Methane on Mars:
Current Knowledge, Earth Analogues, and Principal issues

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Center for Astrobiology &
Solar System Exploration Division
NASA's Goddard Space Flight Center

Mars III
Les Houches
March 31, 2010

Major Scientific Contributors

1997 - 2010
CH_4, H_2O, HDO, O_2

Geronimo Villanueva
Robert E. Novak
Tilak Hewagama
Boncho P. Bonev
Michael A. DiSanti
Avi M. Mandell
Michael D. Smith

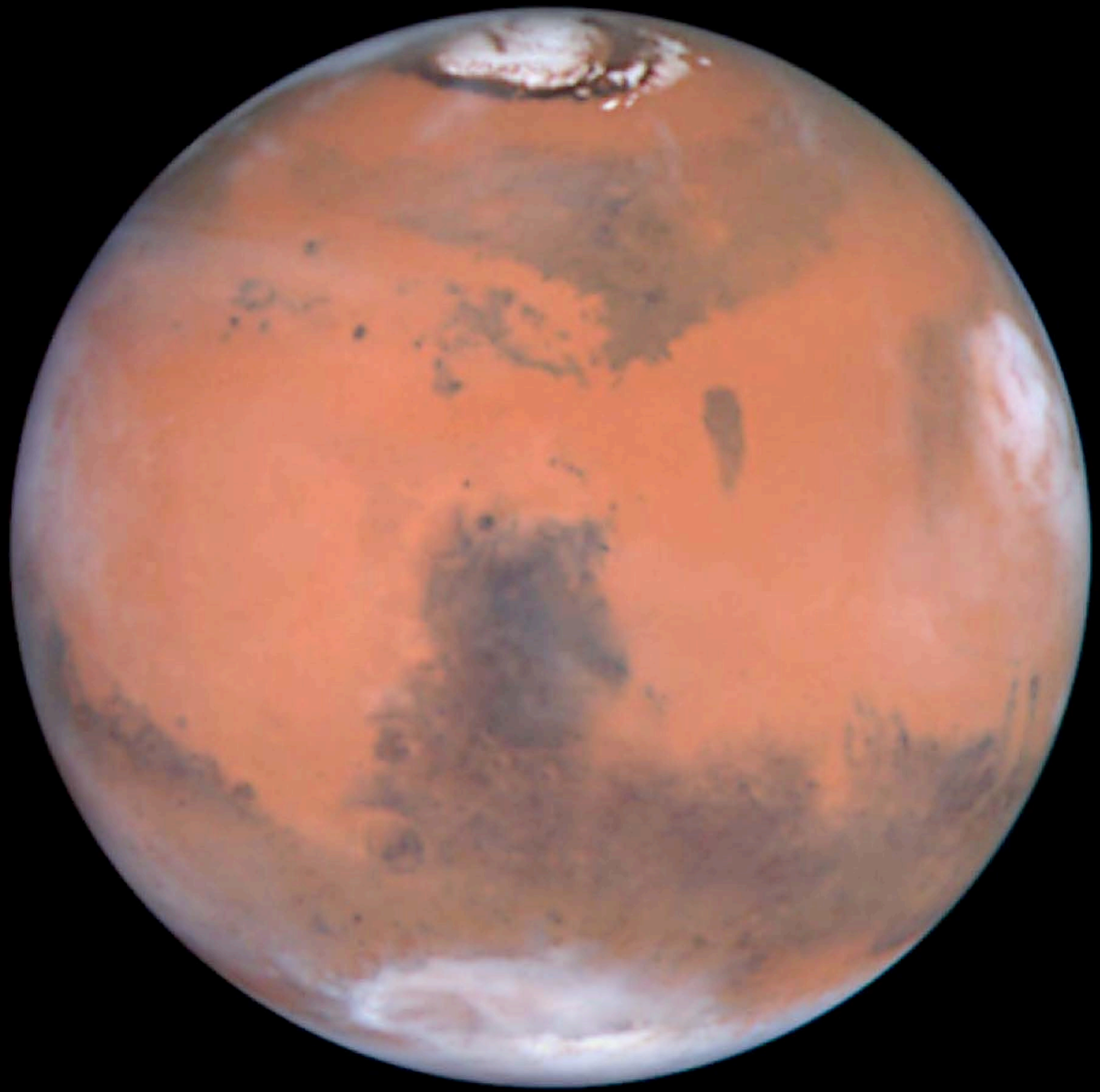
1989 - 1997
H_2O, HDO, H_2O_2, CH_4

Gordon Bjoraker
Donald E. Jennings
Vladimir Krasnopolsky
Harold P. Larson

1976 - 1984
CO_2, NH_3, O_3

David Buhl
Drake Deming
Fred Espenak
Theodor Kostiuk
David Zipoy

Is (or was) Mars *WET* ? (and *ALIVE*?)



The Evolving Search for a Habitable Mars

Φ1 – Earth's twin (a rich biosphere; eucaryotes)

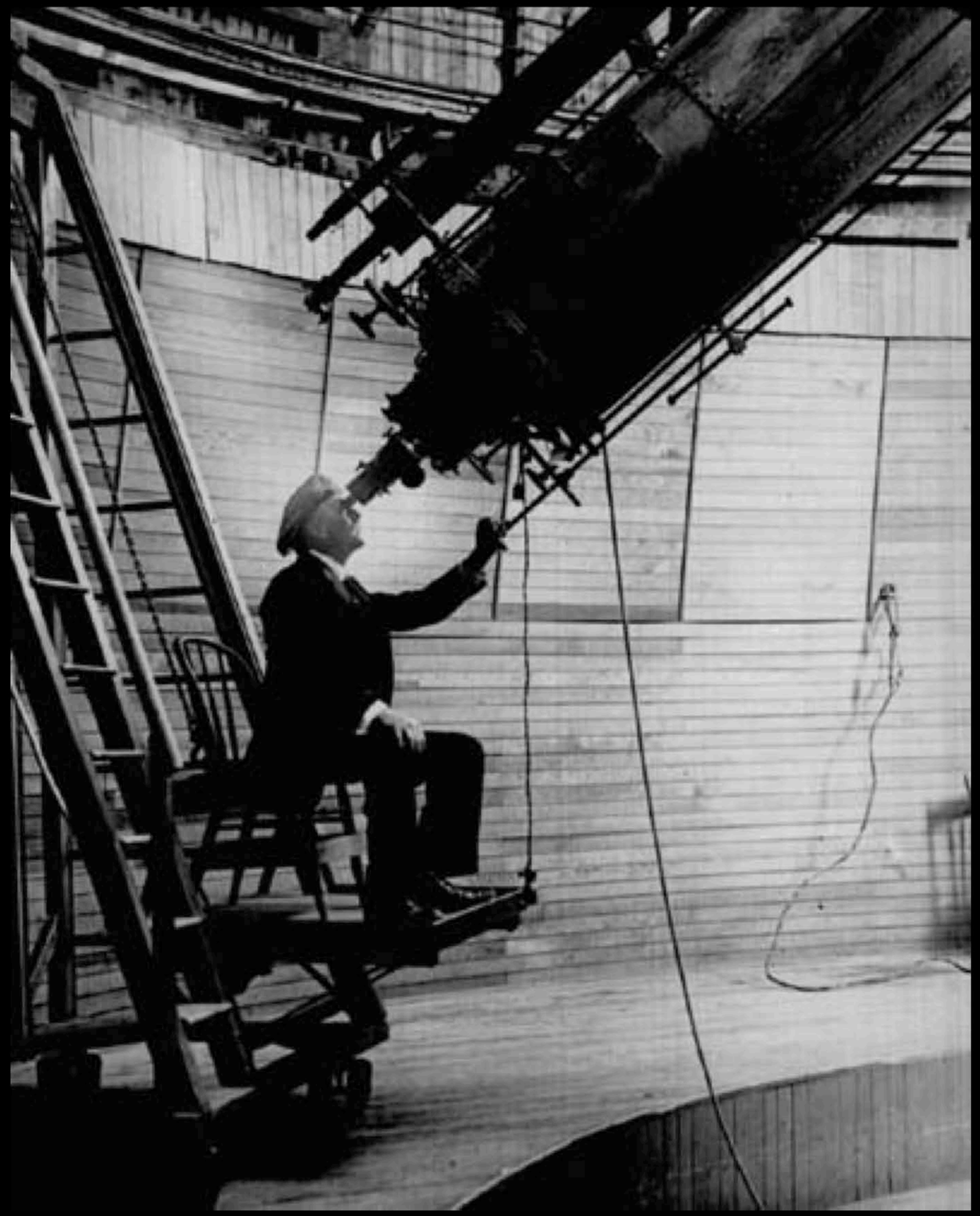
Φ2 – A global biosphere (but sparse; microbes)

Φ3 – A 'remnant' biosphere (in 'niches'; microbes)

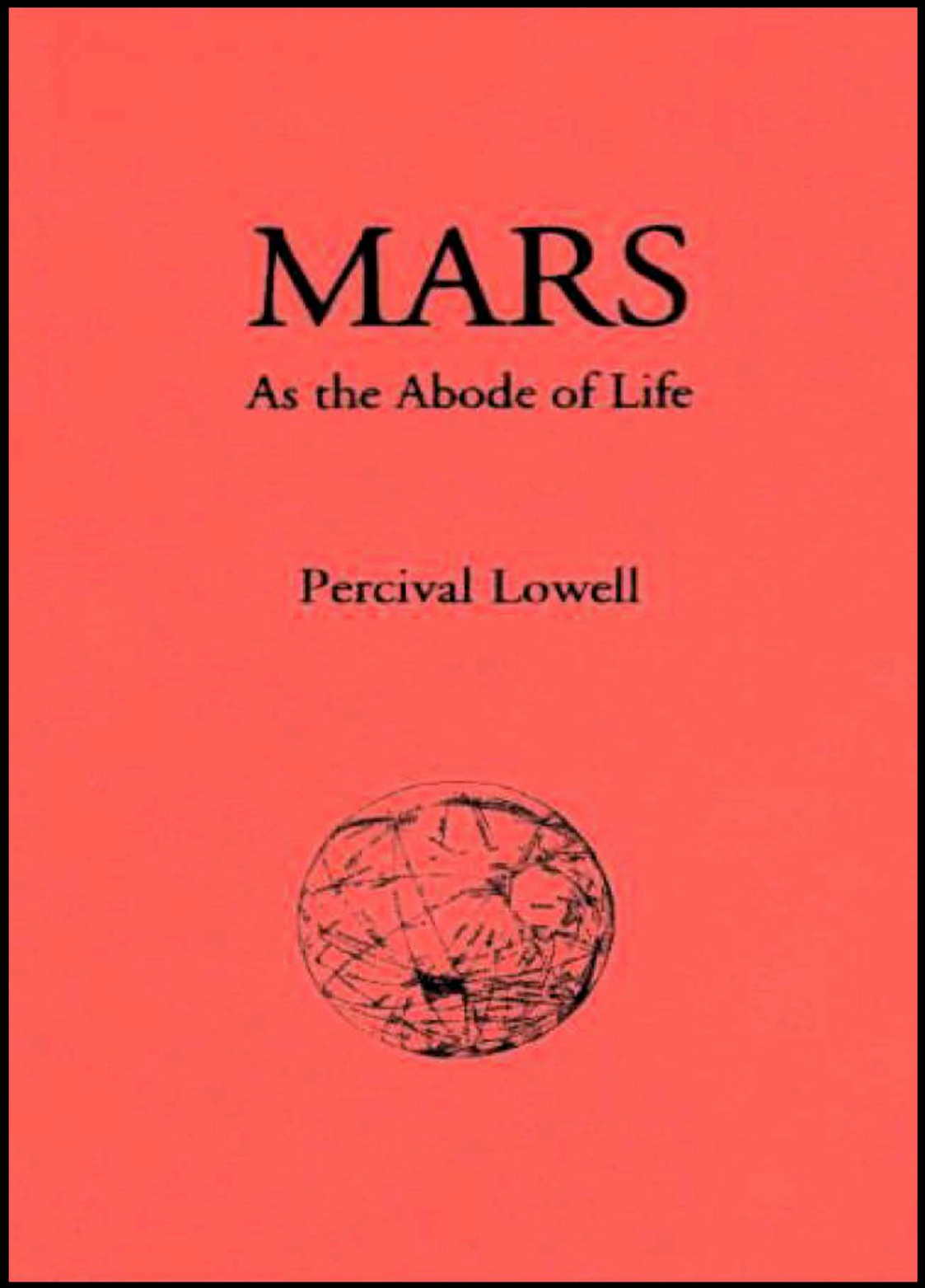
Φ4 – Follow-up and Exploitation

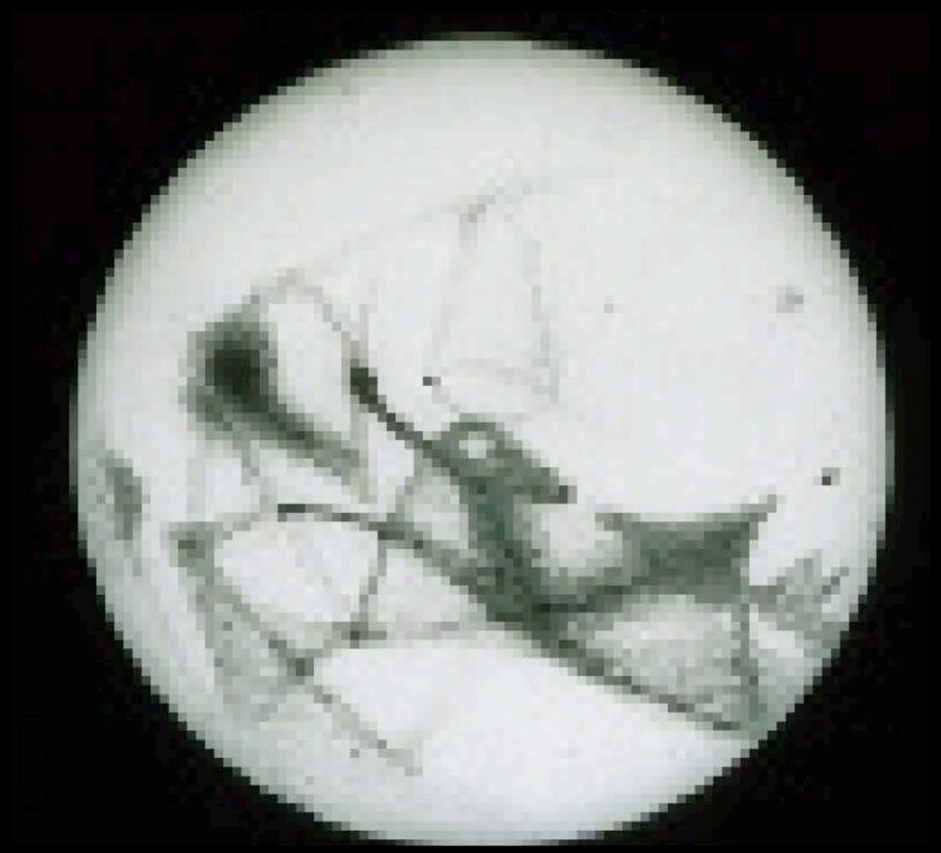
Φ1 – Fantasies : 1880 - 1920

Percival Lowell



Φ1 – Fantasies : 1880 - 1920





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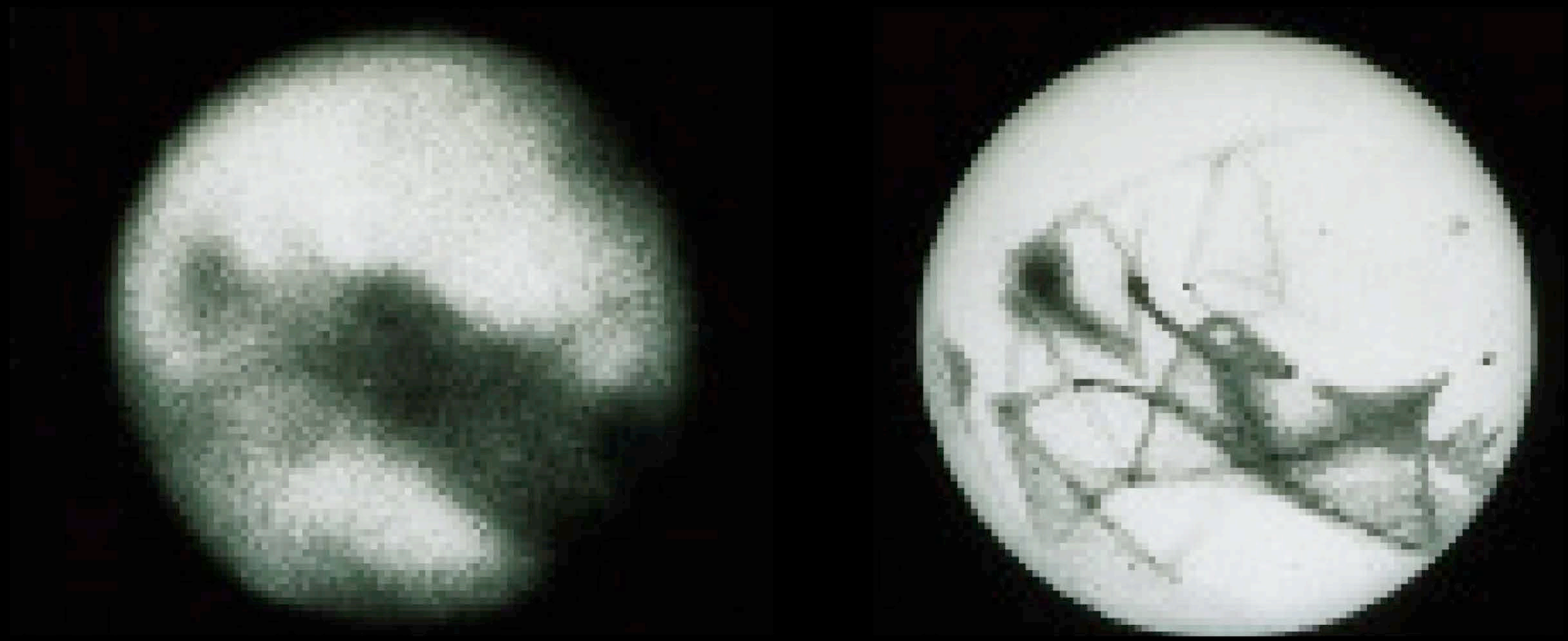


mumma.28feb07.7

Serious inquiry resumes in the era of Space Exploration:

Mariner 4, 7, & 9

Viking 1 & 2

Phobos

Mars Express

Mars Exploration Rovers

Phoenix Lander

and many more ---

Serious inquiry resumes in the era of Space Exploration:

Mariner 4, 7, & 9

A heavily cratered surface, thin CO_2 atmosphere, little water, no vegetation.

Viking 1 & 2

Early 70s marked the end of Φ1 !

Phobos

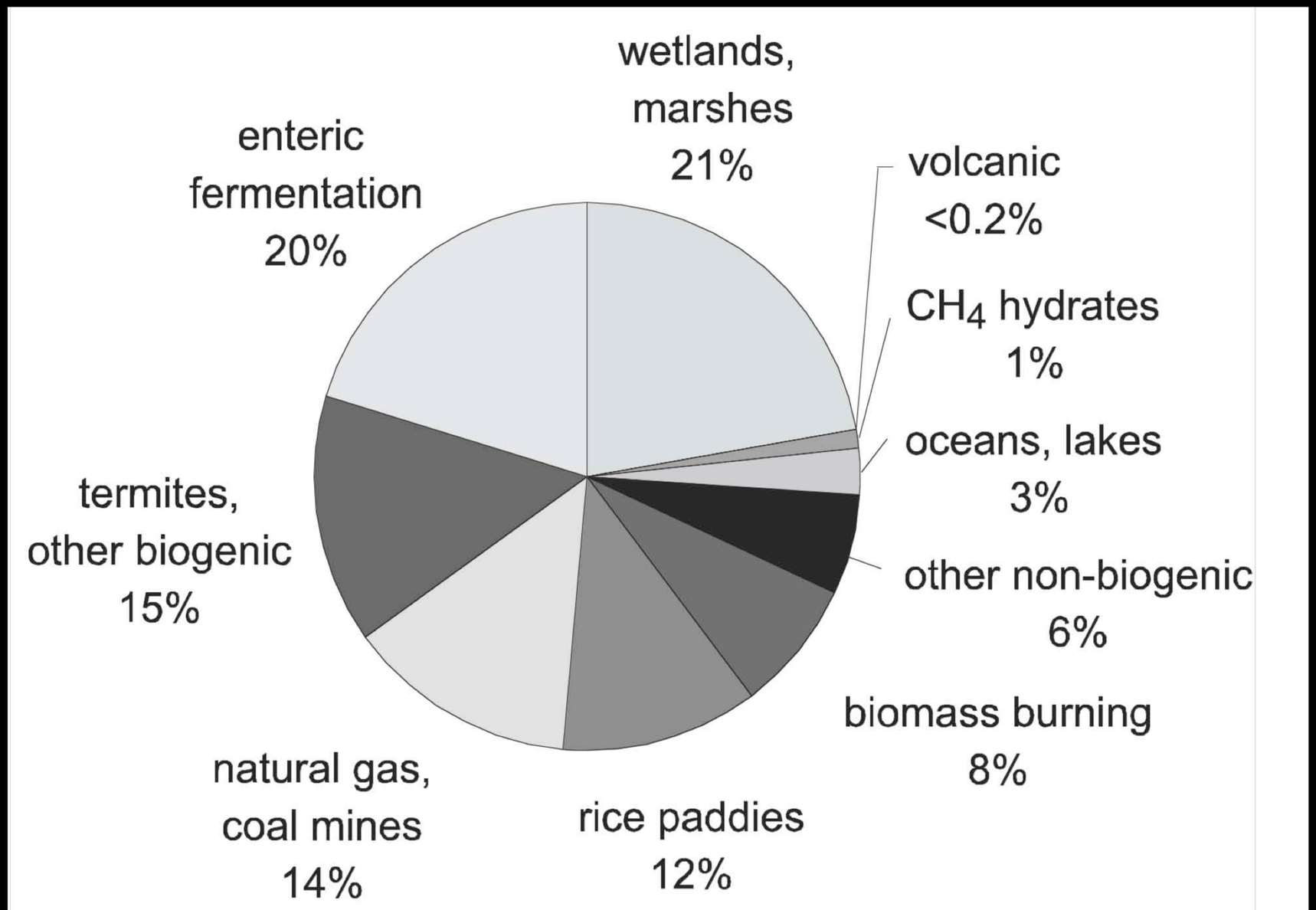
Mars Express

Mars Exploration Rovers

Phoenix Lander

and many more ---

Sources of Terrestrial Methane



After Atreya et al. 2006; Paul and Clark 1996

Spectral Searches for Methane on Mars

1969 - Pimentel — Mariner 7 IR	Announced but later retracted
1974 – Maguire 1977 — Mariner 9 IRIS	**< 20 ppb**

Serious inquiry resumes in the era of Space Exploration:

Mariner 4, 7, & 9

Viking 1 & 2

Atmospheric O_2 detected, global water cycle studied; no organics in soil & no respiration products produced.

Phobos

Late 1970s marked the end of Φ2 !

Mars Express

Mars Exploration Rovers

Phoenix Lander

and many more ---

Serious inquiry resumes in the era of Space Exploration:

Mariner 4, 7, & 9 — **It's Dead, Jim!!**

Viking 1 & 2 — **Not so fast, Bones! What about <u>Early</u> Mars?**

Phobos — **S/C emphasis shifted to early (extinct) life & 30-year emphasis on geosignatures.**

Mars Express

Mars Exploration Rovers

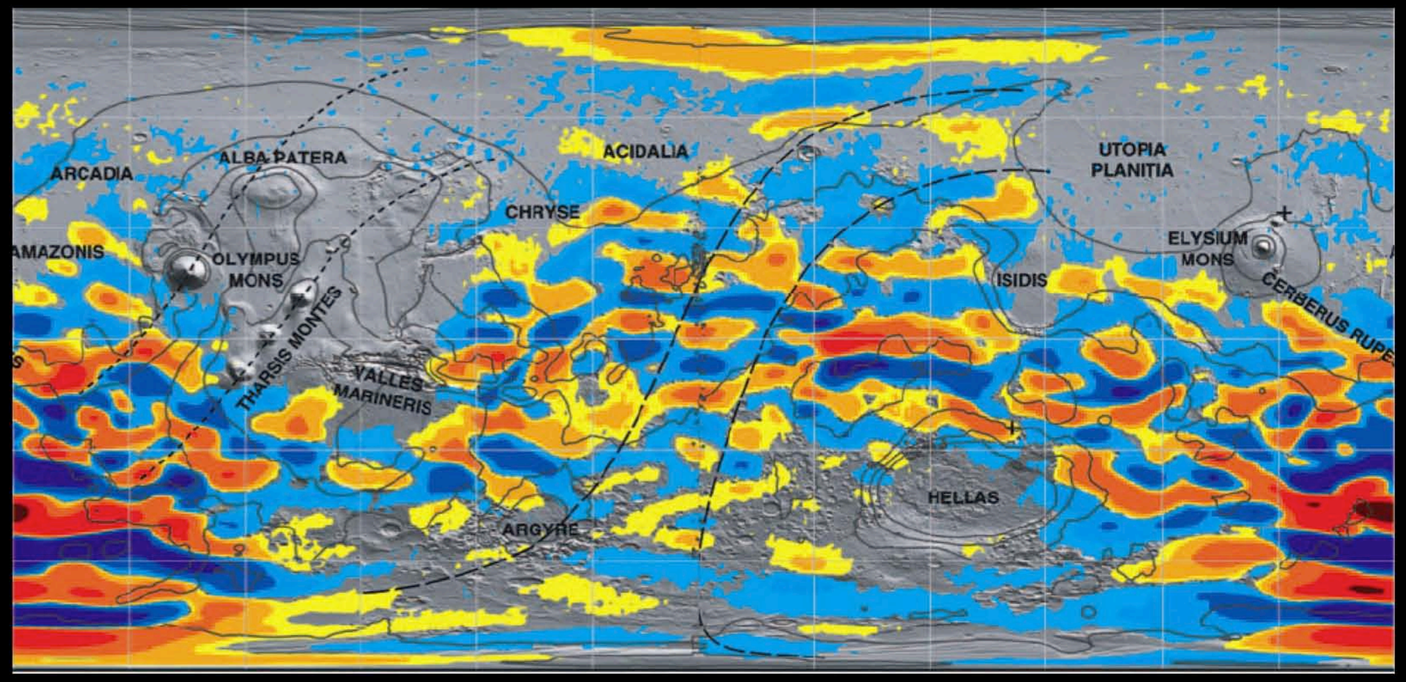
Phoenix Lander

and many more ---

“Pointers” on Current Mars

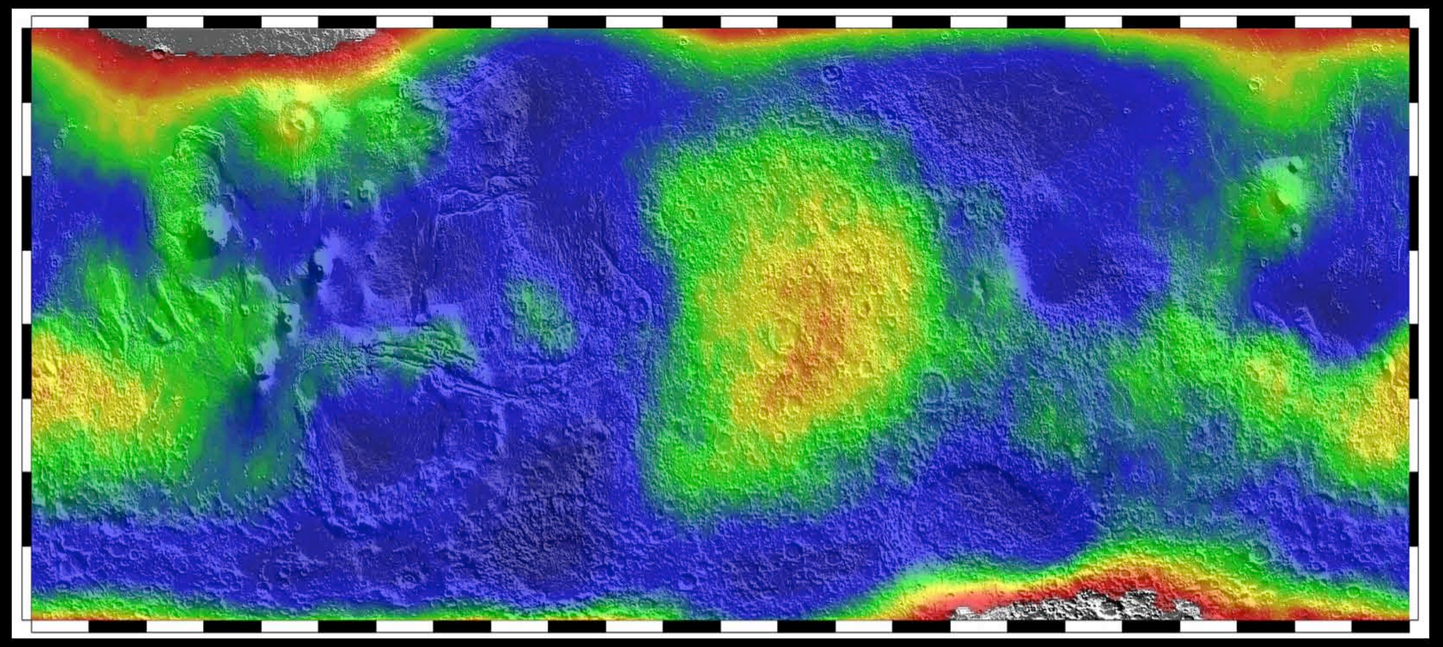
MGS – Mag
Remnant magnetic field

Acuña et al. 1999,
Connerney et al. 2005



Mars Odyssey
Sub-surface hydrogen
(epi-thermal neutrons)

