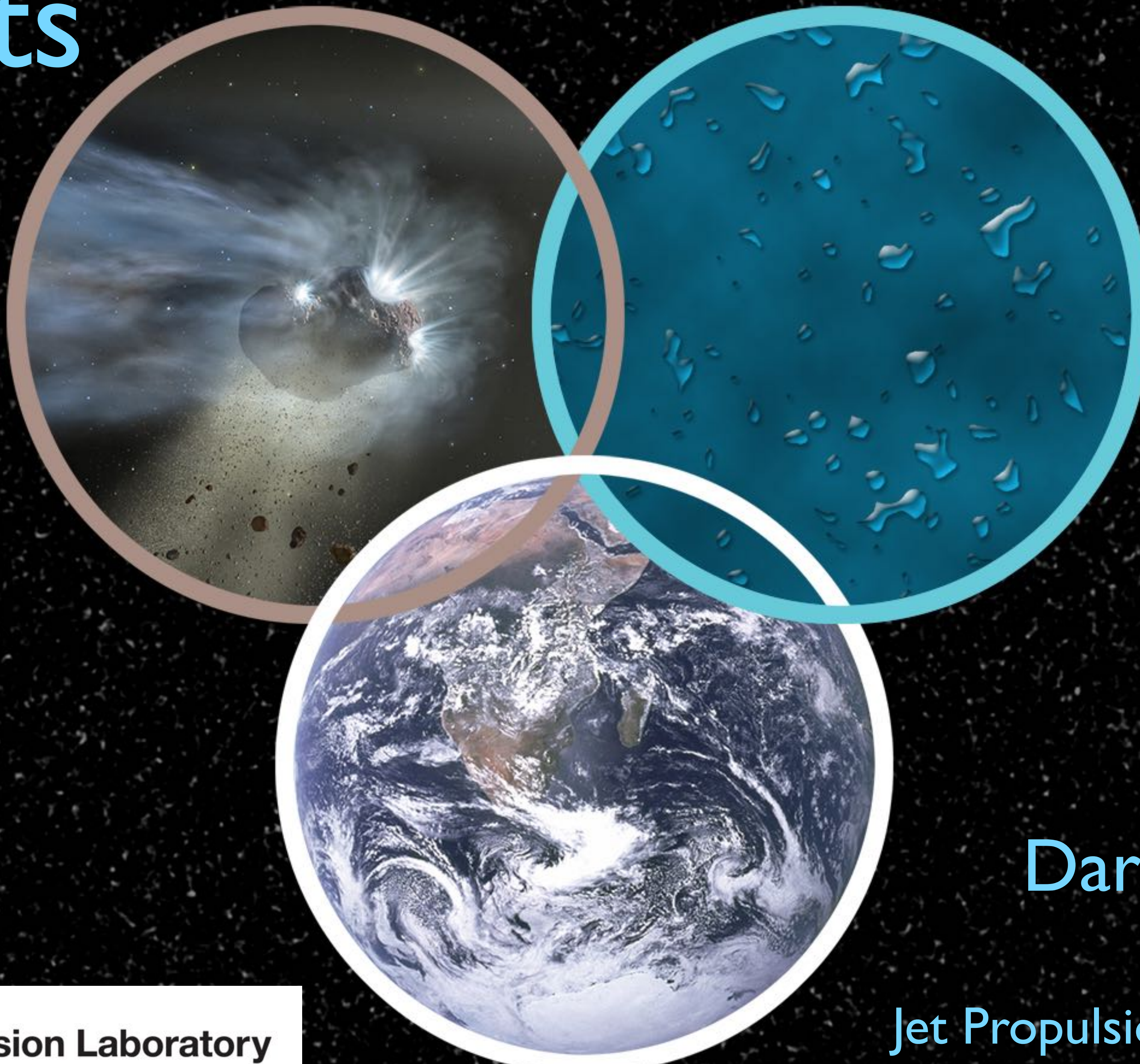
Ocean-Like Water in Hyperactive Comets



Darek Lis

Jet Propulsion Laboratory
California Institute of Technology

Jet Propulsion Laboratory
California Institute of Technology

SOFIA Tele-Talk, July 10, 2019

NASA/Origins

NASA/Origins

How Did We Get Here?

RESEARCH ARTICLE | ASTRONOMY

Ethyl alcohol and sugar in comet C/2014 Q2 (Lovejoy)

Nicolas Biver[1,*], Dominique Bockelée-Morvan[1], Raphaël Moreno[1], Jacques Crovisier[1], Pierre Colom[1], Dariusz C. Lis[2,3], Aage Sandqvist[4], Jérémie Boissier[5], Didier Despois[6] and Stefanie N. Milam[7]

+ Author Affiliations

*Corresponding author. E-mail: nicolas.biver@obspm.fr

Science Advances 23 Oct 2015:
Vol. 1, no. 9, e1500863
DOI: 10.1126/sciadv.1500863

RESEARCH ARTICLE | SPACE SCIENCES

Prebiotic chemicals—amino acid and phosphorus—in the coma of comet 67P/Churyumov-Gerasimenko

Kathrin Altwegg[1,2,*], Hans Balsiger[1], Akiva Bar-Nun[3], Jean-Jacques Berthelier[4], Andre Bieler[1,5], Peter Bochsler[1], Christelle Briois[6], Ursina Calmonte[1], Michael R. Combi[5], Hervé Cottin[7], Johan De Keyser[8], Frederik Dhooghe[8], Bjorn Fiethe[9], Stephen A. Fuselier[10], Sébastien Gasc[1], Tamas I. Gombosi[5], Kenneth C. Hansen[5], Myrtha Haessig[1,10], Annette Jäckel[1], Ernest Kopp[1], Axel Korth[11], Lena Le Roy[2], Urs Mall[11], Bernard Marty[12], Olivier Mousis[13], Tobias Owen[14], Henri Rème[15,16], Martin Rubin[1], Thierry Sémon[1], Chia-Yu Tzou[1], James Hunter Waite[10] and Peter Wurz[1]

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*Corresponding author. Email: kathrin.altwegg@space.unibe.ch

Science Advances 27 May 2016:
Vol. 2, no. 5, e1600285
DOI: 10.1126/sciadv.1600285

- Glycine detected in comets, but not in the ISM
- Over 100 amino acids found in meteorites (compared to 20 in terrestrial proteins)
- Comets and asteroids might have delivered life's all important building blocks and water needed for life to thrive

How Did We Get Here?

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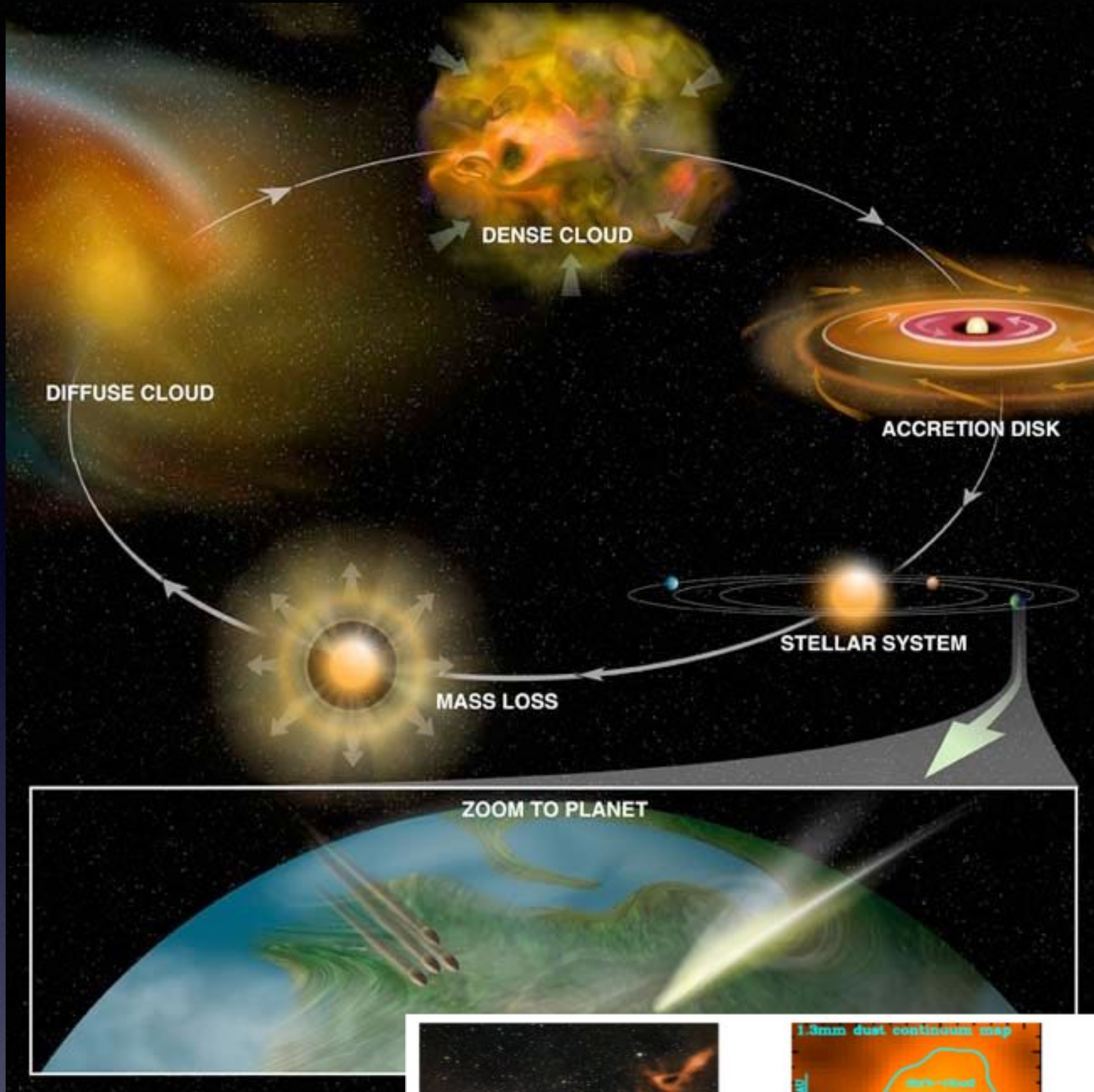
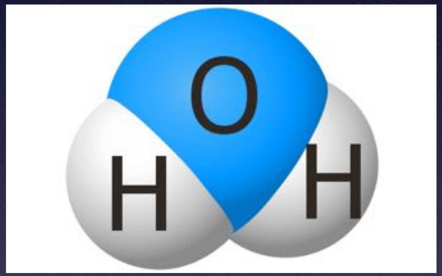
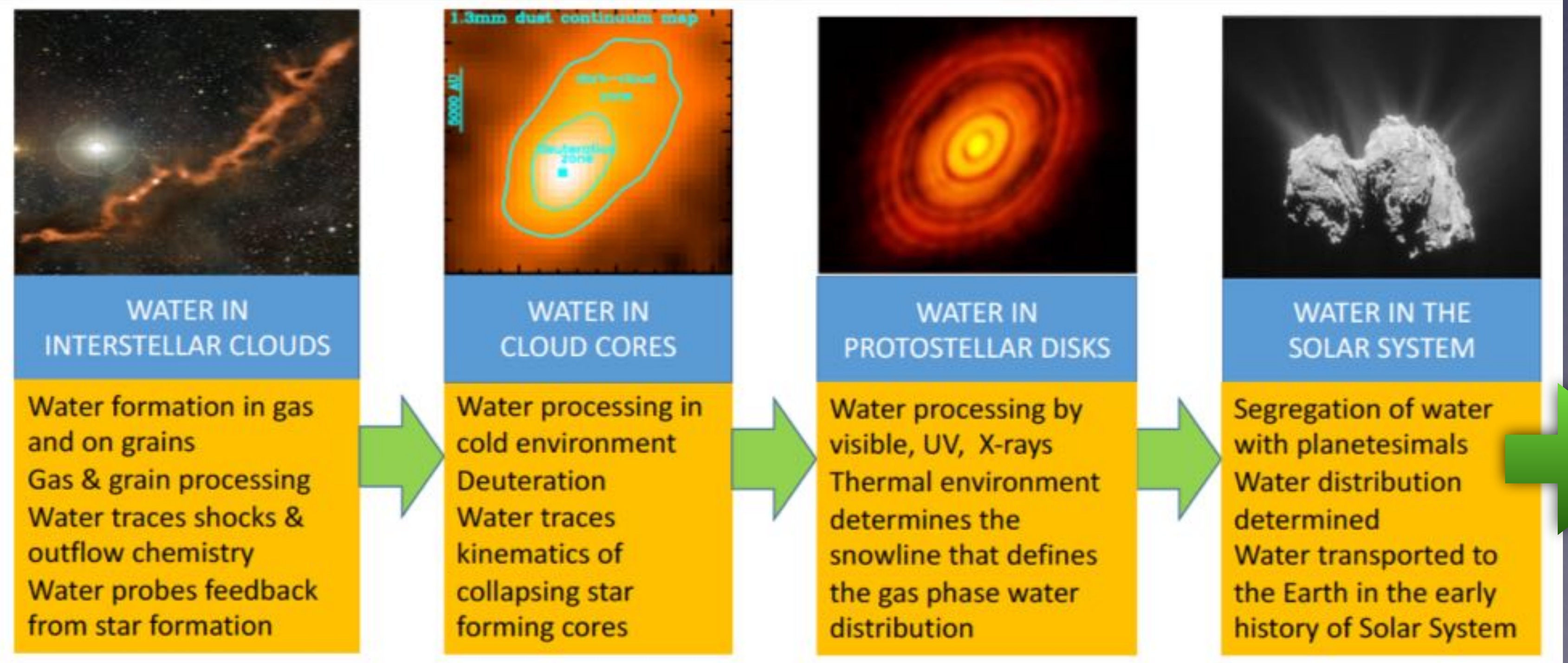
1 **Synthesis**
Many of life's basic building blocks, such as amino acids, are formed in space and fall to Earth.

- Glycine detected in comets, but not in the ISM
- Over 100 amino acids found in meteorites (compared to 20 in terrestrial proteins)
- Comets and asteroids might have delivered life's all important building blocks and water needed for life to thrive
- *"Many of life's building blocks, such as amino acids are formed in space and fall to Earth"*

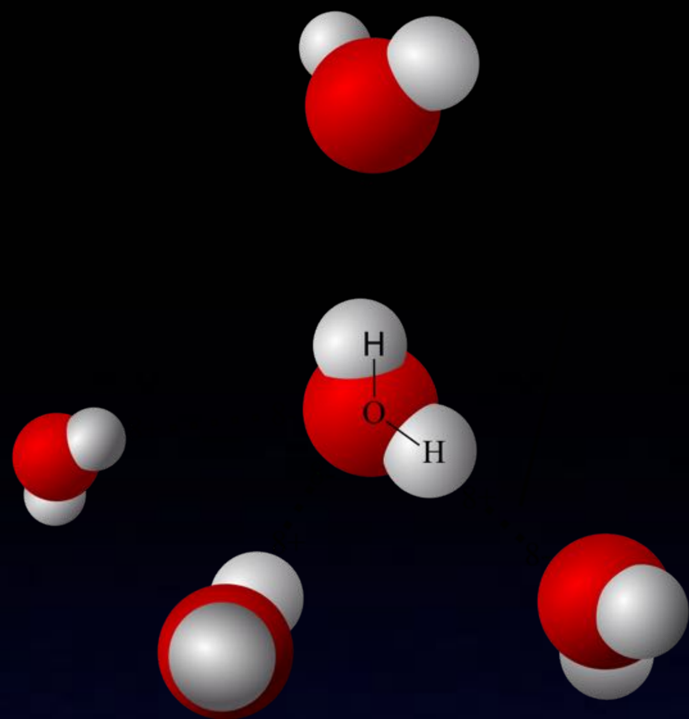
Cosmic Inheritance of Water





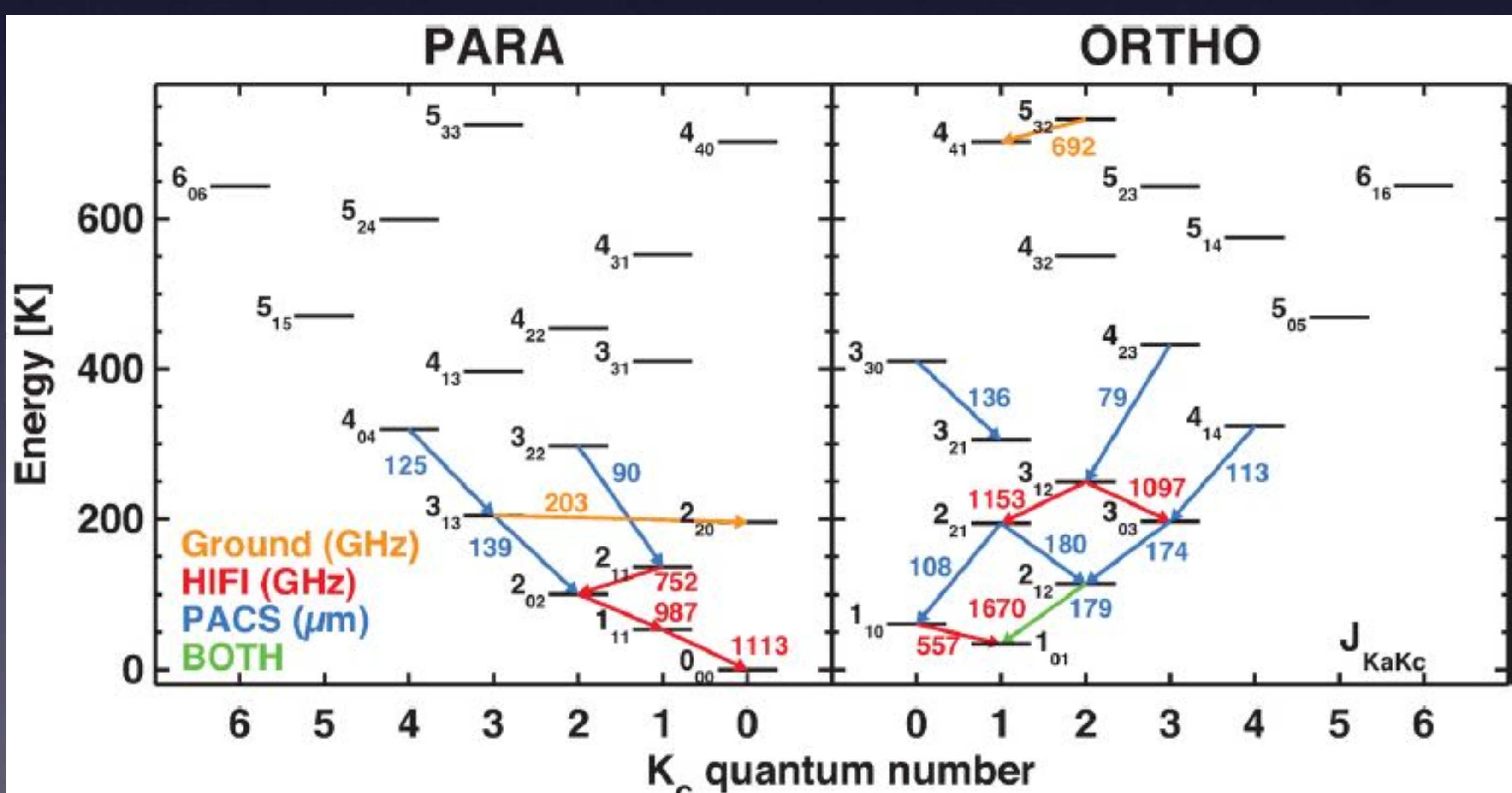


Images: NRAO/NASA

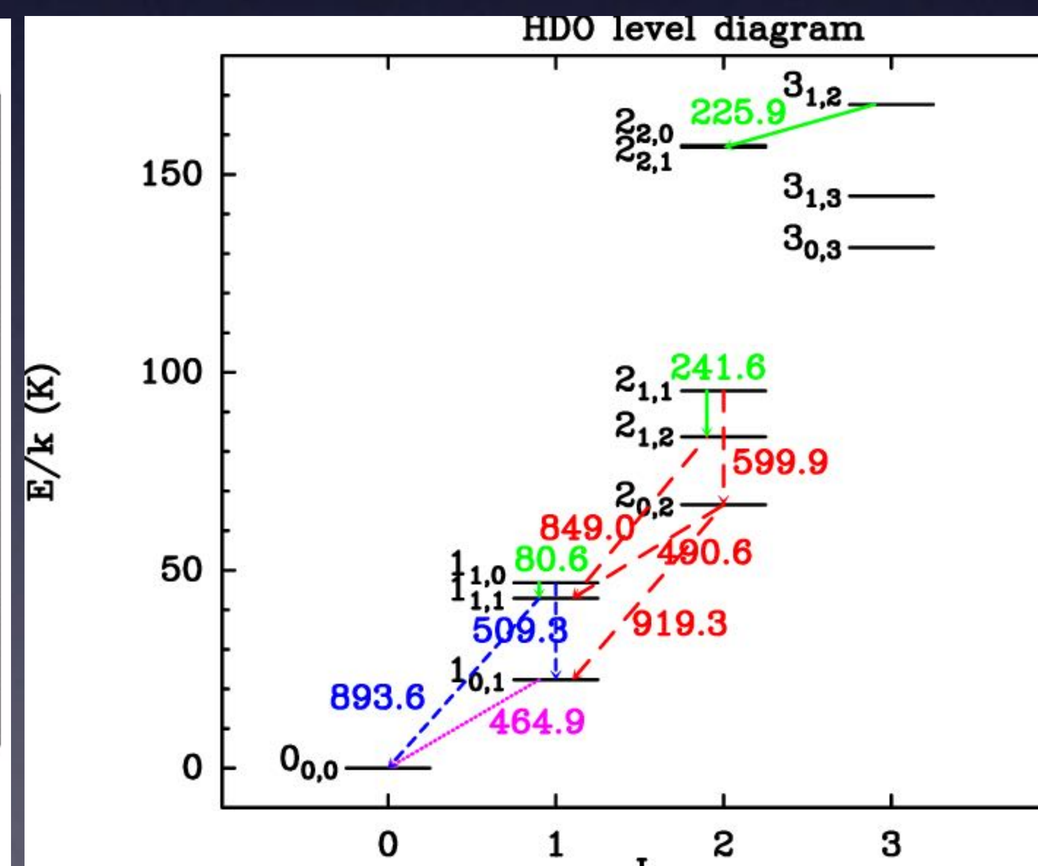


Observations of Cold Water

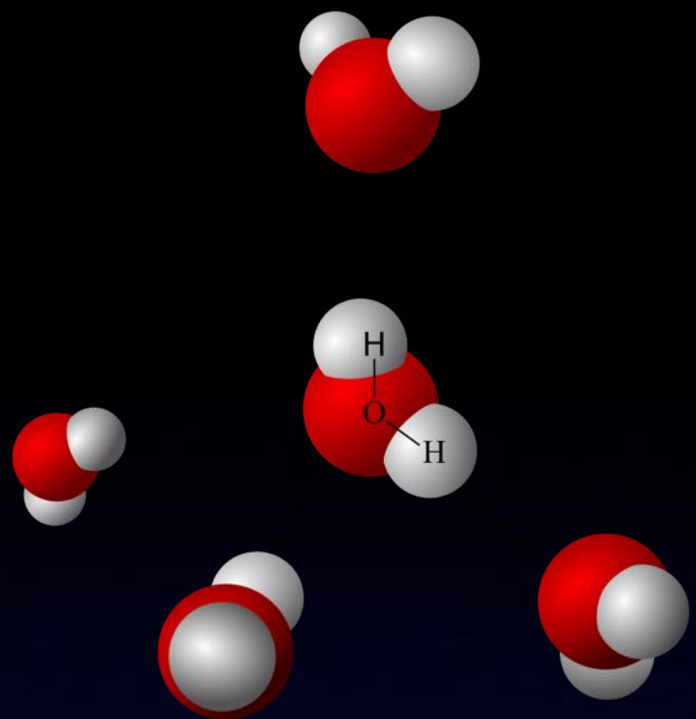
- Atmosphere opaque at the frequencies of the low-energy water lines
- Even SOFIA cannot observe cold water, but it can observe water-18 and HDO



