Remote Studies of Organics in Cometary Comae

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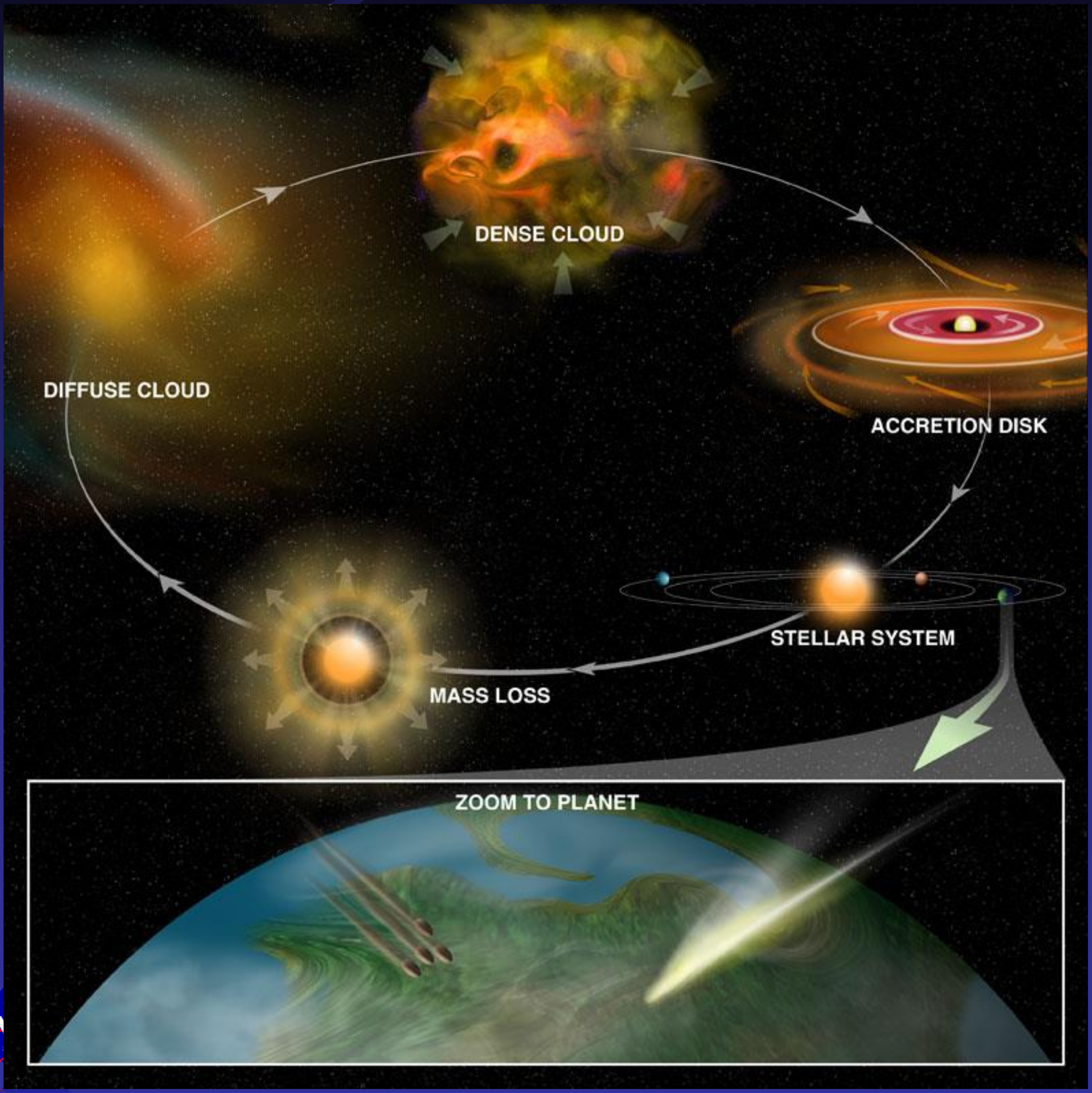
Comets- Interstellar inheritance?



Pristine material from early Solar System?

- Pristine from molecular cloud
- Processing in presolar nebula

Complex Organics

- Inventory
- Sample return
- Missions

Isotope ratios

- Origin, formation and evolution of the Solar System (ex : Earth's Water)
- ISM-comet connection

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Some of the Known Interstellar Molecules

2		3		4	5	6	7	8	9	10
H_2	CH^+	H_2O	C_3	NH_3	SiH_4	CH_3OH	CH_3CHO	CH_3CO_2H	CH_3CH_2OH	$CH_3(C\equiv C)_2CN$
OH	CN	H_2S	HNC	H_3O^+	CH_4	NH_2CHO	CH_3NH_2	HCO_2CH_3	$(CH_3)_2O$	$(CH_2OH)_2$
SO	CO	SO_2	HCN	H_2CO	CHOOH	CH_3CN	CH_3CCH	CH_3C_2CN	CH_3CH_2CN	CH_3COCH_3
SO^+	CS	NNH^+	CH_2	H_2CS	$HC\equiv CCN$	CH_3NC	CH_2CHCN	C_7H	$H(C\equiv C)_3CN$	
SiO	C_2	HNO	NH_2	HNCO	CH_2NH	CH_3SH	$H(C\equiv C)_2CN$	H_2C_6	$H(C\equiv C)_2CH_3$	**11**
SiS	SiC	CCS	HOC^+	HNCS	NH_2CN	C_5H	C_6H	CH_2OHCHO	C_8H	$H(C\equiv C)_4CN$
NO	CP	NH_2	NaCN	CCCN	H_2CCO	HC_2CHO	$c\text{-}CH_2OCH_2$	NH_2CH_2CN	C_3H_6	$CH_3OC(O)CH_3$
NS	CO^+	H_3^+	MgNC	HCO_2^+	C_4H	$CH_2{=}CH_2$	$H_2CC(OH)H$	CH_3CHNH		C_2H_5OCHO
HCl	HF	NNO	AlNC	CCCH	$c\text{-}C_3H_2$	H_2C_4				**12**
NaCl	SiH	HCO	SiCN	$c\text{-}C_3H$	CH_2CN	HC_3NH^+				$n\text{-}C_3H_7CN$
KCl	HO^+	HCO^+	SiNC	CCCO	C_5	C_5N				$c\text{-}C_6H_6$
AlCl	PO	OCS	H_2D^+	C_3S	SiC_4	$c\text{-}H_2C_3O$				$i\text{-}C_3H_7CN$
AlF	HD	CCH	KCN	HCCH	H_2C_3	HNCHCN				**13+**
PN	TiO	HCS^+	MgCN	$HCNH^+$	HCCNC					$H(C\equiv C)_5CN$
SiN	AlO	c-SiCC	HCP	HCCN	HNCCC					C_{60}
NH	ArH+	CCO	H_2O^+	H_2CN	H_2COH^+					C_{70}
CH	SH	AlOH	CCP	$c\text{-}SiC_3$	HC(O)CN					
		CCN		C_3N^-	CH_3O					
				HSCN	NH_4+					
					HNCNH					

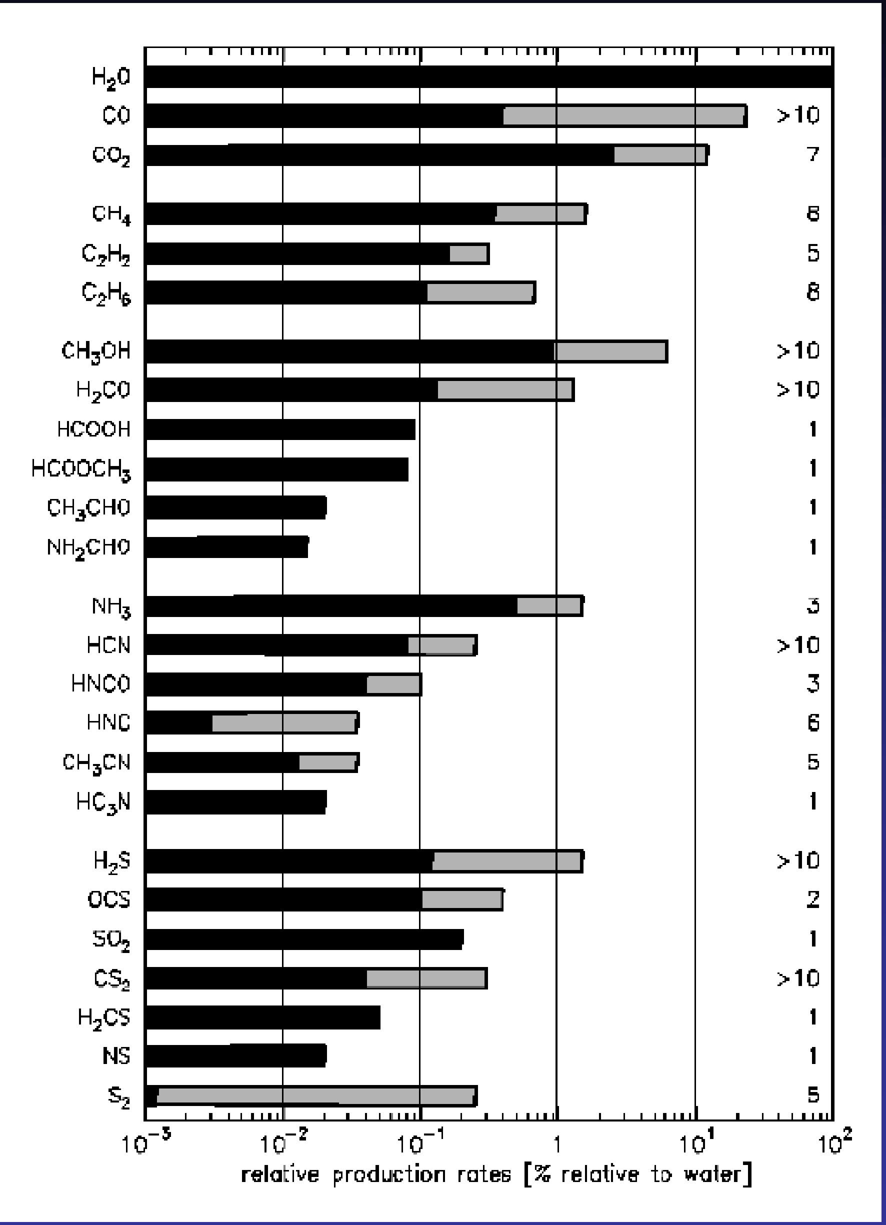
>15 ions
6 rings
>100 Carbon Molecules
11 Silicon Species
9 Metal Containing Molecules

Total >200
As of 2018

http://www.astro.uni-koeln.de/cdms/molecules

PRE-ROSETTA Comae molecules

- 25+ molecules known from remote surveys (many more from Giotto)
- Nucleus composition or coma chemistry?
  - Need spatially-resolved maps to determine the origins



Bockelée-Morvan et al., Comets II, 2005

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Solar System Connection?

Connecting the simple chemistry found in the Interstellar Medium to the complex chemistry found in Meteorites, IDPs, and NOW Comets.