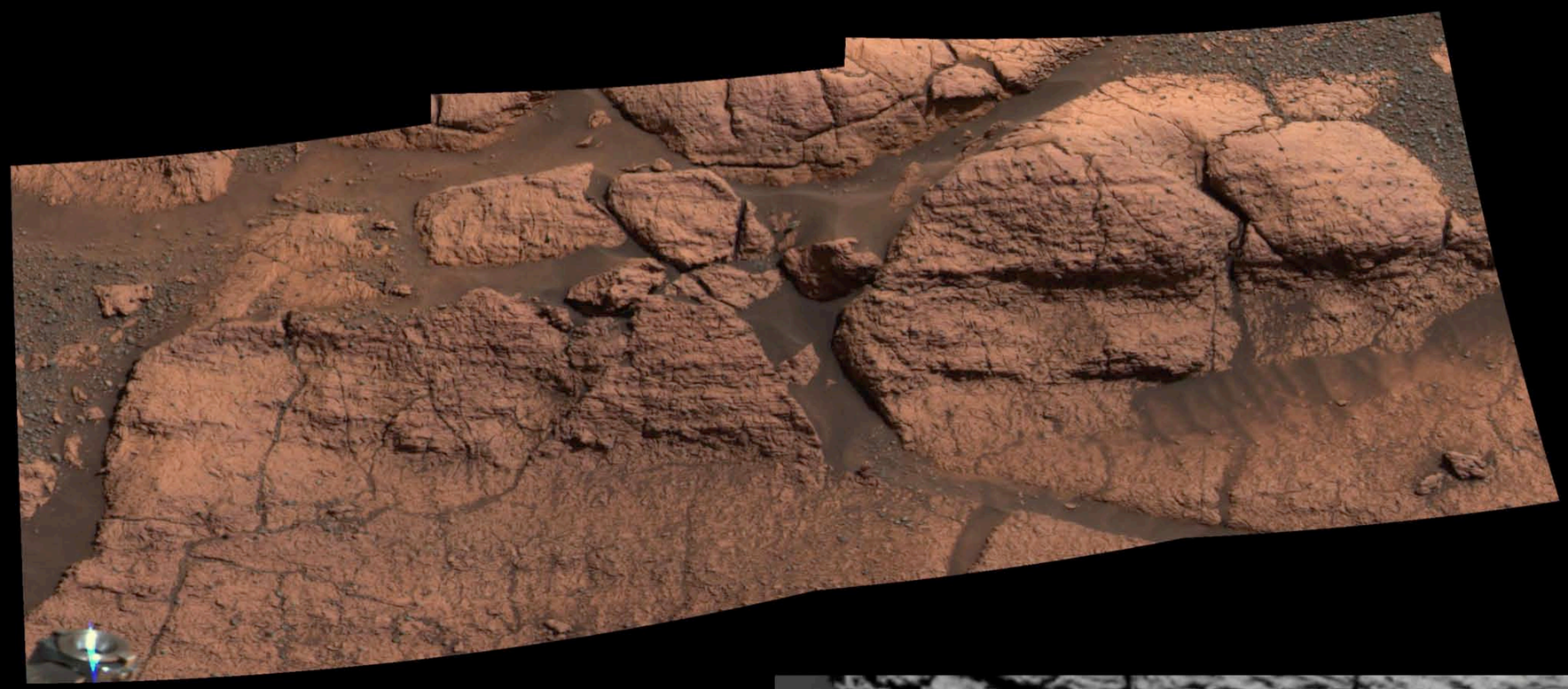
Boynton et al. 2004, 2007



MGS – TES Hematite (!)

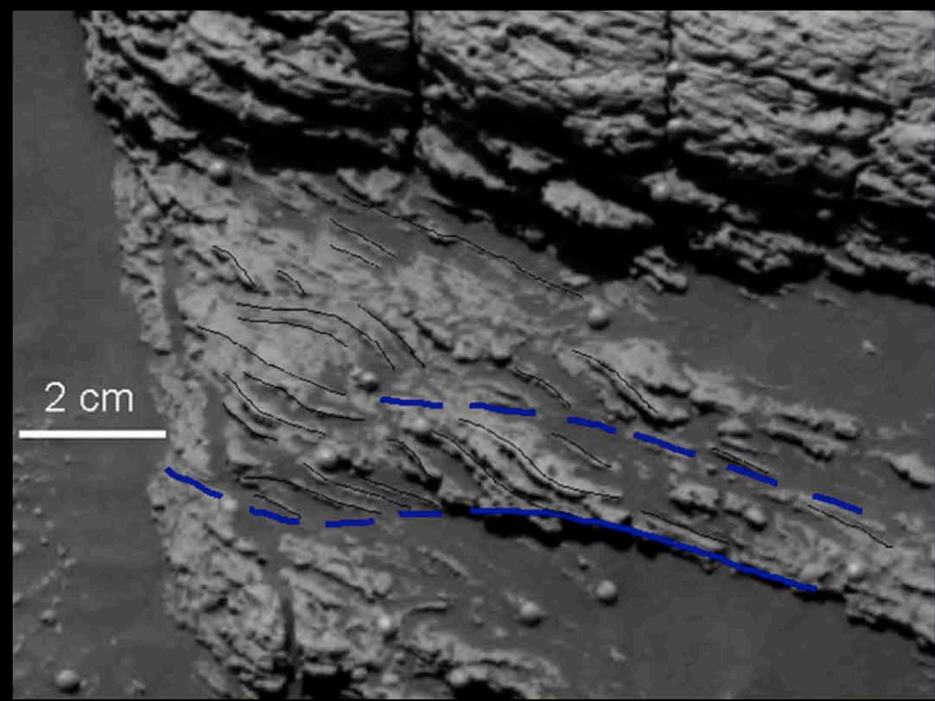
HST: Mars in 1995

Opportunity at Meridiani Planum



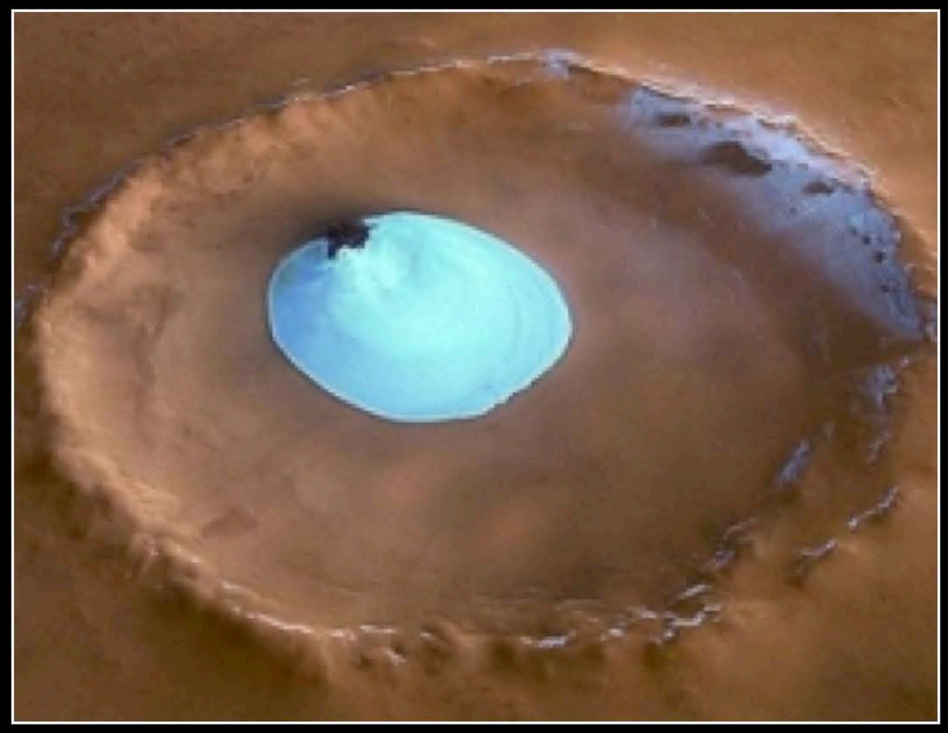
Ancient Mars had a salty sea.

NASA & S. Squyres



Water on Mars: current activity

HST: Mars in 1995



MeX: Mars in 2005

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1974 - Maguire 1977 — Mariner 9 IRIS	**< 20 ppb**	
1988 - Bjoraker, Jennings, Mumma, Krasnopolsky 1997 KPNO 4-m FTIR + GSFC post-disperser	**70 ± 40 ppb**	Global
1997 - Lellouch et al. 2000 — Infrared Space Observatory	**< 50 ppb**	
1999 - Krasnopolsky, Owen, Maillard 2004 — CFHT FTIR	**10 ± 3 ppb**	
2003 - Mumma et al. 2003 — NASA IRTF/ CSHELL — Gemini South/Phoenix	**40 -250 ppb, variable** **> 40-60 ppb, variable**	Local
2004 - Formisano et al. 2004 — Mars Express (PFS)	**10 - 130 ppb, variable**	

Spectral Searches for Methane on Mars

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Local

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2004 - Formisano et al. 2004 — Mars Express (PFS) — **10 - 130 ppb, variable**

- Geminale et al. 2008 - PFS seasonal & spatial variations **15 ± 4 ppb, global mean**

2003 – Mumma, Villanueva, Novak et al. 2009 — Active Release in Northern Summer 2003

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Viking 1 & 2

Phobos

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Phoenix Lander

and many more ---

2003 on. Ground-based and orbital searches for methane suggest local variations.

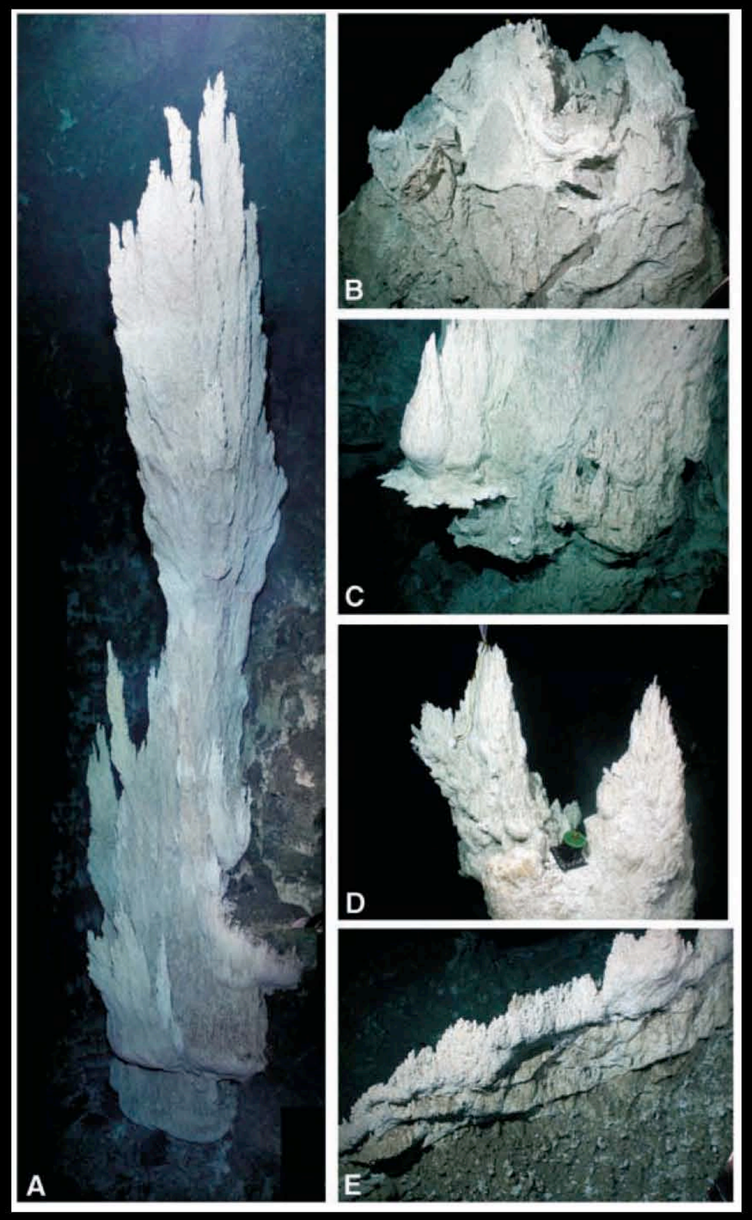
These mark the beginning of Φ3 !

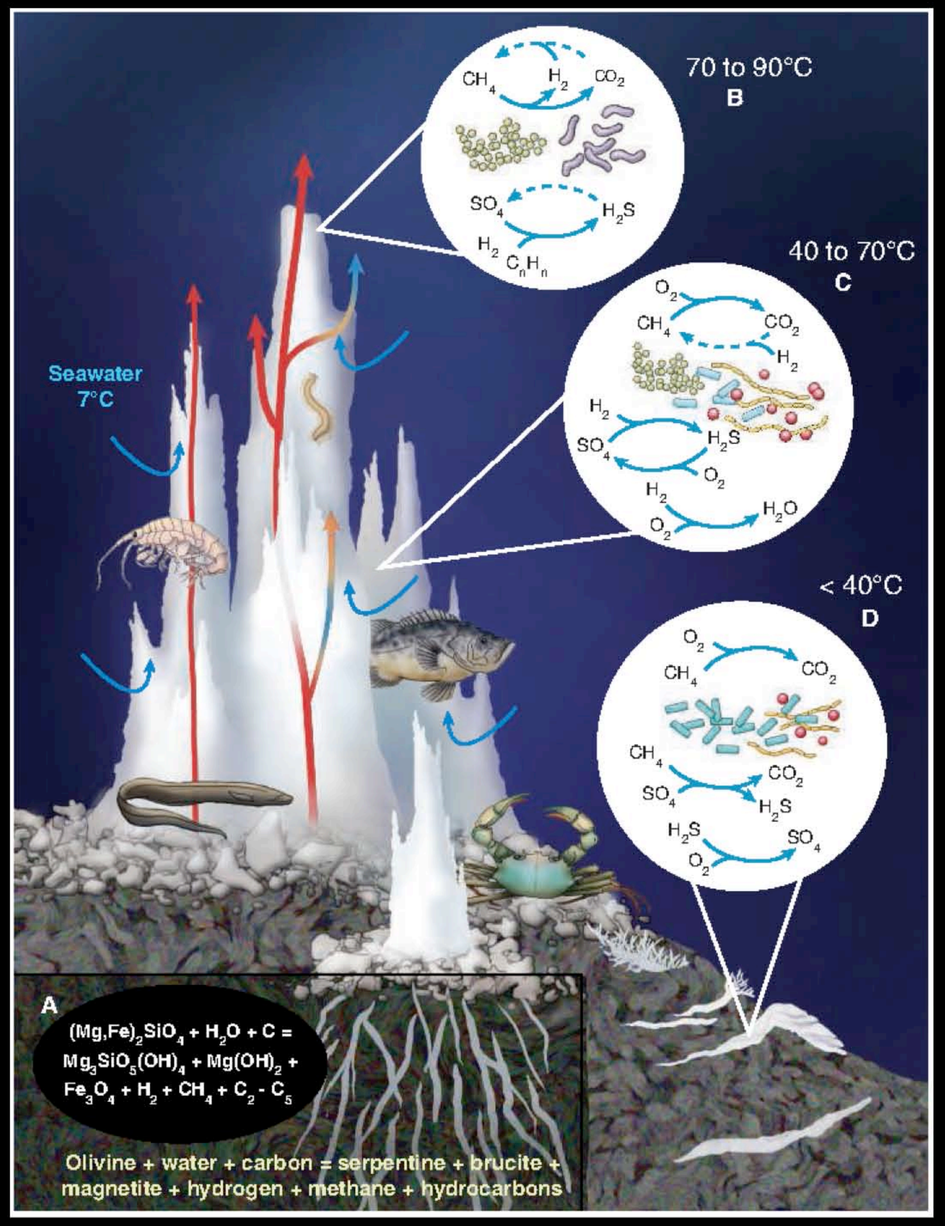
Tests of Biology vs. Geology

Test the "big four" gases :

- ✓ Carbon dioxide
- ✓ Water
- ✓ Oxygen
- ✓ Methane

Methane Production - Terrestrial Analogues





Peridotite-hosted serpentinization

Kelly et al. Science 2005

Boetius Science 2005

Black smokers

Kimberlite pipes

H_2O radiolysis

mantle (CO_2, H_2O, heat)

microbial

etc.

The Evolving Search for a Habitable Mars

Φ1 – Earth's twin (a rich biosphere; eucaryotes)

Φ2 – A global biosphere (but sparse; microbes)

Φ3 – A 'remnant' biosphere (in 'niches'; microbes)

Φ4 – Follow-up and Exploitation:
Biology, Geology, or both ?

Tests of Biology vs. Geology

Test the "big four" gases :

- ✓ Carbon dioxide
- ✓ Water
- ✓ Oxygen
- ✓ Methane

Along with: C_nH_{2n+2}, NH_3, N_2O, H_2S, CH_3SH, …

And also: Their isotopologues (D/H, $^{13}C/^{12}C$, $^{15}N/^{14}N$, …)

Searching for Methane

- The measurement approach
- Improvements in Analysis
- Latest results

R-Branch

Q-Branch

P-Branch

Simulated spectrum of Mars methane ν_3

3080 3060 3040 3020 3000 2980 2960

Simulated terrestrial extinction

3080 3060 3040 3020 3000 2980 2960

Mars spectrum affected by terrestrial extinction

R2 R1 R0 P2 P4

3080 3060 3040 3020 3000 2980 2960

Frequency in wavenumbers [cm^{-1}]

CH_4 :

3 nuclear spin species,

A, E, F

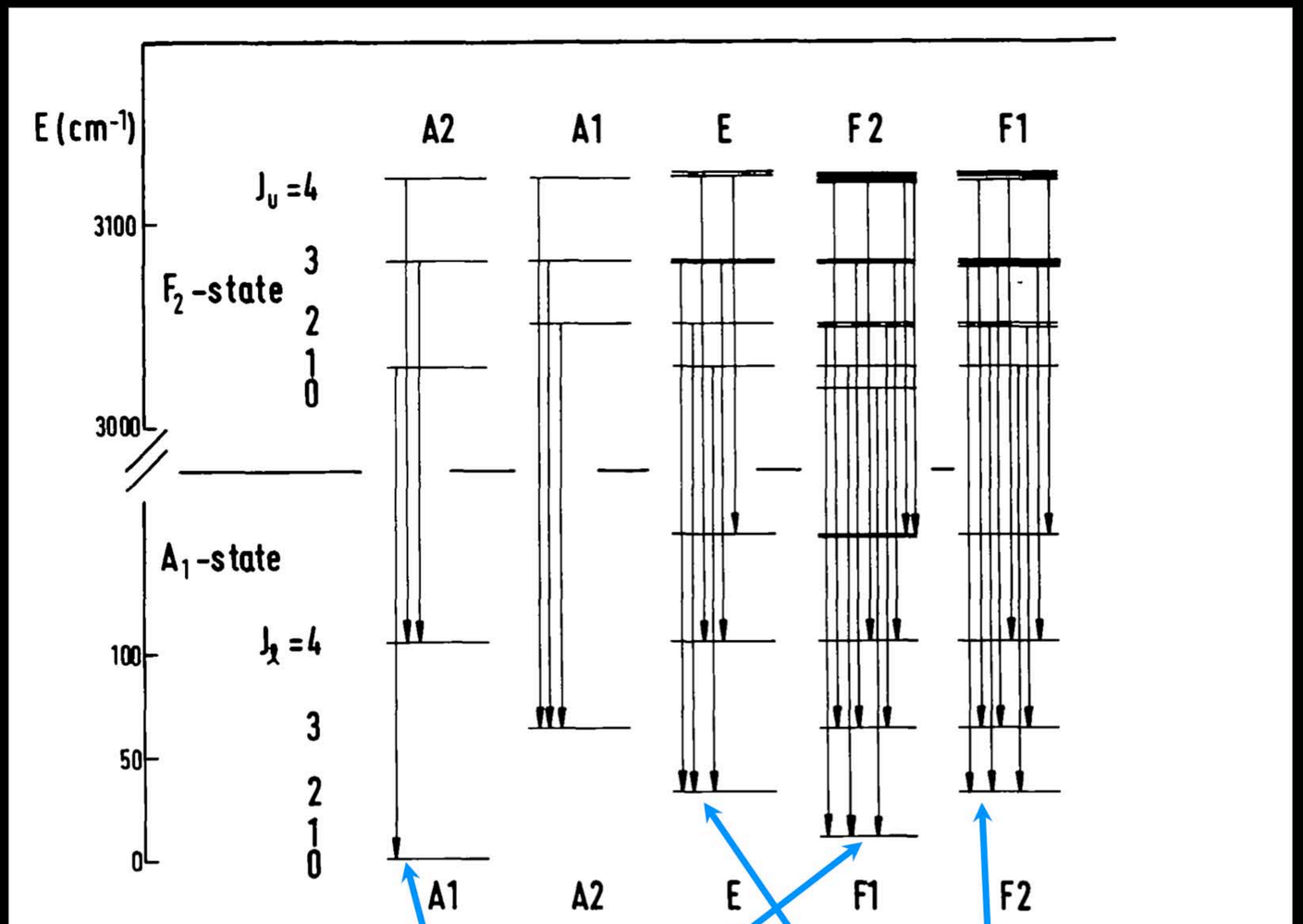
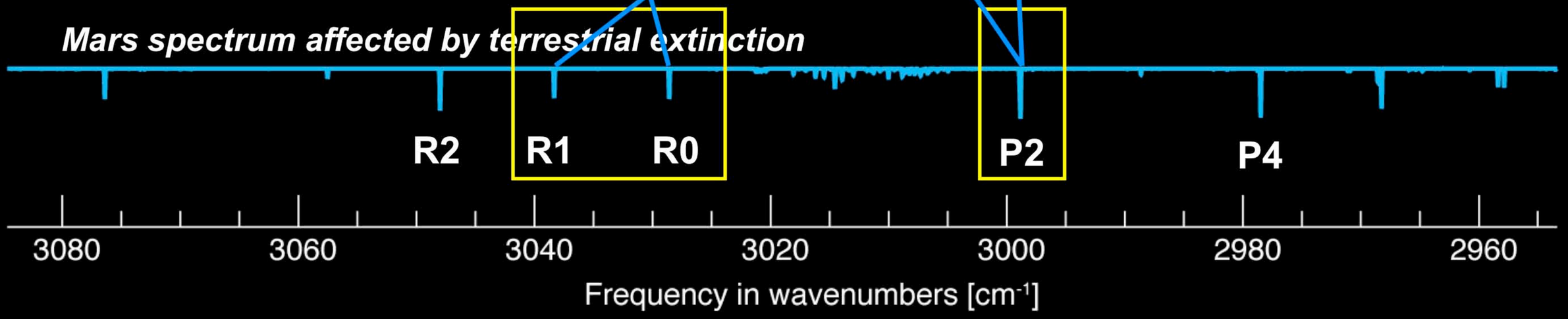
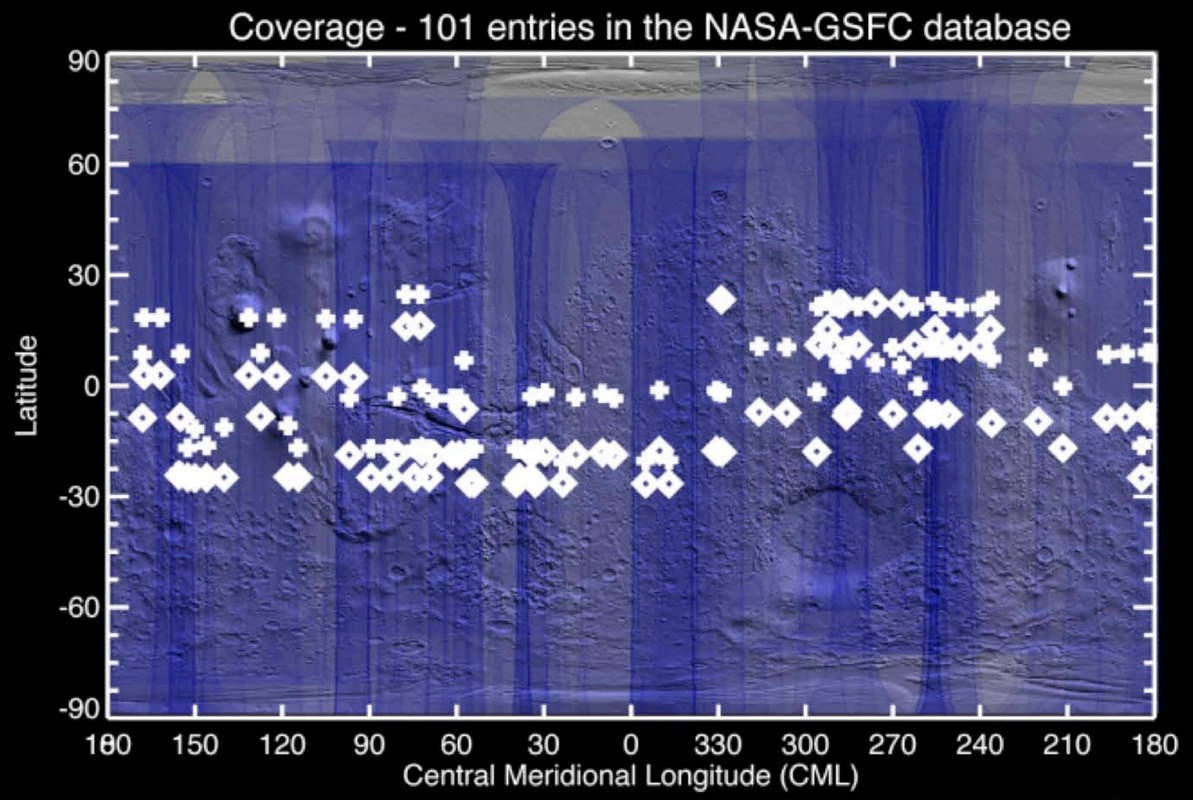


