Solar system planetary science with ALMA

+ some results from Herschel observations

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Outline of the talk

- Short introduction about the planetary atmospheric studies & their submm observations.
- Solar system observations with **Herschel**: some highlights.
- Observations of Venus with mm/submm interferometers, as a possible scientific target of **ALMA**.

planetary atmosphere...

what processes control the planetary atmosphere?

Radiation

thermal structure,
energy budget,
cloud microphysics

Dynamics

material momentum transport,
atmospheric escape

Chemistry

composition,
atmospheric evolution,
cloud microphysics,
heterogeneous

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temperature sounding

doppler wind

IR~mm spectroscopy

cloud image/tracking

thermal/geostrophic wind

- Submm heterodyne observations are an effective tool to study planetary atmosphere (as shown in SMILES talk).

planetary atmosphere…

key parameters when designing observations

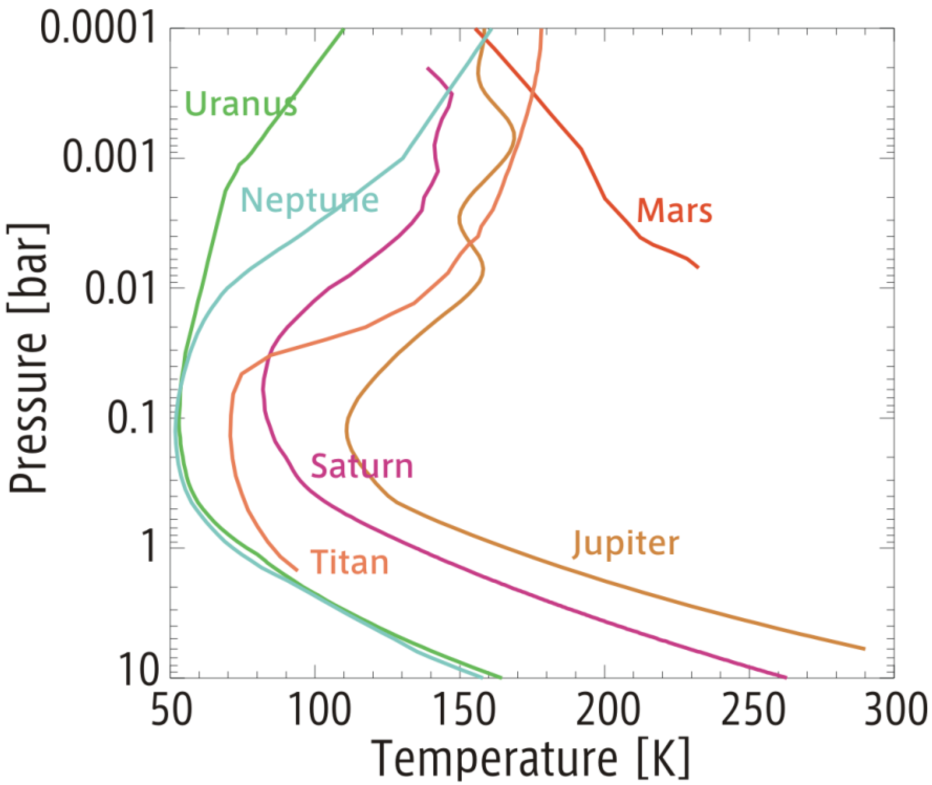
Planetary atmosphere = phenomena with diverse spatial/ temporal scales…

- Spatial resolution & Spatial coverage
- Time resolution & Time coverage, Continuous monitoring
- Spectral (velocity, energy) resolution

→ **“Observations & Modeling (Assimilation)”**

planetary atmosphere…

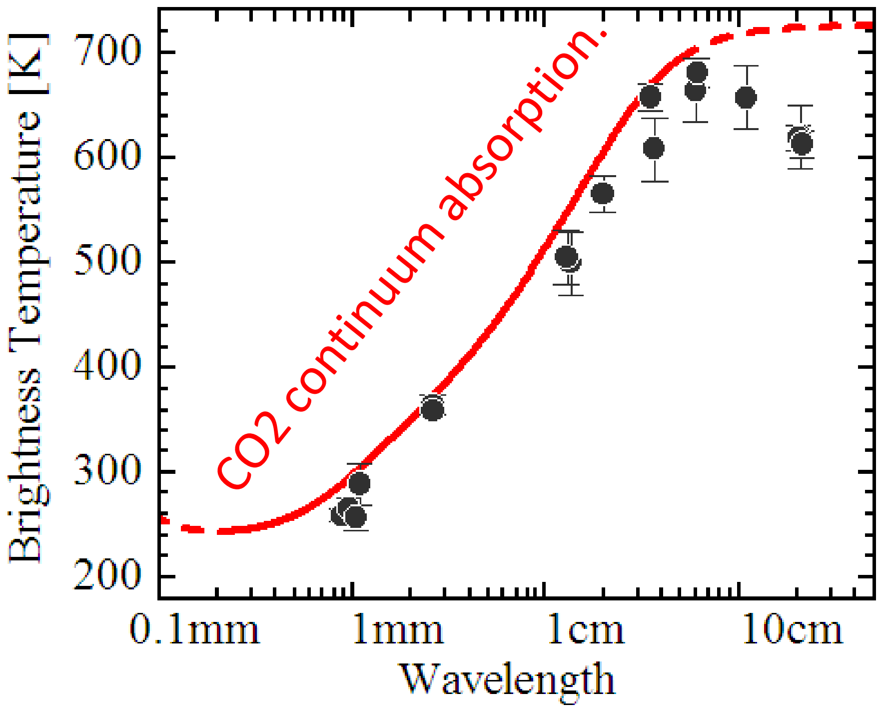
submm emission…from which altitude of the atmosphere?



- Most of the planets in the solar system have thicker atmosphere compared than Earth’s.
- Dominant atmospheric opacity source is “**continuum (collision-induced) absorption**”.

planetary atmosphere…

submm emission…from which altitude of the atmosphere?



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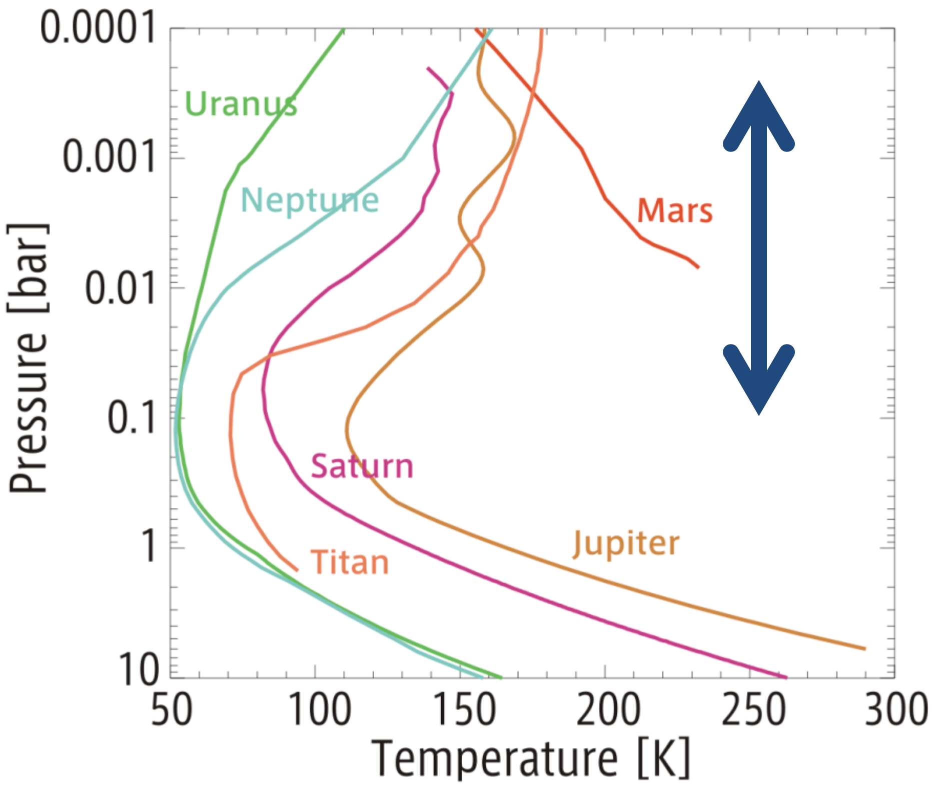
For example: Venus continuum emission in cm-submm.

