Tracing the gas composition of Titan´s atmosphere with Herschel and ground-based telescopes

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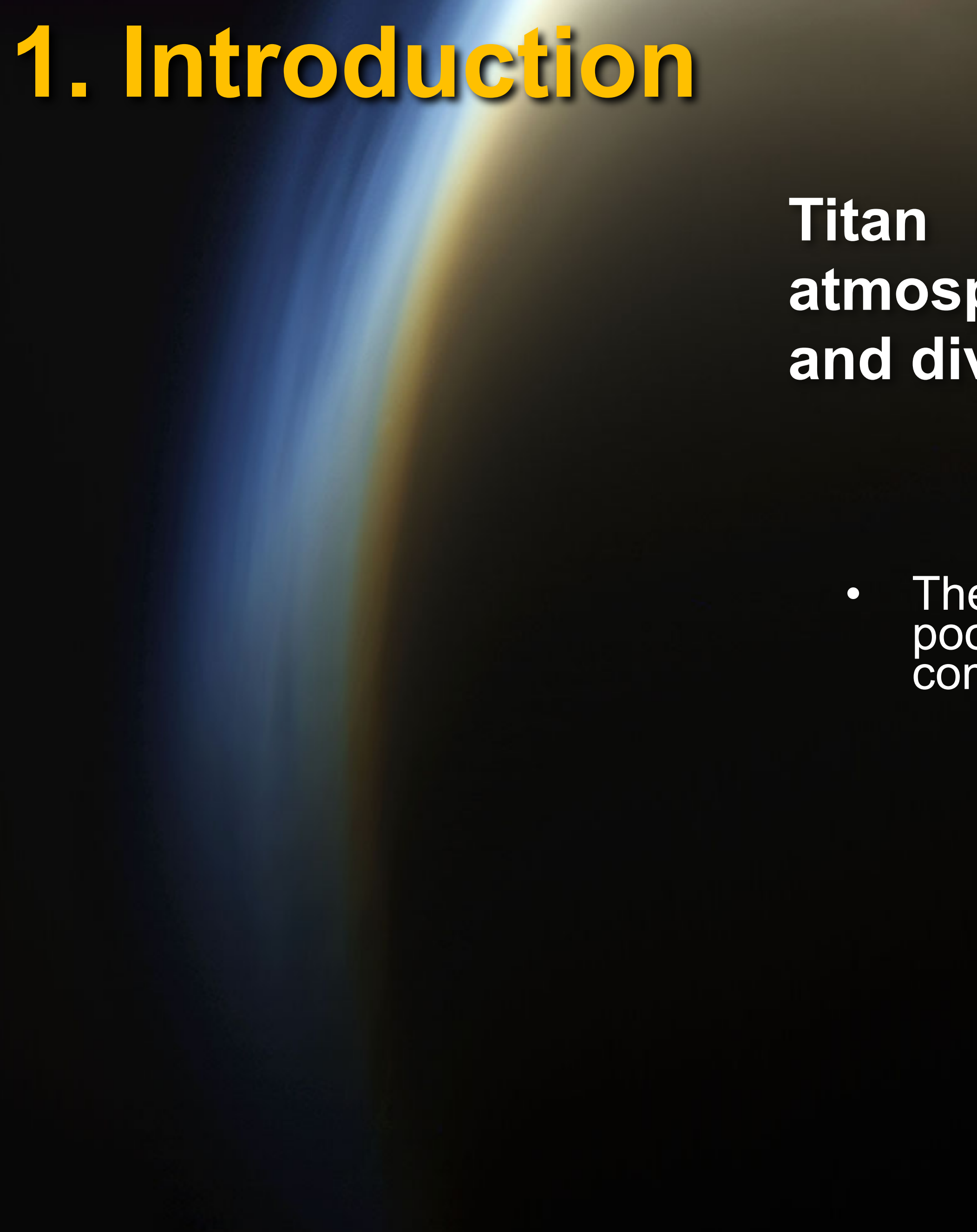
Moreno R., Courtin R., Lellouch E., Sagawa H.; Hartogh P., Swinyard B., Lara M., Feuchtgruber H., Jarchow C. , Fulton T., Cernicharo J., Bockelée-Morvan D., Biver N., Banaszkiewicz M., González A., Shulyak D. & HssO Team

Herschel 10 years after launch- May 13-14, 2019, ESAC

MAX-PLANCK-GESELLSCHAFT

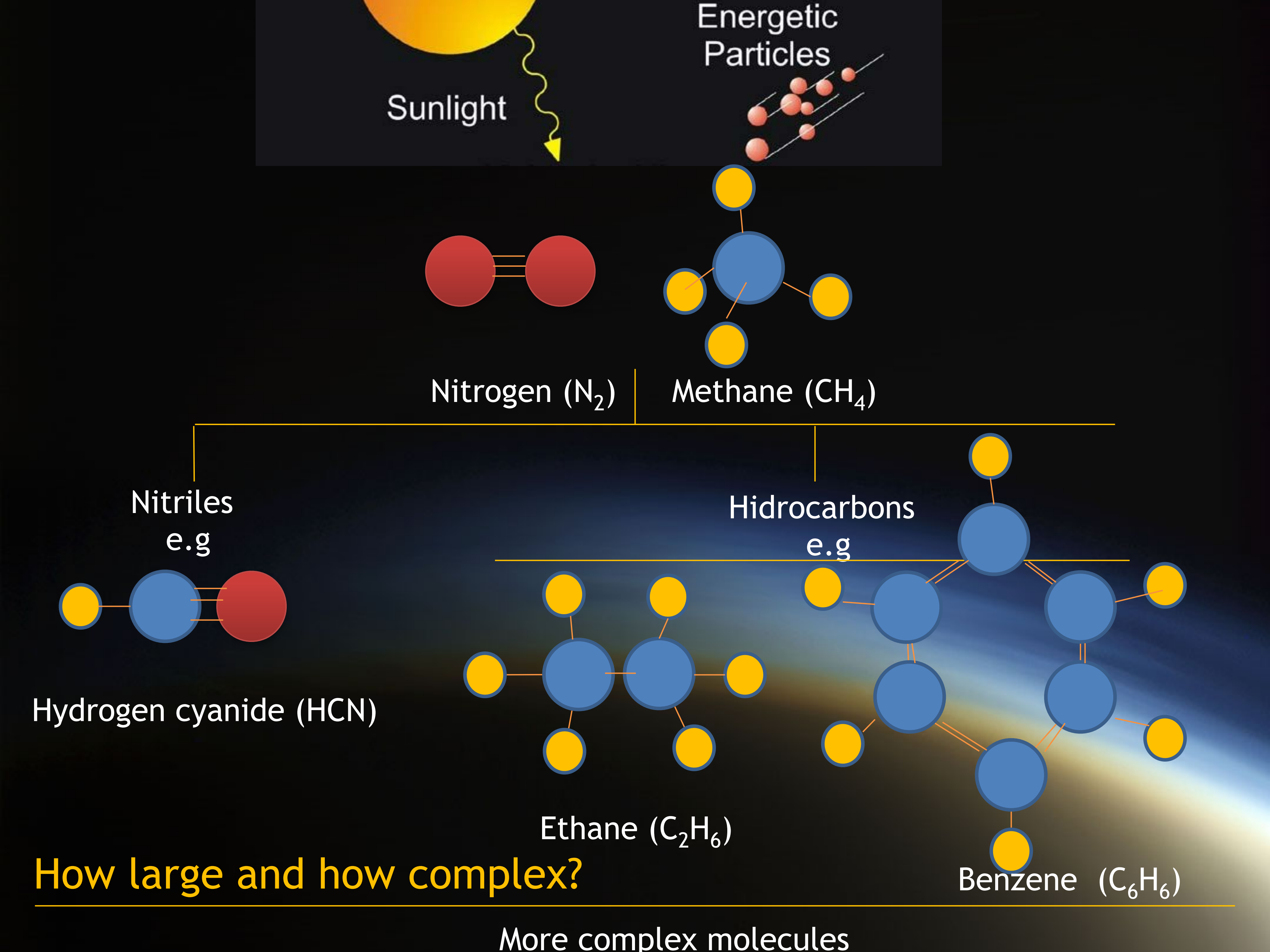


1. Introduction

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 complex


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

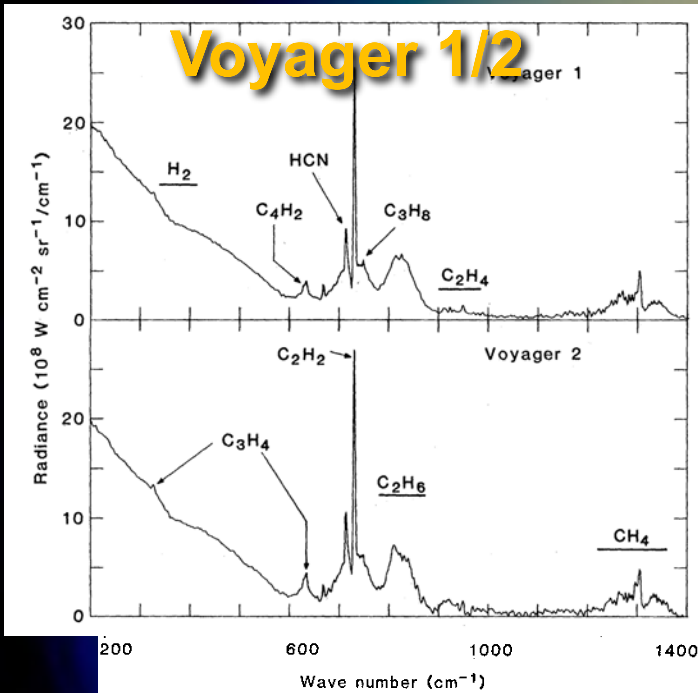
1. Introduction

Why Titan?

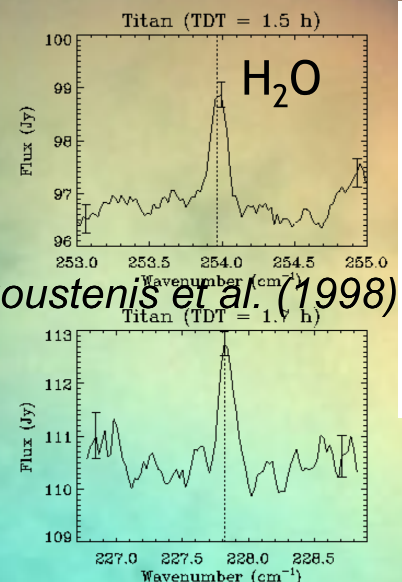
Sensitive observations of the constituents of the atmosphere are essential to constructing models of the Titans´s atmosphere and its history.

1. Introduction

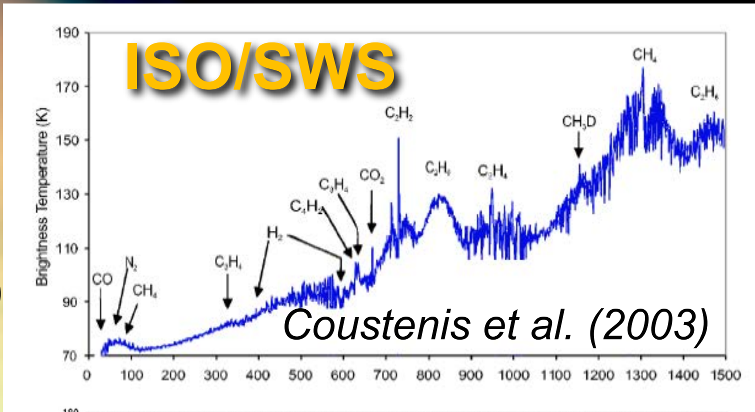
Spectroscopy of Titan has been already performed by:



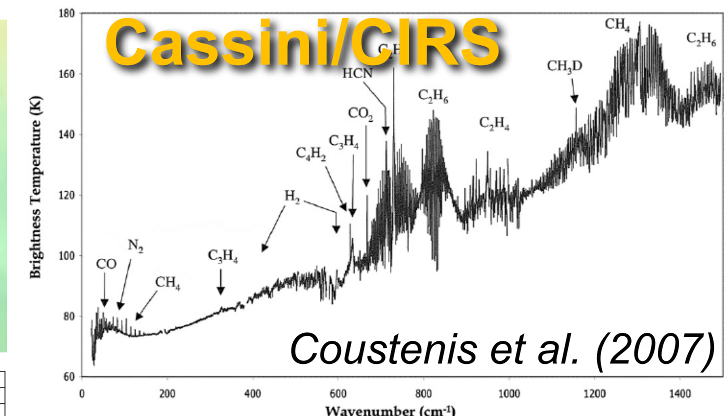
Hanel et al., Science, v 215, 1982



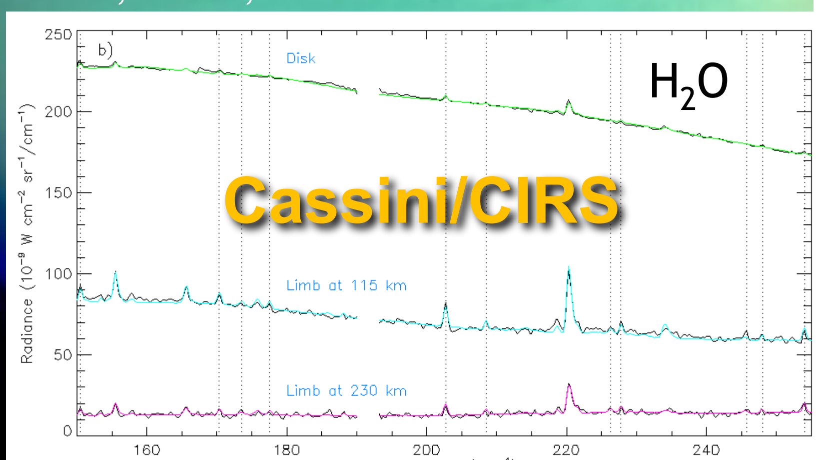
Coustenis et al. (1998)



Coustenis et al. (2003)

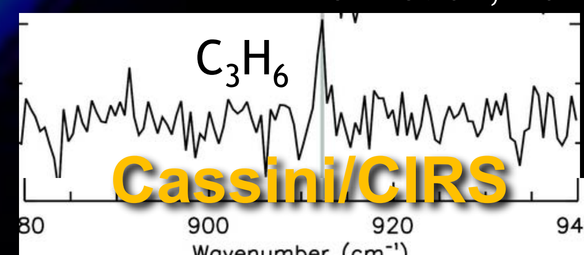


Coustenis et al. (2007)



Cottini et al., 2012

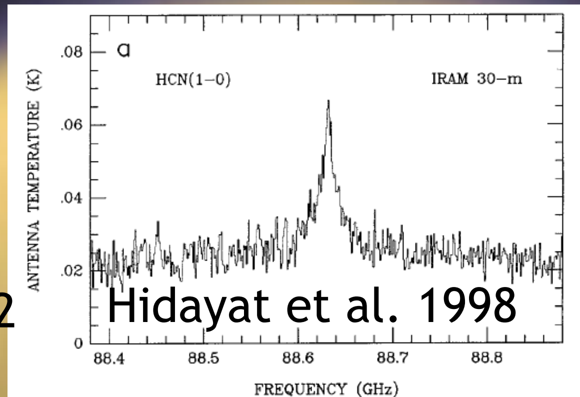
Nixon et al., 2013

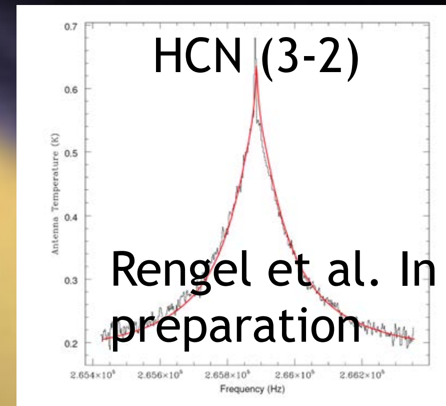


Ground-based observations have also improved our knowledge of Titan's atmospheric composition:

