Spectroscopy of atmospheric trace gases on Titan with Herschel: Advances and Discoveries

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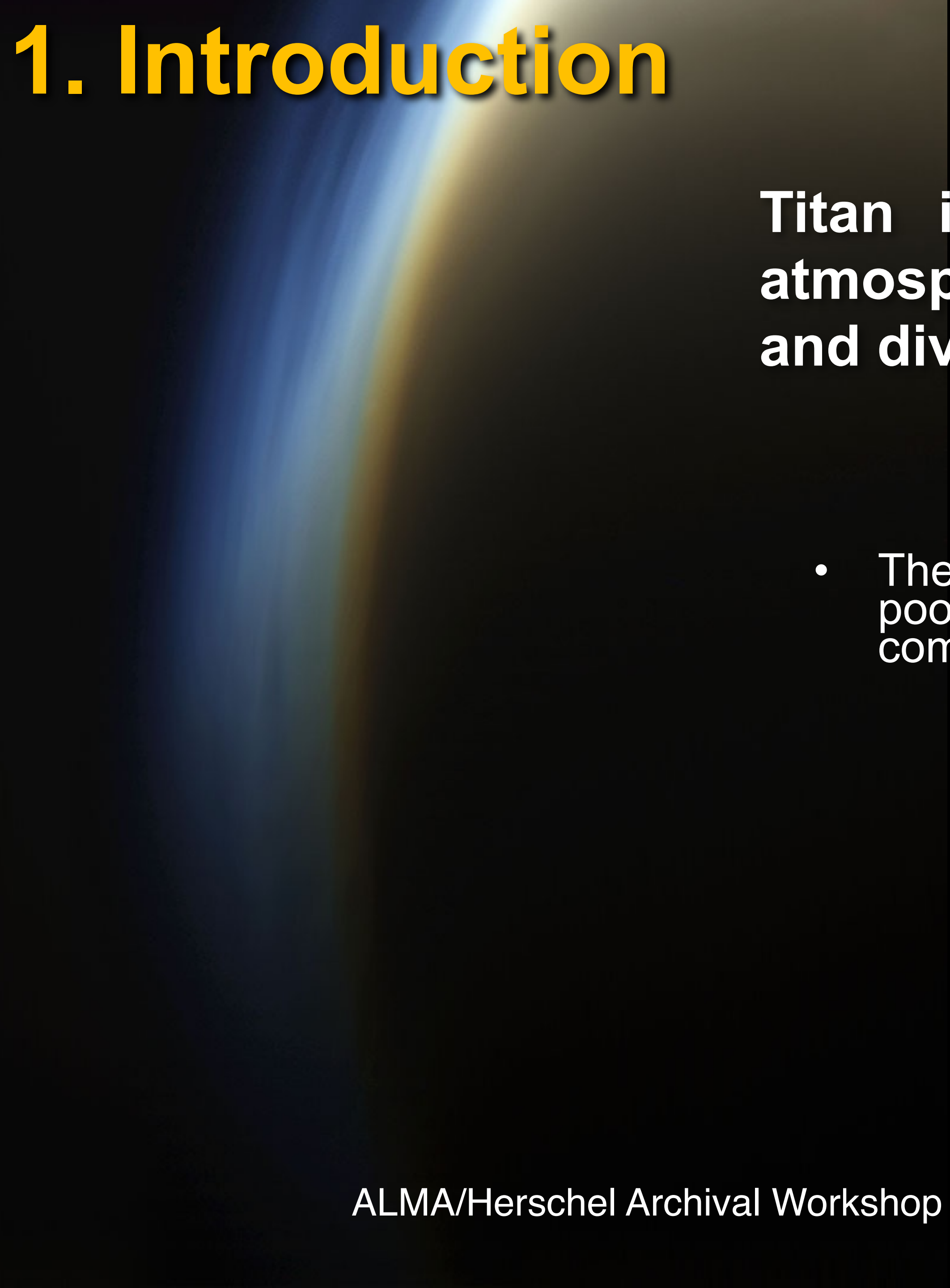
Moreno R., Courtin R., Lellouch E., Sagawa H.; Hartogh P., Swinyard B., Lara M., Feuchtgruber H., Jarchow C. , Fulton T., Cernicharo J., Bockelée-Morvan D., Biver N., Banaszkiewicz M., González A.

ALMA/Herschel Archival Workshop - Garching, 15-17 April 2015

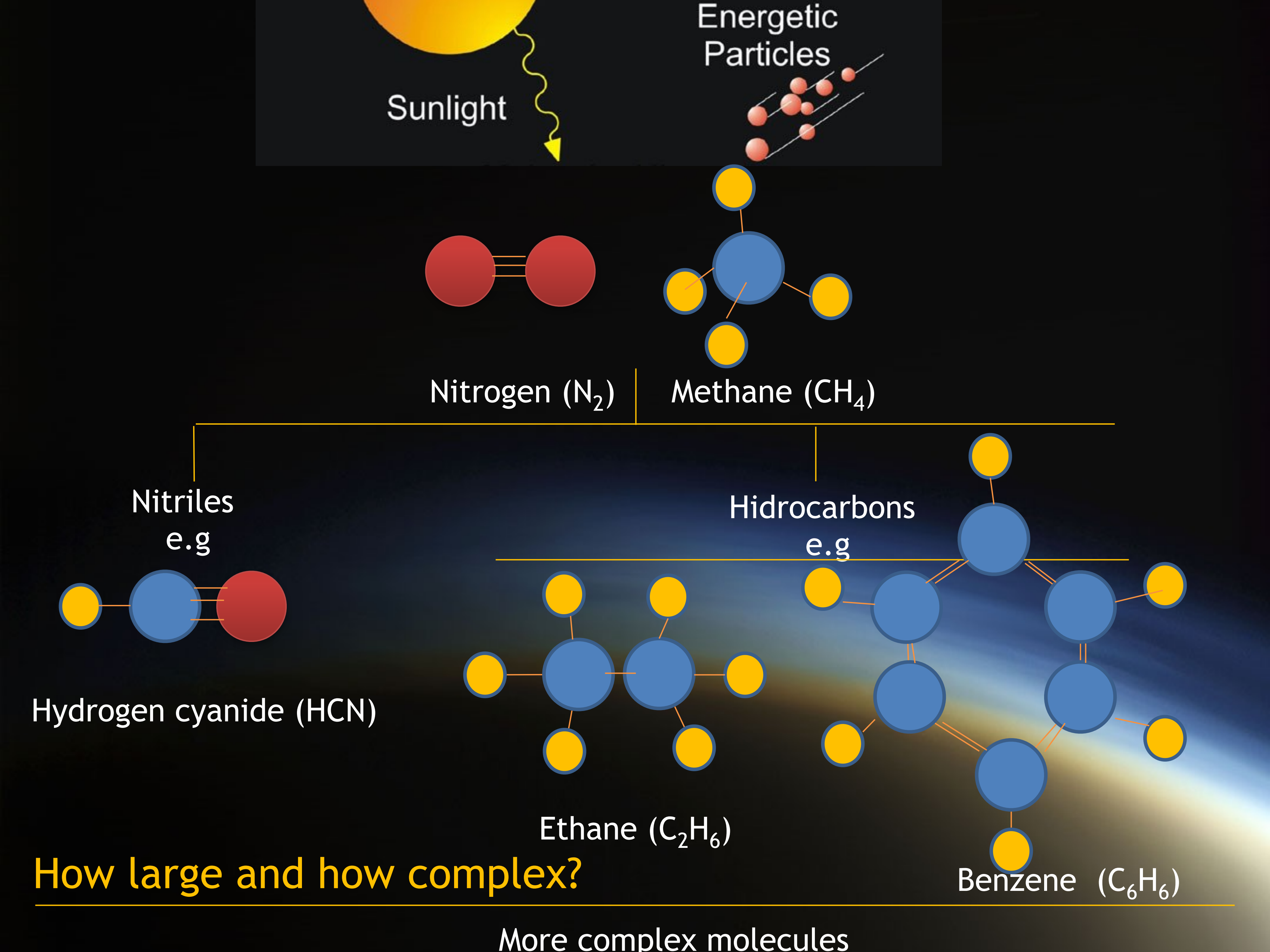
1. Introduction



Why Titan?

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

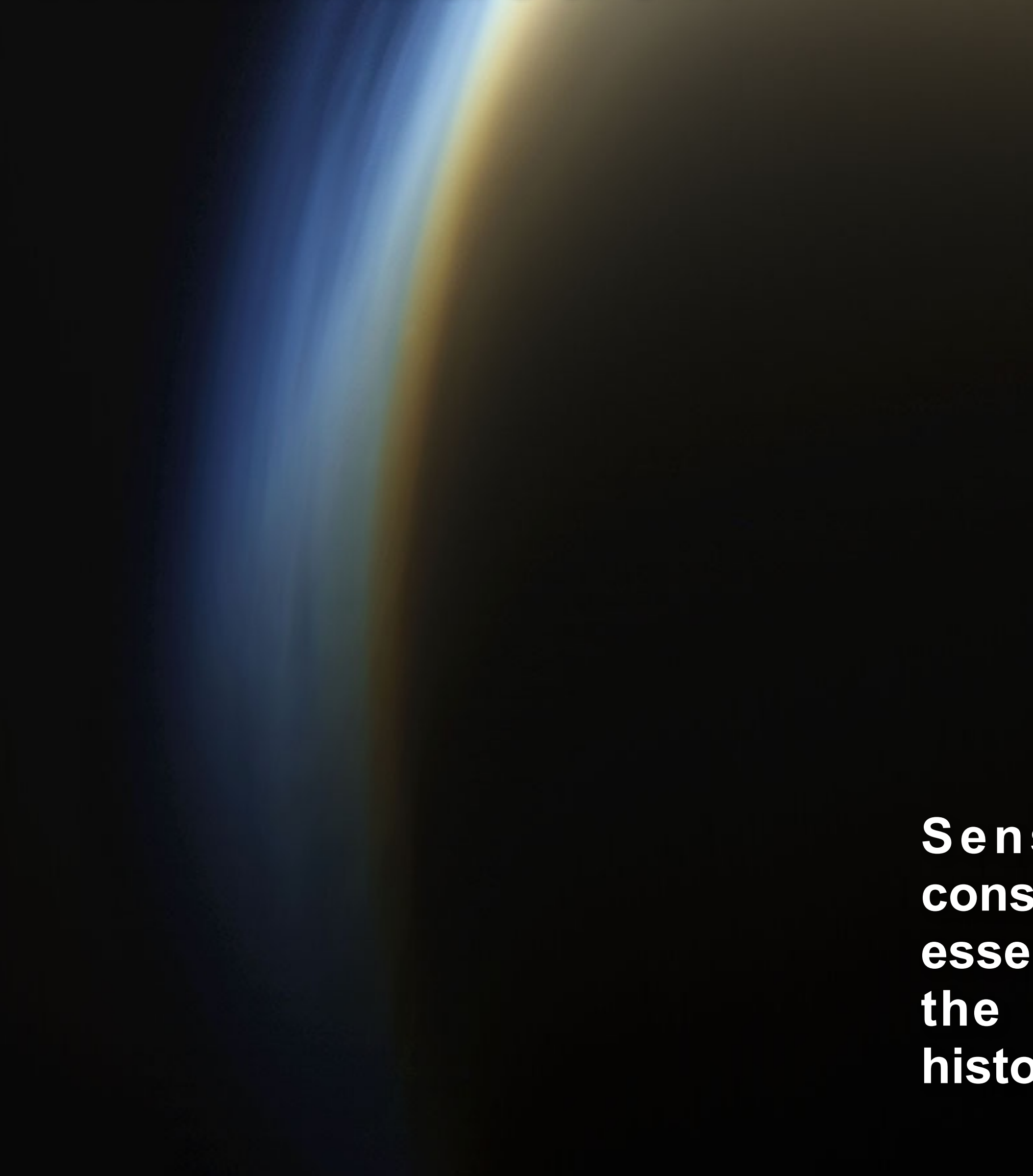
- The origin of Titan‘s atmosphere is poorly understood and its chemistry is complex



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

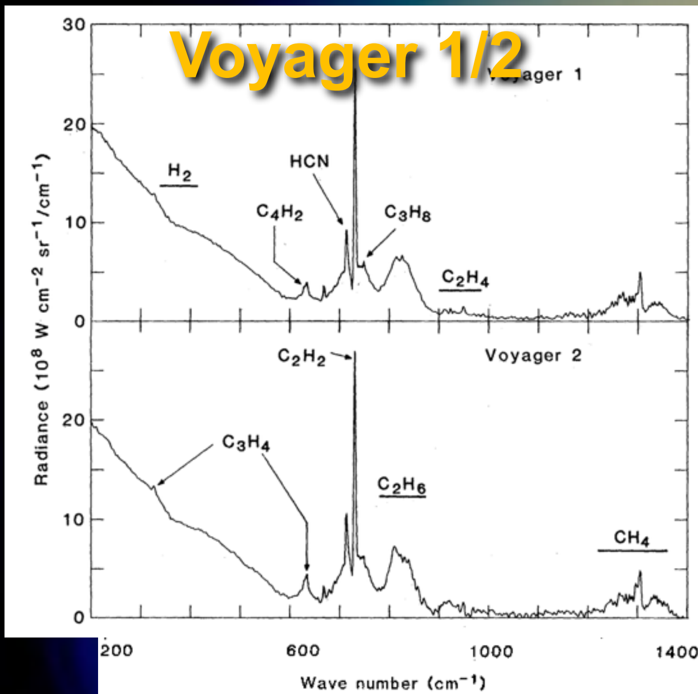
Why Titan?



