Tracing the Oxygen-related Gas Composition of Titan's atmosphere with Herschel

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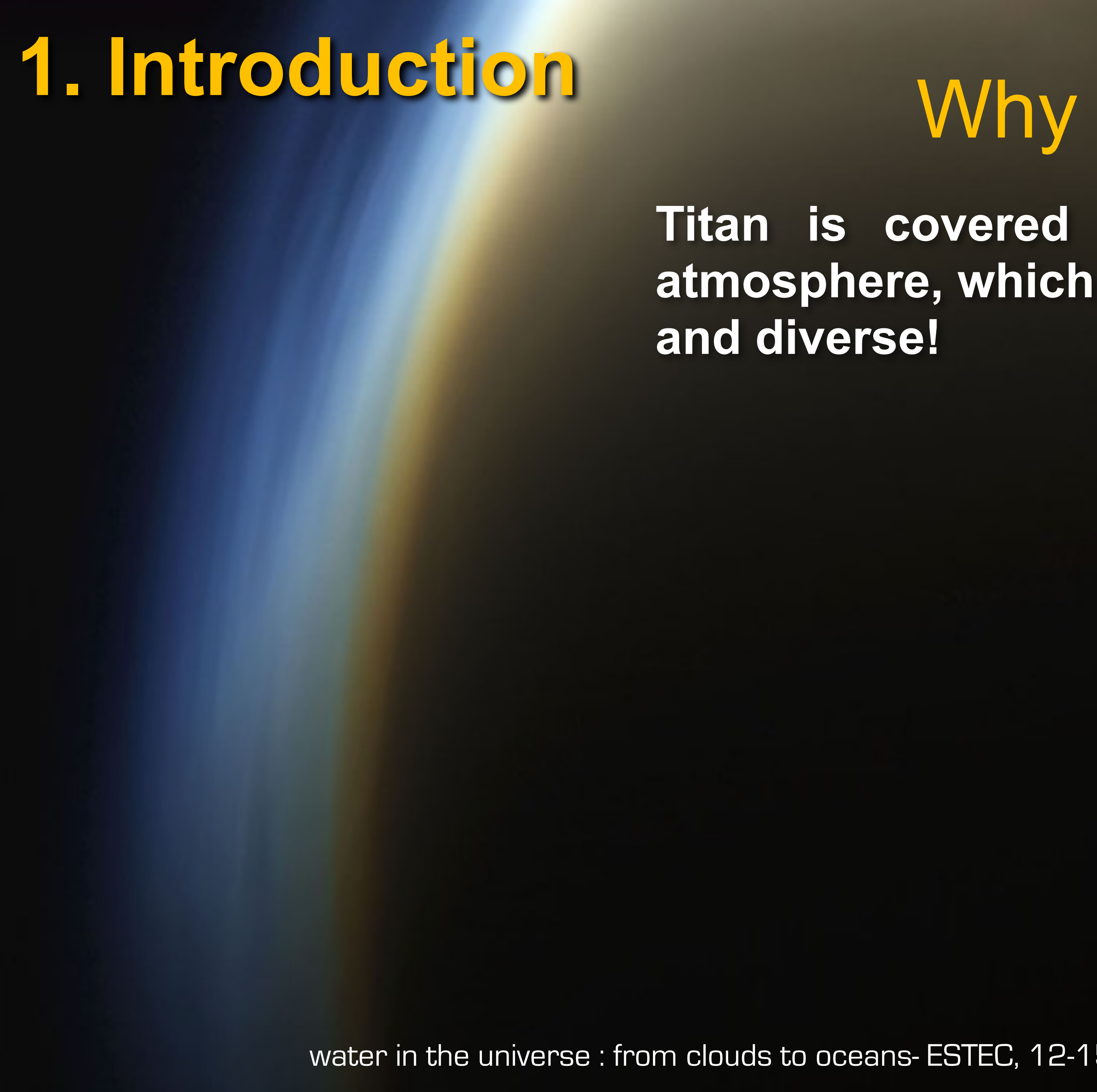
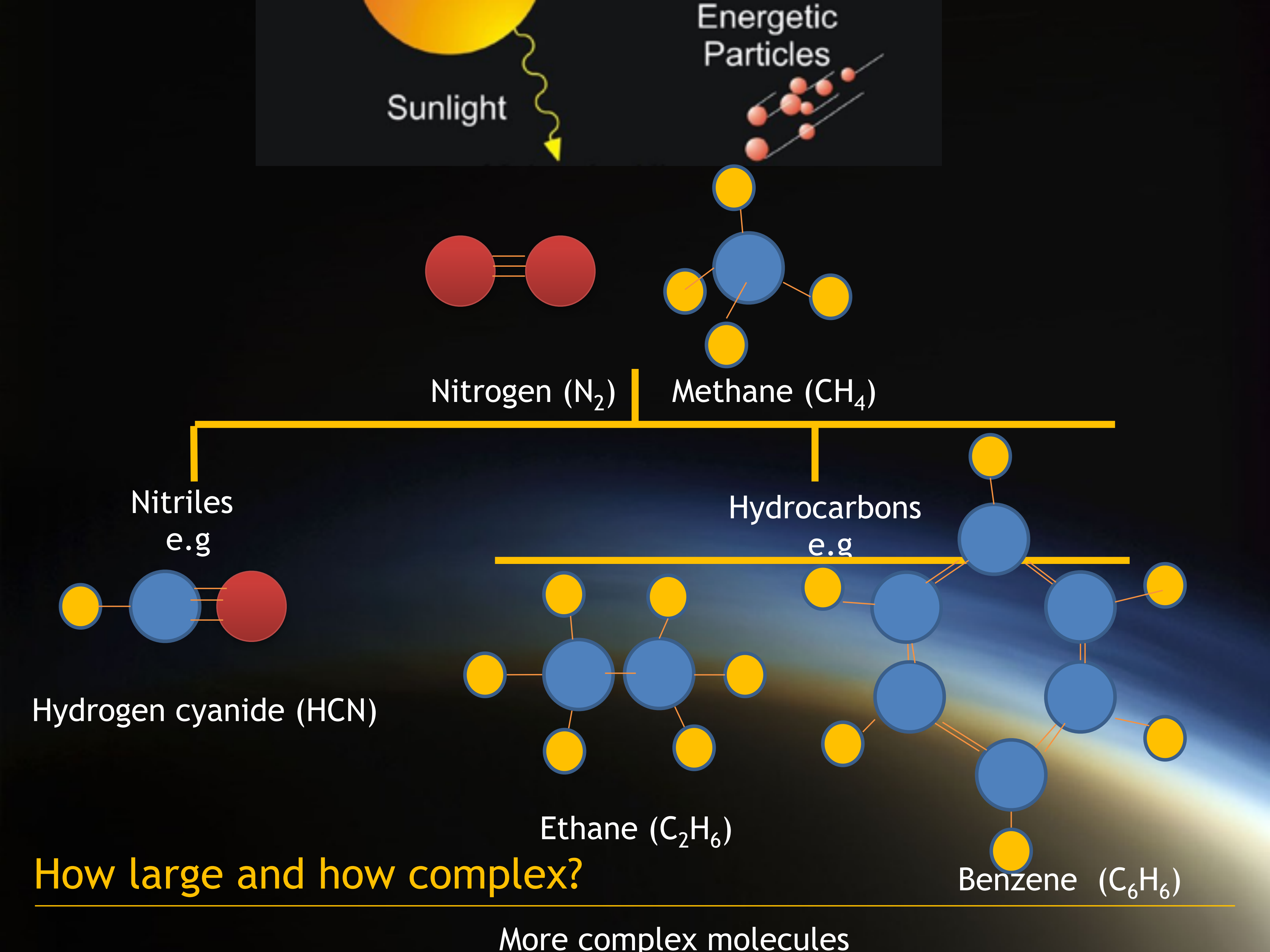
Moreno R., Courtin R., Lellouch E., Sagawa H., Hartogh P., Swinyard B., Lara M., Feuchtgruber H., Jarchow C. , Fulton T., Cernicharo J., Bockelée-Morvan D., Biver N., Banaszkiewicz M., González A.

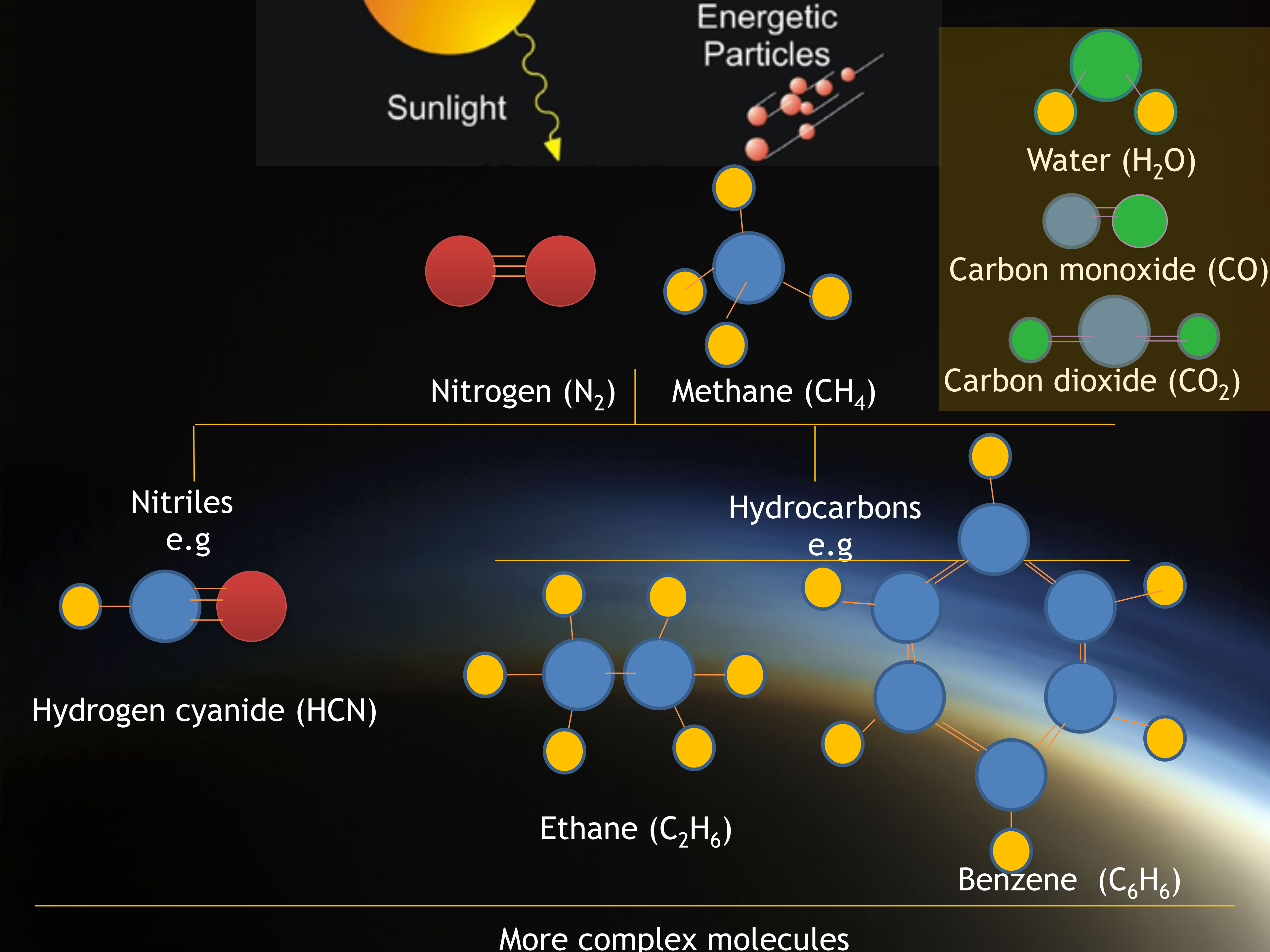
1. Introduction



Why Titan?

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

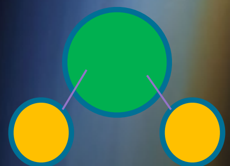

Sunlight
Energetic Particles
Nitrogen (N_2)
Methane (CH_4)
Nitriles e.g
Hydrocarbons e.g
Hydrogen cyanide (HCN)
Ethane (C_2H_6)
Benzene (C_6H_6)
How large and how complex?
More complex molecules



Energetic Particles
Sunlight
Water (H_2O)
Carbon monoxide (CO)
Carbon dioxide (CO_2)
Nitrogen (N_2)
Methane (CH_4)
Nitriles e.g
Hydrocarbons e.g
Hydrogen cyanide (HCN)
Ethane (C_2H_6)
Benzene (C_6H_6)
More complex molecules

1. Introduction

Why Titan?



