

Chemical and isotopic properties of interstellar comet 3I/ATLAS



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SF2A 2026

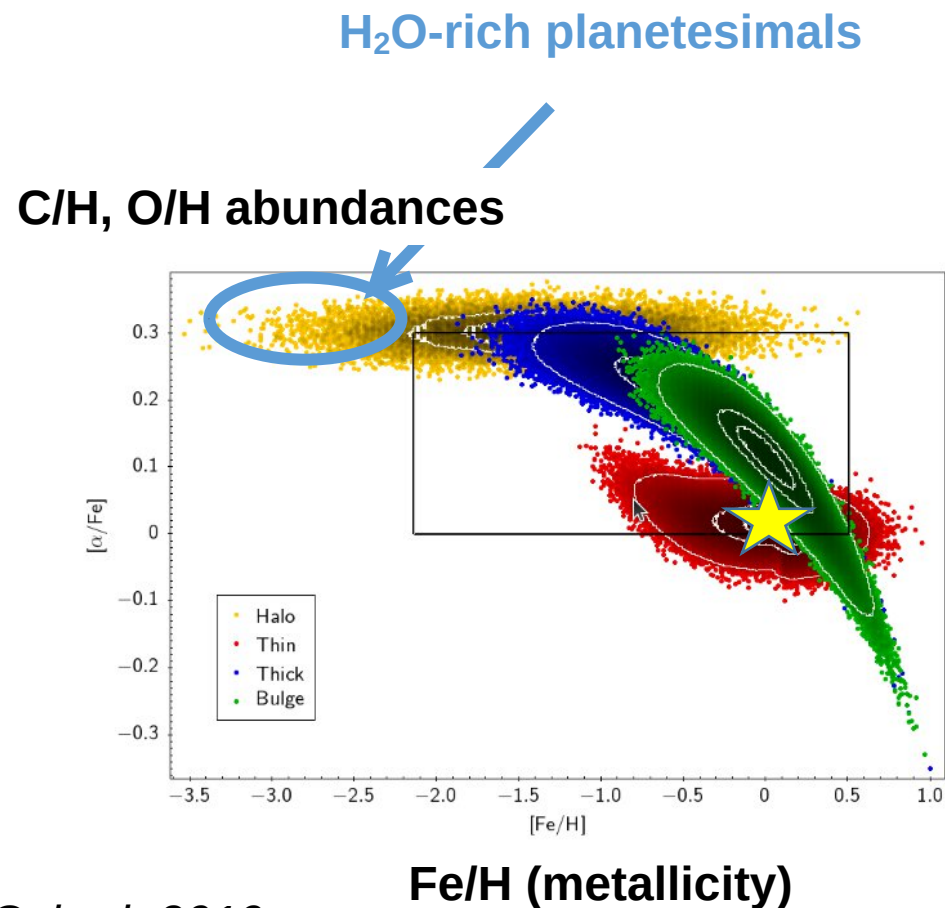
Introduction

Interstellar comets :

=> means to understand planet formation in **planetary systems** other than our own, throughout the Galaxy

The molecular and isotopic composition of planetesimals depend on :

- ✓ the galactic environment (e.g. star metallicity)
- ✓ physical conditions in the parent molecular cloud
 - e.g. temperature, ionization field (UV) affect the chemical network
- ✓ processes in the natal protoplanetary disk
 - e.g. isotopic exchanges for deuterium
- ✓ when and where the comet agglomerated
 - e.g., wrt to the various snowlines

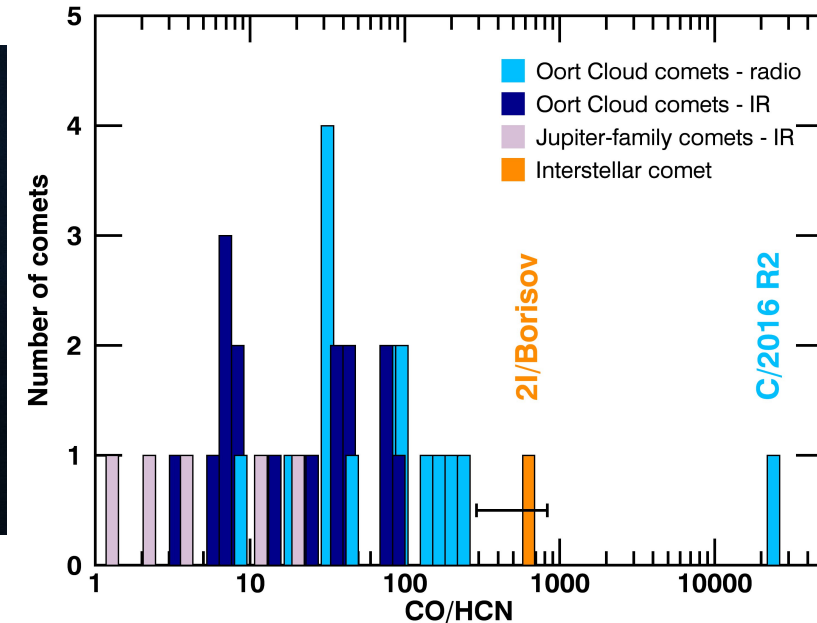
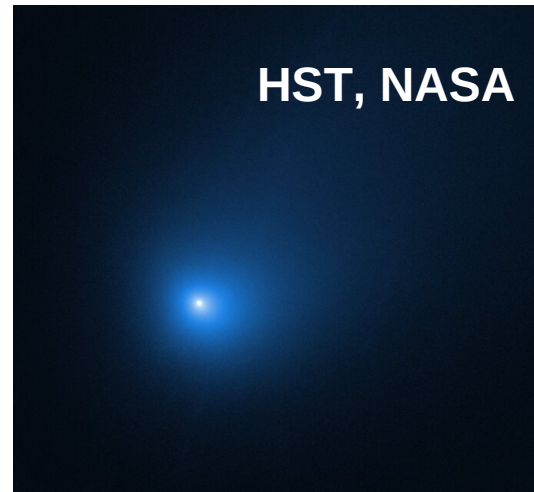


1I/'Oumuamua

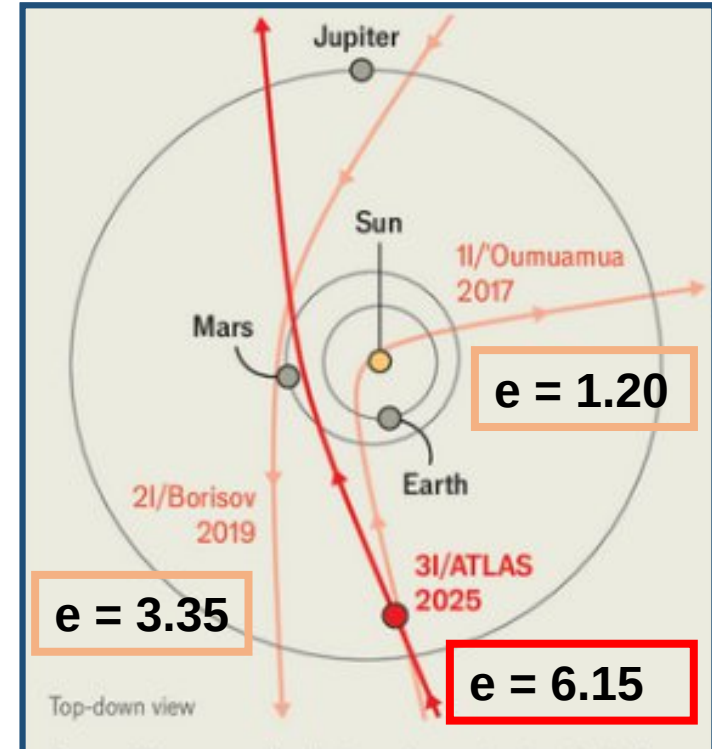
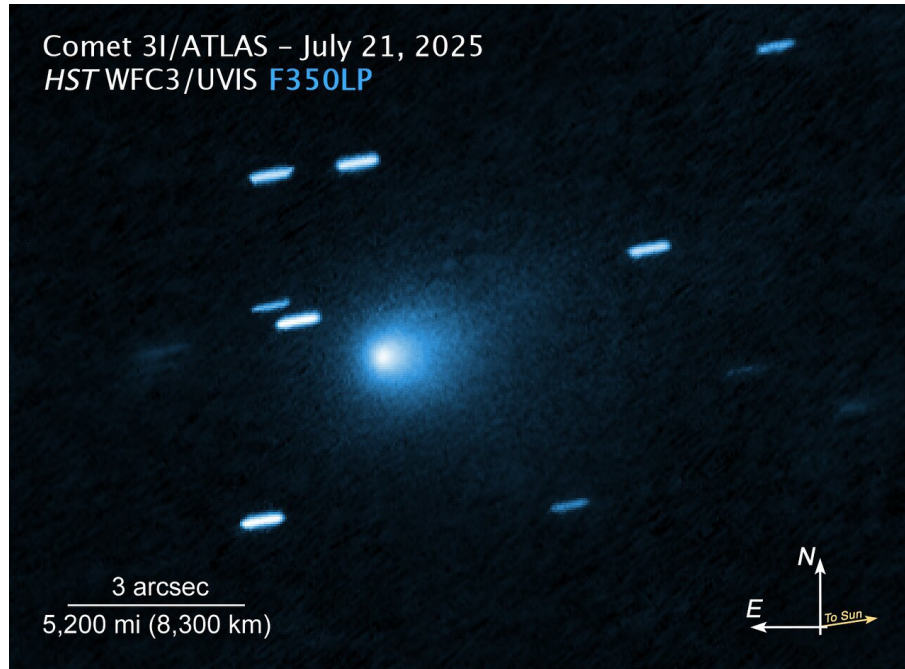


- Discovered in 2017 with PanSTARRS when at 0,2 AU from Earth
- Brief observational campaign
- Coma undetected but non-gravitational forces affecting the orbit : origin disputed (H₂, N₂ outgassing ?)
- Small (200 m equivalent diameter), elongated nucleus, complex rotation
- Red color

2I/Borisov



3I/ATLAS



- Discovered on 1 July 2025 by ATLAS robotic telescope at 4.45 ua from Sun, 3.5 ua from Earth
 - ✓ observable during about 1 year
- Velocity at infinity : 58 km/s
- Perihelion on 29 October 2025 at 1.36 ua from Sun
- **Activity level at perihelion : turned to be 100 times more than comet Borisov**

Pre-discovery observations in May-June 2025 by ZTF and Vera Rubin telescopes, and TESS satellite : was active at 9 au from Sun

Origin of 3I/ATLAS based on its orbit

Search for past stellar encounters using GAIA DR3 (34 M of stars) (Gao+ 2025, Pérez Couto+2026)

- none of the stars is a plausible host
- none of the stars within 500pc caused significant deflection of the orbit

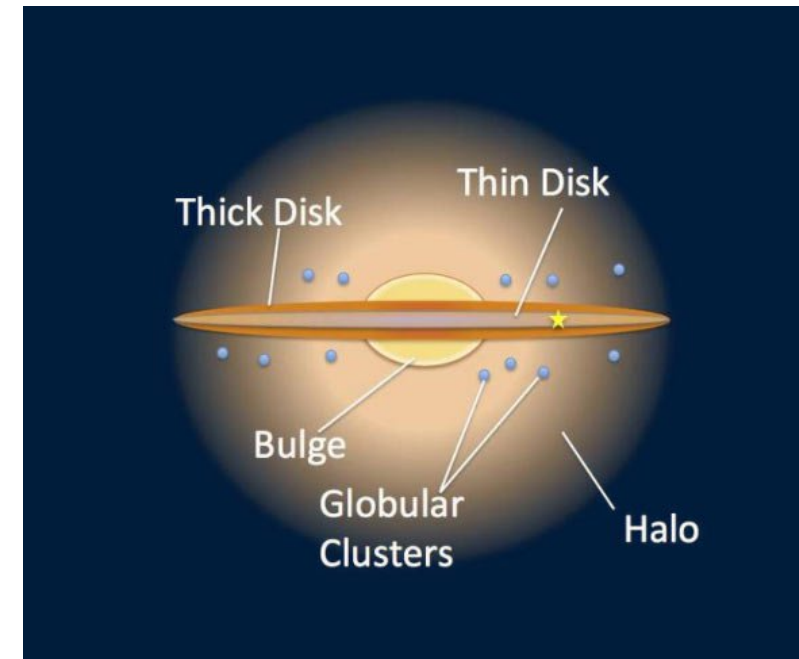
Origin in the Galaxy

Kinematics of 3I/ATLAS supports origin from **Galactic thin disk**
(Gao+ 2025, Pérez-Couto+2026)

- Other argue for a **thick disk origin** (Eubanks+2015)