TABLE I

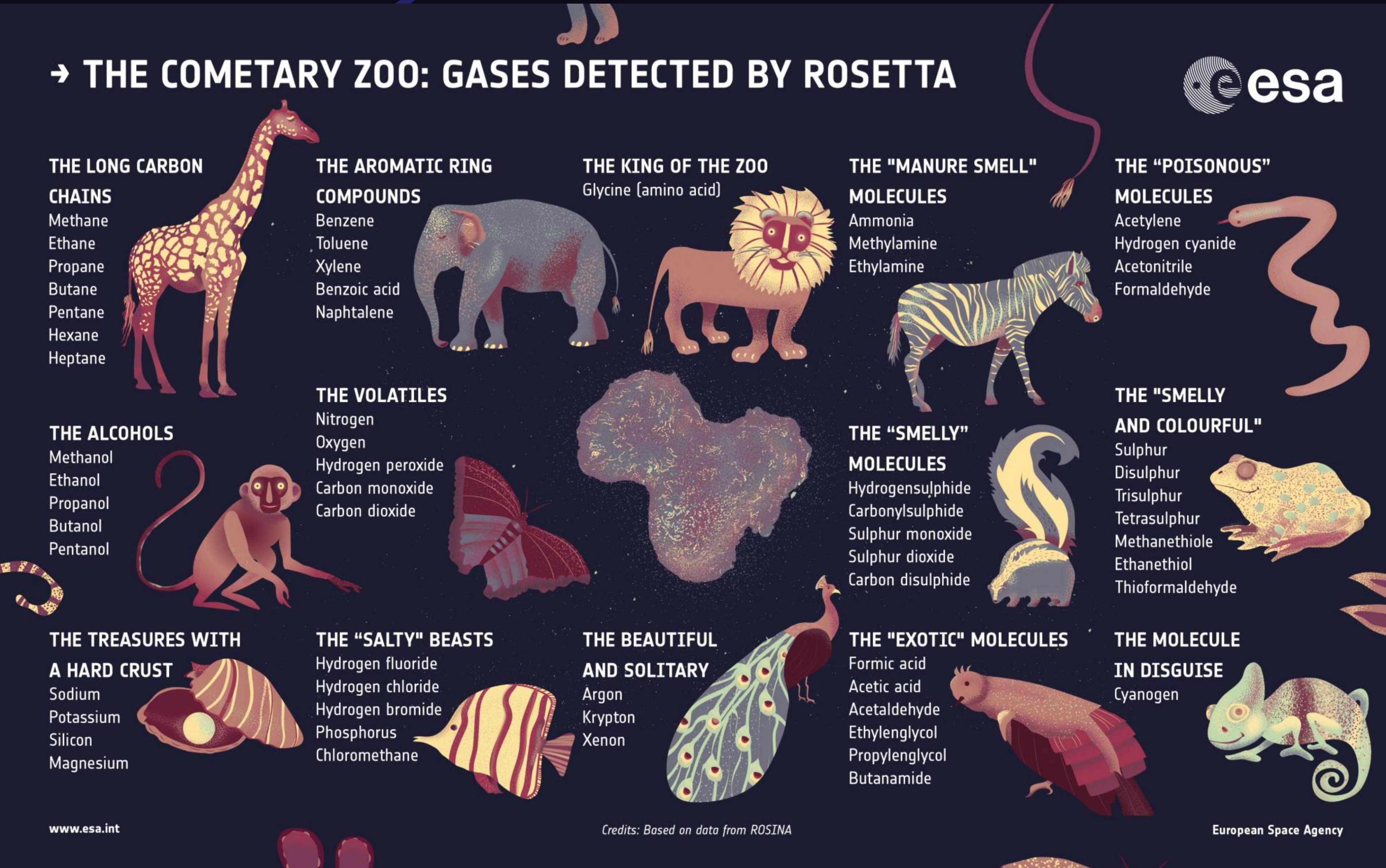
Carbon distribution in the Murchison meteorite

Form		Total C (%)
A. Interstellar grains:		2
Diamonds	(400 ppm)	
SiC	(7 ppm)	
Graphite	(< 2 ppm)	
Fullerenes	(≥ 400 ppm)	
B. Carbonate minerals		2–10
C. Macromolecular (insoluble) carbon		70–80
D. Organic compounds (soluble)		10–20

Amino acids [b]	Amides [b]
Carboxylic acides [c]	Amines [b]
Dicarboxylic acids [b]	Alcohols [b]
Hydroxy acids [b]	Aldehydes and ketones [b]
Phosphonic acids [a]	Aliphatic hydrocarbons [b]
Sulfonic acids [d]	Aromatic hydrocarbons [b]
Basic N-heterocycles [a]	Polar hydrocarbons [c]
Purines and pyrimidines [a]	Sugar alcohols and acids [b]
Pyridine carboxylic acids [a]	

[a] >1 ppm, [b] >10 ppm, [c] >100 ppm, [d] >1000 ppm

Pizzarello, S. (2004) *OLEB*, **34**, 25


→ THE COMETARY ZOO: GASES DETECTED BY ROSETTA
esa
THE LONG CARBON CHAINS
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane
THE AROMATIC RING COMPOUNDS
Benzene
Toluene
Xylene
Benzoic acid
Naphtalene
THE KING OF THE ZOO
Glycine (amino acid)
THE "MANURE SMELL" MOLECULES
Ammonia
Methylamine
Ethylamine
THE "POISONOUS" MOLECULES
Acetylene
Hydrogen cyanide
Acetonitrile
Formaldehyde
THE ALCOHOLS
Methanol
Ethanol
Propanol
Butanol
Pentanol
THE VOLATILES
Nitrogen
Oxygen
Hydrogen peroxide
Carbon monoxide
Carbon dioxide
THE "SMELLY" MOLECULES
Hydrogensulphide
Carbonylsulphide
Sulphur monoxide
Sulphur dioxide
Carbon disulphide
THE "SMELLY AND COLOURFUL"
Sulphur
Disulphur
Trisulphur
Tetrasulphur
Methanethiole
Ethanethiol
Thioformaldehyde
THE TREASURES WITH A HARD CRUST
Sodium
Potassium
Silicon
Magnesium
THE "SALTY" BEASTS
Hydrogen fluoride
Hydrogen chloride
Hydrogen bromide
Phosphorus
Chloromethane
THE BEAUTIFUL AND SOLITARY
Argon
Krypton
Xenon
THE "EXOTIC" MOLECULES
Formic acid
Acetic acid
Acetaldehyde
Ethylenglycol
Propylenglycol
Butanamide
THE MOLECULE IN DISGUISE
Cyanogen
www.esa.int
Credits: Based on data from ROSINA
European Space Agency

ROSETTA in context

- Provide the ground truth for remote observations.
- Native vs. distributed species.
- Isotopes.
- Future sample return?
  - CAESAR

Cometary Comae

Hartley 2 - 4'' refractor
credit: N. Howes

Hartley 2 - EPOXI

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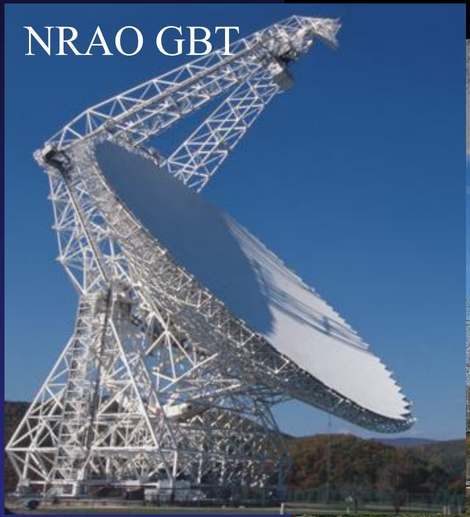
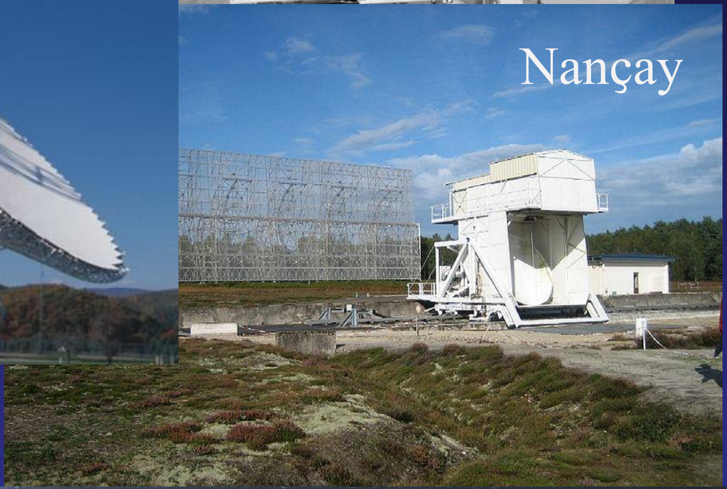
Campaign

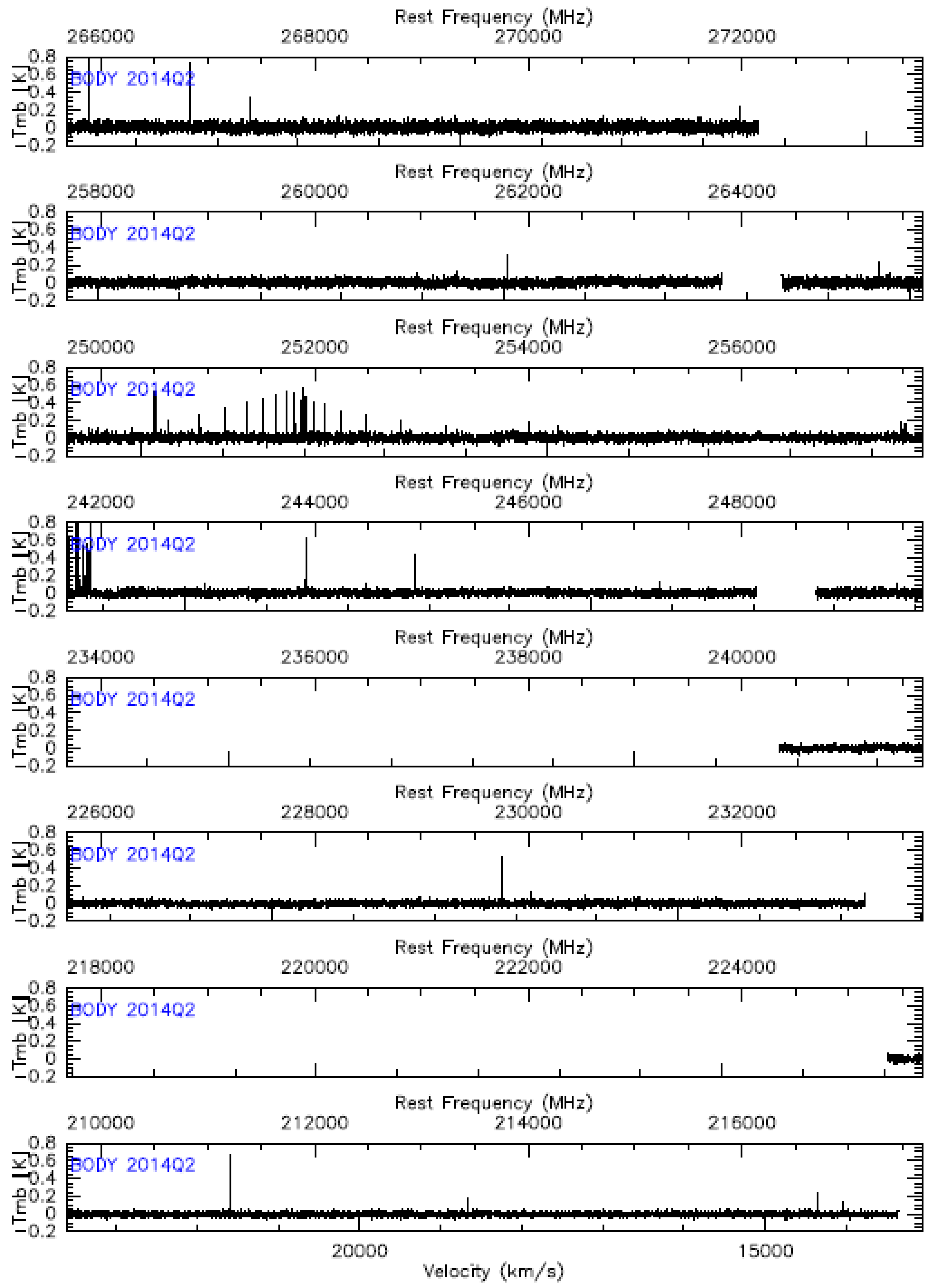
- Dynamic and ‘short’ lived objects.
- Utilizing facilities all over the world (and space).
- OH used as proxy for H2O when needed.
- Simultaneous observations with APEX/ALMA to determine molecular distribution of primary volatiles in the coma.