van Dishoeck et al. 2013



Coutens et al. 2014



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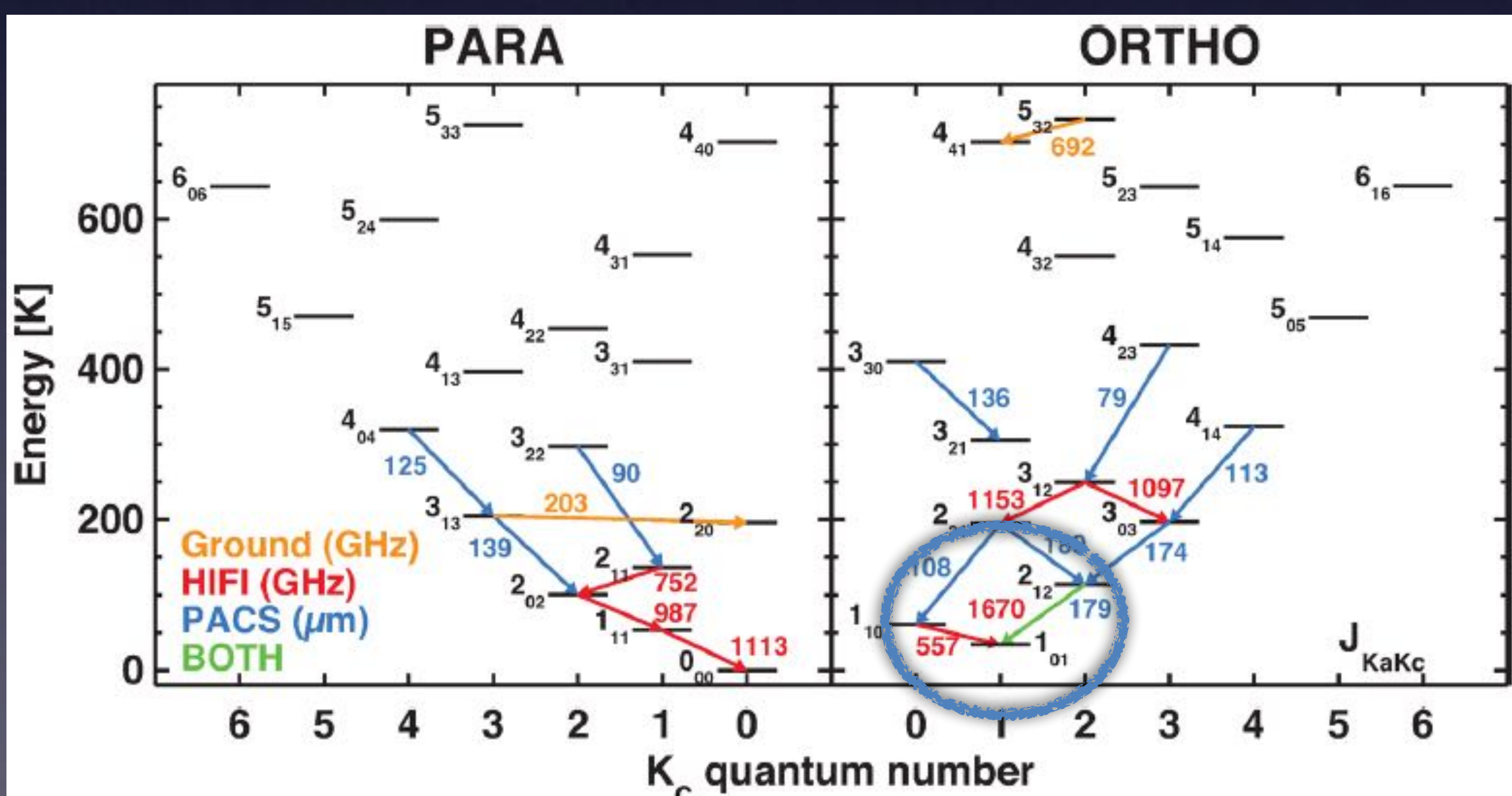

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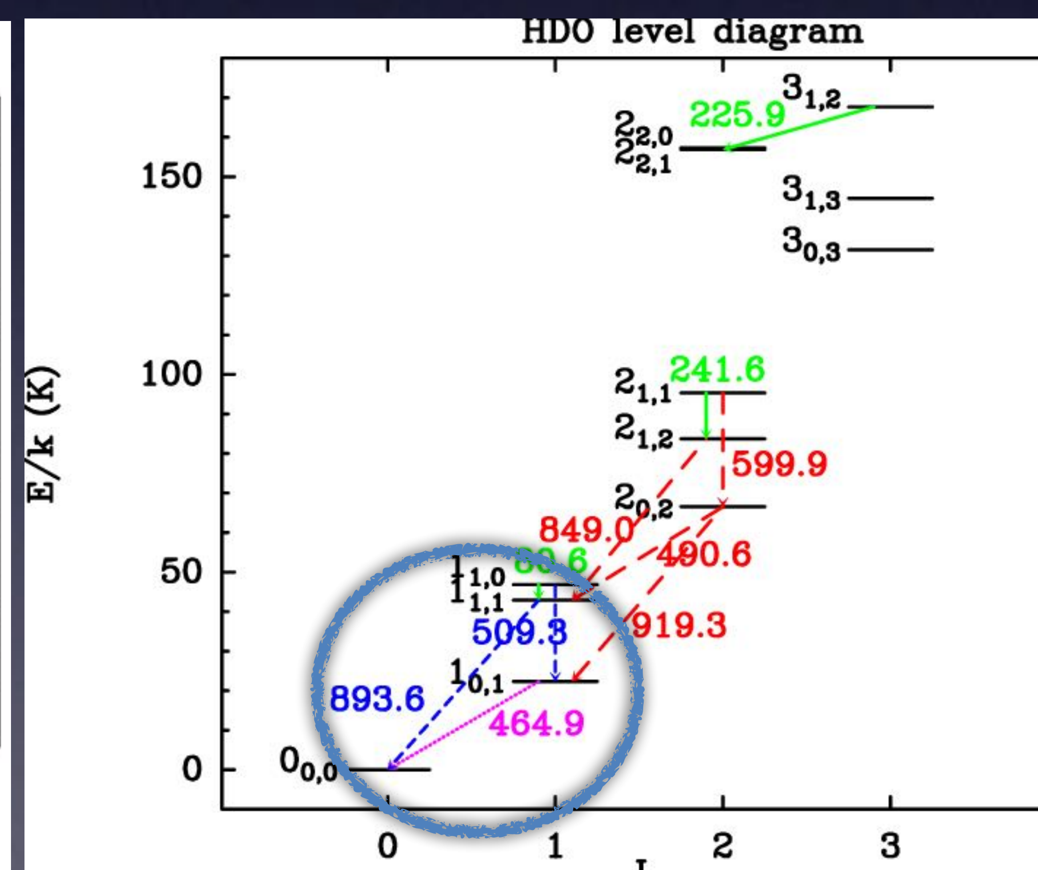
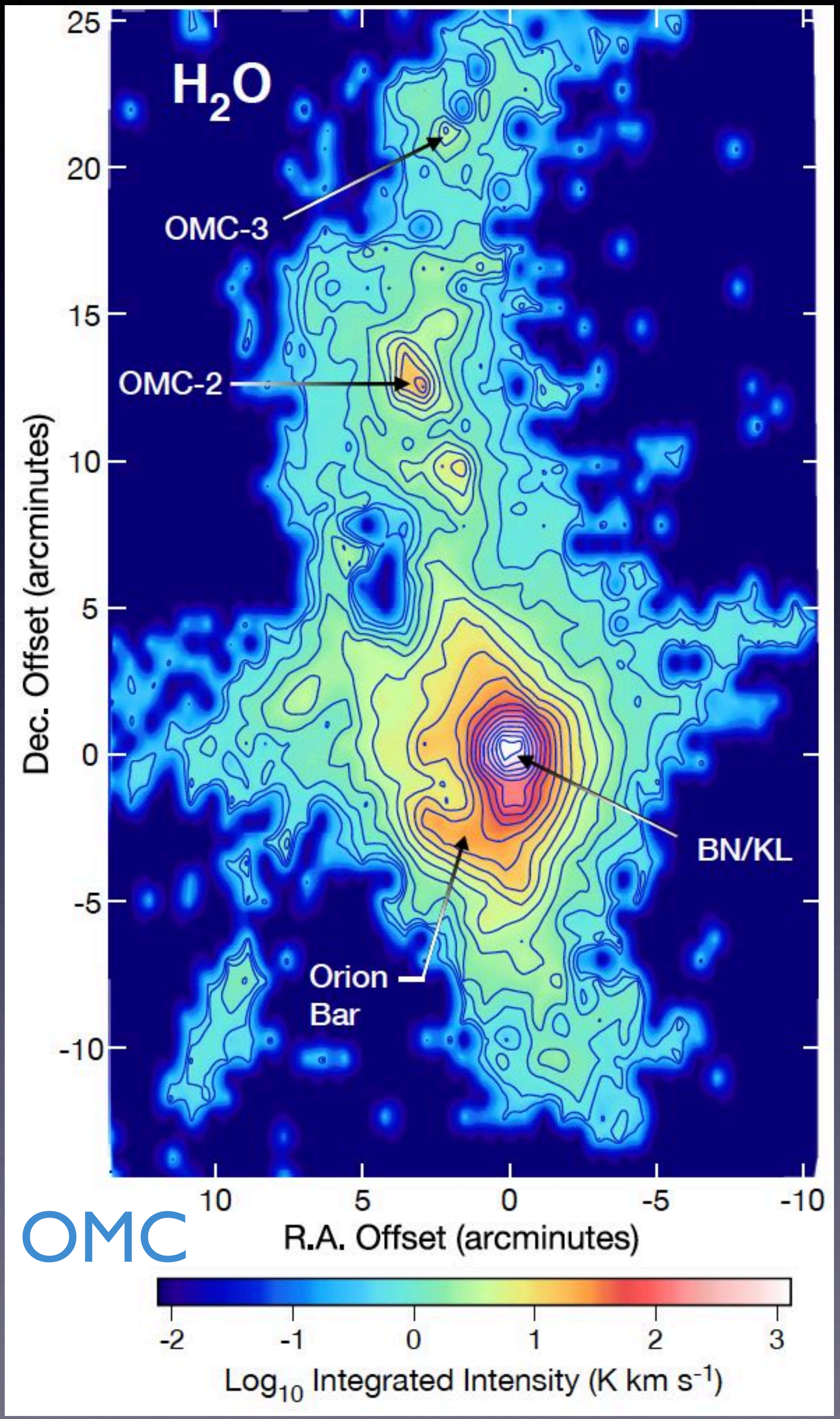