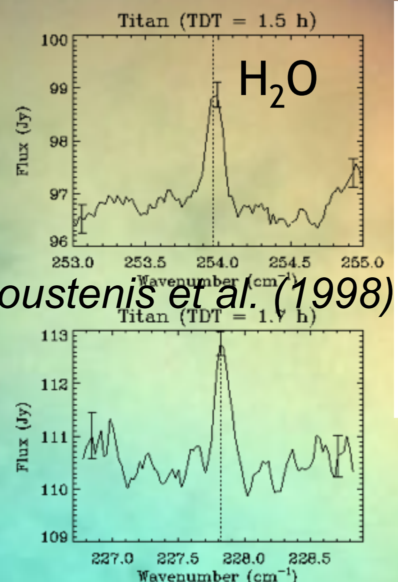
Sensitive observations of the constituents of the atmosphere are essential to constructing models of the Titans´s atmosphere and its history.

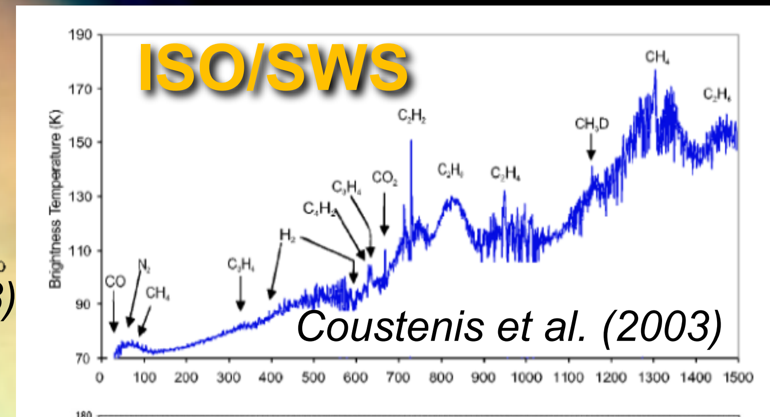
1. Introduction

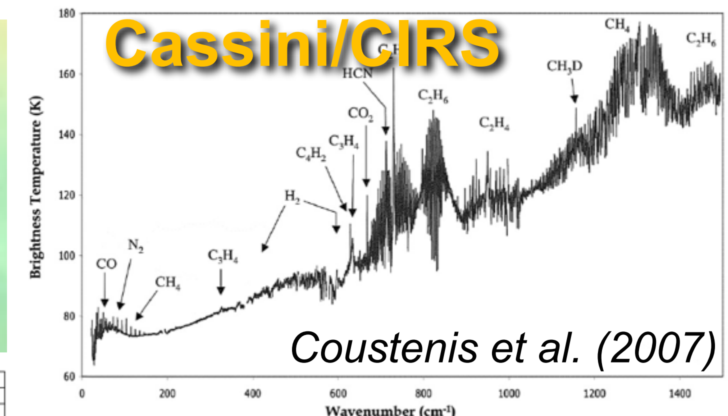
Spectroscopy of Titan has been already performed by:

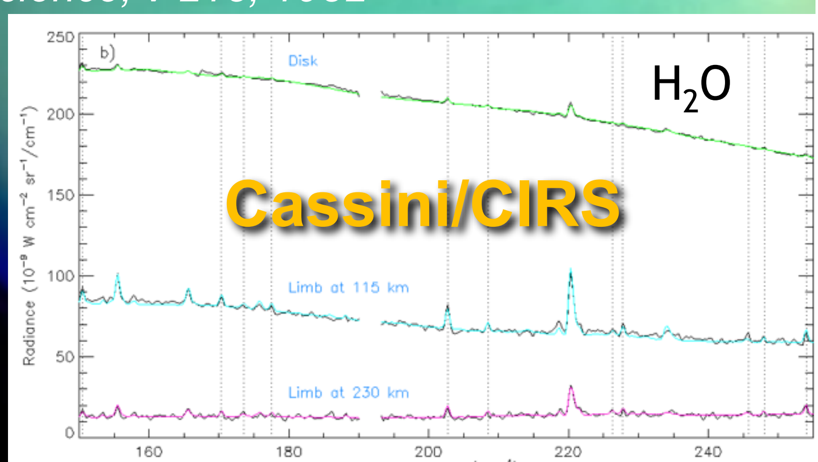


Hanel et al., Science, v 215, 1982



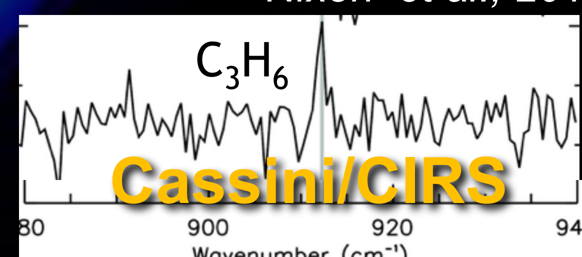






Cottini et al., 2012

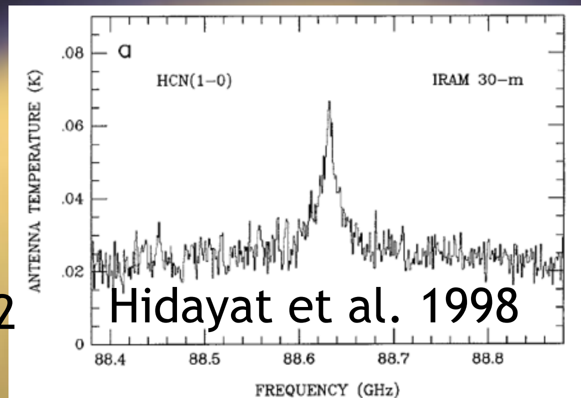
Nixon et al., 2013



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

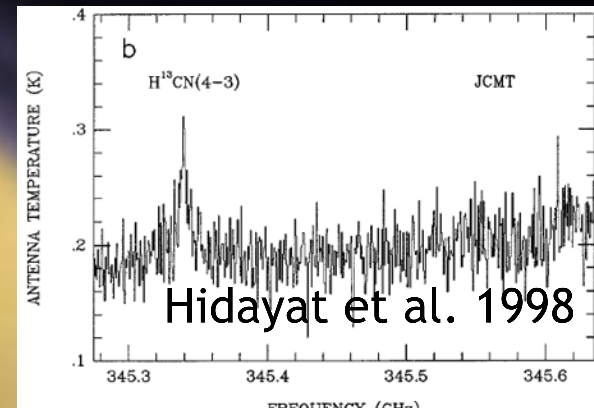
IRAM 30-m:

Marten et al. 2002



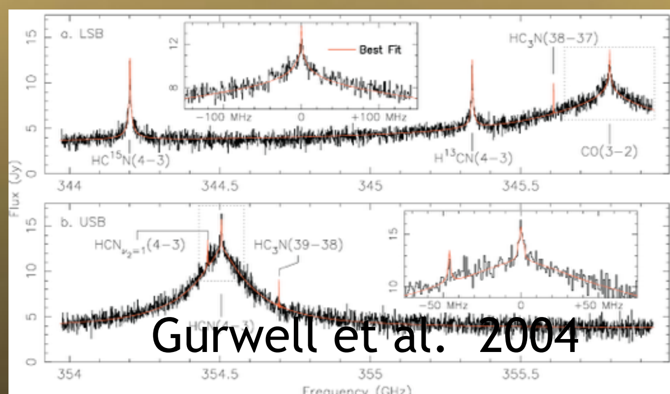
Hidayat et al. 1998

JCMT:



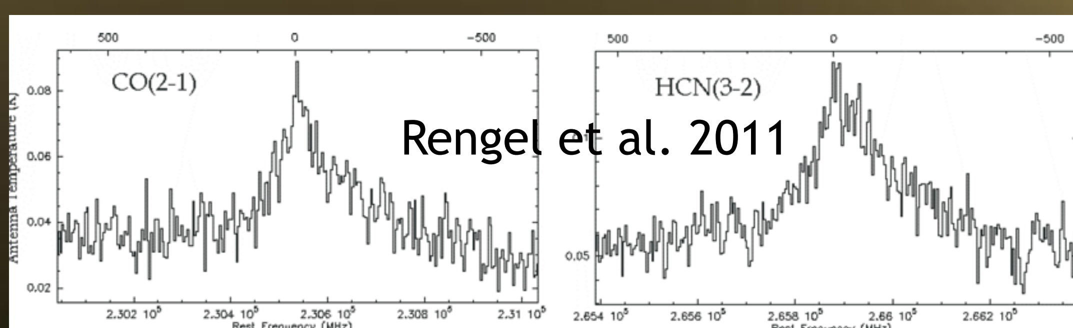
Hidayat et al. 1998

SMA:

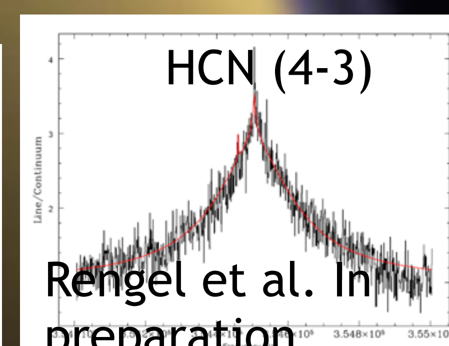


Gurwell et al. 2004

APEX:



Rengel et al. 2011

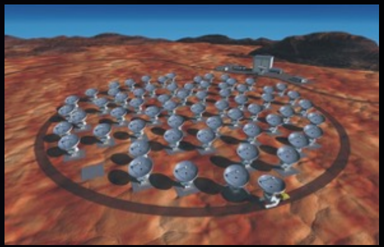


HCN (4-3)

Rengel et al. In preparation

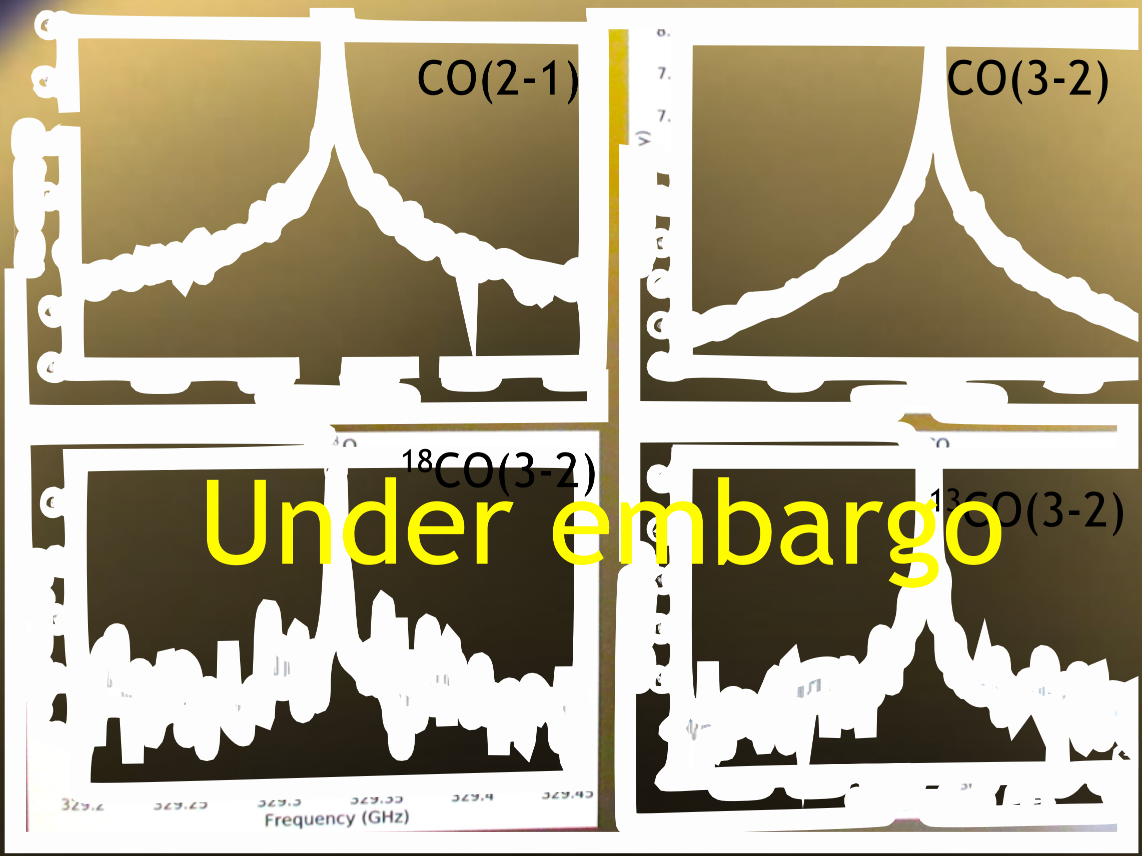
Ground-based observations have also improved our knowledge of Titan's atmospheric composition:

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

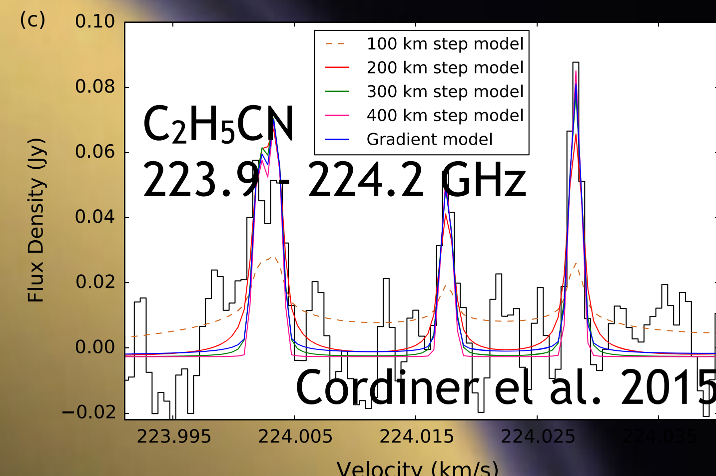


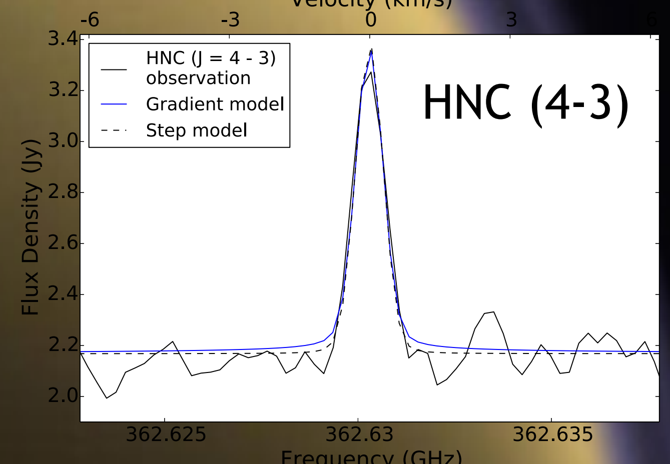
ALMA

ALMA Archive data - 2012



Serigano et al. in preparation





Cordiner et al. 2014

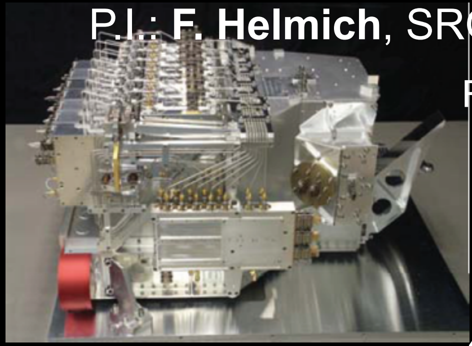
Herschel Era

Credits: ESA

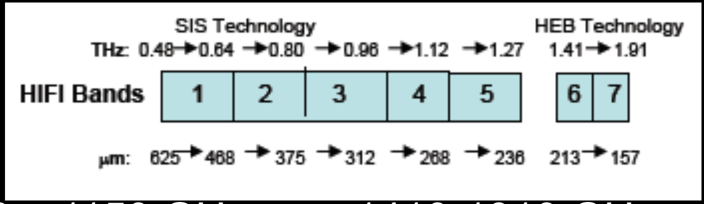
Instruments onboard Herschel:

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

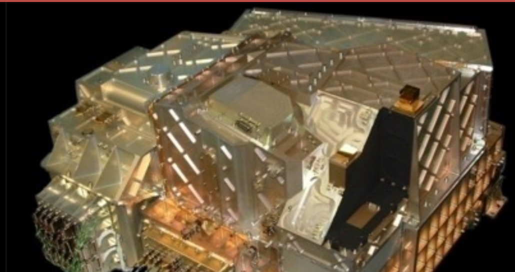
P.I.: **F. Helmich**, SRON



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

Photo**d**etector **A**rray **C**amera and **S**pectrometer (**PACS**).

PI: **A. Poglitsch**, MPE 55 – 210 μm

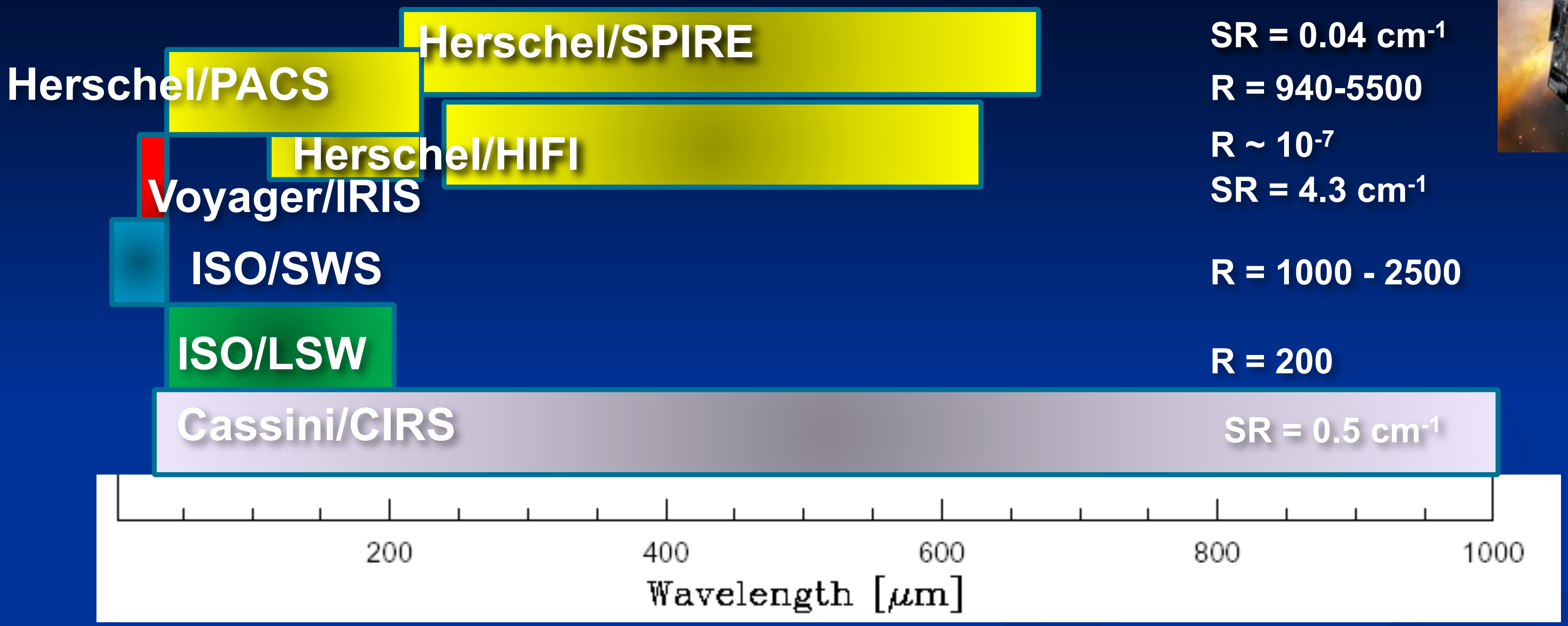
Spectral and **P**hotometric **I**maging **Re**ceiver (**SPIRE**).

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 accesible 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}

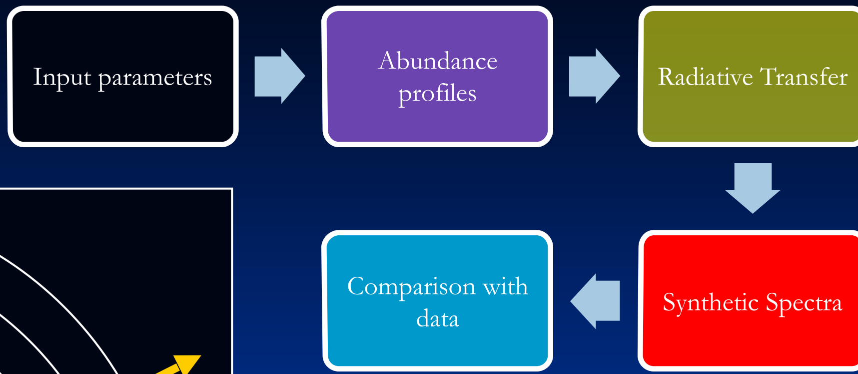
PACS: Full range spectra (51-220 μm or 50-180 cm^{-1}) (twice, 0.63h and 1.1h), R= 1000-5000

