# ➔ Jupiter's deepest and freshest clouds

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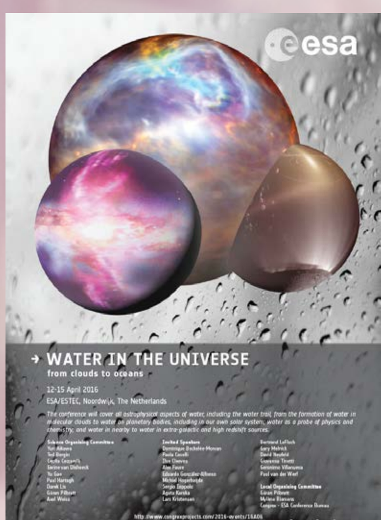
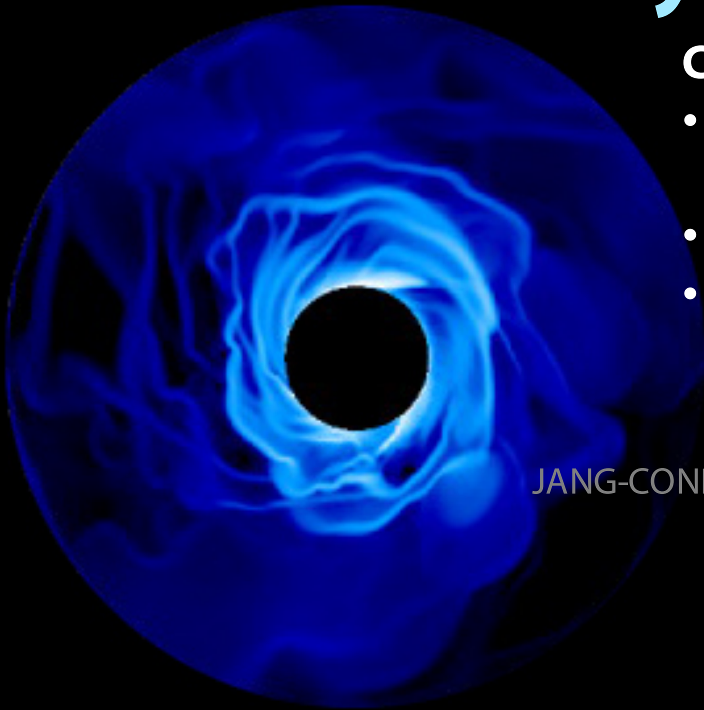



WATER IN THE UNIVERSE, NOORDWIJK
APRIL 15 2016

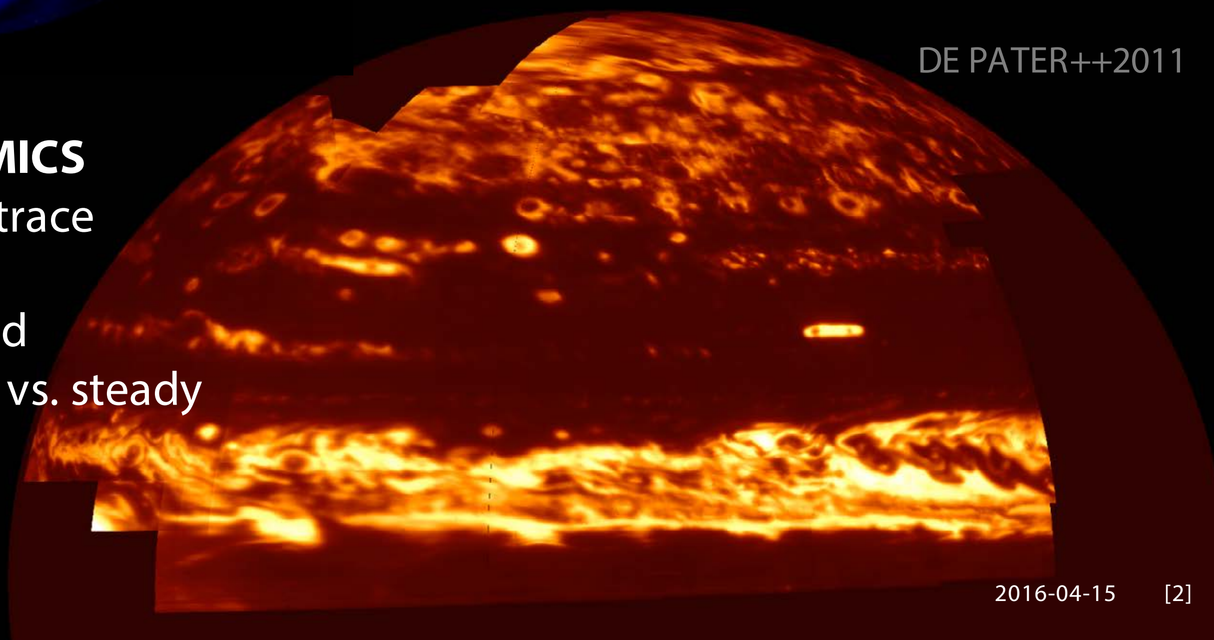
# Motivation: studying water in Jupiter



JANG-CONDELL+BOSS 2007

**COSMOCHEMISTRY**

- Planet formation: core accretion vs. gravitational instability
- Chemical enrichment of the disk
- Planetesimal composition: clathrates, amorphous ice, SCIPs



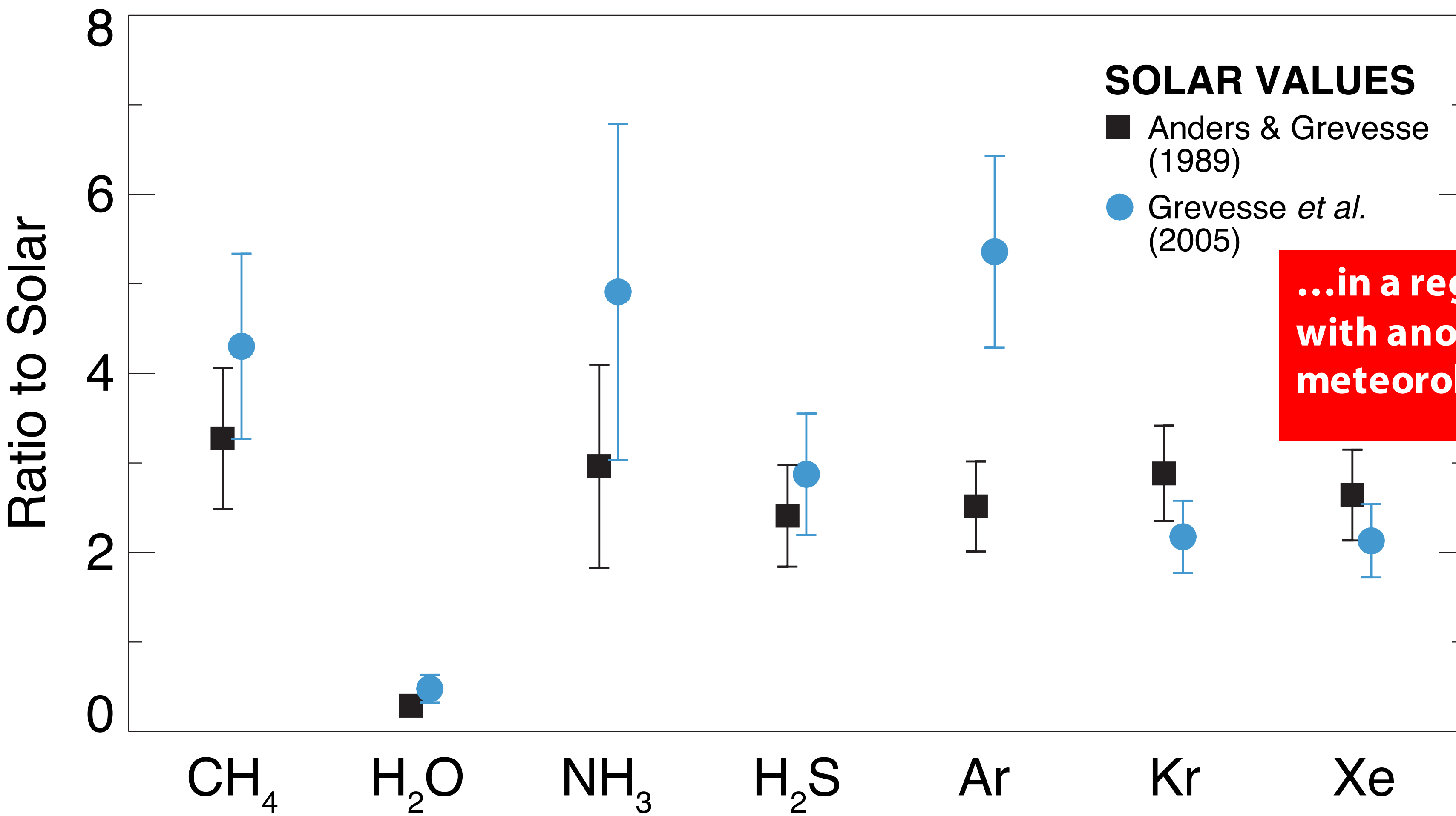
DE PATER++2011

**ATMOSPHERIC DYNAMICS**

- Volatiles and clouds trace dynamical flows
- Water abundance and convection: episodic vs. steady

