The nitrogen isotopic composition of embedded protostars – and first results on $^{14}NH_3/^{15}NH_3$ in comet 67P

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Outline

- Embedded protostars:
  - Single-dish measurements
  - Spatially resolved measurement of NGC 1333 IRAS 2A with IRAM Plateau de Bure
  - First results from the ALMA-PILS survey
- First in situ measurement of the $^{14}N/^{15}N$ ratio in a comet:
  - Preliminary results on the $^{14}NH_3/^{15}NH_3$ ratio in comet 67P/Churyumov–Gerasimenko from Rosetta-ROSINA

The nitrogen isotopic composition of embedded protostars

Key questions

- What **mechanism** is responsible for the observed isotopic variations?

- Do the ^{15}N-enrichments observed in prestellar cores survive into the protostellar phases?
  How does the $^{14}N/^{15}N$ ratio evolve during the star formation process? **Inheritance** vs. **reprocessing**?

- What are the **fractionation routes**?
  What are the **carriers** of the ^{15}N-signature?
  How are they **incorporated** into the solids?

How we measure $^{14}N/^{15}N$ ratios

- Singly substituted molecules (CN, N_2H^+, NH_3)

  Caveat: main isotopologue usually optically thick
  → need to determine optical depth

- Doubly (or multiply) substituted molecules ($H^{13}C^{15}N$, $^{15}NND^+$)

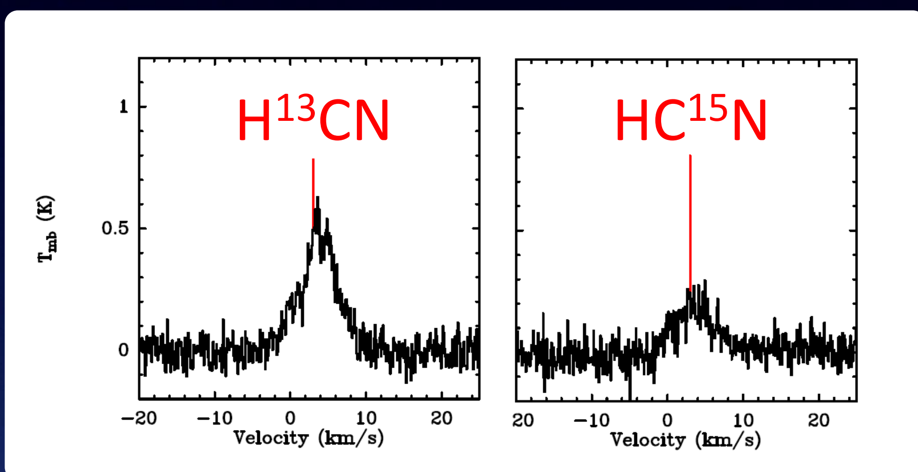
  Caveat: usually very weak lines

- Double isotope methods (HCN, HNC)

  Caveat: relies on another isotopic ratio, e.g. $^{12}C/^{13}C$

Pilot study for protostars

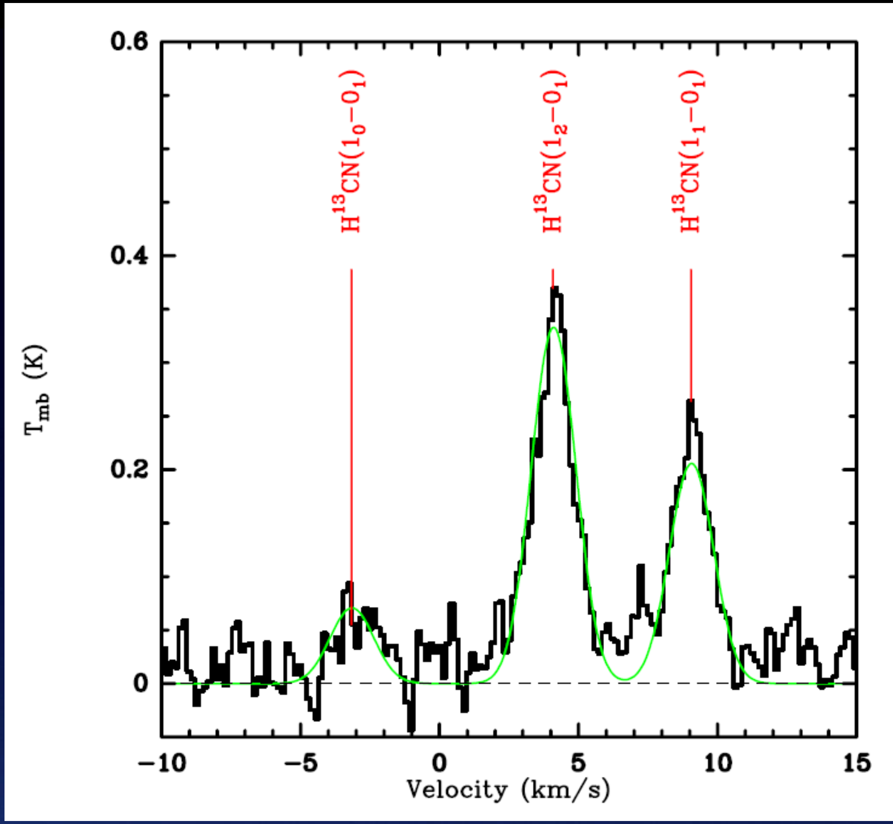
- APEX 12m telescope
- Small sample of 4 protostars: 3 Class 0 , 1 Class I
- HCN and HNC isotopologues ($H^{13}CN$, $HC^{15}N$, $HN^{13}C$, $H^{15}NC$)



$$\frac{^{14}\mathrm{N}}{^{15}\mathrm{N}} = \frac{\mathrm{H^{13}CN}}{\mathrm{HC^{15}N}} \cdot \frac{^{12}\mathrm{C}}{^{13}\mathrm{C}}$$

Check the optical depth

- Hyperfine structure fit: $\tau \sim 0.3$ optically thin

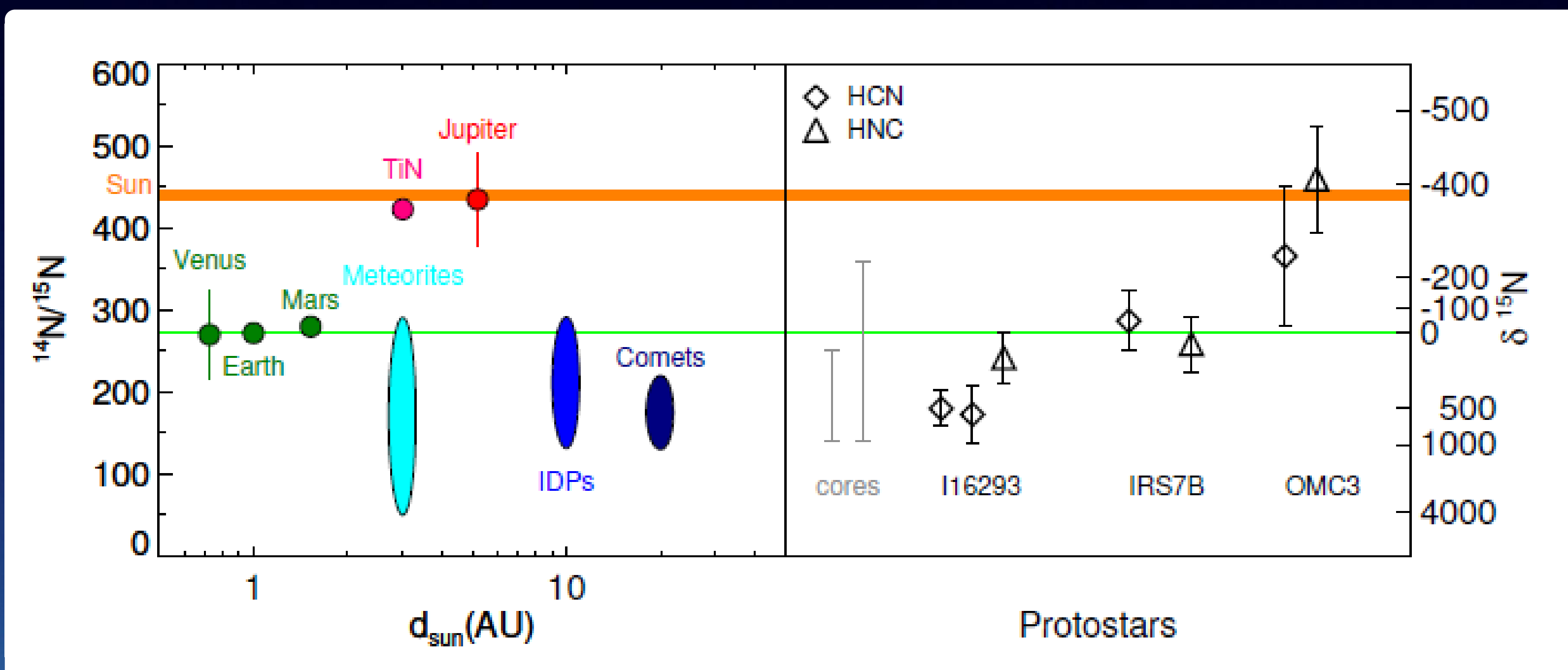


- Radiative transfer modeling

Results from embedded protostars

- ^{15}N-enrichments in HCN in 2/3 sources compared to solar
- Values comparable to comets and meteorites for IRAS 16293
- Nondetection for the Class I protostar

