MAX PLANCK INSTITUTE
FOR SOLAR SYSTEM RESEARCH

MPS

CHARACTERIZING TITAN'S STRATOSPHERIC GAS COMPOSITION:
INSIGHTS FROM SPACE, GROUND, AND AIRBORNE OBSERVATORIES

Miriam Rengel

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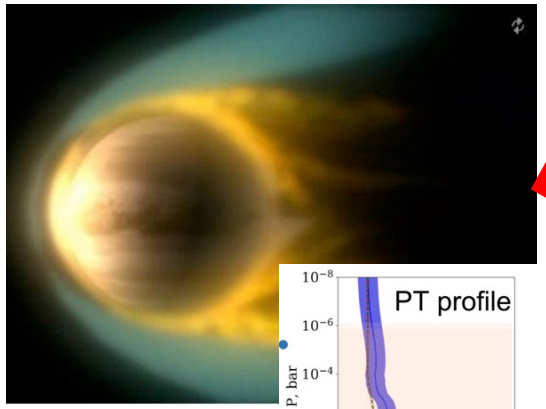
My work focus on:

-The atmospheres of planets (theory, observations and models) → Solar System and beyond

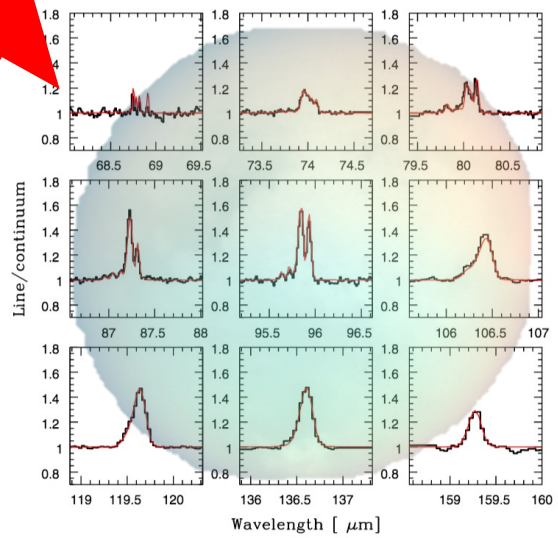
-Astronomy in the infrared and sub-millimetre (spectroscopy and photometry) → solar system

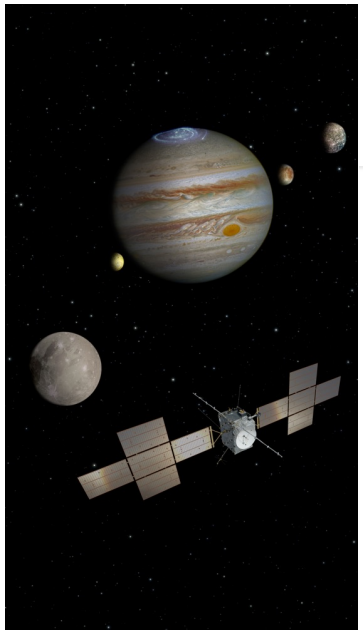
-Involvement in space missions and instrumentation/operations. Past: Rosetta, Herschel, Sentinel-6.

-Science Consortia membership: JUICE/SWI, Ariel, ESO/CRIRES+



Talk by Hartogh





exoplanet diversity
SPP 1992

CRIRES+

Ariel

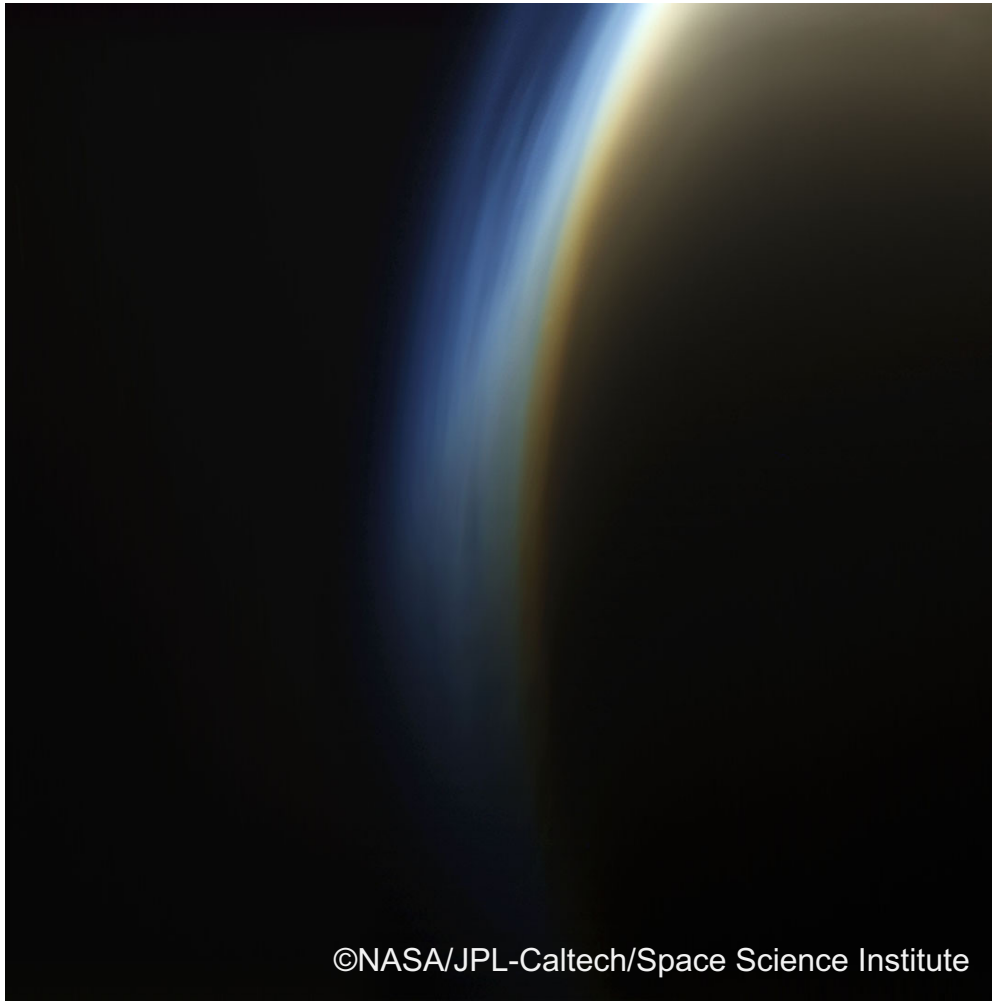
OUTLINE

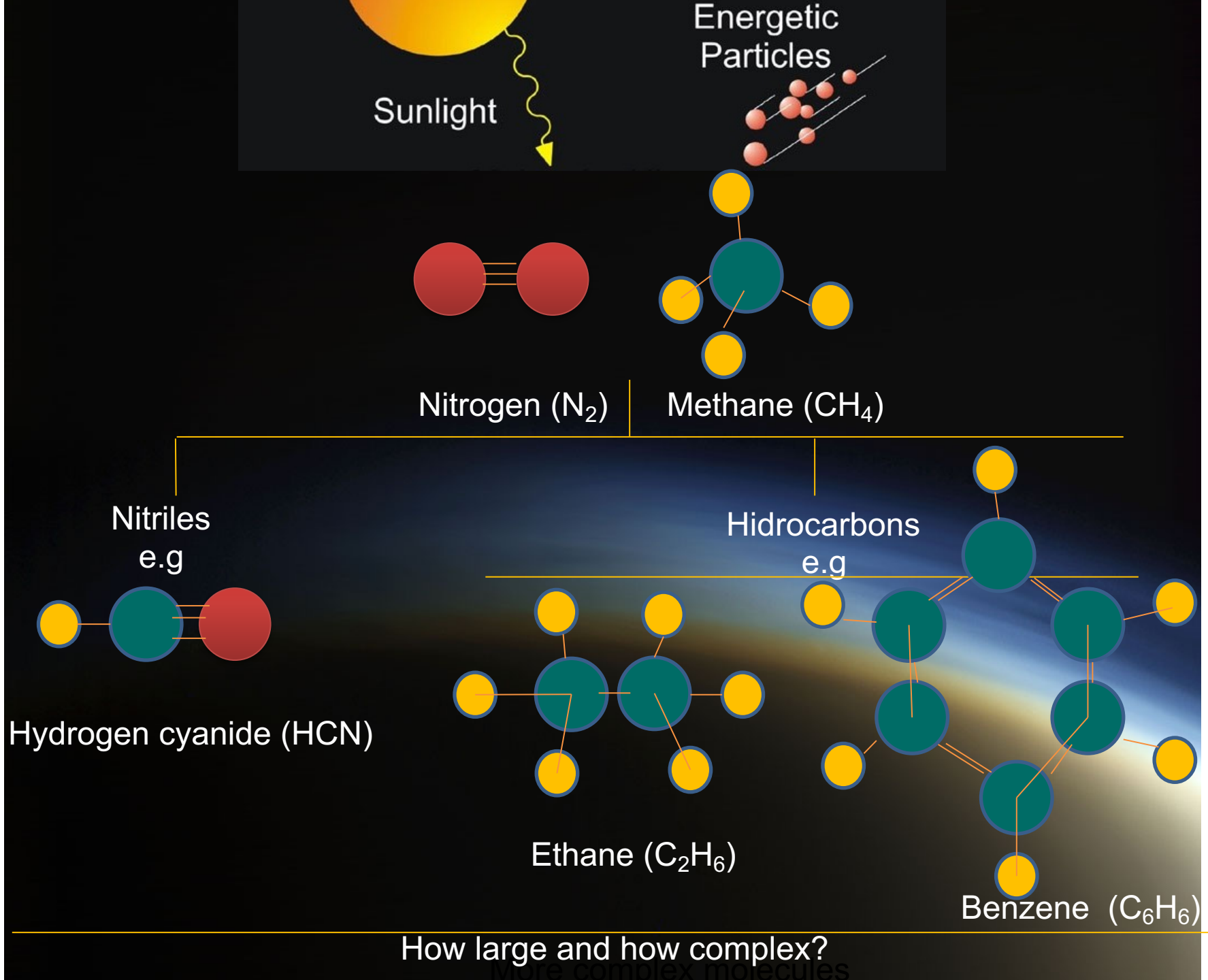
- Motivation
- How characterize planetary atmospheres?
- Titan: Advances and discoveries
- Some outstanding questions
- HCN in Titan
- Insights from SOFIA