Venus CO_2 dense atmosphere = ~800 K at surface. However, at submm domain, the measured BT is 300 K which corresponds to the atmospheric temperature of 50 km altitude.

planetary atmosphere...

submm emission...from which altitude of the atmosphere?



- Most of the planets in the solar system have thicker atmosphere compared than Earth's.
- Dominant atmospheric opacity source is "**continuum (collision-induced) absorption**".

→ Submm observations usually sound the middle atmosphere (stratosphere/mesosphere)

Herschel Solar System Observations

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- Largest space telescope (**3.5 m**).
- Only space observatory which covers the far-IR & submm wavelength region.
- 3 instruments: **SPIRE** (Fourier Transf. Spectr.) / **HIFI** (Heterodyne) / **PACS** (Grating Imag. Spectr. Camera)
- Launched on 14 May 2009, and now in the last phase of mission life.

- **Being free from the opaque Earth atmosphere, very high SNR H2O observations are achieved.**

→ **Promising for Solar System science (HSSO GT KP [Hartogh etal. 2009]).**

Herschel Solar System Observations

Guarantee Time Key Programme

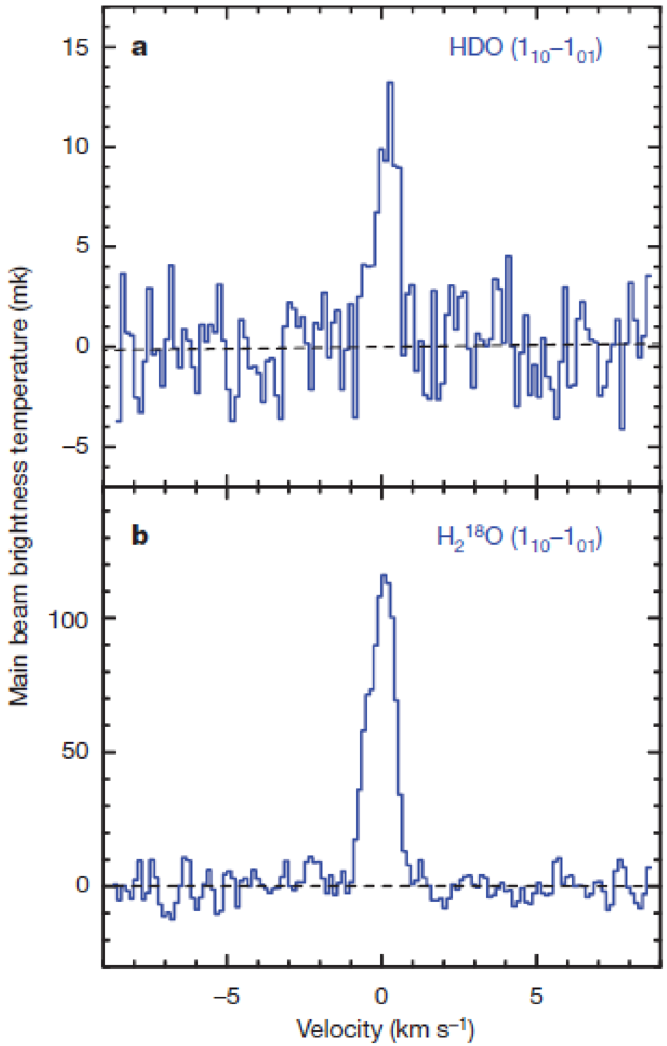
"Water and related chemistry in the Solar system"

PI: P. Hartogh, Max Planck Institute for Solar system research.

+ 50 members from 25 institutes in 10 countries.

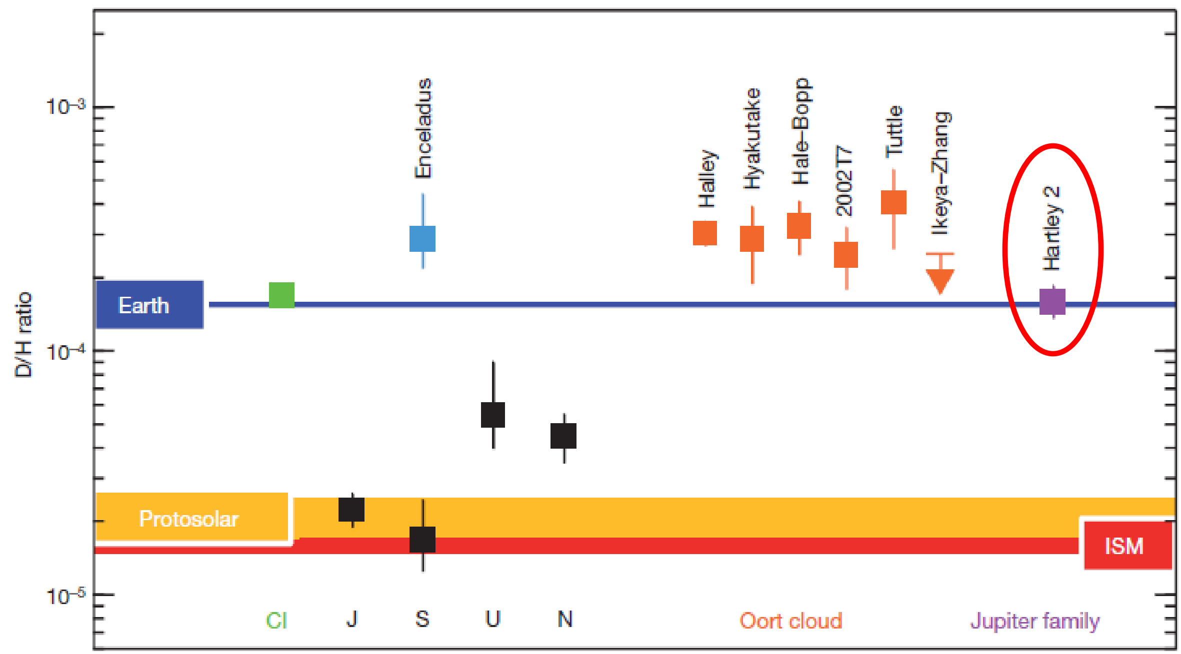
Water is ubiquitous in the Solar System*, being present in gaseous form in all planetary and cometary atmospheres, as ice on the surface and subsurface of Mars, comets, most planetary satellites and distant bodies, and in the liquid phase on Earth. Water plays an important or dominant role in the chemistry of planetary and cometary atmospheres. Comets are sources of water for planets through episodic collisions and continuous production of ice-dust grains.* ***This proposal addresses the broad topic of water and its isotopologues in planetary and cometary atmospheres****.*

HDO/H2O in Comet Hartley 2



1 | **Submillimetre water emission lines from comet 103P/Hartley 2.**

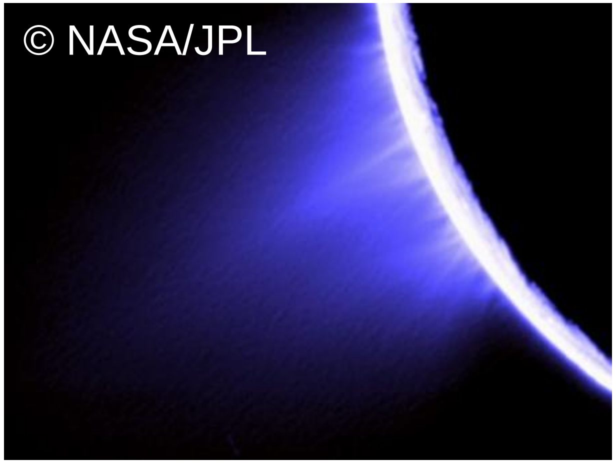
[Hartogh et al. 2012]



Very close D/H value with terrestrial one.