# Jupiter's composition

Galileo Probe mass spec measured volatiles and noble gases…

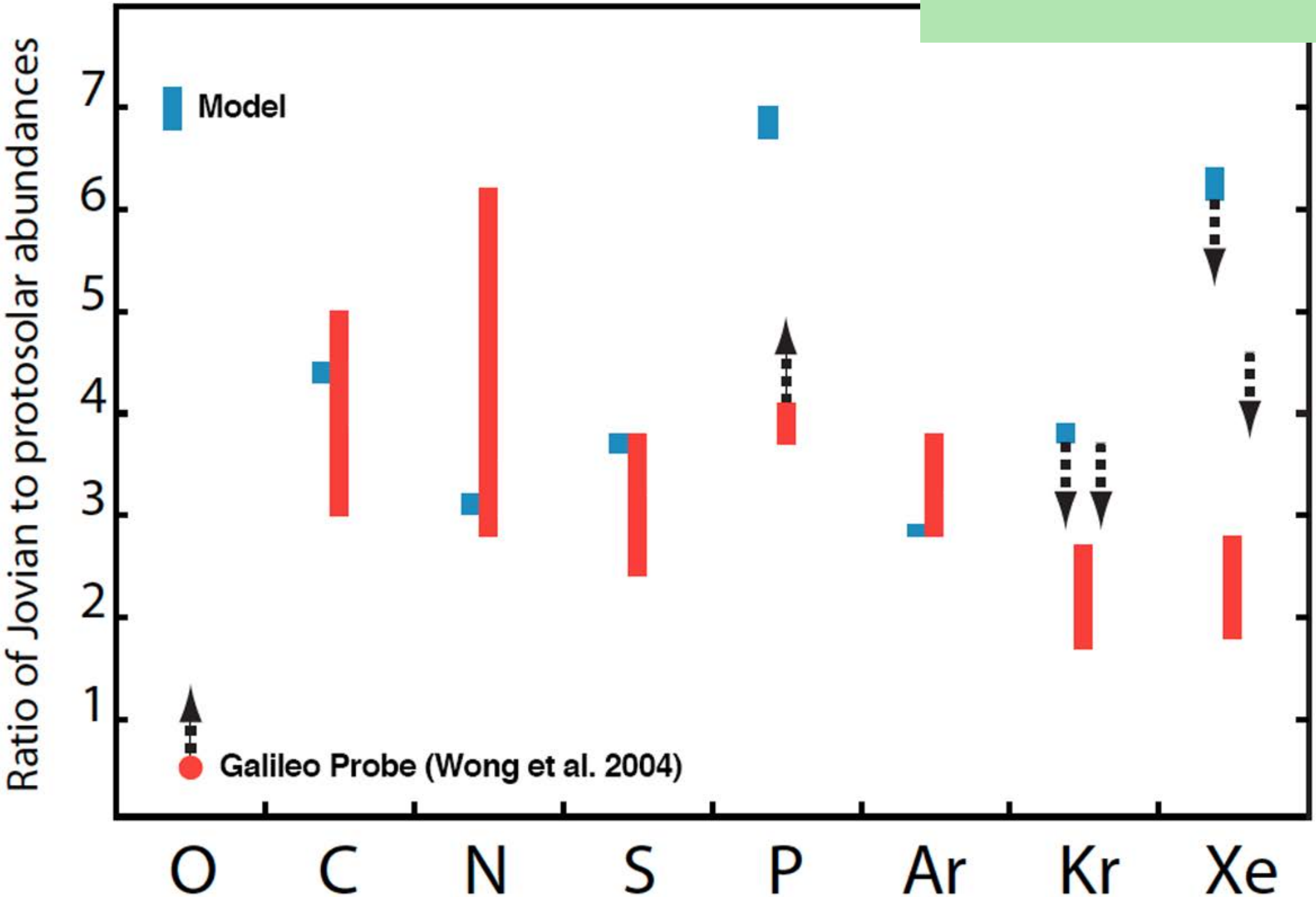



…in a region with anomalous meteorology

WONG++2008 (in *Oxygen in the Solar System*)

# Jupiter's composition

Jupiter's composition is a constraint for planet formation models




MOUSIS++2012

# Jupiter's O/H ratio

O/H uncertain, many indirect constraints

**Table 1.** Summary of measurements relating to the determination of Jupiter's water abundance.

| Measurement technique | Jovian O/H relative to solar | | Strongly affected by model assumptions?[2] | Strongly affected by $H_2O$ spatial distribution?[3] | References |
|---|---|---|---|---|---|
| | Anders & Grevesse (1989)[1] | Grevesse et al. (2005)[1] | | | |
| GPMS | 0.29 ± 0.09 | 0.48 ± 0.16 | | × | Niemann et al. (1998), Wong et al. (2004) |
| 5-µm spectroscopy (gas) | 0.02 | 0.03 | | × | e.g., Bjoraker et al. (1986a,b), Roos-Serote et al. (1999, 2000), also see text |
| 5-µm spectroscopy (clouds) | subsolar, or ≥ 1 | subsolar, or ≥ 1.7 | × | × | Roos-Serote et al. (2004), also see text |
| Clouds at $P \geq 4$ bar | > 0.2 | > 0.3 | | | Banfield et al. (1998), Gierasch et al. (2000), Li et al. (2004) |
| Internal CO source | 2.3, or 0.2-9 | 3.8, or 0.3-15 | × | | Fegley and Lodders (1994), Bézard et al. (2002) |
| Depth of lightning | > 0.7 | > 1.2 | × | | Little et al. (1999), Borucki and Williams (1986) |
| Depth of lightning | > 9 | > 15 | × | | Dyudina et al. (2002), Dyudina et al. (2004), see text |

[1]Solar O/H = $8.53\times10^{-4}$ in Anders and Grevesse (1989) and protosolar O/H = $5.13\times10^{-4}$ in Grevesse et al. (2005).
[2]See text for details about how these measurements are modeled to infer water abundances.
[3]Observations are biased towards regions with lower water vapor mixing ratios, so the deep well-mixed abundance of water is not measured.

WONG++2008 (in *Oxygen in the Solar System*)

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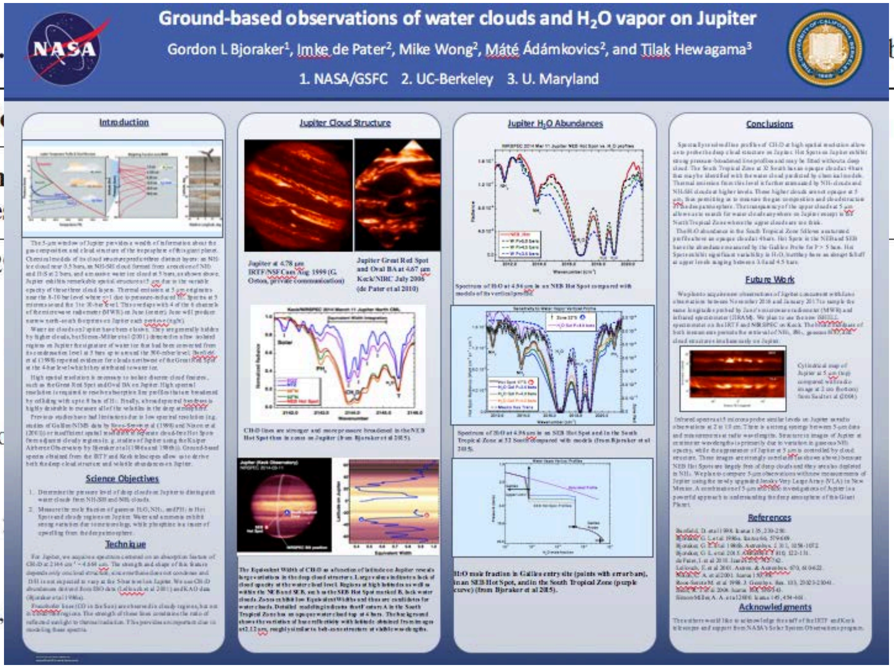


