Tracing the Gas Composition of Titan's Atmosphere with Herschel : Advances and Discoveries

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Moreno R., Courtin R., Lellouch E., Sagawa H.; Hartogh P., Swinyard B., Lara M., Feuchtgruber H., Jarchow C. , Fulton T., Cernicharo J., Bockelée-Morvan D., Banaszkiewicz M., González A.

The Universe explored by Herschel– Noordwijk, 15-18 October 2013

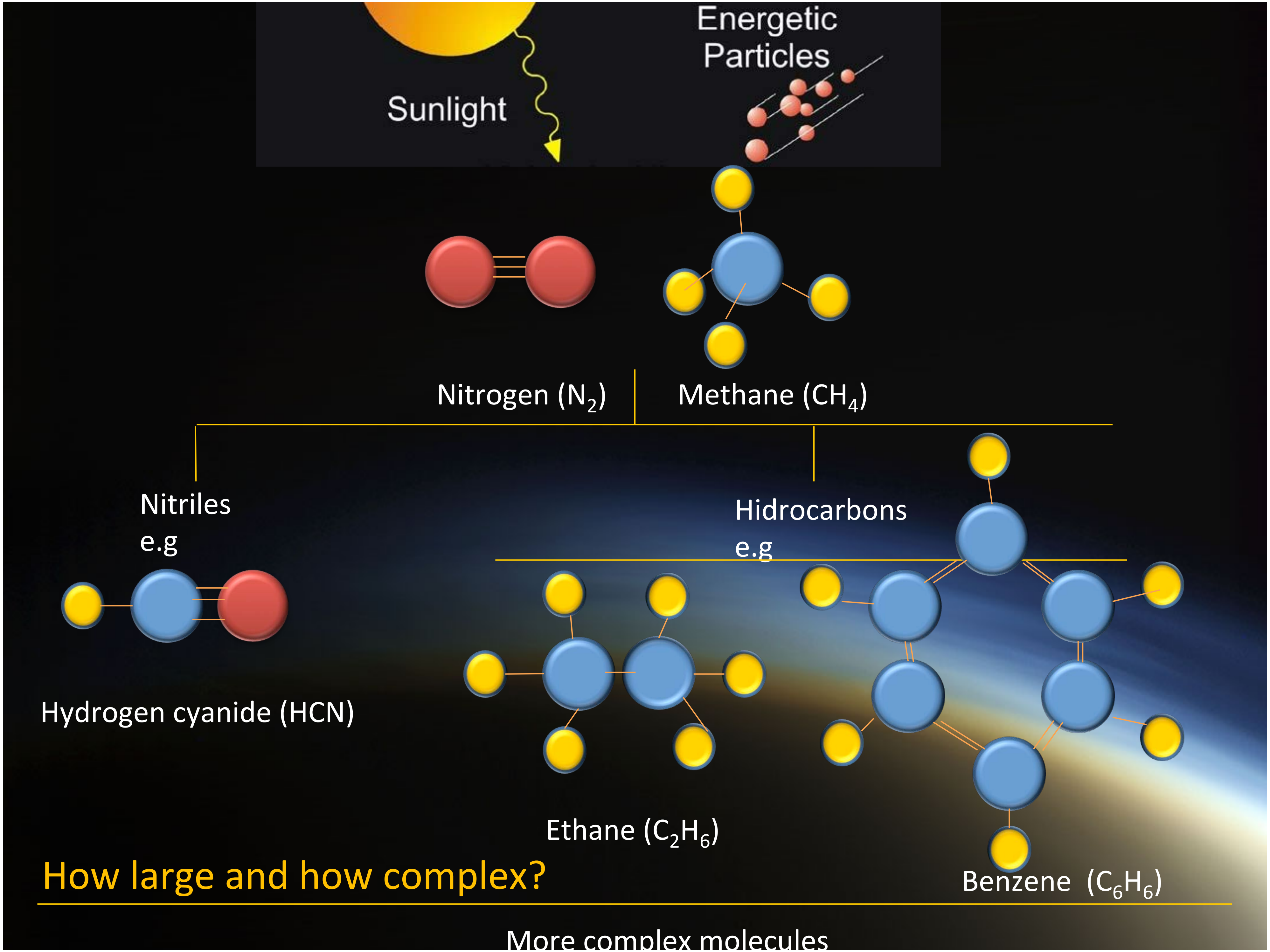
Telescope lens used by Huygens in 1655
Utrecht University Museum

1. Introduction

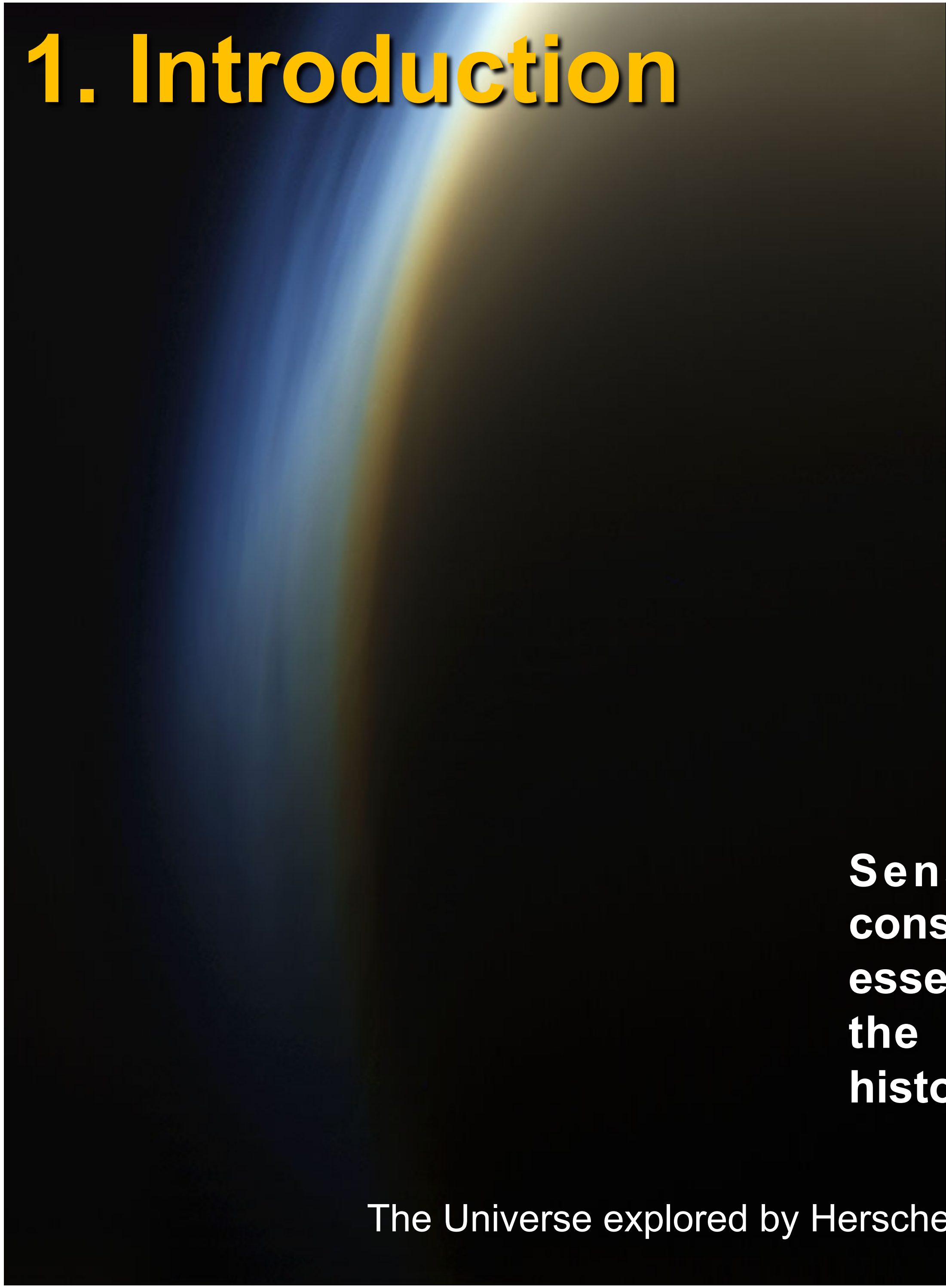
Why Titan?

Titan is covered by a dense atmosphere, which is complex and diverse!

- The origin of Titan's atmosphere is poorly understood and its chemistry is complicated


Energetic Particles
Sunlight
Nitrogen (N_2)
Methane (CH_4)
Nitriles e.g
Hidrocarbons e.g
Hydrogen cyanide (HCN)
Ethane (C_2H_6)
Benzene (C_6H_6)
How large and how complex?
More complex molecules

1. Introduction

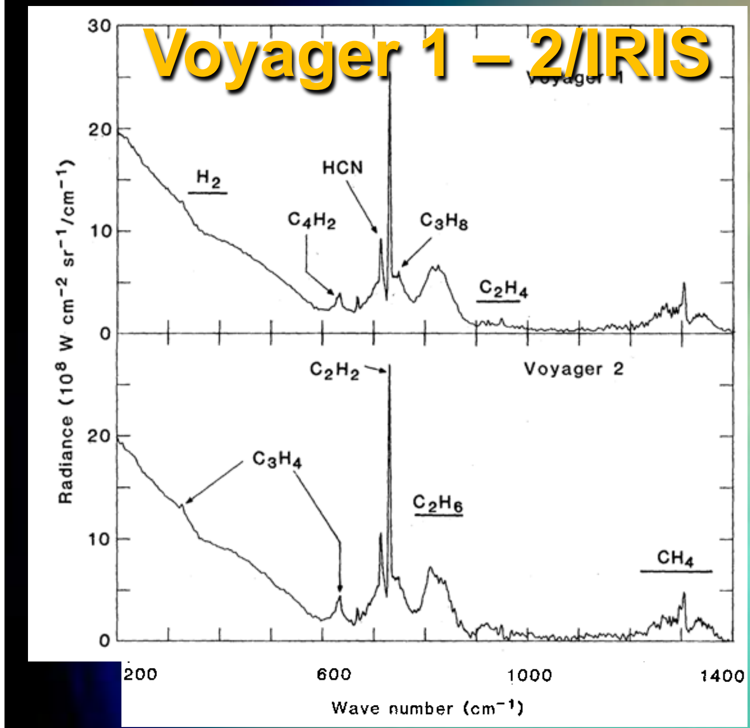


Why Titan?

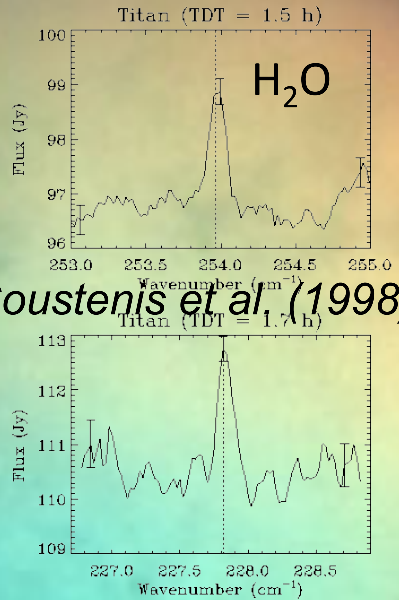
Sensitive observations of the constituents of the atmosphere are essential to constructing models of the Titans´s atmosphere and its history.

1. Introduction

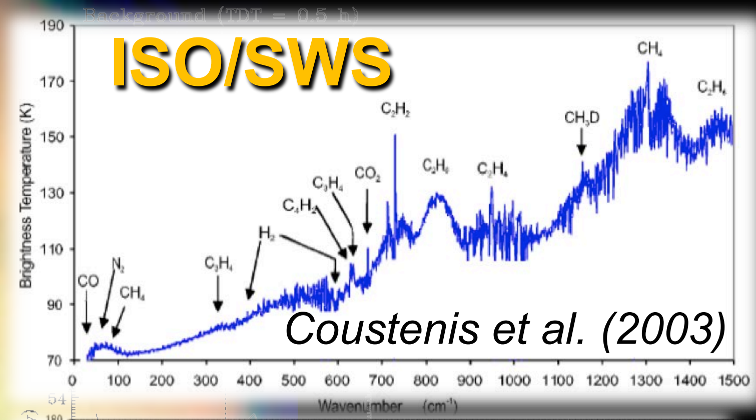
Spectroscopy of Titan has been already performed by:



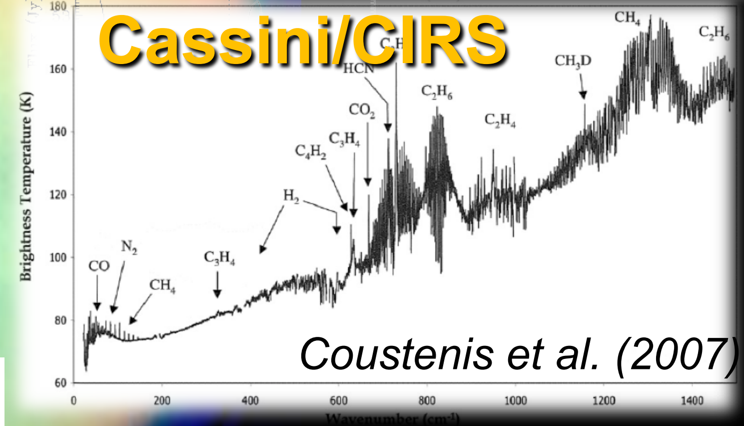
Hanel et al., Science, v 215, 1982



Coustenis et al. (1998)

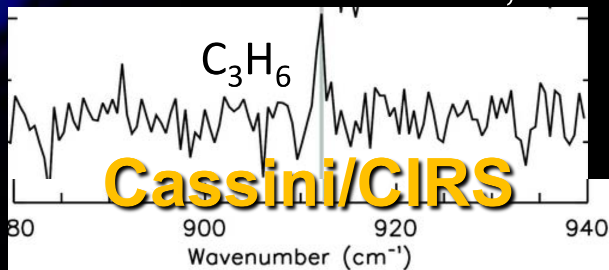


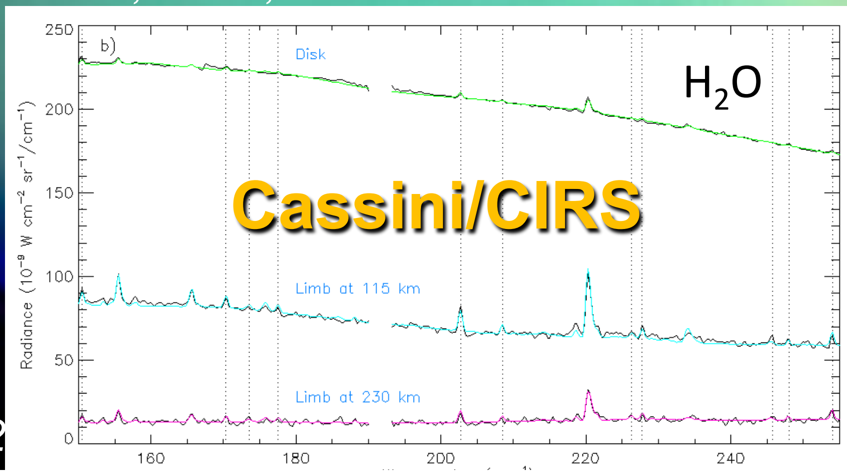
Coustenis et al. (2003)