Broad Band Spectroscopy

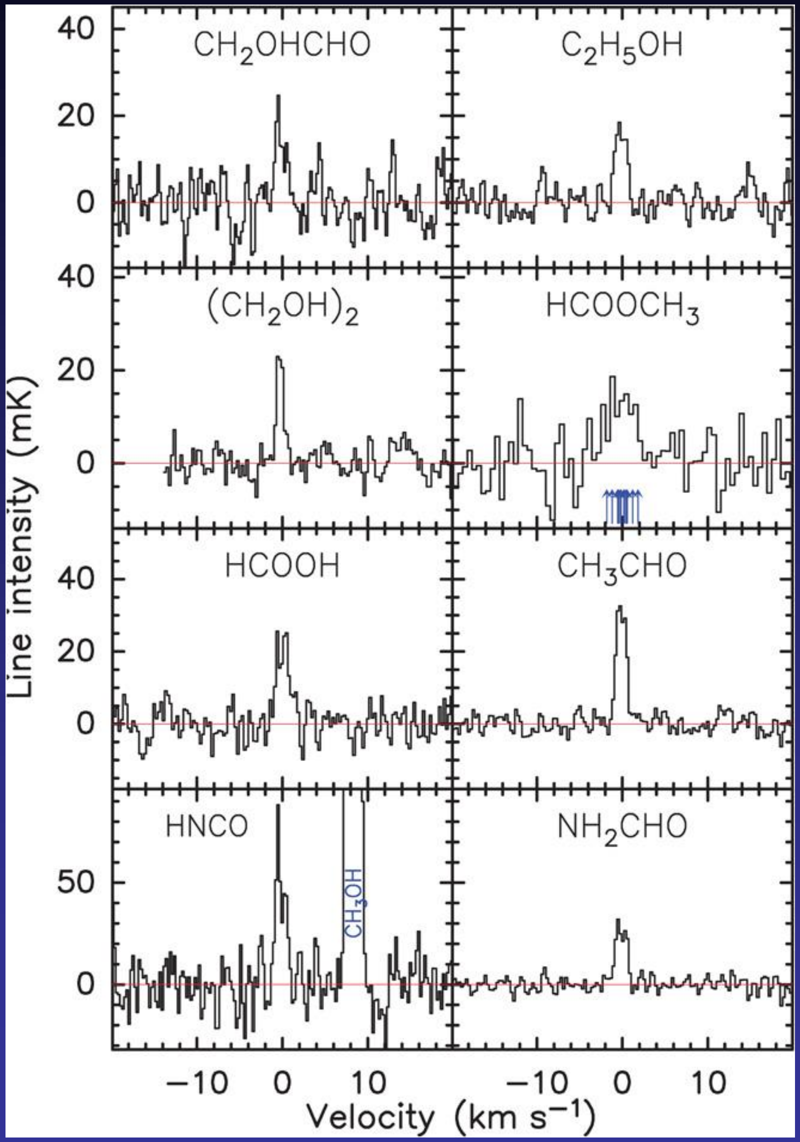
- Multiple lines observed simultaneously.
- Averaging over transitions for new detections.
- Easier to conduct deep searches.



Biver et al. 2015

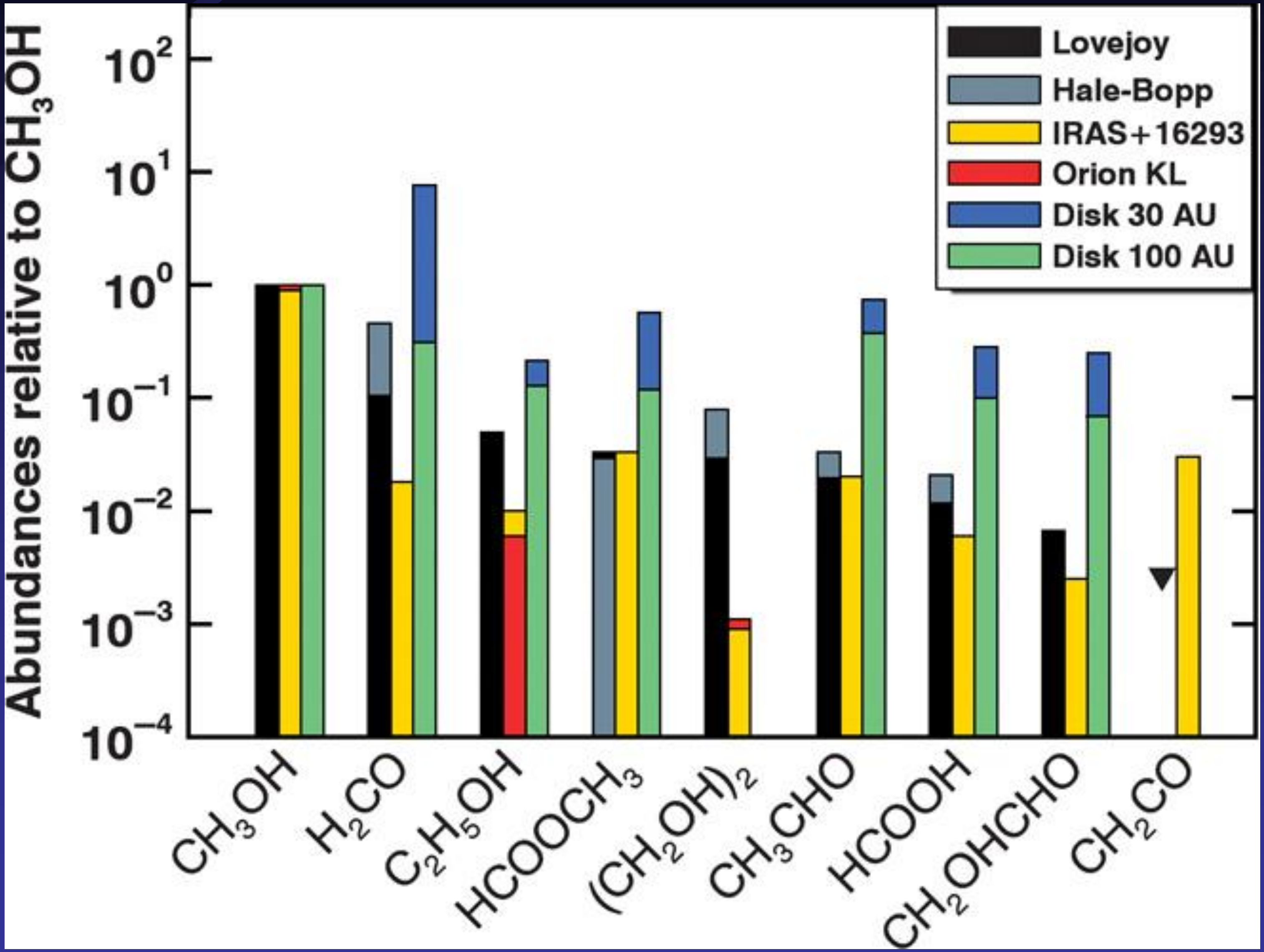
Detection of Complex Organic Molecules (COMs)

- First confirmed detection of ethanol and glycol aldehyde in a comet.
  - *ROSETTA* lander, *Philae*, has tentative detection of glycol aldehyde.
- Based on at least two transitions at >6σ.



Biver et al. 2015

COMs in Comets vs. Star Forming Regions



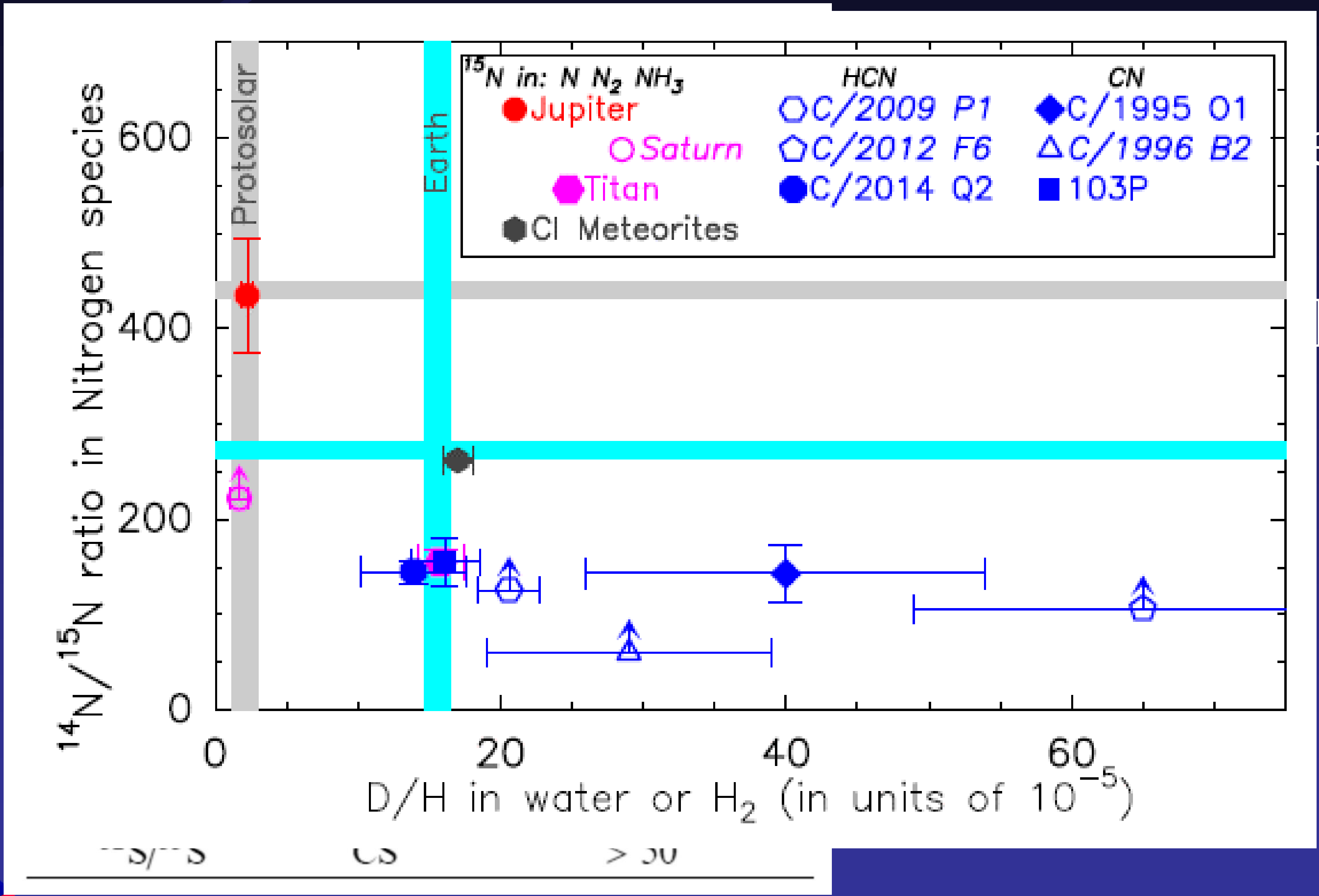
Isotopes as tracers

Isotopic ratio	Molecule	value
Comet C/2012 F6 (Lemmon) Mar.-Apr. 2013		
D/H	H_2O	$6.5 \pm 1.6 \times 10^{-4}$
	HCN	< 0.045
$^{12}C/^{13}C$	HCN	124 ± 64 or $\geq 89^b$
$^{14}N/^{15}N$	HCN	152 ± 72 or $\geq 106^b$
$^{32}S/^{34}S$	CS	20 ± 5
	H_2S	> 3.5
Comet C/2014 Q2 (Lovejoy) Jan. 2015		
D/H	H_2O	$1.4 \pm 0.4 \times 10^{-4}$
	HCN	< 0.006
	H_2S	< 0.017
	H_2CO	< 0.007
$^{12}C/^{13}C$	HCN	109 ± 14
	CH_3OH	> 61
$^{14}N/^{15}N$	HCN	145 ± 12
$^{16}O/^{18}O$	H_2O	499 ± 24^a
$^{32}S/^{34}S$	CS	24.7 ± 3.5
	H_2S	> 7
$^{32}S/^{33}S$	CS	> 50