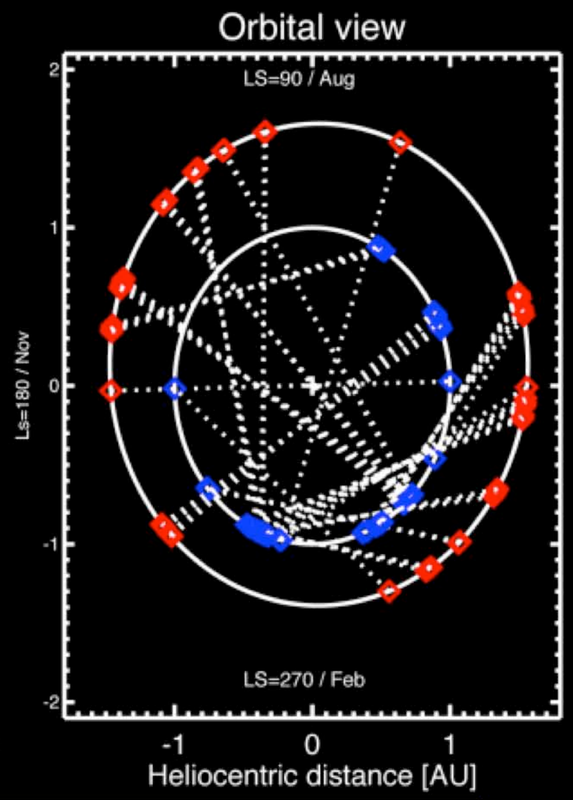
Fig. 2. Lower rotational states of the A_1 ground state and F_2 excited state of the ν_3 vibrational band of CH_4. Rotational levels of one species (A, E or F) can only combine with levels of the same species (After Drapatz et al. A&A 1987)

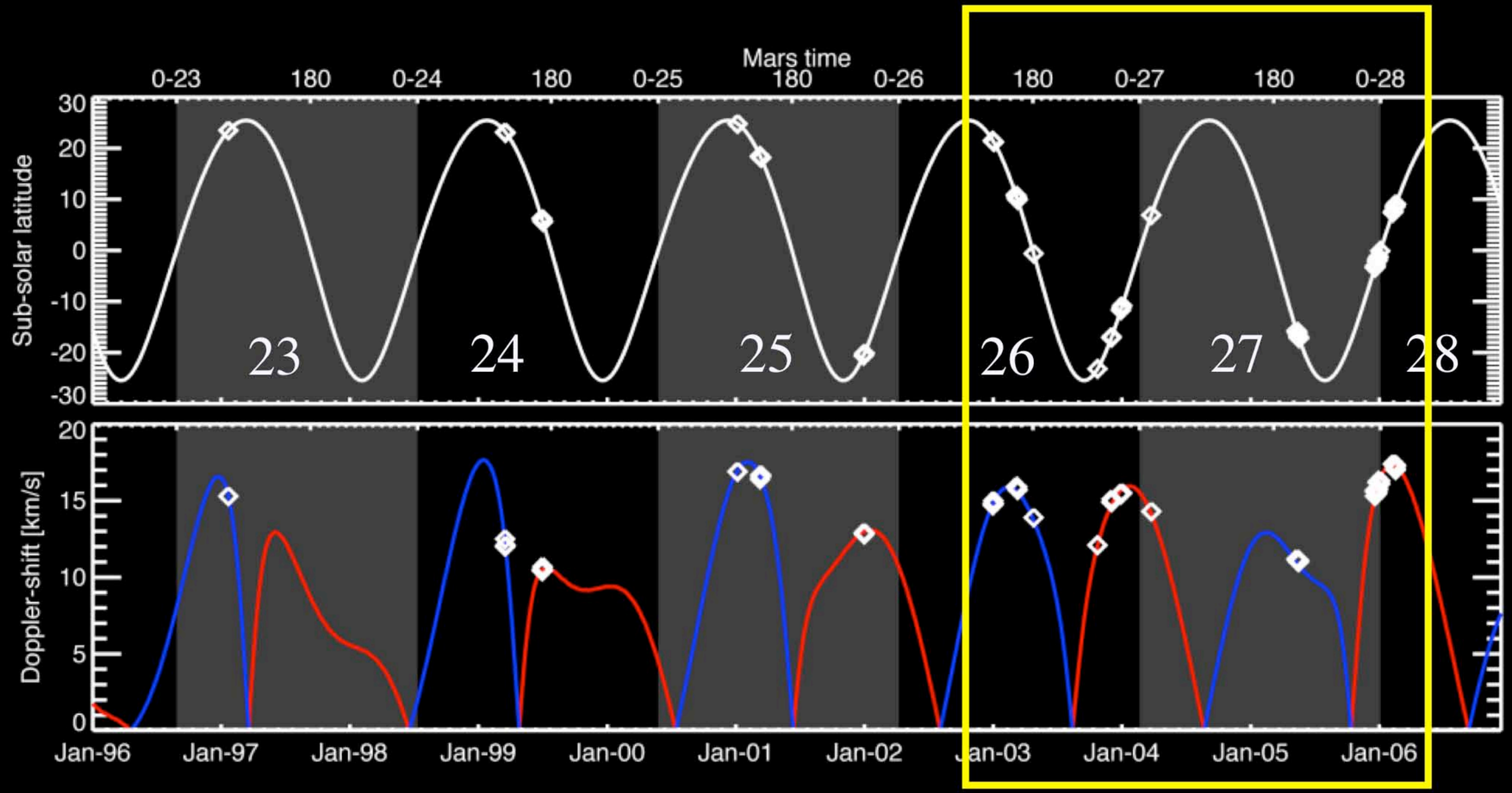


Mauna Kea – A Supreme Site & Fabulous Assets

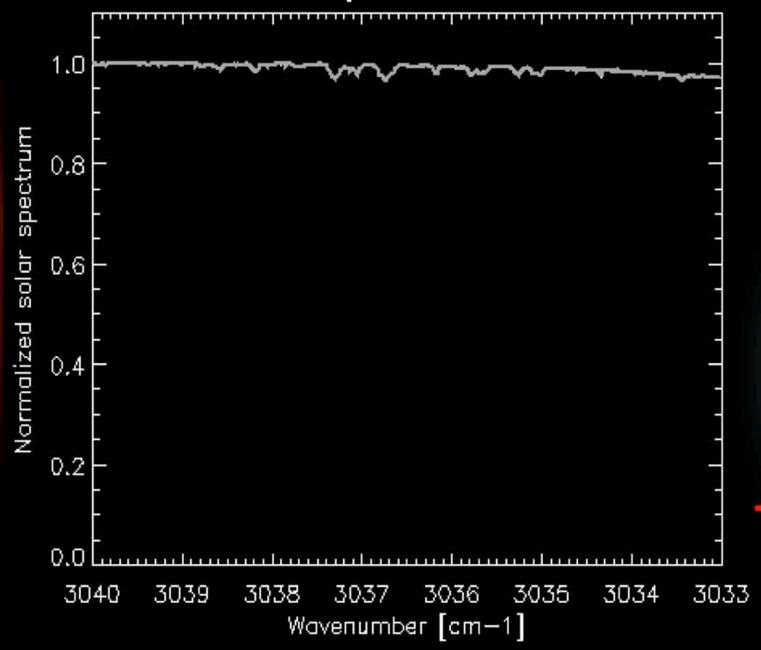
The Goddard Database – Methane Searches 1997 - 2006





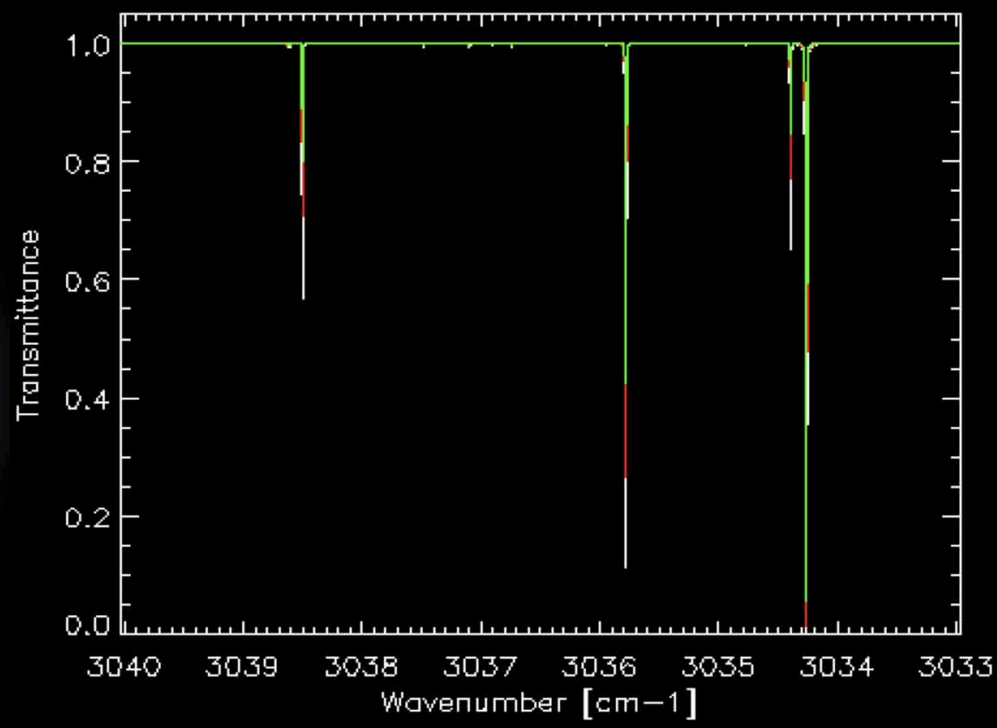


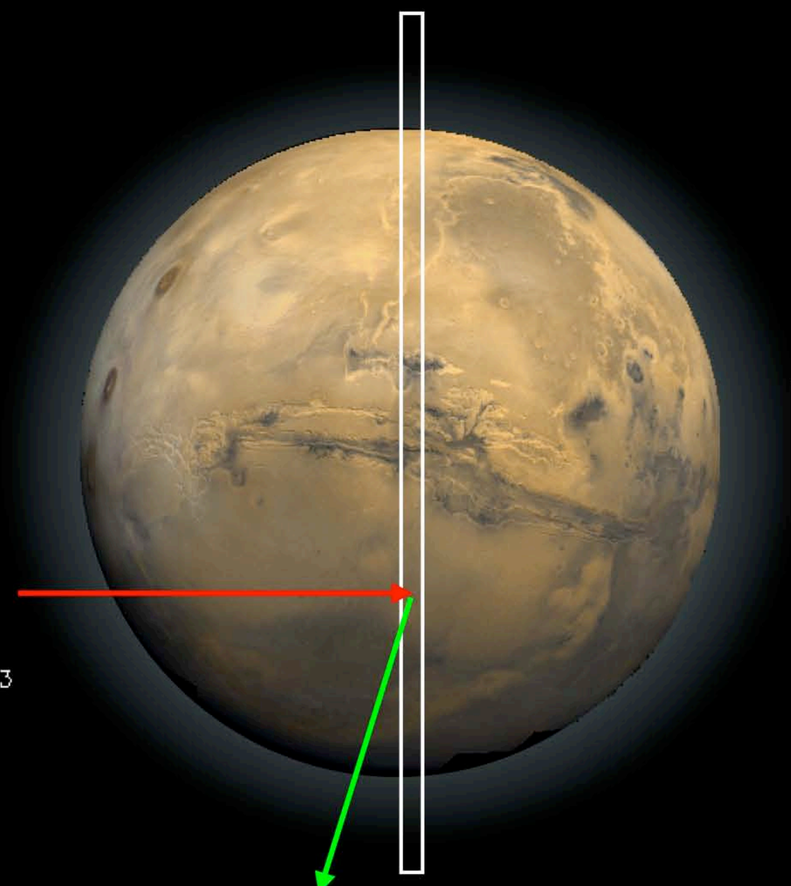
Solar Spectrum



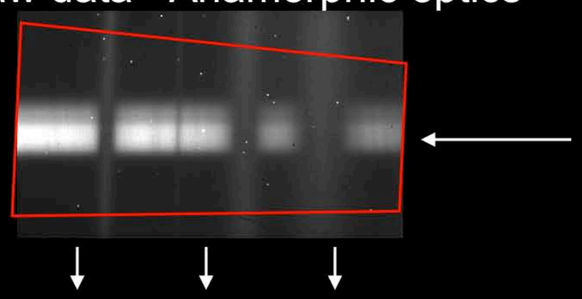
Double path absorption

Sun-Mars, Mars-Earth, Total

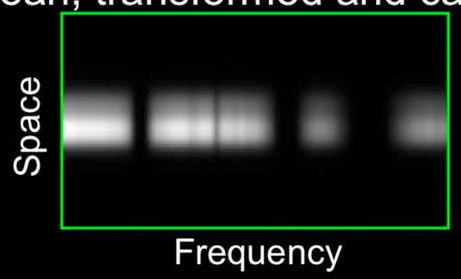


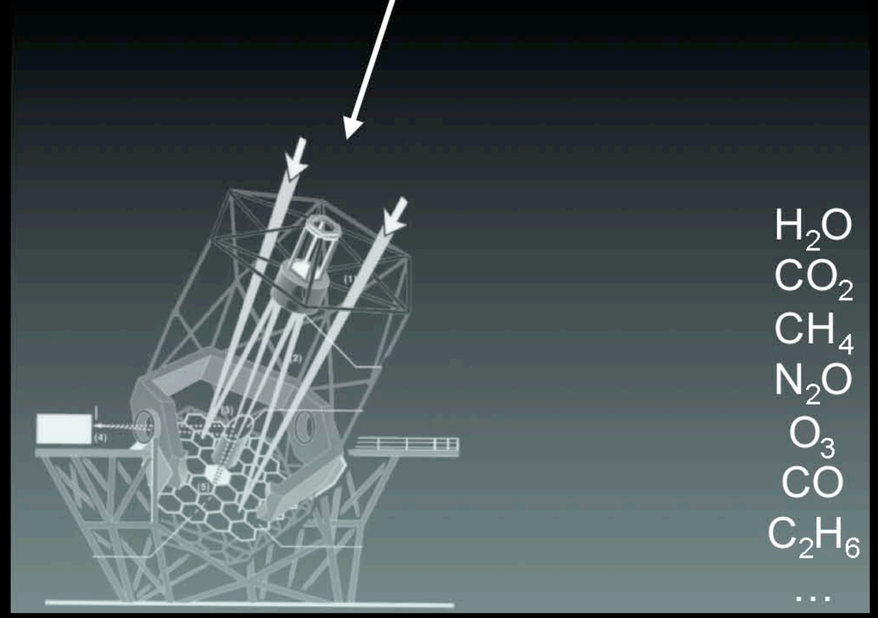


Raw data - Anamorphic optics



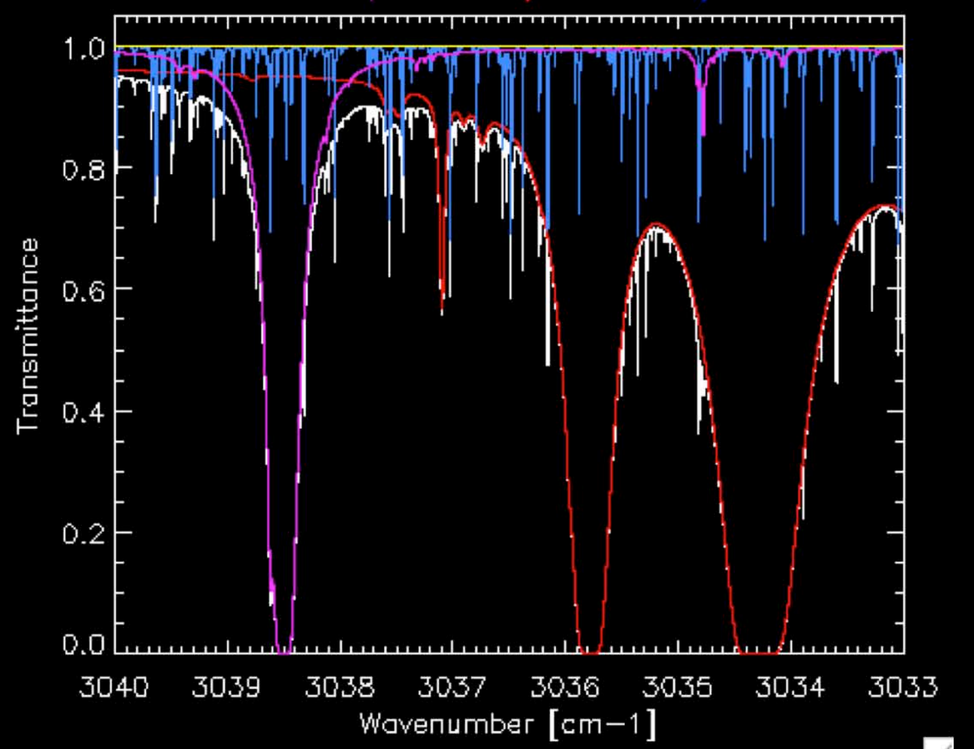
Clean, transformed and calibrated





H_2O
CO_2
CH_4
N_2O
O_3
CO
C_2H_6
…

Methane, Water, Ozone, Total



Analysis Changes Leading to Absolute Extractions (2005 Onward)

Pipeline Processing

From raw spectral-spatial frames to calibrated & registered frames

- Re-sample wavelength scale to milli - pixel accuracy (row-by-row)
- Use non-linear wavelength re-sampling (atmospheric emission)
- Remove second order fringing (Lomb periodogram analysis)
- Remove internal scattered light
- Correct residual dark current
- Correct residual terrestrial radiance

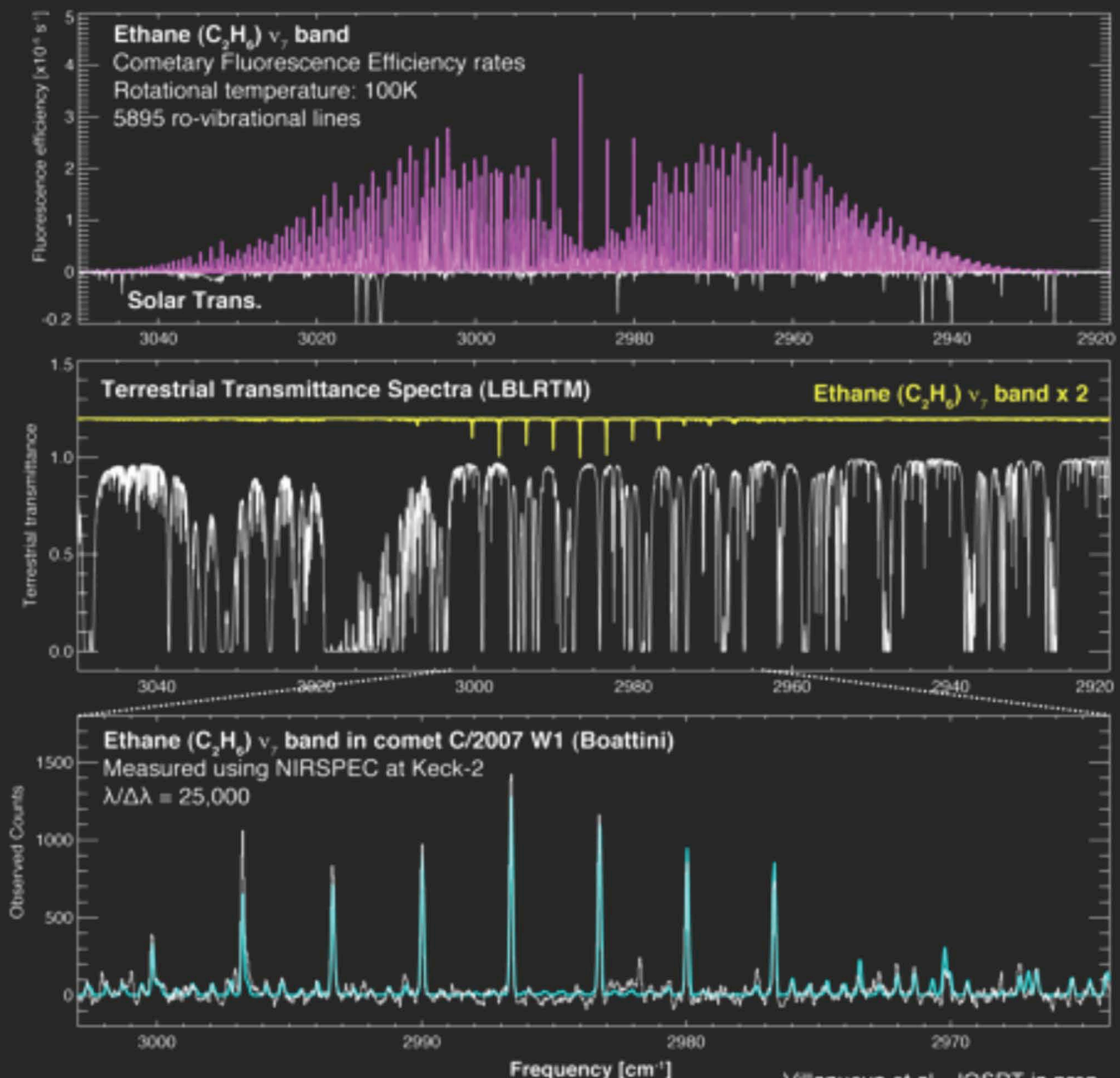
Science Analysis

Atmospheric transmittance -

- Replaced SSP with GenIn2 v4 — and corrected pressure shift code
  - [In 2008: Replaced GenIn2 with LBLRTM]
- Upgraded molecular atlas (now HITRAN ‘08 with additional upgrades)
- Model synthetic spectra using variable resolving power along the slit

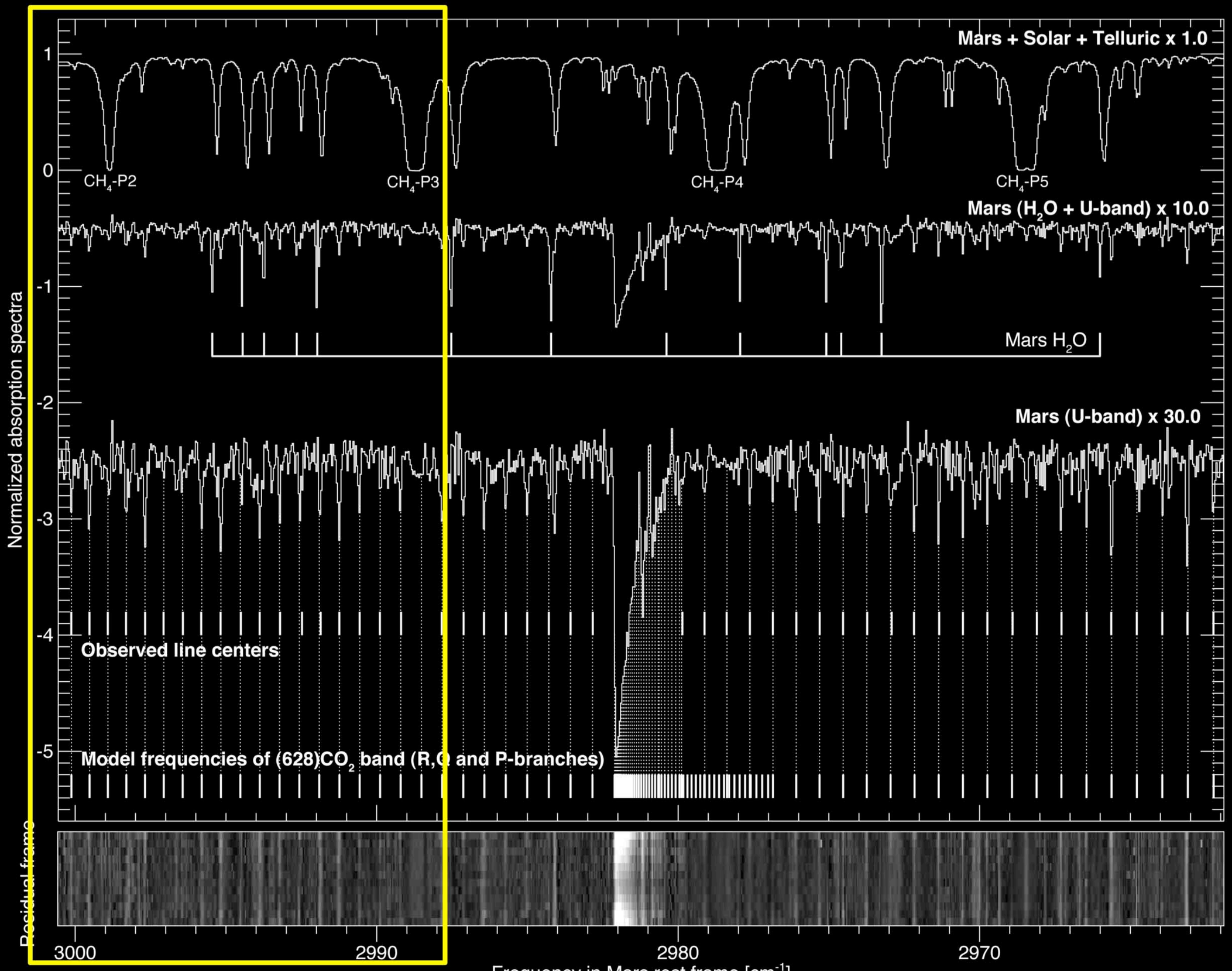
New ethane (C_2H_6) ν_7 terrestrial model

Improving the CH_4 P-branch spectral region



Villanueva et al., JQSRT in prep.