Coustenis et al. (2007)

Nixon et al., 2013



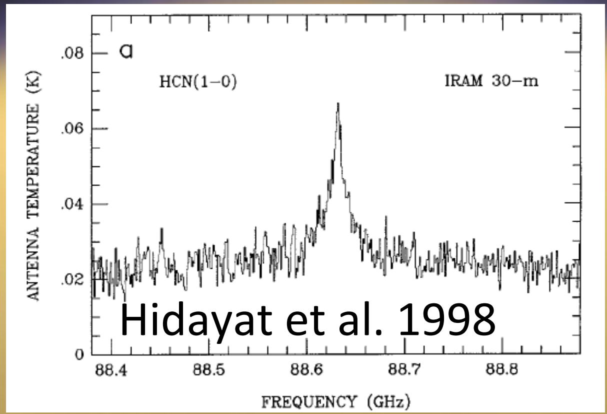


Cottini et al., 2012

Ground-based observations have also improved our knowledge of Titan's atmospheric composition:

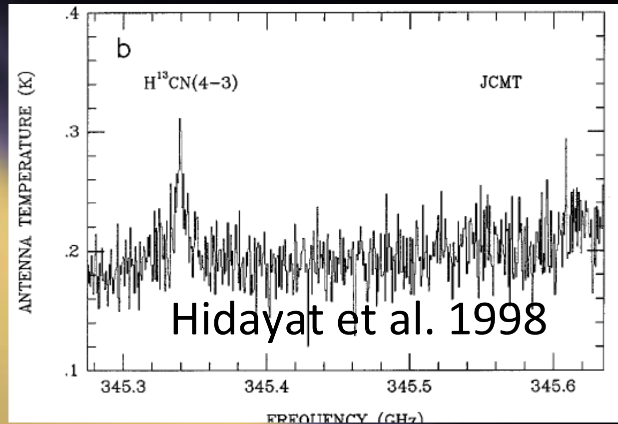
IRAM 30-m:

Marten et al. 2002



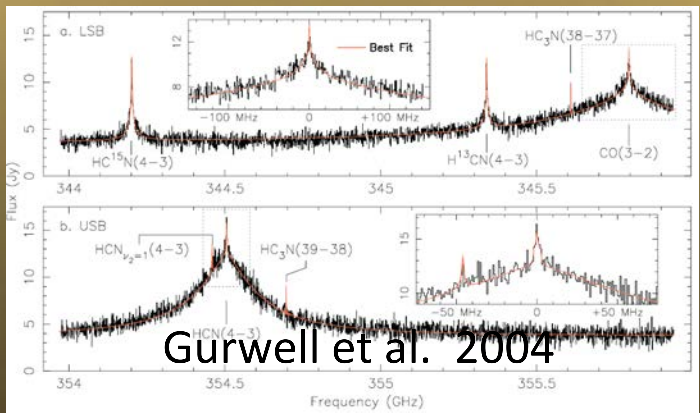
Hidayat et al. 1998

JCMT:



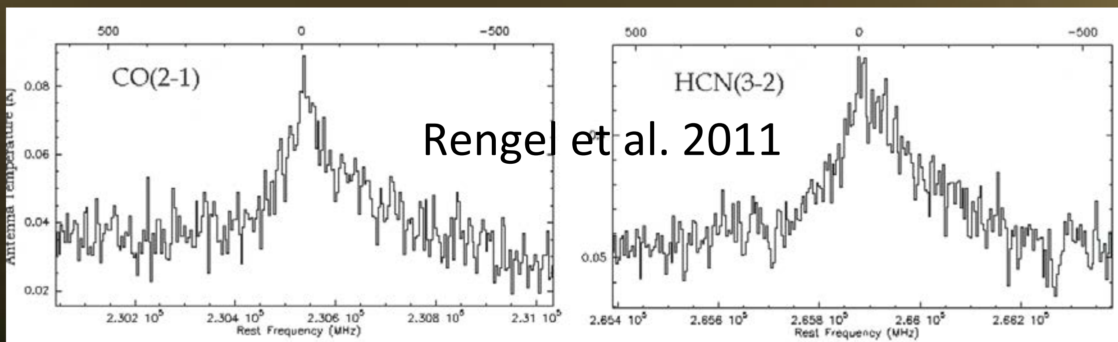
Hidayat et al. 1998

SMA:



Gurwell et al. 2004

APEX:



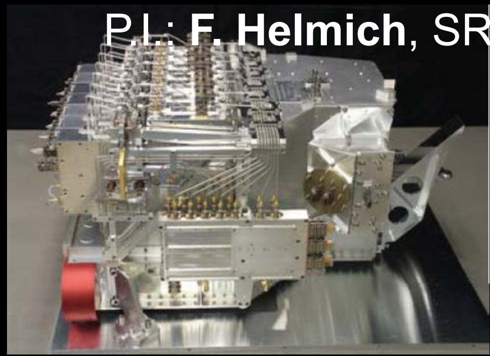
Rengel et al. 2011

Herschel Era

Credits: ESA

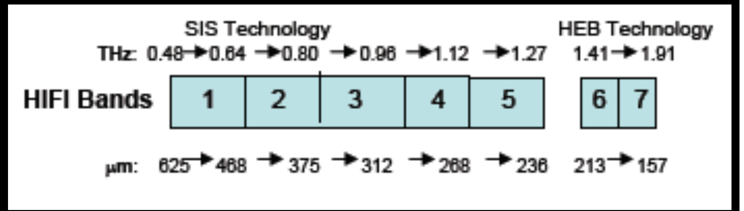
Instruments onboard Herschel:

Heterodyne **I**nstrument for the **F**ar-**I**nfrared (**HIFI**).

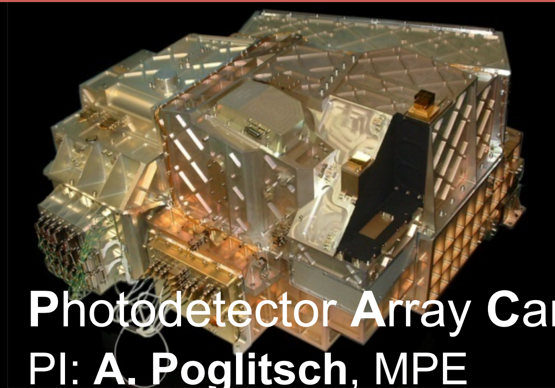


P.I.: **F. Helmich**, SRON

Resolutions: 140, 280, 560 kHz, 1.1 MHz



480 – 1150 GHz 1410-1910 GHz



3 bands in total:

55-72 μm, 72-102 μm and 102-210 μm

Photodetector **A**rray **C**amera and **S**pectrometer (**PACS**).

PI: **A. Poglitsch**, MPE

55 – 210 μm

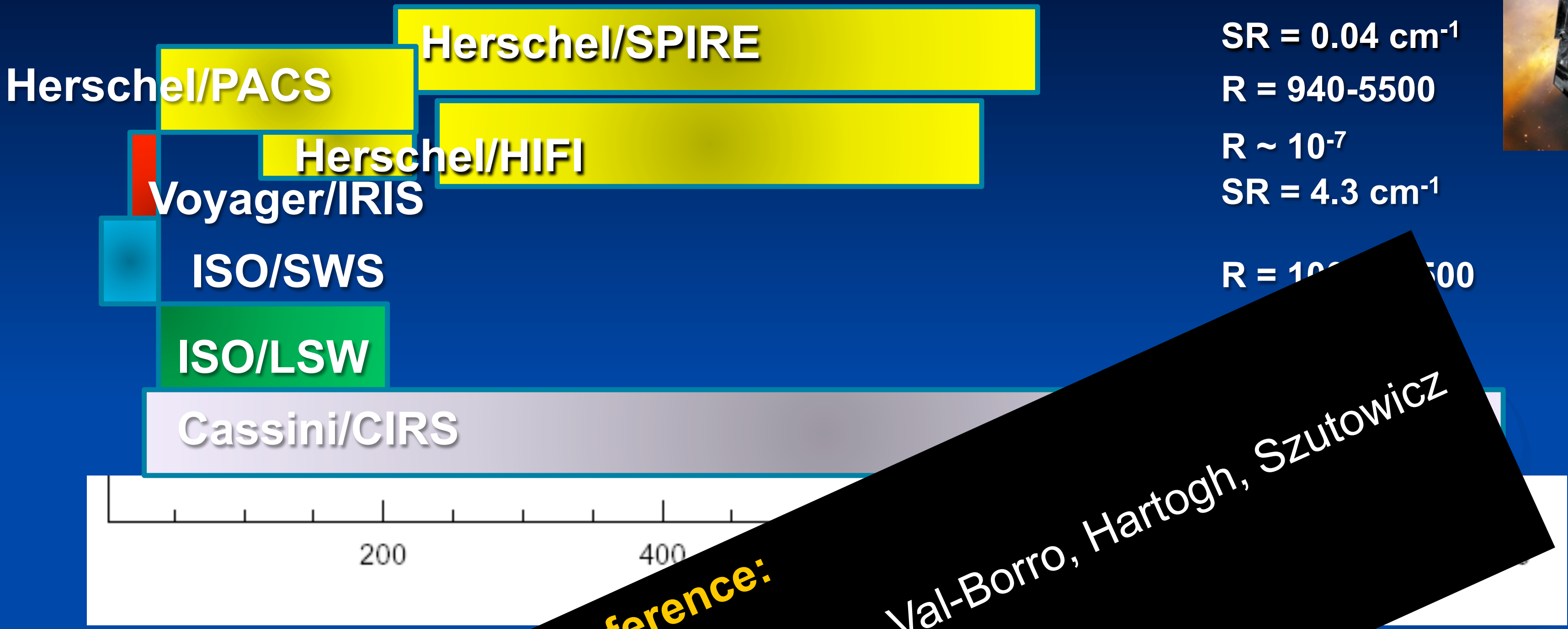
Spectral and **P**hotometric **I**maging **Re**ceiver (**SPIRE**).

PI: **M. Griffin**, Cardiff University

Photometer: 250, 350, 500 μm

Spectrometer: 194- 672 μm.

Titan´s Spectroscopy in the Herschel Era



SR = 0.04 cm^{-1}

R = 940-5500

R ~ 10^{-7}

SR = 4.3 cm^{-1}

R = 10… …500

HssO contributions at this conference:

Talks by Hartogh, Lellouch, Rengel

Posters: Biver, Bockelee-Morvan, Cavalié, de Val-Borro, Hartogh, Szutowicz

HssO web site:

http://www.mps.mpg.de/projects/herschel/HssO/index.htm

In the framewor… …hemistry in the Solar System" (Hs… …d **submm range with high sensi…**

•F… …us rotational transitions of **water** and other t…

•Th… stronger than those accesible from Earth

•HIFI… …IRE higher spectral resolution and sensitivity than previous instrum…ts

Titan´s Observations performed with Herschel

SPIRE: Full range spectrum (194 - 671 μm or 15-50 cm^{-1}) – July 2010, ~8.9h, SR= 0.04 cm-1

PACS: Full range spectra (51-220 μm or 50-180 cm^{-1}) (twice, 0.63h and 1.1h), R= 1000-5000

Dedicated line scans H_2O lines (at 108, 75.4 and 66.4 μm in June 2010, Dec 2010 and July 2011) and CH_4. SR= 0.02, 0.04 and 1.11 μm. ~0.3h

HIFI spectrally-resolved observation of H_2O at 557 GHz (18 cm^{-1} or 538 μm) and at 1097.4 GHz (273 μm) in June 2010, Dec 2010 and June 2011, ~4h each time. SR ~10^6

- All Titan observations are disk-averaged and have to be performed near maximum elongation

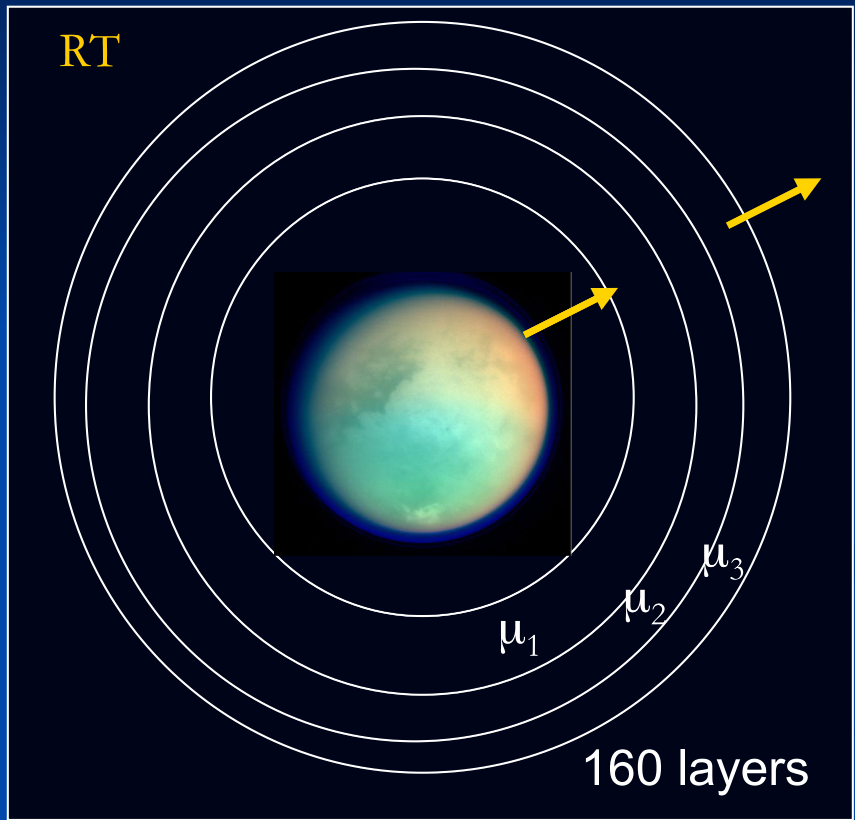
Modeling the Titan spectra
Method

Input parameters → Abundance profiles → Radiative Transfer → Synthetic Spectra → Comparison with data

