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APPLIED PHYSICS LABORATORY

The Origin and Evolution of Nitrogen in Outer Planet Atmospheres through Comparative Planetology

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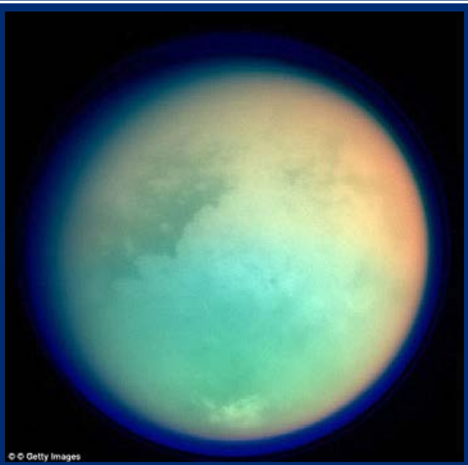
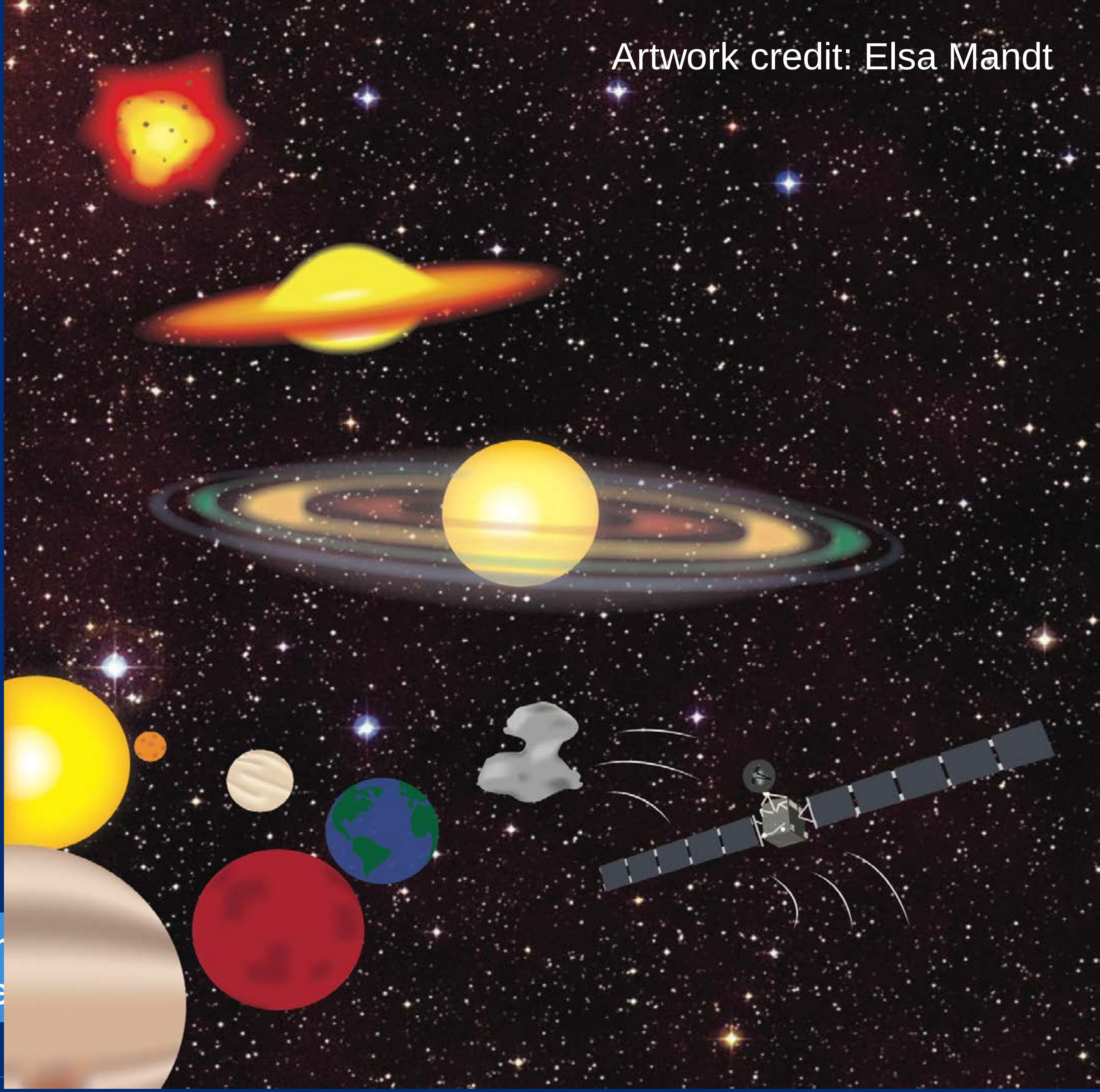
Comparative Planetology is critical for evaluating the origin of volatiles in Solar System bodies

			
Radius (km)	2575	1188	1353
Surface pressure (bar)	1.5	~10^{-12} (*N.H.* flyby)	1.6 x 10^{-5}
Surface temp. (K)	90	~35	> 36
Distance from Sun (AU)	10	30-50	30

Titan, Pluto and Triton have N_2 atmospheres with complex chemistry. Each tells a unique story of Solar System formation and evolution.

Isotopes as Tracers

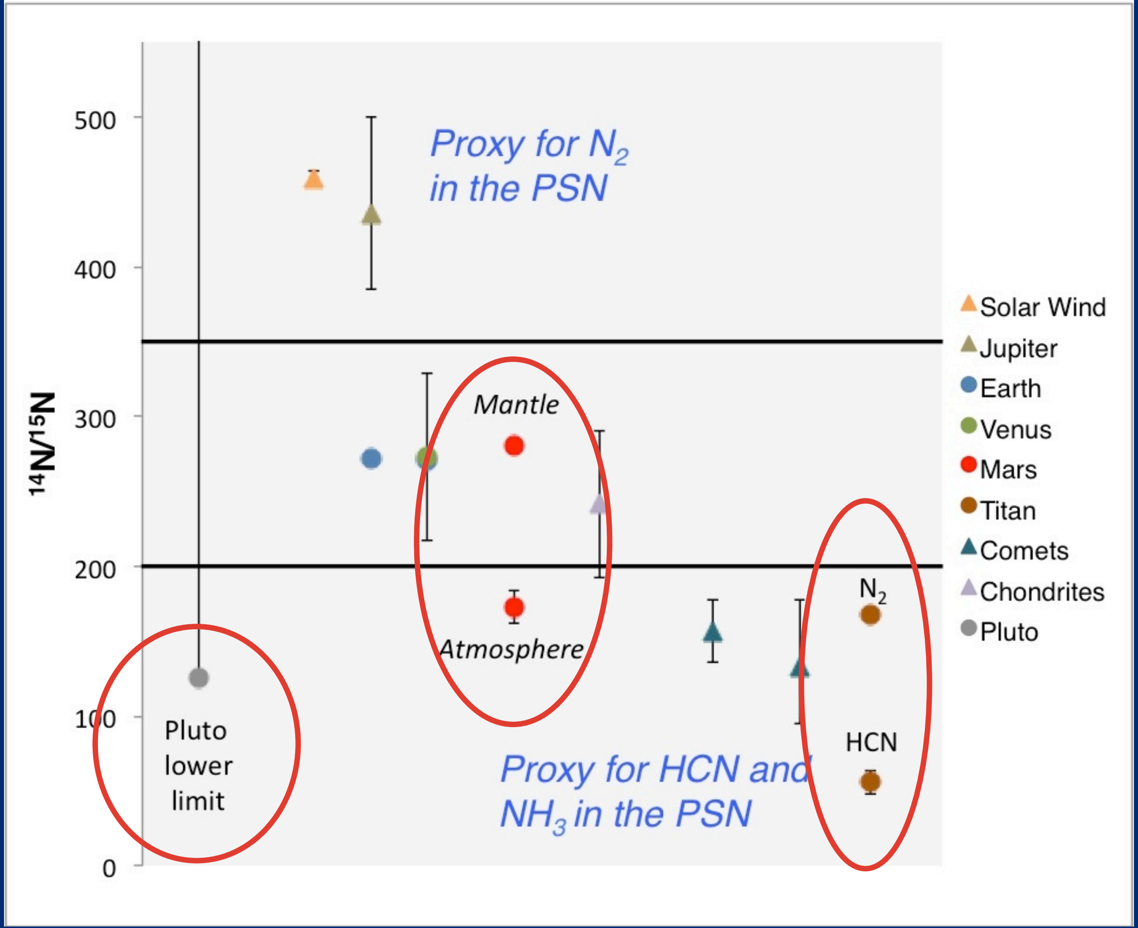
- Processes
  - Venus: original water content
  - Mars: atmospheric loss
  - Titan: photochemistry, escape and evolution
- Can be applied on a larger scale to study Solar System formation and evolution



Artwork credit: Elsa Mandt

Isotopes are useful for tracing short term
proce

Comparative Planetology of the origin of Nitrogen in the Atmospheres of Titan, Pluto and Triton



- Primordial (triangles) ratios represent values preserved from the Protosolar Nebula (PSN)
  - Jupiter
  - Solar Wind
  - Comets
  - Meteorites
- Evolved (circles) ratios have changed over time
  - Terrestrial planets and Titan
  - Not measured: Pluto & Triton

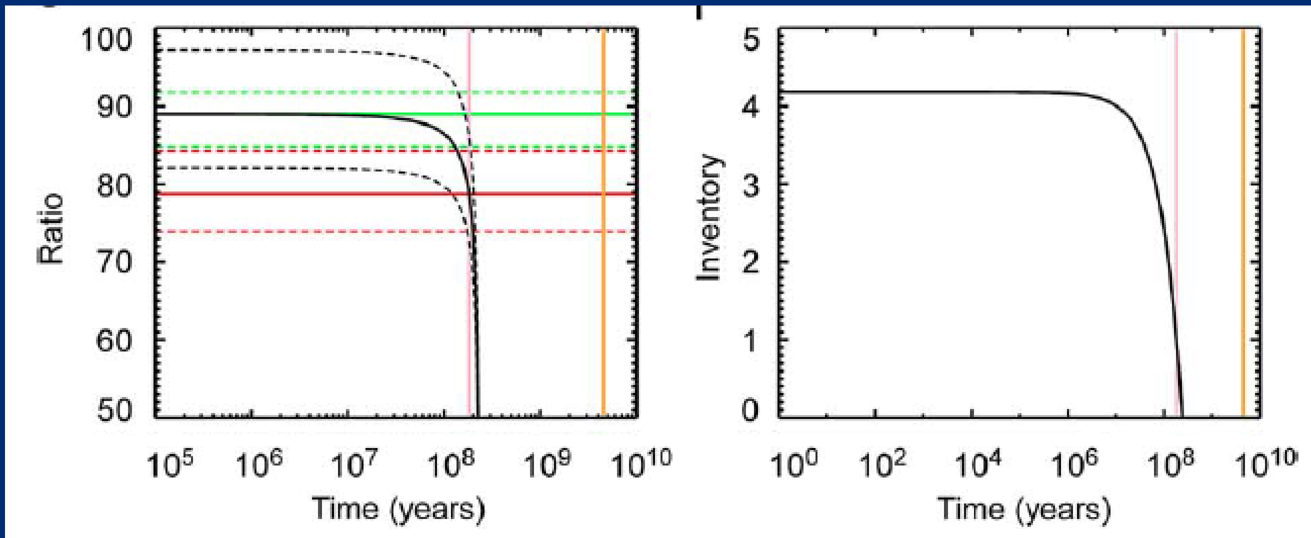
Determining the origin of nitrogen in these atmospheres requires an understanding of how the atmosphere has evolved over time.