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

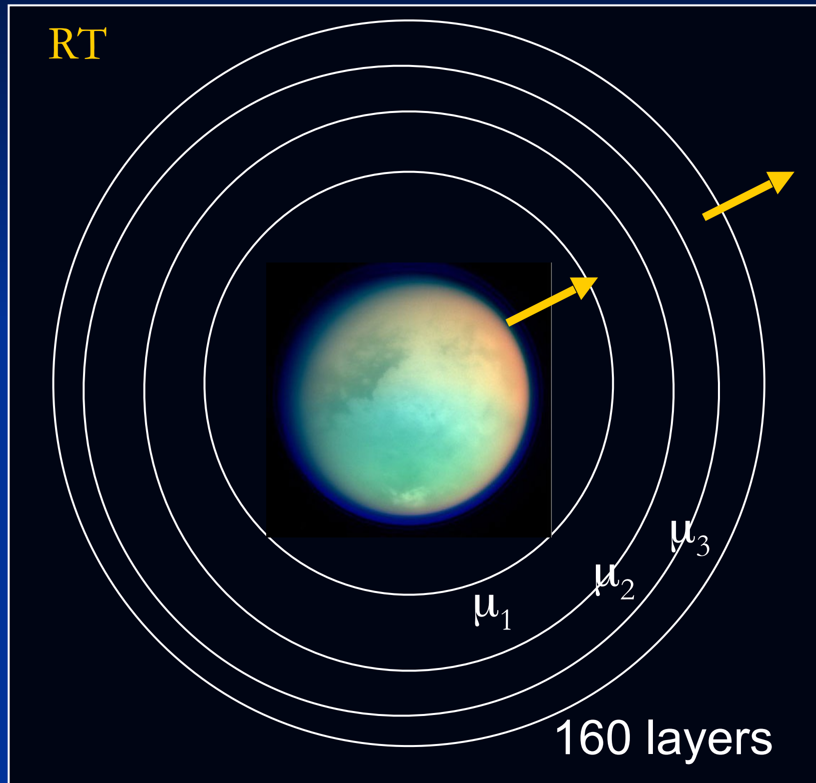
Modeling the Titan spectra
Method



T profile

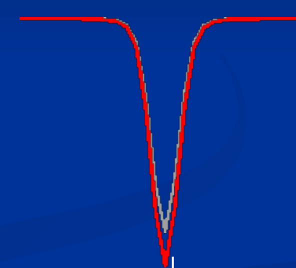
P profile

Vmr profile

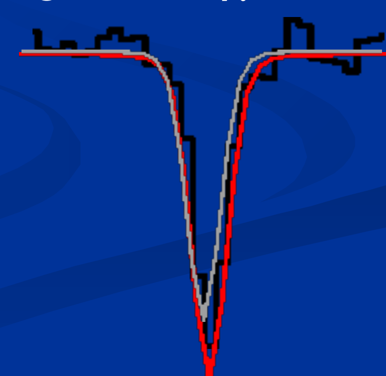


μ_i=absorption coefficient

Synthetic spectra

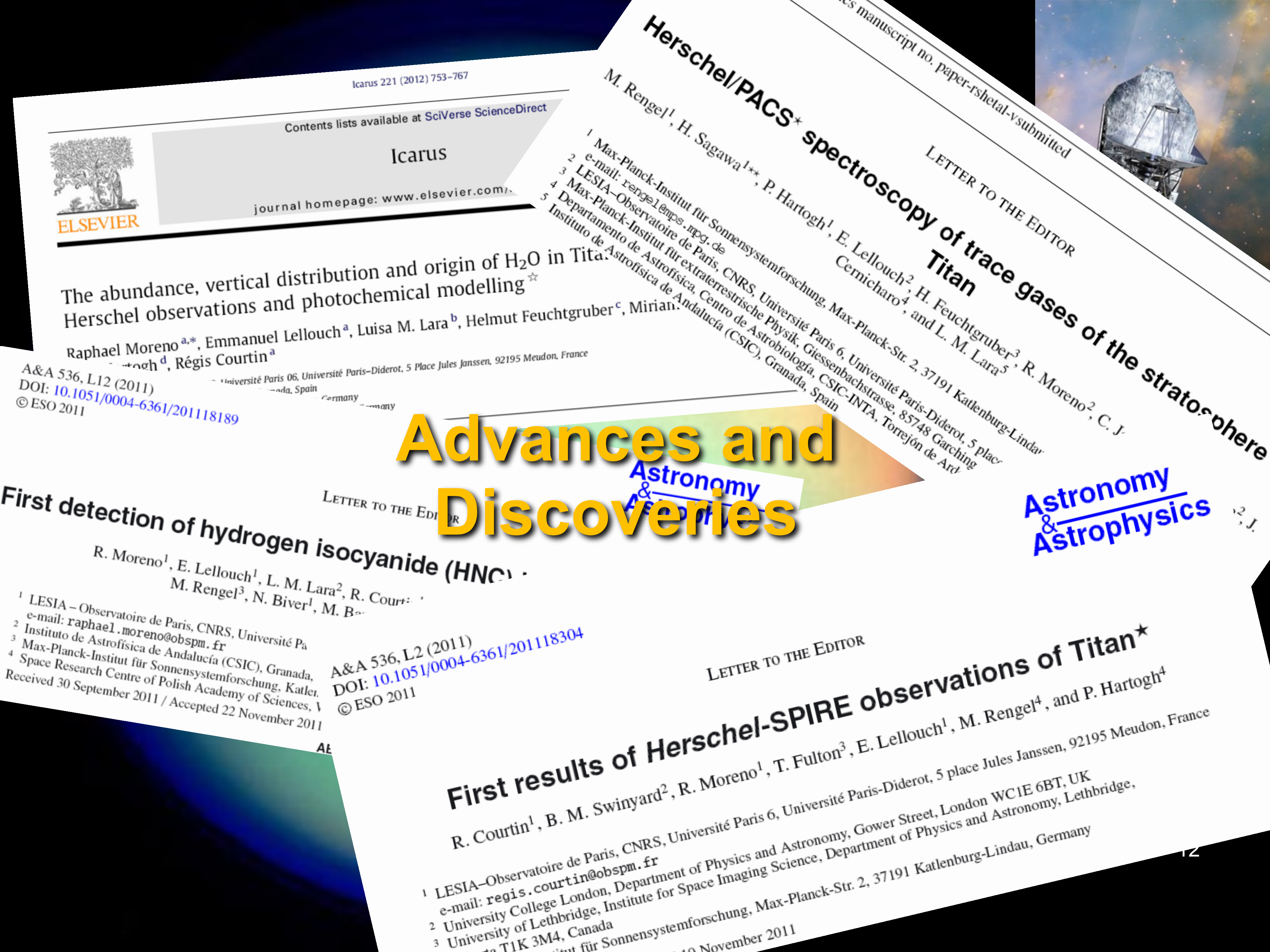


Fitting algorithm: χ^2 statistics



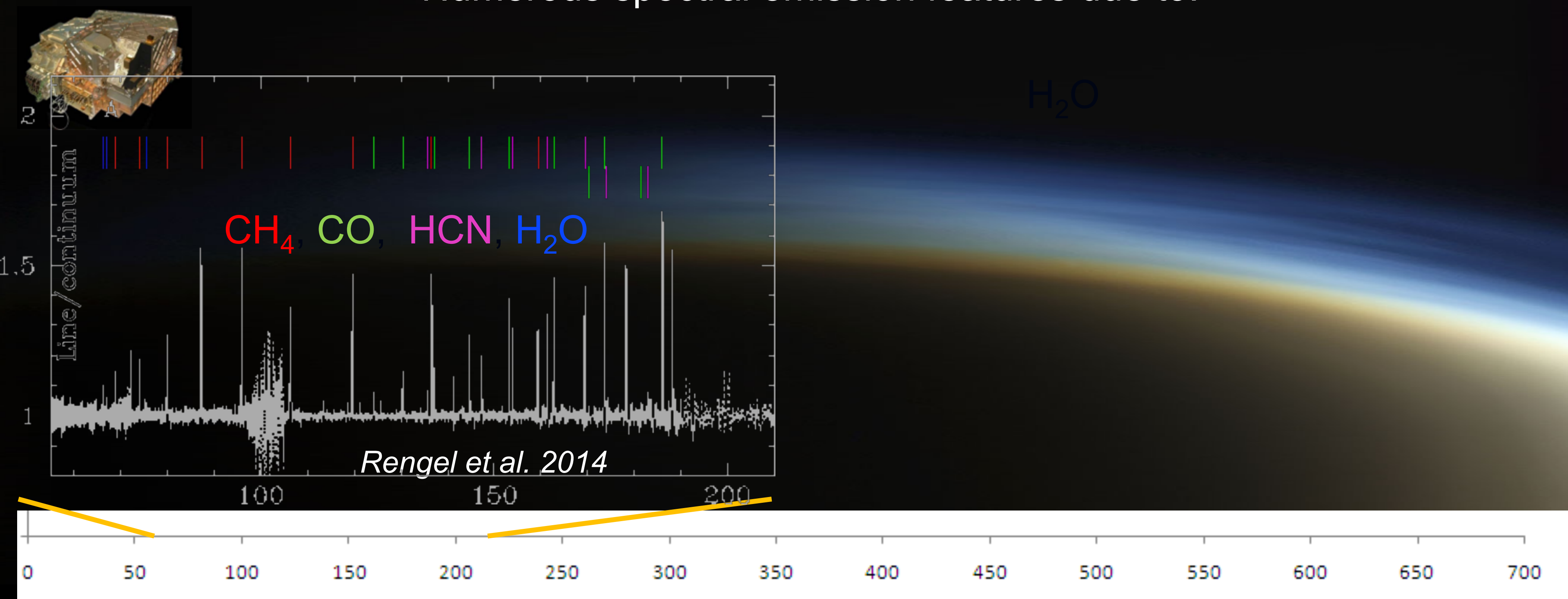
New set of parameters

Advances and Discoveries



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

Numerous spectral emission features due to:



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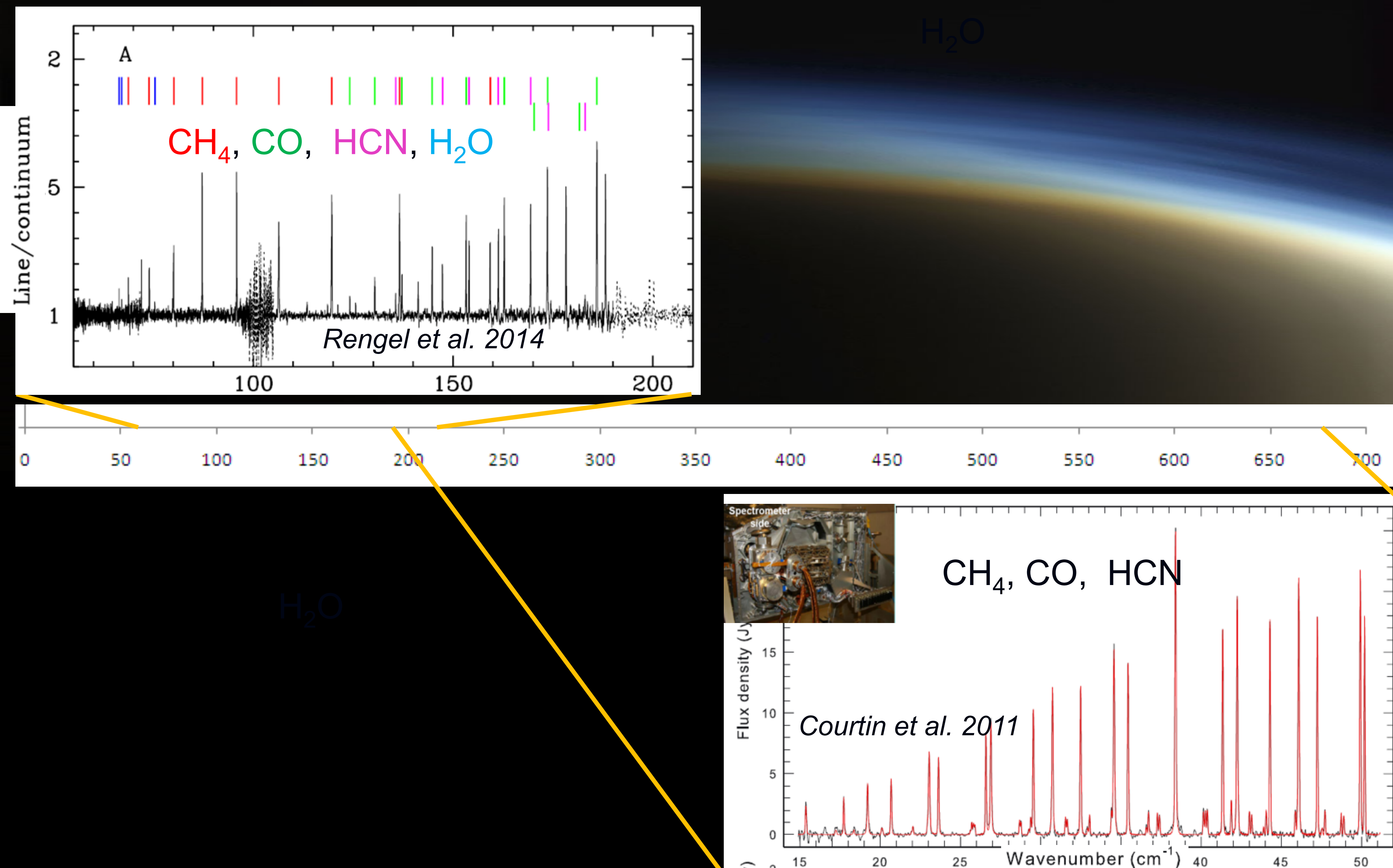

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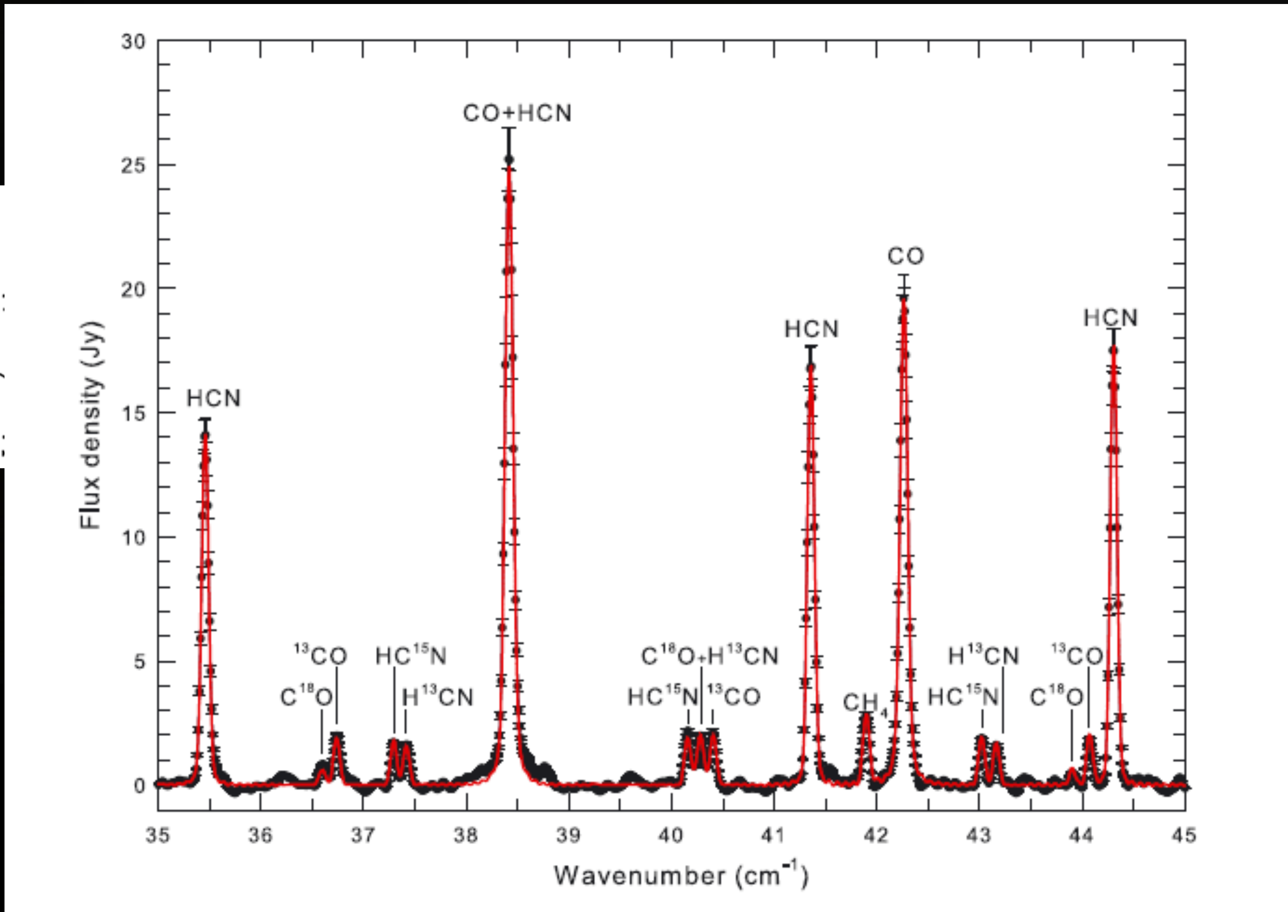
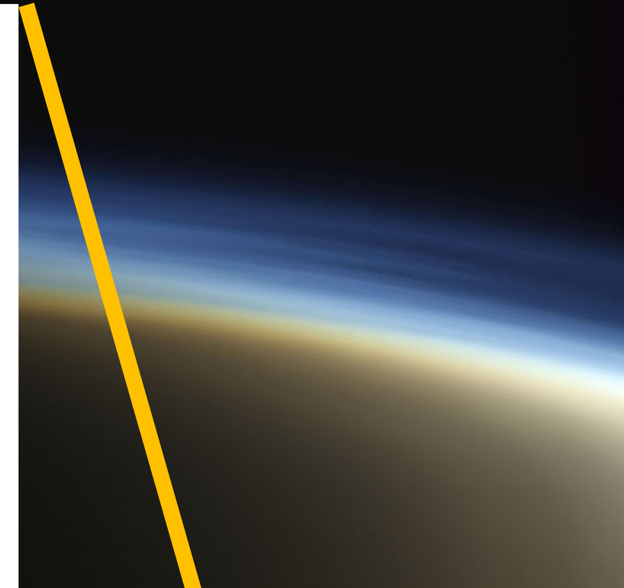
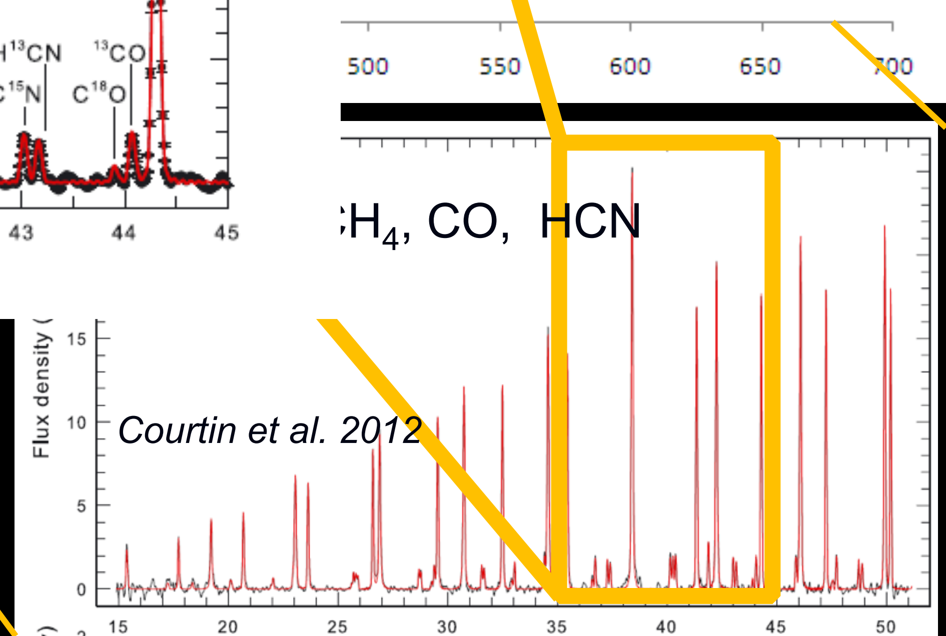