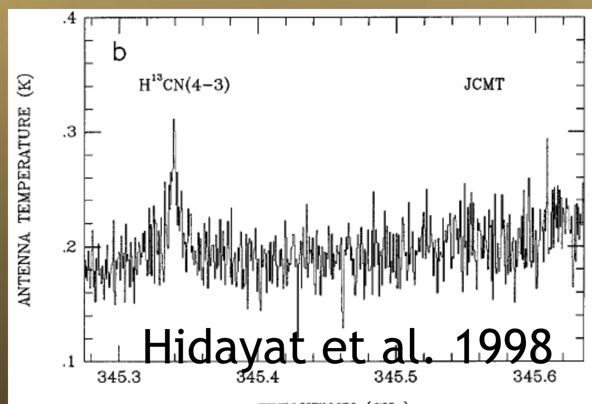
IRAM 30-m:

Marten et al. 2002

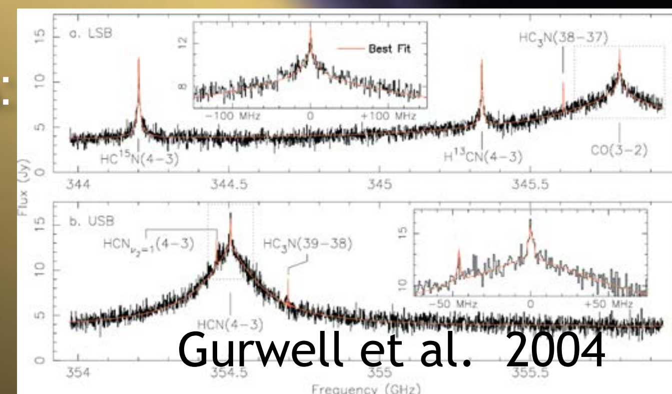




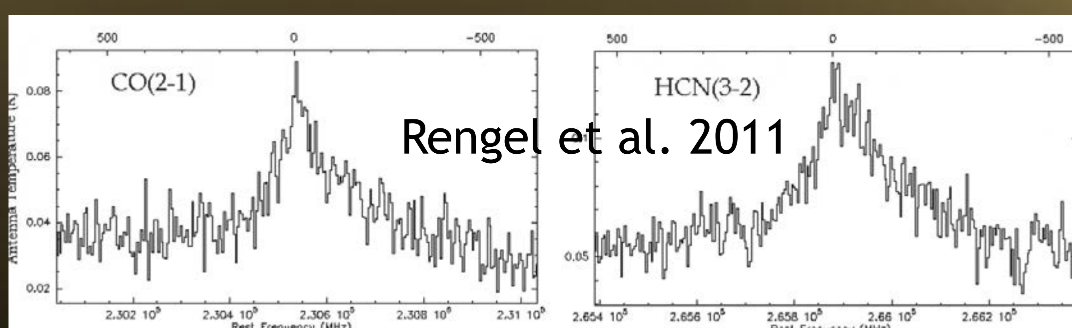
JCMT:

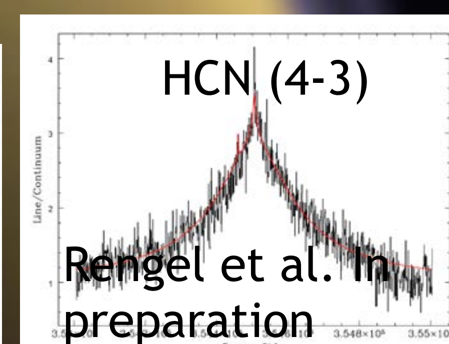


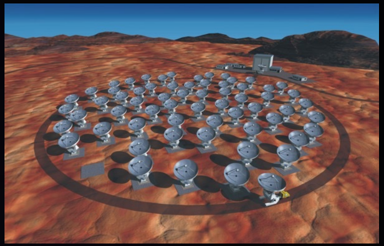
SMA:



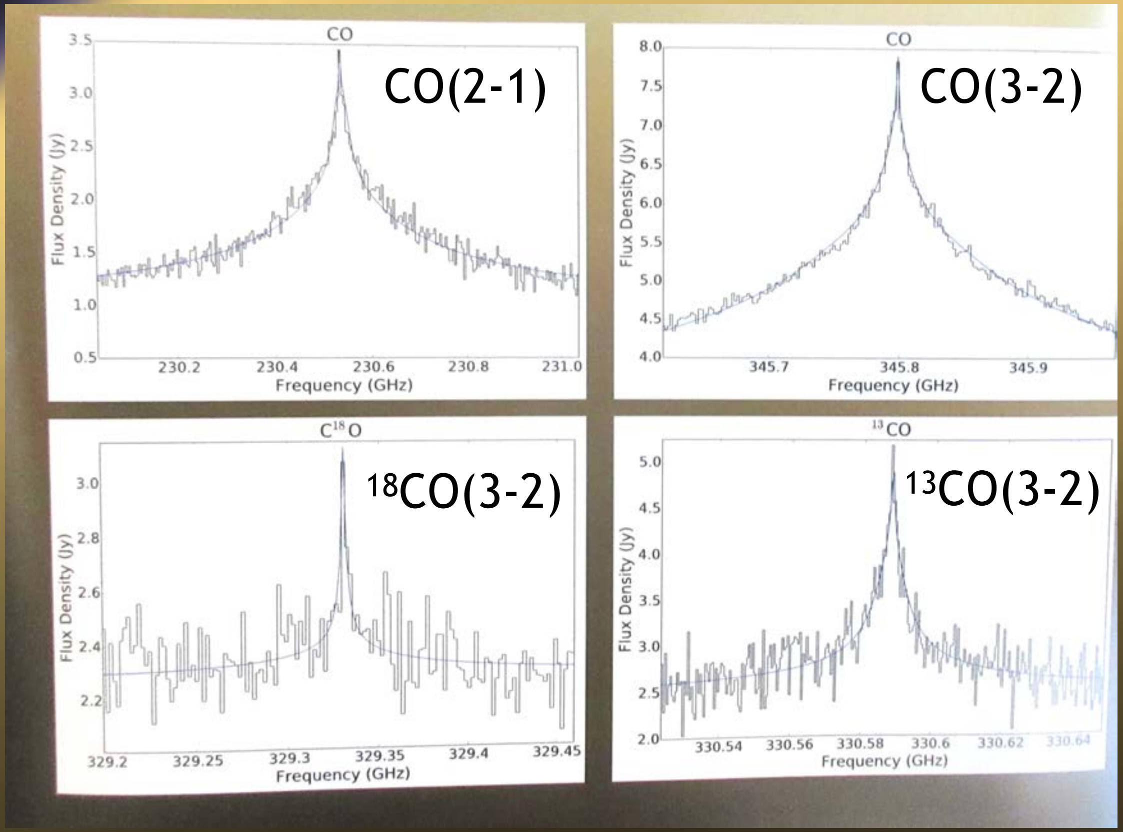
APEX:



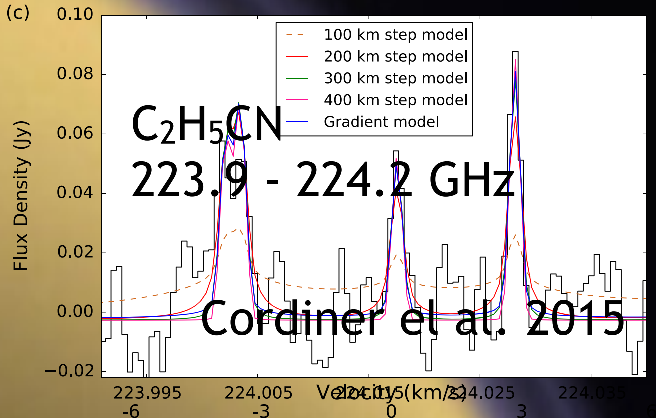


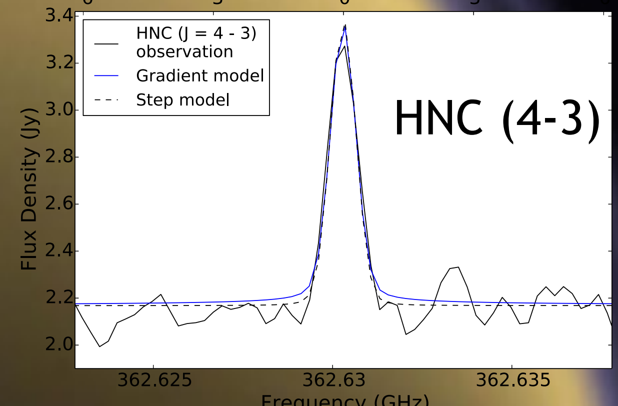


ALMA Archive data - 2012

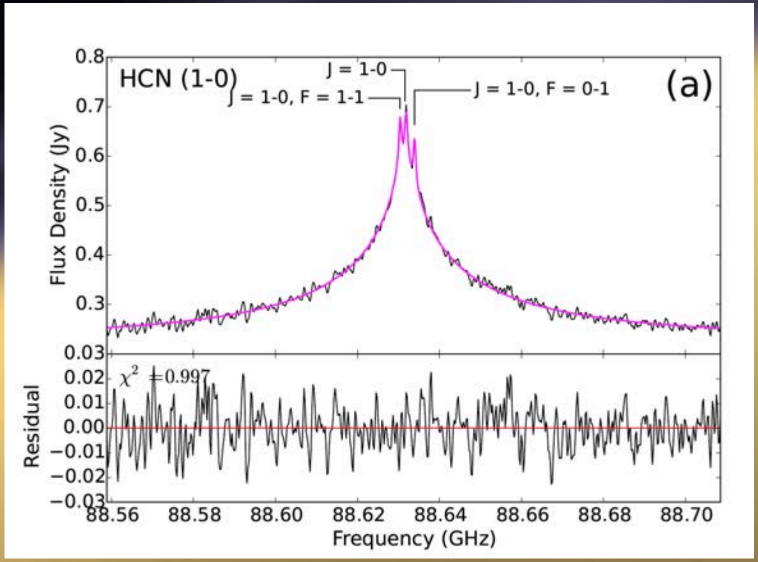


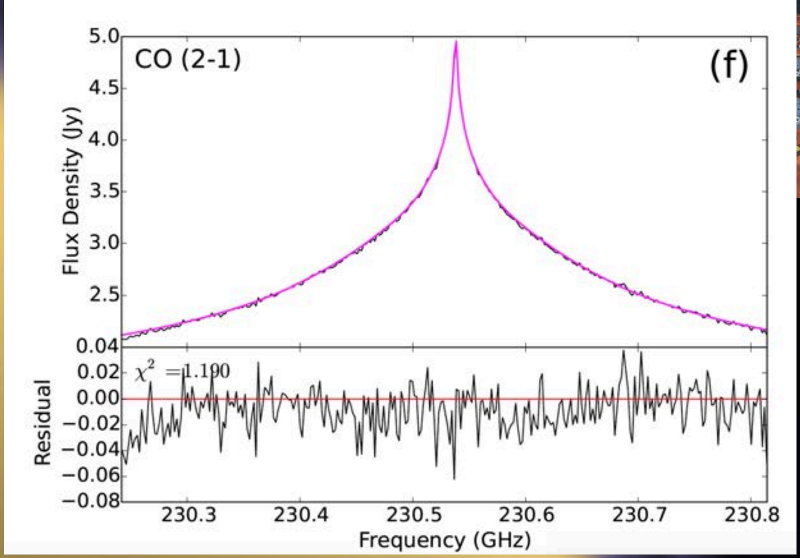
Serigano et al. 2016





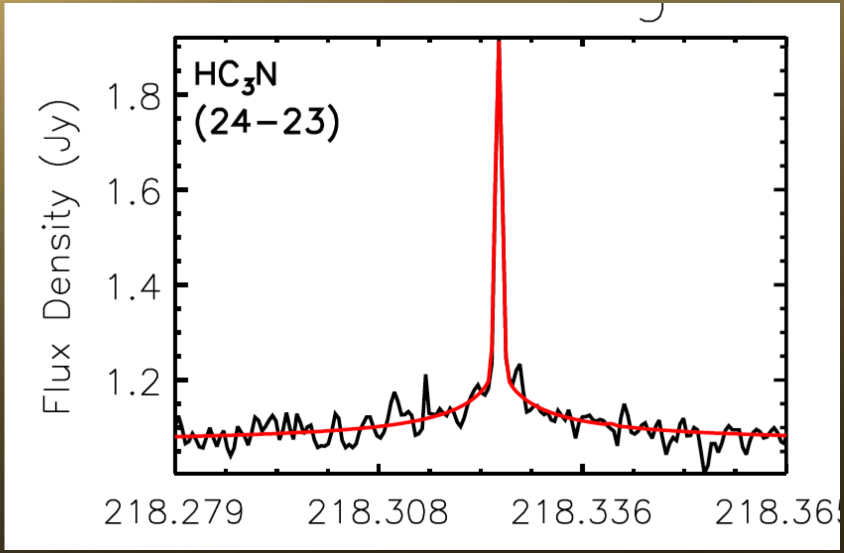
Cordiner et al. 2014

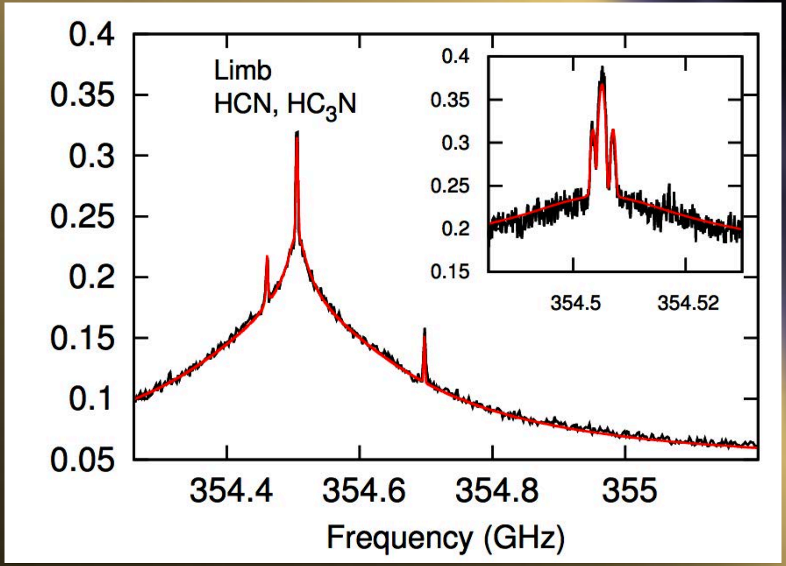




Molter et al. 2016

Molter et al. 2016





Thelens et al. 2019

Lellouch et al. 2019

How we have further improved our knowledge of Titan´s atmospheric composition ?

A new window was opened…

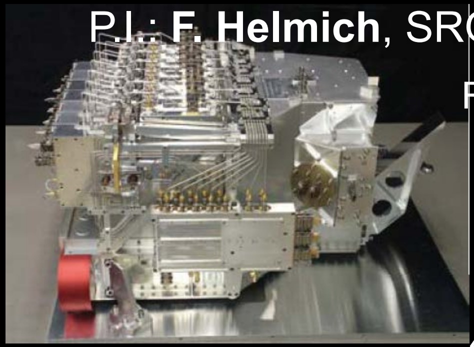
Herschel Era

Credits: ESA

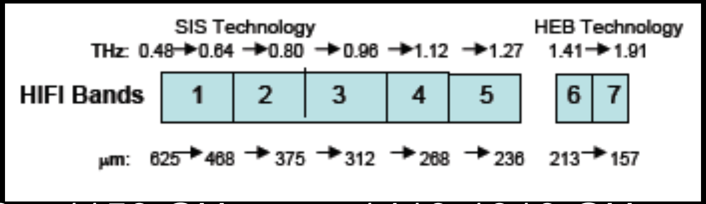
Instruments onboard Herschel:

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 μ

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

PI: **A. Poglitsch**, MPE

55 – 210 μm

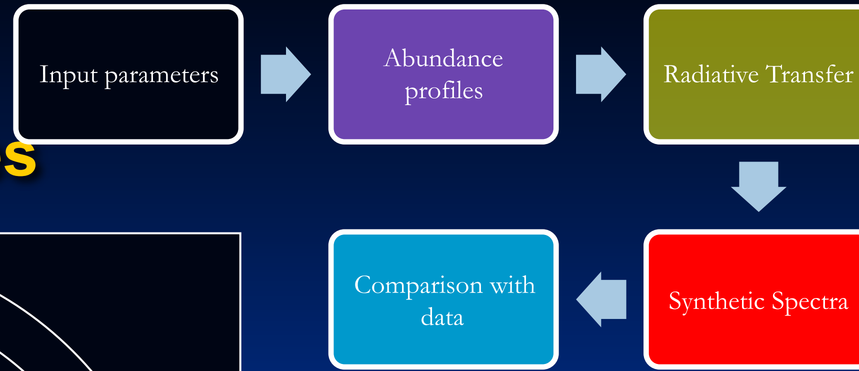
Spectral and **P**hotometric **I**maging **Re**ceiver (**SPIRE**).