Biver et al. 2016

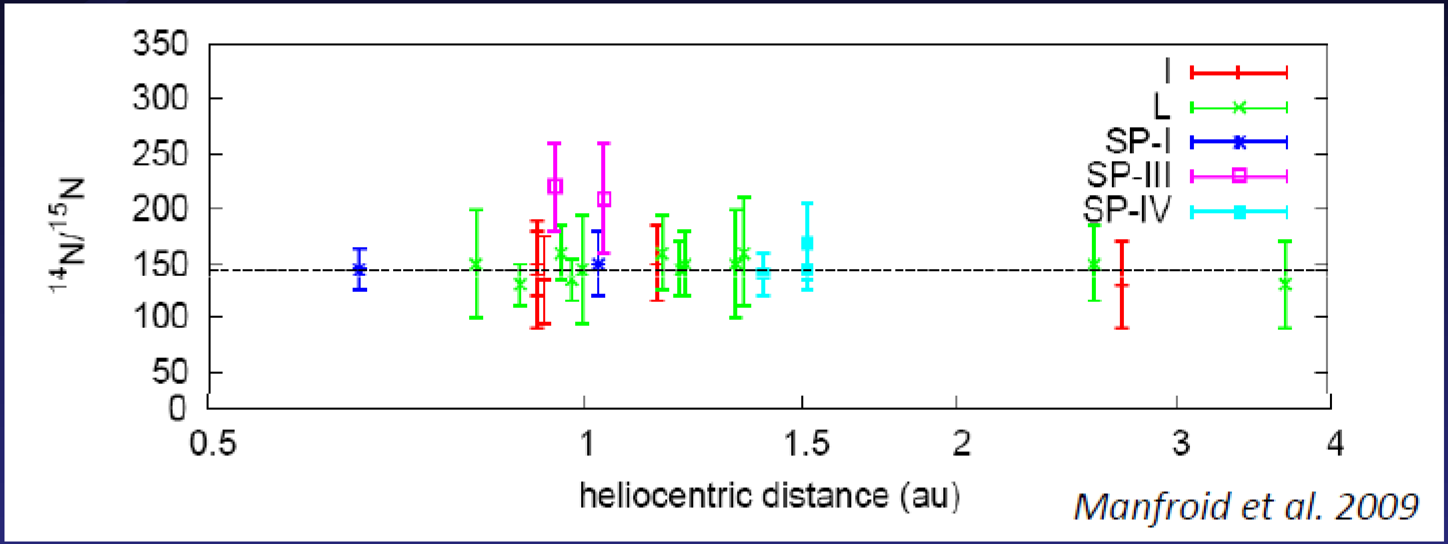
- Access to multiple species in surveys.
- Sensitivity still challenging.

Isotopes as tracers



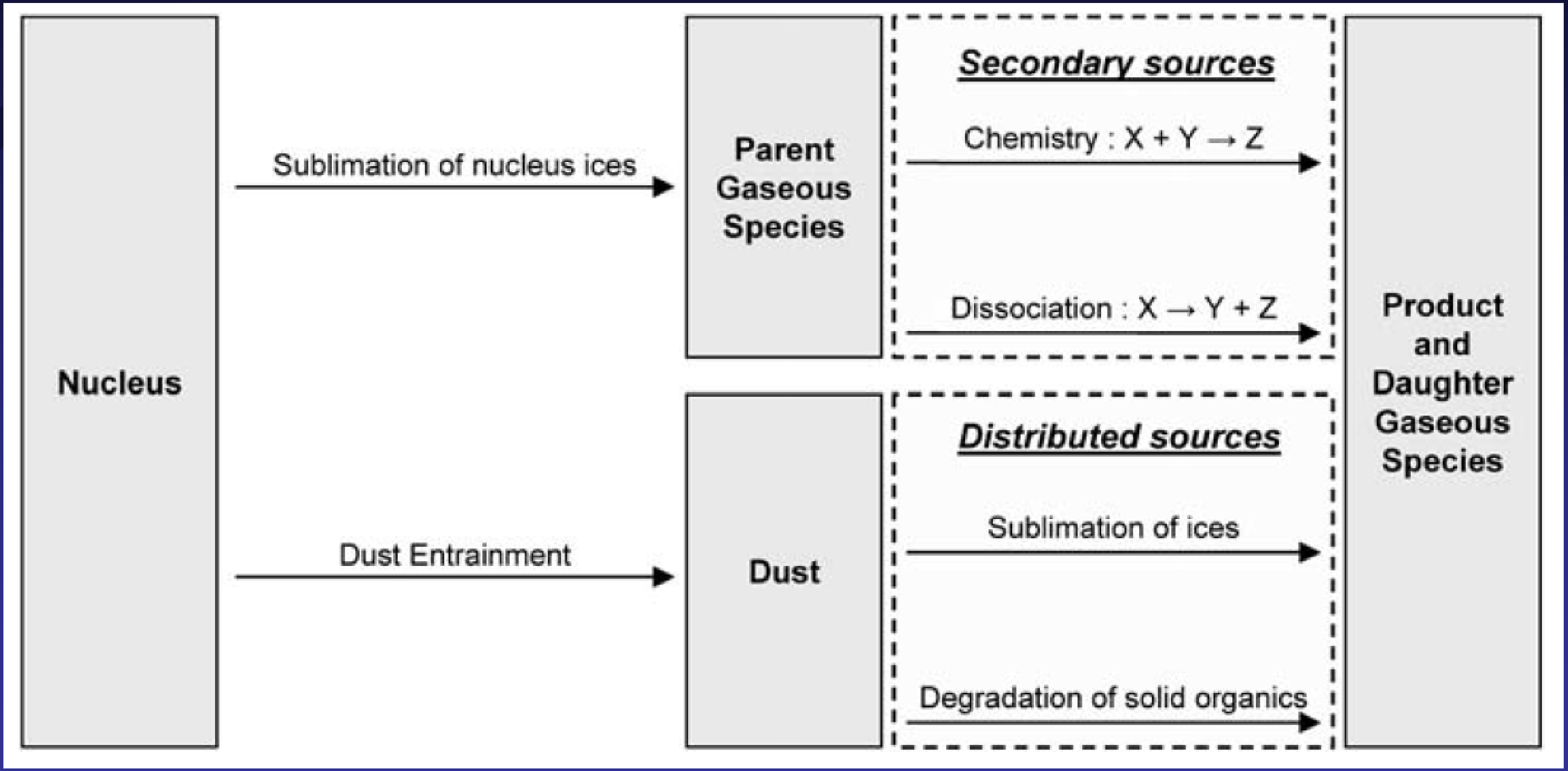
Biver et al. 2016

Nitrogen Anomalies



- Enrichment by a factor of 2 in 15-Nitrogen wrt the terrestrial value (=272) measured in 18 comets (mean = 148+/-6)
- $^{14}N/^{15}N$ identical in JFCs and OCCs
  - From NH2 observations.

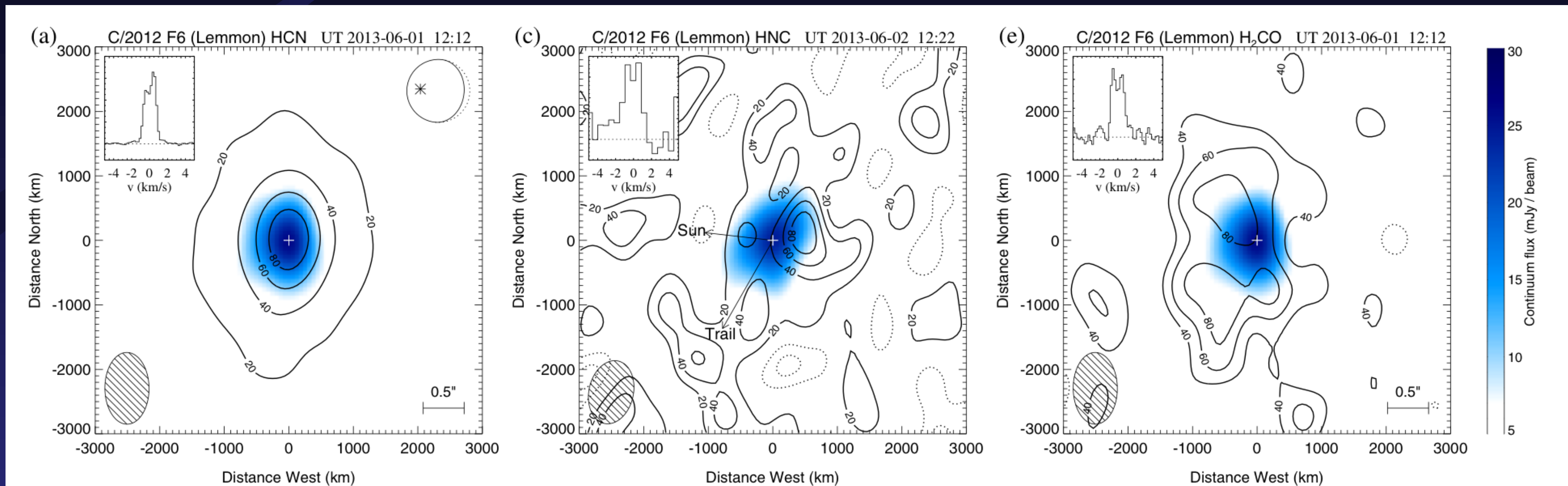
Secondary vs Distributed?