CH_4, CO, HCN



Courtin et al. 2012

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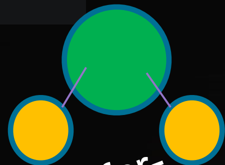
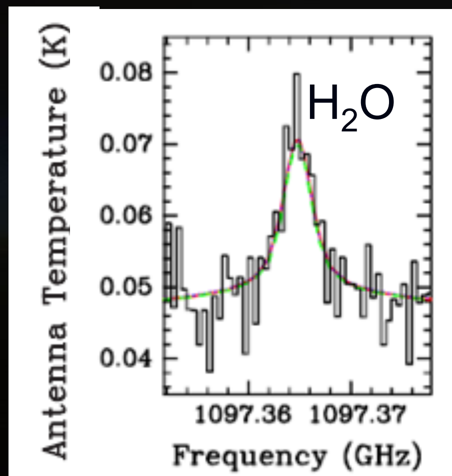
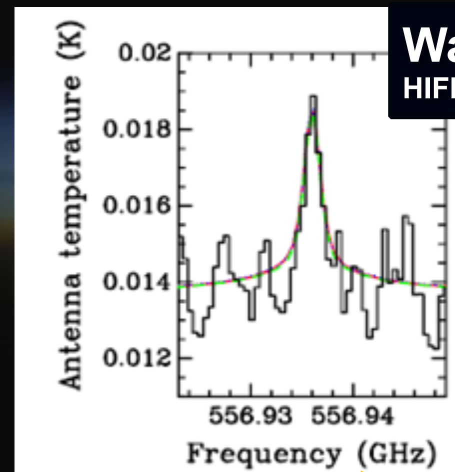
Spectral emission features due to:



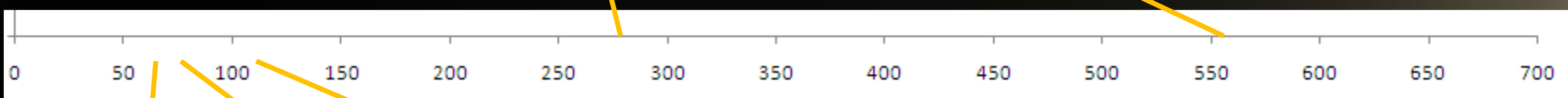
Several H_2O far-IR lines detected for the first time in Titan's atmosphere,

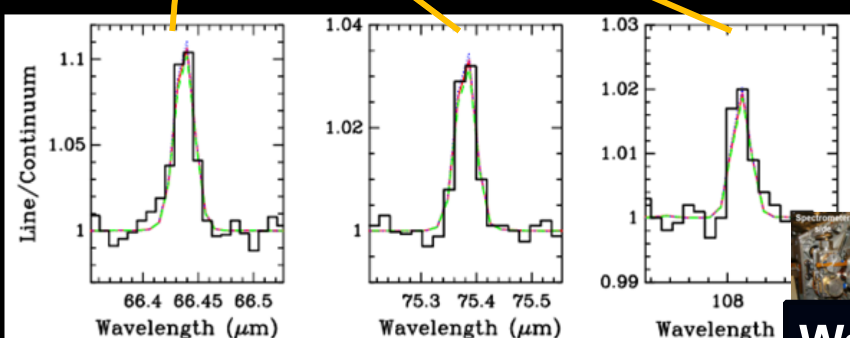




Water Vapour in Titan

HIFI / Herschel





Water Vapour in Titan

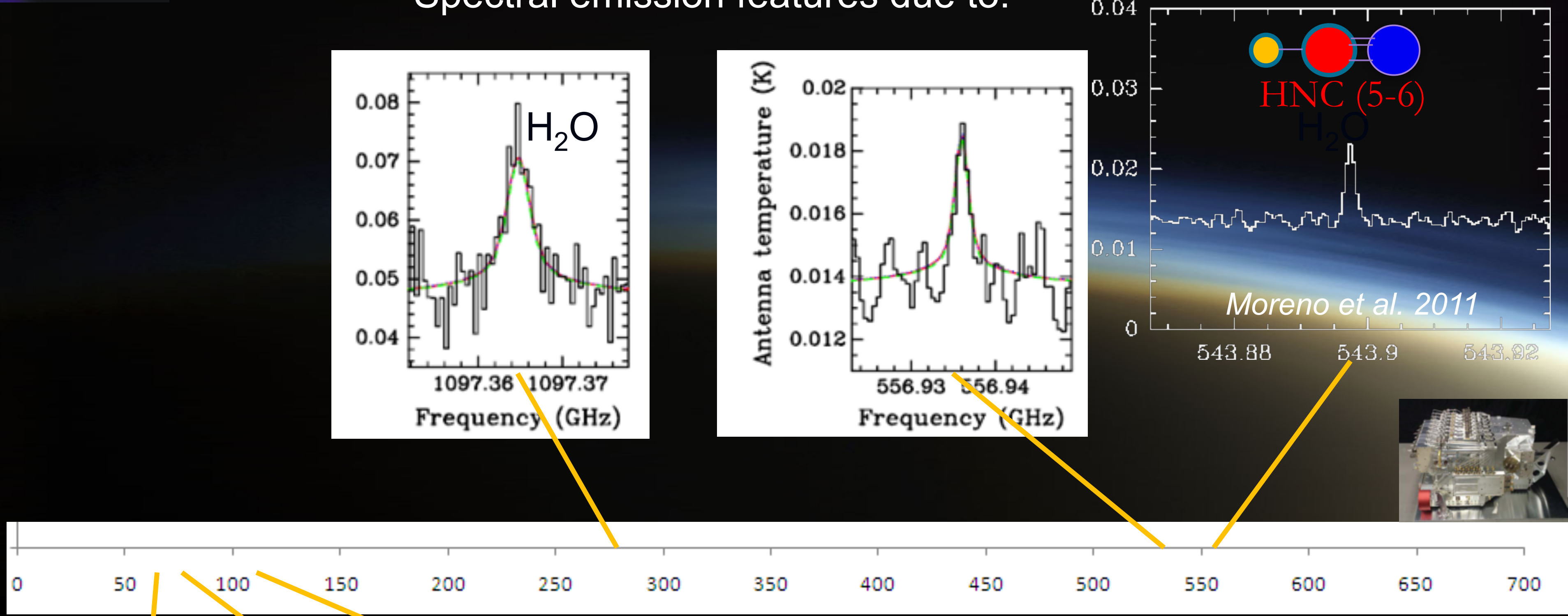
PACS / Herschel

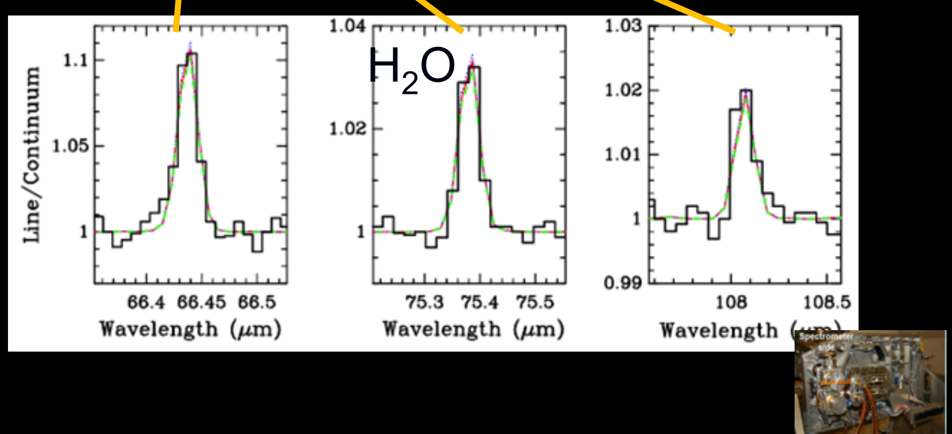
Five dedicated Water vapour line emission with Herschel/PACS and HIFI. Goal: vertical profile of H_2O

Moreno et al. 2012

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

Spectral emission features due to:



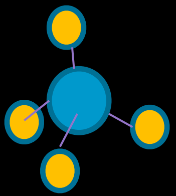


Surprise: Unexpected detection of hydrogen isocyanide (HNC) ➔ a specie not previously identified in Titan´s atmosphere

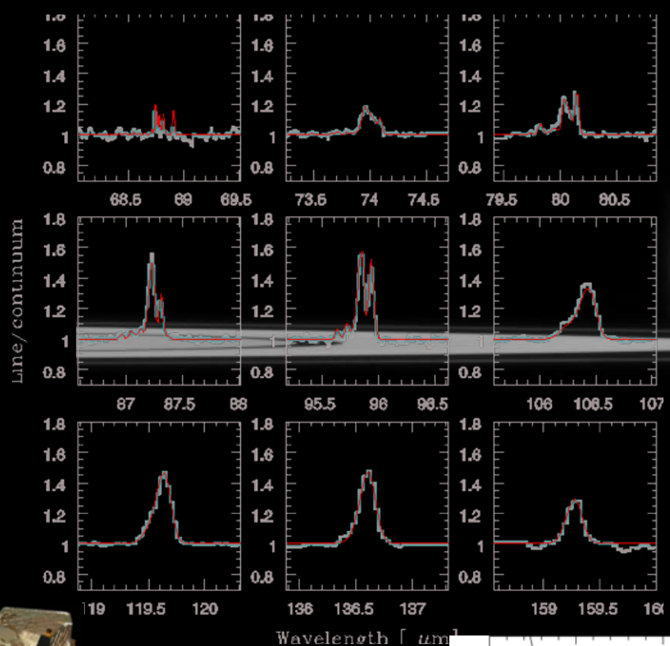
2.- Determination of the abundance of the trace constituents:

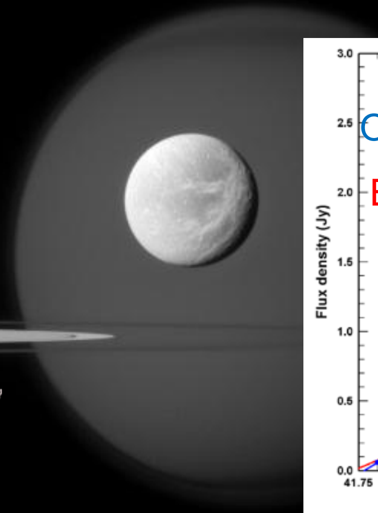
Step 1: Computation of the synthetic spectra for several abundances
Step 2: Calculation of the best-fit

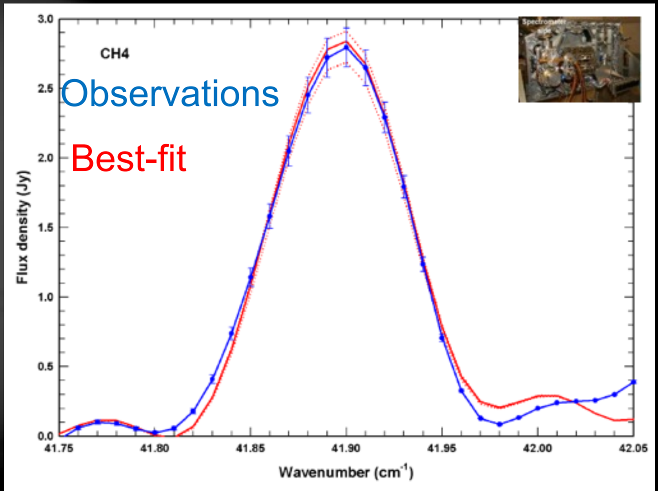
- **CH_4:** Origin unknown



Observed and best-fit simulated CH_4 lines

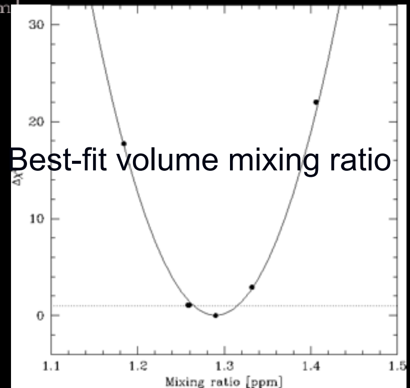






Courtin et al. 2011

Rengel et al. 2014

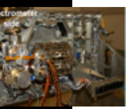


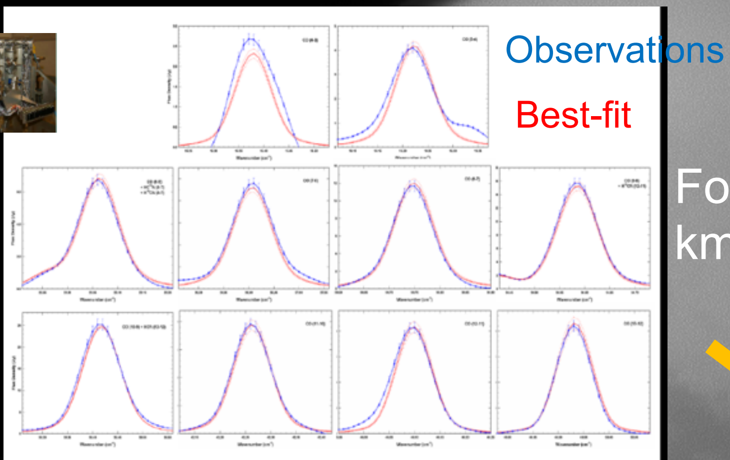
Consistent with previous studies:

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**

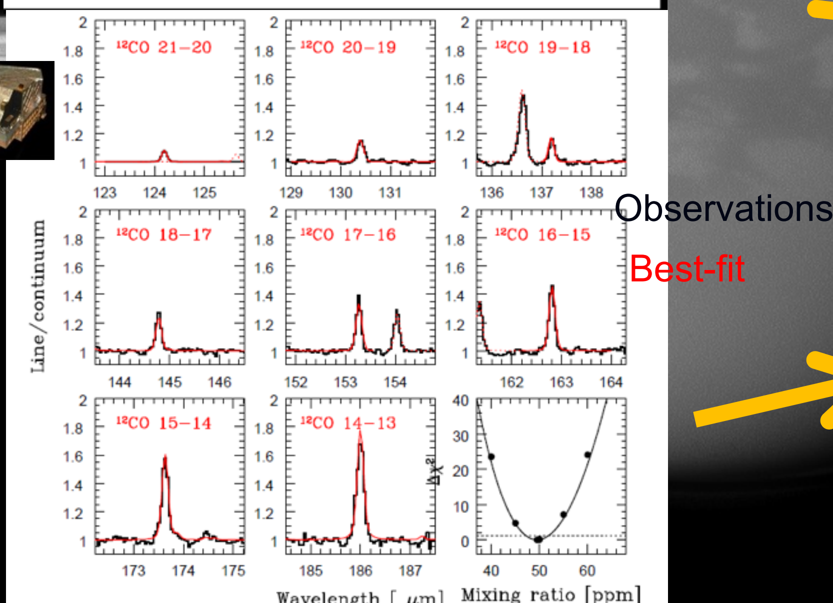
CO: is CO primordial or external ? Viable via precipitation of O or O^+ from Enceladus Torus (*Hörst et al. 2008; Cassidy & Johnson 2010; Hartogh et al. 2011*)

Observed and best-fit simulated CO lines





For the [60-170] km range altitude

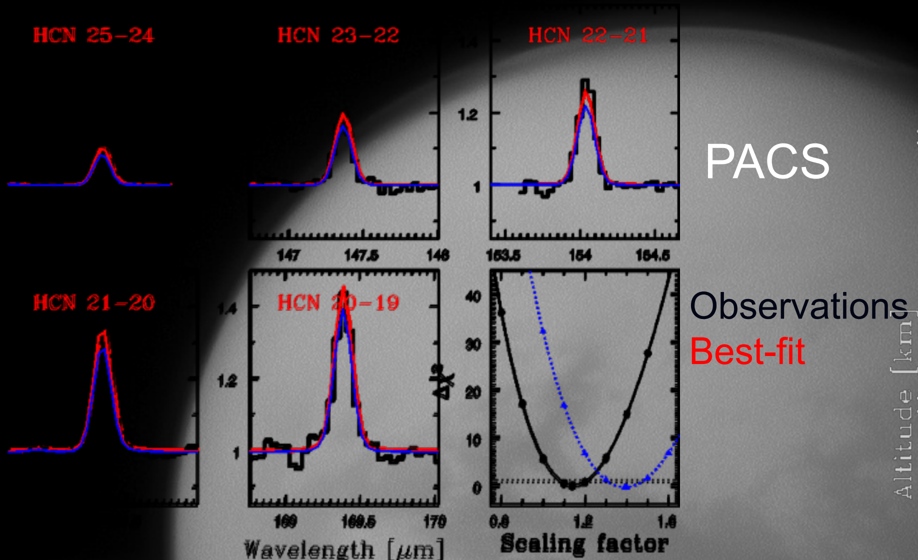


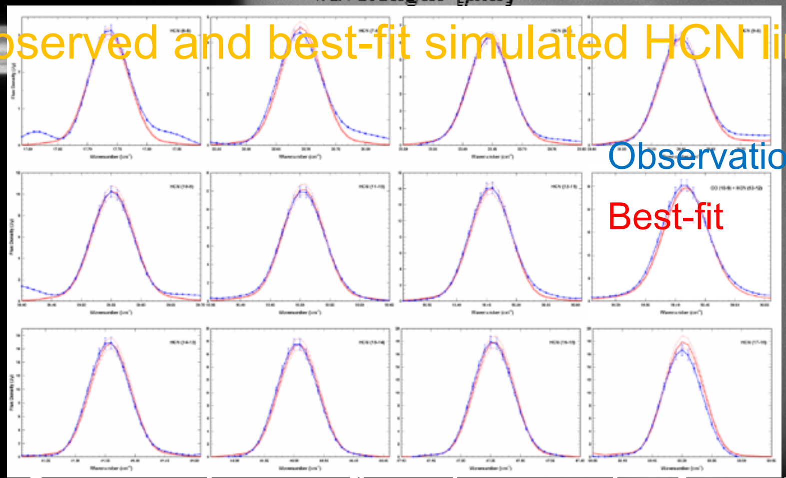
Consistent with previous studies:

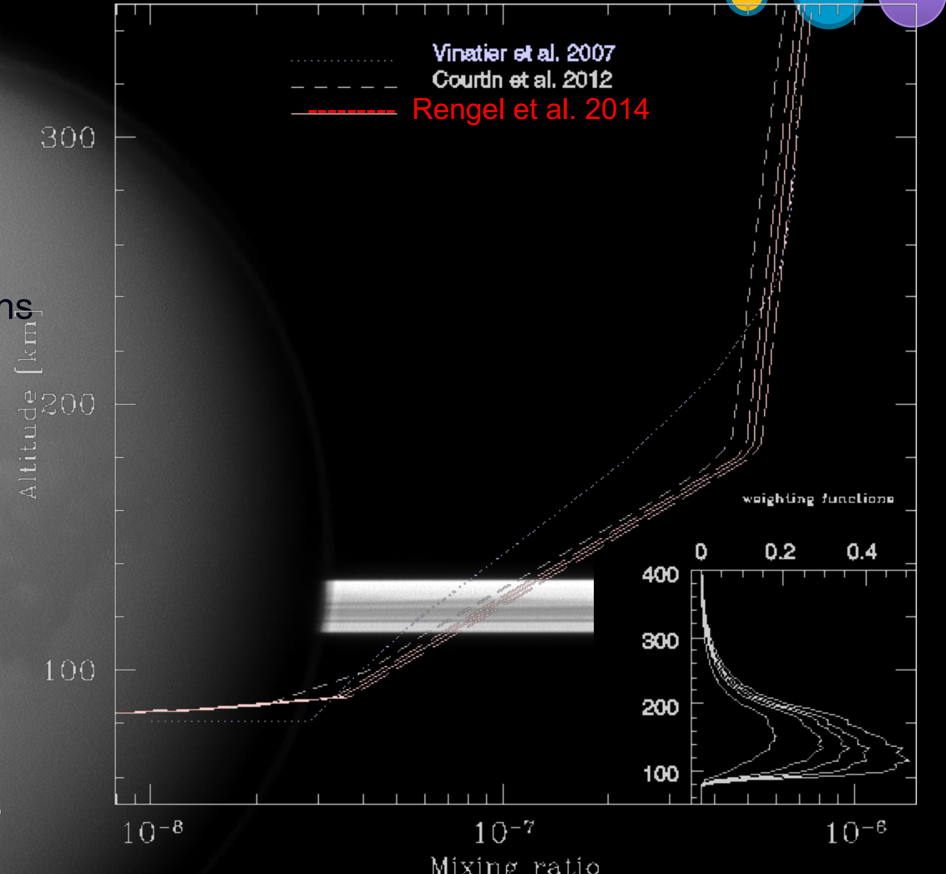
Facility	Value [ppm]	Reference
SPIRE	***40±5***	***Courtin et al. 2011***
CIRS	47±8	De Kok et al 2007
APEX	***30^{+15}_{-8}***	***Rengel et al. 2011***
SMA	51±4	Gurwell et al. 2012
PACS	***49±2***	***Rengel et al. 2014***
ALMA	***46±2***	Serigano et al. in preparation

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







Distribution of HCN, compared with the profile by CIRS

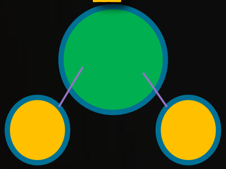
Our results confirm the results from Marten et al. 2002.

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

Rengel et al. 2014

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

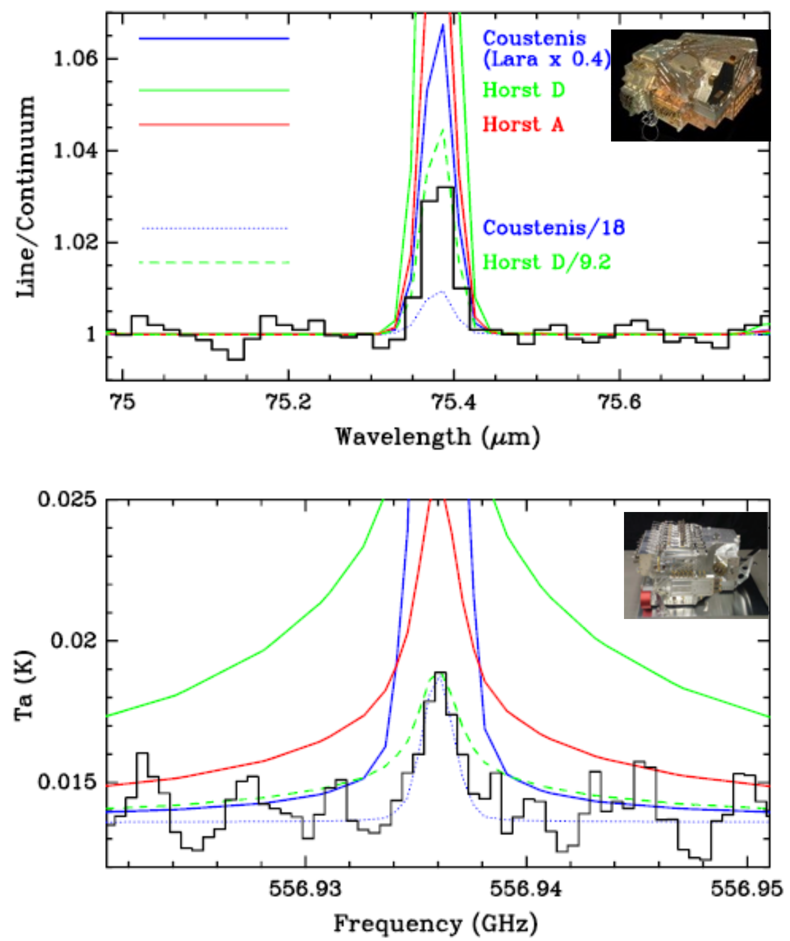
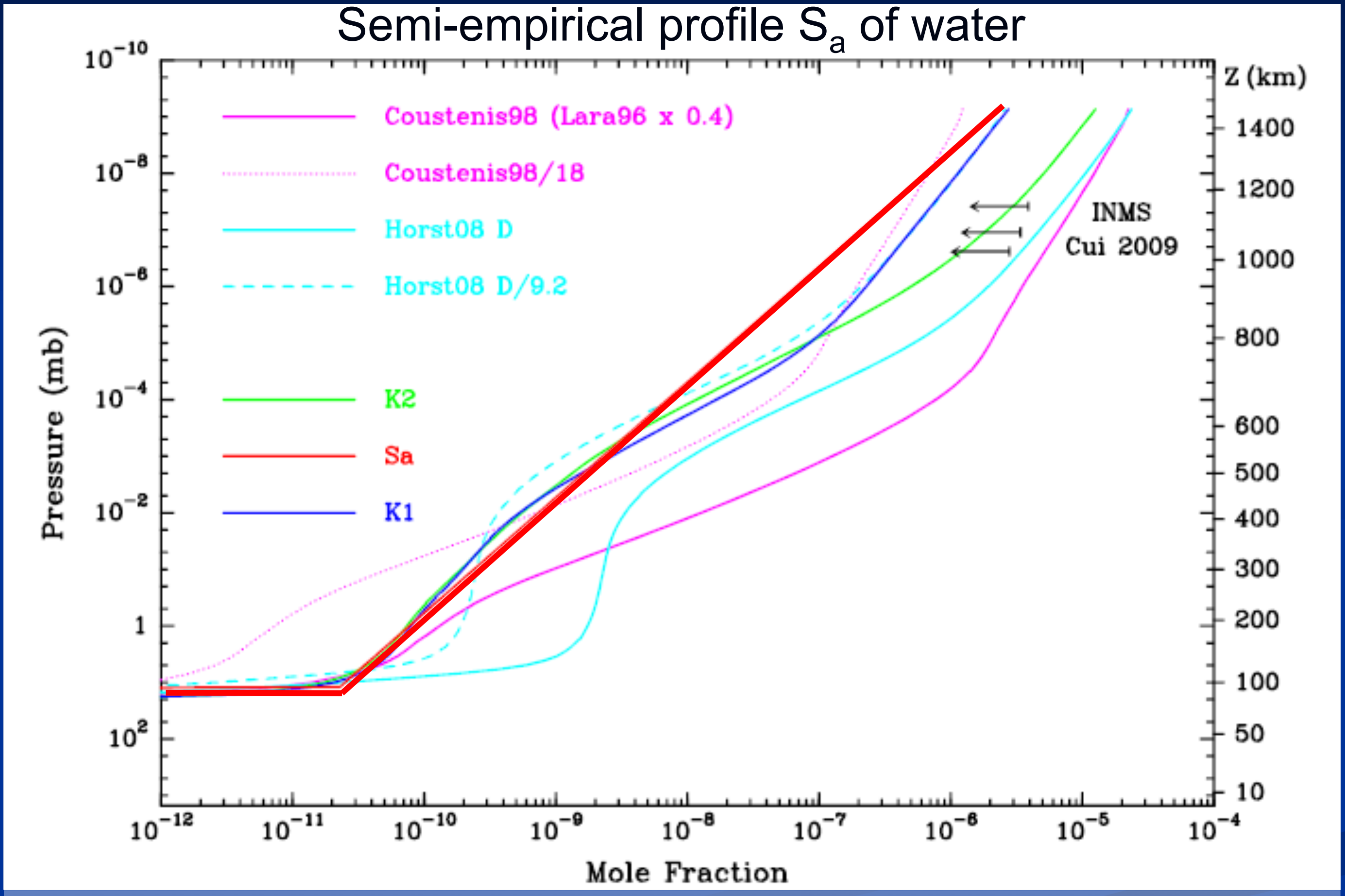