Modeling the evolution of an atmosphere

$$dn/dt = P - L$$

- The inventory of a constituent varies over time based on production and loss processes
- Fractionation occurs when there is a difference in the relative production or loss rates of constituents and their isotopes
  - e.g. Escape – The lighter isotope escapes more easily than the heavier, resulting in a lighter ratio over time
- Fractionation changes the measured ratio in an atmosphere over geologic time scales

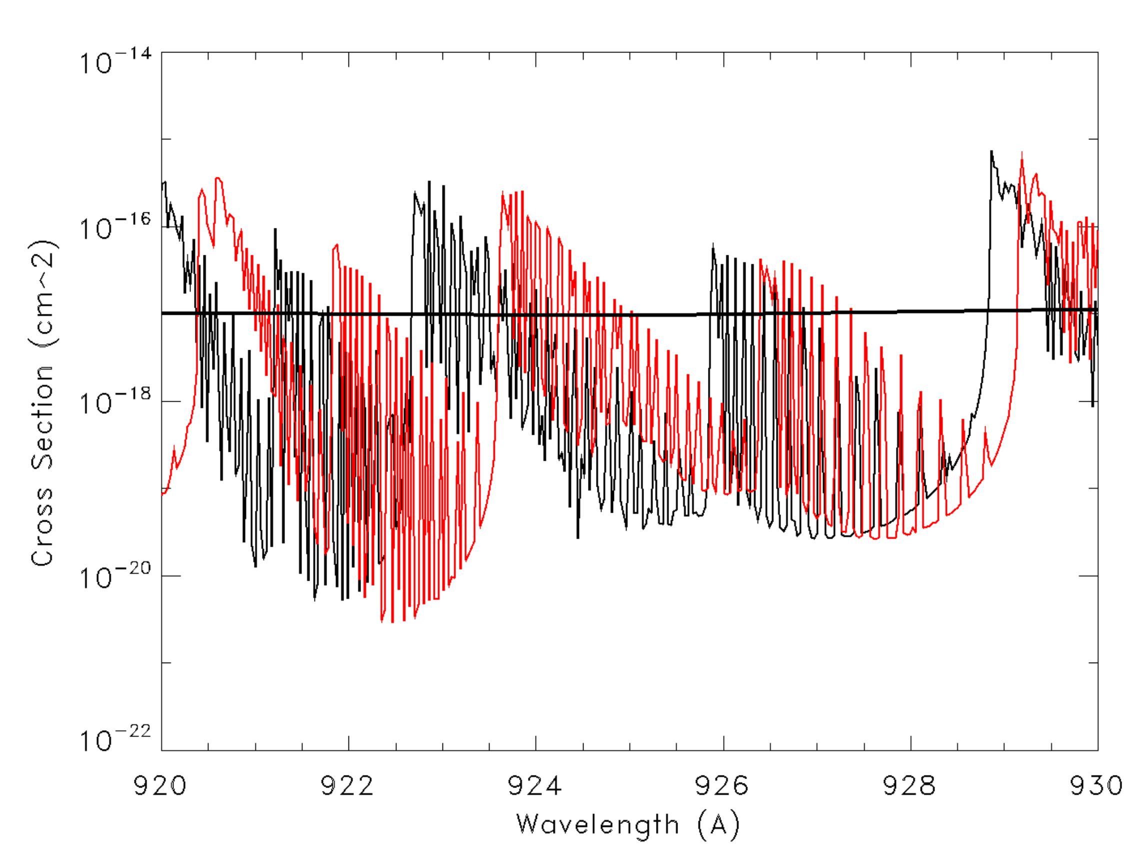
$$f = \text{fractionation factor}$$



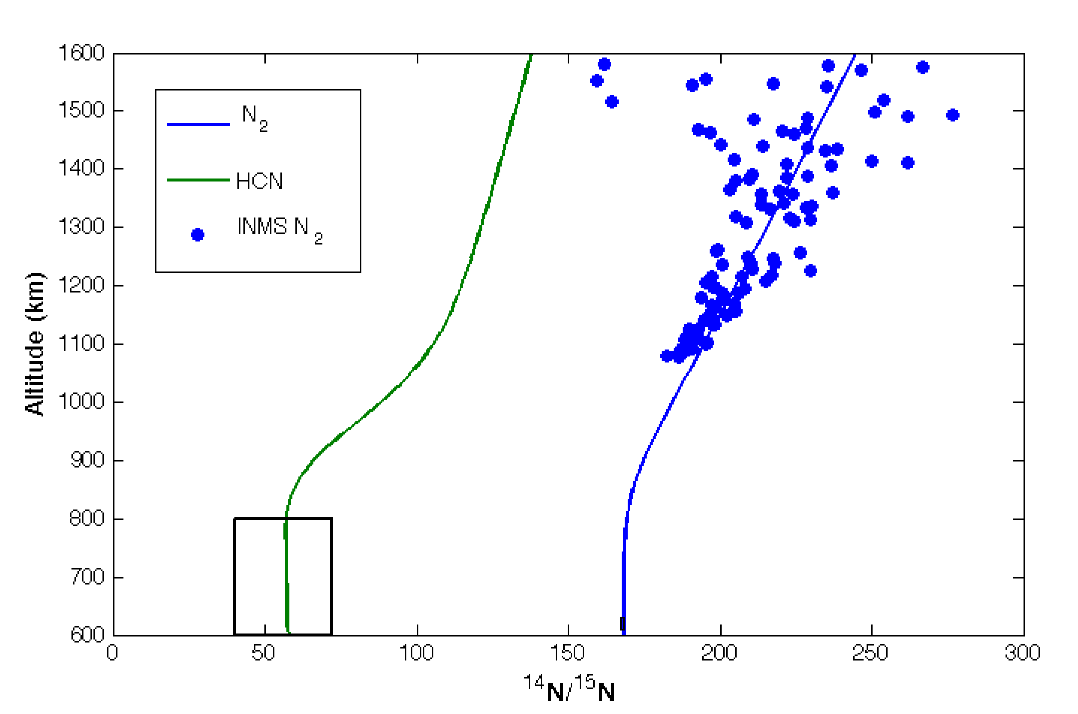
Evolution of $^{12}C/^{13}C$ in CH_4 at Titan shows that methane has not been present over all of Titan's history (Mandt et al., 2009; 2012)

Fractionating Processes in Planetary Atmospheres

Photochemistry – in an N_2-dominated atmosphere makes the ratio higher over time



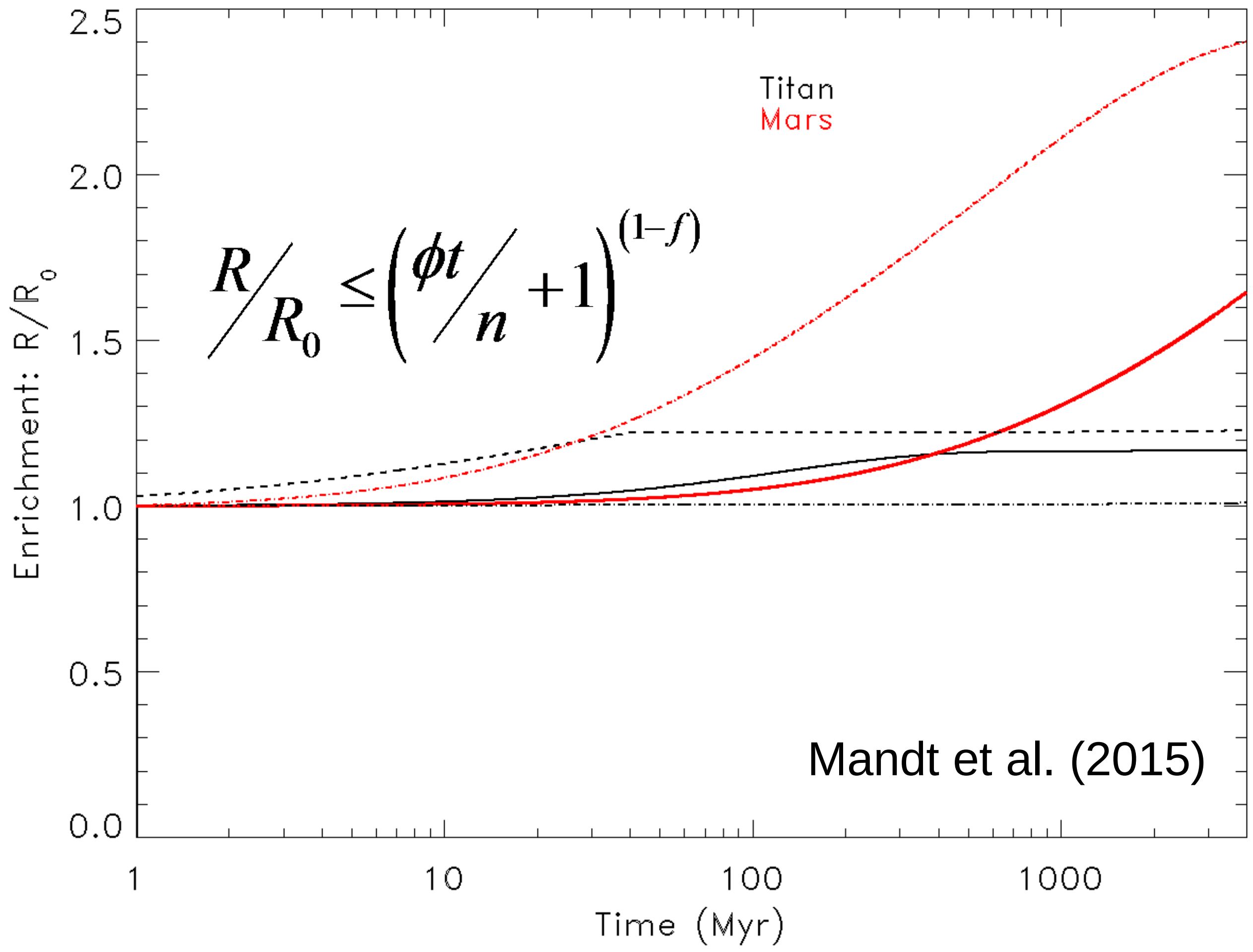
Escape – always makes the ratio lower over time