T profile →

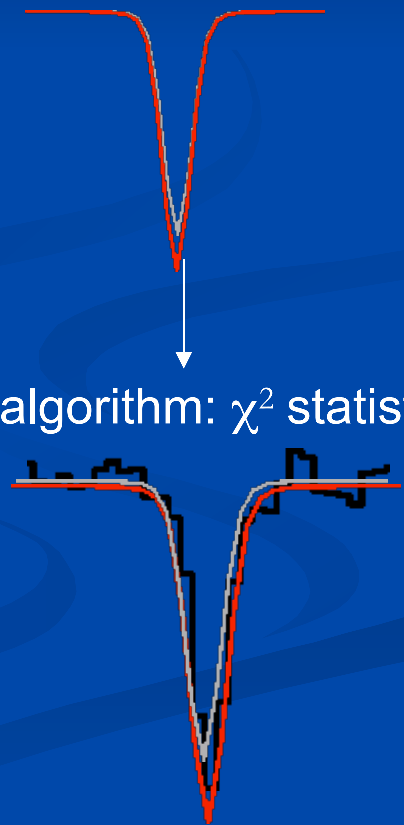
P profile →

Vmr profile →



μ_i=absorption coefficient

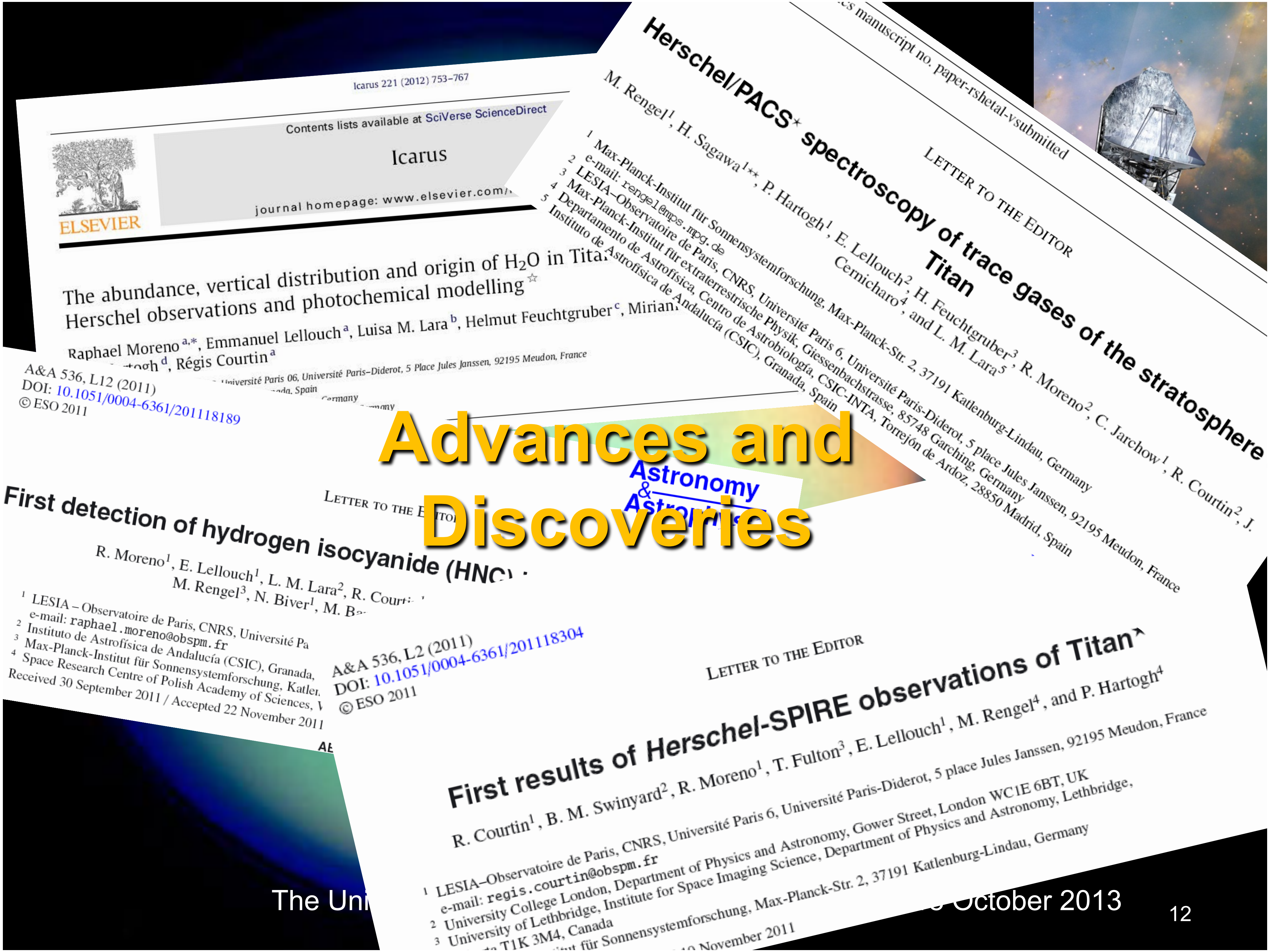
→ Synthetic spectra



Fitting algorithm: χ^2 statistics

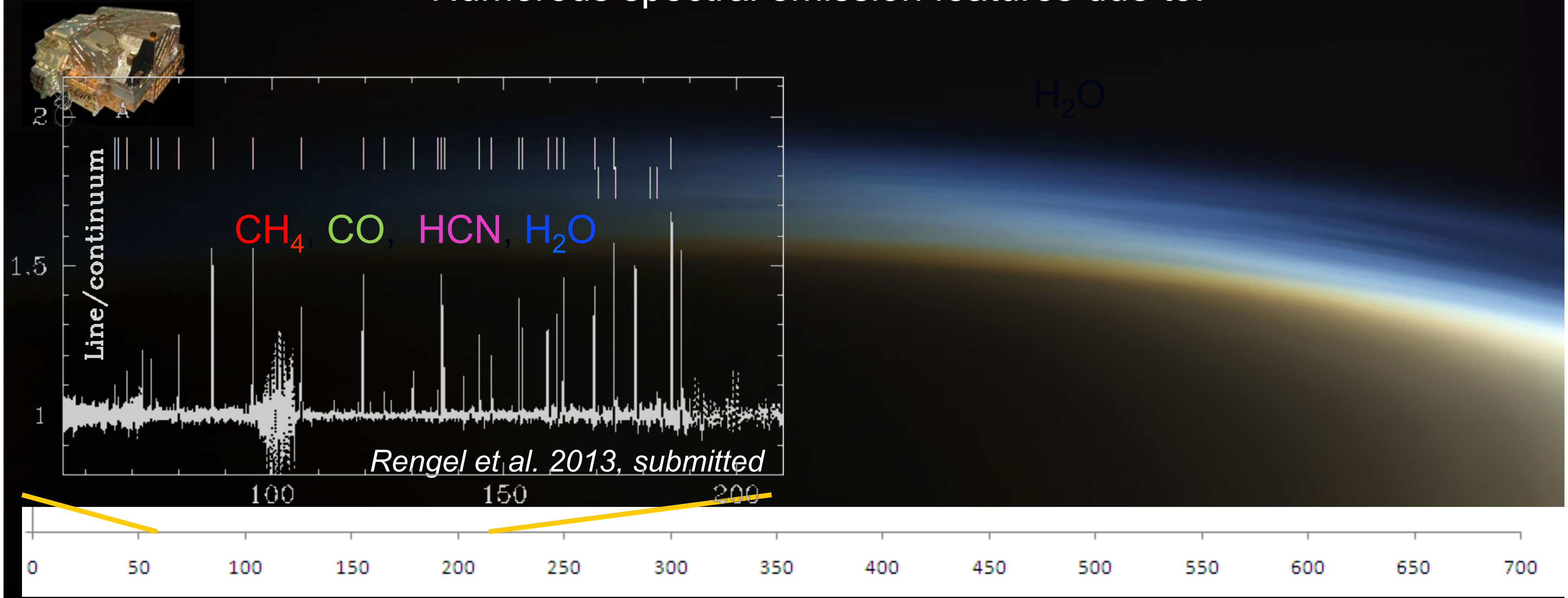
New set of parameters ←

Advances and Discoveries



1.- Molecular Inventory with Herschel /PACS, SPIRE, and HIFI

Numerous spectral emission features due to:



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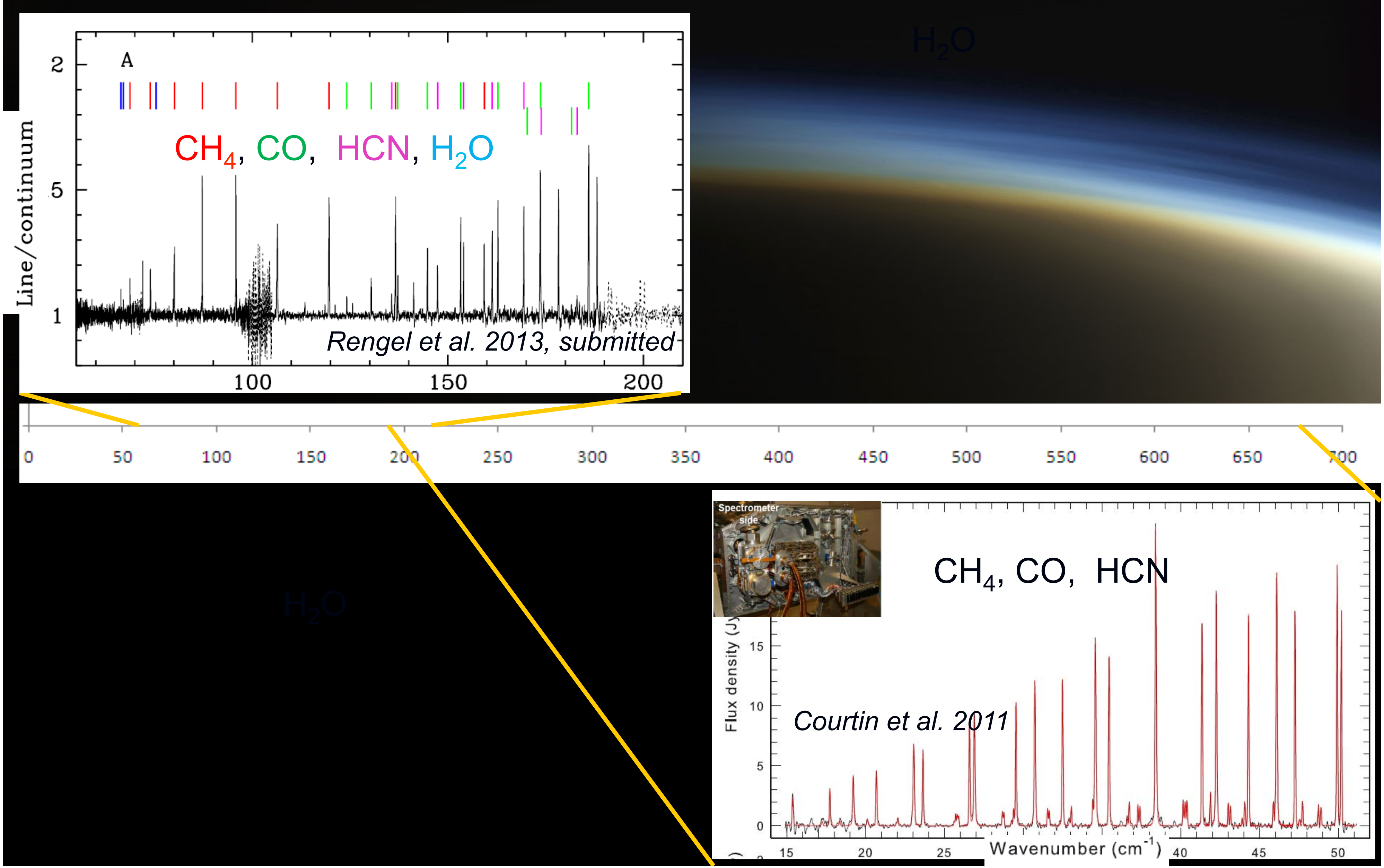

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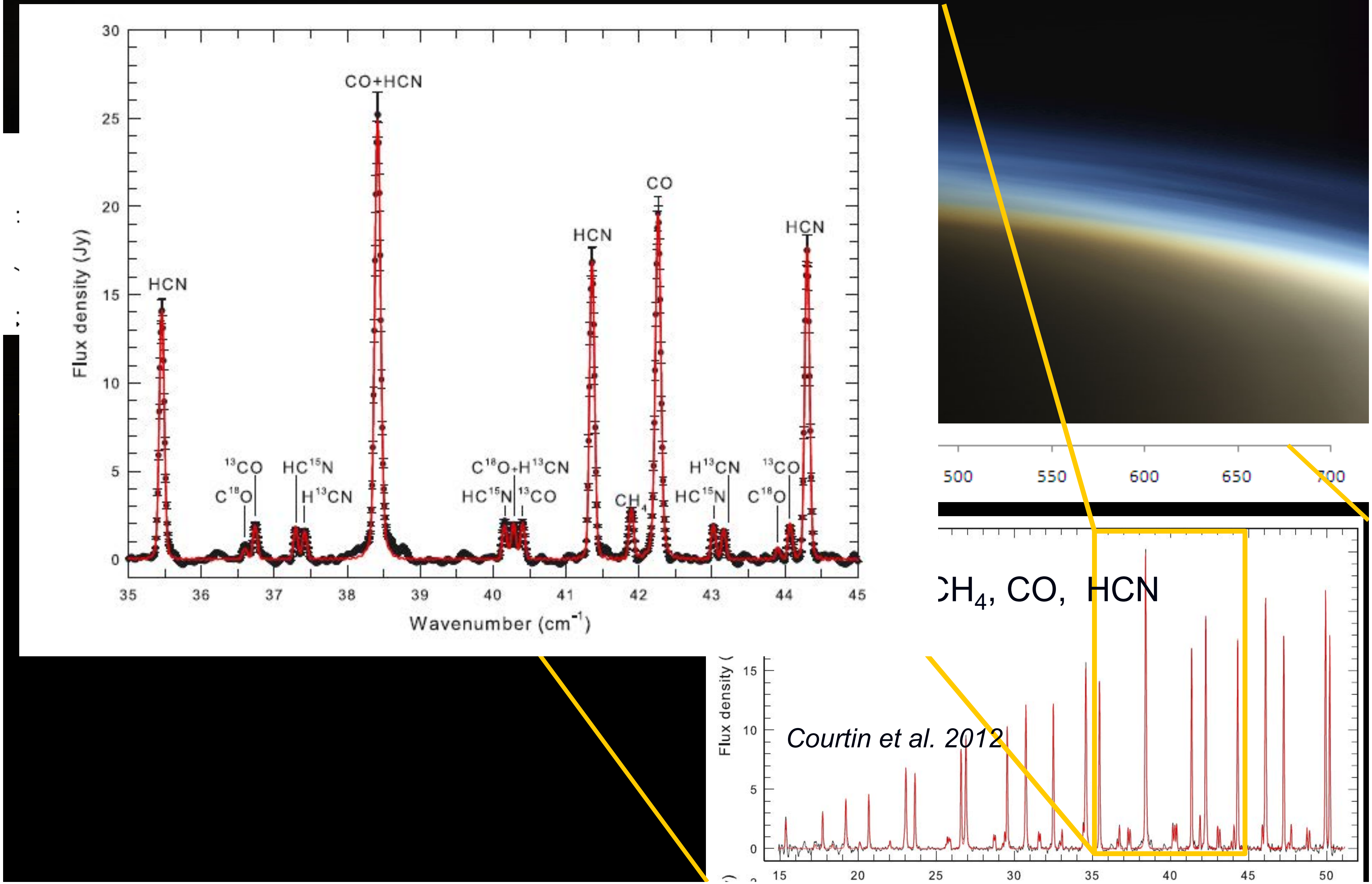

