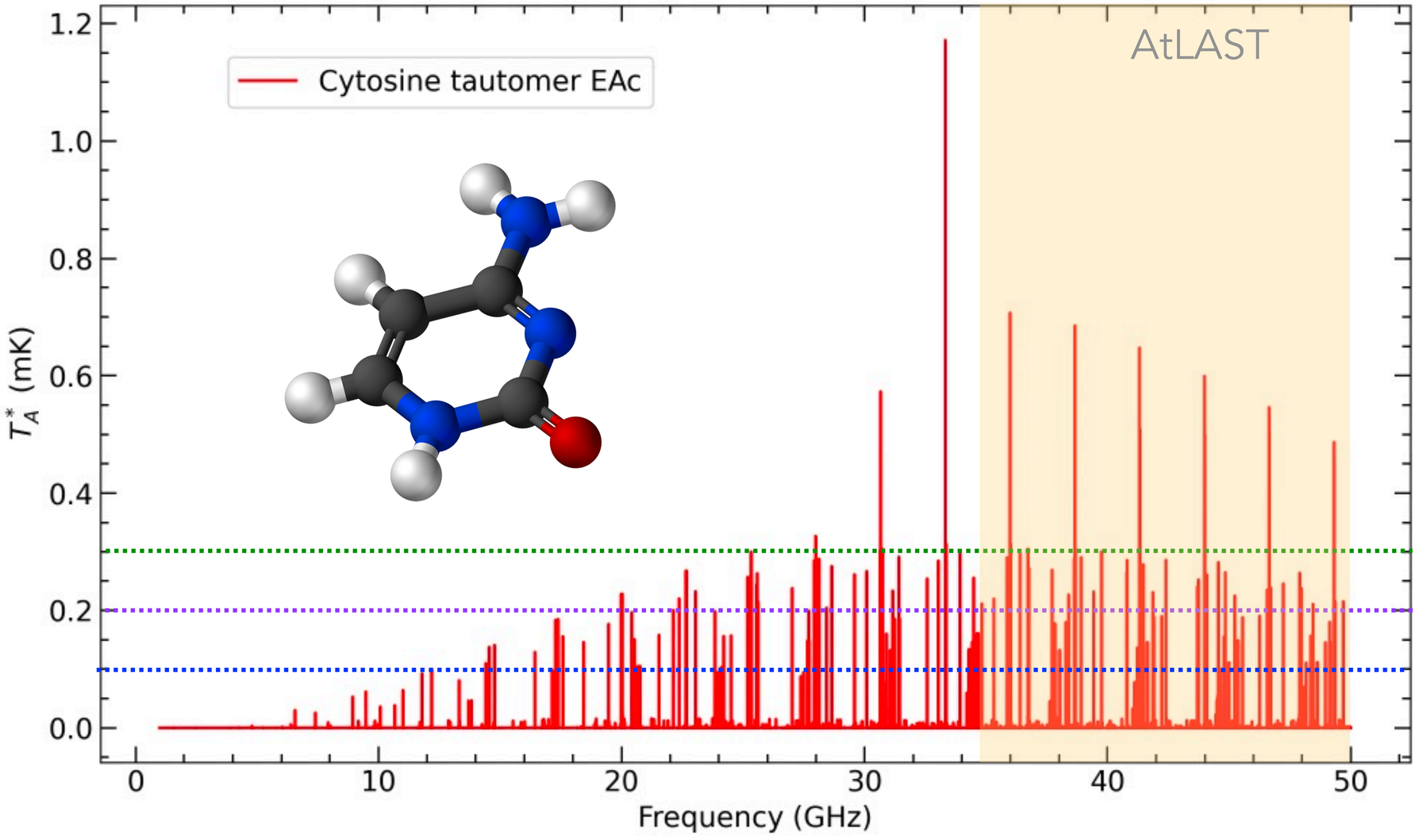


$5\sigma\ /\sqrt{n}$ – 24 hr

σ – 24 hr

$N = 10^{12}\ cm^{-2};\ X = 7.5 \times 10^{-12};\ FWHM = 20$ km s^{-1}

($\nu = 40$ GHz; 60°)