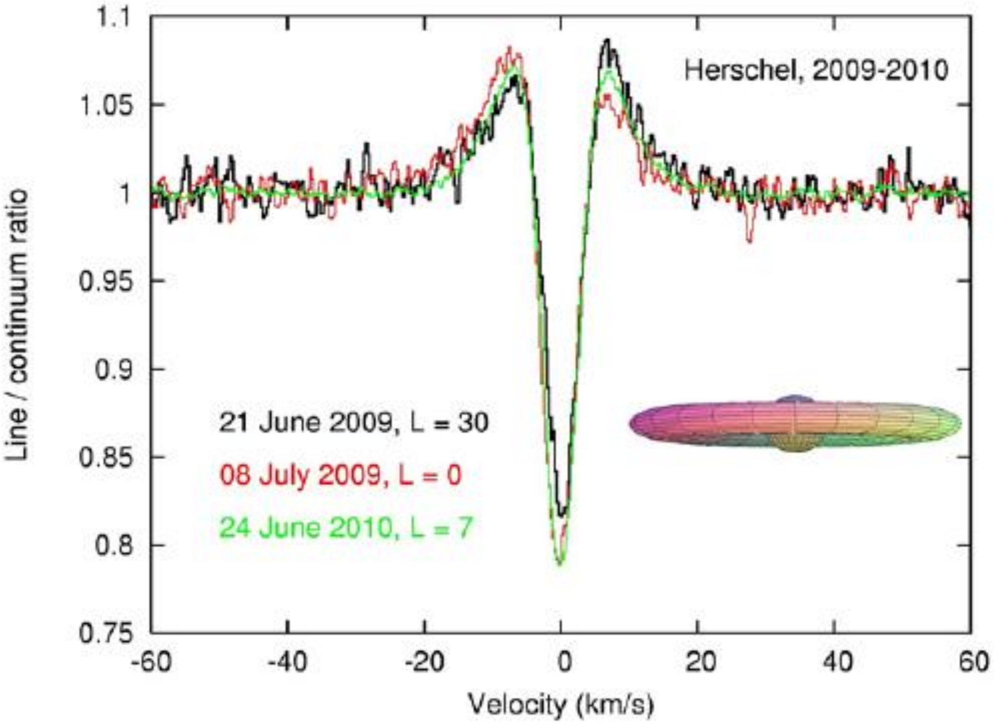
→ Suggesting that some comets can be the reservoir of Earth ocean-like water.

Enceladus H2O torus



Cryovolcanism on Enceladus imaged by Cassini.

[Hartogh et al. 2012]



Cold H2O distributed along the Enceladus orbit absorbs the background hot emission from Saturn.

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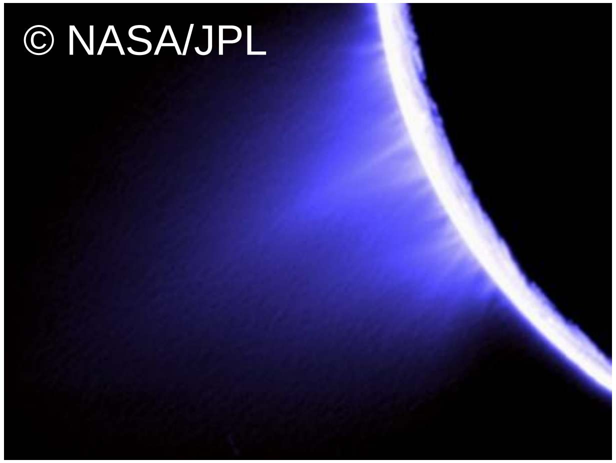

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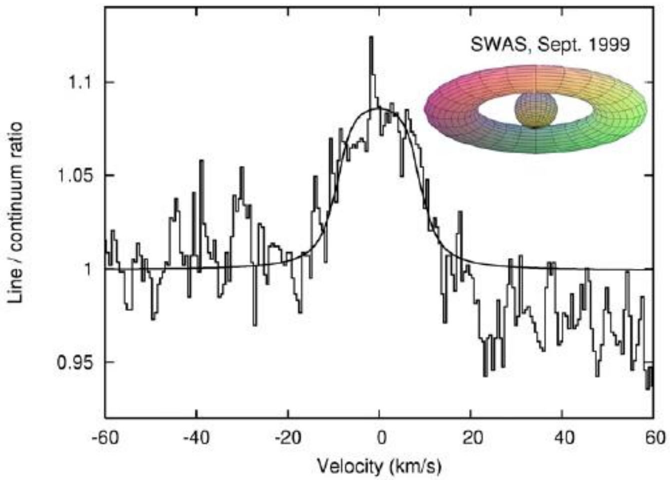

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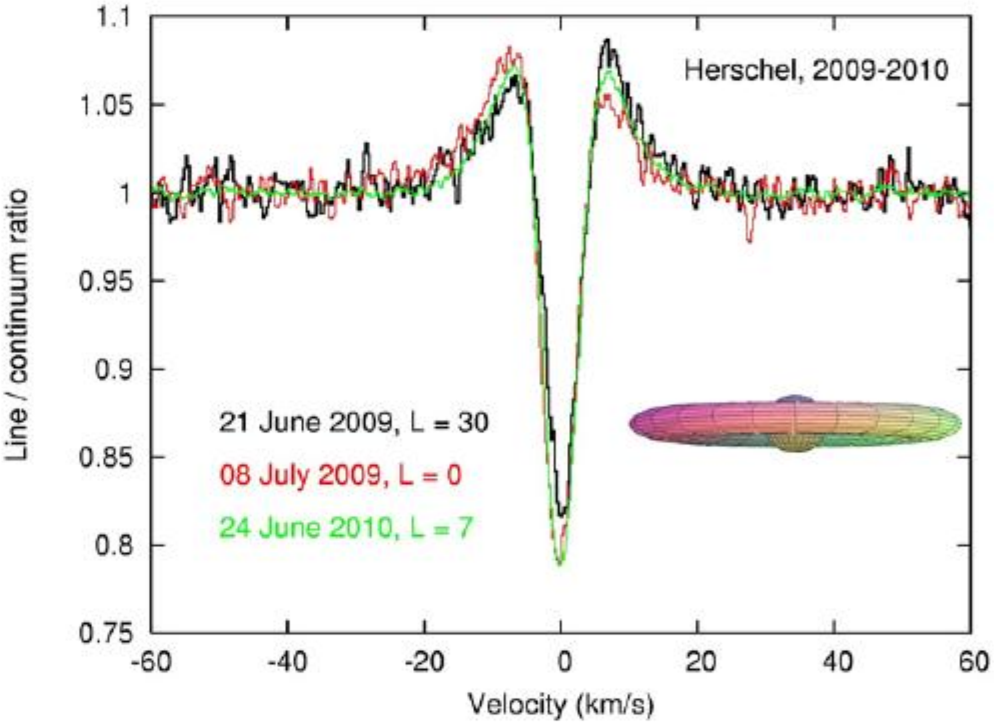

