Tracing the gas composition of Titan´s atmosphere with Herschel: Advances and discoveries

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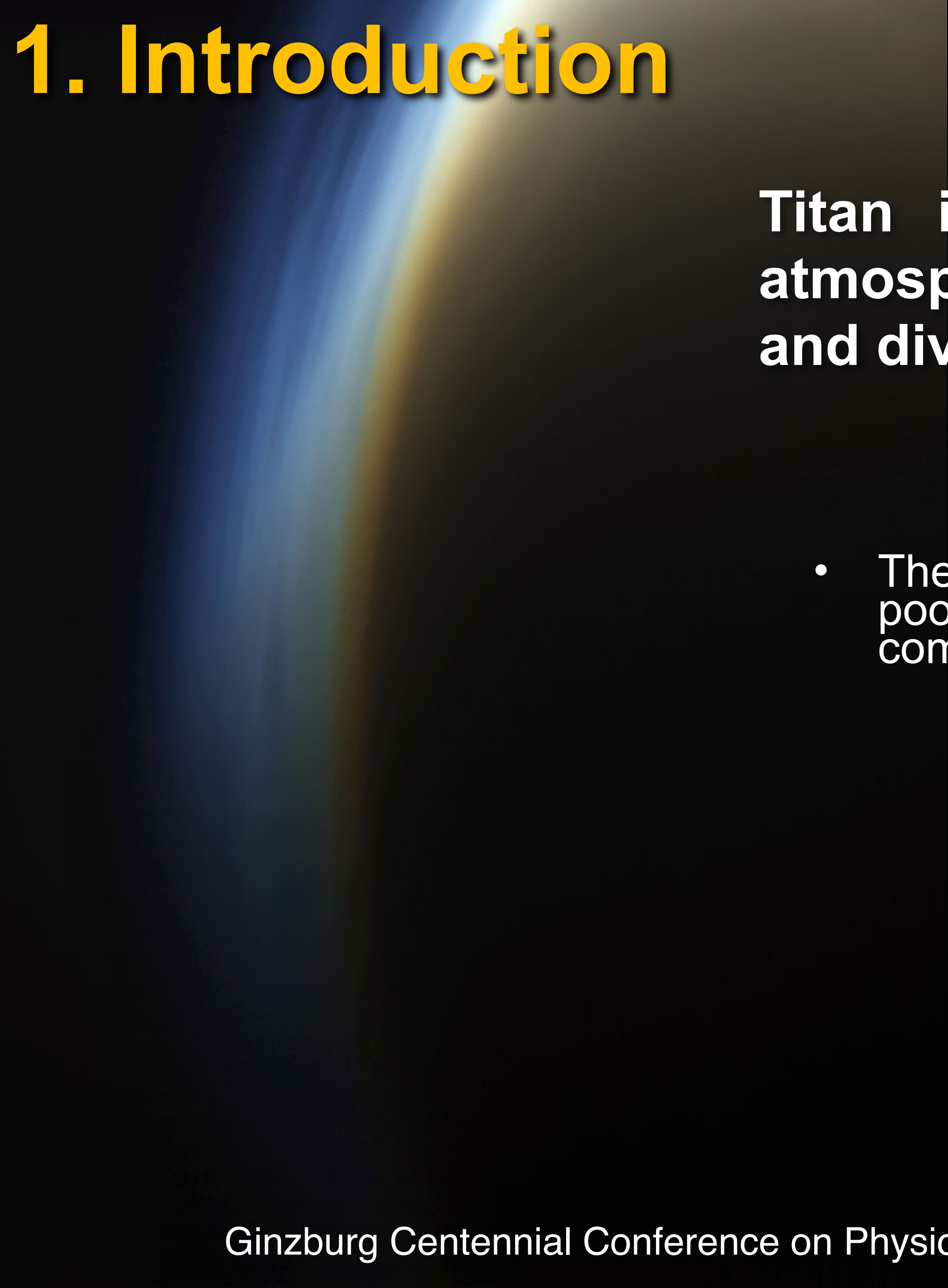
MAX-PLANCK-GESELLSCHAFT

Ginzburg Centennial Conference on Physics - May 29-June 3, 2017, Moscow

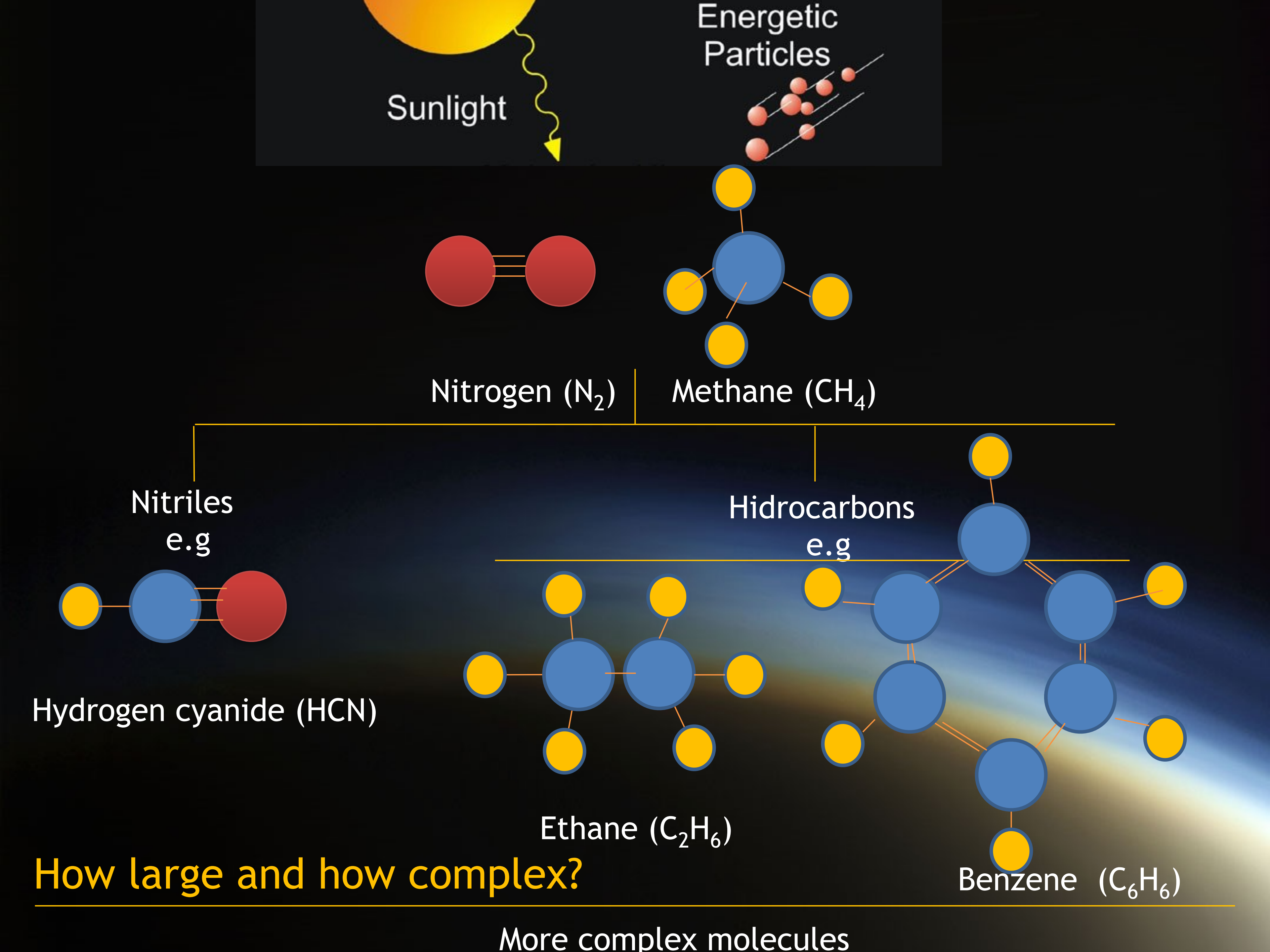
1. Introduction



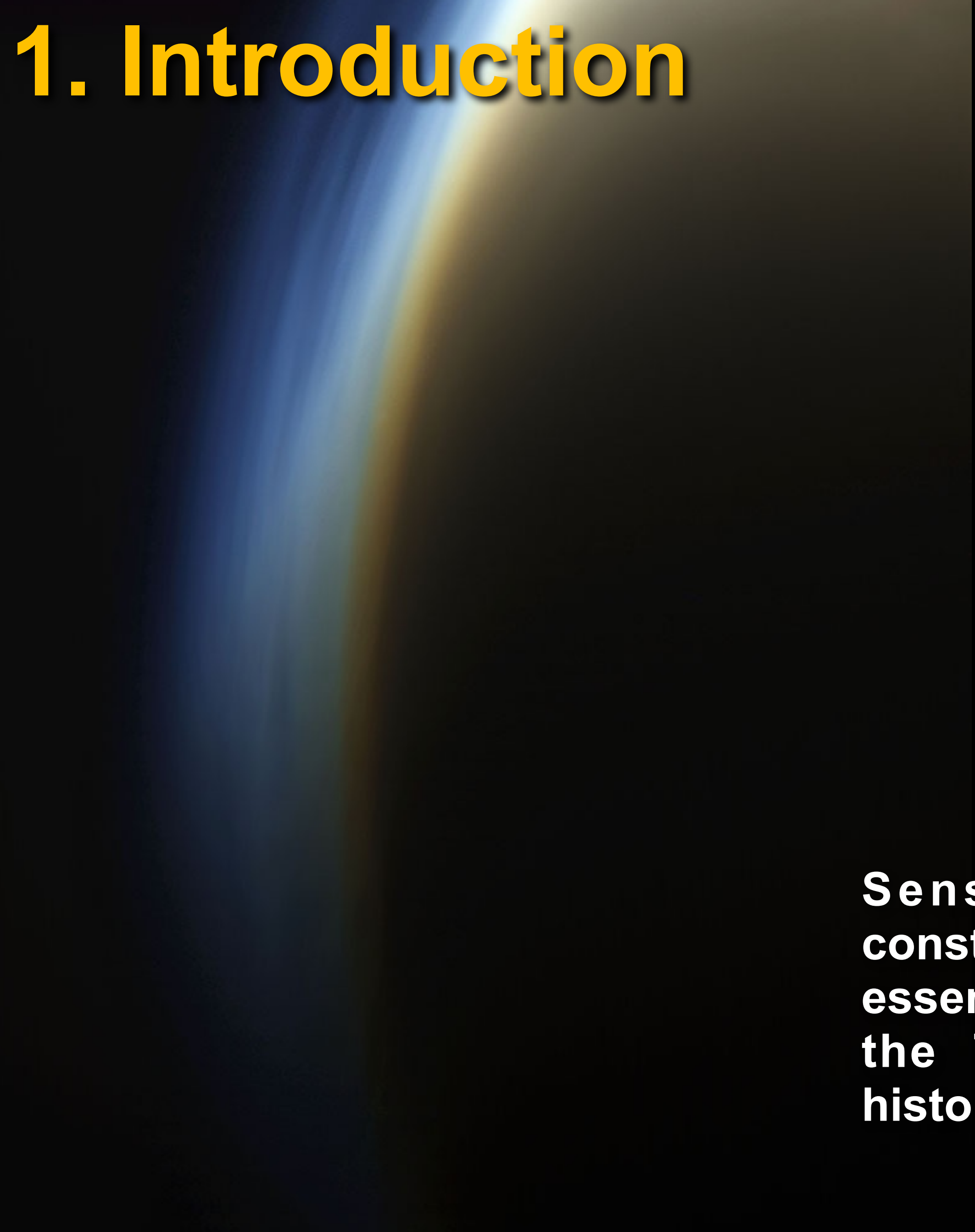
Why Titan?

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
Hydrogen cyanide (HCN)
Hidrocarbons e.g
Ethane (C_2H_6)
Benzene (C_6H_6)
How large and how complex?
More complex molecules

1. Introduction

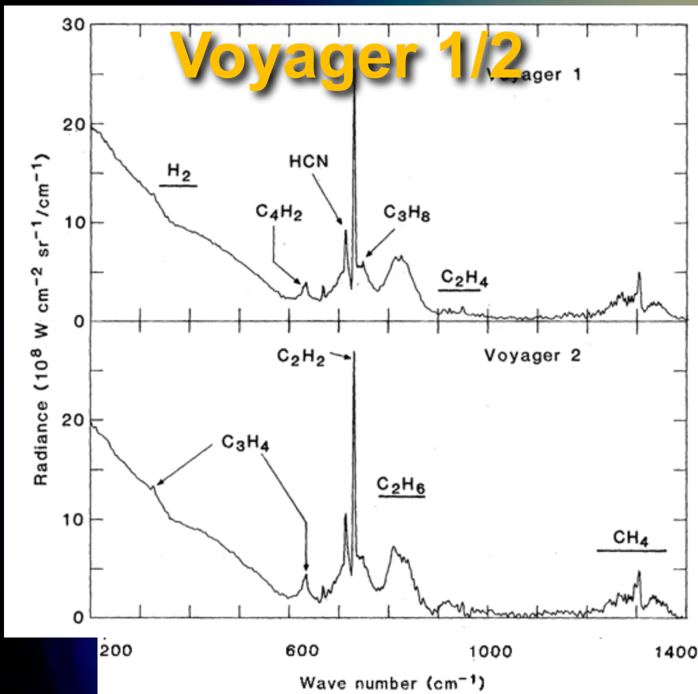


Why Titan?

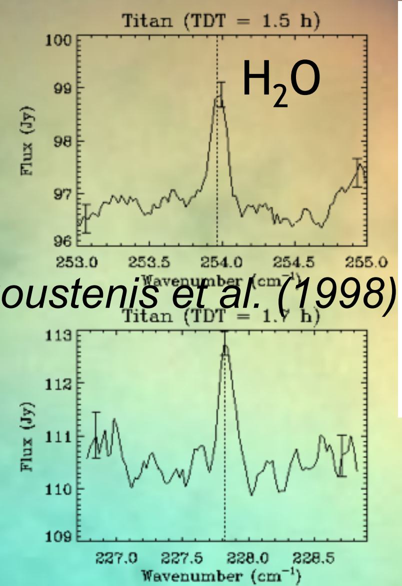
Sensitive observations of the constituents of the atmosphere are essential to constructing models of the Titans´s atmosphere and its history.

