If at First You Don't Succeed: That's Pretty Much Standard Practice – Oddities on the Way to Discovery

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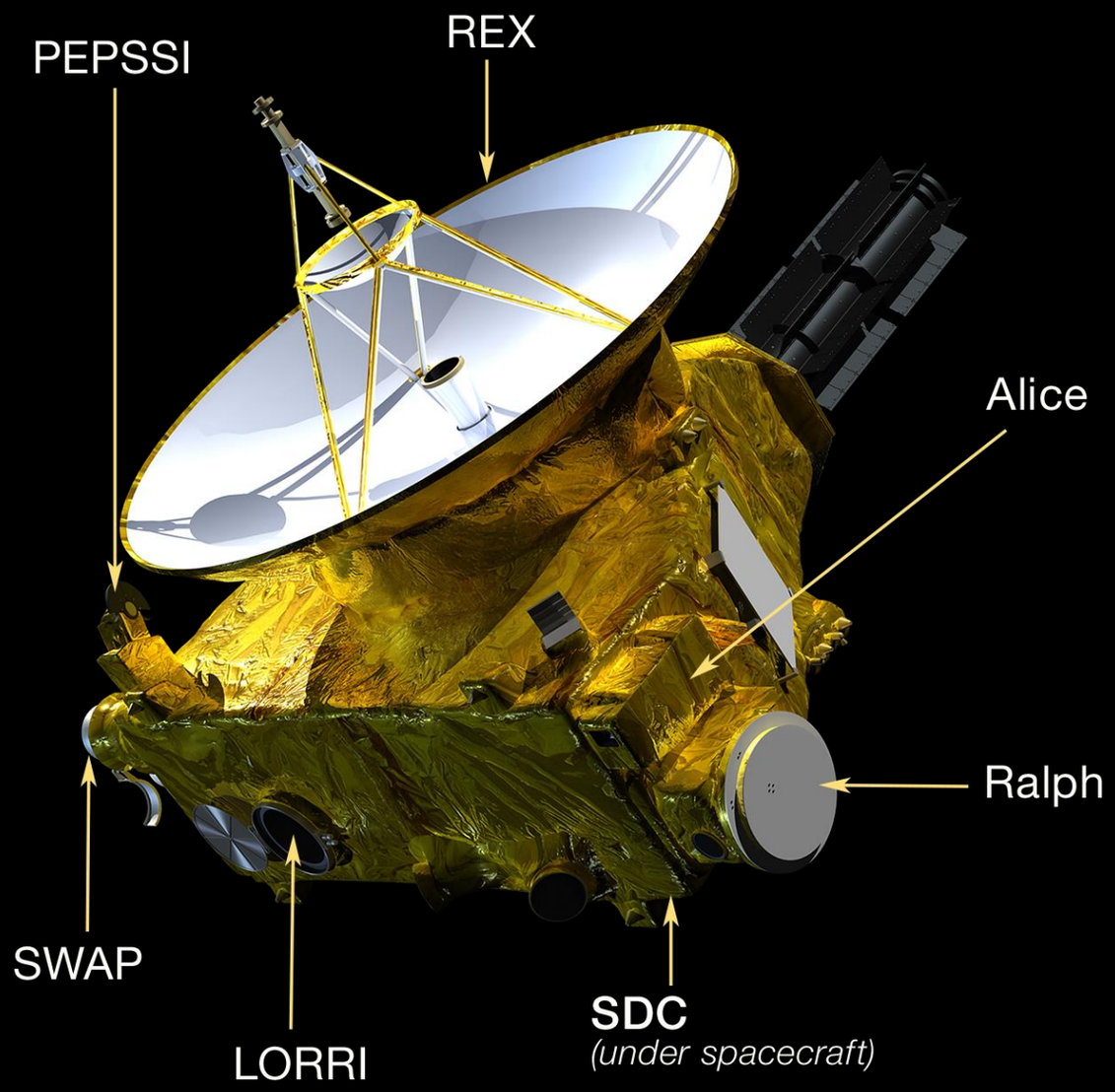
Murphy Never Sleeps

- A Very Condensed Look at Some Remarkable Science Produced by Three Missions with an Emphasis on:
  - The Ralph Instrument on the New Horizons Mission to the Pluto System
  - The TIRS Instrument on Landsat 8
  - The OVIRS Instrument on OSIRIS-REx Sample Return Mission to the asteroid Bennu
- But, Before They Could Produce Data, They had to be Built, Calibrated, and Evaluated/Optimized in Flight
  - Sometimes This Involved “Interesting” Effects and “Exciting” Circumstances