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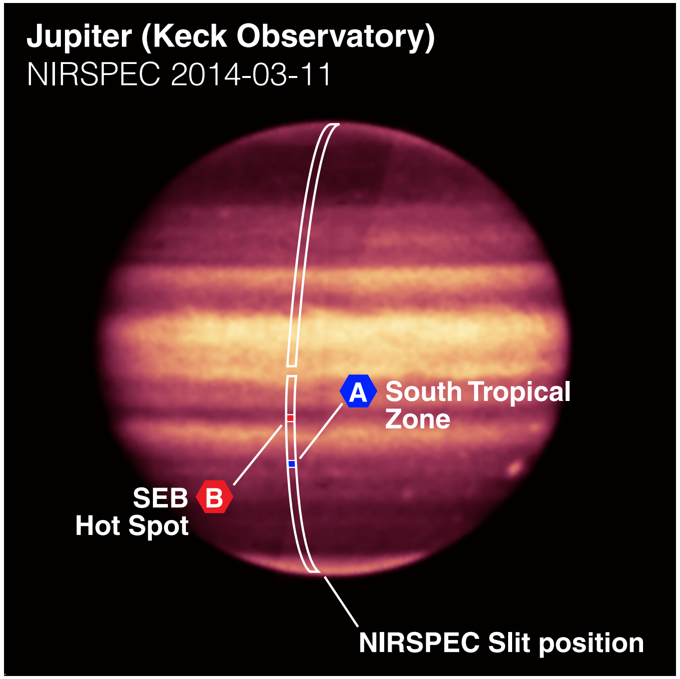
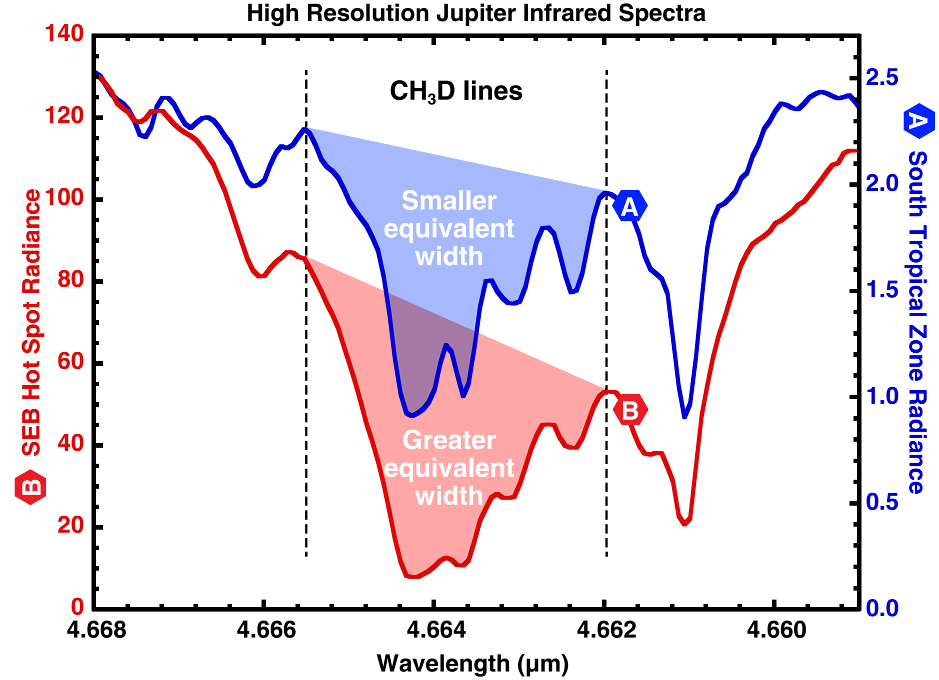
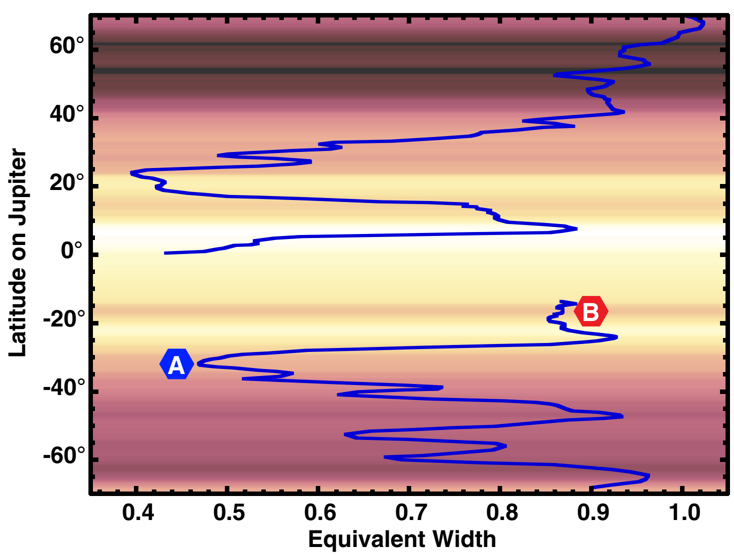
# 5-µm spectroscopic technique




(NASA GSFC NUGGET)

**Team:** Gordon L. Bjoraker (NASA GSFC), Imke de Pater, Michael H. Wong, and Máté Ádámkovics (UC Berkeley)

**Technique:** Use high resolution spectroscopy to measure molecular line shapes in Jupiter's thermal infrared spectrum.

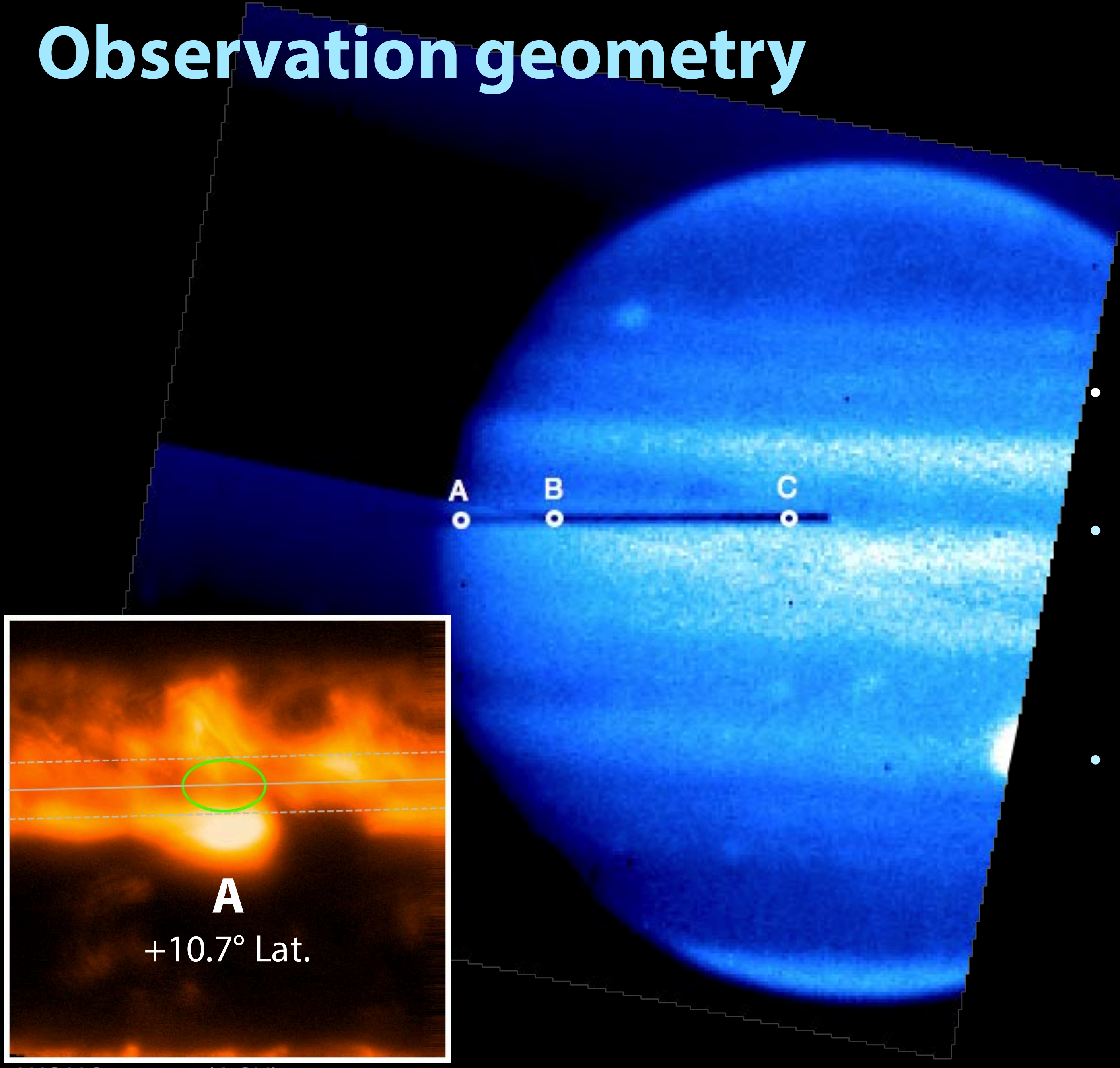
**Significance of the equivalent width:** The $CH_3D$ lines are more broadened at higher pressures. Where the width is small (like in the zone spectrum marked A), it is because a water cloud is present, blocking thermal emission from the deeper atmosphere. The hot spot spectrum (marked B) carries the fingerprint of deep emission—a large equivalent width—so no thick water clouds are found there.

**Finding:** Jupiter's water cloud deck is highly uneven. Our technique peers through upper clouds to find thick water clouds in the major zones.