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

Photometer: 250, 350, 500 μm

Spectrometer: 194- 672 μm.

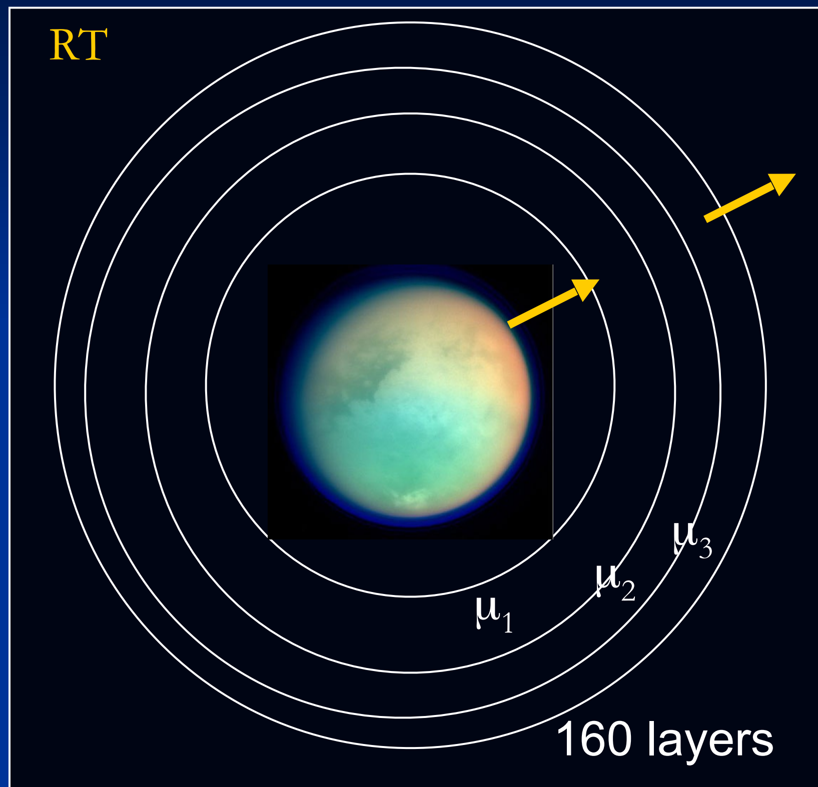
Modeling the Titan spectra
Method to determine abundances



T profile

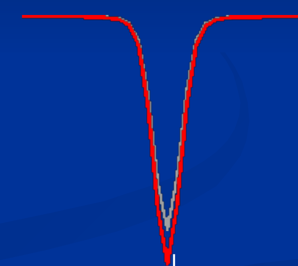
P profile

Vmr profile

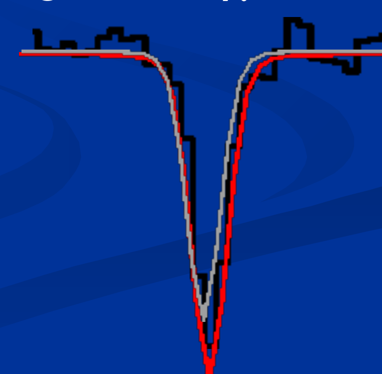


μ_i=absorption coefficient

Synthetic spectra

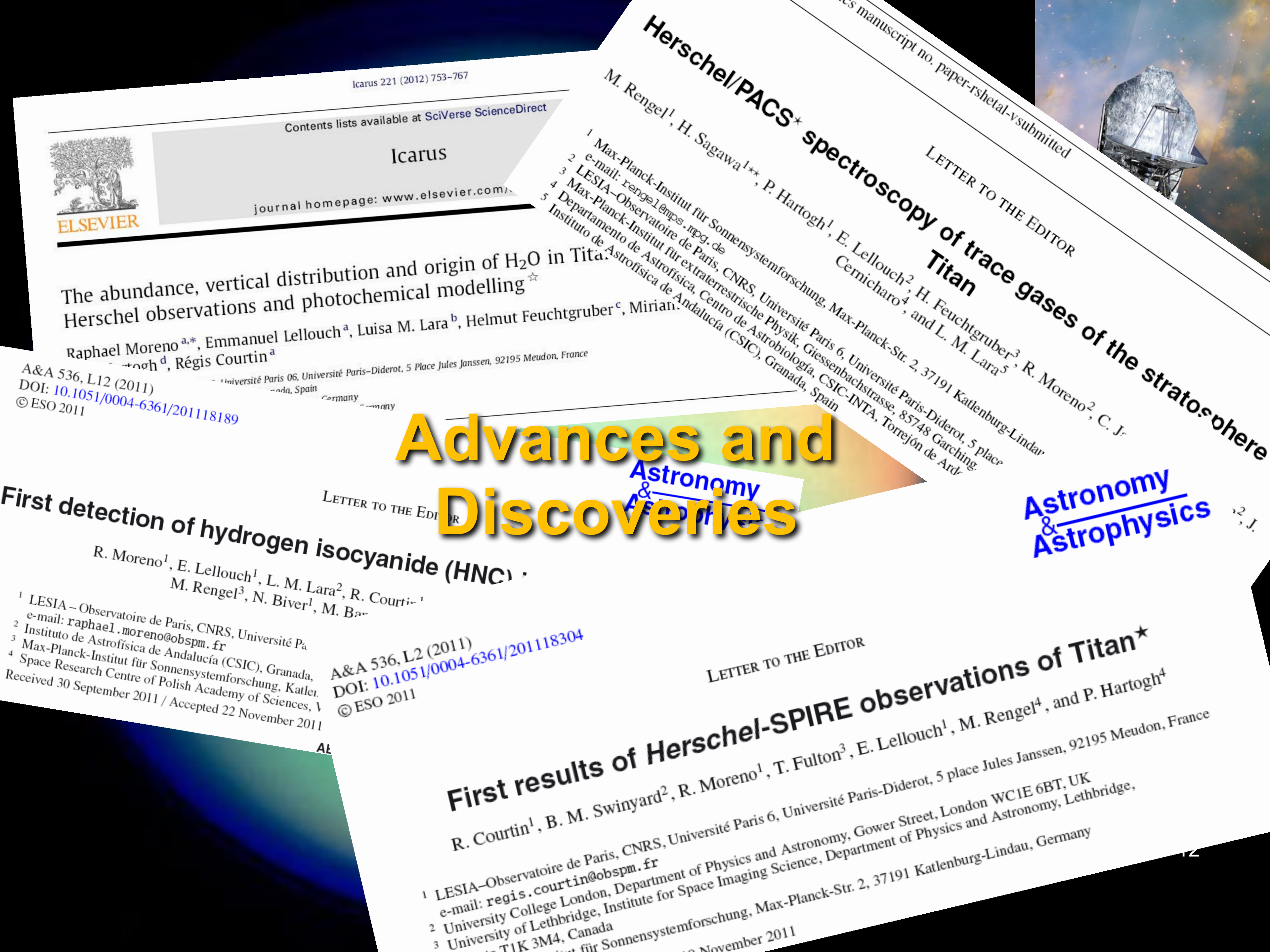


Fitting algorithm: χ^2 statistics



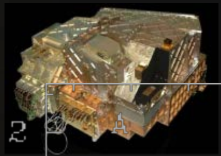
New set of parameters

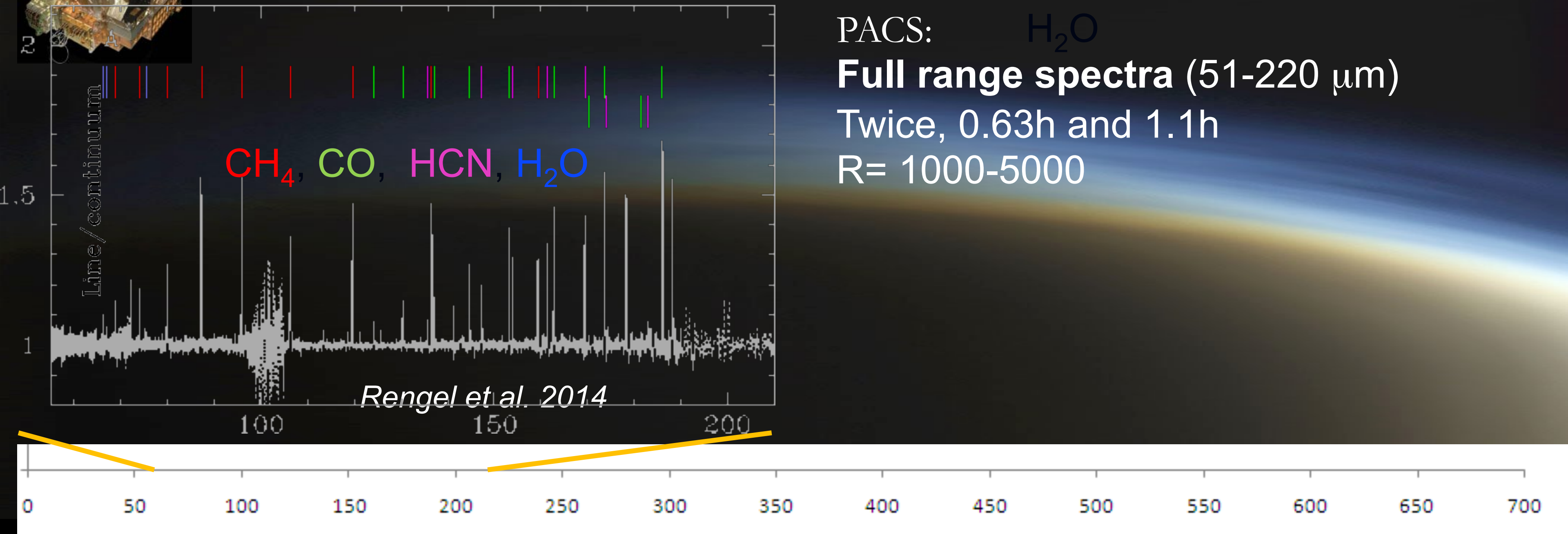
Advances and Discoveries



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

Numerous spectral emission features due to:





PACS: H_2O

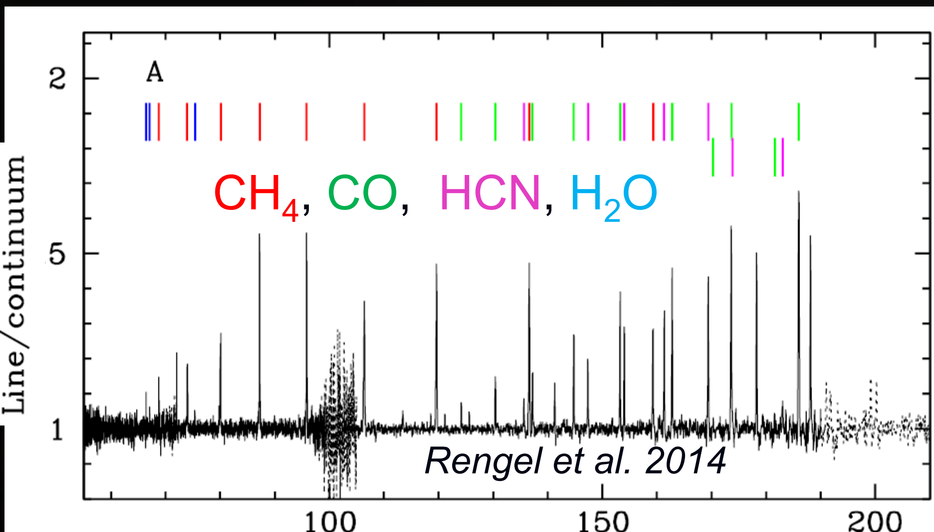
Full range spectra (51-220 μm)

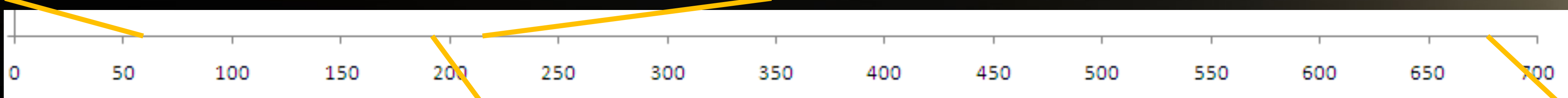
Twice, 0.63h and 1.1h

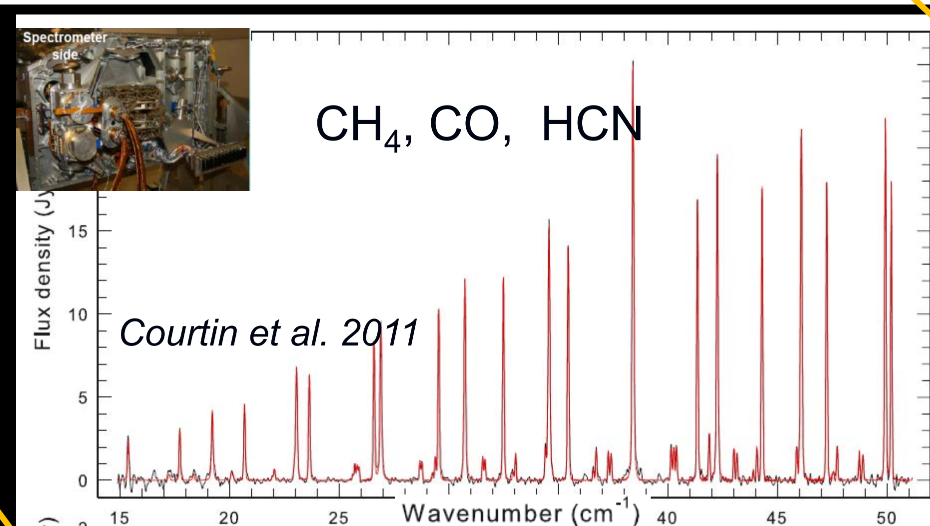
R= 1000-5000

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

Numerous spectral emission features due to:







SPIRE:

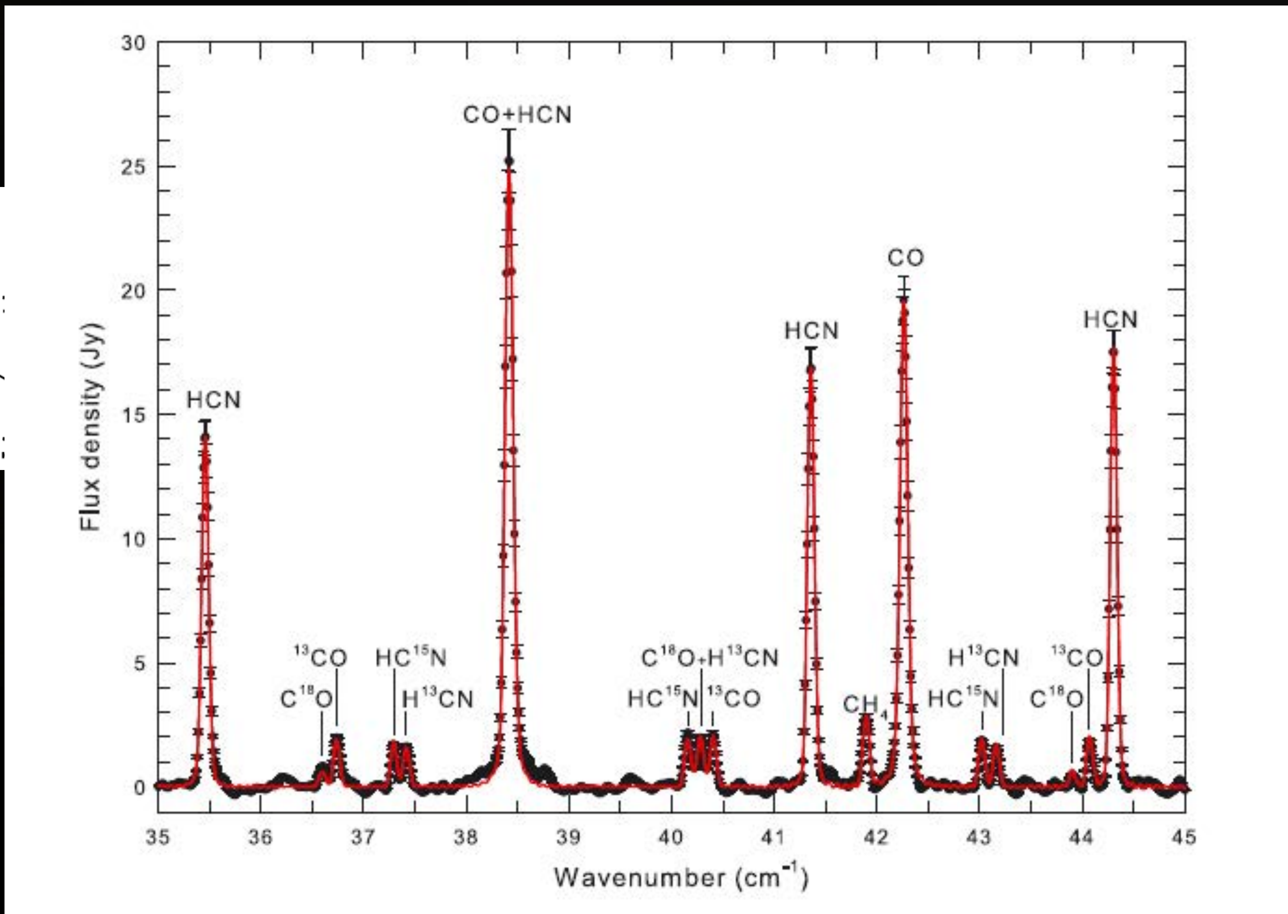
Full range spectrum (194 - 671 μm)