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

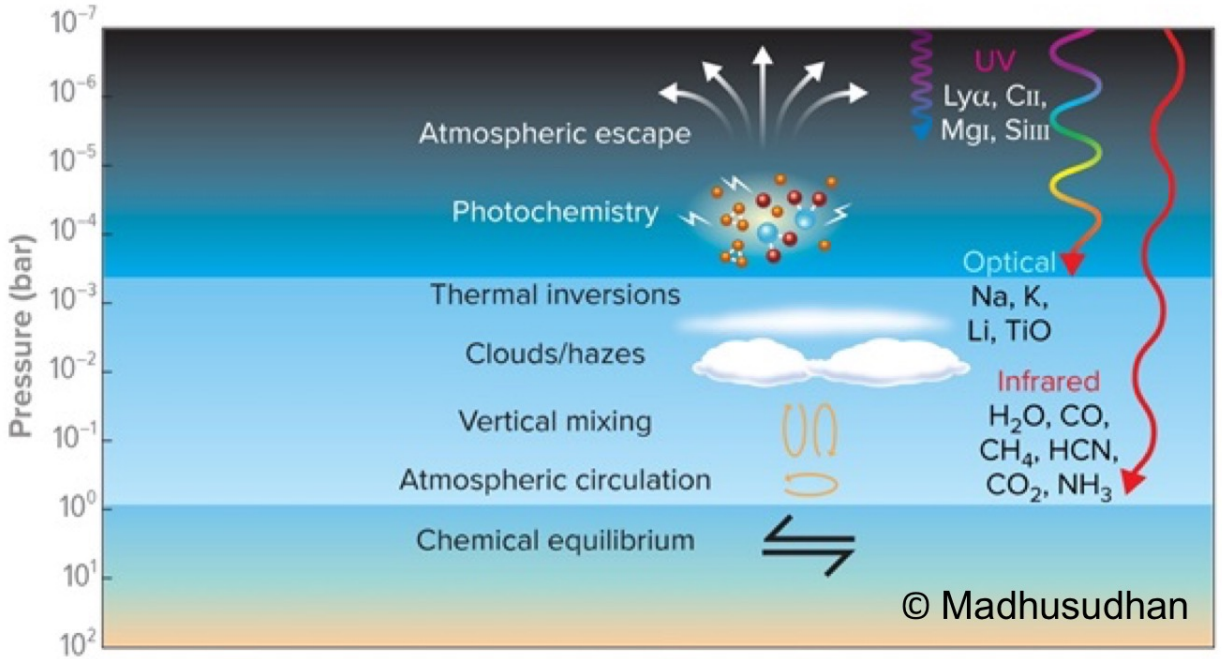
We need sensitive observations of the constituents to constructing models of the Titans´s atmosphere and its history




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

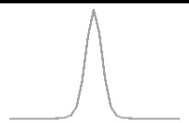
CHARACTERIZING PLANETARY ATMOSPHERES – HOW?

exoplanet diversity
SPP 1992



Different processes are probed by different parts of the electromagnetic spectrum

Observations



Wavelength Resolution

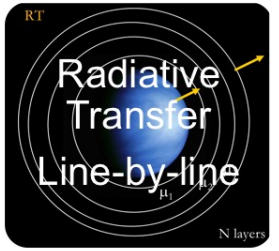
Retrieval Technique

Forward Model

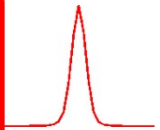
Input parameters

PT profiles
Composition
System parameters

Opacities

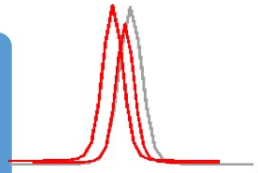


Synthetic Spectra



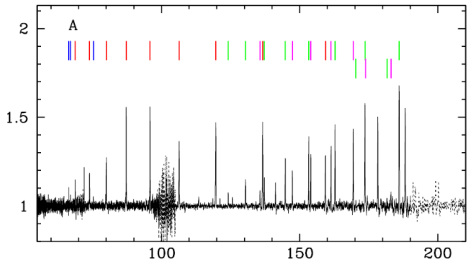
Data Simulation

Comparison with obs

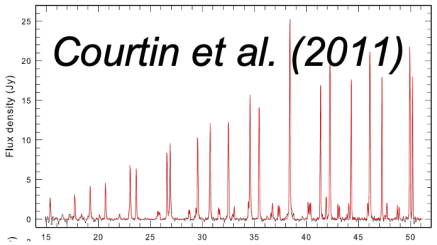


Inversion Algorithm

TITAN: ADVANCES AND DISCOVERIES



Rengel et al. (2014)



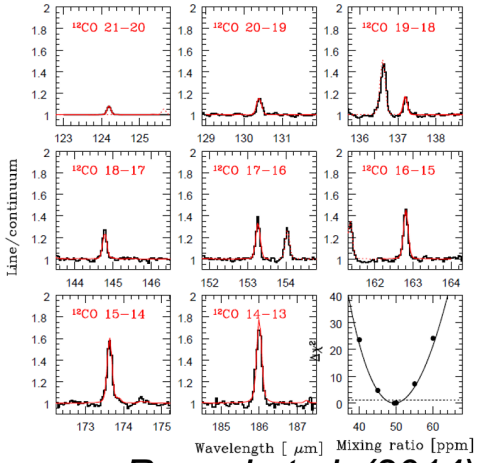
Courtin et al. (2011)

1

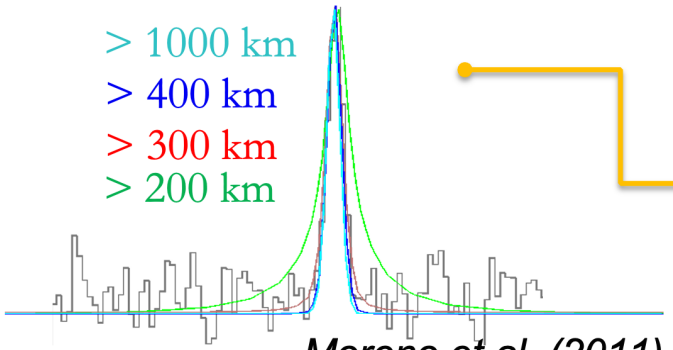
- New line surveys: Herschel: between 51 and 671 μm: CH_4, CO, HCN, H_2O, isotopes

2

- Determination of abundances from space and ground based observations Herschel, APEX, IRAM-30m: CH_4, CO, HCN, H_2O



Rengel et al. (2014)



Moreno et al. (2011)

3

- Detection of new species: Unexpected detection of HNC : Above 400 km, Titan´s atmosphere also contains HNC (also observed with ALMA)

TITAN: ADVANCES AND DISCOVERIES

4

• Measurement of $^{12}C/^{13}C$ and $^{16}O/^{18}O$ ratio

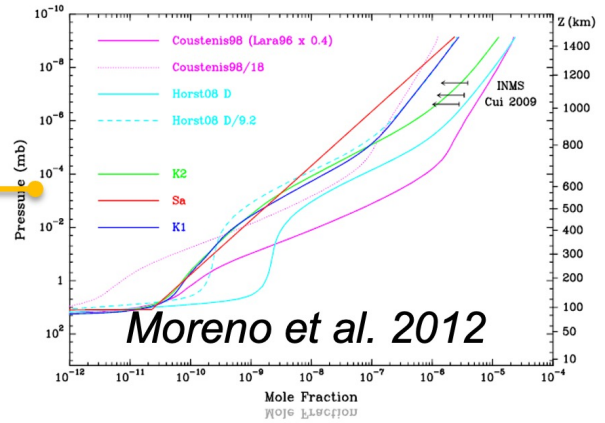
Measurement	$^{16}O/^{18}O$	Reference
JCMT	***~250***	*Owen et al. 1999 (never-published)*
SMA	***400 ± 41***	*Gurwell 2008 (unpublished)*
Herschel/SPIRE	***380 ± 60***	***Courtin et al. 2012***
ALMA	***414 ± 45***	*Serigano et al. 2016*

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

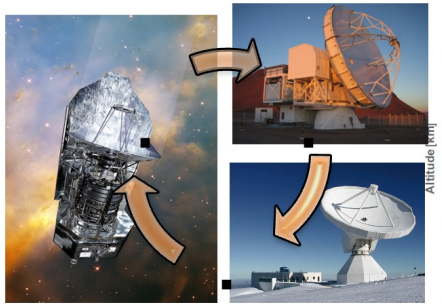
5

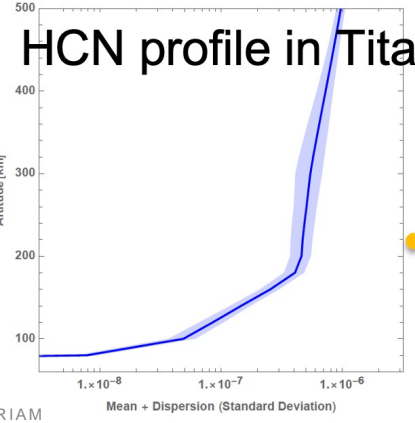
We now know the content of water vapour in Titan (different as the predictions) and from where is coming from