**Reference:** Bjoraker et al. (2015), *Astrophysical Journal* 810, 122.
doi:10.1088/0004-637X/810/2/122

# Observation geometry

2013-01-21
Keck NIRSPEC
+ NIRC2

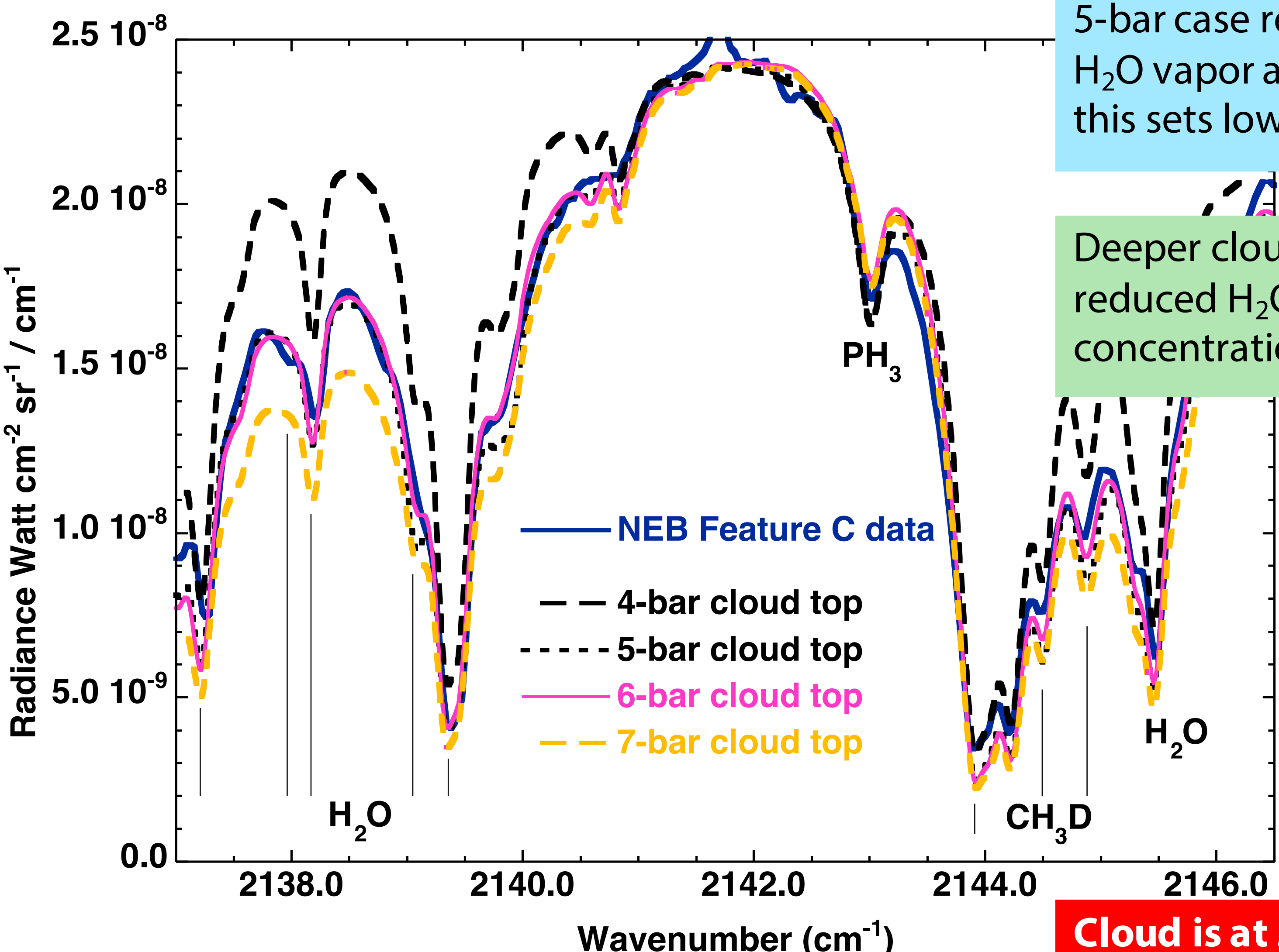



- **"Feature C"** on slit has a deep water cloud
- "Feature A" obviously samples inhomogeneous area

- 2016B: proposing simultaneous Gemini 5-μm imaging + Keck/IRTF hi-res spectroscopy (+Juno)

WONG++2015 (AGU)

# Determining cloud top pressures



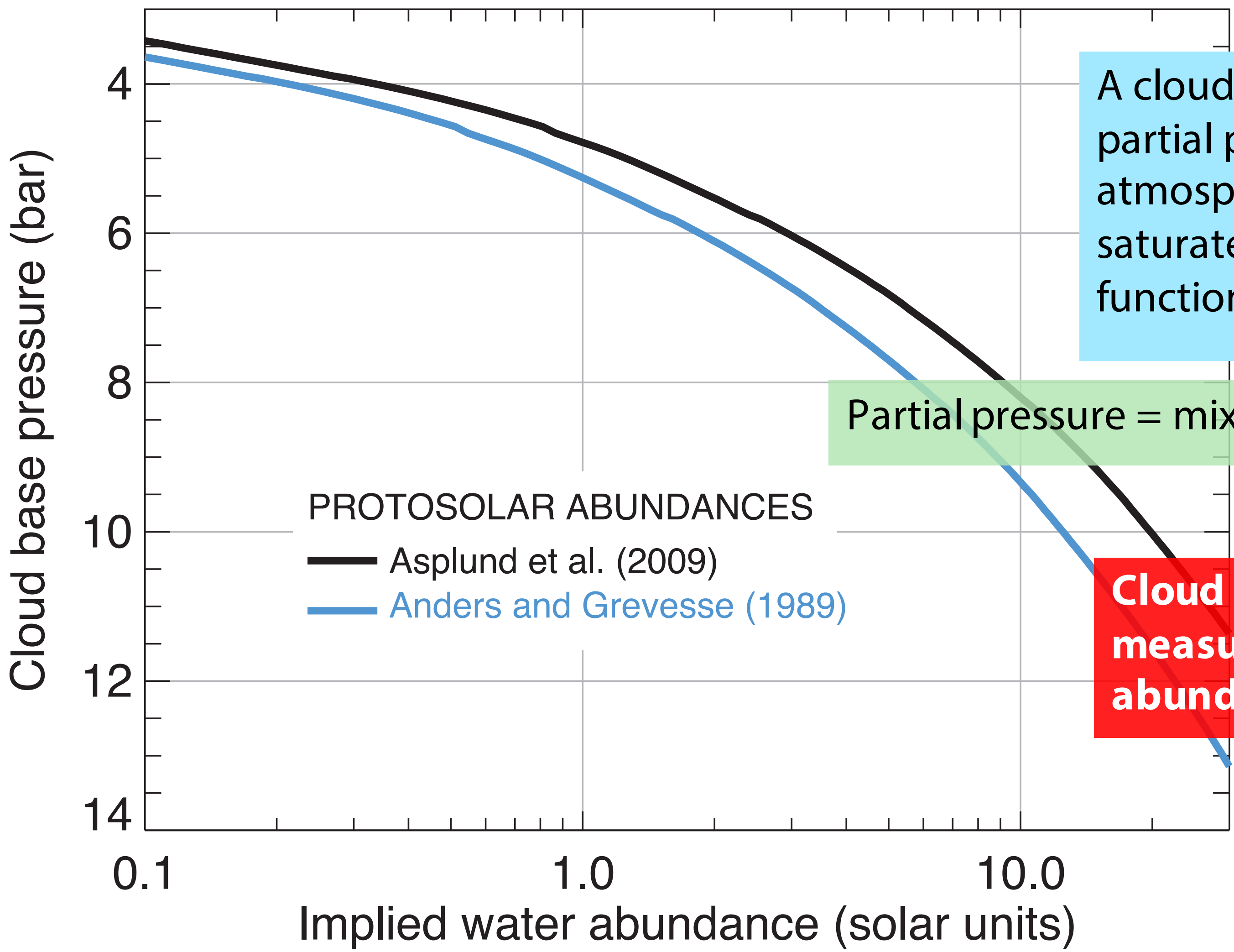

5-bar case requires saturated $H_2O$ vapor above cloud top… this sets lower limit of $P_{cd.top}$

Deeper clouds also fit, but with reduced $H_2O$ vapor concentration above cloud top

**Cloud is at 5 bar or deeper**

WONG++2015 (AGU)

# Cloud height and O/H




A cloud forms where the partial pressure of water in the atmosphere equals the saturated vapor pressure (a function of temperature)

Partial pressure = mixing ratio * $P_{atmos.}$

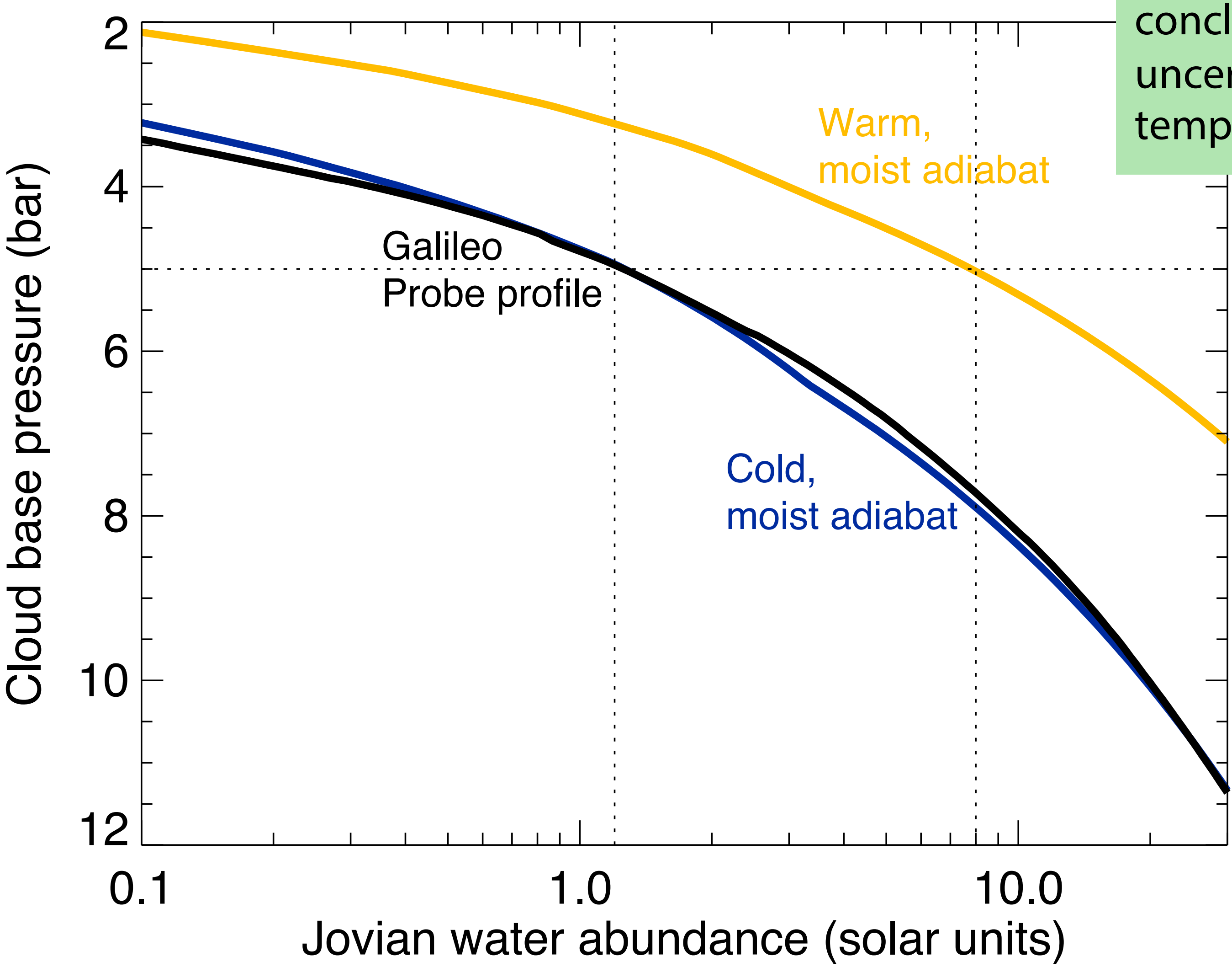
**Cloud base pressure measurement yields water abundance measurement**