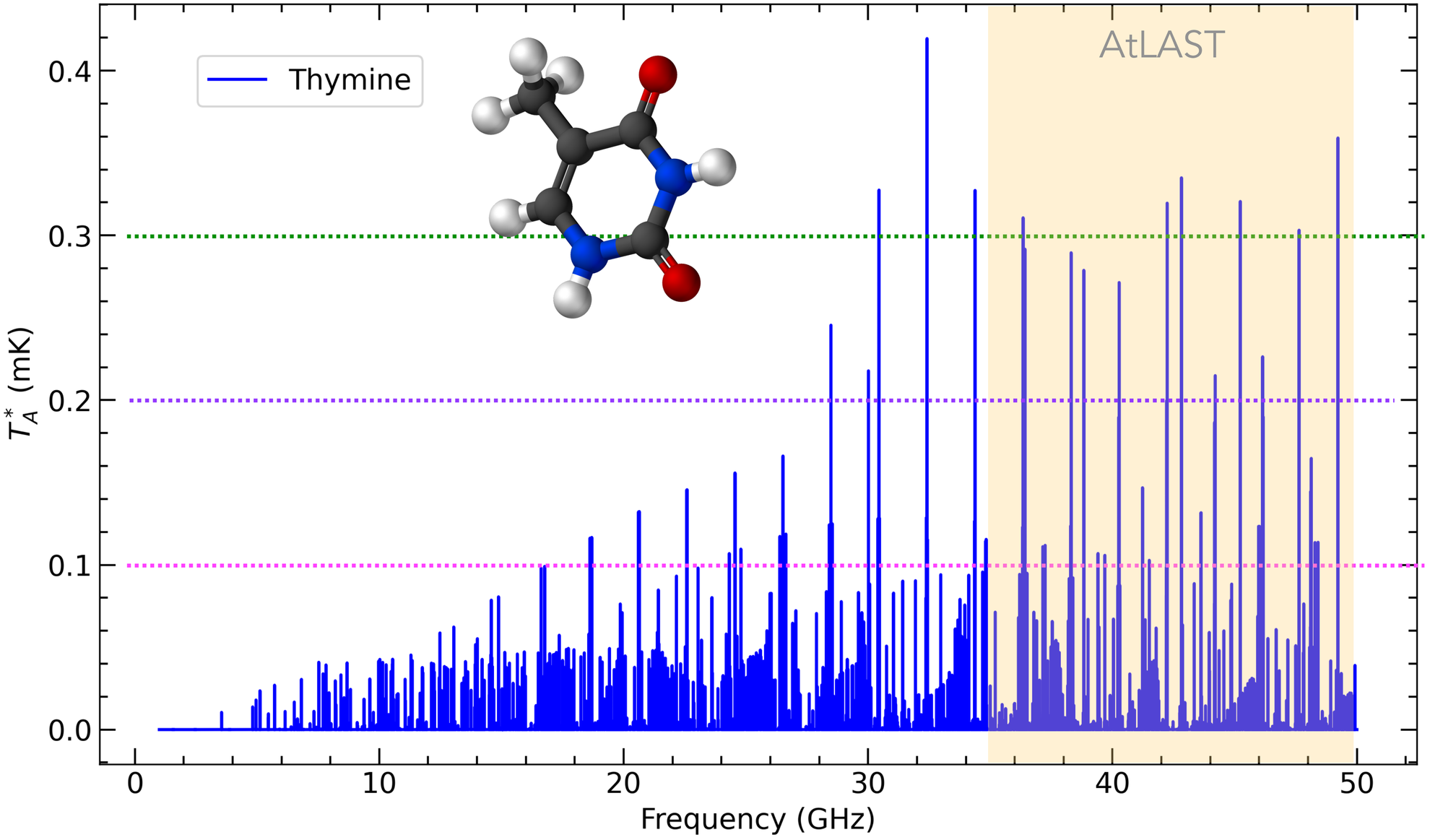
$5\sigma/\sqrt{n}$ – 24 hr

$5\sigma/\sqrt{n}$ – 54 hr

$5\sigma/\sqrt{n}$ – 219 hr

$N = 10^{12}\ cm^{-2};\ X = 7.5 \times 10^{-12};\ FWHM = 20\ \mathrm{km\ s^{-1}}$

(ν = 40 GHz; 60°)