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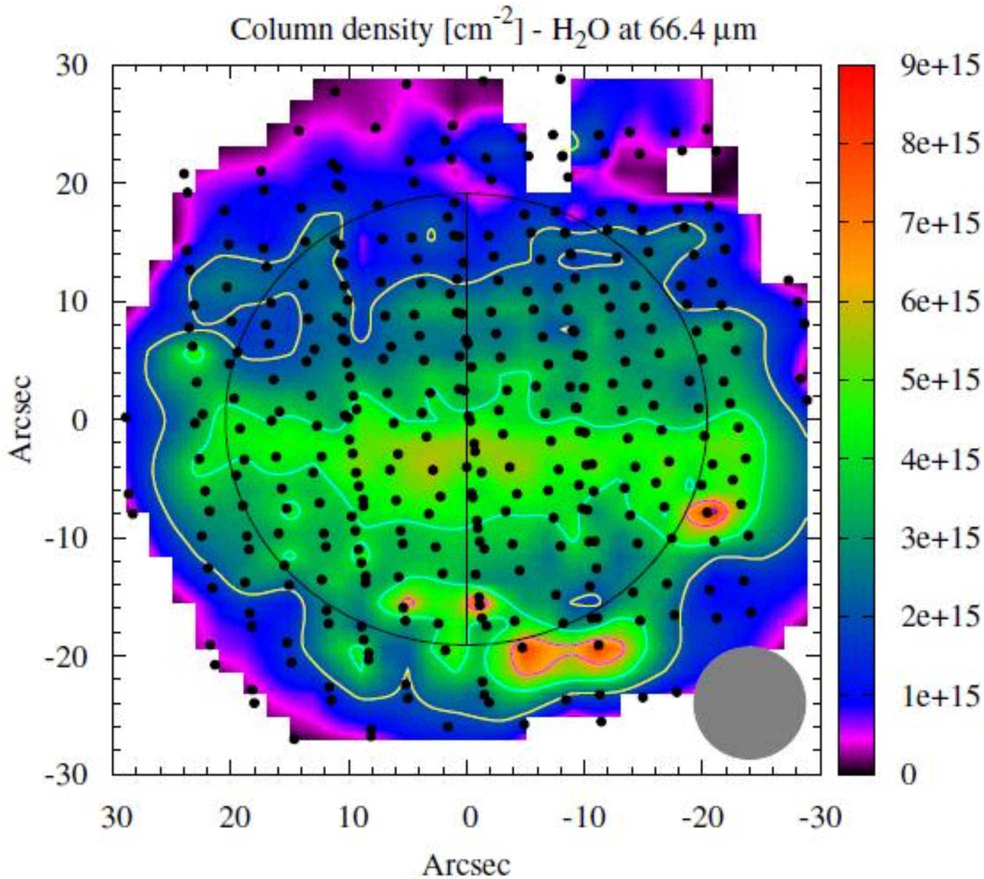
Source of H2O in Jupiter



[Cavalie et al., submitted to A&A]

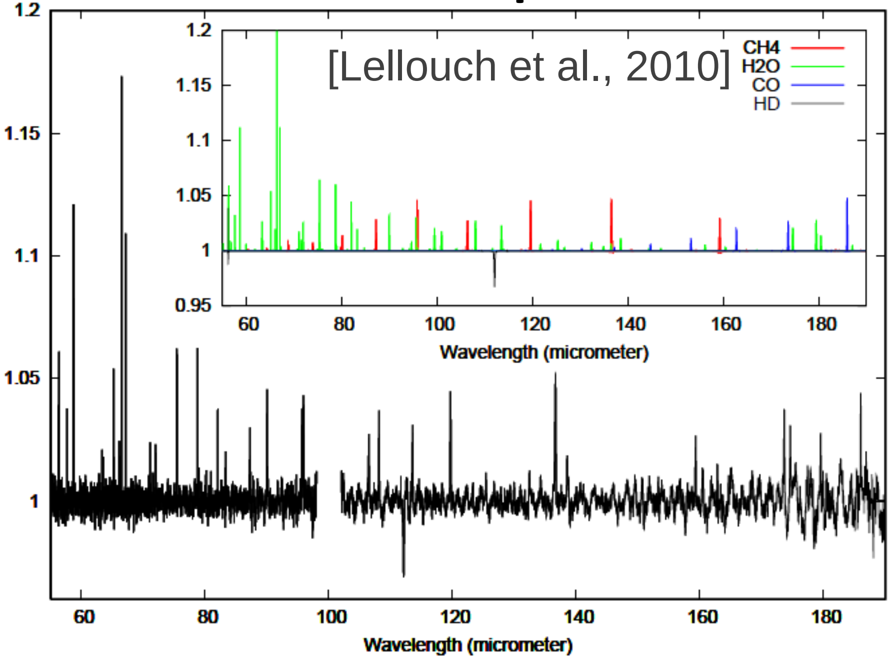
H2O map from PACS data shows a strong north-south asymmetry.

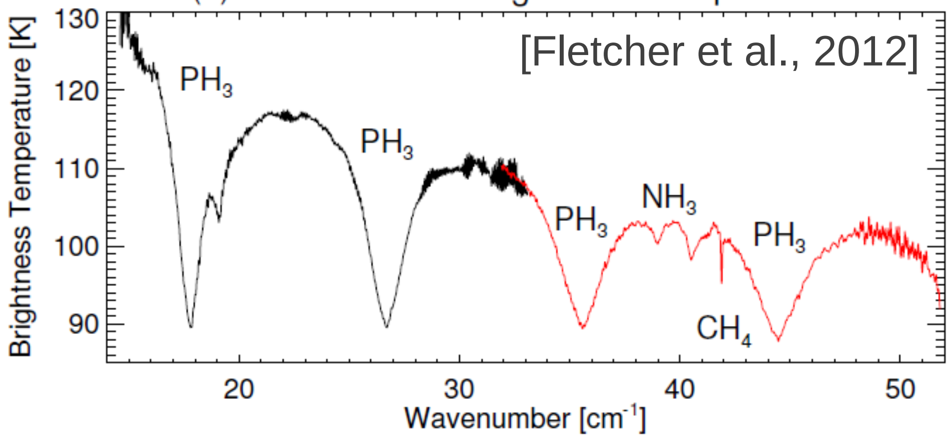
Suggesting that the most dominant source of Jovian stratospheric H2O is the injection by SL-9 impact.

→ further understandings will be brought with ALMA.