Wampfler et al. 2014



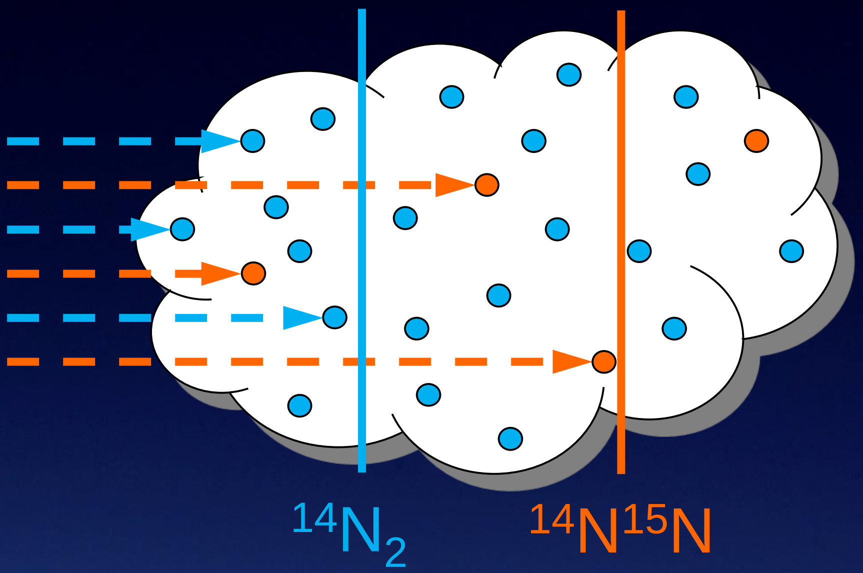
Fractionation mechanisms

- Chemical fractionation: $^{15}N + {}^{14}N_2H^+ \rightleftharpoons {}^{14}N + {}^{15}N^{14}NH^+ + \Delta E$

  e.g. Terzieva & Herbst 2000
  Rodgers & Charnley 2008
  Wirström et al. 2012
  Hily-Blant et al. 2013
  Roueff et al. 2015

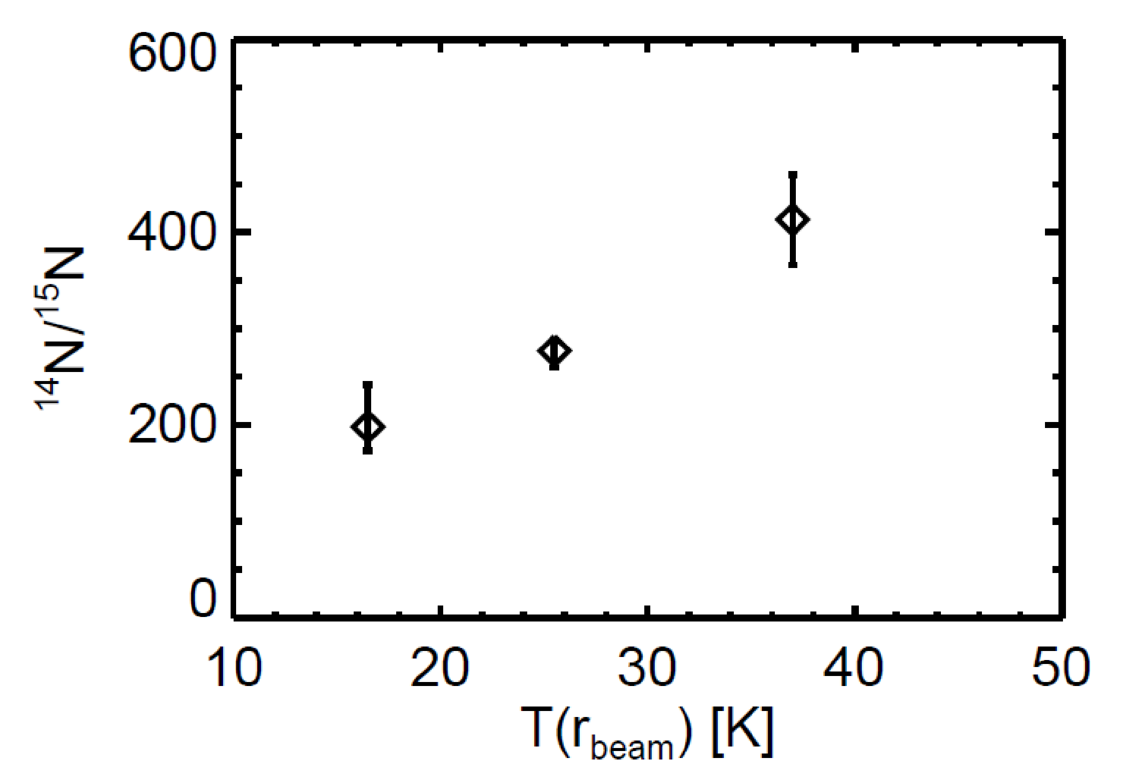
- Isotopically selective photochemistry (self-shielding of N_2)

  e.g. Croteau et al. 2011, Lyons et al. 2009, Heays et al. 2014, Visser et al. in prep.



- Combination of both? Ad-/desorption effects?

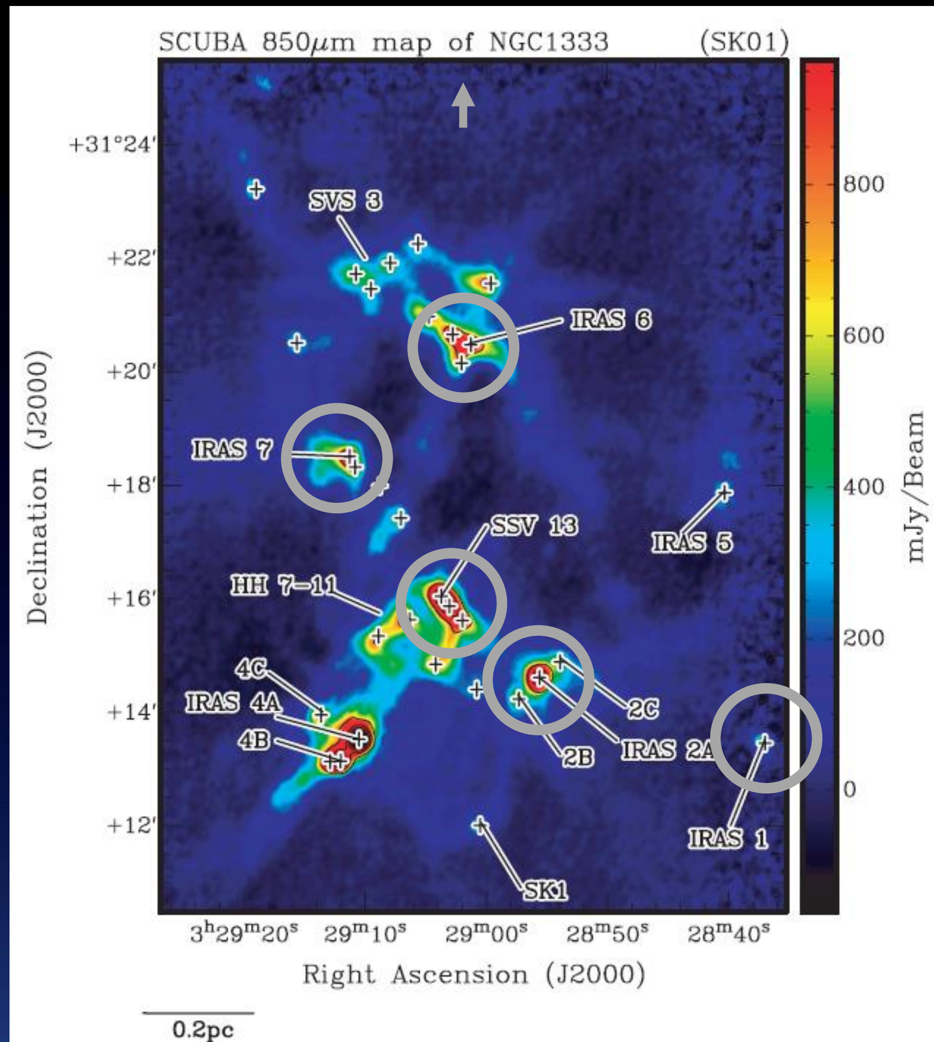
Chemical fractionation or photochemistry?