Water (H_2O)

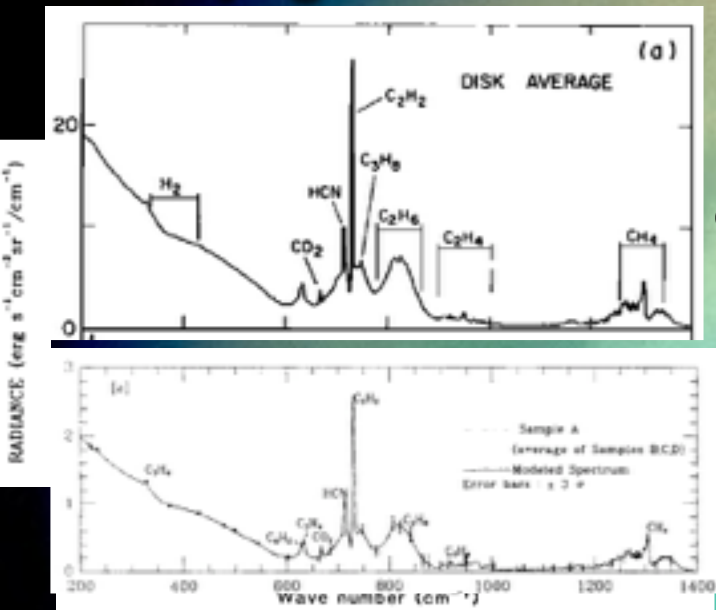
Carbon monoxide (CO)

- What are the abundances of these species?
- What is the origin of them in Titan´s atmosphere?
- What are the implications for the formation and evolution of Titan?

1. Introduction

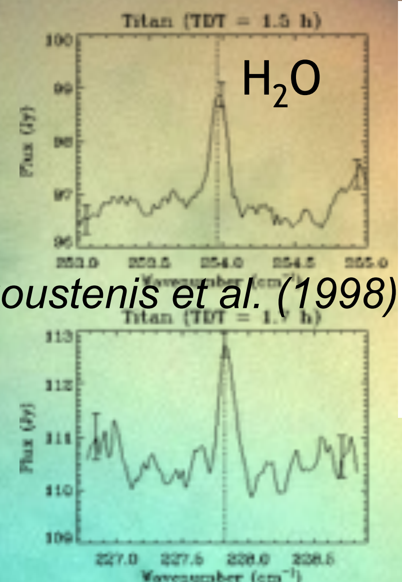
Oxygen-related Spectroscopy of Titan has been already performed by:

Voyager 1 – 2/IRIS



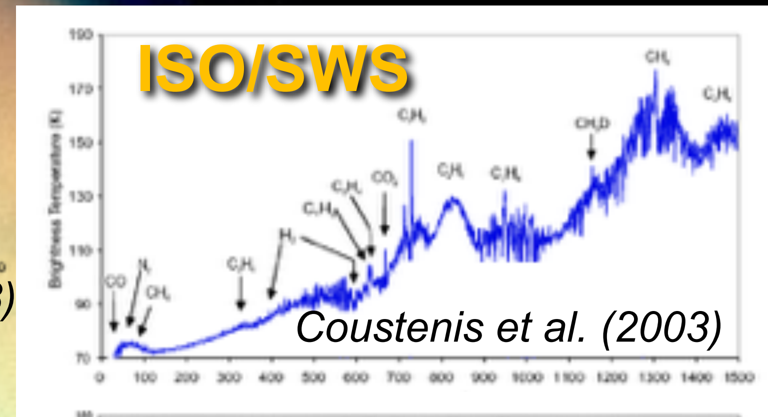
Samuelson et al.1983;
Letourneur and Coustenis 1993

ISO/SWS



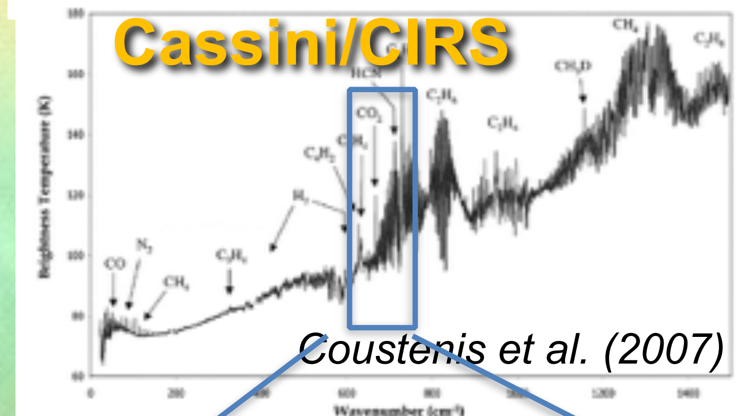
Coustenis et al. (1998)

ISO/SWS

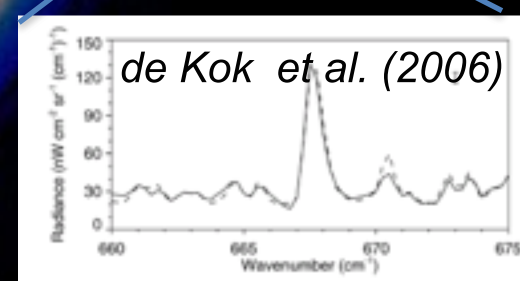


Coustenis et al. (2003)

Cassini/CIRS

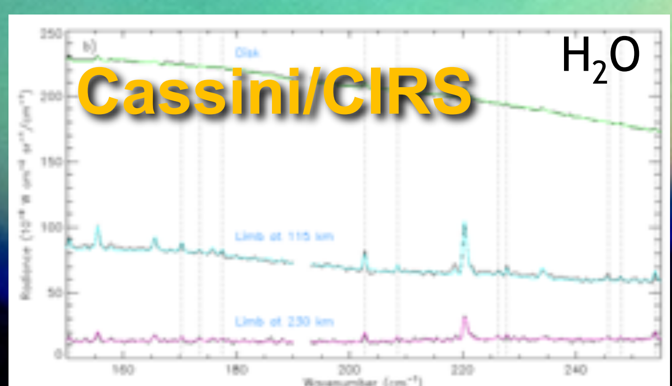


Coustenis et al. (2007)



de Kok et al. (2006)

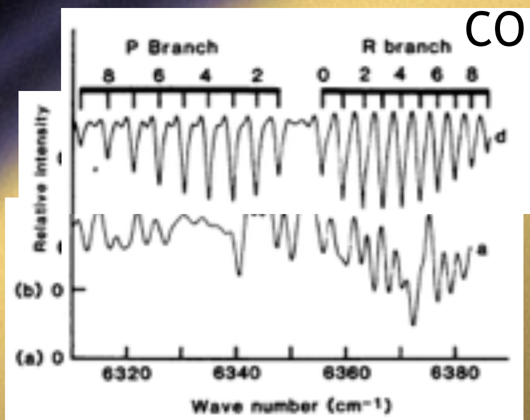
Cassini/CIRS



Cottini et al., 2012

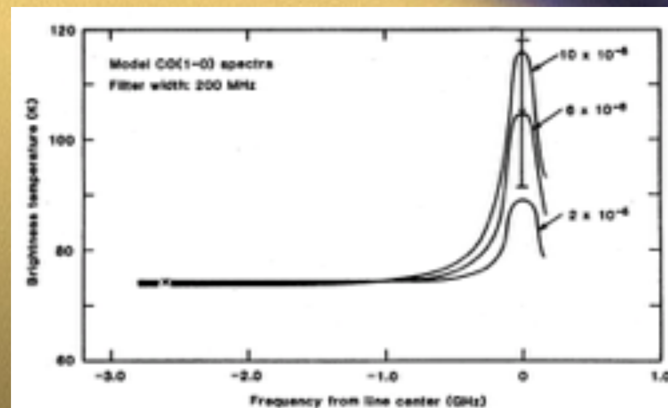
Ground-based observations have also improved our knowledge of Titan's oxygen-related atmospheric composition:

4-m Mayall Telescope



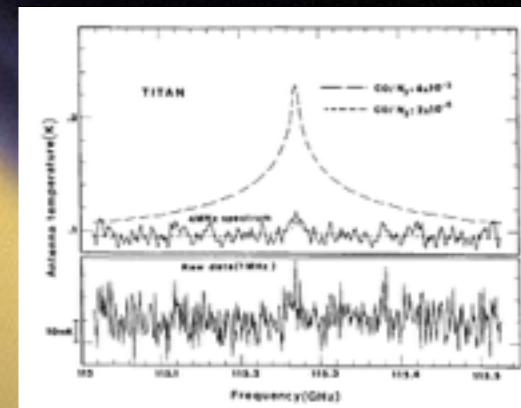
Lutz et al. 1983

OVRO



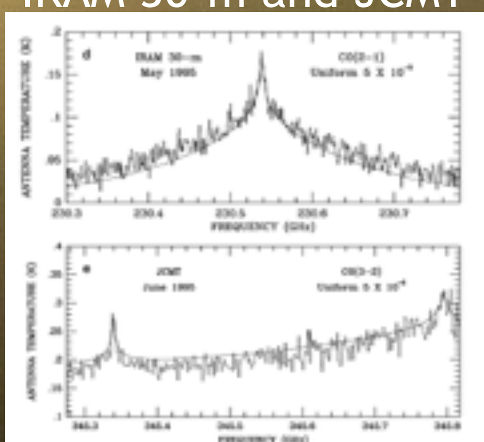
Muhleman et al. 1984

IRAM 30-m



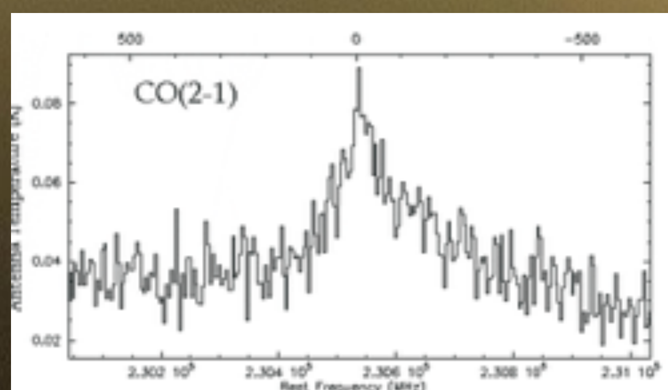
Marten et al. 1988

IRAM 30-m and JCMT



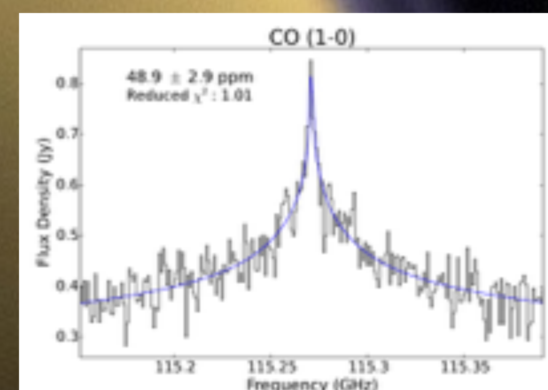
Hidayat et al. 1998

APEX



Rengel et al. 2011

ALMA



Serigano et al. 2016

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

A new window was opened…

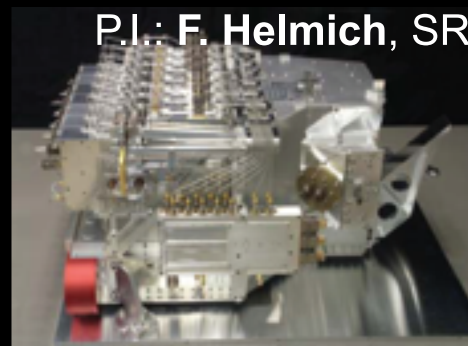
Herschel Era

Instruments onboard Herschel:

Credits: ESA

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

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



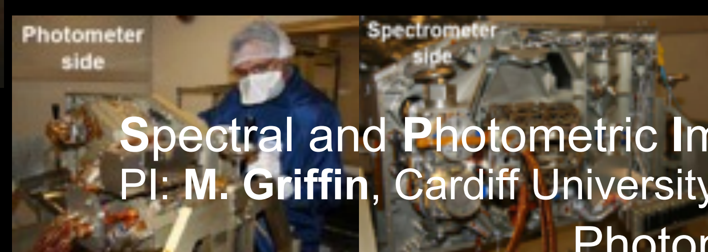
Resolutions: 140, 280, 560 kHz, 1.1 MHz

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



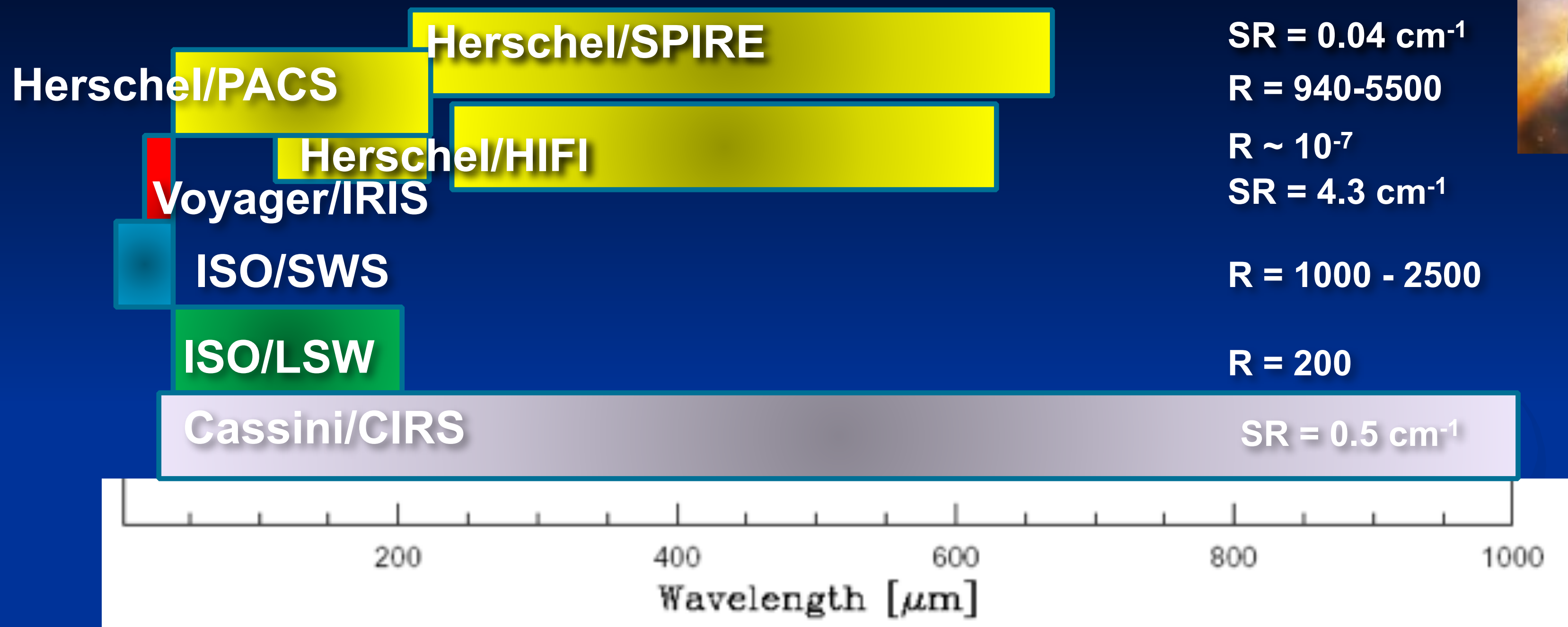
Spectral and **P**hotometric **I**maging **Re**ceiver (**SPIRE**).

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

Photometer: 250, 350, 500 µm

Spectrometer: 194- 672 µm.

Titan´s Spectroscopy in the Herschel Era

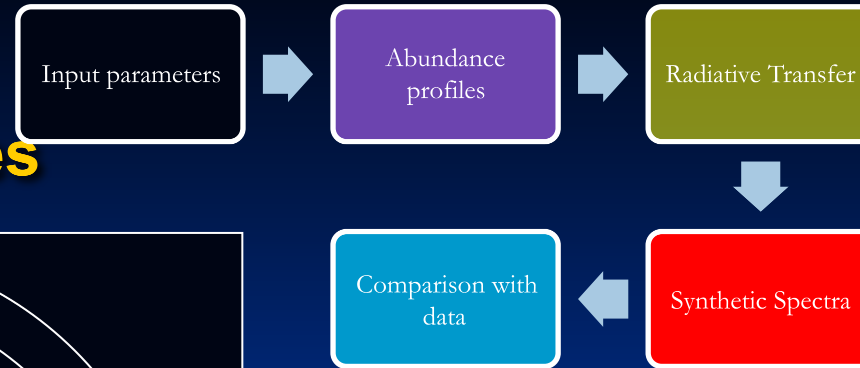


In the framework of the KP „*Water and related chemistry in the Solar System*" (PI: Hartogh) ⇨

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

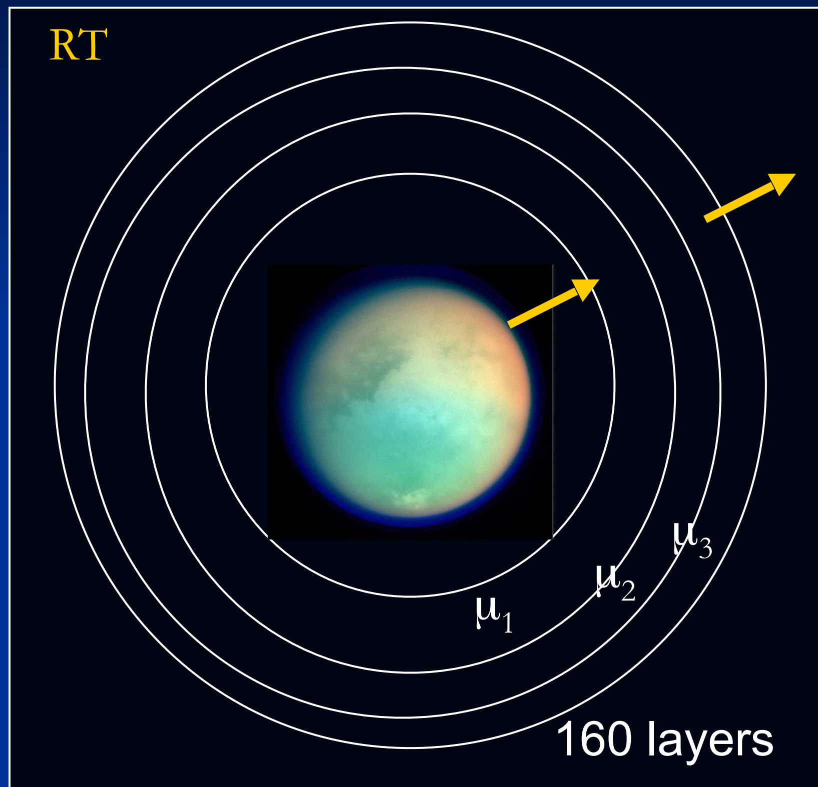
Modeling the Titan spectra
Method to determine abundances



T profile

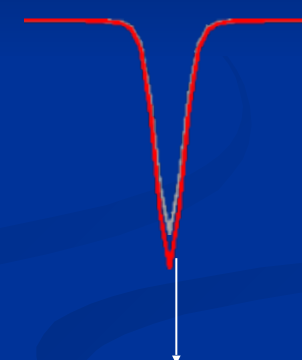
P profile

Vmr profile

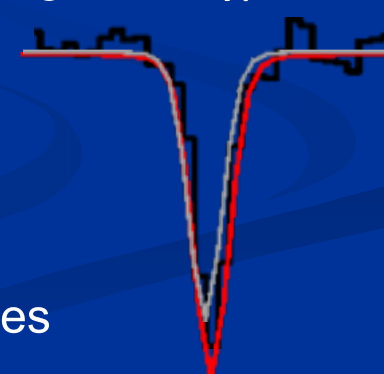


μ_i=absorption coefficient

Synthetic spectra



Fitting algorithm: χ^2 statistics



New set of parameters

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

2.- Oxygen-related Gas Composition of Titan's atmosphere: CO

Is CO primordial or external ?

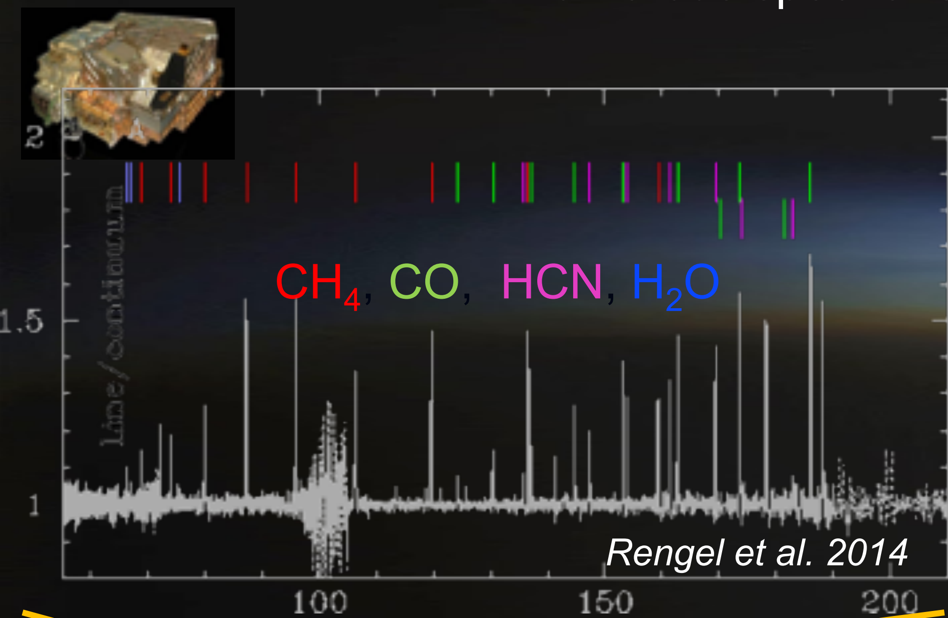
Possible Origin

- 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*

1.27 ± 0.03
Best-fit volume mixing ratio

CO with Herschel /PACS and SPIRE

Numerous spectral emission features due to:

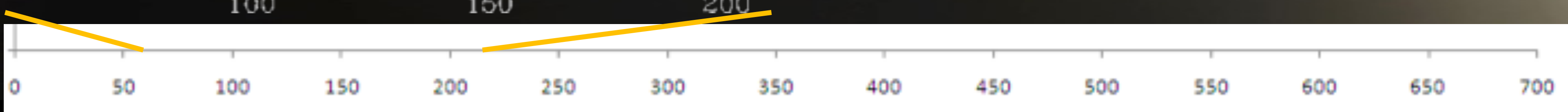


PACS:

Full range spectra (51-220 μm)

