Exploring terrestrial planets with SOFIA

Current challenges and future prospects

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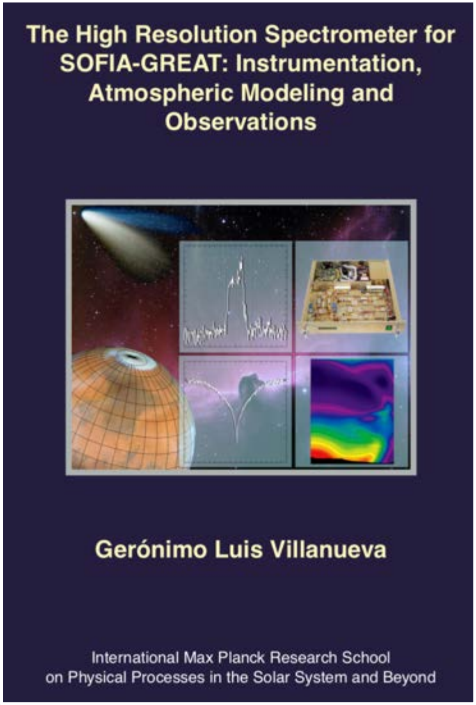
Some initial ideas – Deriving water profiles on Mars with SOFIA/GREAT

(Villanueva 2004, Ph.D. thesis)



The High Resolution Spectrometer for SOFIA-GREAT: Instrumentation, Atmospheric Modeling and Observations

Gerónimo Luis Villanueva

International Max Planck Research School
on Physical Processes in the Solar System and Beyond

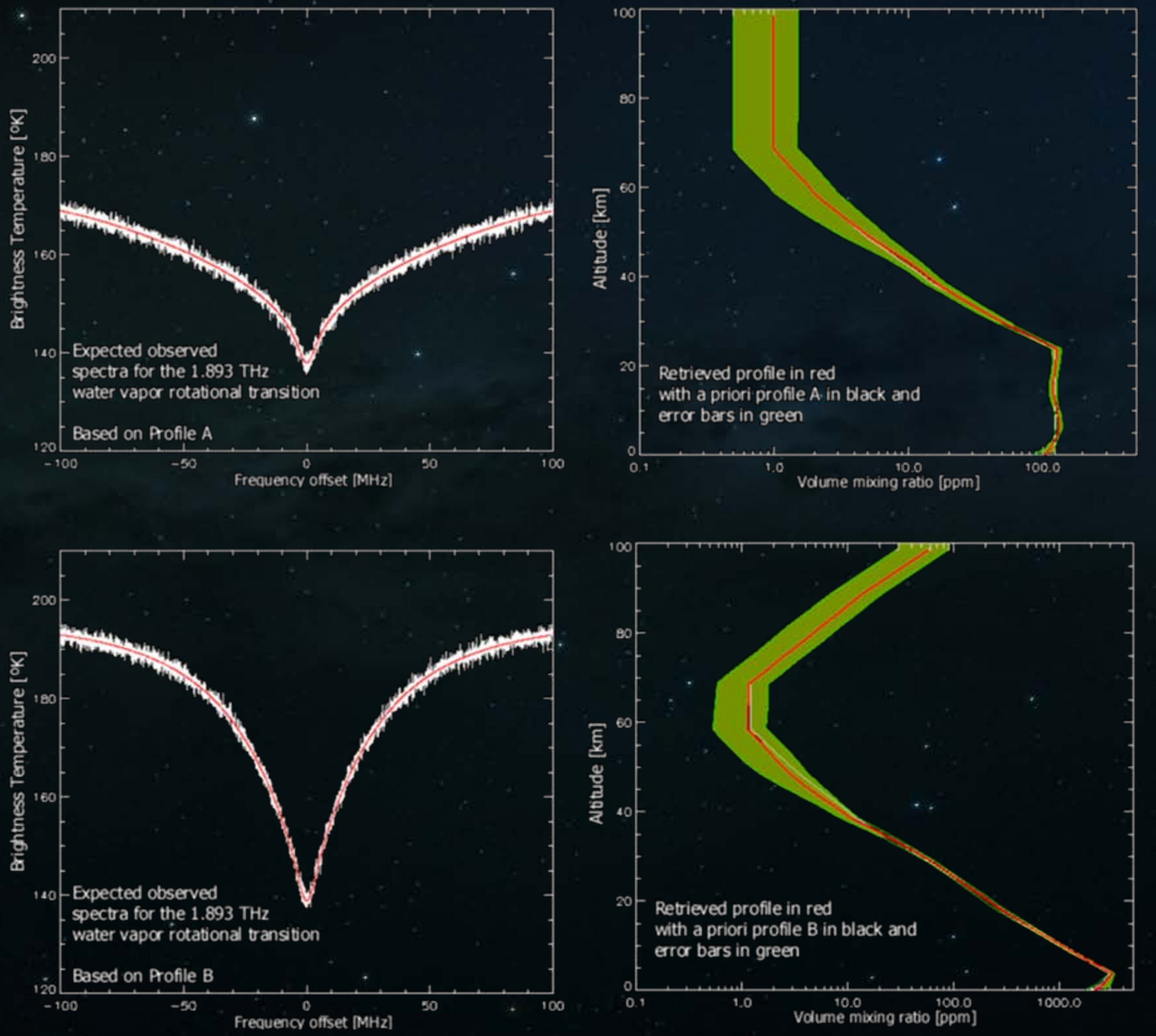
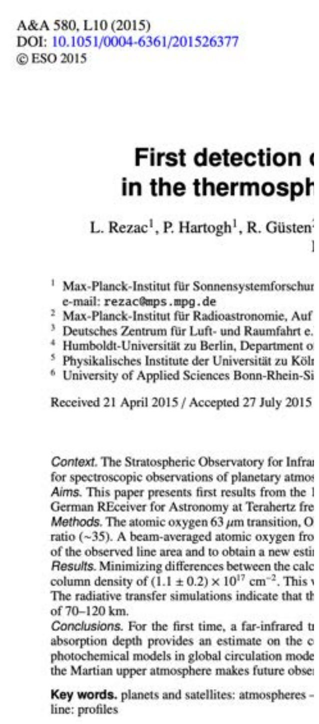


Figure 1.3: [Left] Simulated spectral lines for the rotational transition of the water vapour molecule at 1.8936 THz, based on a modelled Martian atmosphere. Fitted line in red. [Right] Possible retrieved profiles of water vapour. The retrieved profile in red, in black the a priori profile and the error bars in green



A&A 580, L10 (2015)
DOI: 10.1051/0004-6361/201526377
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First detection
in the thermosph

