

An overview of the properties of the interstellar comet 3I/ATLAS



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Rosetta/OSIRIS/MPS

Comets

Their properties provide key insights into the formation of the Solar System.

Cometary ices:

- Deuterium-rich complex molecules (with D/H ratios) similar to those found in the ISM
=> likely formed in the protostellar phase

Refractory material:

- 50/50 mix of organic matter and minerals
- Presence of high-T minerals found in asteroid samples and formed near the proto-Sun
=> large-scale radial mixing in the solar nebula

Highly porous bodies composed of hierarchical aggregates of 100-nm units:

=> witnesses of planetesimal formation

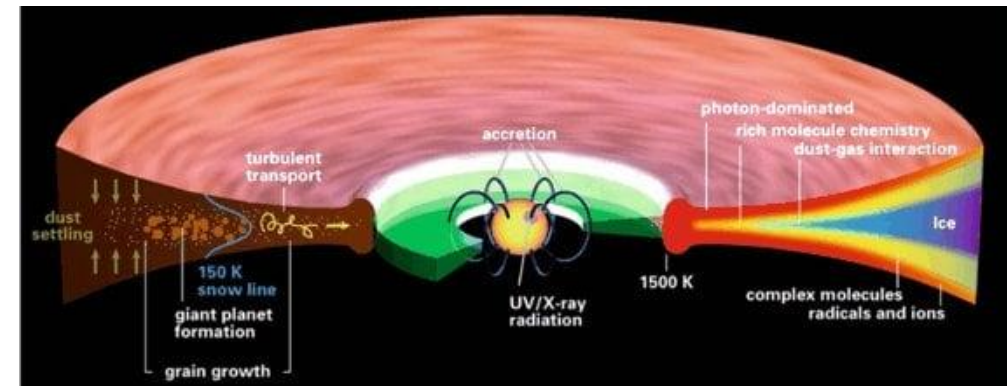
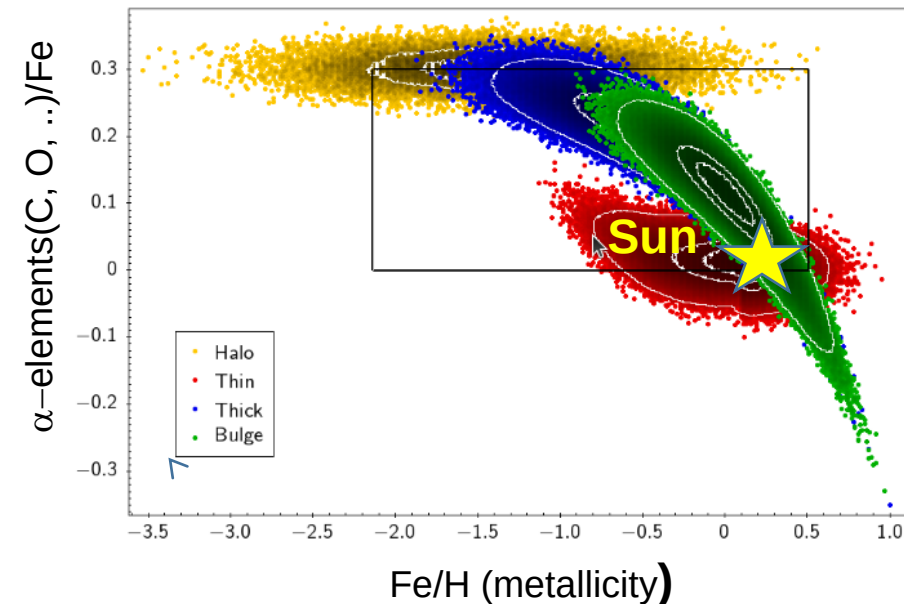
Interstellar comets

A complementary way to understand planet formation in **planetary systems** other than our own

Cabral+2019

The molecular and isotopic composition of icy 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 reduce the D-enrichment in water acquired in the parent molecular cloud
 - ✓ radial mixing
- **when and where the comet agglomerated**
 - ✓ e.g., wrt to the various snowlines

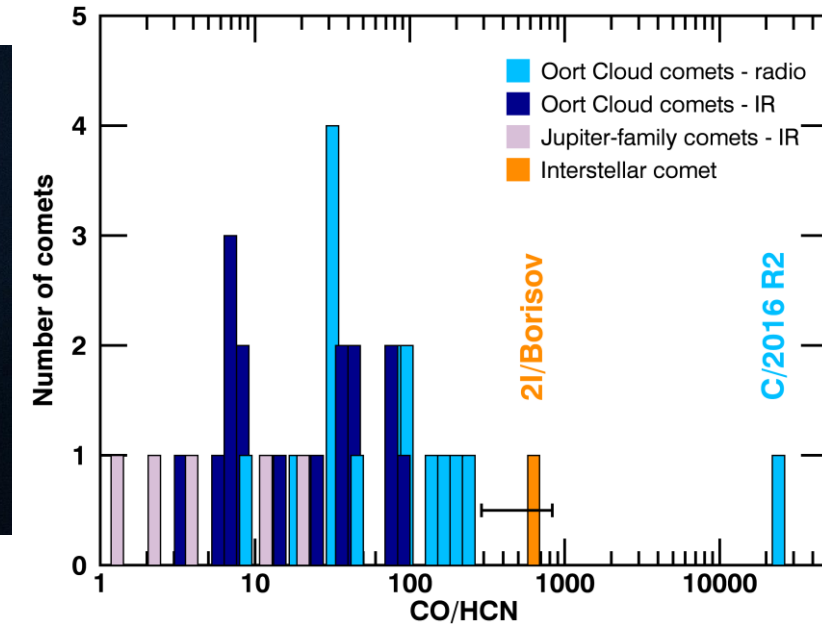


1I/'Oumuamua

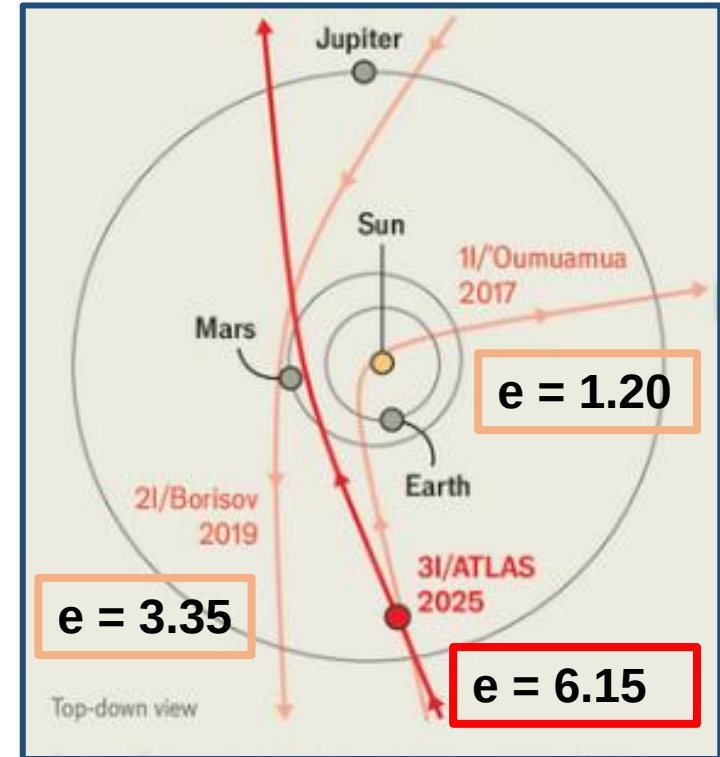
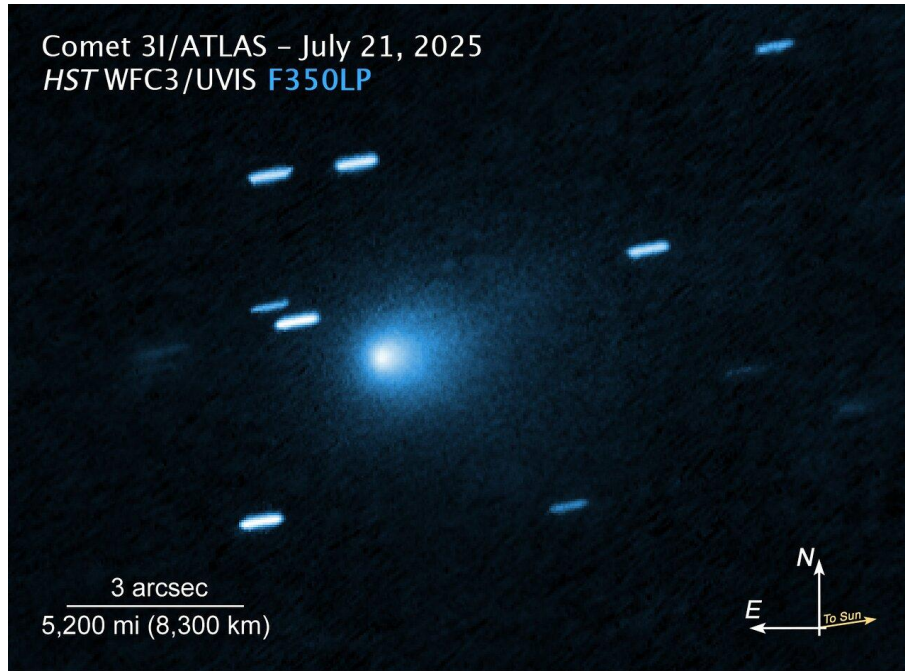


- Discovered in 2017 with PanSTARRS when at 0.2 AU from Earth
 - ✓ Brief observational campaign
 - ✓ Small (200 m equivalent diameter), elongated nucleus, complex rotation, red color
- Coma undetected but **non-gravitational forces affecting the orbit** : origin disputed (H_2 , N_2 outgassing ?)