Twice, 0.63h and 1.1h

R= 1000-5000



CO with Herschel /PACS and SPIRE

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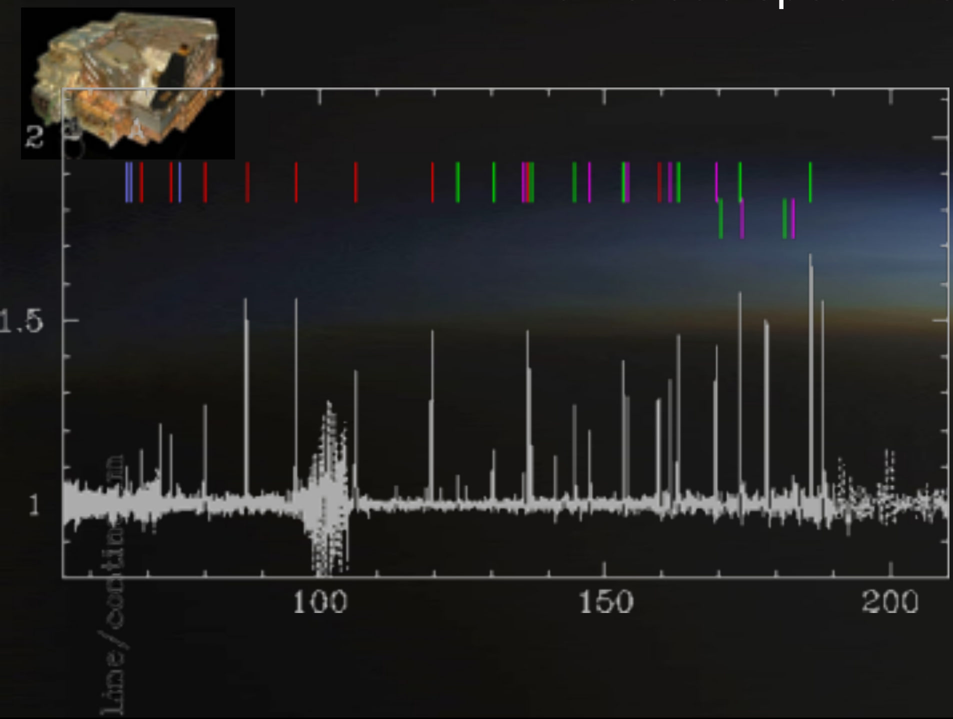
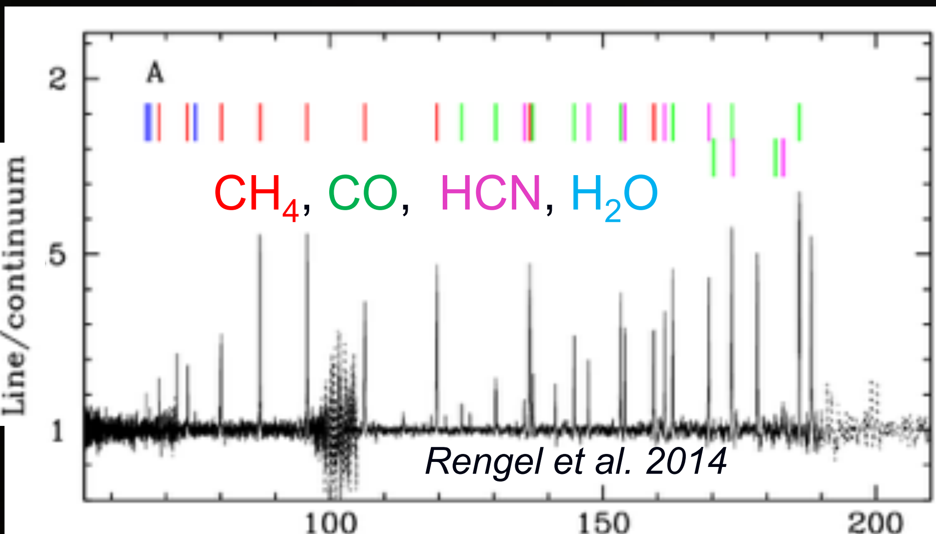
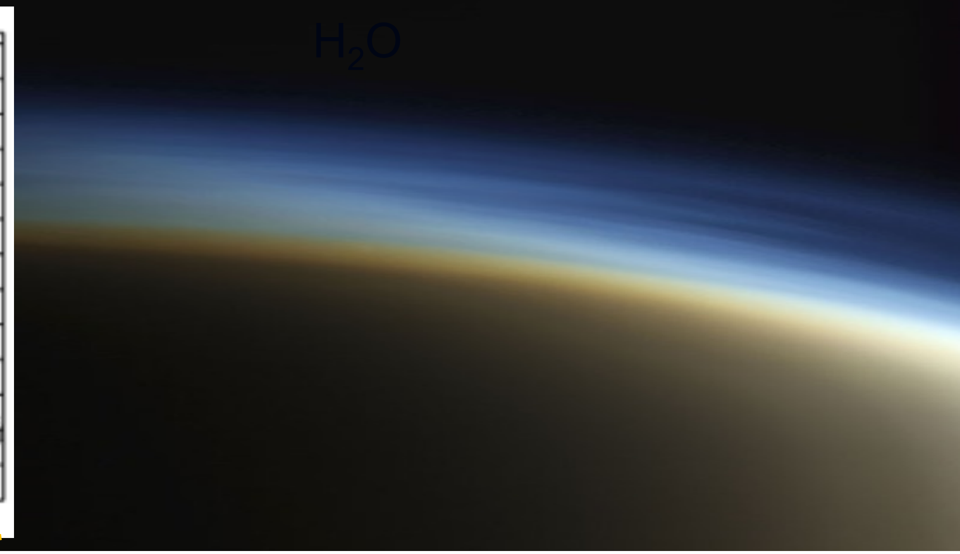


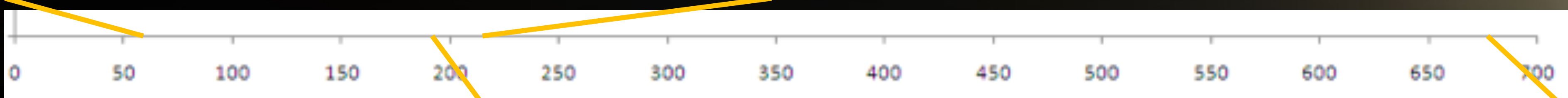
CH_4 CO HCN H_2O

CO with Herschel /PACS and SPIRE

Numerous spectral emission features due to:





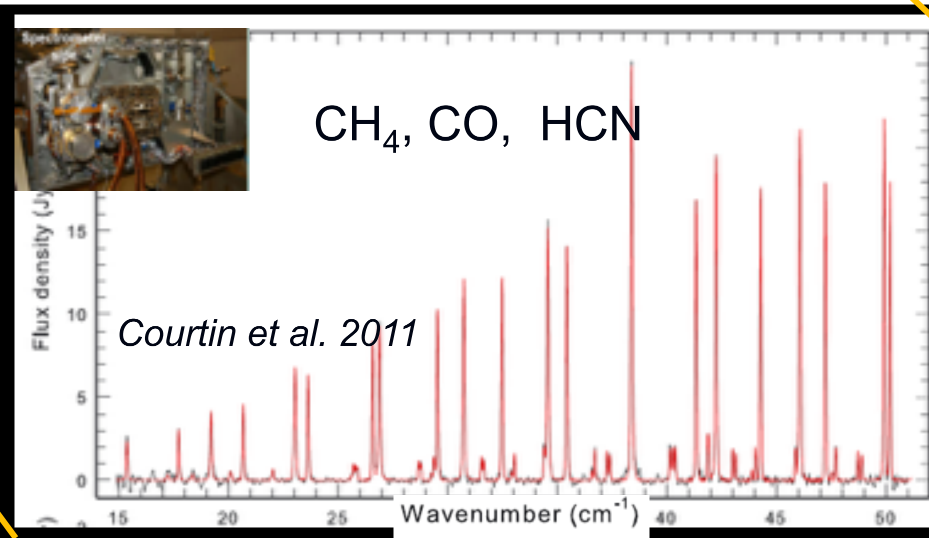


SPIRE:

Full range spectrum (194 - 671 μm)

July 2010, ~8.9h,

SR= 0.04 cm^{-1}



CO with Herschel /PACS and SPIRE

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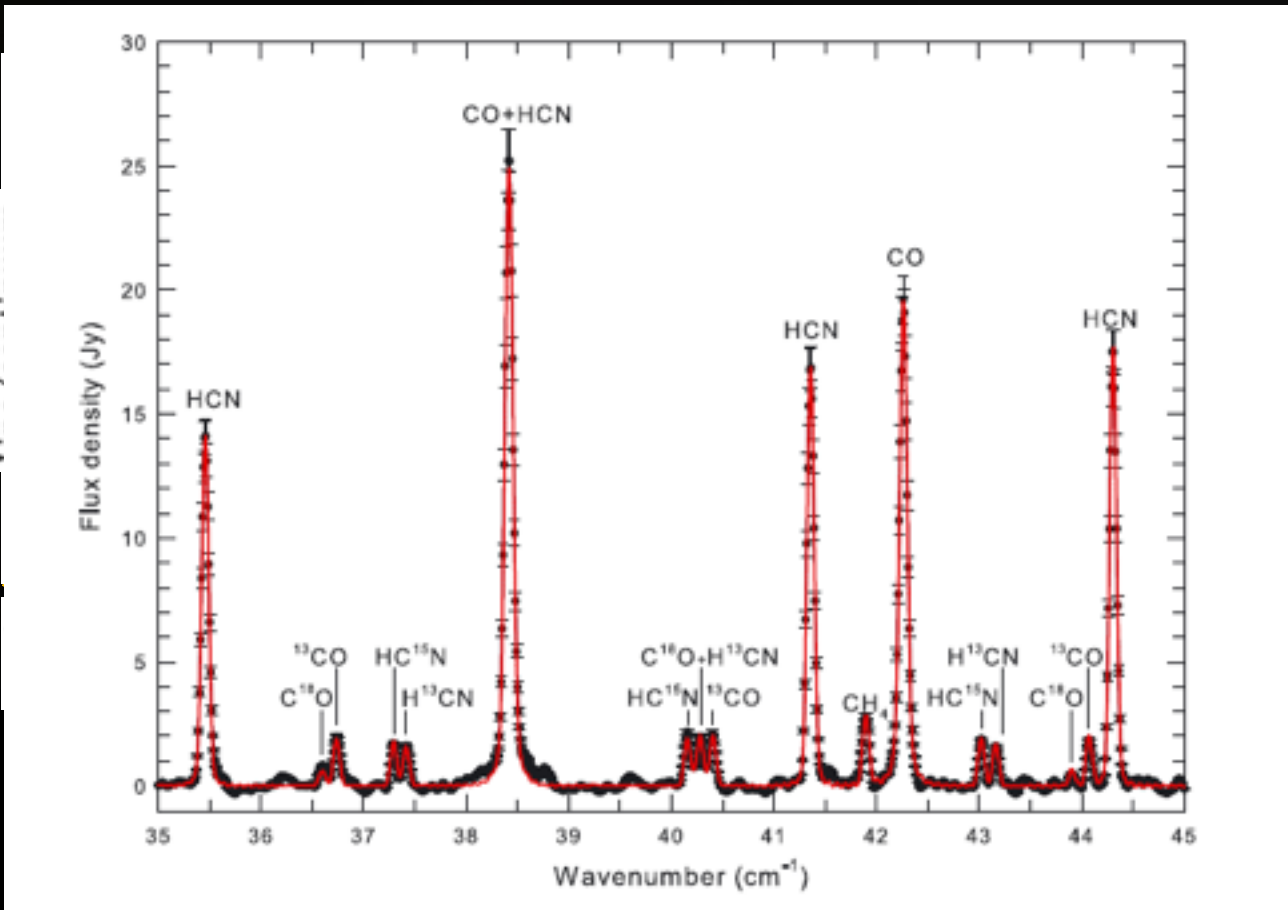
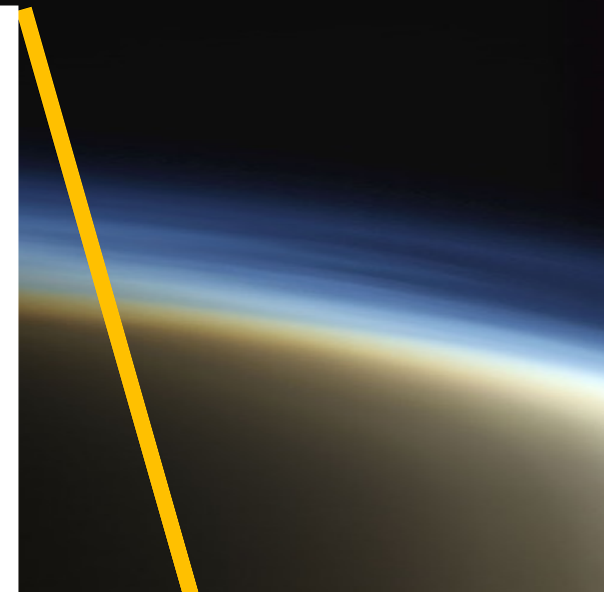
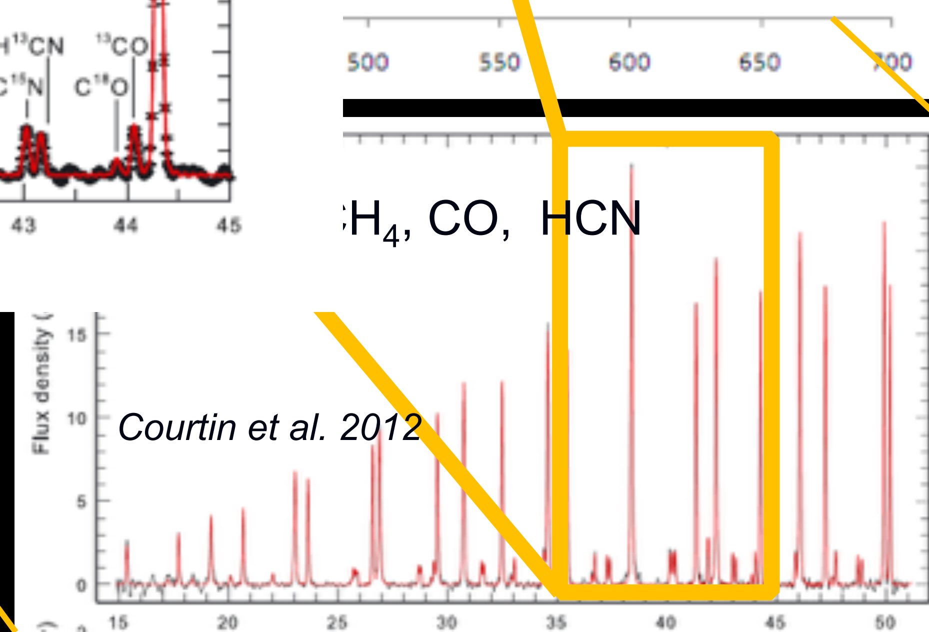