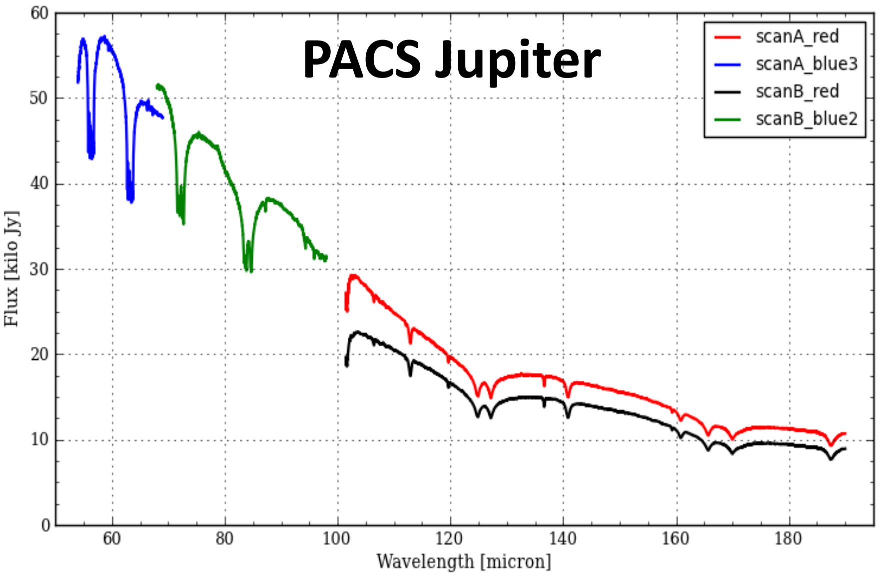
Spectral atlas

PACS Neptune

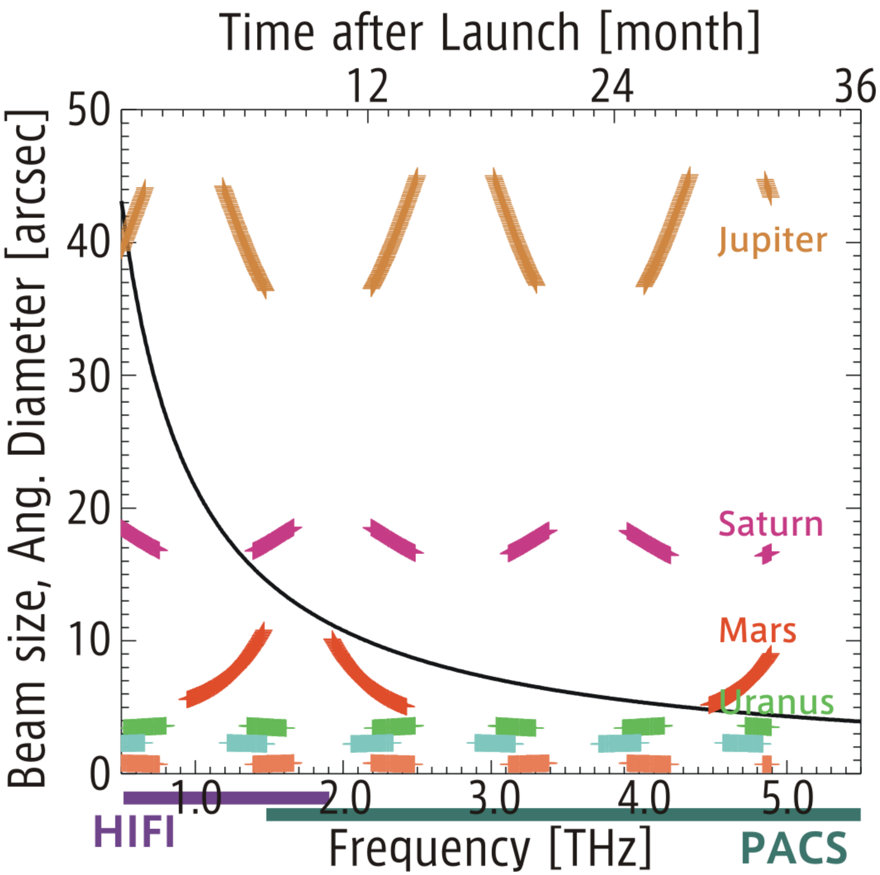




PACS Jupiter



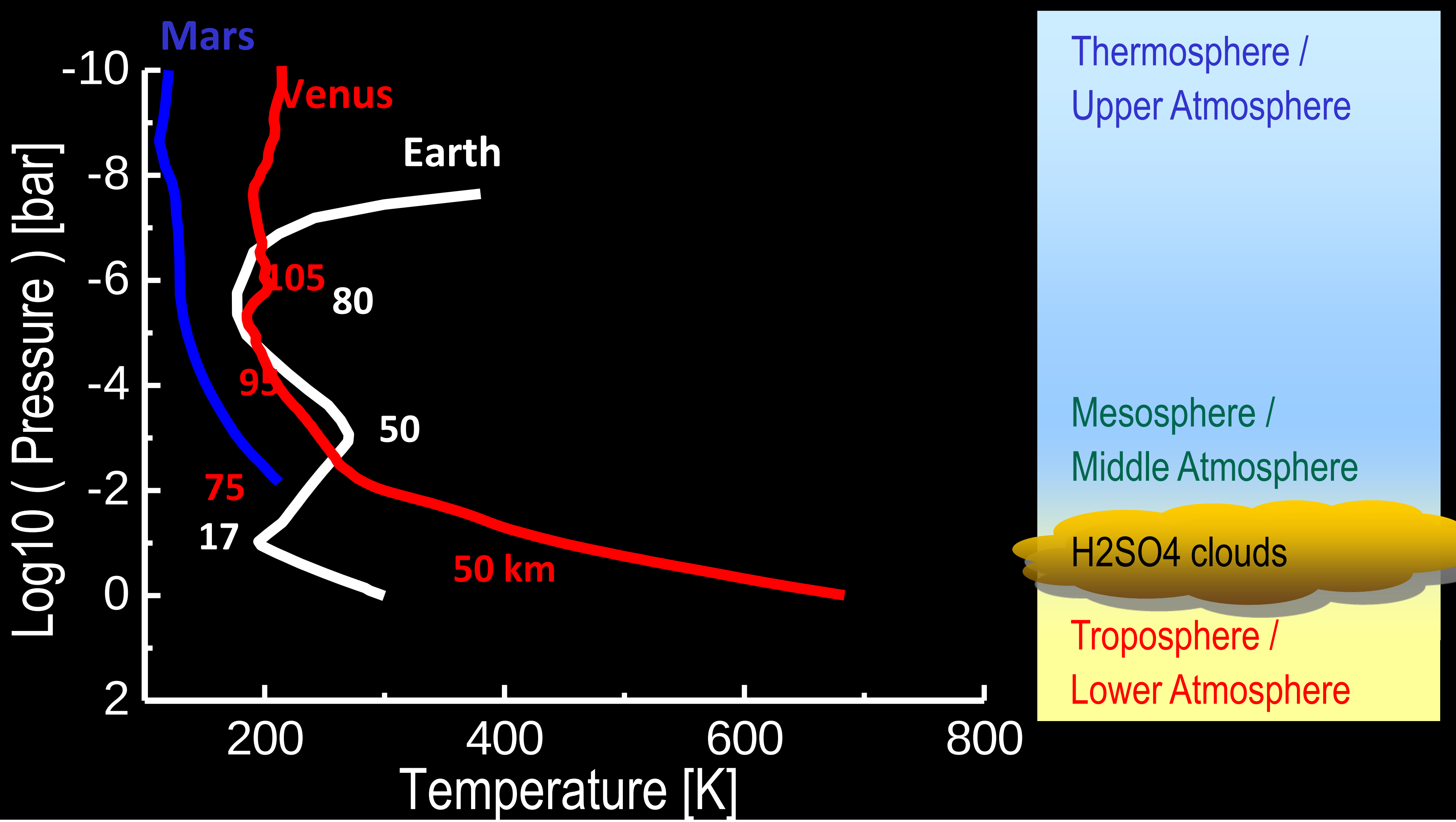
ALMA – another break through



Visibility window of Herschel and its beam size (spatial resolution).

- Herschel/HIFI, which frequency resolution is very powerful for planetary observations, has almost no chance to spatially resolve the planet disks.
- No inner Solar system objects!
- **ALMA** = High spatial resolution + High frequency resolution.
- Objects close to Sun can be also accepted.