1. Introduction

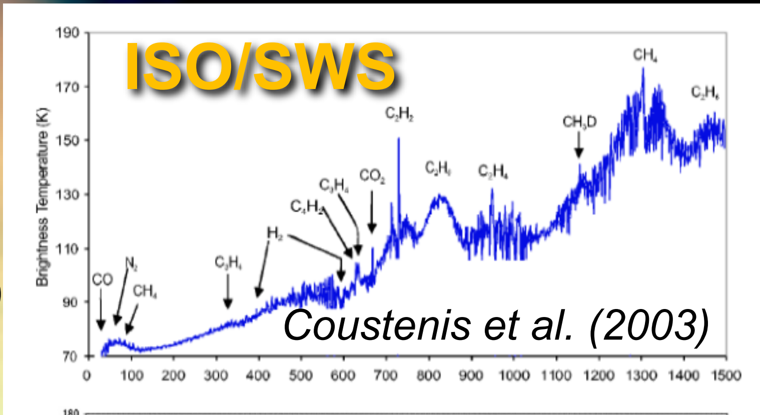
Spectroscopy of Titan has been already performed by:



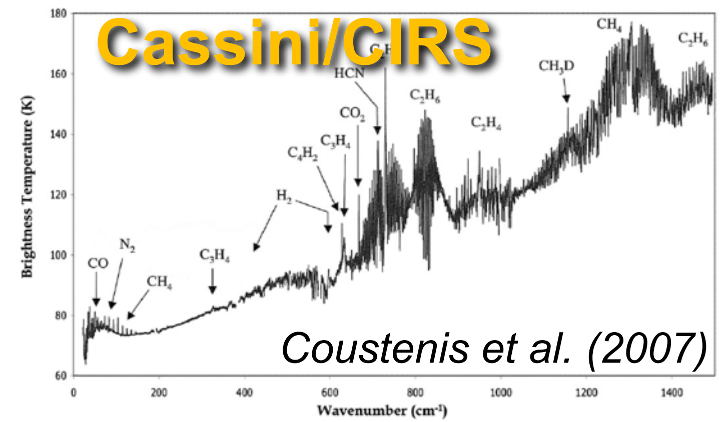
Hanel et al., Science, v 215, 1982



Coustenis et al. (1998)

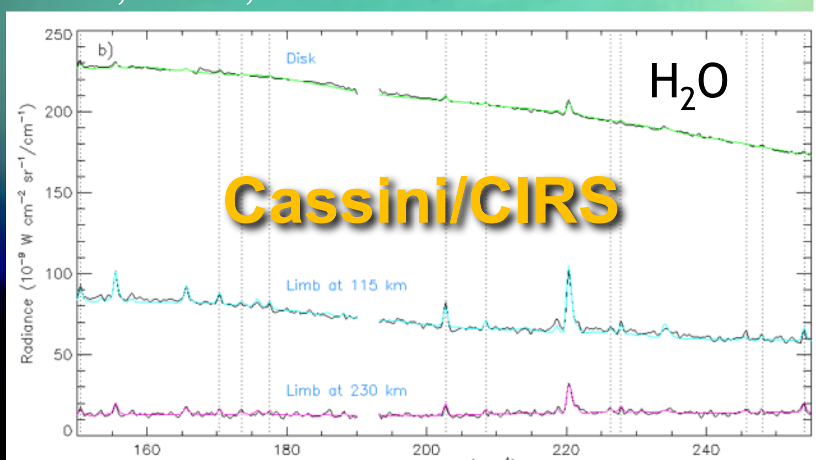


Coustenis et al. (2003)

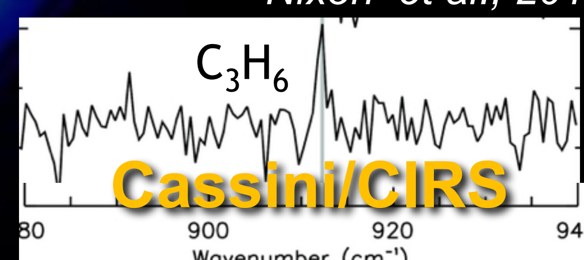


Coustenis et al. (2007)

Cottini et al., 2012



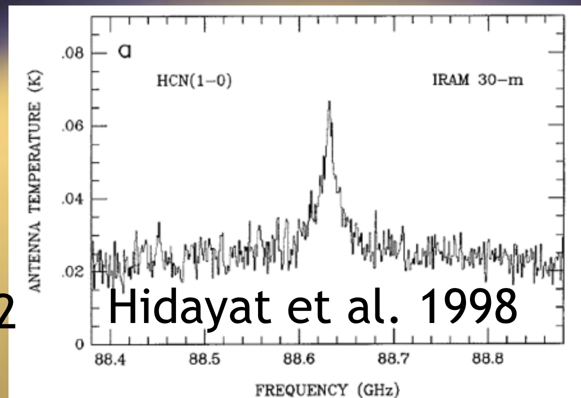
Nixon et al., 2013



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

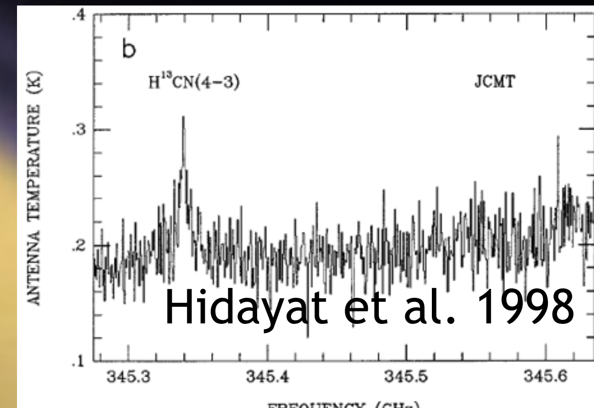
IRAM 30-m:

Marten et al. 2002



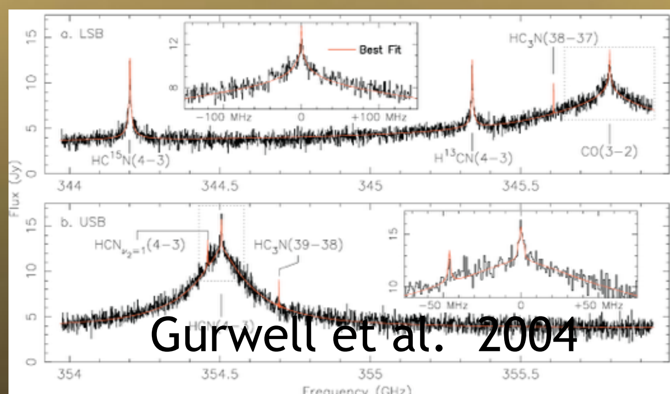
Hidayat et al. 1998

JCMT:



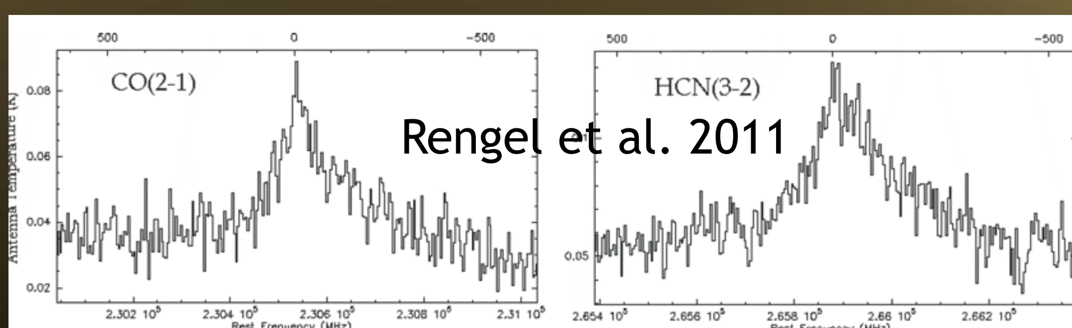
Hidayat et al. 1998

SMA:

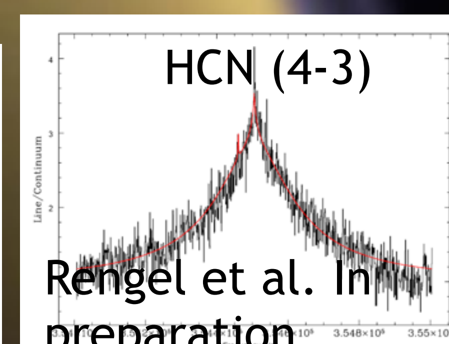


Gurwell et al. 2004

APEX:



Rengel et al. 2011



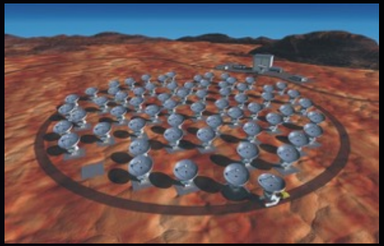
HCN (4-3)

Rengel et al. In preparation

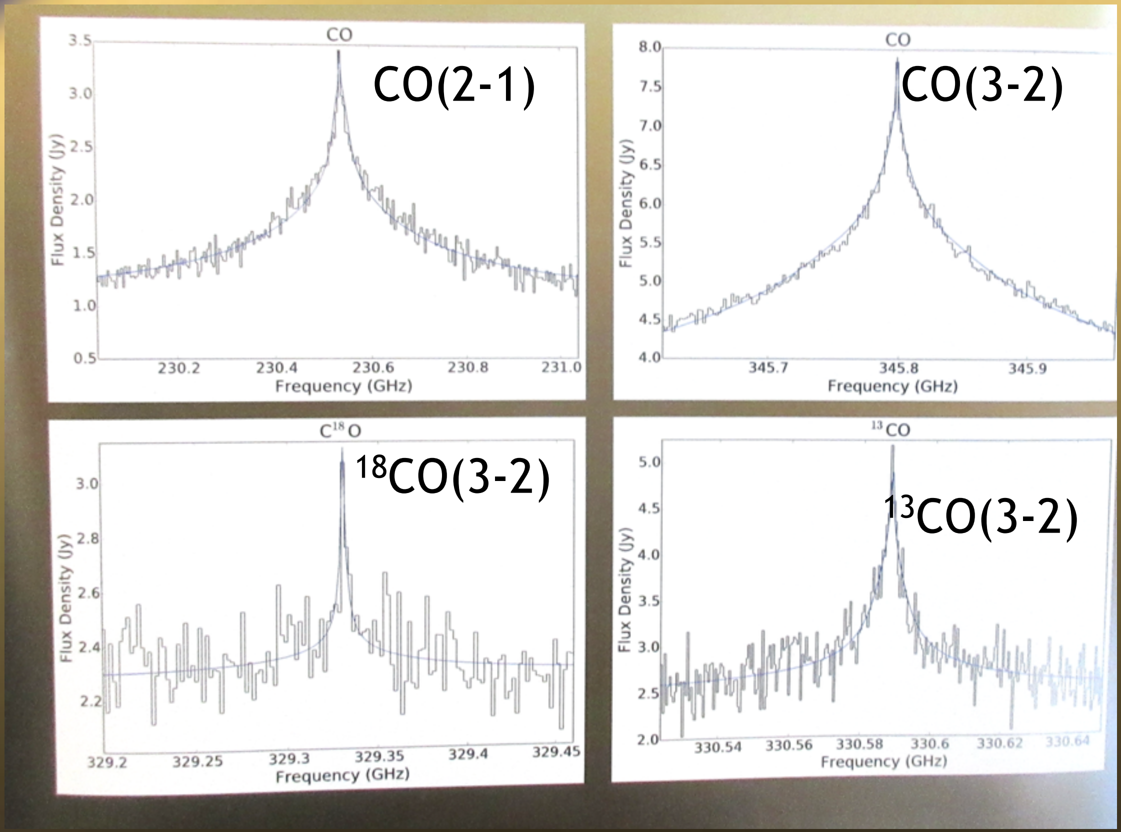
Ground-based observations have also improved our knowledge of Titan's atmospheric composition:

ALMA

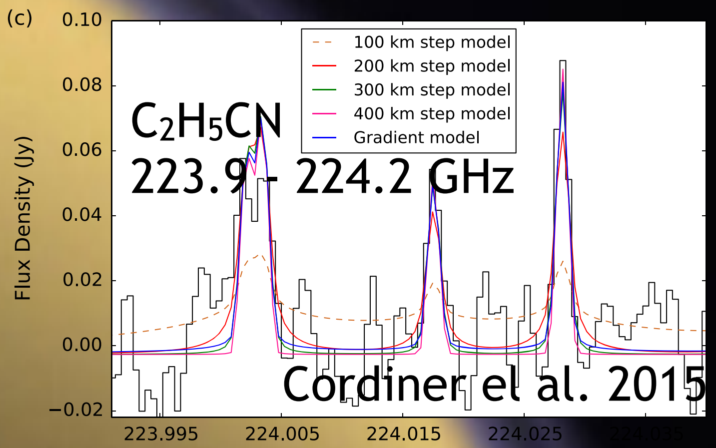
Titan and other Solar System bodies are often used by ALMA to obtain the absolute flux scale for the science target.

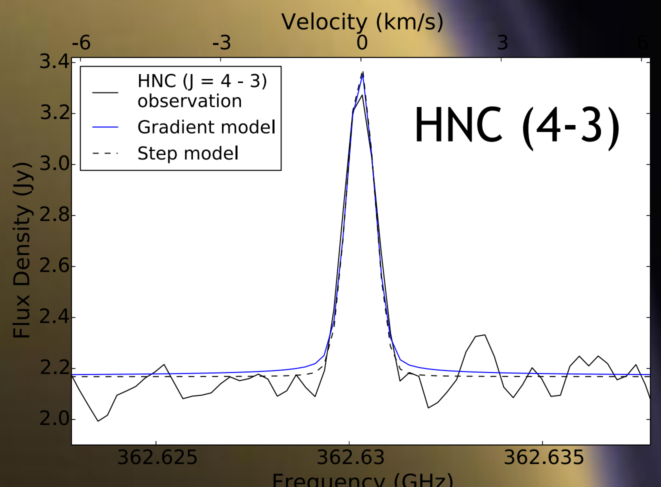


ALMA Archive data - 2012



Serigano et al. 2016





Cordiner et al. 2014

How we can further improve our knowledge of Titan´s atmospheric composition ?

A new window was opened…

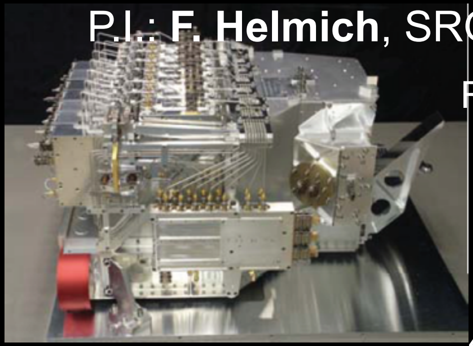
Herschel Era

Credits: ESA

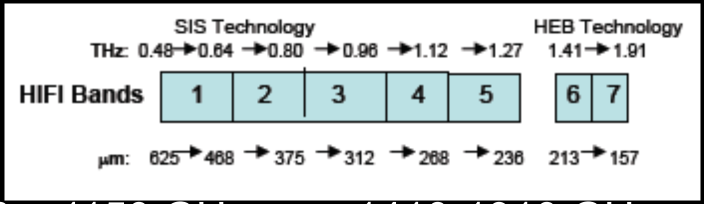
Instruments onboard Herschel:

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

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

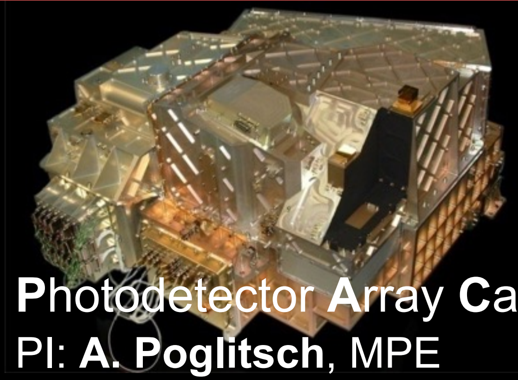


Resolutions: 140, 280, 560 kHz, 1.1 MHz



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

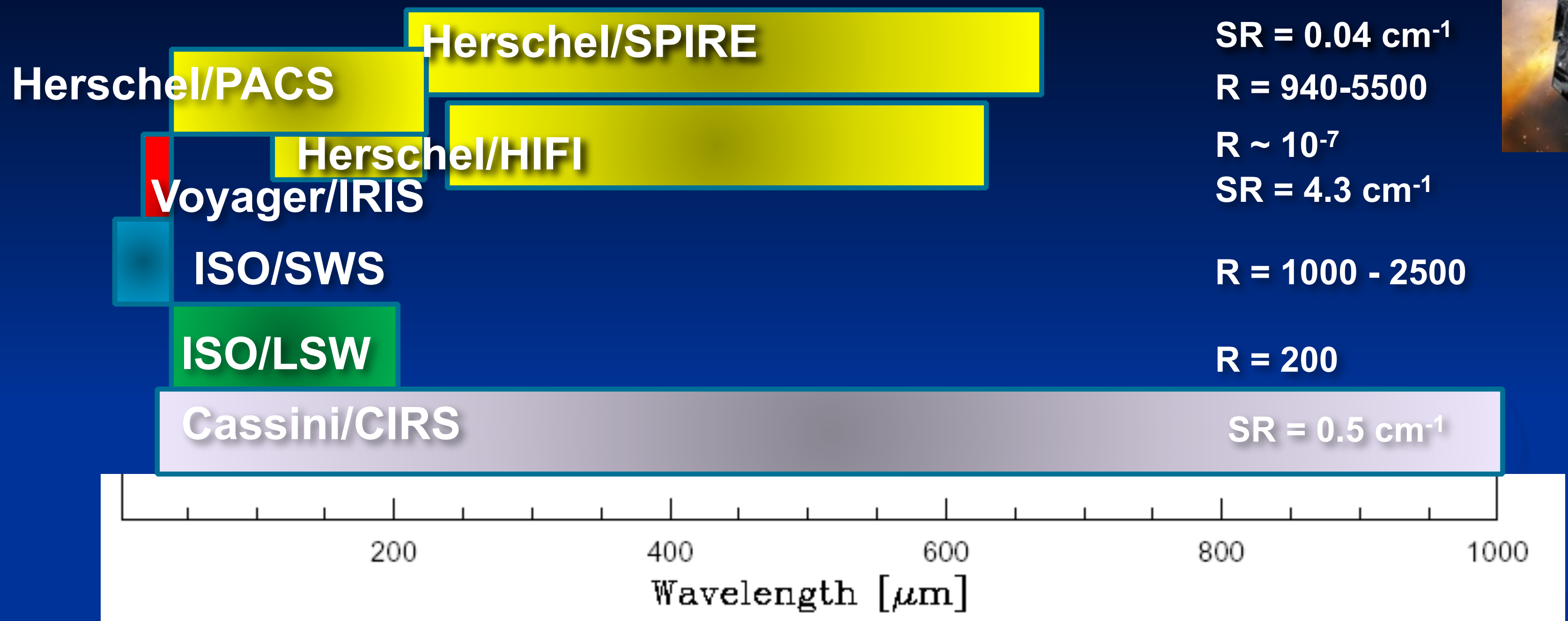
Spectral and **P**hotometric **I**maging **Re**ceiver (**SPIRE**).