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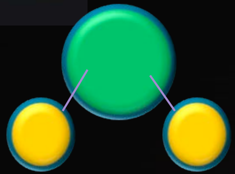
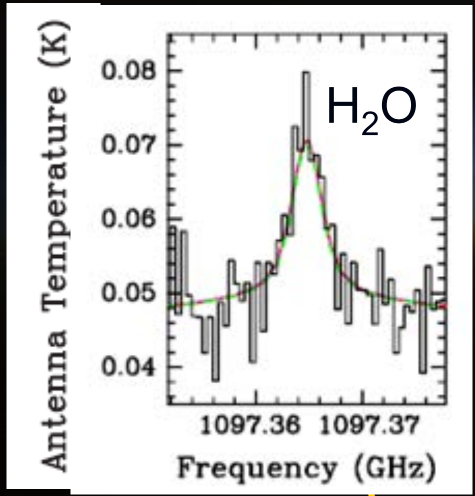
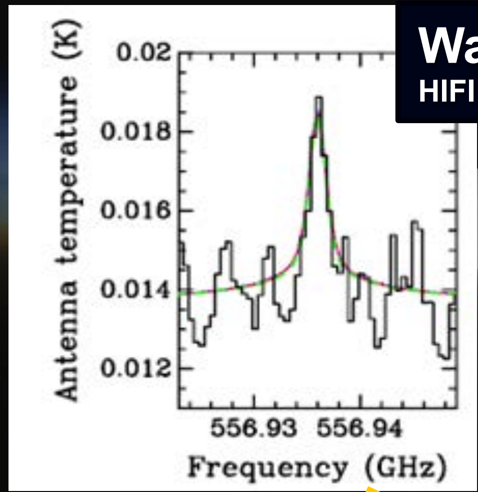
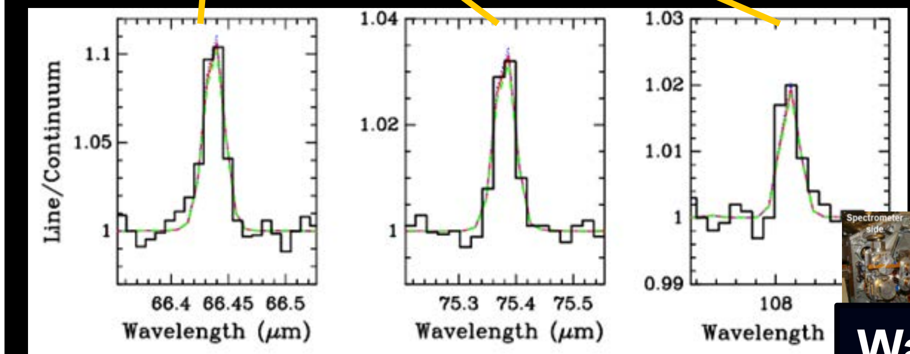


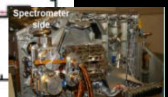
Several H_2O far-IR lines detected for the first time in Titan's atmosphere,





Water Vapour in Titan
HIFI / Herschel





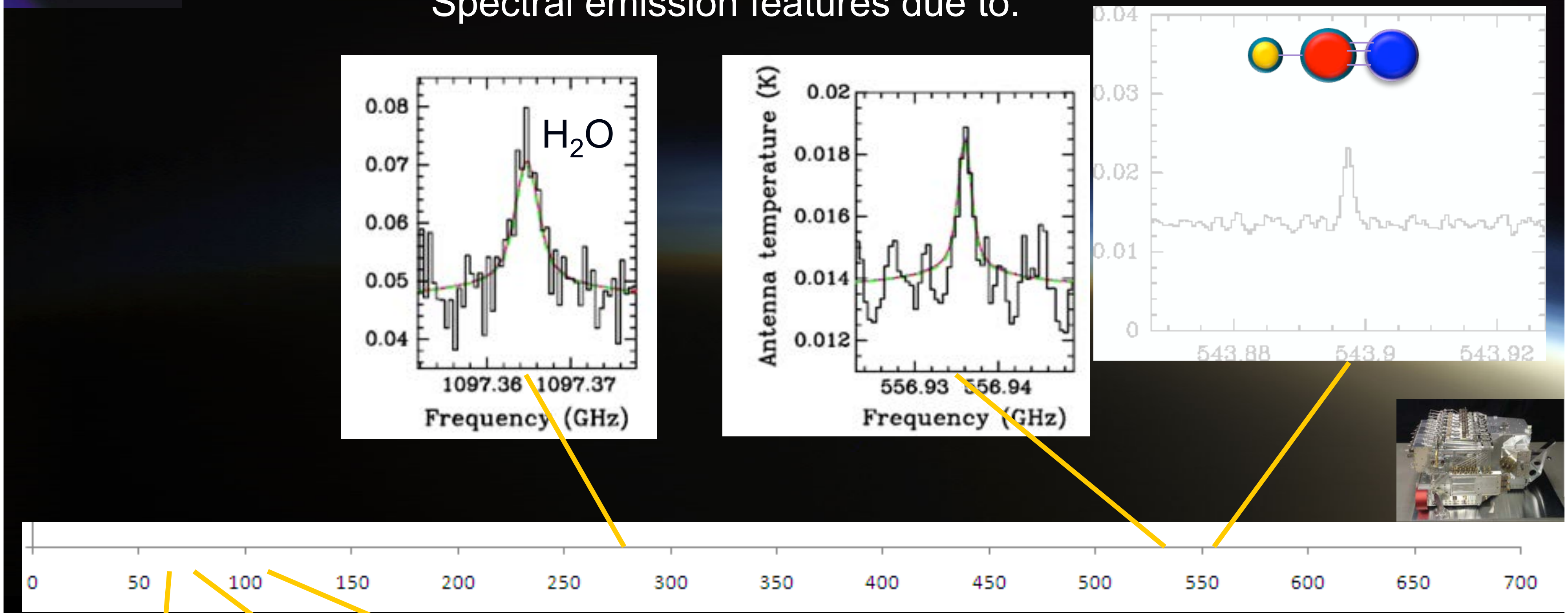
Water Vapour in Titan
PACS / Herschel

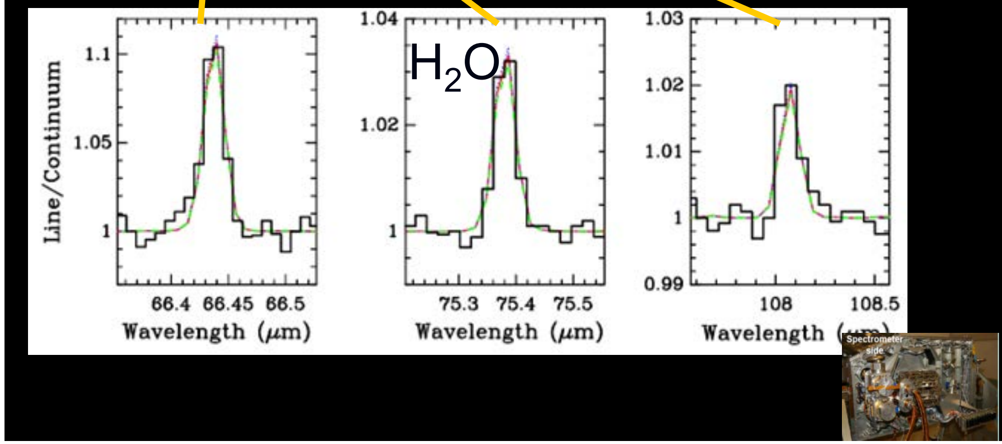
Five dedicated Water vapour line emission with Herschel/PACS and HIFI. Goal: vertical profile of H_2O

Moreno et al. 2012

1.- Molecular Inventory with Herschel /PACS, SPIRE , and HIFI

Spectral emission features due to:



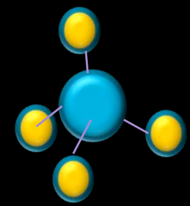


Surprise: Unexpected detection of hydrogen isocyanide (HNC) ➔ a specie not previously identified in Titan´s atmosphere

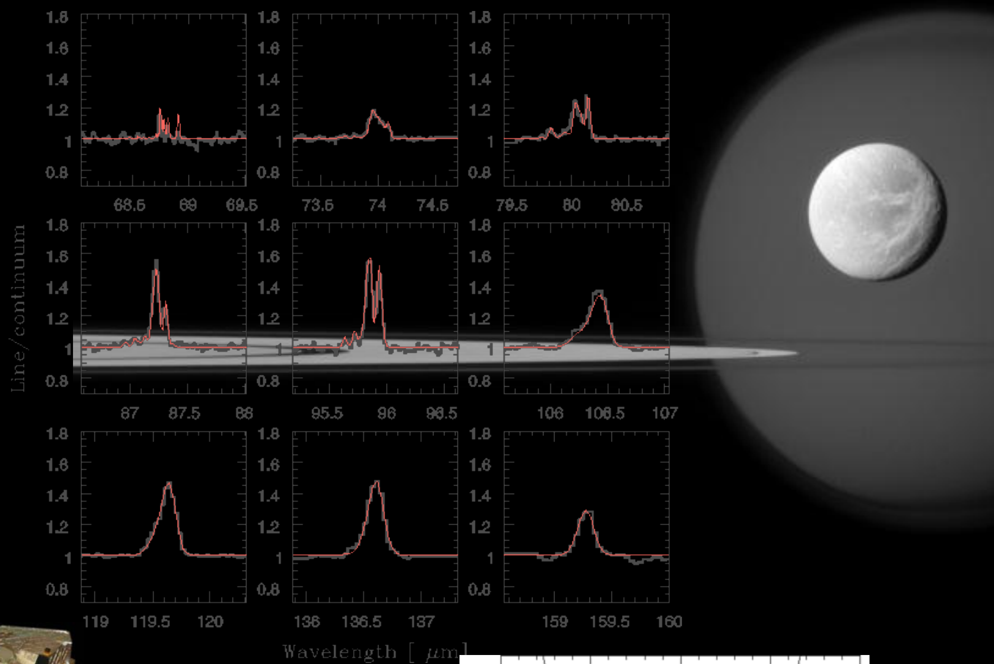
2.- Determination of the abundance of the trace constituents:

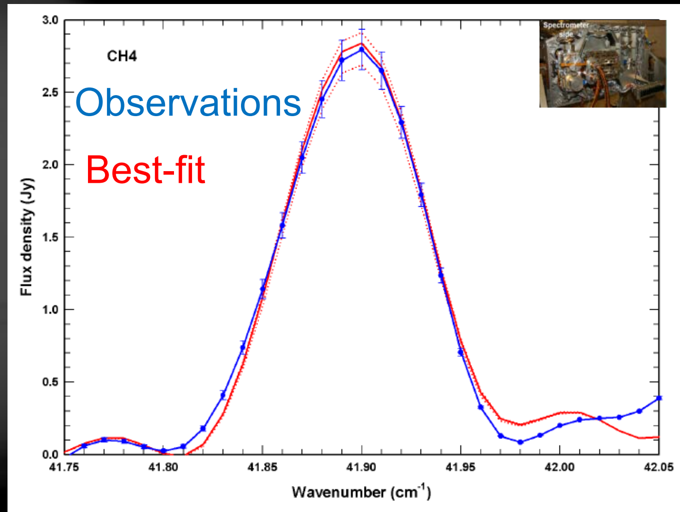
Step 1: Computation of the synthetic spectra for several abundances
Step 2: Calculation of the best-fit

- **CH_4:** Origin unknown

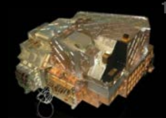


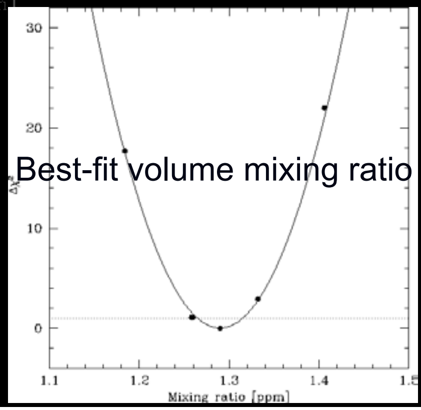
Observed and best-fit simulated CH_4 lines





Courtin et al. 2011





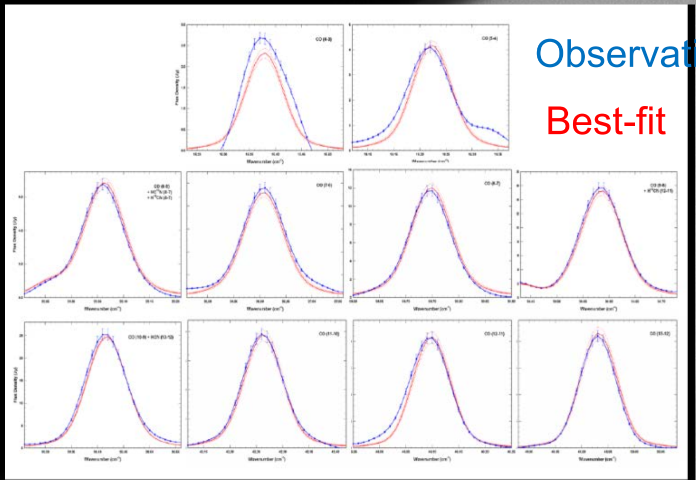
Rengel et al. 2013, submitted

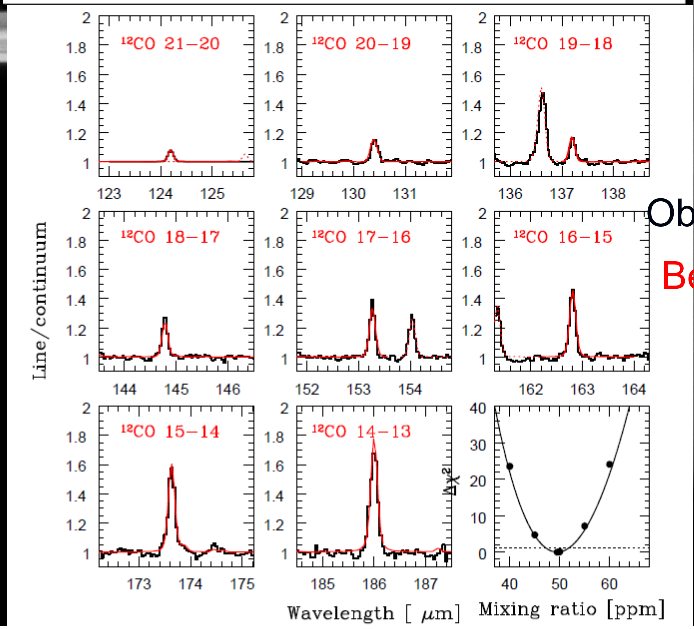
Consistent with previous studies:

Facility	Value	Reference
CIRS	1.6±0.5%	Flasar et al. 2005
GCMS	1.48±0.09%	Niemann et al. 2010
SPIRE	**1.33 ±0.07%**	**Courtin et al. 2011**
PACS	**1.27 ±0.03**	**Rengel et al. submitted**

CO: is CO primordial or external ? Viable via precipitation of O or O^+ from Enceladus Torus (*Hörst et al. 2008; Cassidy & Johnson 2010; Hartogh et al. 2011*)

Observed and best-fit simulated CO lines





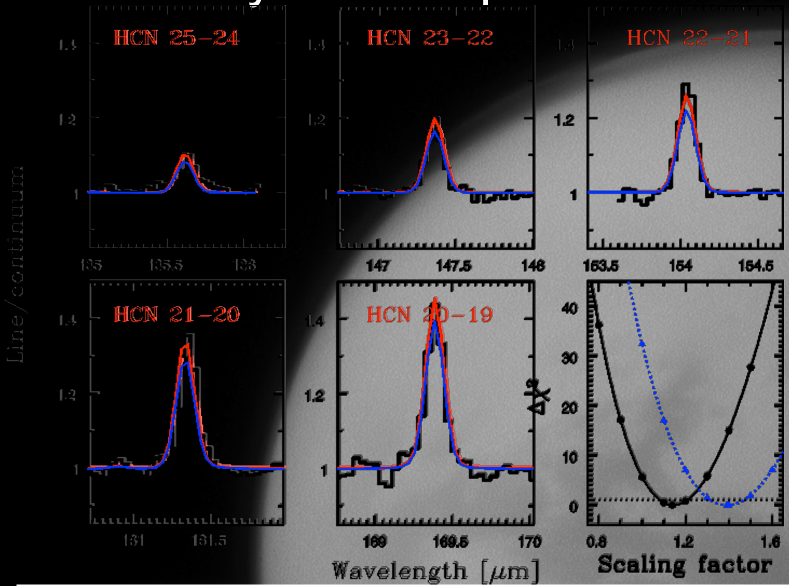
For the [60-170] km range altitude

Consistent with previous studies:

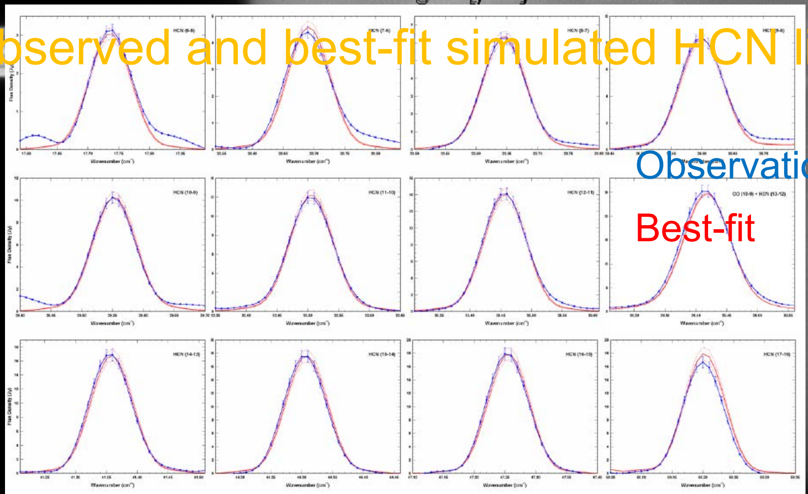
Facility	Value [ppm]	Reference
SPIRE	**40±5**	**Courtin et al. 2011**
CIRS	47±8	De Kok et al 2007
APEX	30^{+15}_{-8}	Rengel et al. 2011
SMA	51±4	Gurwell et al. 2012
PACS	**49±2**	**Rengel et al. submitted**

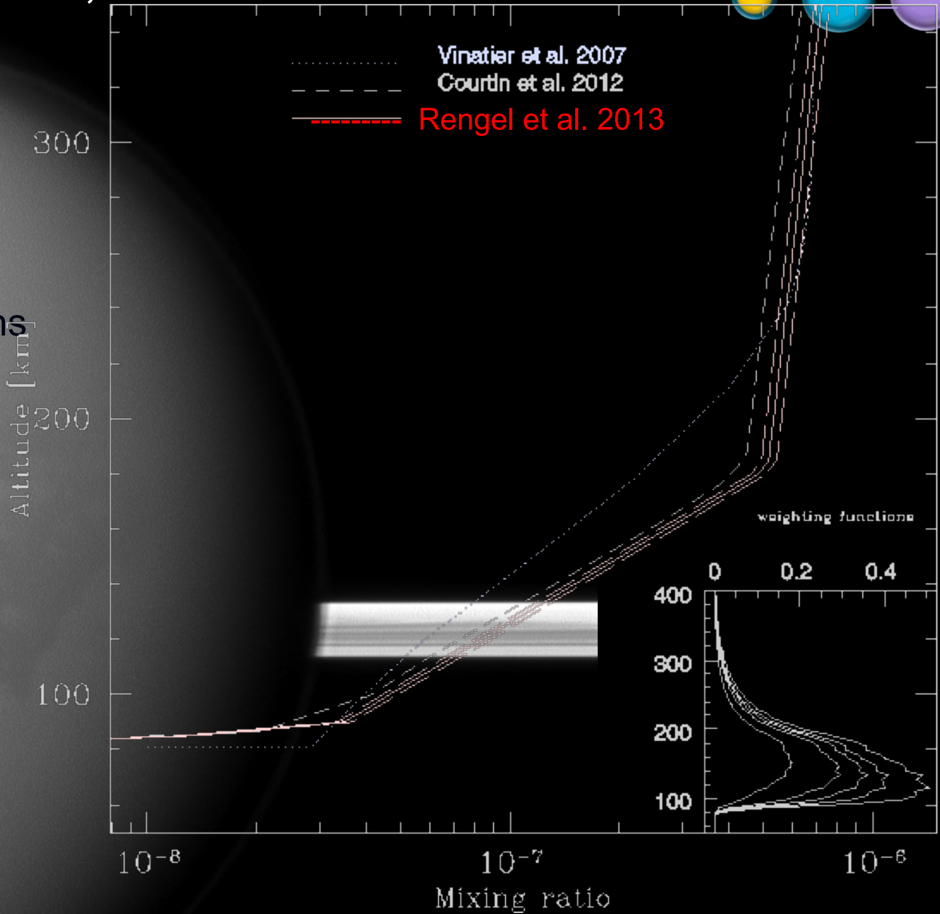
HCN vertical distribution **Generated photochemically**

- We scaled the distribution from the one by Marten et al 2002, computed the synthetic spectra for several factors, and calculated best-fit



Observed and best-fit simulated HCN lines





Distribution of HCN, compared with the profile by CIRS

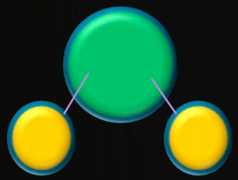
Our results confirm the results from Marten et al. 2002.

The CIRS distribution misfits the PACS observations at 1-σ level

Rengel et al. 2013, submitted

3.- Determination of the abundance of the trace constituents: Water vertical distribution

H_2O: Origin: a puzzle



- None of the previous water models provides an adequate simultaneous match to the PACS and HIFI observations

- → Photochemical models for water must be revised

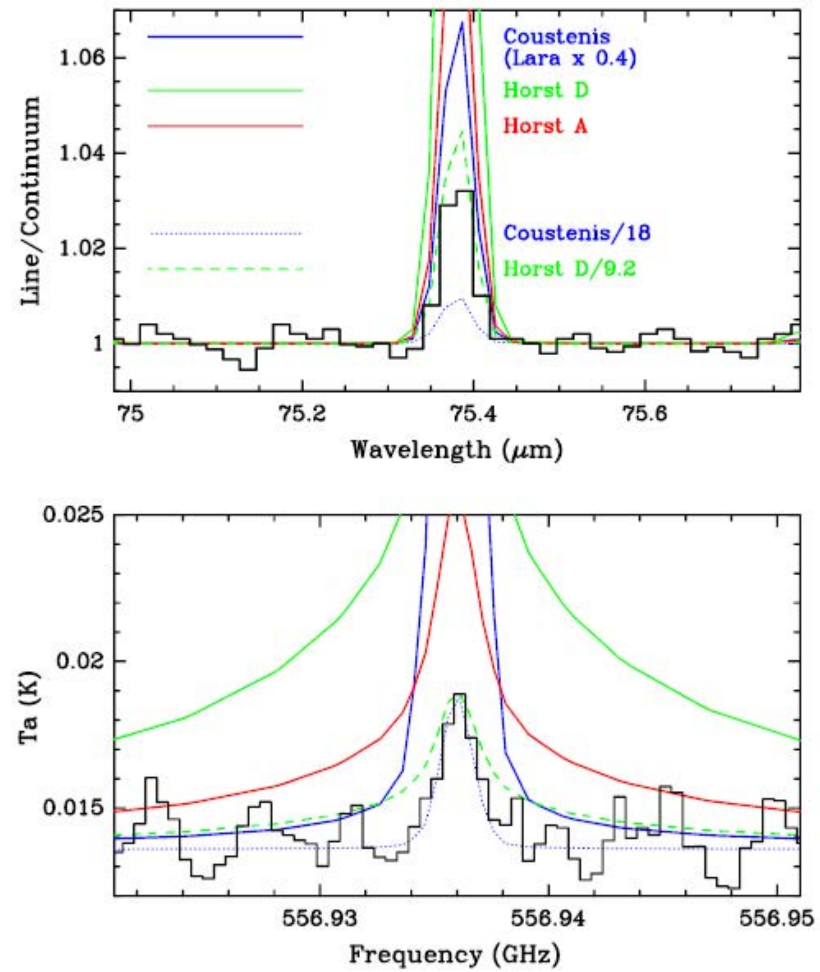
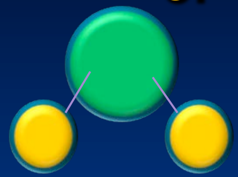


Fig. 7. Synthetic spectra computed considering several previously proposed H_2O profiles: Coustenis et al. (1998), Hörst et al. (2008) (model D and model A), and rescaled versions of these models. None of the models provides an adequate simultaneous match to the PACS observation at 75 μm (top) and HIFI at 557 GHz (bottom).

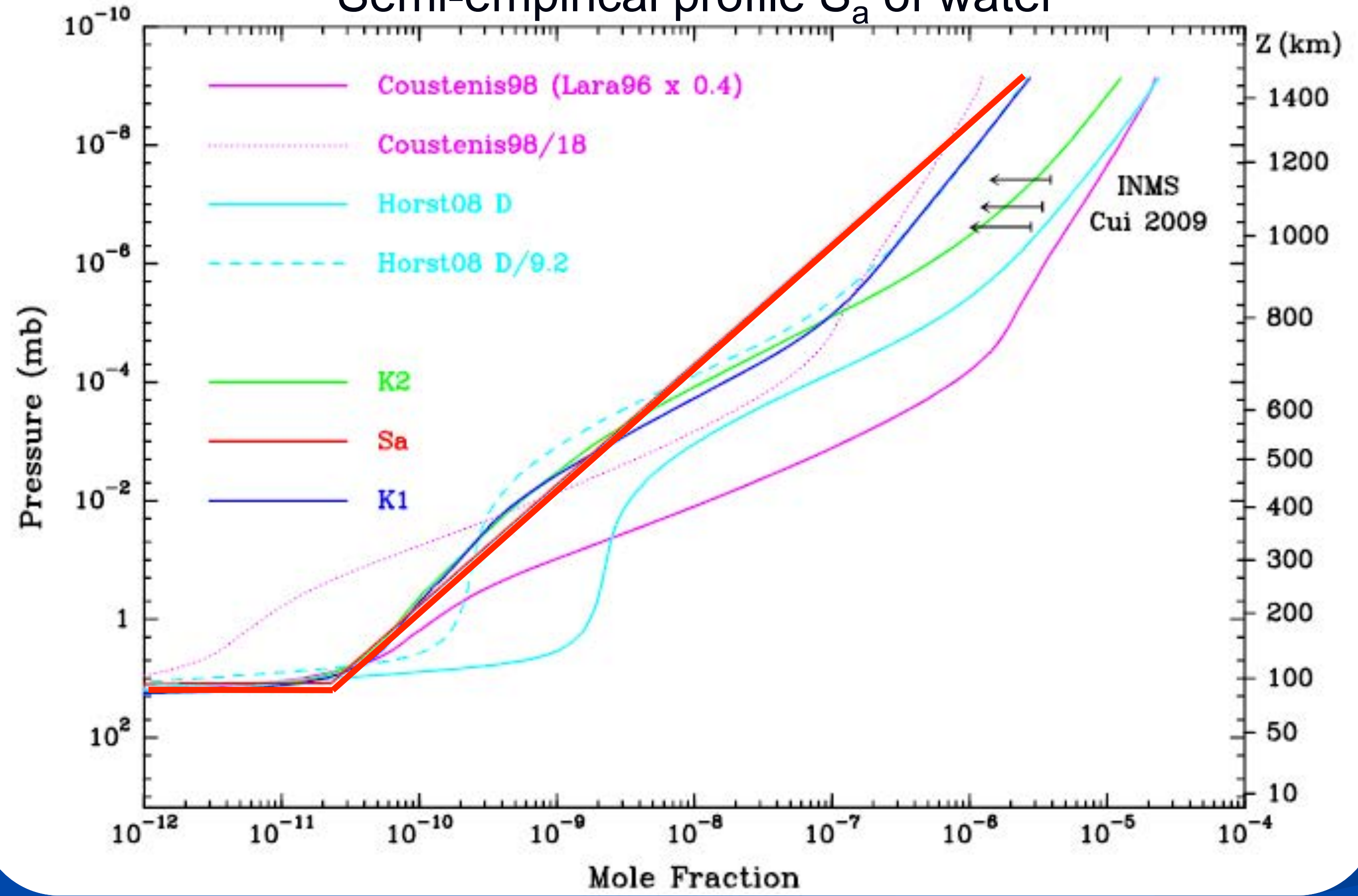
3.- Determination of the abundance of the trace constituents: Water vertical distribution