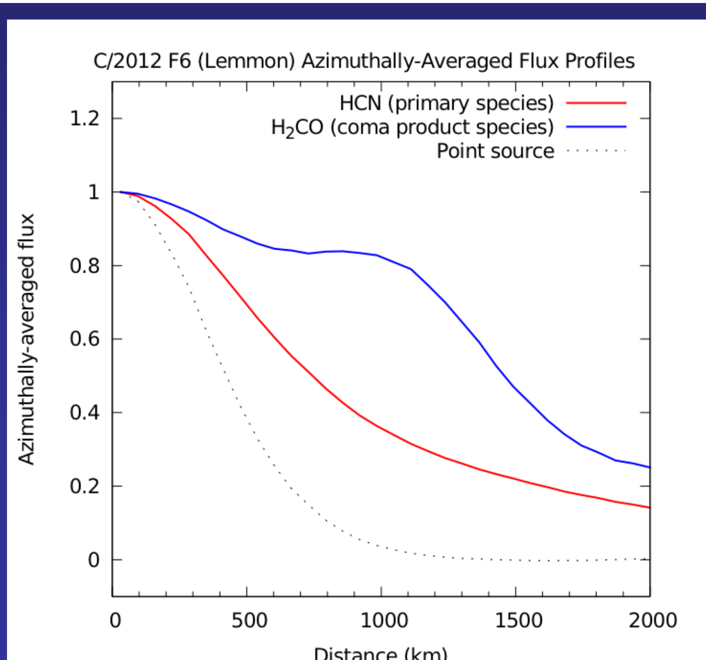


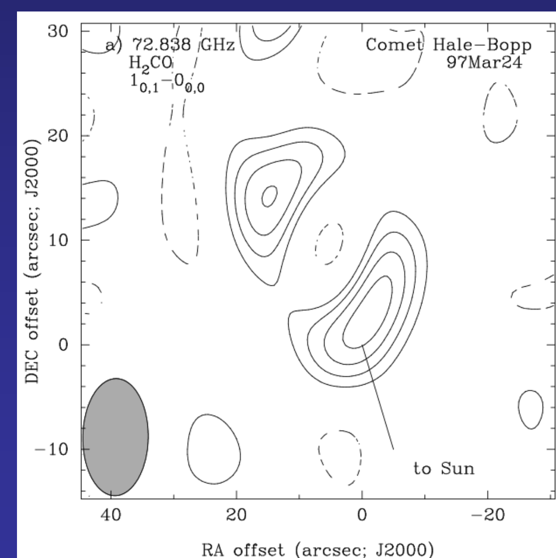
ALMA’s new look on comets

Extended dust sources of coma molecules

Comet C/2012 F6 (Lemmon)



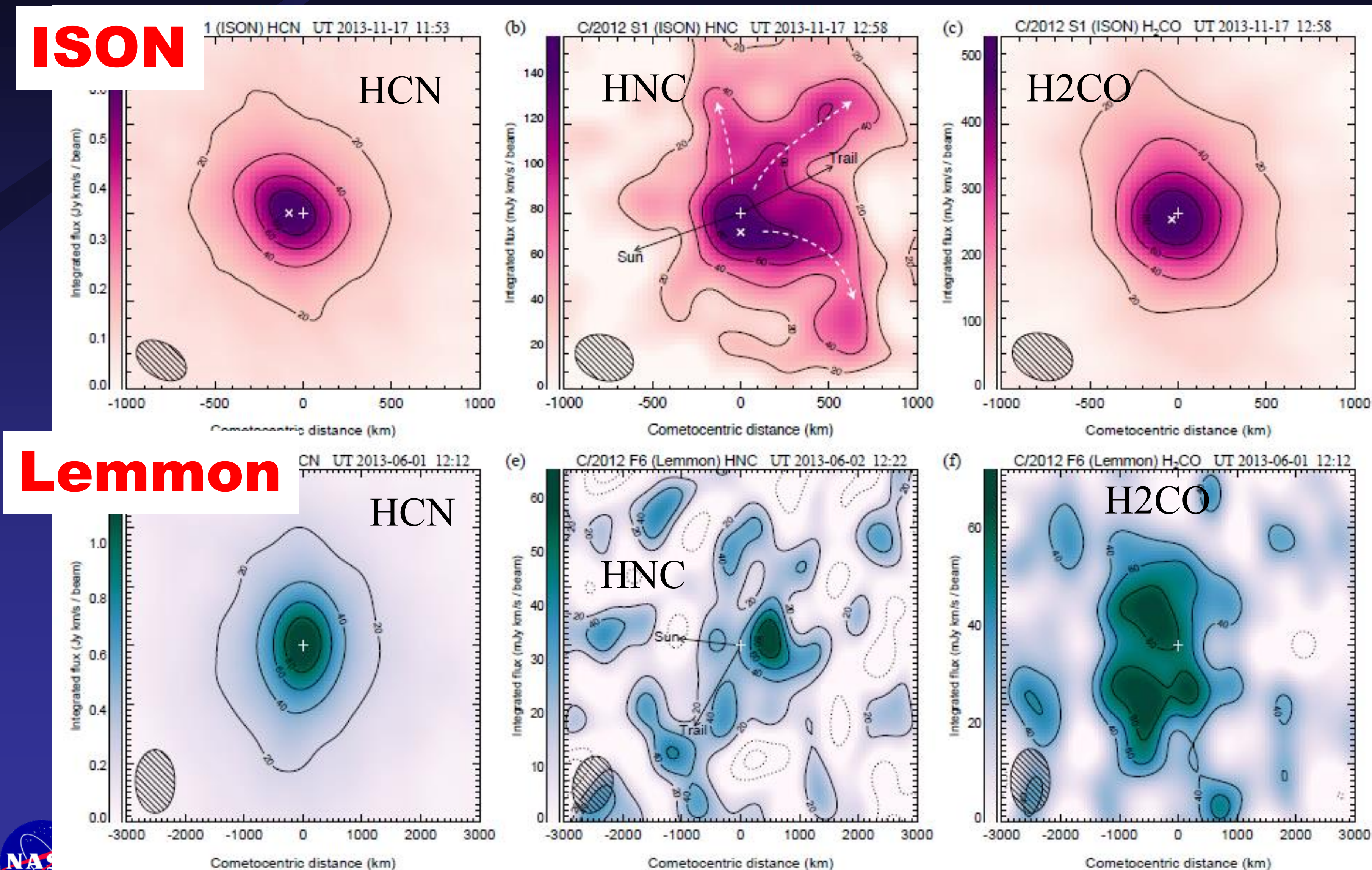




Remijan 2003
Milam+2006

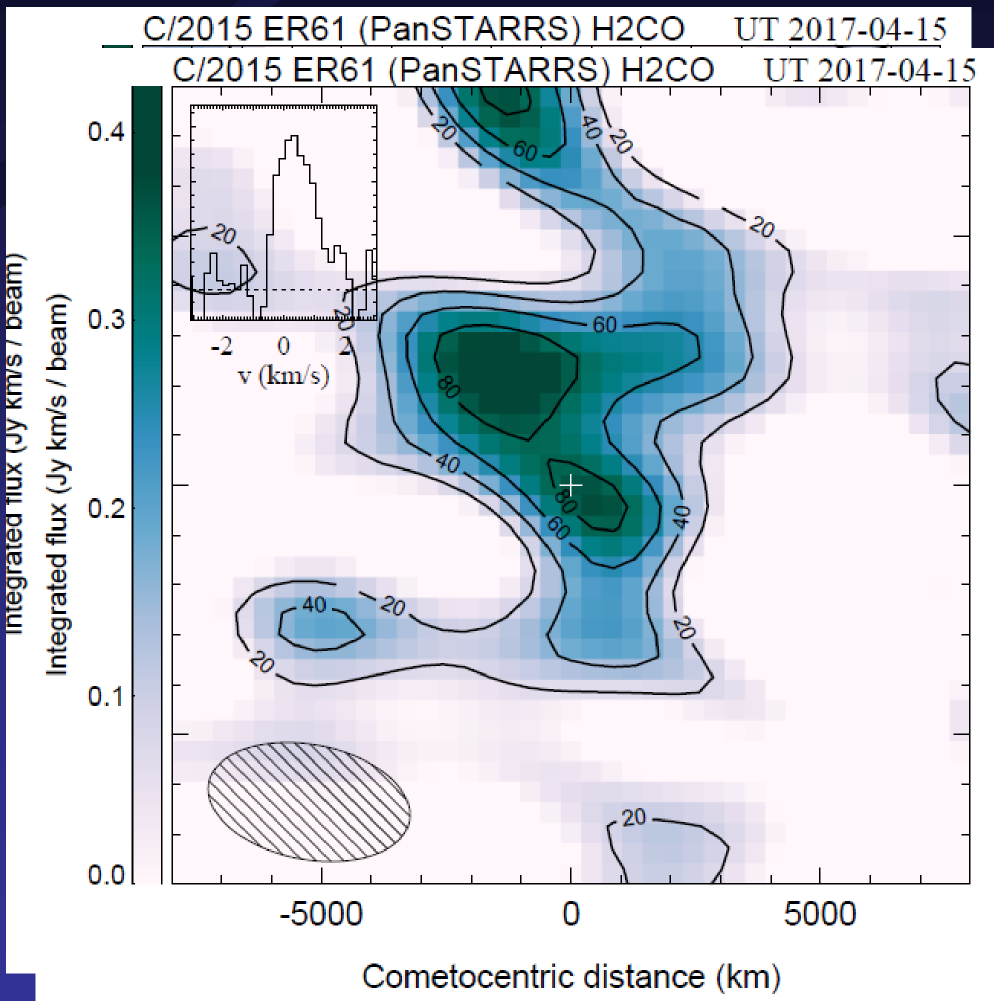
Cordiner et al. 2014

Molecular Origins?