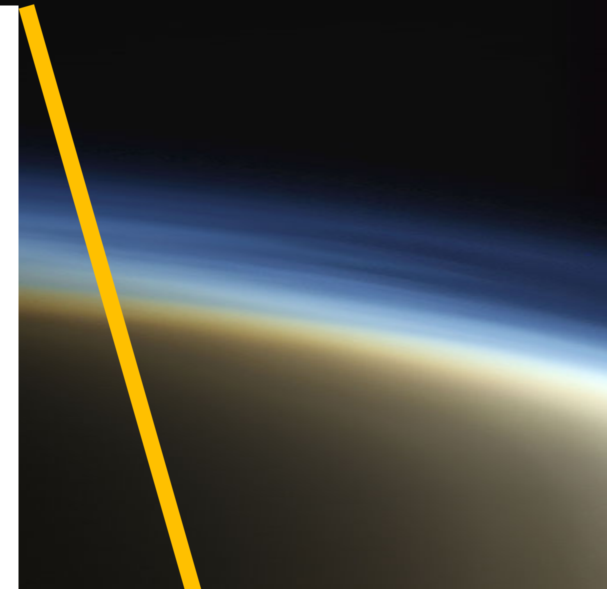
July 2010, ~8.9h,

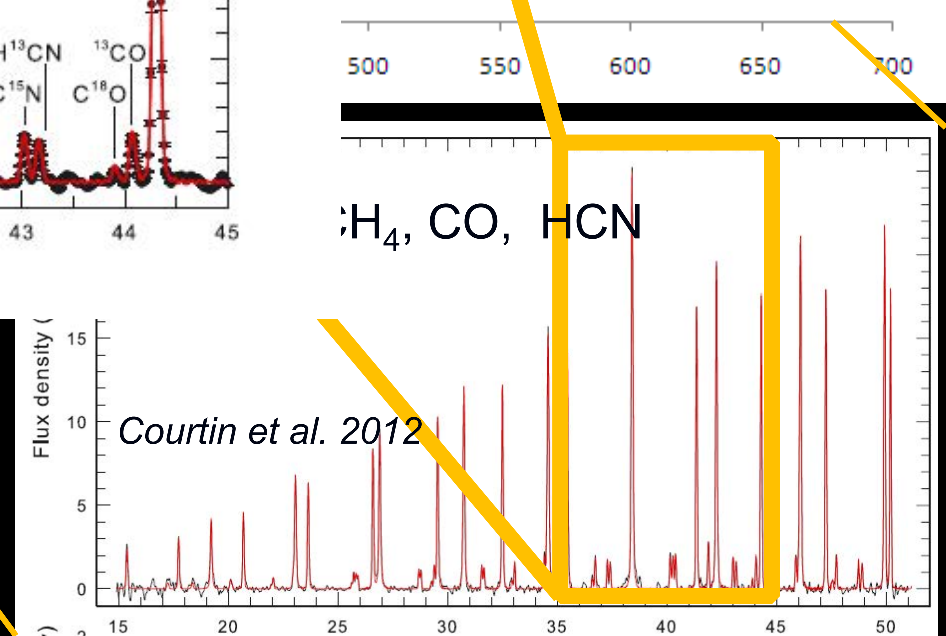
SR= 0.04 cm^{-1}

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

Numerous spectral emission features due to:

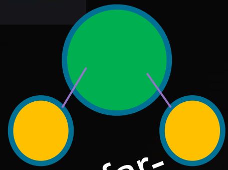




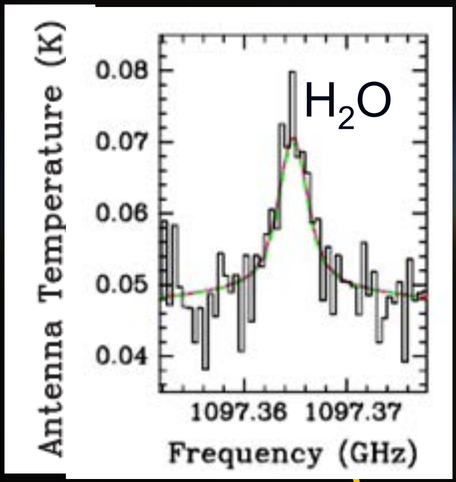


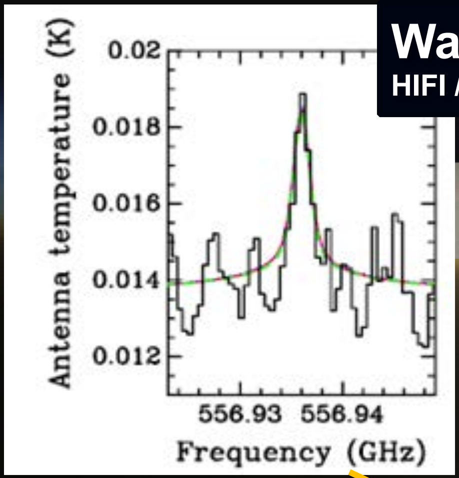
2.- Molecular Inventory with Herschel /PACS, SPIRE , and HIFI

Spectral emission features due to:

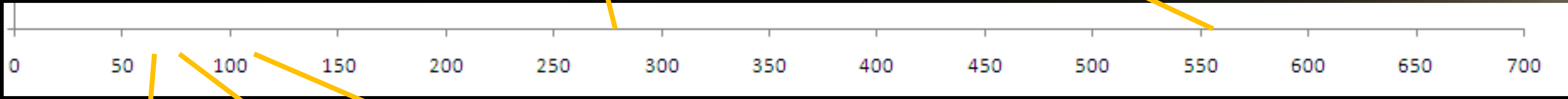


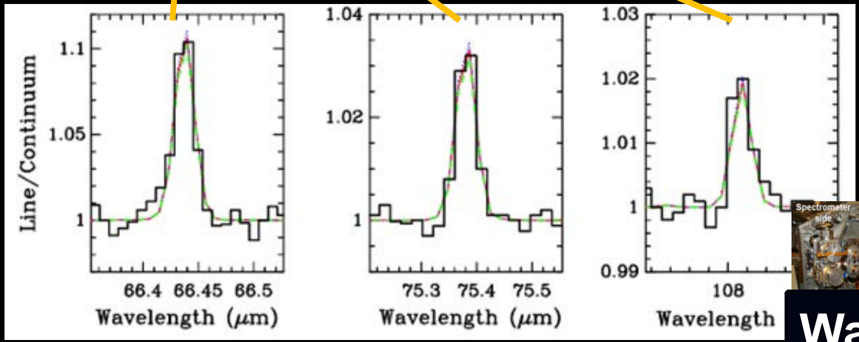
Several H_2O far-IR lines detected for the first time in Titan's atmosphere,





Water Vapour in Titan
HIFI / Herschel





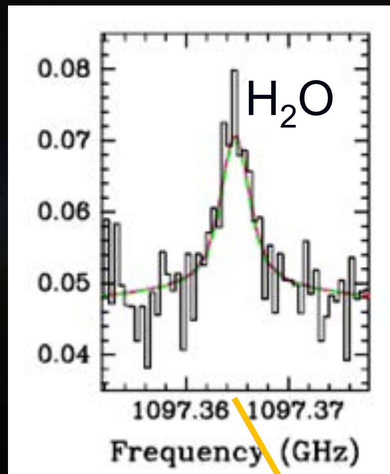
Water Vapour in Titan
PACS / Herschel

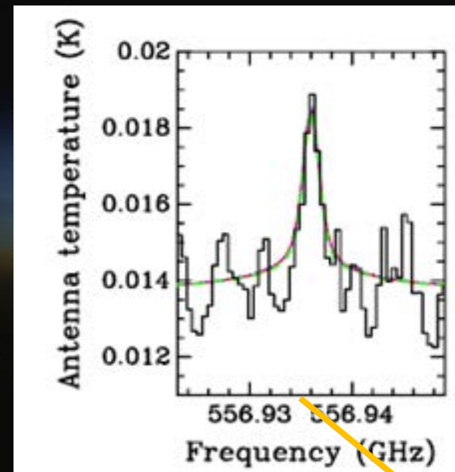
Five dedicated Water vapour line emission with Herschel/PACS and HIFI. Goal: vertical profile of H_2O

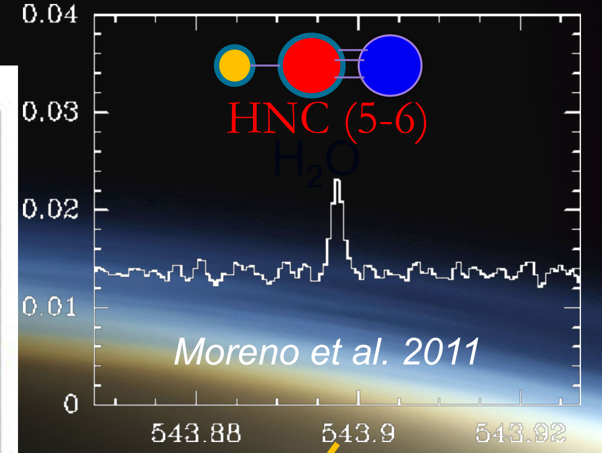
Moreno et al. 2012

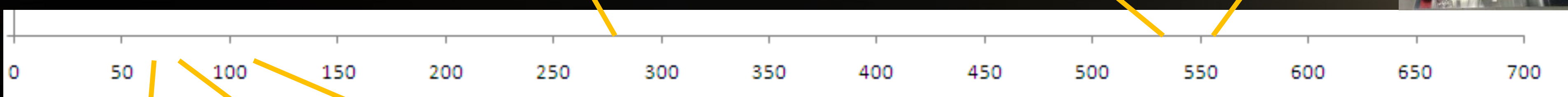
2.- Molecular Inventory with Herschel /PACS, SPIRE , and HIFI

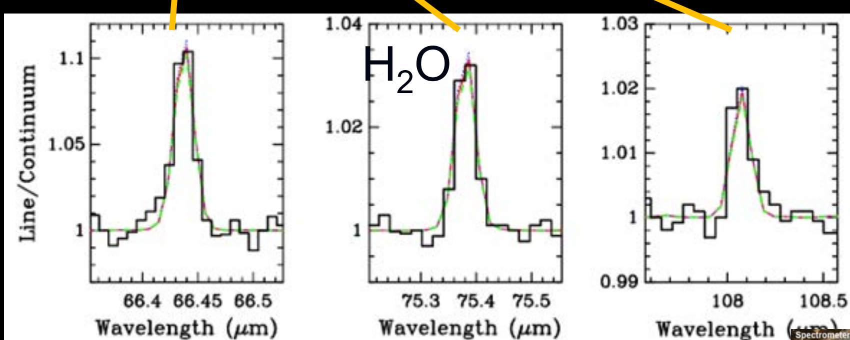
Spectral emission features due to:











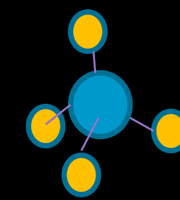
Surprise: Unexpected detection of hydrogen isocyanide (HNC) ➔ a specie not previously identified in Titan´s atmosphere

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

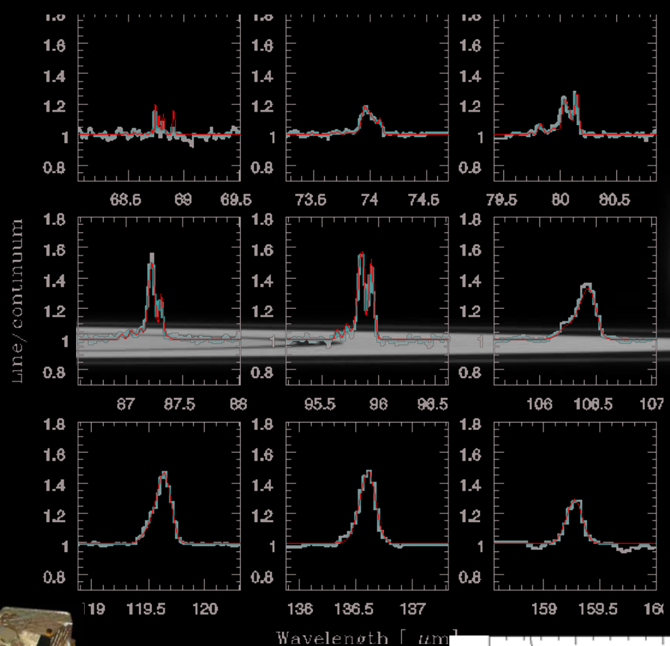
Step 1: Computation of the synthetic spectra for several abundances

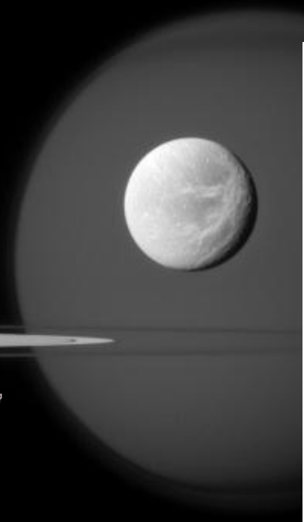
Step 2: Calculation of the best-fit

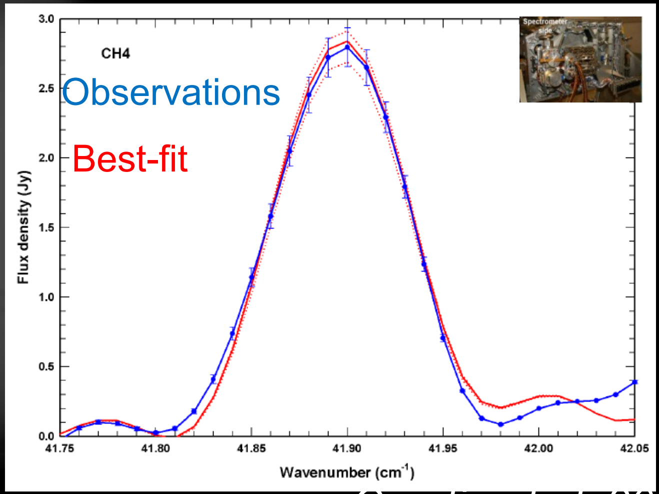
- **CH_4:** Origin unknown



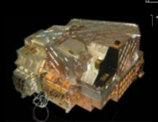
Observed and best-fit simulated CH_4 lines



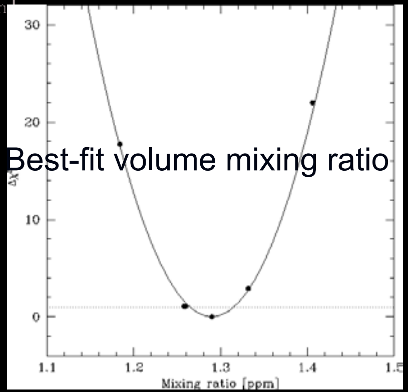




Courtin et al. 2011



Rengel et al. 2014



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. 2014**

Gas Composition of Titan’s atmosphere: CO

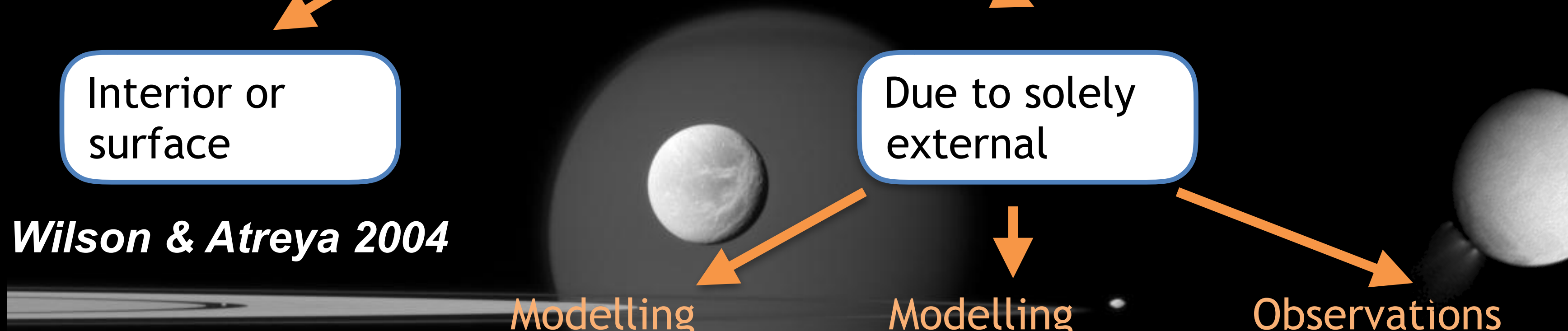
Is CO primordial or external ?