Fractionation occurs due to production and loss of the constituent of interest – escape and photochemistry are both loss processes

Atmospheres Evolve Differently: Nitrogen isotopes at Titan do not evolve significantly, but Mars isotopes do

- Titan
  - Origin of nitrogen traced by primordial ratio
  - Look for upper limit – only evaluate escape
  - Origin must be NH_3 from the Protosolar Nebula
- Mars
  - Titan can't evolve much, what about Mars?
  - Mars can because the loss rate relative to the column density is so much larger than Titan's

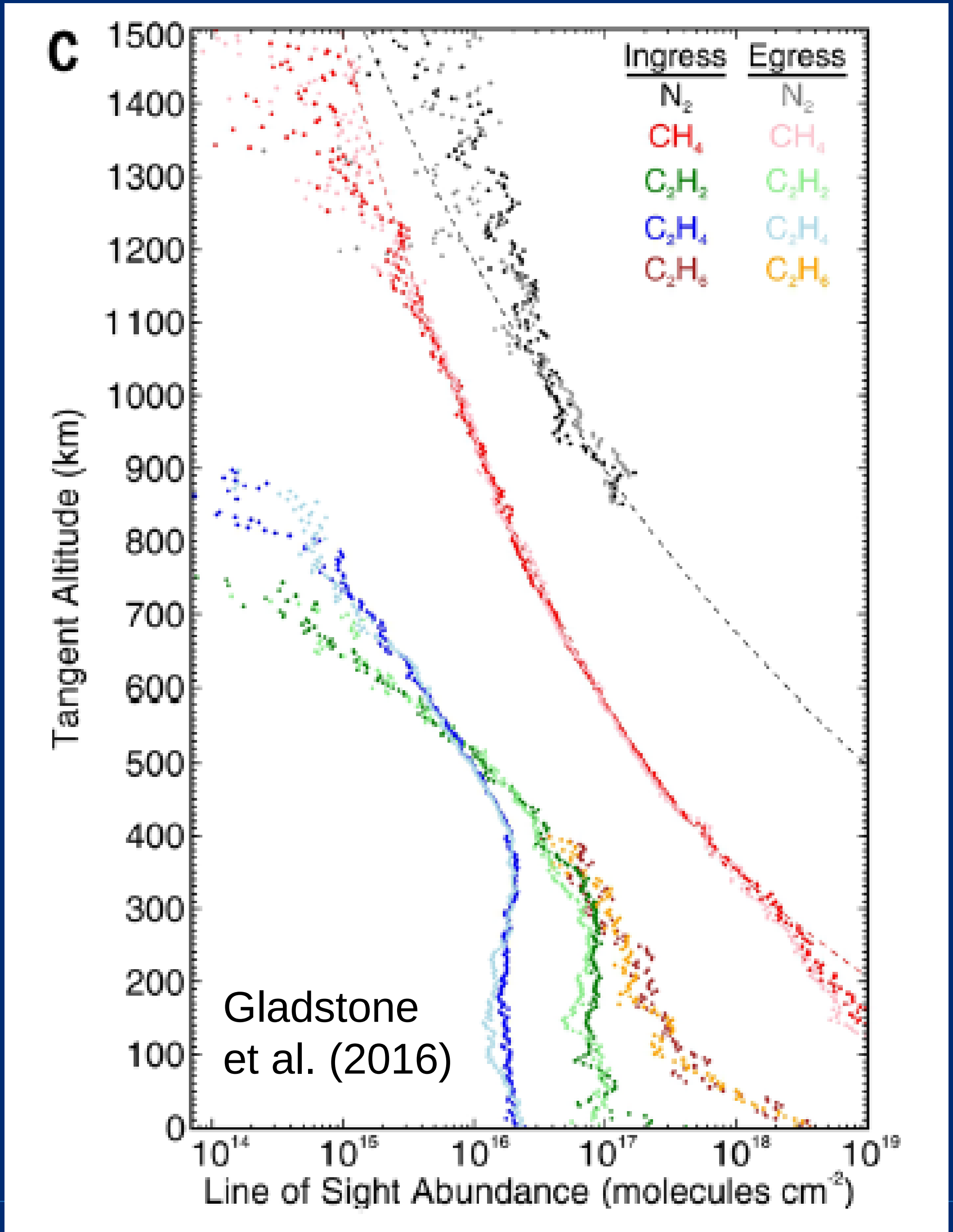


$$R/R_0 \le \left(\phi t/n + 1\right)^{(1-f)}$$

What about Pluto's Nitrogen?

- Origin of nitrogen
  - Start with assumed primordial: N_2 or NH_3
  - Evaluate evolution to current ratio
- Escape is slow – *Jeans*
- How effective is photochemistry?
  - ALMA lower limit for $^{14}N/^{15}N$ in HCN (Lellouch et al., 2017)
  - Can we use this to constrain N_2?

The New Horizons observations showed that Pluto has new processes to consider

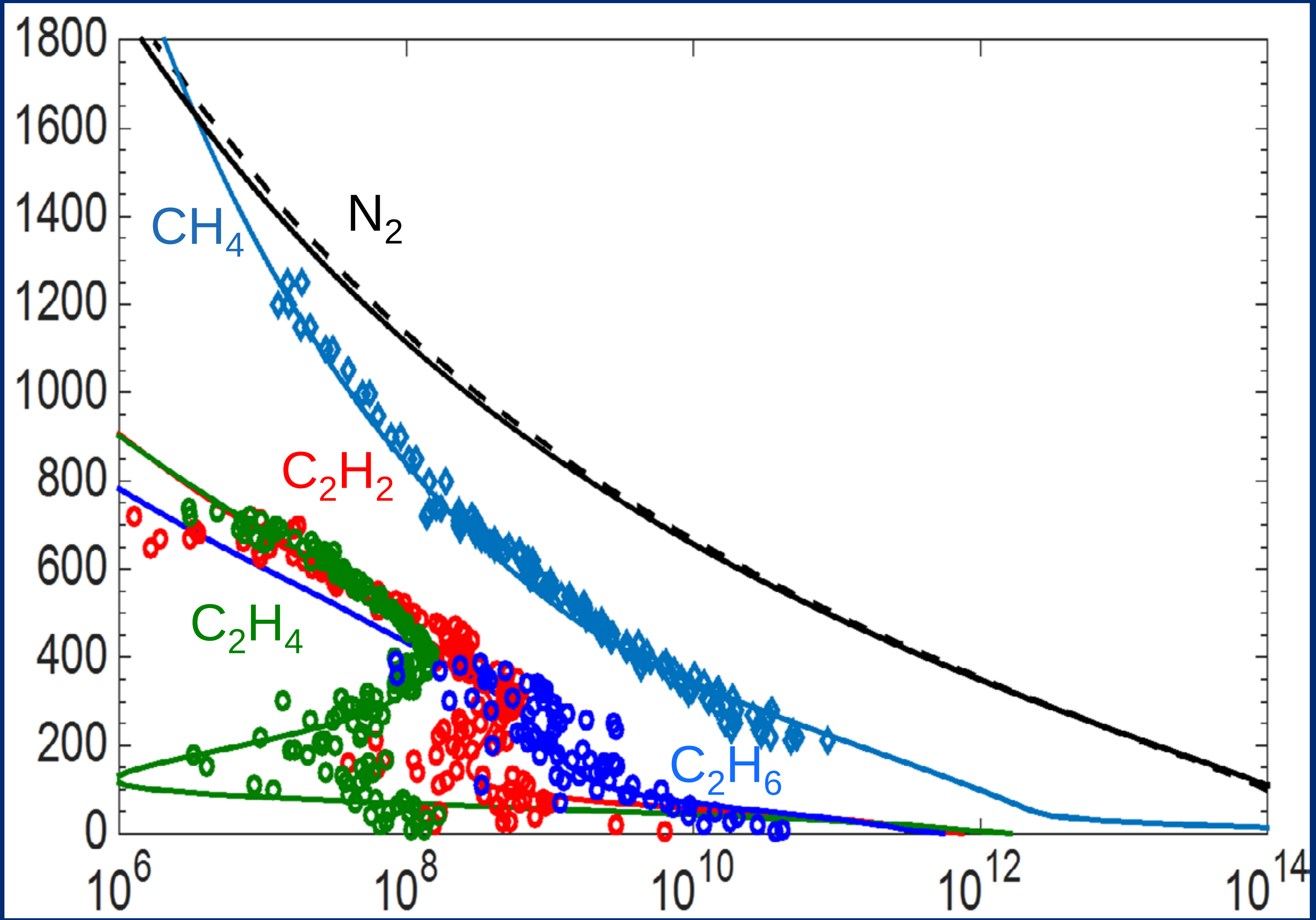


Gladstone et al. (2016)