Cordiner et al. 2014

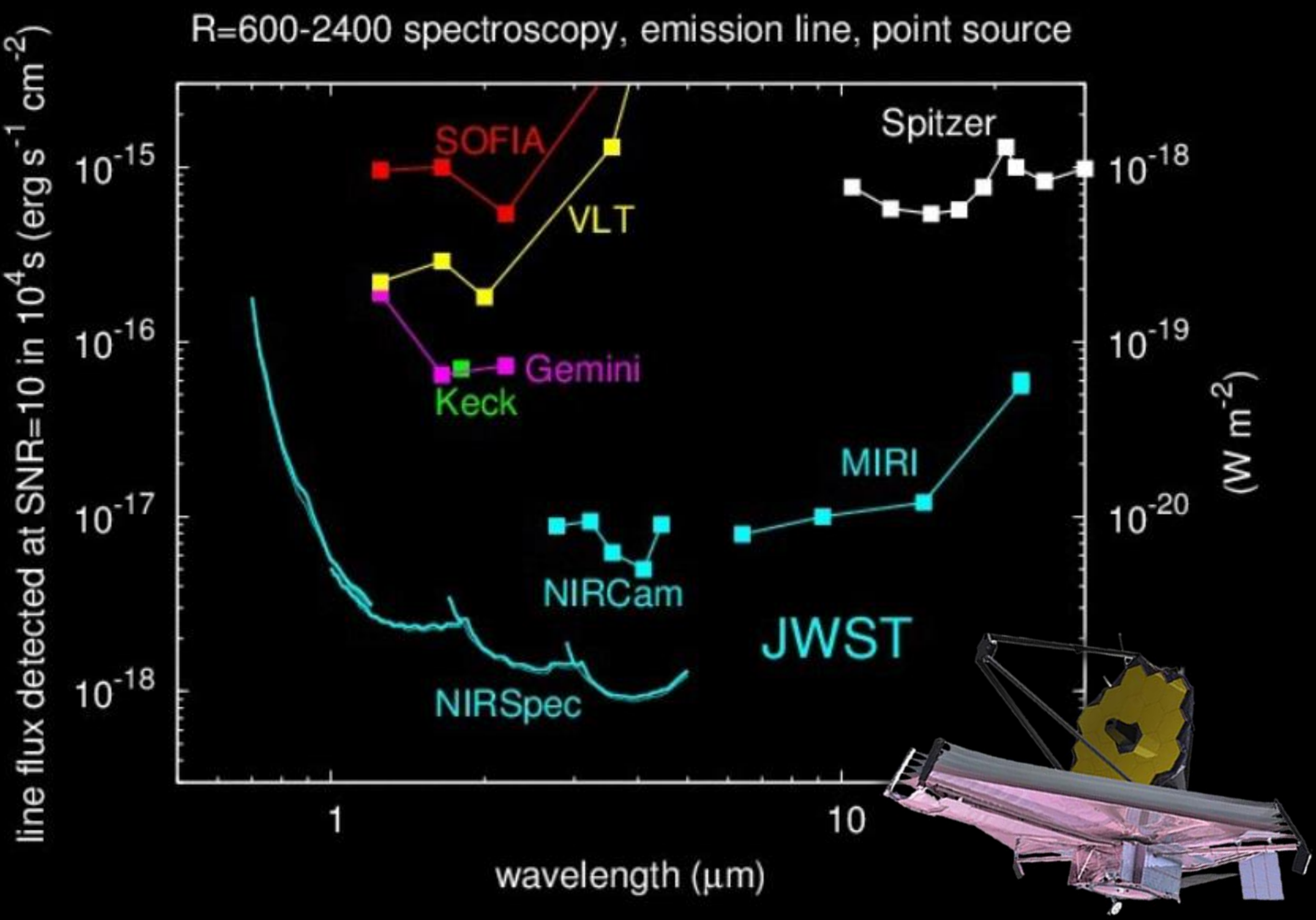
More comets with ALMA



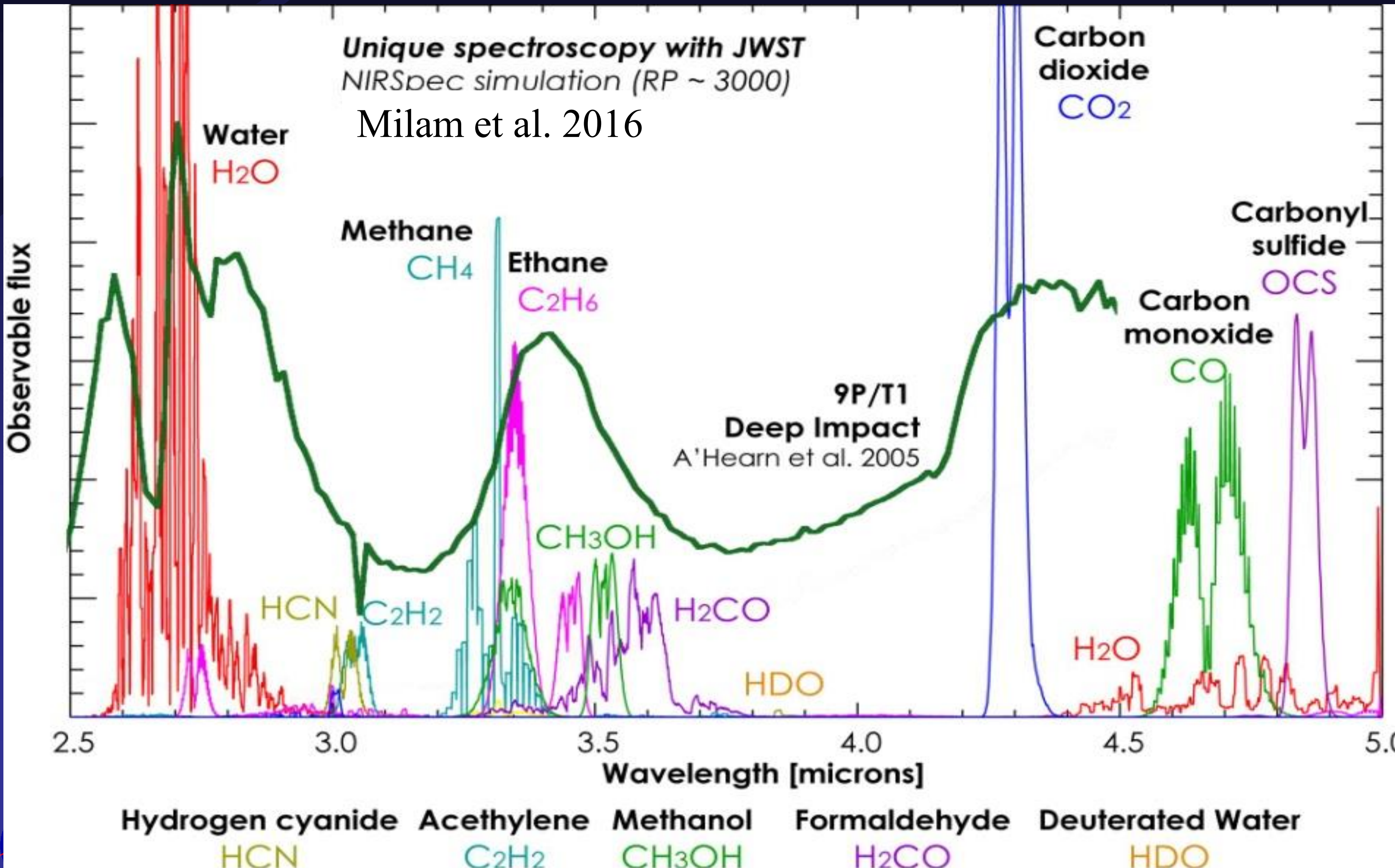
- Comet ER61
- ACA observations – later followed up with 12m array.
- Still see distributed source in H2CO.

Milam, Cordiner ++ , in prep.