Wampfler et al., 2014, A&A 572, A24

Trend of increasing ^{15}N-enrichment with decreasing outer envelope temperature would be in favour of low-temperature chemistry, but statistics insufficient

Small survey in NGC 1333



Walsh et al. 2007, ApJ 655, 958 with data from Sandell & Knee 2001, ApJ 546, L49

6 protostars in the same molecular cloud to avoid background variations, with different temperatures

Chemical fractionation or photochemistry?

Preliminary!

Source sample in NGC 1333, Onsala 20m data.
Trend not confirmed.

$^{14}N/^{15}N$ ratios in prestellar cores & protostars

	HCN	HNC	CN	NH_3	NH_2D	N_2H^+
L1544	140-360	>27	510±70		>700	1000±200
L1498	167	>90	476±70	619±100		
L183	140-250		$530^{+570}/_{-180}$			
L1521E	151±16					
L1521F	>51	24-31 (?)	539±118			
Barnard 1b	$330^{+60}/_{-50}$	$225^{+75}/_{-45}$	$290^{+160}/_{-80}$	$300^{+55}/_{-40}$	$230^{+105}/_{-55}$	$400^{+100}/_{-65}$ >600
N1333 IRAS 4					>270	
N1333 DCO^+					$360^{+260}/_{-110}$	
N1333				344±173		
L134N(S)					$530^{+570}/_{-180}$	
L1689N					$810^{+600}/_{-250}$	$330^{+170}/_{-100}$
Cha-MMS1		135				
L1262 core				356±107		
L1262 YSO				453±247		
IRAS 03282					250±40	
IRAS 16293A	177±20	242±32				observed
R CrA IRS7B	287±36	259±34	229±50			observed
OMC-3 MMS6	366±86	460±65				observed

solar (441±6)
enriched
depleted

Different tracers make comparison challenging!

What we learned from single-dish data

- ^{15}N-enrichments in HCN similar to prestellar cores observed in (some) Class 0 protostars

- Relative fractionation among tracers

- Some indications for spatial variations
(e.g. Hily-Blant et al. 2013, Icarus 223, 582)

… and what we did not learn

- Single-dish $^{14}N/^{15}N$ ratios only provide spatially averaged measurement

  → so far inconclusive on fractionation mechanism

- Different radial signatures expected for chemical fractionation and isotope selective photochemistry

  → spatially resolved observations

Spatially resolved observations

NGC 1333 IRAS 2A (Class 0 protostar) with IRAM PdBI

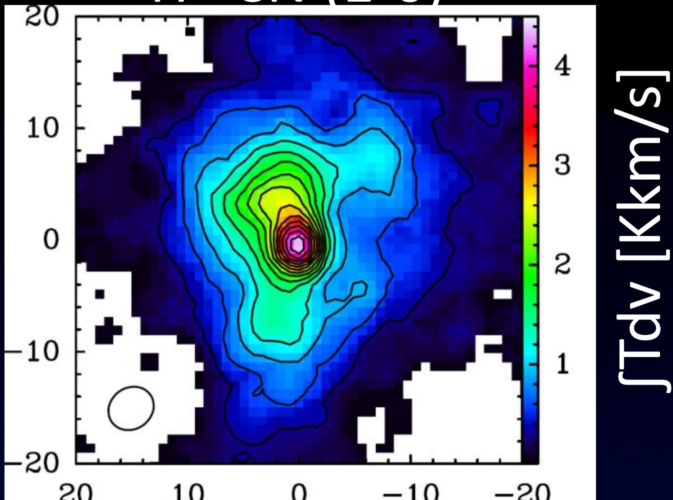
1 track each in C and D configuration

Short spacings from the 30m

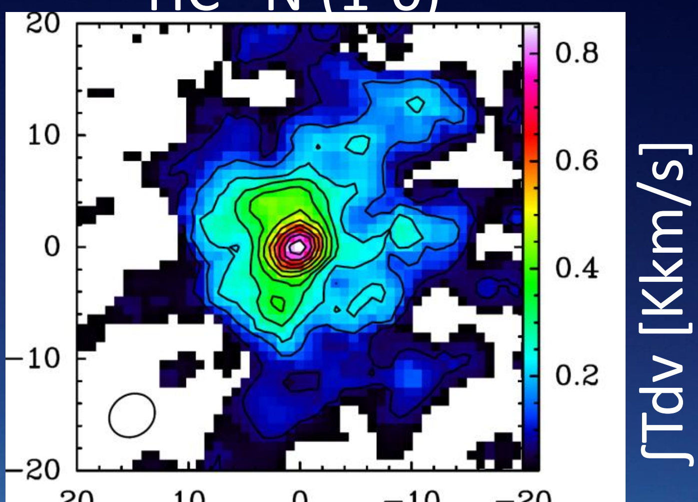
Preliminary results

$^{14}N/^{15}N$ (using $^{12}C/^{13}C$ = 69)

$H^{13}CN$ (1-0)



$HC^{15}N$ (1-0)

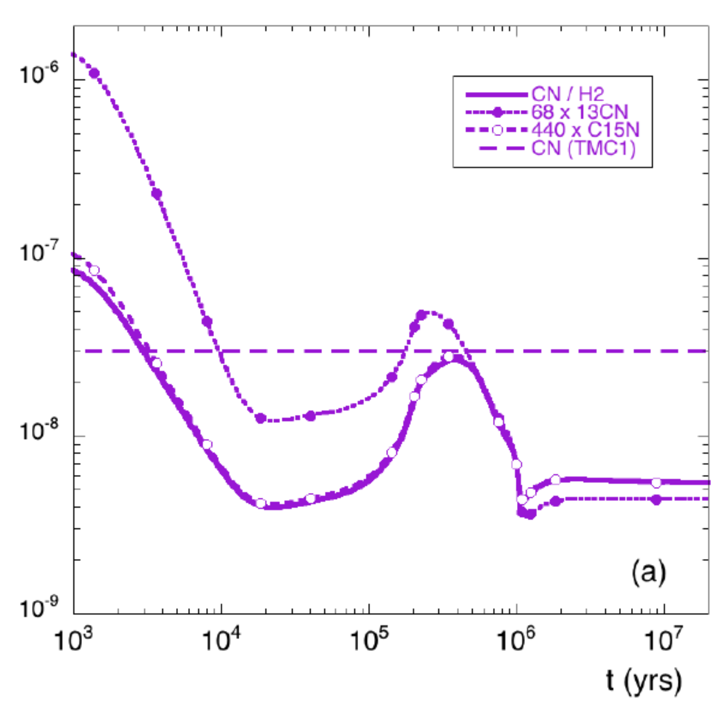


Wampfler et al. in prep.

$^{14}N/^{15}N$ ratio varies by factor ~2 along outflow axes. Caused by irradiation/photochemistry?