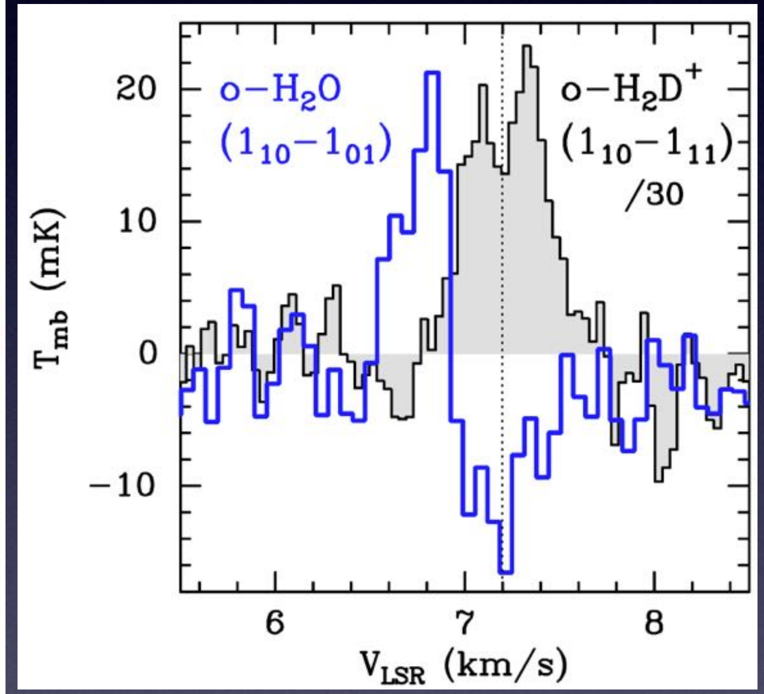
Coutens et al. 2014

Water Trail with Herschel



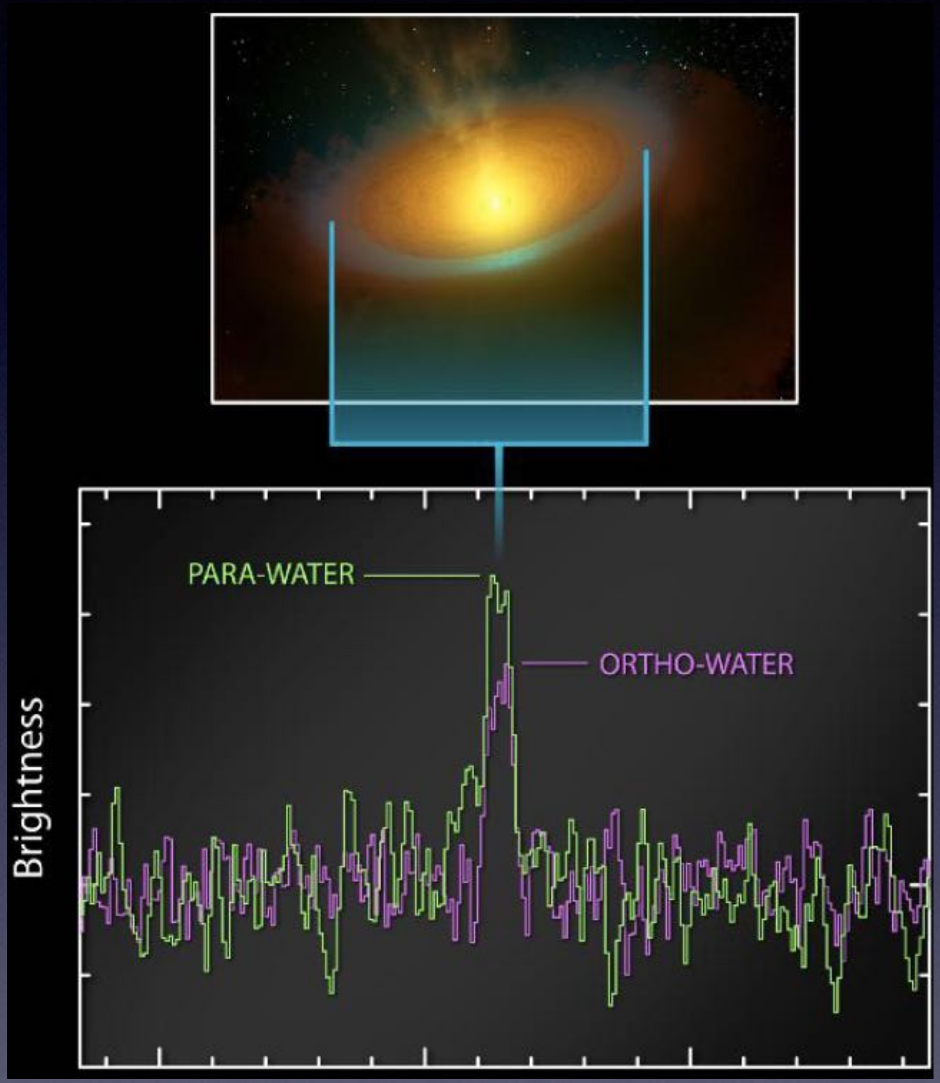
Melnick et al. 2019

L1544



Caselli et al. 2012

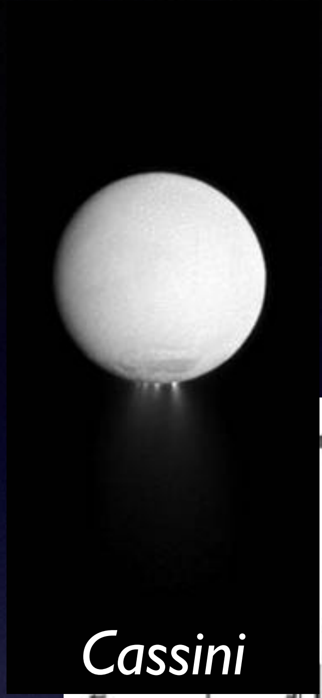
TW Hydrae

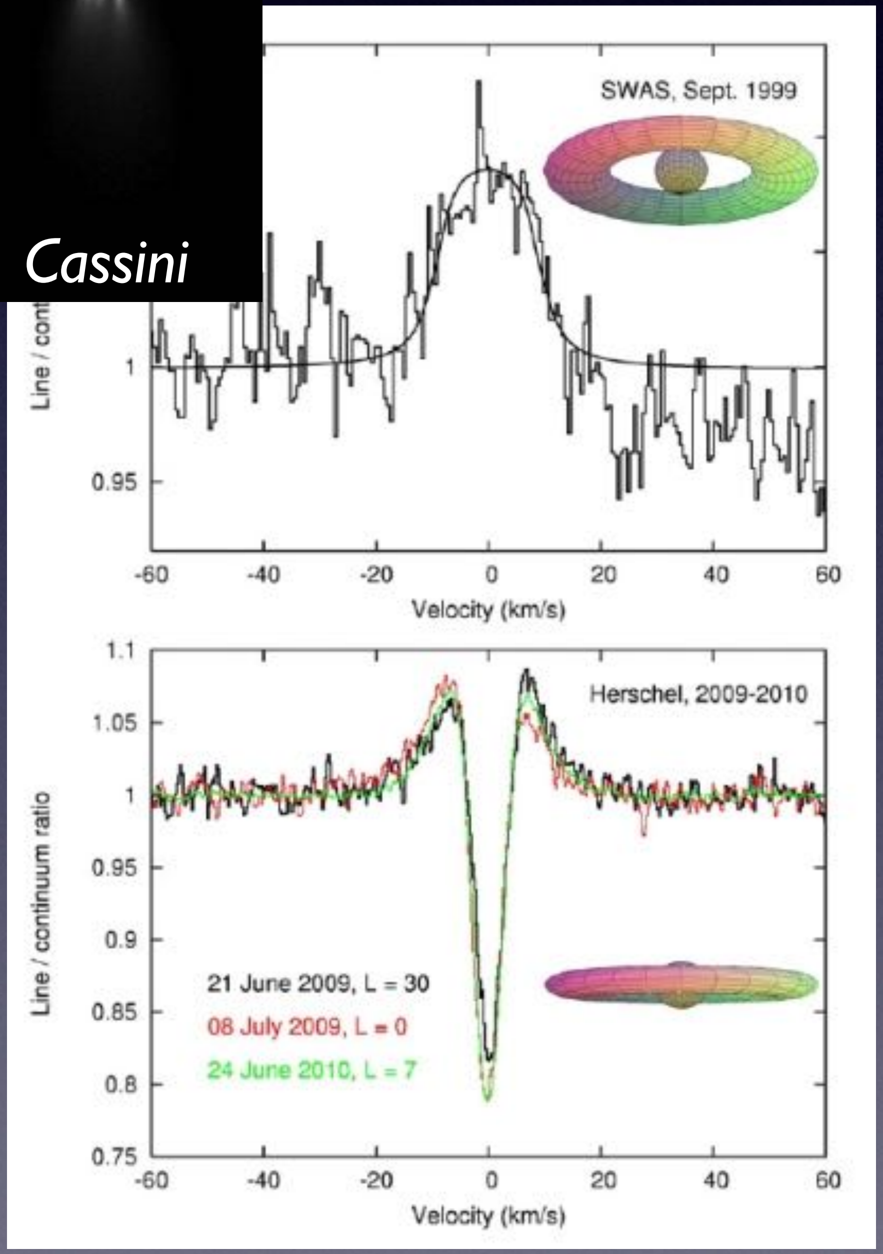


Hogerheijde et al. 2011

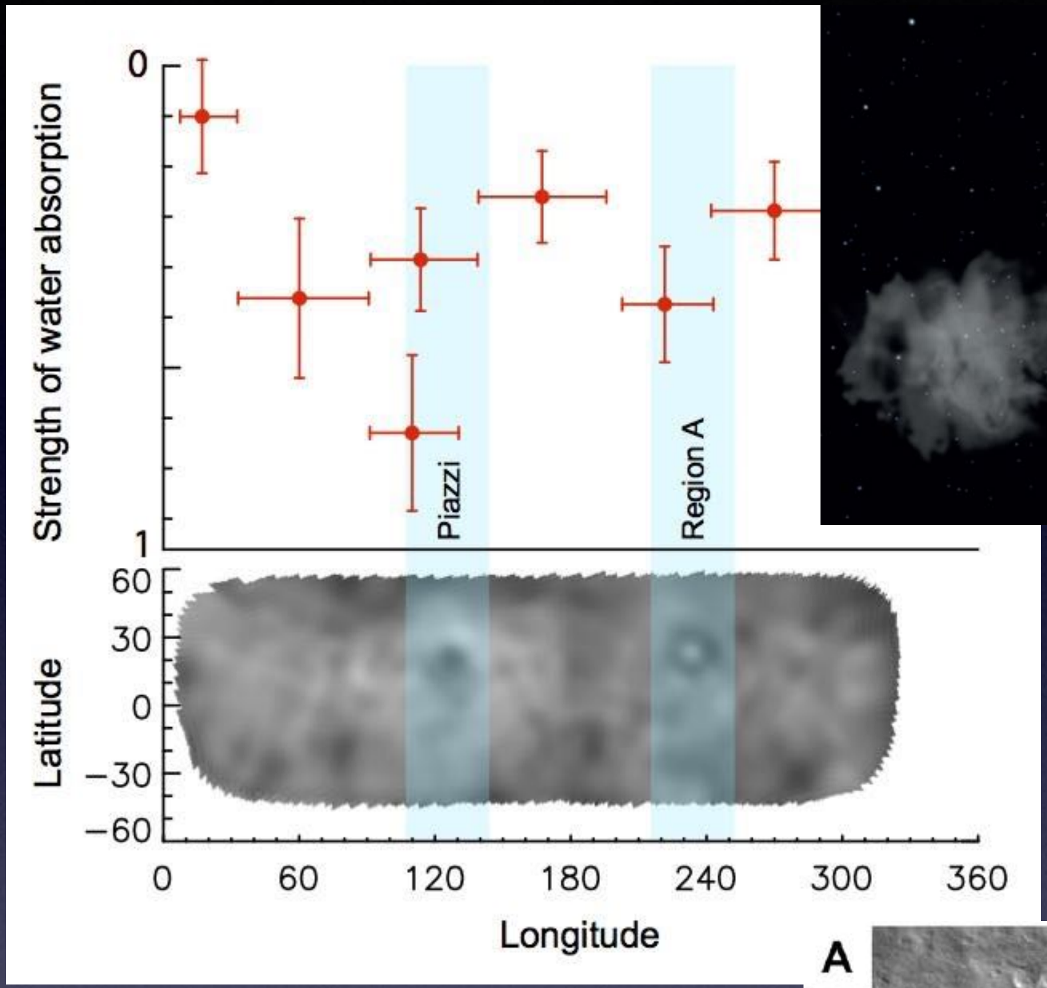
- Clouds ➟ Cores ➟ Disks ➟ Planetary systems
- Origin of Solar System materials

Water in the Solar System



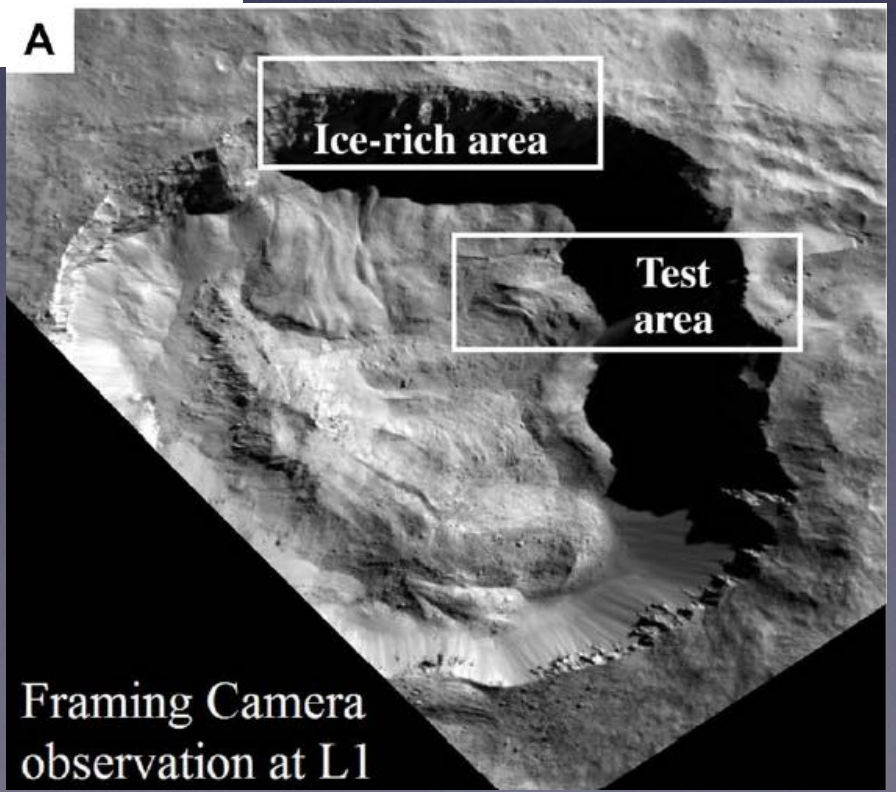


Enceladus — Hartogh et al. 2011



Cumpis 2014

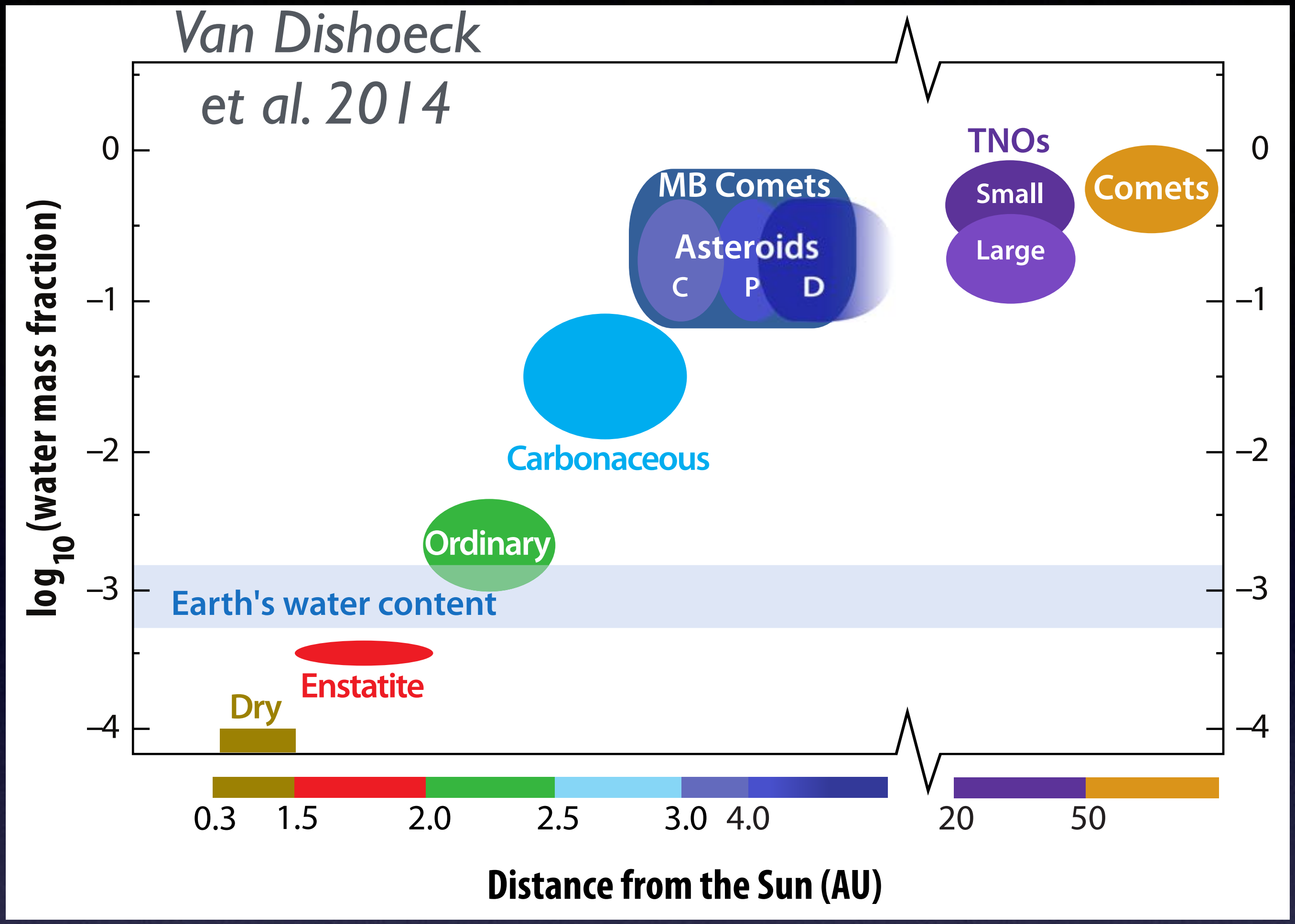
Ceres — Küppers et al. 2014

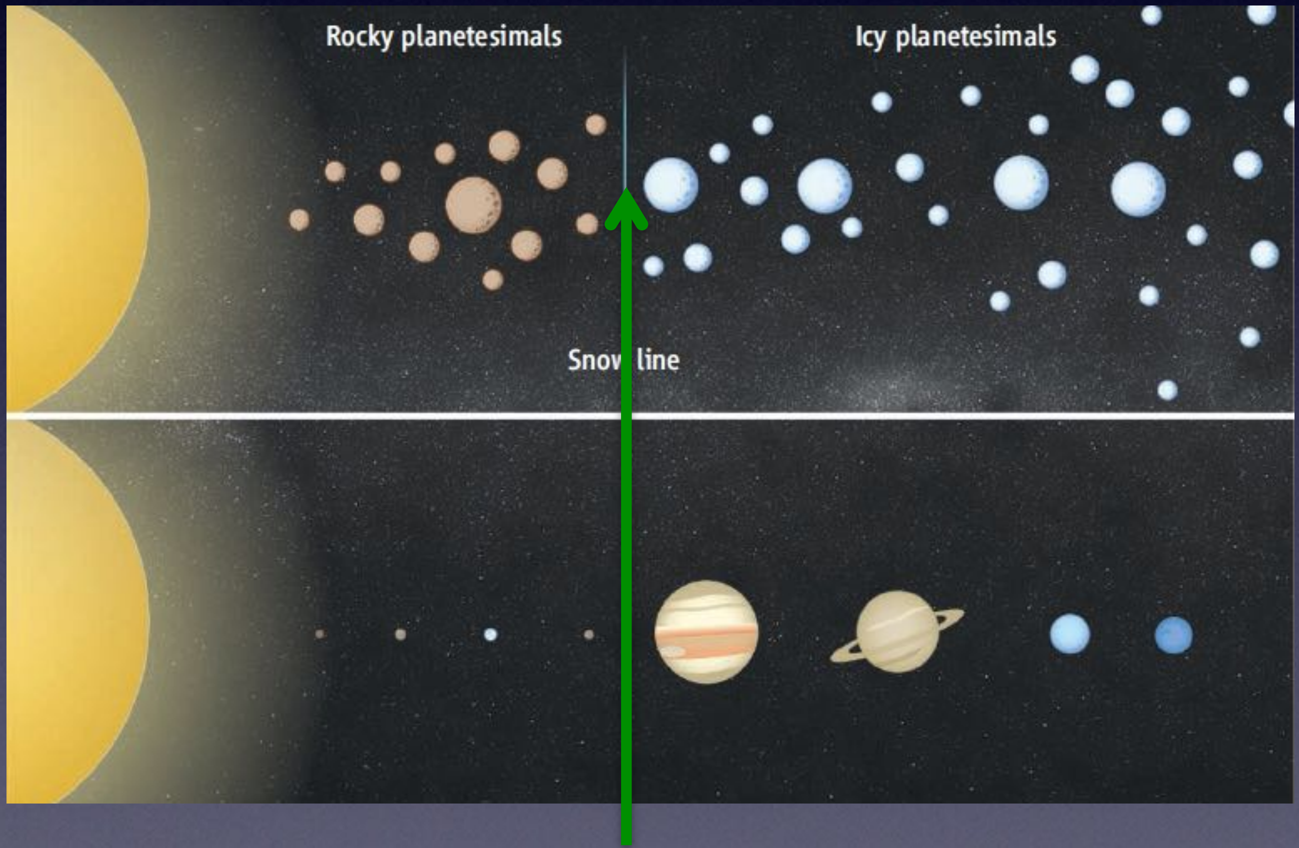


Dawn, Juling Crater — Raponi et al. 2018

- Galilean satellites — origin of water in the atmosphere not well understood
- Main belt comets

Once upon a time the Earth accreted dry



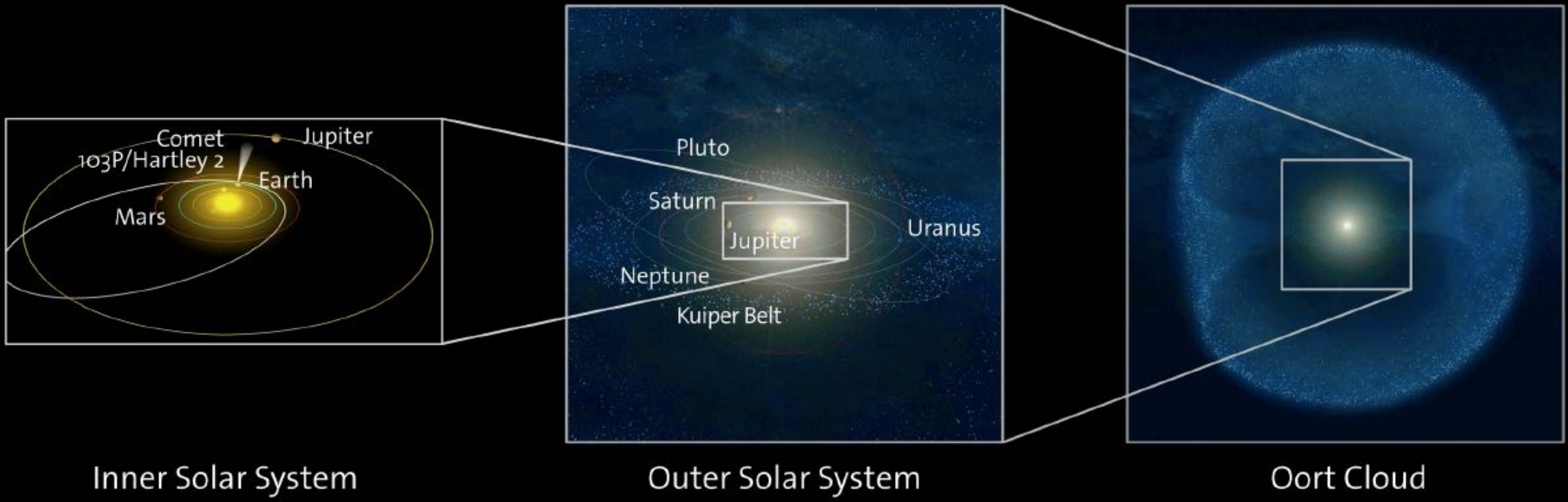


Snow Line

Akeson 2011

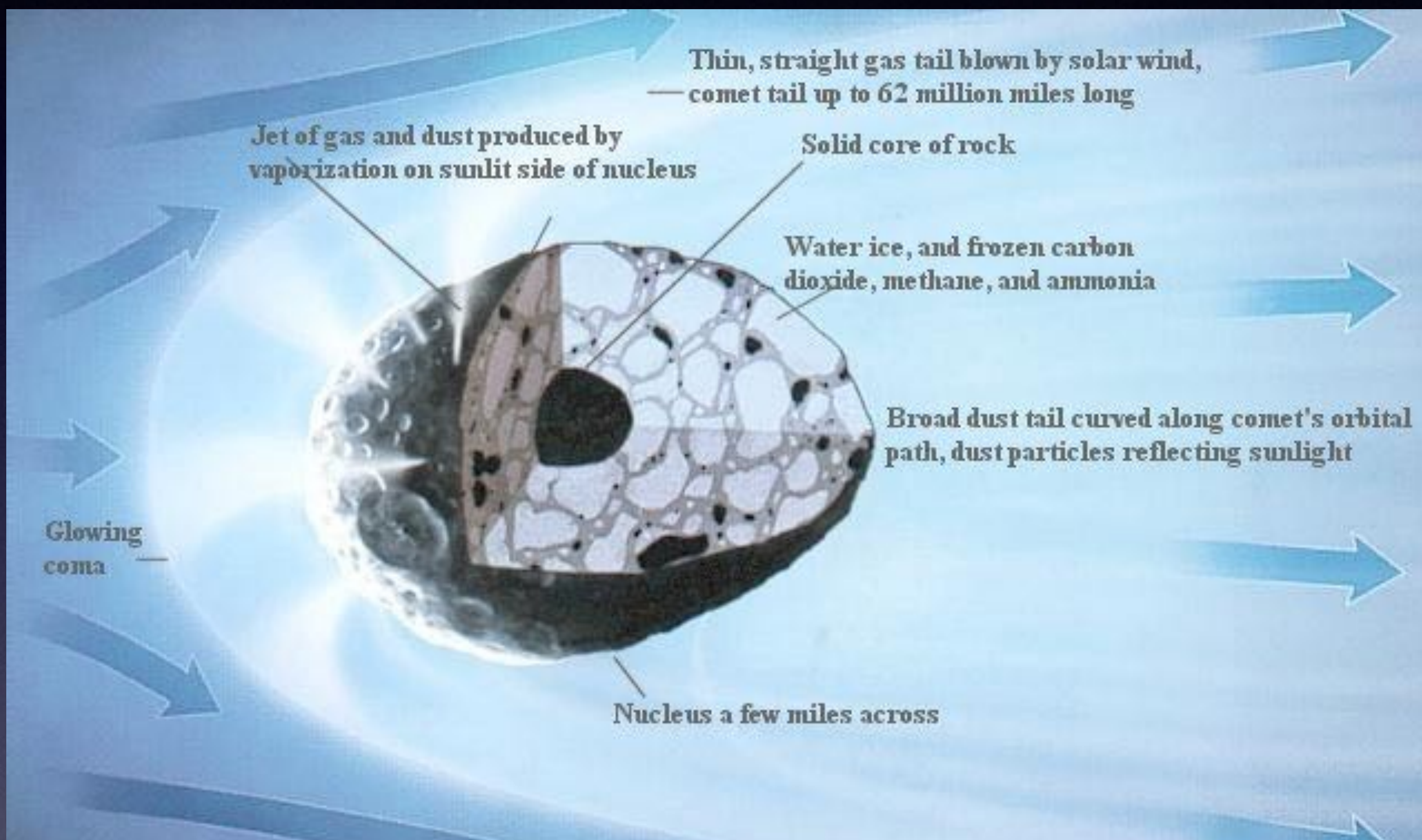
- Temperature in the terrestrial planet zone was too high for water ice to exist
- Water and organics were most likely delivered by comets or asteroids
- Isotopic ratios provide a fingerprint for studying the origin and history of Solar System materials