WONG++2008

# Cloud height and O/H

O/H ≥ 1.2 x solar

conclusion is robust to uncertainties in the temperature profile




WONG++2015 (AGU)

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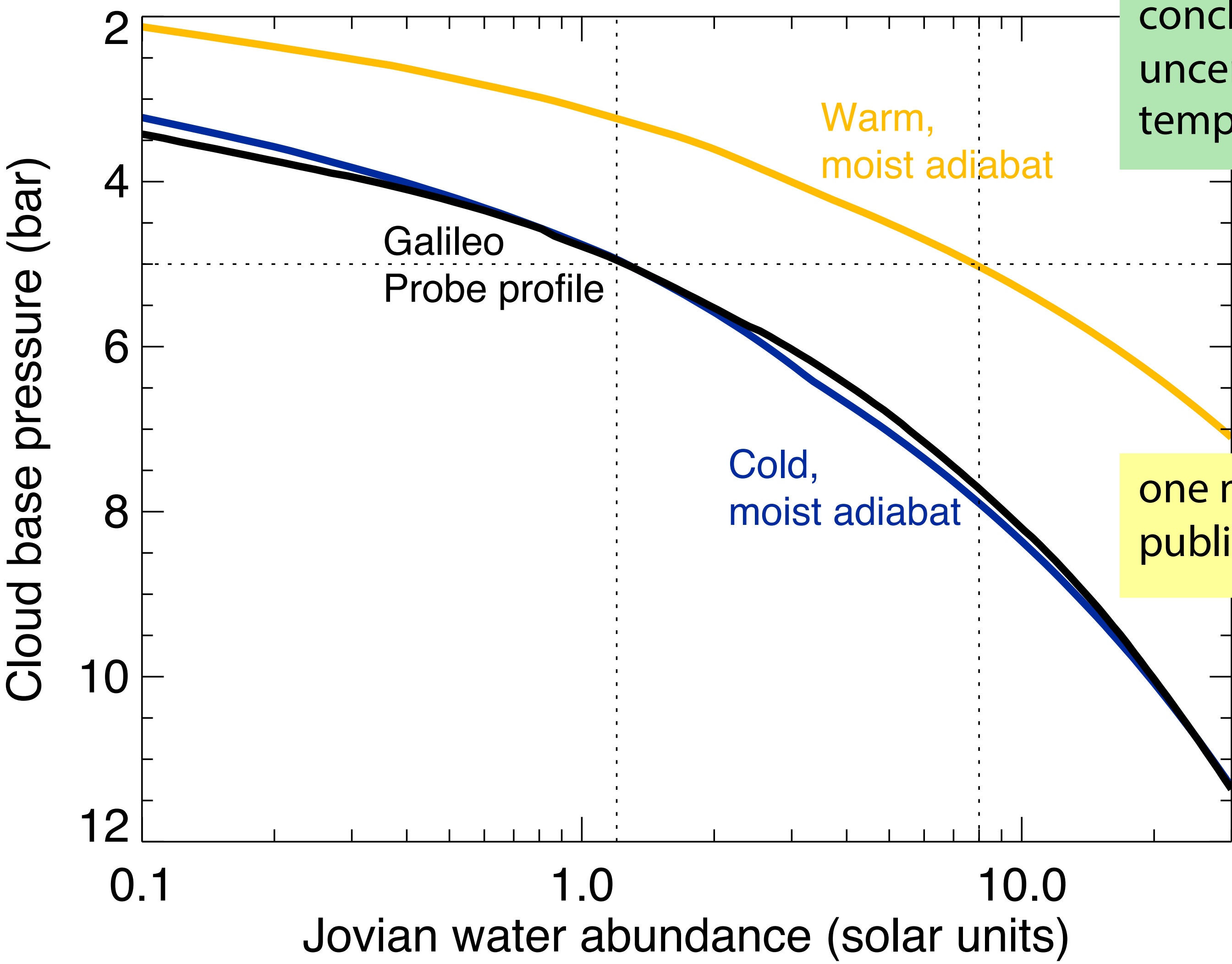
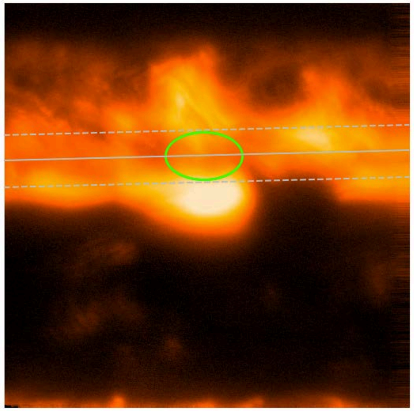


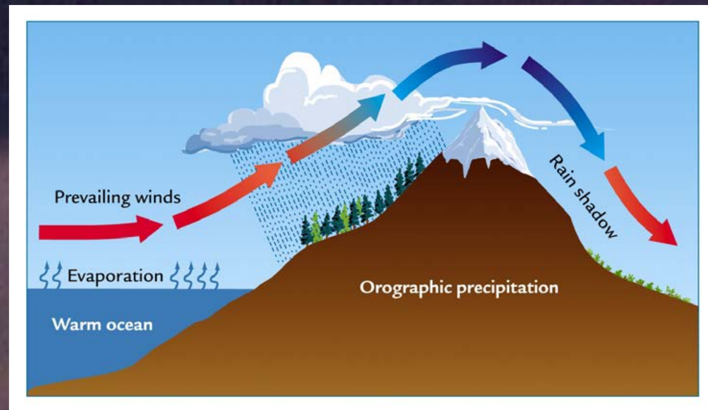

WONG++2015 (AGU)

conclusion is robust to uncertainties in the temperature profile

one more test before publishing: inhomogeneity



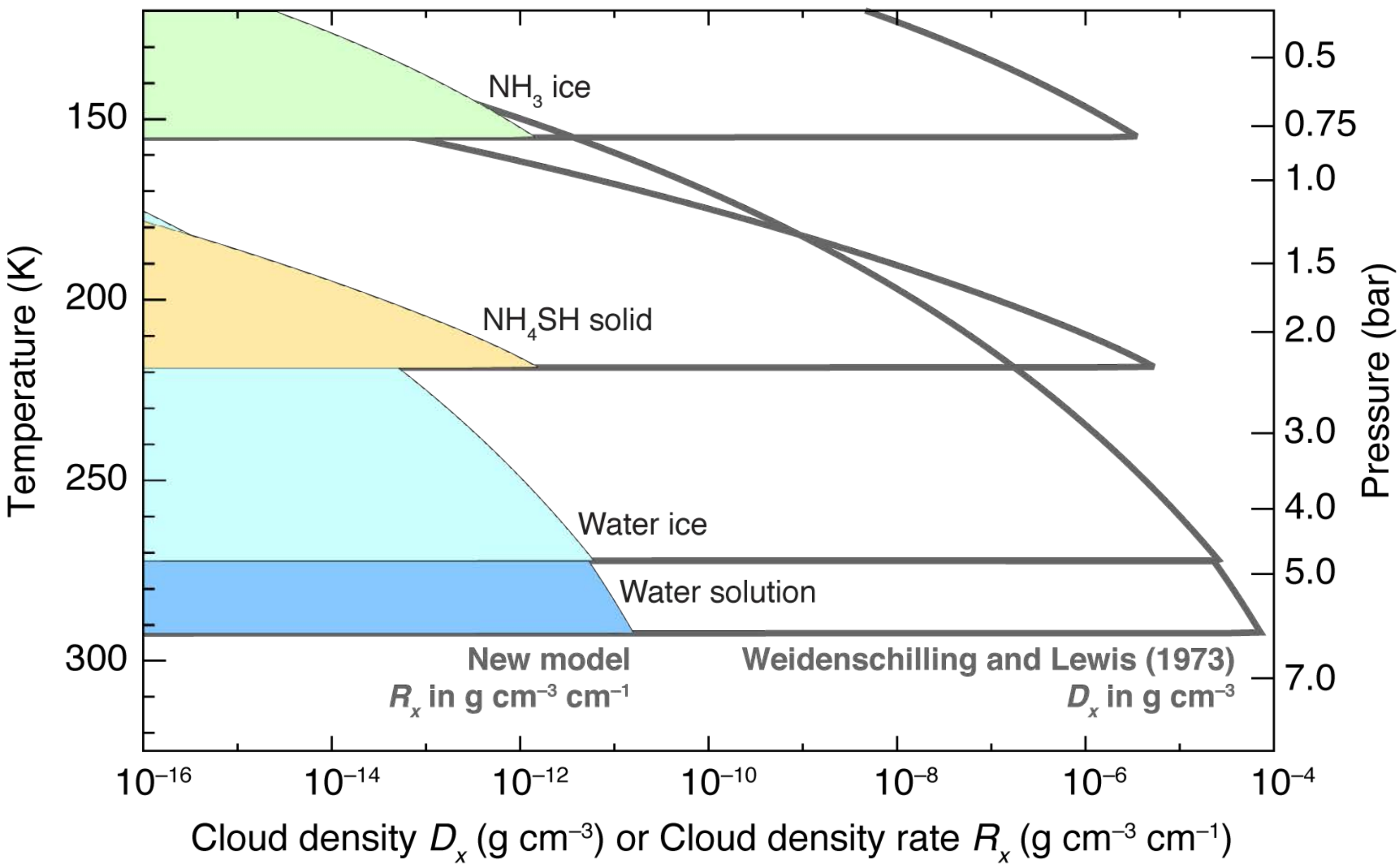
# Clouds and volatiles: dynamical tracers