The role of the $^{12}C/^{13}C$ ratio

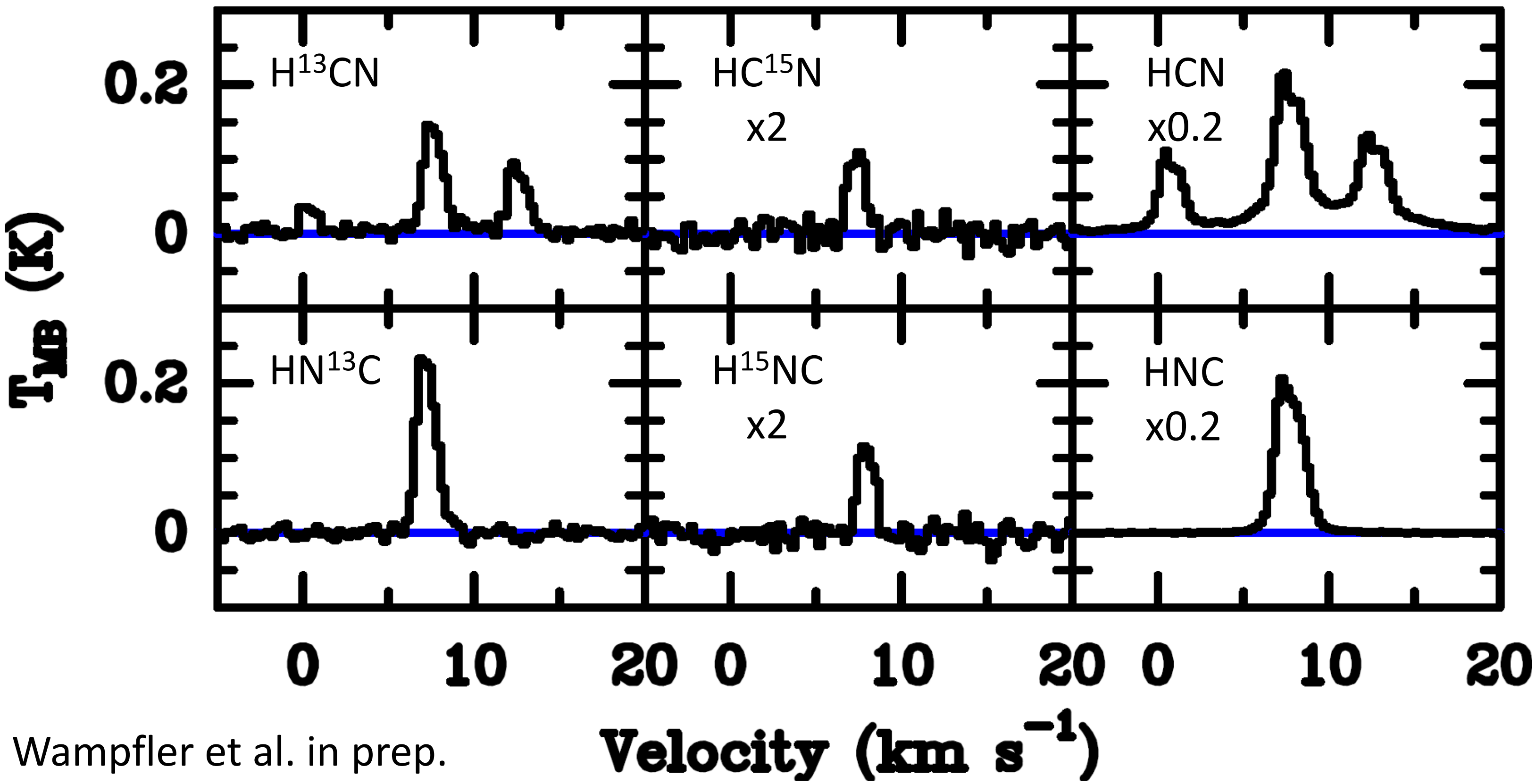
Do $H^{13}CN/HC^{15}N$, $HN^{13}C/H^{15}NC$, $^{13}CN/C^{15}N$ etc. mainly reflect $^{12}C/^{13}C$ variations, not $^{14}N/^{15}N$?



Roueff et al. 2015

→ Observations for $^{12}C/^{13}C$ measurement with NOEMA & 30m just completed

Constraints from single-dish data



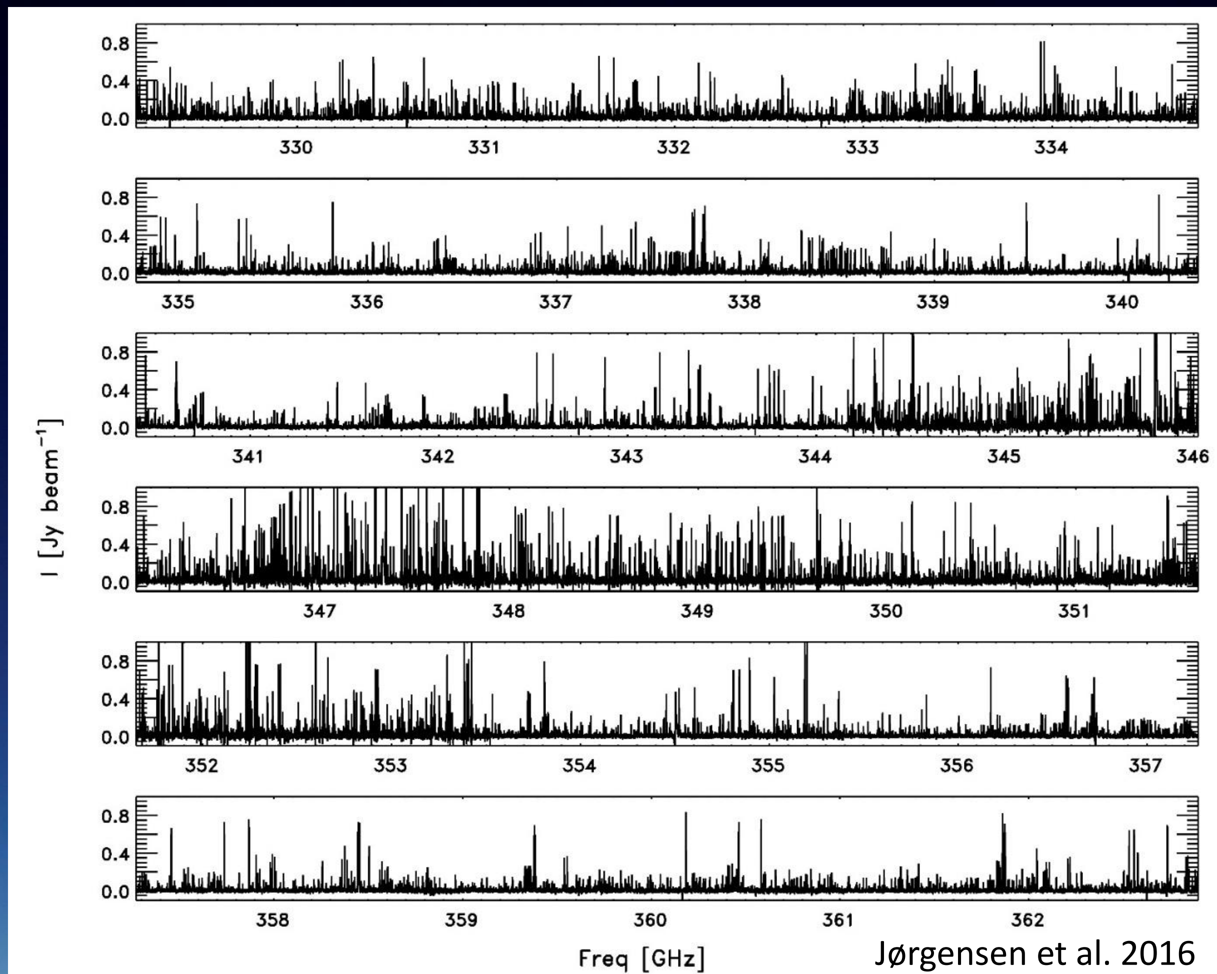
Wampfler et al. in prep.

$^{14}N/^{15}N$ (and $^{12}C/^{13}C$) ratios from common tracers (HCN,HNC, NH_2D, CN, N_2H^+) using OSO 20m

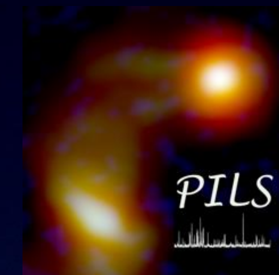
Analysis in progress → indications for $^{12}C/^{13}C < 70$

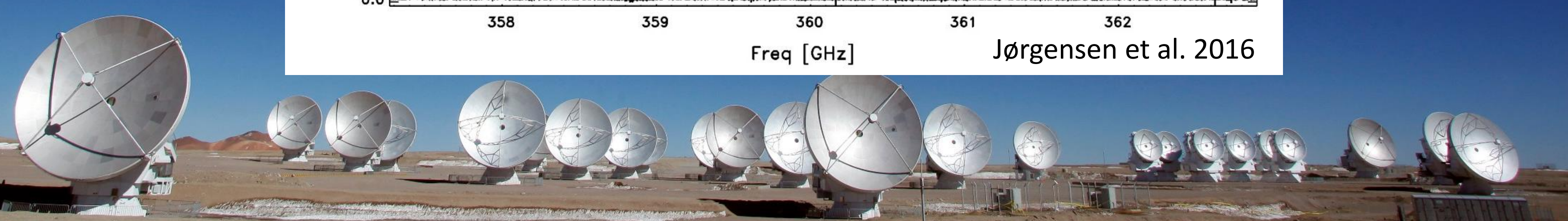
Protostellar Interferometric Line Survey (PILS)

IRAS 16293-2422 - ALMA band 7



Jørgensen et al. 2016





First results on ^{15}N from the PILS survey

- $^{15}NH_2CHO$:
  blending, close to noise level
  $^{14}N/^{15}N > 100$ (Coutens et al. 2016)

- $H^{15}NCO$:
  line frequencies too uncertain for clear line assignment
  $^{14}N/^{15}N > 138$ (Coutens et al. 2016)

  (for offset position around source B, based on standard $^{12}C/^{13}C$)

What about simple species?