Semi-empirical profile S_a of water



exoplanet diversity
SPP 1992





6

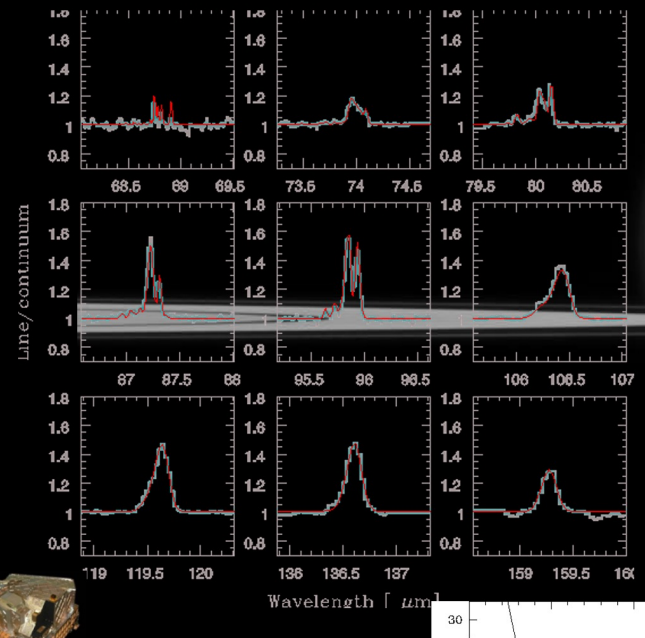
Reliable and consistest data sets: HCN abundance vertical profile as reference

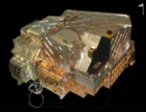
Rengel et al. 2022

SOME OUTSTANDING QUESTIONS

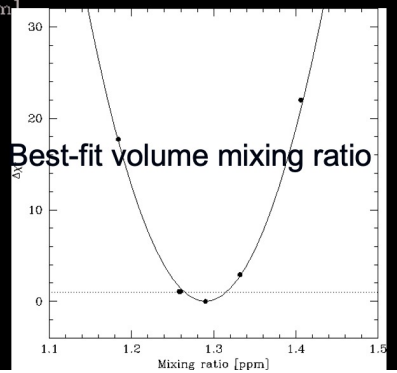
- **CH_4:** Origin unknown

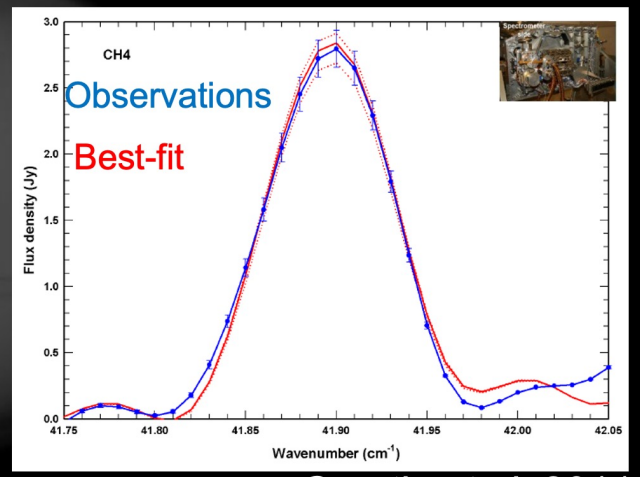
Observed and best-fit simulated CH_4 lines





Rengel et al. 2014



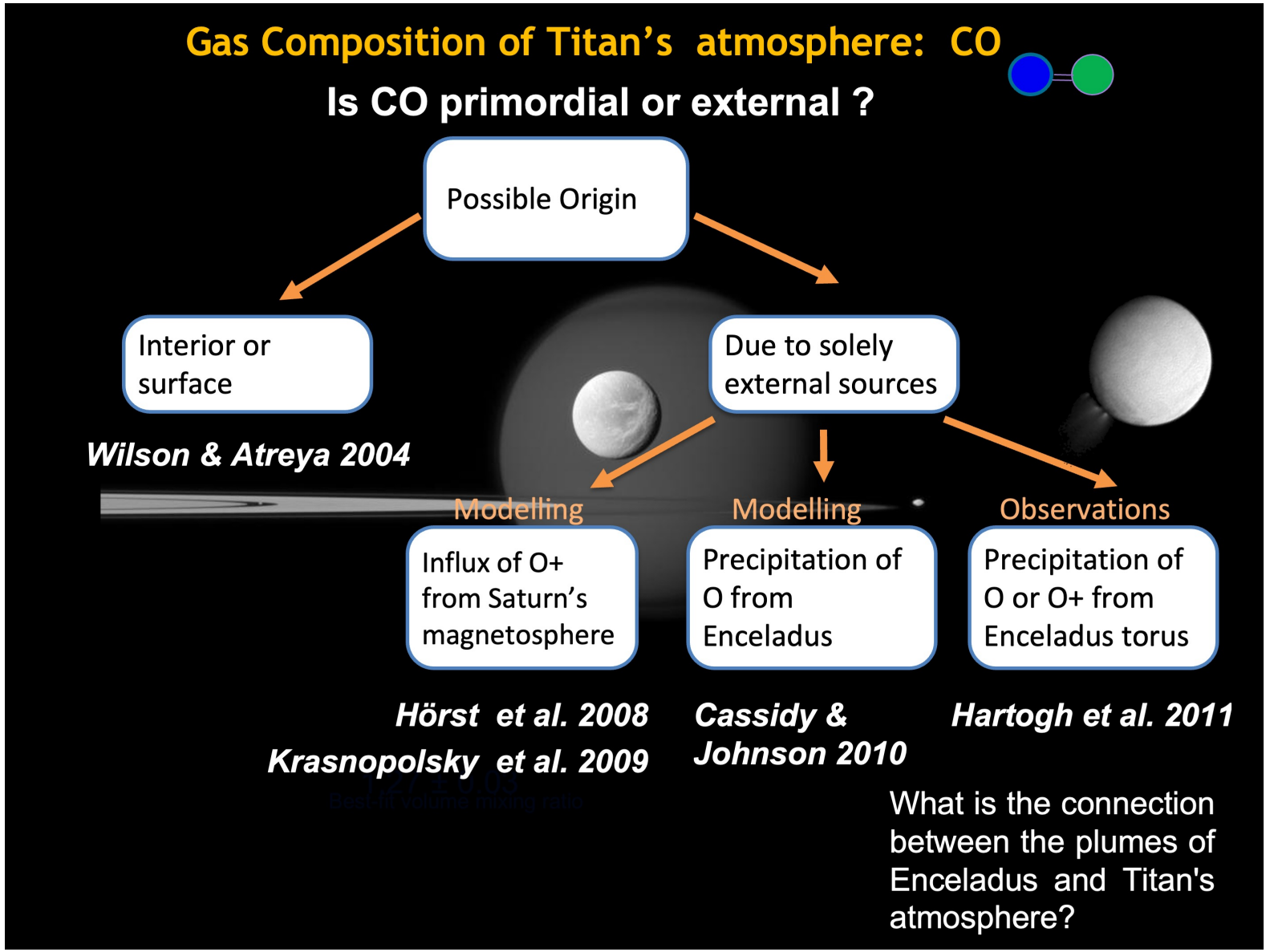


Courtin et al. 2011

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**

SOME OUTSTANDING QUESTIONS



SOME OUTSTANDING QUESTIONS

Deriving isotopic ratios

Deviations from values of other bodies?

No

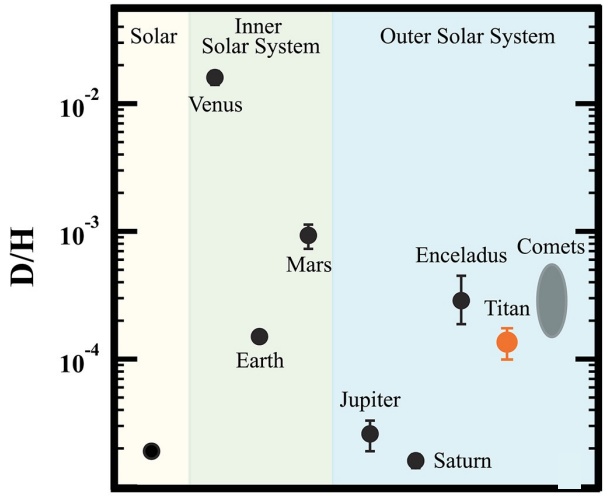
Yes

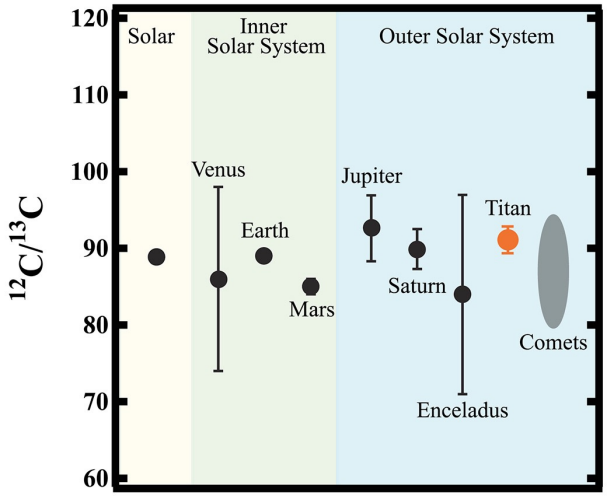
Primordial differences

Emerged on time

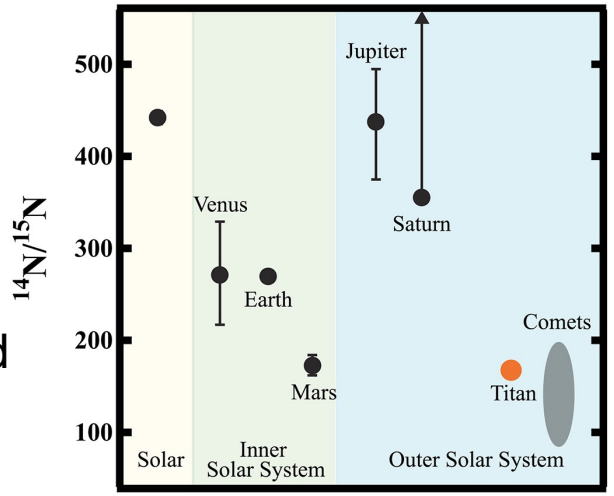
No significant fractionation

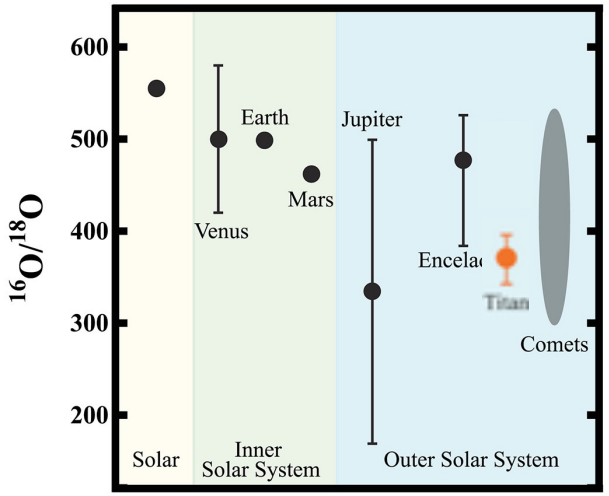
N in Titan and Saturn came from different reservoirs