Formation time

- kinematic age of 3-11 Gyr : old object in an early formed (metal-poor) system



The observing campaign of 3I/ATLAS

- Since its discovery, 3I/ATLAS has been observed by nearly all observational facilities from ground and space
- Including space missions : Exomars/TGO, Mars-Express, Europa-Clipper, JUICE etc
- 66 published papers already



Nucleus size

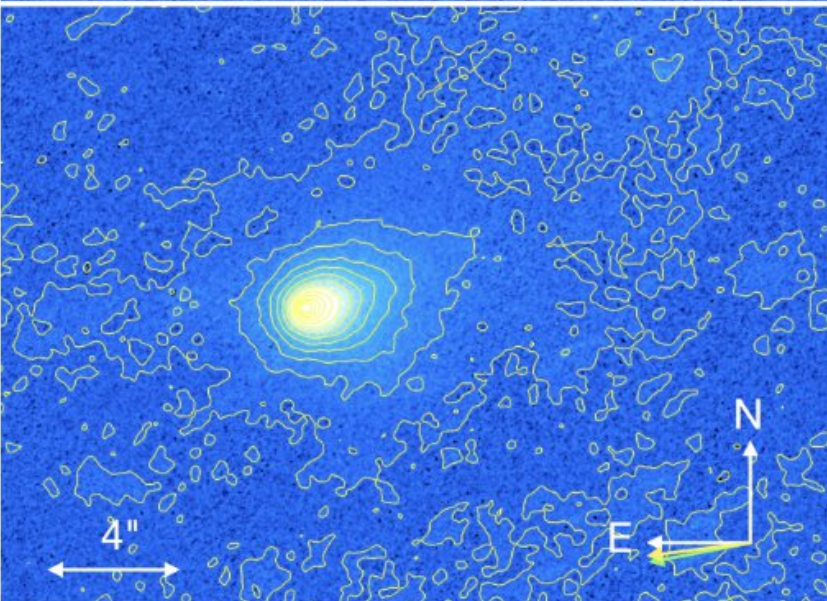
HST

3I/ATLAS
UT 2025 July 21

Sun



$r_H = 3.83 \text{ au}$



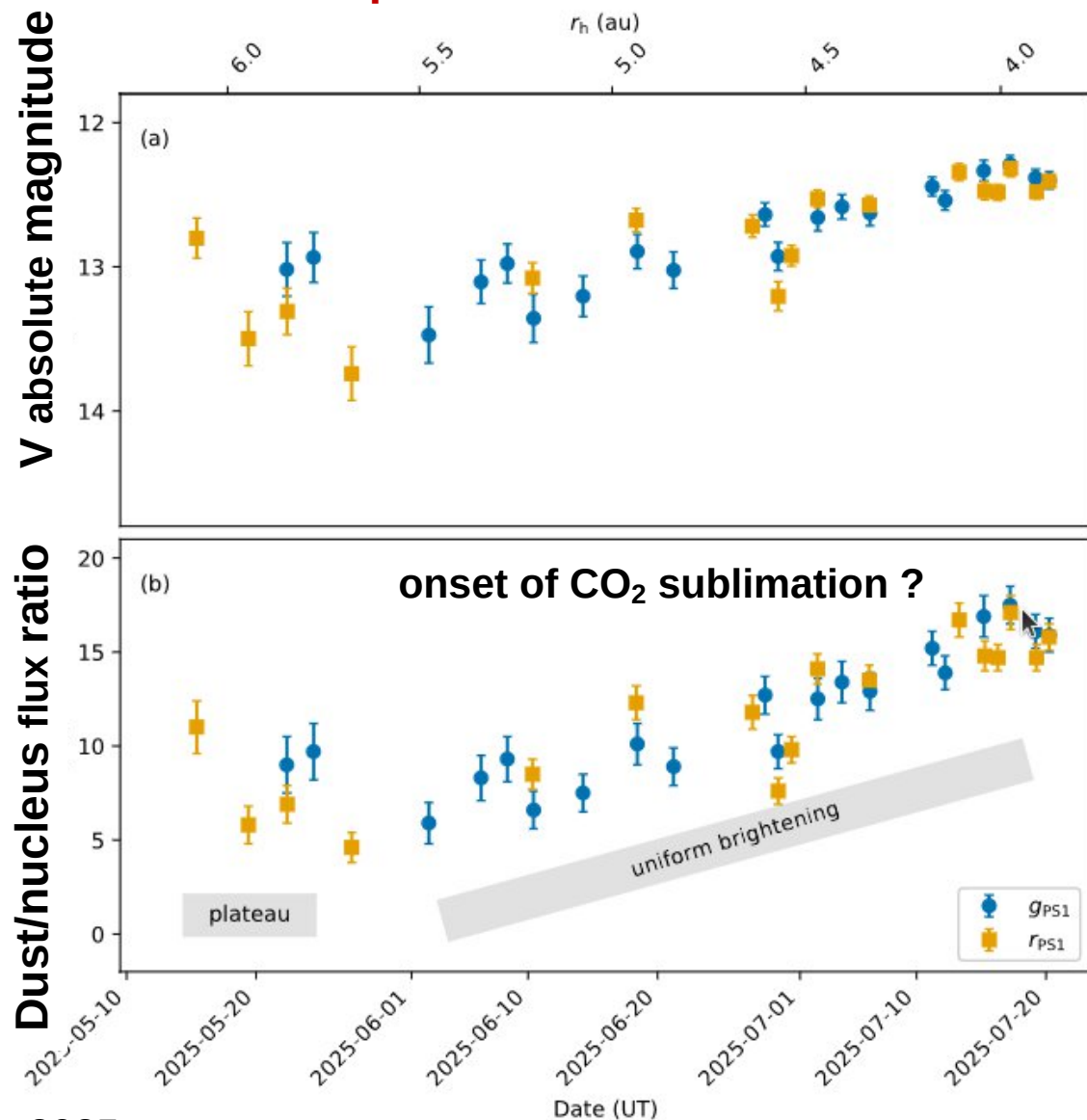
Comparisons of Nucleus Size Estimates of 3I/ATLAS

Nucleus Radius (km)	Source	Method
0.26–0.37	T. M. Eubanks et al. (2025)	Nongravitational effect
0.41–0.53	J. C. Forbes & H. Butler (2025)	Nongravitational effect
1.3 ± 0.2 1.5 ± 0.1^a	Hui+2026	Nucleus extraction Nongravitational effect
>2.5	R. Cloete et al. (2025)	Nongravitational effect
<2.8	D. Jewitt et al. (2025)	Nucleus extraction
≈ 4	This work	Aperture photometry
$\leq 6.3 \pm 0.8^b$	C. O. Chandler et al. (2025)	Surface profile comparison
$<11 \pm 1^b$	D. Z. Seligman et al. (2025)	Aperture photometry

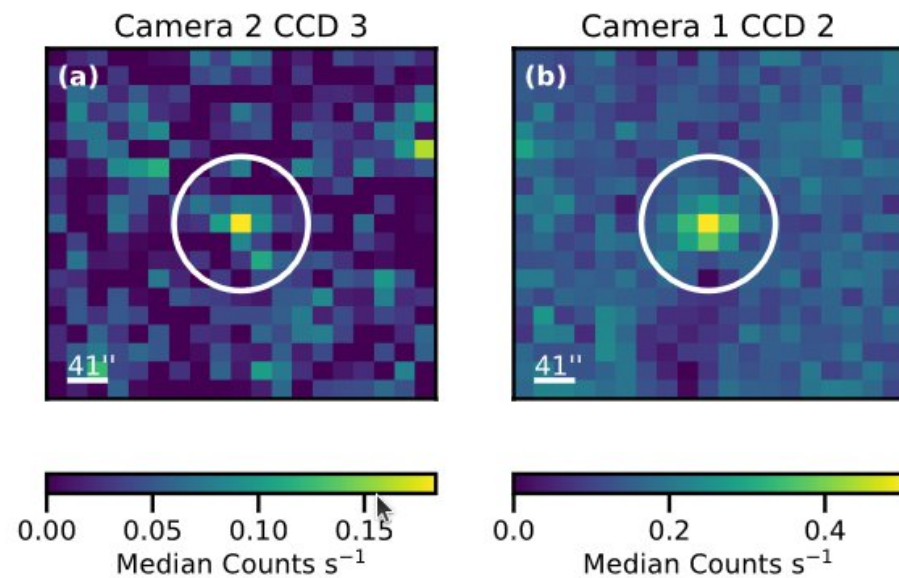
- ✓ Nucleus radius $R_n = 1.3 \text{ km}$ assuming $p_v = 0.04$
- ✓ Non-gravitational acceleration (rocket effect) supports a small nucleus