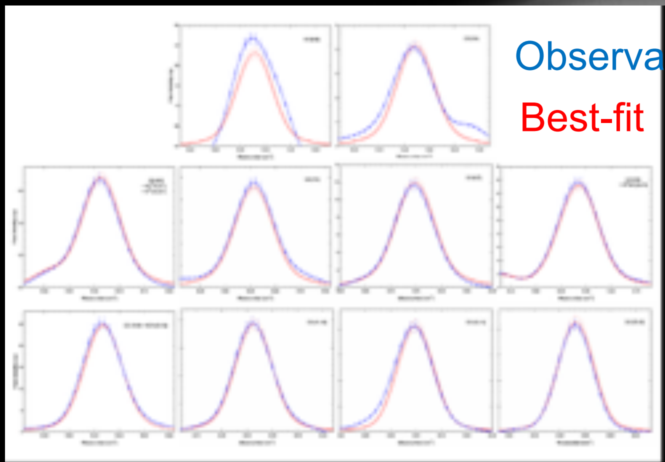




H_4, CO, HCN

Courtin et al. 2012

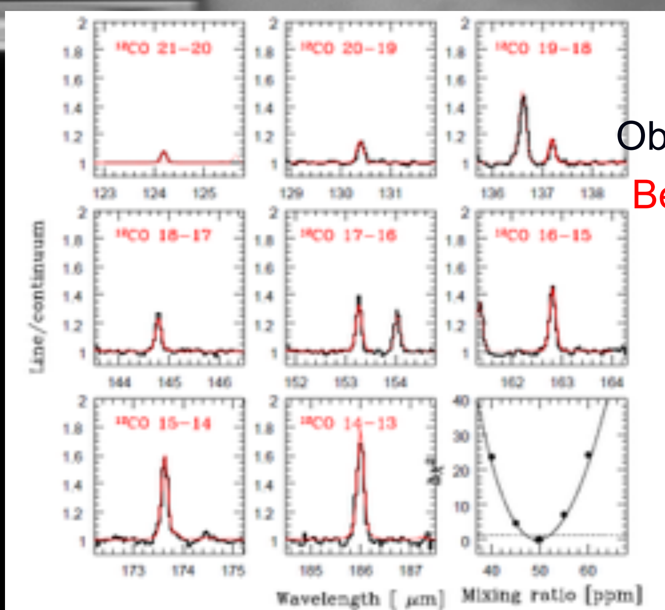
Observed and best-fit simulated CO lines



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

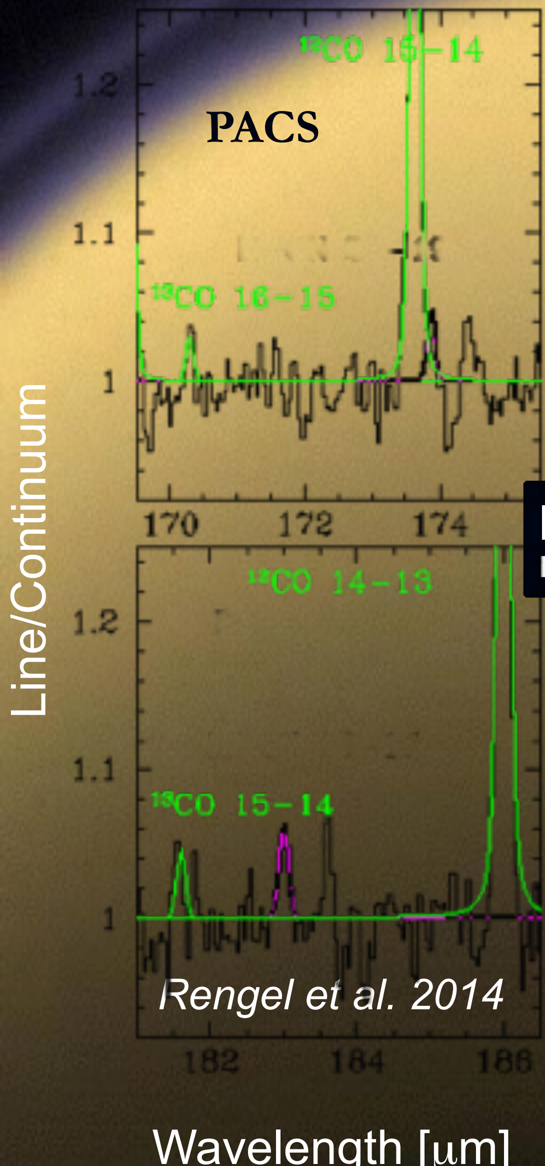
Isotopic ratio $^{12}C/^{13}C$ in CO

Detection of the isotopes:

• ^{13}CO(15-14) and (16-15) but marginal

Results: PACS SPIRE

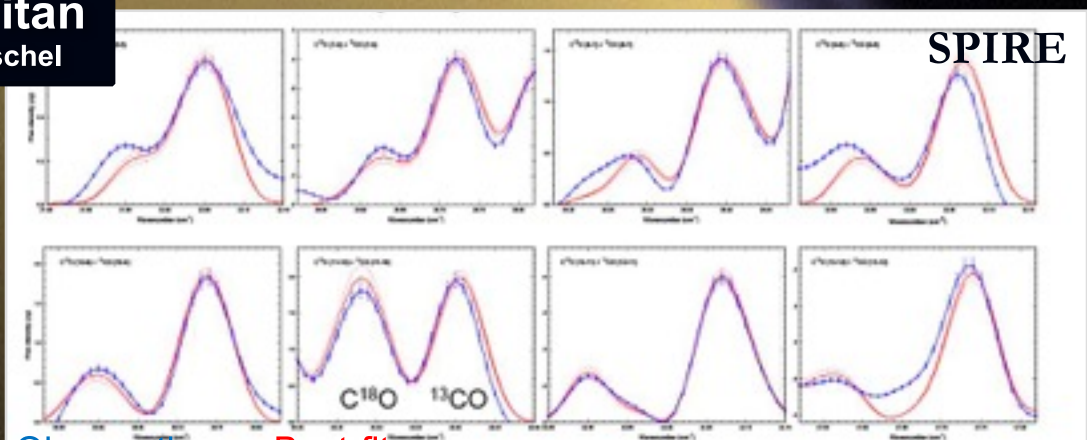
$^{12}C/^{13}C$ in CO : 122 ± 62 87± 6



Rengel et al. 2014

Isotopes in Titan
PACS – SPIRE / Herschel

^{13}CO and ^{18}CO



Courtin et al. 2011

Consistent with previous works

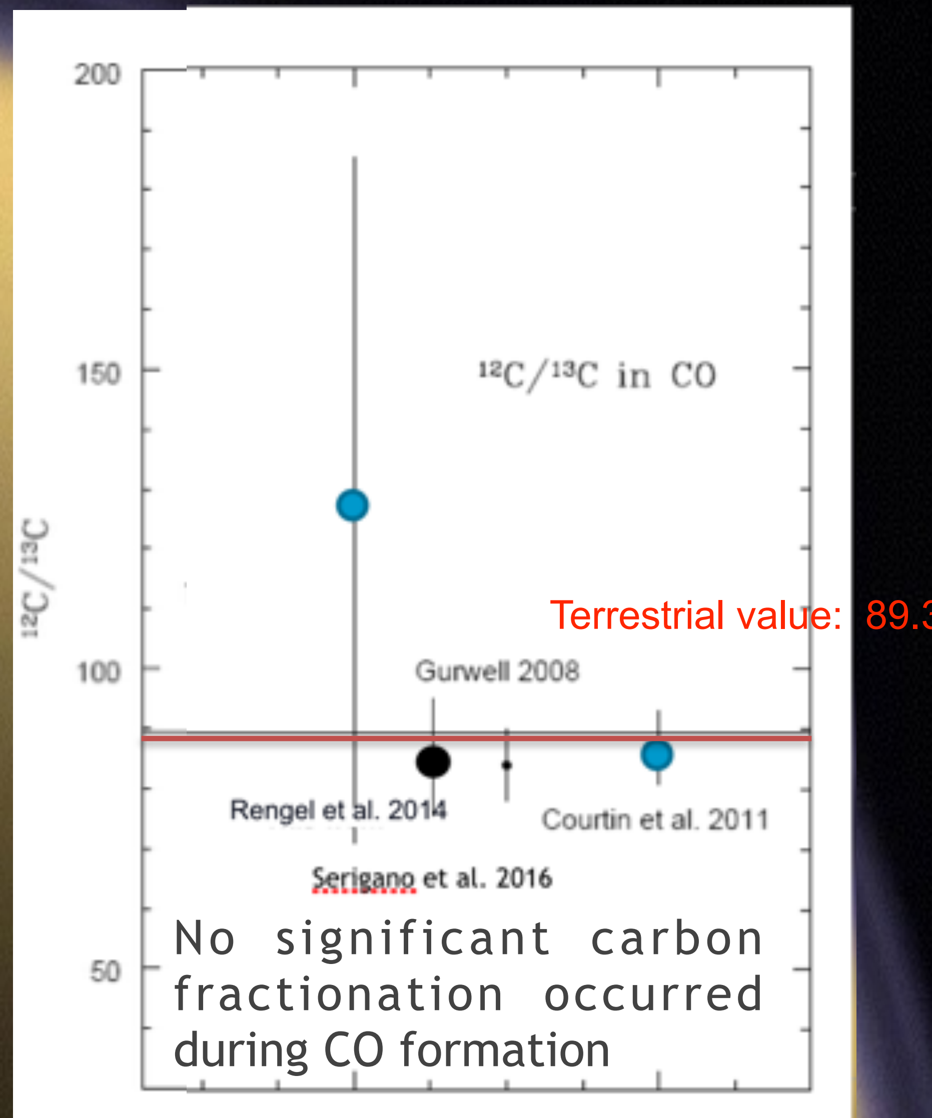
Isotopic ratio $^{12}C/^{13}C$ in CO

Deriving isotopic ratios

Deviations from values of other bodies?