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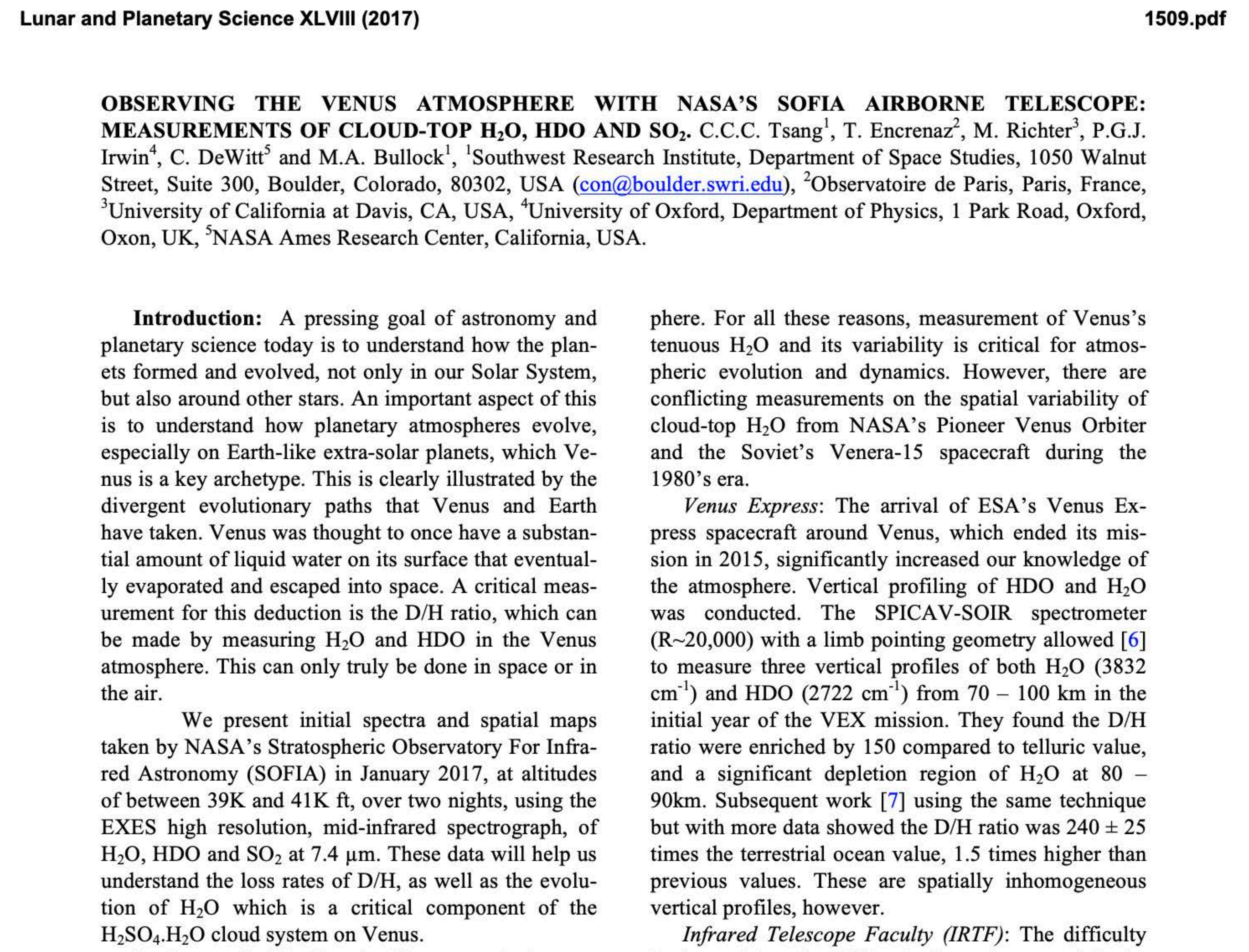
Received 21 April 2015 / Accepted 27 July 2015

Context. The Stratospheric Observatory for Infra
for spectroscopic observations of planetary atmos
Aims. This paper presents first results from the
German REceiver for Astronomy at Terahertz fre
Methods. The atomic oxygen 63 μm transition, O
ratio (~35). A beam-averaged atomic oxygen fro
of the observed line area and to obtain a new esti
Results. Minimizing differences between the calc
column density of $(1.1 \pm 0.2) \times 10^{17}$ cm^{-2}. This
The radiative transfer simulations indicate that th
of 70–120 km.
Conclusions. For the first time, a far-infrared t
absorption depth provides an estimate on the c
photochemical models in global circulation mode
the Martian upper atmosphere makes future obse

Key words. planets and satellites: atmospheres –
line: profiles



Lunar and Planetary Science XLVIII (2017) **1509.pdf**

OBSERVING THE VENUS ATMOSPHERE WITH NASA'S SOFIA AIRBORNE TELESCOPE: MEASUREMENTS OF CLOUD-TOP H_2O, HDO AND SO_2. C.C.C. Tsang[1], T. Encrenaz[2], M. Richter[3], P.G.J. Irwin[4], C. DeWitt[5] and M.A. Bullock[1], [1]Southwest Research Institute, Department of Space Studies, 1050 Walnut Street, Suite 300, Boulder, Colorado, 80302, USA (con@boulder.swri.edu), [2]Observatoire de Paris, Paris, France, [3]University of California at Davis, CA, USA, [4]University of Oxford, Department of Physics, 1 Park Road, Oxford, Oxon, UK, [5]NASA Ames Research Center, California, USA.

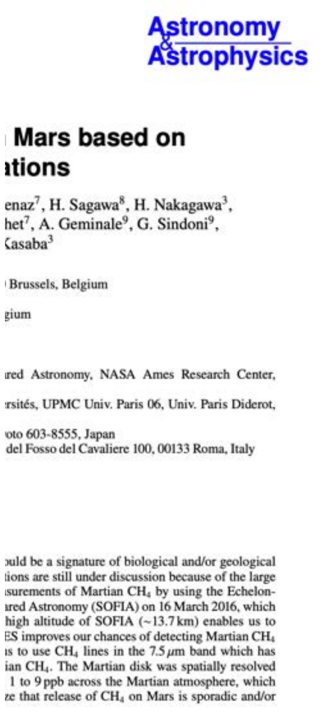
Introduction: A pressing goal of astronomy and planetary science today is to understand how the planets formed and evolved, not only in our Solar System, but also around other stars. An important aspect of this is to understand how planetary atmospheres evolve, especially on Earth-like extra-solar planets, which Venus is a key archetype. This is clearly illustrated by the divergent evolutionary paths that Venus and Earth have taken. Venus was thought to once have a substantial amount of liquid water on its surface that eventually evaporated and escaped into space. A critical measurement for this deduction is the D/H ratio, which can be made by measuring H_2O and HDO in the Venus atmosphere. This can only truly be done in space or in the air.

We present initial spectra and spatial maps taken by NASA's Stratospheric Observatory For Infrared Astronomy (SOFIA) in January 2017, at altitudes of between 39K and 41K ft, over two nights, using the EXES high resolution, mid-infrared spectrograph, of H_2O, HDO and SO_2 at 7.4 µm. These data will help us understand the loss rates of D/H, as well as the evolution of H_2O which is a critical component of the $H_2SO_4.H_2O$ cloud system on Venus.

phere. For all these reasons, measurement of Venus's tenuous H_2O and its variability is critical for atmospheric evolution and dynamics. However, there are conflicting measurements on the spatial variability of cloud-top H_2O from NASA's Pioneer Venus Orbiter and the Soviet's Venera-15 spacecraft during the 1980's era.

Venus Express: The arrival of ESA's Venus Express spacecraft around Venus, which ended its mission in 2015, significantly increased our knowledge of the atmosphere. Vertical profiling of HDO and H_2O was conducted. The SPICAV-SOIR spectrometer (R~20,000) with a limb pointing geometry allowed [6] to measure three vertical profiles of both H_2O (3832 cm^{-1}) and HDO (2722 cm^{-1}) from 70 – 100 km in the initial year of the VEX mission. They found the D/H ratio were enriched by 150 compared to telluric value, and a significant depletion region of H_2O at 80 – 90km. Subsequent work [7] using the same technique but with more data showed the D/H ratio was 240 ± 25 times the terrestrial ocean value, 1.5 times higher than previous values. These are spatially inhomogeneous vertical profiles, however.