Pre-discovery data : early activity

ZTF telescope



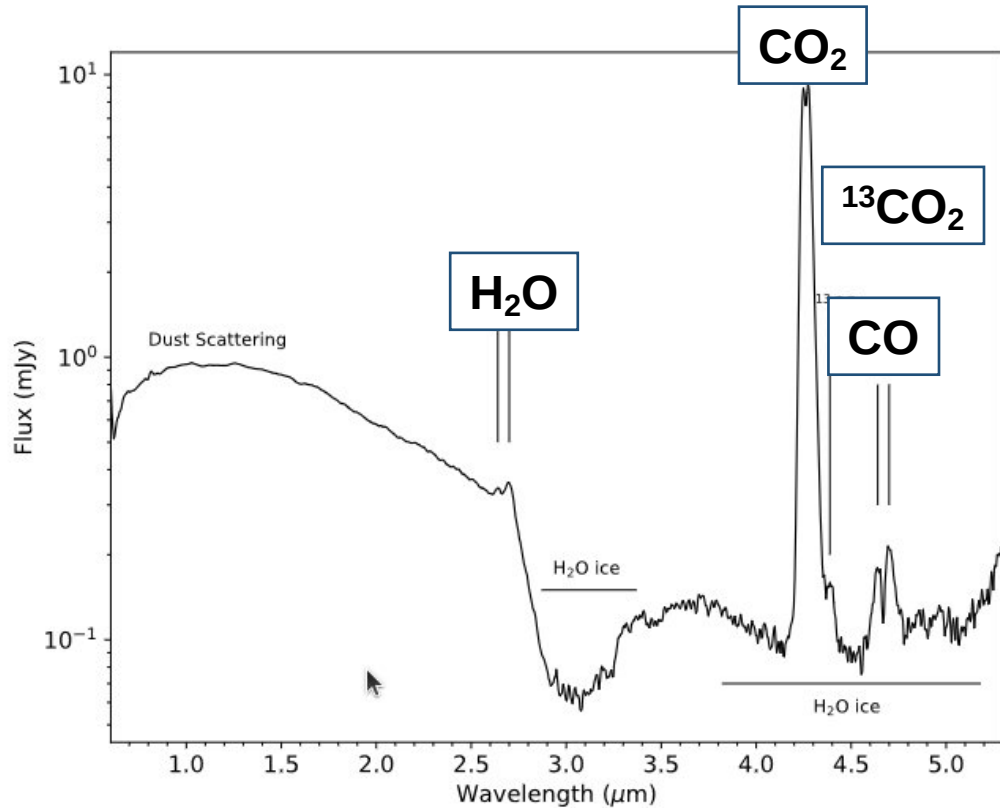
TESS, May 2025 comet@ 6au



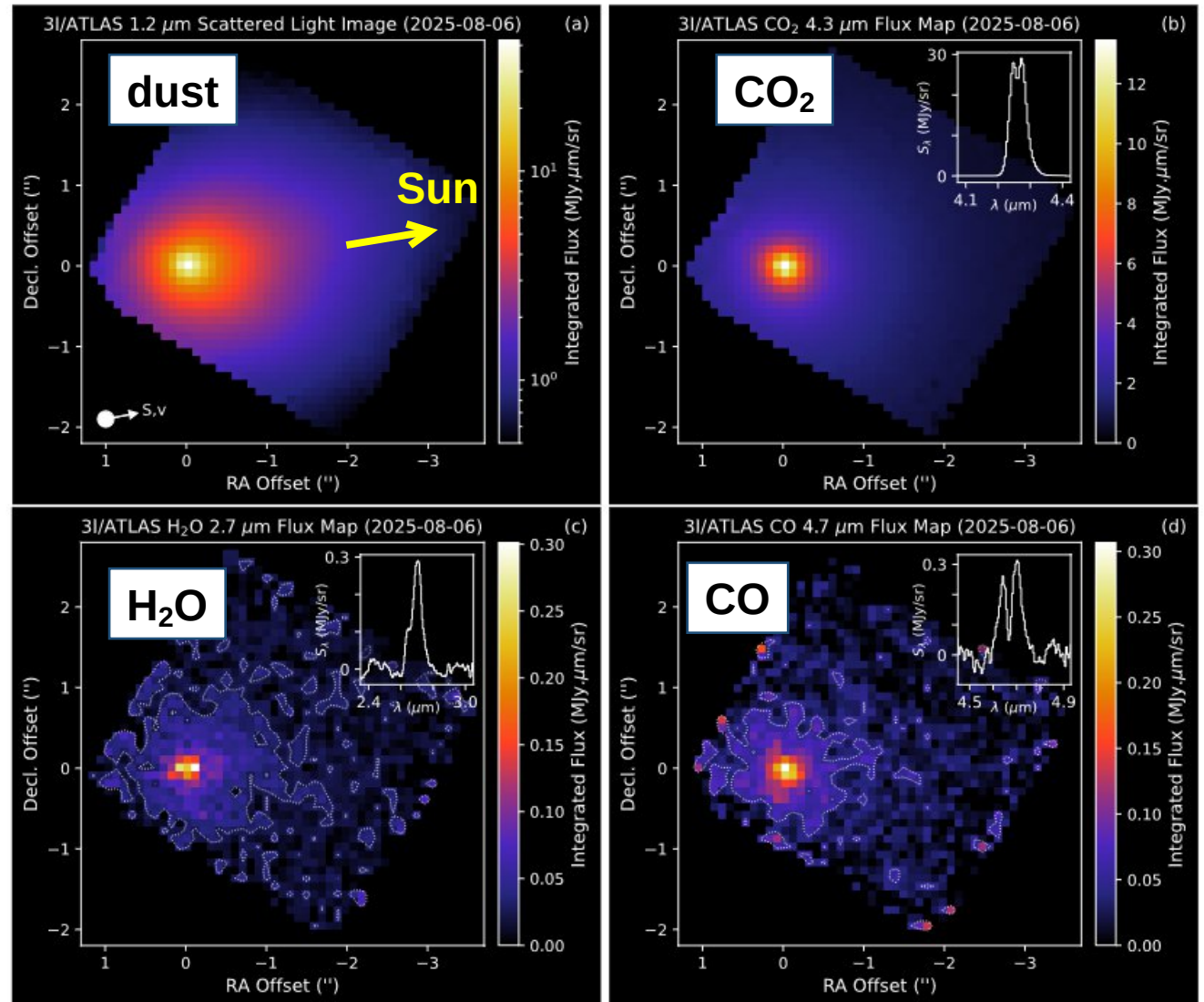
Feinstein+2025

CO₂, driver of distant activity - pre-perihelion

JWST comet@3.32 au (6 Aug. 2025)

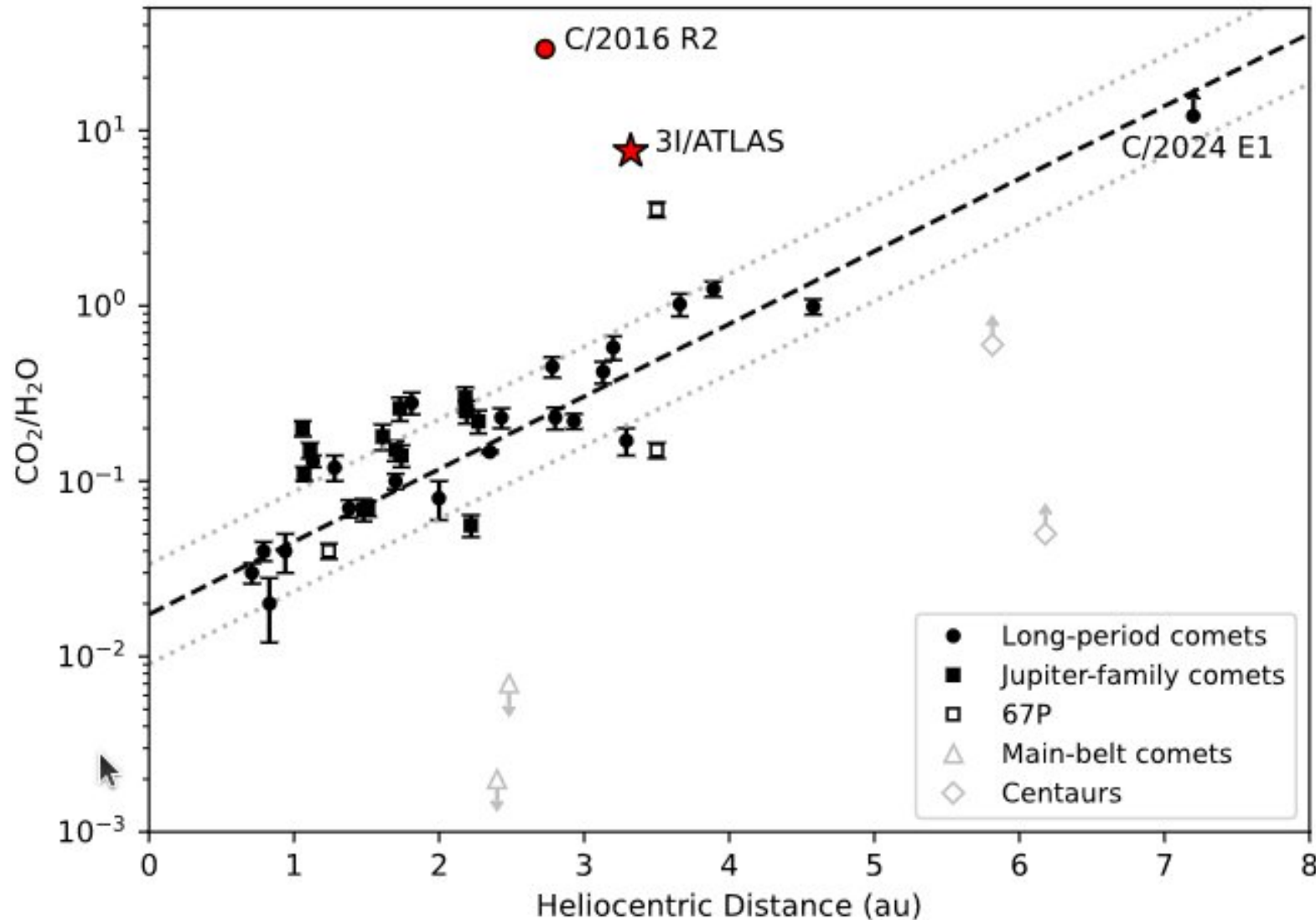


$$Q(\text{CO}_2) = (1.70 \pm 0.01) \times 10^{27} \text{ s}^{-1}$$
$$Q(\text{CO}) = (3.7 \pm 0.2) \times 10^{26} \text{ s}^{-1}$$
$$Q(\text{H}_2\text{O}) = (2.23 \pm 0.08) \times 10^{26} \text{ s}^{-1}$$



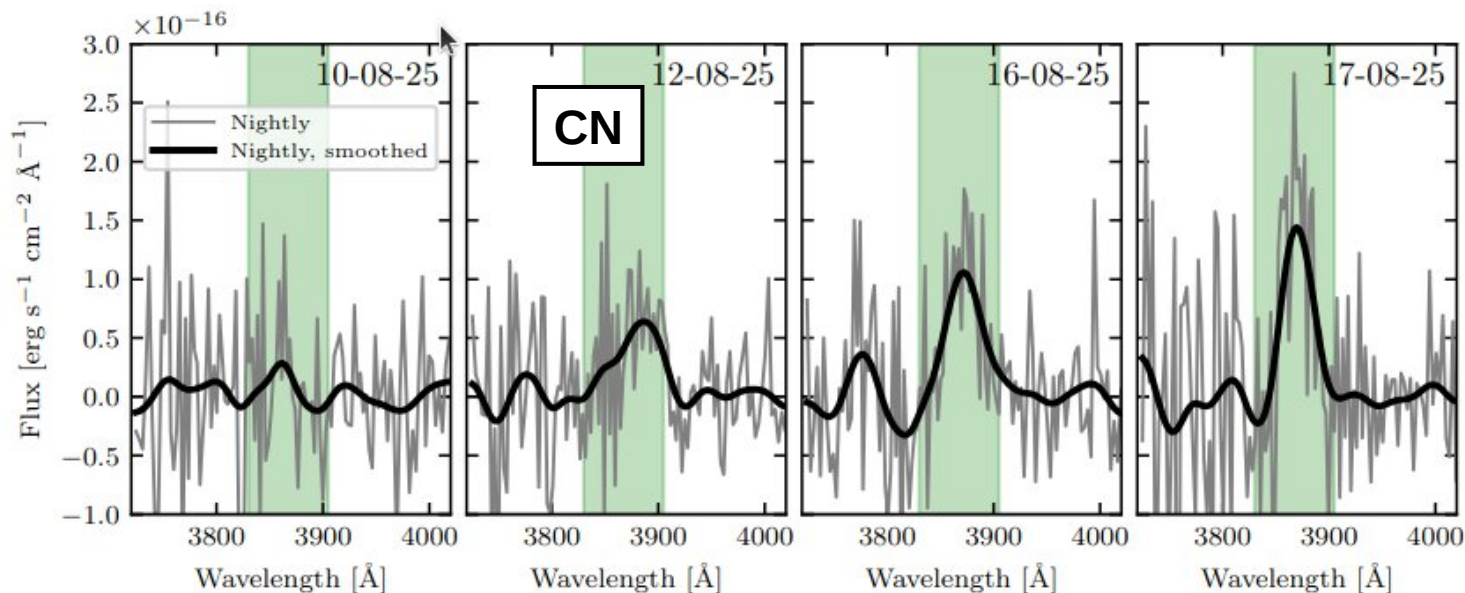
Cordiner+2025

3I/ATLAS, a CO₂-rich comet



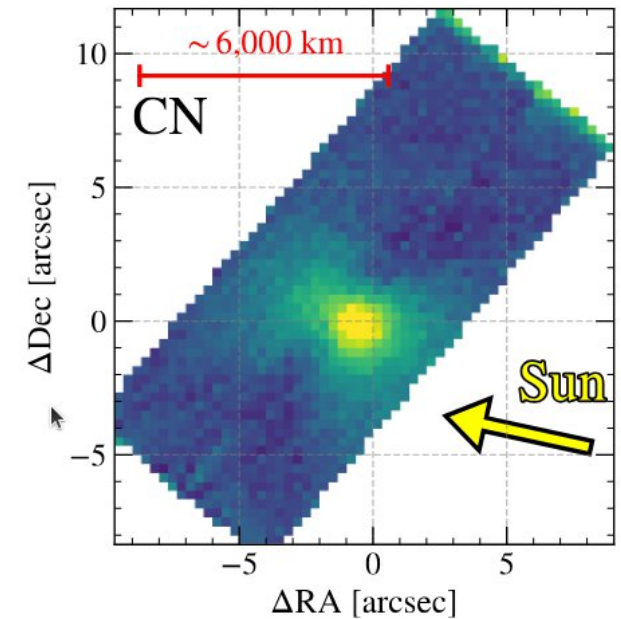
The quest for spectral signatures in the optical domain

MDM observatory comet@2.9-3.2 au (10-17 Aug. 2025)



Salazar Manzano+2025

Keck comet@ 2.7 au (24 Aug. 2025)



Hoogendam+2024

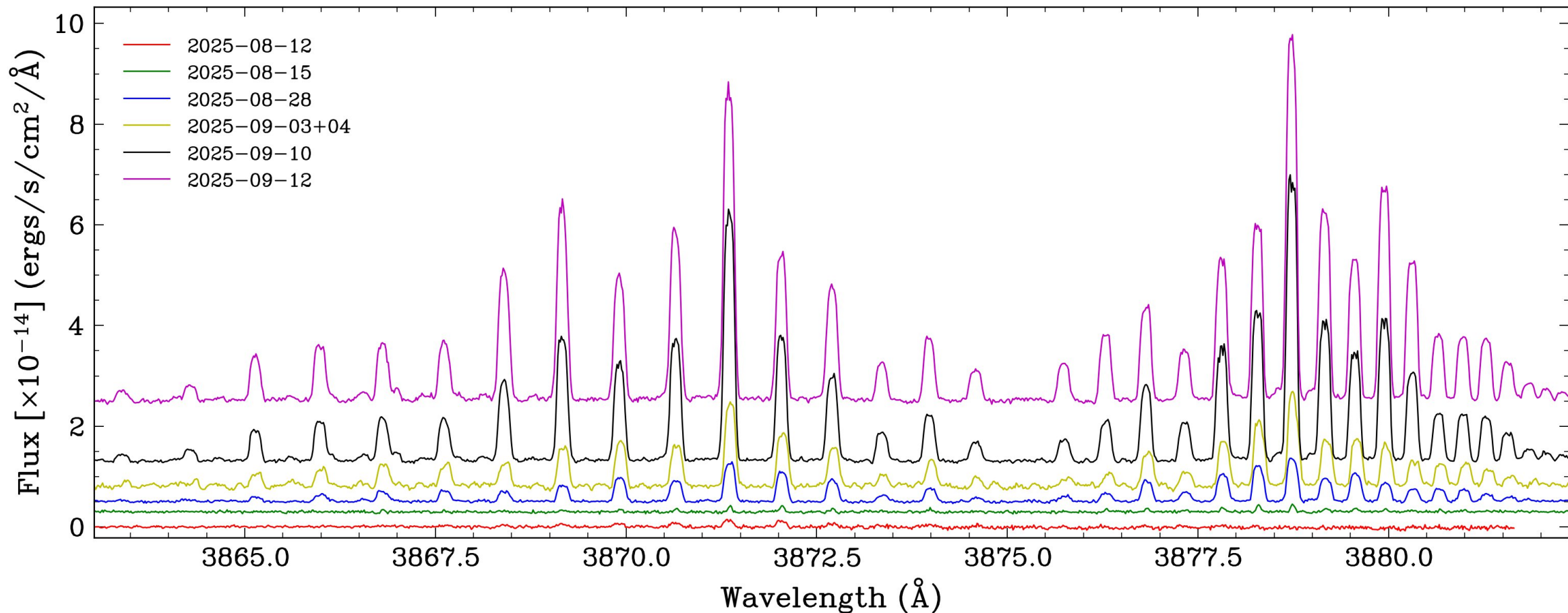
$Q(\text{CN})$ from 4.8 to $7.2 \times 10^{24} \text{ s}^{-1}$

the monitoring of CN emission has been performed with several facilities : VLT, Keck, Lowell Obs., TRAPPIST, etc