No → No significant fractionation

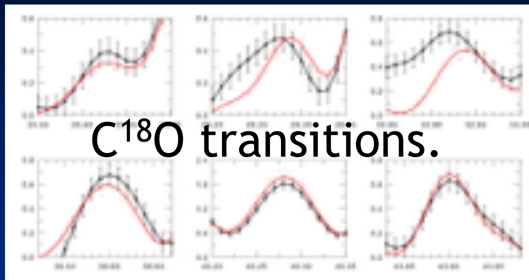
Yes → Primordial differences | Emerged on time



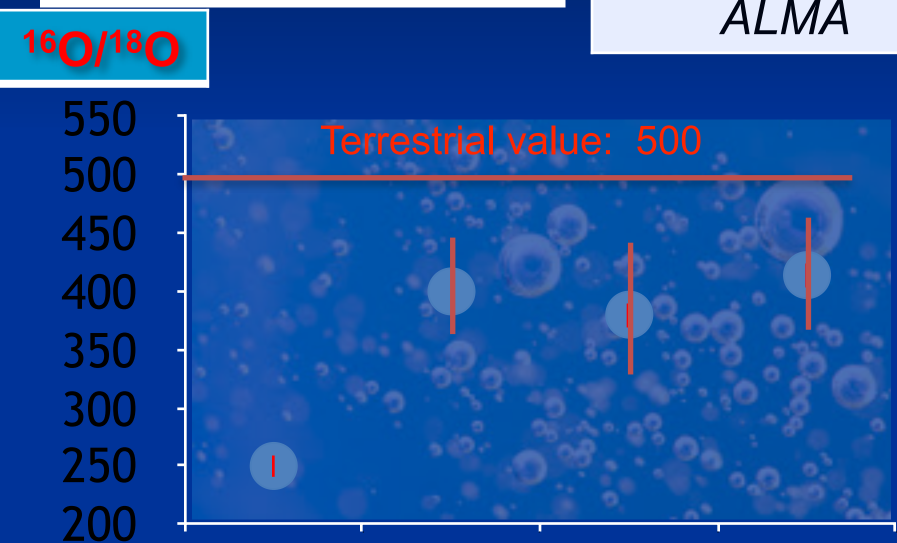
No significant carbon fractionation occurred during CO formation

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*



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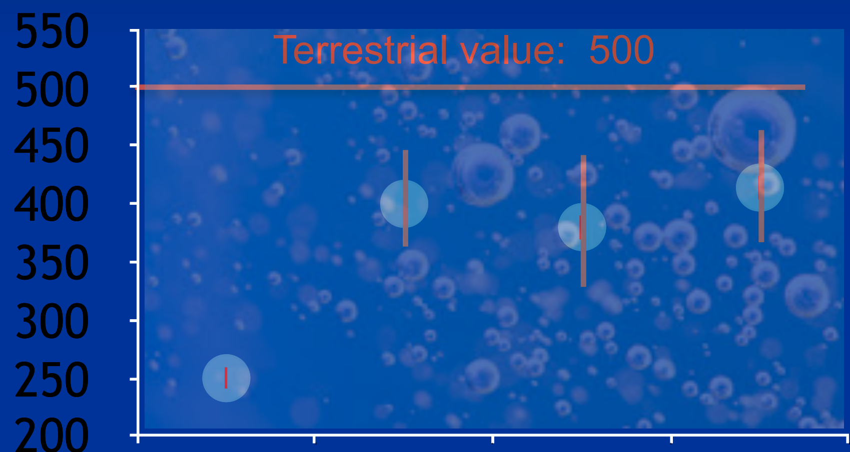
$^{16}O/^{18}O$



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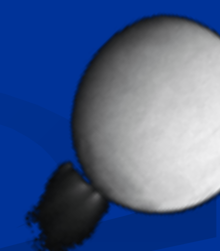
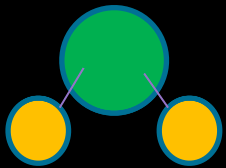


Precipitation of O^+ or O from the Enceladus Torus

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

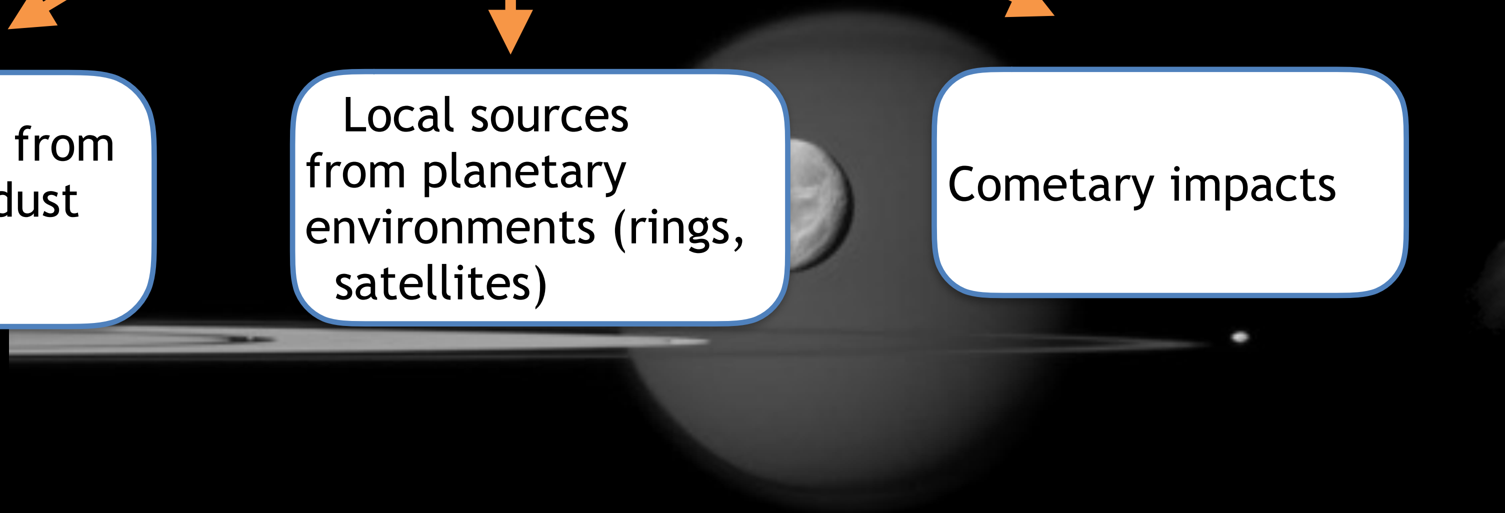
3.- Oxygen-related Gas Composition of Titan's atmosphere: H_2O



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



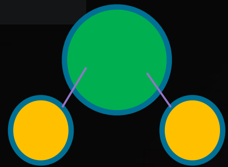
What is the vertical profile of H_2O?

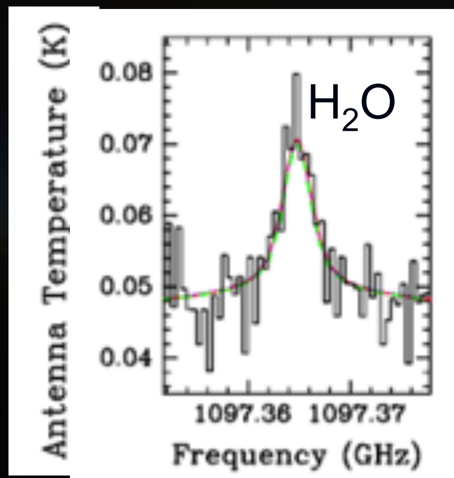
Can we disentangle the various sources?

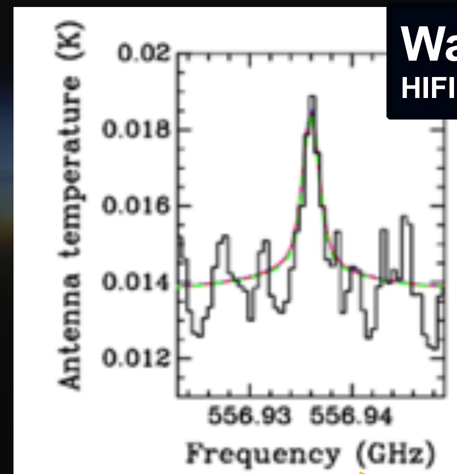
1.27 ± 0.03

Best-fit volume mixing ratio

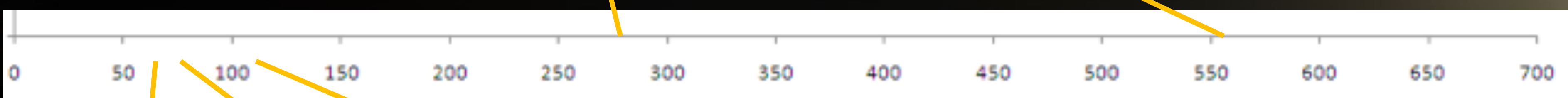
Water Inventory with Herschel /PACS and HIFI