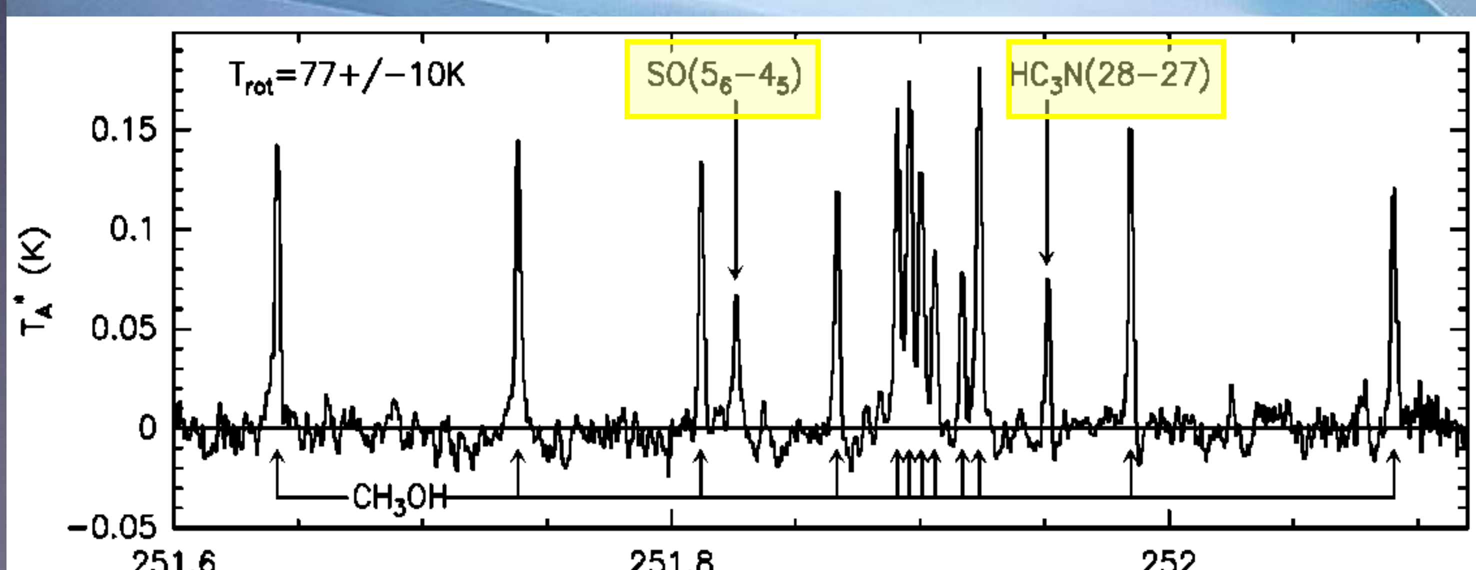
Comets



- Comets are among the most primitive bodies formed before planets and asteroids
- *Jupiter Family comets* originate in the Kuiper Belt, or associated scattered disc, beyond the orbit of Neptune
- *Long-period comets* come from the Oort cloud, but formed in the Jupiter-Neptune region
- Sent toward the Sun by gravitational perturbations from the outer planets or nearby stars, or due to collisions

Comets in the Submillimeter



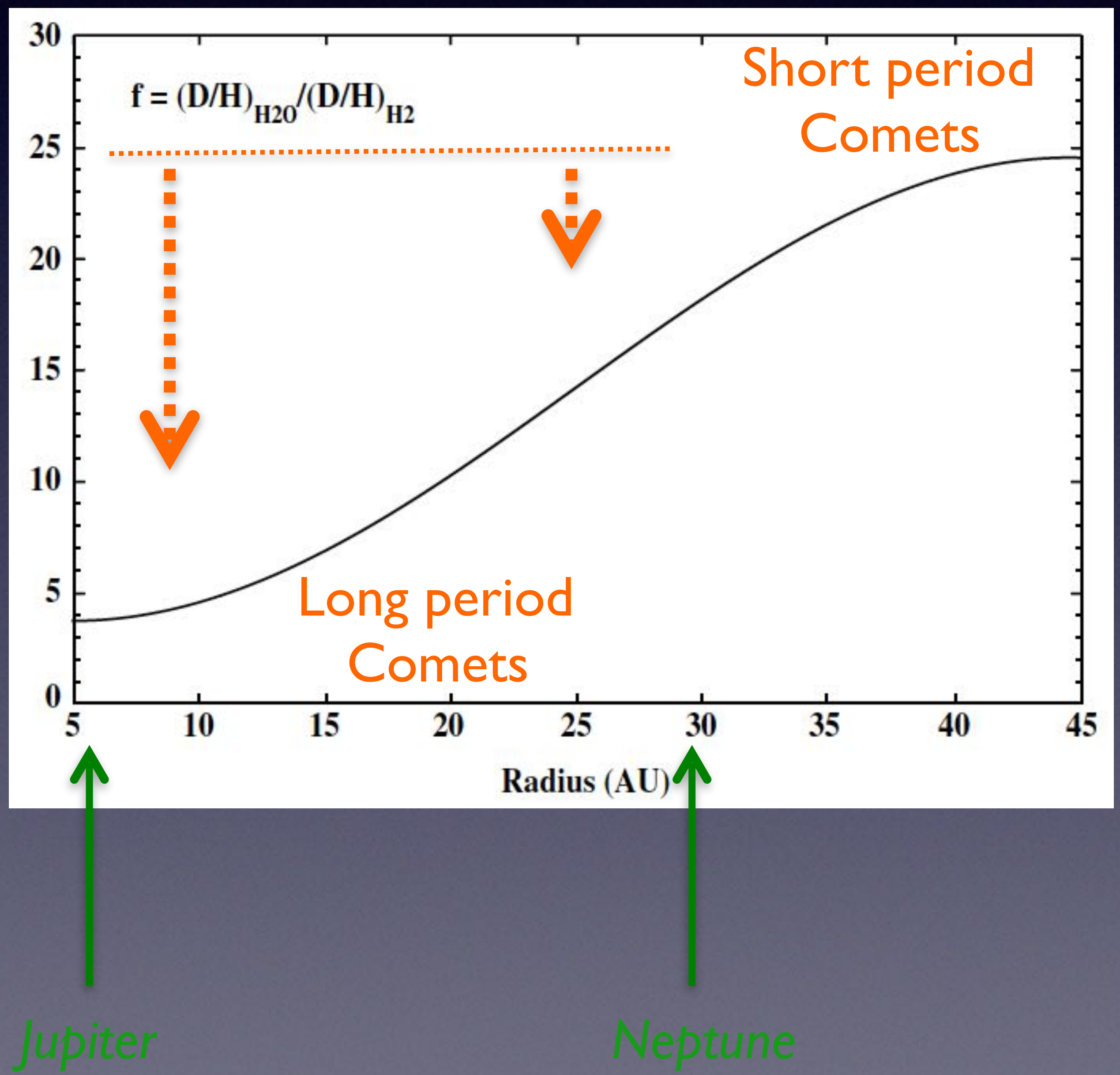


Hale-Bopp/CSO

- (Sub)millimeter wavelengths are well matched to the cold environments of cometary atmospheres (T~40–100 K)
- Main volatile is water, but over two dozen species have been detected, primarily using radio techniques
- Isotopic ratios provide key information about the origin and evolution of cometary ices
- They can be measured in cometary atmospheres through remote sensing

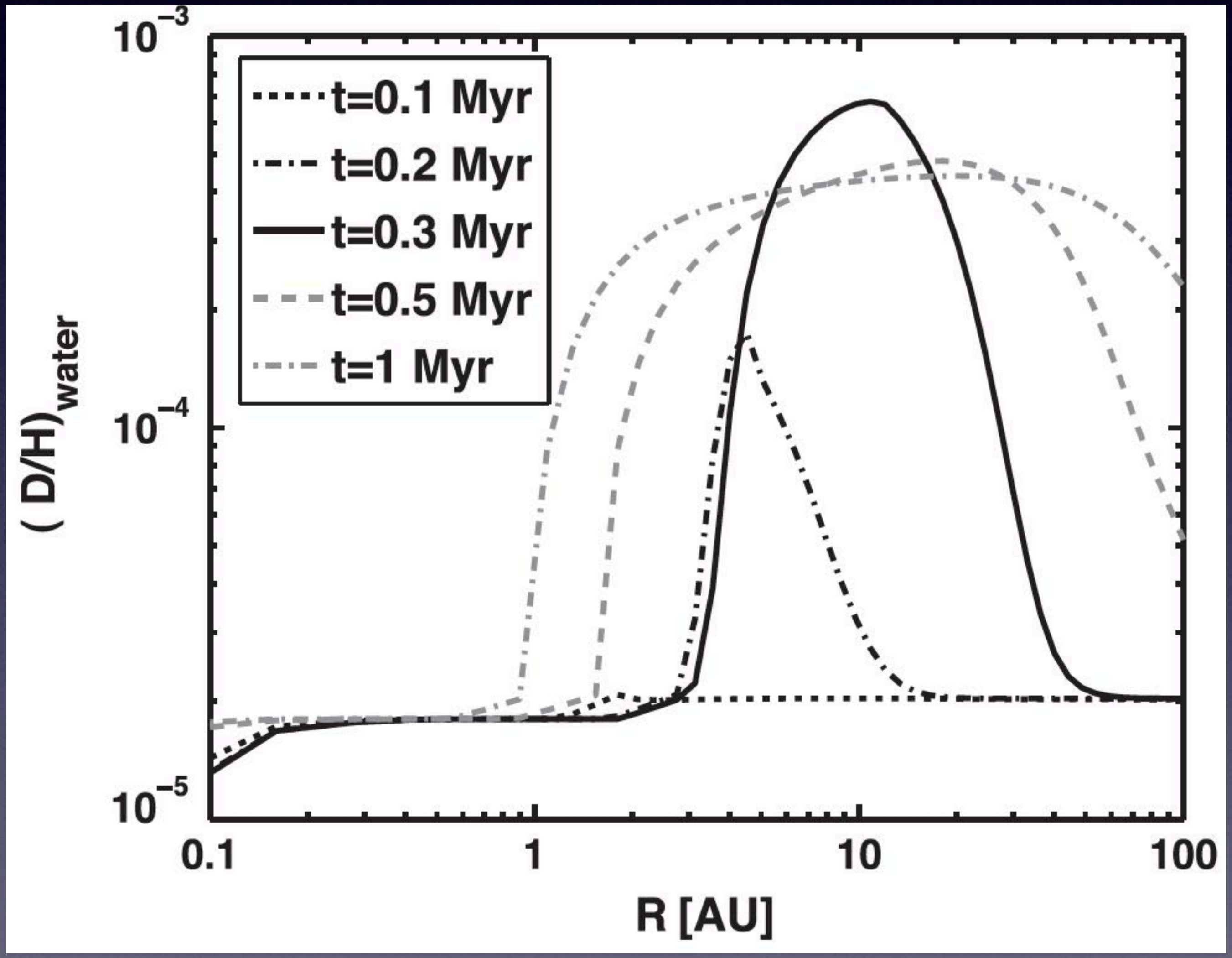
"Textbook" D/H in Water in the Solar Nebula

- Variations in the D/H ratio: progressive isotopic exchange reactions between HDO and H_2
- Water was initially synthesized by interstellar chemistry with a high D/H ratio (>7.2×10^{-4}; highest value measured in clay minerals)
- The D/H ratio in the solar nebula then gradually decreased with time
- Turbulent mixing of grains condensed at different epochs and locations in the solar nebula ➟ D/H gradient



Horner et al. 2007

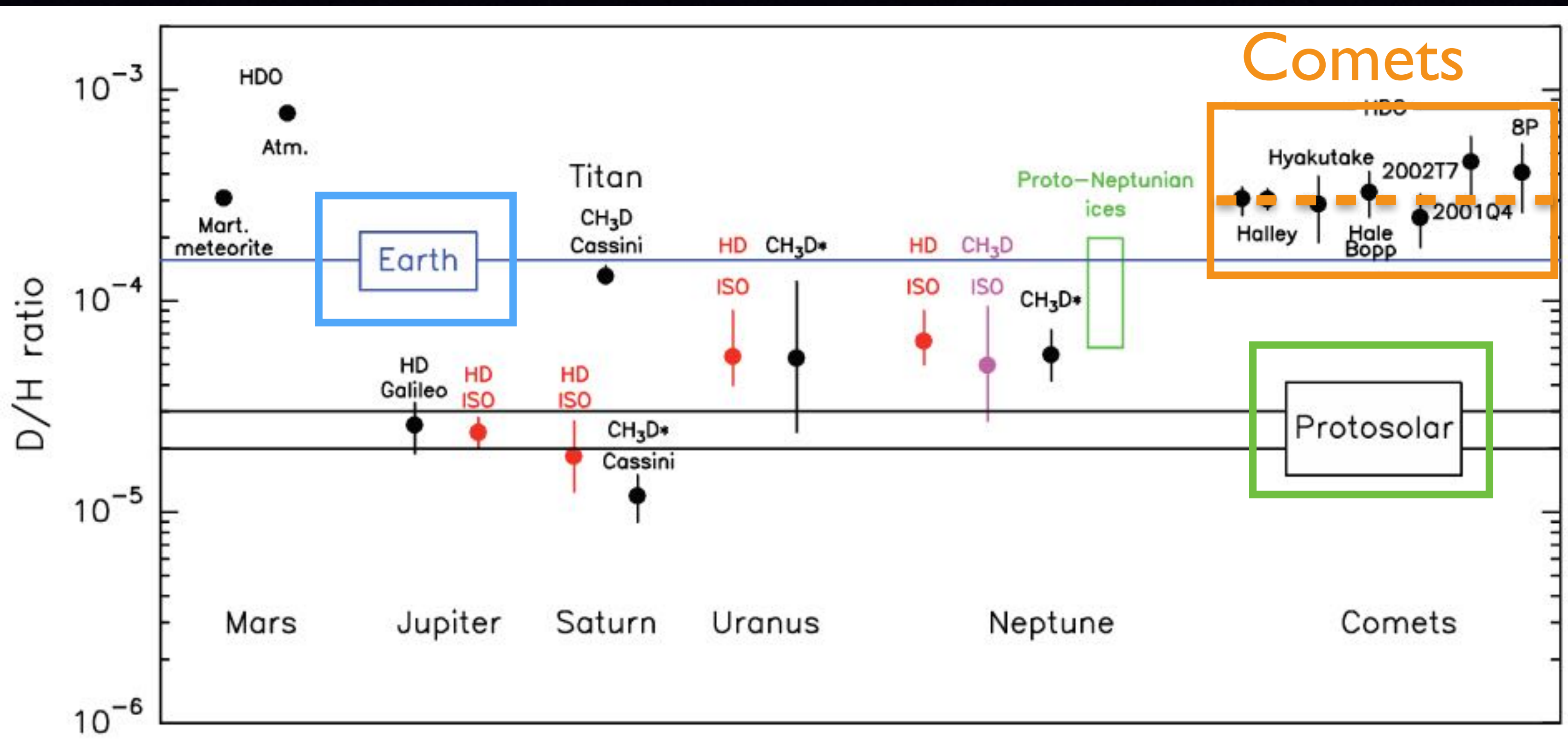
Other D/H Models



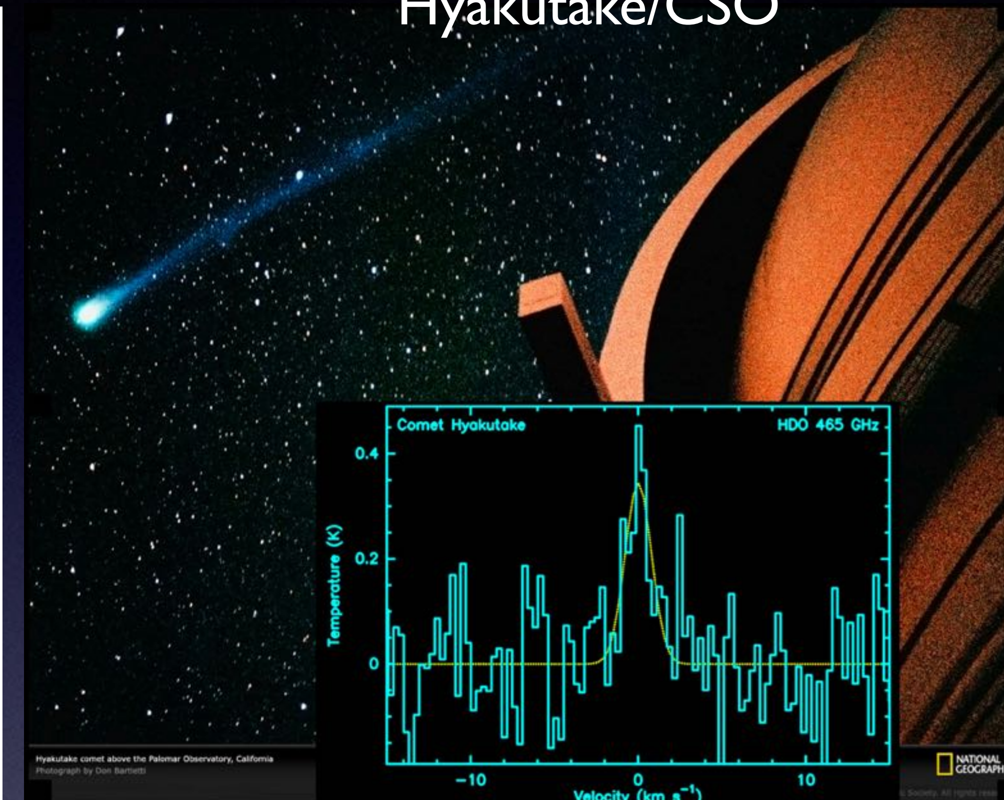
- A coupled dynamical and chemical model
- D/H may *decrease* in the outer regions
- Water thermally processed in the inner disk transported outward

Yang et al. (2013)

D/H Pre-Herschel

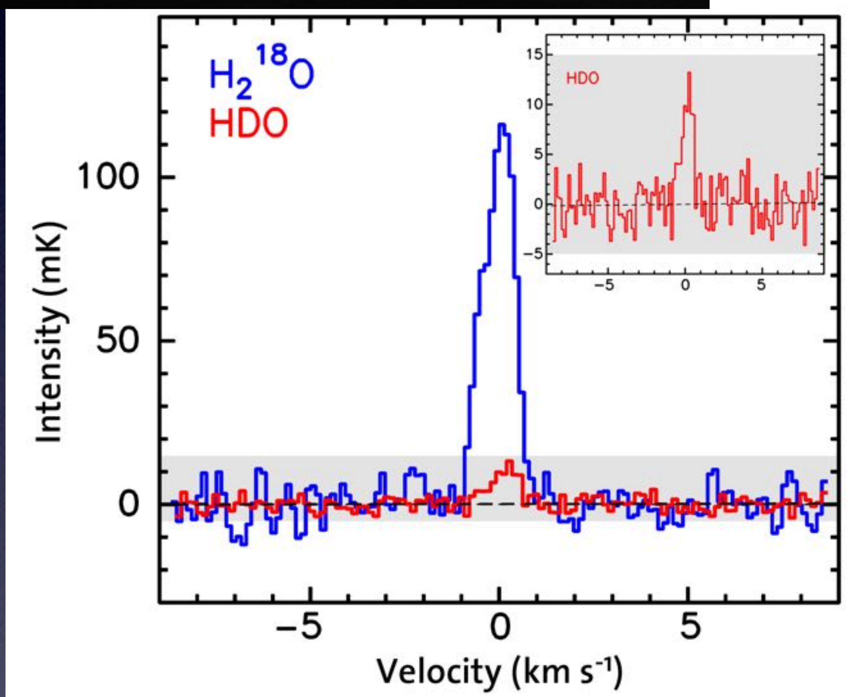


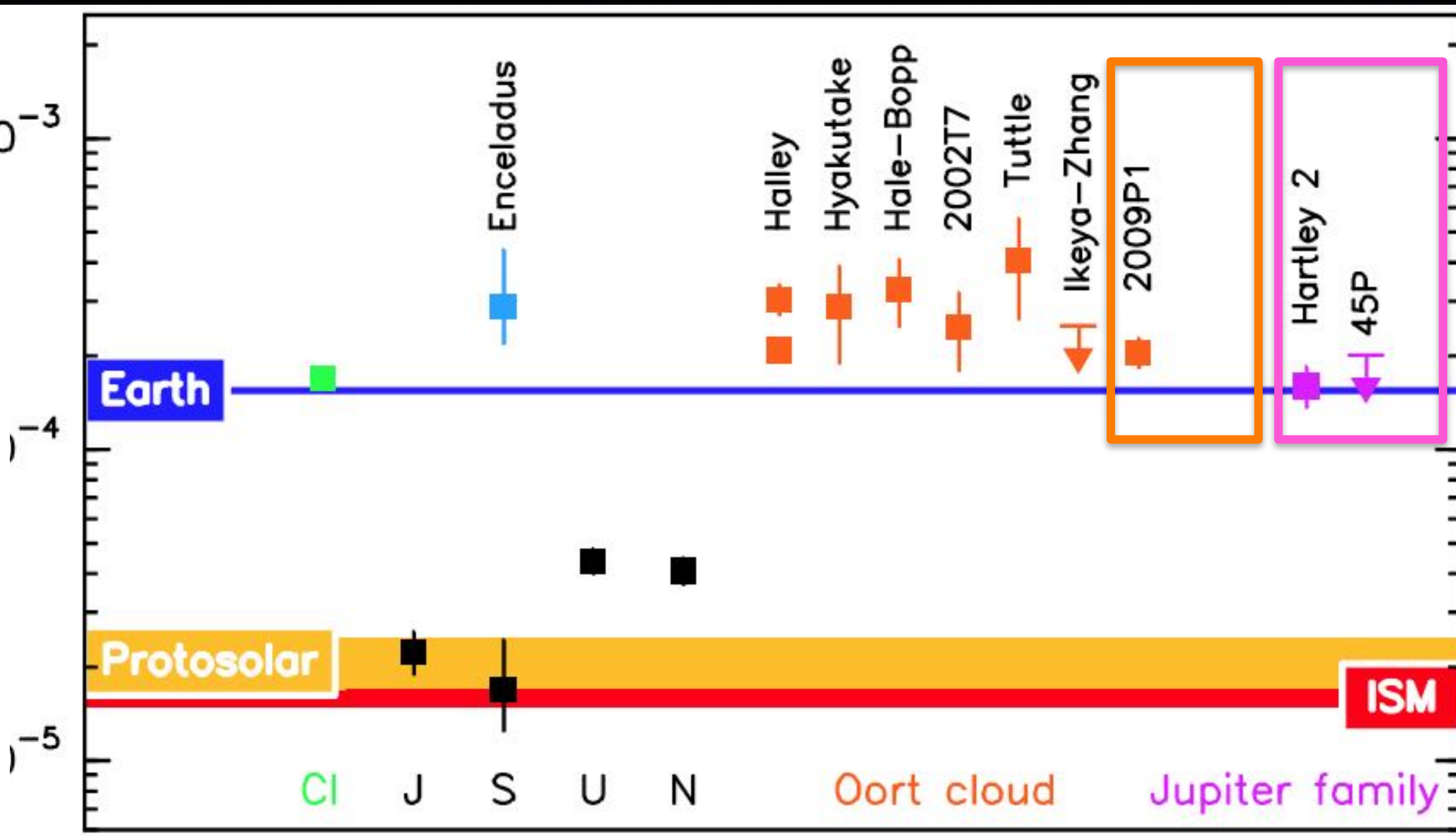
Hyakutake/CSO



- Protosolar D/H ratio in H_2 is ~2.5×10^{-5} (same as the Big Bang)
- Earth's ocean ratio (Vienna Standard Mean Ocean Water) is 1.56×10^{-4} — *Mantle water?*
- D/H in water in Oort cloud comets is ~3×10^{-4} — *Jupiter Family comets?*
- Most probable source of Earth water: ice-rich reservoir in the outer asteroid belt
- Comets could have contributed less than 10% of the Earth's water