Venus: Introduction



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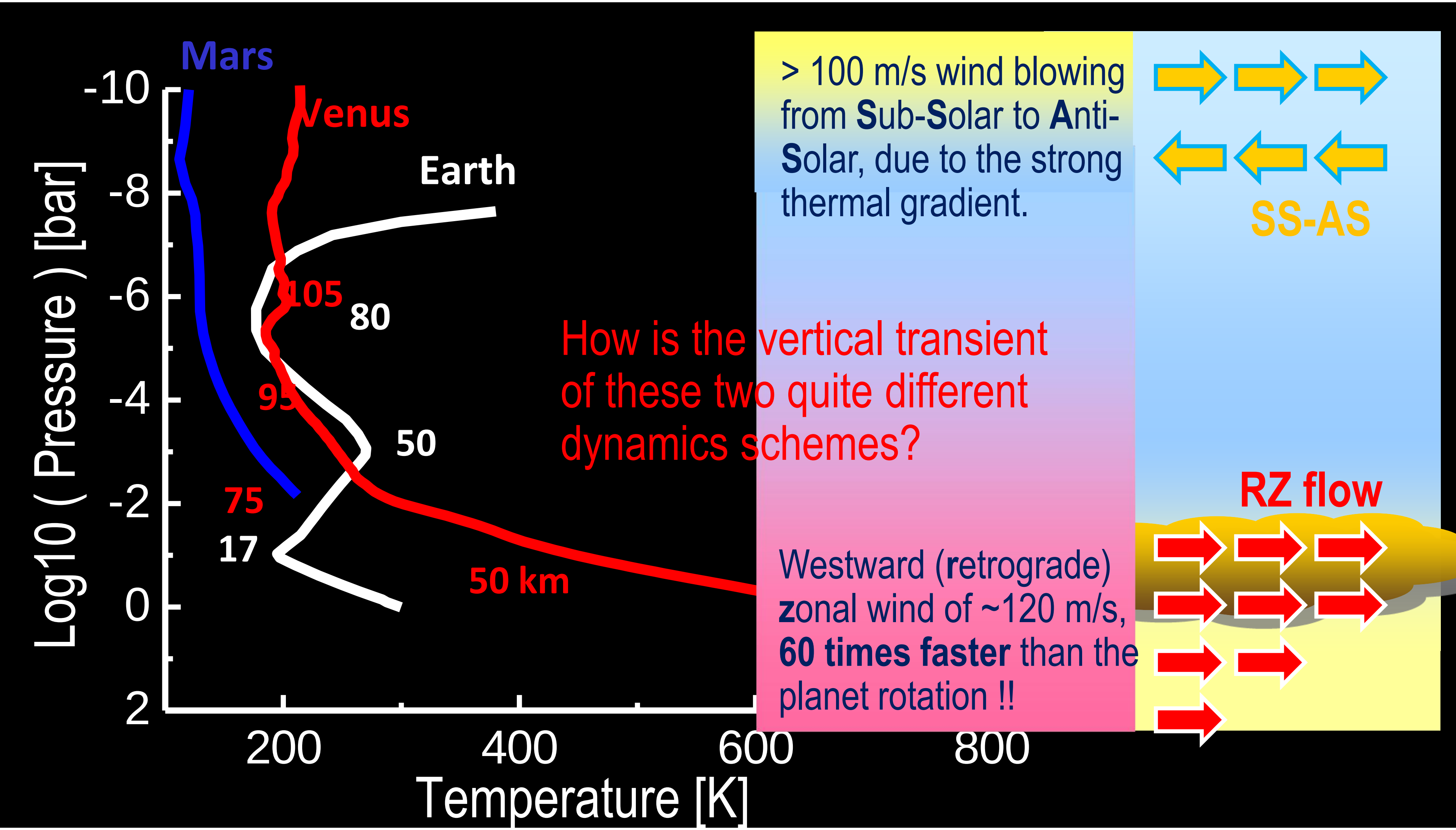
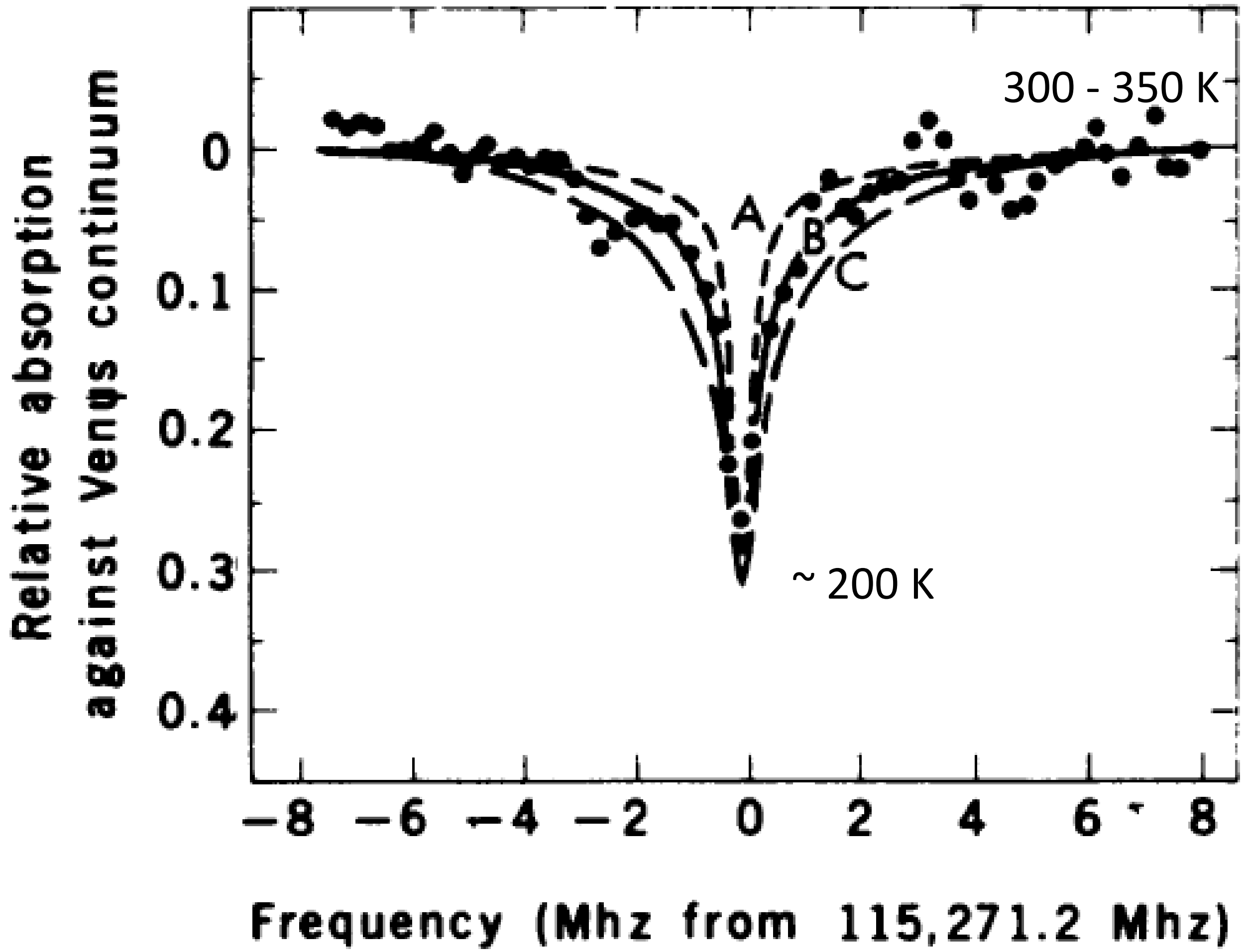


Venus: CO observations

First detection of CO (1-0) in Venus. [Kakar et al., **1976**]