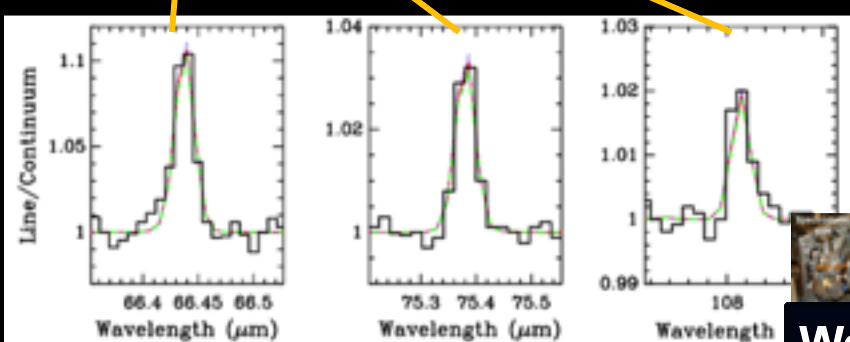






Water Vapour in Titan
HIFI / Herschel



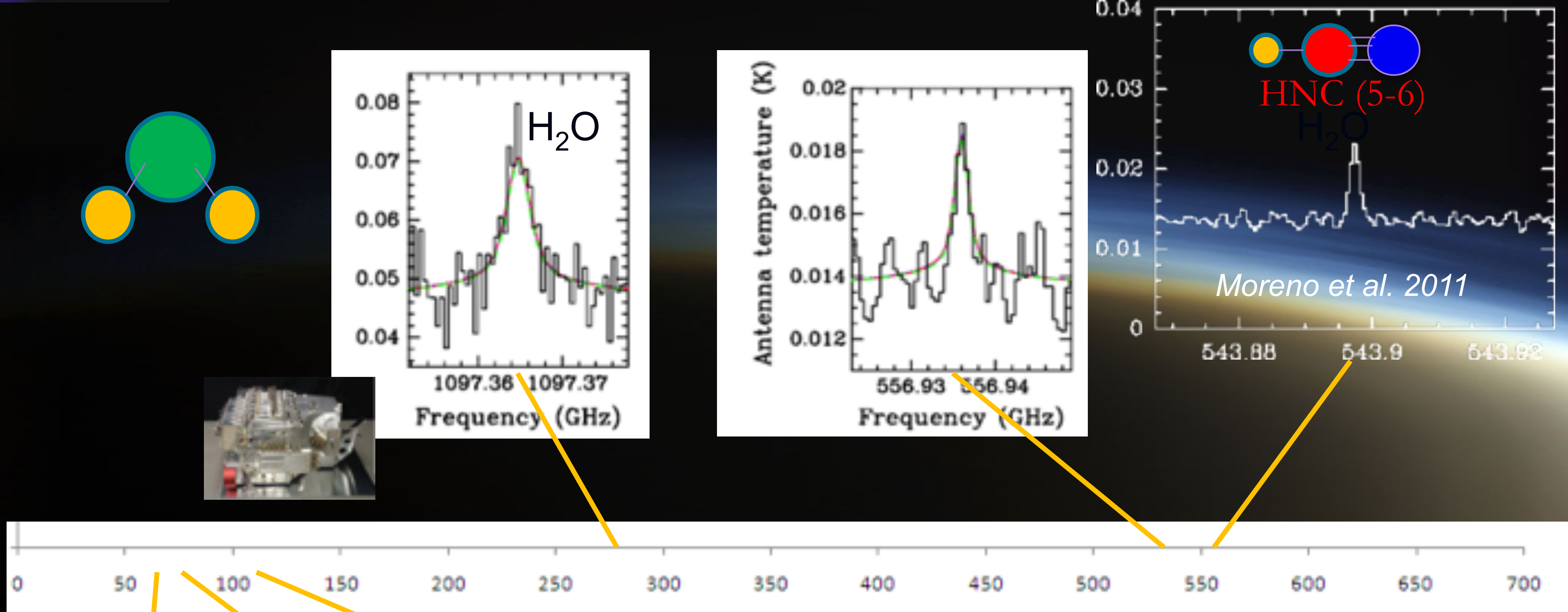


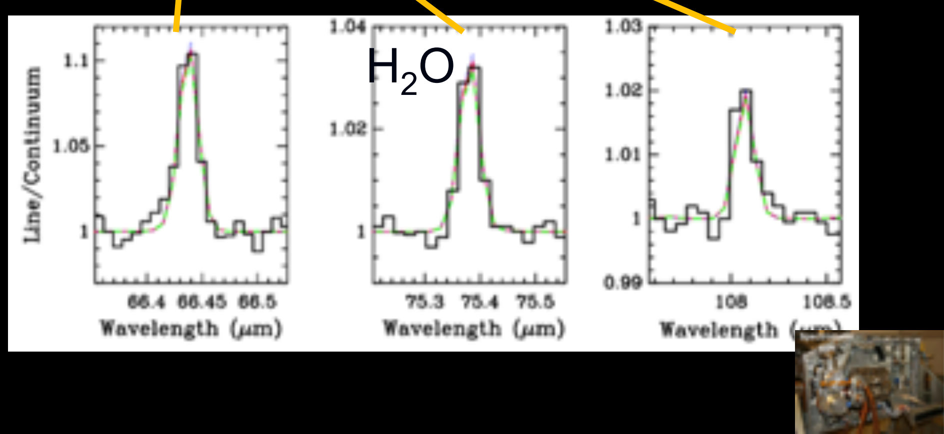
Water Vapour in Titan
PACS / Herschel

Five dedicated Water vapour line emission with Herschel/PACS and HIFI

Moreno et al. 2012

Water Inventory with Herschel /PACS and SPIRE





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

Water vertical distribution

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

- → Photochemical models for water must be revised

Observations vs. previous models

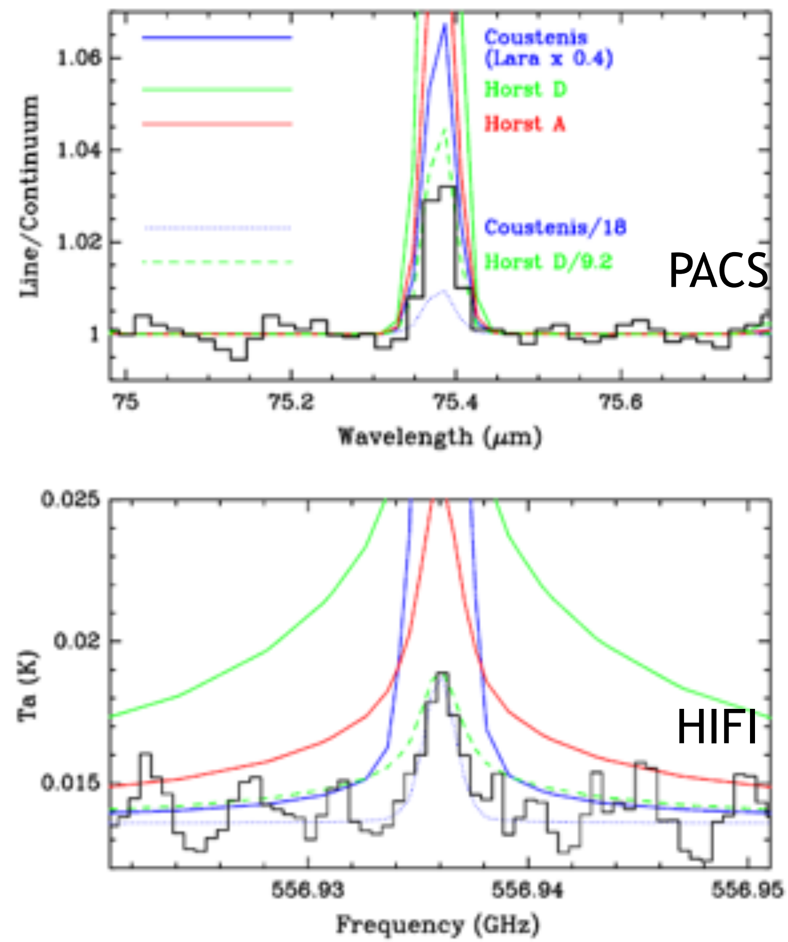
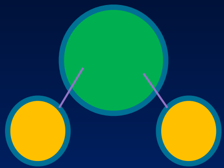


Fig. 7. Synthetic spectra computed considering several previously proposed H_2O profiles: Coustenis et al. (1998), Hörst et al. (2008) (model D and model A), and rescaled versions of these models. None of the models provides an adequate simultaneous match to the PACS observation at 75 μm (top) and HIFI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

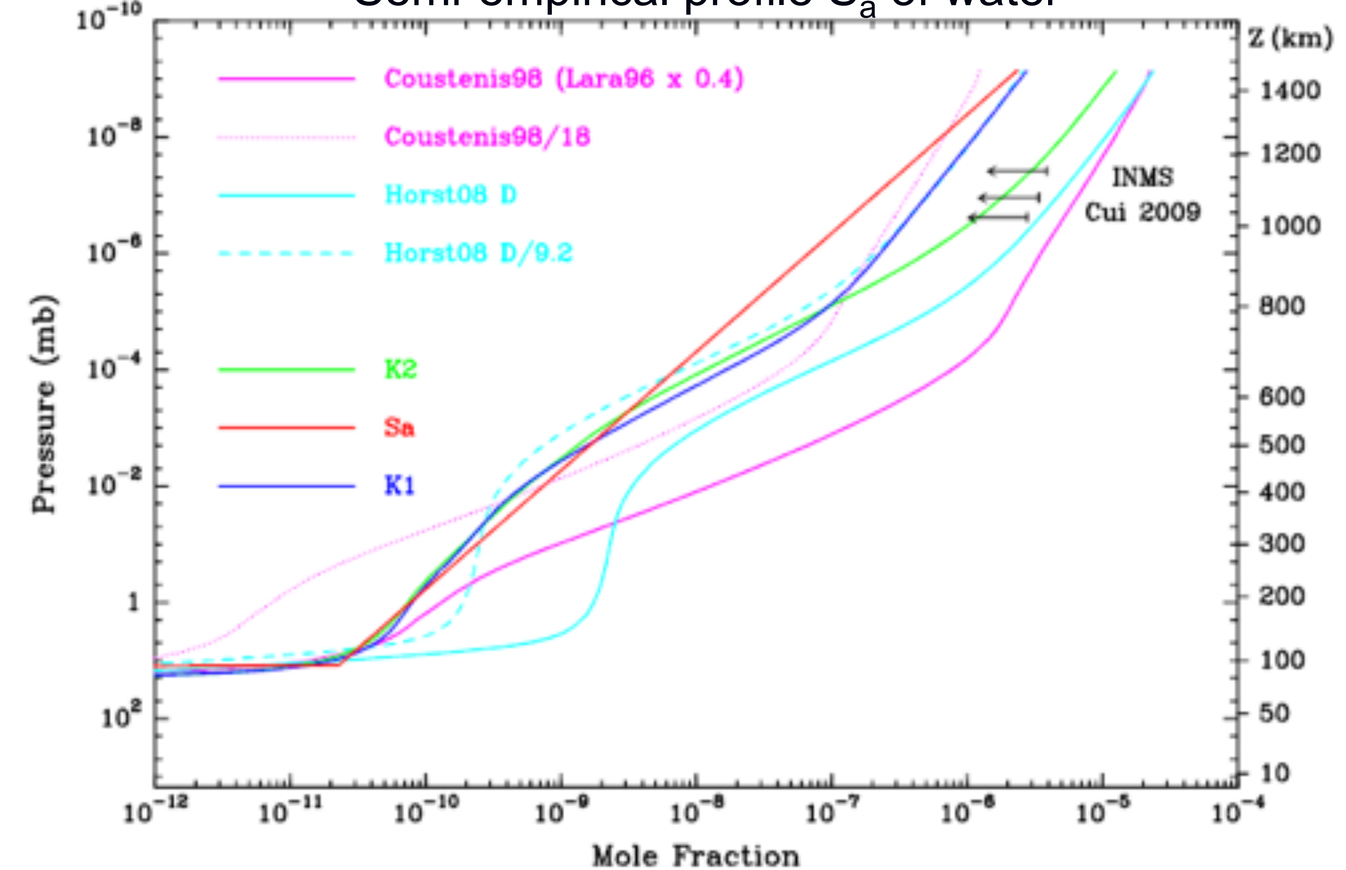
Determination of the abundance of the trace constituents: Water vertical distribution



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

q_0 is the mixing ratio at the reference pressure level p_0

Semi-empirical profile S_a of water

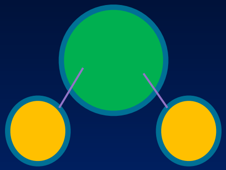


S_a:

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

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



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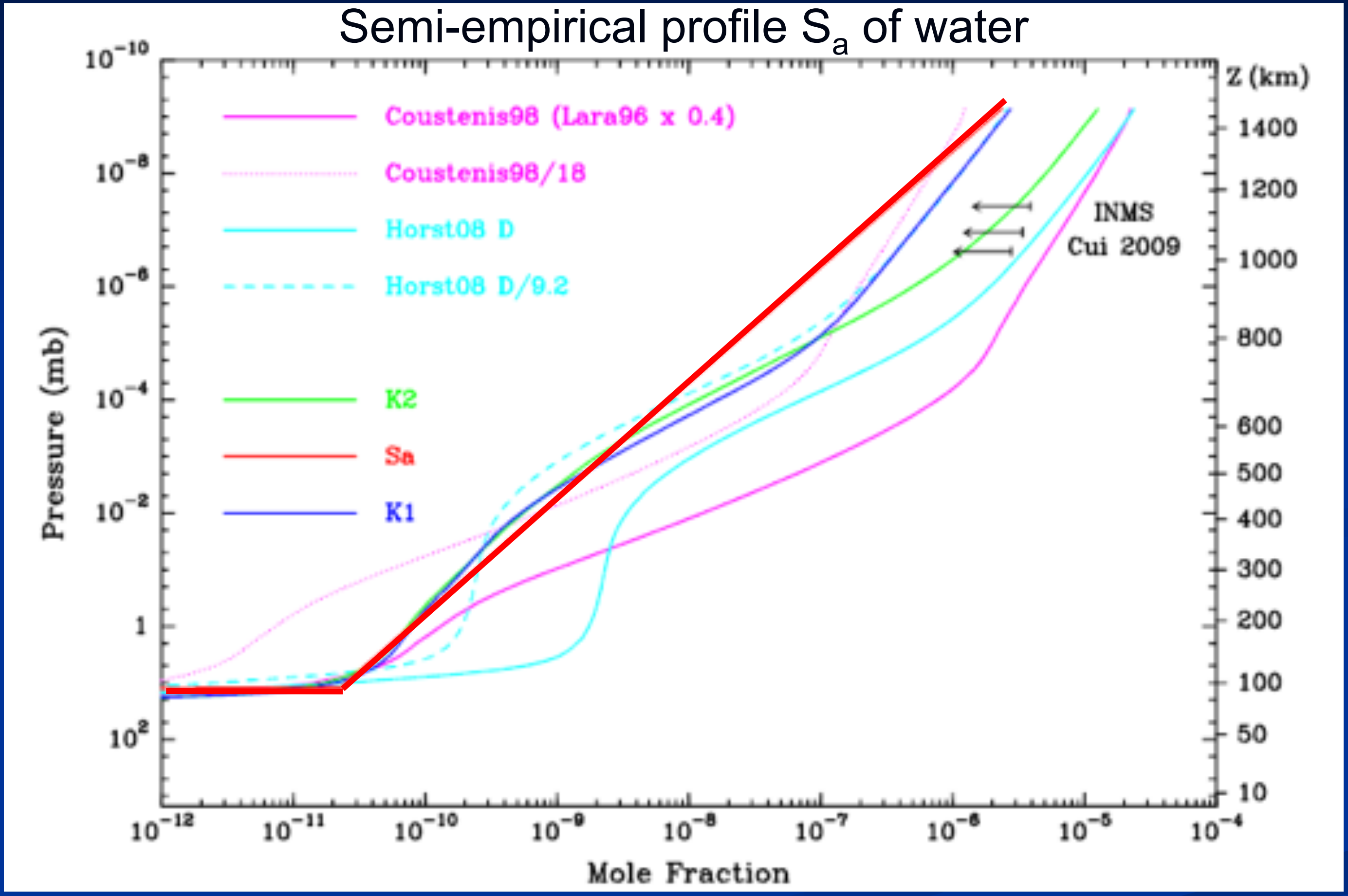