Uplift: cloudy, humid

Subsidence: clear, dry

# Jupiter's cloud layers

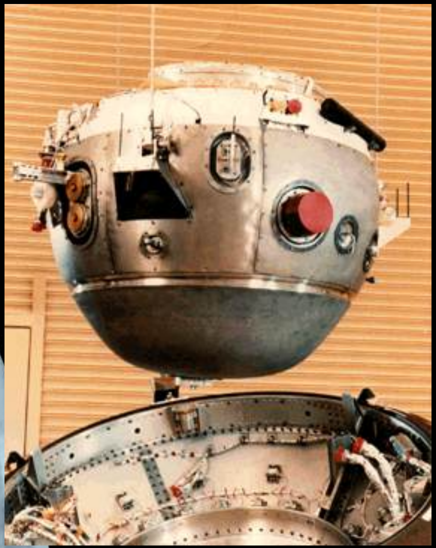



WONG++2015

Cloud compositions and bases predicted by thermochemical equilibrium

2015 "Fresh Clouds" paper updates cloud density calculation wrt original 1973 model

# Galileo Probe site clouds

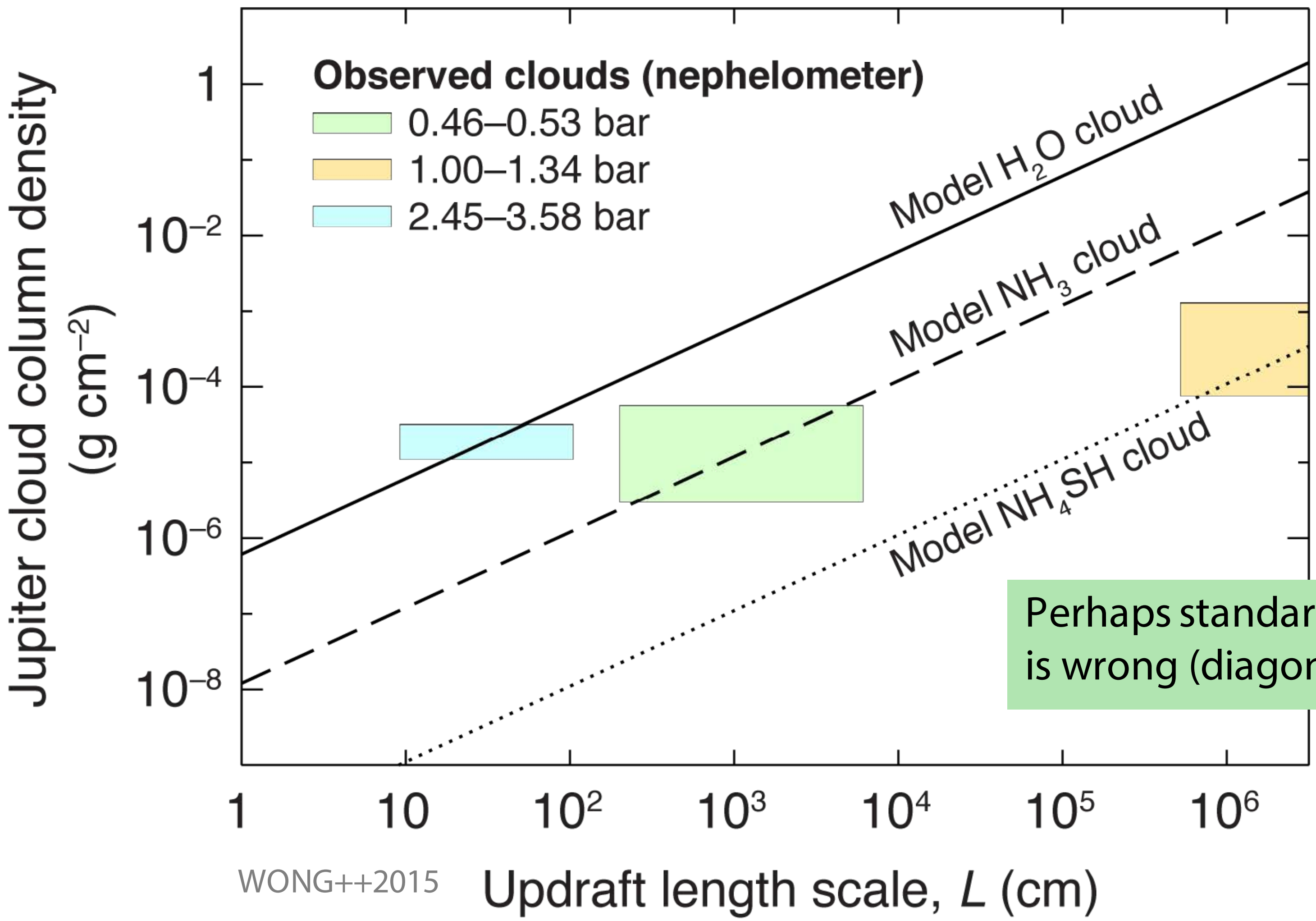


Galileo Probe Nephelometer measured aerosol opacity during descent

RAGENT++1998

AMNH *Dark Universe* planetarium show (2013)

# Galileo Probe site clouds



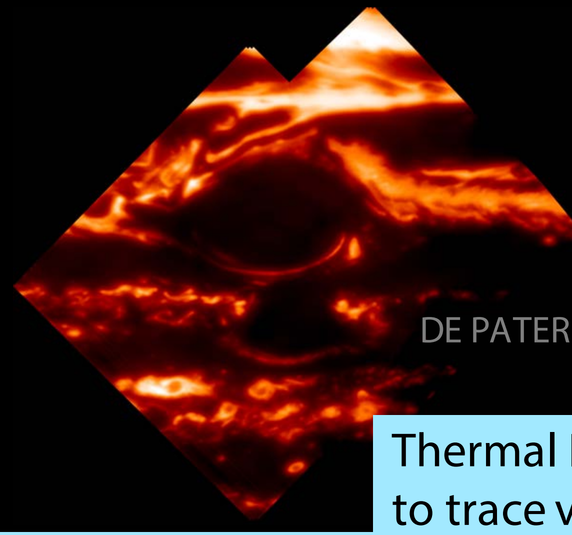

WONG++2015

Something strange with middle cloud: very high updraft length scale, in a region characterized by large-scale downwelling

Perhaps standard model chemistry is wrong (diagonal line)