Possible Origin

Interior or surface

Wilson & Atreya 2004

Due to solely external



Modelling

Influx of O+ from Saturn’s magnetosphere

Modelling

Precipitation of O from Enceladus

Observations

Precipitation of O or O+ from Enceladus torus

Hörst et al. 2008

Krasnopolsky et al. 2009

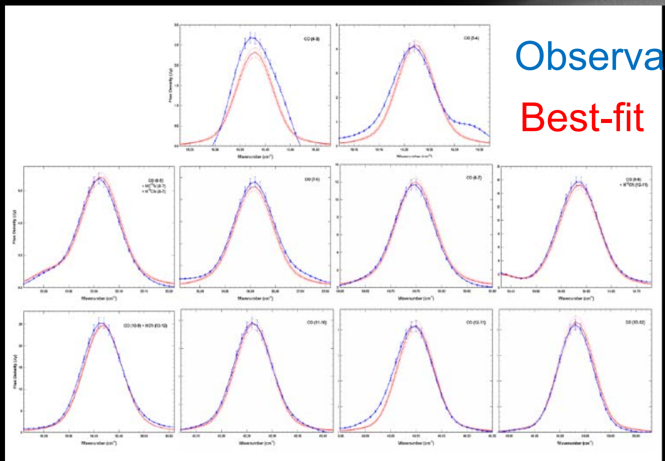
Cassidy & Johnson 2010

Hartogh et al. 2011

1.27 ± 0.03

Best-fit volume mixing ratio

Observed and best-fit simulated CO lines



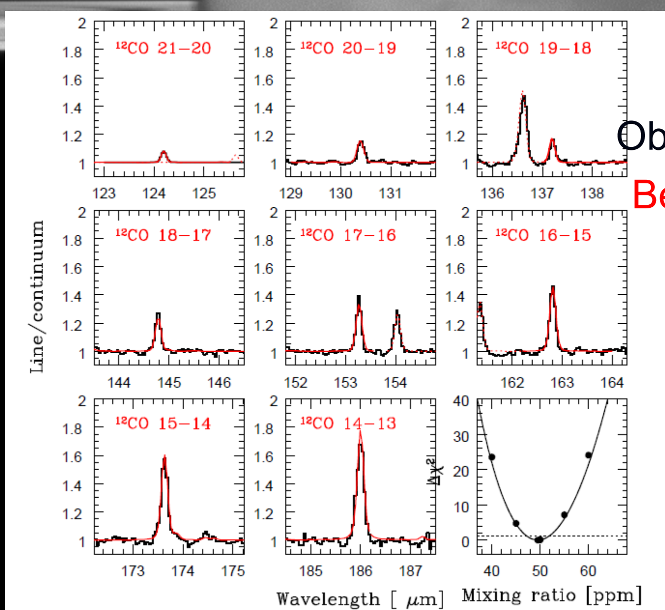
Observations

Best-fit

For the [60-170] km range altitude

Consistent with other 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. 2014***
ALMA	***46±2***	Serigano et al. 2016

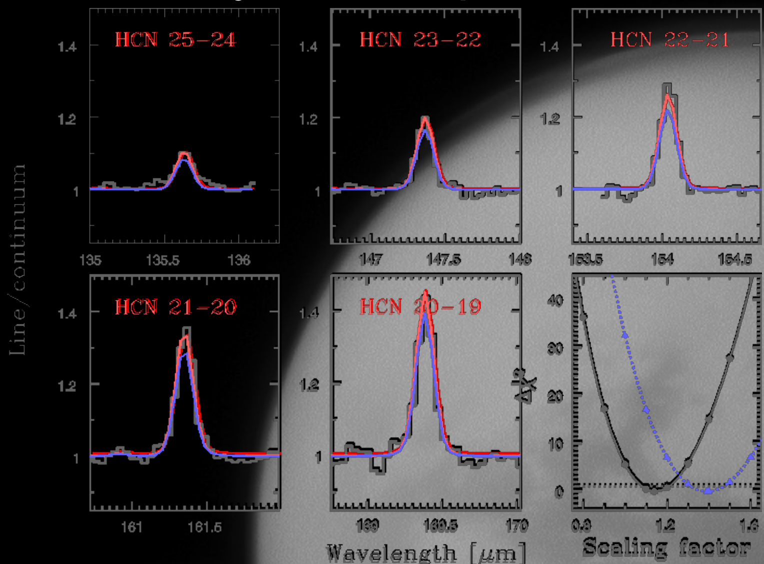


Observations

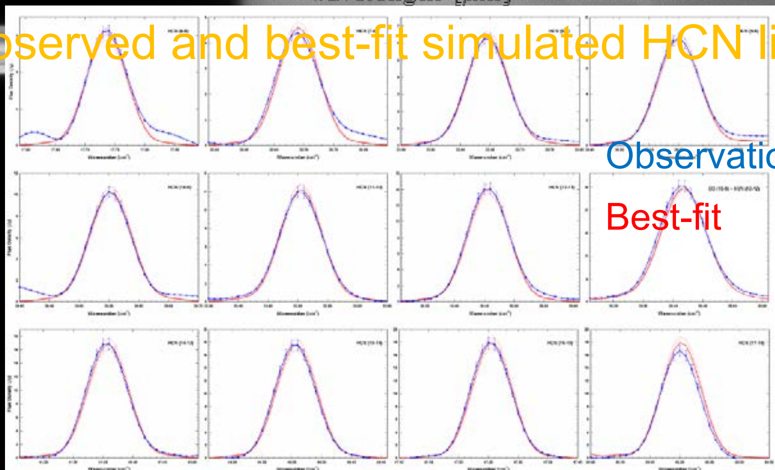
Best-fit

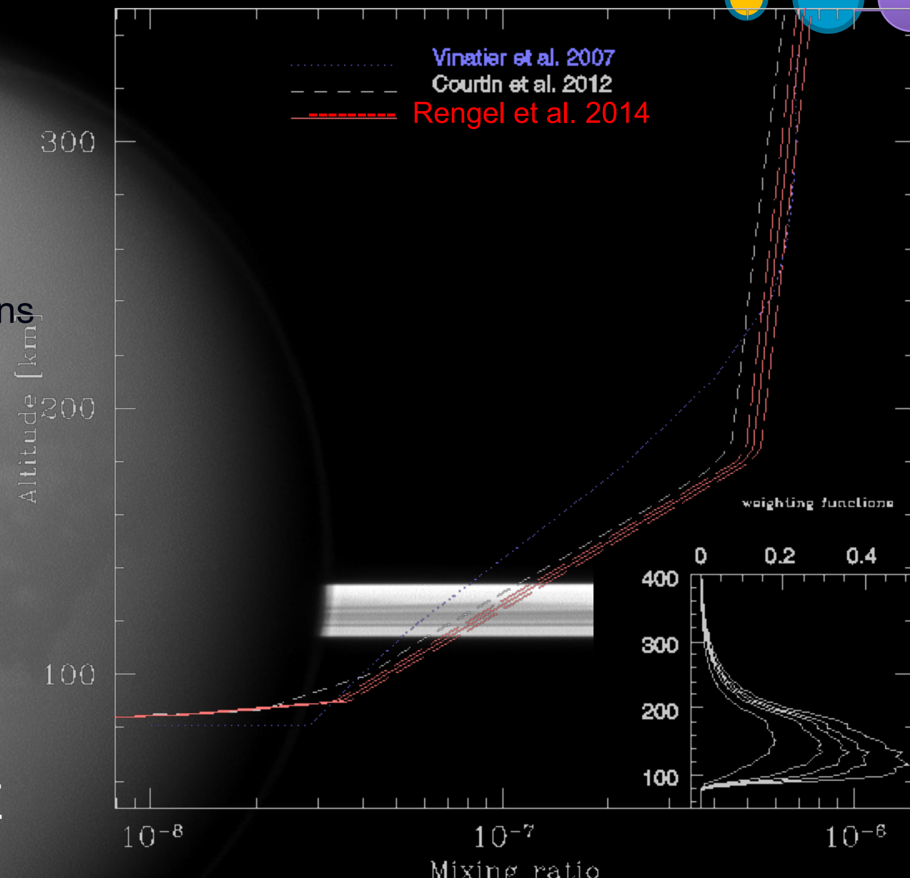
HCN vertical distribution **Generated photochemically**

- 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.

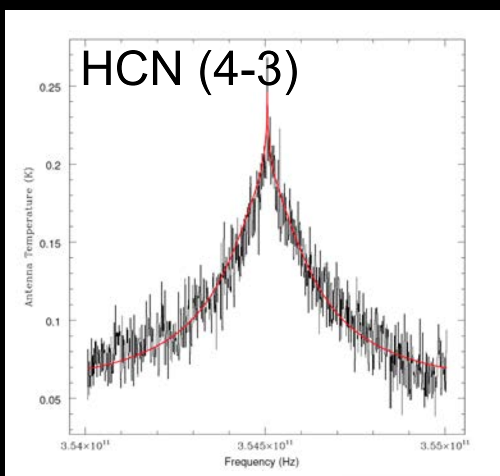
The CIRS distribution misfits the PACS observations at 1-σ level

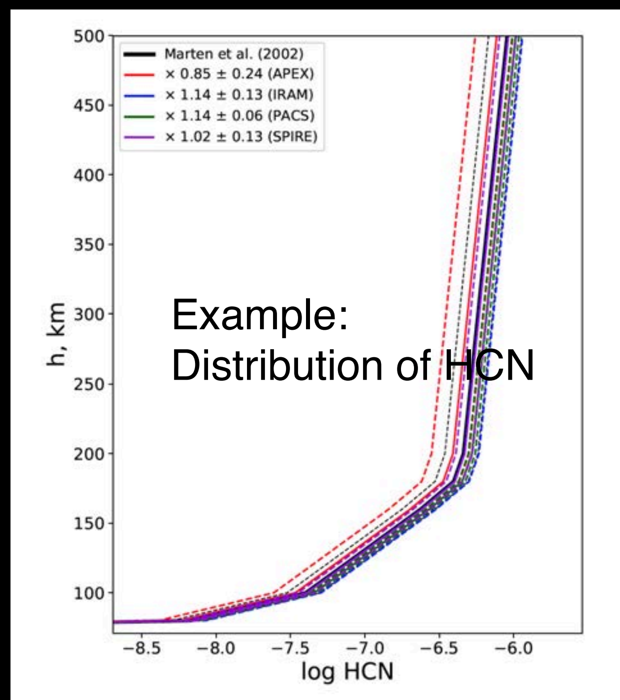
Rengel et al. 2014

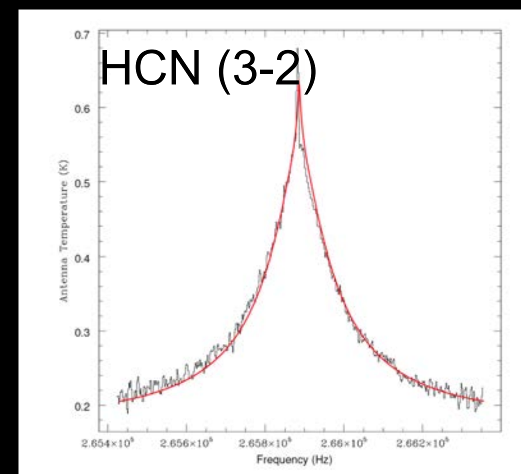
Complementary HCN ground-based observations

Time allocated. Projects:
•SV 081.F-9812(A), 21.3.08-27.6.08
•E-085.C-0910A-2010, 16.6.10-17.6.10

Time allocated. Projects:
•Proposal 145-10, 19 March 2011







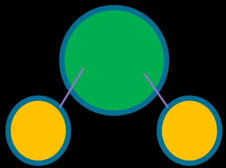
Measured HCN at similar epochs and with different transitions exhibit similar abundance distributions.

Rengel et al. in preparation

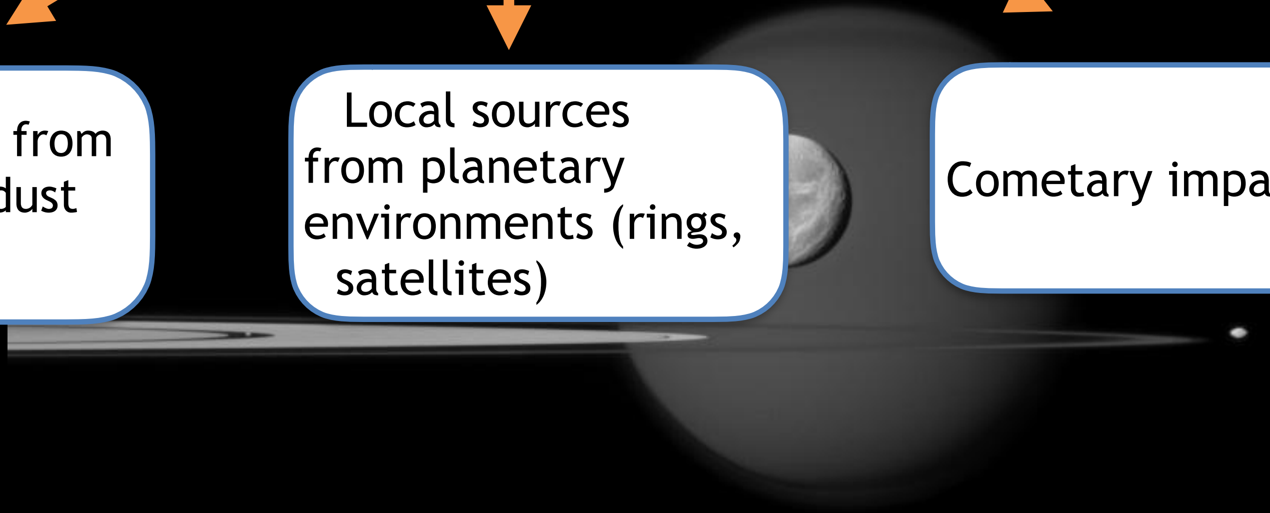
This cross-validation lets to drive reliable and consistent measurements

Gas Composition of Titan’s atmosphere: H_2O

What is the origen of water in Titan?



Possible Origin



Permanent flux from interplanetary dust particles

Local sources from planetary environments (rings, satellites)

Cometary impacts

What is the vertical profile of H_2O?

Can we disentangle the various sources?