$L_s = 156°$ late northern summer Geocentric velocity : -15.9 km/sec

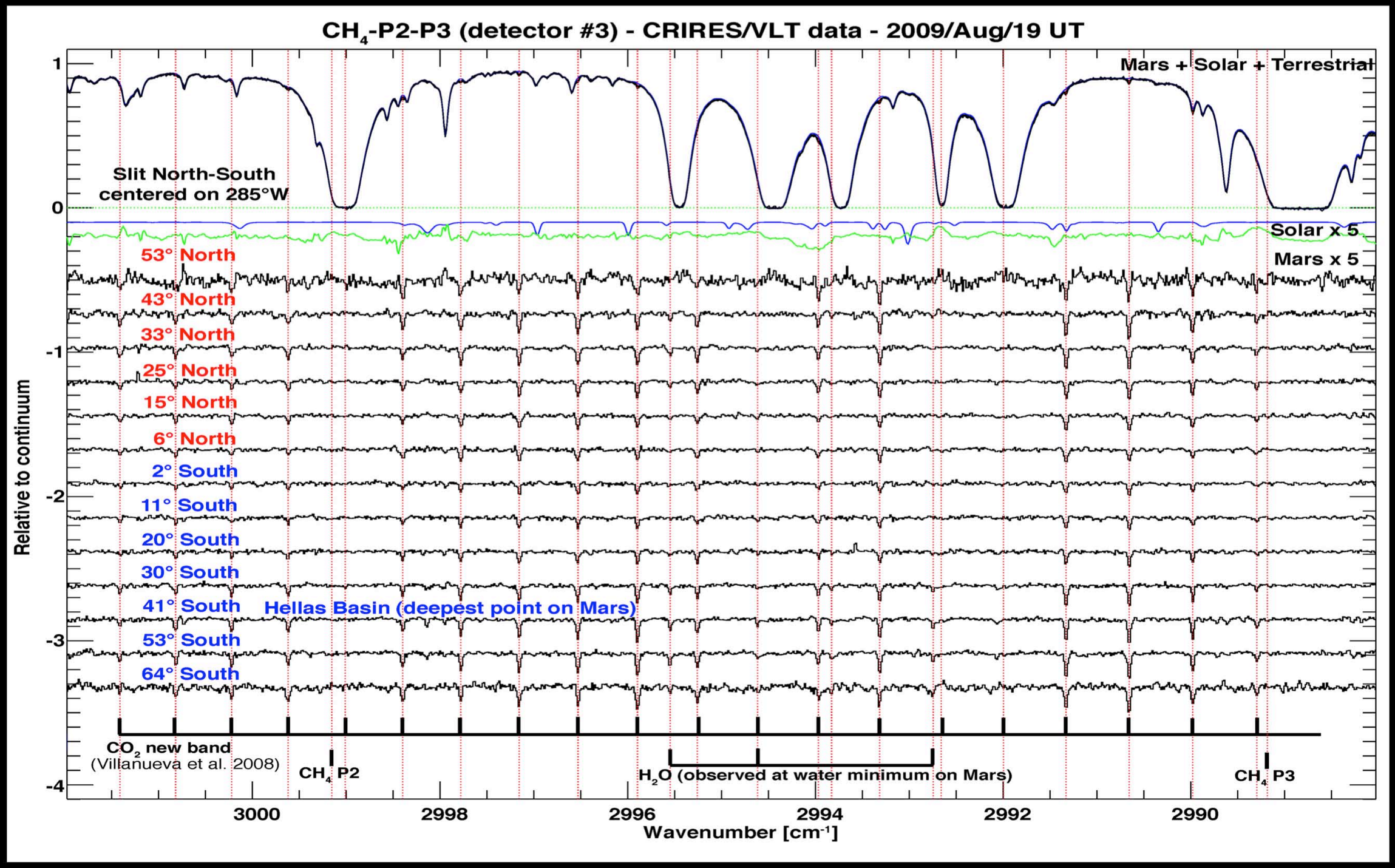


Methane on Mars

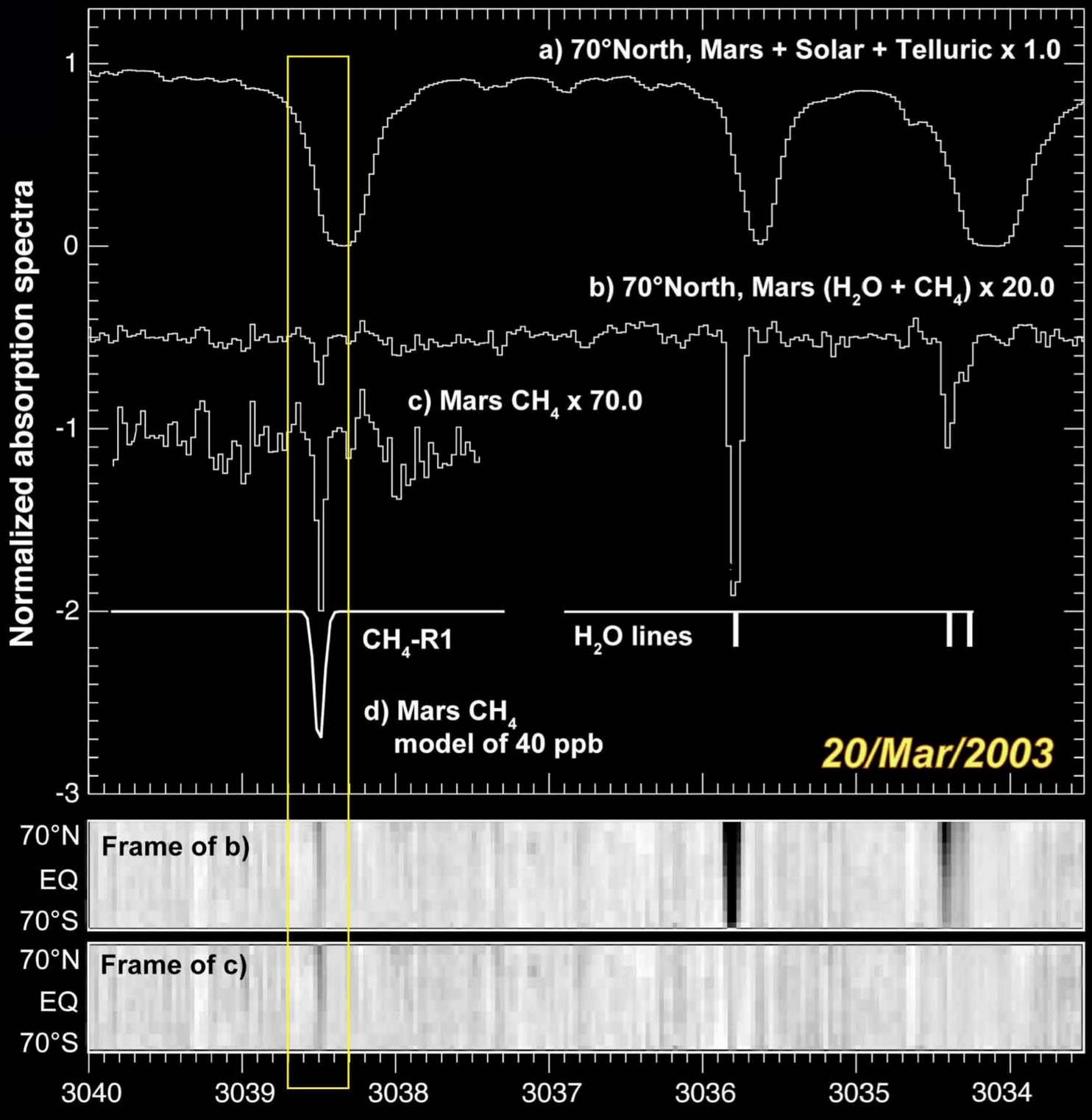
M. J. Mumma, G. L. Villanueva, R. E. Novak, et al.

CRIRES $L_s = 325°$ NH mid-winter Geocentric velocity : – 9.4 km/sec

D1 3041.01 - 3025.36 D2 3021.06 - 3006.25 D3 3002.36 - 2988.37 D4 2984.80 - 2971.62

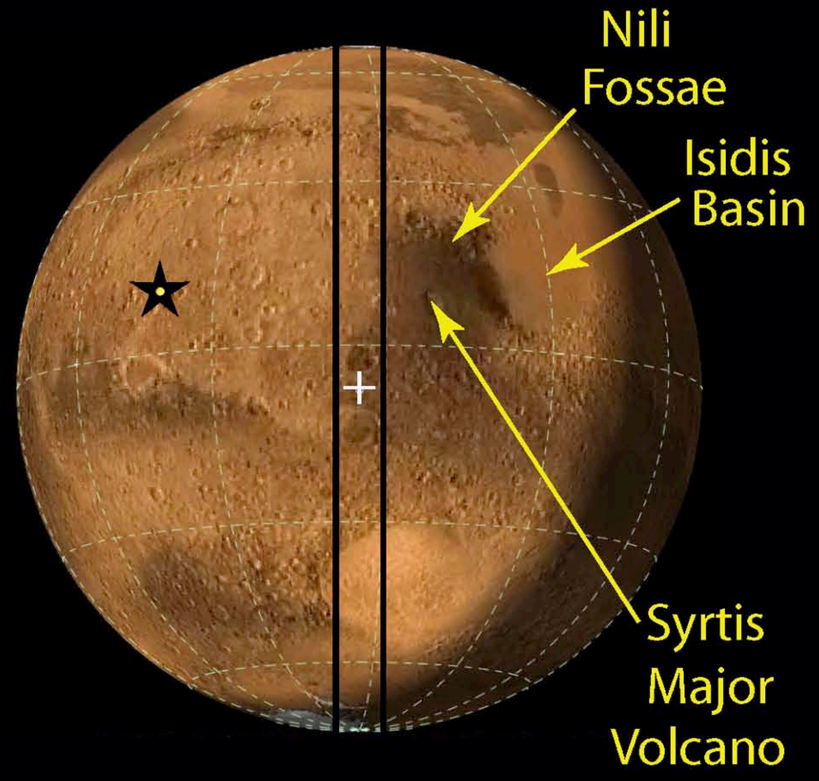


Clear Detections of Methane and Water on Mars



Northern late-summer

$L_s = 155°$

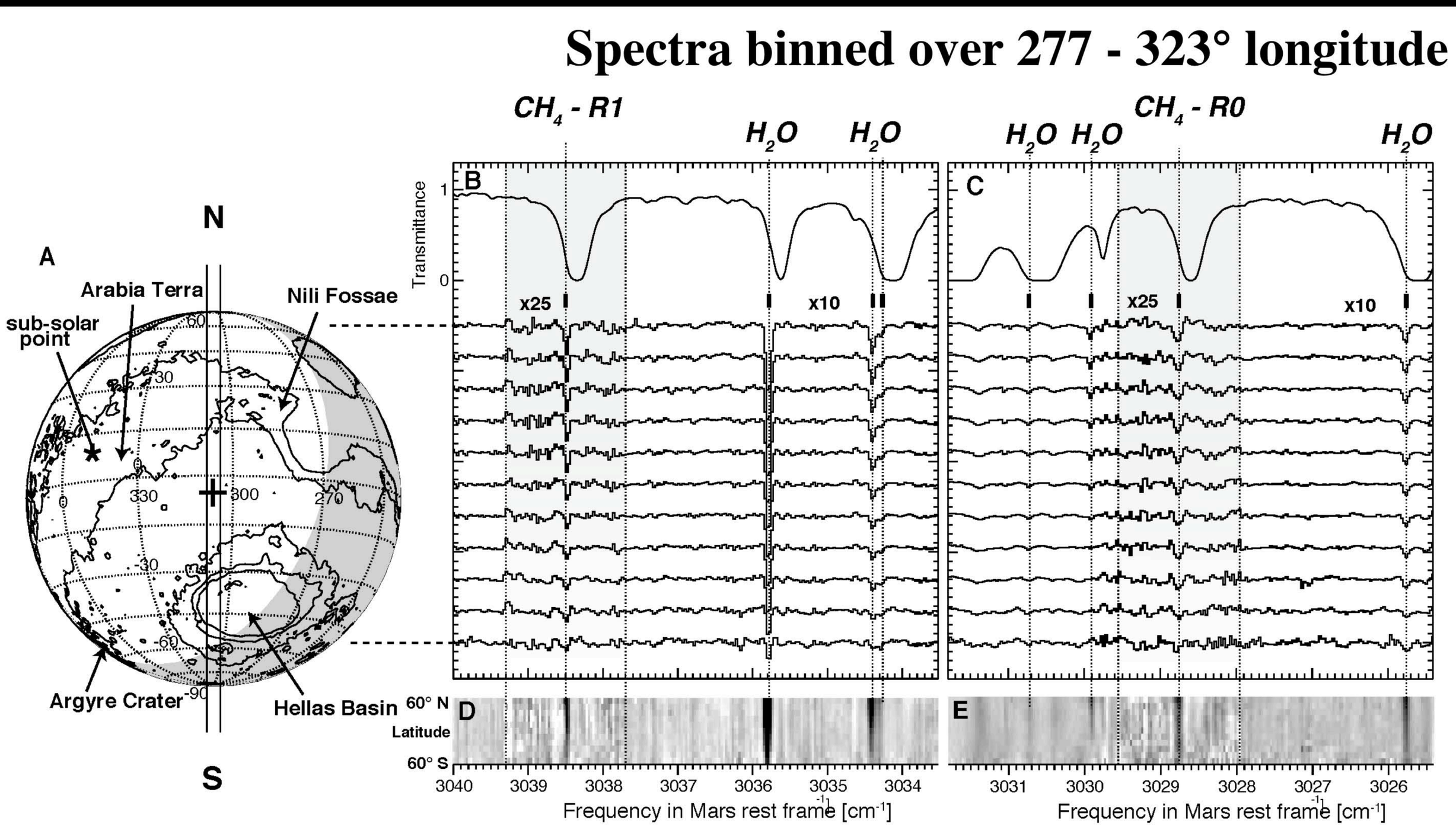


Both gases are enhanced towards the North

Mumma, Villanueva, Novak, et al. (Science 2009)

March 20 & 21, 2003 $L_s = 155°$ Northern summer

Two independent lines of methane are detected, and they show the same latitudinal dependence

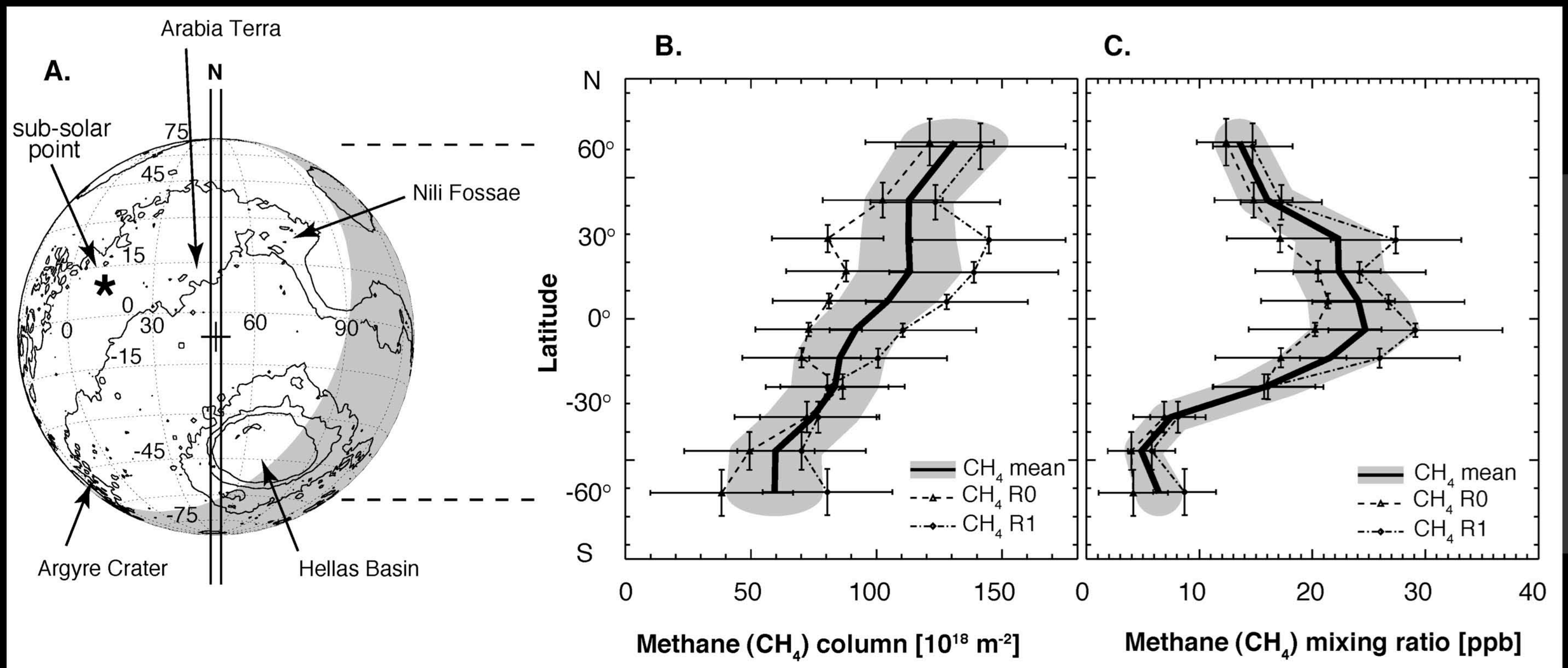


Mumma, Villanueva, Novak, et al. (Science 2009)

Additional Checks are Satisfied

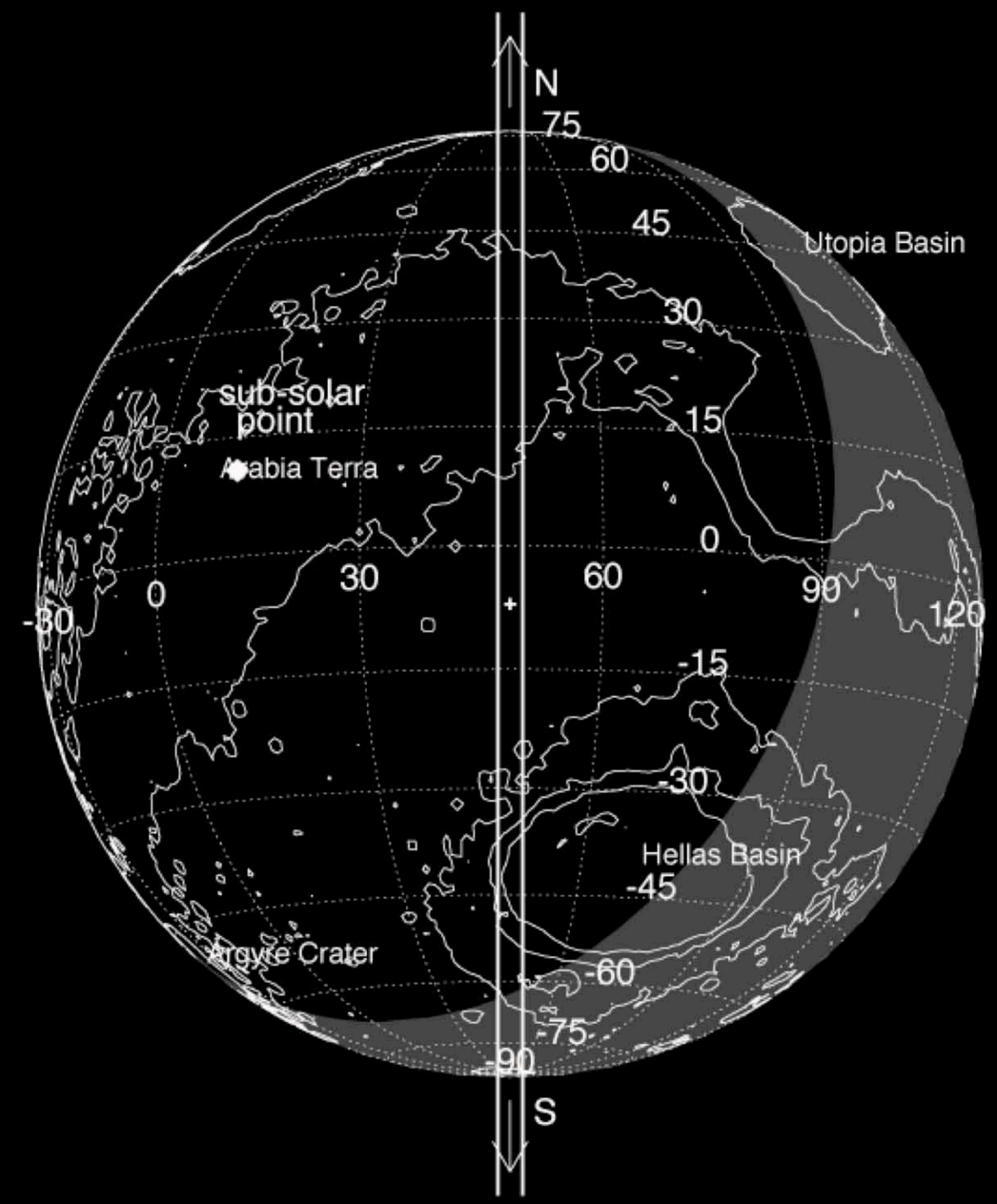
The column abundances obtained from two independent lines of methane agree within errors.
The mixing ratios obtained from two independent lines of methane agree within errors (right).
A pronounced maximum in mixing ratio is seen over equatorial latitudes (right).

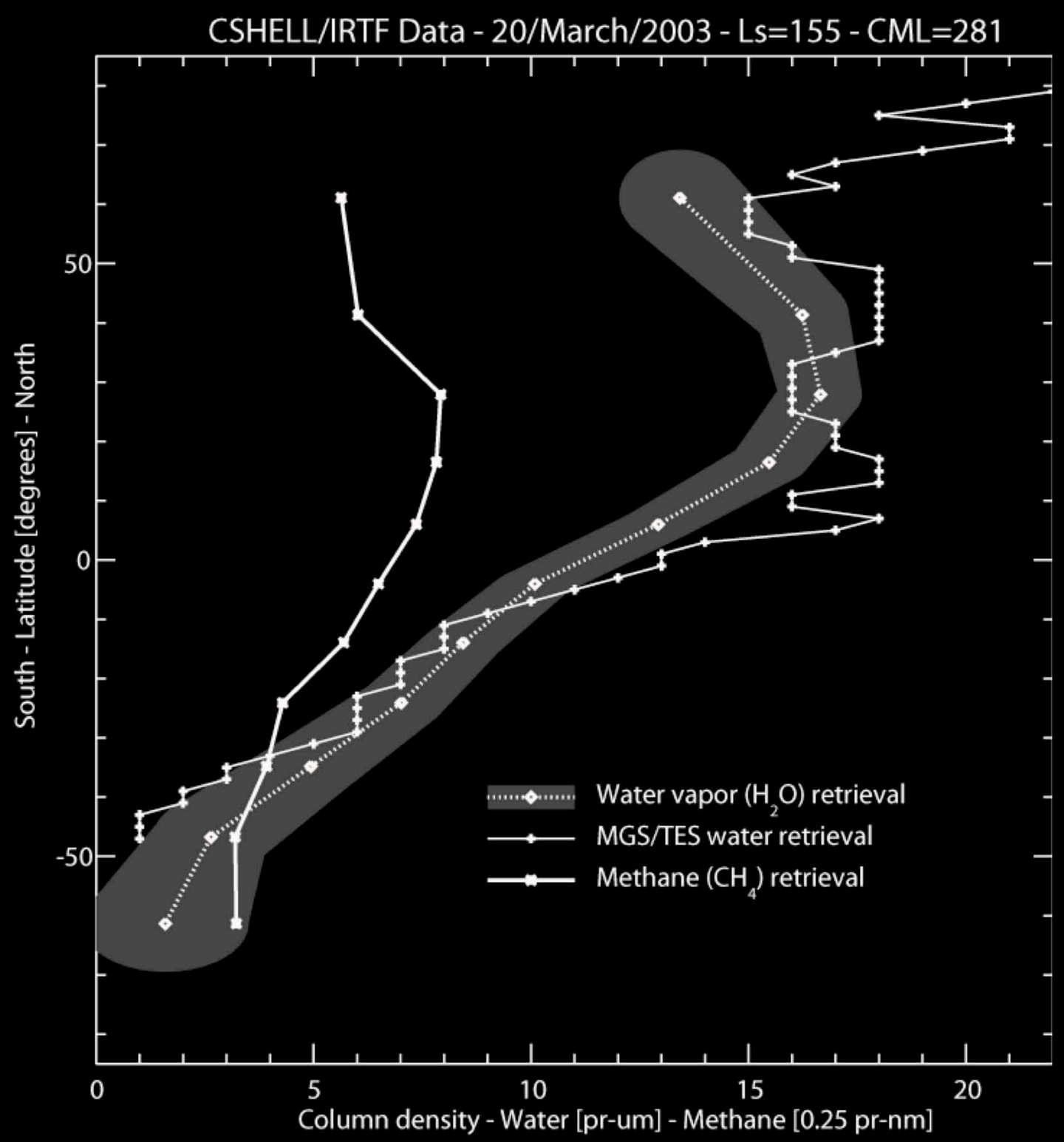
Two more methane lines are detected (the P2 doublet) during Southern spring (not shown).



Mumma, Villanueva, Novak, et al. (Science 2009)

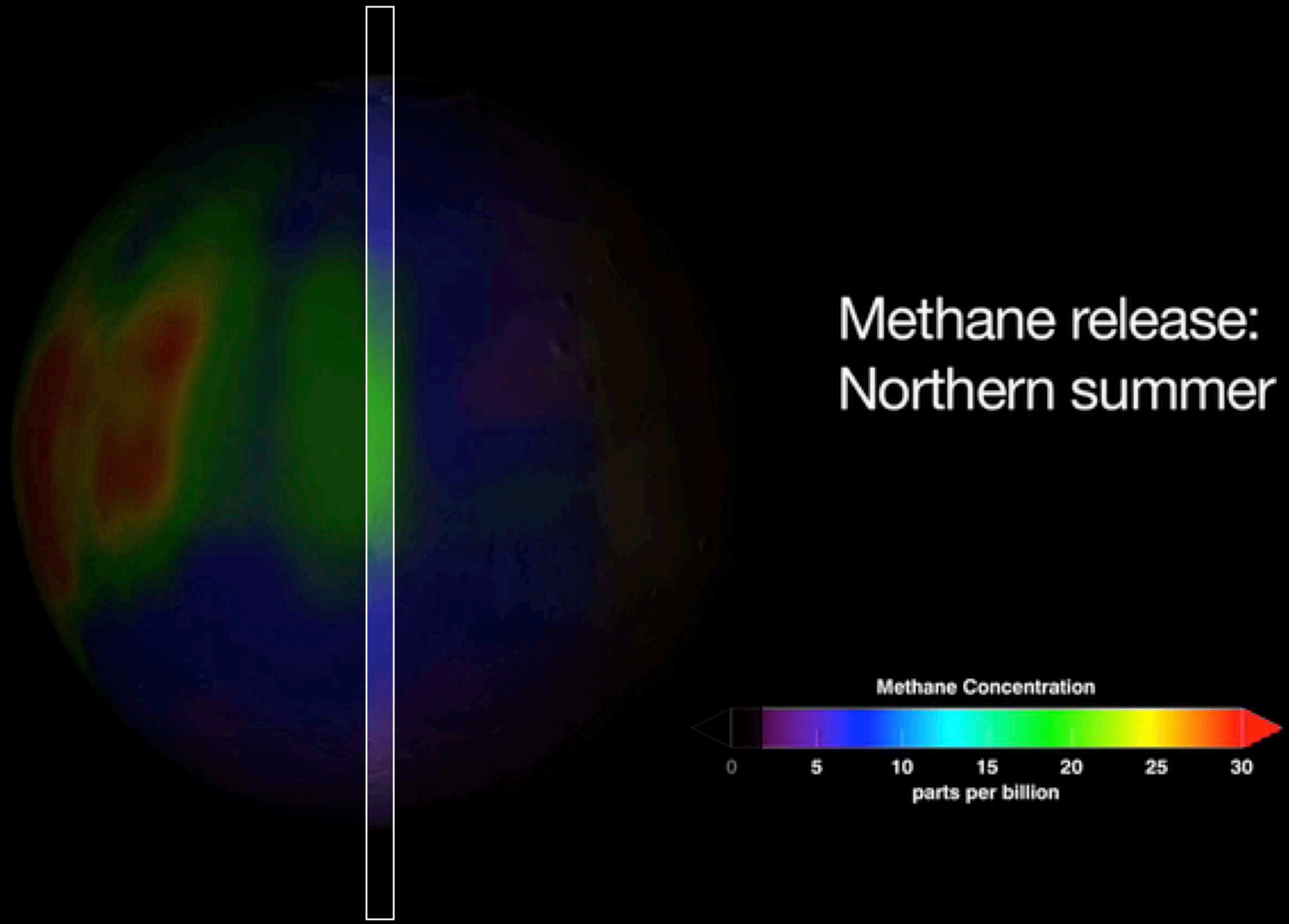
Ground Truth: The Water vapor retrievals agree with TES