Infrared Telescope Faculty (IRTF): The difficulty



Astronomy & Astrophysics

Mars based on
ations

enaz[7], H. Sagawa[8], H. Nakagawa[3],
het[7], A. Geminale[9], G. Sindoni[9],
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del Fosso del Cavaliere 100, 00133 Roma, Italy

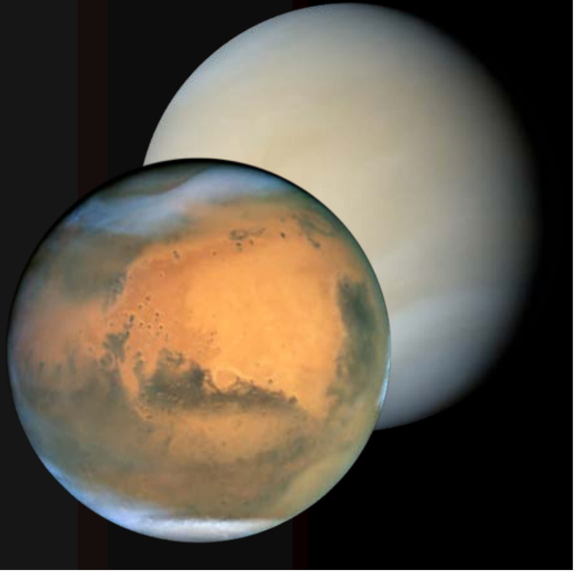
uld be a signature of biological and/or geological
ions are still under discussion because of the large
surements of Martian CH_4 by using the Echelon-
red Astronomy (SOFIA) on 16 March 2016, which
high altitude of SOFIA (~13.7 km) enables us to
ES improves our chances of detecting Martian CH_4
s to use CH_4 lines in the 7.5 μm band which has
ian CH_4. The Martian disk was spatially resolved
1 to 9 ppb across the Martian atmosphere, which
ze that release of CH_4 on Mars is sporadic and/or

Imaging / photometry of planets ($\lambda/\delta\lambda<500$)

- Studies of atmospheric morphology
- Surface and aerosols/cloud investigations

Pros: requires relatively simpler instrumentation.

Cons: extreme competition from orbiters and space telescopes.

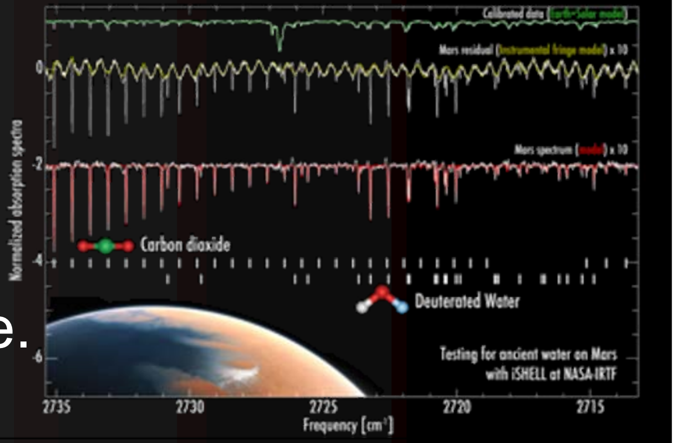


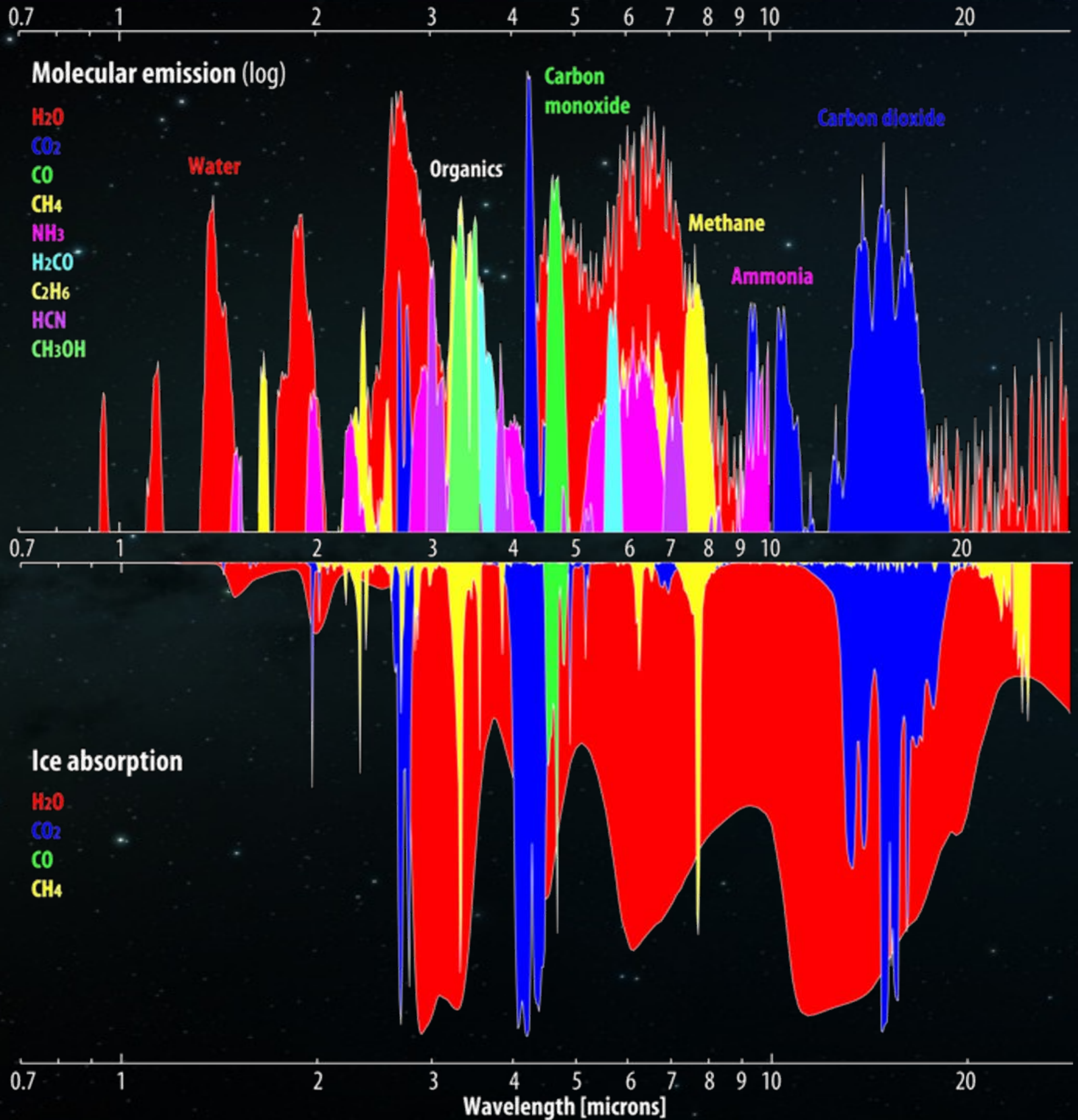
High-resolution spectroscopy ($\lambda/\delta\lambda>10{,}000$)

- Atmospheric composition (e.g., trace gases, isotopes) studies.
- Kinematics and profiling by excitation

Pros: prime for ground-based and SOFIA, instruments too bulky and complex for space.

Cons: complex instrumentation, data interpretation and relatively smaller community.





Planetary Spectrum Generator

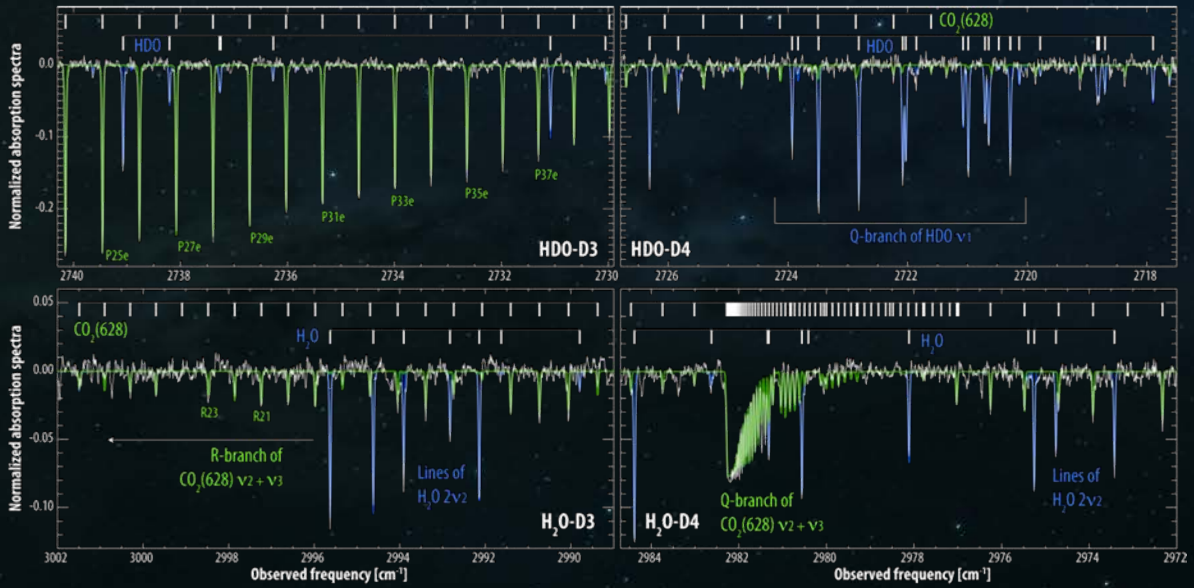
(Villanueva+2018)