VLT/UVES, mid-August to mid-September

E. Jehin, private communication

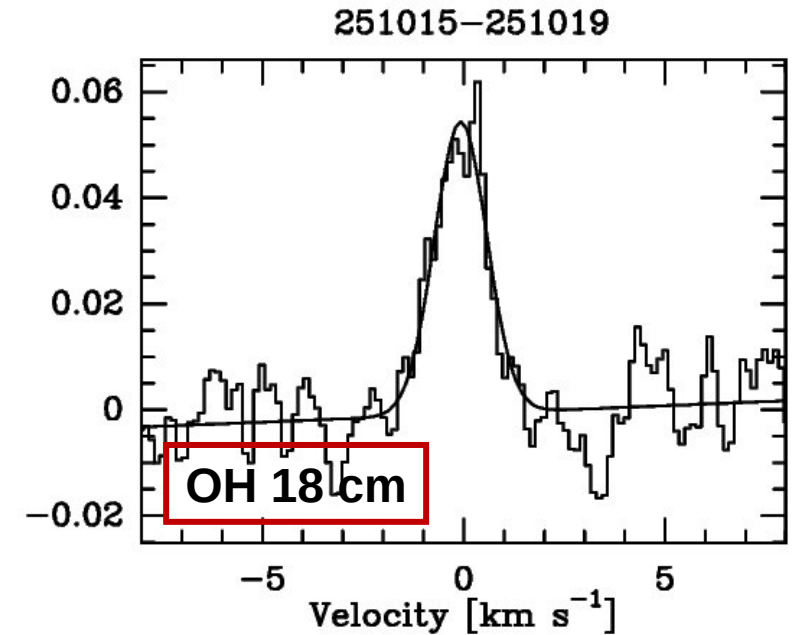
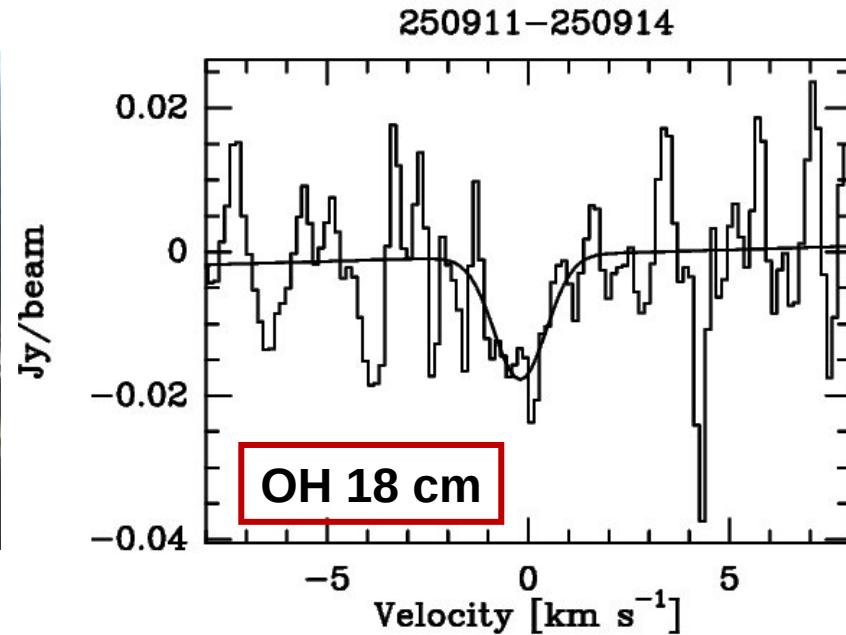
Evolution of CN emission band at VLT



$Q(\text{CN}) \sim 2 \cdot 10^{25}$ mol/s on mid-September (2.2 ua)

Water production two weeks before perihelion

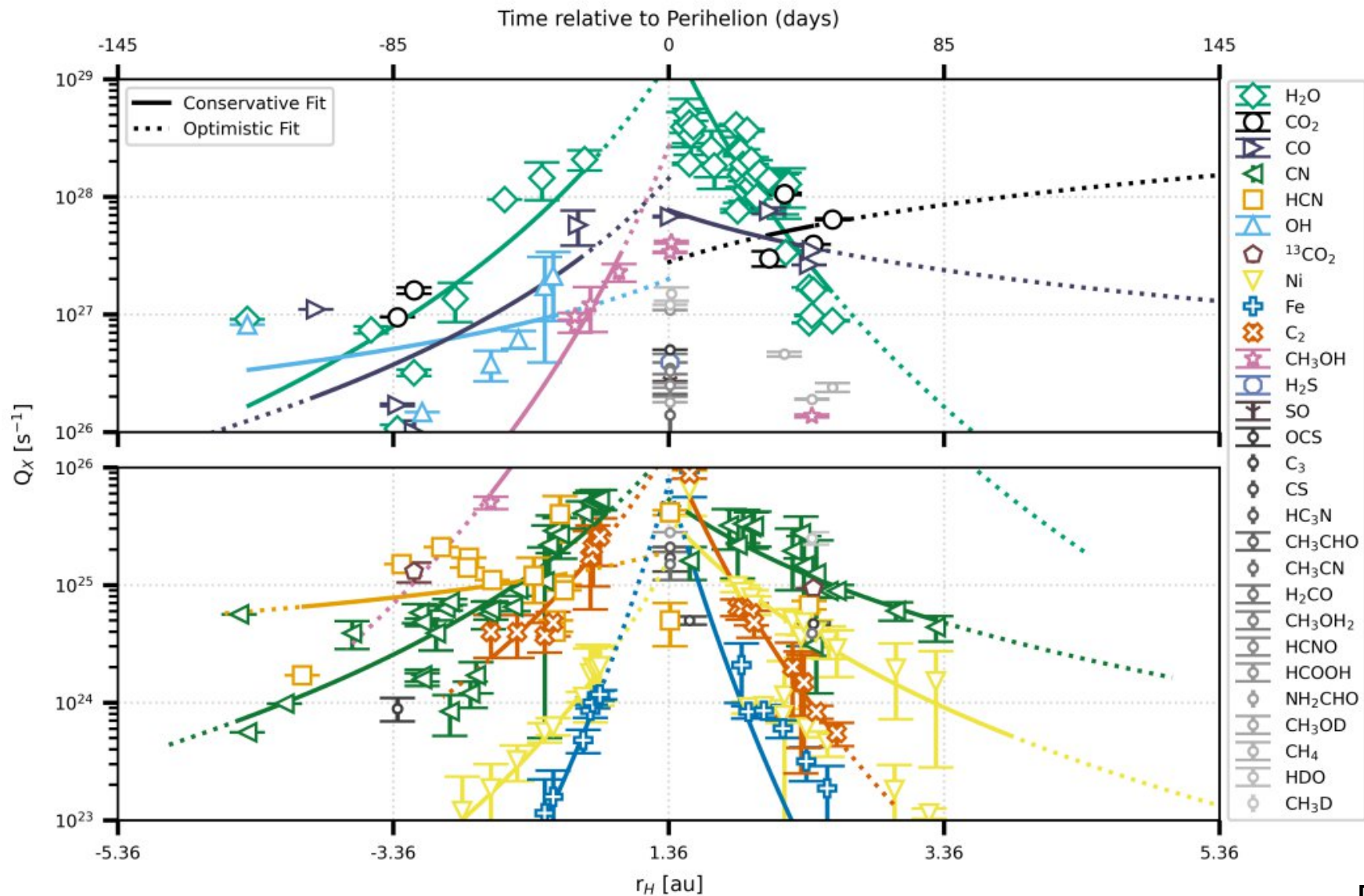
Nançay radio telescope comet @2.1au and 1.44 ua



Crovisier+2025

- water production rates estimated to 2.5 and 6 10^{28} mol/s
- **a quite active comet !**

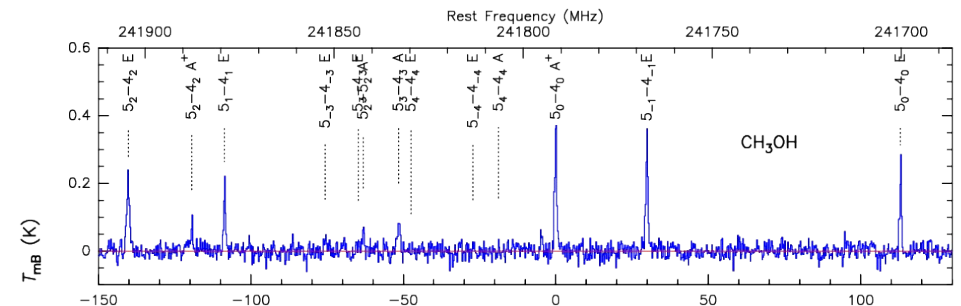
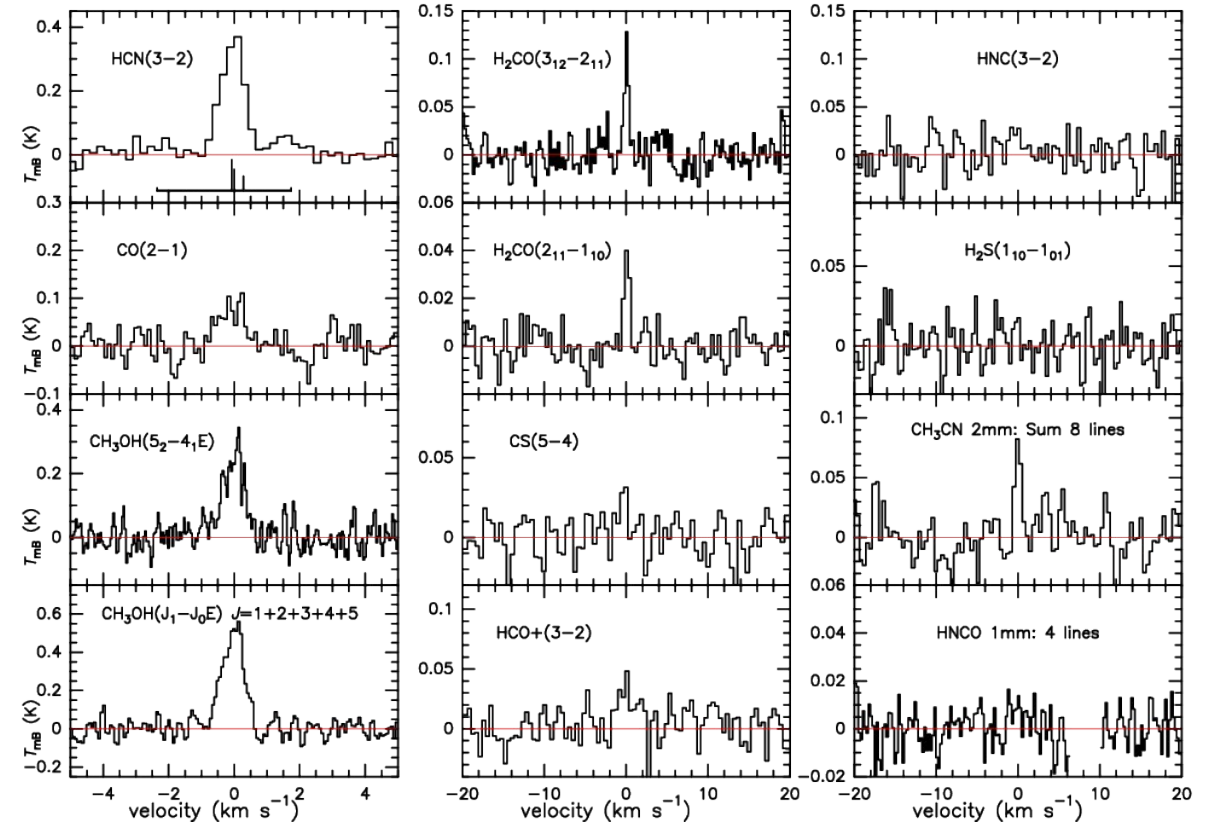
Compilation of production rate measurements