# Clouds and volatiles: mapping dynamics

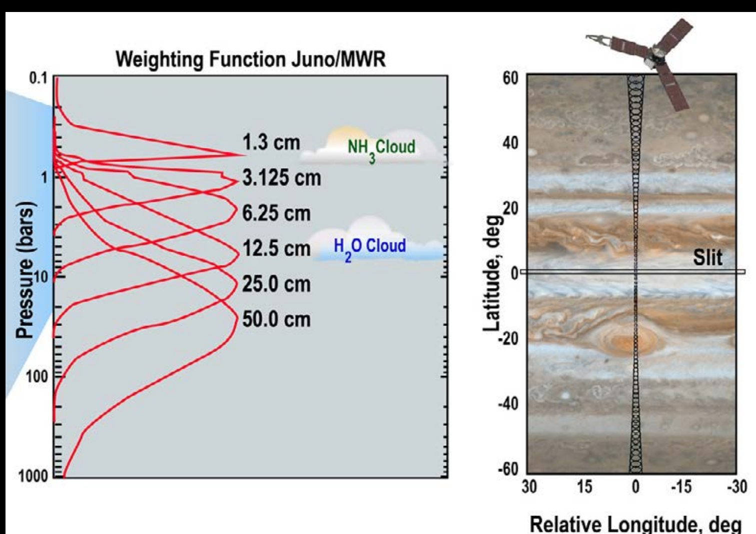
DE PATER++2016 **(EMBARGOED !!)**



DE PATER++2010

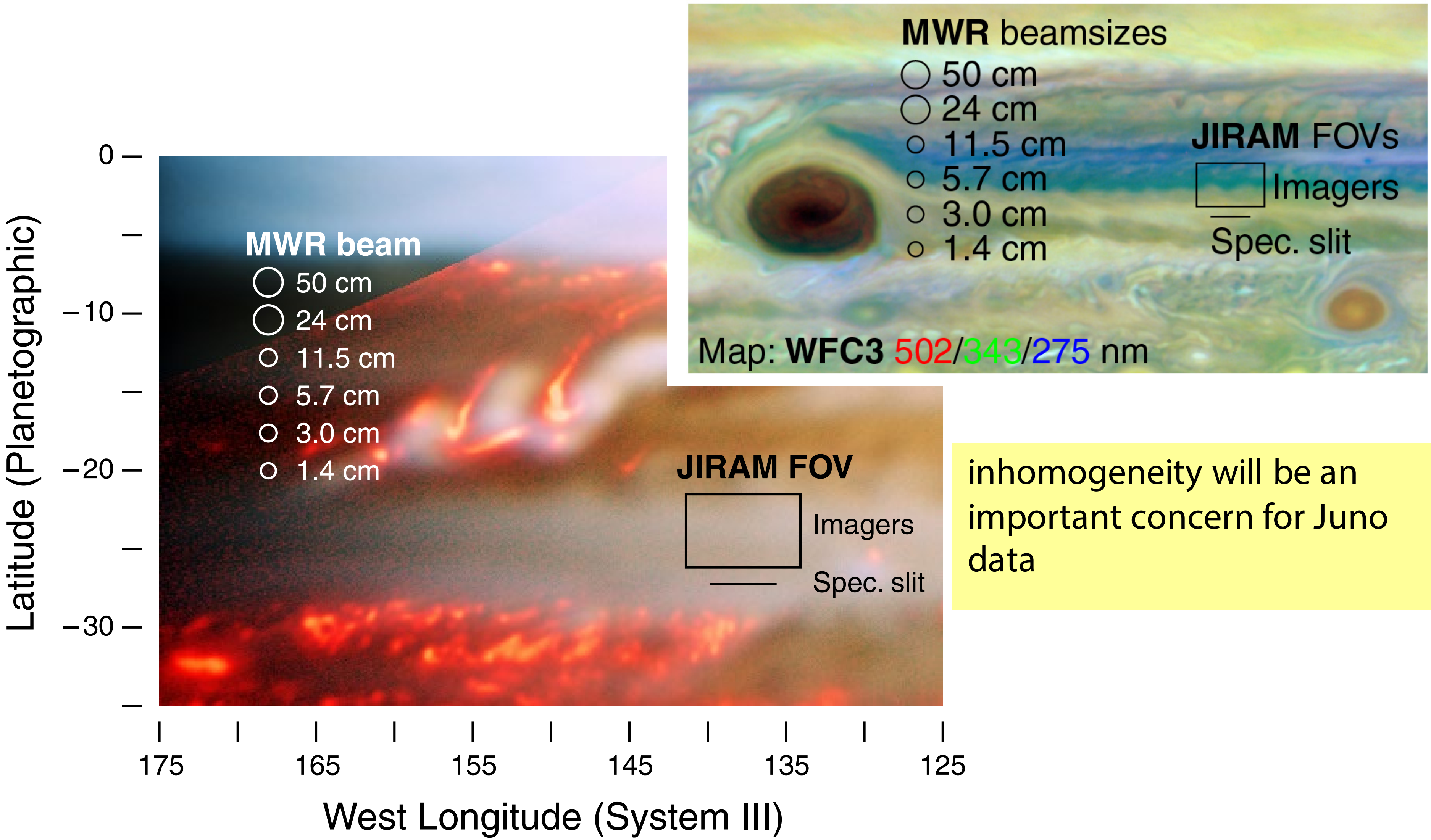
Thermal IR: Use clouds to trace vertical flows 0.5–2 bar

Radio: Use $NH_3$ gas to trace vertical flows 0.5–8 bar



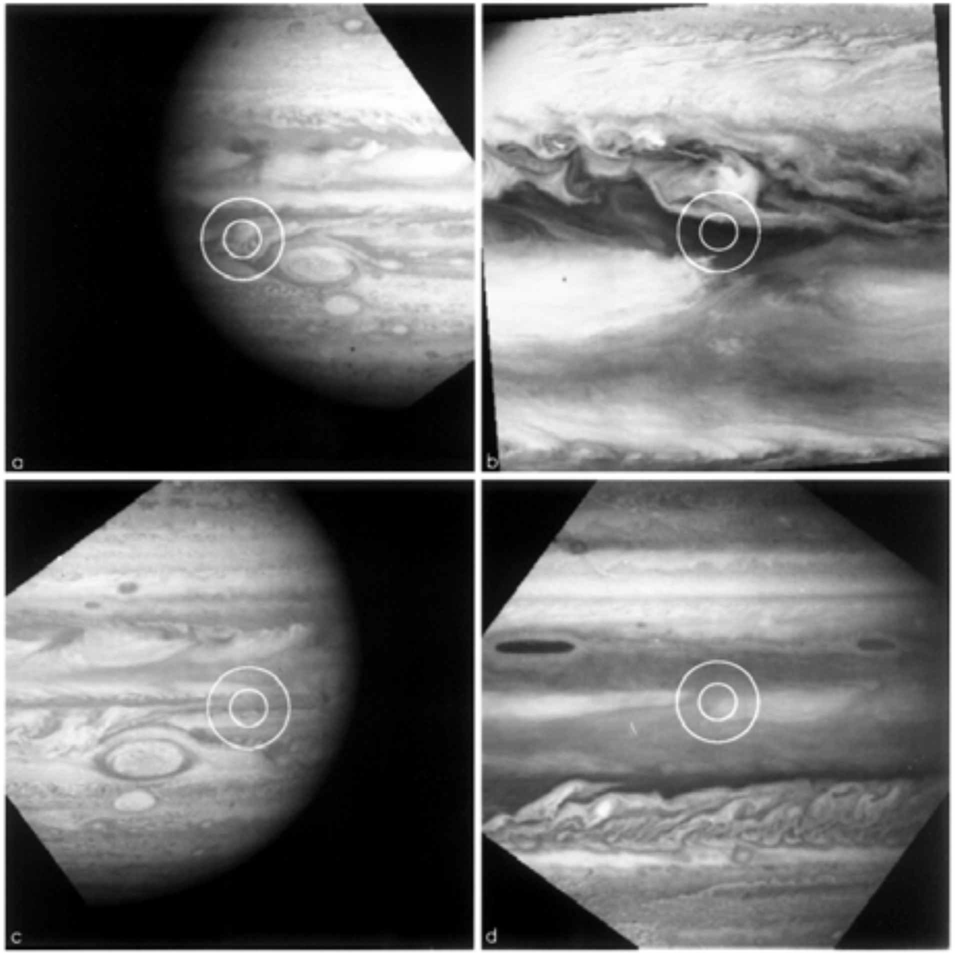

Juno: Longest λ channels sensitive to H2O gas, should detect same features seen in VLA C band (3.5–7.5 cm) map above

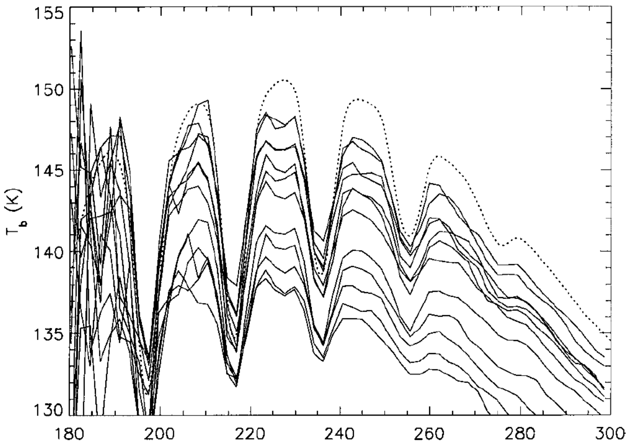
# Regional/global context for Juno




inhomogeneity will be an important concern for Juno data

# $H_2O$ ice signatures



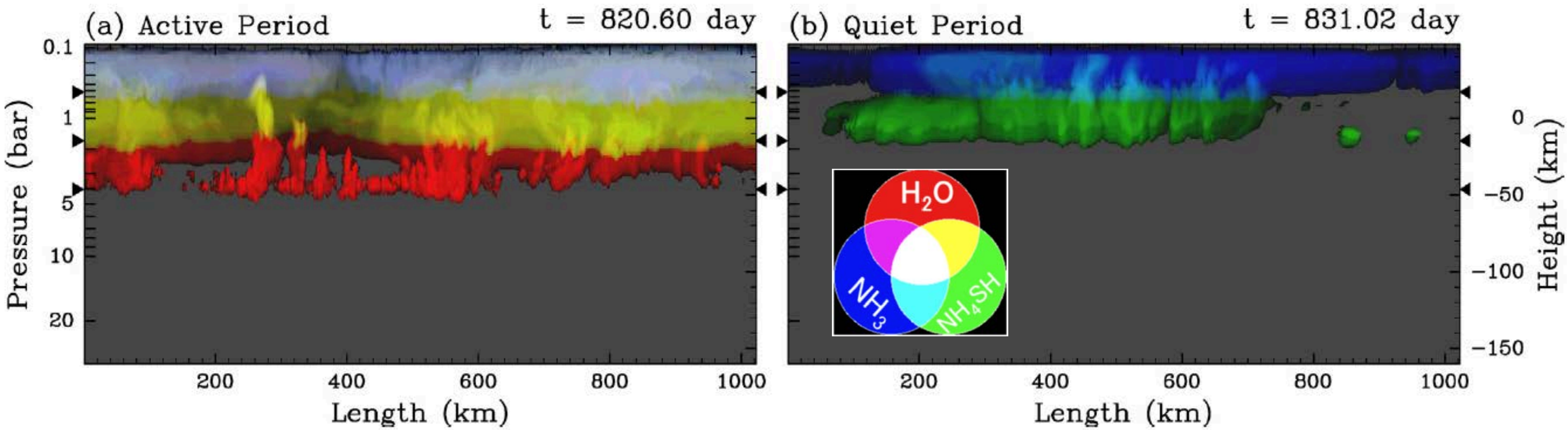




SIMON-MILLER++2000

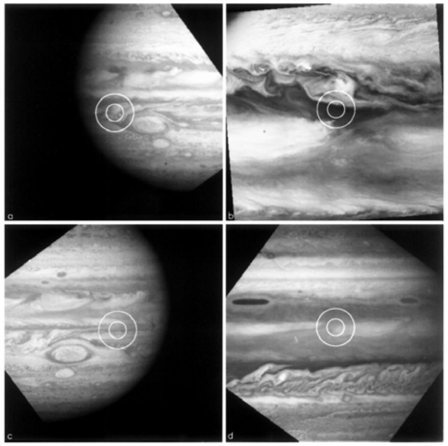
44-µm $H_2O$ ice signature detected in Voyager IRIS spectra