D/H Herschel

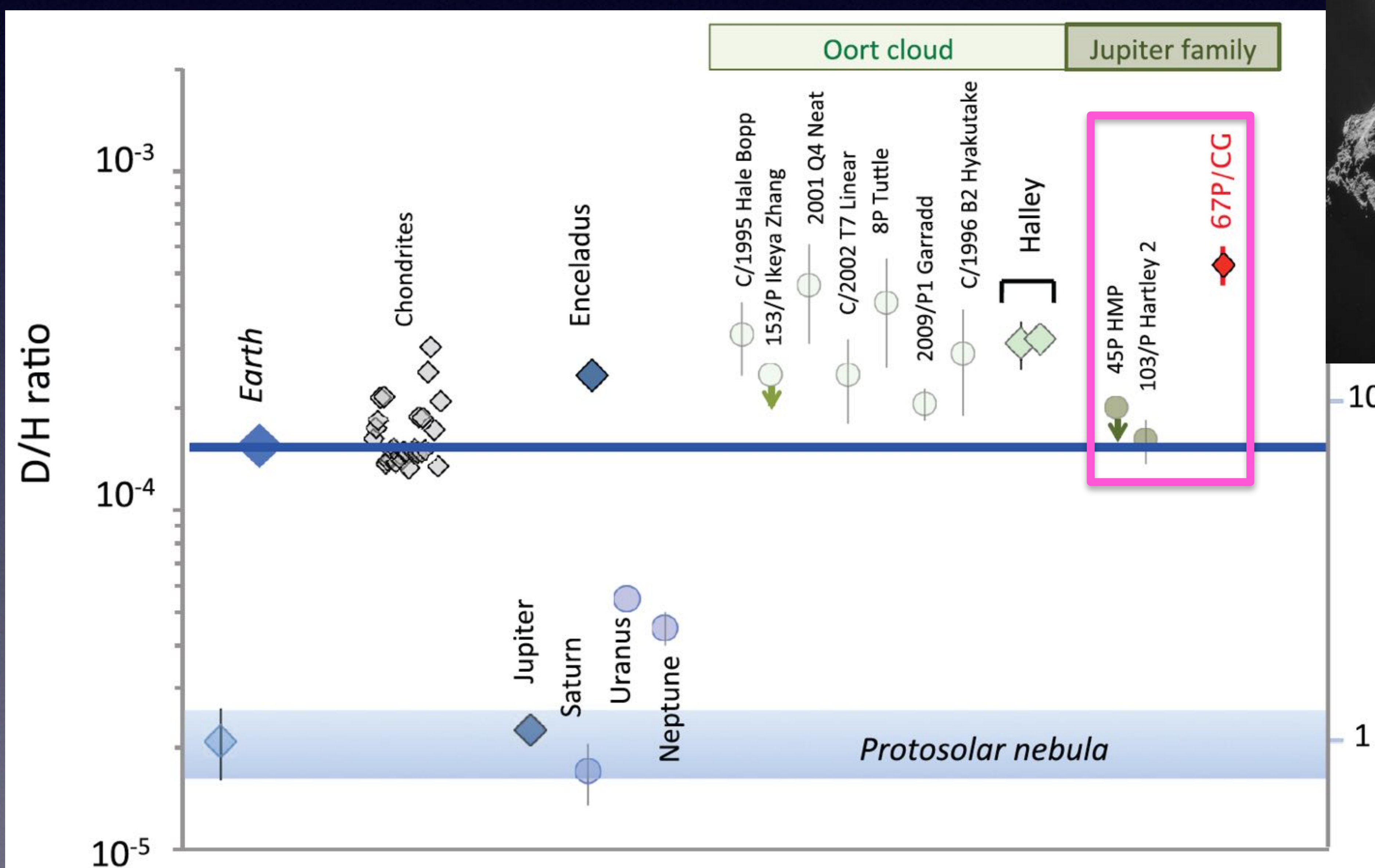




Hartogh et al. 2011, Lis et al. 2013, Bockelée-Morvan et al. 2012

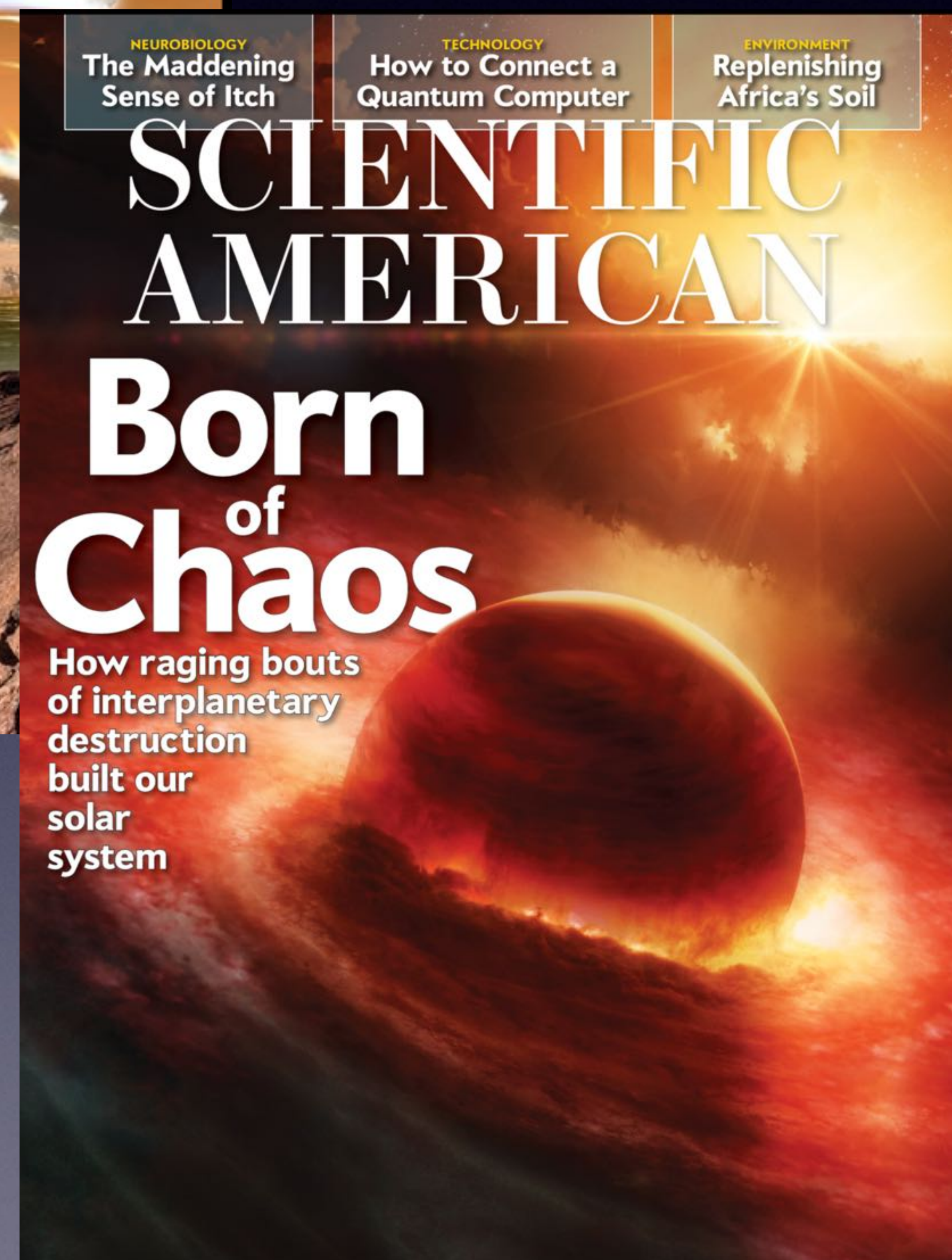
- D/H in two Jupiter Family comets consistent with the VSMOV value
- A low D/H value measured in an Oort cloud comet
- The high pre-Herschel D/H values are *not representative* of all comets

D/H Rosetta



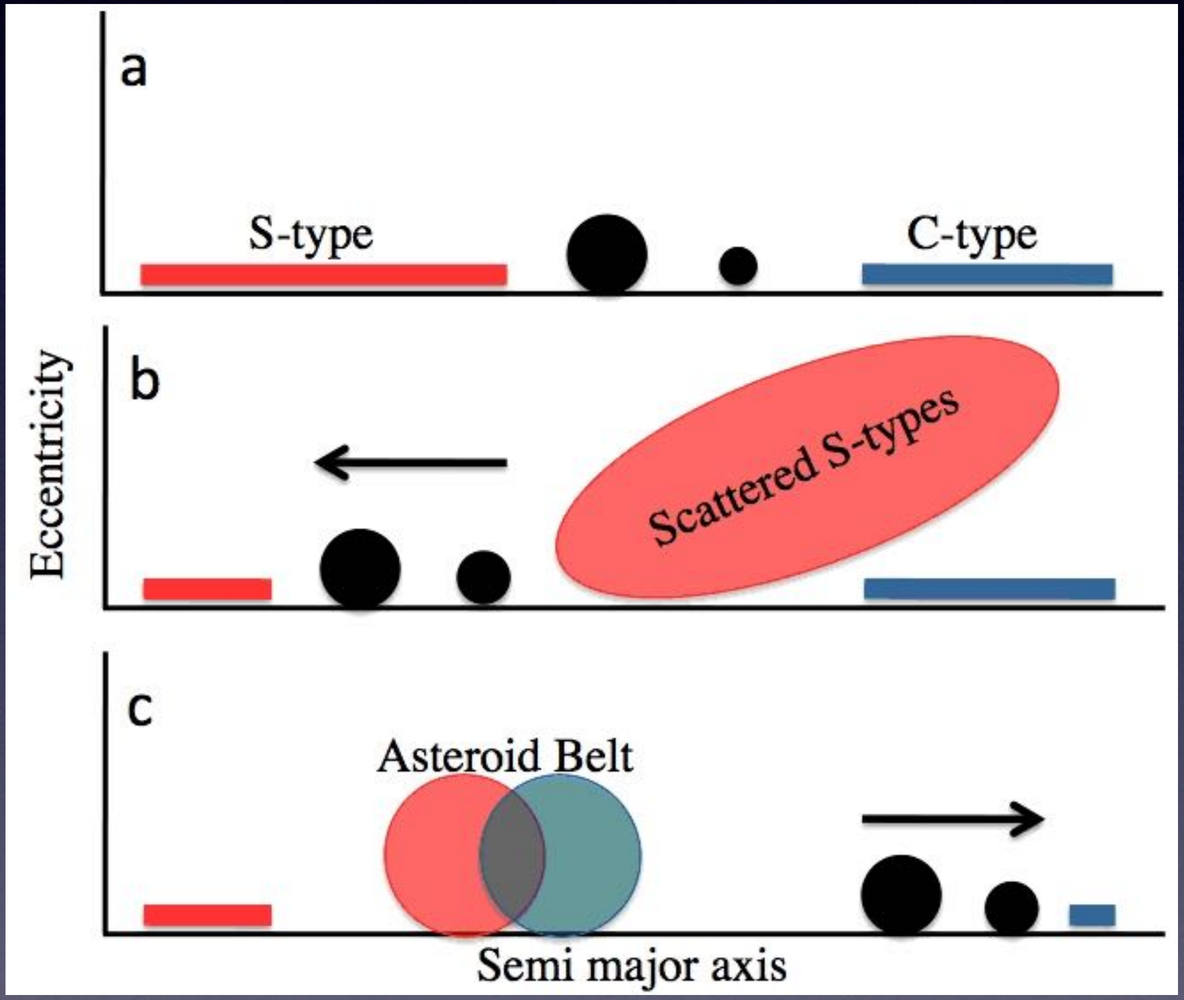
- Confirmed by Rosetta
- 67P Churyumov-Gerasimenko
- D/H three times VSMOW
- No trends with physical or dynamical parameters

Altwegg et al. 2015

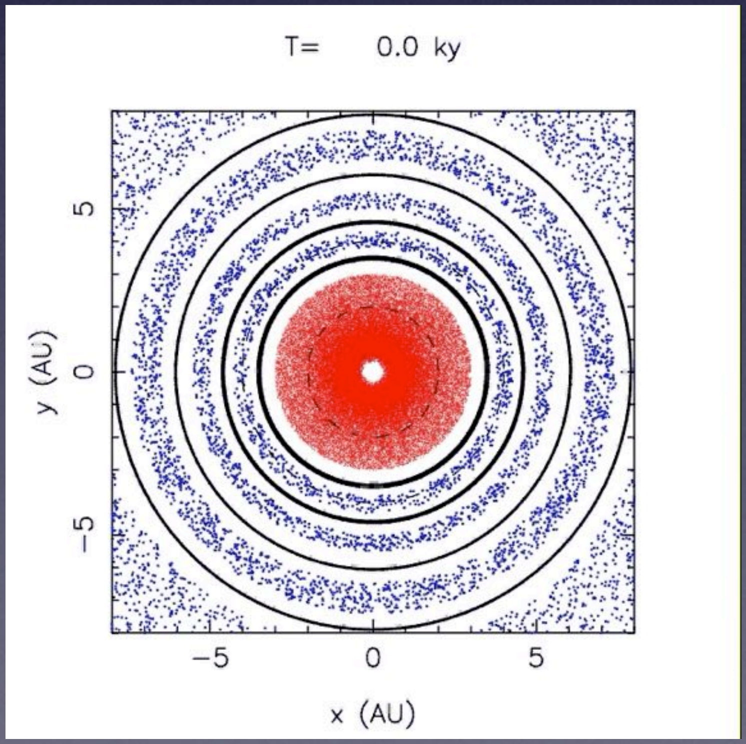


- Radiometric dates of major impact events on the Moon ~4 billion years ago
- "Late Heavy Bombardment" — 600 million years after Solar System formation
- Hard to explain in quiescent and stable Solar System

Grand Tack Model

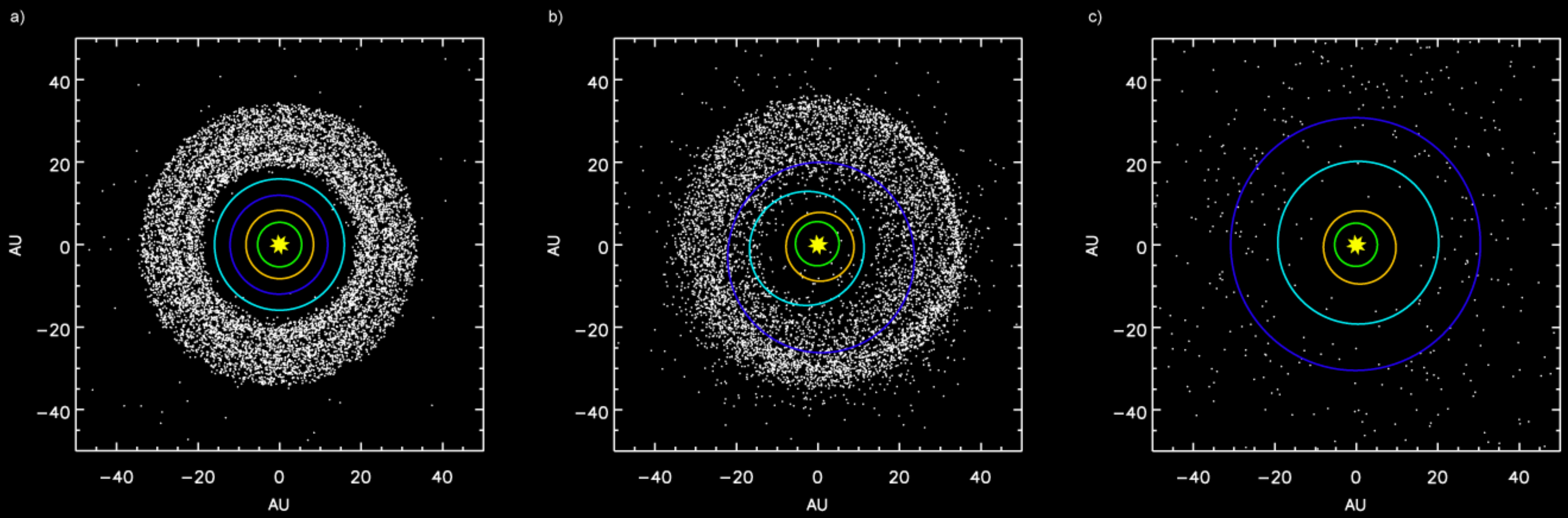


- Inward then outward migration of Jupiter and Saturn leads to complete disappearance of the gas disk
- Happens within first ~5 Myr



Walsh et al. 2011

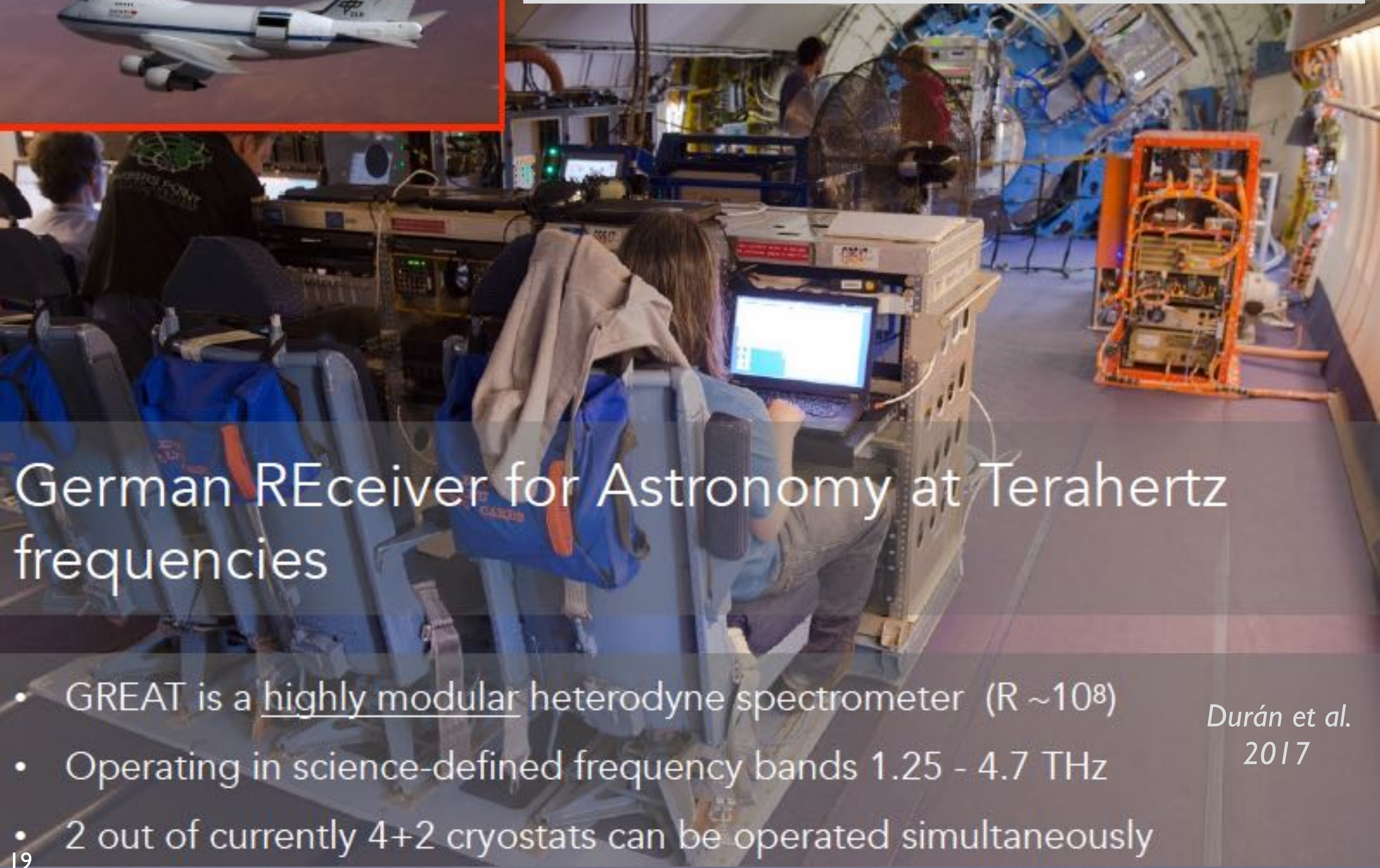
Nice Model



- Early Solar System much more compact, giant planets on circular orbits
- After ~500 Myr Saturn migrates into 1:2 orbital resonance with Jupiter
- Orbital eccentricities increase destabilizing the planetary system
- Ice giants plough into the planetesimal disk scattering them — Late Heavy Bombardment

Gomes et al. 2005; Tsiganis et al. 2005; Morbidelli et al. 2005

What Can SOFIA Do?