No significant carbon fractionation occurred

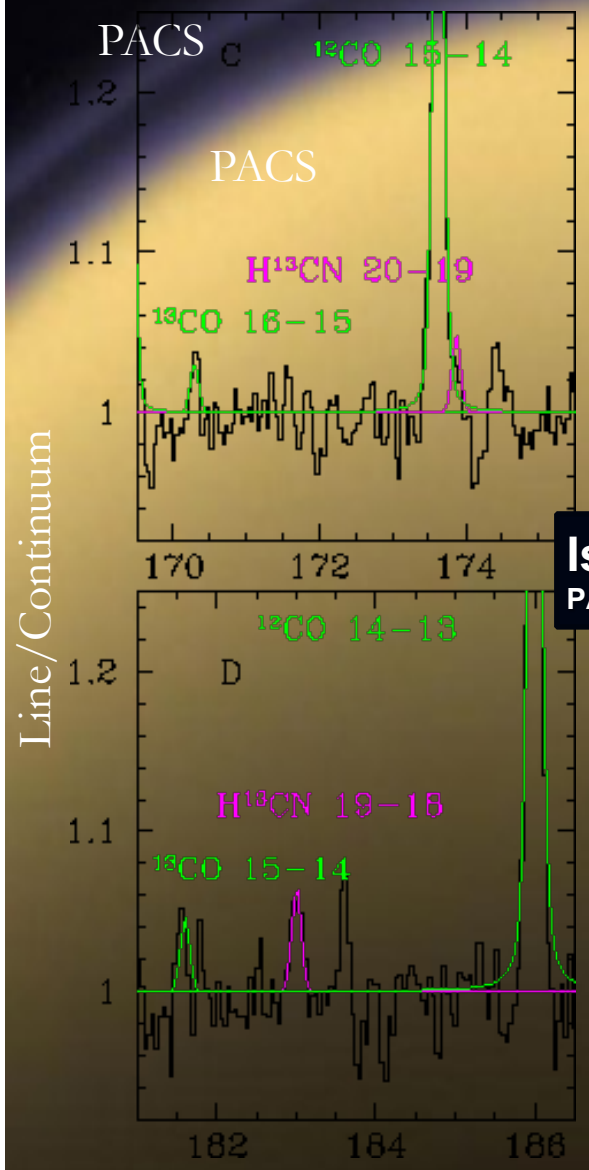




enrichment of ^{18}O

Adapted from Hörst et al. 2017

MORE ACCURATE ISOTOPIC RATIO MEASUREMENTS
$^{12}C/^{13}C$ IN CO AND HCN

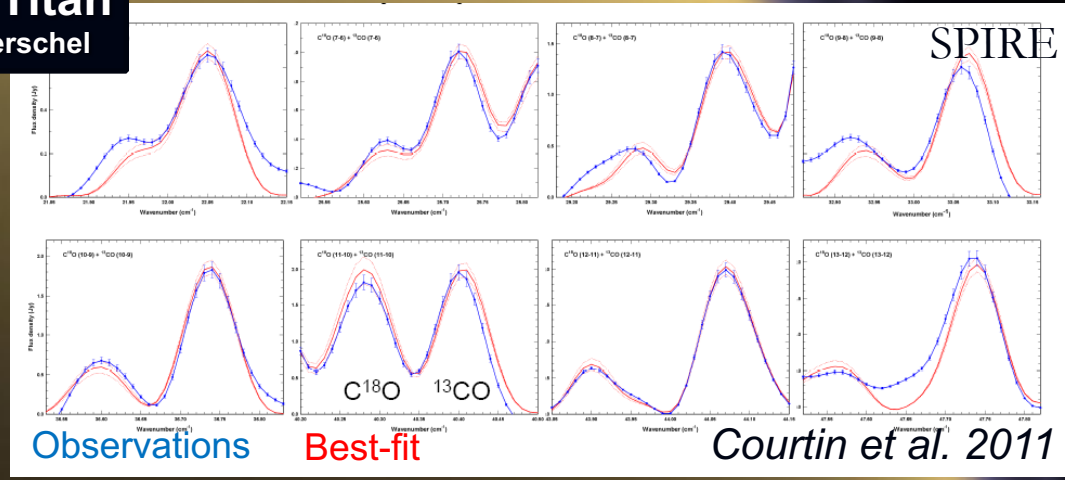


Detection of the isotopes:
- ^{13}CO (15-14) and (16-15)
- H^{13}CN (19-18) and (20-19) but marginal

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

Isotopes in Titan
PACS – SPIRE / Herschel

^{13}CO and ^{18}CO



Consistent with previous works

Rengel et al. 2014

exoplanet diversity
SPP 1992

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HCN IN TITAN: SPACE AND GROUND SYNERGY STUDY

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Denis Shulyak[1,2], Paul Hartogh[1], Hideo Sagawa[3], Raphael Moreno[4], Christopher Jarchow[1], Dieter Breitschwerdt[5]

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[2]Instituto de Astrofísica de Andalucía - CSIC, Granada, Spain
[3]Faculty of Science, Kyoto Sangyo University, Japan
[4]LESIA – Observatoire de Paris, CNRS, Meudon, France
[5]Zentrum für Astronomie und Astrophysik, Technische Universität Berlin, Germany

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In which of these exoplanets´atmospheres has HCN been detected and likely identified?

A. HAT-P-1b

B. HD189733b

C. WASP-12b, WASP-63b

D. HD 209458 b, 55 Cancri e, WASP-63b

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D. HD 209458 b, 55 Cancri e, WASP-63b

What is the most HCN-rich atmosphere in the Solar System

A. Pluto

B. Titan

C. Neptune

D. Jupiter

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A. Pluto

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How and where is generated HCN in Titan´s atmosphere?

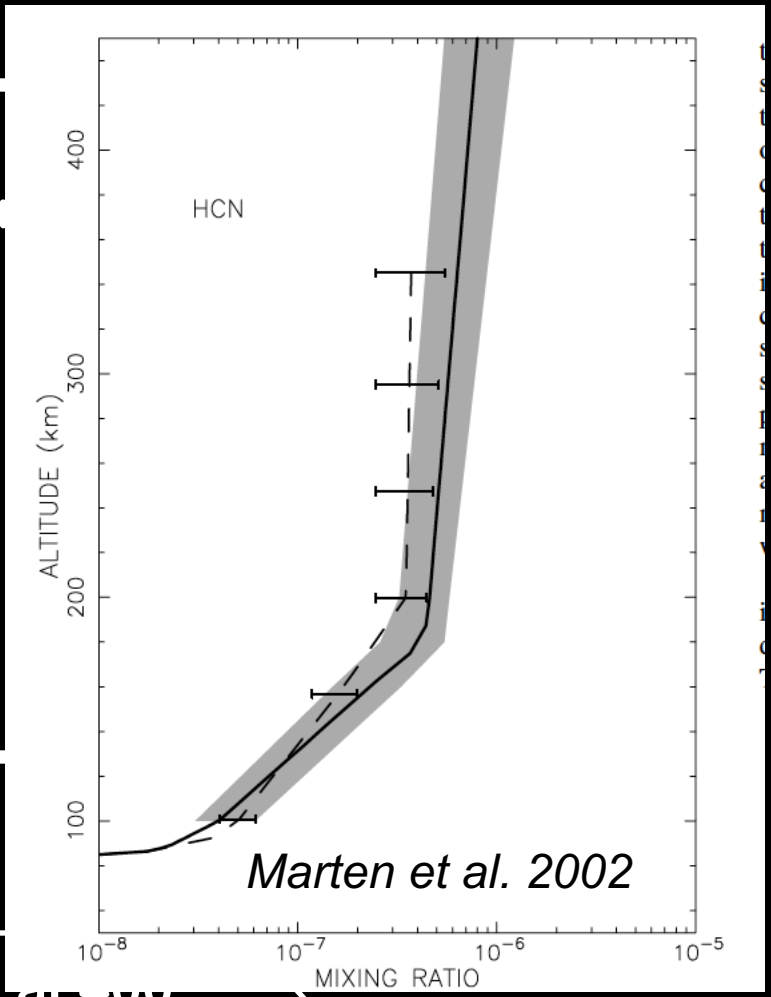
A. Meteor impacts, at 800 km

B. By lightning, at 400 km

C. Photochemically, at 300 km

D. By bacteria, at the surface

How and where is generated HCN in Titan atmosphere?