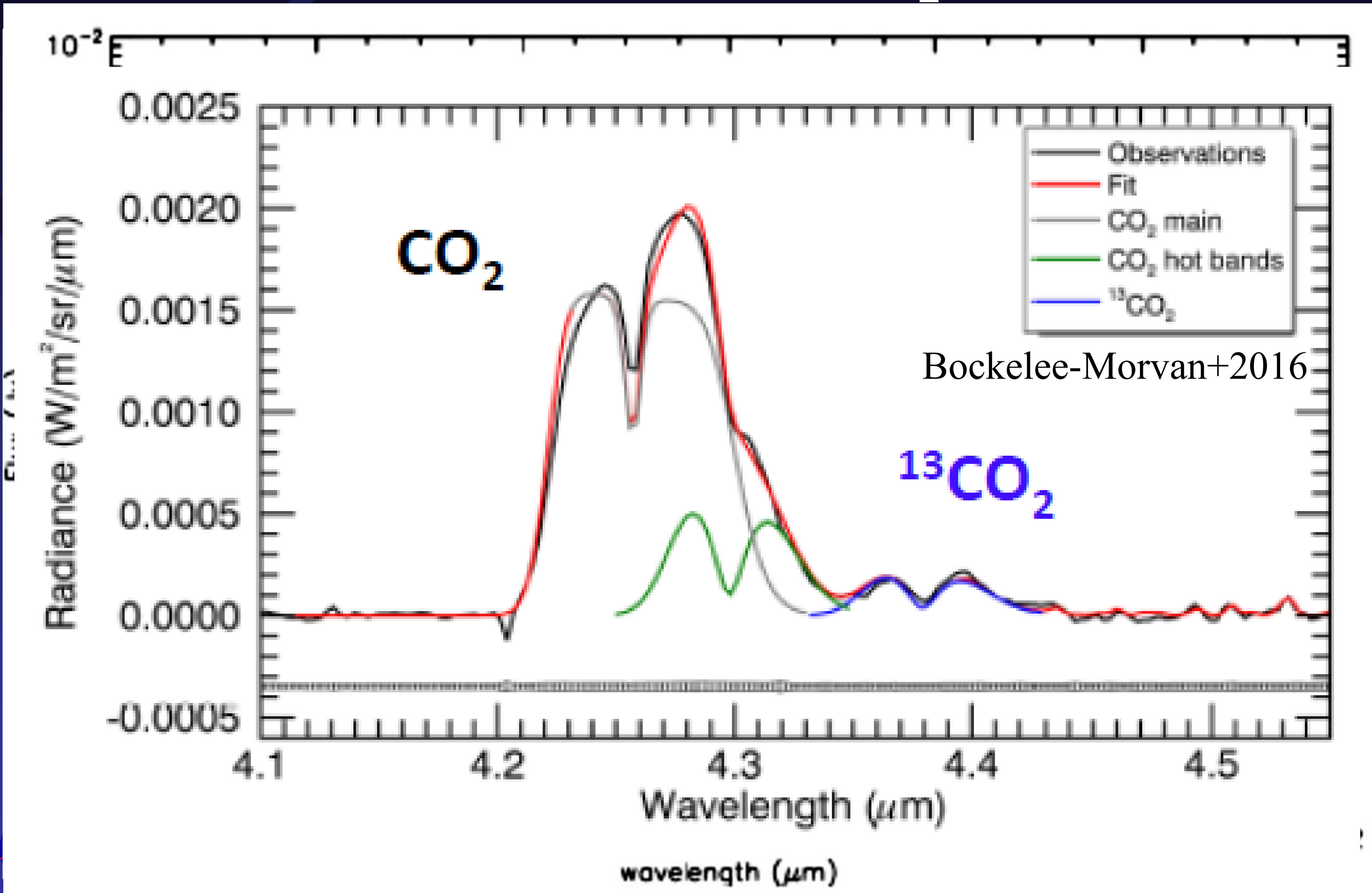
JWST Sensitivity



Simulated Comet Spectra

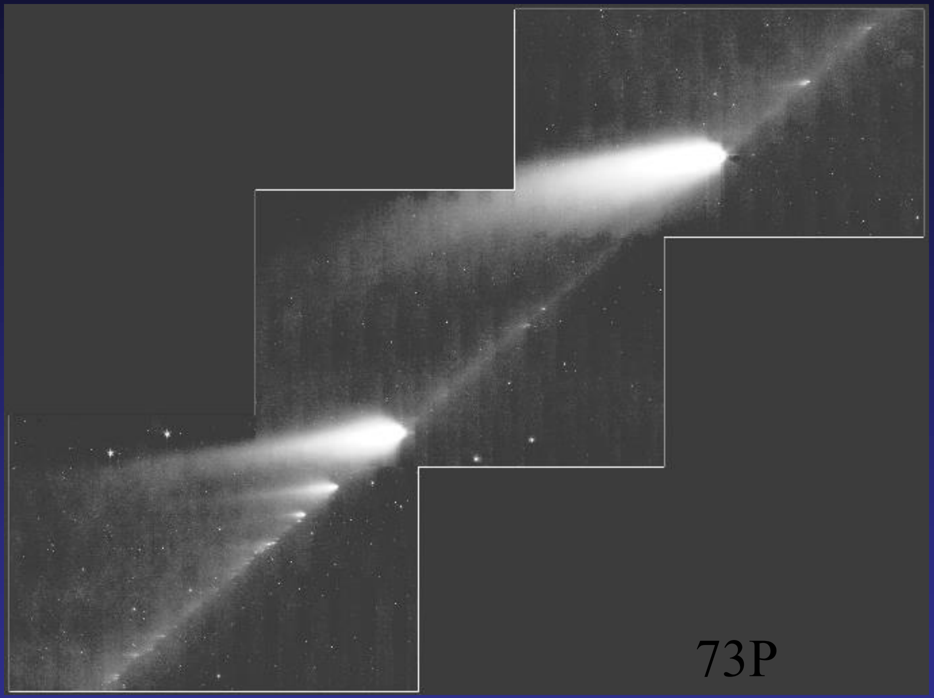


Simulated Comet Spectra

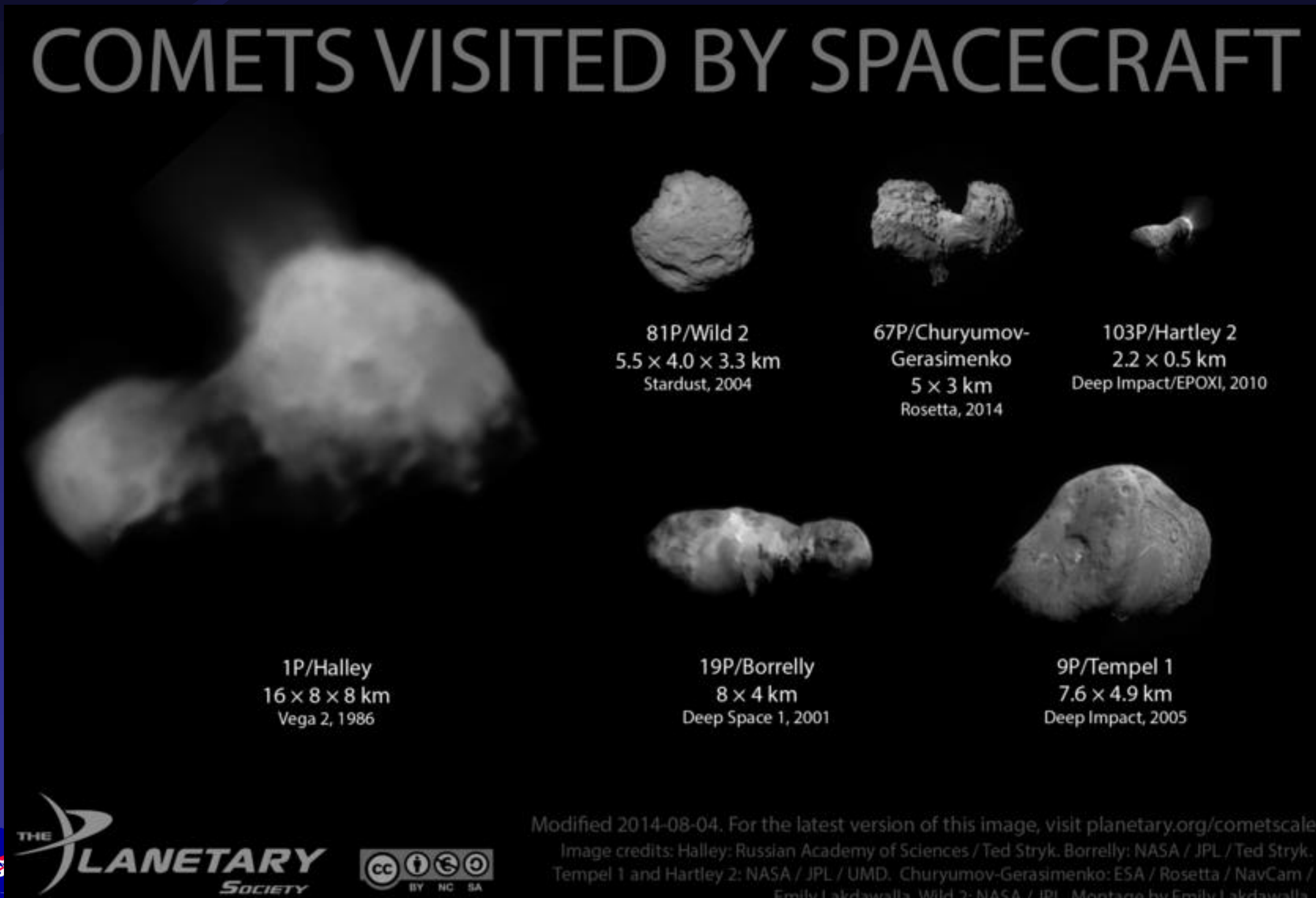


Cometary Impact on "Biomolecules"

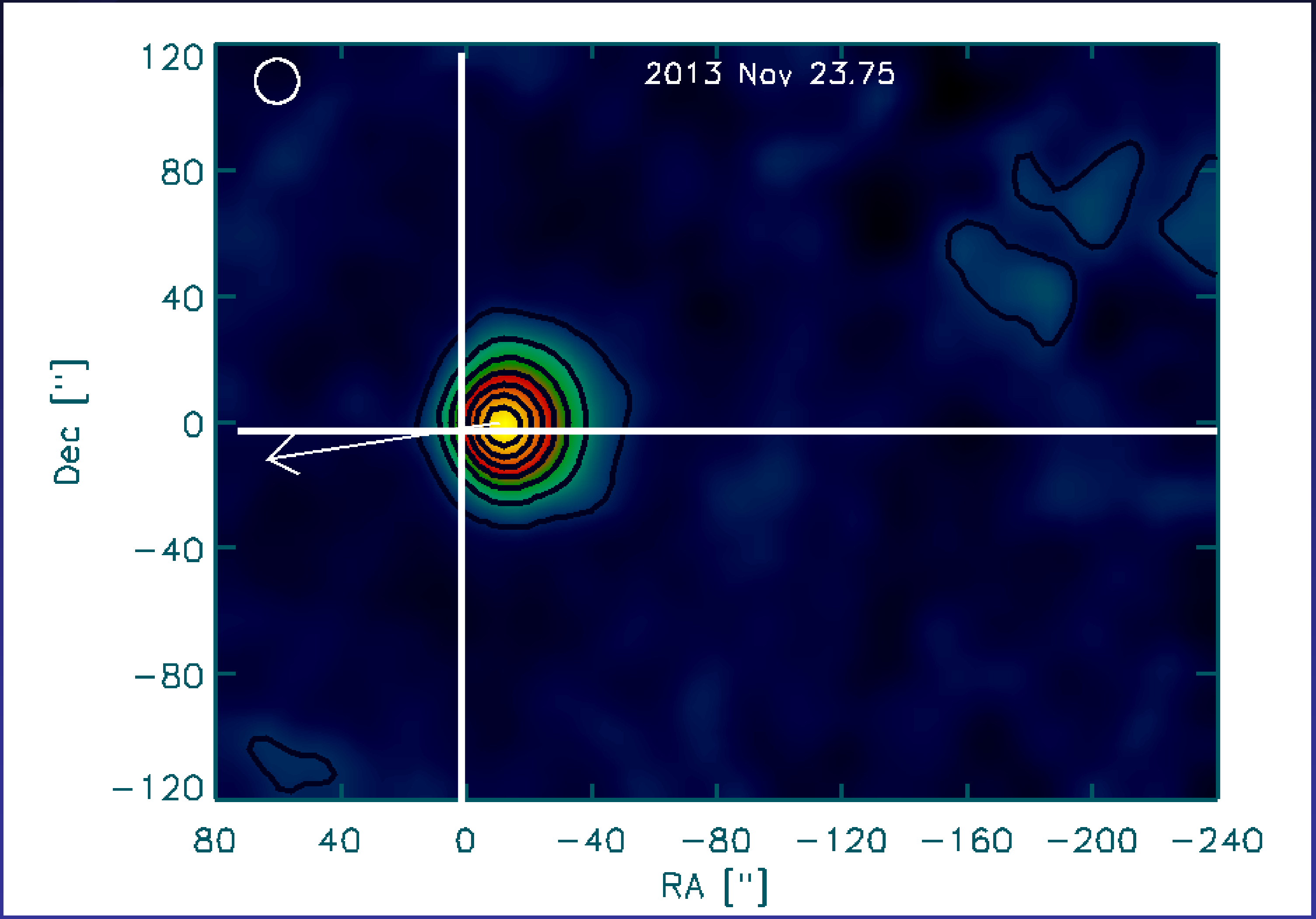
- Comets are typically aggregates of smaller bodies.
- Dissociation of the parent body has been observed in multiple targets.
- Fragmentation
- Distributed source?



Cometary Impact on "Biomolecules"