1.27 ± 0.03

Best-fit volume mixing ratio

Water vertical distribution

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

- → Previous photochemical models for water must be revised

Observations vs. previous models

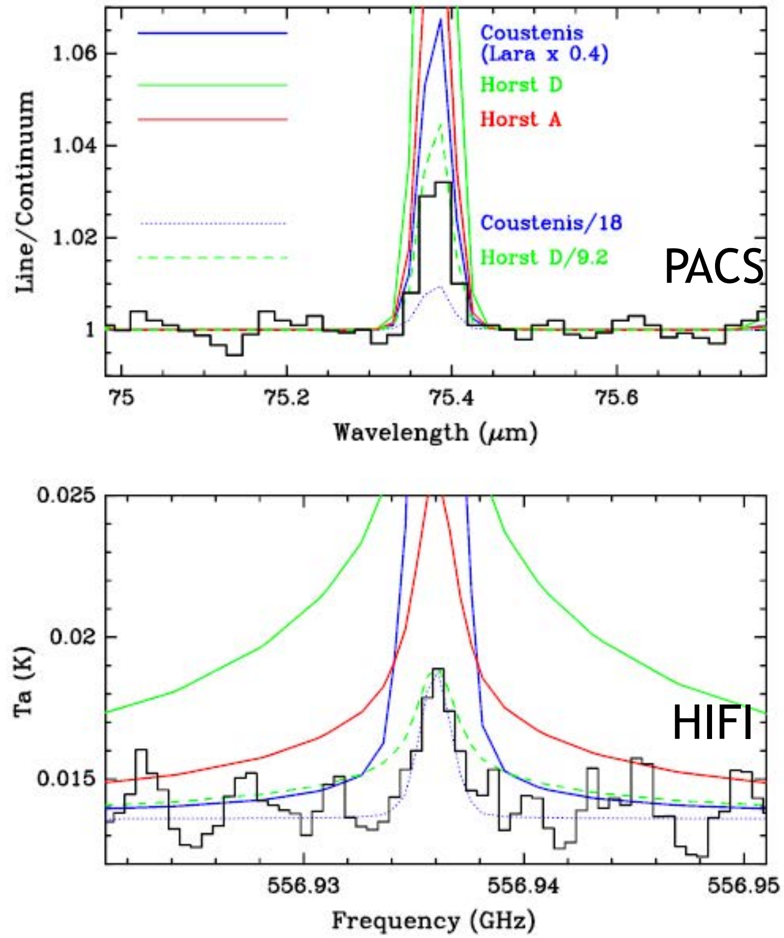
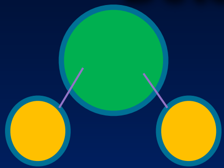


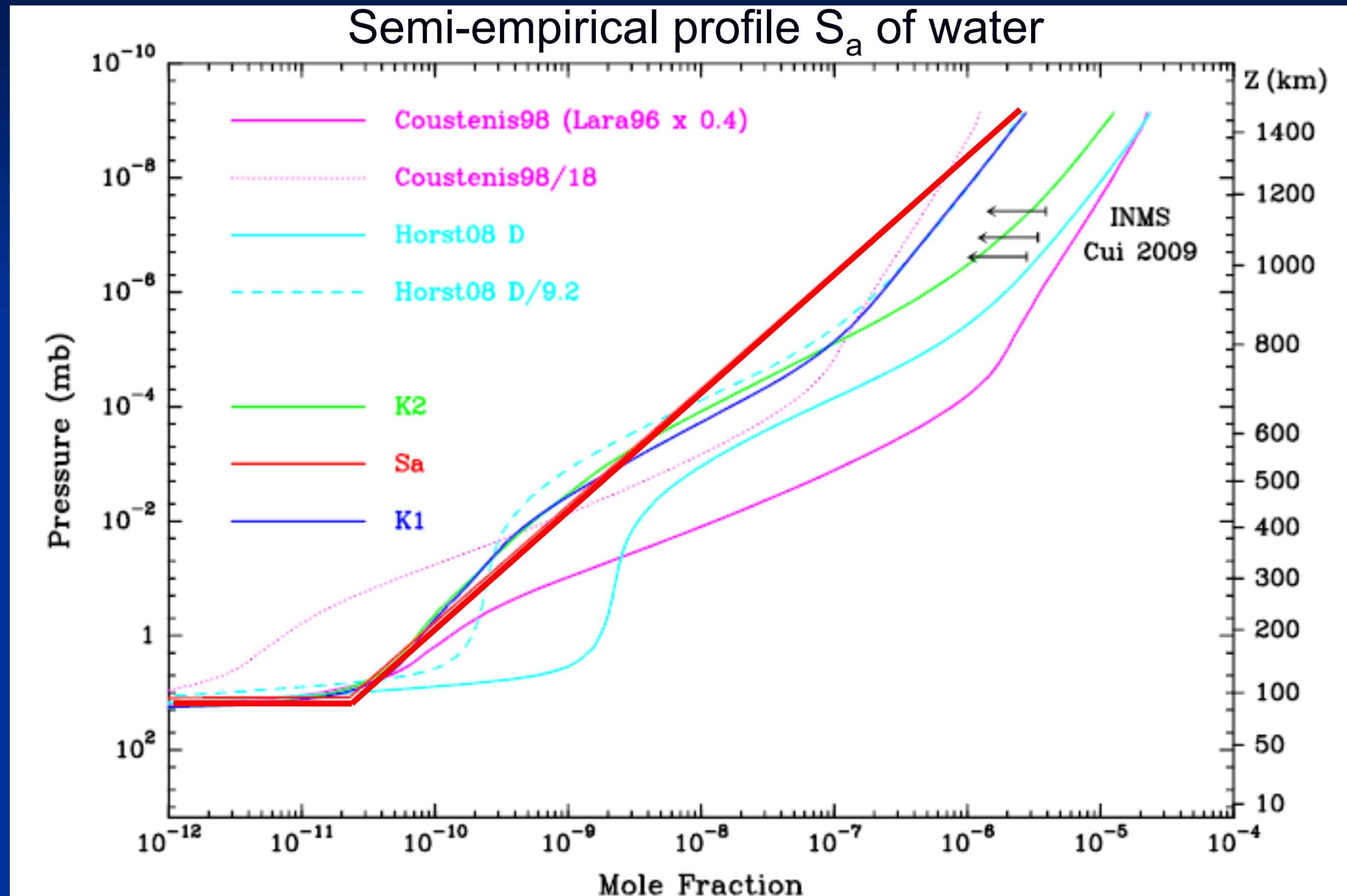
Fig. 7. Synthetic spectra computed considering several previously proposed H_2O profiles: Coustenis et al. (1998), Hörst et al. (2008) (model D and model A), and rescaled versions of these models. None of the models provides an adequate simultaneous match to the PACS observation at 75 μm (top) and HIFI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

Determination of the abundance of the trace constituents: Water vertical distribution



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

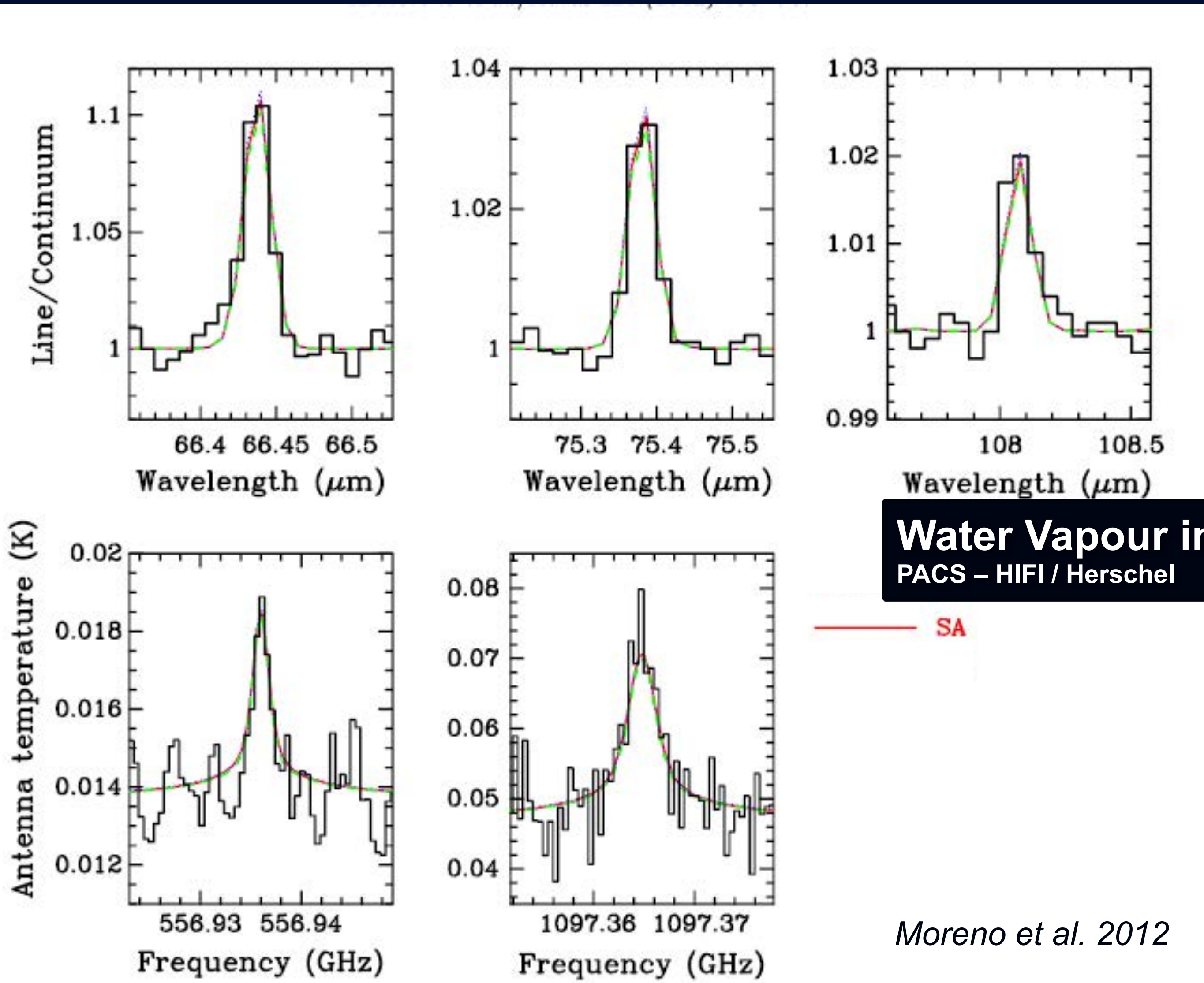
q_0 is the mixing ratio at the reference pressure level p_0



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}.

Moreno et al. 2012



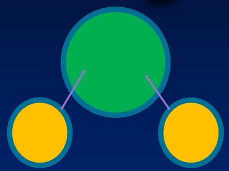
Water Vapour in Titan

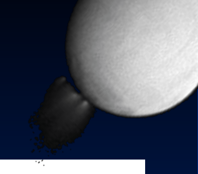
PACS – HIFI / Herschel

Moreno et al. 2012

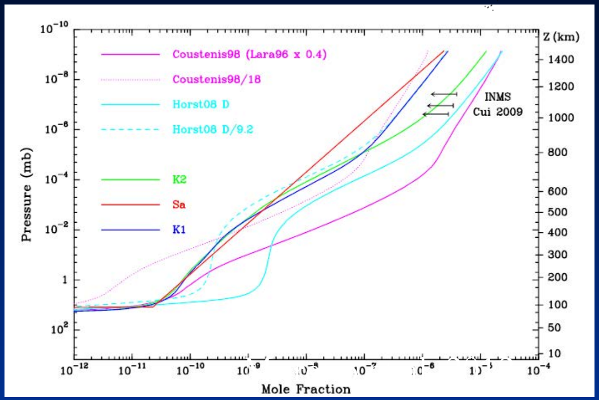
Observed and synthetic spectra

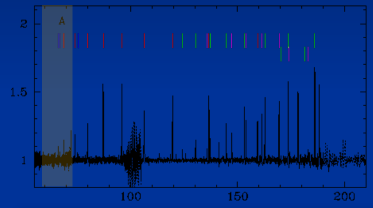
H_2O



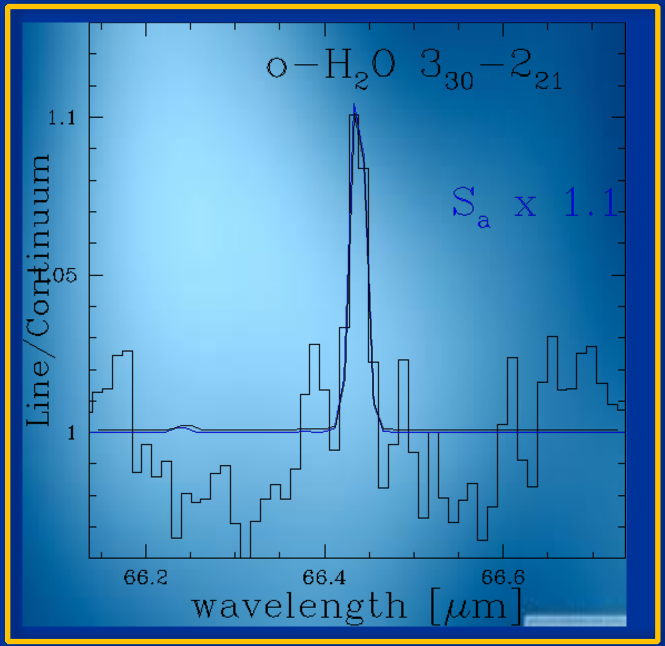


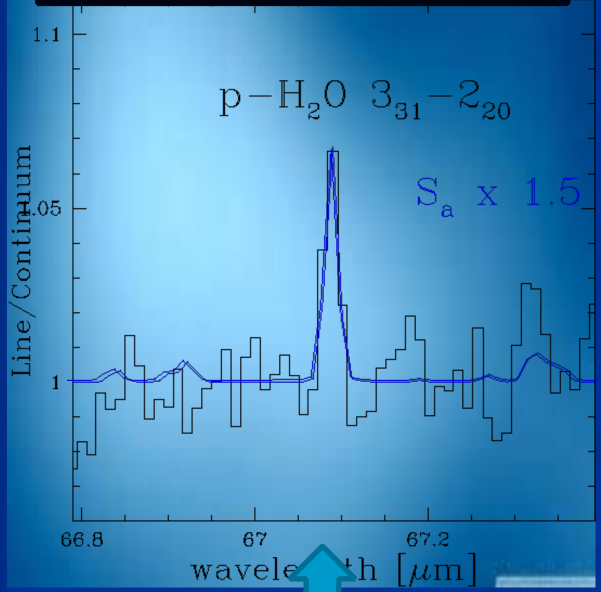
The S_a distribution is also compatible with the PACS lines from the full scan: computations of the synthetic spectra with S_a (*Moreno et al. 2012*).

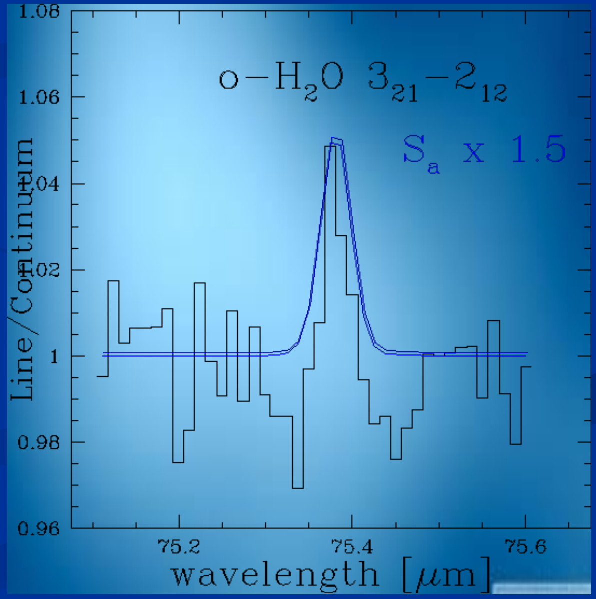




Water Vapour in Titan
PACS / Herschel





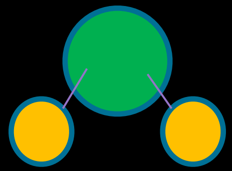


Detection for first time

Rengel et al. 2014

Gas Composition of Titan's atmosphere: H_2O

What is the origen of water in Titan?