https://psg.gsfc.nasa.gov

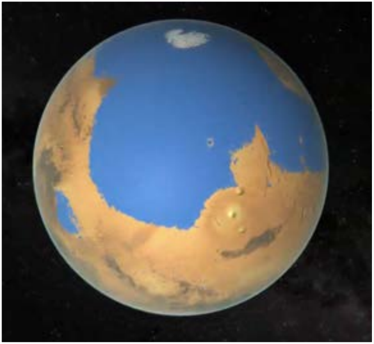
Methane on Mars, as a proxy for activity

Discovery of methane on Mars with NASA-IRTF and Keck at 3.3 um
Mumma, Villanueva, et al. , *Science*, 2009

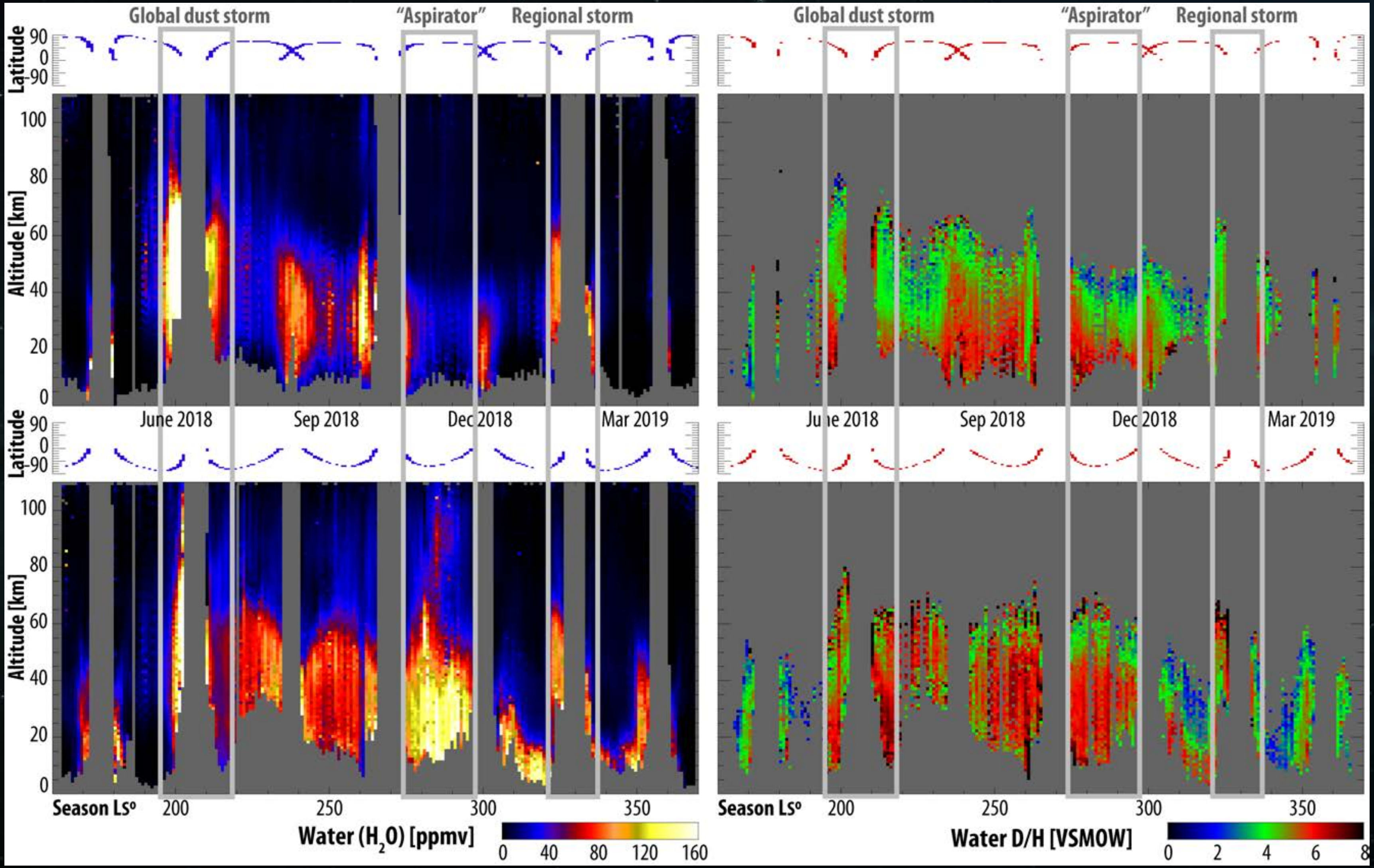
Water isotopic ratios – Tracing a wet past



Identification of isotopic D/H anomalies on Mars (2.7 to 3.3 um)
Villanueva, et al. 2015, *Science*, 2015



Vertical retrievals of water and its D/H – ExoMars/TGO



Tracking water as it escapes from Mars

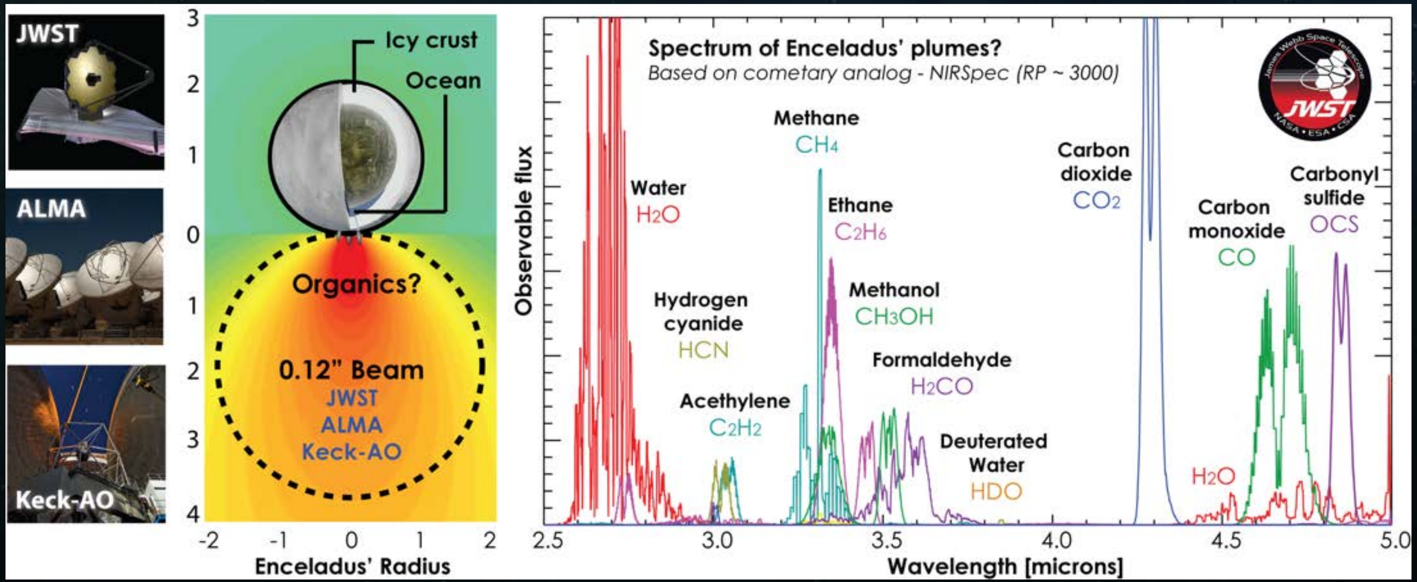
Villanueva, et al. 2020, *Science Advances*, Submitted