2I/Borisov



3I/ATLAS



- Discovered on 1 July 2025 by ATLAS robotic telescope at 4.45 ua from Sun, 3.5 ua from Earth
 - ✓ Pre-discovery observations (TESS, ZTF, Vera Rubin): was active at 9 au from Sun
- 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 2I/Borisov (and 10 times more than 67P) => a quite active comet**

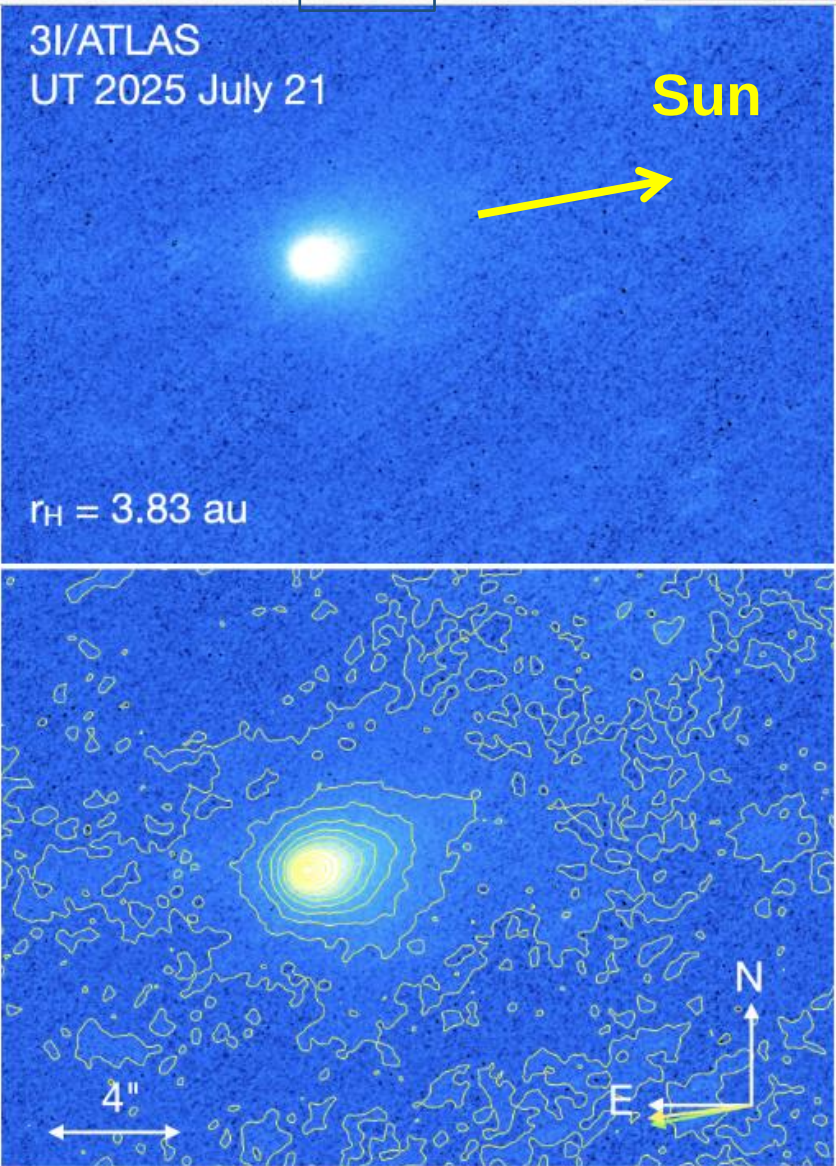
Large observing campaign using nearly all facilities from ground and space including space missions : Exomars/TGO, Mars-Express, Europa-Clipper, JUICE etc

Nucleus size



Nucleus size

HST



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
$\lesssim 4$	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

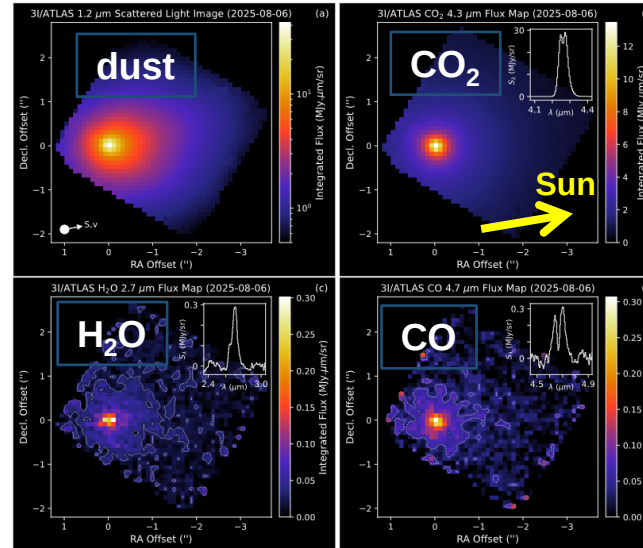
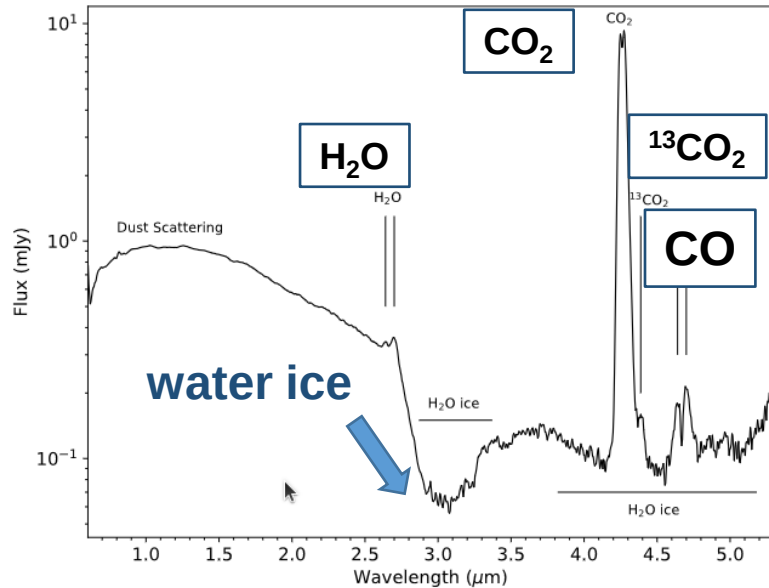
- ✓ Nucleus radius $R_n = 1.3$ km assuming $p_v = 0.04$
- ✓ Non-gravitational acceleration (rocket effect) supports a small nucleus

Molecular composition

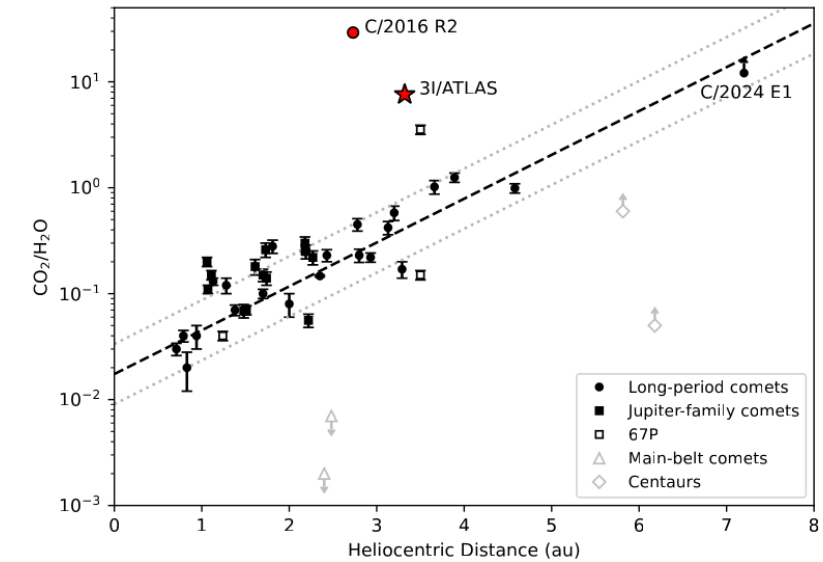


CO₂ and CO drivers of distant activity

JWST comet@3.32 au (6 Aug. 2025)



CO₂/H₂O production rate ratio

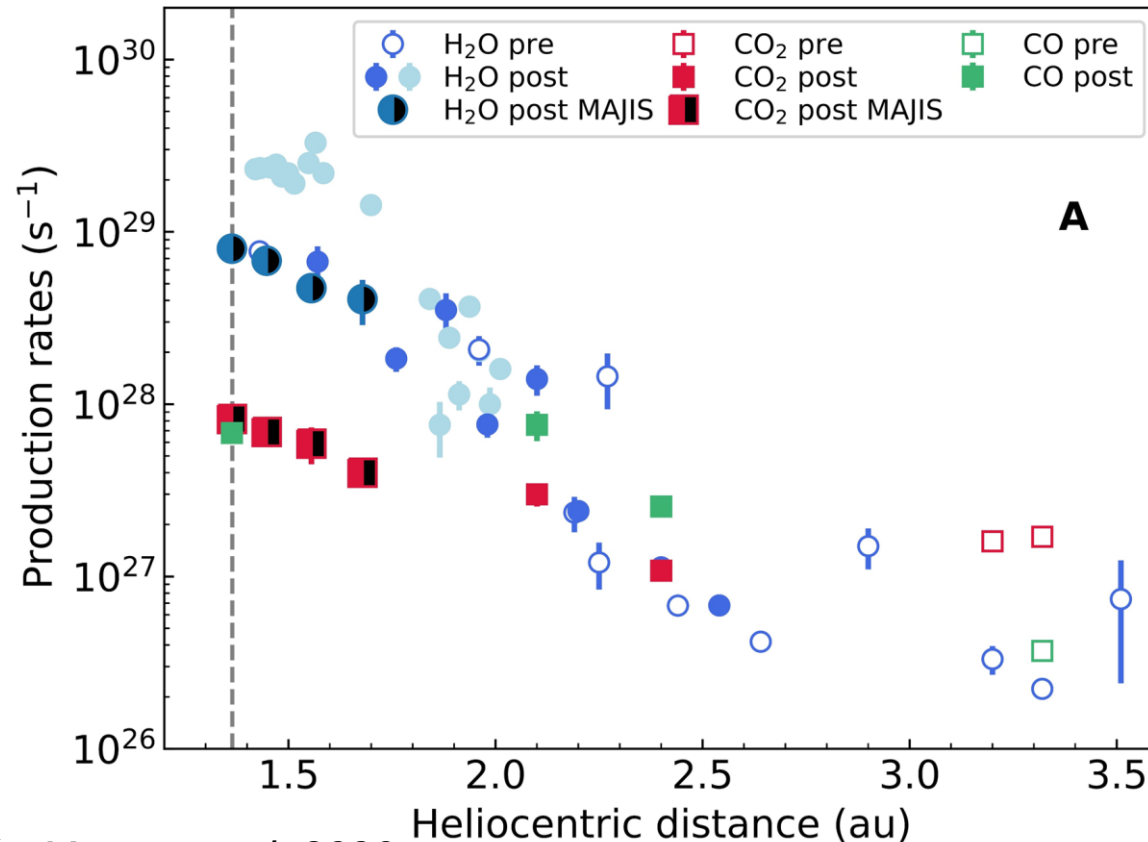


Cordiner+2025

- Pre-perihelion @ 3.32 au: CO₂ production dominating over CO production
 $Q(\text{CO}_2)/Q(\text{H}_2\text{O}) = 8$; $Q(\text{CO})/Q(\text{H}_2\text{O}) = 1.7$

= > **High CO, CO₂ abundances indicate 3I/ATLAS formation beyond the CO₂ snow line**

Evolution of the production of the main species



Bockelée-Morvan et al. 2026

Several lines of evidence that H₂O is **subliming from icy grains in the coma**:

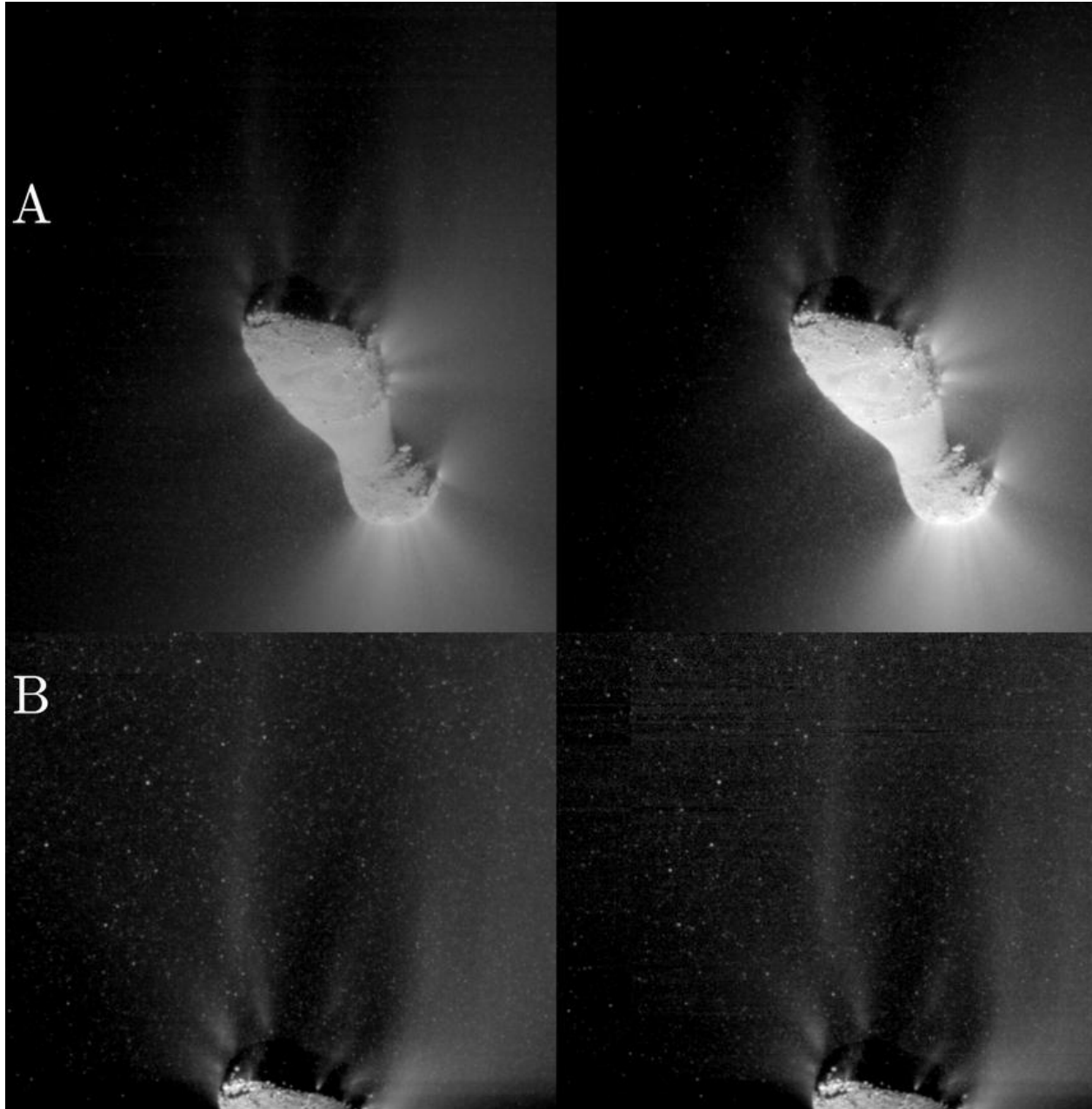
- ✓ Water ice signatures
- ✓ Aperture dependence of H₂O production rates
- ✓ H₂O radial distribution at large r_h
- ✓ H₂O production at perihelion requires a icy area fraction of the nucleus of 200%

3I/ATLAS is an **hyperactive comet** as 103P/Hartley studied by the Deep Impact mission

This introduces biases when comparing abundance measurements, and when comparing 3I/ATLAS to other comets

- High CO & CO₂ productions at perihelion: 10% wrt H₂O
- Low gas velocities => activity driven by sub-surface release of CO and CO₂ releasing icy chunks

103P/Hartley 2, the prototype of hyperactive comets

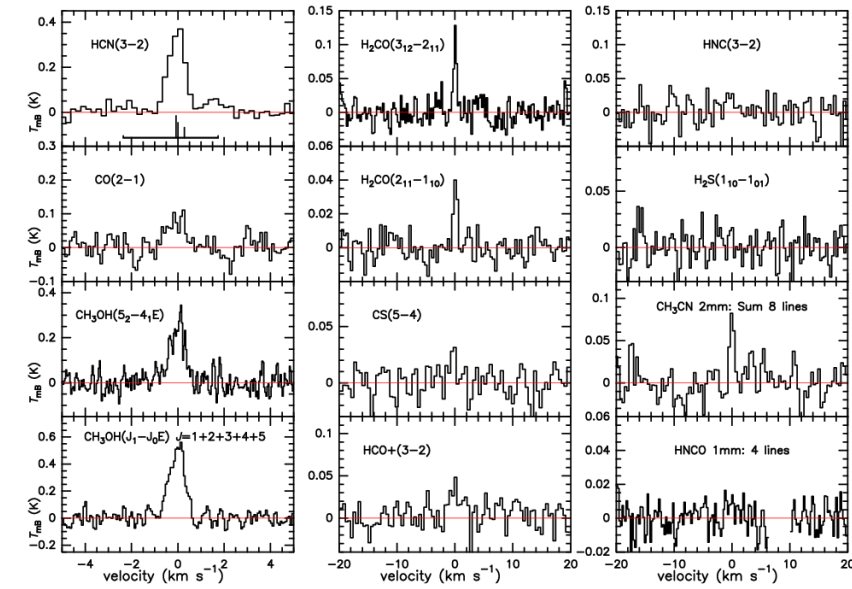


EPOXI/Deep Impact/NASA

Other gas phase species

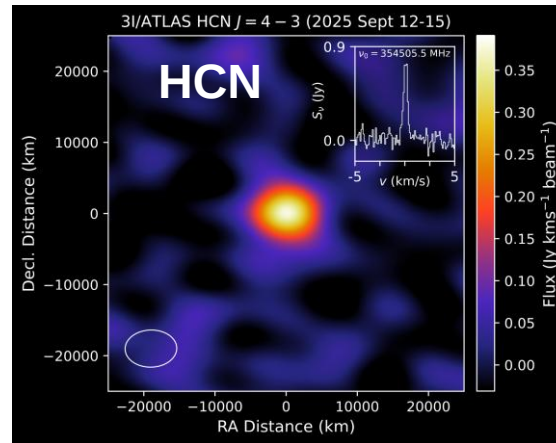
- **Microwave** (e.g. IRAM, ALMA): CO, HDO, CH₃OH,, H₂CO, CS, OCS, HCN, CH₃CN
- **Infrared** (e.g. JWST, VLT, JUICE): H₂O, CO₂, CO, CH₃OH, CH₄, CO
- **Optical, UV** (e.g. VLT, HST): OH, CO⁺, CO₂⁺, CN, C₂, C₃, NH, NH₂, NiI, FeI, N₂⁺,