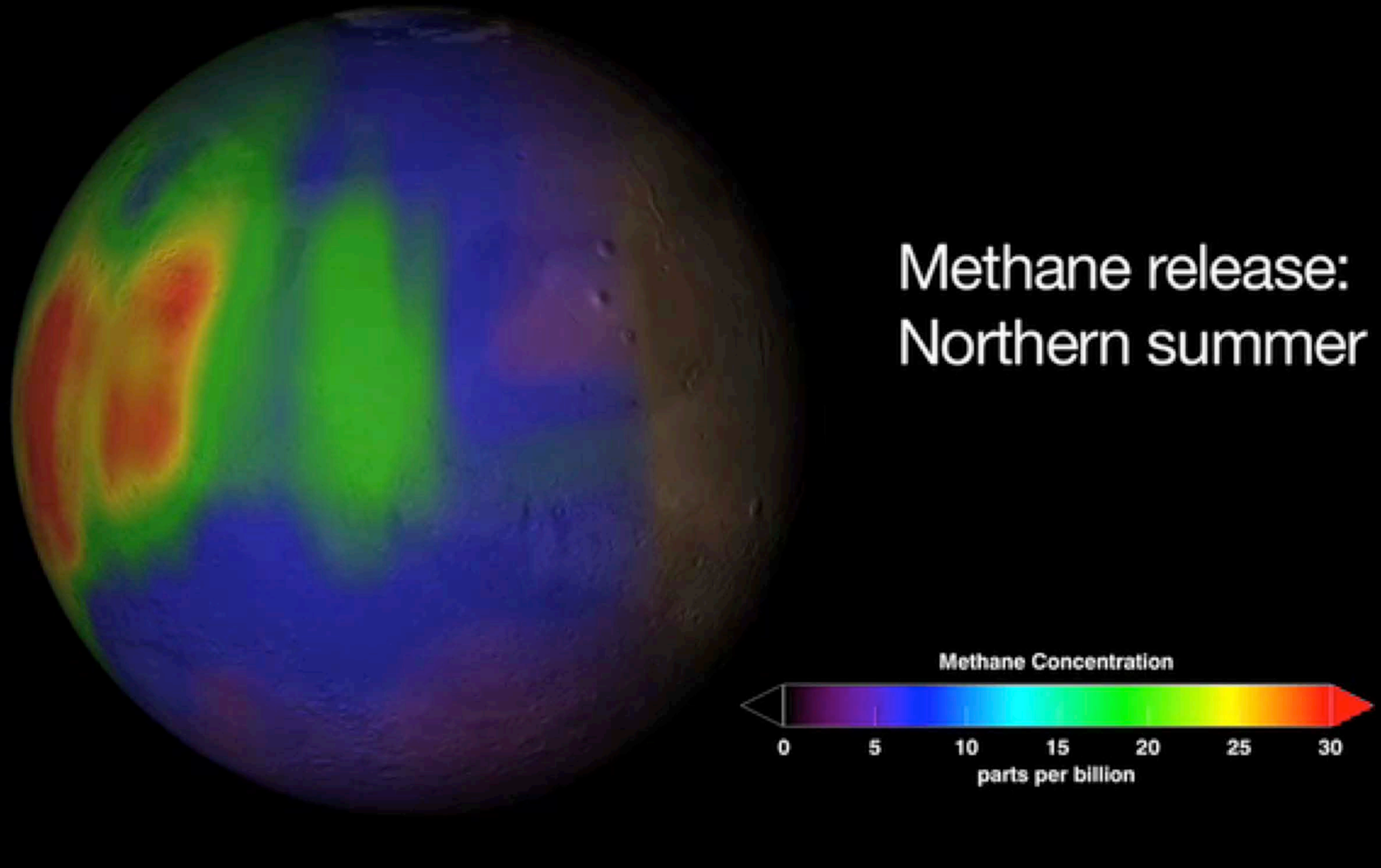


Mumma, Villanueva, Novak, et al. (Science 2009)

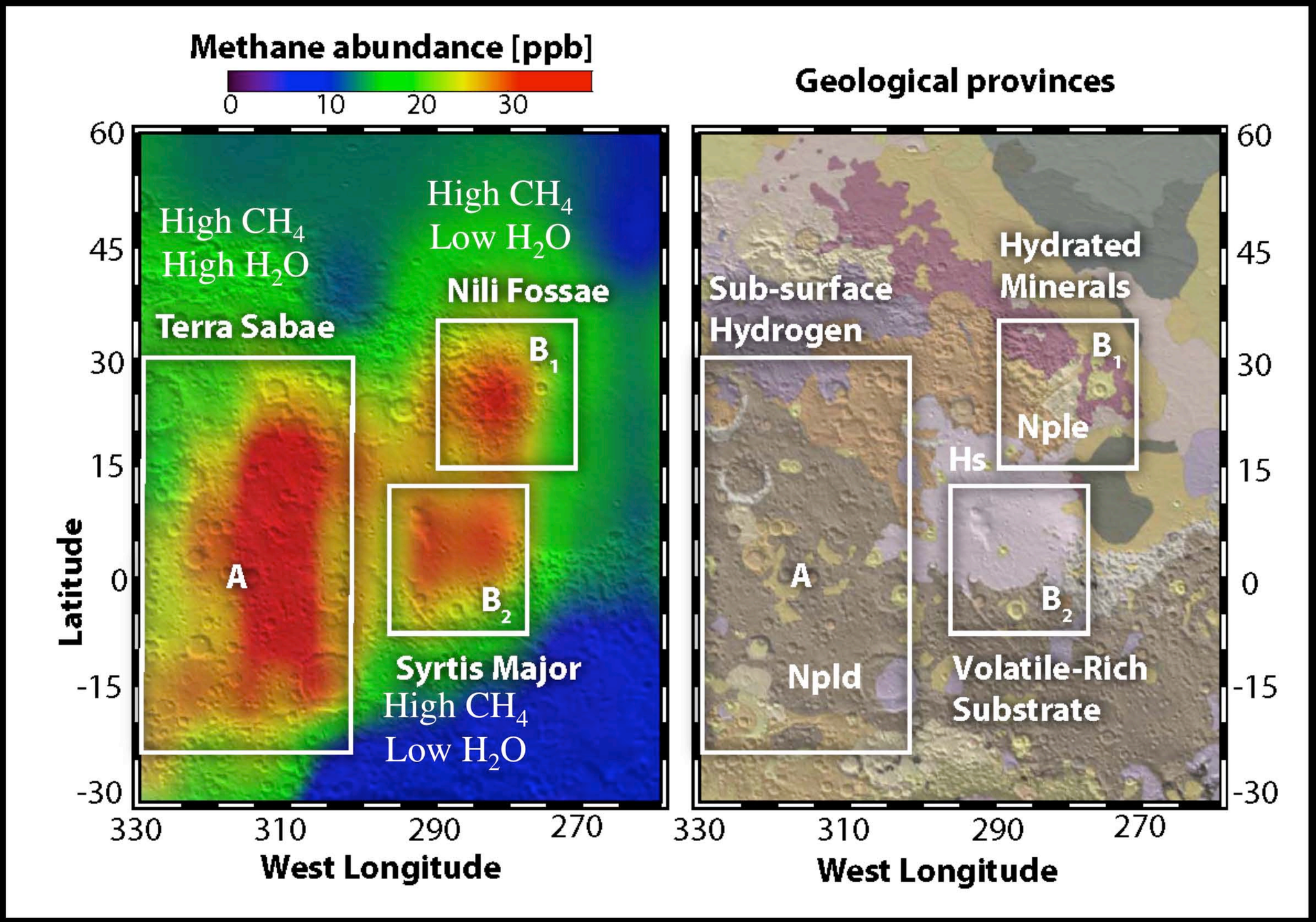
Mapping the Methane Plumes on Mars



The Discovery of Methane Plumes on Mars

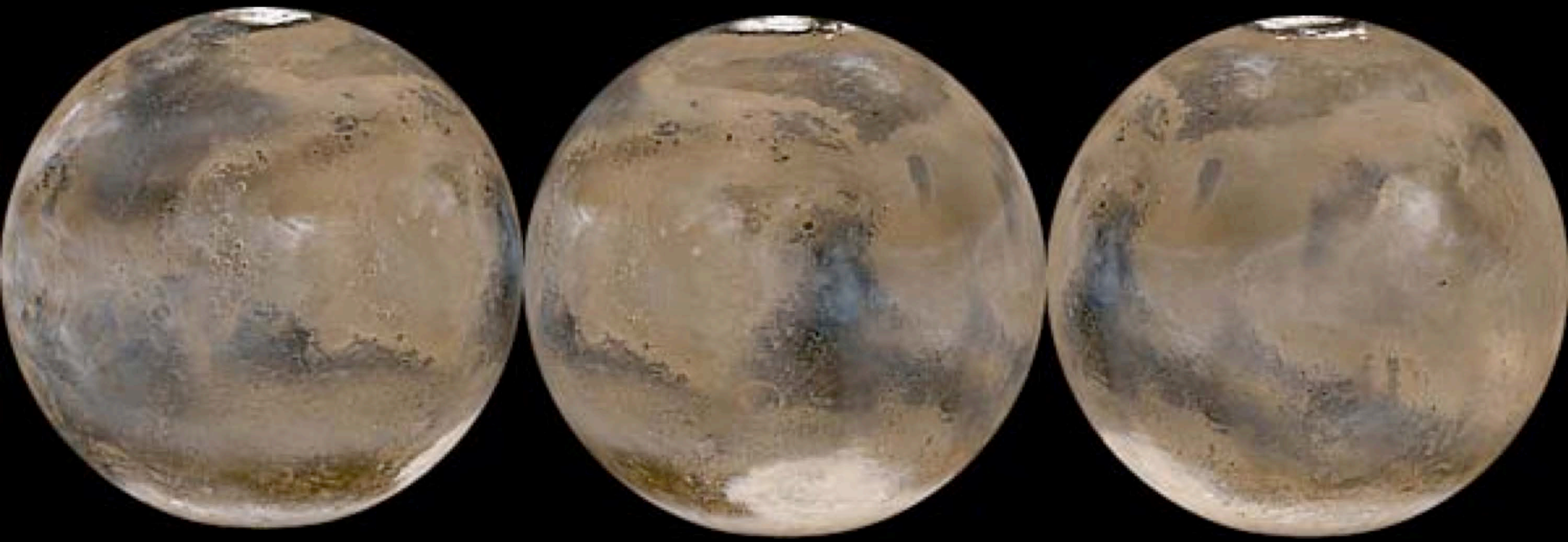


Seeing-limited Spatial Maps reveal local methane plumes on scales of 500 km.
Is the release relatively uniform over these regions – or is it strongly localized?



Mumma, Villanueva, Novak, et al. (Science 2009)

Mars on UT 14 Feb 2003 (Northern mid-summer, L_s 137.8°)



CML 0° W
MOC2-326d

CML 300° W
MOC2-326e

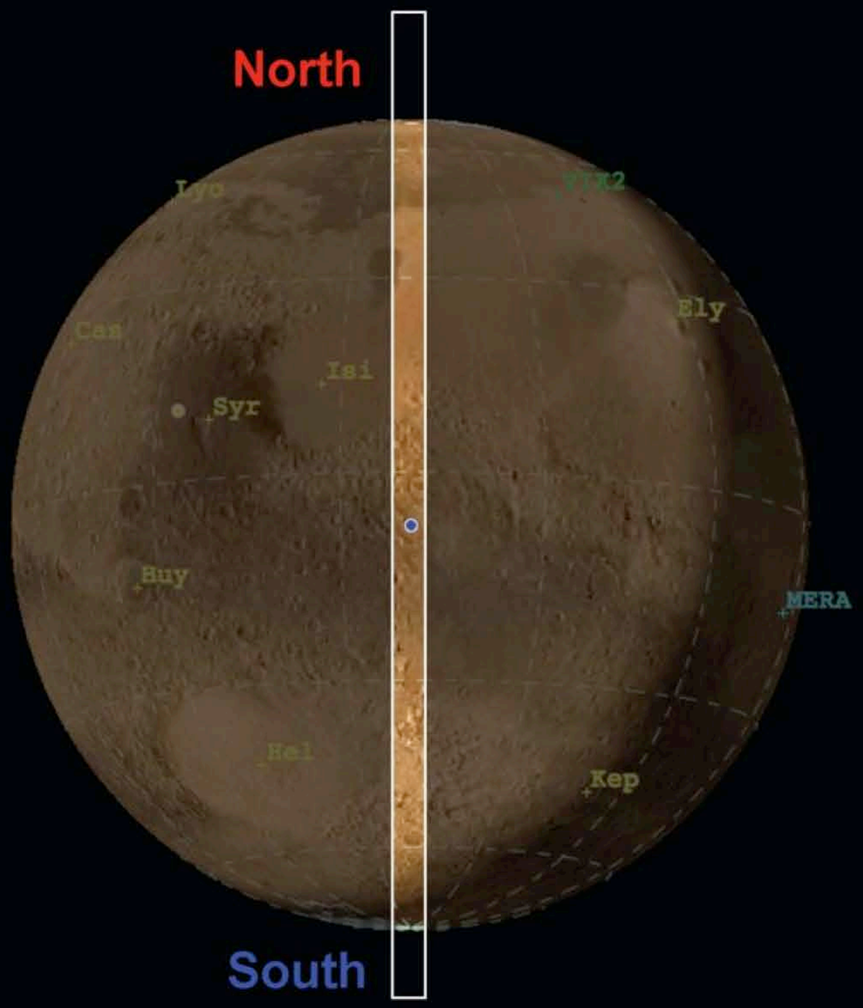
CML 240° W
MOC2-326f

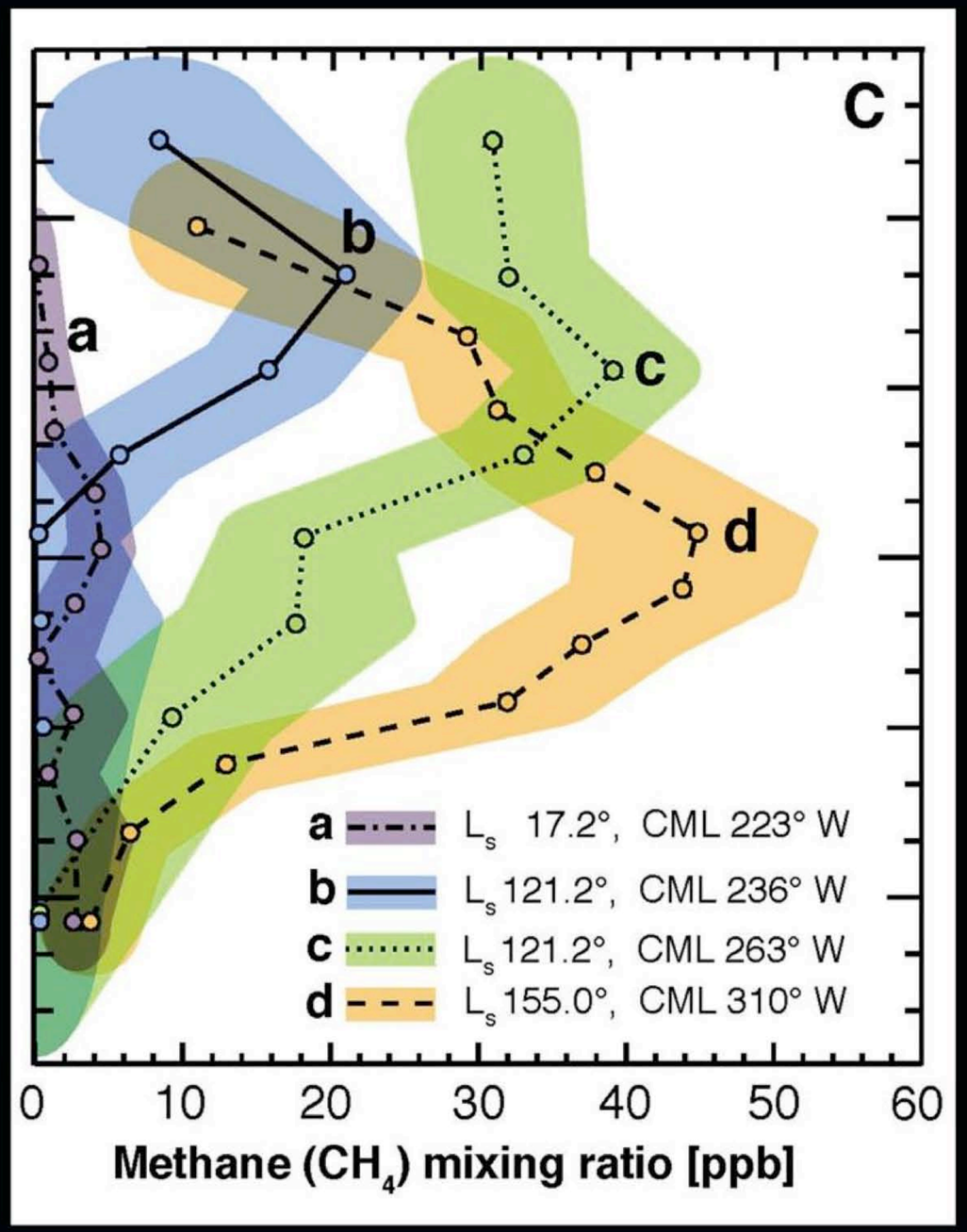
B. C. Cantor, K. S. Edgett, and M. C. Malin, MSSS 2003
http://www.msss.com/mars_images/moc/2003/04/04/globalviews/

Methane varies with latitude, longitude, and season.
The maximum release moves southward with the Sun.
Methane is nearly absent at vernal equinox (after Southern winter).

Northern Summer - Mar. 2003

Vernal Equinox - Jan. 2006

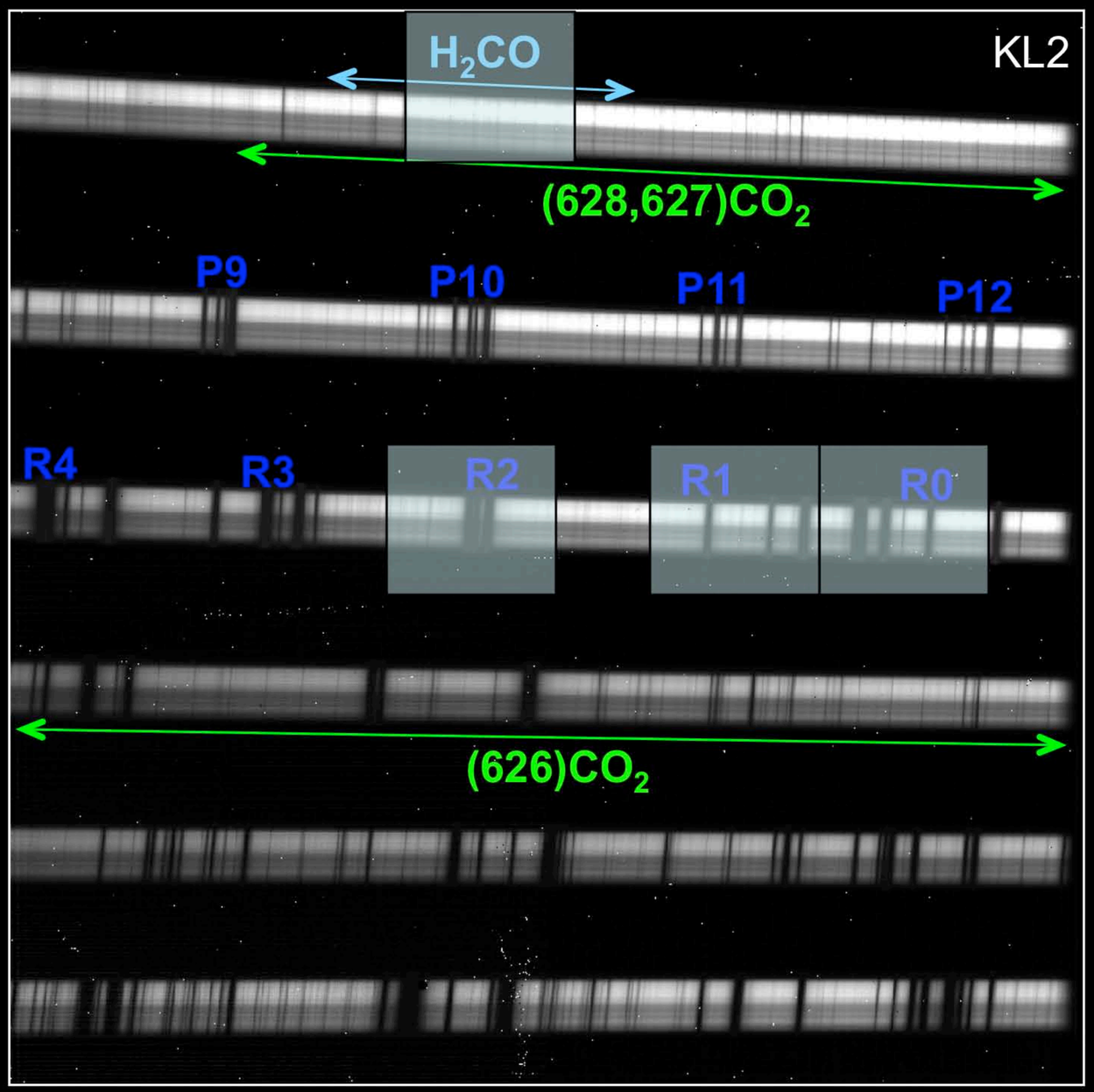


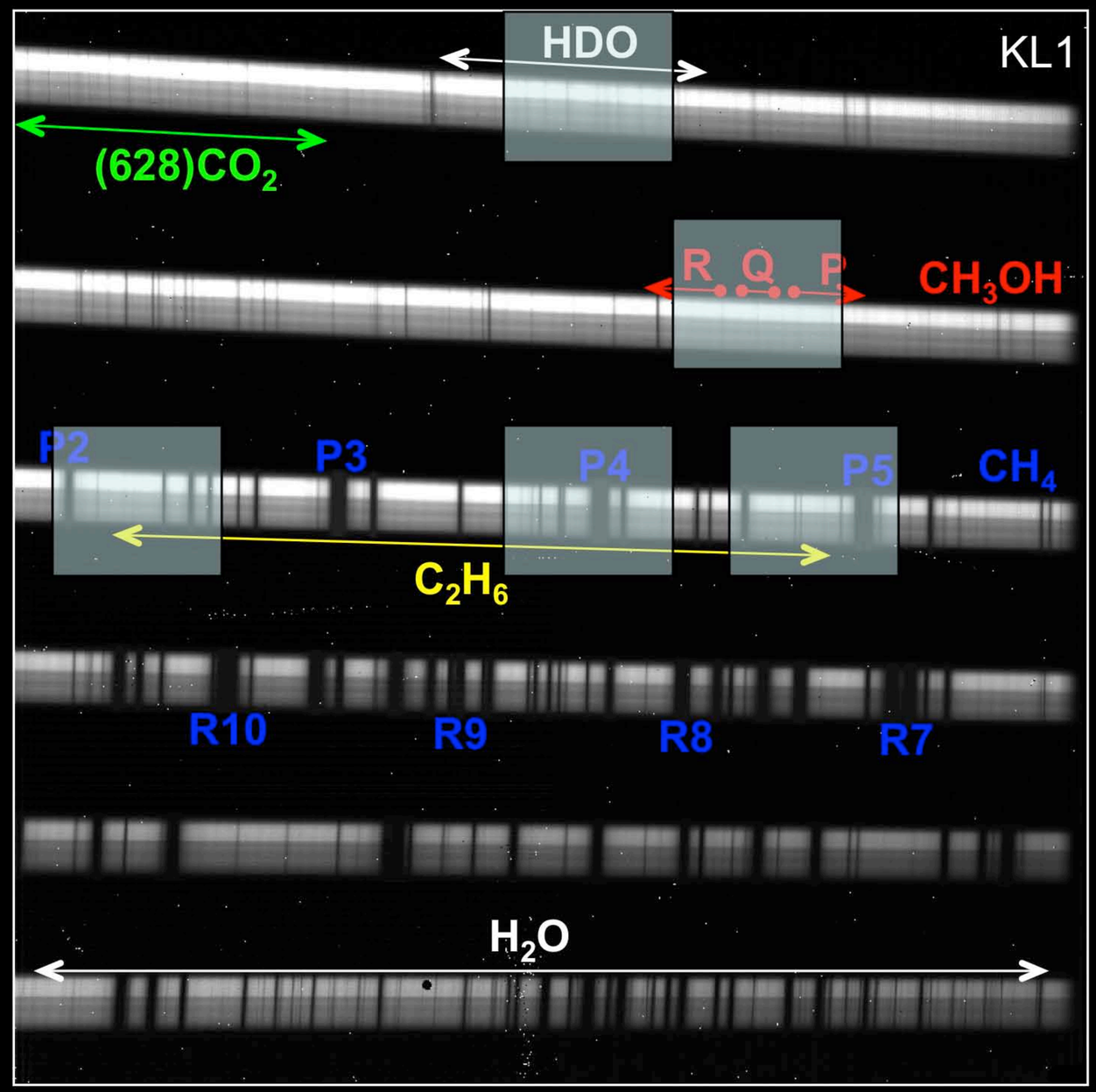


The World's Premier Optical – Infrared Observatory

NIRSPEC Today : CSHELL settings = shaded boxes

Data taken on 5/January/2006 (L_S=352)

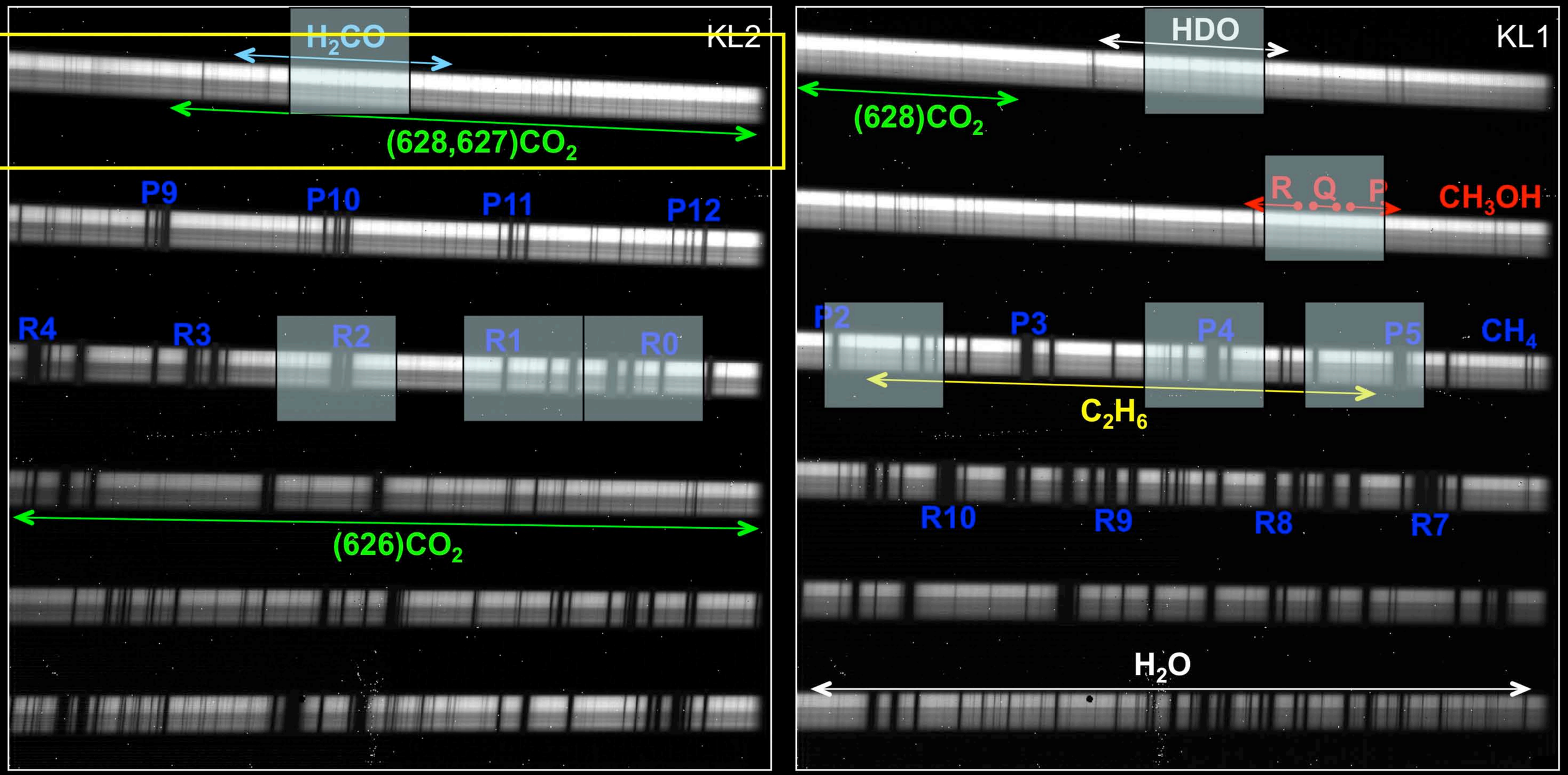




Frequencies between 2700-3400 cm^{-1} (3.7-2.9μm)