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

Photometer: 250, 350, 500 µm

Spectrometer: 194- 672 µm.

Titan´s Spectroscopy in the Herschel Era



In the framework of the KP „*Water and related chemistry in the Solar System*" =>
Exploration of the FIR and submm range with high sensitivity

- 55 – 671 µm is a rich region with numerous rotational transitions of **water** and other trace gases
- These line transitions are stronger than those accessible from Earth
- HIFI/PACS/SPIRE higher spectral resolution and sensitivity than previous instruments

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}

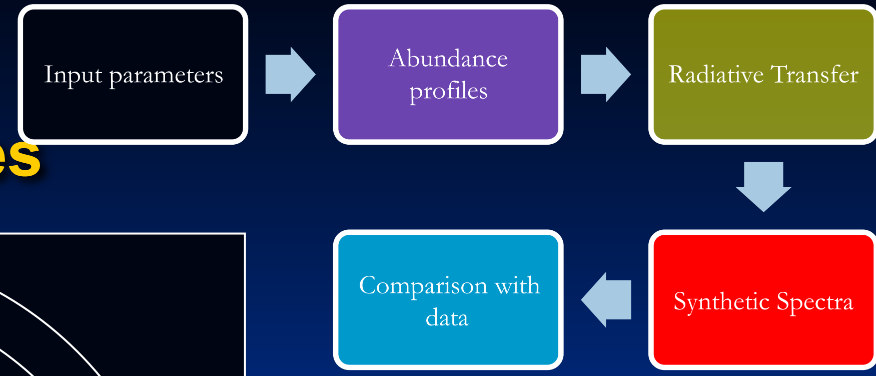
PACS: **Full range spectra** (51-220 μm or 50-180 cm^{-1}) (twice, 0.63h and 1.1h), R= 1000-5000

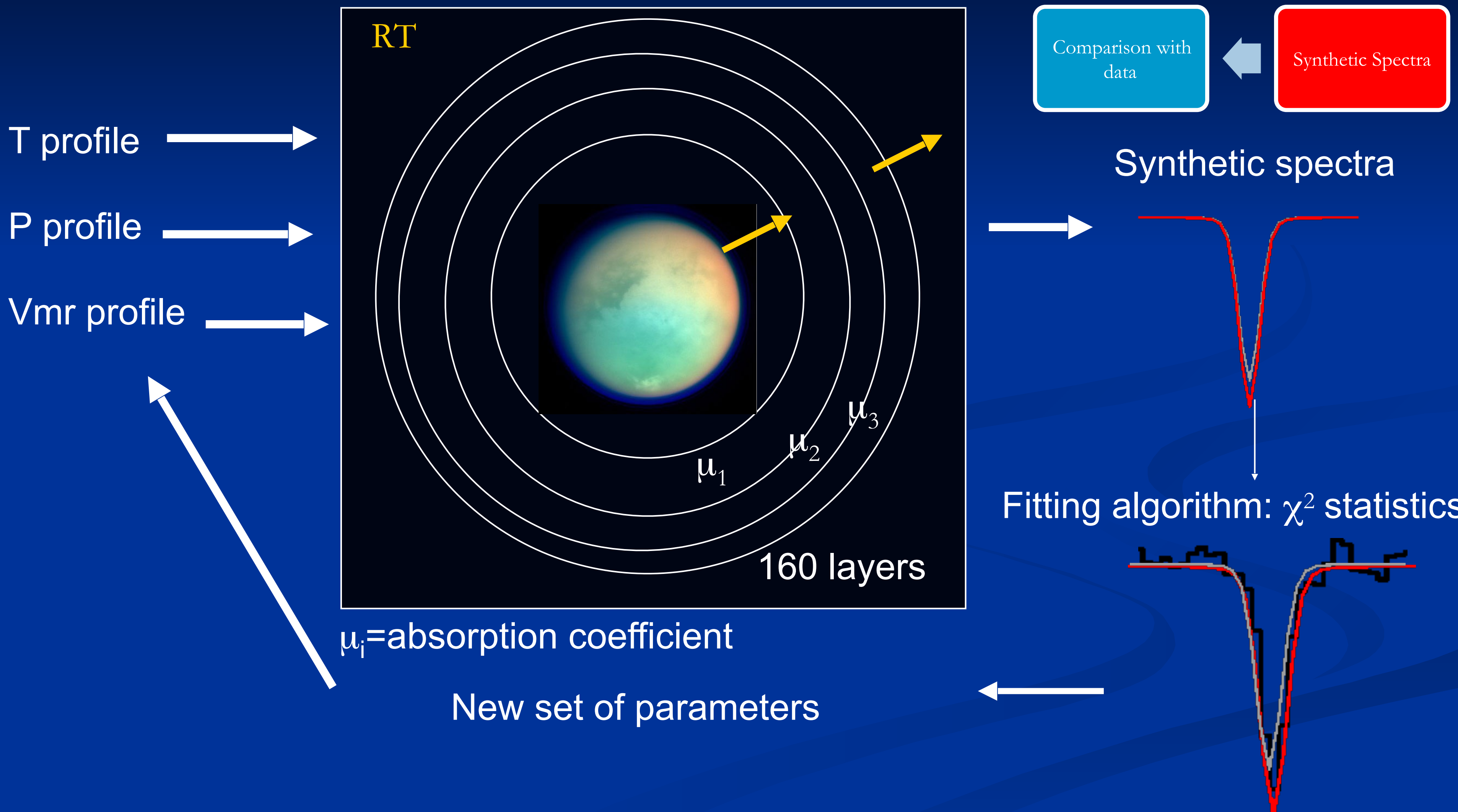
Dedicated line scans **H_2O** lines (at 108, 75.4 and 66.4 μm in June 2010, Dec 2010 and July 2011) and **CH_4**. SR= 0.02, 0.04 and 1.11 μm. ~0.3h

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 to determine abundances





Advances and Discoveries

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ELSEVIER

The abundance, vertical distribution and origin of H_2O in Tita... Herschel observations and photochemical modelling ☆

Raphael Moreno [a,*], Emmanuel Lellouch [a], Luisa M. Lara [b], Helmut Feuchtgruber [c], Miriam ... ...togh [d], Régis Courtin [a]

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LETTER TO THE EDITOR

Herschel/PACS* spectroscopy of trace gases of the stratosphere ... Titan

M. Rengel[1], H. Sagawa[1**], P. Hartogh[1], E. Lellouch[2], H. Feuchtgruber[3], R. Moreno[2], C. J... Cernicharo[4], and L. M. Lara[5]

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Astronomy & Astrophysics

A&A 536, L12 (2011)
DOI: 10.1051/0004-6361/201118189
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LETTER TO THE EDITOR

First detection of hydrogen isocyanide (HNC) ...

R. Moreno[1], E. Lellouch[1], L. M. Lara[2], R. Courti...[1], M. Rengel[3], N. Biver[1], M. Ba...

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4 Space Research Centre of Polish Academy of Sciences, ...

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Astronomy & Astrophysics

A&A 536, L2 (2011)
DOI: 10.1051/0004-6361/201118304
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LETTER TO THE EDITOR

First results of Herschel-SPIRE observations of Titan*

R. Courtin[1], B. M. Swinyard[2], R. Moreno[1], T. Fulton[3], E. Lellouch[1], M. Rengel[4], and P. Hartogh[4]

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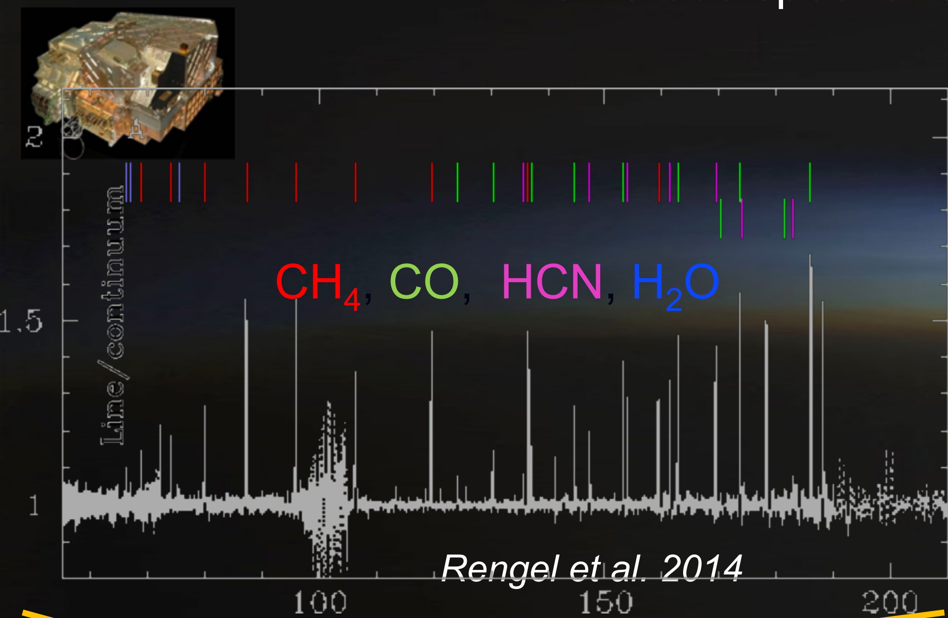
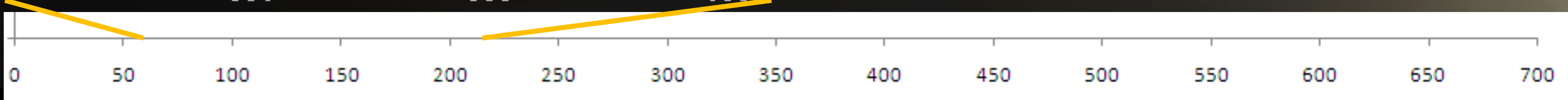
... für Sonnensystemforschung, Max-Planck-Str. 2, 37191 Katlenburg-Lindau, Germany
... November 2011

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

Numerous spectral emission features due to:





PACS:

Full range spectra (51-220 μm)

Twice, 0.63h and 1.1h

R= 1000-5000

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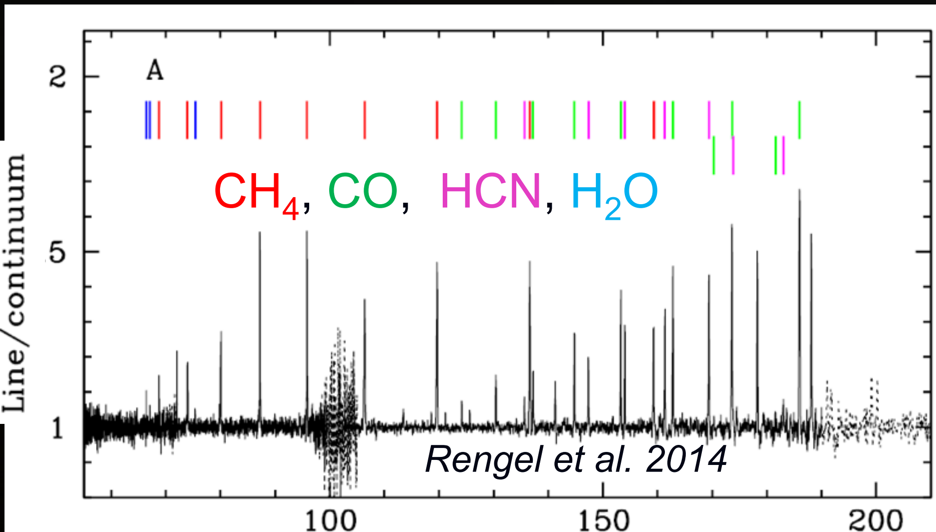
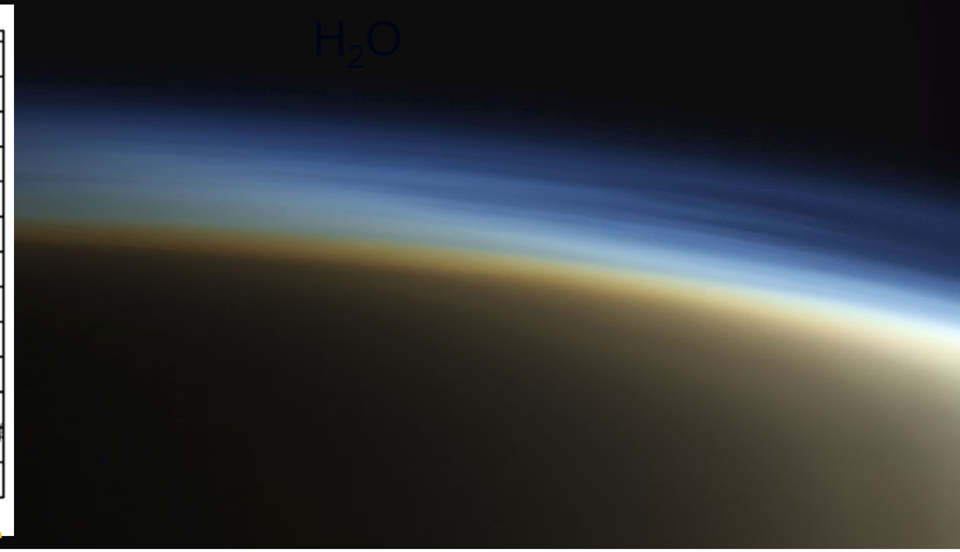
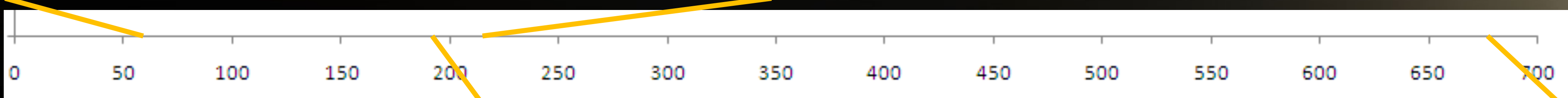




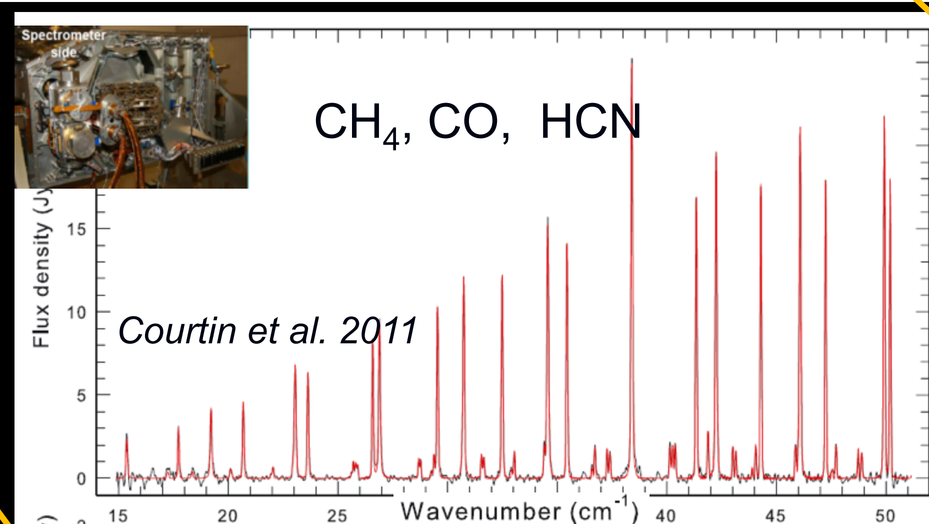


SPIRE:

Full range spectrum (194 - 671 μm)

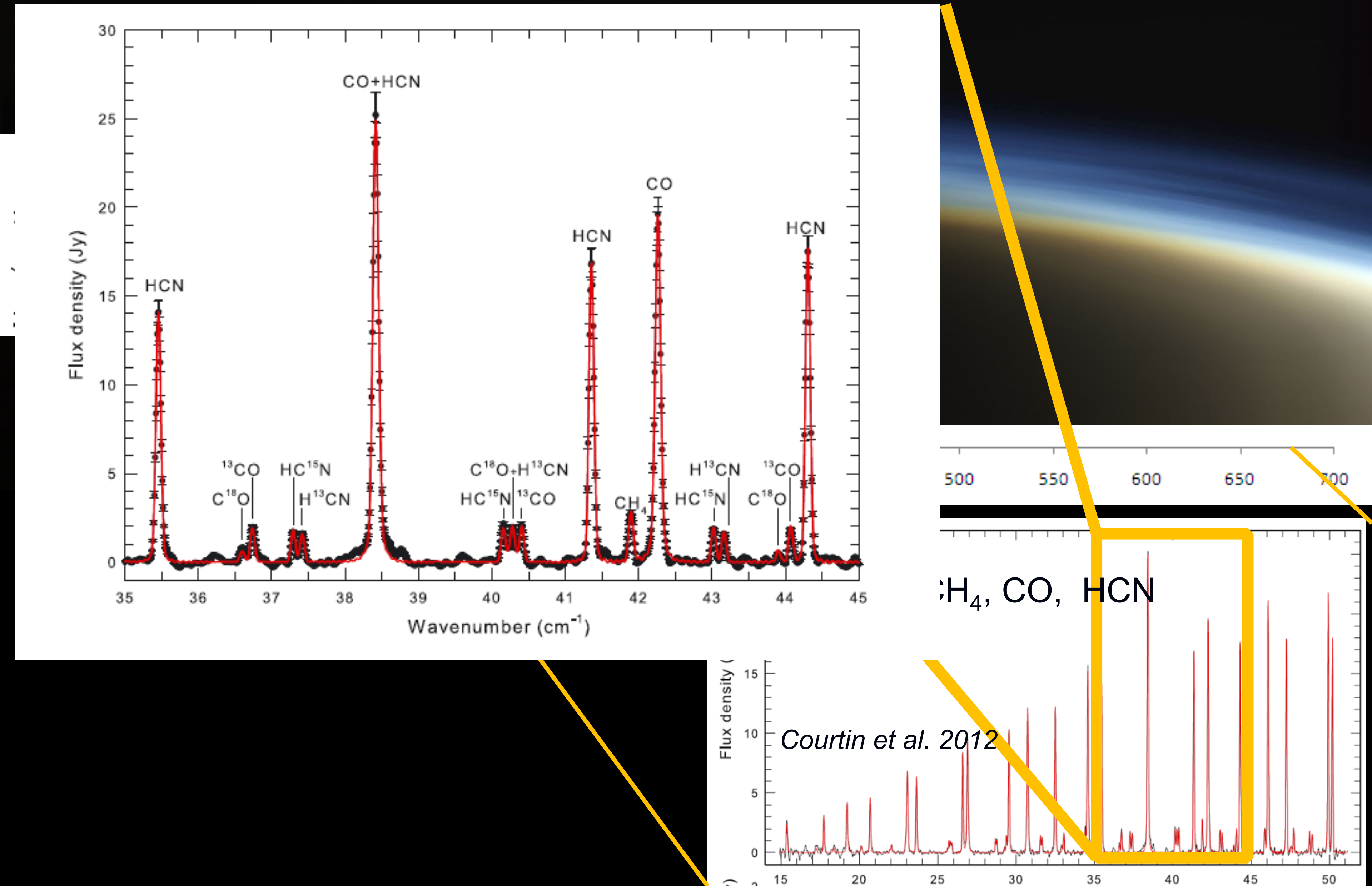
July 2010, ~8.9h,

SR= 0.04 cm^{-1}



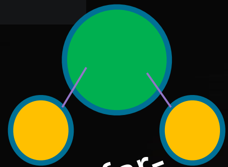
2.- Molecular Inventory with Herschel /PACS, SPIRE , and HIFI

Numerous spectral emission features due to:

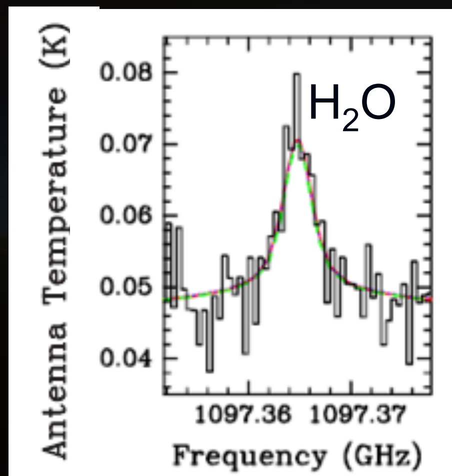


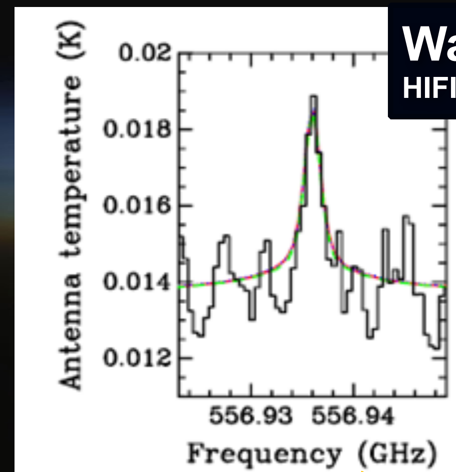
2.- Molecular Inventory with Herschel /PACS, SPIRE , and HIFI

Spectral emission features due to:

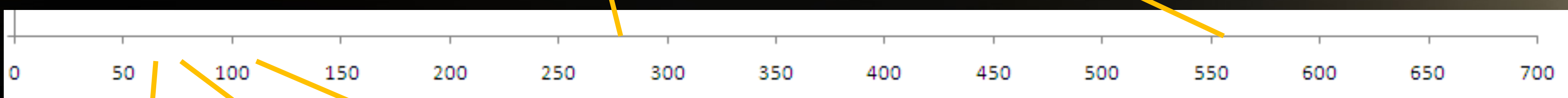


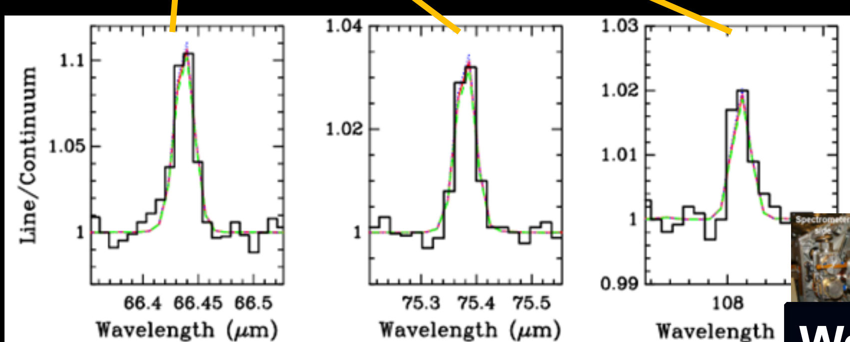
Several H_2O far-IR lines detected for the first time in Titan's atmosphere,





Water Vapour in Titan
HIFI / Herschel





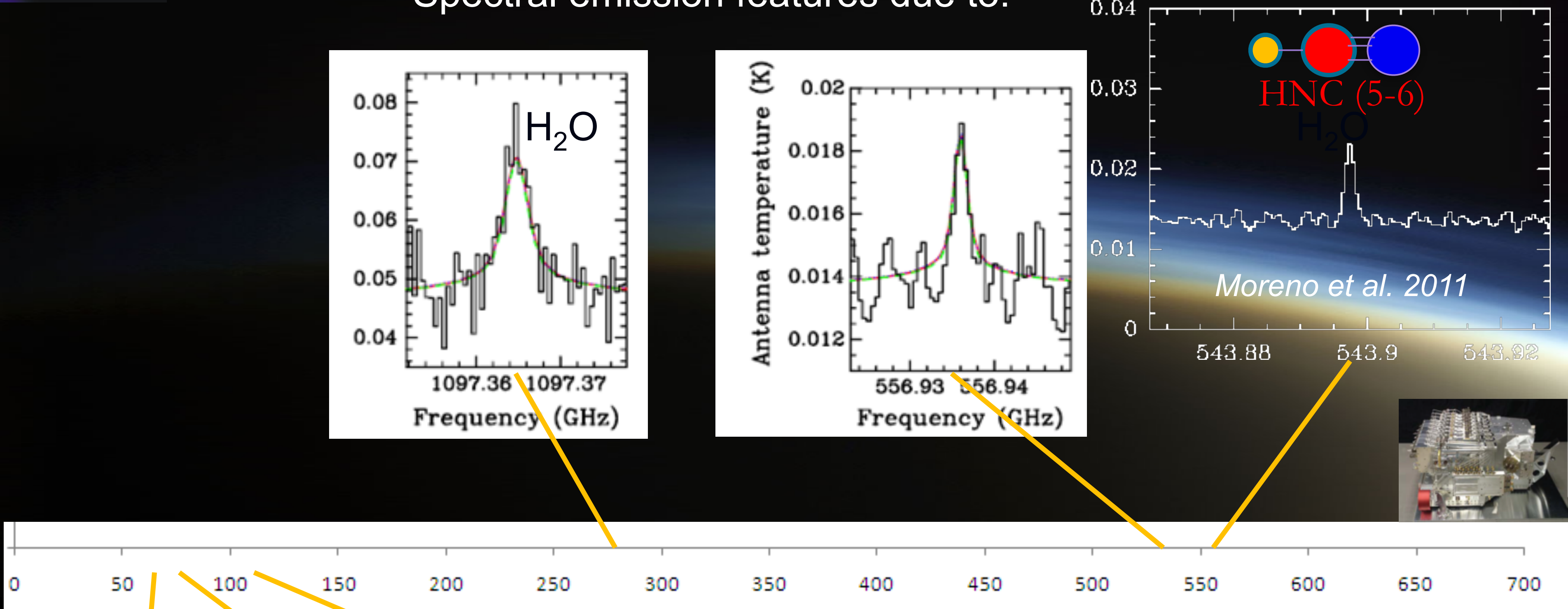
Water Vapour in Titan
PACS / Herschel

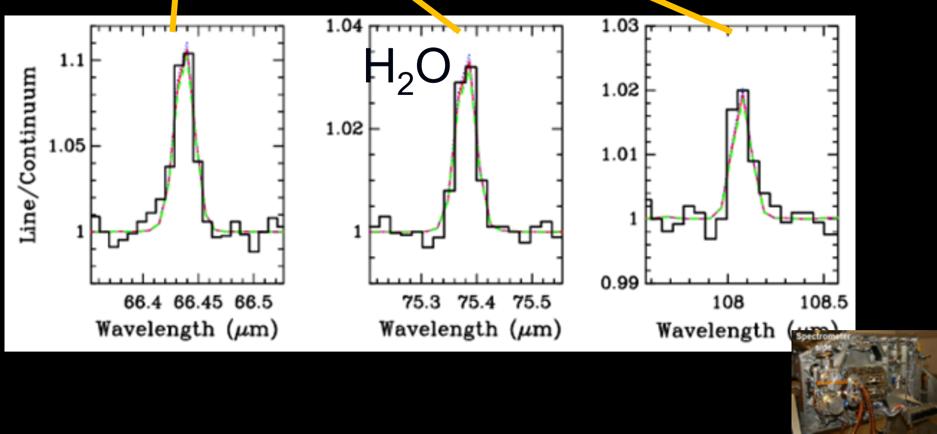
Five dedicated Water vapour line emission with Herschel/PACS and HIFI. Goal: vertical profile of H_2O

Moreno et al. 2012

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

Spectral emission features due to:



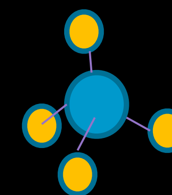


Surprise: Unexpected detection of hydrogen isocyanide (HNC) ➔ a specie not previously identified in Titan´s atmosphere

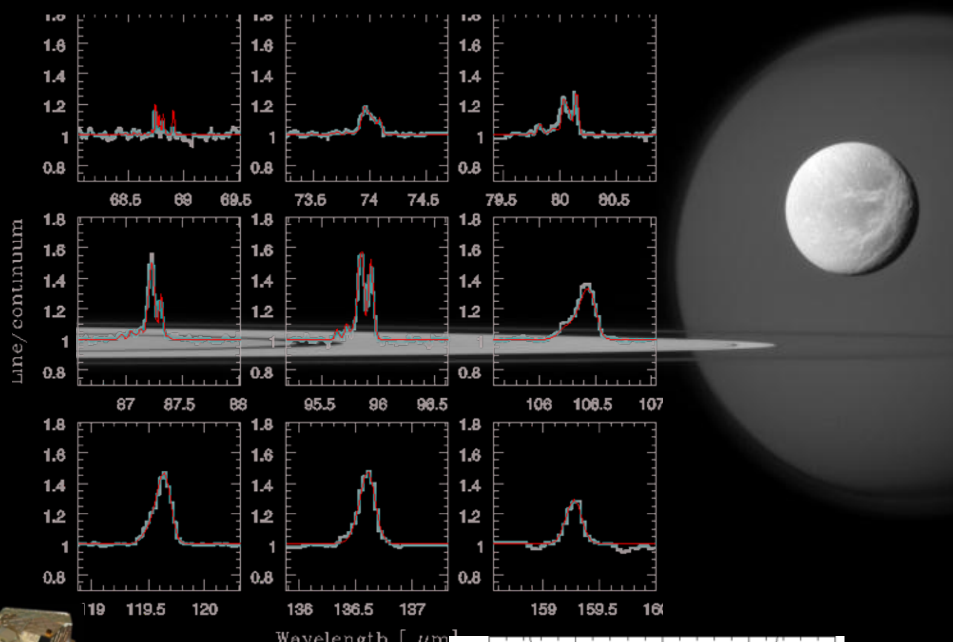
3.- Determination of the abundance of the trace constituents:

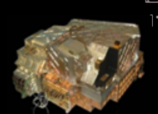
Step 1: Computation of the synthetic spectra for several abundances
Step 2: Calculation of the best-fit

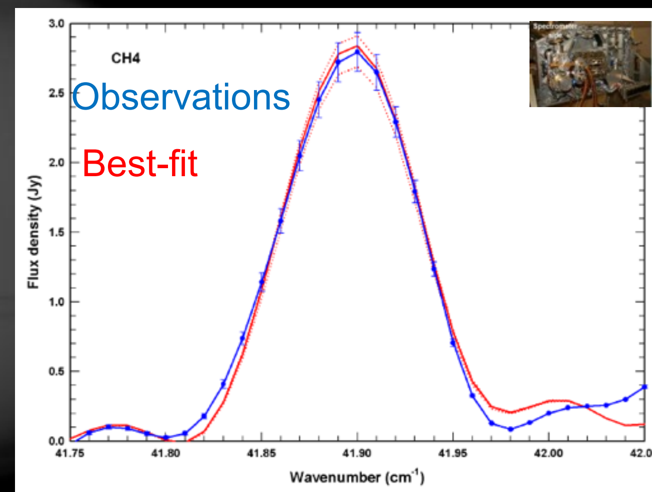
- **CH_4:** Origin unknown



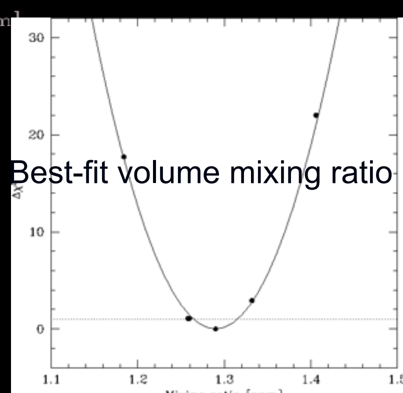
Observed and best-fit simulated CH_4 lines