- Titan is hit by a D >1.5 km comet every ~4 million years on average
- scarcity of primordial noble gases in its atmosphere

Possible Origin

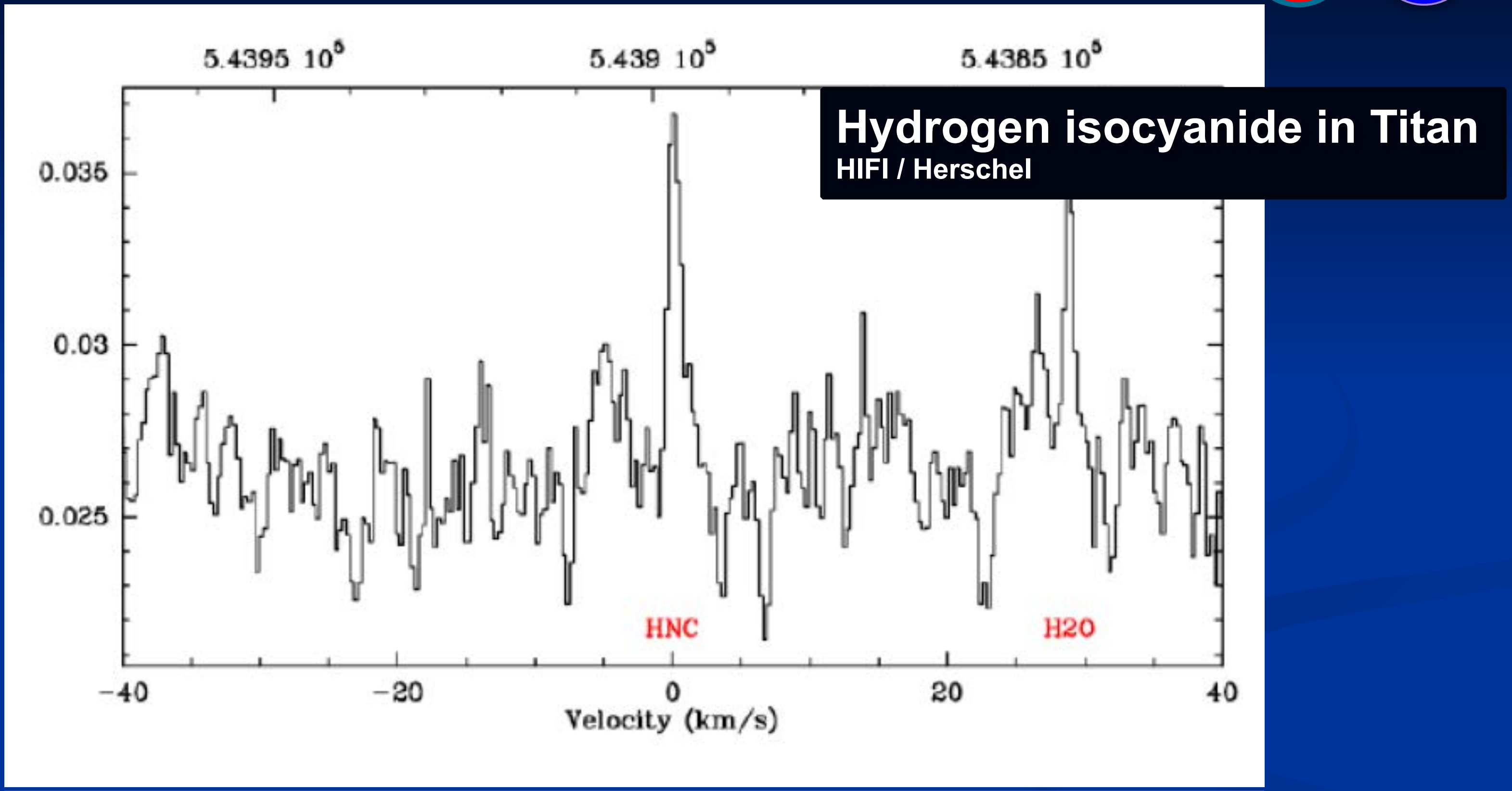
- Permanent flux from interplanetary dust particles
- Local sources from planetary environments: **Enceladus activity**
- Cometary impacts

Hartogh et al. 2011
Moreno et al. 2012

H_2O profile can be reproduced by invoking a OH/H_2O influx of (2.7–3.4) 10^5mol $cm^{-2}s^{-1}$

Reflects a temporal change in the oxygen influx into Titan

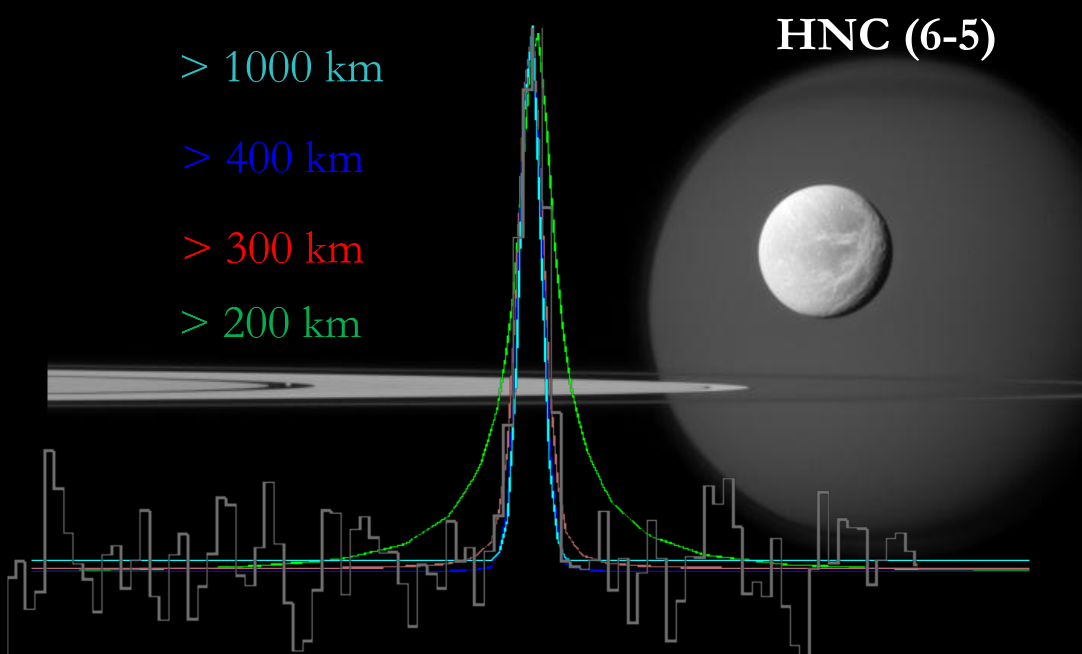
Determination of the abundance of the trace constituents: HNC



First detection of HNC in the Titan´s atmosphere

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

Models of the HNC 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:

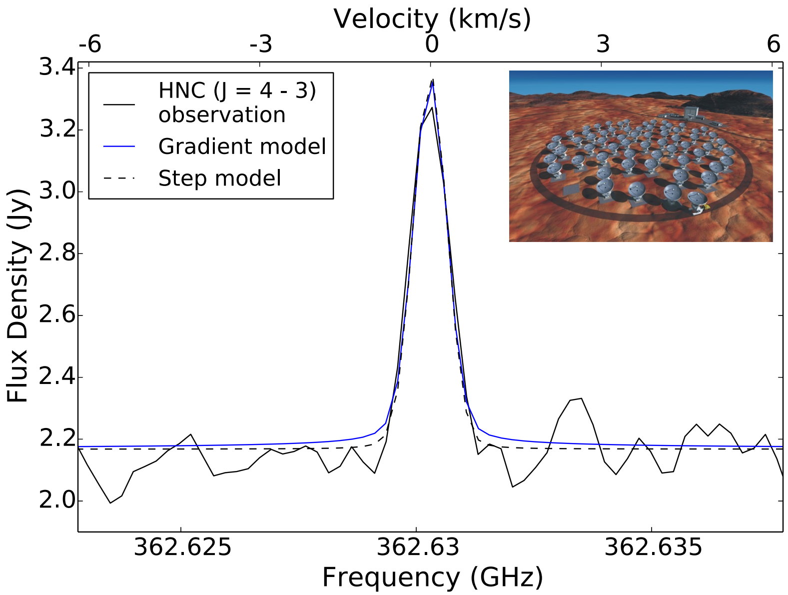
$(1.4\text{–}5) \times 10^5$ s →we expect diurnal variations of HNC

Is HNC restricted to the ionosphere?

Best fits:

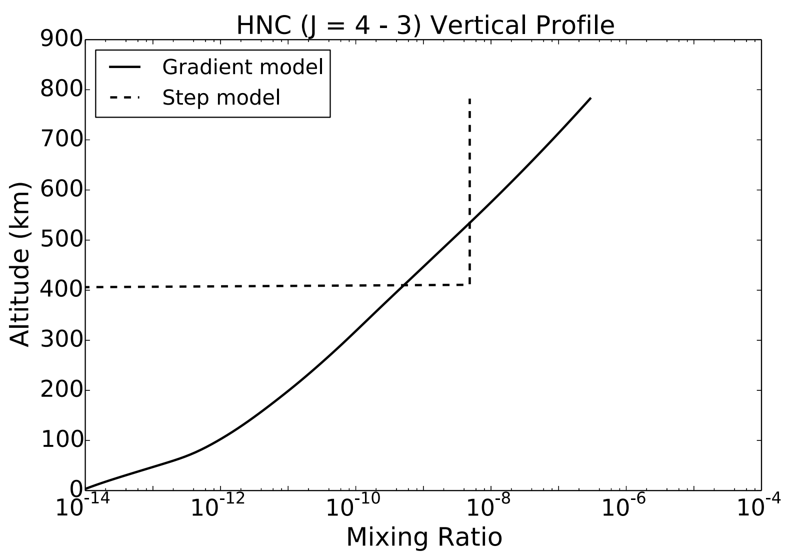
Profile	$\geq z_0$ (km)	Mixing ratio	Column (cm^{-2})
A	1000	$6.0^{+1.5}_{-1.0} \times 10^{-5}$	6.3×10^{12}
B	900	$1.4^{+0.3}_{-0.3} \times 10^{-5}$	6.9×10^{12}

Moreno et al. 2011

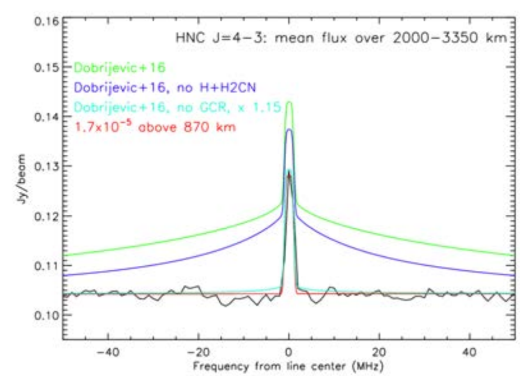


Facility	Value	Reference
HIFI	***4.5 $^{+1.2}_{-1.0}$ ppb***	***Moreno et al. 2011***
ALMA	***4.85 ± 0.28 ppb***	***Cordiner et al. 2014***

Emission models that take into account the shapes of the resolved spectral line profiles confirm the result of Moreno et al. (2012) that HNC is predominantly confined to altitudes > 400 km.

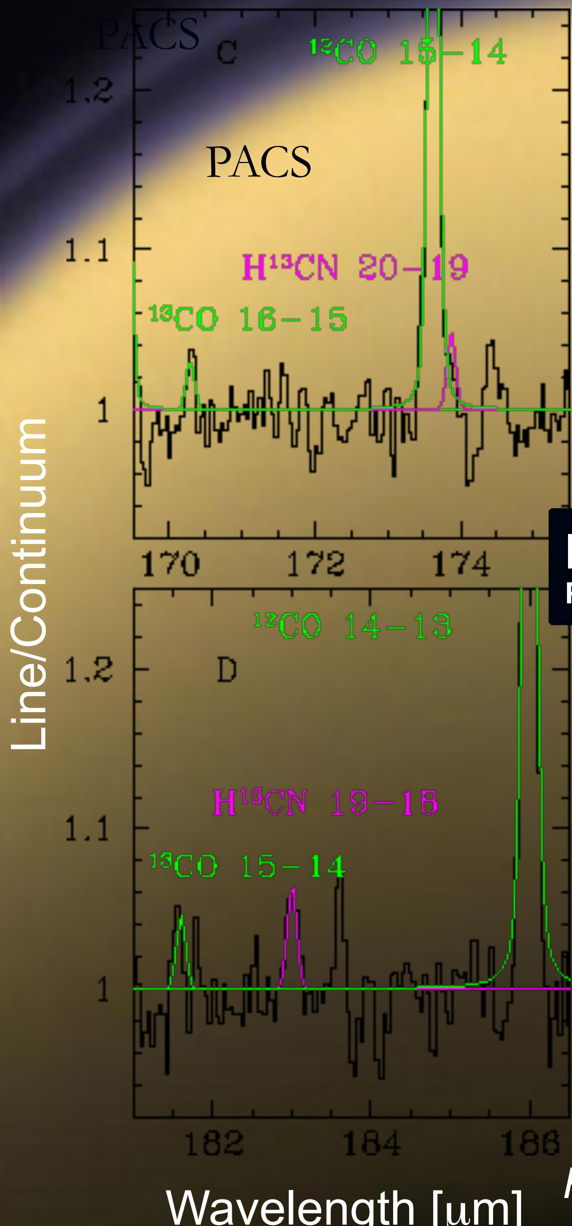


Cordiner et al. 2014



HNC distribution is restricted to Titan's thermosphere above ~870 km altitude (Lellouch et al. 2019).

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



Rengel et al. 2014

Detection of the isotopes:
- ^{13}CO(15-14) and (16-15)
- $H^{13}CN$ (19-18) and (20-19)

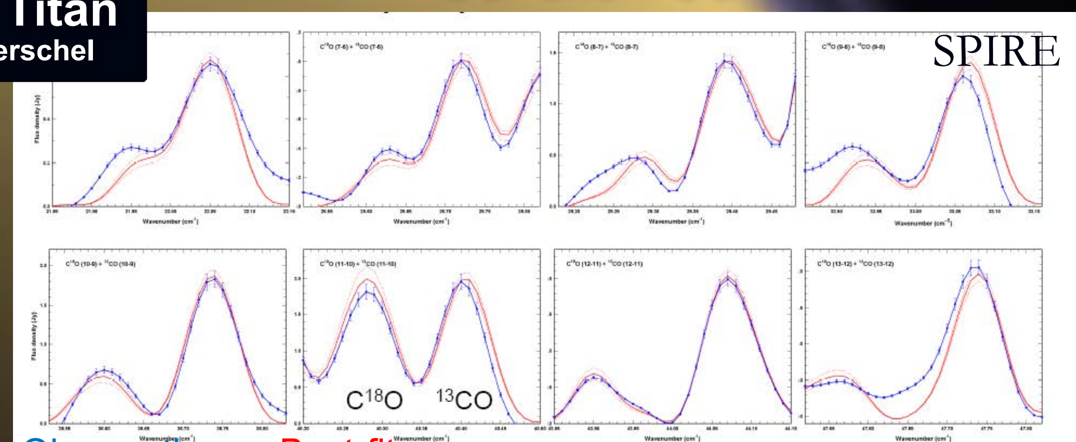
but marginal

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

Isotopic ratio $^{12}C/^{13}C$ in CO

Deriving isotopic ratios

Deviations from values of other bodies?