NIRSPEC Today : CSHELL settings = shaded boxes

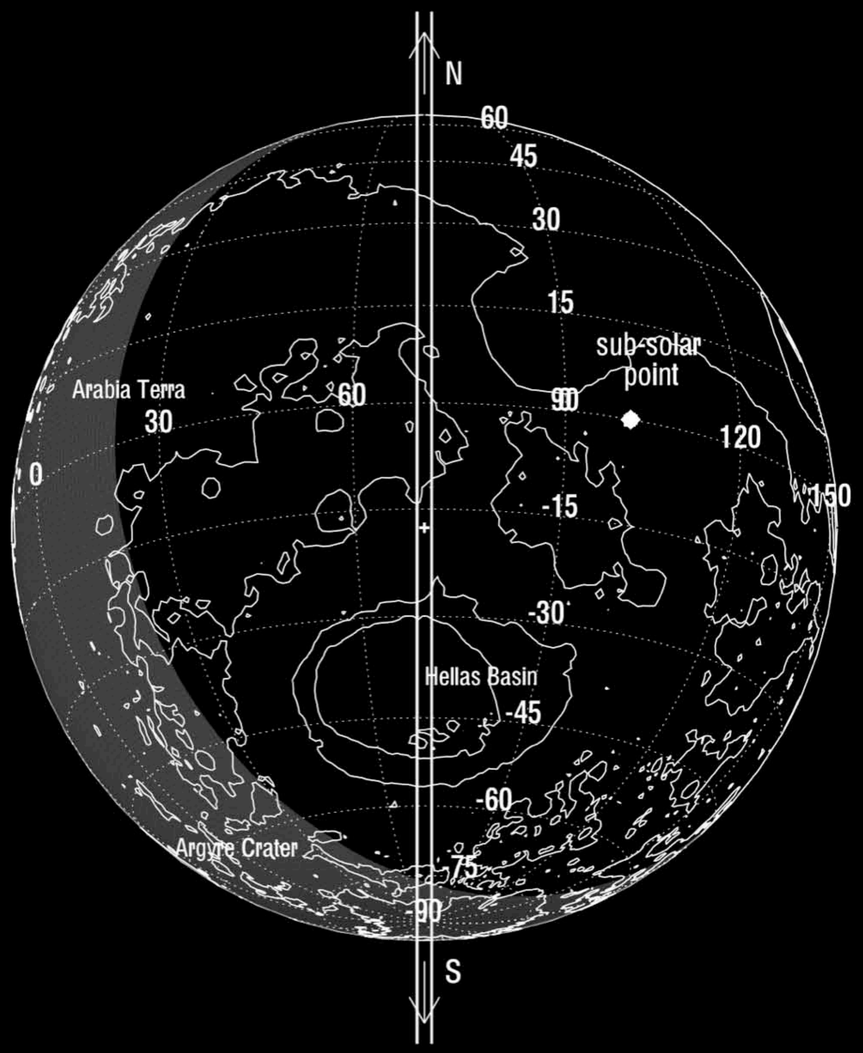
Data taken on 5/January/2006 (L_S=352)

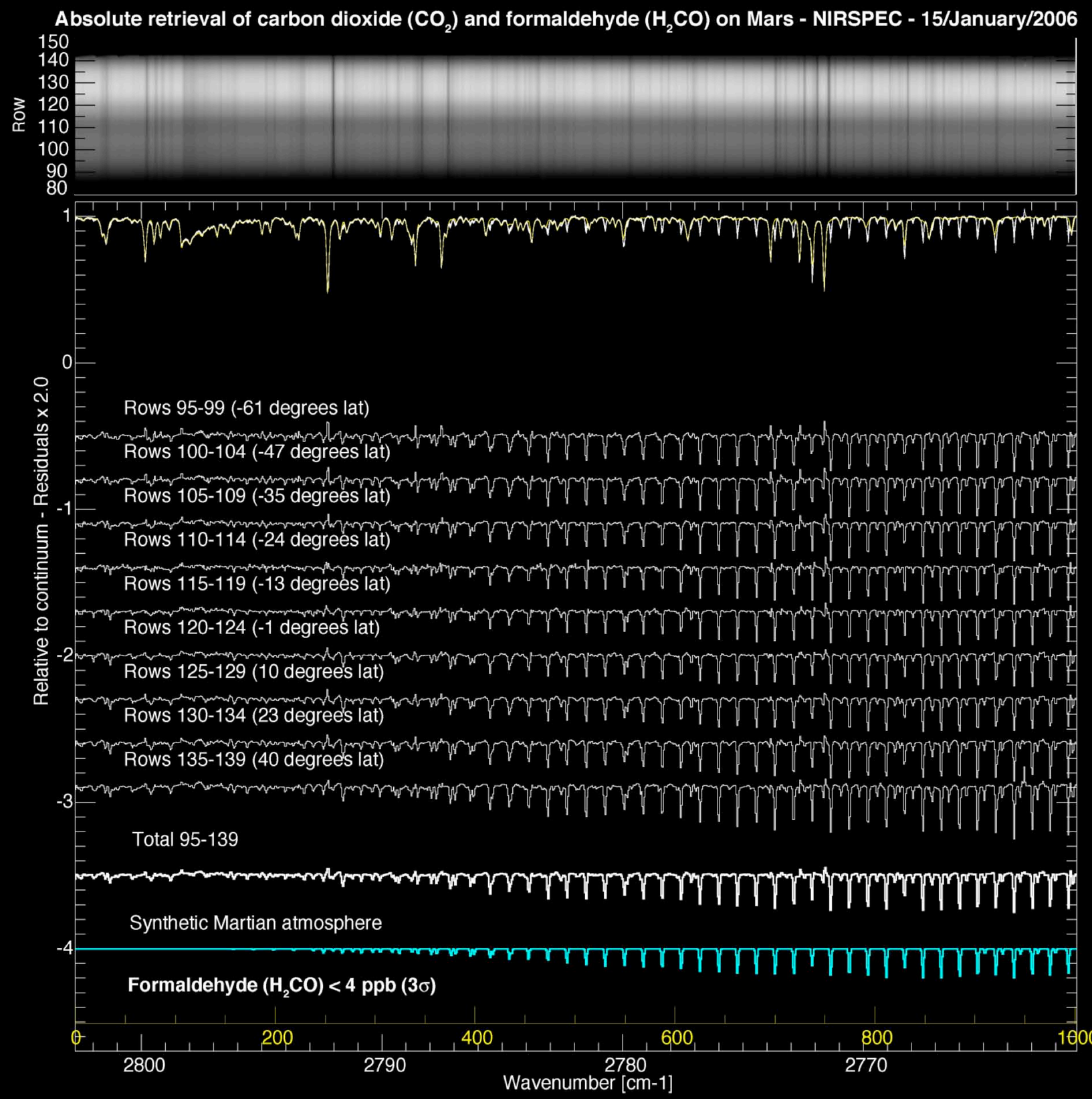


Frequencies between 2700-3400 cm^{-1} (3.7-2.9μm)

Keck – 2

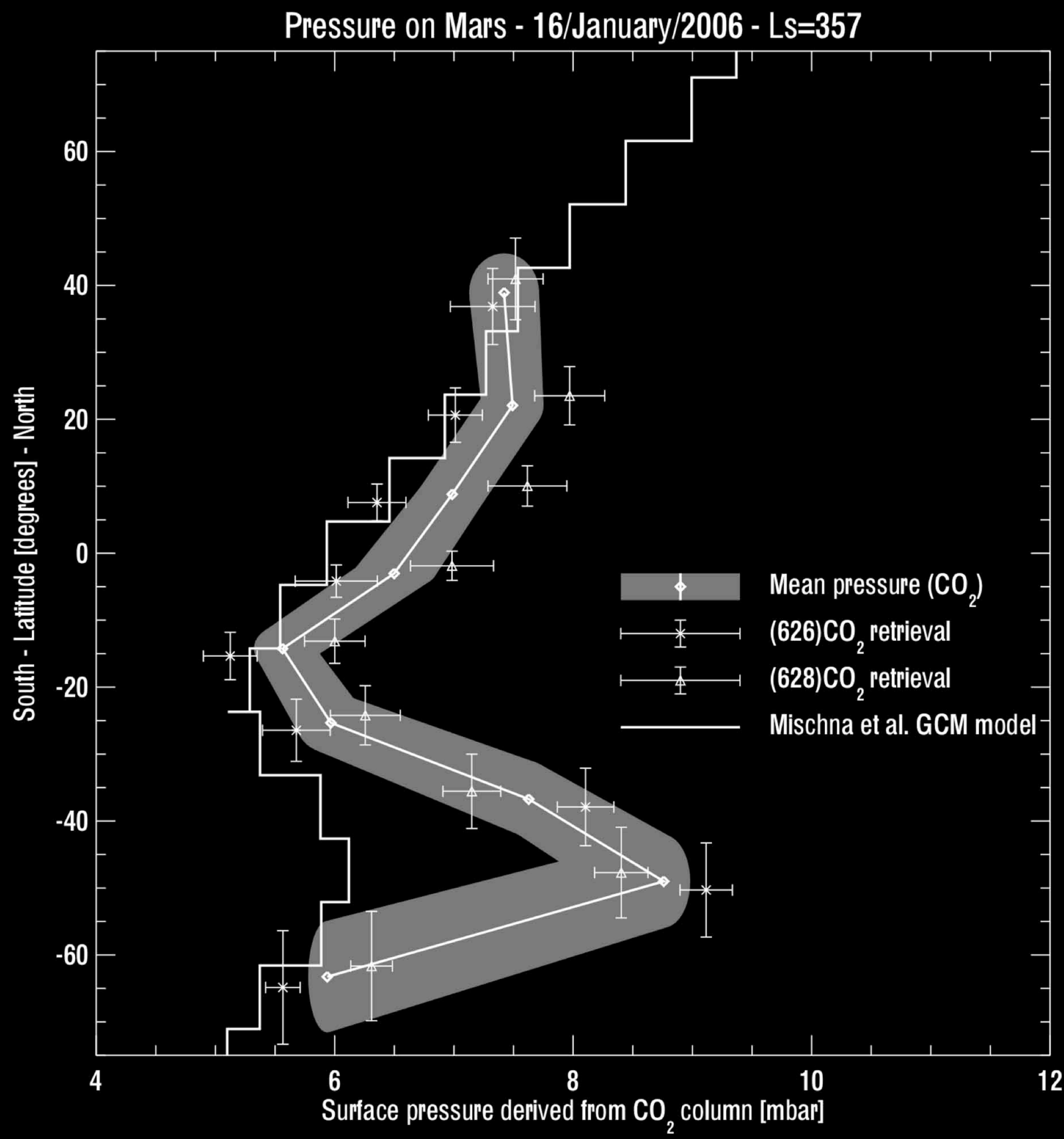
Jan 2006

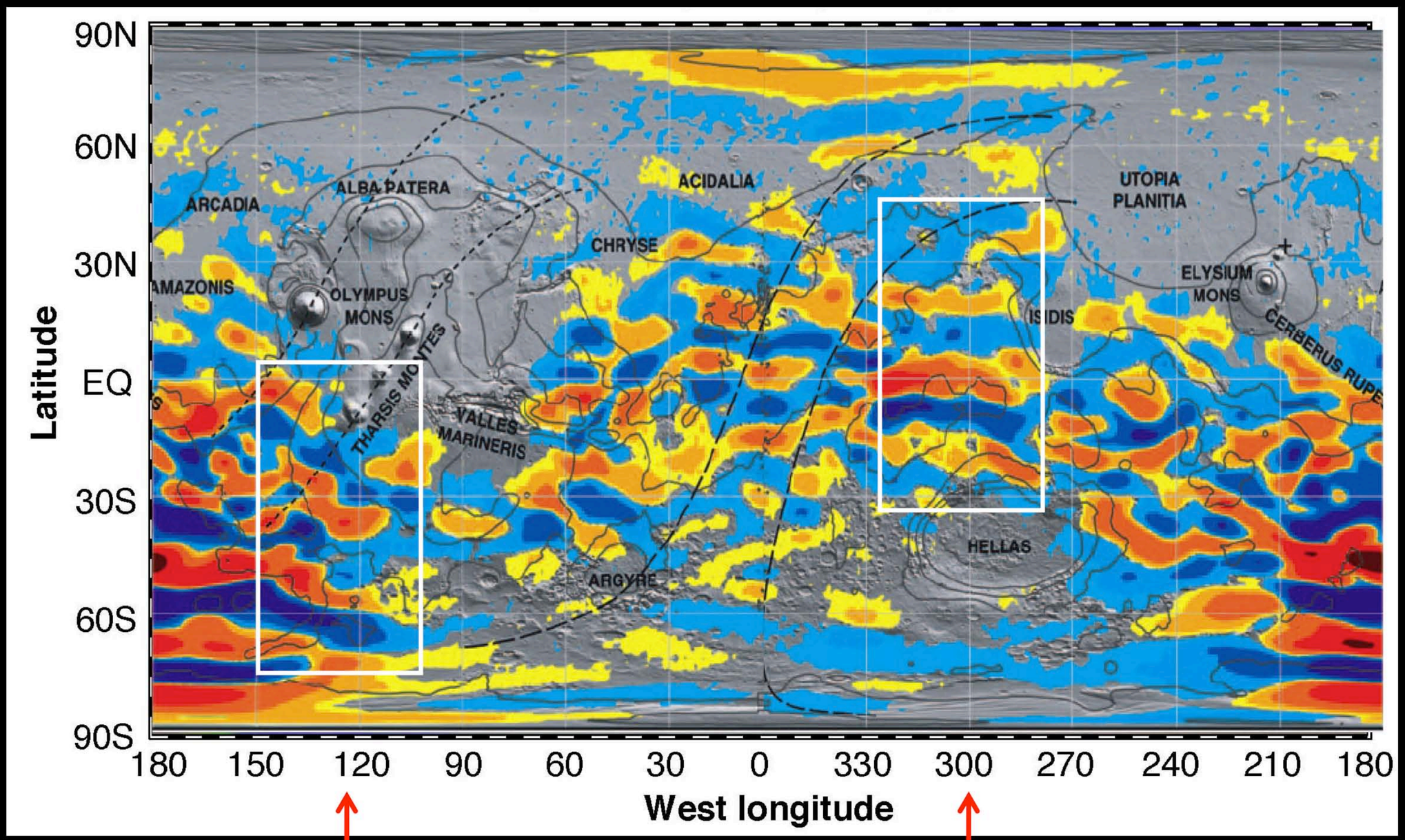




Keck – 2

Jan 2006



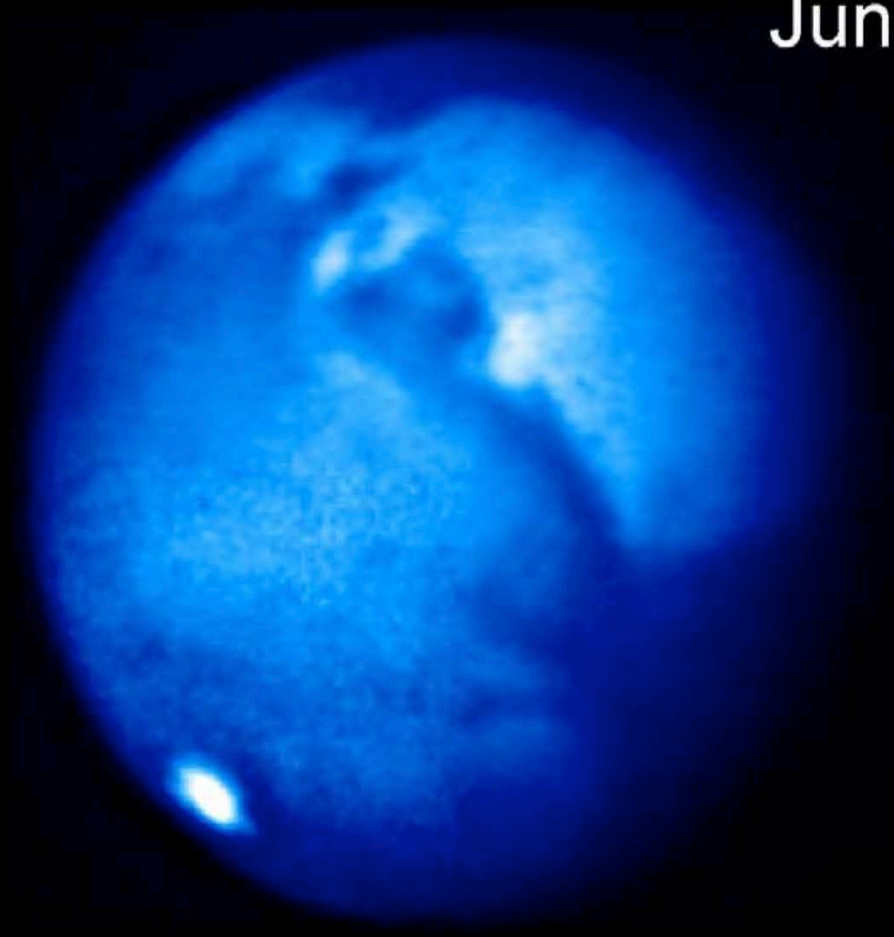


Maximum abundance Observed at L_s 220° (mid-spring in South)

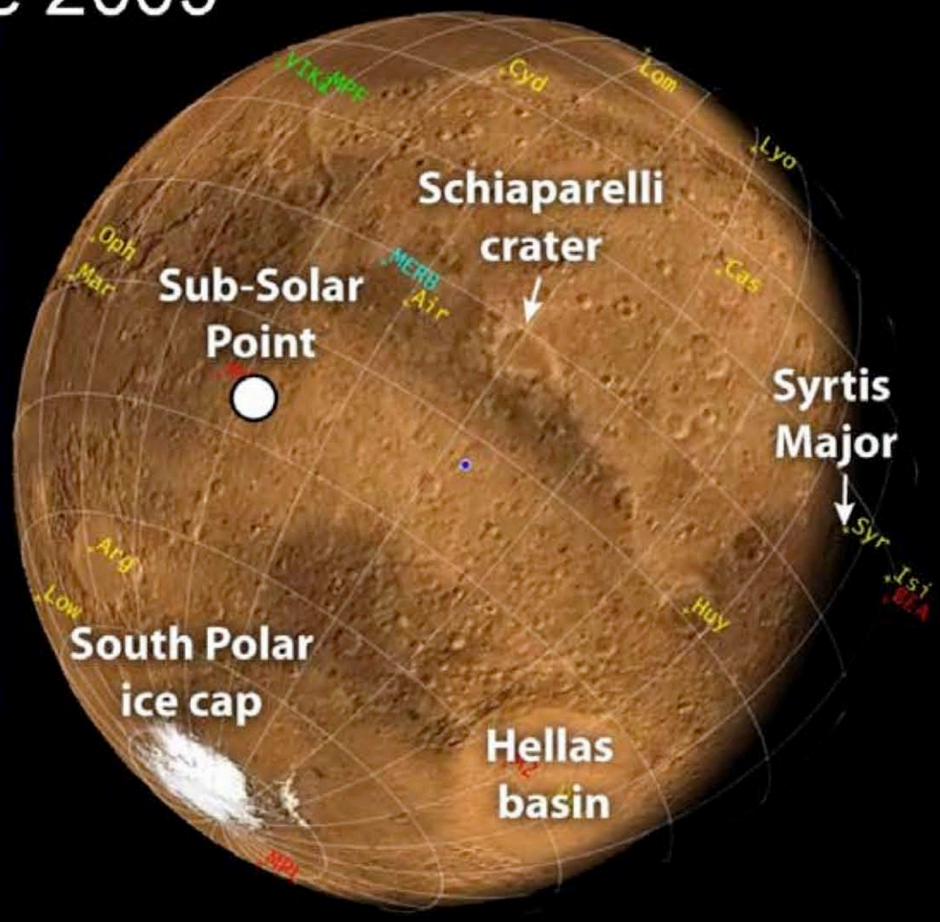
Maximum abundance Observed at L_s 155° (late summer in North)

Mars as Observed with Keck-2

using NIRC2 with Adaptive Optics (AO)
June 2009



Keck AO Image
Infrared light



Satellite Image
Visible light

Data Processing: G. L. Villanueva, M. J. Mumma (NASA-GSFC)
Observations: A. R. Conrad, R. D. Campbell, J. E. Lyke (WMKO)

Mars Express

PFS

R-Branch

Q-Branch

P-Branch

Simulated spectrum of Mars methane ν_3

3080 3060 3040 3020 3000 2980 2960

Simulated terrestrial extinction

3080 3060 3040 3020 3000 2980 2960

Mars spectrum affected by terrestrial extinction

R2 R1 R0 P2 P4

3080 3060 3040 3020 3000 2980 2960

Frequency in wavenumbers [cm^{-1}]

PFS – Geminale et al. 2008

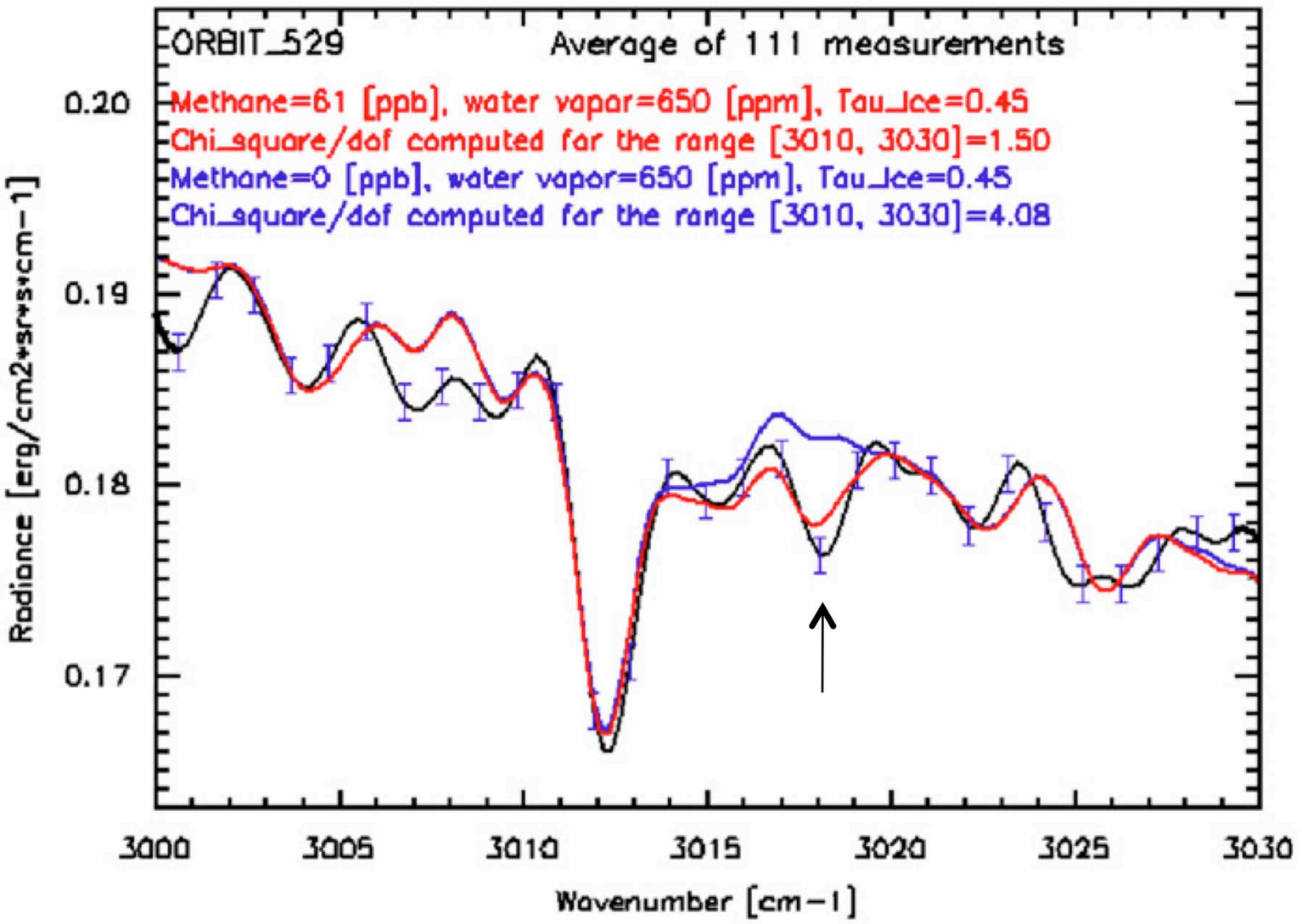
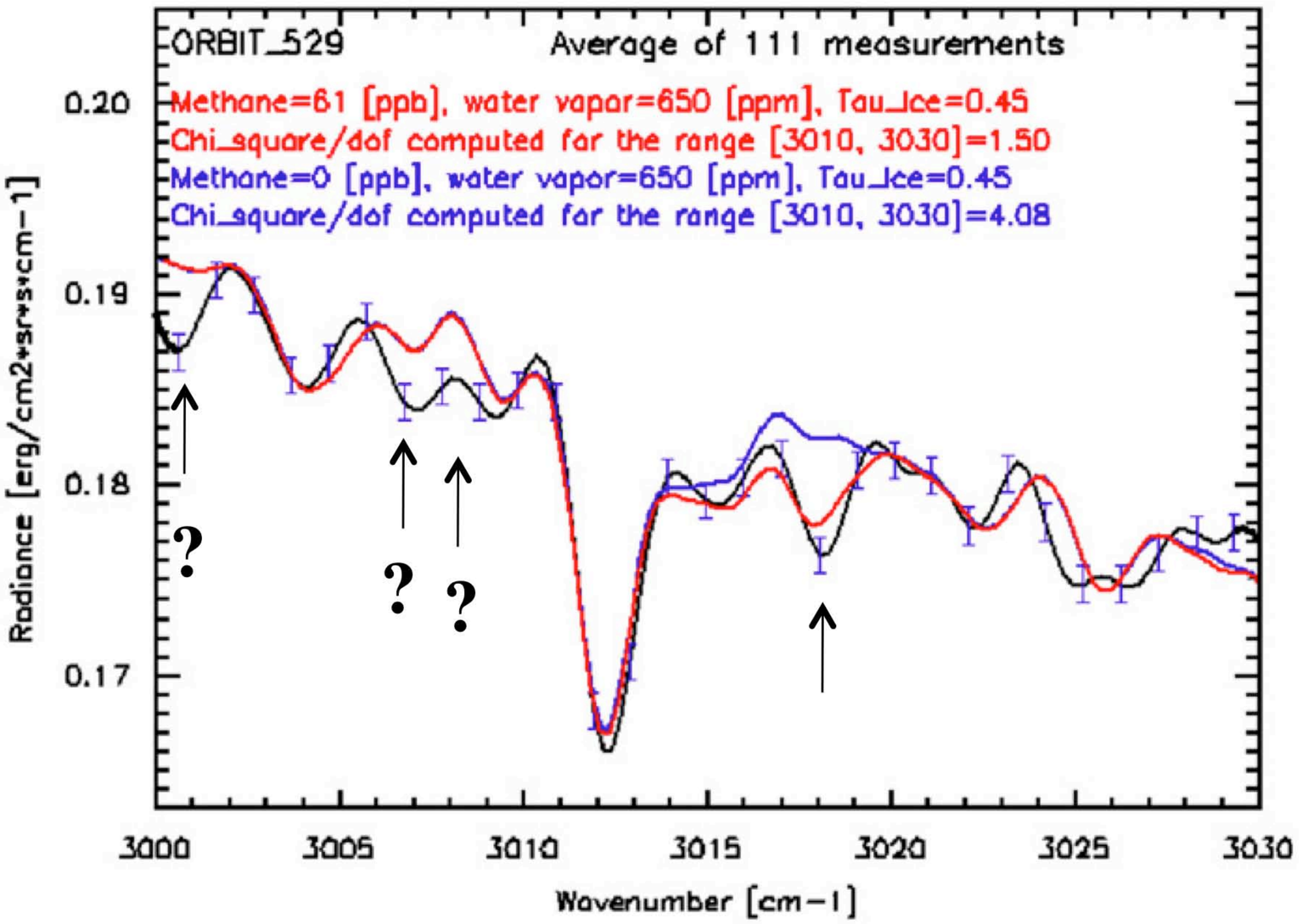


Fig. 1. PFS spectrum average of 111 measurements in orbit 529. The black curve is the measured spectrum at high sampling (zeroes added to ifg); the blue curve is the synthetic spectrum without methane but with water vapour and water ice aerosols. The red curve is the synthetic spectrum with methane and the other components as in the blue curve. With methane χ^2 decreases from 4.08 to 1.50.