Observations with the 30-m telescope at perihelion



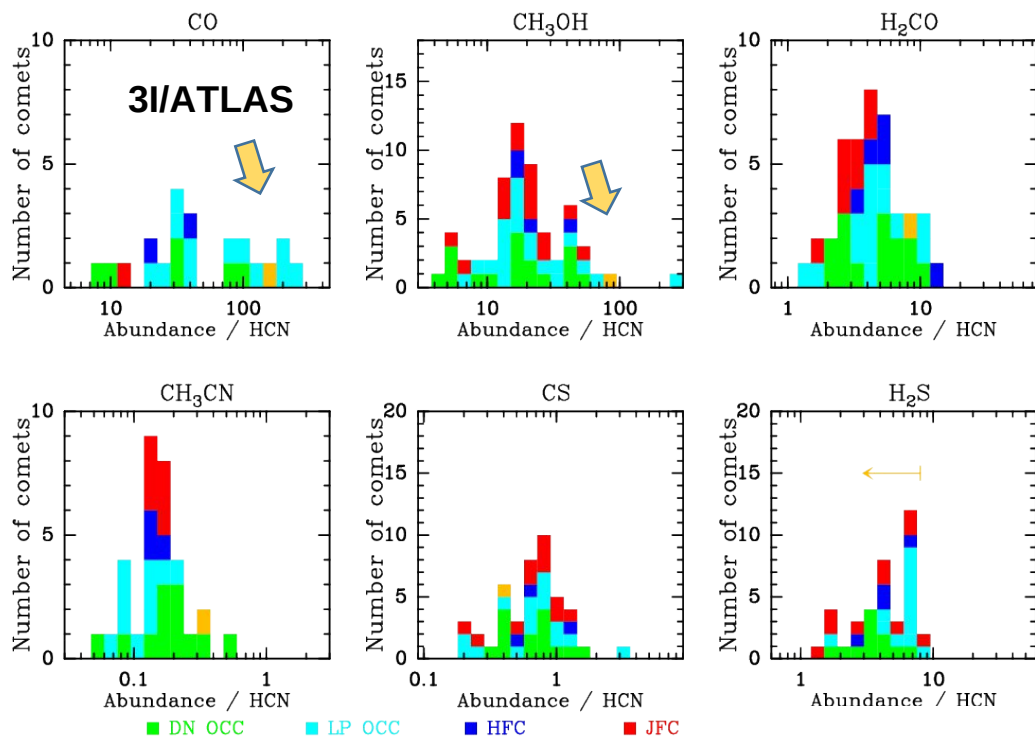
- 6 molecules detected: CH₃OH, CO, H₂CO, CS, HCN, CH₃CN



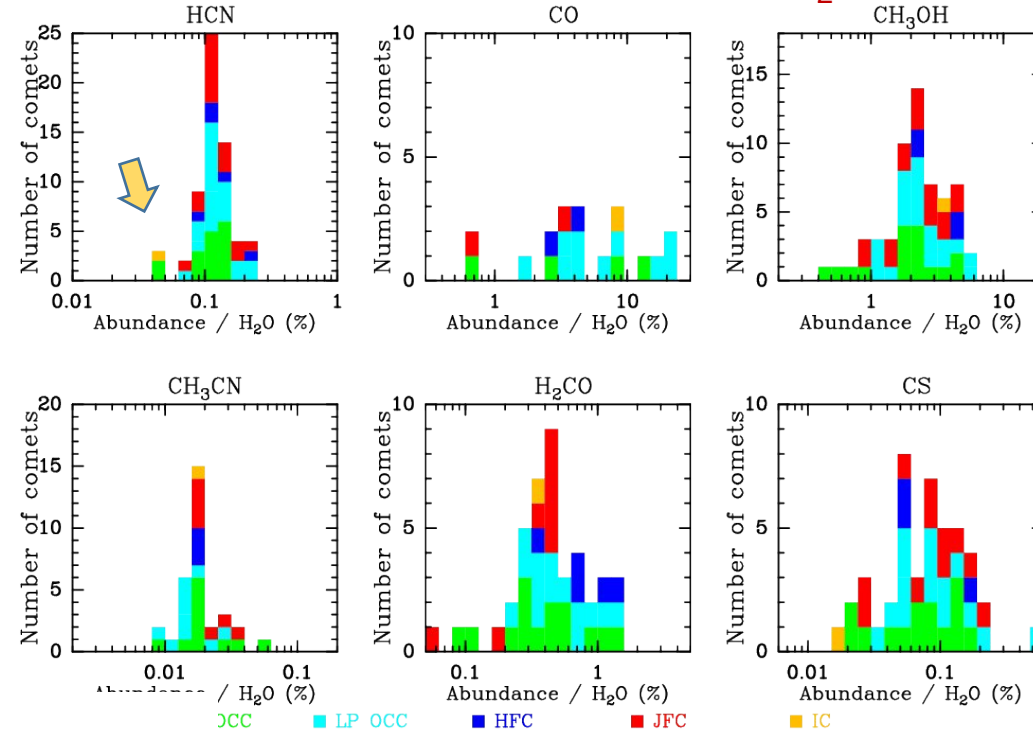
Biver et al. 2026

Comparison with solar system comets

Abundances relative to HCN

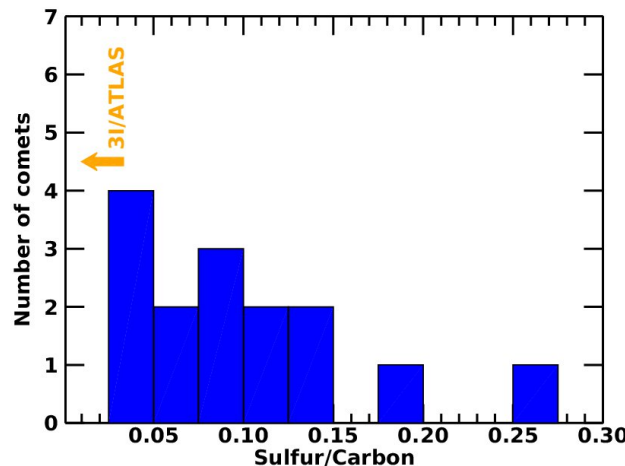


Abundances relative to H₂O



- Most molecules have enriched abundances with respect to HCN
- But HCN/H₂O depletion for 3I

Low ratio sulfur/Carbon



3I composition is atypical

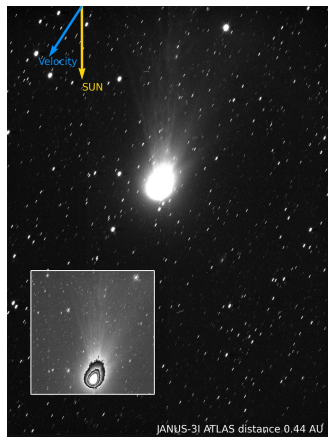
Also atypical : the low velocity of the gases derived from the line widths
=> activity driven by molecules heavier than H₂O

Observations with JUICE near perihelion



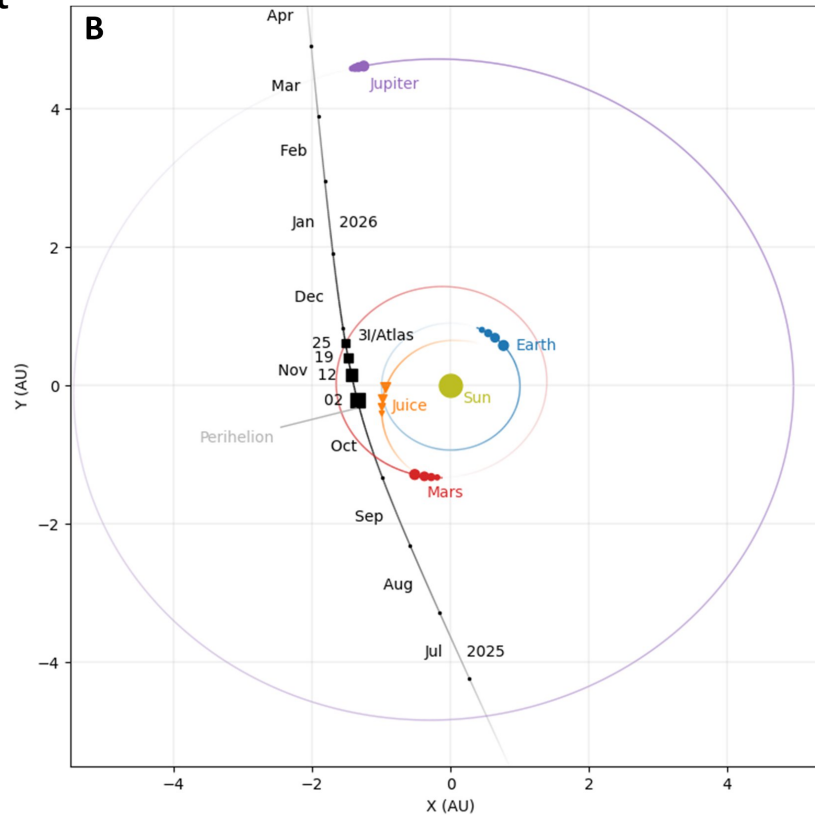
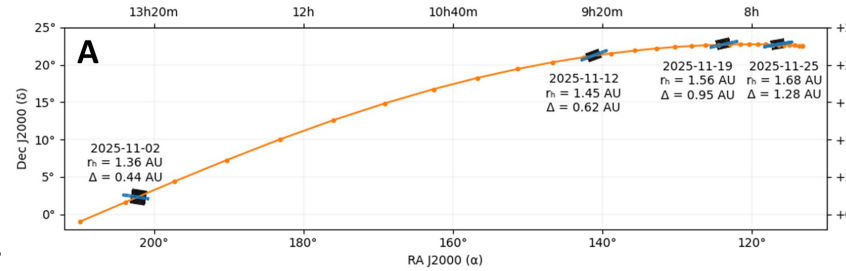
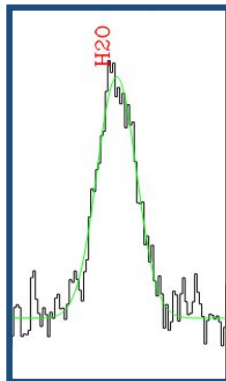
excellent configuration for observations from JUICE: at 0.44 au from JUICE and large solar elongation

JANUS camera

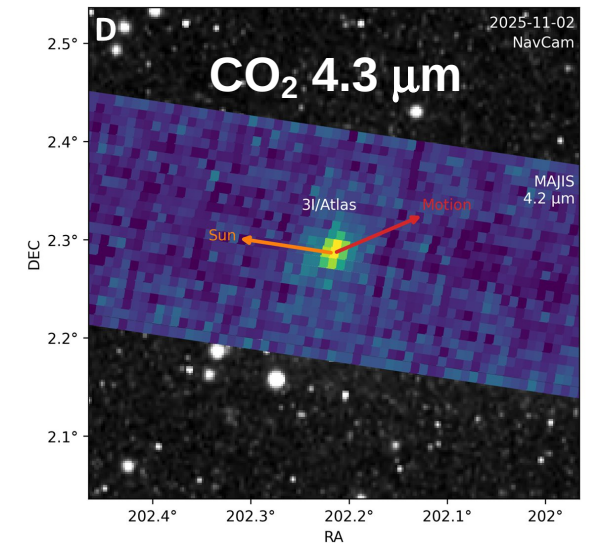
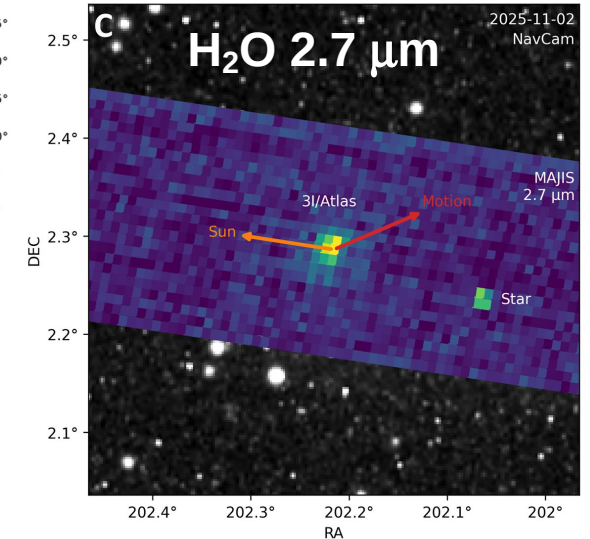