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**

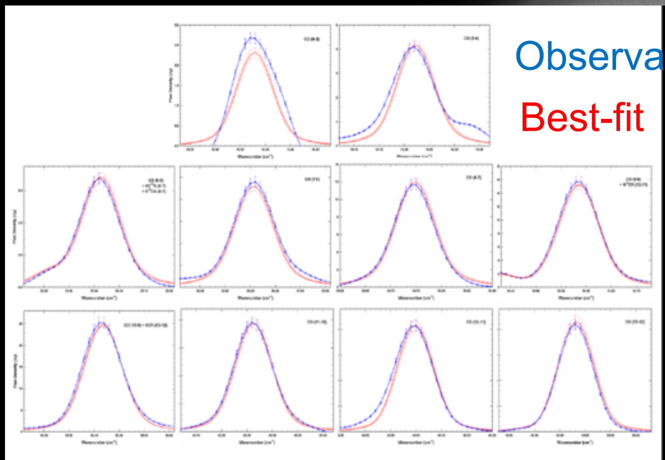
Gas Composition of Titan's atmosphere: CO

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
    - ***Hörst et al. 2008***
    - ***Krasnopolsky et al. 2009***
  - Modelling: Precipitation of O from Enceladus
    - ***Cassidy & Johnson 2010***
  - Observations: Precipitation of O or O+ from Enceladus torus
    - ***Hartogh et al. 2011***

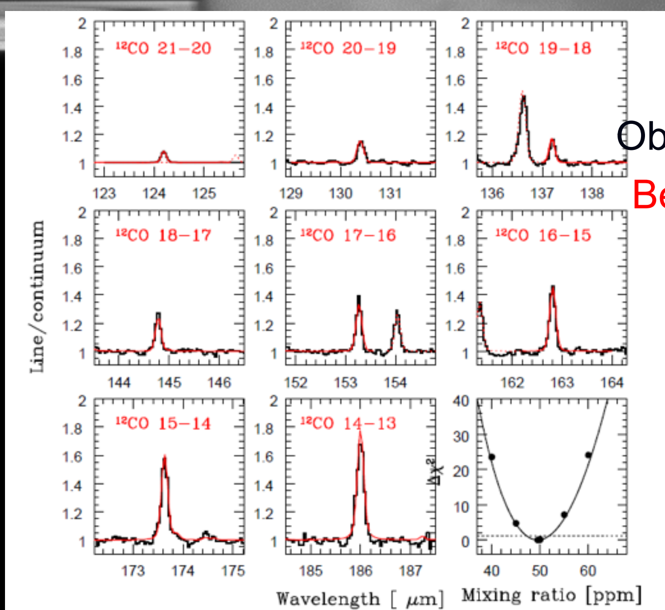
Observed and best-fit simulated CO lines



Observations

Best-fit

For the [60-170] km range altitude



Observations

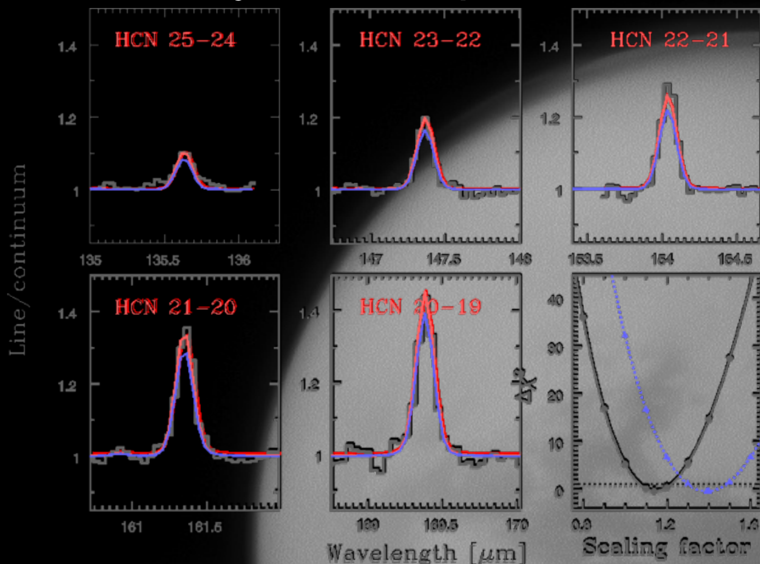
Best-fit

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

HCN vertical distribution **Generated photochemically**

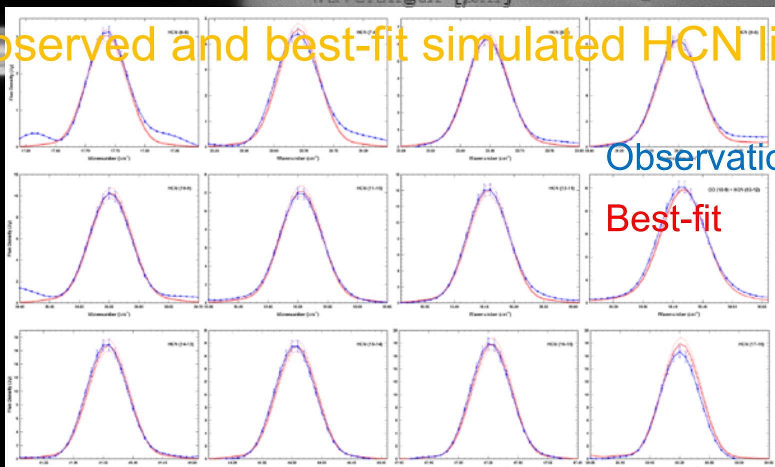
- We scaled the distribution from the one by Marten et al 2002, computed the synthetic spectra for several factors, and calculated best-fit



PACS

Observations

Best-fit

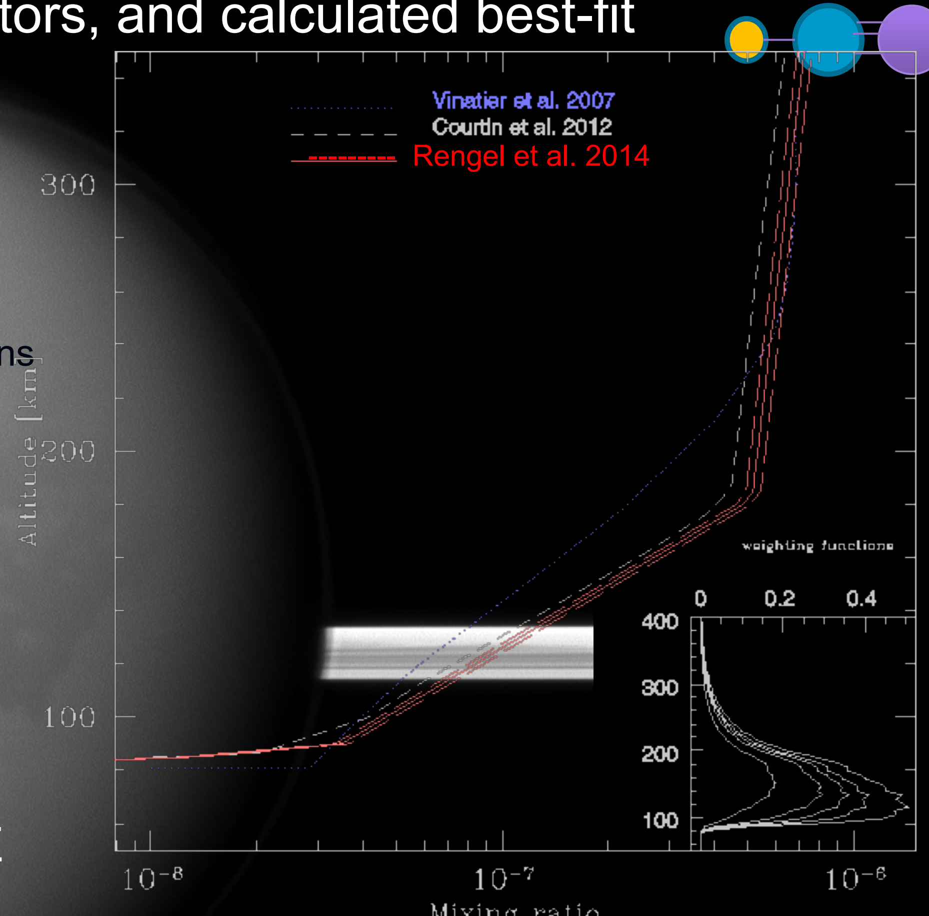


Observed and best-fit simulated HCN lines

Observations

Best-fit

SPIRE



Distribution of HCN, compared with the profile by CIRS

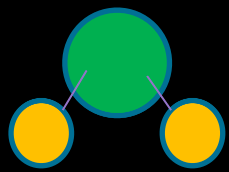
Our results confirm the results from Marten et al. 2002.

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

Rengel et al. 2014

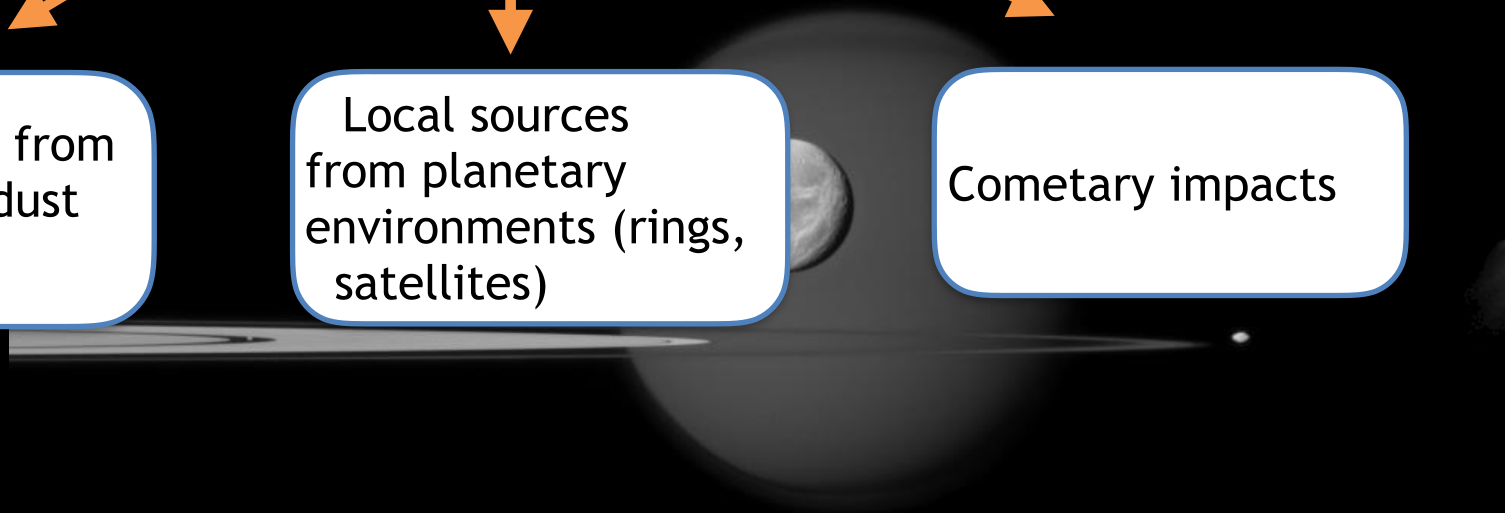
Gas Composition of Titan's atmosphere: H_2O

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

Observations vs. previous models

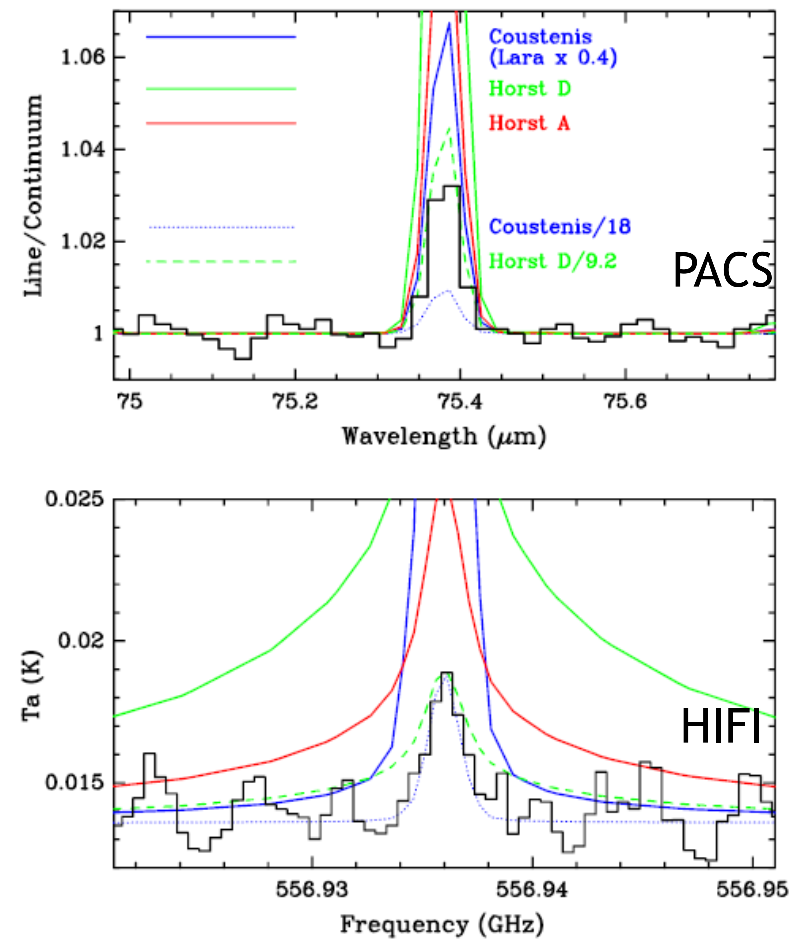


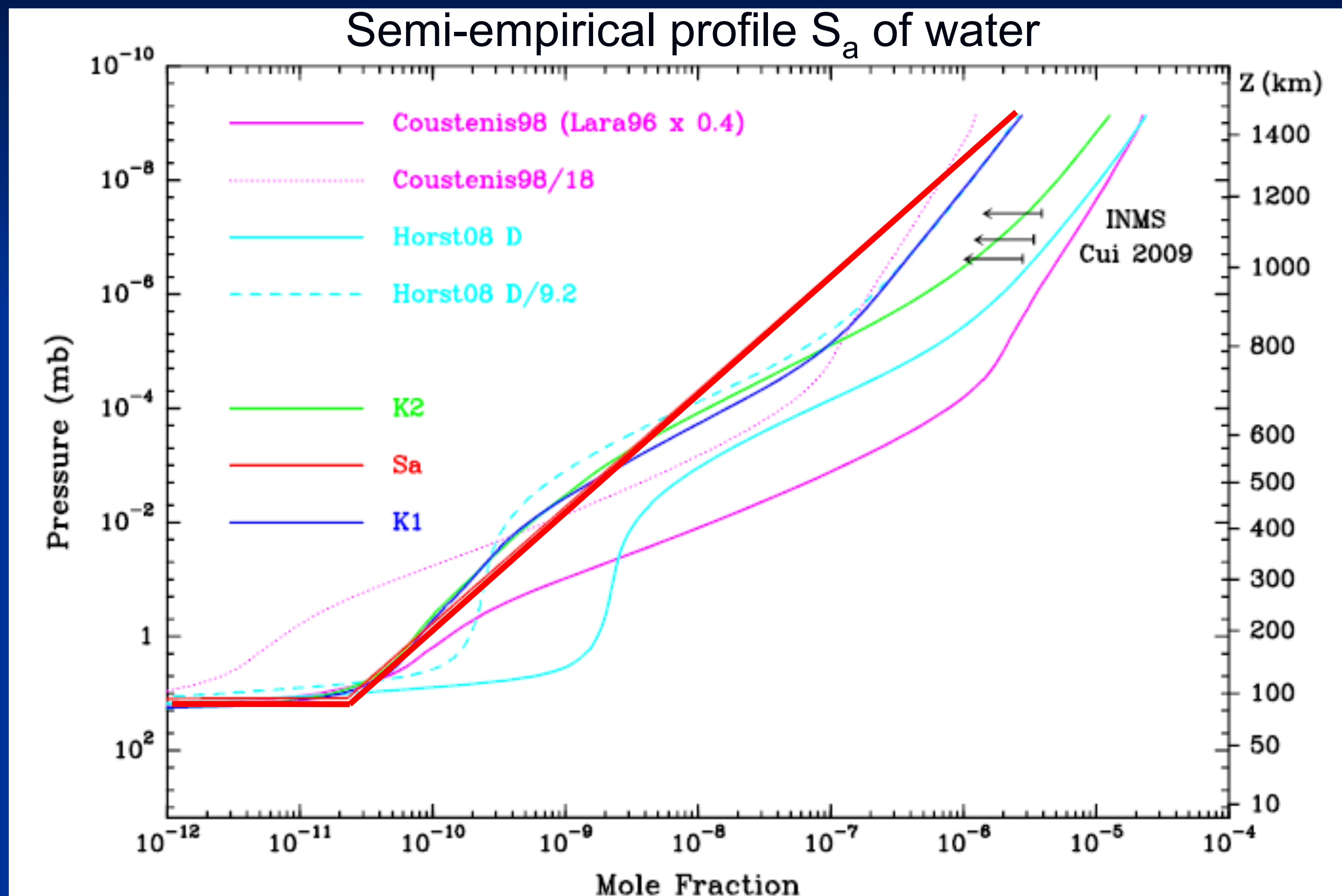
Fig. 7. Synthetic spectra computed considering several previously proposed H_2O profiles: Coustenis et al. (1998), Hörst et al. (2008) (model D and model A), and rescaled versions of these models. None of the models provides an adequate simultaneous match to the PACS observation at 75 μm (top) and HIFI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