Pressure dependence law as $q=q_0(p_0/p)^n$

q_0 is the mixing ratio at the reference pressure level p_0

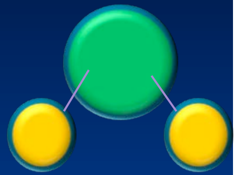
Semi-empirical profile S_a of water

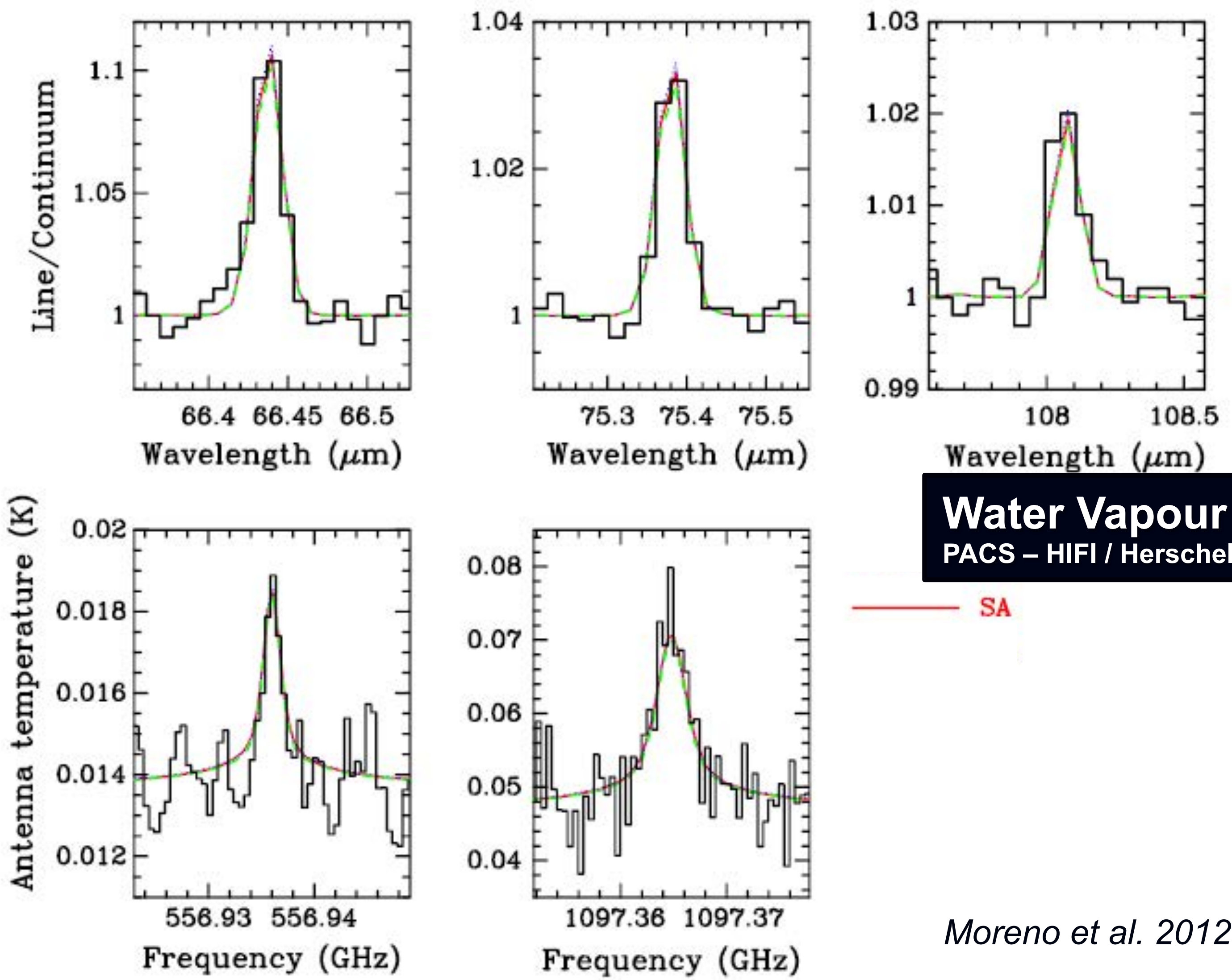


Moreno et al. 2012

S_a:

q_0 = 2.3 x10^{-11} at p_0 = 12.1 mbar
n = 0.49
Column density: 1.2 (± 0.2) 10^{14} cm $^{-2}$.



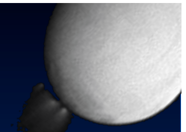


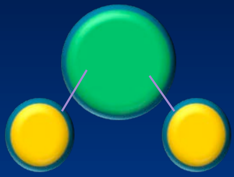
Water Vapour in Titan
PACS – HIFI / Herschel

Moreno et al. 2012

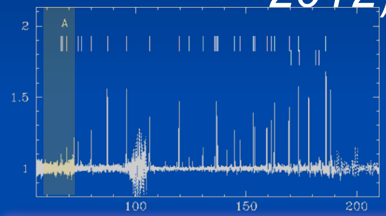
Observed and synthetic spectra

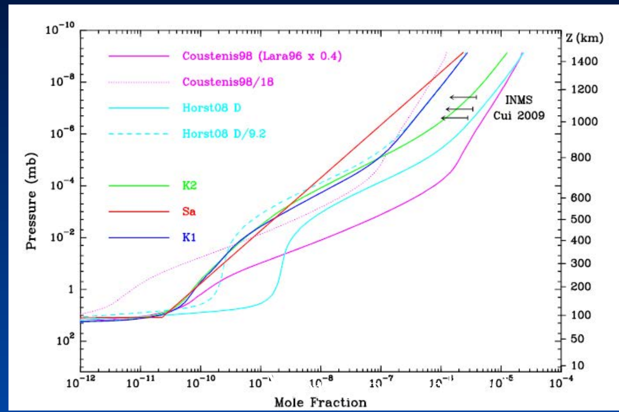
H_2O. Viable via Enceladus plume activity (Hartogh et al. 2011; Moreno et al. 2012).



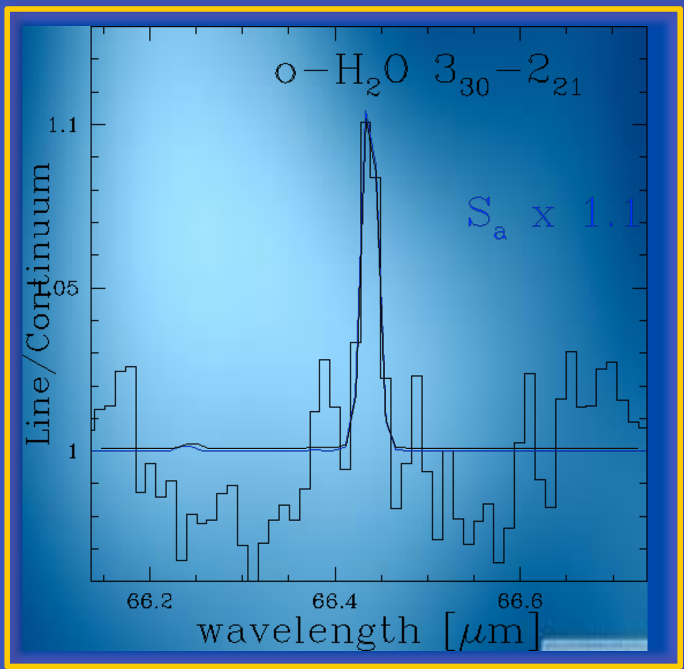


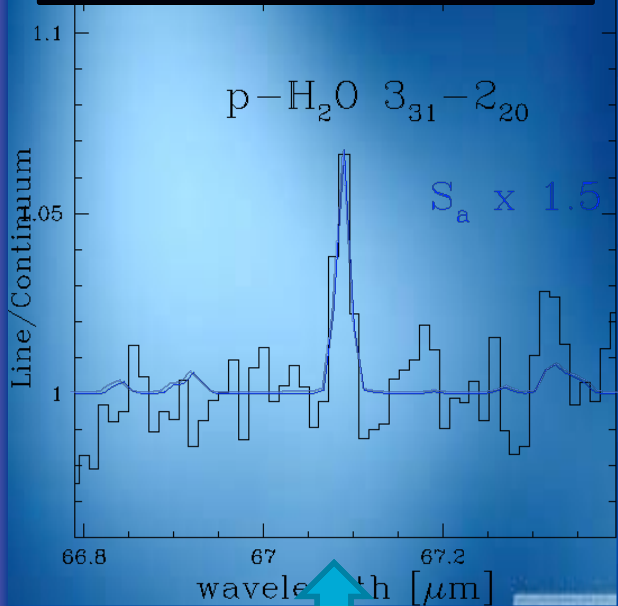
The S_a distribution is also compatible with the PACS lines from the full scan: computations of the synthetic spectra with S_a (*Moreno et al. 2012*).