IRAM 30-m



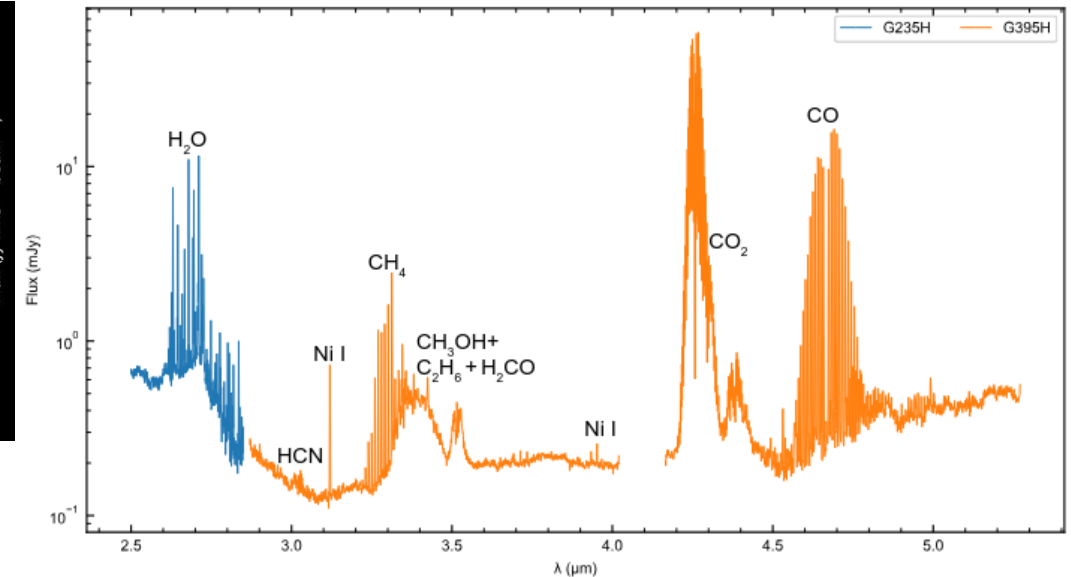
Biver et al. 2026

ALMA



Roth et al. 2026

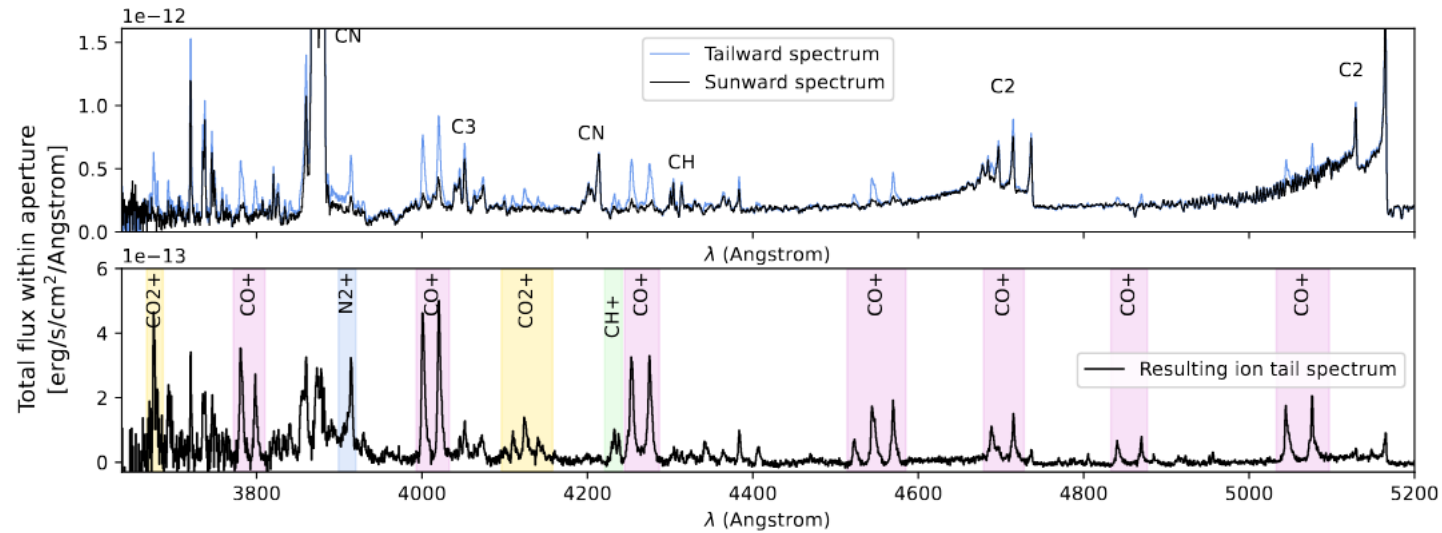
JWST



Roth et al. 2026

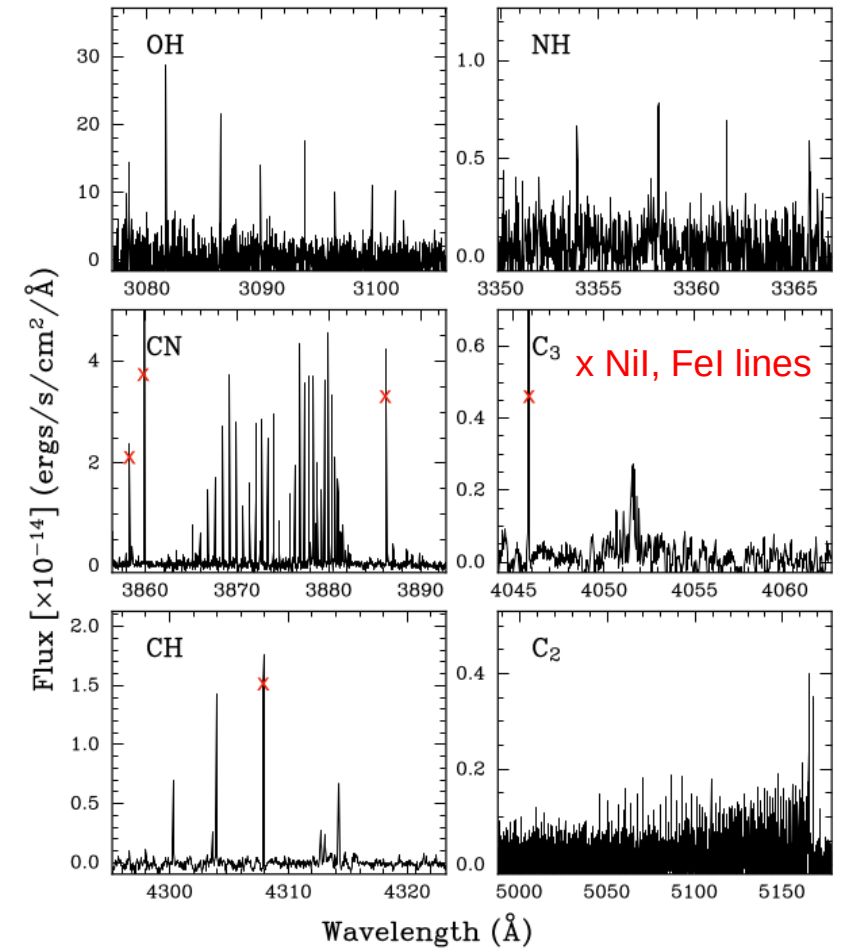
Other gas phase species (optical)

WHT/WEAVE LIFU



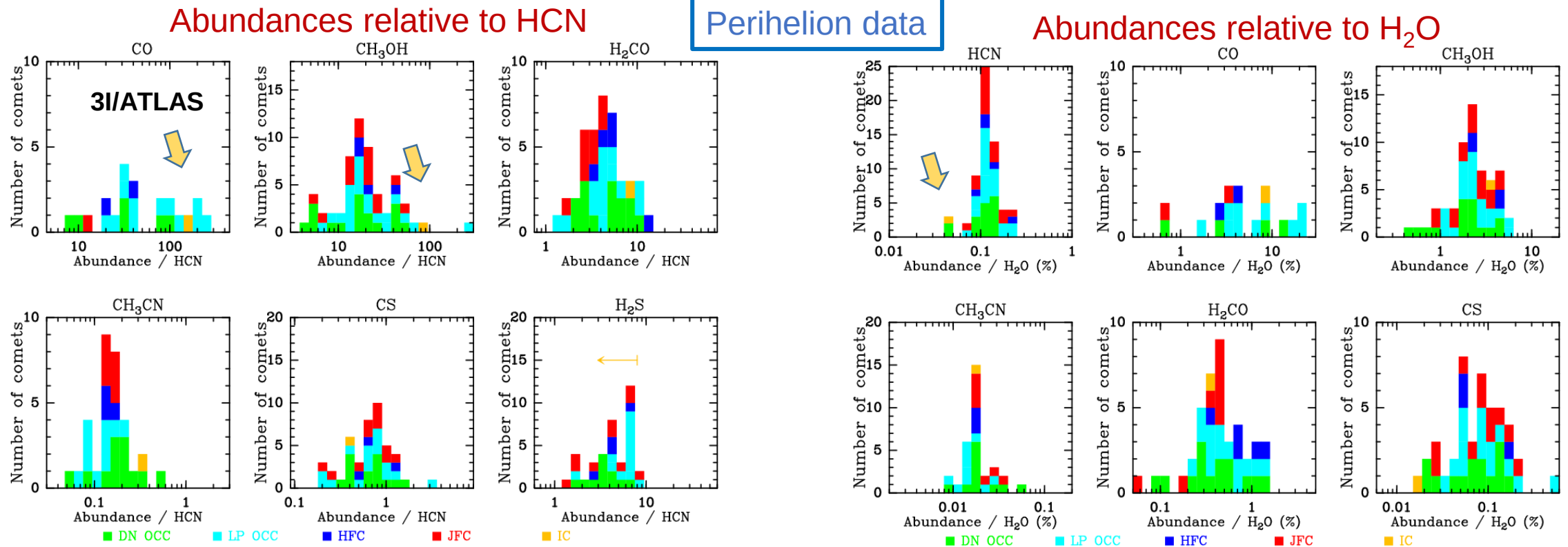
Ferrellec et al. 2026

VLT/UVES



Aravind+2026

Comparison with solar system comets

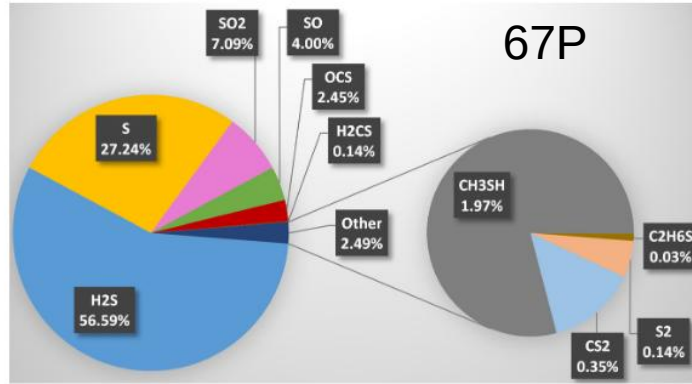


Biver et al. 2026

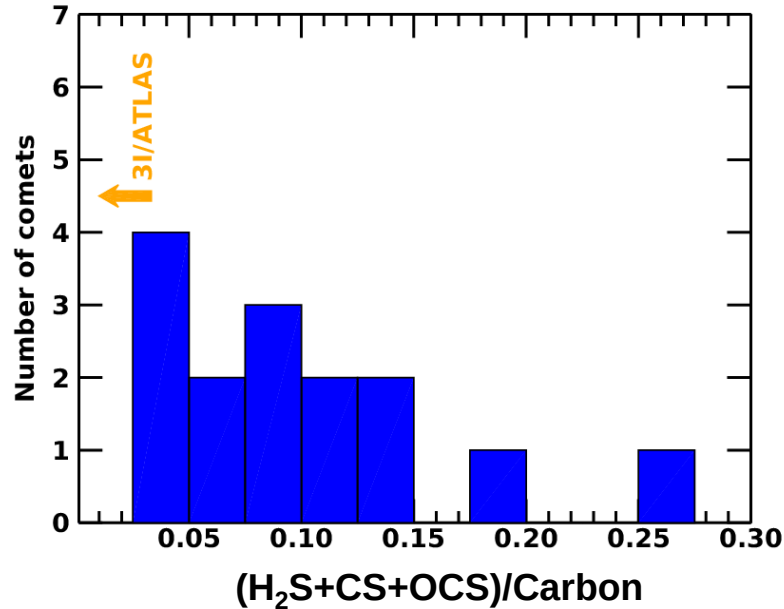
- Most molecules have **enriched** abundances with respect to HCN, **except CS which is depleted**
- Apparent HCN/H₂O depletion for 3I, but H₂O is released from icy particles
- Strong CS/H₂O depletion

Molecular abundances in 3I's coma are atypical

Evidence for sulfur depletion

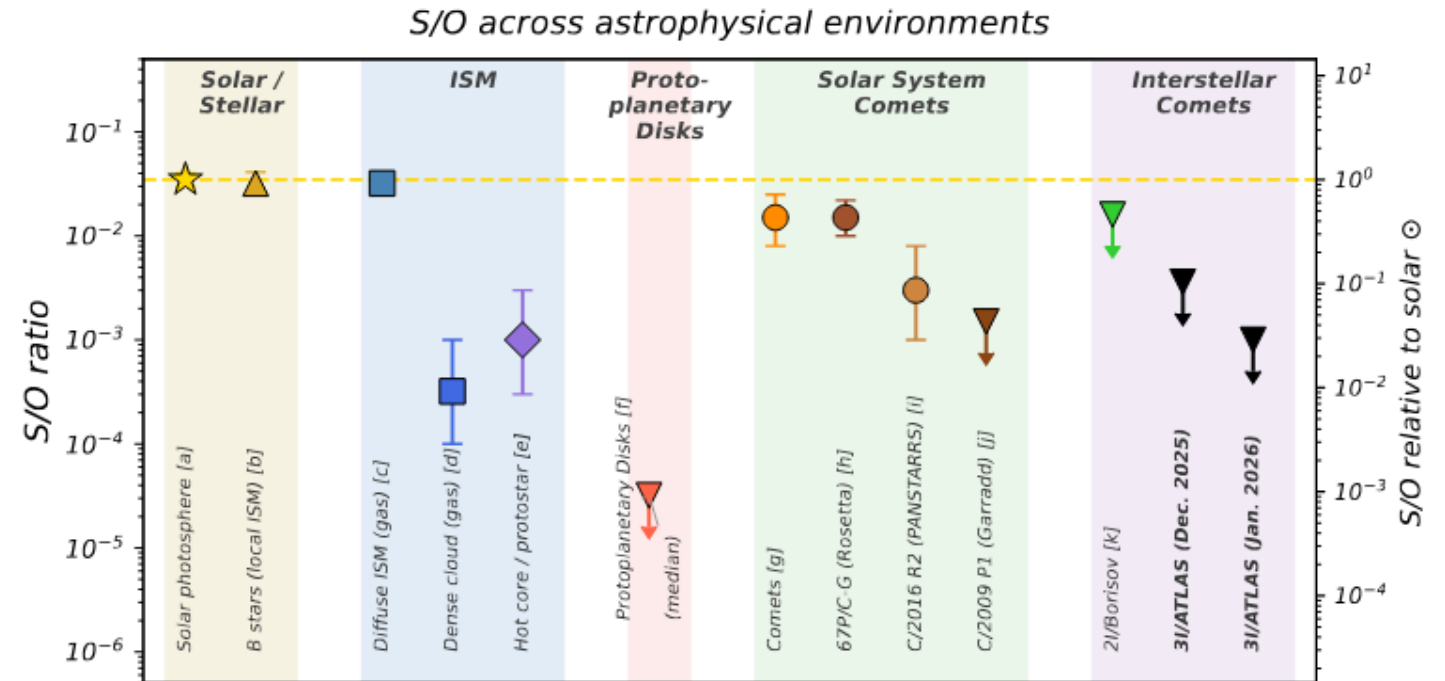


Calmonte+ 2017



Biver et al. 2026

Depletion of atomic sulfur probed by HST (UV)