- None of the previous water models provides an adequate simultaneous match to the PACS and HIFI observations
- → Photochemical models for water must be revised

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

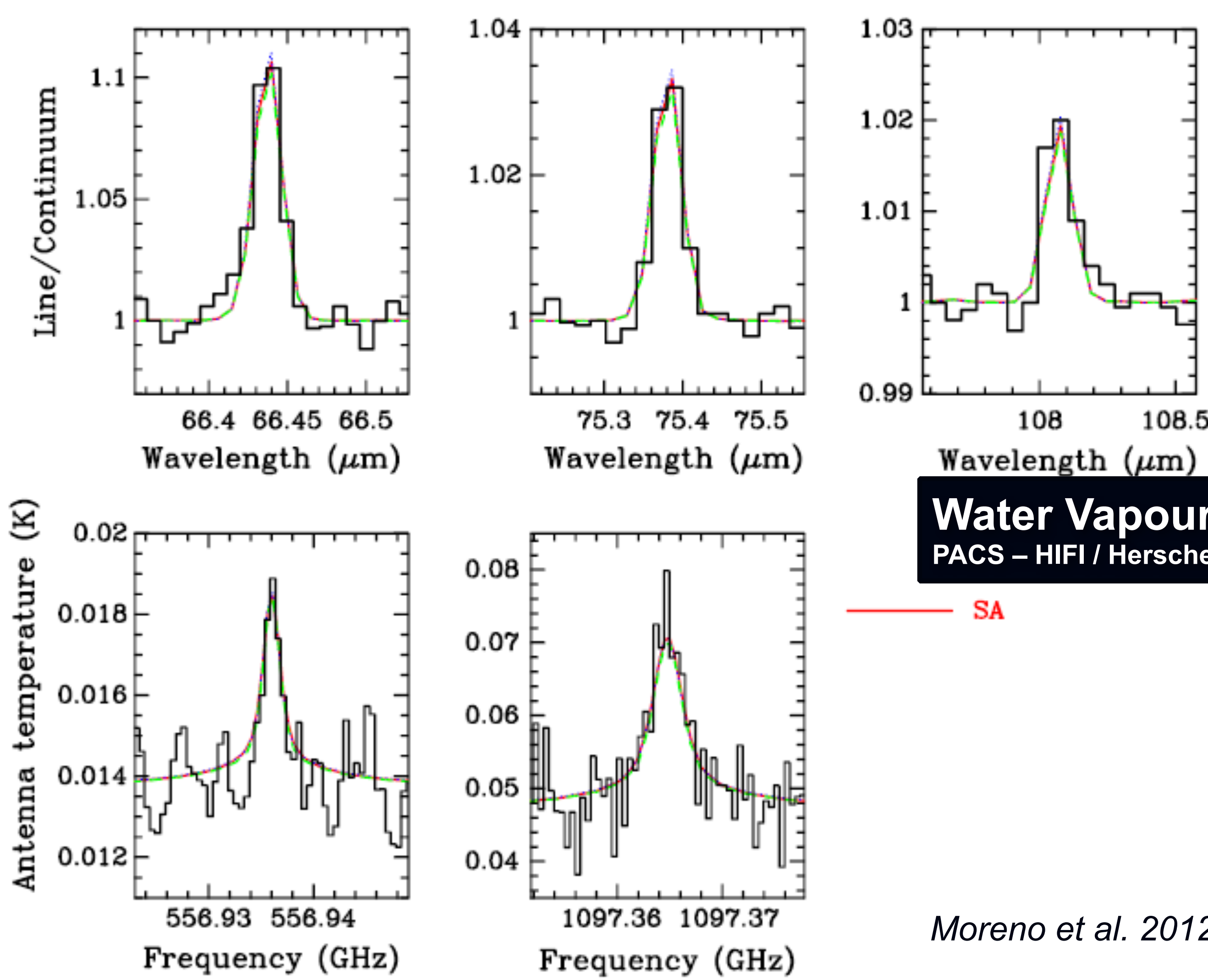


S_a:

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

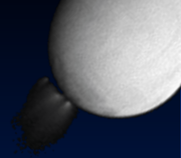
Moreno et al. 2012

Water Vapour in Titan
PACS – HIFI / Herschel

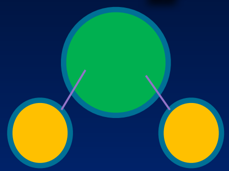


Moreno et al. 2012

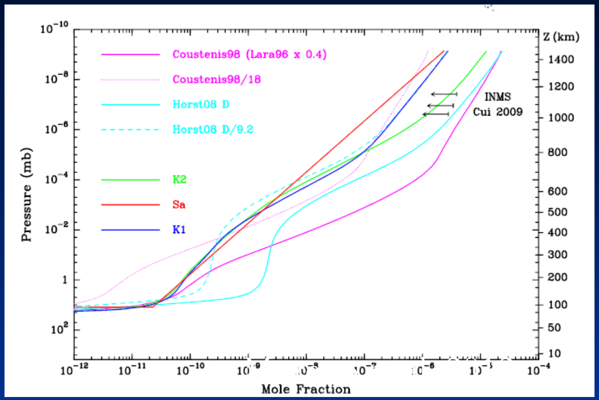
Observed and synthetic spectra

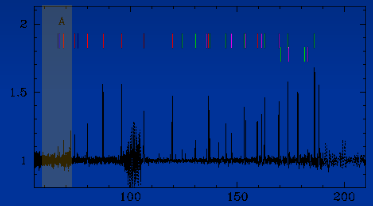


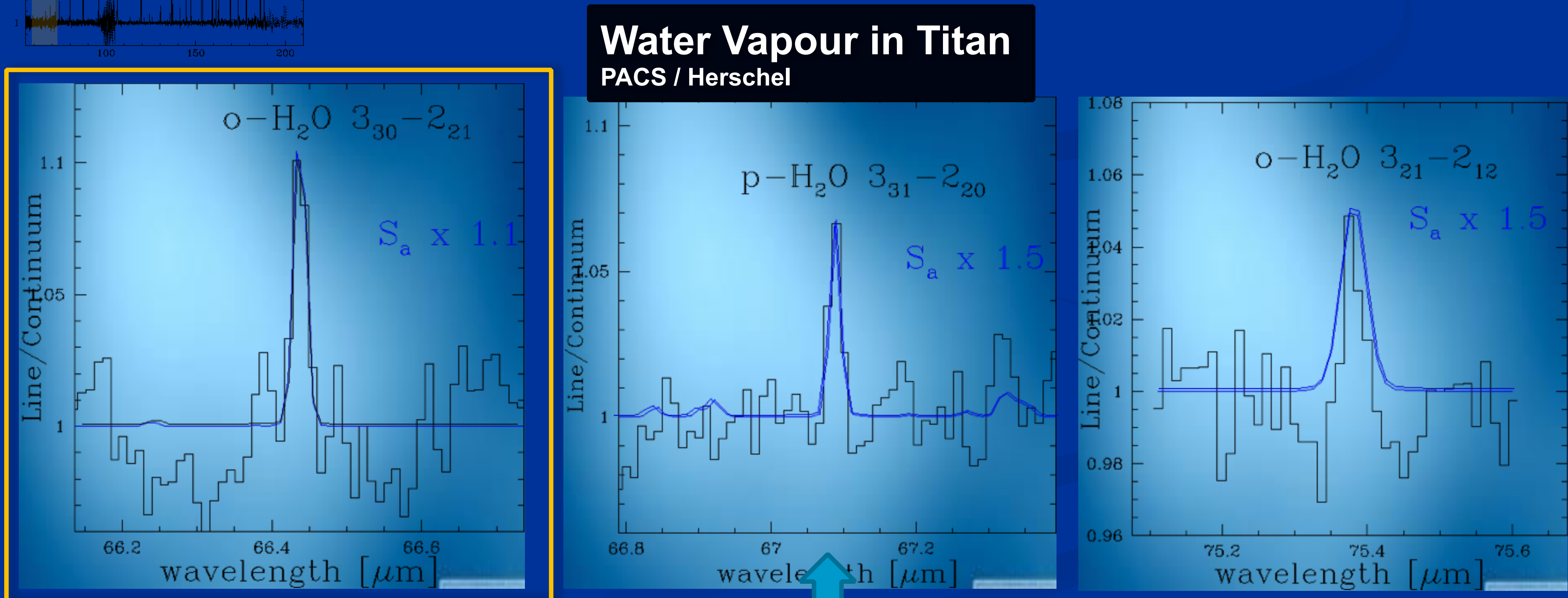
H_2O



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*).





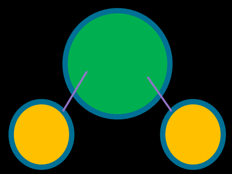


Detection for first time

Rengel et al. 2014

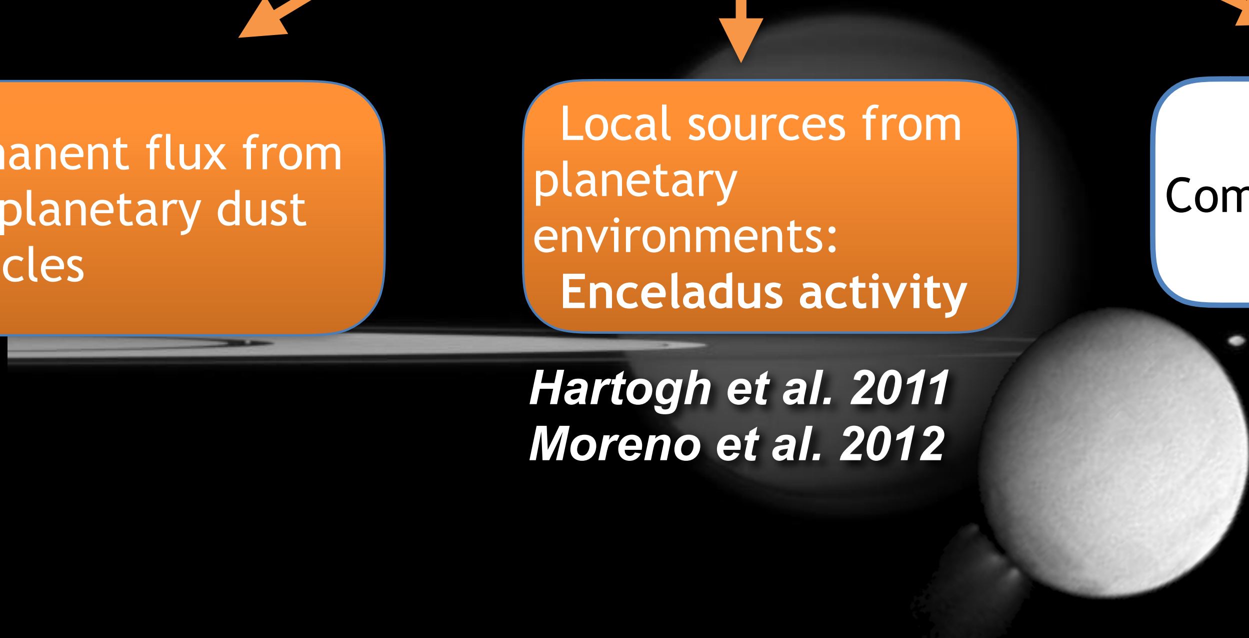
Oxygen-related Gas Composition of Titan's atmosphere: H_2O