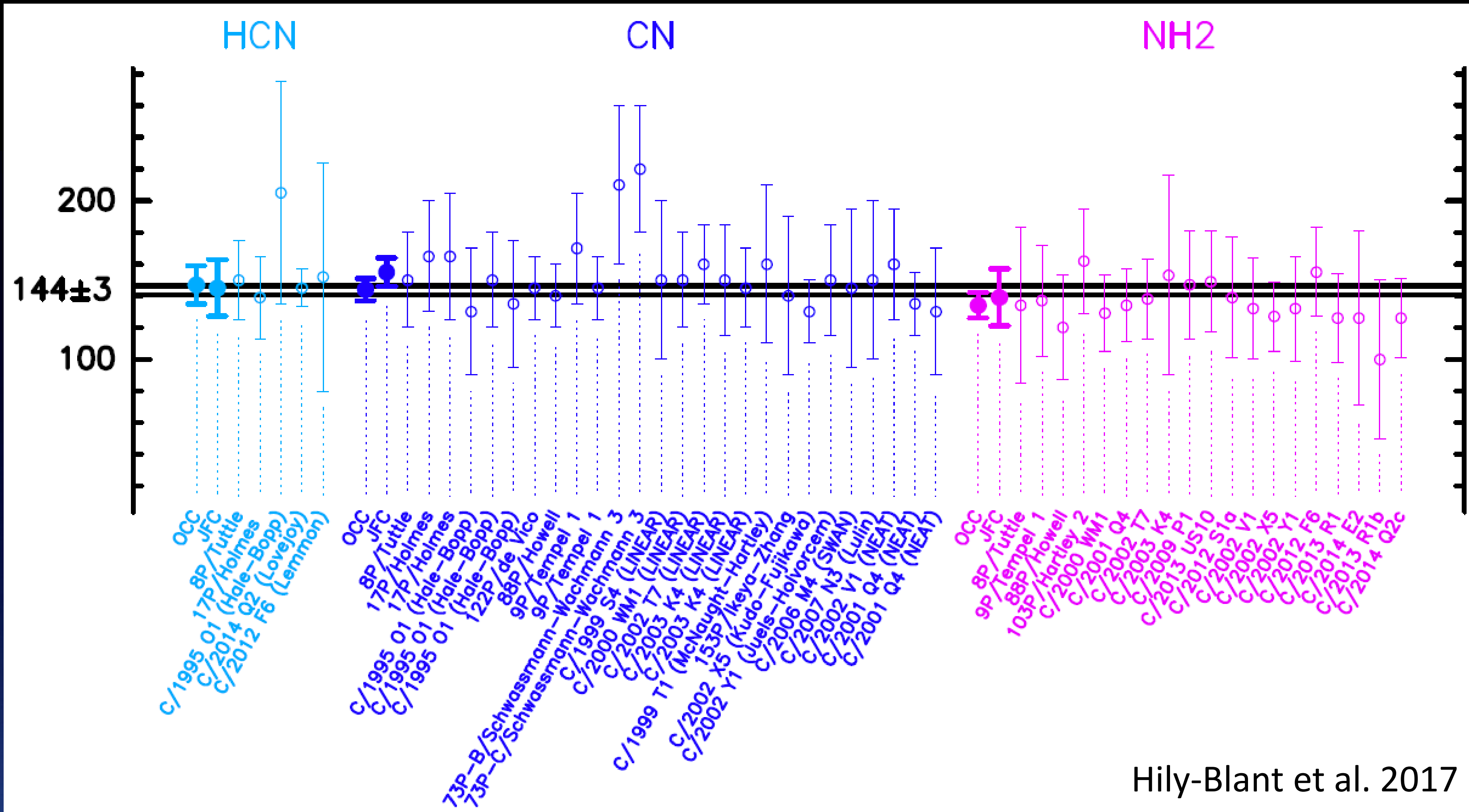
- CN: absorption
- Detections of $HC^{15}N$, $H^{15}NC$
  (only 1 line each, absorption!)
- $H^{13}C^{15}N$, $H^{15}N^{13}C$ tentative (only 1 line)

^{15}N follow-up for PILS

- ALMA cycle 5 project in band 6

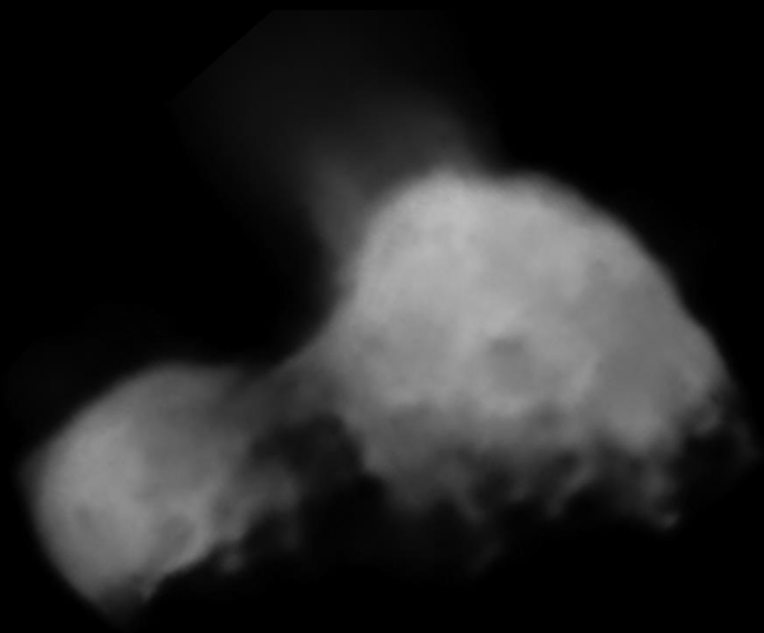
$^{14}NH_3/^{15}NH_3$ in comet 67P/Churyumov–Gerasimenko

$^{14}N/^{15}N$ in comets (ground-based data)



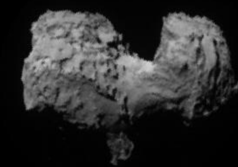
- Ground-based observations of comets indicate a very homogeneous nitrogen isotopic composition

Comets visited by spacecraft



1P/Halley
16 × 8 × 8 km
Vega 2, 1986

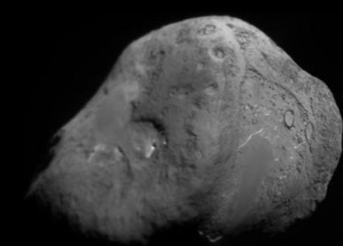
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004



67P/Churyumov-Gerasimenko
5 × 3 km
Rosetta, 2014

103P/Hartley 2
2.2 × 0.5 km
Deep Impact/EPOXI, 2010

19P/Borrelly
8 × 4 km
Deep Space 1, 2001



9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005

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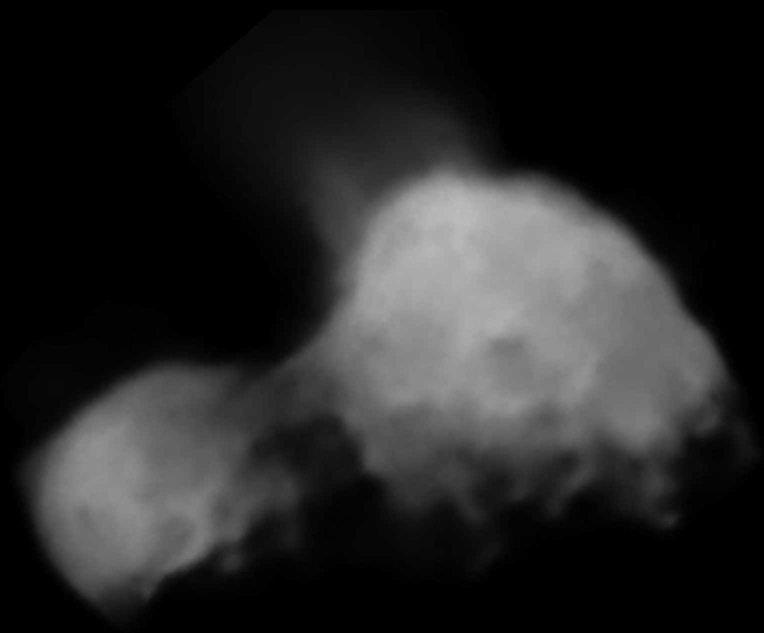
Comets visited by spacecraft