PFS – Geminale et al. 2008



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PFS – Geminale et al. 2008

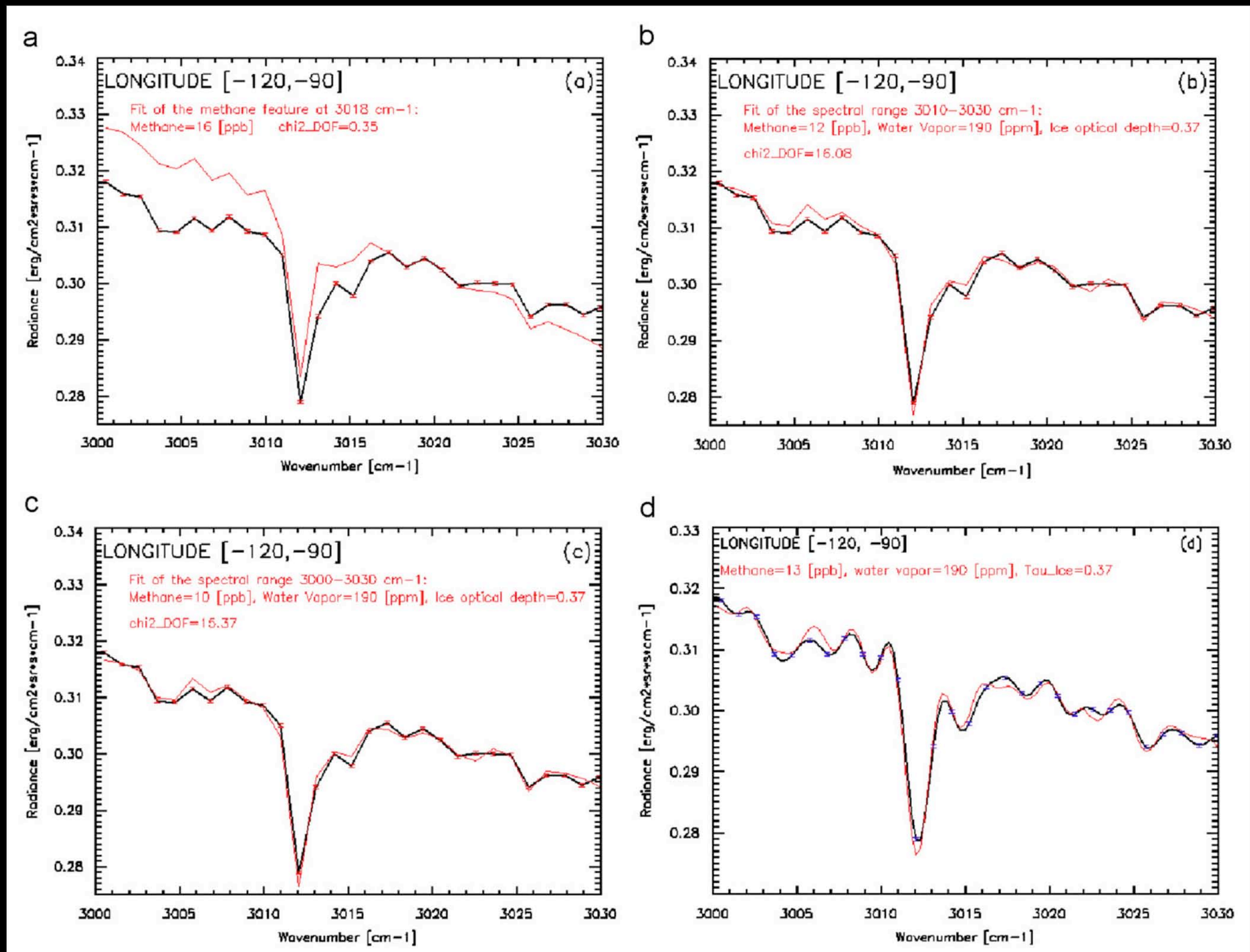


Fig. 2. The black curve is the average of 1221 observed spectra selected in regions of longitude range −120°, −90° and the red curve is the synthetic spectrum we compute to match only the observed methane feature (a), the range 3011–3030 cm^{-1} (b), the entire range (c). (d) Shows the same spectrum at high sampling with the resulting fit.

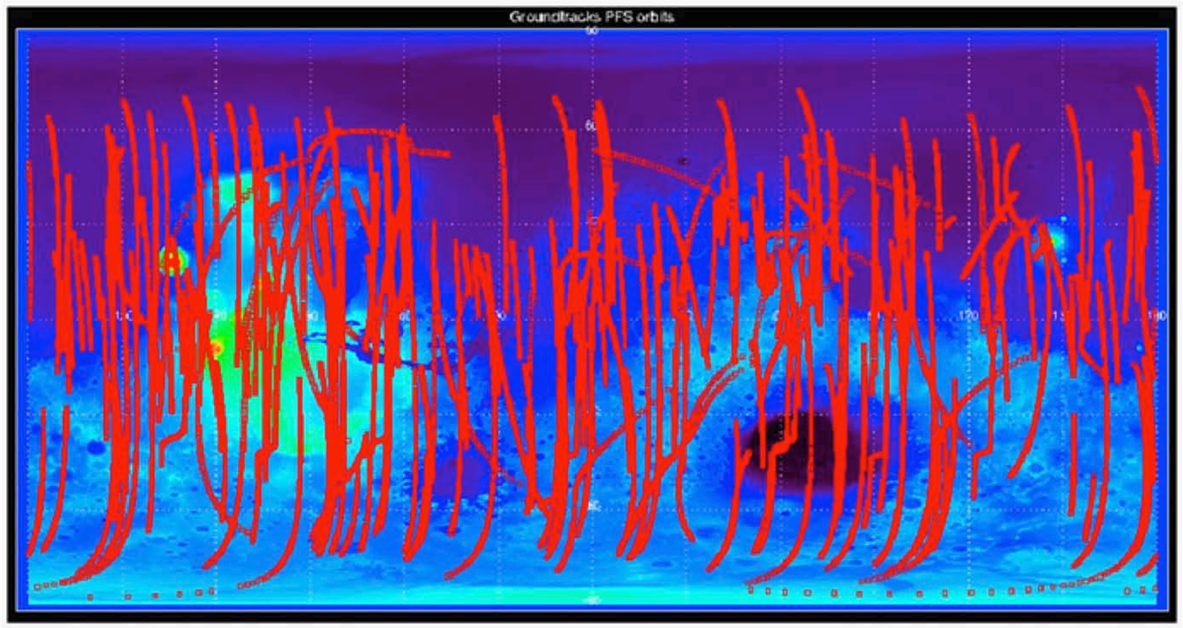


Fig. 3. Geographical distribution of the measurements used for the seasonal study.

PFS – Geminale et al. 2008

Variation with Season

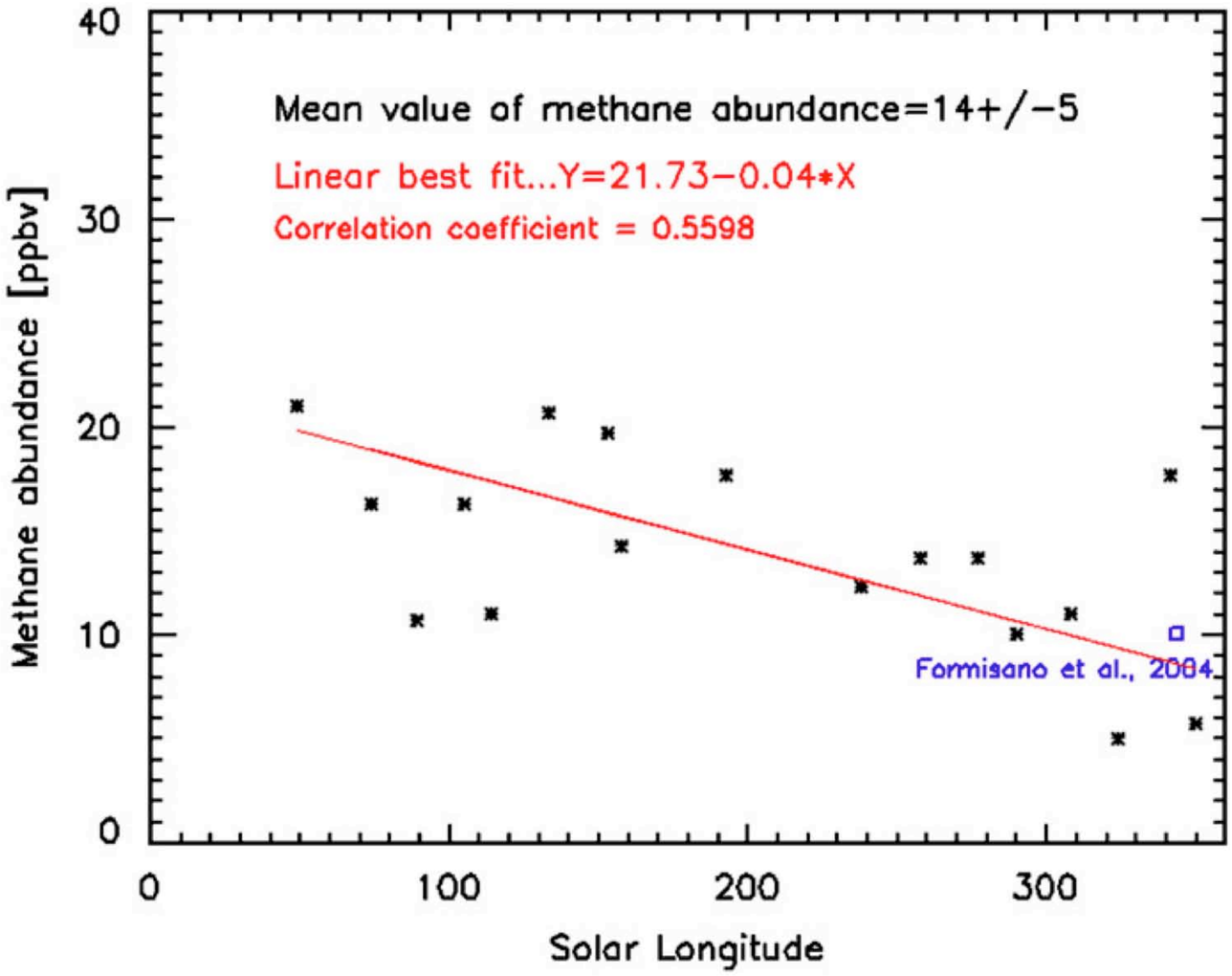


Fig. 4. Methane mixing ratio variation with L_S.

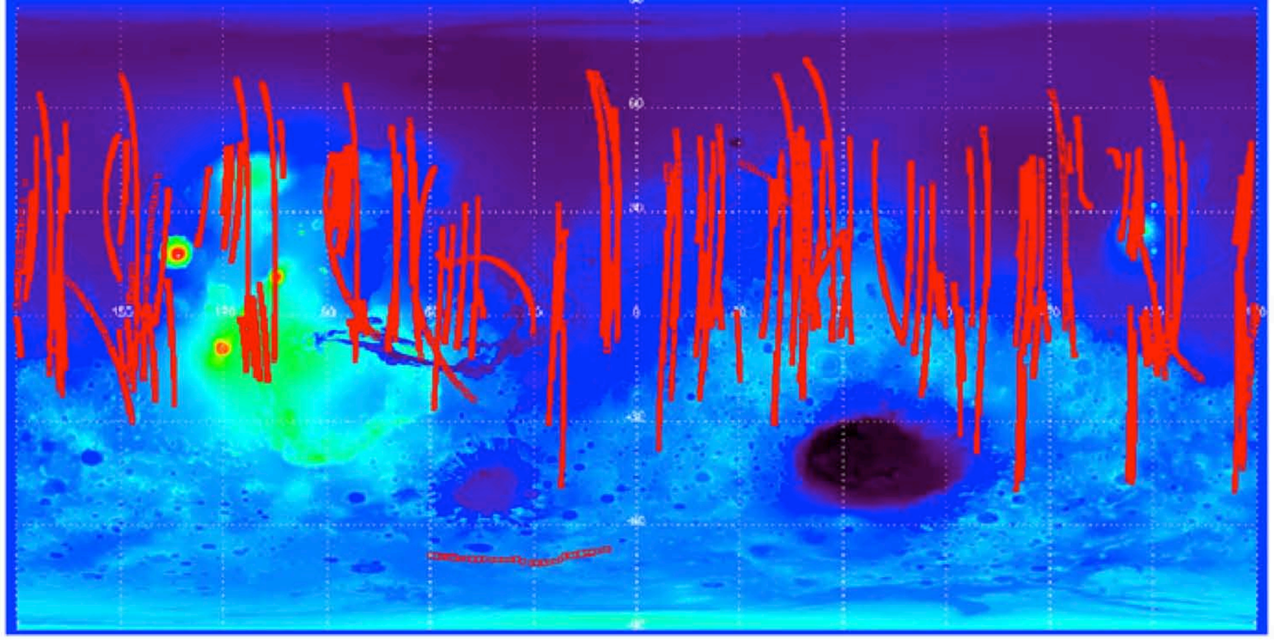


Fig. 7. Geographical distribution of the measurements used for the spatial (longitudinal) study.

PFS – Geminale et al. 2008

Variation with Longitude

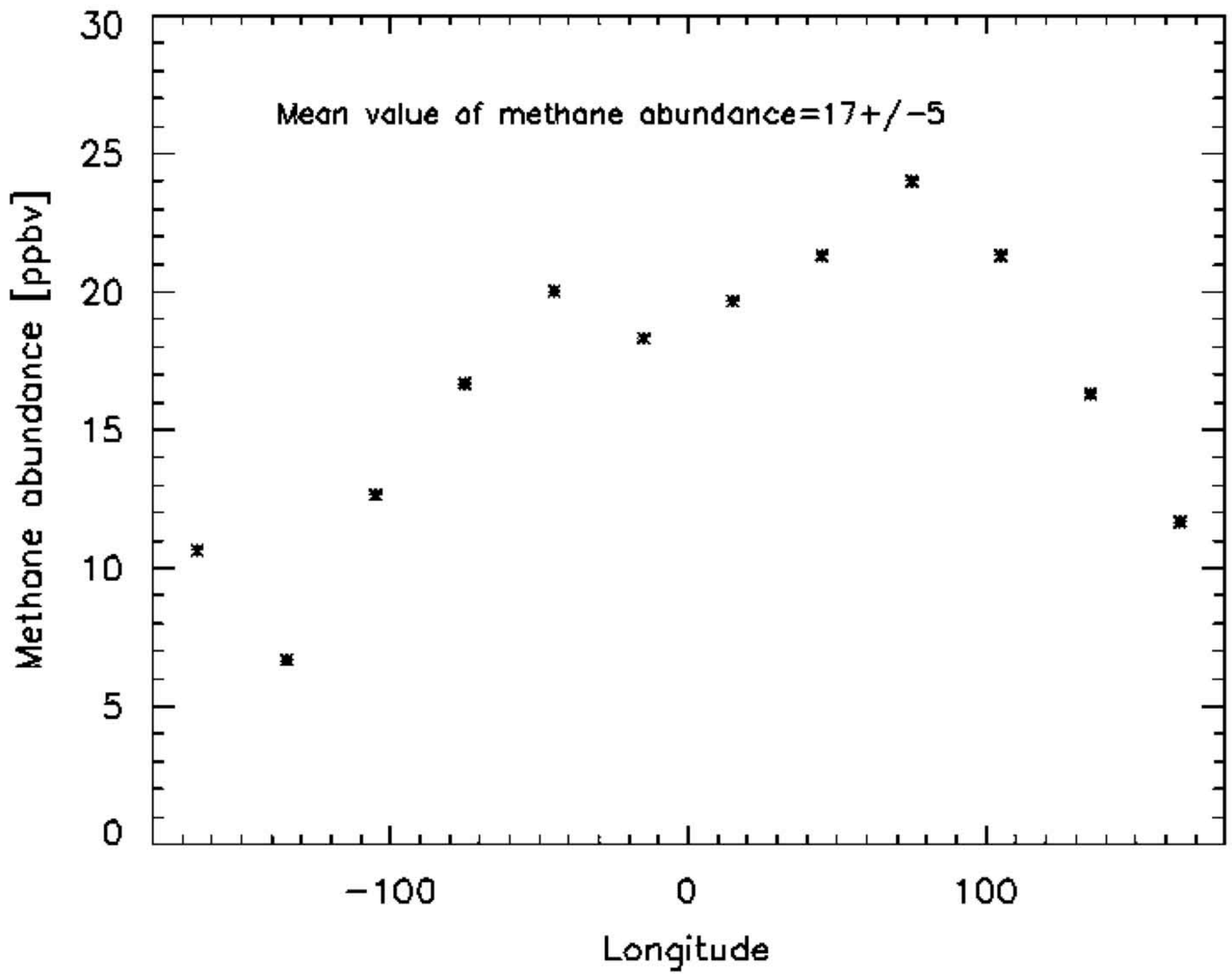


Fig. 8. Methane mixing ratio variation with longitude.

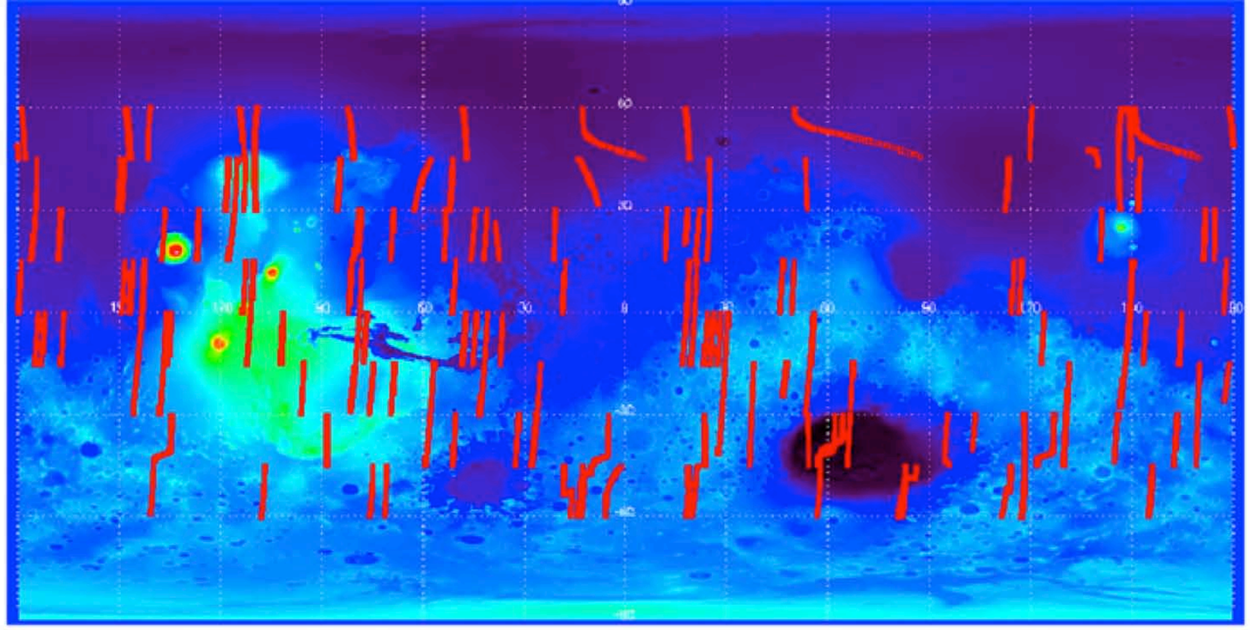


Fig. 10. Geographical distribution of the measurements used for the spatial (latitudinal) study.

PFS – Geminale et al. 2008

Variation with Latitude

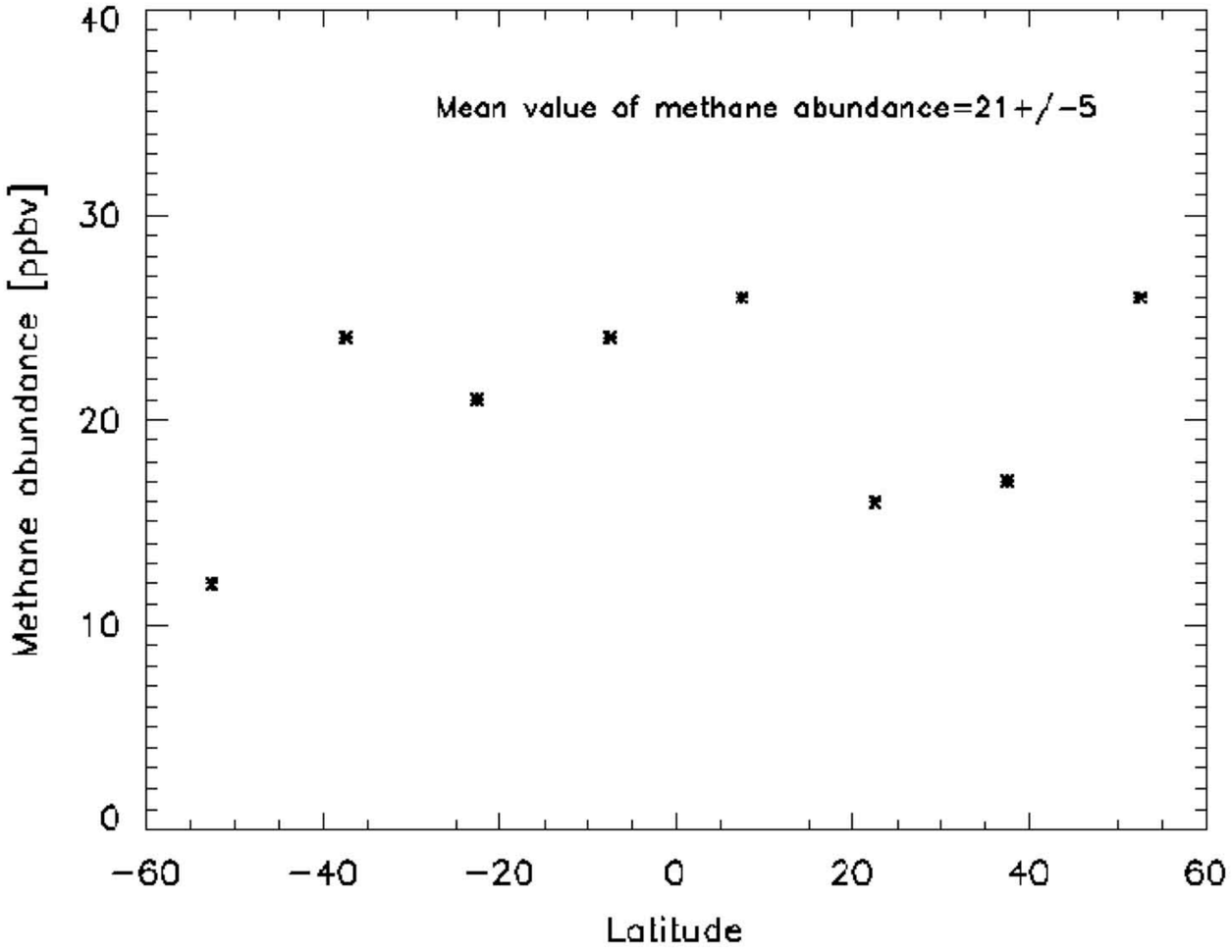


Fig. 11. Methane mixing ratio variation with latitude.

Methane Issues

? Origins —

When was it produced ? (recent vs. ancient)

How was it produced ? (abiotic vs. biotic)

reduce carbon in mantle (CO_2, H_2O, heat)

release H_2 : serpentinization, pyrite production, H_2O radiolysis

microbes metabolize H_2, reduce CO, CO_2 or acetate to methane

How is it released? Is it seasonal?

thermal activation of near-surface? (supra-permafrost)

by opening pores /fractures in scarps ? (sub-permafrost)

? Sinks —

Atmospheric – triboelectric, photochemical, other?