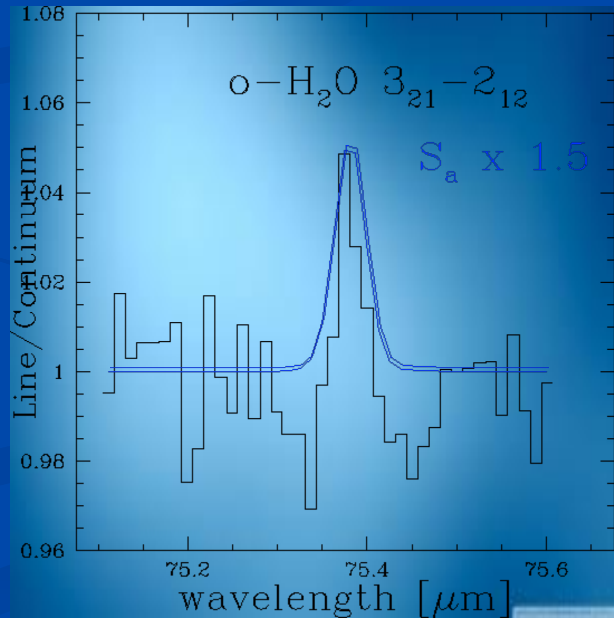




Water Vapour in Titan
PACS / Herschel



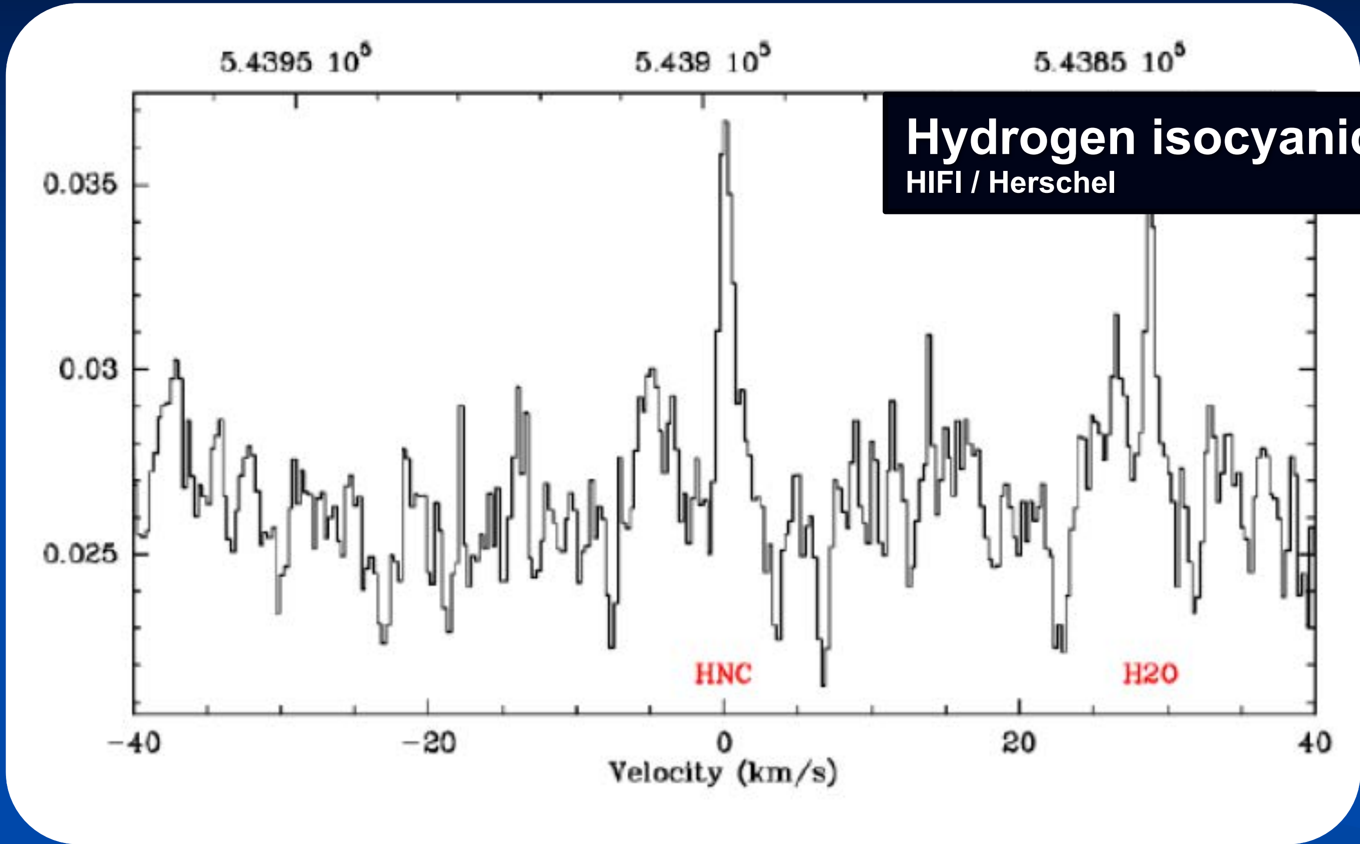




Detection for first time

Rengel et al. 2013, submitted

3.- Determination of the abundance of the trace constituents: HNC

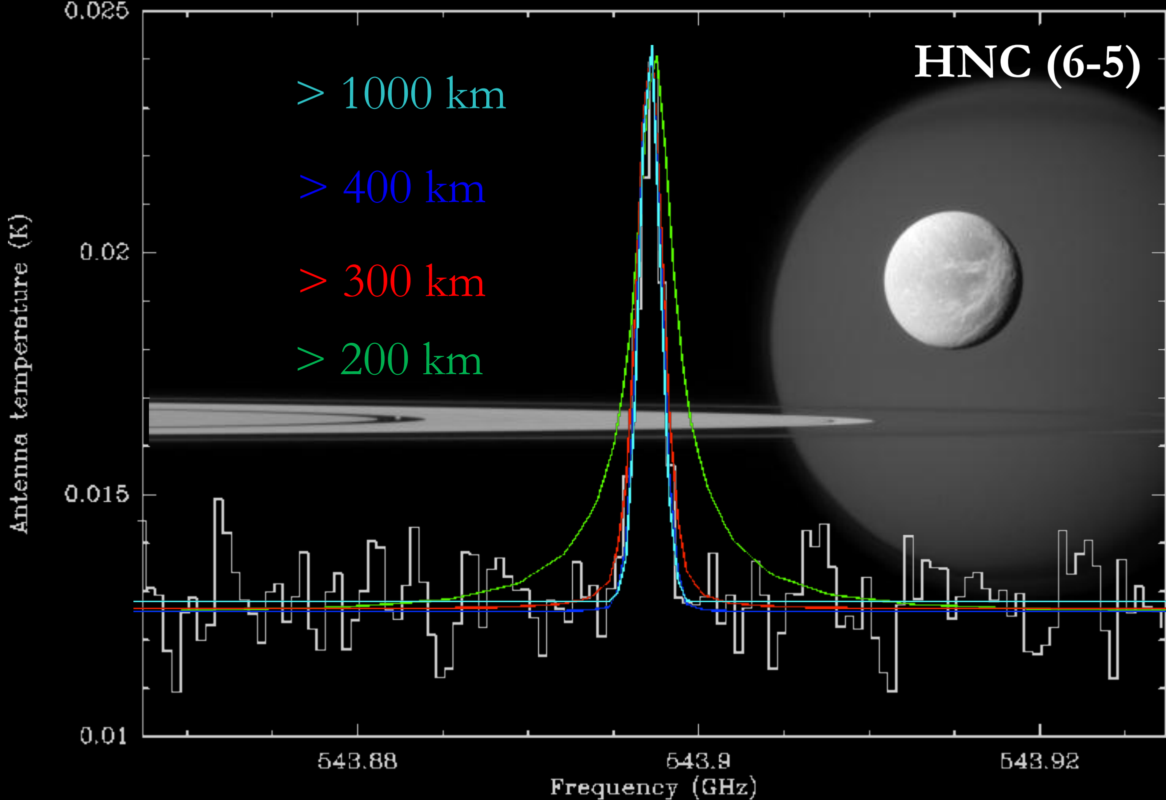


Hydrogen isocyanide in Titan
HIFI / Herschel

First detection of HNC in the Titan´s atmosphere

HNC distribution: the bulk of HNC is located above 400 km

Models of the HCN line: constant mixing ratio above a given altitude



Origin: reactions

$HCNH^+ + e^- \rightarrow HNC + H$		(1a)
$\rightarrow HCN + H$		(1b)
$XH^+ + HNC \rightarrow X + HCNH^+$		(2)
$HNC + H \rightarrow HCN + H$		(3)
$CH_3 + HNC \rightarrow CH_3CN + H$		(4)
$\rightarrow CH_4 + CN$		

Possible chemical lifetime:

$(1.4\text{–}5) \times 10^5$ s → we expect diurnal variations of HNC

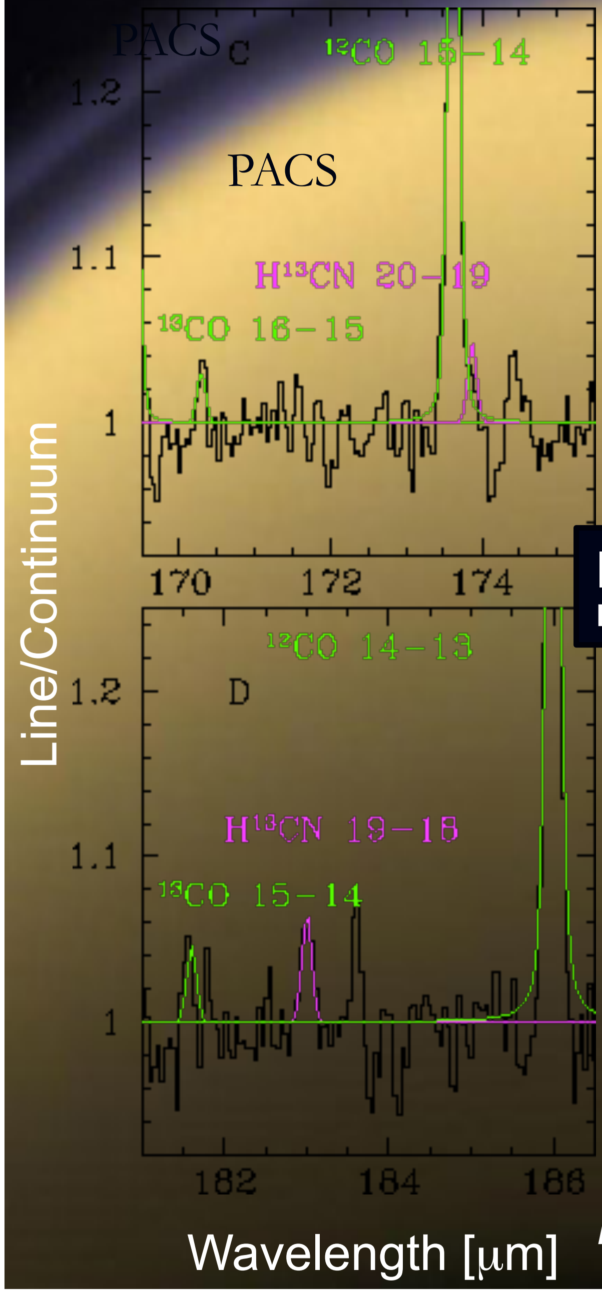
Is HNC restricted to the ionosphere?

Best fits:

Profile	$\geq z_0$ (km)	Mixing ratio	Column (cm^{-2})
A	1000	$6.0^{+1.5}_{-1.0} \times 10^{-5}$	6.3×10^{12}
B	900	$1.4^{+0.3}_{-0.3} \times 10^{-5}$	6.9×10^{12}

Moreno et al. 2011

4.- Isotopic ratios $^{12}C/^{13}C$ in CO and HCN



Detection of the isotopes:

- ^{13}CO(15-14) and (16-15)
- H^{13}CN (19-18) and (20-19)

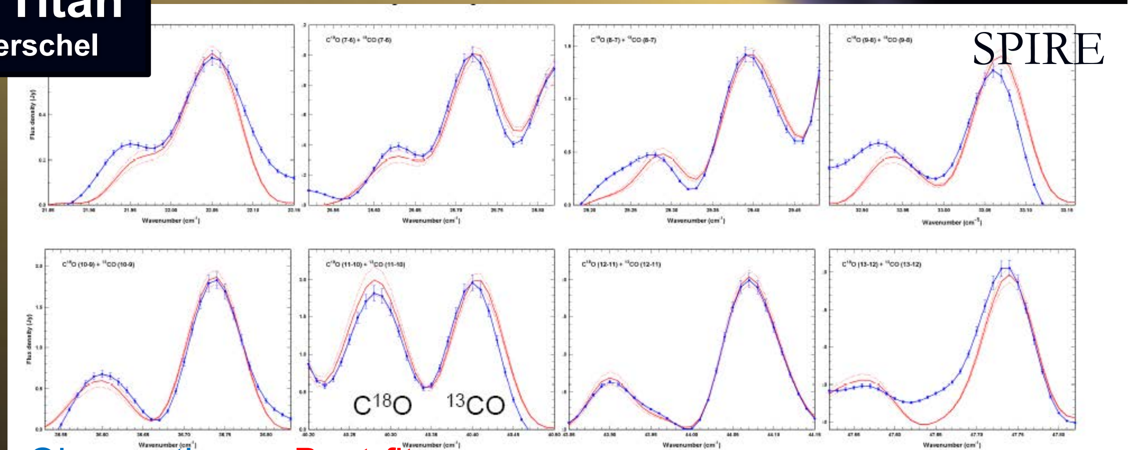
but marginal

Results:

	PACS	SPIRE
$^{12}C/^{13}C$ in CO	122 ± 62	87± 6
$^{12}C/^{13}C$ in HCN	65 ± 30	96 ± 13

Isotopes in Titan
PACS – SPIRE / Herschel

^{13}CO and ^{18}CO

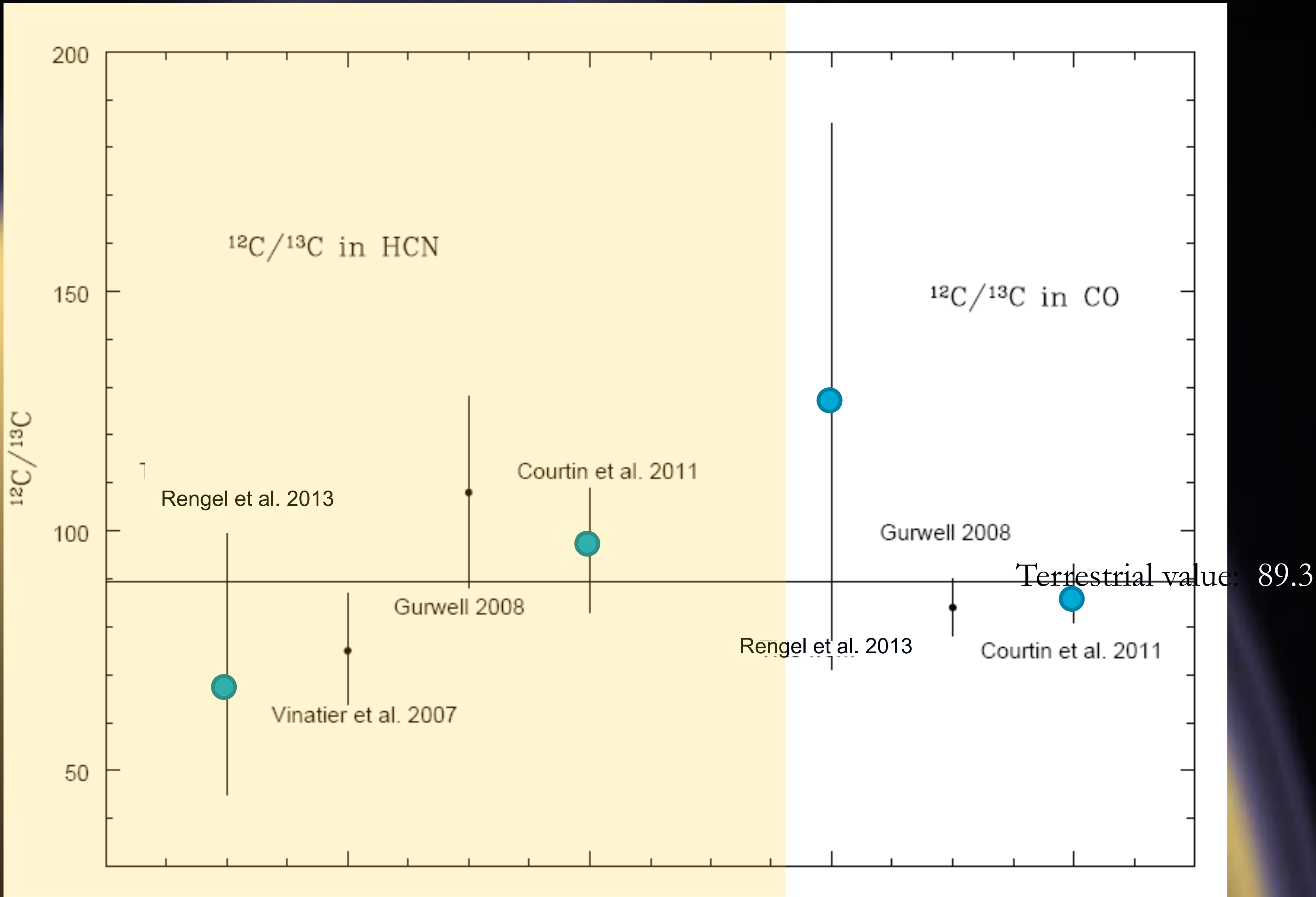


Courtin et al. 2011

Consistent with previous works

Rengel et al. 2013, submitted

The $^{12}C/^{13}C$ isotopic ratio in Titan



4.- Isotopic ratios $^{14}N/^{15}N$ in HCN and $^{16}O/^{18}O$ in CO

Measurement	$^{14}N/^{15}N$	Reference
IRAM-30m	60-70	Marten et al. 2002
SMA	72 ± 9 or 94 ±13	Gurwell 2004
Cassini/CIRS	56 ± 8	Vinatier et al. 2007
Huygens/GCMS (in N_2)	183 ± 5	Niemann et al. 2010
Herschel/SPIRE	76 ± 6	Courtin et al. 2012

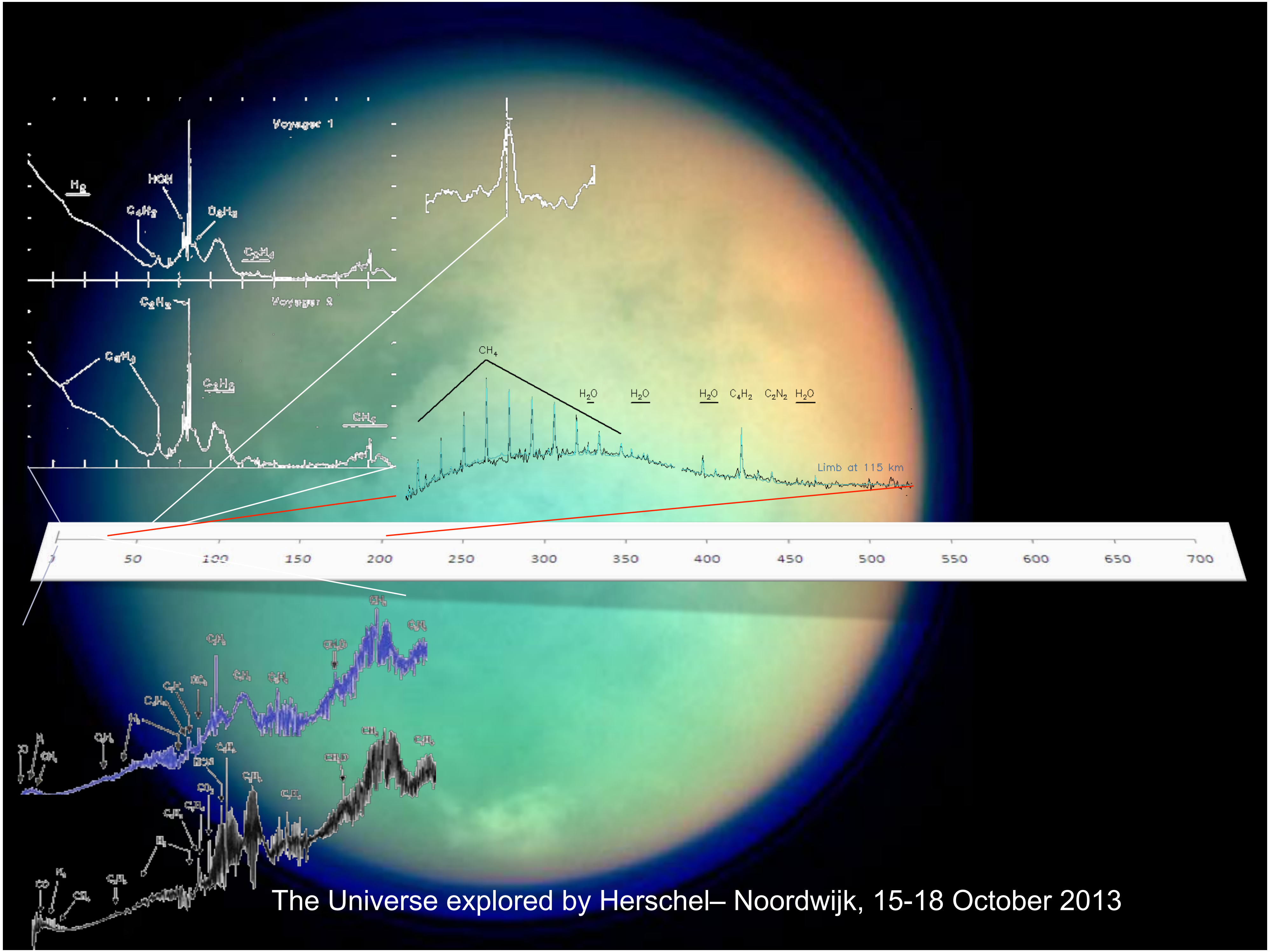
(Earth = 272)