First direct detection of water on Europa amid a quiescent state (many non-detections)

Paganini, Villanueva, et al., Nature Astr., 2020 – Keck at 3.1 um

Infrared probing of ocean worlds is powerful

e.g., Villanueva / Hammel / Milam et al, JWST-GTO program



Exploring terrestrial planets with SOFIA

Villanueva+2020, GSFC

Keck / VLT
Diameter: 10m
Optical to 5um
High-resolution
Adaptive optics

ALMA
66 antennas of 12m
Radio / THz
High-resolution
Interferometer

GMT
Diameter: 25 m
Optical to 2.5 µm
Four first light inst.
Adaptive optics

E-ELT
Diameter: 39 m
Optical to 14 µm
Six phase-A inst.
AO, WF, spec, MOS

TMT
Diameter: 30 m
Optical to 2.5 µm
Three phase-A inst.
AO, WF, spec, MOS

Hubble (HST)
Diameter: 2.4m
0.1 to 1.7 µm
Moderate resolution
Diverse inst. suite

TESS
Diameter: 0.1m
FOV 24 x 24 degree^2
Imaging / photometry
No spectroscopy

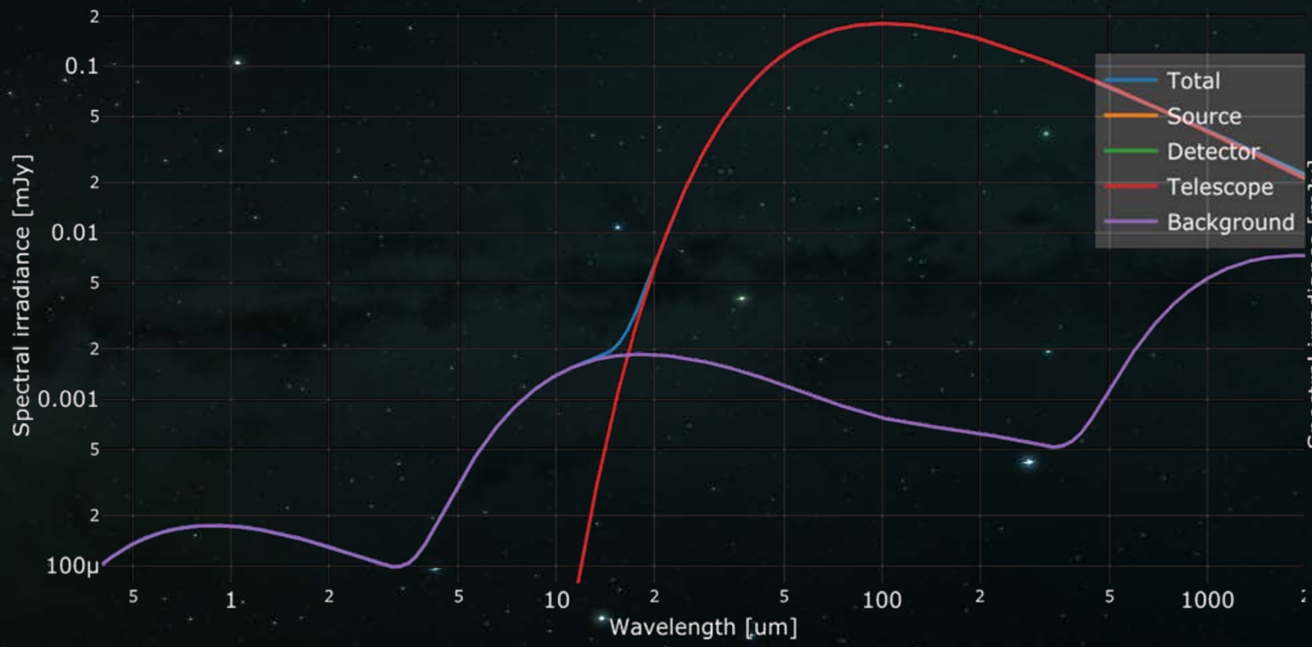
JWST
Diameter: 6.5m
0.6 to 28.5 µm
Moderate resolution
Diverse inst. suite
Ultra-cold (50K)

WFIRST
Diameter: 2.4m
0.4-1 µm
Wide-field camera
Coronagraph
Contrast 10^{-9}

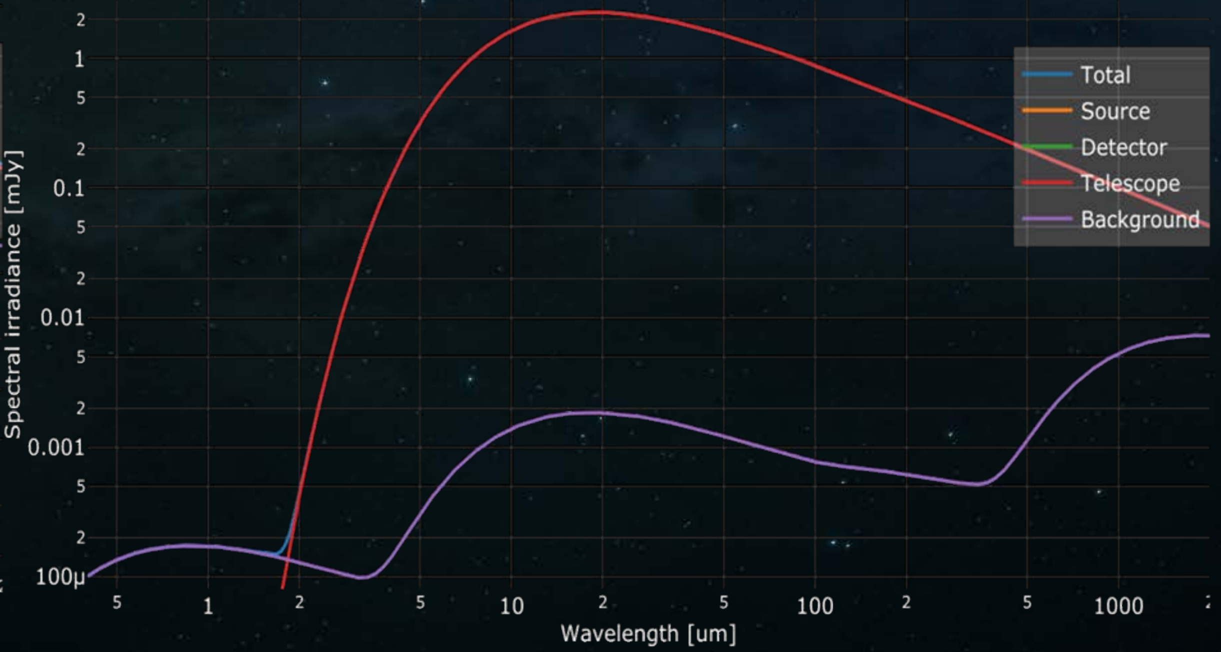
LUVOIR / OST
Diameter: >6m
UV, Optical, IR
Coronagraph
Wide-field camera
UV and O/IR insts.

Where is SOFIA's niche in this context?