Lessons from the C_2H_y profiles

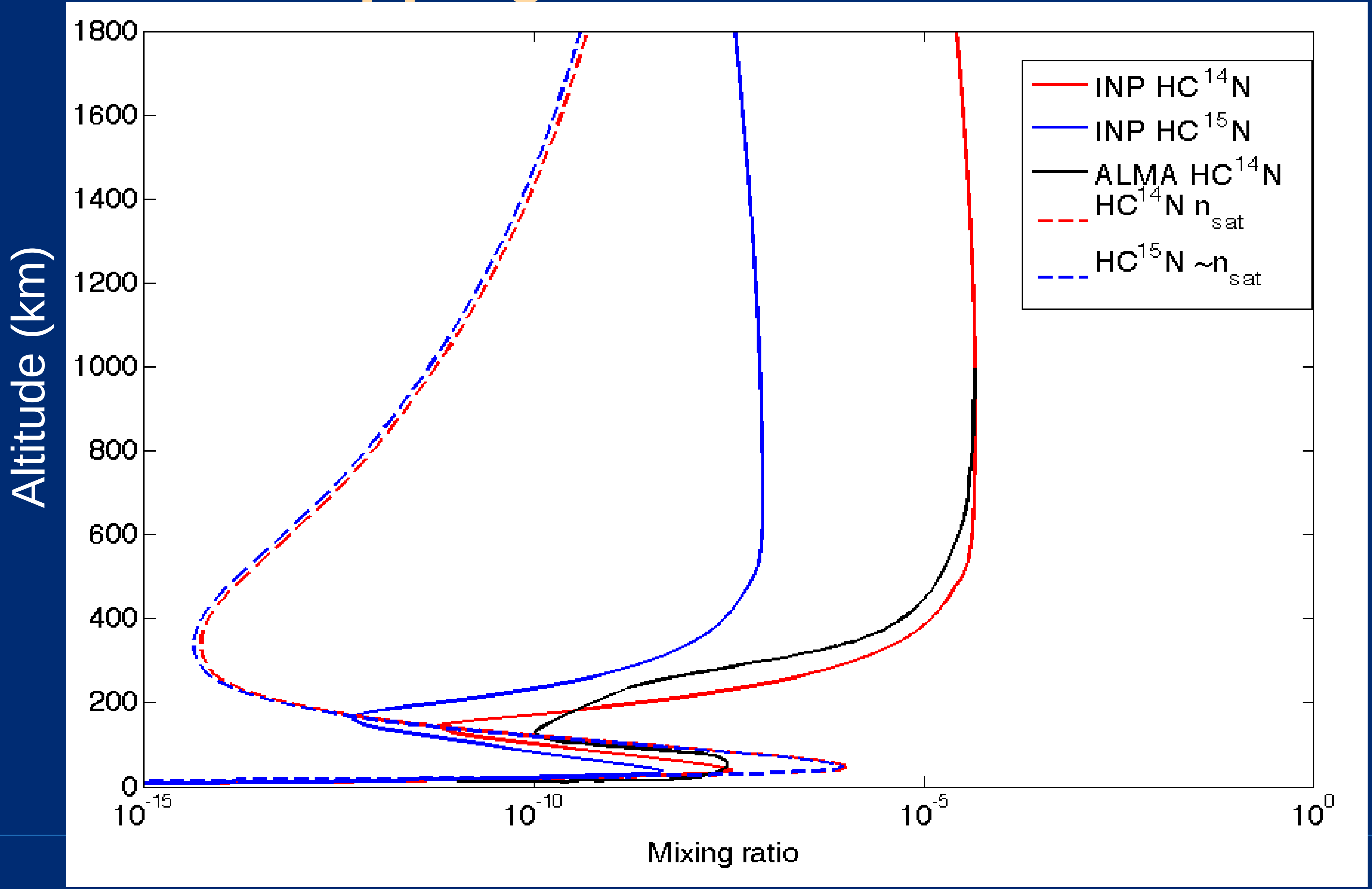
Atmospheric inversion – add loss processes (Willacy et al. 2016 for Titan)

- Condensation not efficient
- Aerosol trapping
  - Efficiency decreases with altitude
  - Aerosol properties change
- *Pluto's aerosols are sticky!* *(Dimitrov & Bar-Nun, 2002)*
  - Stickiness inversely proportional to aerosol surface area
  - Life cycle of growing, aging, descending
  - Hardening with aging like on Titan



Luspay-Kuti et al. (2017)

As shown for Titan, HCN affected by condensation and aerosol trapping

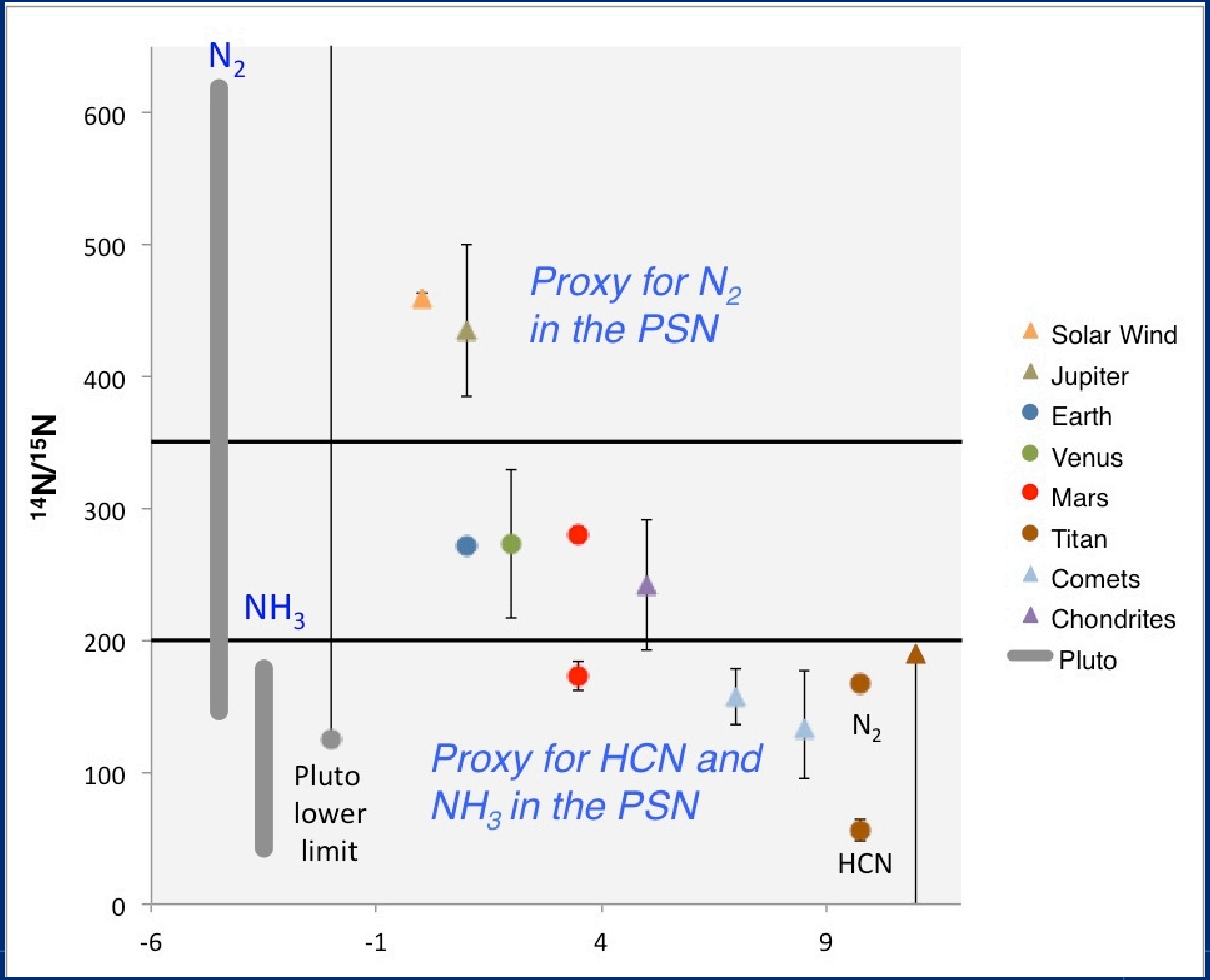


Nitrogen fractionation at Pluto is not as clear as at Titan

Parameter	Titan			Pluto: F10.7=110	
	Max	**Mod**	**Min**	**Chem**	**Full**
$^{14}N_2$ Production ($cm^{-2}s^{-1}$)	1.17×10^9	9.46×10^8	7.41×10^8	4.37×10^5	4.49×10^5
$^{14}N_2$ Loss ($cm^{-2}s^{-1}$)	1.76×10^9	1.35×10^9	9.29×10^8	9.60×10^5	9.72×10^5
$^{14}N^{15}N$ Production ($cm^{-2}s^{-1}$)	1.28×10^7	1.04×10^7	8.22×10^6	1.62×10^3	1.67×10^3
$^{14}N^{15}N$ Loss ($cm^{-2}s^{-1}$)	2.37×10^7	1.80×10^7	1.24×10^7	3.55×10^3	3.58×10^3
$^{14}N/^{15}N$ in N_2 column density	169.2	169.2	169.1	449.8	450.0
$^{14}N/^{15}N$ in HCN column density	106.3	101.2	82.6	449.5	43.5
$^{14}N/^{15}N$ observed in N_2	167.6±0.6			n/a	
$^{14}N/^{15}N$ observed in HCN	68.6±15.7			> 125	
f_{p1} from HCN observations	2.44±0.56			n/a	
f_{p1} based on HCN	1.59	1.67	2.05	1.00	10.34
f_{p2} based on loss rates	1.56	1.58	1.86	0.83	0.83