Fig. 7. Synthetic spectra computed considering several previously proposed H_2O profiles: Coustenis et al. (1998), Hörst et al. (2008) (model D and model A), and rescaled versions of these models. None of the models provides an adequate simultaneous match to the PACS observation at 75 μm (top) and HIFI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

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



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

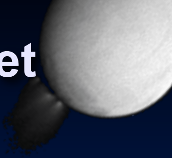
q_0 is the mixing ratio at the reference pressure level p_0

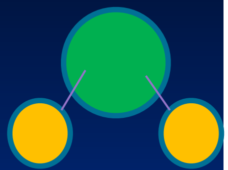
S_a:

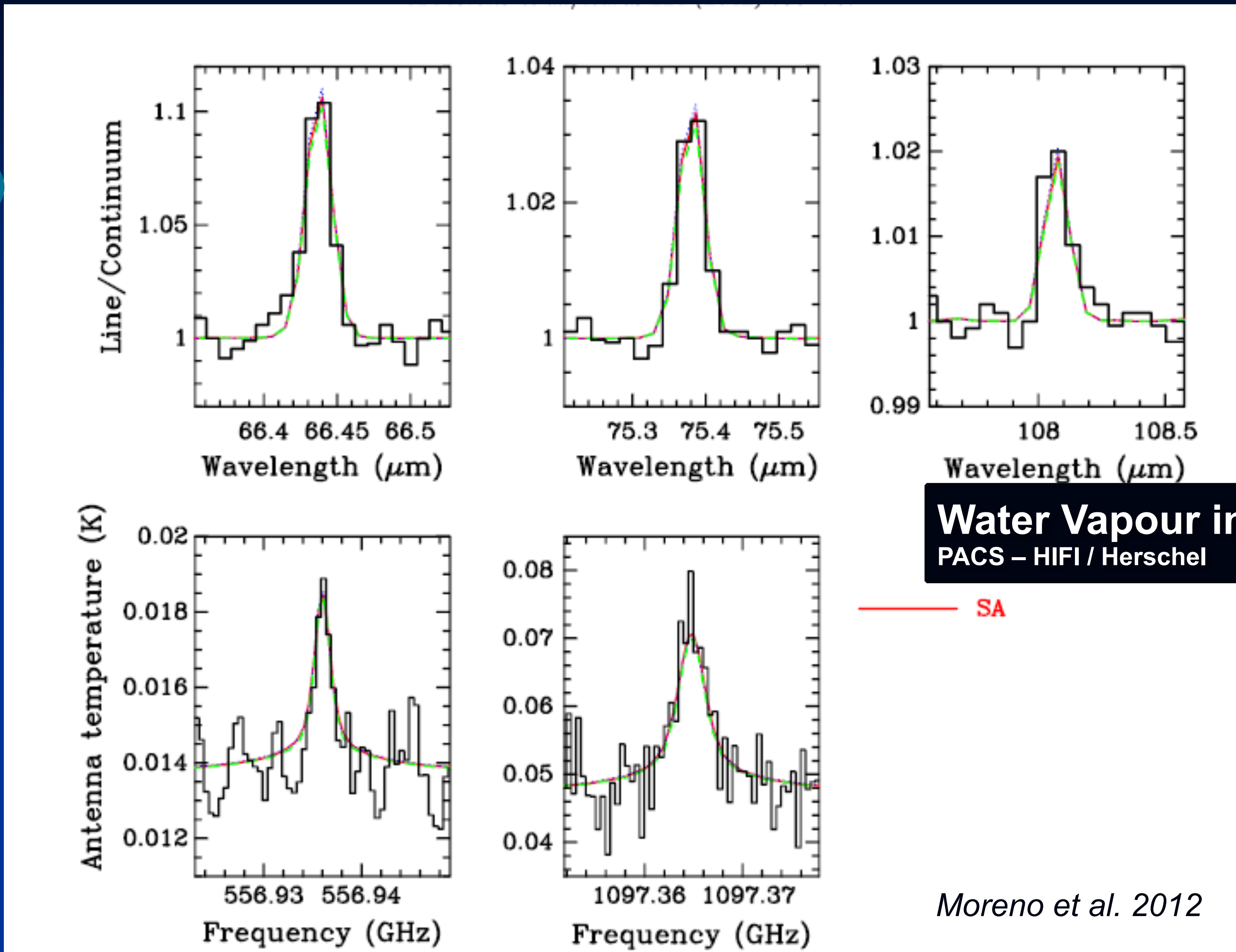
q_0 = 2.3 x10^{-11} at p_0 = 12.1 mbar
n = 0.49
Column density: 1.2 (± 0.2) 10^{14} cm $^{-2}$.

Moreno et al. 2012

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





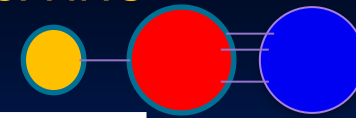


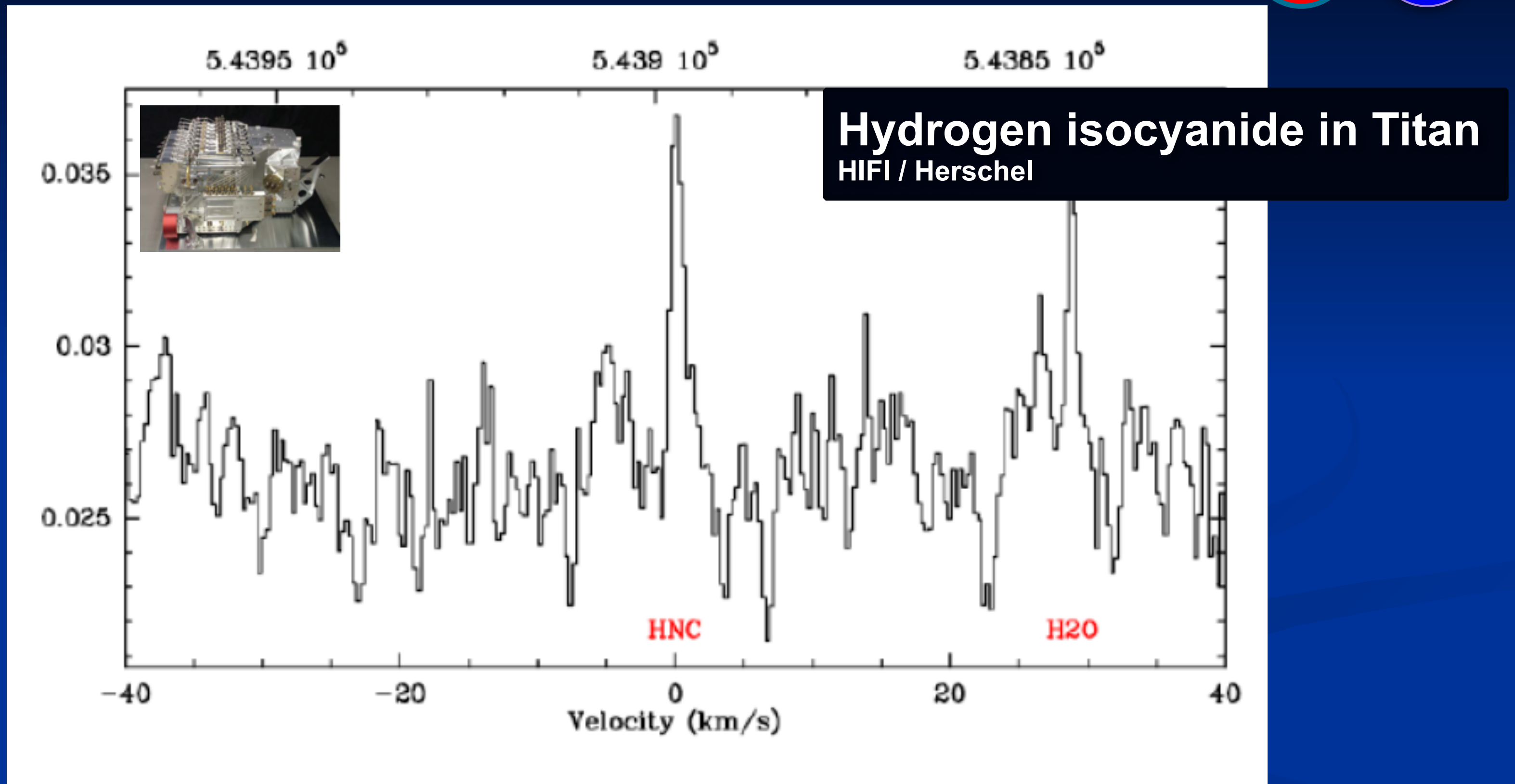
Water Vapour in Titan
PACS – HIFI / Herschel

Moreno et al. 2012

Observed and synthetic spectra

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

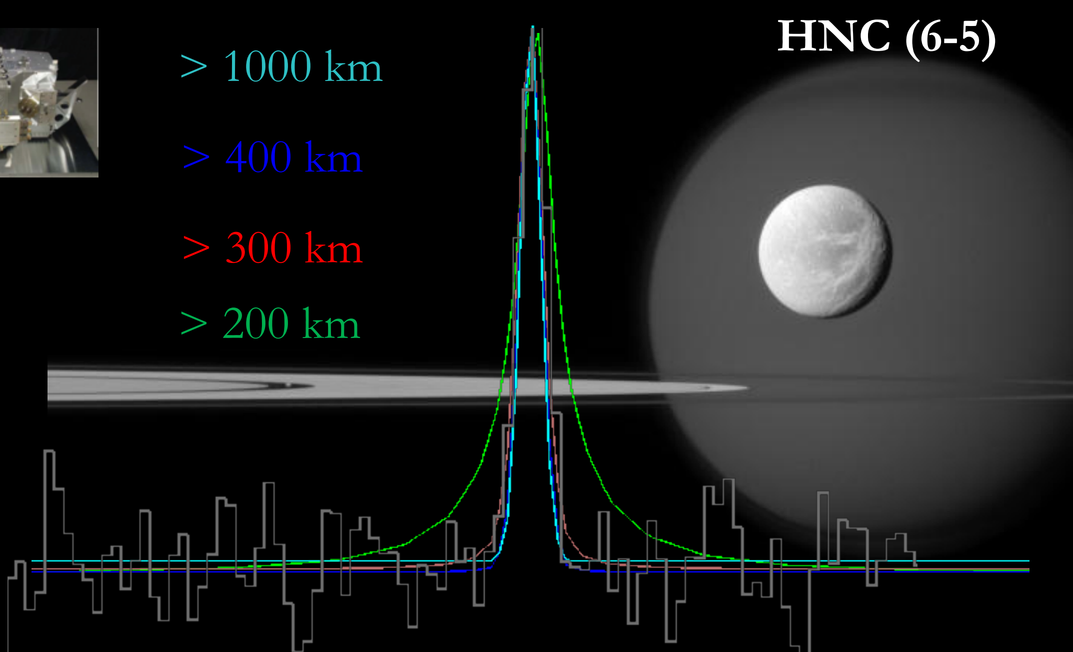




First detection of HNC in the Titan´s atmosphere

▪ **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:

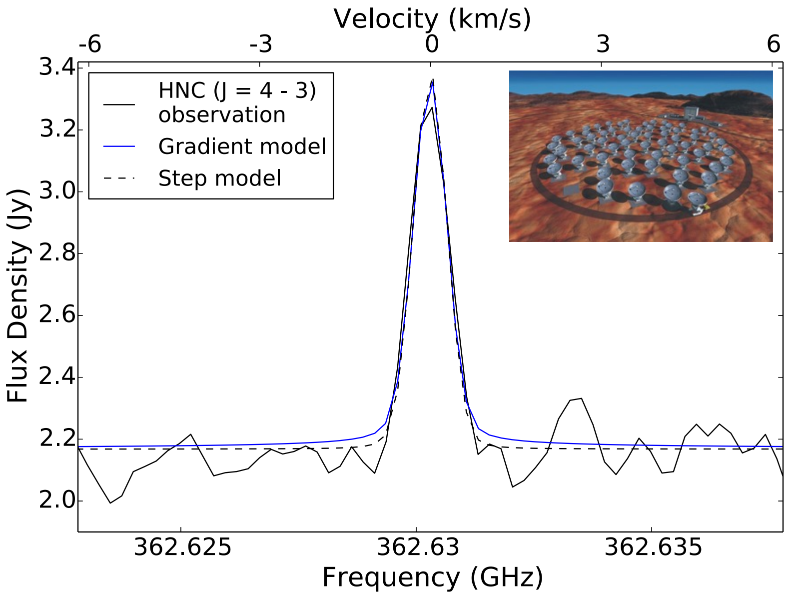
$(1.4–5) \times 10^5$ s → we expect diurnal variations of HNC

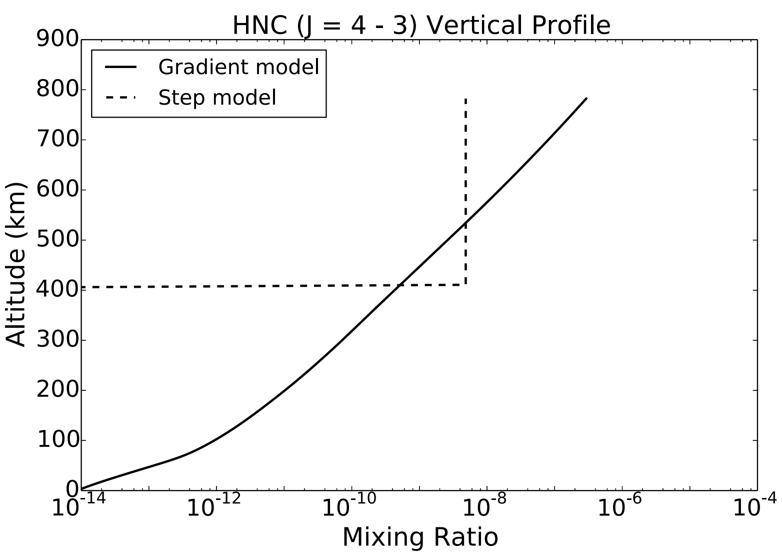
Is HNC restricted to the ionosphere?