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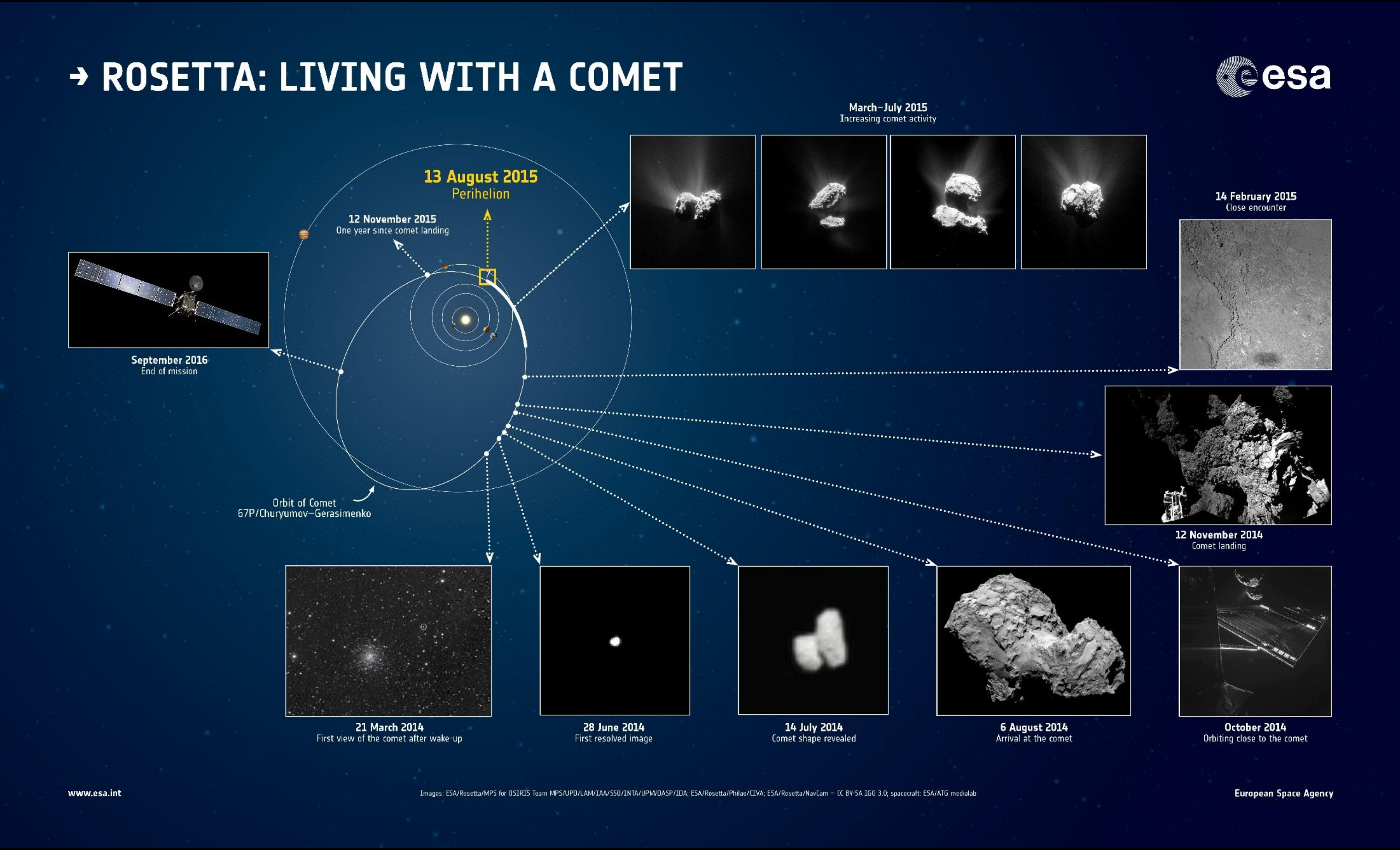
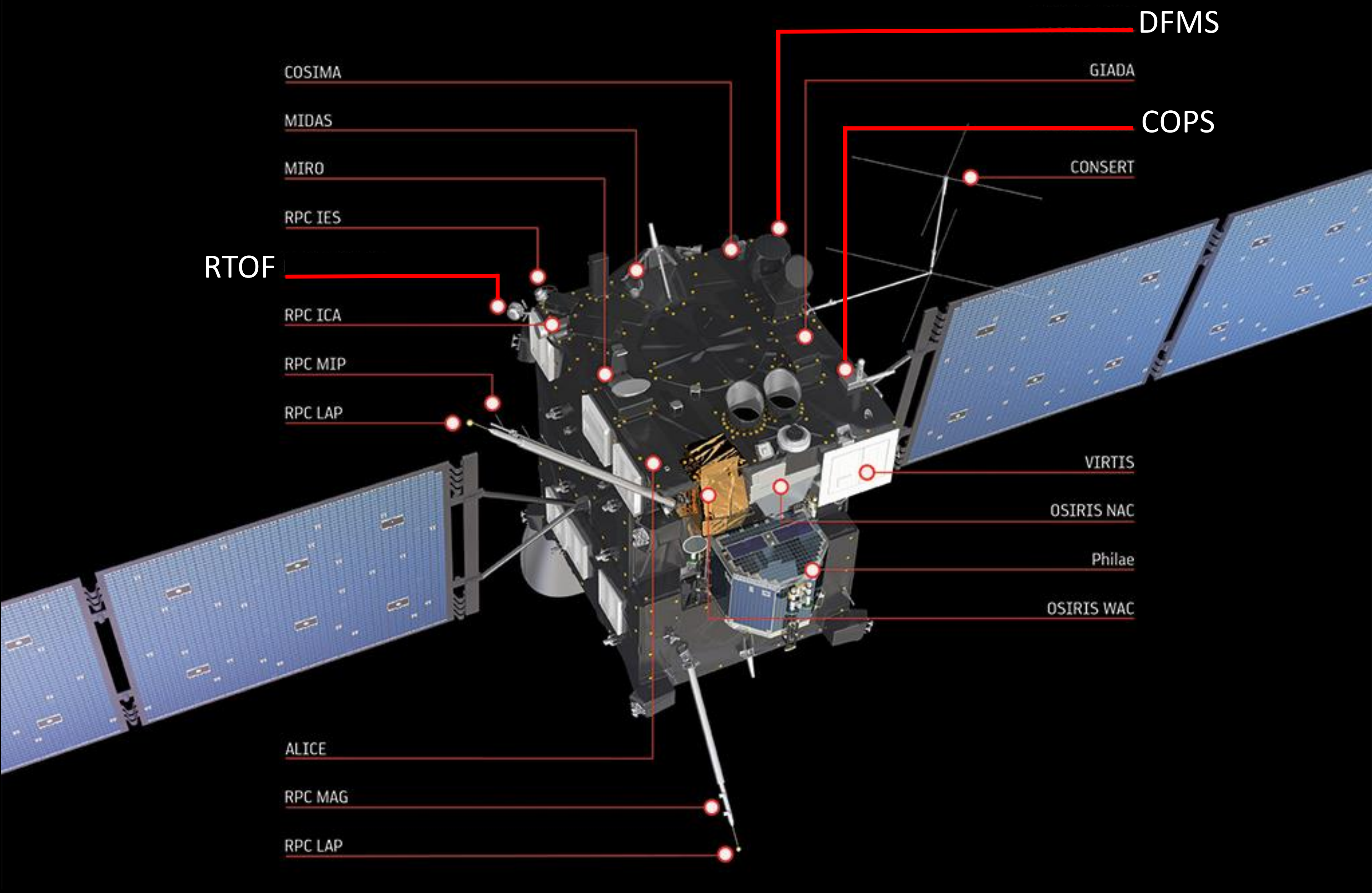
The Rosetta mission



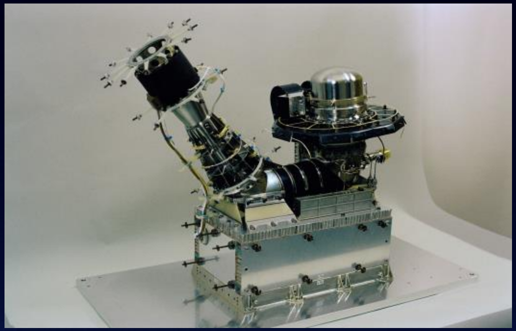
Rosetta-ROSINA



Rosina instrument suite

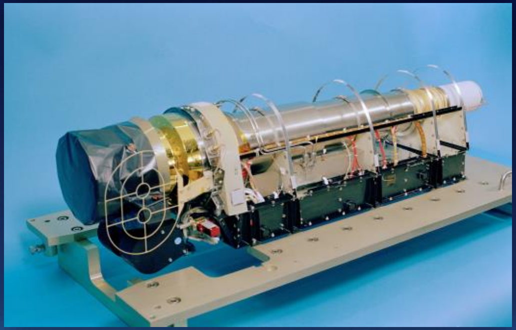
COPS – Cometary Pressure Sensor

- measures total neutral particle density and velocity
- measures total neutral gas density (10^5 to 10^{11} cm^{-3})
- serves as safety instrument for Rosetta