Submillimeter Wave Instrument (SWI)

H₂O@557GHz



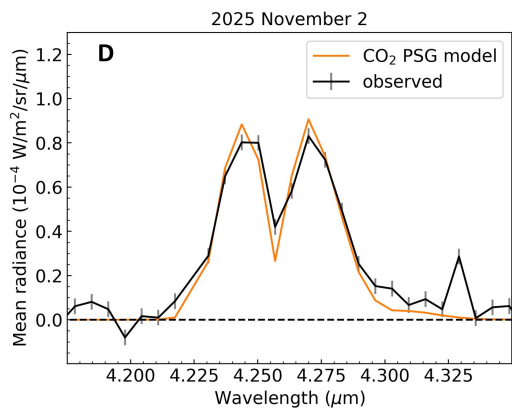
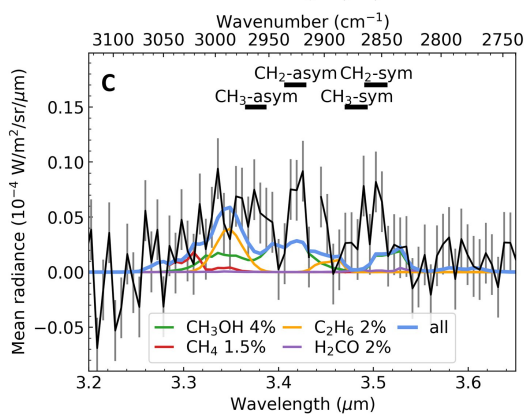
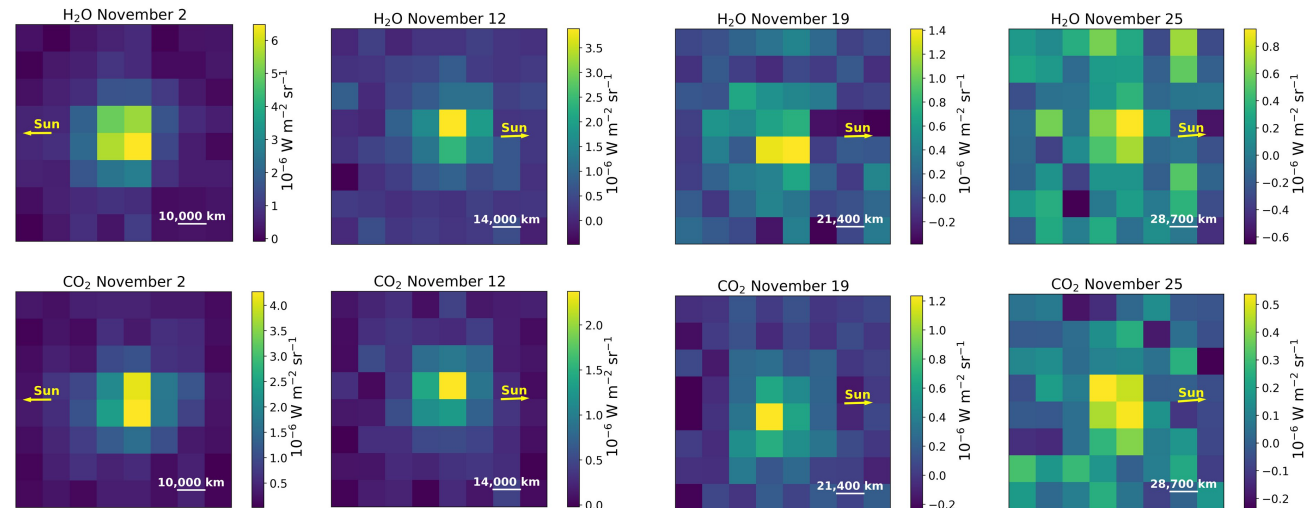
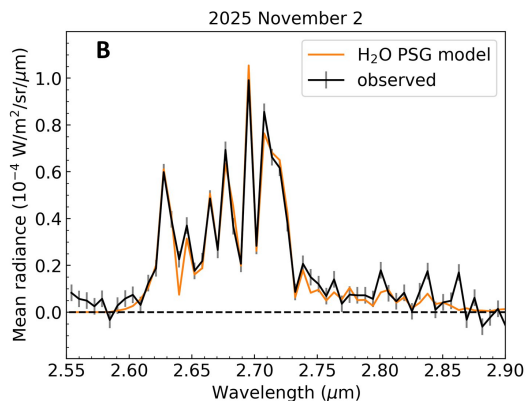
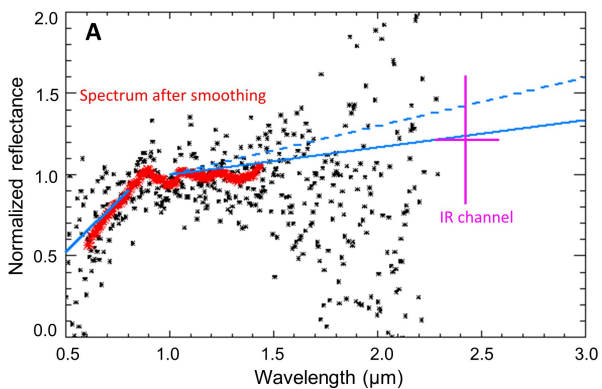
MAJIS



Bockelée-Morvan, Poulet, et al., submitted

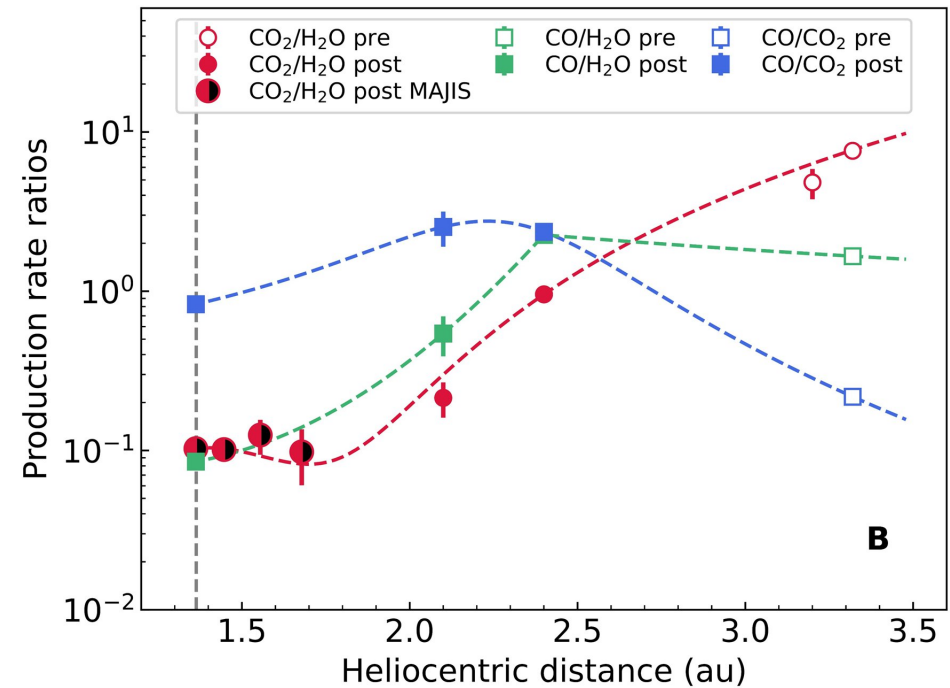
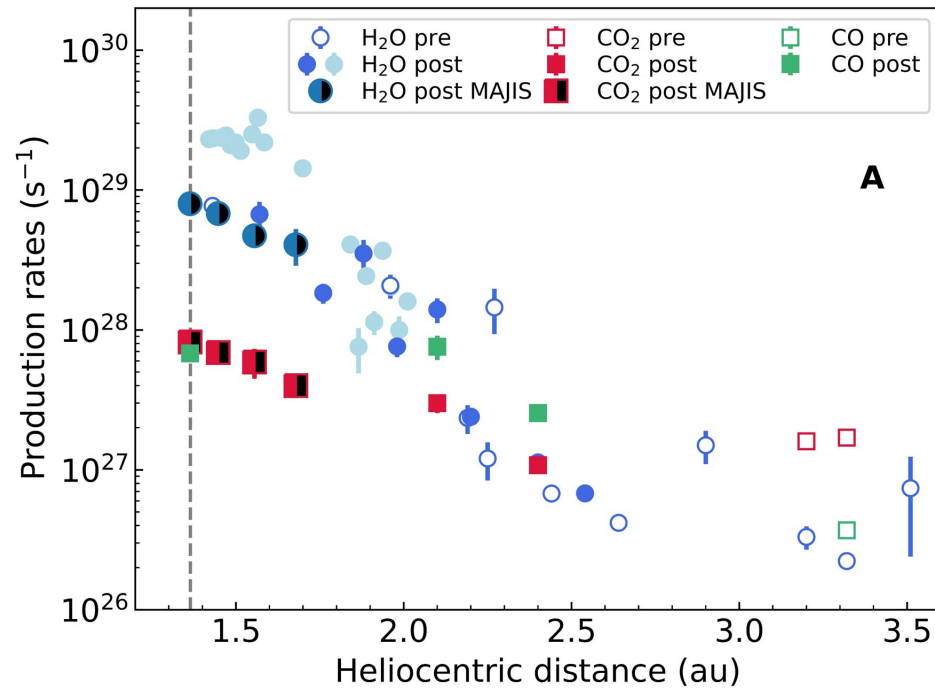
Data from MAJIS: spectro-imaging from 0.5 to 5.6 μm

Bockelée-Morvan, Poulet, et al., submitted



- **Red dust color** at $\lambda < 0.9 \mu\text{m}$ (15% per 100 nm)
- consistent with organic-rich dust
- **Detection of H₂O and CO₂** from 1.36 to 1.68 au
- **Detection of the 3.4- μm band**
 - ✓ residual peaks at the frequency of -CH₂ and -CH₃ stretching modes
 - ✓ identification elusive

Key measurements for investigating the evolution of the activity of 3I/ATLAS



Main findings H_2O :

- H_2O production rate much smaller than from SOHO/SWAN
- radial distribution consistent with near nucleus production
- H_2O production higher than the nucleus can produce :
 - ✓ 3I/ATLAS is an hyperactive comet with H_2O production from icy grains near nucleus

Main findings CO_2 :

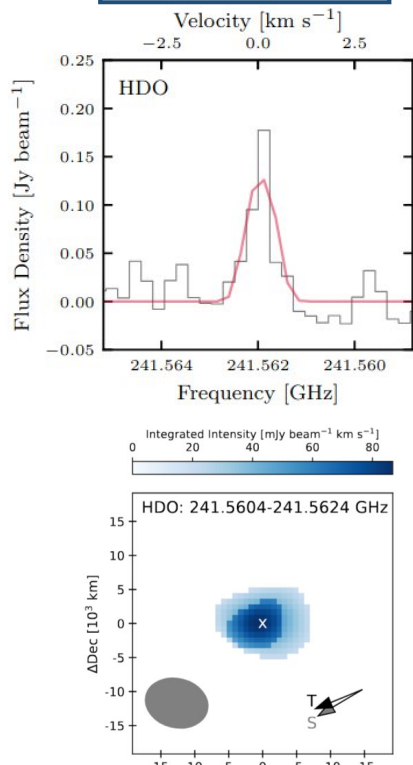
- $\text{CO}_2/\text{H}_2\text{O} = 10\%$ at perihelion in MAJIS FOV
 - ✓ but likely much higher at the nucleus
- $\text{CO}_2/\text{CO} \sim 1$
- $\text{C}/\text{O} > 0.17$: implies formation above CO_2 snowline in the parent protoplanetary disk