Uncertainty in Chemical Fractionation: Evolution at Pluto Poorly Constrained

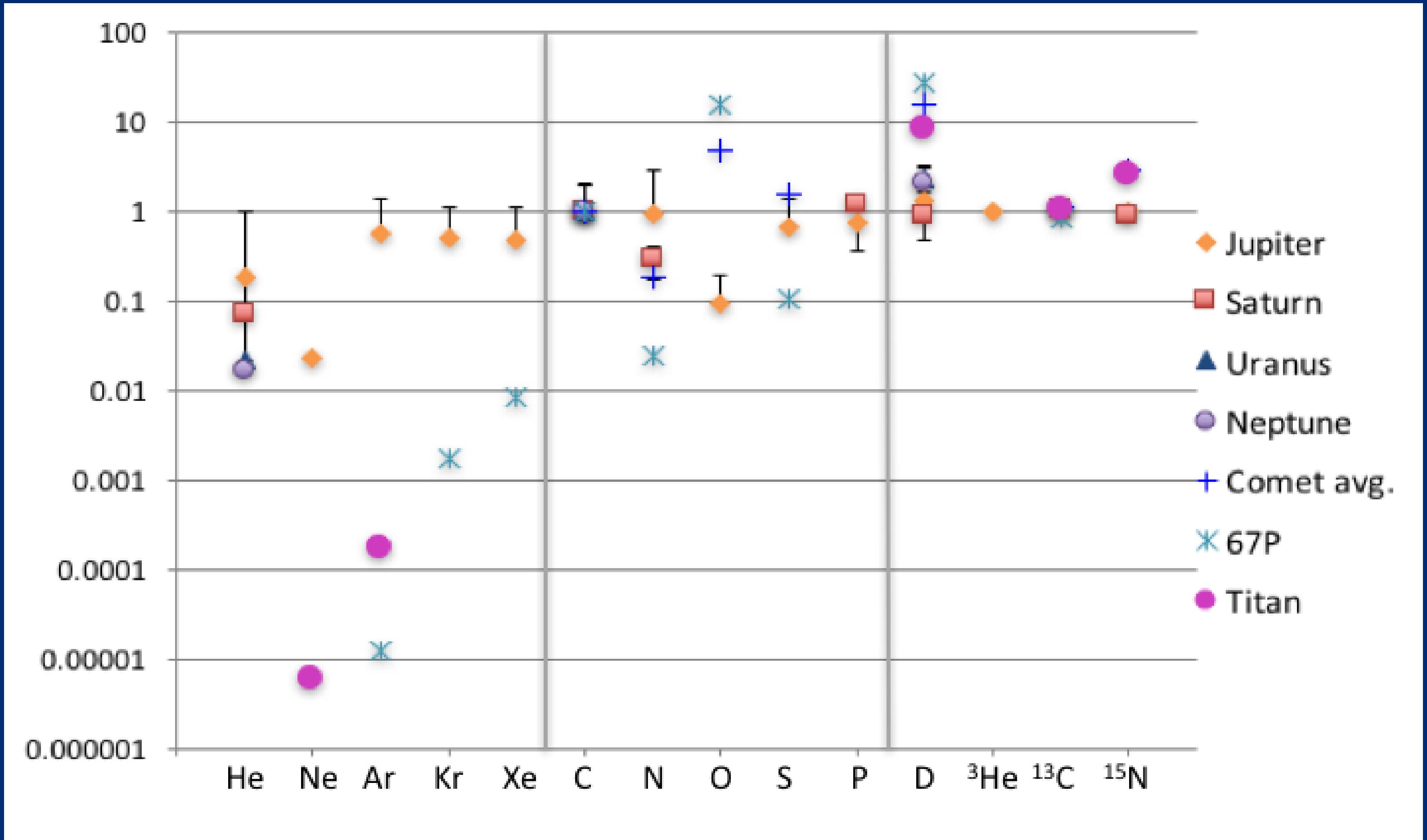
- Self-shielding
  - Major impact on nitrogen isotope chemistry at Titan
  - Very little effect at Pluto
- Condensation and aerosol trapping
  - Appear to have major impact on nitrogen isotopes in HCN
  - Not in agreement with observations
  - What isotope effect are we missing?
- Implications for Triton
  - Lower escape rates than Pluto
  - Same issues with chemistry
  - An Ice Giants mission to Neptune would answer questions about Pluto and Triton



Summary and Next Steps

- Titan
  - Originated as NH_3 in the PSN
  - Cold conditions for building blocks
  - Next step is noble gas comparisons with Rosetta results
- Pluto and Triton
  - Condensation and aerosols are a major problem
  - Need more modeling studies
  - More observations with ALMA
- Future mission needs
  - Measurements of noble gas abundances and isotope ratios
  - More comparative planetology studies
  - Let's go to the Ice Giants!!

Abundances of Measured Species Relative to Measured Carbon compared to Solar Abundances Relative to Solar Carbon



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Photochemical fractionation: 2 methods

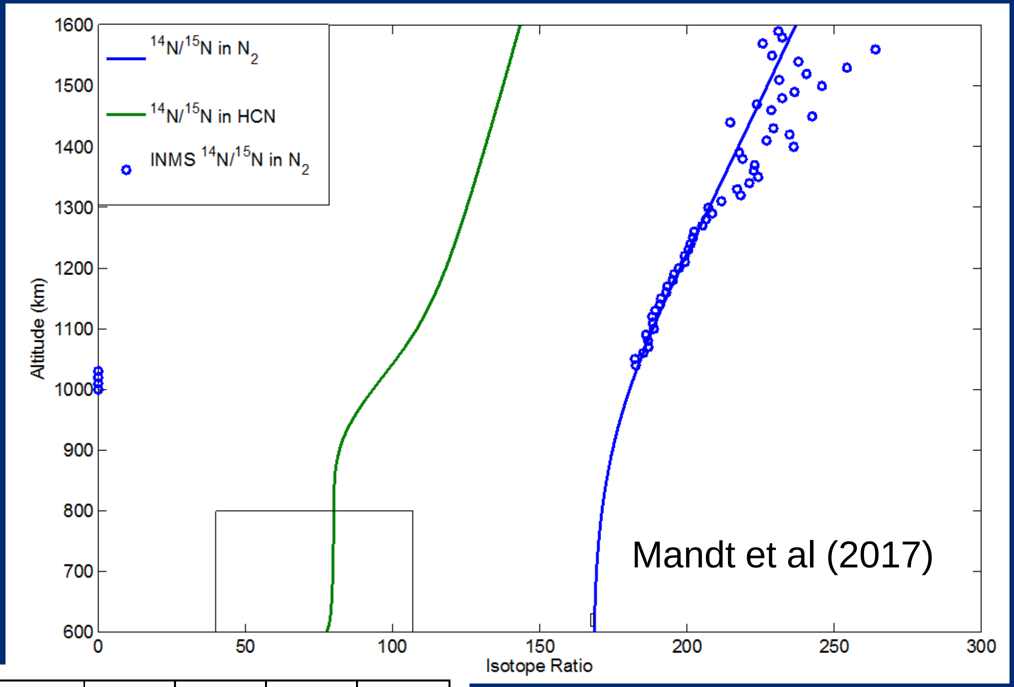
- Observations of $^{14}N/^{15}N$ in N_2 and a photochemical product

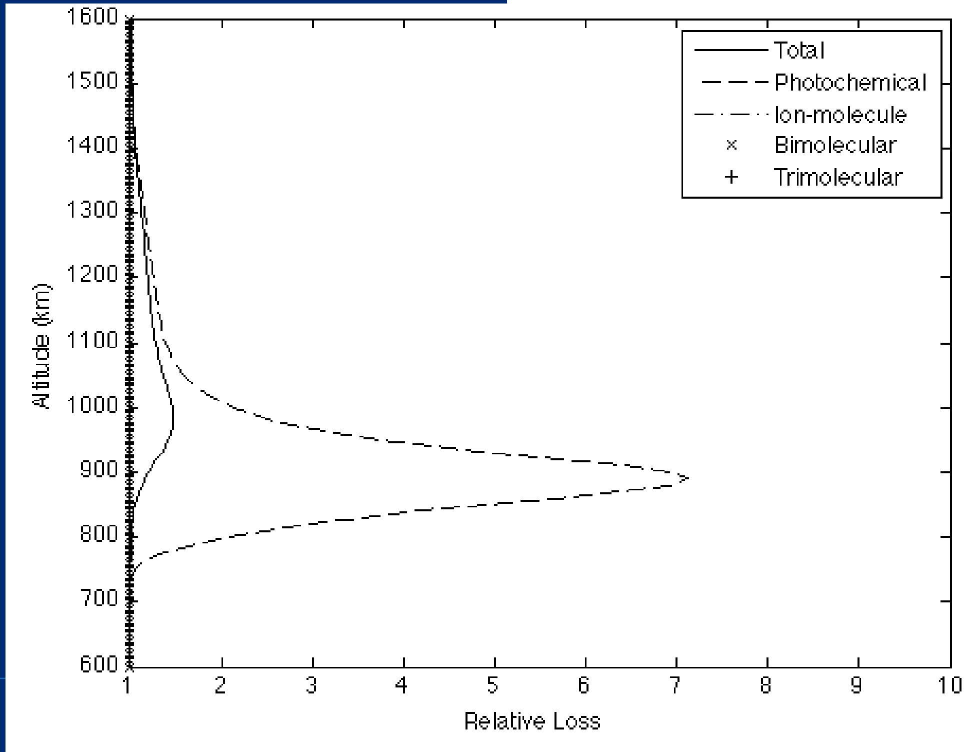
$$f = \frac{R_{\text{reactant}}}{R_{\text{product}}}$$