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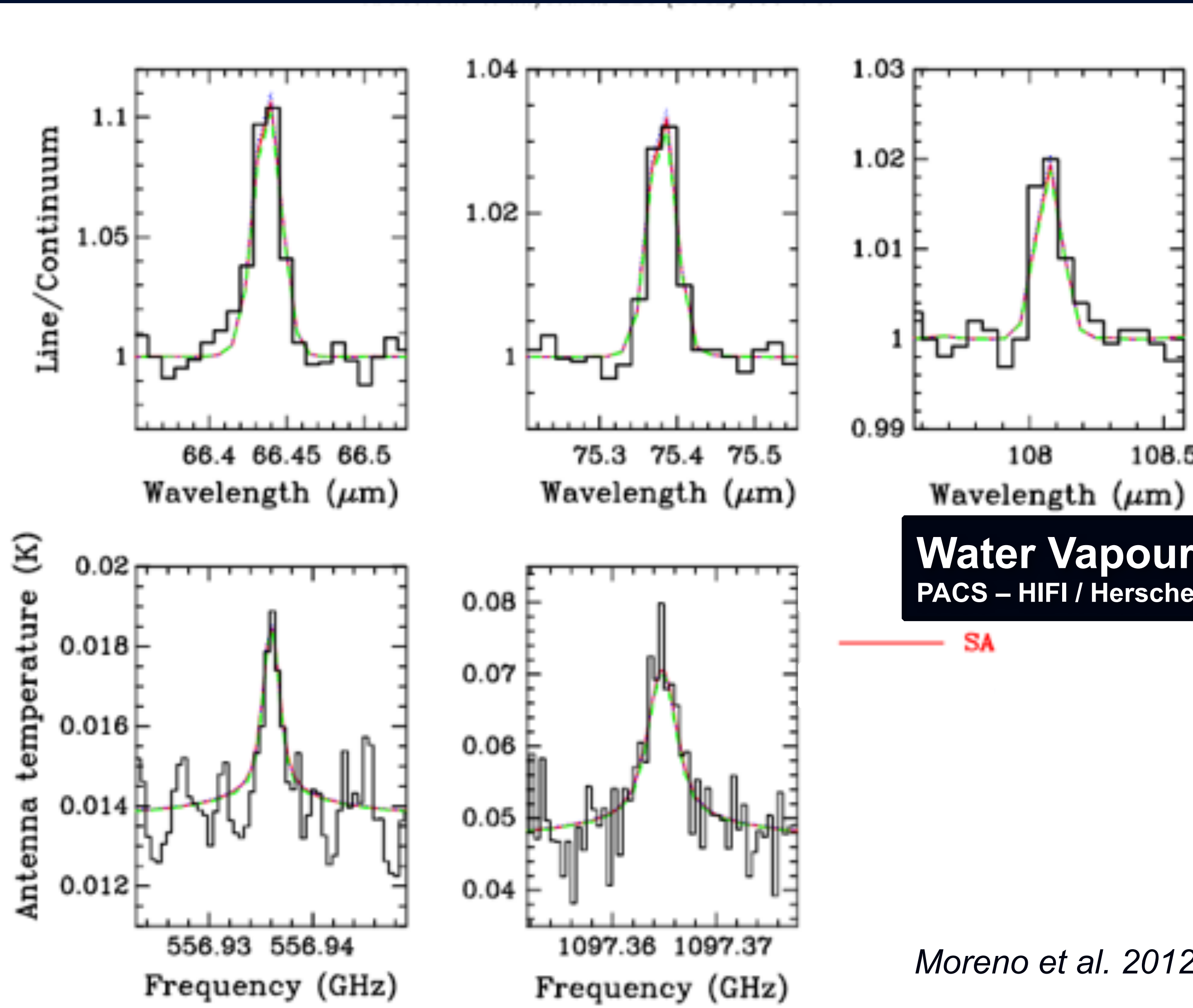
Moreno et al. 2012

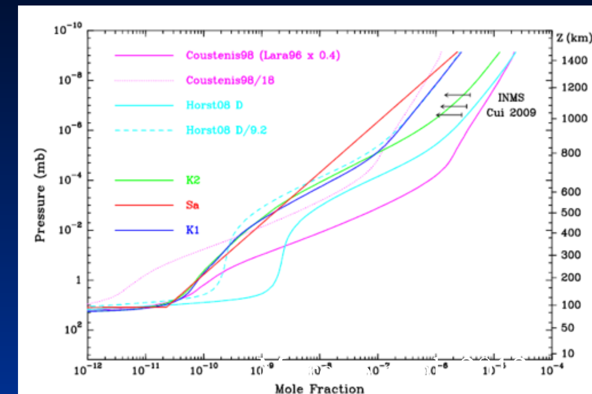
Water Vapour in Titan
PACS – HIFI / Herschel

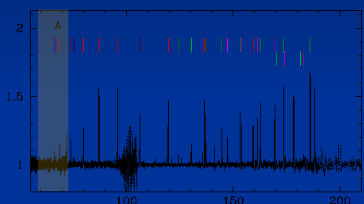


Moreno et al. 2012

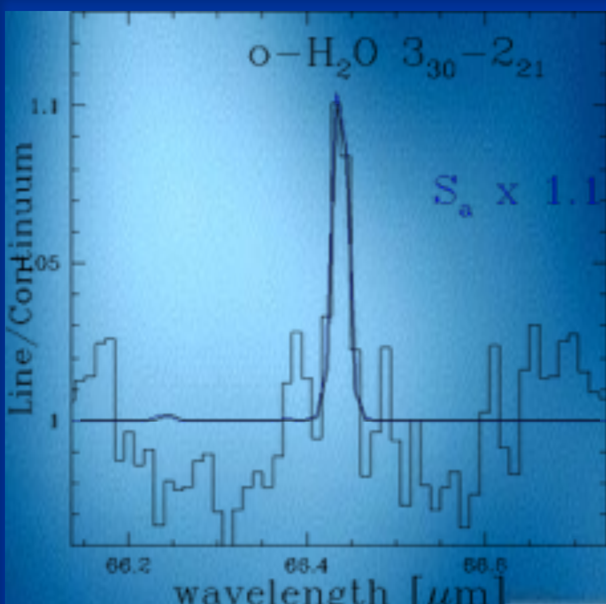
Observed and synthetic spectra

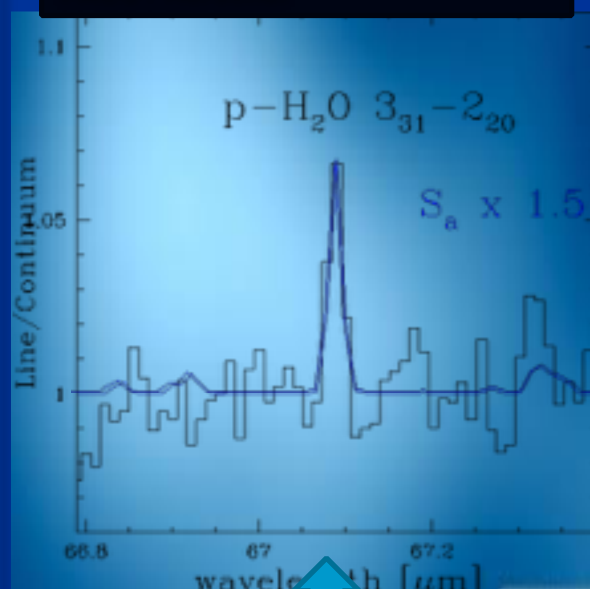
The S_a distribution is also compatible with the PACS lines from the full scan: computations of the synthetic spectra with S_a (*Moreno et al. 2012*).

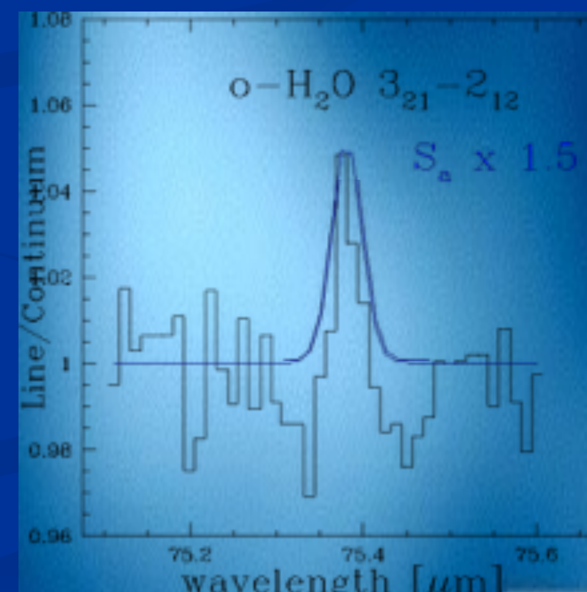




Water Vapour in Titan
PACS / Herschel





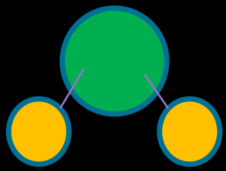


Detection for first time

Rengel et al. 2014

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

What is the origen of water in Titan?



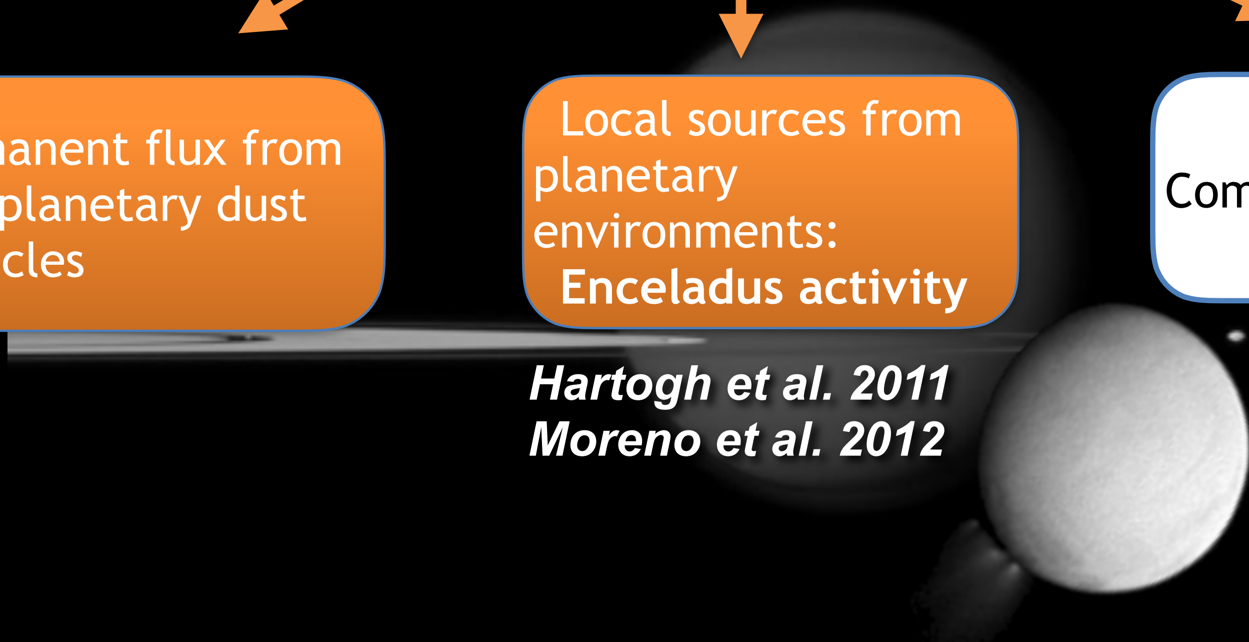
- Titan is hit by a D >1.5 km comet every ~4 million years on average
- scarcity of primordial noble gases in its atmosphere

Possible Origin

Permanent flux from interplanetary dust particles

Local sources from planetary environments:
Enceladus activity

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}

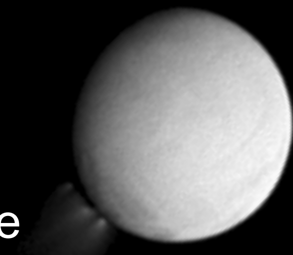
Reflects a temporal change in the oxygen influx into Titan

4.- Conclusion

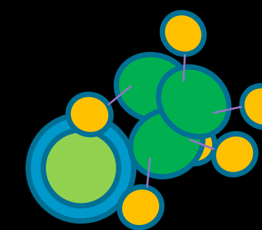
Herschel´s Legacy

- New Survey between 51 and 671 μm: CH_4, **CO**, HCN, **H_2O**, **isotopes**
- Determination of abundances
- Unexpected detection of HNC
- Measurement of $^{12}C/^{13}C$ and $^{16}O/^{18}O$ ratio

Emerged oxygen-related Implications:

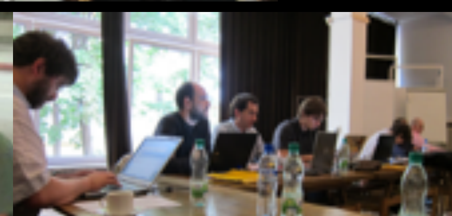


- ^{18}O enrichment in Titan´s atmosphere: Precipitation of O^+ or O from the Enceladus plume activity ($^{16}O/^{18}O$)



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

HsSO



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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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