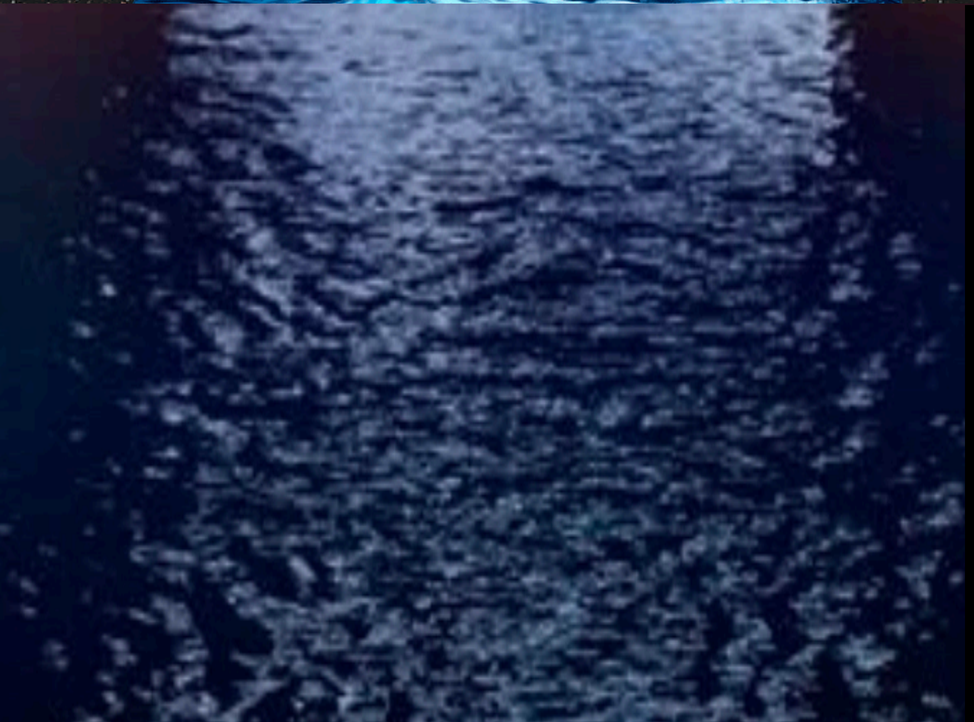
$5\sigma\ /\sqrt{n}$ – 24 hr

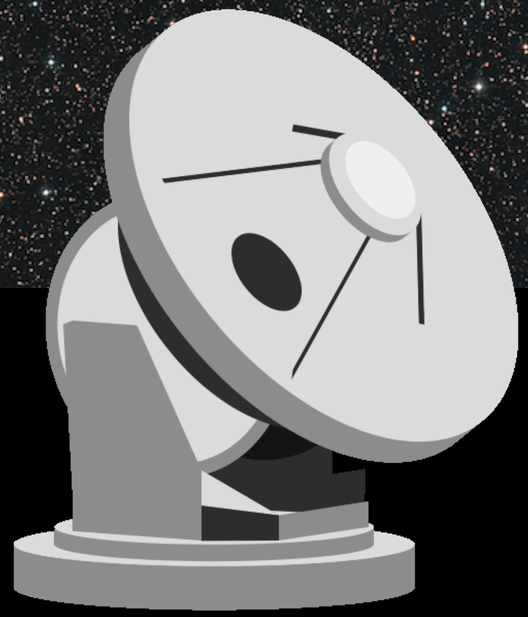
$5\sigma/\sqrt{n}$ – 54 hr

$5\sigma/\sqrt{n}$ – 219 hr

Take away message

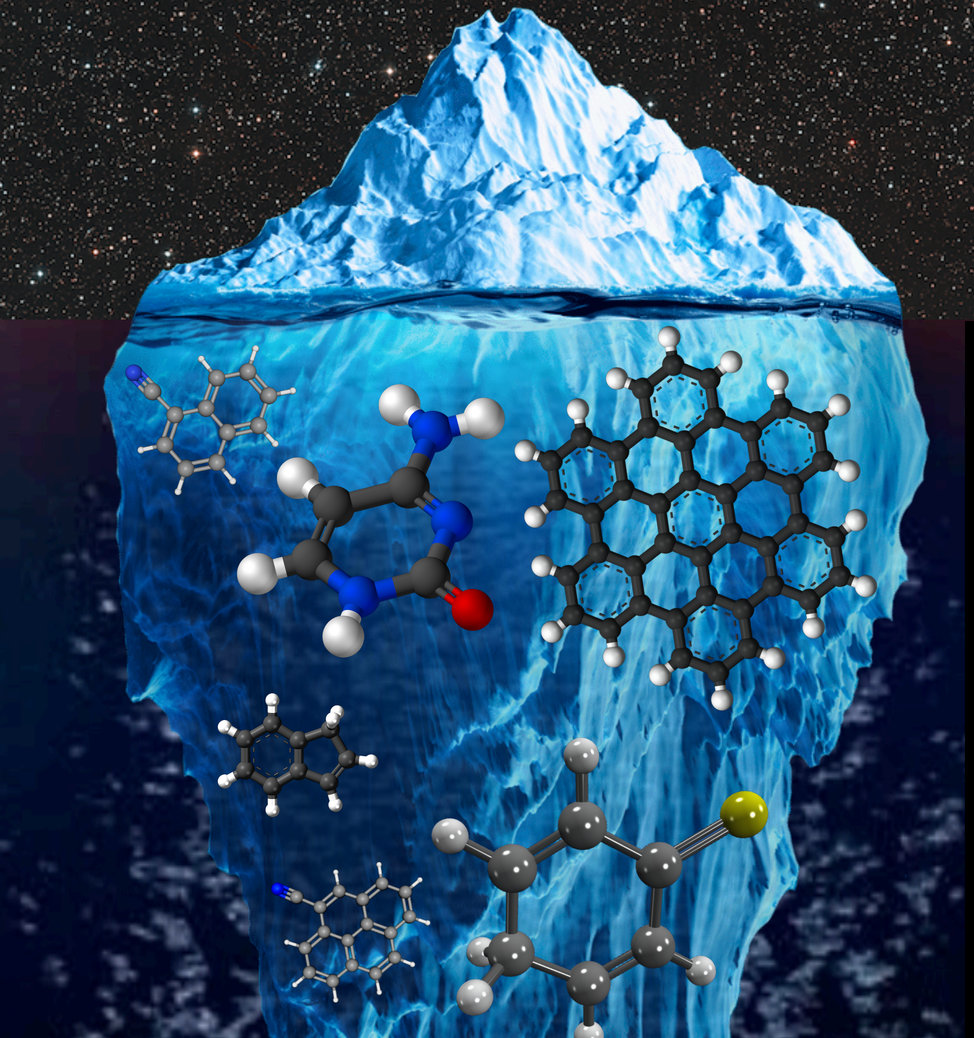
Ultra-sensitive broadband spectral surveys at Q-band

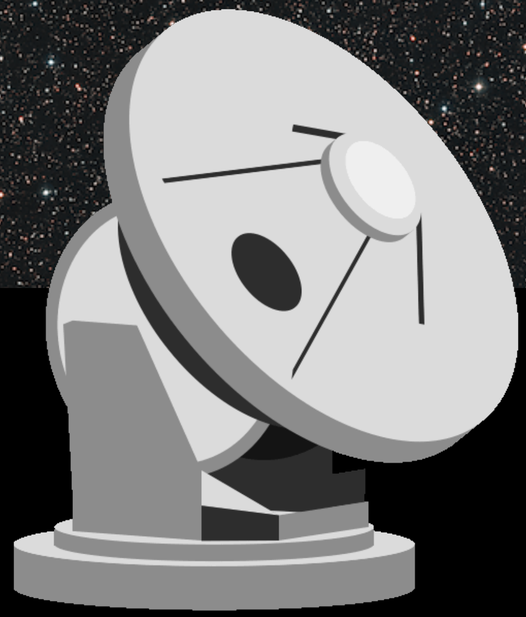




Take away message