Noolan et al. 2026

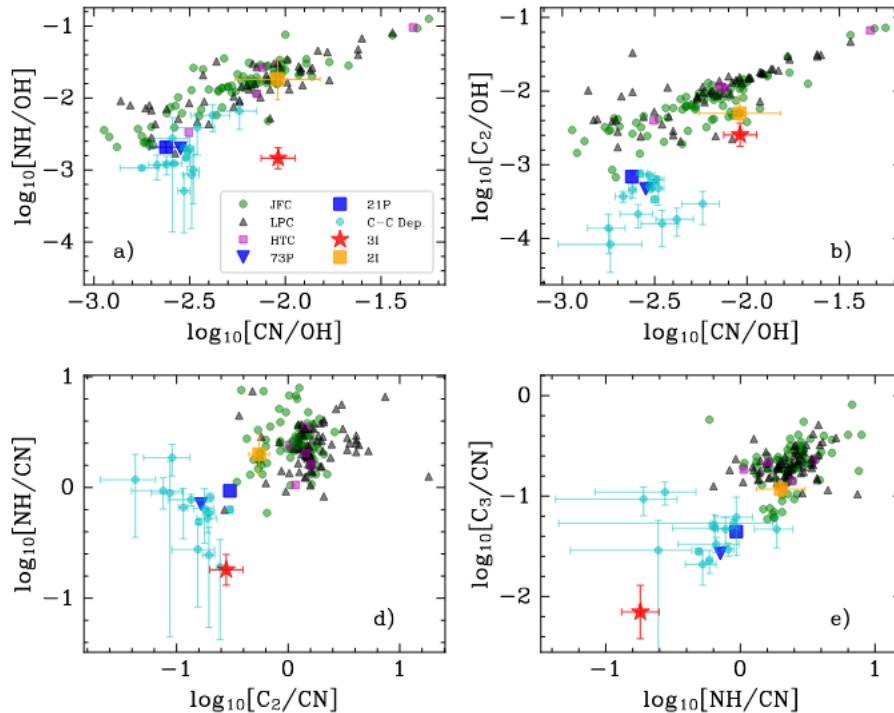
- Missing sulfur reservoir in refractory material such as FeS ?
- 3I formed in a S-poor galactic environment, as expected for regions with massive star formation rich in supernovae ejectas ?

Insights from optical spectroscopy - 1

- 3I/ATLAS presents similarity with the family of « **strongly carbon-chain depleted comets** » (Giacobini-Zinner family) showing strong depletion in C_2 , C_3 , and NH/NH_2 (Aravind+2026)
 - ✓ GZ-family (all are JFCs) composition is proved to be indicative of formation conditions (Bair & Schleicher 2025), **possibly low-T environment**.

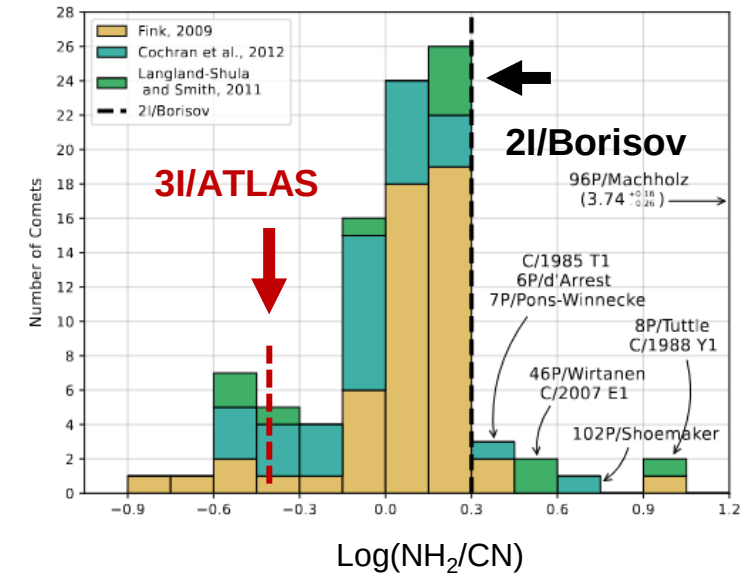
GZ-family

3I/ATLAS



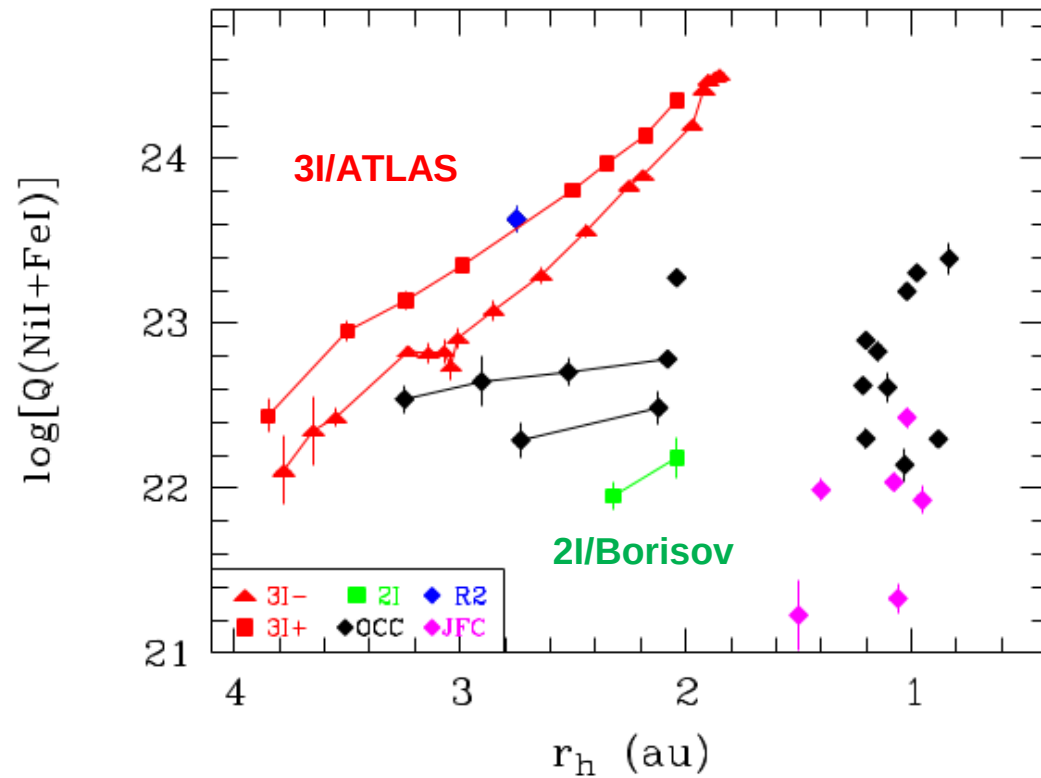
Aravind+2026

Bannister+2025, Kawakita+2026



3I/ATLAS and 2I/Borisov display distinct properties.

Insights from optical spectroscopy - 2



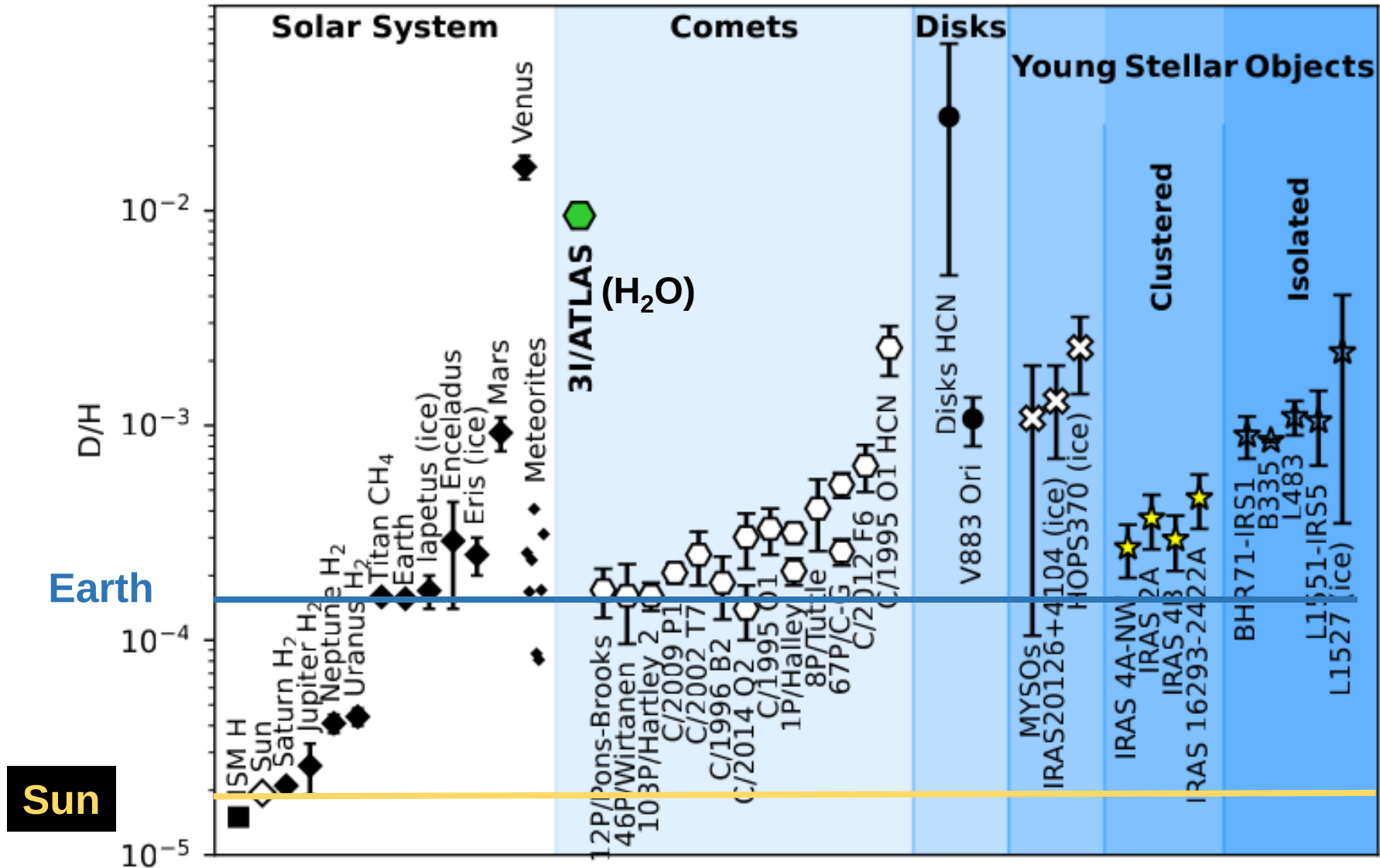
Hutsémekers+2026

- 3I/ATLAS is **N₂-rich** ($\text{N}_2/\text{CO} > 2\%$) => **low-T accretion** (< 20 K) (*Ferellec et al. 2026*)
- **Abundant FeI and NiI atoms** released, consistent with $\text{Fe}(\text{CO})_5$, $\text{Ni}(\text{CO})_4$ sublimation
✓ linked to abundant CO ?