- Model the loss of $^{14}N_2$ and $^{14}N^{15}N$ with validation

$$f = {}^{L_2}\!/_{L_1} \cdot {}^{1}\!/_{R}$$

- Both methods have limitations



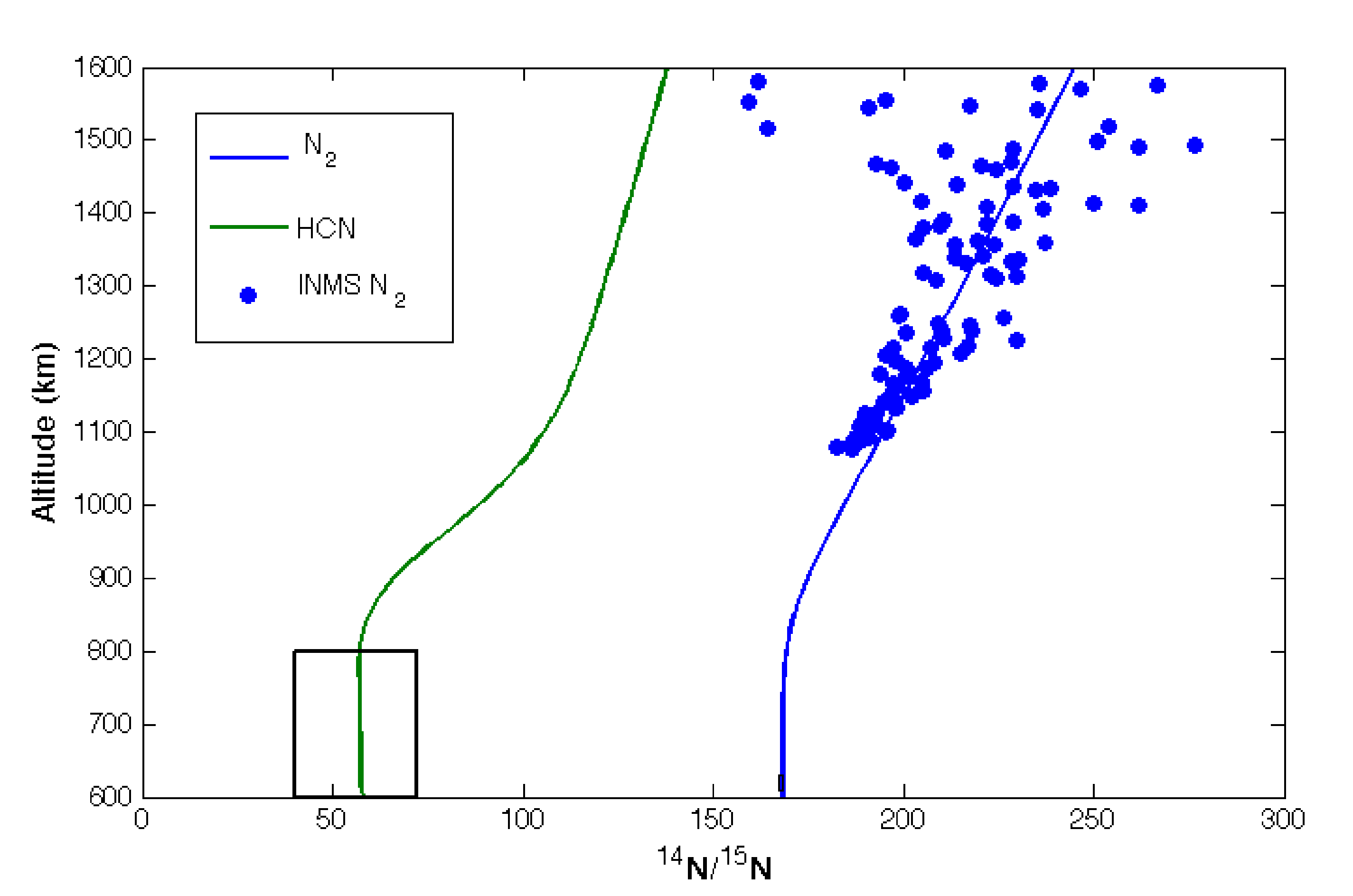


Titan observations allow for both methods to be used.

Models produce reasonable agreement with measurements.

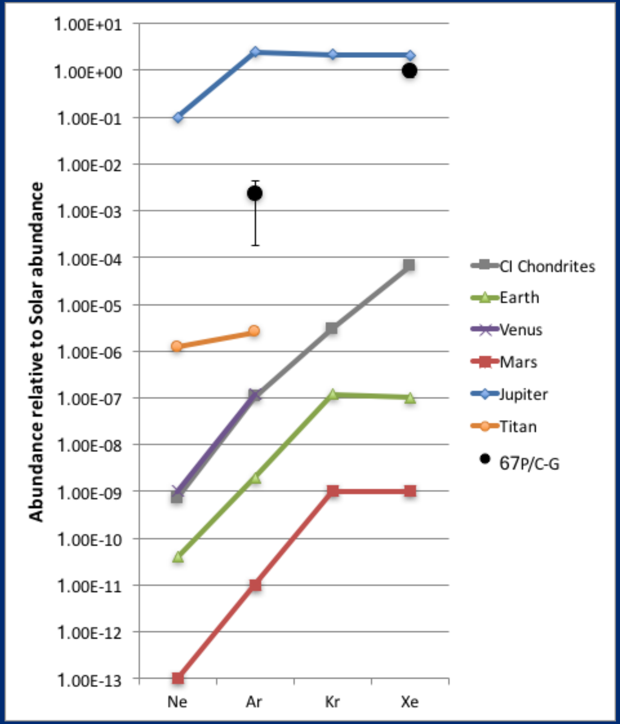
Escape fractionation

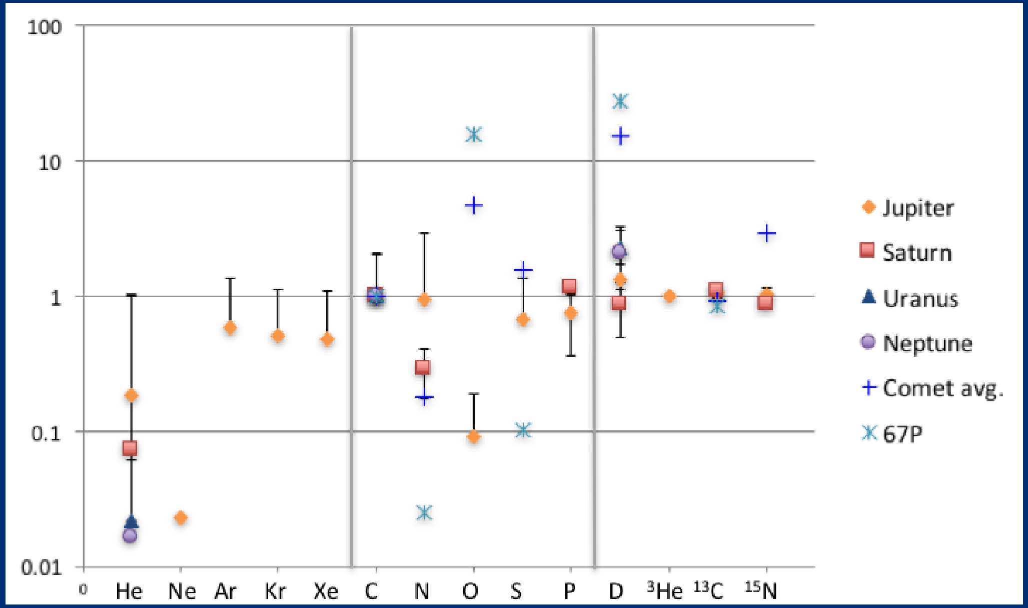
- Atmospheric models are needed to constrain how escape fractionates the isotopes
  - Sputtering
    - Ratio at the surface
    - Homopause and exobase
    - Temperature profile
  - Jeans escape
    - Exobase parameters
  - Hydrodynamic escape
    - Critical mass for escape
- Best results when models are validated with observations

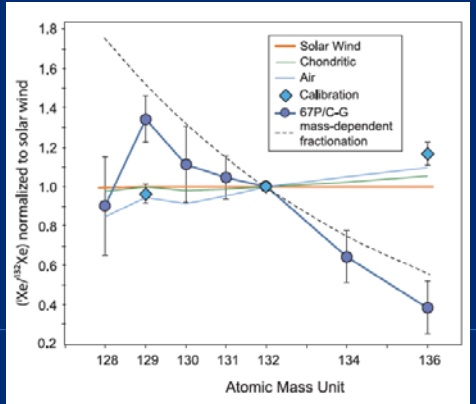


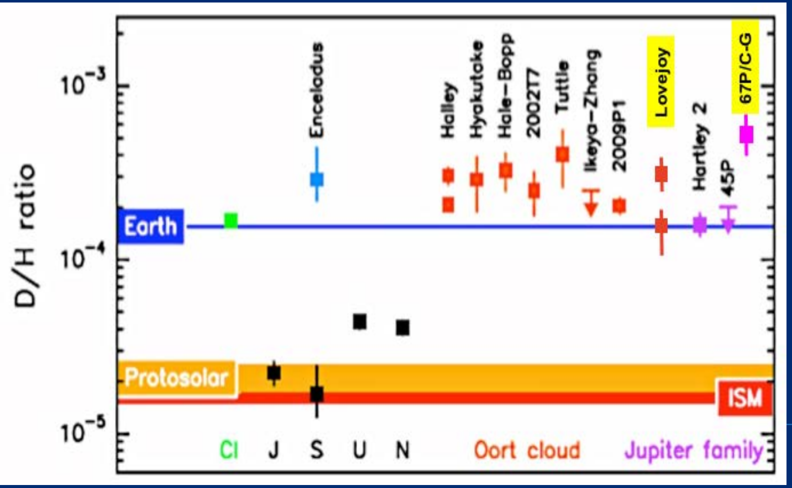
Rosetta, a single comet mission with a powerful instrument, has contributed significantly to our understanding of the composition of the Solar System

- D/H ratio in water highest yet, but varies by a factor of 2 among measurements (Altwegg et al. 2014, 2017)
- Two noble gas measurements, with isotopologues (Balsiger et al. 2016; Marty et al. 2017)
- Bulk abundances and isotope ratios of Carbon (Le Roy et al. 2015; Haessig et al. 2017)