50:50

A. Meteor impacts, at 800 km

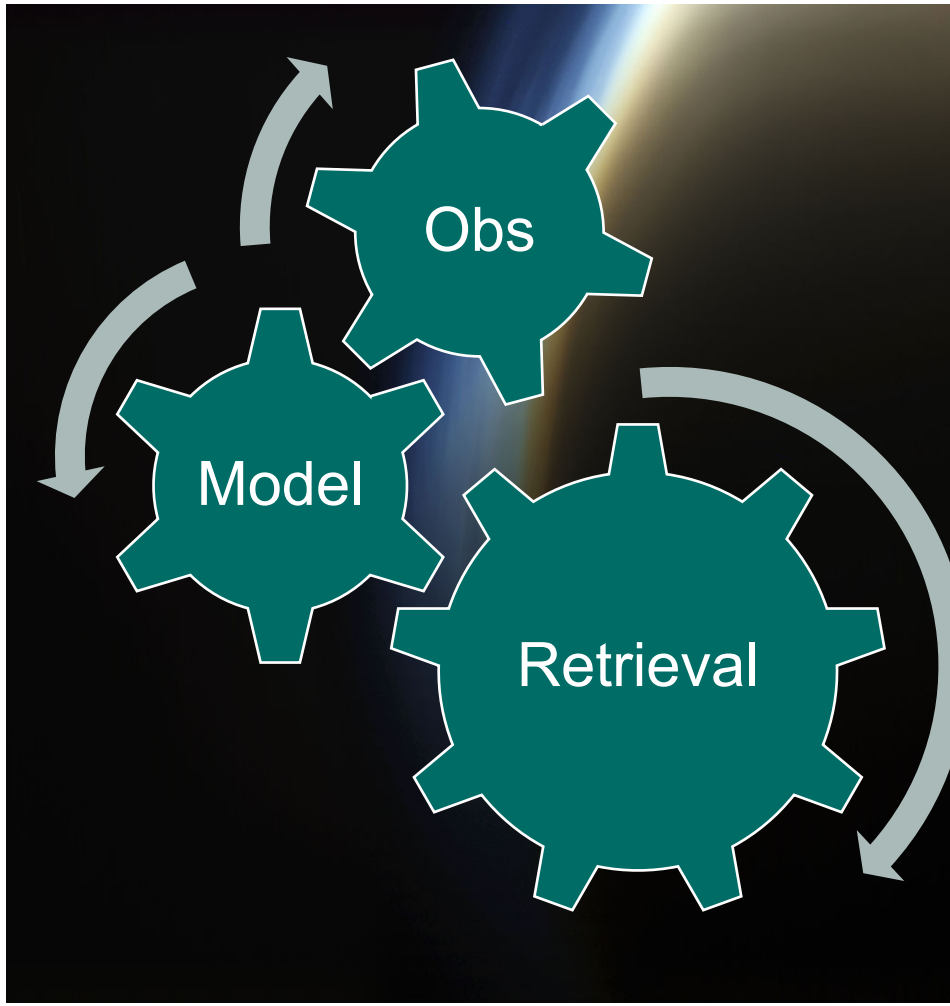
B. By lightning, at 400 km

C. Photochemically, at 300 km

D. By bacteria, at the surface

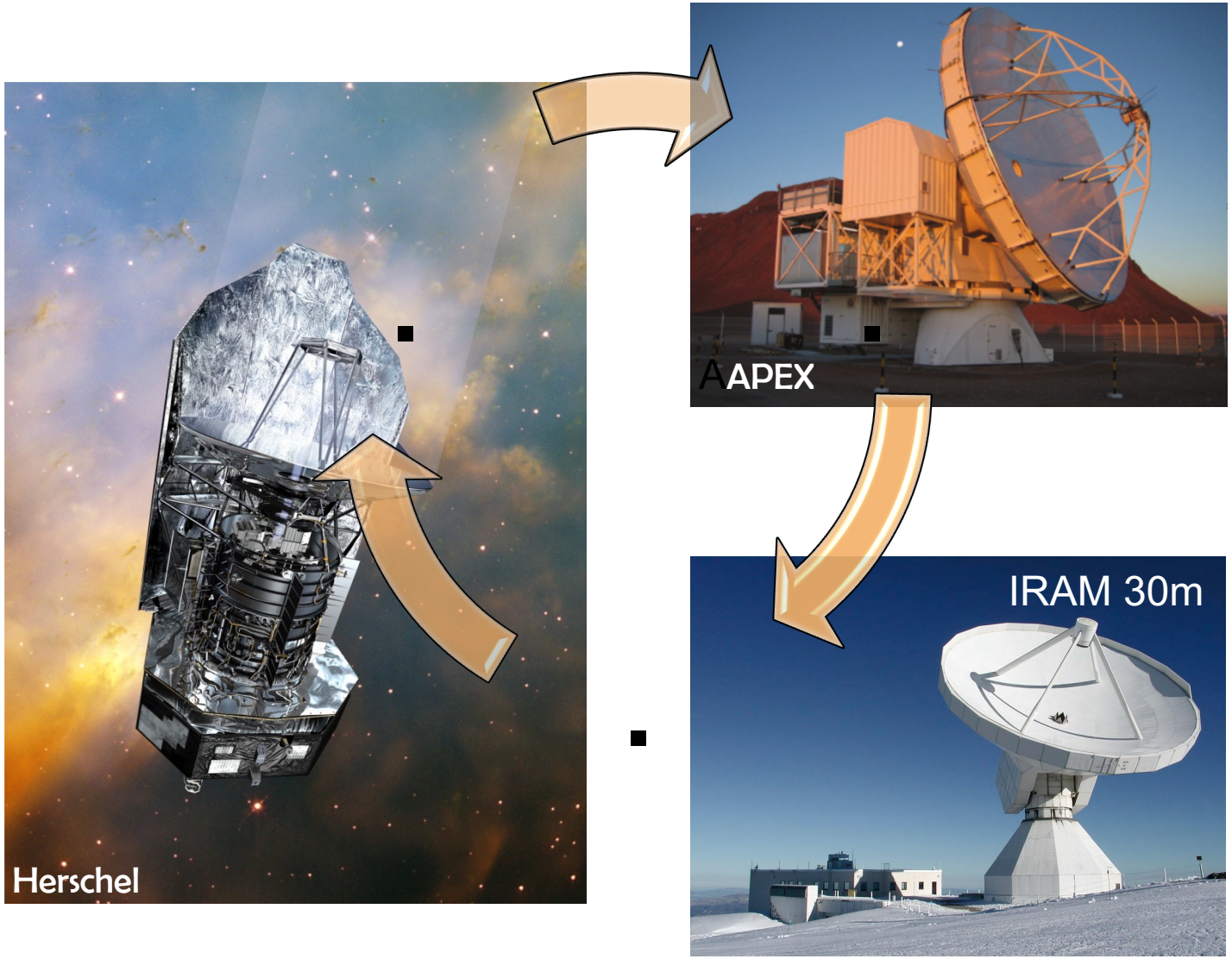
WHY HCN? - WHICH INPUT PROFILE TO USE?

- HCN can be formed in a N_2 dominated atmosphere.
- In N-dominated hot super-Earth atmospheres, HCN is a tracer of a high C/O ratio (Rimmer & Rugheimer 2019, Zilinskas et al. 2020).
- HCN becomes a prioritised specie in observations of hot super-Earths.
- Different chemical pathways may lead the HCN production and destruction in diverse atmospheres.



We need a HCN vertical distribution reference!
We use Titan as a starting point

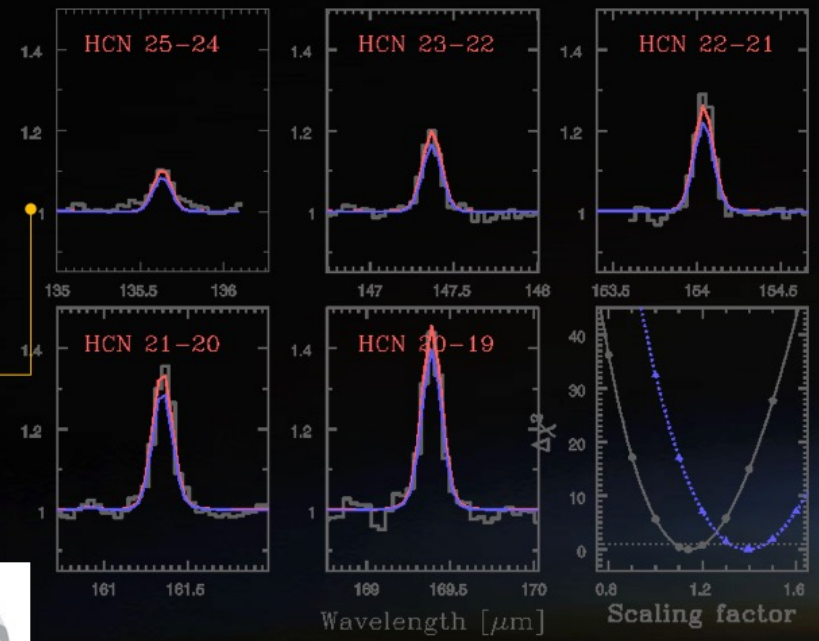
OBSERVING SIMULTANEOUSLY THE HCN TITAN SPECTRA



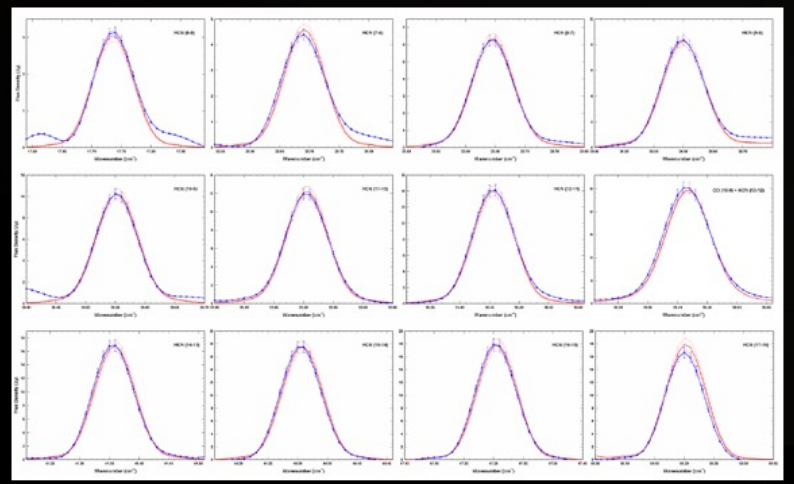
Space-based measurements, aided by comprehensive ground validation provide **reliable** and **consistent** data sets

A quantitative link between the infered HCN abundances obtained by Herschel and ground-based observations is required to assessing the **quality** of the data/results and **cross-validating** them.