Isotopic composition



Deuterium



Cordiner+2026

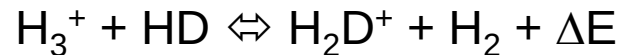
Isotopic measurements from ALMA and JWST:

Deuterium

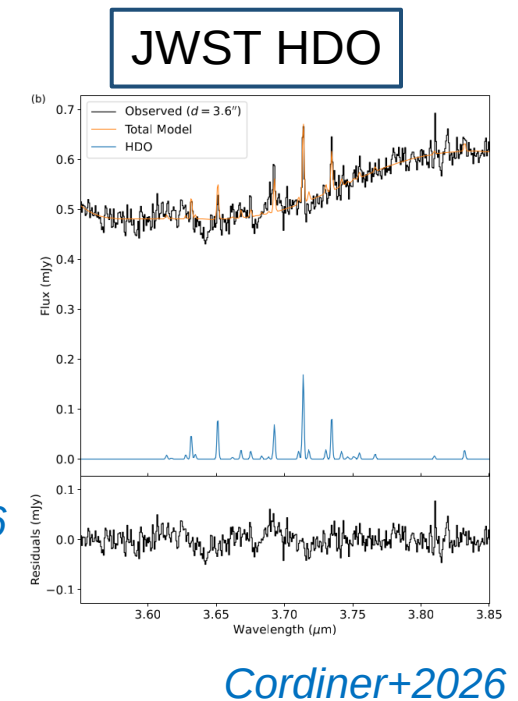
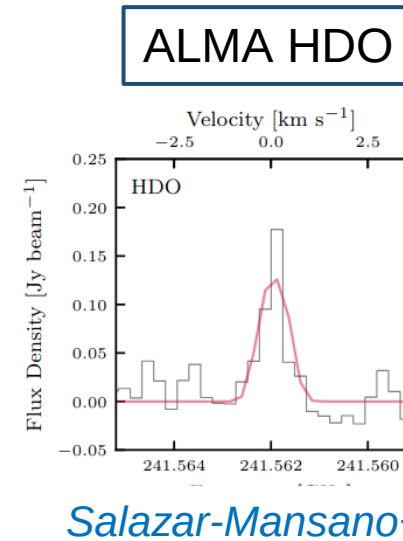
- HDO detected with ALMA & JWST
- CH₃D detected with JWST (Roth et al. 2026)

- ✓ D/H in H₂O = 0.98 +/- 0.06 %
- ✓ D/H in CH₄ = 3.31 +/- 0.34 %
- ✓ > 20 times values in Solar System comets

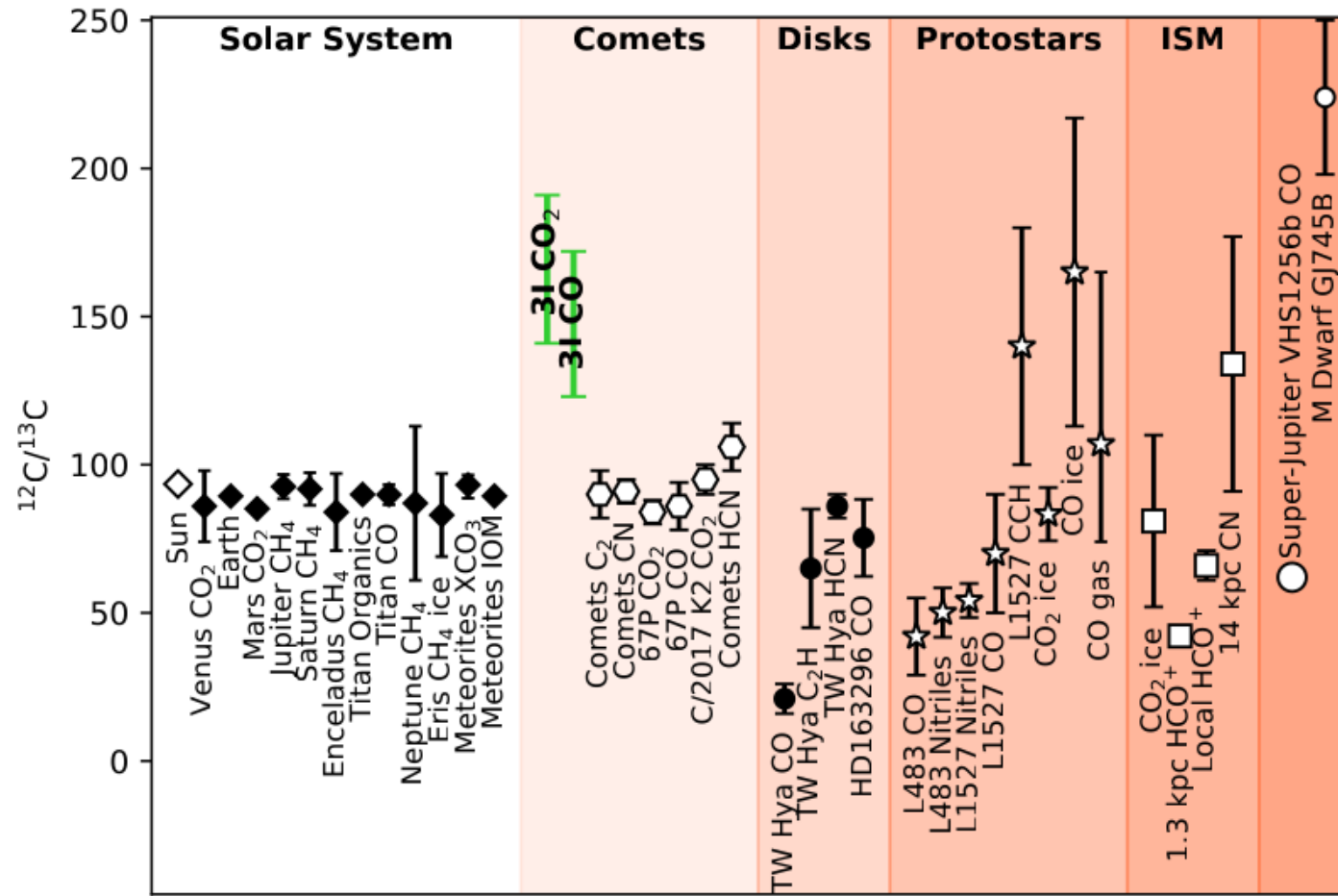
Deuterium fractionation occurs mainly in the pre-stellar phase :



- 3I's high D/H can be explained by **a low-metallicity, relatively dense environment** (Furuya+2026)



Carbon



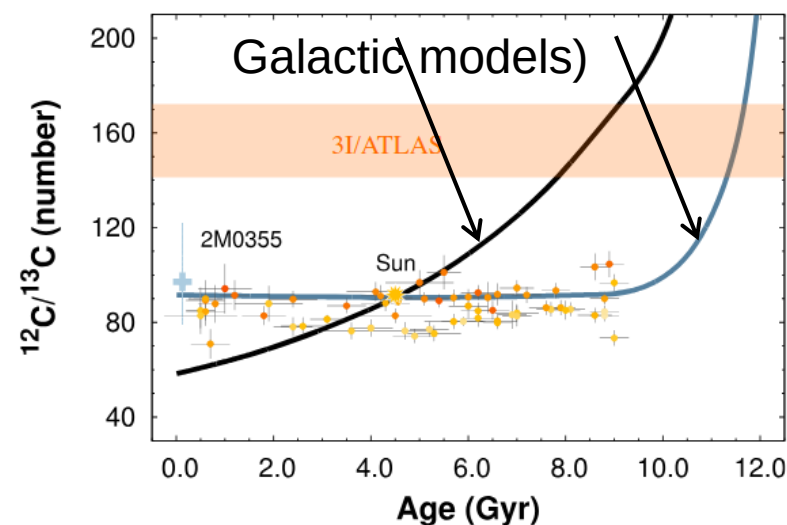
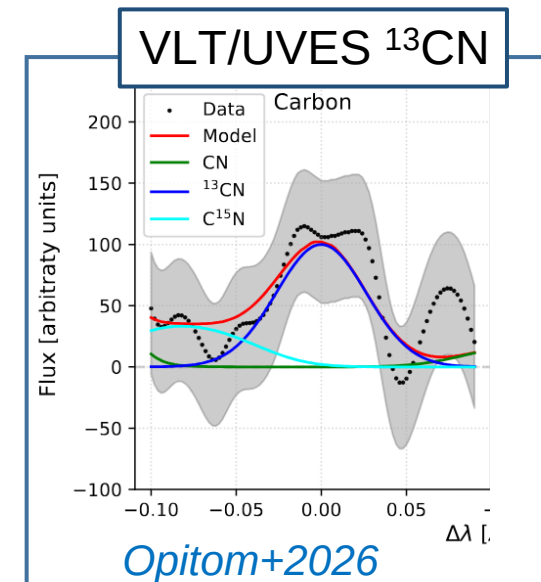
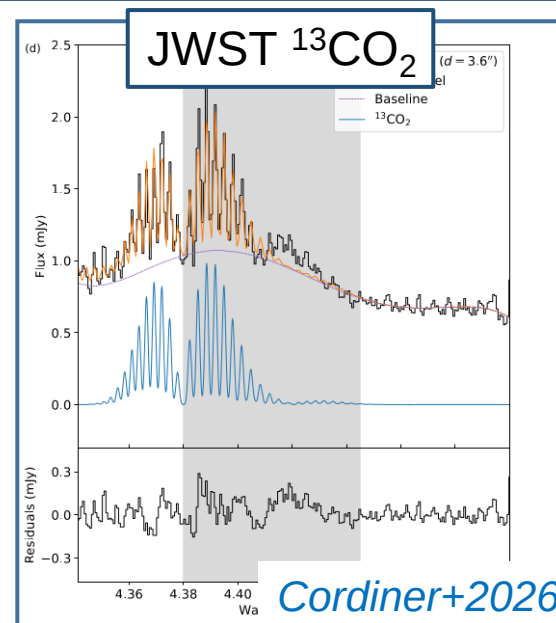
Cordiner+2026