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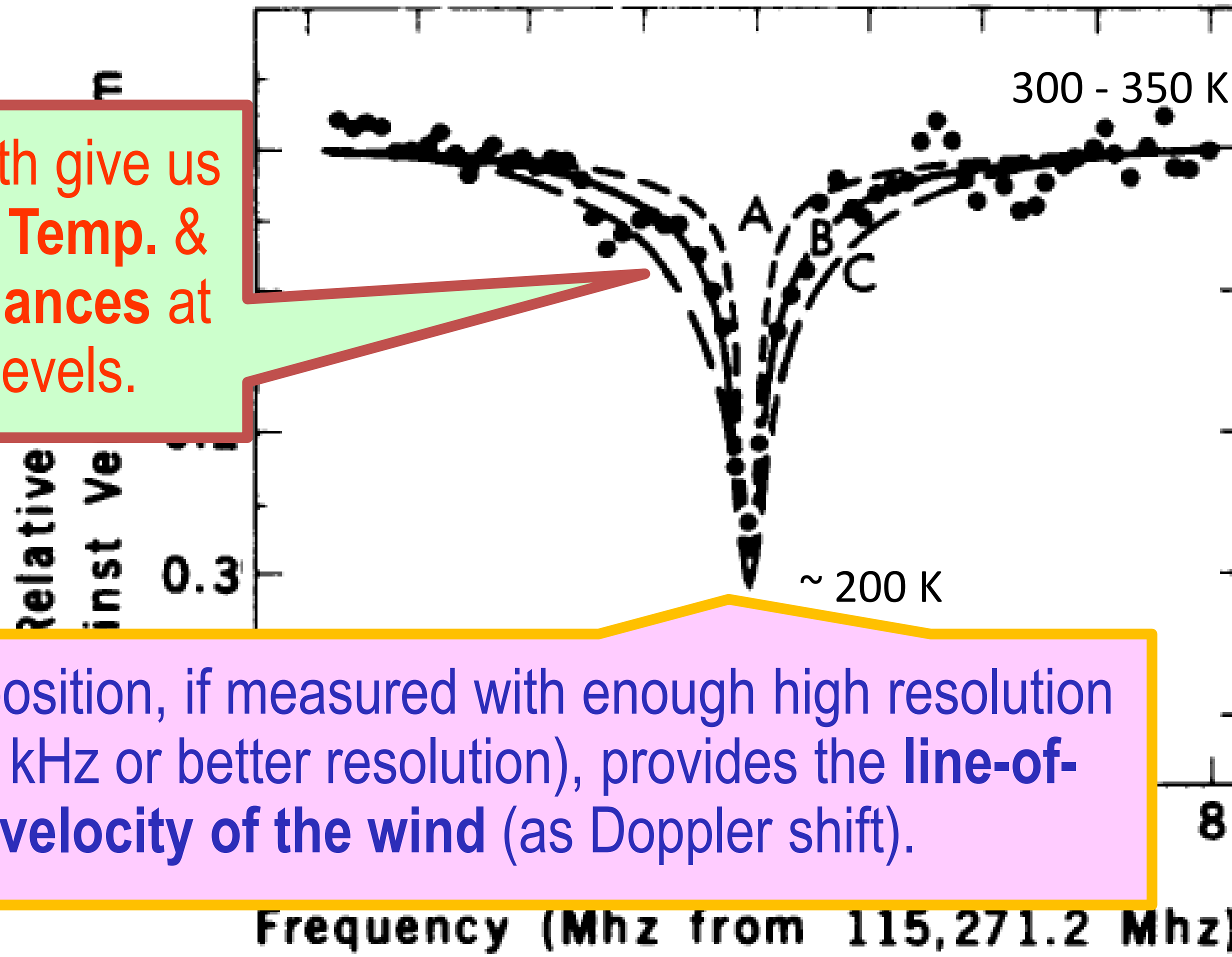
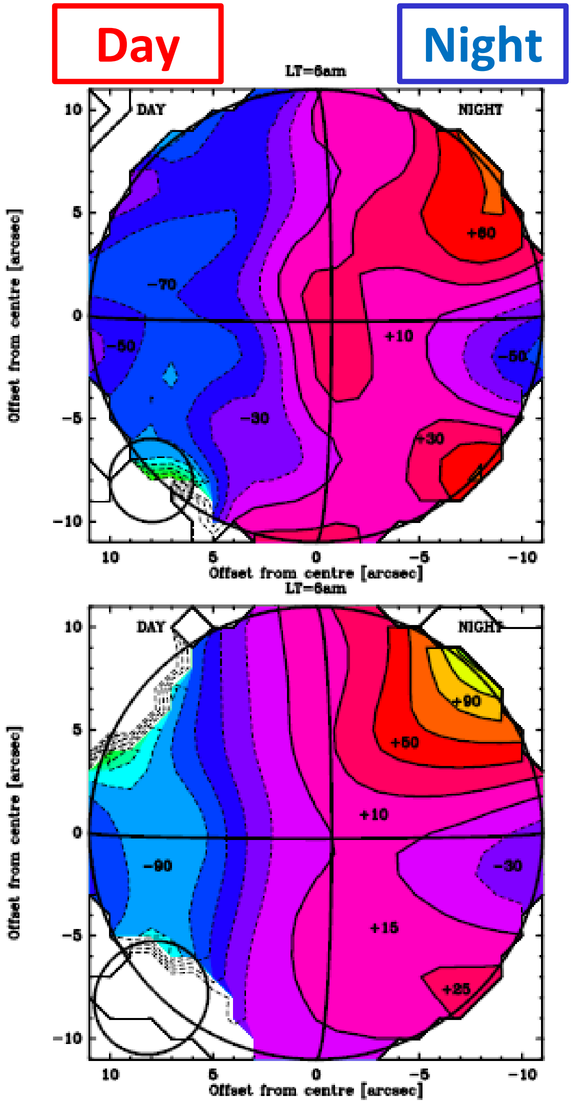


Line shape & depth give us the information of **Temp.** & **Molecular abundances** at various pressure levels.

Line position, if measured with enough high resolution (~100 kHz or better resolution), provides the **line-of-sight velocity of the wind** (as Doppler shift).

Venus: Wind measurements



赤 ＝ Red shift/観測者から遠ざかる方向.

青 ＝ Blue shift/観測者に近づく方向.

Doppler wind velocity map derived from SMA CO (1-0) measurements [Moullet et al., 2012].

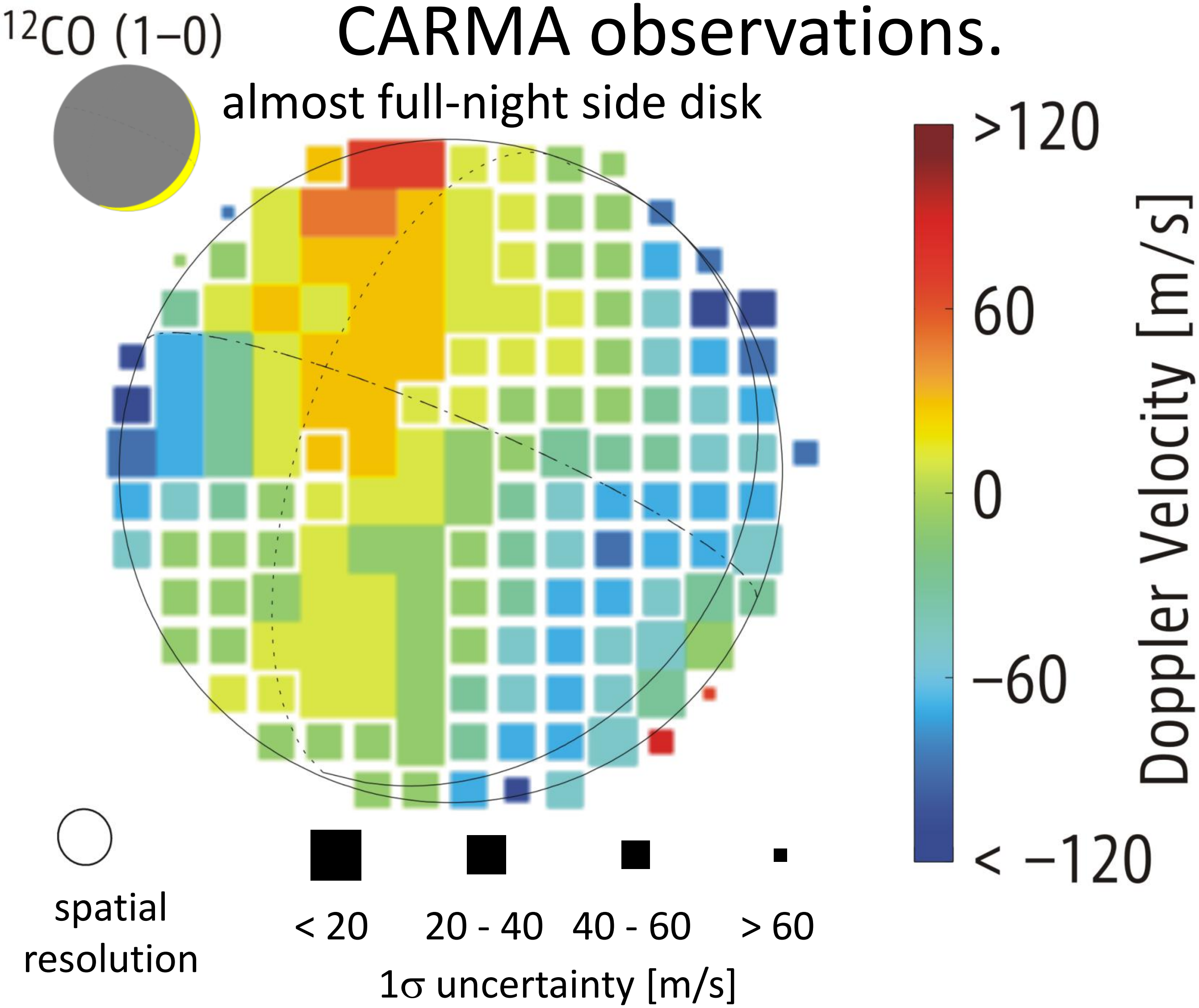
Winds at altitudes around 95 km are observed.