Sub-surface (oxidants) – peroxides, perchlorates

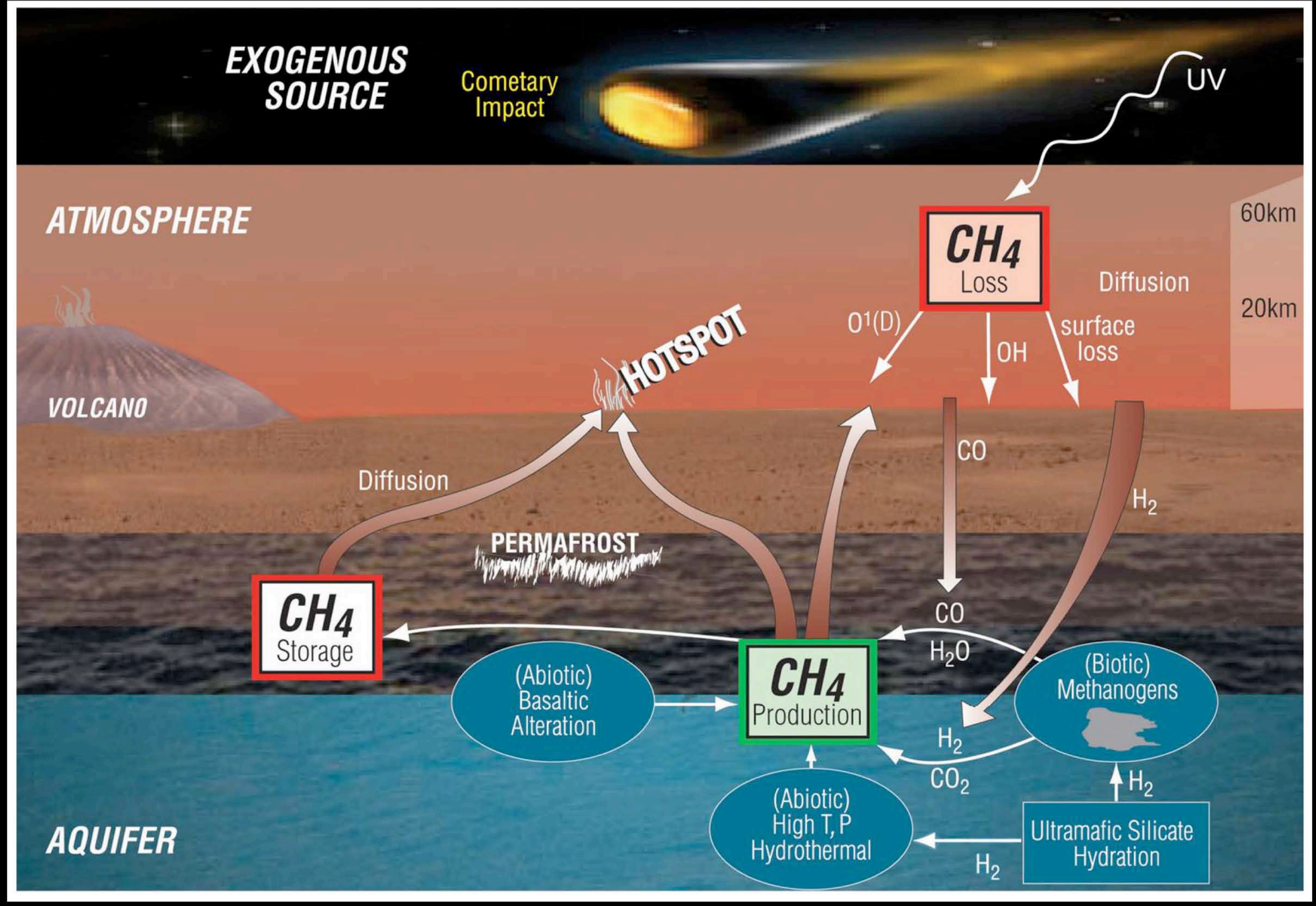
Sequestering (adhesion, gettering)

? Re-charge Mechanism (if released annually)

END

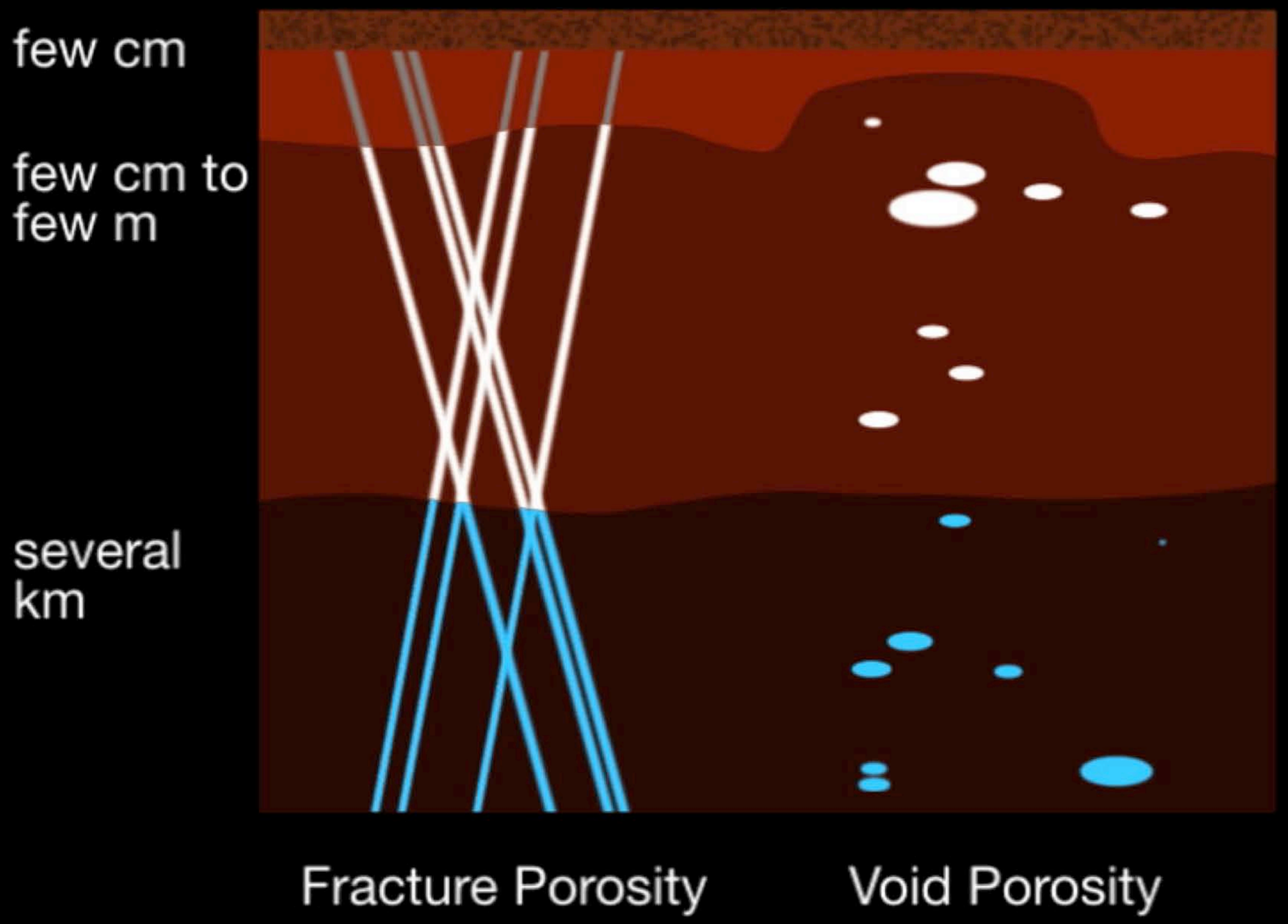
Backup slides

Potential Sources of Methane on Mars



Graphic credit: Atreya et al. Astrobiology 2006

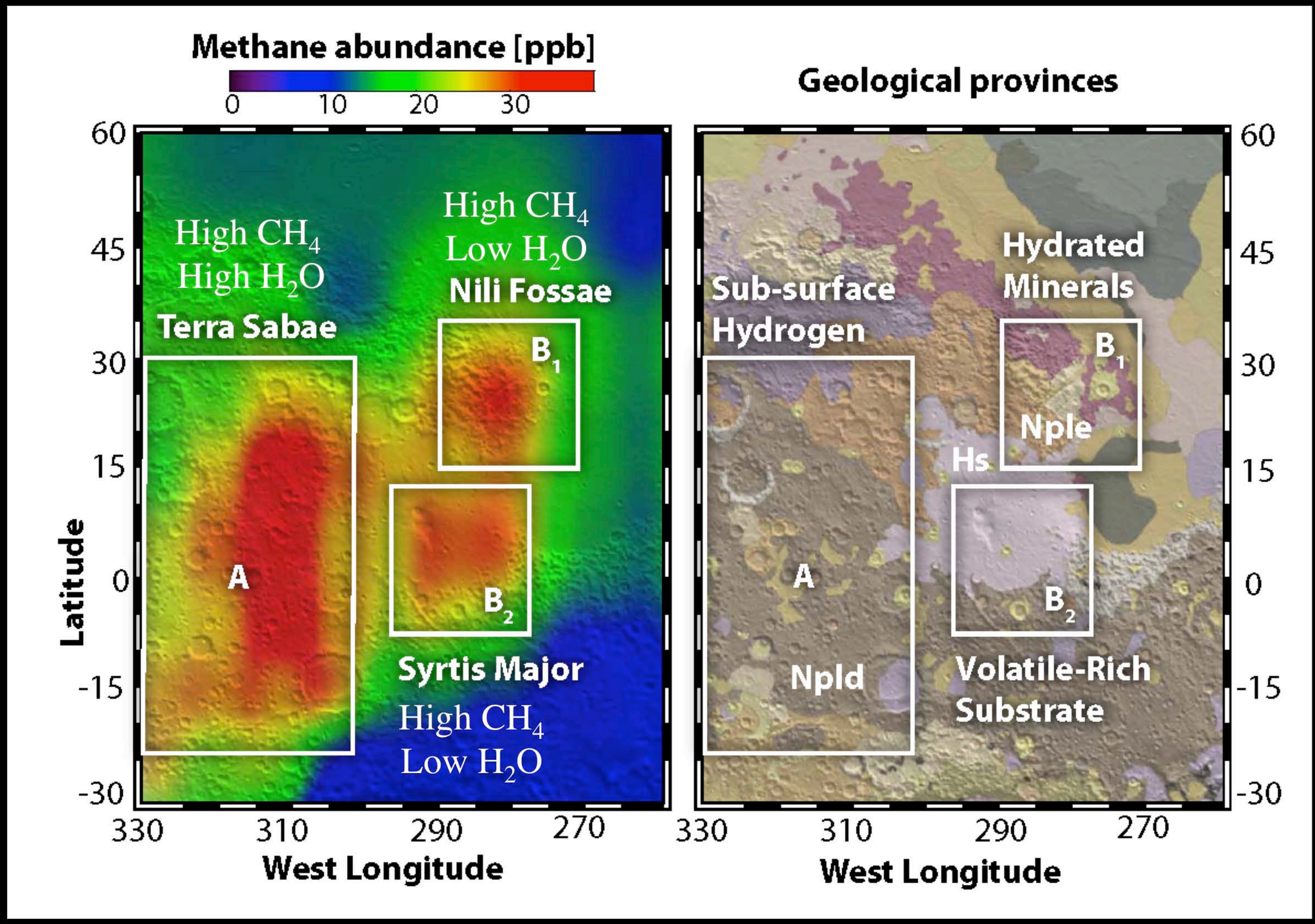
Plausible Habitable Zones on Mars



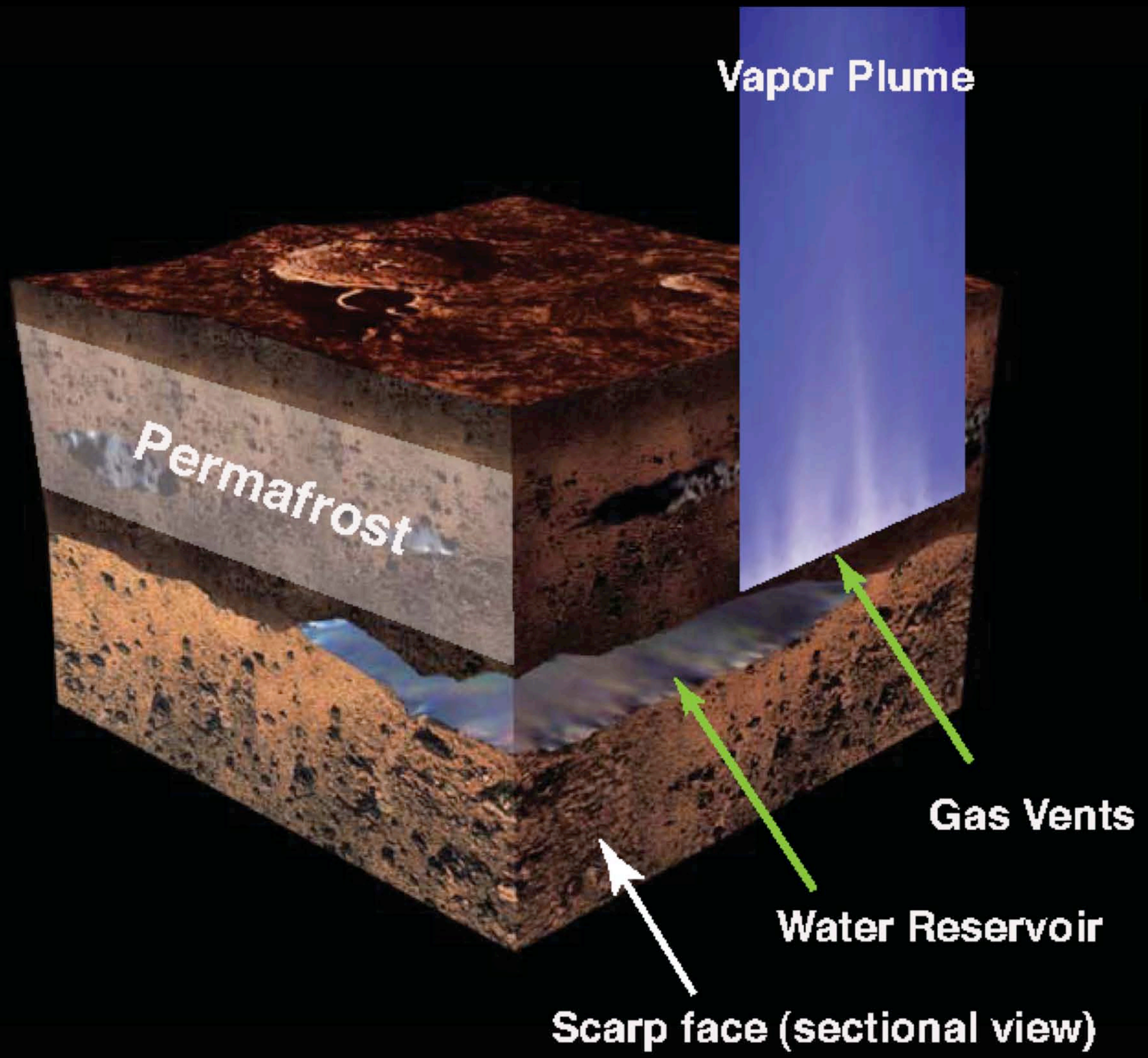
Visualization credits: L. Pratt (Indiana University) and NASA GSFC

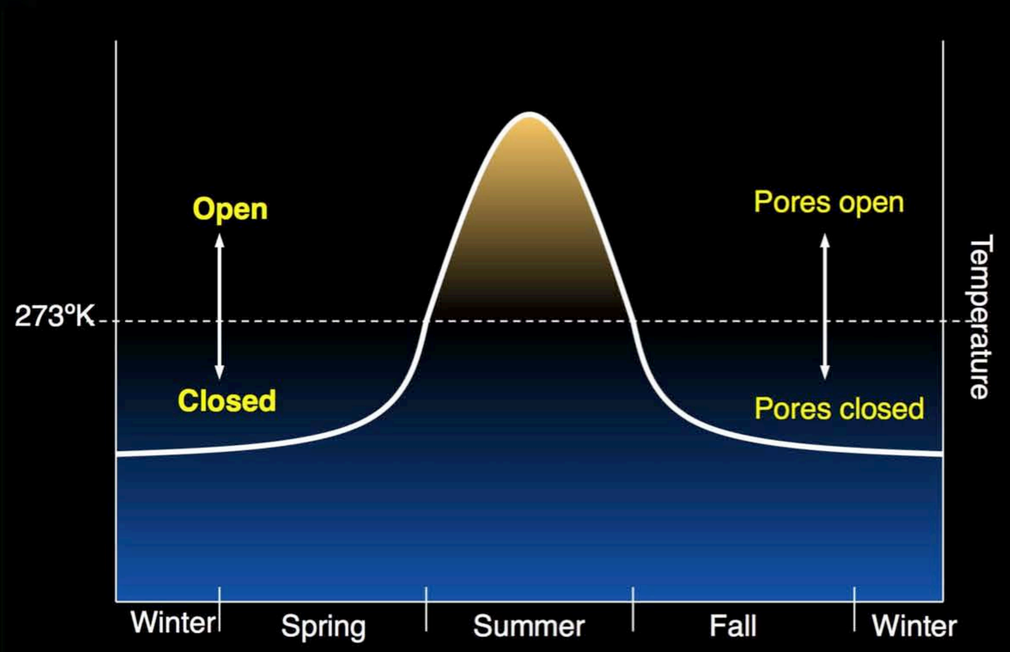
Mumma, Villanueva, Novak, et al. (Science 2009)

Resolution-limited Spatial Maps reveal local methane plumes on scales of 500 km. Is the release relatively uniform over these regions – or is it strongly localized?



Concept: Surface ices control Seasonal release of gases





Summary of Observational Evidence

- **Four lines of Methane are detected: R1, R0, P2 (doublet)**
  - *R1 is detected on successive dates Jan. 11 & 12, 2003*
  - *R1 and R0 are detected on successive dates March 20 & 21, 2003*
    - *The mixing ratios derived from individual lines agree*
  - *P2 is detected in May 2005*

- ***Strong temporal changes are found***
  - *Plumes are seen with peak mixing ratios up to 60 ppbv*
  - *At vernal equinox methane is 3 ppbv or less at locations sampled*
  - *The implied methane lifetime is less than one year*

- ***Methane varies with location***
  - *The plume content in March 2003 is ~ 19,000 metric tons*
    - *The source strength in March 2003 is ~ 1 kg/sec*
    - *A strong peak is seen over Nili Fossae*
    - *A strong peak is seen over Syrtis Major (South-east quadrant)*
  - *CH_4 is detected near Arsia Mons & Terra Sabena, in Southern Spring*

- ***Methane and water are sometimes correlated, but not always so.***

Major Conclusions

Methane is released locally on Mars – the source strength rivals terrestrial gas seeps

Seasonal access to sub-permafrost regions, and/or wide-spread surface activity, is implied

Some release zones are correlated with geologically interesting features

Hydrated terrain, where craters show lobate ejecta associated with ice-rich soil

Nili Fossae, a region rich in phyllosillicates and carbonates

Syrtis Major, a volcano whose SE quadrant shows evidence of sub-surface collapse

Arsia Mons, site of the largest mountain glacier on Mars, and extensive Fossae

The lifetime of atmospheric methane is less than one Mars year

This requires a new model for its destruction, perhaps by oxidants on airborne soil particles

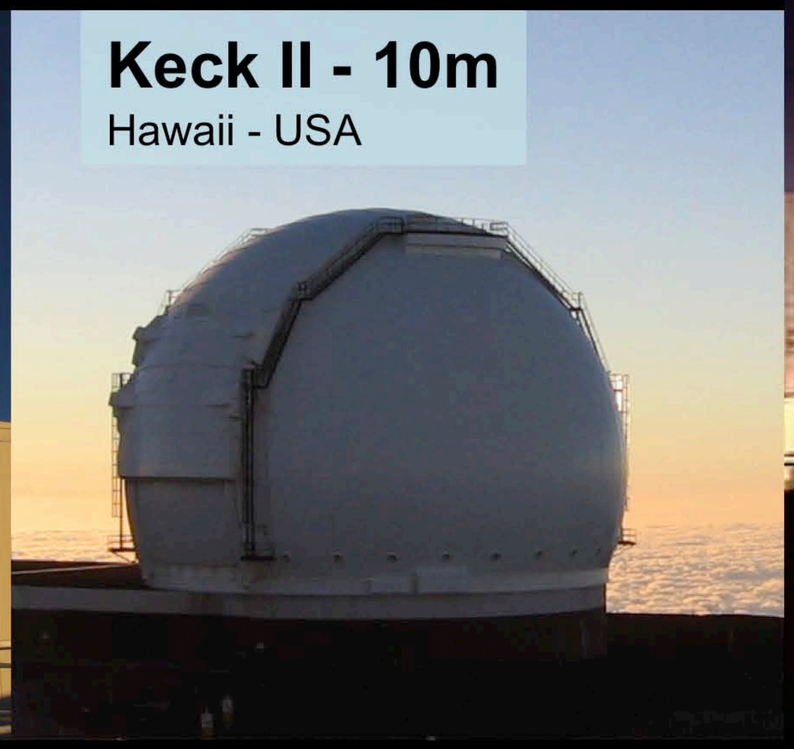
The Big Question: Is this methane produced by Biology, by Geochemistry, or by both?

Much follow-0n work is needed to address this fundamental question

The Current Campaign

12 observing runs August 19 – December 16
11 observing runs March 27 – June 9

CRIRES $\lambda/\delta\lambda$ ~100,000 0.2” x 30” slit
NIRSPEC $\lambda/\delta\lambda$ ~ 40,000 0.44” x 24” slit
CSHELL $\lambda/\delta\lambda$ ~ 40,000 0.5” x 30” slit
CRIRES – UT1 AO, without re-imaging 0.086” pixels
NIRSPEC – Keck 2 AO, with re-imaging 0.018” pixels



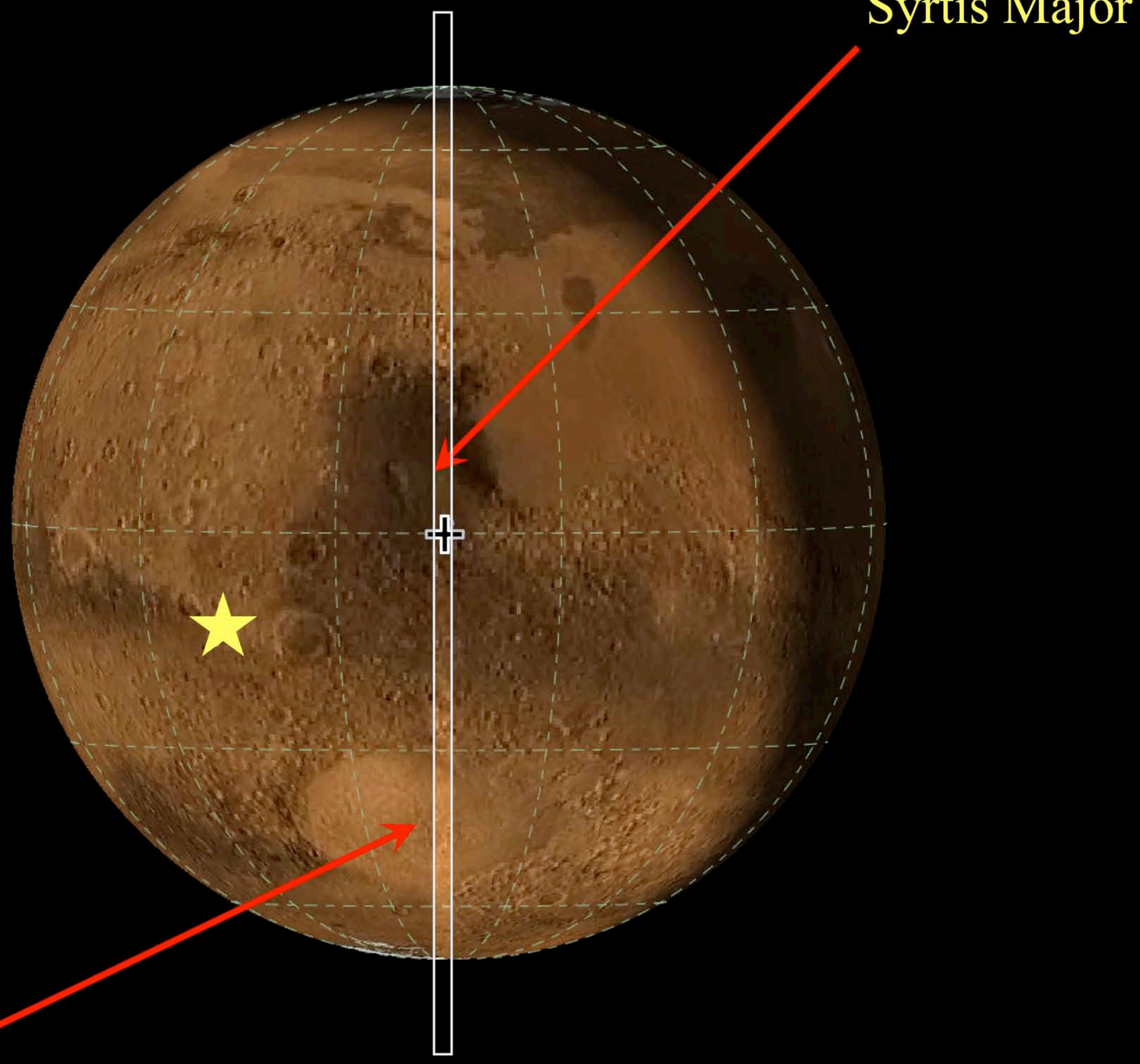
CRIRES on Mars - First night
UT 19 August 2009 10:20

Mars Diameter 5.6 arcsec
Geocentric velocity : – 9.4 km/sec
L_s = 325° mid NH winter

VLT Paranal:

airmass	1.8
PWV	3.9 mm
FWHM	0.7 arcsec
AO	open loop

CRIRES 0.2” slit, 0.086” pixels
Centered on 285° W



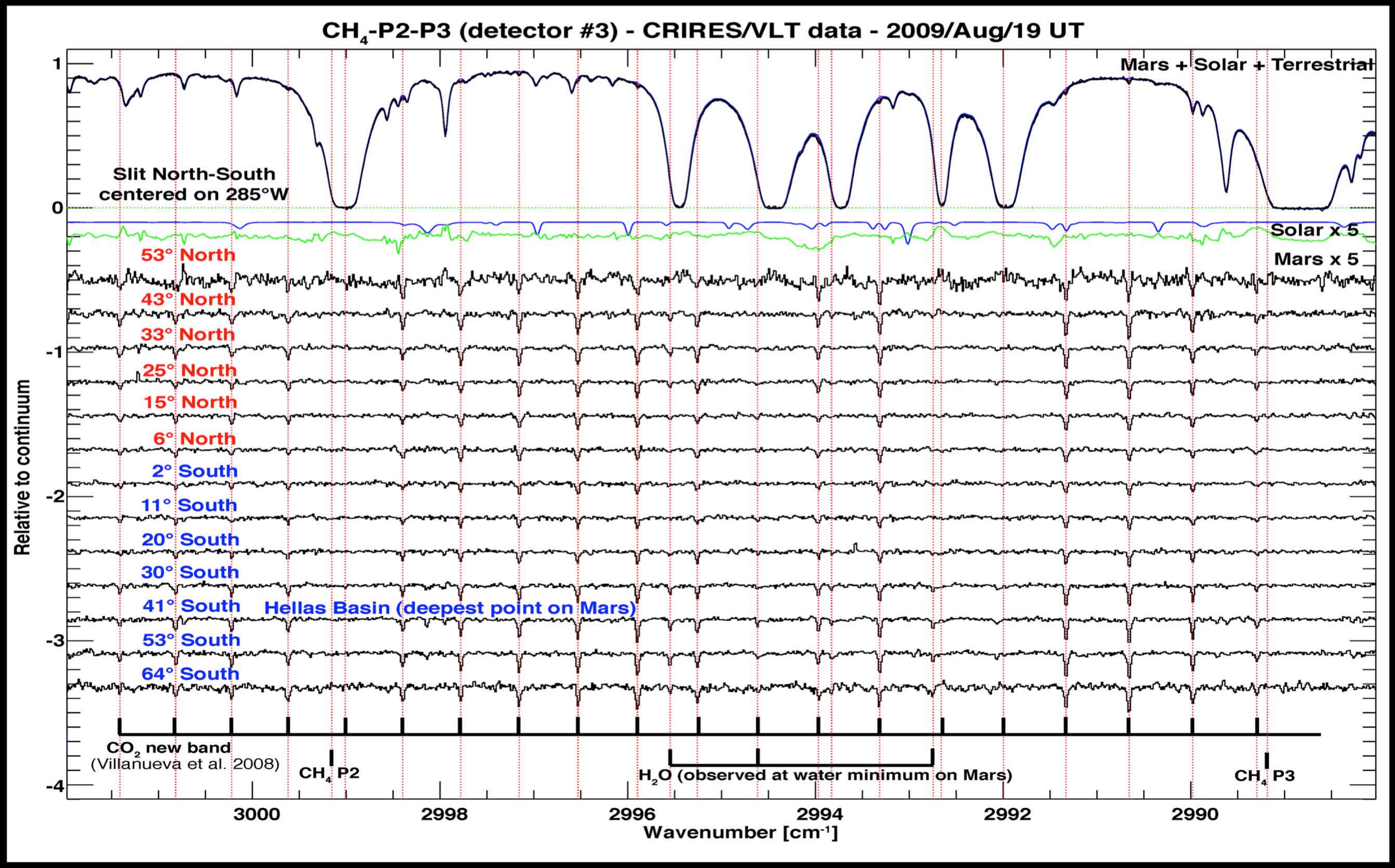
NASA GISS Mars24 5.5

Methane on Mars

M. J. Mumma, G. L. Villanueva, R. E. Novak, et al.

CRIRES $L_s = 325°$ NH mid-winter Geocentric velocity : – 9.4 km/sec

D1 3041.01 - 3025.36 D2 3021.06 - 3006.25 D3 3002.36 - 2988.37 D4 2984.80 - 2971.62



Testing the nature of methane production

Biology vs. geochemistry

Deepest Search for Biomarker gases –

H_2S, N_2O, C_2H_6, ...

Deepest Search for Volcanogenic gases –

SO_2 .....

The Evolving Search for a Habitable Mars

Φ1 – Earth's twin (a rich biosphere; eucaryotes)

Φ2 – A global biosphere (but sparse; microbes)

Φ3 – A 'remnant' biosphere (in 'niches'; microbes)

Φ4 – Follow-up and Exploitation: ExoMars!

Biology, Geology, or both ?