German REceiver for Astronomy at Terahertz frequencies

- GREAT is a <u>highly modular</u> heterodyne spectrometer (R ~10^8)
- Operating in science-defined frequency bands 1.25 - 4.7 THz
- 2 out of currently 4+2 cryostats can be operated simultaneously

Durán et al. 2017

upGREAT

upGREAT	Low Frequency Array : LFA	1810 - 1950	OH lines, [CII],CO series, [OI]	7 x 2 Pixels (2 Pol)	Cryo-Cooler	[CII]
		1830 - 2070				
	High Frequency Array : HFA	4744	[OI]	7 Pixels	Cryo-Cooler	[OI]

4GREAT

Channel	CH1	CH2	CH3	CH4
RF Bandwidth [GHz]	492 – 630	892 – 1100	1200-1500	2490 - 2700
IF Bandwidth [GHz]	4 – 8	4 – 8	0.5 – 3.5	0.5 – 3.5
Mixer	SIS	SIS	HEB	HEB
	Herschel HIFI - 1	Herschel HIFI - 4	GREAT -L1	GREAT - M-HD
			[NII]	HD

- HFA + LFA
- HFA + 4G

Durán et al. 2017

upGREAT

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	High Frequency Array : HFA	4744	[OI]	7 Pixels	Cryo-Cooler	[OI]

4GREAT

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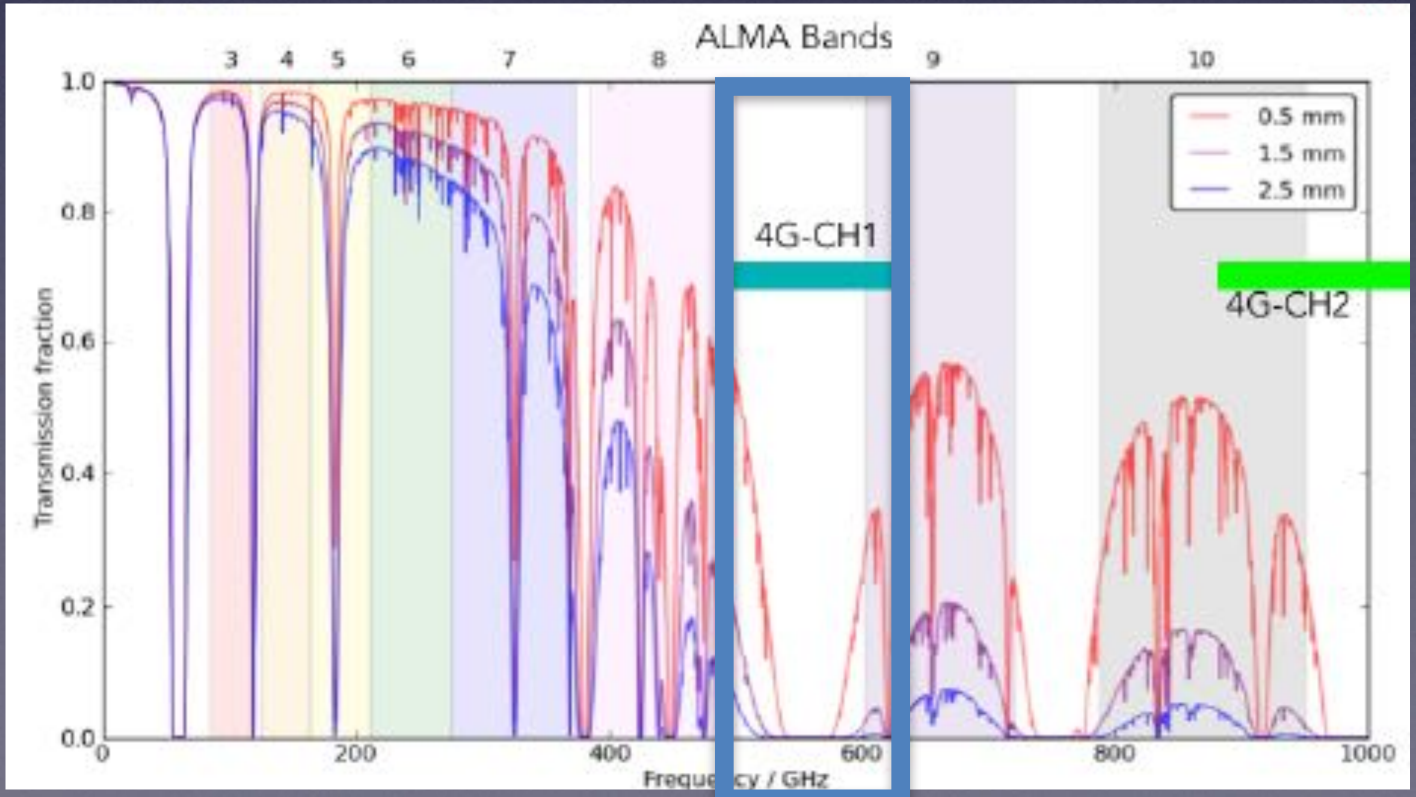
Mixe	SIS	SIS	HEB	HEB
	Herschel HIFI - 1	Herschel HIFI - 4	GREAT -L1	GREAT - M-HD
			[NII]	HD

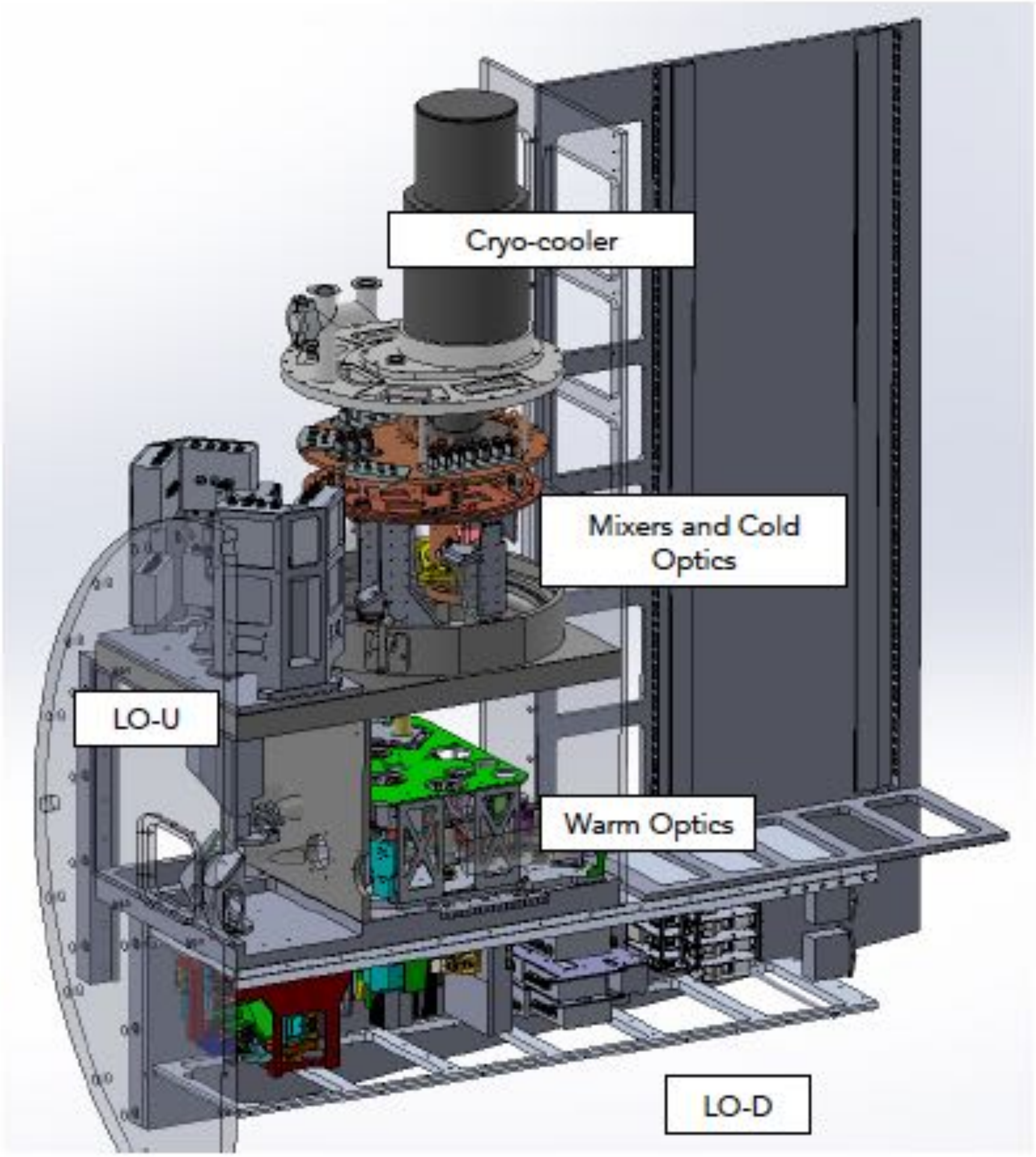


- HFA + LFA
- HFA + 4G

Durán et al. 2017

4GREAT: How does it look like?

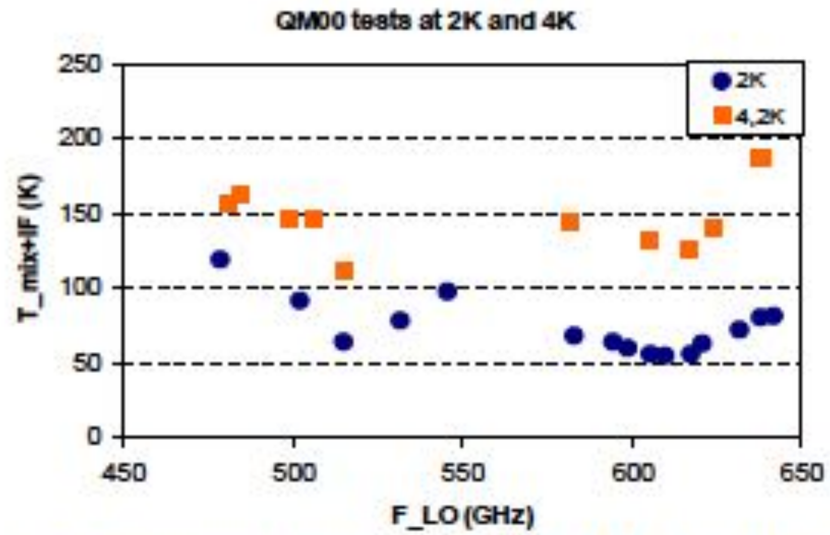
- Operation in parallel with other "GREAT" cryostats
- 4 colors co-aligned on sky.
- The signal from sky is separated to feed the four detectors simultaneously
- Closed-cycle cooler
- Lowest frequency for CH1 : 492 GHz. Optics constraints.
- 4 individual solid state local oscillator sources, allowing independent tuning.



Durán et al. 2017

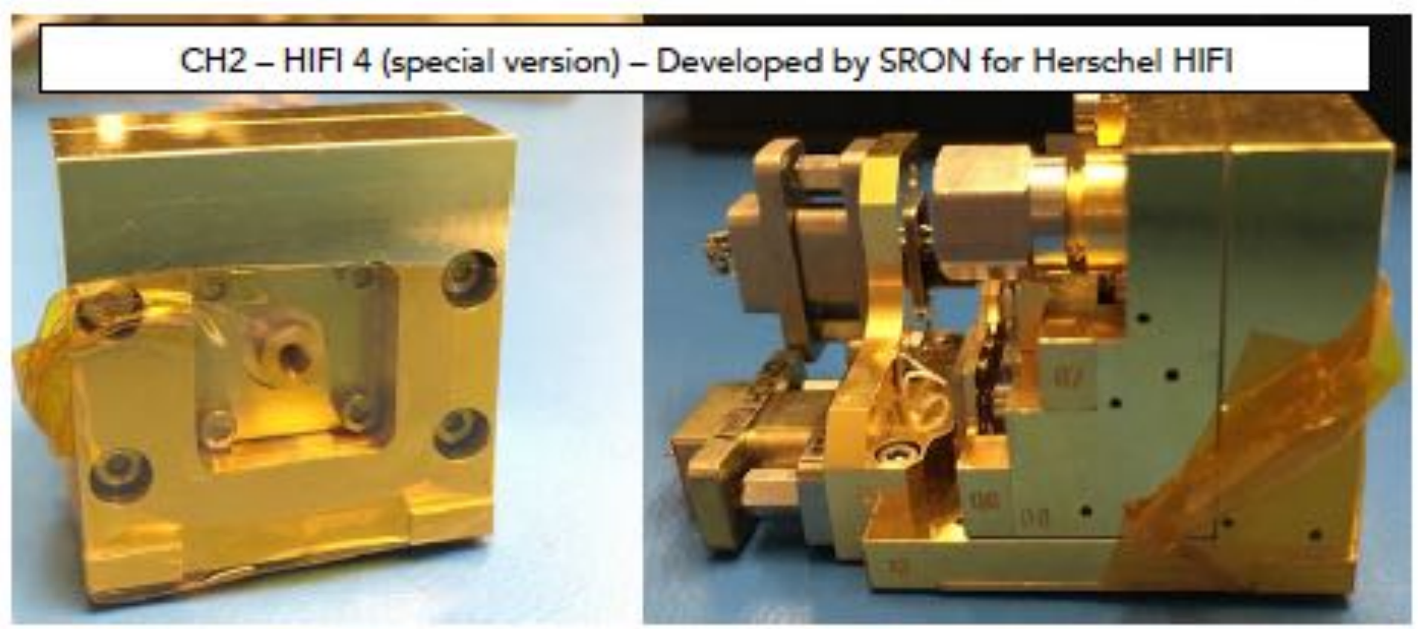
4GREAT: Mixers – SIS: CH1 and CH2

CH1 – HIFI 1 : Developed by LERMA for Herschel HIFI



Channel 1 - Noise temperature for QM00 at 2K and 4.2K. Data provided by LERMA

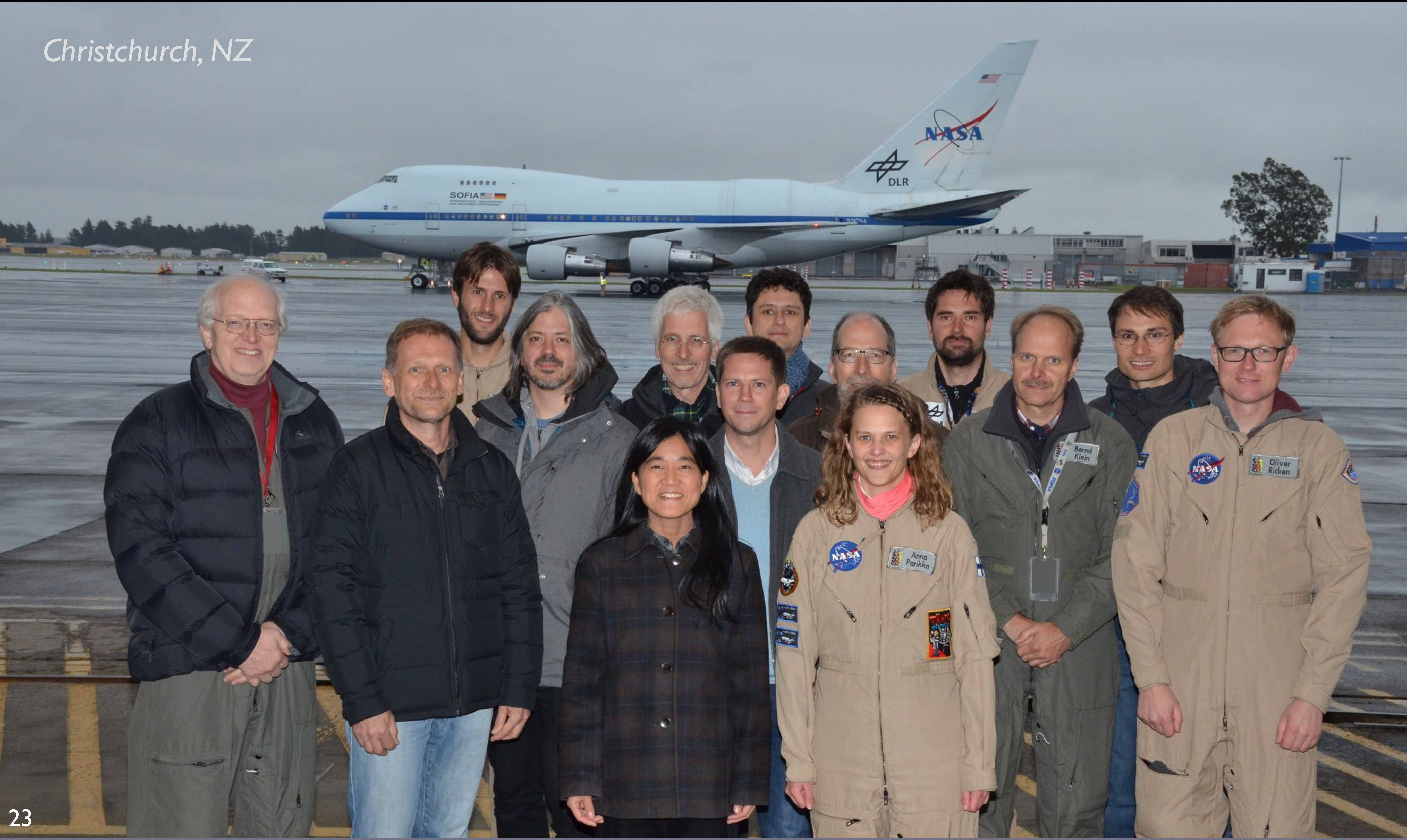
Band	Technology	Tsys	Manufacturer	Remark
CH1	SIS	300	LERMA	HIFI-1
CH2	SIS	500	SRON	HIFI-4



CH2 – HIFI 4 (special version) – Developed by SRON for Herschel HIFI

Durán et al. 2017

Commissioning — July 2017

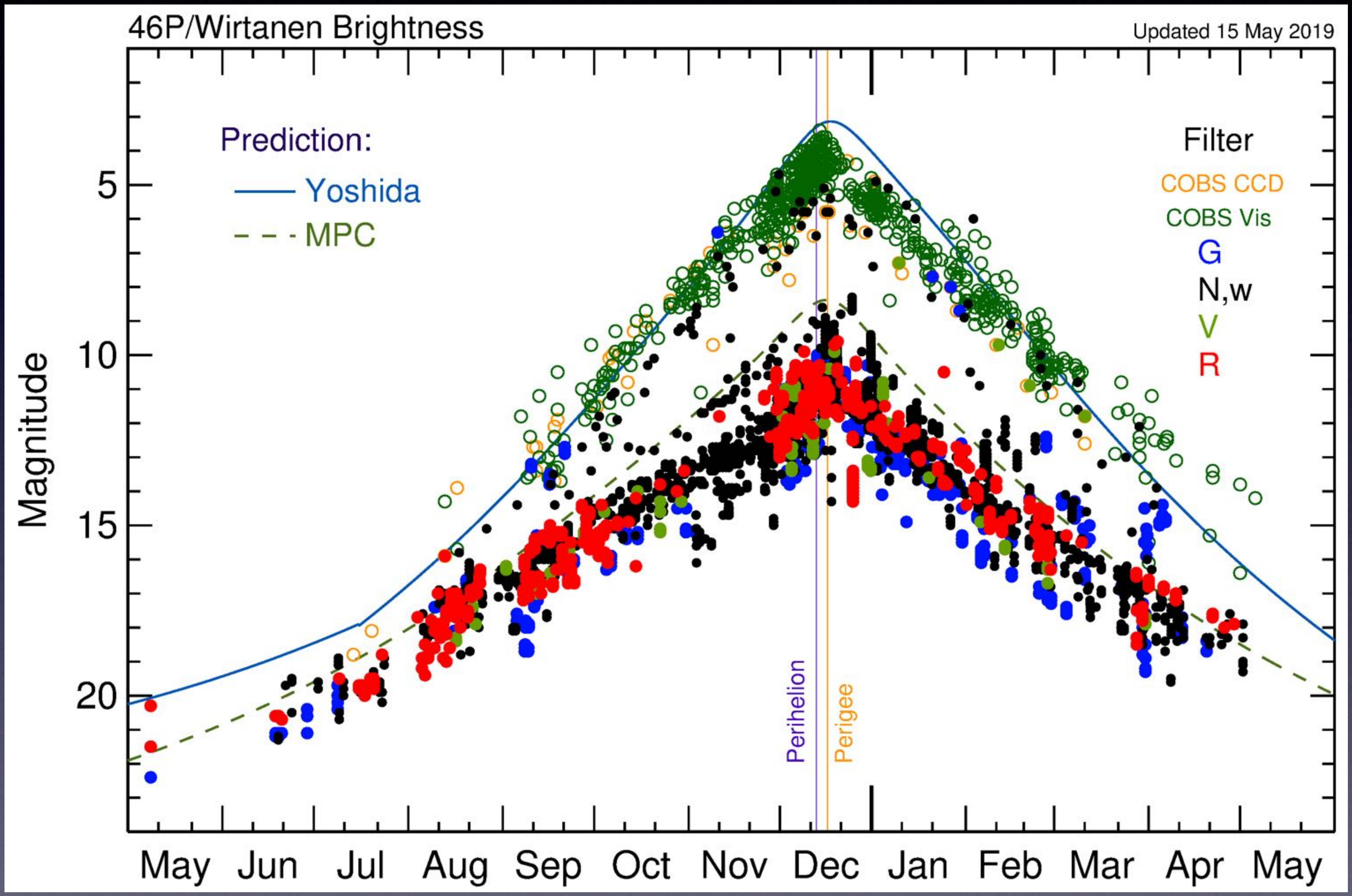


Wirtanen — December 2018

Image: V. Cheng

- Jupiter-family comet, orbital period 5.4 years
- Original target of the *Rosetta* mission