Isotopic measurements from JWST and VLT: Carbon

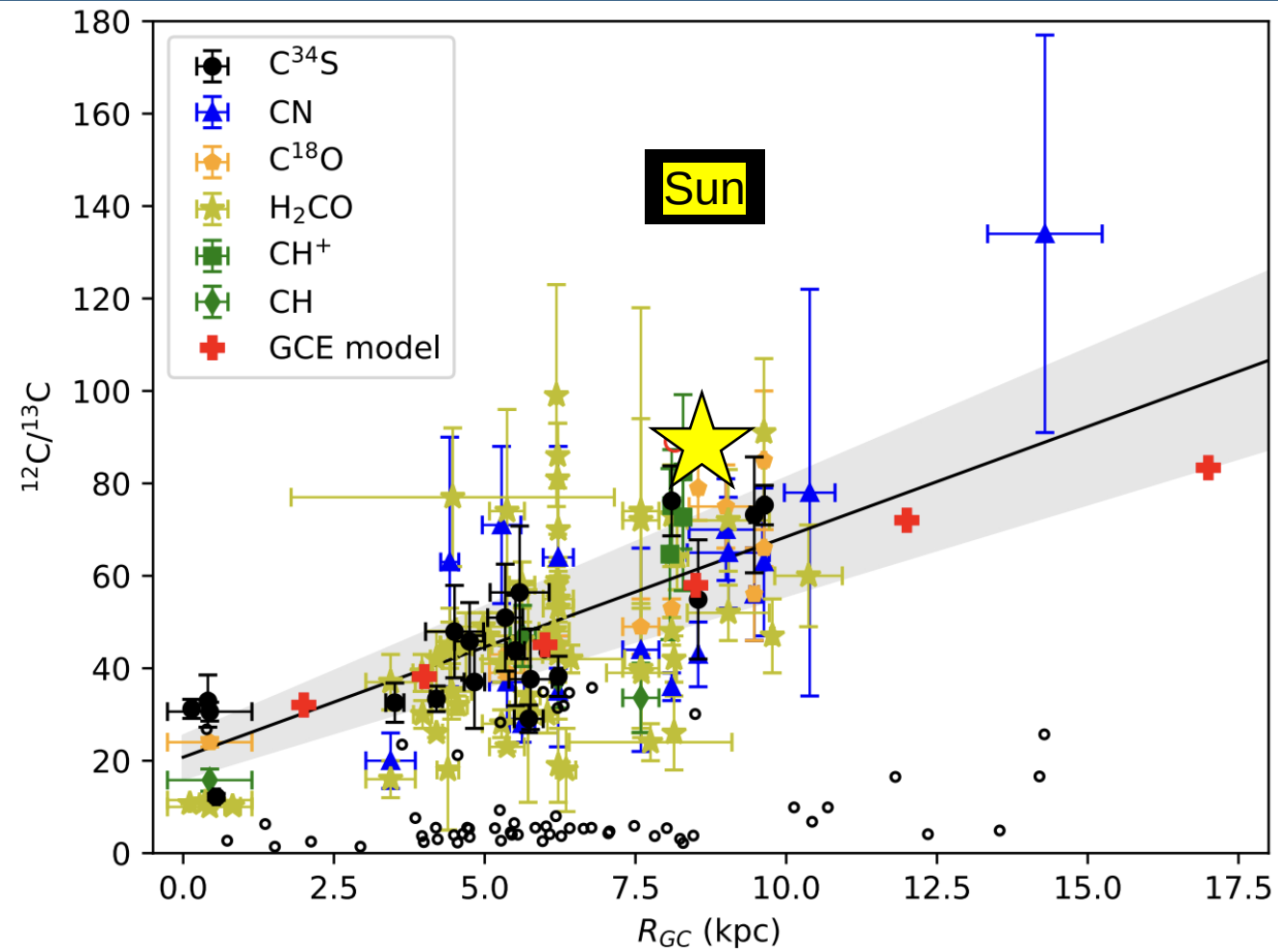
- High $^{12}\text{C}/^{13}\text{C}$ measured in CO , CO_2 and CN

	$^{12}\text{C}/^{13}\text{C}$
CO_2	141–191
CO	123–172
CN	147 (+87, -40)

- novae explosions involving white dwarfs lead to an enrichment in ^{13}C over time
= > 3I/ATLAS is very old (11 Gyr ?)
- formation in **the outer edges, metal-depleted**, of the Galaxy ? Small trend for higher $^{12}\text{C}/^{13}\text{C}$ observed and predicted

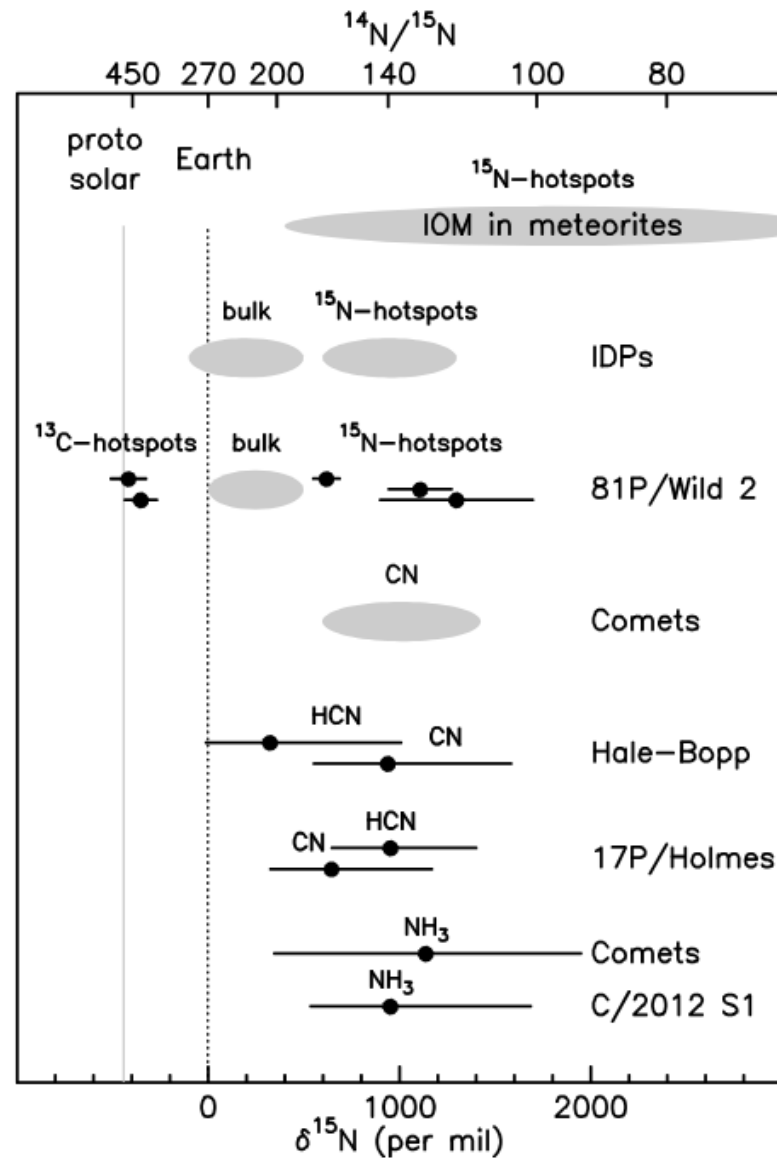


$^{12}\text{C}/^{13}\text{C}$ in the Galaxy



Yan et al. 2023

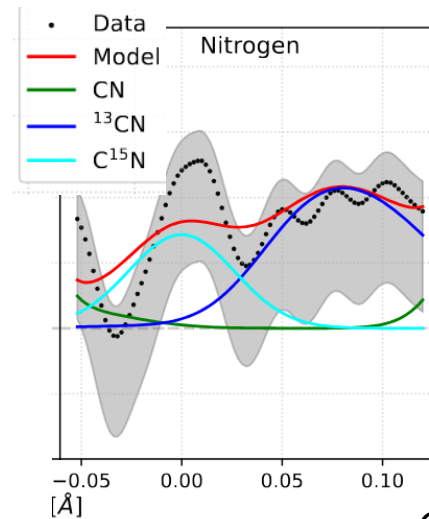
Nitrogen ($^{14}\text{N}/^{15}\text{N}$)



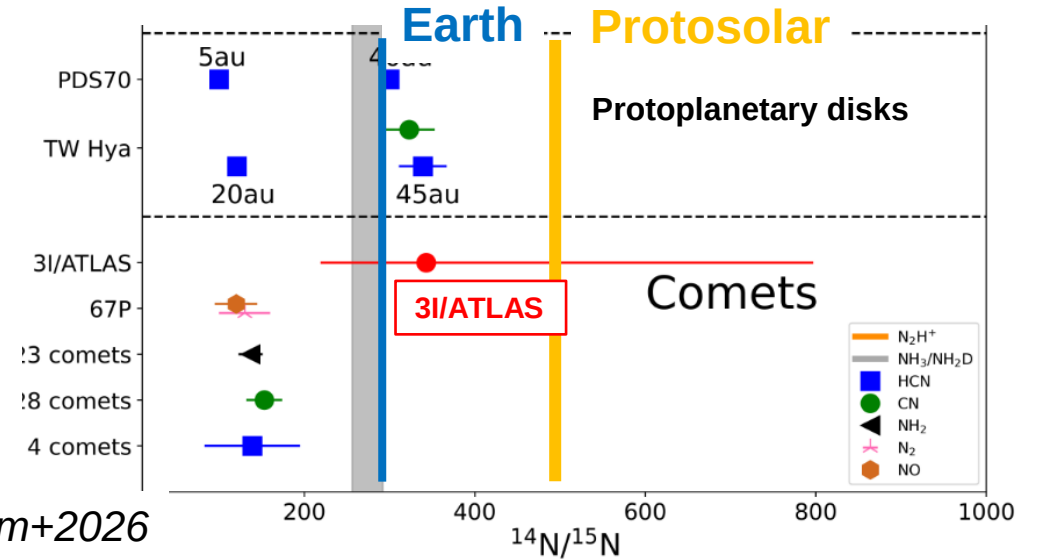
Bockelée-Morvan et al. 2015

Isotopic measurements from VLT/UVES: Nitrogen

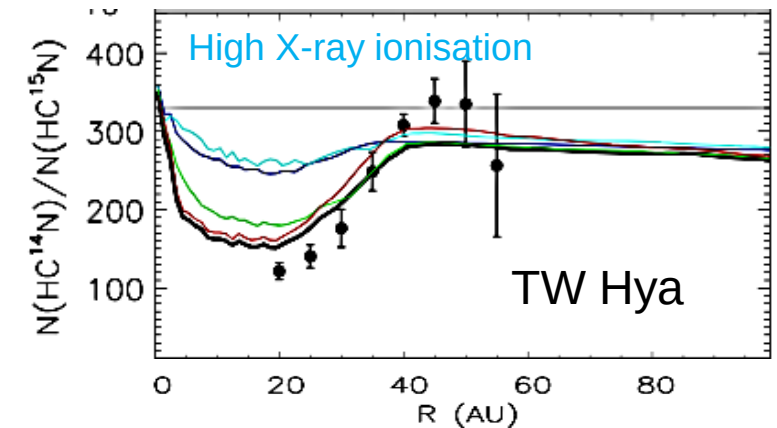
- $^{14}\text{N}/^{15}\text{N}$ in 3I/ATLAS is **higher** than in Solar System comets



Opitom+2026



- N_2 isotope selective photodissociation** explains **low $^{14}\text{N}/^{15}\text{N}$** in comets and protoplanetary disks (Visser+2018, Lee+2021)
 - ✓ ^{15}N enhancement depends on numerous parameters, e.g. C/O, X-ray ionization
 - ✓ low ^{15}N enhancement in the **low-density outermost regions**
 => **a possible explanation for 3I/ATLAS**