A JWST type observatory (50K)



A LUVOIR type observatory (270K)



Sensitivity study

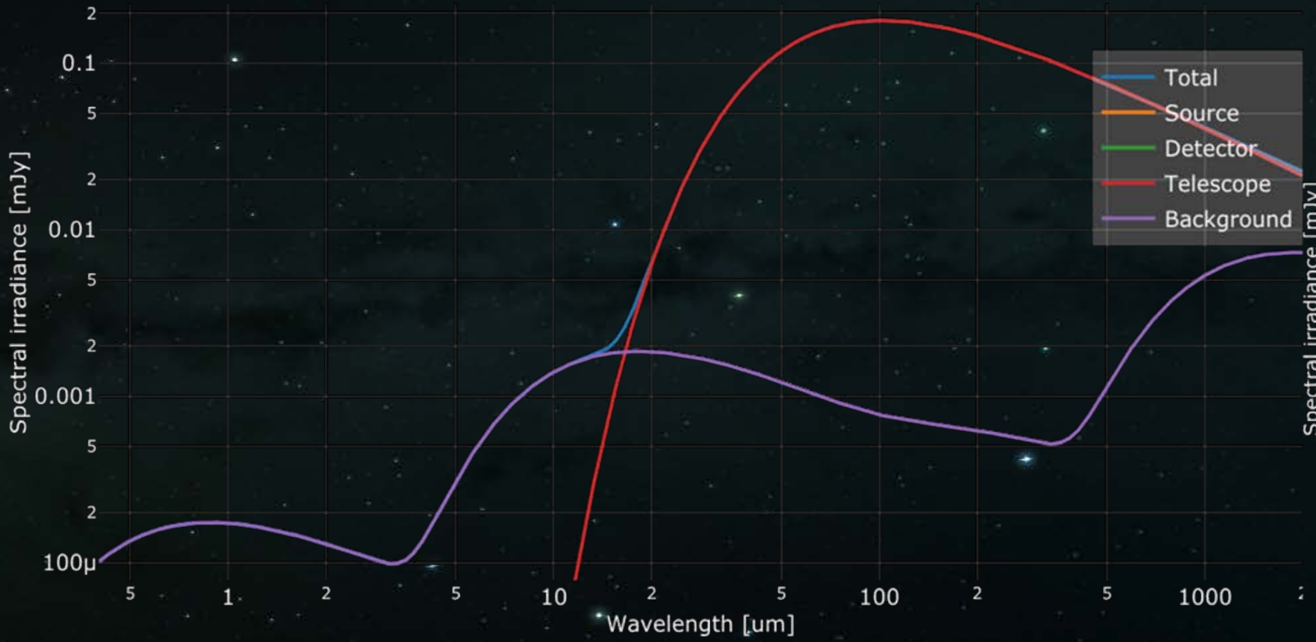
Diameter: 2.5 m
FOV: 1 arcsec
Zodi: 2x polar

Integration time: 1 hour
Efficiency: 100%
Emissivity: 10%

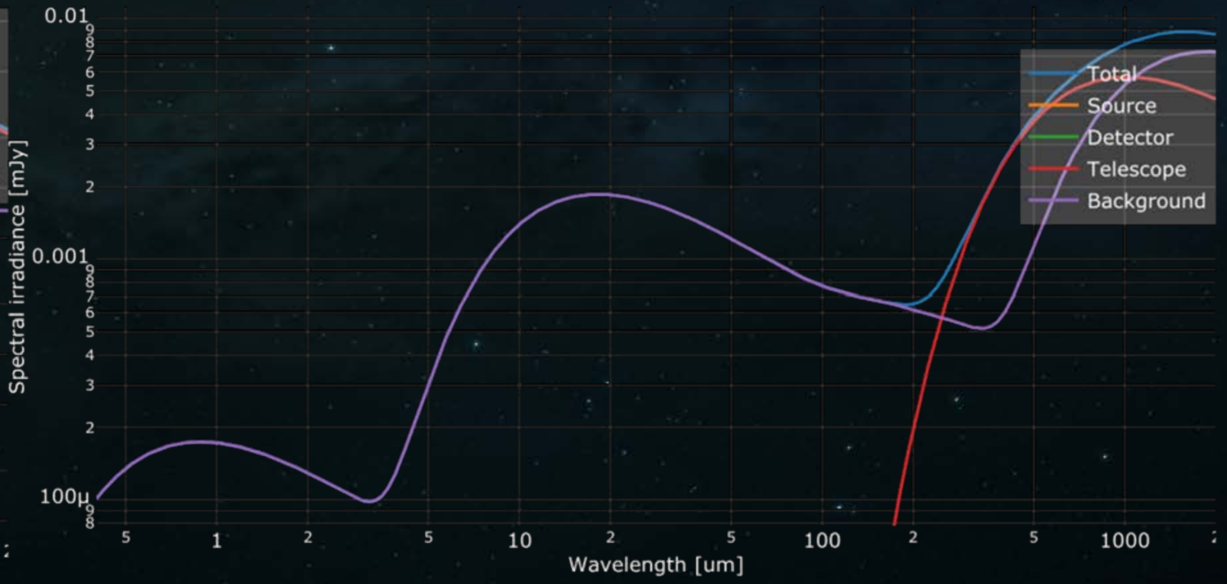
Planetary Spectrum Generator
(Villanueva+2018)
https://psg.gsfc.nasa.gov

Where is SOFIA’s niche in this context?

A JWST type observatory (50K)



An Origins (OST) type observatory (5K)



Sensitivity study

Diameter: 2.5 m
FOV: 1 arcsec
Zodi: 2x polar

Integration time: 1 hour
Efficiency: 100%
Emissivity: 10%

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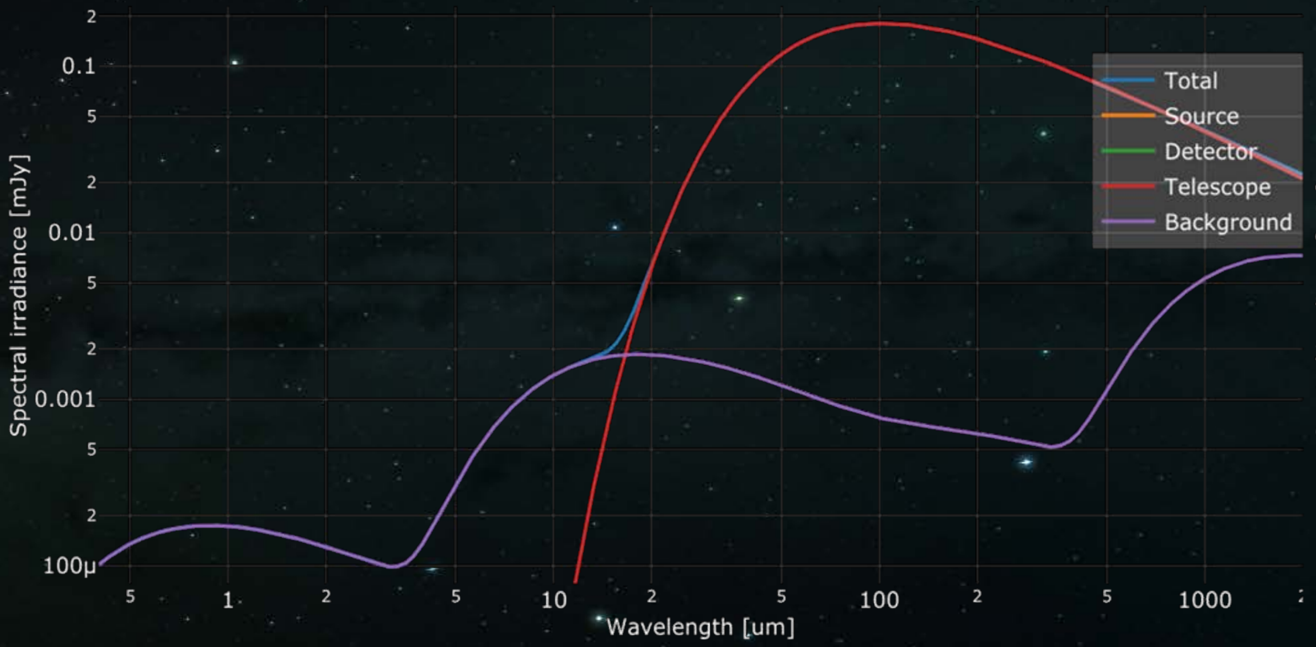
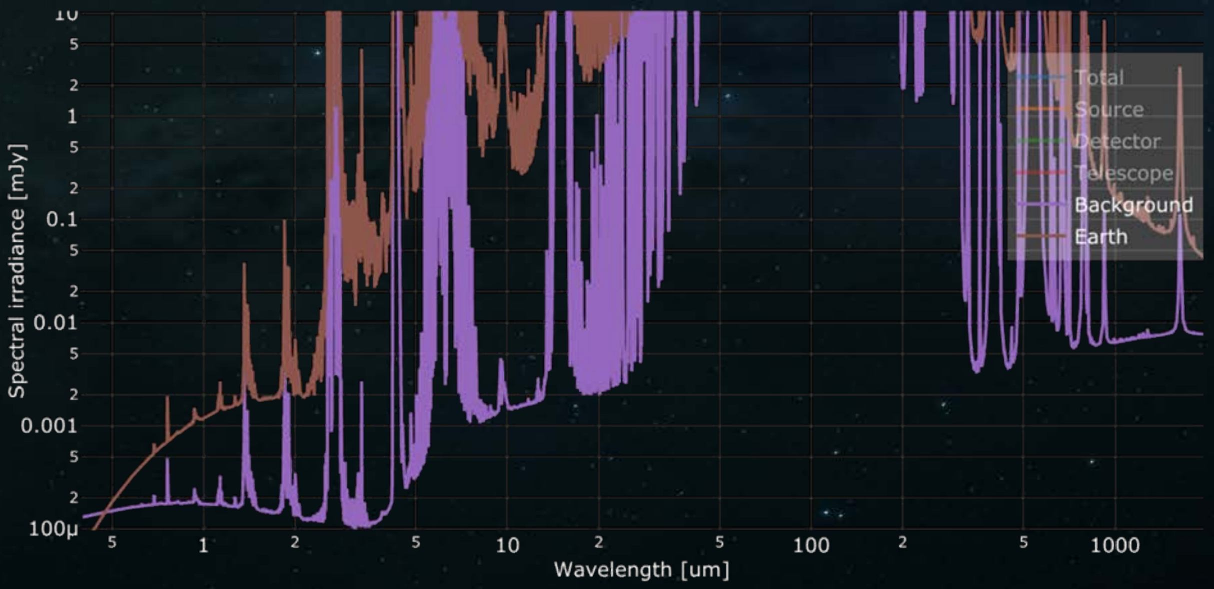
Where is SOFIA's niche in this context?