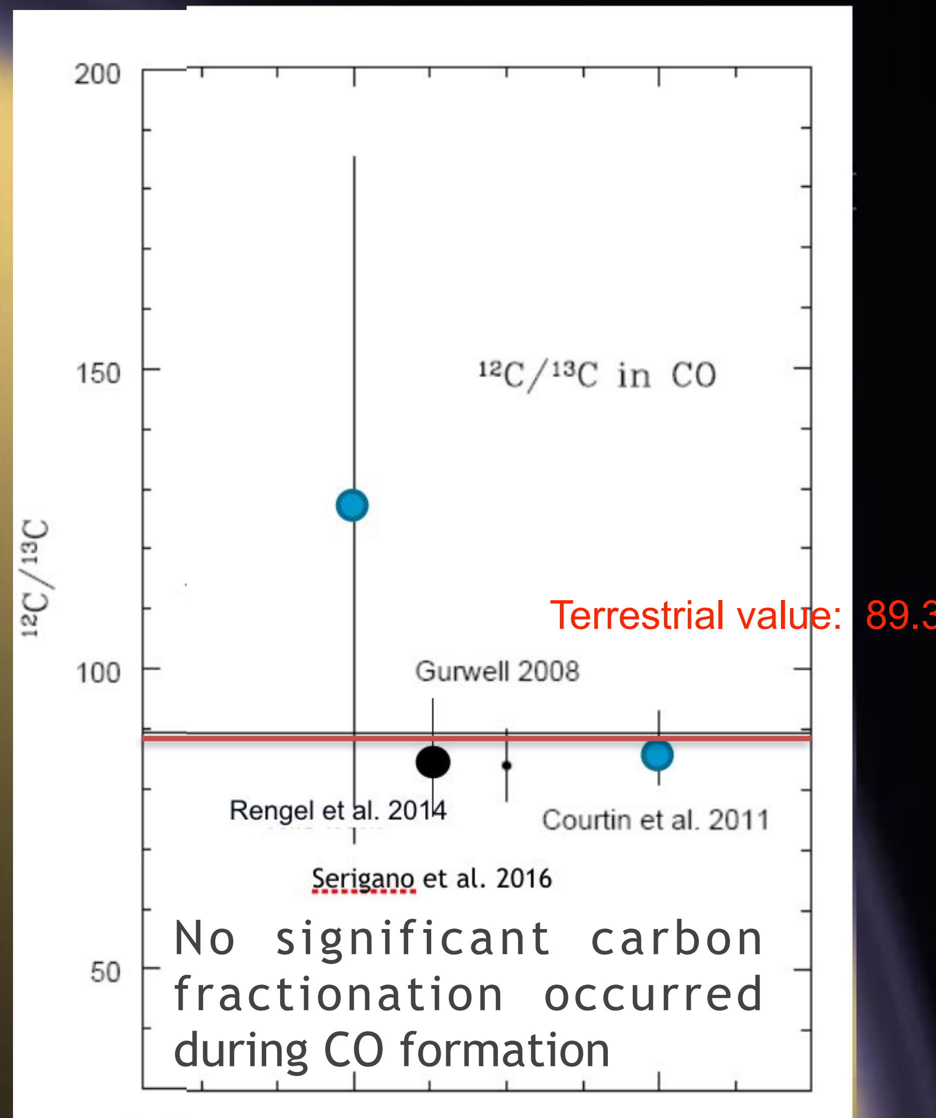
No

Yes

Primordial differences

Emerged on time

No significant fractionation



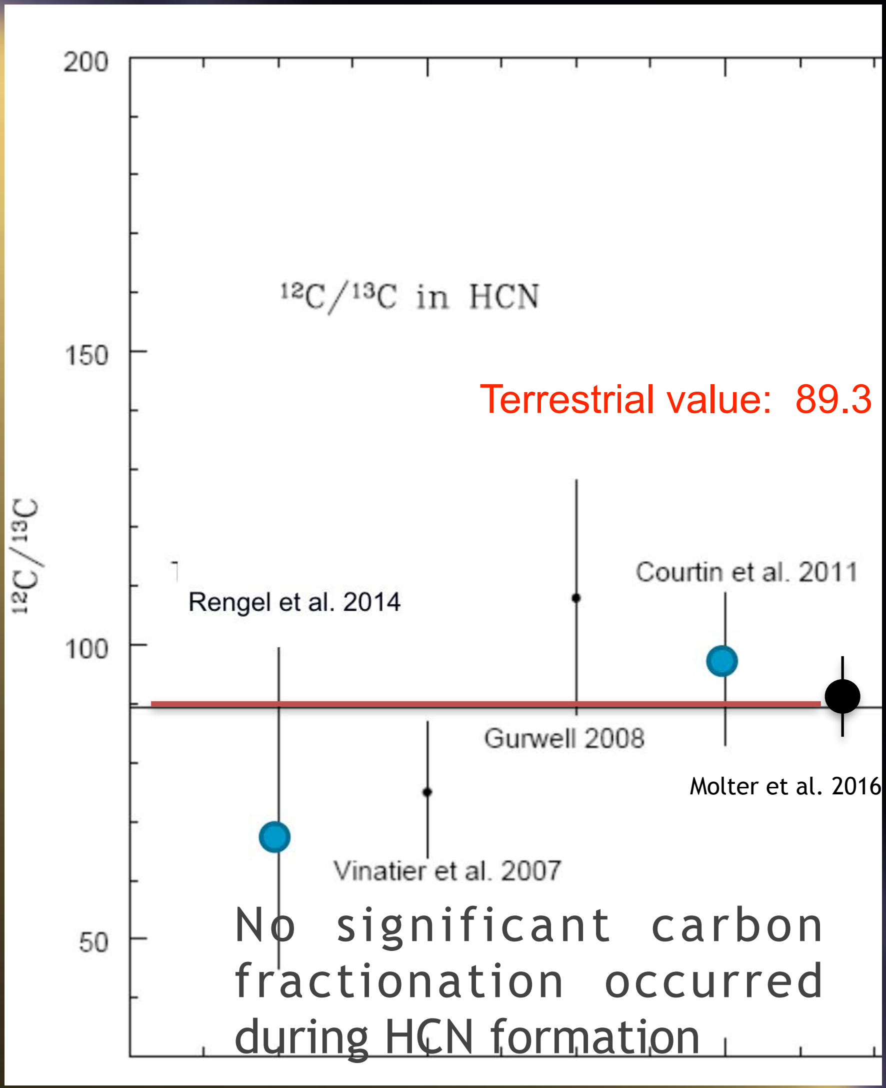
Isotopic ratio $^{12}C/^{13}C$ in HCN

Deriving isotopic ratios

Deviations from values of other bodies?

No → No significant fractionation

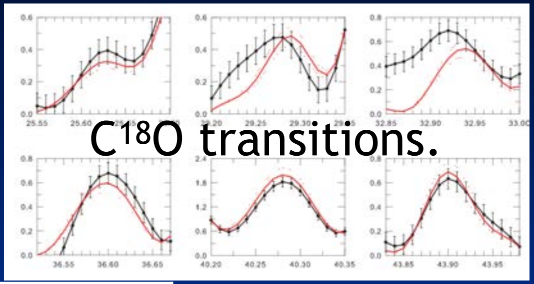
Yes → Primordial differences / Emerged on time



No significant carbon fractionation occurred during HCN formation

Isotopic ratio $^{16}O/^{18}O$ in CO

Courtin et al. 2012



$^{16}O/^{18}O$

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***
ALMA	***414 ± 45***	*Serigano et al. 2016*

Terrestrial value: 500

- 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 (enrichment of ^{18}O).

What is the origin?

Isotopic ratio $^{16}O/^{18}O$ in CO

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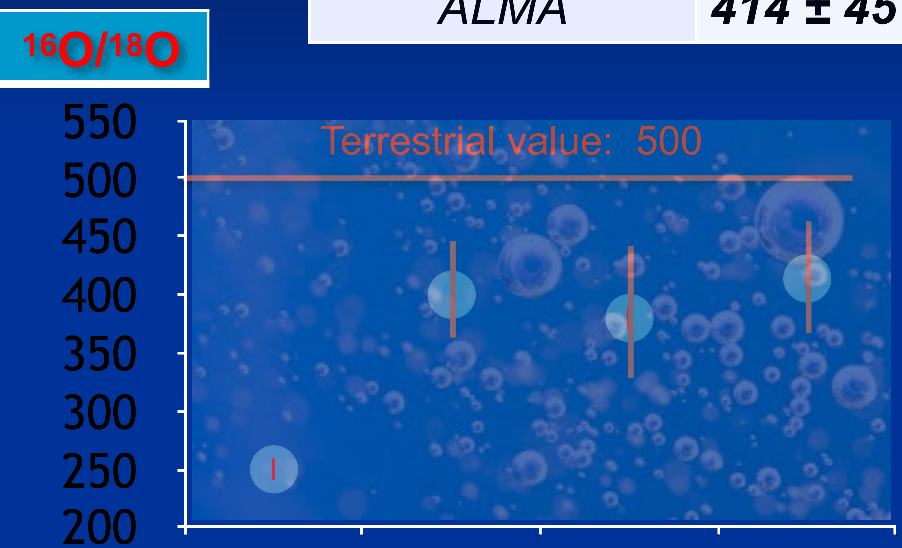

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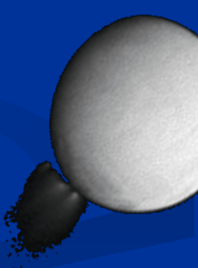
What is the origin?



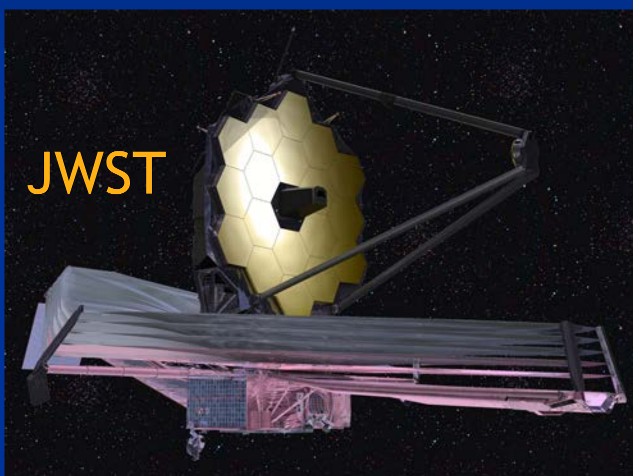
Precipitation of O^+ or O from the Enceladus Torus

Further investigations :
- evolution of oxygen on Titan
- Oxygen processes in Titan’s atmosphere

5.- Future – Synergy with Herschel

- CASSINI/CIRS (extended mission), until 2017. Flybys of Titan.

- JWST

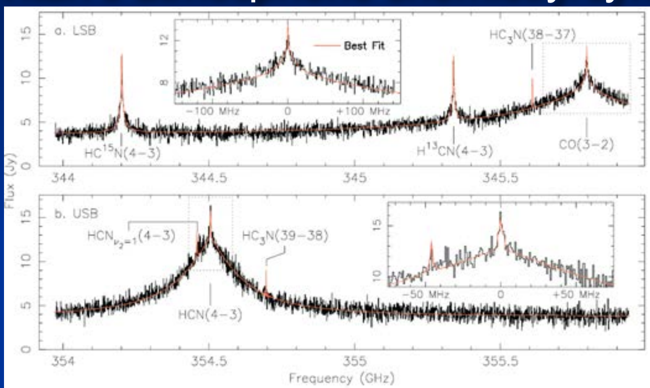


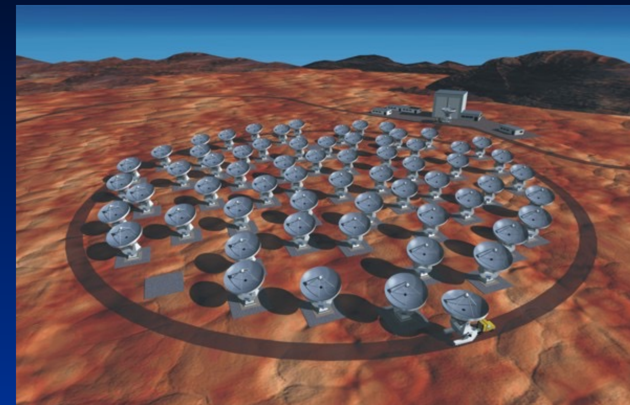
- Science Focus Group with key science themes:
  - Titan´s composition of the middle atmosphere
  - Objectives: Long-term monitoring of the changing spatial distributions of gases, clouds and hazes —> reveal the interplay of chemistry and dynamics

Future – Synergy with Herschel

- ALMA :

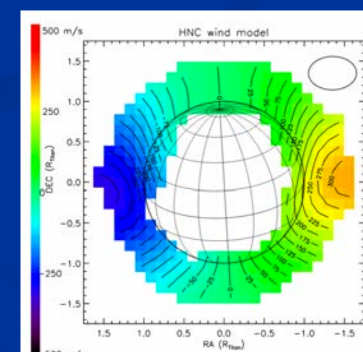
Titan's atmospheric chemistry/dynamics





Gurwell 2004

SMA 850 micron unresolved observations



Lellouch et al. 2019

- Search for more complex species
- 3D-mapping and monitoring: seasonal variations
- Dynamics/photochemistry coupling
- Direct measurement of mesospheric (500 km) winds
- Additional observations at higher angular resolution (up to 0.005") will allow for more accurate isotopic ratios and species abundances

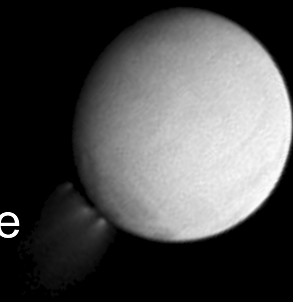
- SOFIA

6.- Conclusion

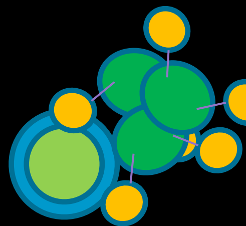
Herschel´s Legacy

- Survey between 51 and 671 μm: CH_4, **CO**, HCN, **H_2O**, **isotopes**
- Determination of abundances
- Unexpected detection of HNC : Above 400 km, Titan´s atmosphere also contains HNC
- Measurement of $^{12}C/^{13}C$ and $^{16}O/^{18}O$ ratio

Emerged oxygen-related Implications:



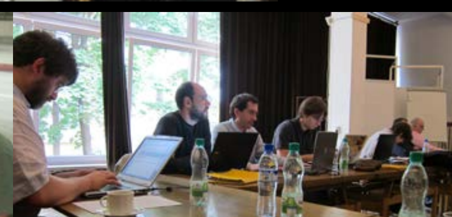
- ^{18}O enrichment in Titan´s atmosphere: Precipitation of O^+ or O from the Enceladus plume activity ($^{16}O/^{18}O$)



- We now know the content of water vapour in Titan (different as the predictions) and from where is coming from

- Titan’s HCN and CO data acquired at different and similar epochs (Herschel, APEX and IRAM) shows a great similarly of recorded spectra

HssO



Acknowledgments

- HIFI has been designed and built by a consortium of institutes and university departments from across Europe, Canada and the United States under the leadership of SRON Netherlands Institute for Space Research, Groningen, The Netherlands and with major contributions from Germany, France and the US. Consortium members are: Canada: CSA, U.Waterloo; France: CESR, LAB, LERMA, IRAM; Germany: KOSMA, MPIfR, MPS; Ireland, NUI Maynooth; Italy: ASI, IFSI-INAF, Osservatorio Astrofisico di Arcetri-INAF; Netherlands: SRON, TUD; Poland: CAMK, CBK; Spain: Observatorio Astronómico Nacional (IGN), Centro de Astrobiología (CSIC-INTA). Sweden: Chalmers University of Technology - MC2, RSS & GARD; Onsala Space Observatory; Swedish National Space Board, Stockholm University - Stockholm Observatory; Switzerland: ETH Zurich, FHNW; USA: Caltech, JPL, NHSC.

- PACS has been developed by a consortium of institutes led by MPE (Germany) and including UVIE (Austria); KUL, CSL, IMEC (Belgium); CEA, OAMP (France); MPIA (Germany); IFSI, OAP/AOT, OAA/CAISMI, LENS, SISSA (Italy); IAC (Spain). This development has been supported by the funding agencies BMVIT (Austria), ESA-PRODEX (Belgium), CEA/CNES (France), DLR (Germany), ASI (Italy), and CICT/MCT (Spain). Additional funding support for some instrument activities has been provided by ESA.

- SPIRE has been developed by a consortium of institutes led by Cardiff University (UK) and including Univ. Lethbridge (Canada); NAOC (China); CEA, LAM (France); IFSI, Univ. Padua (Italy); IAC (Spain); Stockholm Observatory (Sweden); Imperial College London, RAL, UCL-MSSL, UKATC, Univ. Sussex (UK); and Caltech, JPL, NHSC, Univ. Colorado (USA). This development has been supported by national funding agencies: CSA (Canada); NAOC (China); CEA, CNES, CNRS (France); ASI (Italy); MCINN (Spain); SNSB (Sweden); STFC, UKSA (UK); and NASA (USA).