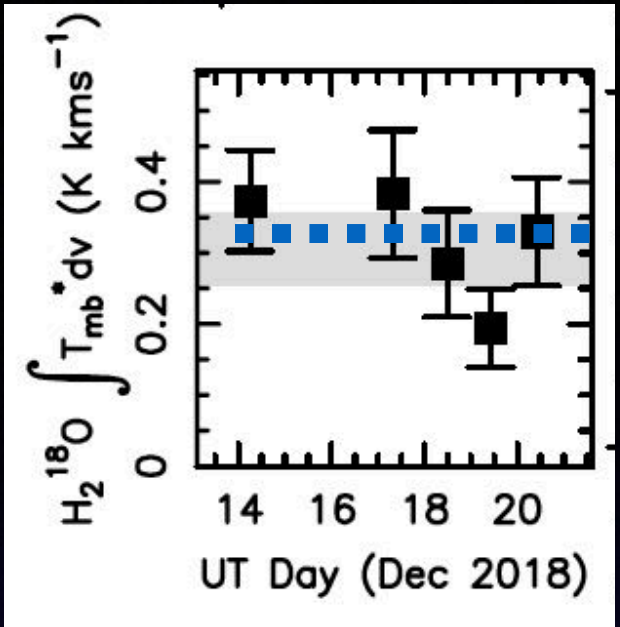
Wirtanen — December 2018



- Perihelion on December 12 at 1.055 au from the Sun
- Closest approach on December 16 at 0.08 au from the Earth
- Five SOFIA flights between December 14 and 20 (GT+DDT)

Image: U. Maryland

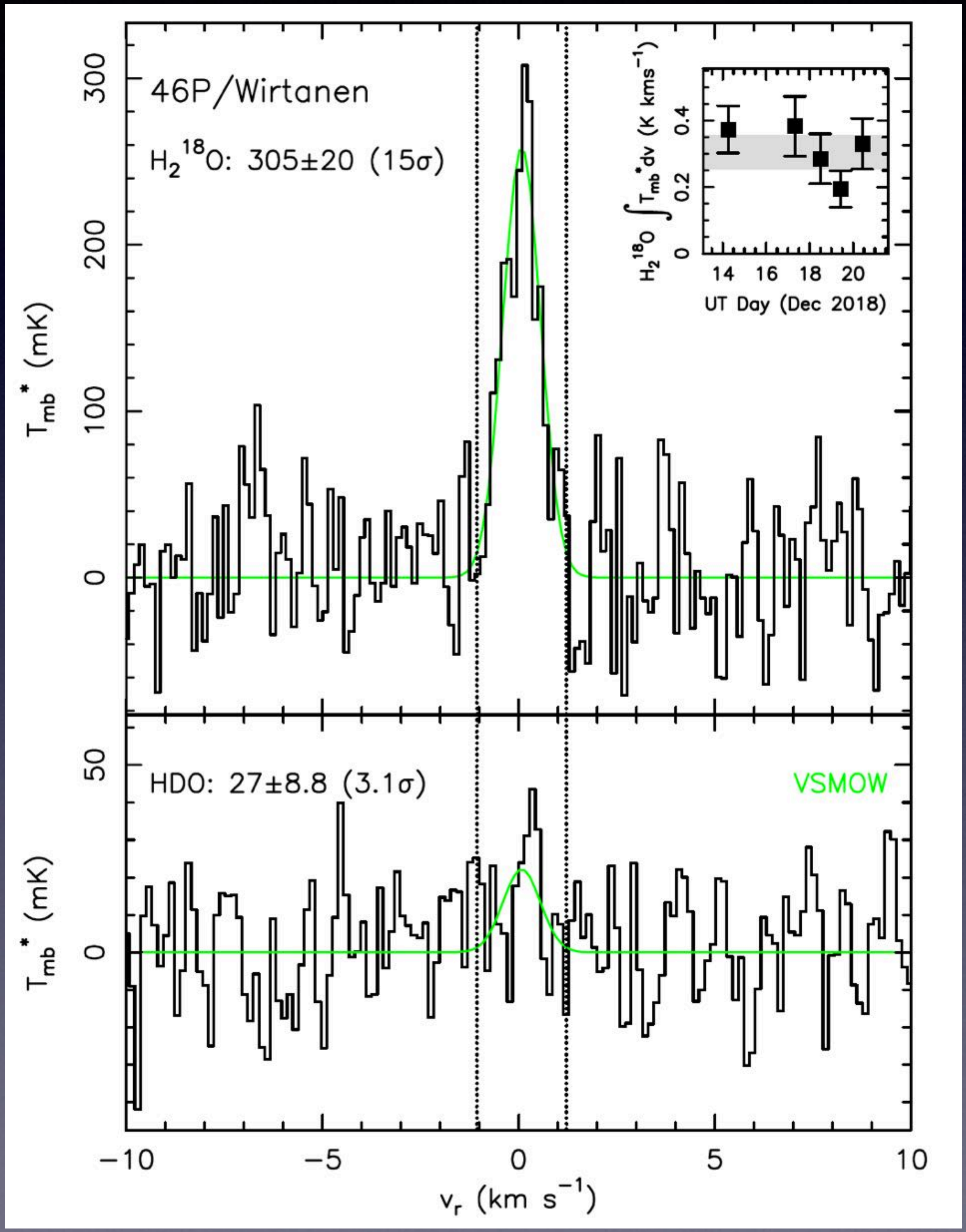
SOFIA Observations



Flight	UT time	r_h	Δ	$t(H_2{}^{18}O)$	$\sigma(H_2{}^{18}O)$	t(HDO)	σ(HDO)
	(hr)	(au)	(au)	(min)	(mK)	(min)	(mK)
1	Dec 14, 4.89–7.47	1.056	0.079	16.5	80	29.2	43
2	Dec 17, 7.56–9.68	1.057	0.078	7.2	125	30.8	38
3	Dec 18, 9.59–12.17	1.058	0.078	13.8	112	30.3	37
4	Dec 19, 9.78–12.00	1.059	0.079	14.9	85	25.6	42
5	Dec 20, 9.83–12.33	1.060	0.081	11.6	105	34.1	31

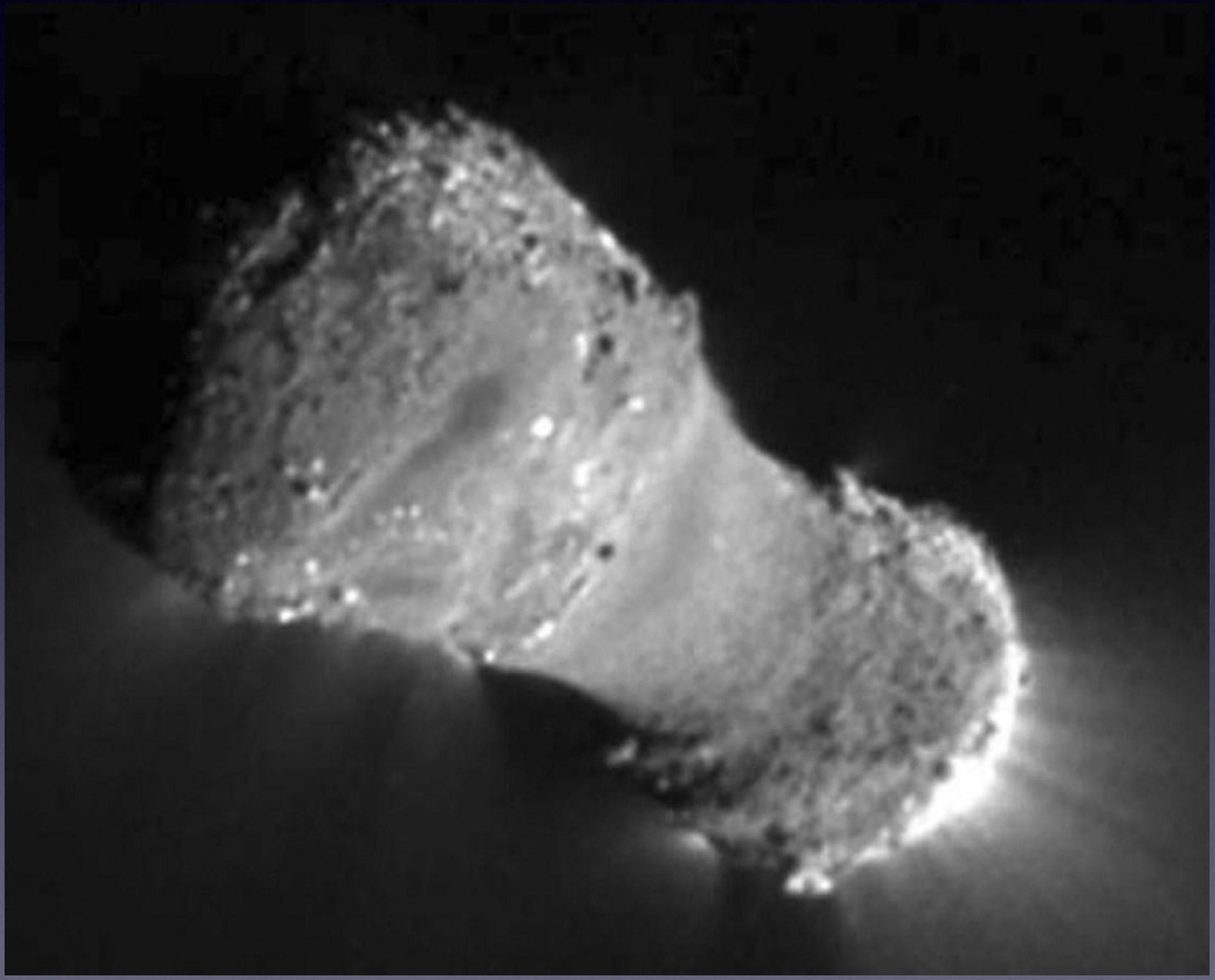
- Flight time ~3 h per flight — longest time allowed by the flight planning
- Total on-source integration time 64 and 150 min for $H_2{}^{18}O$ and HDO, respectively

SOFIA Observations



- $H_2^{18}O$: 305±20 mK km s^{-1} (15.3 σ)
- HDO: 27±8.8 mK km s^{-1} (3.1 σ)
- D/H = $(1.61 \pm 0.65) \times 10^{-4}$ including statistical, calibration, modeling, and $^{16}O/^{18}O$ ratio uncertainties
- Third Jupiter-family comet with a D/H ratio consistent with the Earth's ocean value
- What is special about the comets with a low D/H ratio?

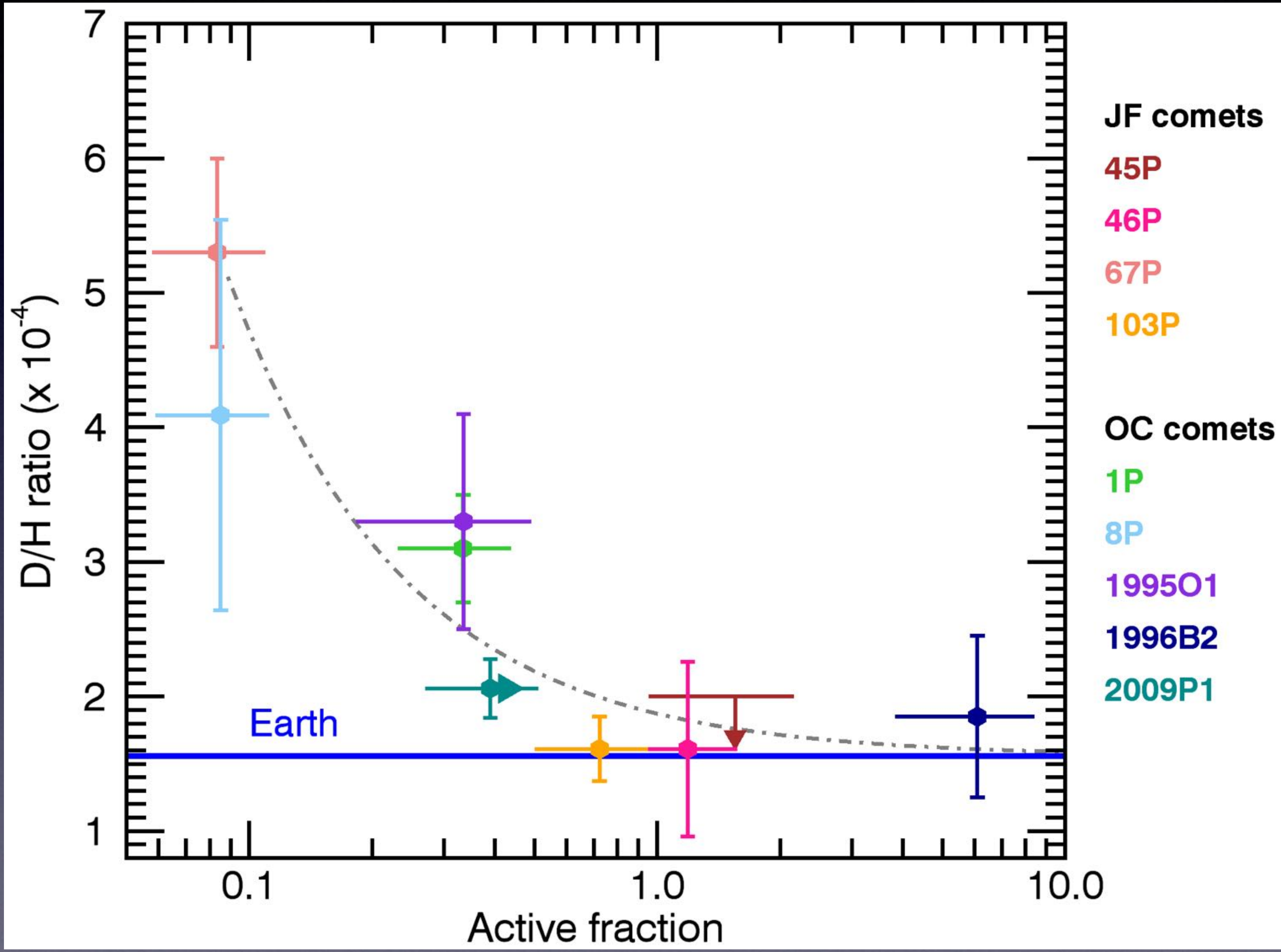
Hyperactive Comets



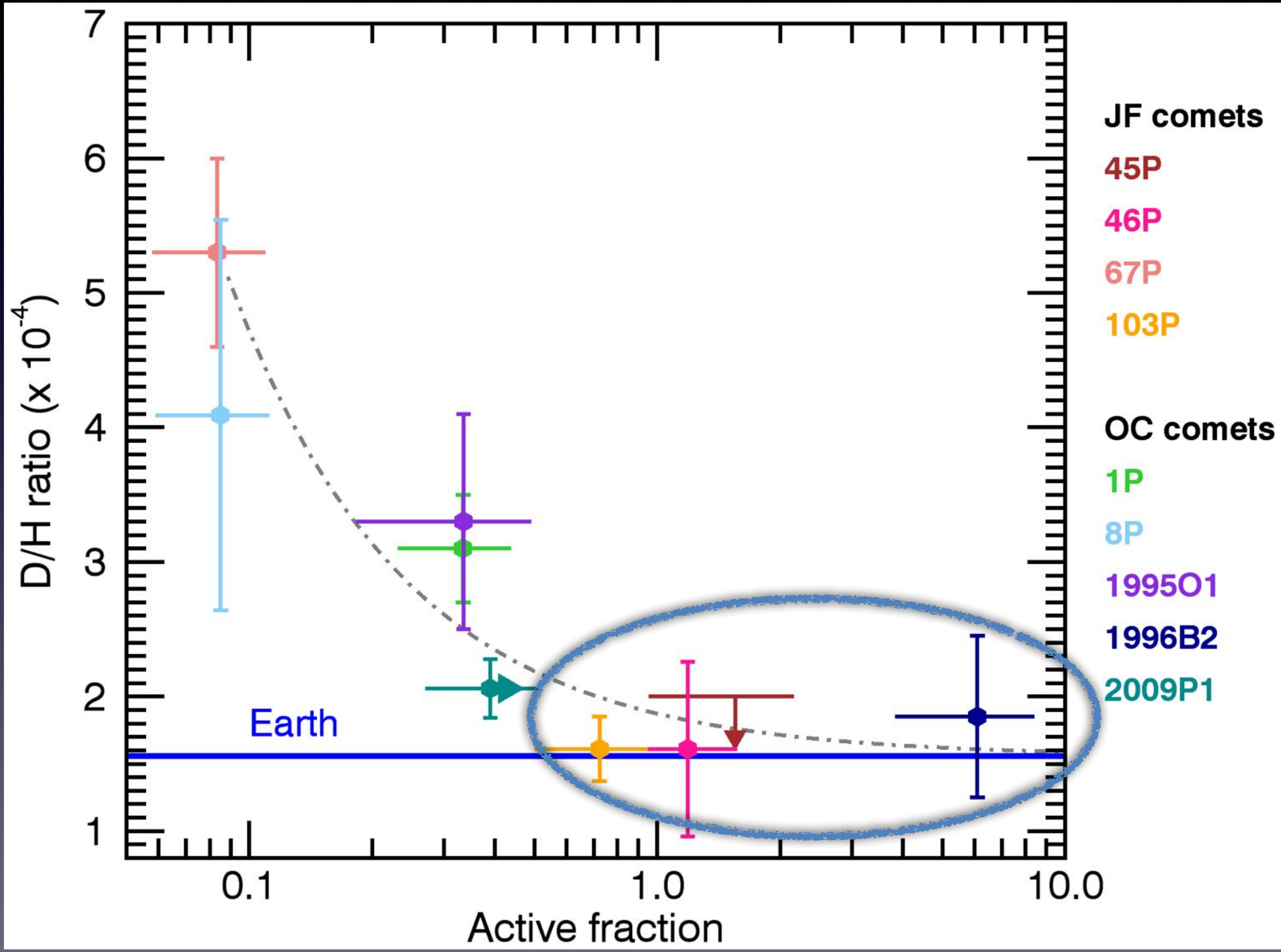
103P/Hartley — Deep Impact/EPOXI

- Emit more water molecules than can be expected given the size of the nucleus
- Presence of sublimating water-ice-rich particles in the coma
- Archetype 103P/Hartley studied by Deep Impact — both icy grains and water overproduction were observed
- Active fraction: ratio of the active surface area to the total nucleus surface
- A comprehensive set of water production rates from SWAN on SOHO (Combi et al. 2019)

D/H vs. Active Fraction

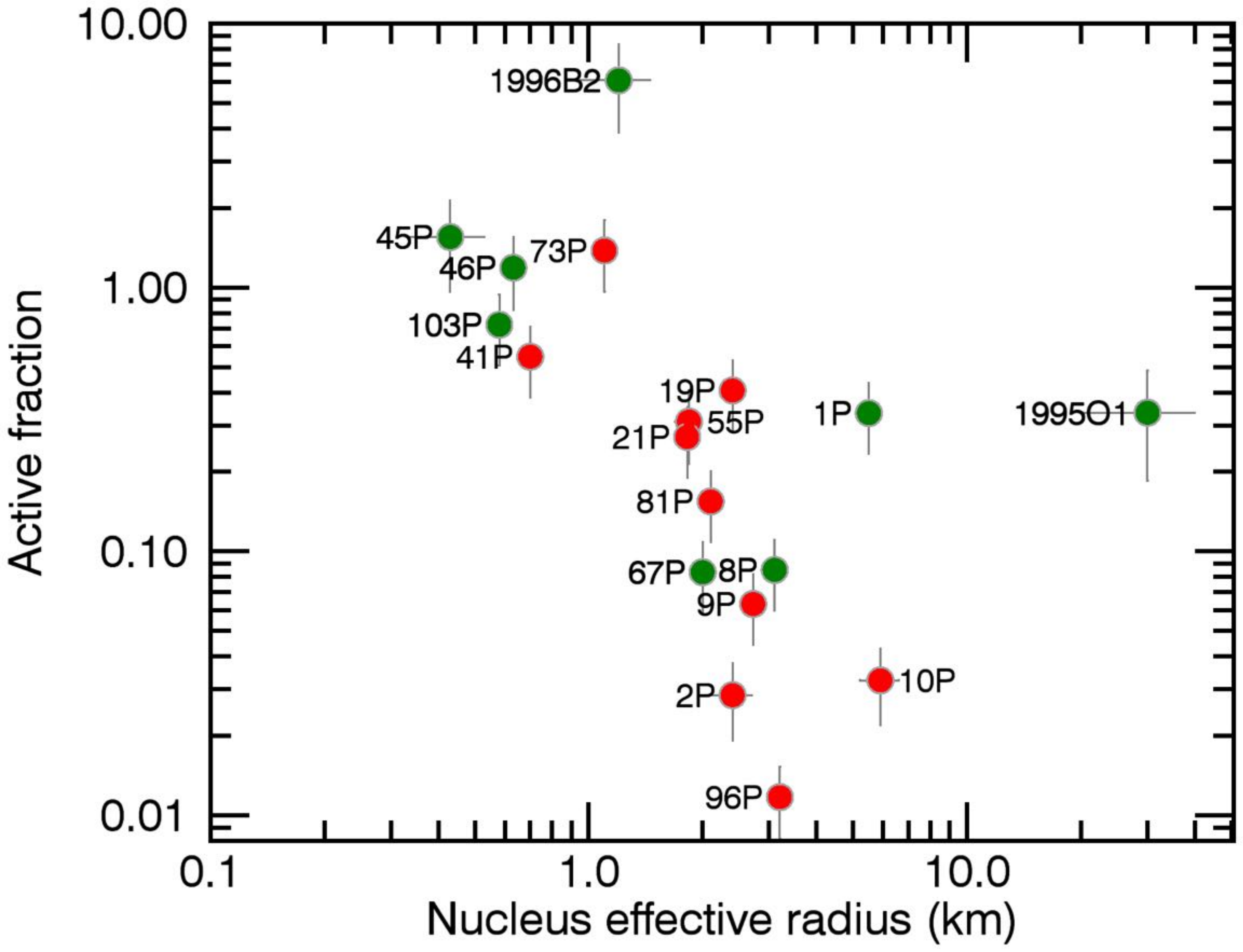


D/H vs. Active Fraction



- Comets with active fraction above 0.5 typically have terrestrial D/H ratios
- Large reservoir of ocean-like water in the outer Solar System

Possible Interpretations?