Application to Exoplanet Systems

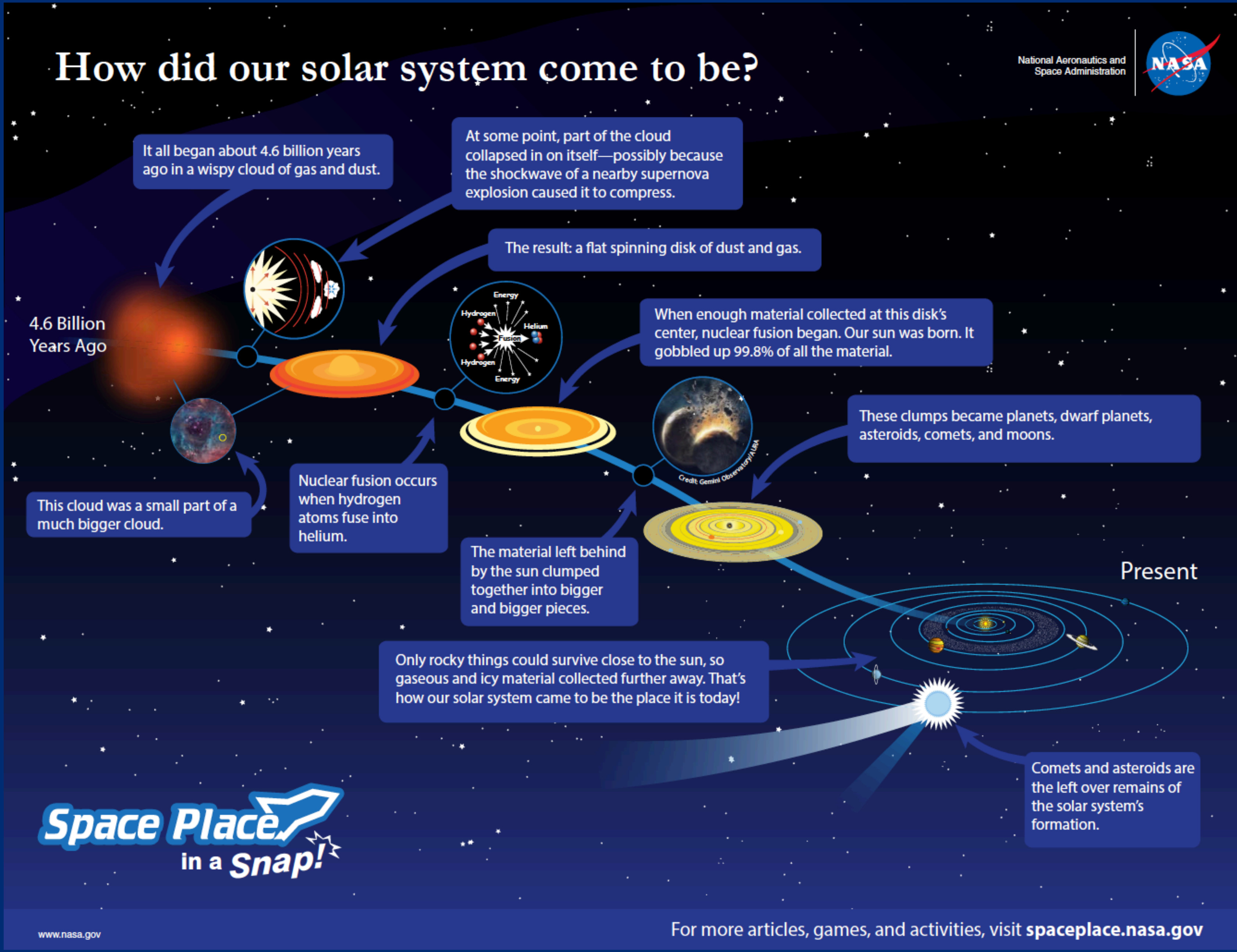
Near Term Goals →	Mid-Term Goals →	Long-Term Goals →

• In the Solar System
  • Measurements with current capabilities
  • Photochemistry
  • Formation models
• Laboratory studies
  • Reactions
  • Sublimation
  • Condensation
• Exoplanets
  • Molecule detection
  • Understand haze
  • Advance models
	• In the Solar System
	  • New remote & in situ measurement capabilities
	  • Advanced models
	• Laboratory studies
	• Exoplanets
	  • New detections & abundance
	  • Model current atmosphere
	  • Model formation and evolution
		• In the Solar System
		  • Multiple sample returns – Moon, asteroids, comets, Mars, etc.
		• Laboratory studies
		• Exoplanets
		  • Isotope detection & abundances in multiple planets of same system
		  • More modeling

→ Use the solar system as an analog for exoplanet observations →		

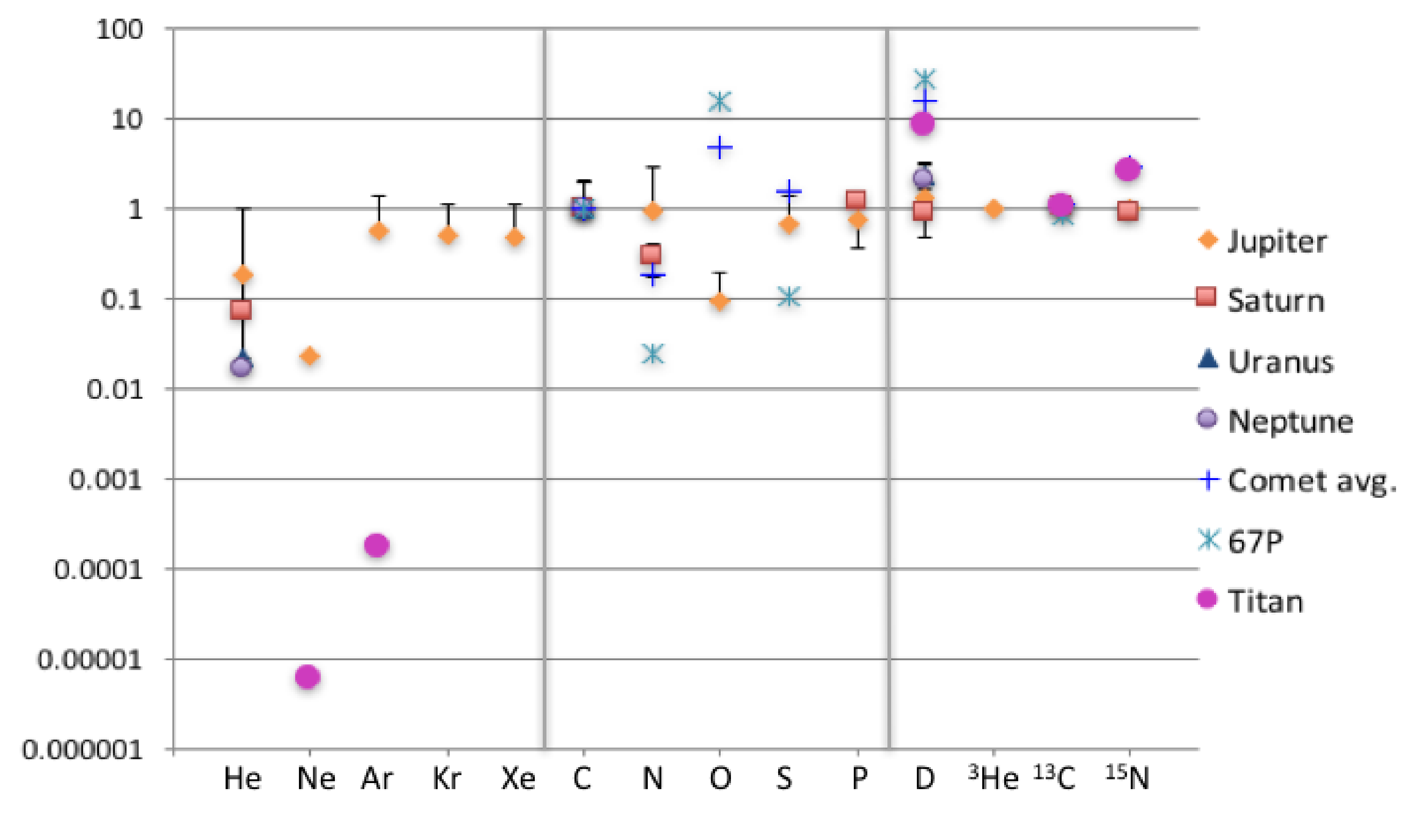
A mission to the Ice Giants advances NASA Goals:

- Formation
  - How did the solar system form?
  - Giant planets and small bodies are time capsules of formation
- Evolution
  - Atmospheres evolve over time
- Comparative Planetology
  - Small icy bodies are time capsules
  - Larger icy bodies have atmospheres that evolved



A mission to the Ice Giants could help us to understand how icy bodies like Pluto and Triton formed and the history of the Neptune system

- Titan isotopes are similar to comets
  - What about cometary noble gases?
- Pluto and Triton
  - If their nitrogen originated as N_2, primordial ratio will be like Jupiter
  - Atmospheric evolution could make the current ratio more like NH_3
- Comets, Titan, Pluto and Triton
  - Composition is an essential tool for understanding how much icy bodies contributed to the gas giants
  - A big question is how the ice giants compare to the gas giants?