A JWST type observatory (50K)



A ground-based observatory (Maunakea)



Sensitivity study

Diameter: 2.5 m
FOV: 1 arcsec
Zodi: 2x polar

Integration time: 1 hour
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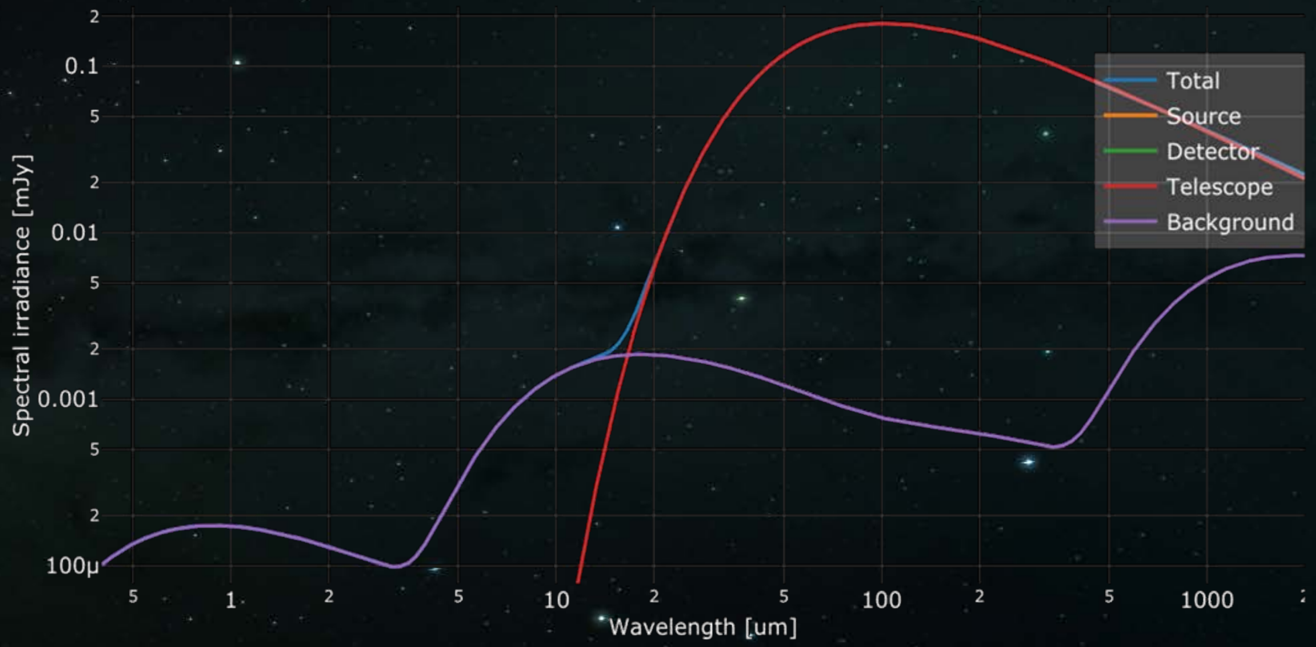
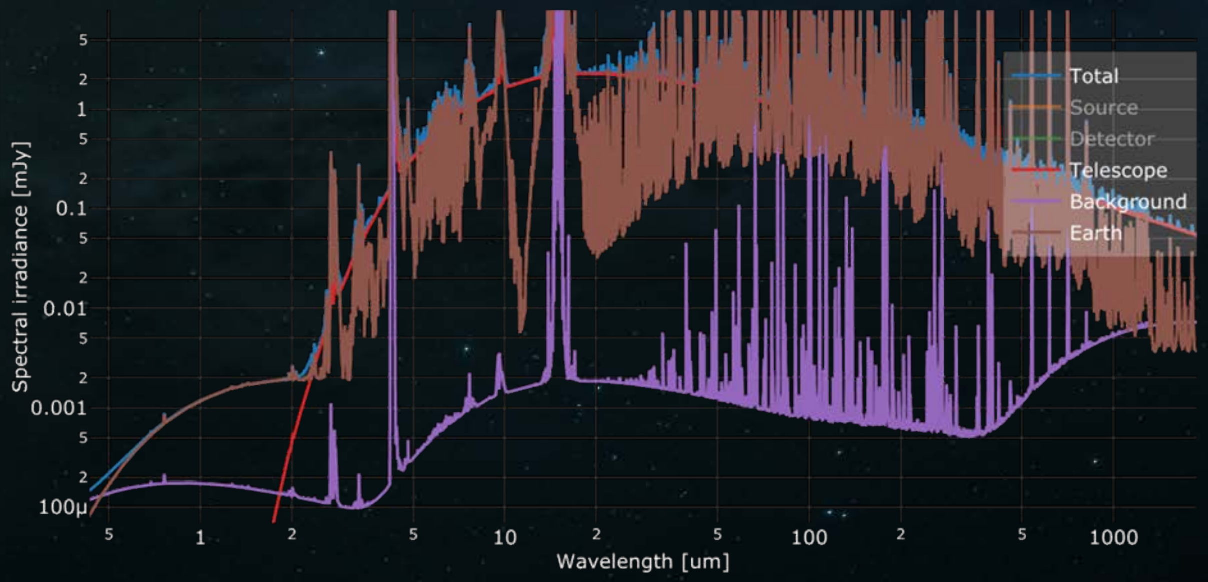
Where is SOFIA's niche in this context?