Ultra-sensitive broadband spectral surveys at Q-band

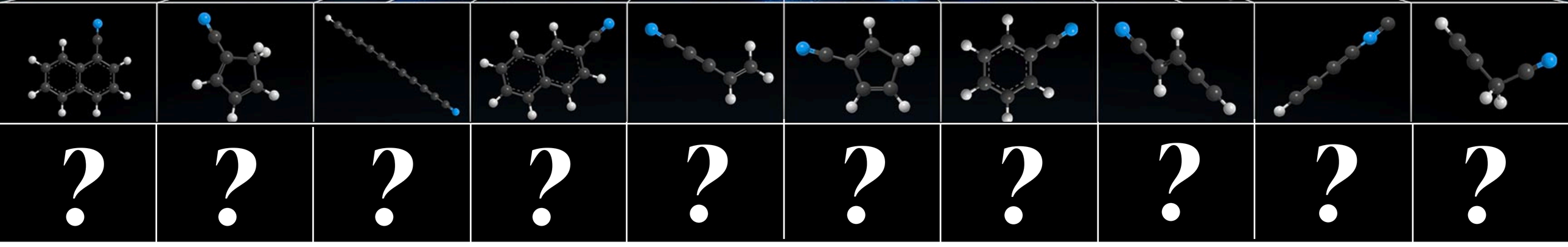




Unveil the chemical feedstock in the ISM, and its potential role in triggering prebiotic chemistry

Unveiling the aromatic Galaxy with AtLAST

Víctor M. Rivilla
Centro de Astrobiología (CAB), CSIC-INTA, Madrid



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