DFMS – Double Focussing Mass Spectrometer

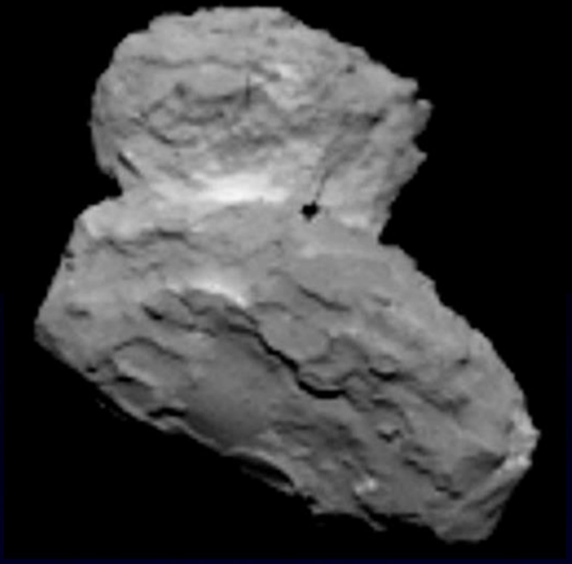
- mass range: 12 to 150 u/e
- mass resolution:
  $m/\Delta m \approx$ 3’000 (at 1% peak height) (@ mass 28)
  $m/\Delta m \approx$ 9’000 (at 50% peak height)
- high dynamic range (10^8)



RTOF – Reflectron-type Time Of Flight Mass Spectrometer

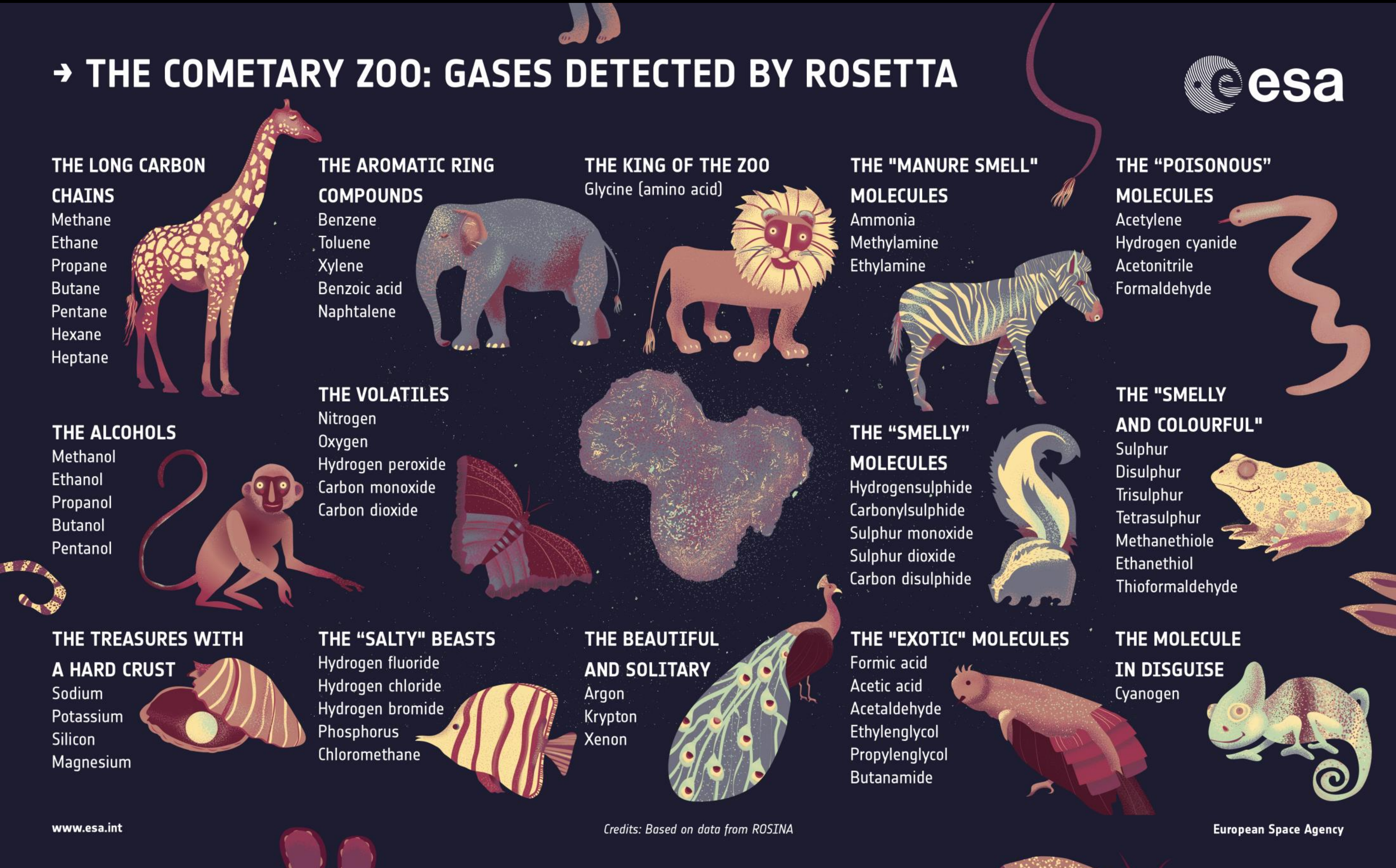
- mass range: 1 to 1’100 u/e
- mass resolution: $m/\Delta m \approx 450$ (at 50% peak height)
- high dynamic range

Portrait of 67P

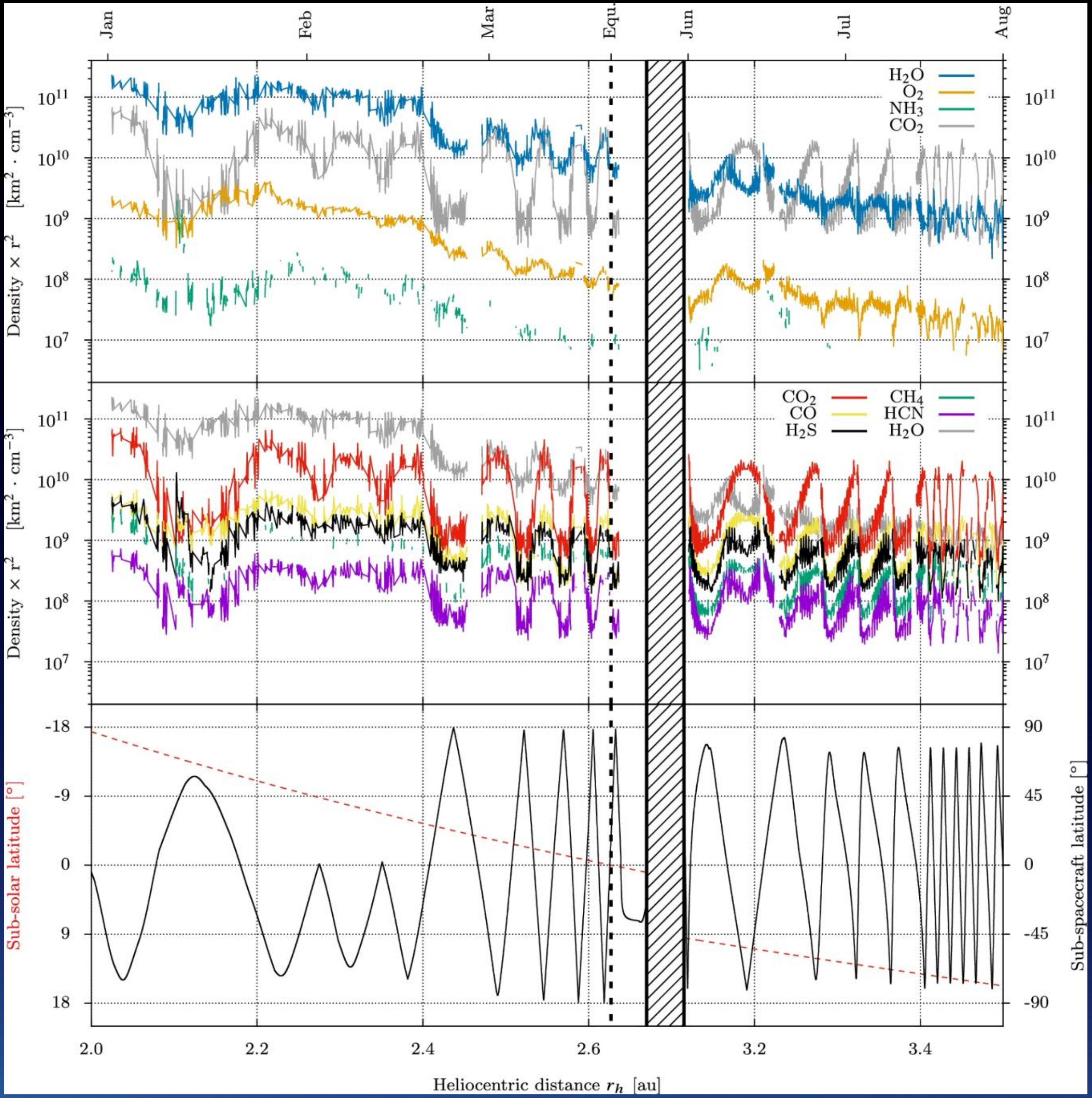


- Longest dimension: 4.1 km
- Rotation period: 12.4 (12.0) h
- Orbital period: 6.5 yrs
- Perihelion distance: 1.25 AU
- Rotation axis tilt: 68°
- Density: 0.5 g cm^{-3}
- Porosity: 75%
- Low reflectance: 5%
- Dust-to-gas ratio: ~4:1 by mass (highly debated!)