Locations consistent with vigorous convection, or equatorial wave

# $H_2O$ ice signatures

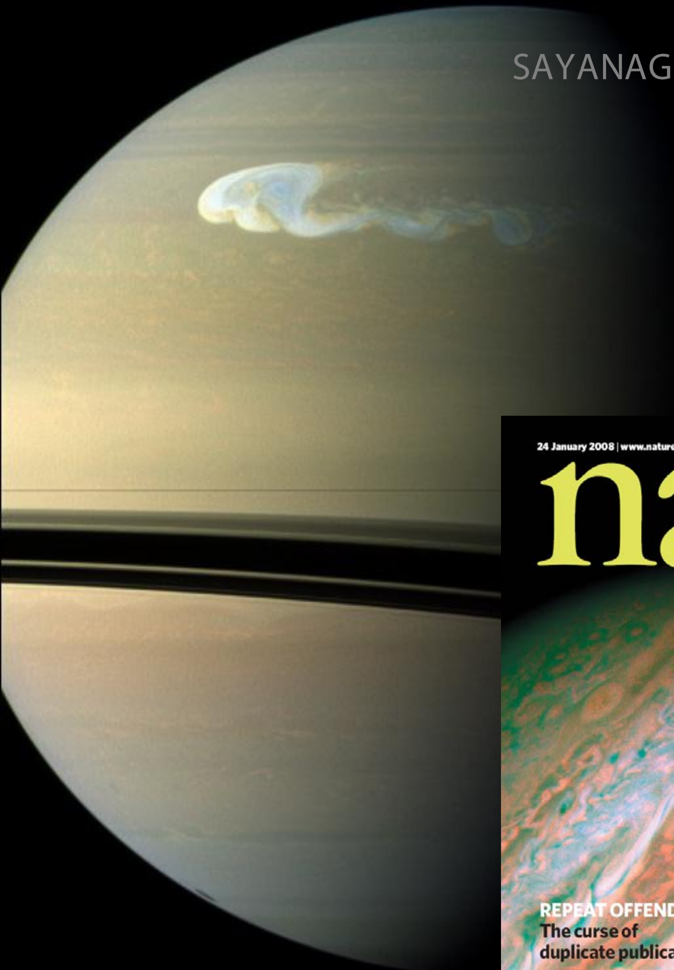



SUGIYAMA++2014



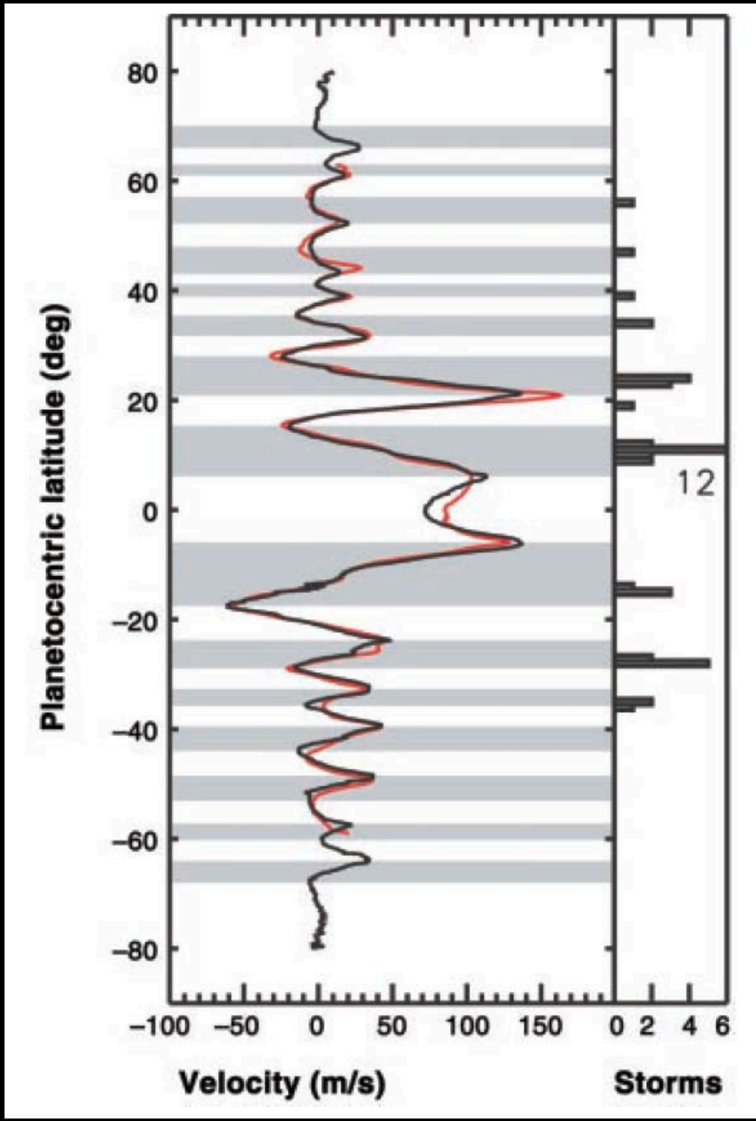
Model: In active convective conditions, cloud tops contain every type of jovian condensate, including water ice

# Episodic vs. steady convection



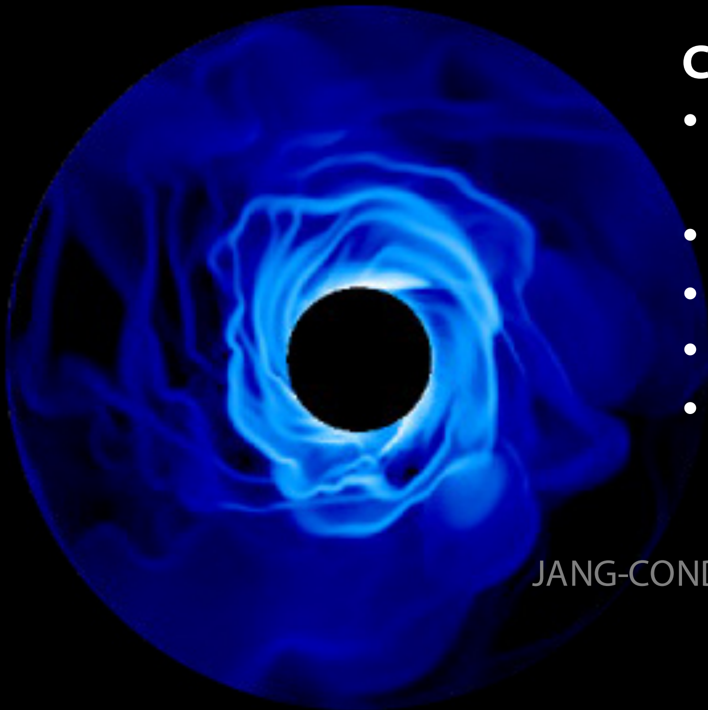
SAYANAGI++2013


SÁNCHEZ-LAVEGA++2008




PORCO++2003

# Conclusions



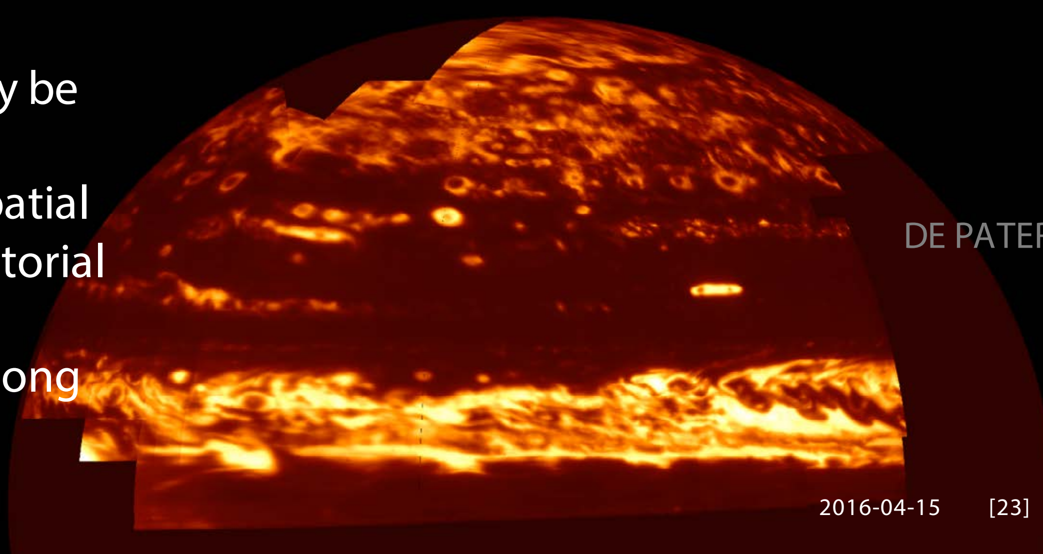
JANG-CONDELL+BOSS 2007

**COSMOCHEMISTRY**

- O/H ≥ 1.2x solar, based on spectroscopic determination of cloud heights
- Depth of lightning places similar lower limit
- Other volatiles ~3x solar
- Still need Juno to figure out what the O/H is !!
- But, we know 0.12x solar from Galileo Probe cannot be representative of bulk O/H

**ATMOSPHERIC DYNAMICS**

- Standard cloud chemistry may be wrong for $H_2S$ chemical sink
- Juno should see significant spatial variation, at least due to equatorial wave
- Convective style may vary among planets, controlled by $H_2O$ abundance



DE PATER++2011