A JWST type observatory (50K)



SOFIA observatory



Warmer SOFIA struggles in the 2 to 20 um when compared to JWST

Sensitivity study

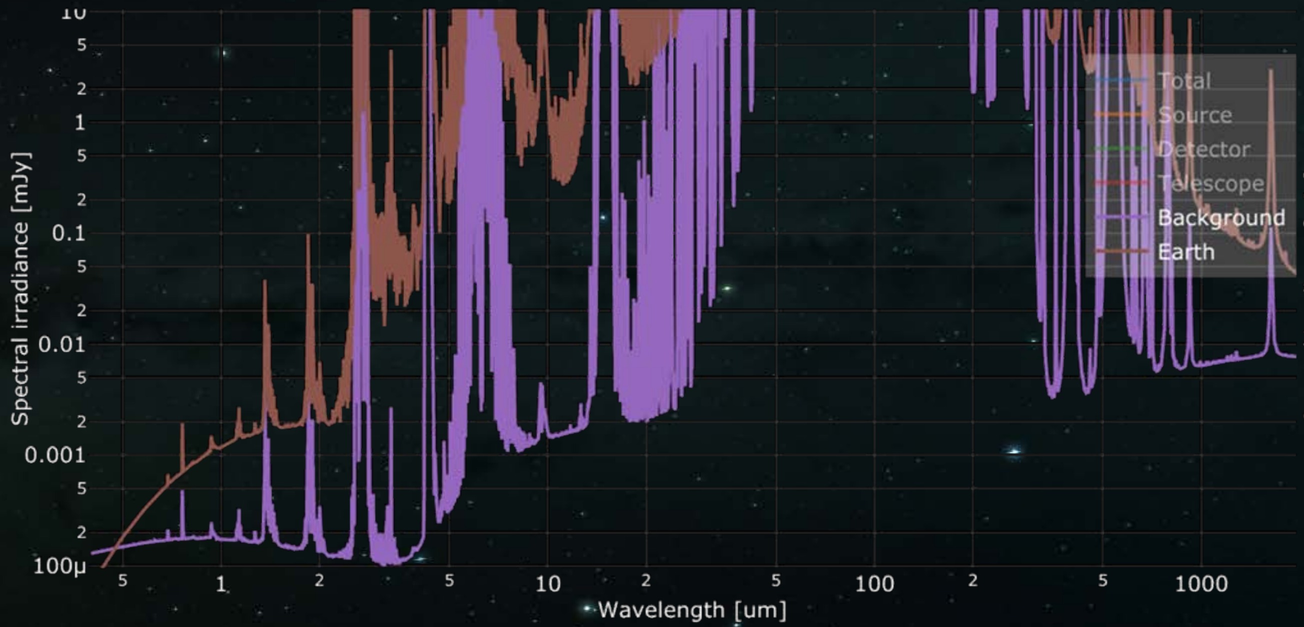
Diameter: 2.5 m
FOV: 1 arcsec
Zodi: 2x polar

Integration time: 1 hour
Efficiency: 100%
Emissivity: 10%

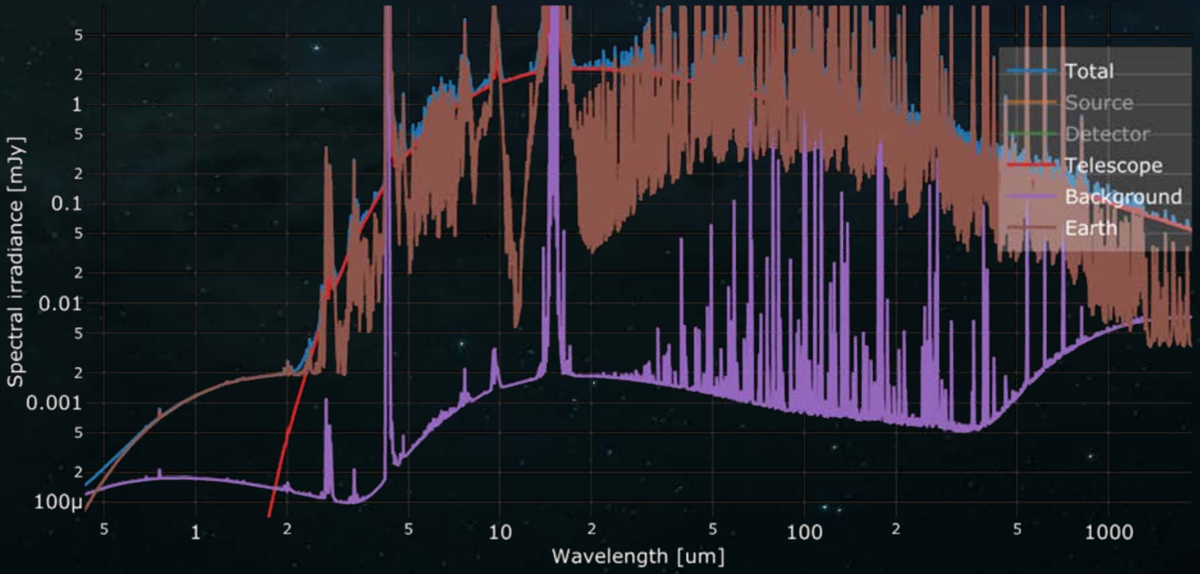
Planetary Spectrum Generator
(Villanueva+2018)
https://psg.gsfc.nasa.gov

Where is SOFIA's niche in this context?

Ground-based observatory (Maunakea)



SOFIA observatory



SOFIA provides unique access in the 20 to 600 um region

Sensitivity study

Diameter: 2.5 m
FOV: 1 arcsec
Zodi: 2x polar

Integration time: 1 hour
Efficiency: 100%
Emissivity: 10%

Planetary Spectrum Generator
(Villanueva+2018)
https://psg.gsfc.nasa.gov

Where is SOFIA's niche in this context?

Sub-mm/THz (100 to 1000 um, or <3 THz) – SOFIA is competitive

- SOFIA provides access to H_2O, OH, other key species and their isotopologues which are blocked from ground-based observatories (e.g., ALMA)
- This is a sweet spot for SOFIA (e.g., 4GREAT, upGREAT)
- Limited spatial resolution and accessible lines may restrict the possible science cases.

Far-Infrared (20 to 100 um) – SOFIA niche

- This area is only accessible from space, yet typically at modest resolutions.
- High-resolution spectroscopy (e.g., HIRMES) would provide unprecedented access to new science (e.g., gPAHs, complex organics).
- As demonstrated by Cassini/CIRS (7 to 1000 um) for Titan this is a key spectral region to perform detailed molecular characterizations.
- OST/SPICA would provide unprecedented access to this region, yet in >15-20 years.

Where is SOFIA's niche in this context?

Mid-Infrared (5 to 20 um) – Strong competition from JWST in the near future

- SOFIA provides sensitivity to water and its isotopologues, not accessible from ground.
- This is the prime region of PAHs and many key molecular and solid state features.
- Strong competition by colder JWST, with orders of magnitude better sensitivity, yet high-resolution spectroscopy (e.g., EXES) will remain competitive.

Near-Infrared (2 to 5 um) – Strong competition from JWST and ELTs

- The 2-5 um region targets the CH stretch (most hydrocarbons), water, CO and CO_2 (only accessible from space). It is sensitive to strong molecular lines in absorption and in emission.
- Greater sensitivity from space and better spatial resolution from ground (AO) and ELTs make this a tough spectral region to compete for SOFIA.

Where is SOFIA's niche in this context?

Optical and up to IR K-band (0.3 to 2 um) – Extreme competition from ELTs, JWST and space (e.g., HST, LUVOIR), very crowded field

- **PROs**: Perhaps the biggest astronomical community.
- Extreme competition in sensitivity from space (HST, JWST, LUVOIR) and spatial resolution from ground and AO systems. No notable gains w.r.t. to ground.

UV – Competition from HST and LUVOIR in the future

- Modest gains in sensitivity w.r.t. to ground-based
- There is no planned big observatory to probe the UV beyond HST
- UV probing requires special optical coatings.

Main SOFIA's niche: high-resolution spectroscopy (l/dl>10,000) beyond 10 microns. Modest science cases for terrestrial planets, but plenty for organic rich bodies (e.g., comets, ocean worlds, Titan, disks)

Thank you

PSG Spectroscopy Tool: psg.gsfc.nasa.gov