Isotopic measurements from ALMA and JWST

Deuterium

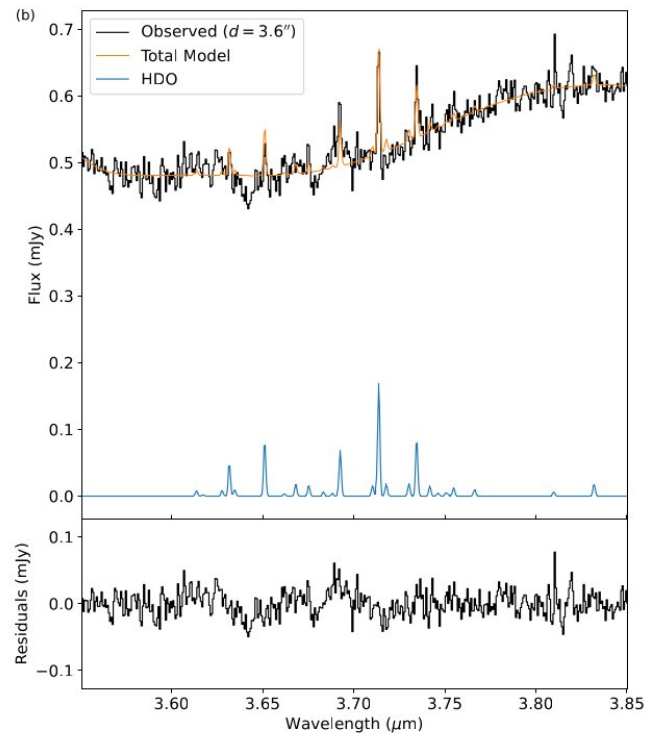
- HDO detected with ALMA & JWST
- CH₃D detected with JWST

ALMA HDO



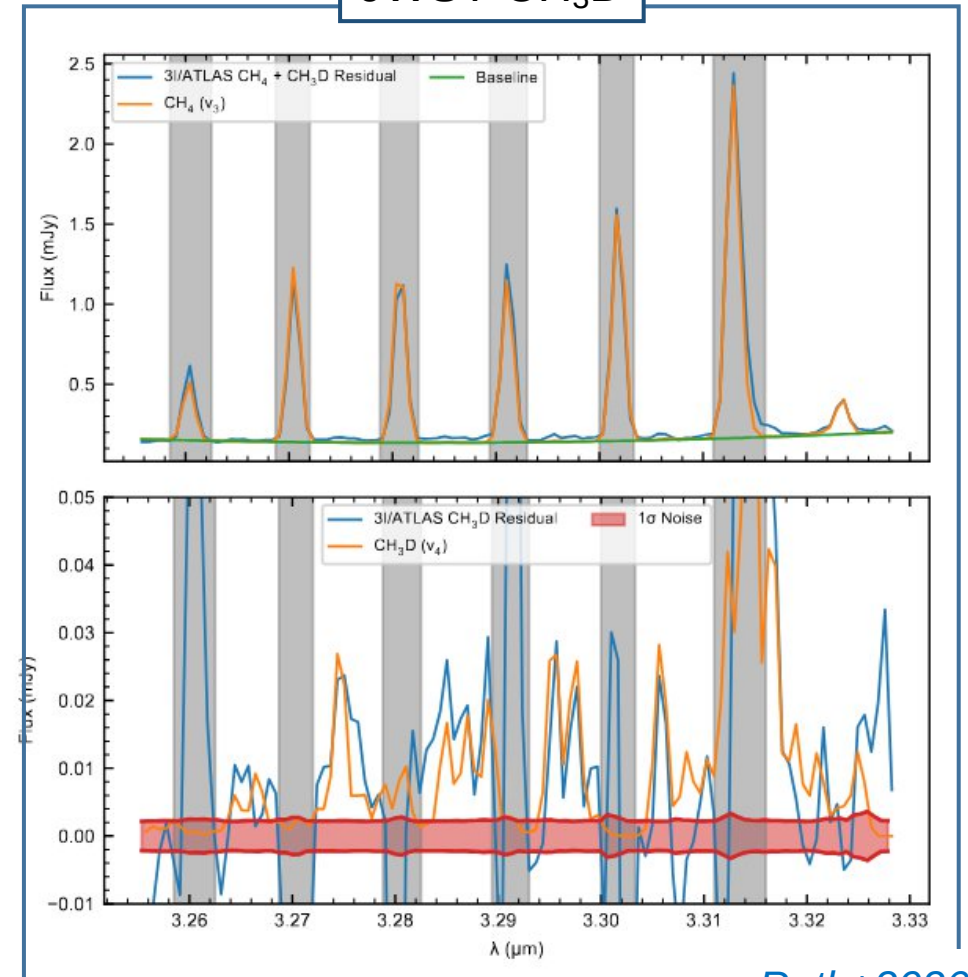
Salazar-Mansano+2026

JWST HDO



Cordiner+2026

JWST CH₃D



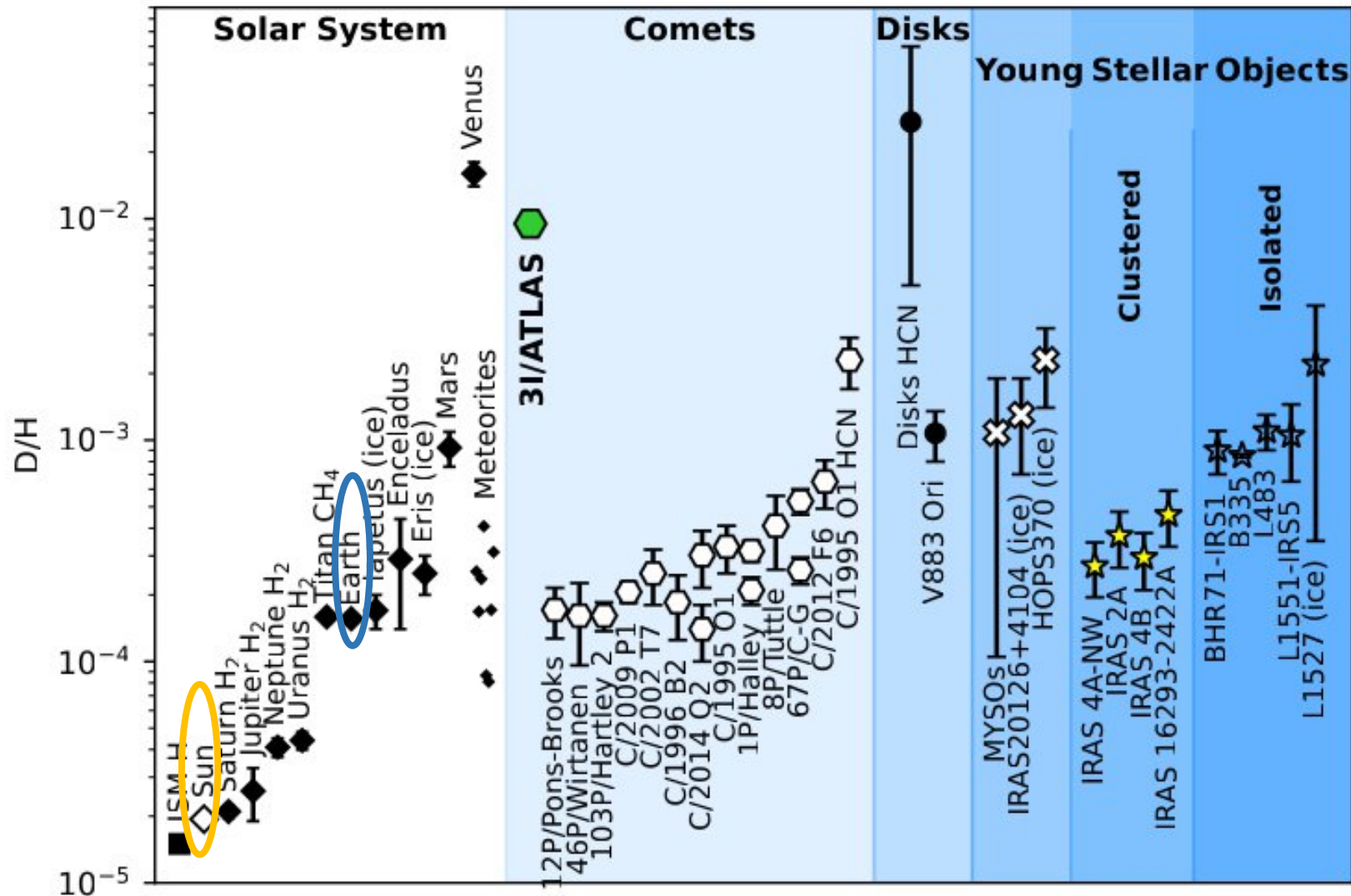
Roth+2026

- ✓ D/H in H₂O = 0.98 +/- 0.06 %
- ✓ D/H in CH₄ = 3.31 +/- 0.34 %

=> both are 4 times higher than in comet 67P

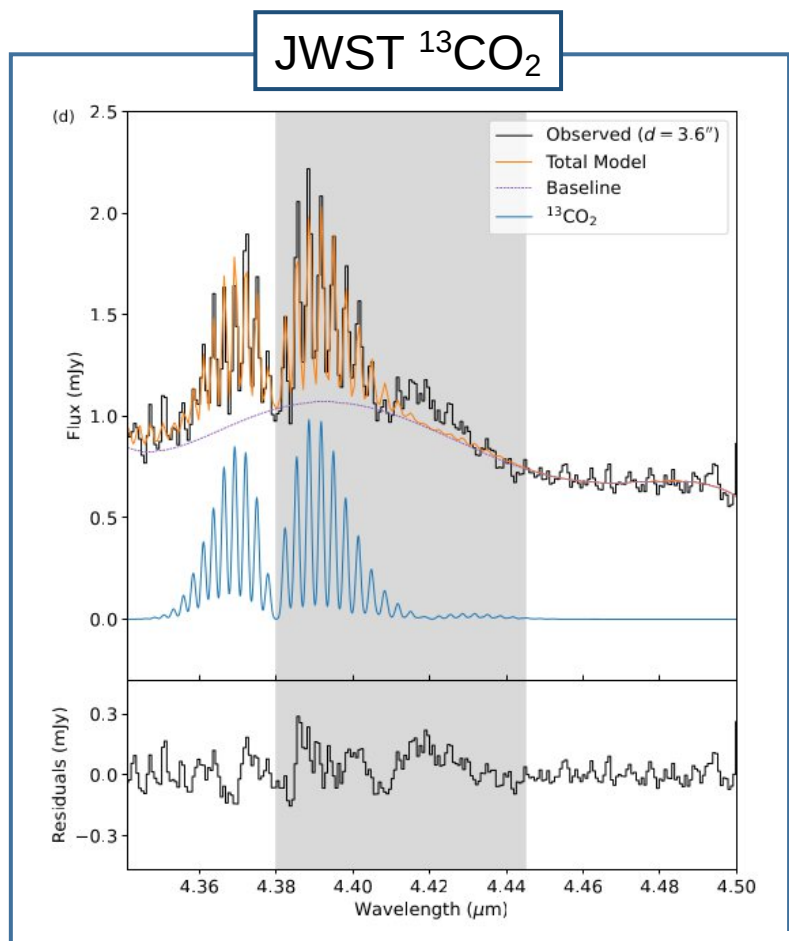
Deuterium fractionation occurs mainly in the pre-stellar phase :

- implies low-T environment and high ionization conditions (UV and cosmic ray fluxes)
- expected in the vicinity of the low-metallicity regions of intense, massive star-formation