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

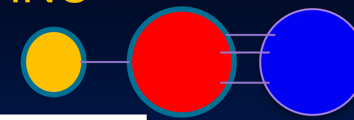
Hartogh et al. 2011
Moreno et al. 2012

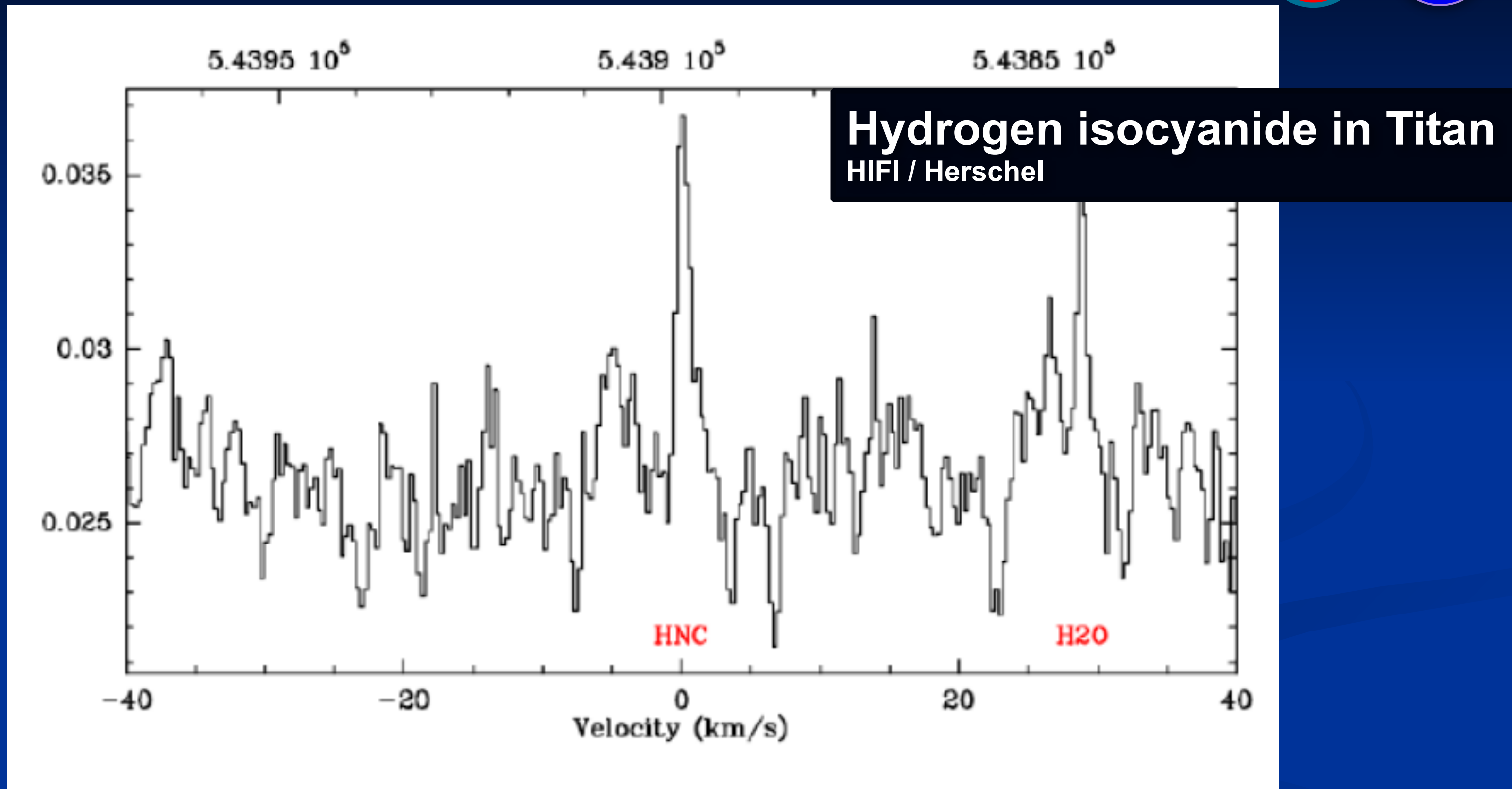
Cometary impacts

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

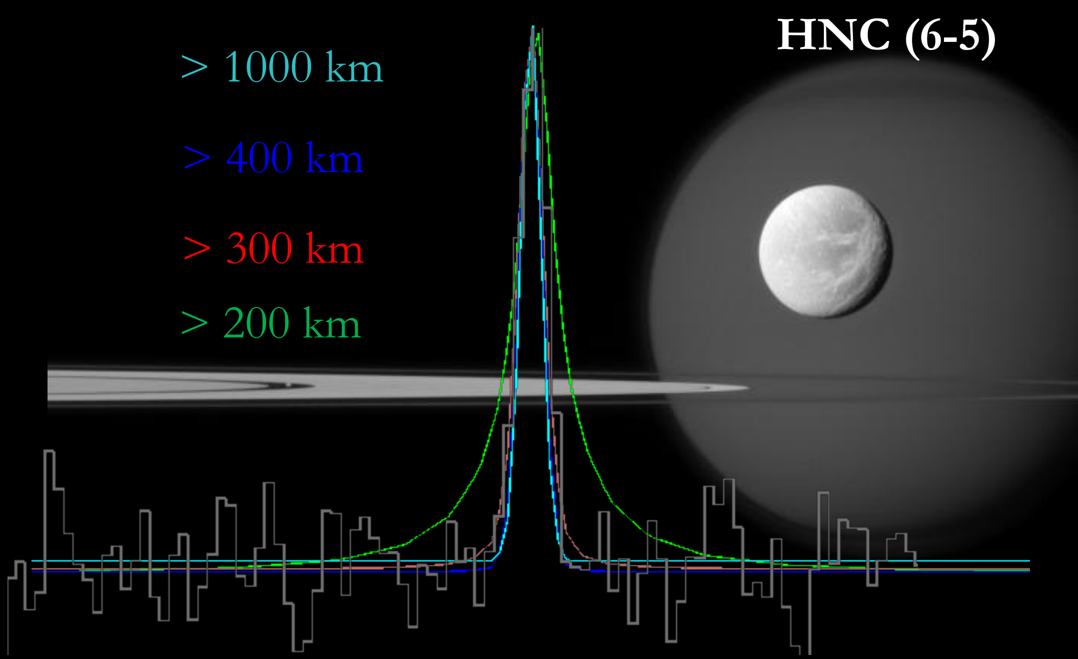




First detection of HNC in the Titan´s atmosphere

- **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

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

Possible chemical lifetime:

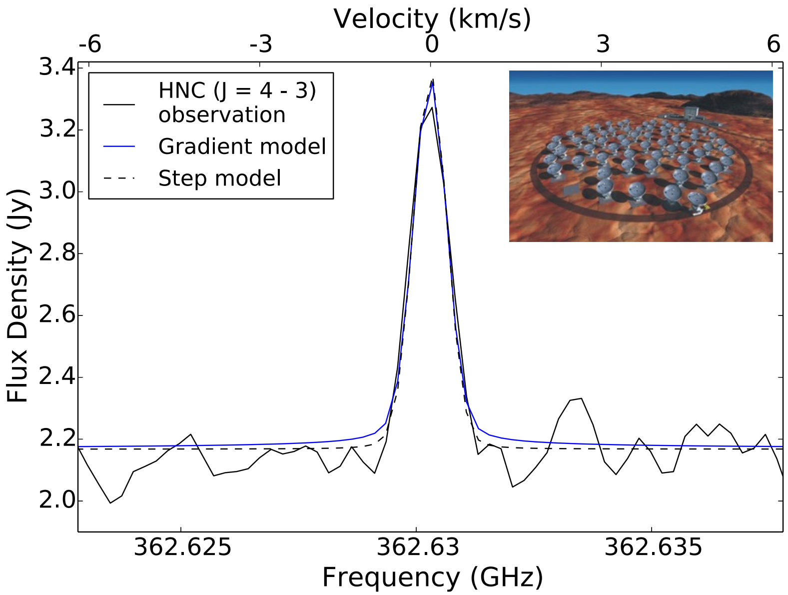
$(1.4\text{–}5) \times 10^5$ s →we expect diurnal variations of HNC

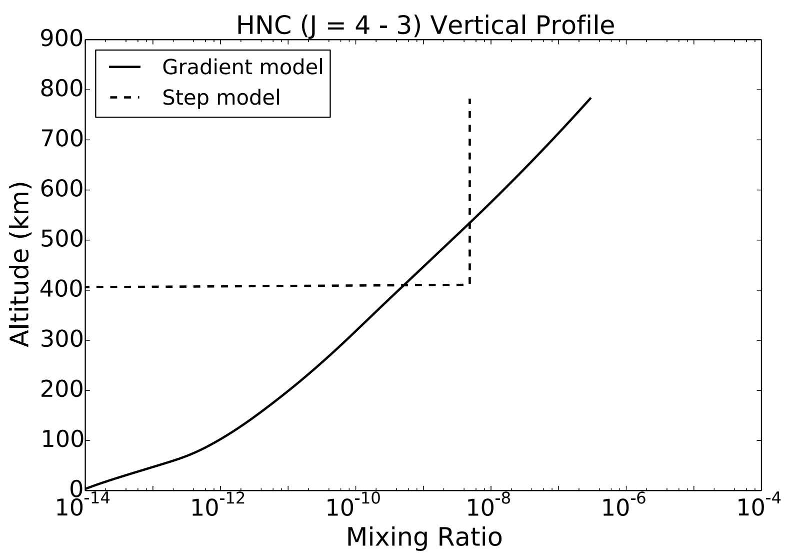
Is HNC restricted to the ionosphere?

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





Cordiner et al. 2014

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.

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

Detection of the isotopes:

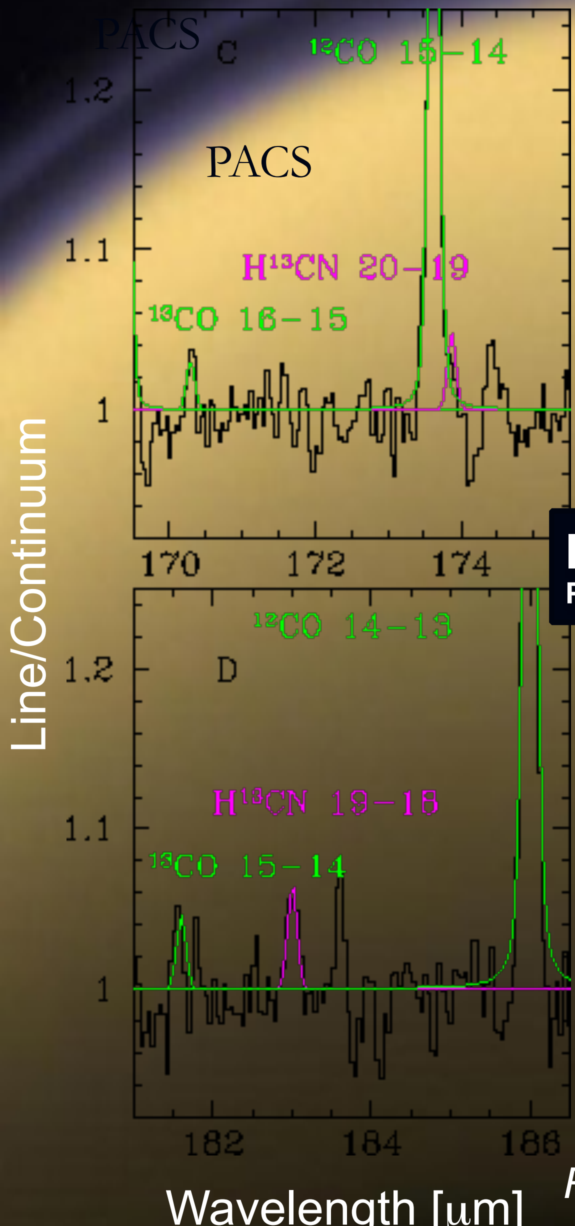
- ^{13}CO(15-14) and (16-15)
- $H^{13}CN$ (19-18) and (20-19)

but marginal

Results:

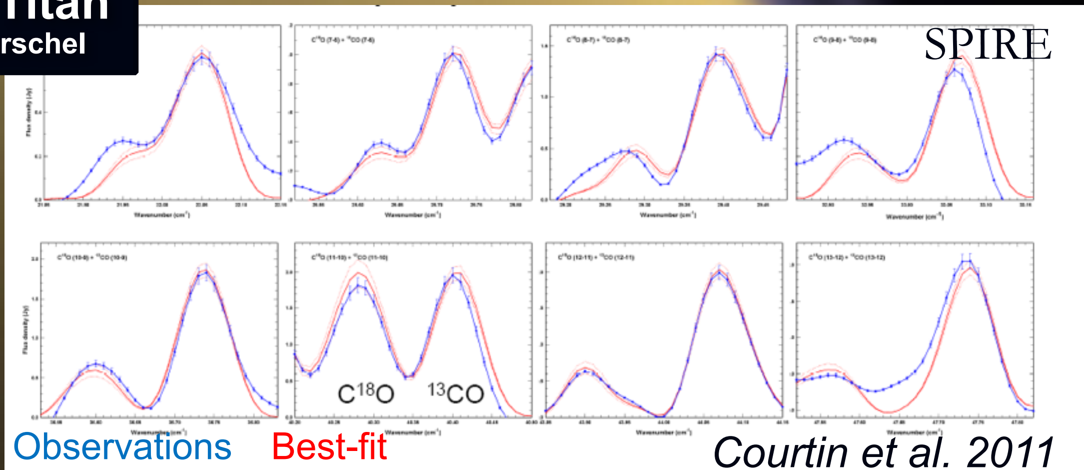
	PACS	SPIRE
$^{12}C/^{13}C$ in CO	122 ± 62	87± 6
$^{12}C/^{13}C$ in HCN	65 ± 30	96 ± 13

Isotopes in Titan
PACS – SPIRE / Herschel



Rengel et al. 2014

^{13}CO and ^{18}CO



Courtin et al. 2011

Consistent with previous works

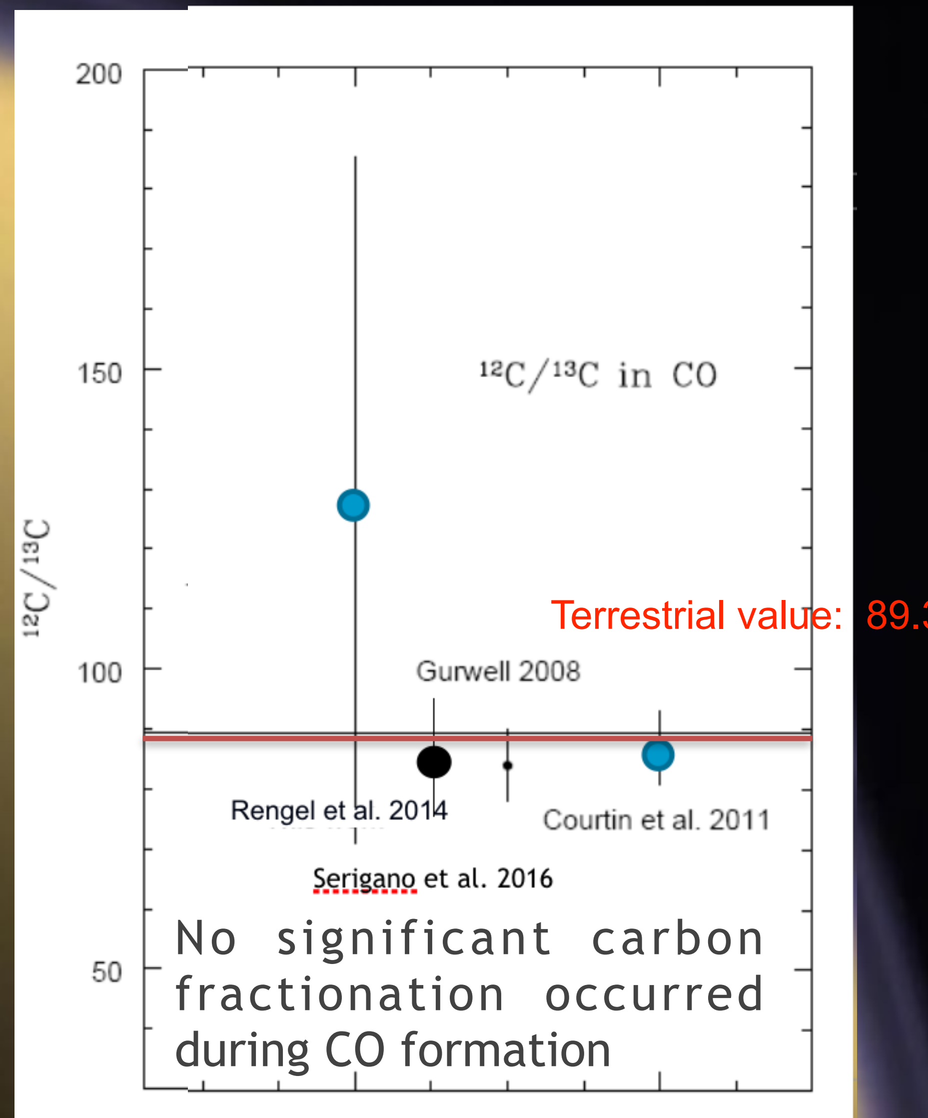
Isotopic ratio $^{12}C/^{13}C$ in CO

Deriving isotopic ratios

Deviations from values of other bodies?