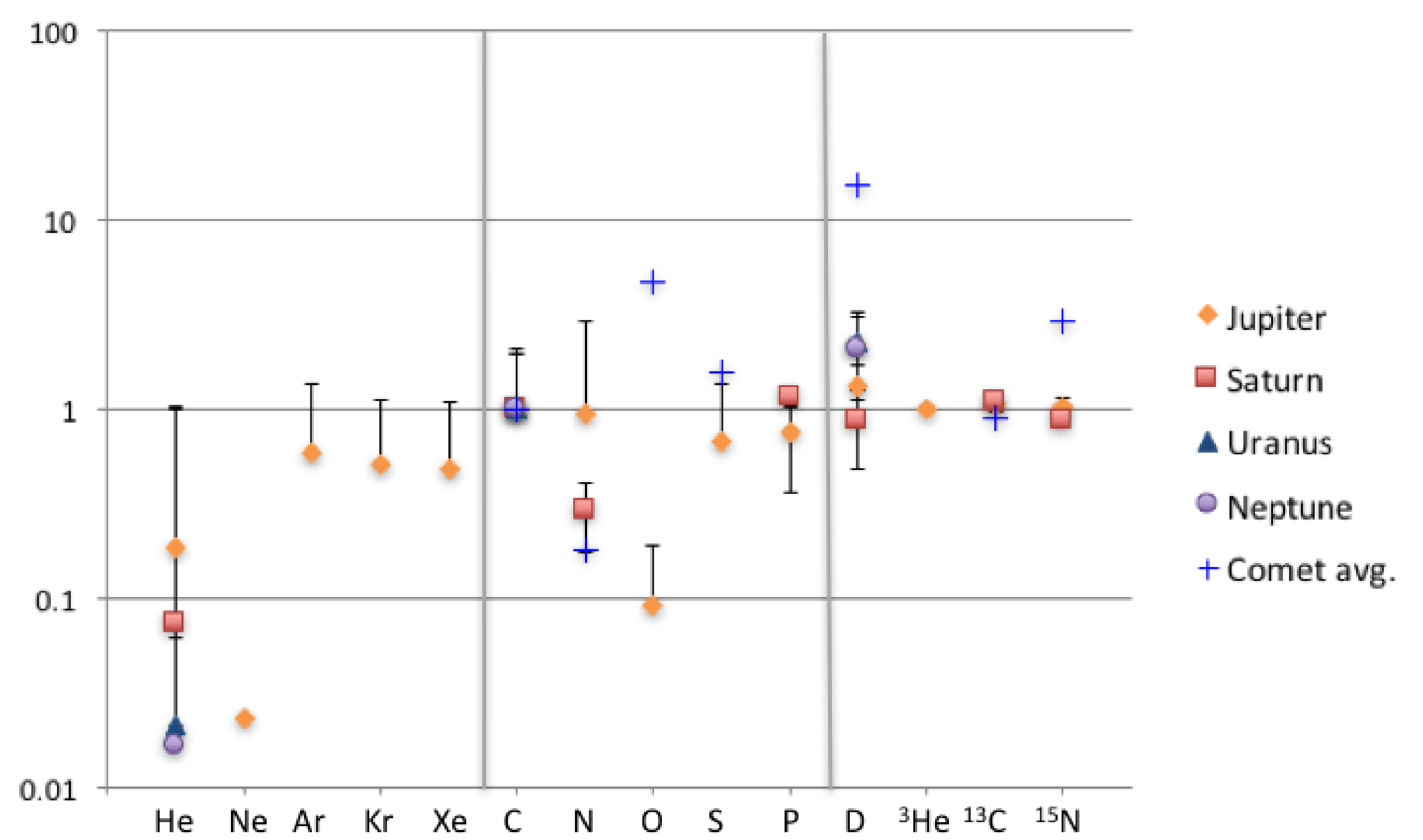
NASA Planetary Science Questions

- Science Questions
  - How did life begin and evolve on Earth?
  - How did the Solar System evolve?
  - How did the Sun's family originate?
  - What are the characteristics of the Solar System?
- Strategic objective from 2014 plan: Ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere
  - How did our solar system form and evolve?
  - Is there life beyond Earth?
  - What are the hazards to life on Earth?

The overall picture of Solar System composition is limited: An Ice Giants mission is needed

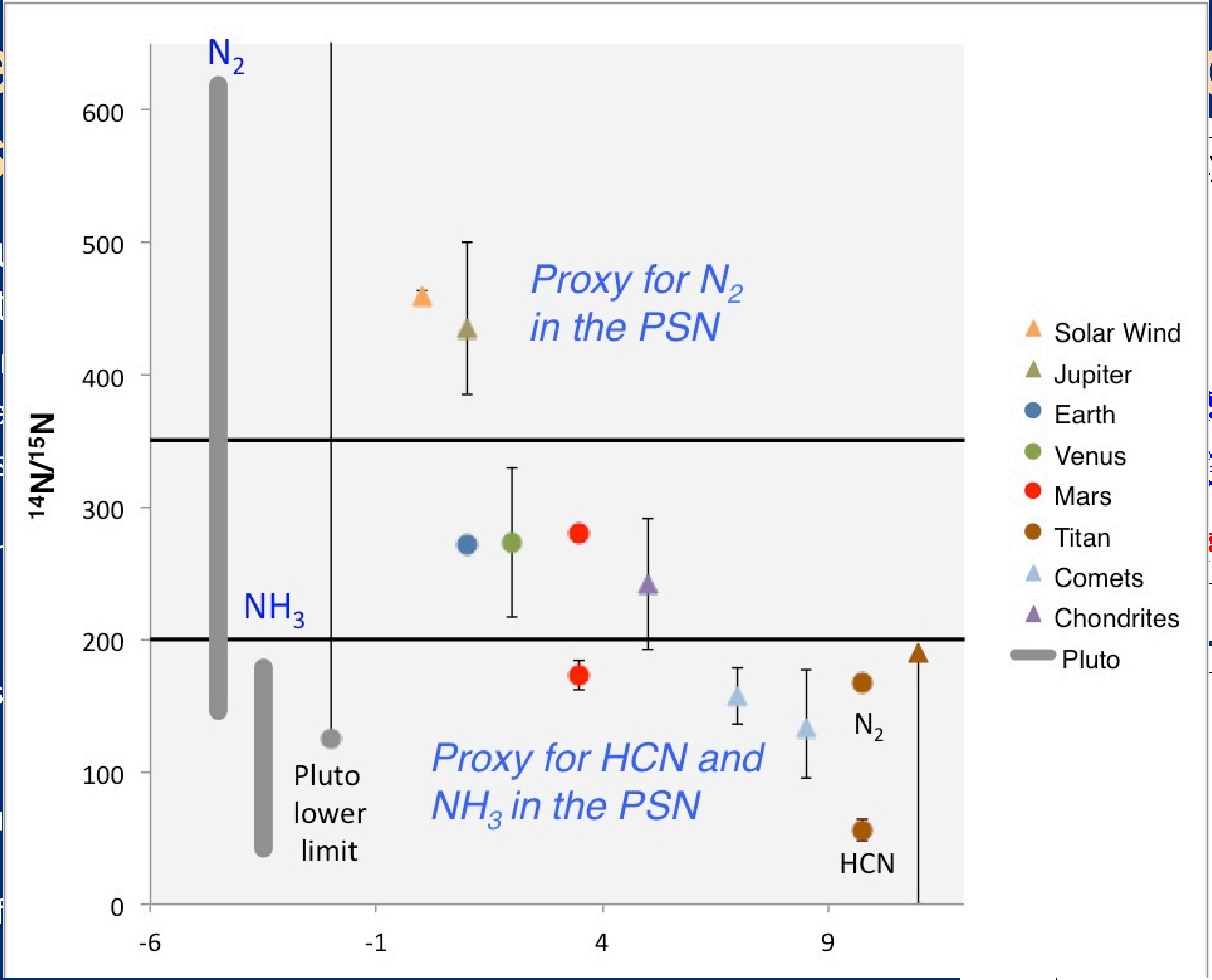
- Most important measurements for Origins research
  - Noble gases
  - Isotope ratios
- Limitations
  - Small number of samples
  - Large uncertainties
- The Rosetta mission is an important analogy for addressing this need

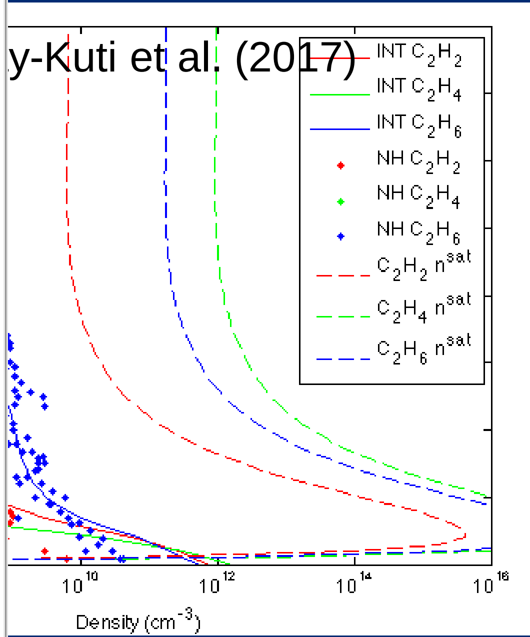
Abundances of Measured Species Relative to Measured Carbon compared to Solar Abundances Relative to Solar Carbon

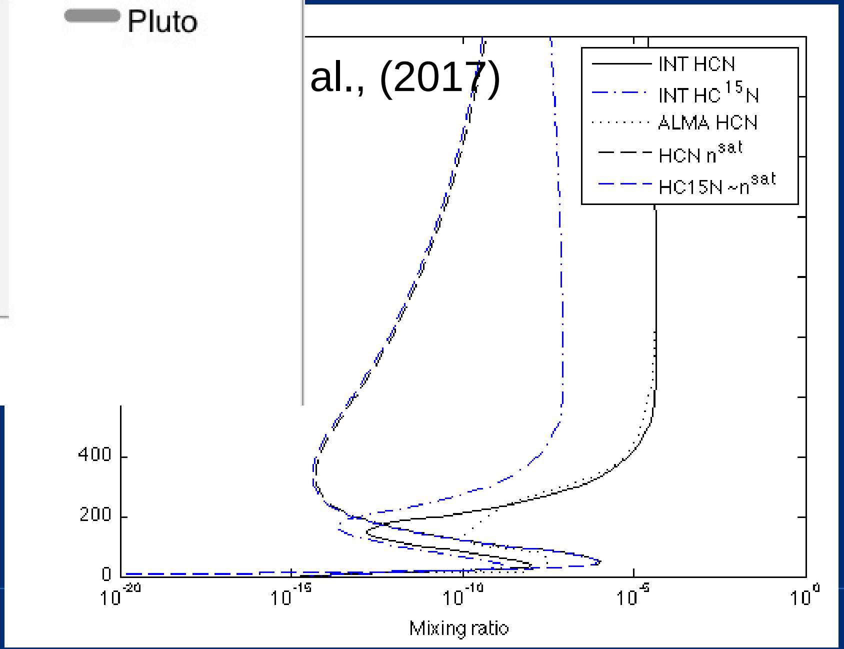


We applie dict a current is

- What is the sou component of t
  - N_2 if formatio
  - NH_3 for highe
  - Origin tells us
- Limitation of cu
  - No $^{14}N/^{15}N$ in
  - ALMA lower l
  - No noble gas
- Modeling
  - Only option u observations
  - Limitations of influence the







- Triton is the ideal target for comparative planetology with Pluto!

Outputs of modeling the evolution of the isotopic ratios

Time scale

- The time scale can be derived by integrating the production and loss equation over time for both the light and heavy isotopes

$$dn/dt = P - L$$

Total Inventory

- The fractionation factor defines the total amount of a species fractionated using the Rayleigh distillation relationship

$$\frac{n_1^0}{n_1} = \left(\frac{R}{R_0}\right)^{(1/(1-f))}$$

Initial Ratio

- If the initial ratio is not known, but the processes are well-understood, upper and/or lower boundaries can be determined
- Determining an initial ratio has implications for the formation of Titan