Wind goes from dayside hemisphere to nightside (= SS-AS), with a strong latitudinal variation.

At the nightside Equator, the direction becomes opposite (= Impact of RZ flow).

Venus: Wind measurements

CARMA observations.



Large spatial inhomogeneity !!

ALMA → Using higher J lines of CO will sounds higher altitudes; which helps us to understand physical meaning of this inhomogeneity.

Venus: atmospheric chemistry

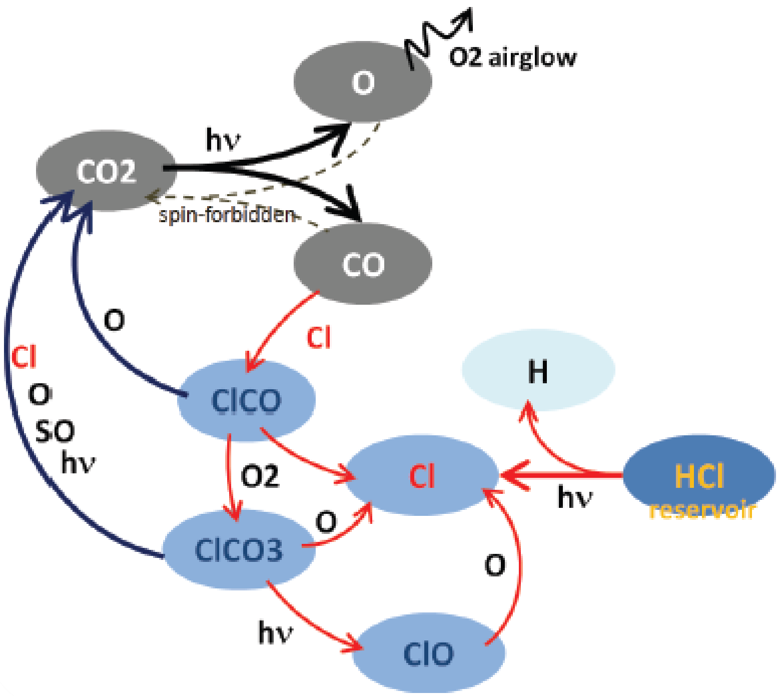
- ALMA opens new observation frequency bands (e.g., Band-9).
  → New species can be measured.

- ALMA's high spatial resolution. → Signals from limb can be measured without being diluted (i.e. limb sounding!). This improves sensitivity to minor species.

- ALMA's high sensitivity. → Snap-shot like synthesis imaging, which is important to separate spatial and temporal variations.

Venus: atmospheric chemistry

What control the stability of Venus CO_2 atmosphere?



Venus CO_2 atmosphere easily photo-dissociates into CO and O.

Direct recombination of CO + O → CO_2 is spin-forbidden, therefore there should be certain mechanisms to recover CO_2 atmosphere (otherwise, all CO_2 can be changed into CO and O_2).

→ **ClOx & SOx catalytic reaction** may be the key to answer this problem.

Venus: atmospheric chemistry

Cl-chemistry is important not only in Earth but also in Venus.

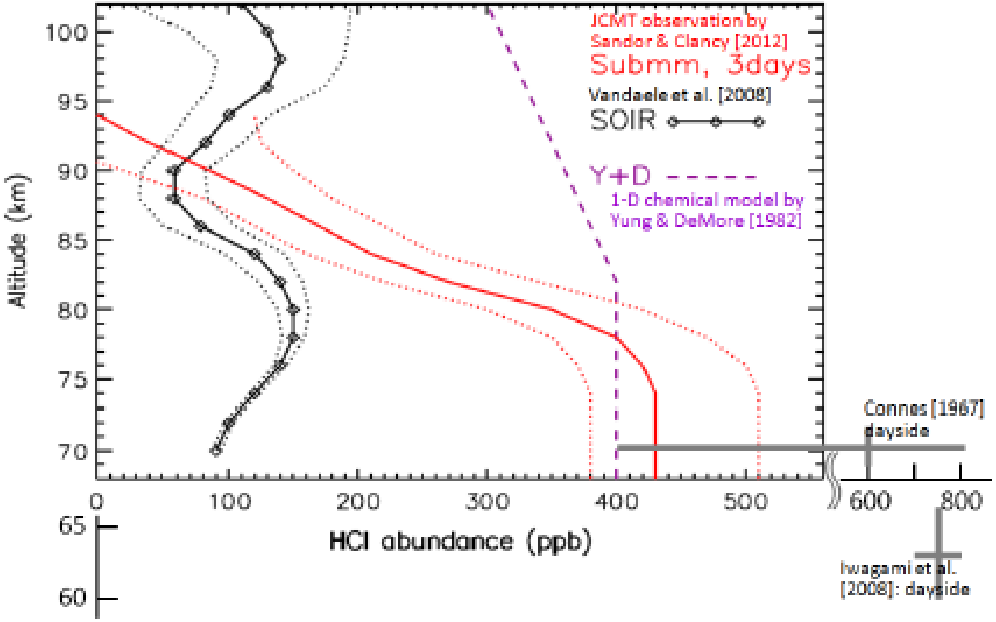


Fig. 2 HCl vertical profile in Venus, observed by JCMT (red), Venus Express SOIR (black), and numerical experiment of chemical transport model by Yung and DeMore [1982] (purple). Also results from the near infrared wavelength ground based observations are shown. Figure is after Sandor & Clancy (2012) with a small modification.

Venus HCl was detected by JCMT observations [Sandor & Clancy, 2012].

Large discrepancy from model results!

→ Much rapid photochemical destruction of HCl than the model assumptions ?? and/or strong downward transport of HCl which removes it from the mesosphere ??

Venus: atmospheric chemistry

Cl-chemistry is important not only in Earth but also in Venus.

ALMA band-9 receiver can observe HCl and ClO, which is the main reservoir and the main active chlorine, simultaneously.

With ALMA's high sensitivity & high spatial resolution, HCl vertical profile can be constrained more precisely compared to previous JCMT results.

→ Enables to improve the reaction rate parameters.

And we learned from SMILES that these species on Earth have **diurnal variations**.

→ **How about on Venus??**

Venus on 10 Oct 2013

Venus : RA 16h02m58.3s Dec −23d29m42.1s,
Doppler shift about −12.8 km/s
Diameter: 20.0″, dayside = 59% of the disk,
FOV of 12-m antenna @ 612 GHz = 10.1″

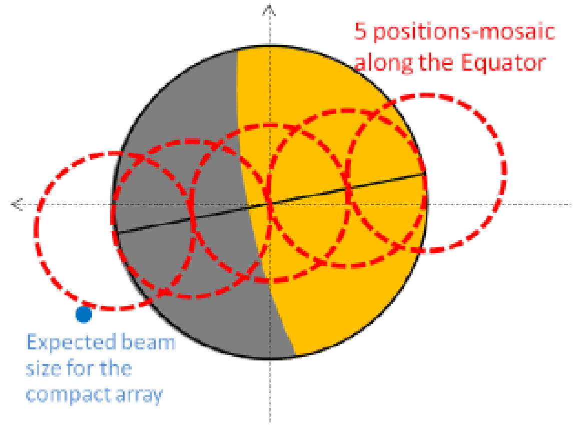


Fig. 5 Schematic figure of the proposed observation geometry, for 10th October 2013 as an example.

...last words

ALMA can strongly accelerate the characterization of planetary atmospheres.

Radiation ⇄ **Dynamics** ⇄ **Chemistry**

Radiation
thermal structure,
energy budget,
cloud microphysics

Dynamics
material momentum transport,
atmospheric escape

Chemistry
composition,
atmospheric evolution,
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heterogeneous

What ALMA can not do is:

- Constant monitoring to cover a long-scale time variation.
- Sounding deep atmospheres (due to submm continuum opacity).