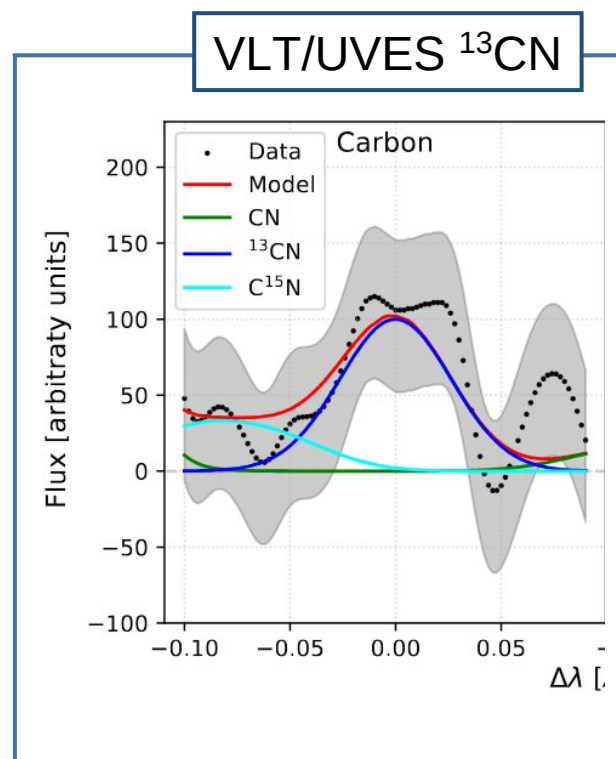


Isotopic measurements from JWST and UVES/VLT : Carbon

- $^{12}\text{C}/^{13}\text{C}$ measured in CO, CO₂ and CN

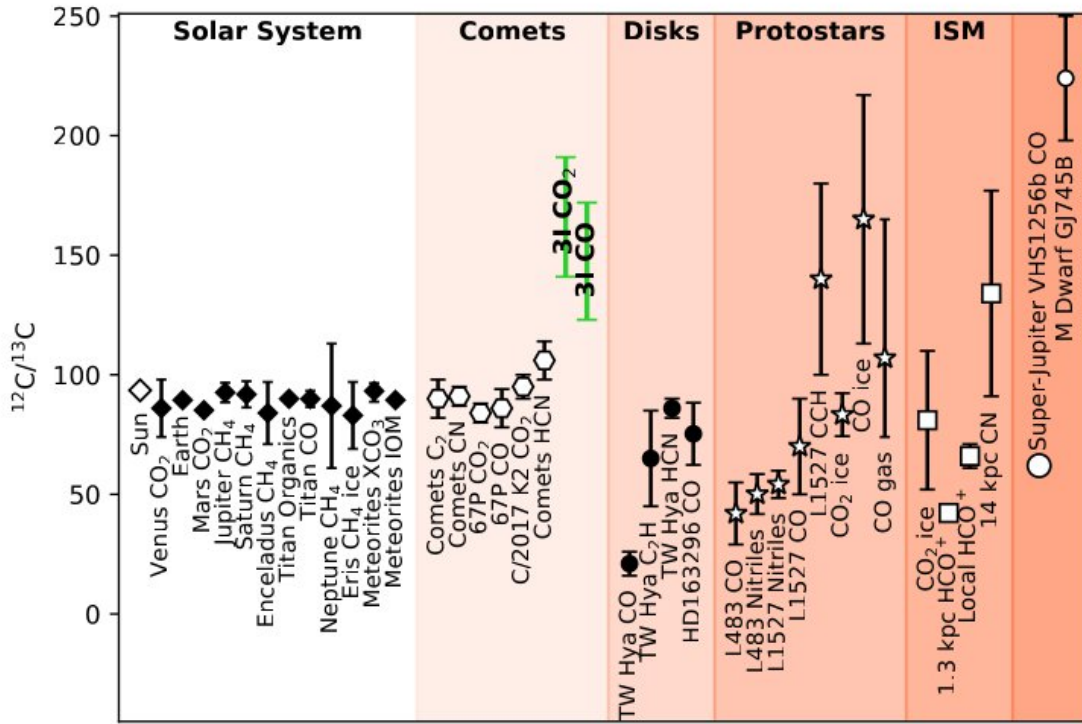


Cordiner+2026



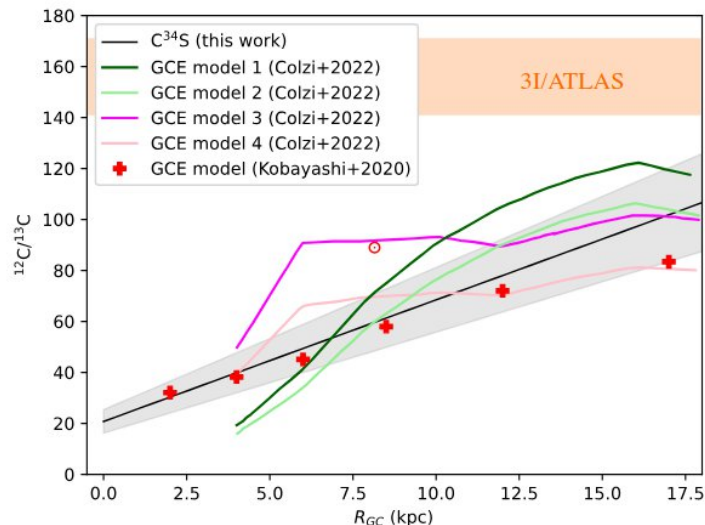
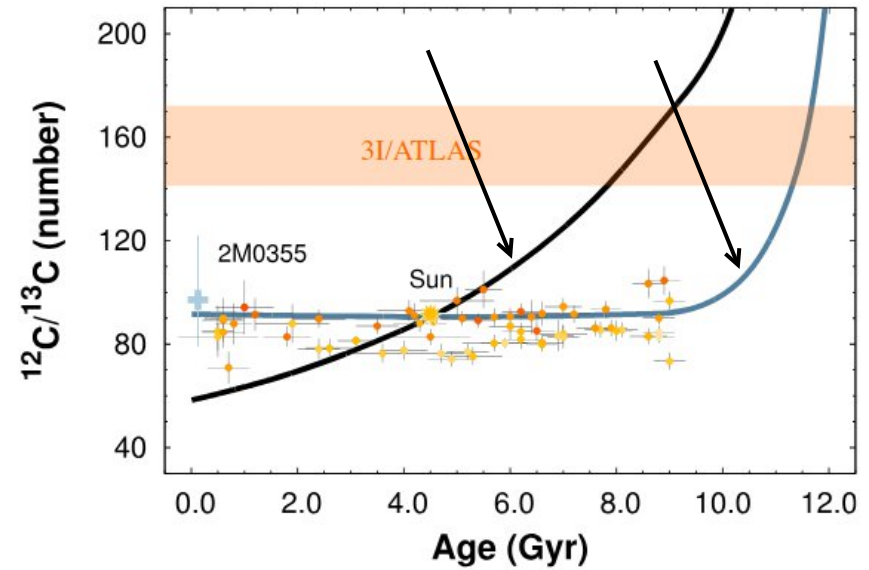
Opitom+2026

	$^{12}\text{C}/^{13}\text{C}$
CO ₂	141–191
CO	123–172
CN	147 (+87, -40)



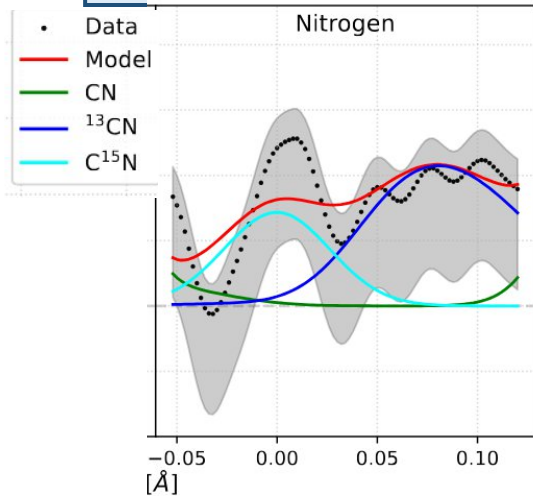
3I is very old

Models of galactic chemical evolution with ^{13}C production from novae with white dwarfs of different range of masses (nearby galactic regions)

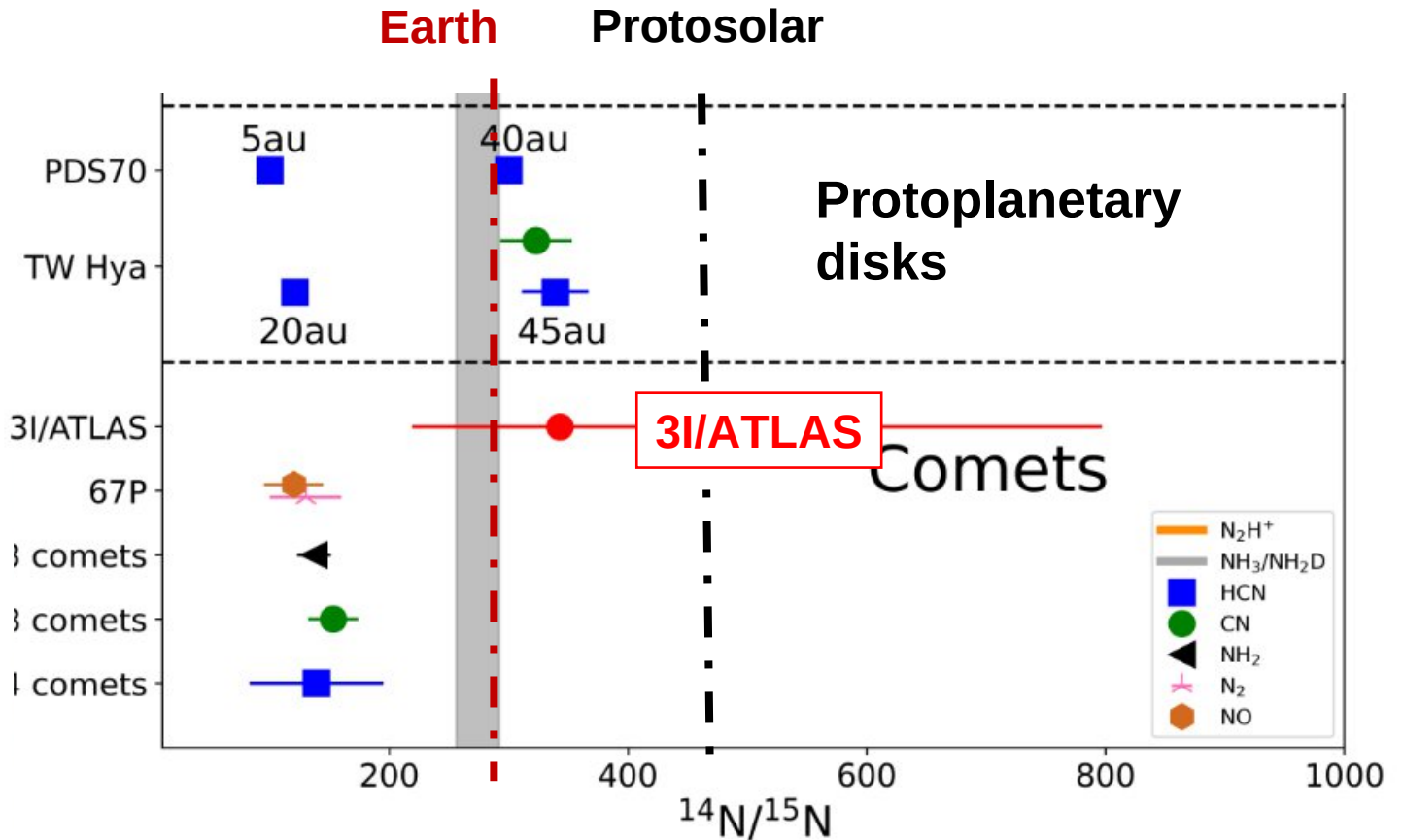
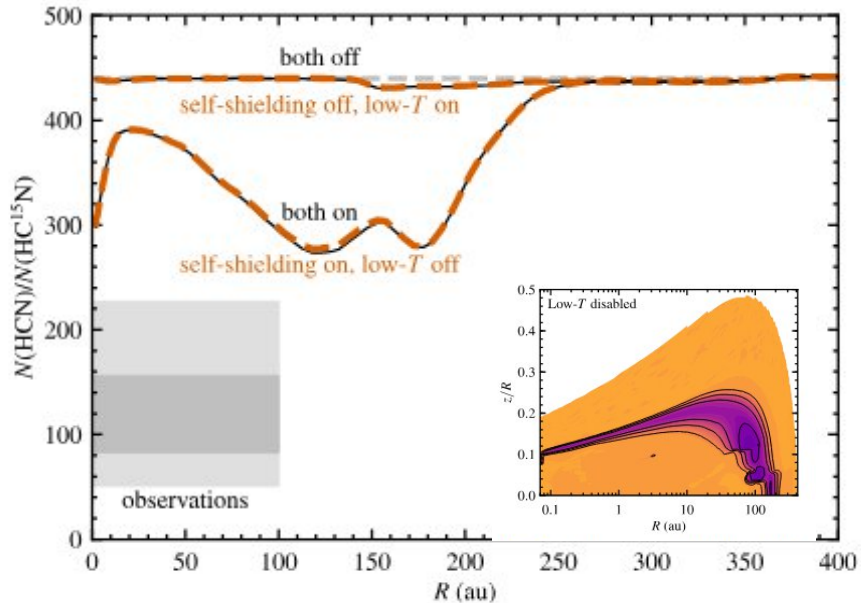


and possibly 3I formed in the outer edges of the Galaxy in a metal-depleted environment : higher $^{12}\text{C}/^{13}\text{C}$ expected

Isotopic measurements from VLT/UVES : Nitrogen



N isotopic fractionation (Visser+2018)



$^{14}\text{N}/^{15}\text{N}$ in 3I is higher than in Solar System comets

Conclusion

3I/ATLAS presents distinct compositional and isotopic properties from solar system comets

Galactic environment	old, distant, metal-poor	High $^{12}\text{C}/^{13}\text{C}$, high dynamic age
Parent molecular cloud	Cold, high ionisation rate	High D/H, distinct molecular composition
Parent protoplanetary disk	Limited isotopic exchanges ?	High D/H
Parent protoplanetary disk	Formation beyond CO_2 (or even CO) snow lines	High CO, CO_2 abundances
Parent protoplanetary disk	Formation of 3I in outer regions ?	Higher $^{14}\text{N}/^{15}\text{N}$ than in Solar System comets. Less efficient selective dissociation of N_2