No → No significant fractionation

Yes → Primordial differences / Emerged on time



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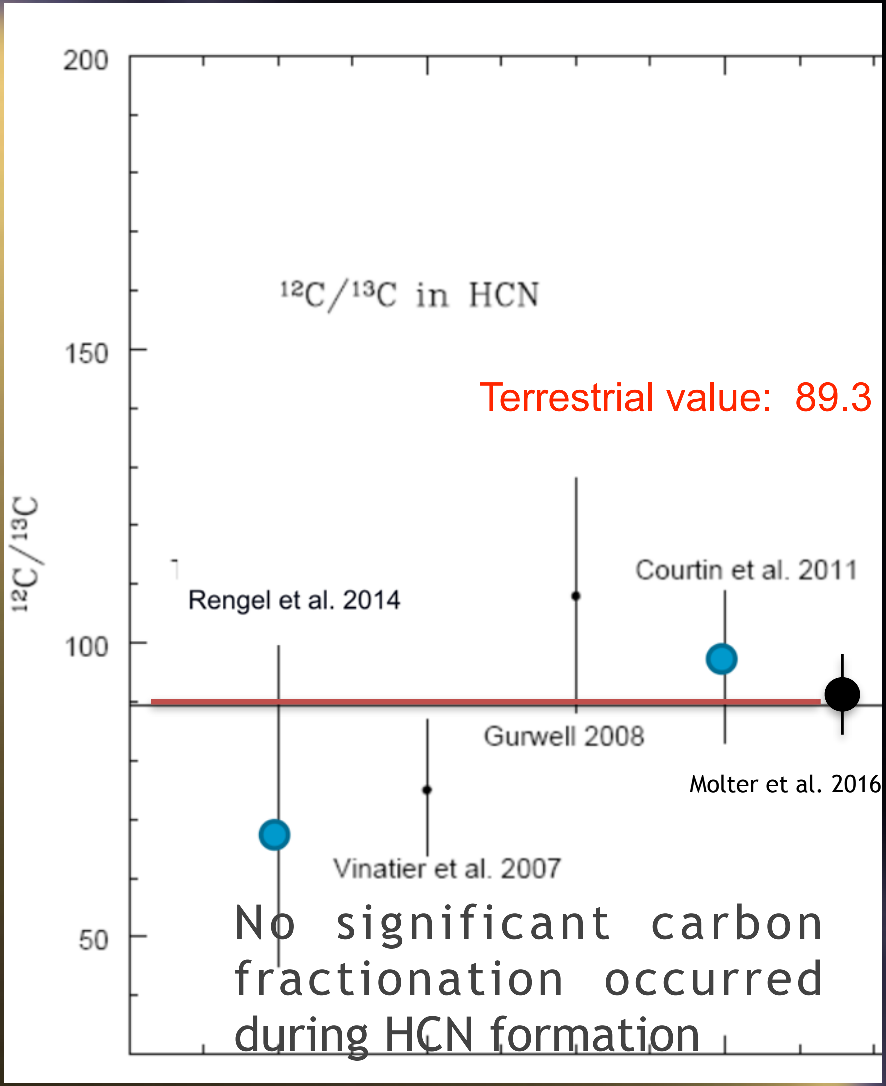


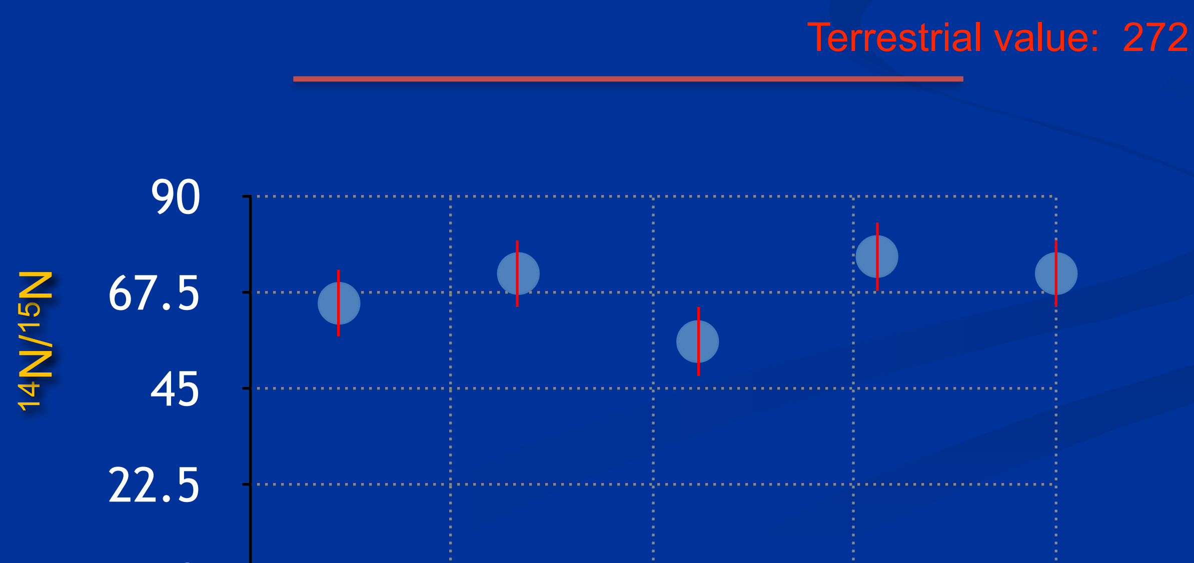
No significant carbon fractionation occurred during HCN formation

Isotopic ratios $^{14}N/^{15}N$ in HCN

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***
ALMA	*72.3 ± 2.2*	*Molter et al. 2016*

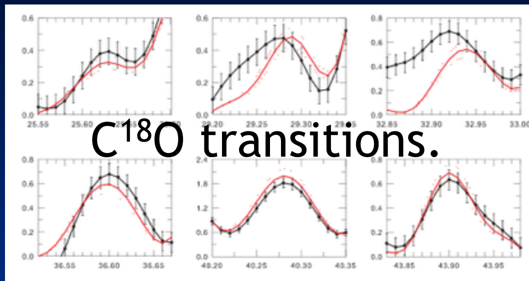
Photolytic fractionation of $^{14}N^{14}N$ and $^{14}N^{15}N$

(Earth = 272)



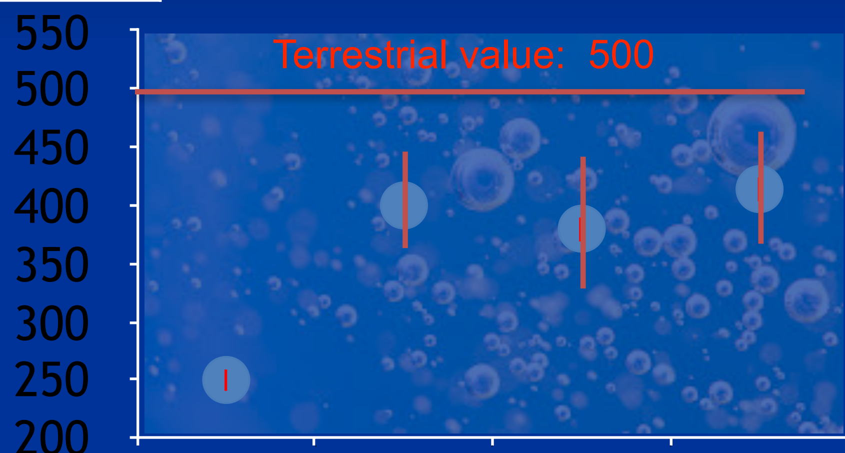
Isotopic ratio $^{16}O/^{18}O$ in CO

Courtin et al. 2012



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*

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



- 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

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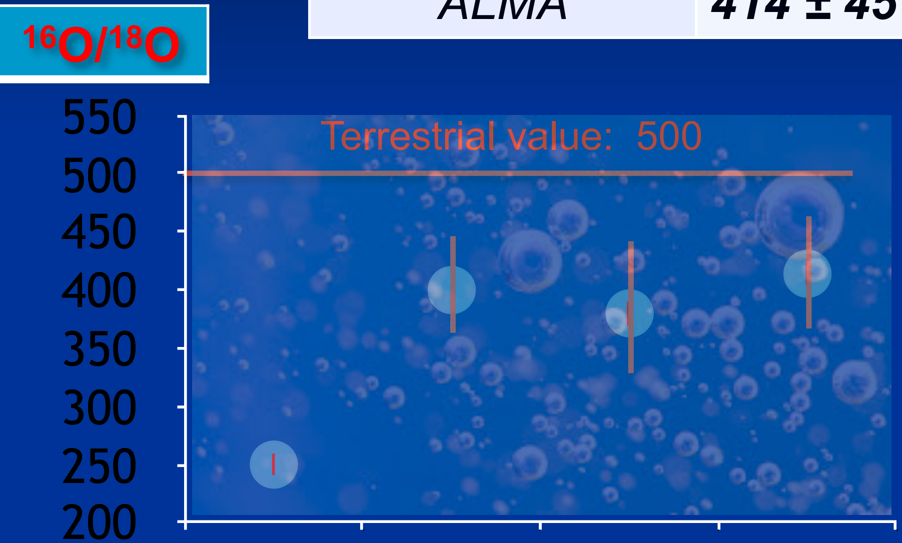

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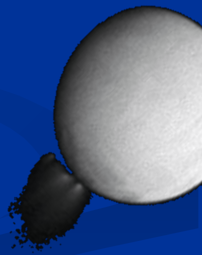


Precipitation of O^+ or O from the Enceladus Torus

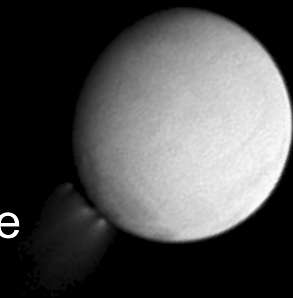
Further investigations :
- evolution of oxygen on Titan
- Oxygen processes in Titan's atmosphere

5.- Conclusion

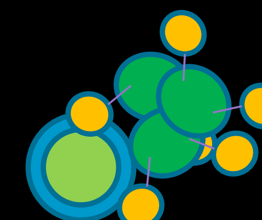
Herschel´s Legacy

- New 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 ($^{16}O/^{18}O$)

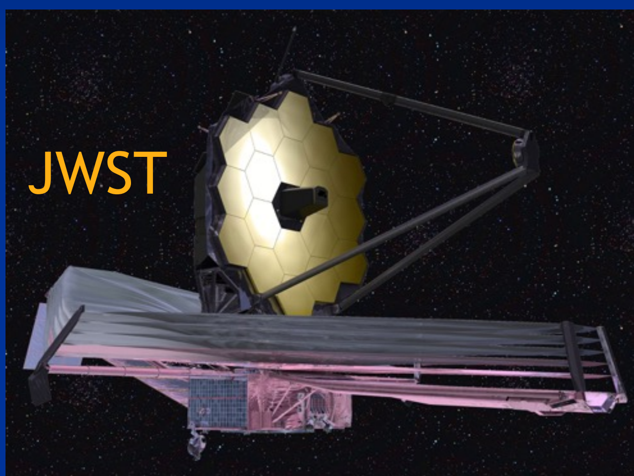


- We now know the content of water vapour in Titan (different as the predictions) and from where is coming from

Future – Synergy with Herschel

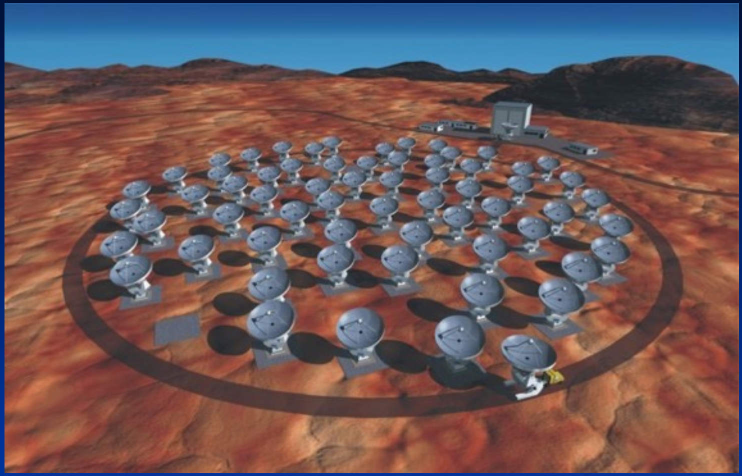
- CASSINI/CIRS (extended mission), until 2017. All flybys of Titan are done.

- JWST



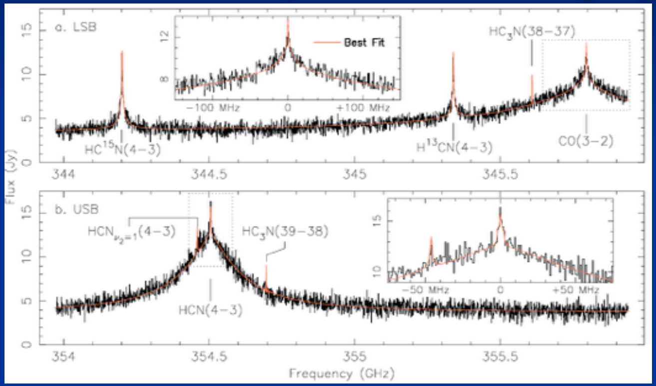
- Science Focus Group with key science themes:
  - Titan´s composition of the middle atmosphere
  - Objectives: Long-term monitoring of the changing spatial distributions of gases, clouds and hazes —> reveal the interplay of chemistry and dynamics

Future – Synergy with Herschel



- ALMA :

Titan's atmospheric chemistry/dynamics



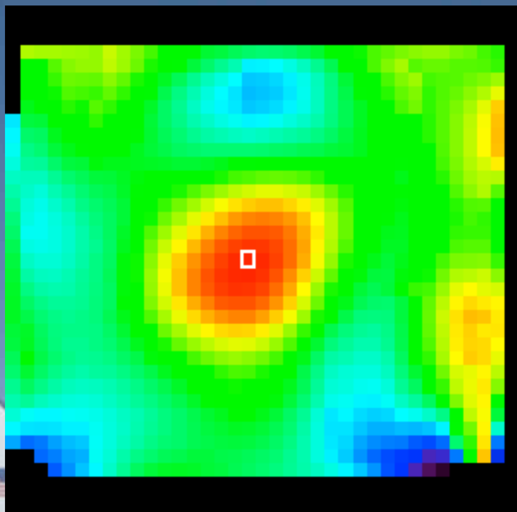
SMA 850 micron unresolved observations

Gurwell 2004

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

HCN by SOFIA/FIFI-LS

Titan at 169 microns (continuum):

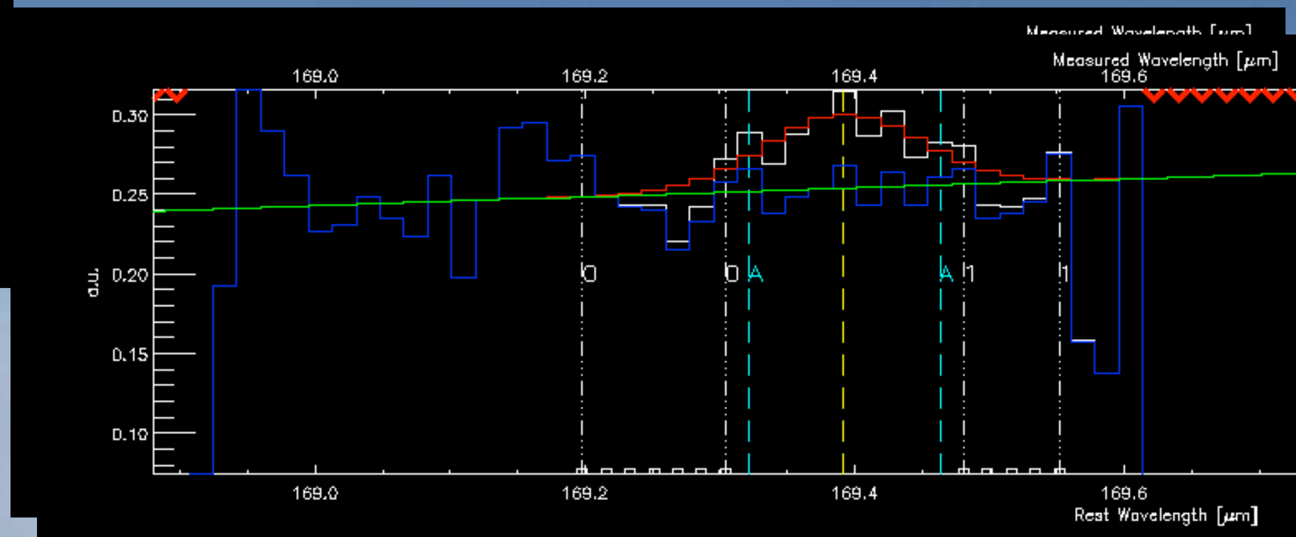


- observations on 26 February 2016
- 30 min

Proposal 04_0093, P.I: Rengel

First observations of Titan with SOFIA!

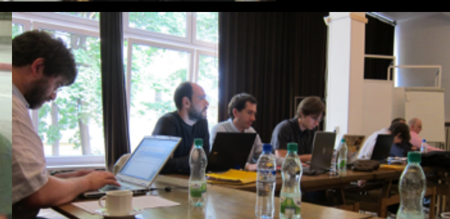
HCN (20-19) at 169.3 microns











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- 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.

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