Observed and best-fit simulated HCN lines



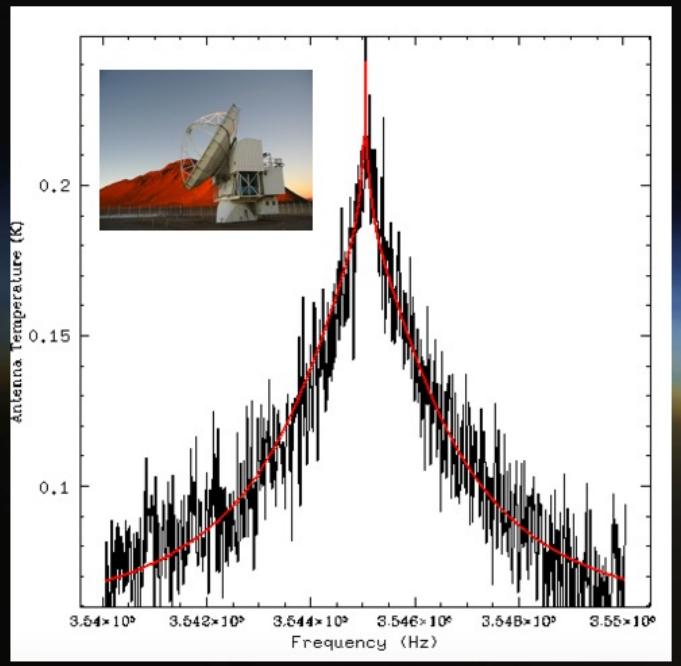
Rengel et al. 2014



Courtin et al. 2012

Forward model: line-by-line RT model (home made)

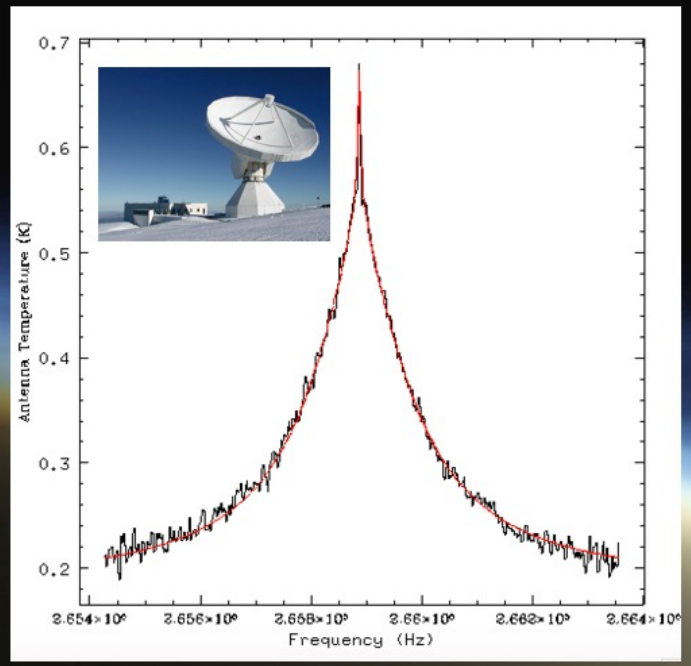
HCN (4-3)



Resolution: 122 KHz, S/N = 8

Bandwidth of 1 GHz

HCN (3-2)



Resolution: 4 MHz, S/N = 36

Bandwidth of 4 GHz

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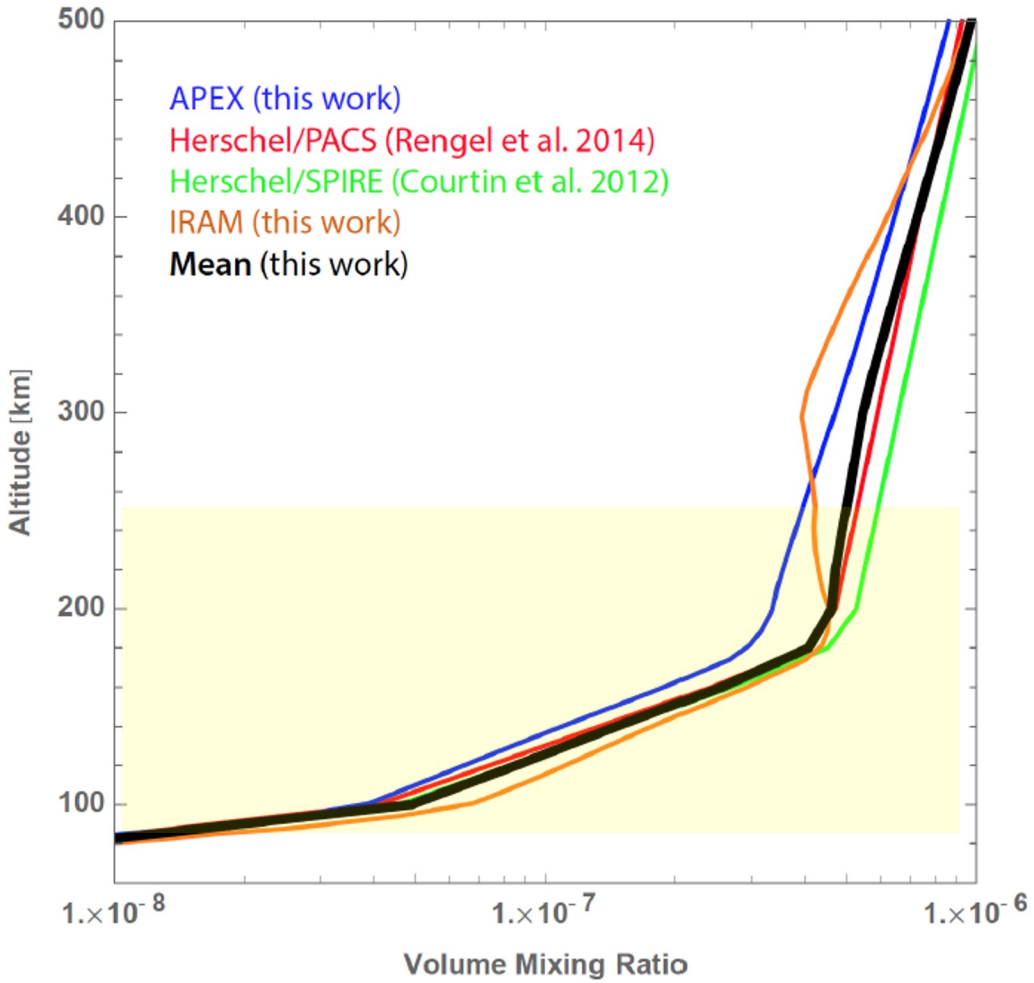
RESULTS: RETRIEVED HCN PROFILES

Inversion algorithm: OE (home made)

Measured HCN abundances on Titan with data acquired from space and ground at similar epochs and with different transitions exhibit similar abundance distributions

This cross-validation lets to drive reliable and consistent measurements



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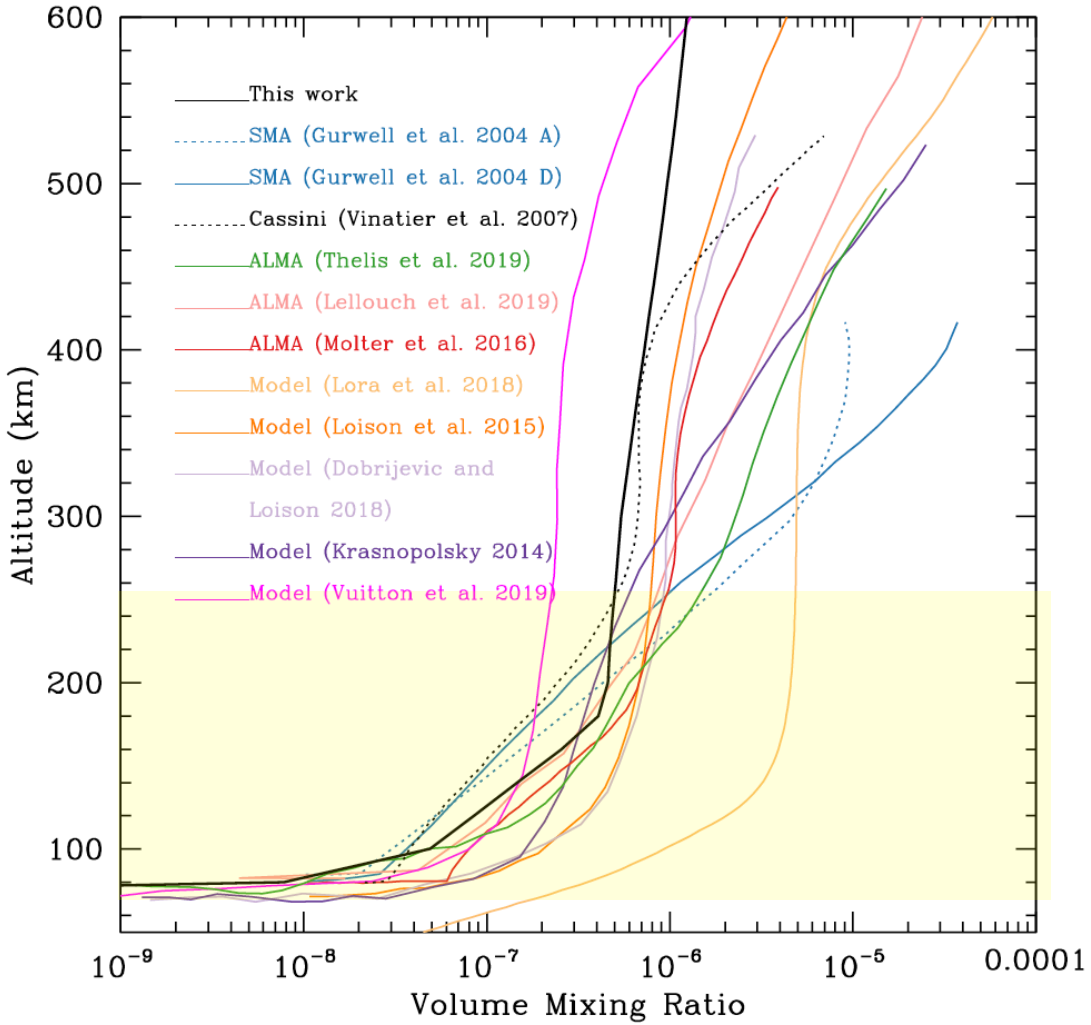
MEAN HCN PROFILE COMPARED WITH PROFILES FROM THE LITERATURE