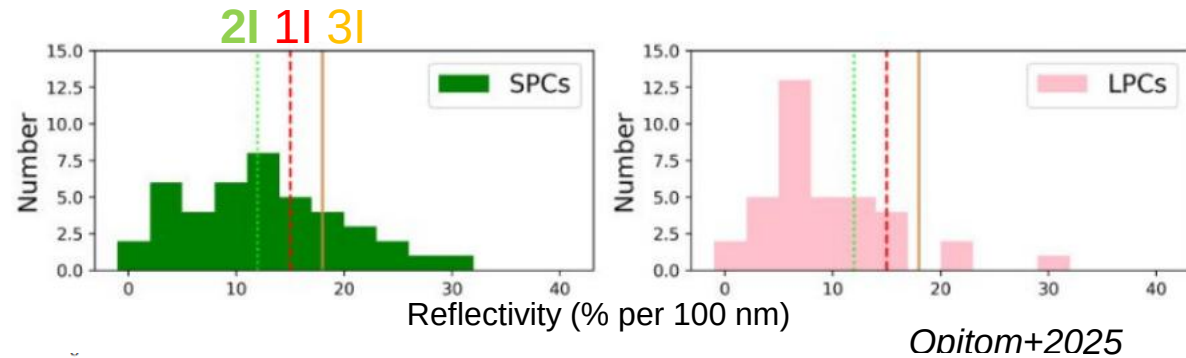


Lee+ 2021

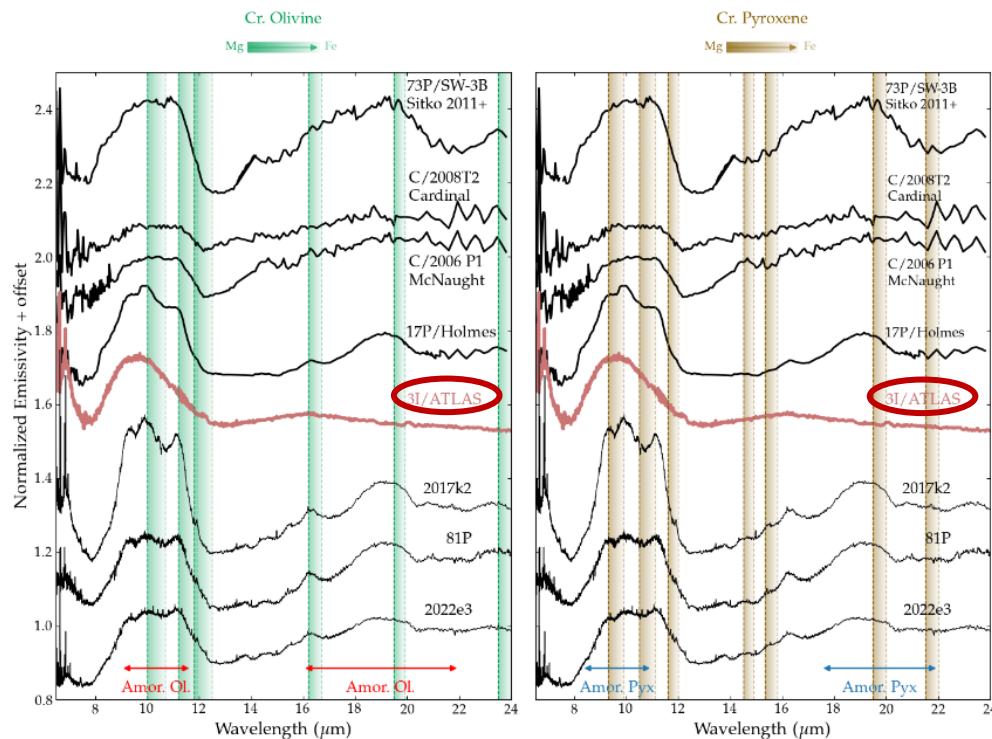
Refractories



3I/ATLAS did not incorporate high-T minerals

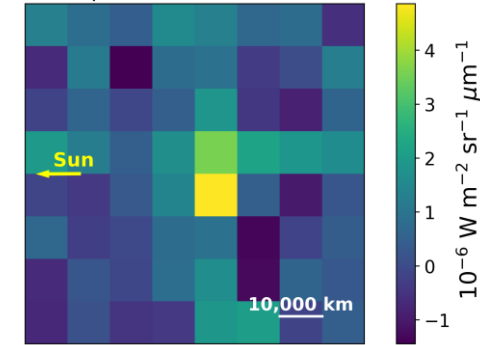


- Many observers report that the dust color in the optical is very red:
=> **high abundance of organics**

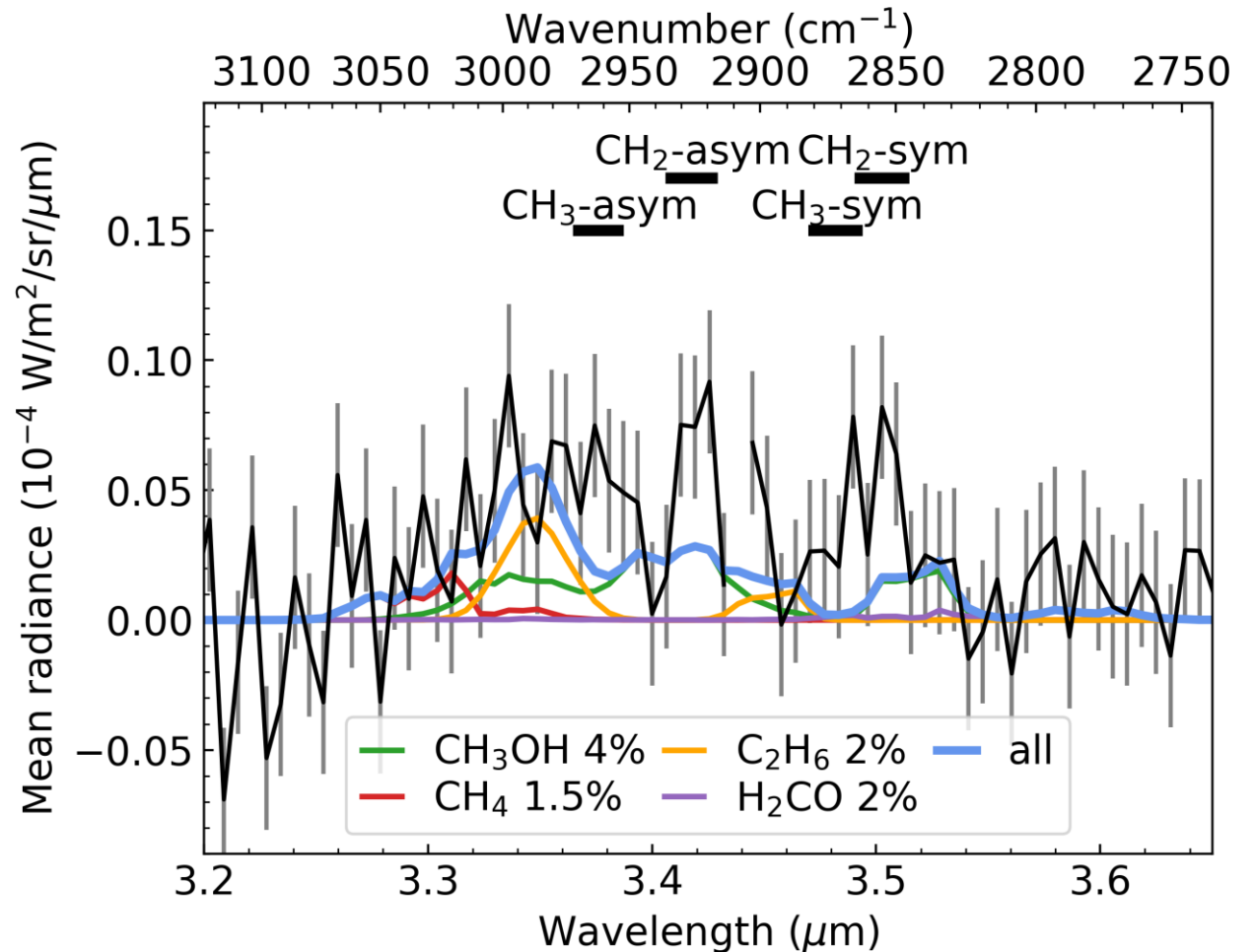


- JWST/MIRI spectra
- ✓ Signatures of crystalline olivines and pyroxenes are absent
- ✓ unlike solar system comets **silicates are essentially in amorphous form, essentially olivine**
=> **3I did not incorporate materials formed near the host star**
=> **Low-turbulence medium ?**

Detection of the 3.4 μm C-H band with MAJIS/JUICE



- In comets, major contributors are $\text{CH}_3\text{OH} + \text{C}_2\text{H}_6$
- In 3I, residual emission with peaks coinciding with CH_2 and CH_3 symmetric and asymmetric stretching modes
- no aromatic signatures at 3.28 μm
- Emission from complex organics with aliphatic carbon chains ?



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

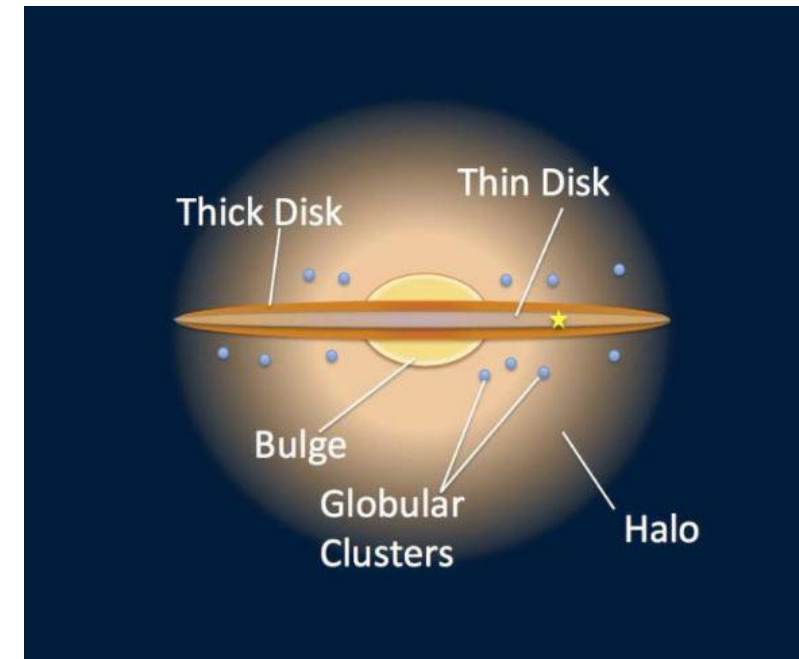
Origin in the Galaxy

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



Conclusions

3I/ATLAS presents distinct compositional and isotopic properties wrt Solar System comets

Galactic environment	old, possibly distant, metal-poor, S-poor	High $^{12}\text{C}/^{13}\text{C}$, high D/H, high dynamic age, low S
Parent molecular cloud	Cold, specific chemistry	High D/H, distinct molecular composition
Parent protoplanetary disk	Limited isotopic exchanges and radial mixing	High D/H, only amorphous silicates
Parent protoplanetary disk	Formation beyond CO_2 (or even CO) snow lines	High CO, CO_2 , N_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)