Photolytic fractionation of $^{14}N^{14}N$ and $^{14}N^{15}N$

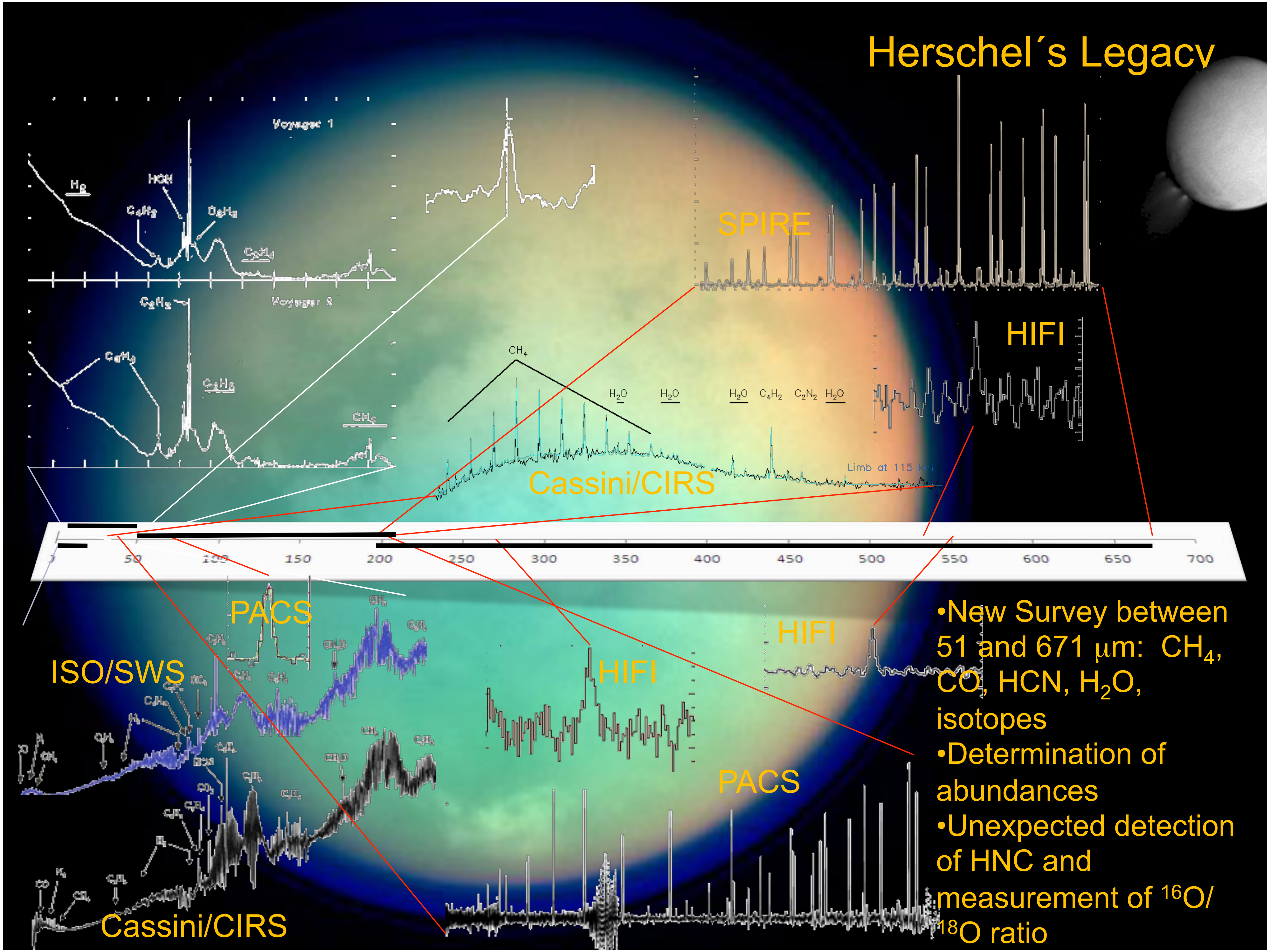
Measurement	$^{16}O/^{18}O$	Reference
JCMT	~250	Owen et al. 1999 (never-published)
SMA	400 ± 41	Gurwell 2008 (unpublished)
Herschel/SPIRE	380 ± 60	Courtin et al. 2012

First documented measurement of Titan´s $^{16}O/^{18}O$ in CO, value 24% lower than the Terrestrial ratio (Earth = 500) ➔ $^{16}O/^{18}O$ depletion in Titan

Precipitation of O^+ or O from the Enceladus Torus

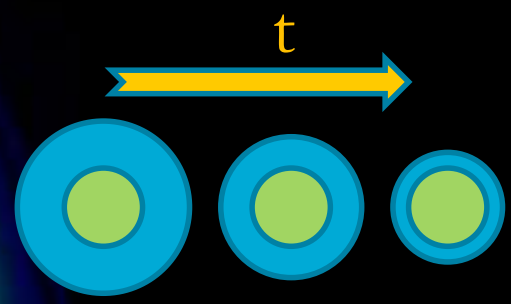


Voyager 1
Voyager 2
CH4
H2O
H2O
H2O
C4H2
C2N2
H2O
Limb at 115 km
50
100
150
200
250
300
350
400
450
500
550
600
650
700
The Universe explored by Herschel– Noordwijk, 15-18 October 2013

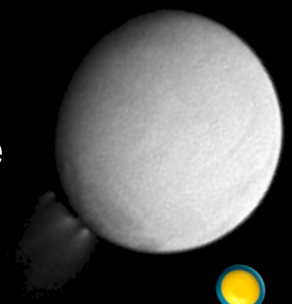

Herschel´s Legacy
Voyager 1
Voyager 2
SPIRE
HIFI
Cassini/CIRS
Limb at 115 km
PACS
ISO/SWS
HIFI
HIFI
PACS
Cassini/CIRS
50
100
150
200
250
300
350
400
450
500
550
600
650
700
•New Survey between 51 and 671 μm: CH4, CO, HCN, H2O, isotopes
•Determination of abundances
•Unexpected detection of HNC and measurement of 16O/18O ratio

Emerged Implications:

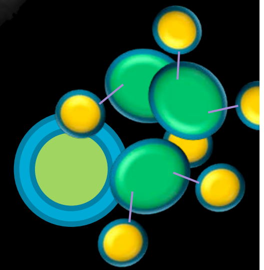
Herschel studies point to



- A denser primitive Titan´s atmosphere : much of the Titan´s atmosphere has been lost over geologic time ($^{14}N/^{15}N$)

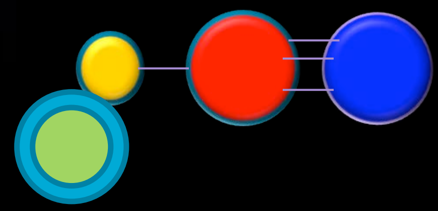


- ^{18}O enrichment in Titan´s atmosphere: Precipitation of O^{+} or O from the Enceladus plume activity ($^{16}O/^{18}O$)



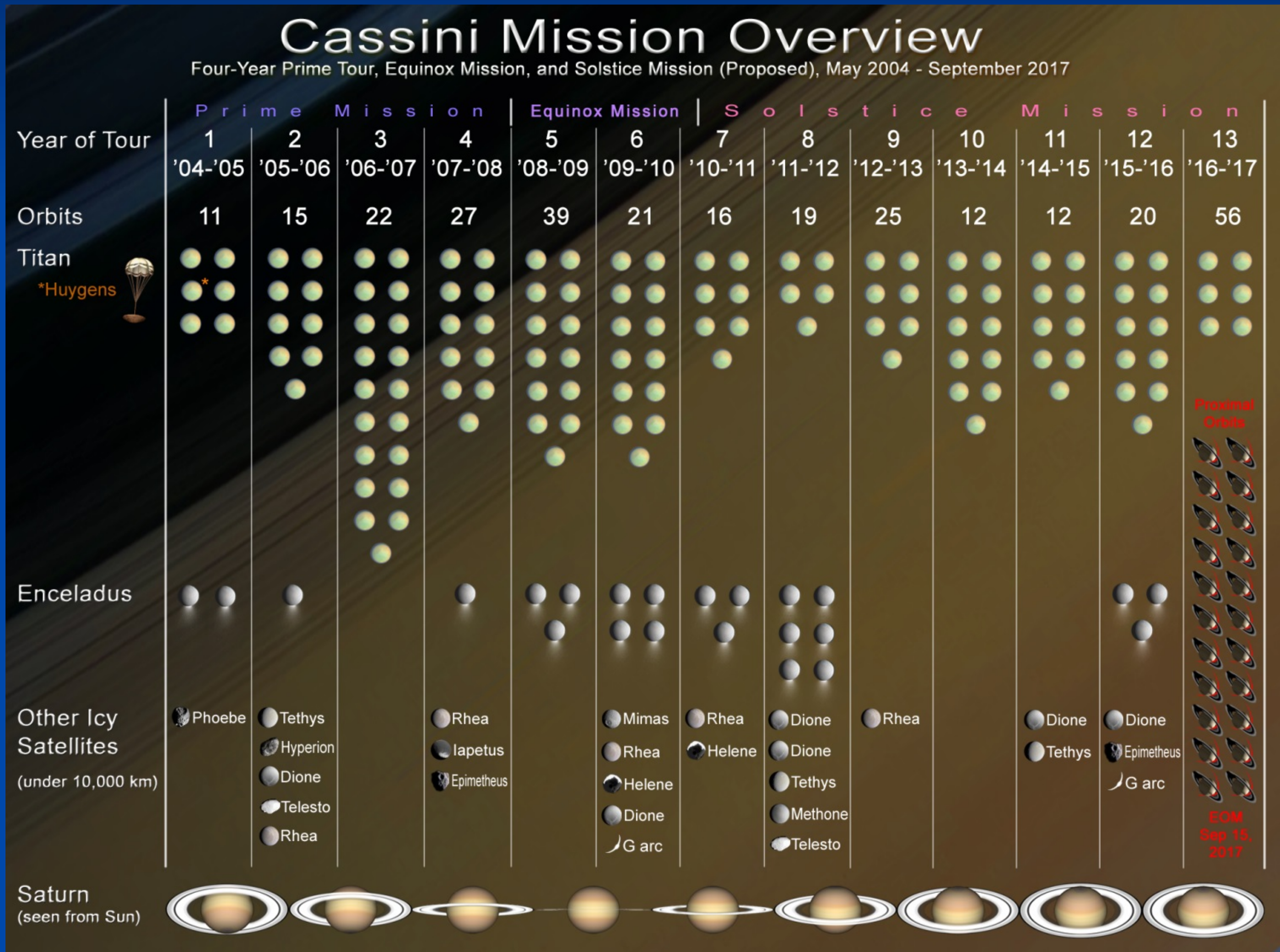
- The content of water vapour in Titan is different as the predictions → Models require a revision

- Above 400 km, Titan´s atmosphere also contains HNC

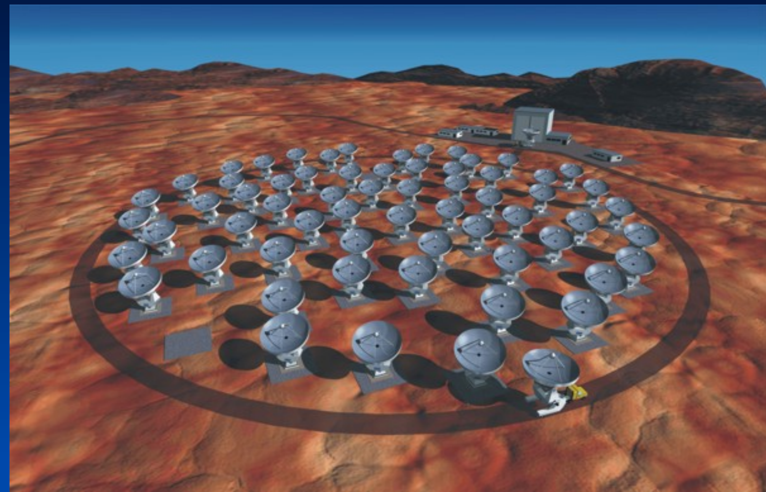


Future – Synergy with Herschel

- CASSINI/CIRS (extended mission), until 2017. 56 more flybys of Titan.

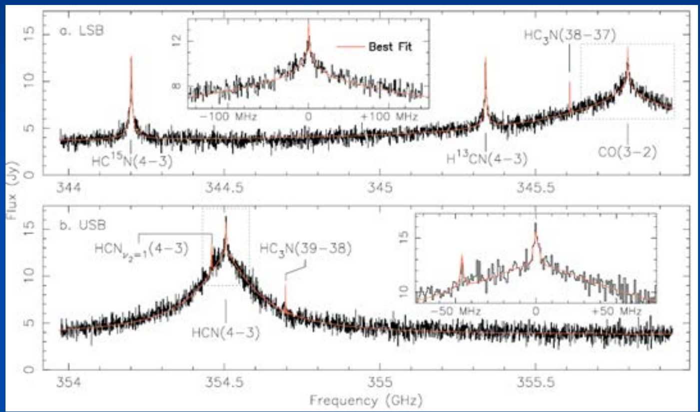


Future – Synergy with Herschel



- ALMA :

Titan’s atmospheric chemistry/dynamics



SMA 850 micron unresolved observations

Gurwell 2004

- Search for more complex species
- 3D-mapping and monitoring: seasonal variations

→ Dynamics/photochemistry coupling

→ Direct measurement of mesospheric (500 km) winds

→ Isotopic ratios

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