Consistent with those derived from SMA, ALMA and Casinni/CIRS
Photochemistry models needs revision (< 150 km and > 400 km)



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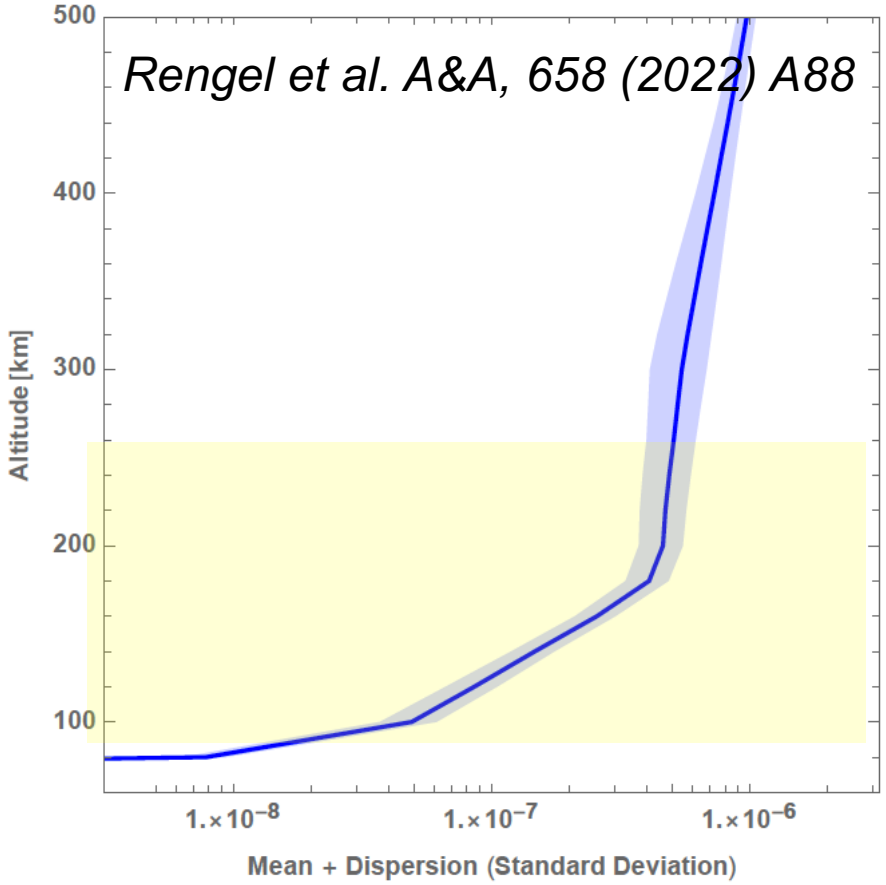
MEAN HCN PROFILE: A REFERENCE

HCN profile



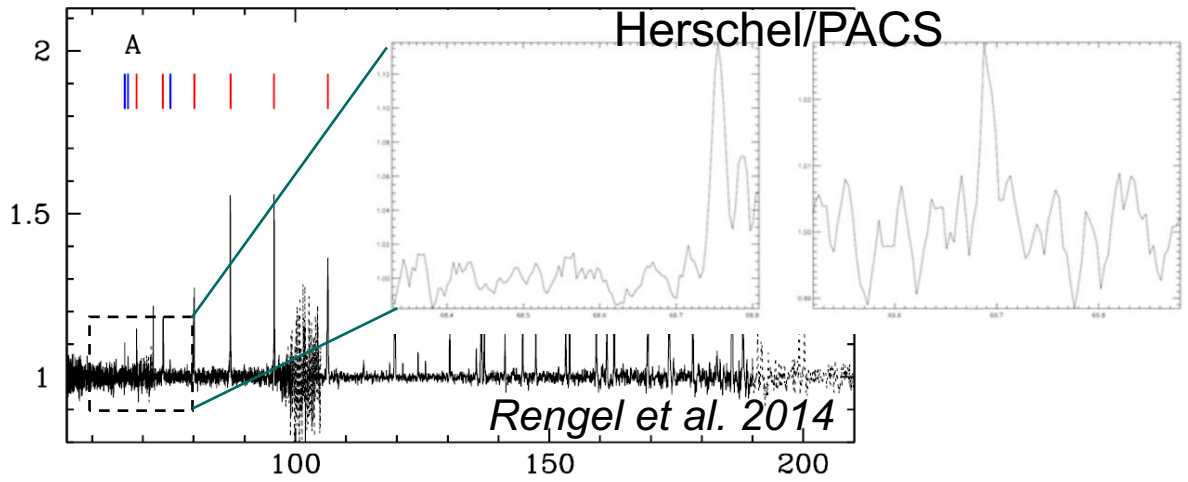
Guide to understand what to expect in a N-dominated atmosphere