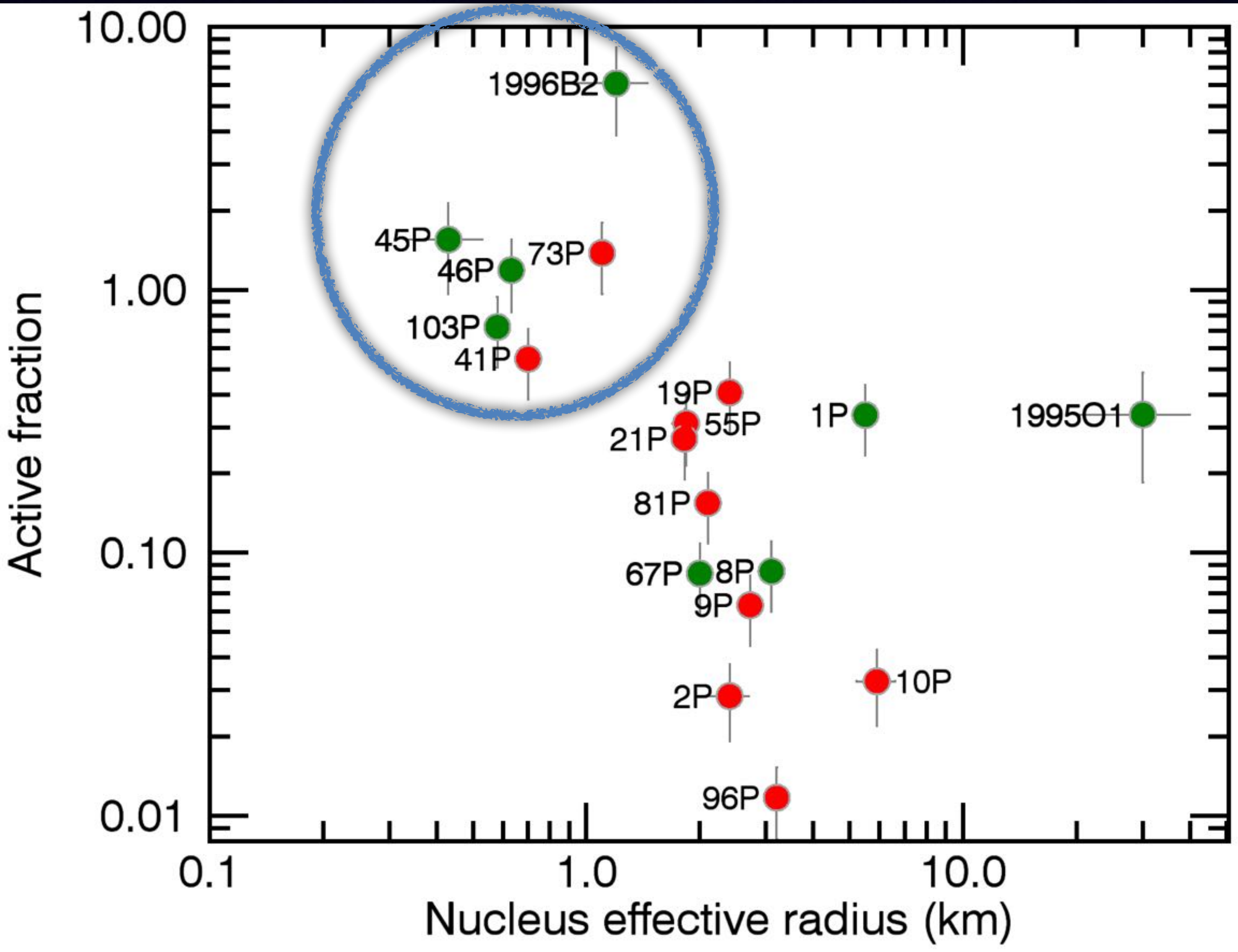


- Hyperactive comets are ice-rich objects that formed just outside the snow line
- Observed anti-correlation between active fraction and nucleus size argues against this
- Planetesimals outside the snow line are expected to undergo rapid growth

- Formed in the outer Solar System from water thermally processed in the inner disk (Yang model)

- Isotopic properties of water outgassed from the nucleus and icy grains may be different
- Need laboratory measurements

Possible Interpretations?



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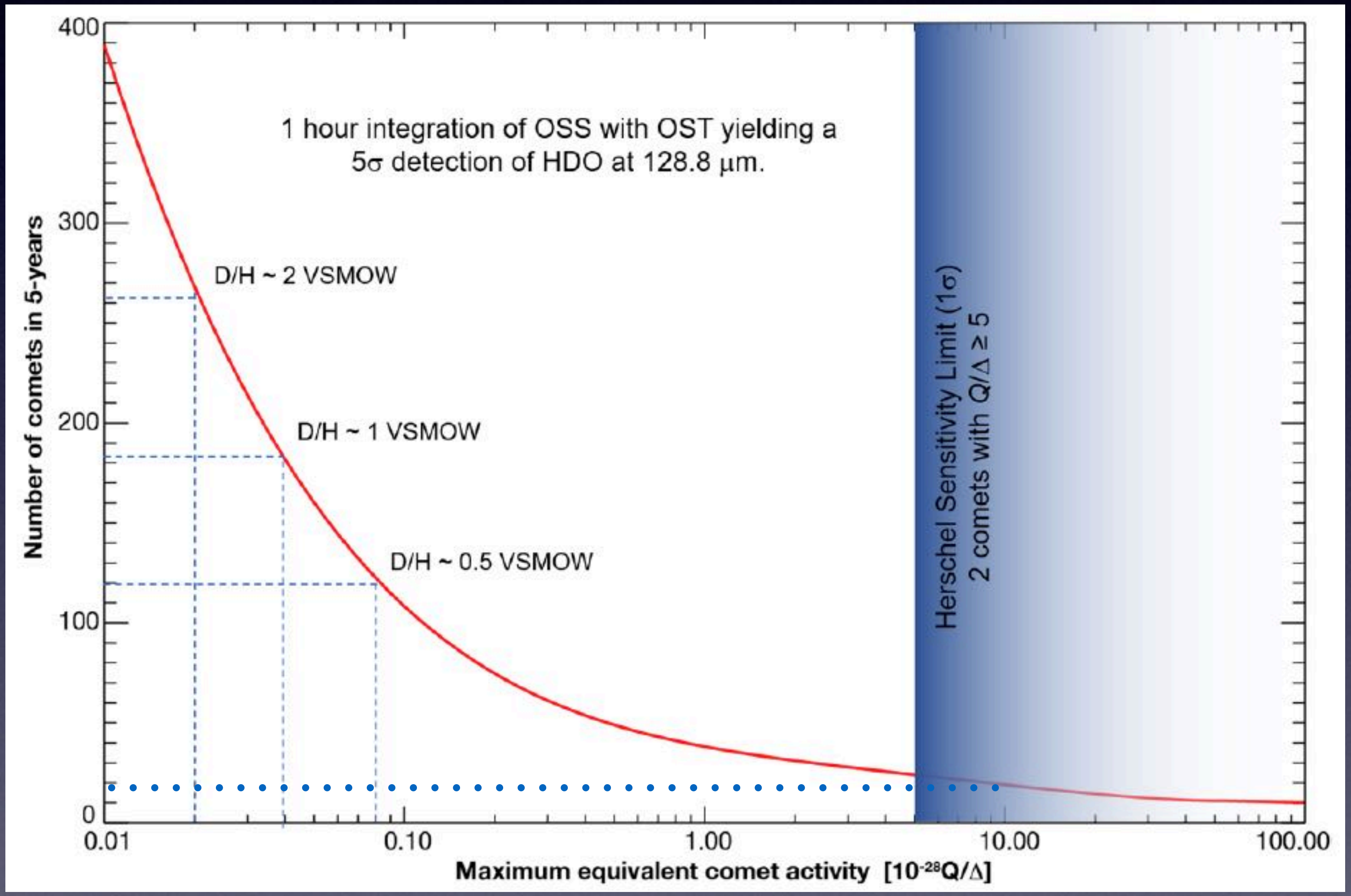
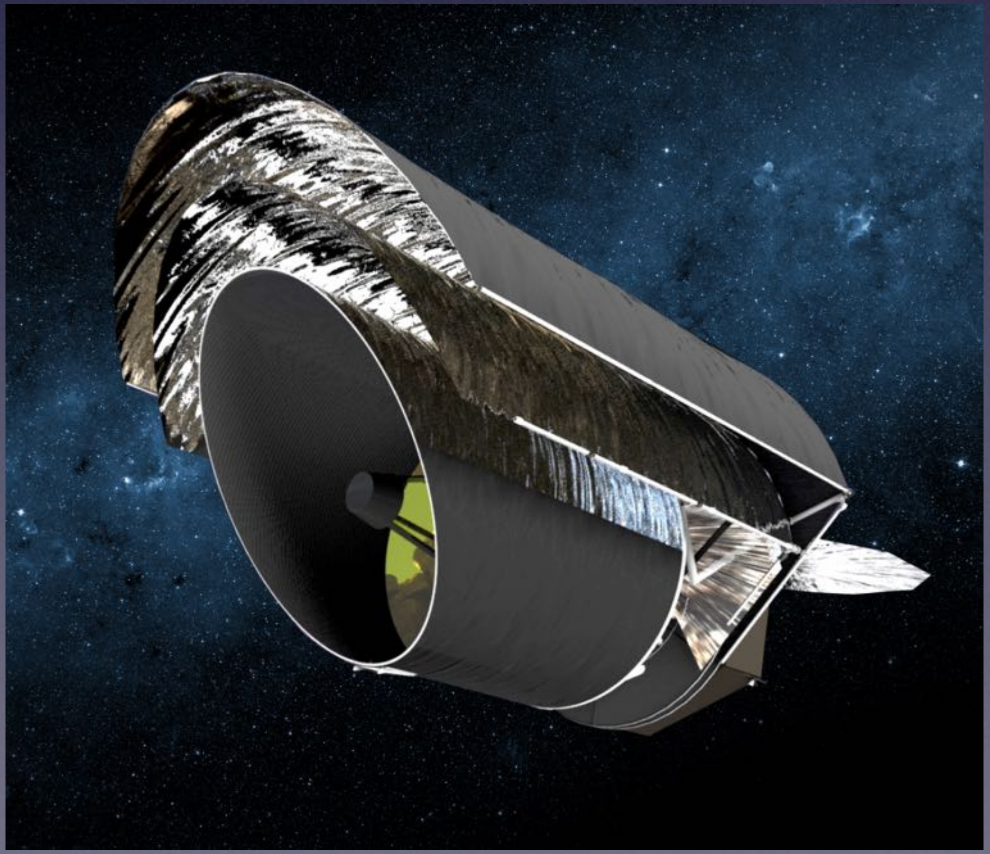
Where Do We Go from Here?

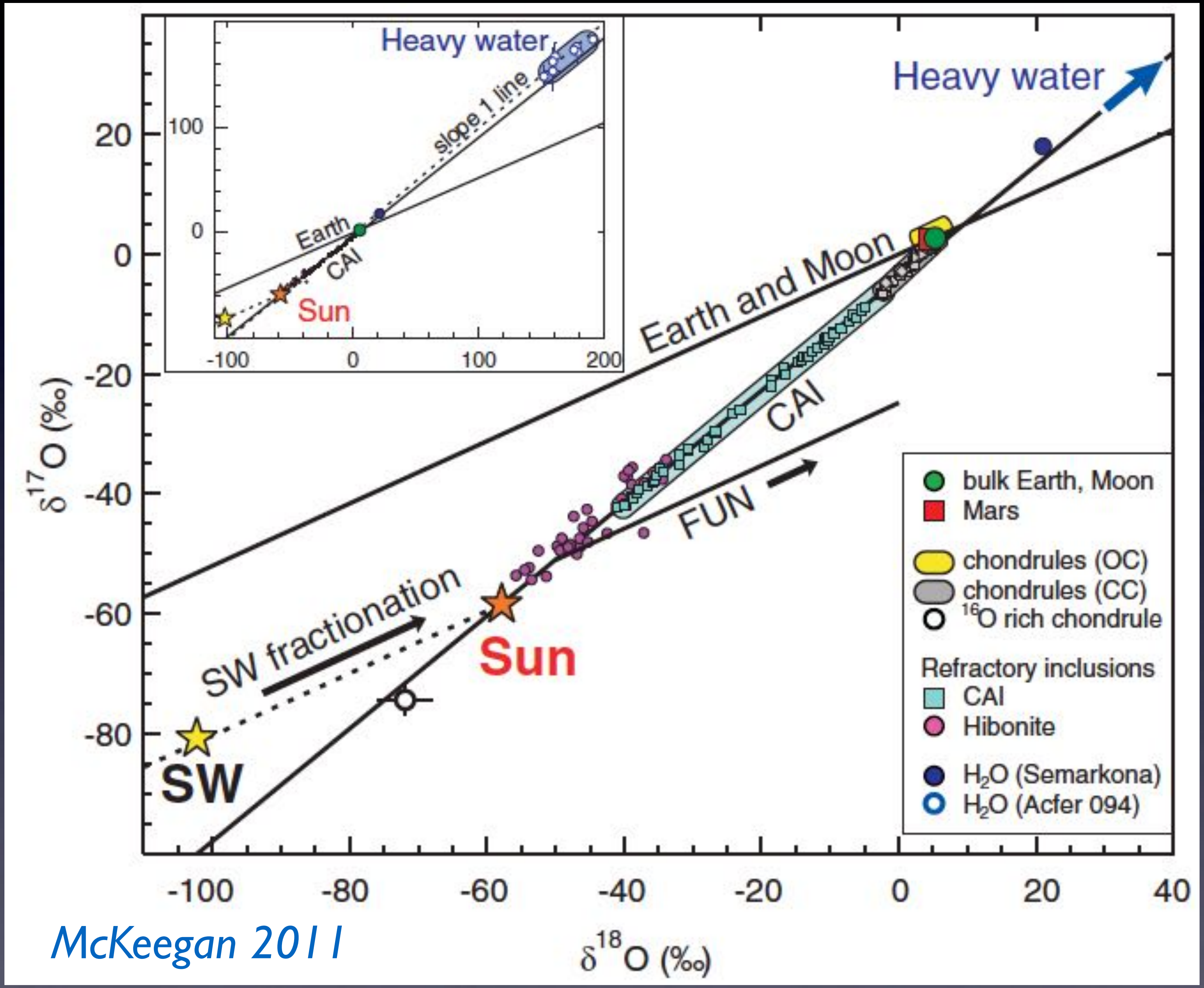


- Figure of Merit (FOM) = $Q(H_2O)/\Delta$(au)
- Wirtanen: $7.7\times10^{27}s^{-1}/0.08$ au=1×10^{29}
- Expect ~1 measurement per year with SOFIA
- *Origins* will be able to measure D/H ratio in hundreds of comets



NASA, Origins

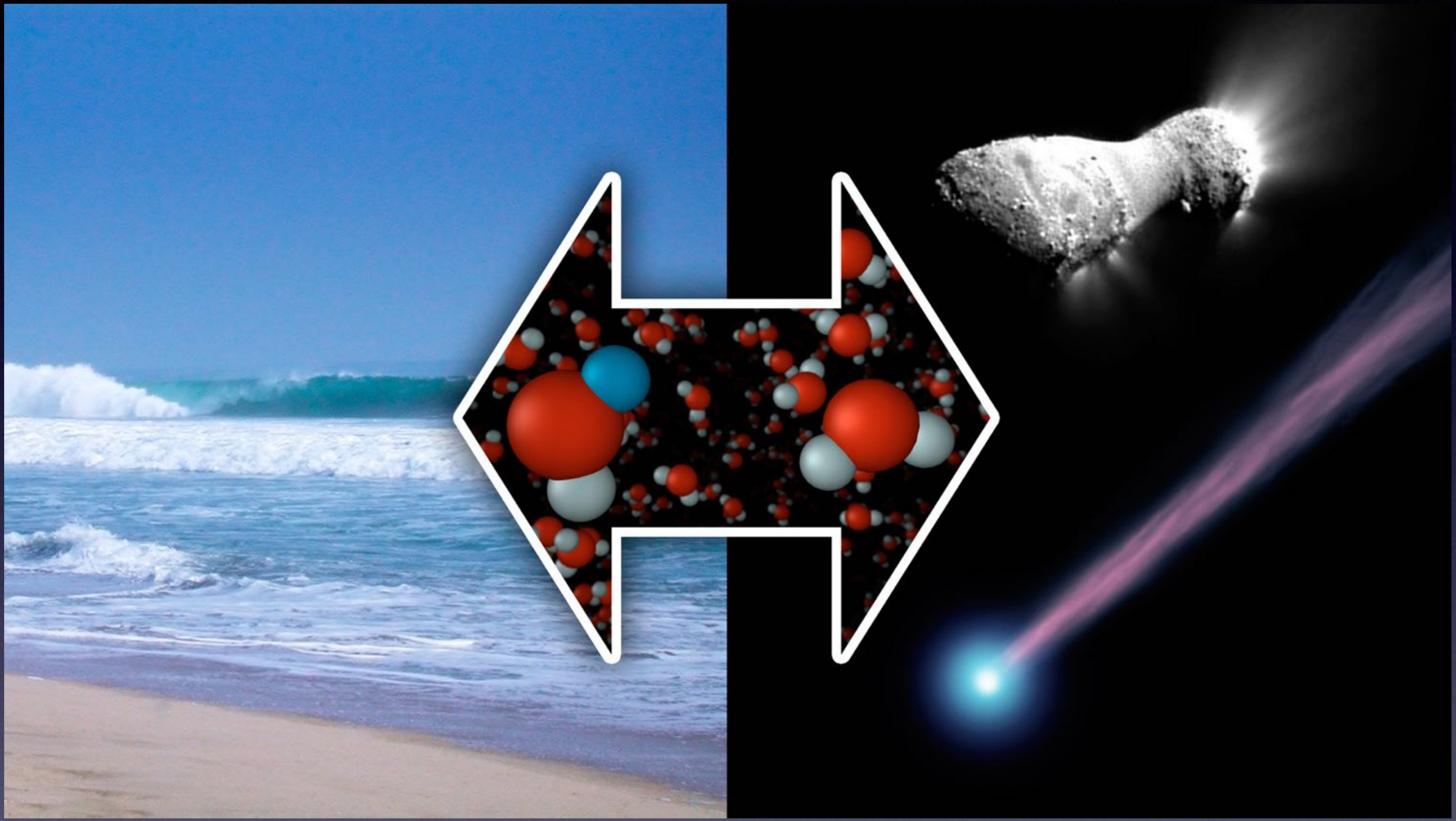
Oxygen Isotopic Ratios



McKeegan 2011

- Expect mass dependent fractionation: fractionation of $^{17}O/^{16}O$ half of that of $^{18}O/^{16}O$
- Mass independent fractionation observed — why?

Summary



- Measurements of isotopic ratios in a large sample of comets, including Main Belt comets, are key for understanding the origin of the Earth's water
- With a long term, focused program, SOFIA can double the number of existing D/H measurements during its lifetime
- *Origins* or a dedicated Discovery or Explorer class mission is needed to provide a statistically significant sample

Jet Propulsion Laboratory
California Institute of Technology