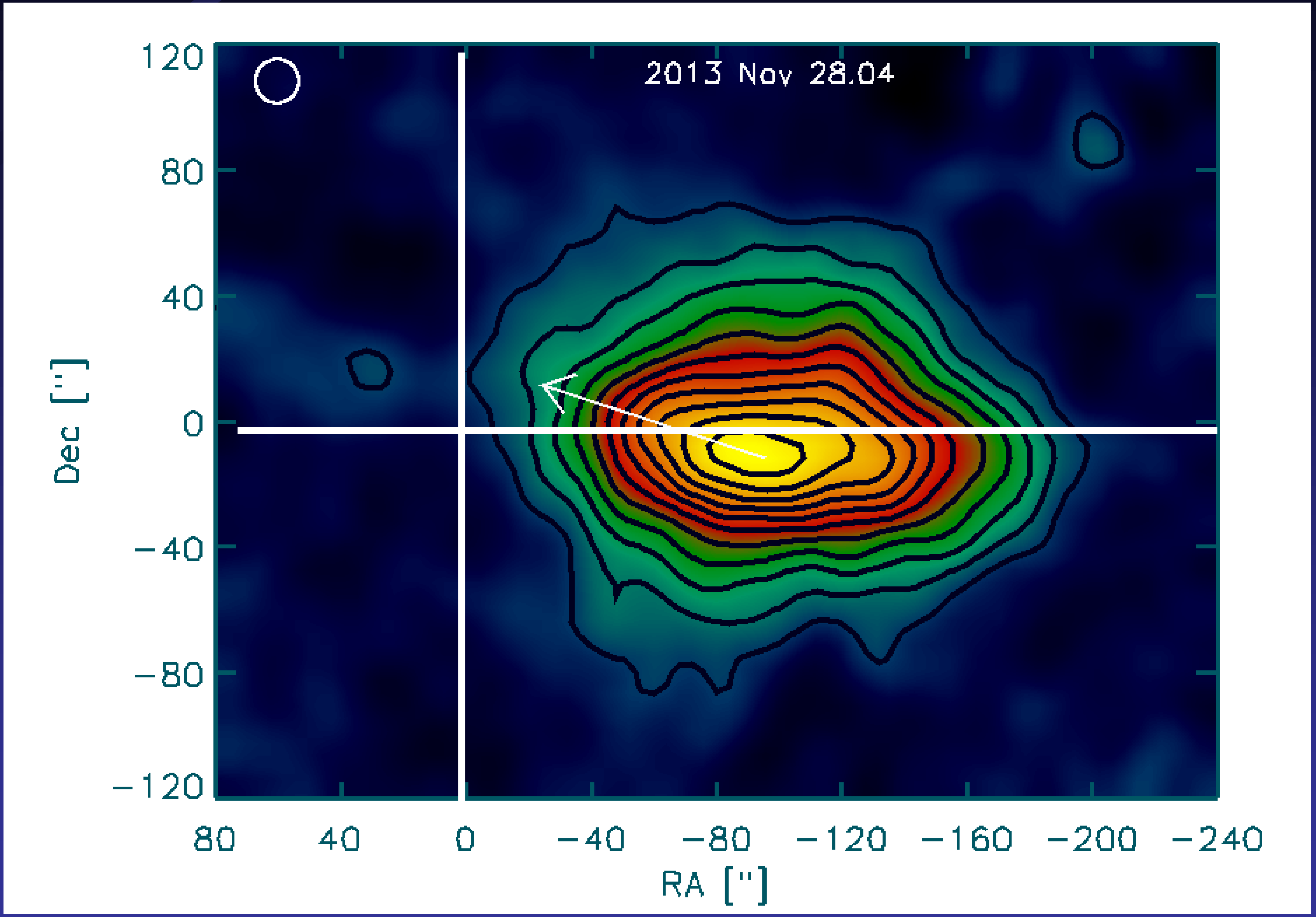


Comet ISON
JCMT Scuba2 850 um images



Keane++2017

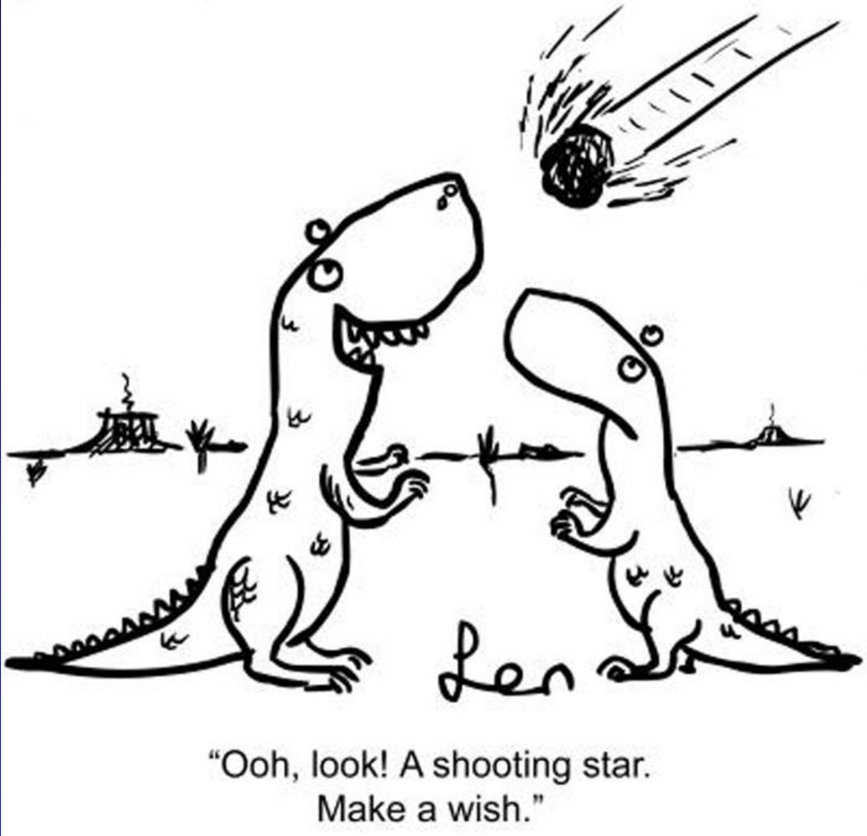
JCMT Scuba2 850 um images



Keane++2017

Summary

- Sample return and direct missions are limited (biased?).
  - Necessary for ground-truth.
- Remote observations give us population studies.
- Broadband surveys are key for detection of less abundant species.
- Interferometers are key for probing distribution.
- Future missions with access to key species for surveys (D/H).
  - SPICA, OST



ORIGINS Space Telescope

Me, Myself, and I, and Collaborators

Martin Cordiner[1,2], *Anthony Remijan*[3], *Jeremie Boissier*[5], *Nicolas Biver*[4], Steven Charnley[1], Pierre Colom[4], Jacques Crovisier[4], Michael Mumma[1], Dominique Bockelee-Morvan[4], Geronimo Villanueva[1,2], Lucas Paganini[1,2], Dariusz Lis[6], Yi-Jehng Kuan[7], *Iain Coulson*[8], *Jacqueline Keane*[9], Karen Meech[9]

[1]NASA GSFC, [2]Catholic University of America, [3]NRAO, [4]Observatoire de Paris-Meudon, [5]IRAM, [6]LERMA, Observatoire de Paris and Caltech, [7]ASIAA, [8]Joint Astronomy Center, [9]University of Hawai'i

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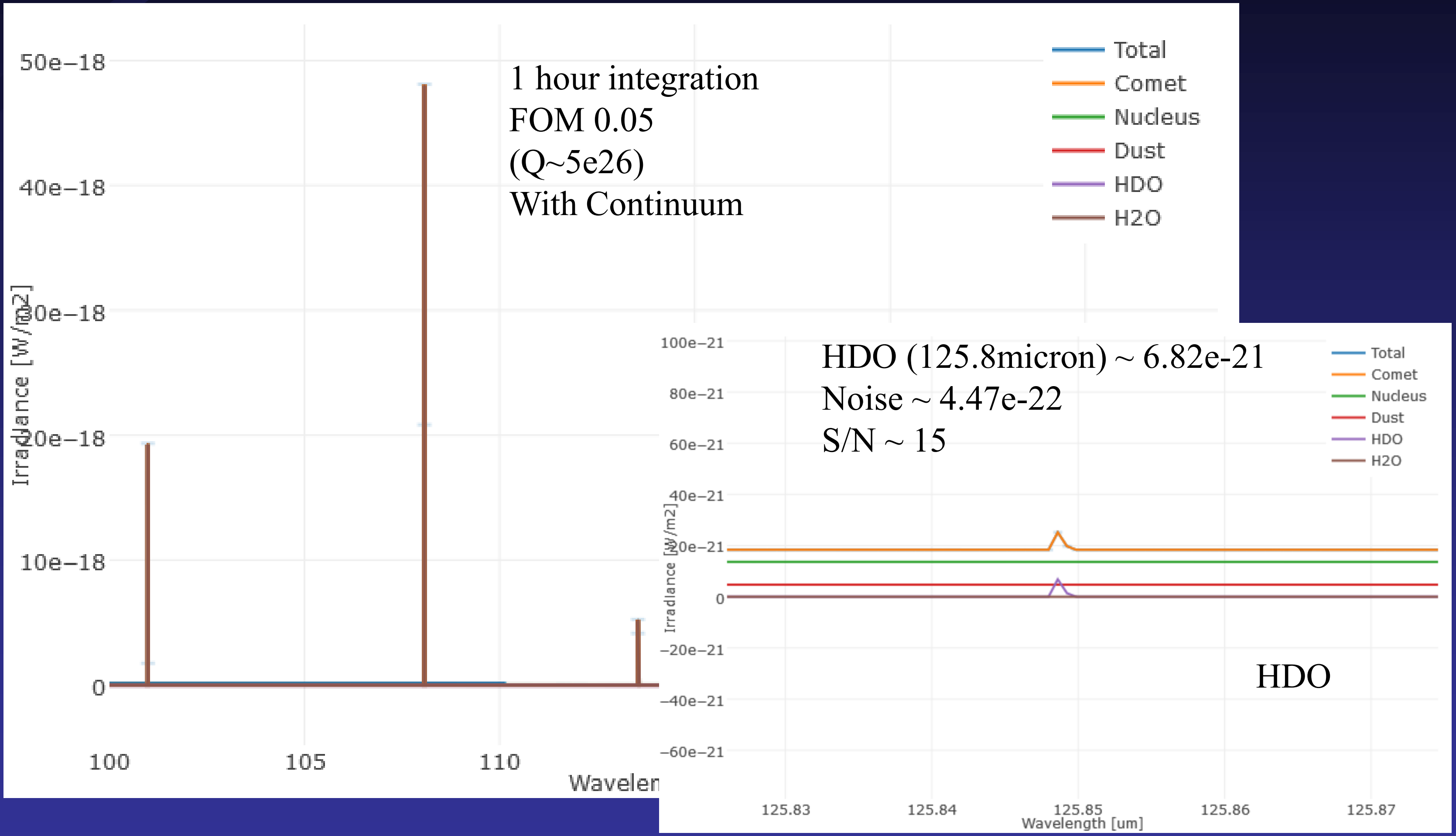
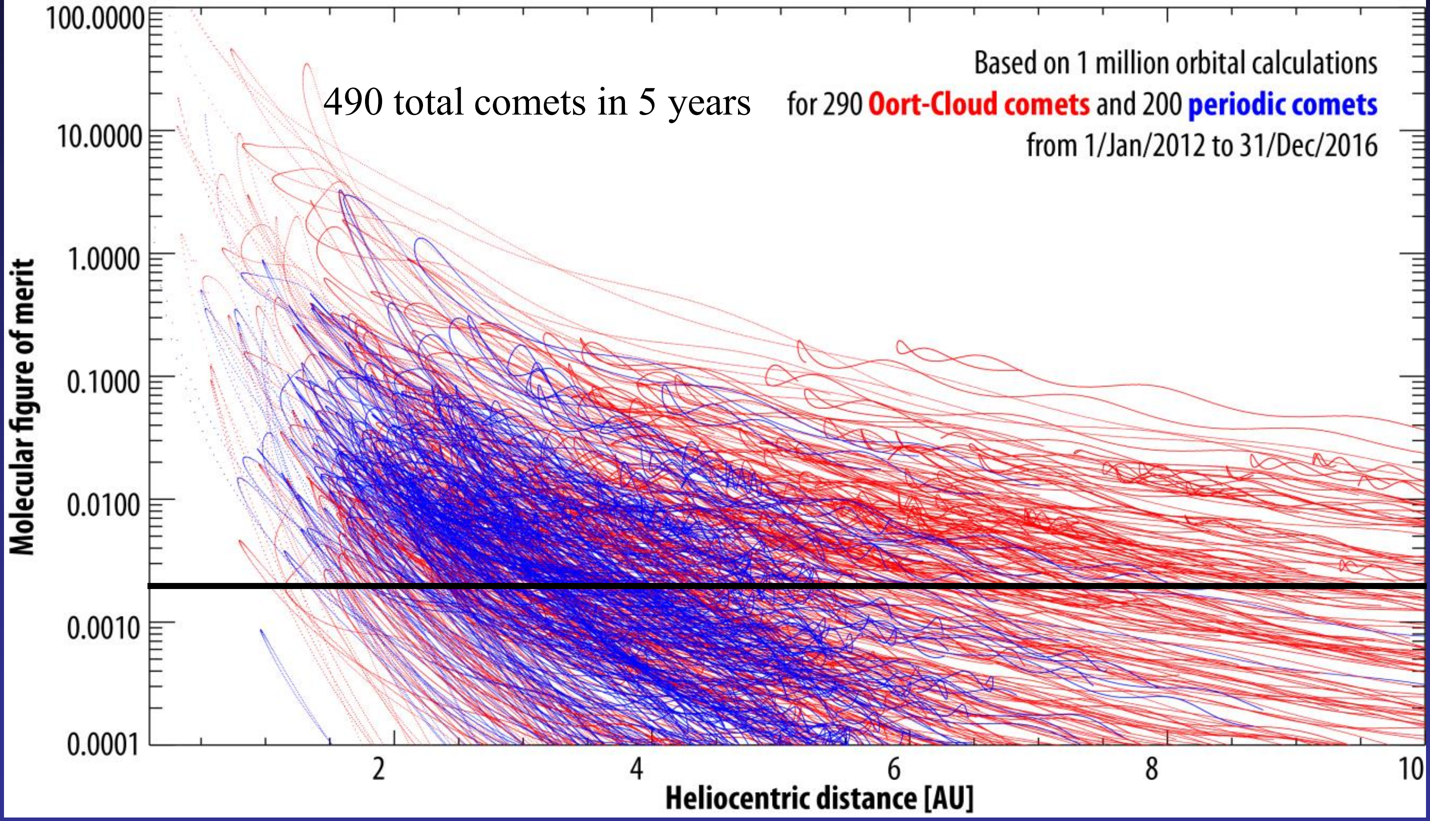
OST simulation



OST can survey ~100 comets in D/H



PSG 5 sigma l