Molecular inventory of 67P

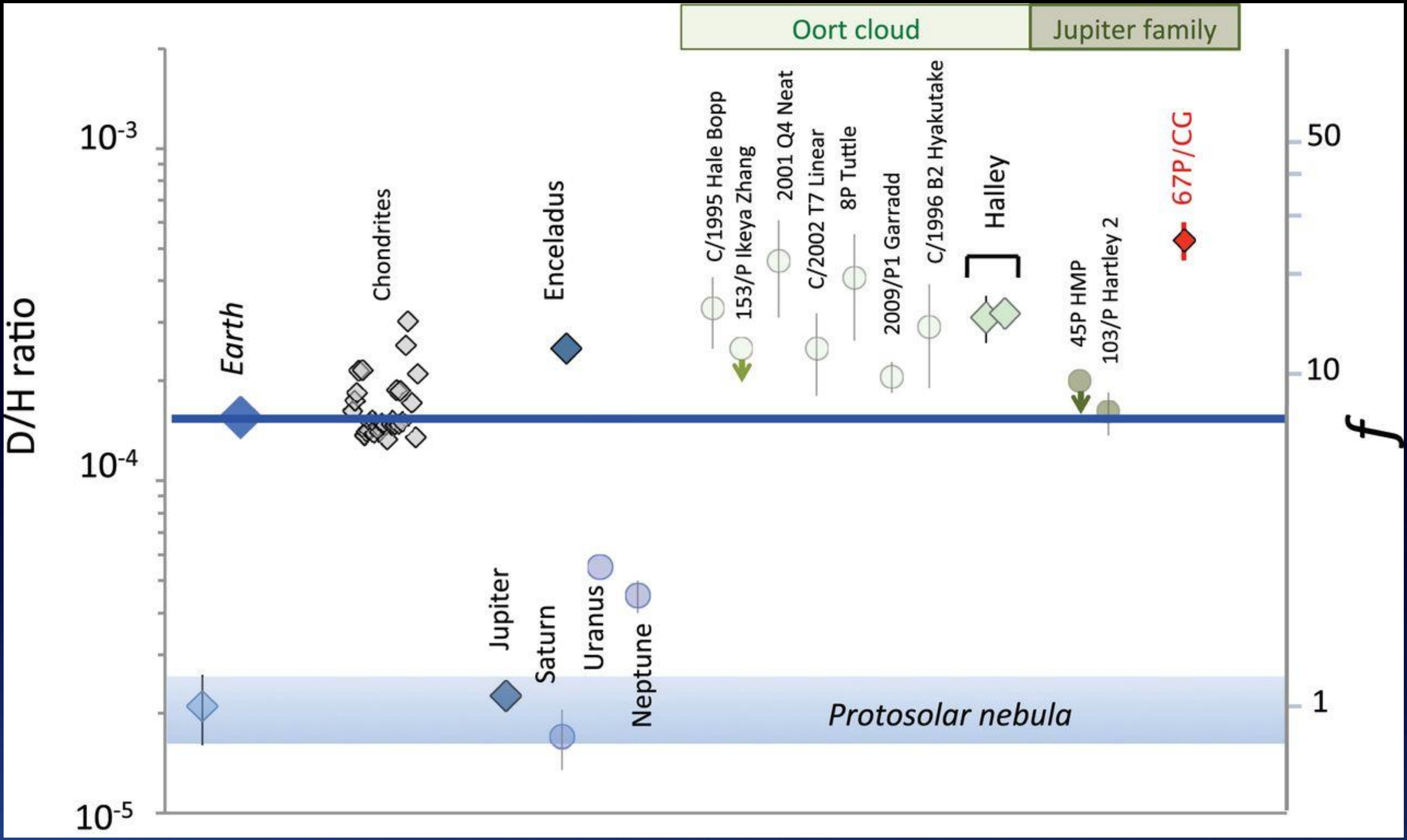


Minor species following H_2O vs. CO_2



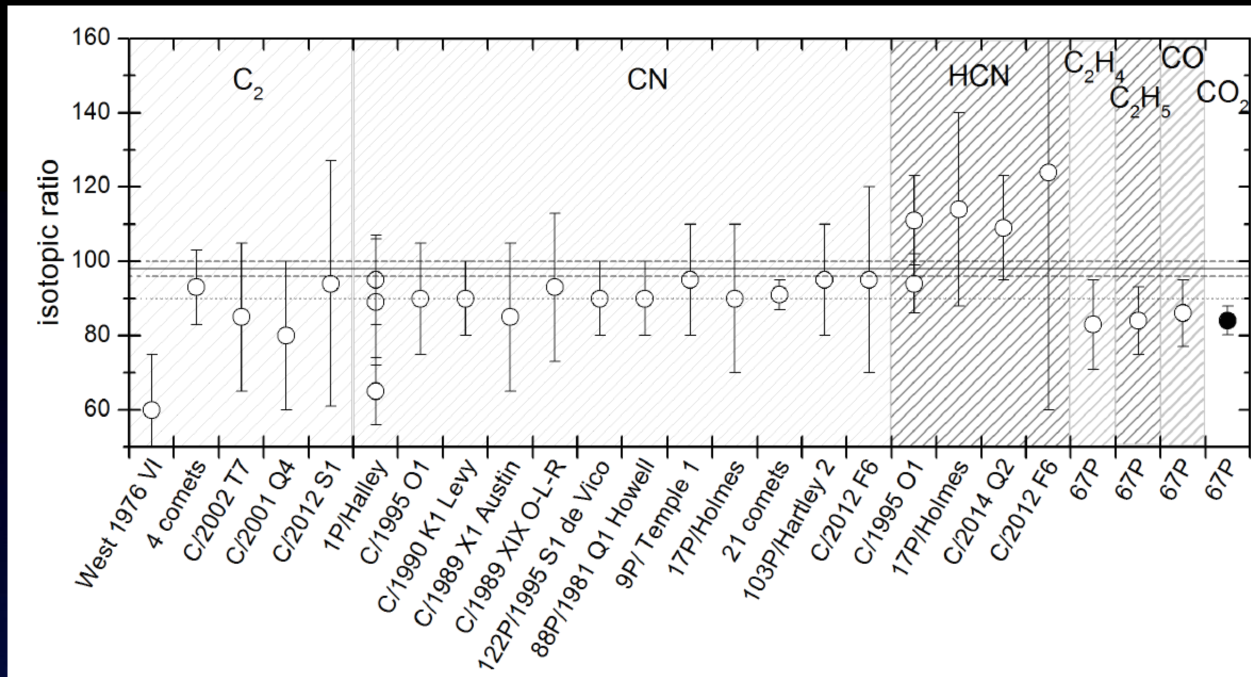
Gasc et al. 2017

D/H in water



Altwegg et al. 2015, Science 347

$^{12}C/^{13}C$ in 67P



Hässig et al. , 2017

- $^{12}C/^{13}C$ in CO_2: 84 ± 4 (Hässig et al., 2017)
- $^{12}C/^{13}C$ in CO: 86.0 ± 8.5 (Rubin et al., 2017)
- $^{12}C/^{13}C$ in C_2H_4: 83.6 ± 11.8 (Rubin et al., 2017)
- $^{12}C/^{13}C$ in C_2H_5: 85.5 ± 9.0 (Rubin et al., 2017)
- Earth: 89 (Meija et al., 2016)
- Solar wind 98 ± 2 (Hashizume et al., 2004)

Summary

- $^{14}N/^{15}N$ around IRAS 2A varies by factor ~2
- First results from PILS:
  - NH_2CHO: $^{14}N/^{15}N > 100$ (Coutens et al. 2016)
  - HNCO: $^{14}N/^{15}N > 138$ (Coutens et al. 2016)
  - CH_3CN: (Calcutt et al. in prep.)
- Comprehensive sets of $^{14}N/^{15}N$ and $^{12}C/^{13}C$ ratios needed for more protostars

Open questions

- What **mechanism** is responsible for the observed isotopic variations?

- Why are there such large variations of the $^{14}N/^{15}N$ ratio among the solar system bodies, but the nitrogen isotopic composition of comets is quite homogeneous (unlike their D/H)?

- Why is the NH_3 of comets enriched in ^{15}N, but no ^{15}N-enrichments are observed in the ISM/around protostars?