Input for Hot super-Earths atmosphere modelling for example

As a reference in preparation for future observations

FOLLOW-UP PROJECT BEHIND HERSCHEL/PACS EXPLOITED BY SOFIA/FIFI-LS

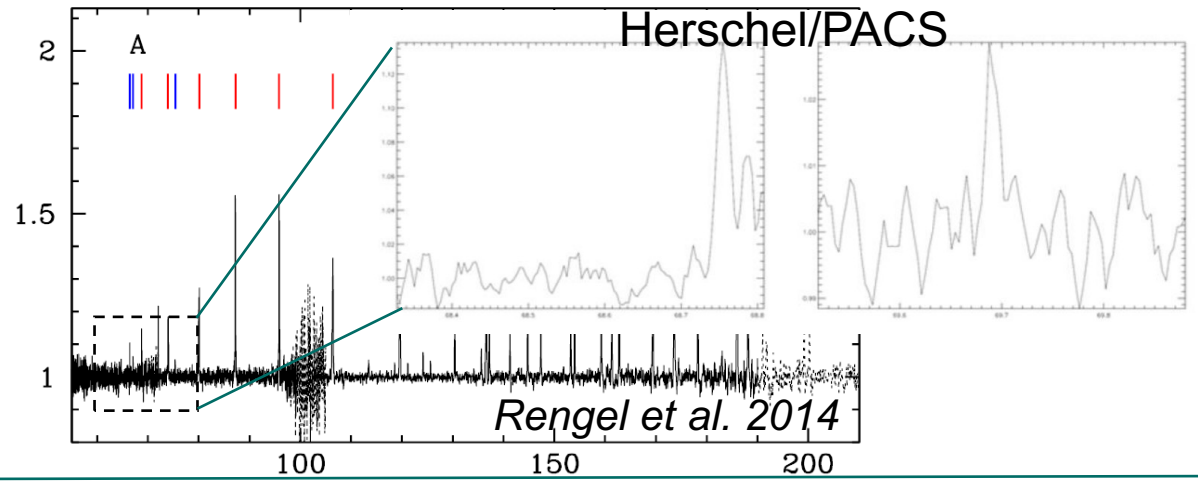
Identify features

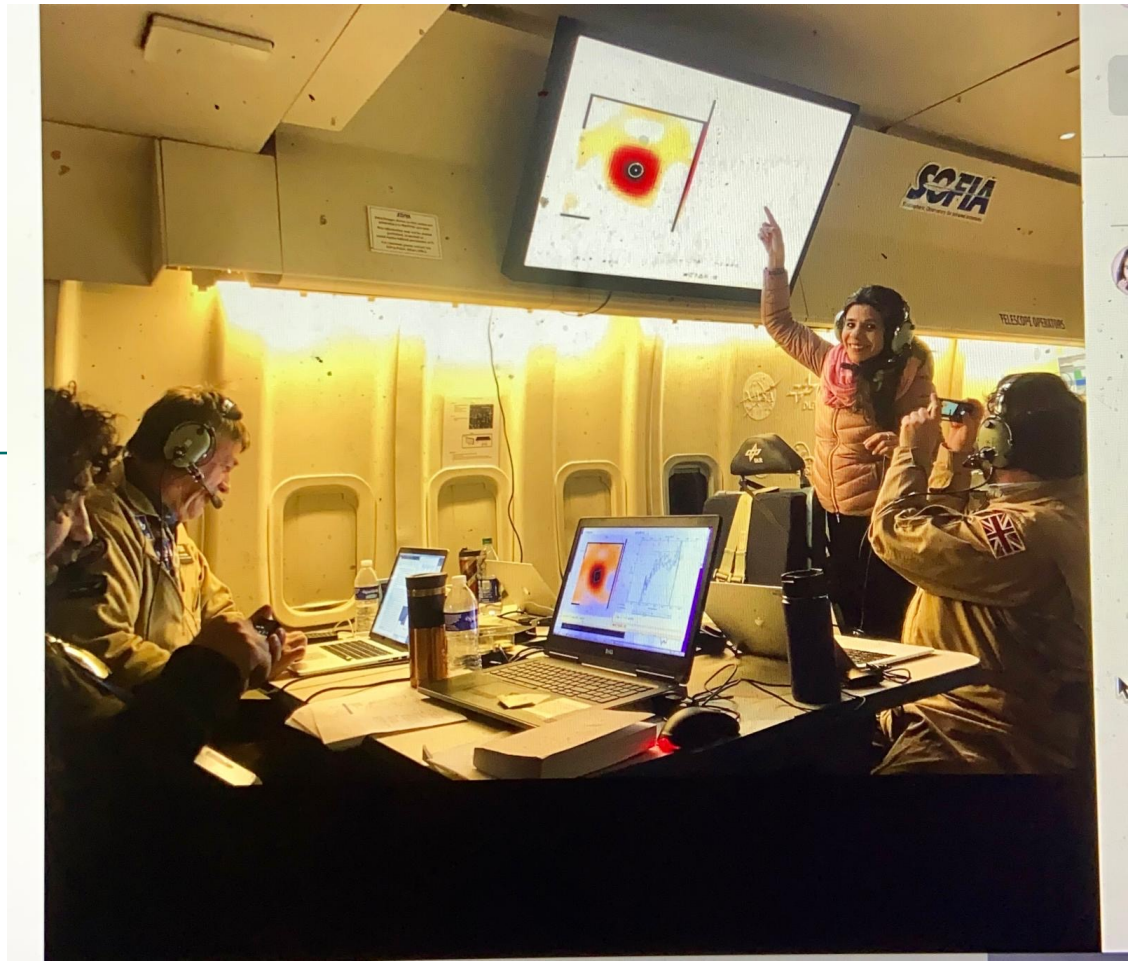


FOLLOW-UP PROJECT BEHIND HERSCHEL/PACS EXPLOITED BY SOFIA/FIFI-LS

Proposal 07_0219, cycle 7, PI: Rengel
FIFI-LS detection

Identify features





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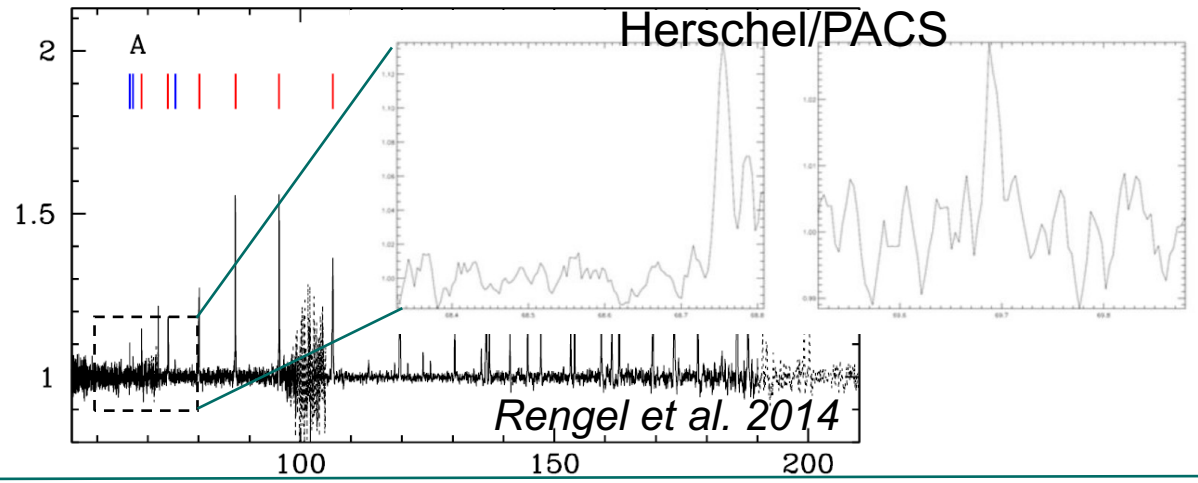
Identify features



68.58 microns

C_2H_2?
A new specie?

It is C_2H_2!

69.69 microns

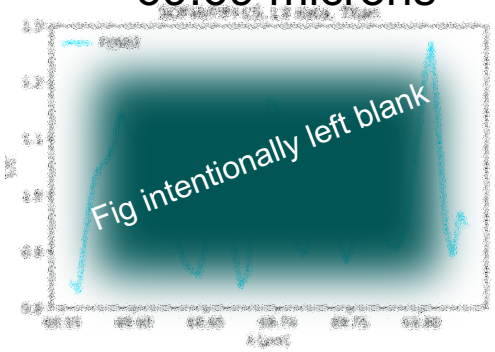
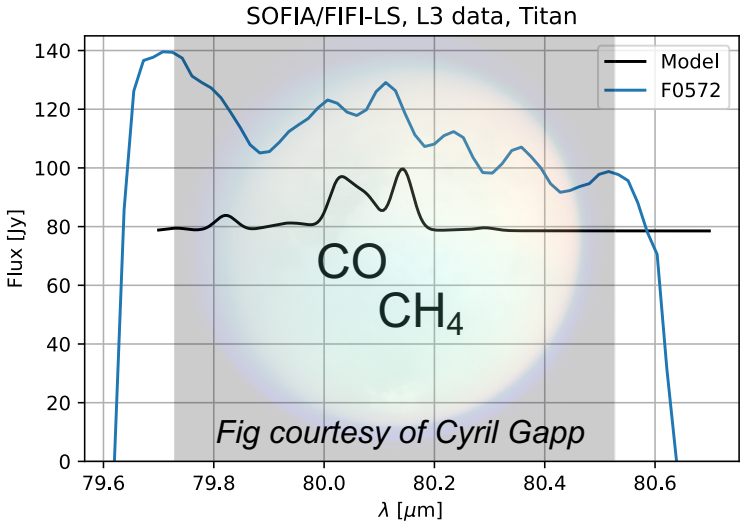


Fig courtesy of Cyril Gapp

Study CH_4 temporal variability

FIFI-LS detection
-87.3 microns
-80.1 microns

Forward model:
PSG

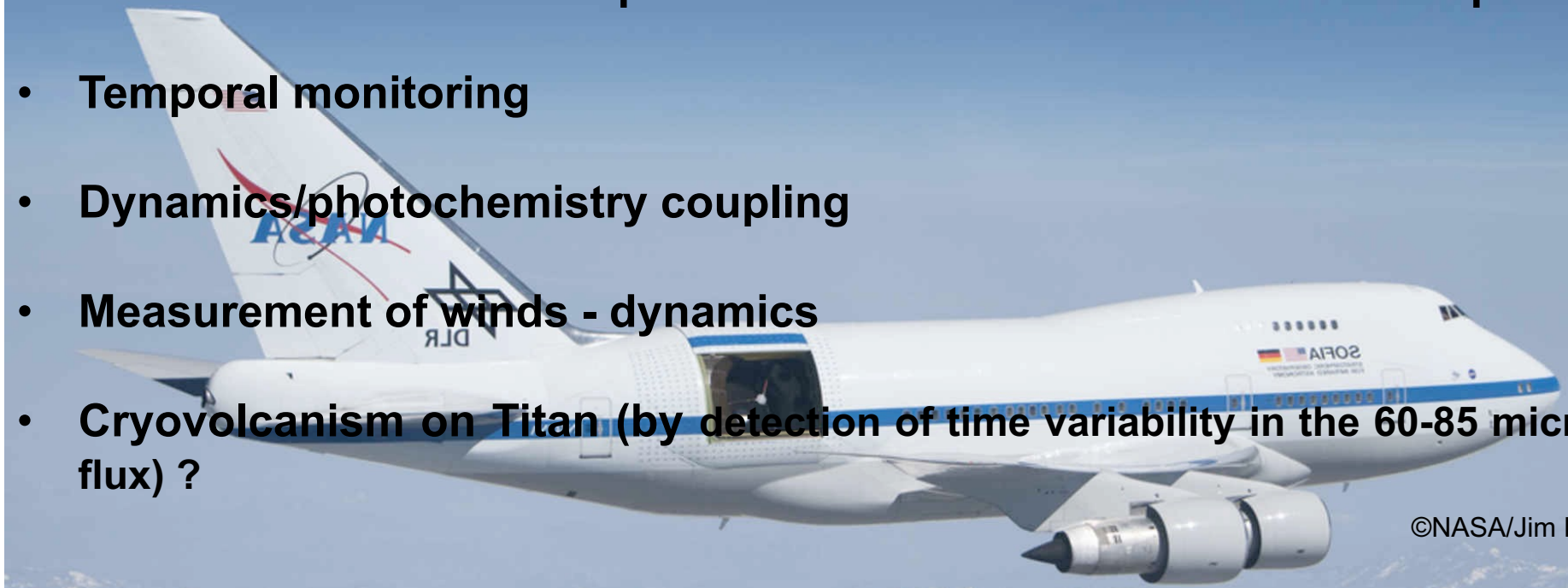


Next:
-Retrieve abundances
-Compare with measured abundances in other epochs

Rengel et al. in preparation

Open Science questions that have potential to be solved with airborne instrumentation

- **Investigations on chemical compositions. Search for more complex species,**
- **New and more accurate isotopic ratios and species abundances**
- **Origin of Titan's methane**
- **Connection between the plumes of Enceladus and Titan's atmosphere**
- **Temporal monitoring**
- **Dynamics/photochemistry coupling**
- **Measurement of winds - dynamics**
- **Cryovolcanism on Titan (by detection of time variability in the 60-85 micron flux) ?**



THANK YOU!