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



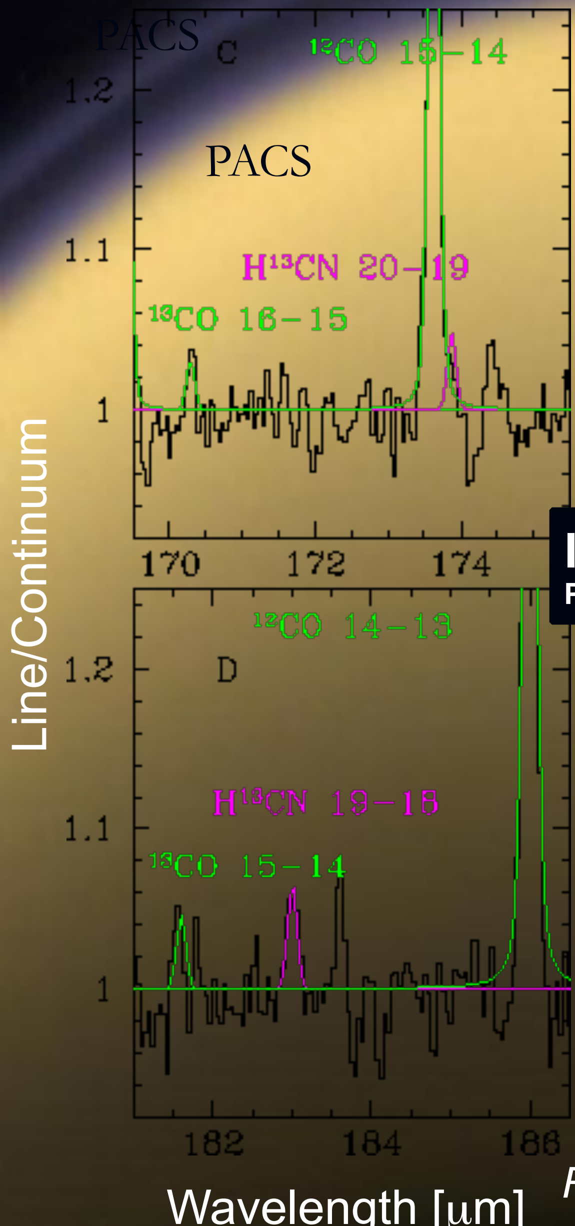


Cordiner et al. 2014

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



Rengel et al. 2014

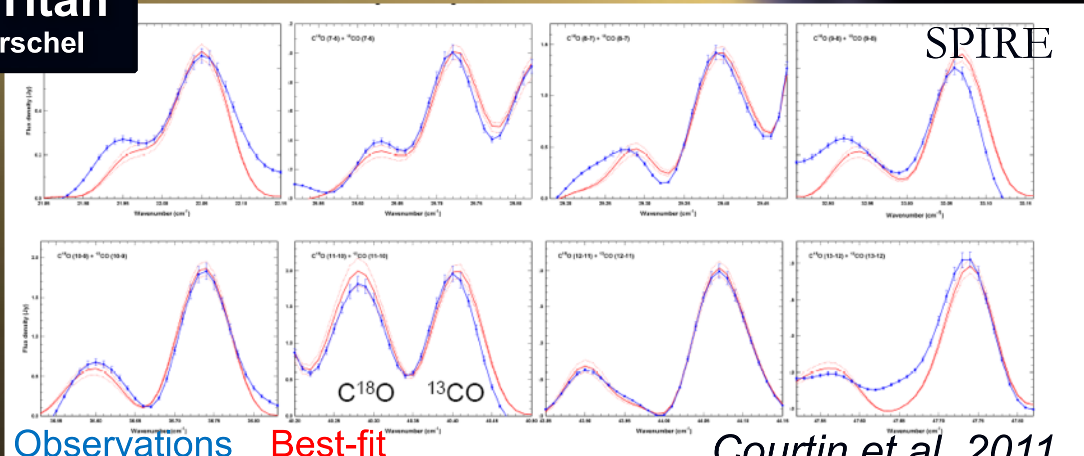
Detection of the isotopes:
- ^{13}CO(15-14) and (16-15)
- $H^{13}CN$ (19-18) and (20-19)

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

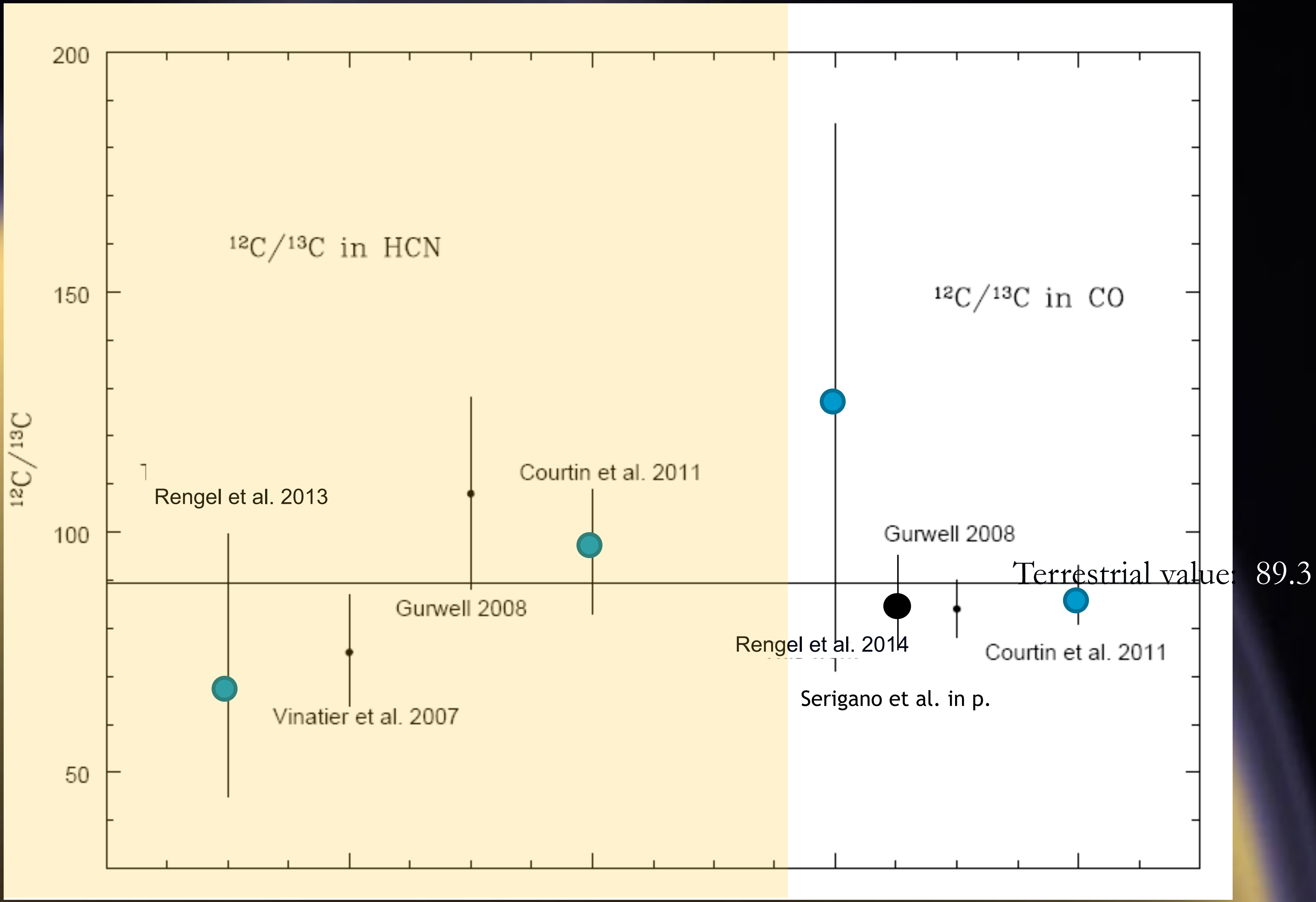
^{13}CO and ^{18}CO



Courtin et al. 2011

Consistent with previous works

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)

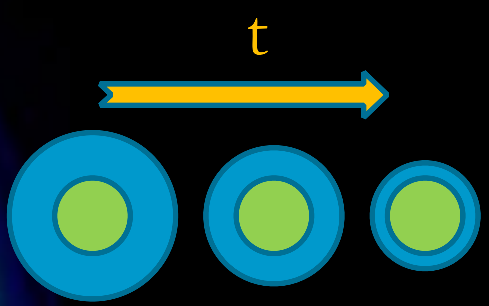
Photolytic fractionation of $^{14}N^{14}N$ and $^{14}N^{15}N$

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*
ALMA	*414 ± 45*	*Serigano et al. (in preparation)*

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

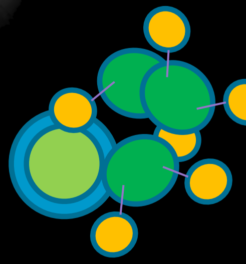
Emerged Implications:



Herschel studies point to

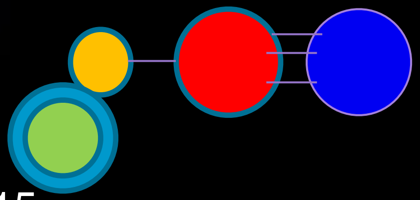
- A denser primitive Titan´s atmosphere : much of the Titan´s atmosphere has been lost over geologic time ($^{14}N/^{15}N$)

- ^{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

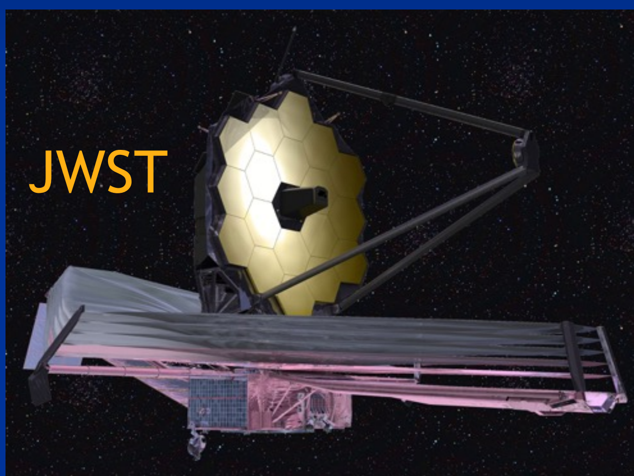
- Above 400 km, Titan´s atmosphere also contains HNC



Future – Synergy with Herschel

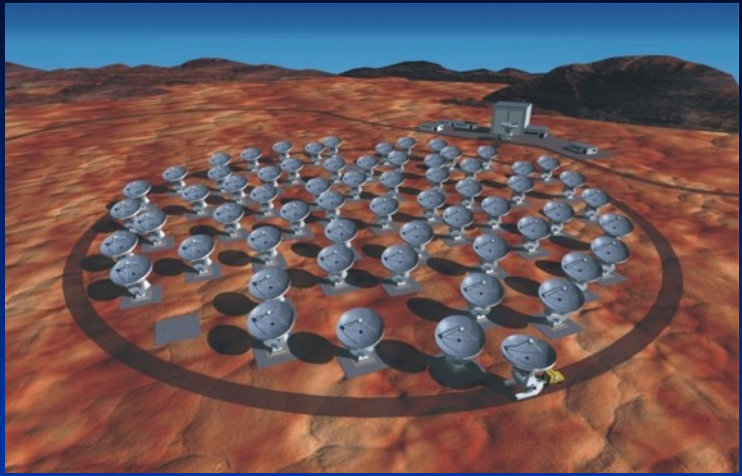
- CASSINI/CIRS (extended mission), until 2017. 17 more flybys of Titan.

- JWST



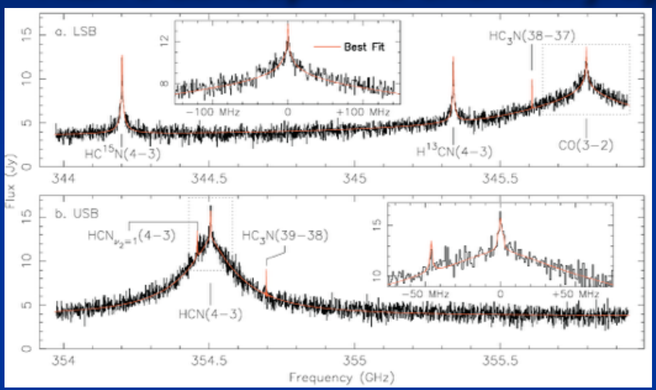
- Science Focus Group with key science themes:
  - Titan´s composition of the middle atmosphere
  - Objectives: Long-term monitoring of the changing spatial distributions of gases, clouds and hazes —> reveal the interplay of chemistry and dynamics

Future – Synergy with Herschel



- ALMA :

Titan's atmospheric chemistry/dynamics



SMA 850 micron unresolved observations

Gurwell 2004

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

à Dynamics/photochemistry coupling

à Direct measurement of mesospheric (500 km) winds

à Additional observations at higher angular resolution (up to 0.005") will allow for more accurate isotopic ratios and species abundances

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