New Horizons Instruments



LORRI: High-Resolution Panchromatic Imager: Geology, Navigation, Searches for Moons and Rings

Ralph: Color Imager and Infrared Composition Mapper

Alice: Ultraviolet Spectral Imager: Atmospheric Searches

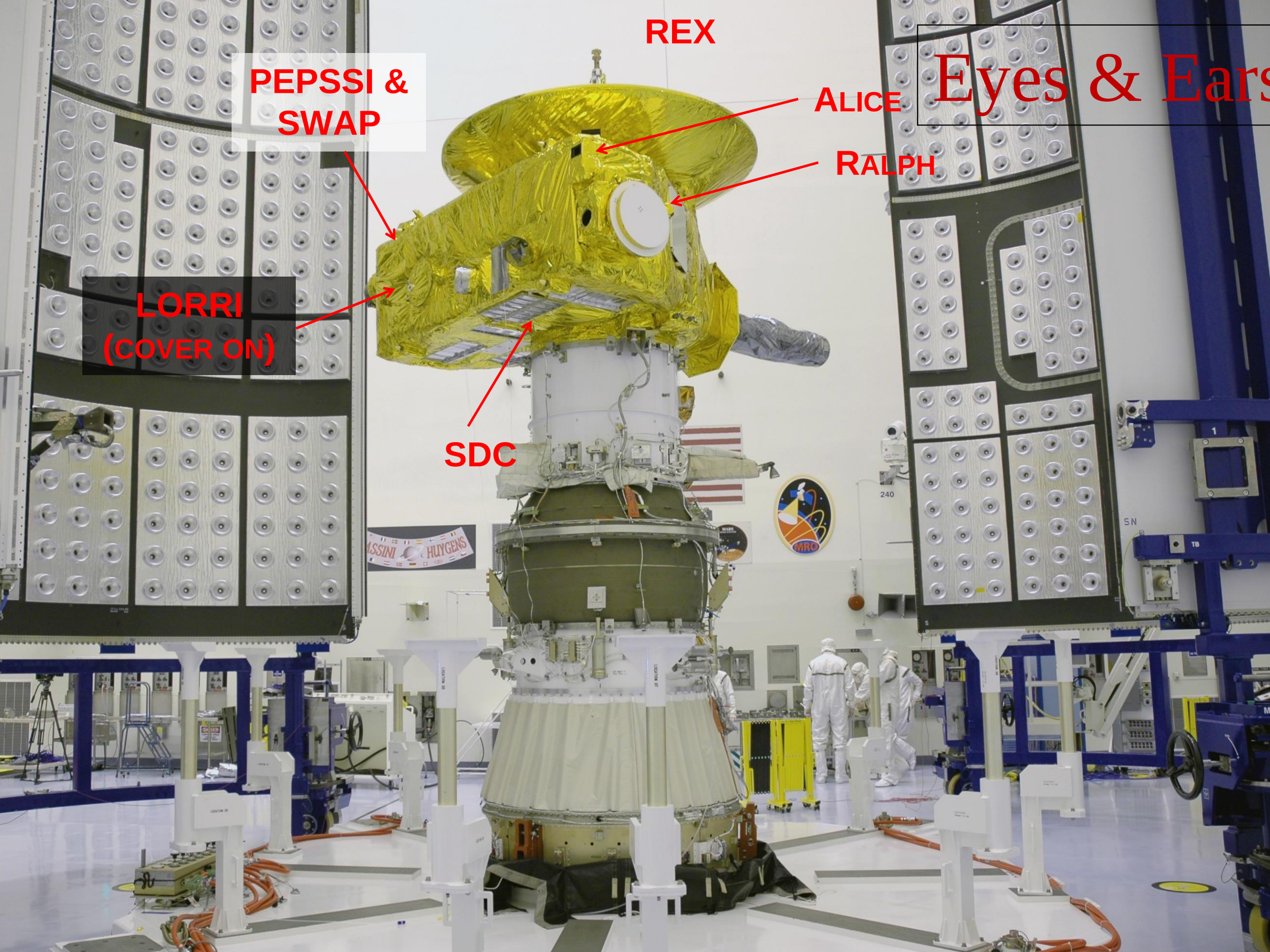
REX: Radio Science Experiment: Surface Temperature and Radar Reflectivity

SWAP: Charged Particle Detector: Solar Wind Interaction with Ultima

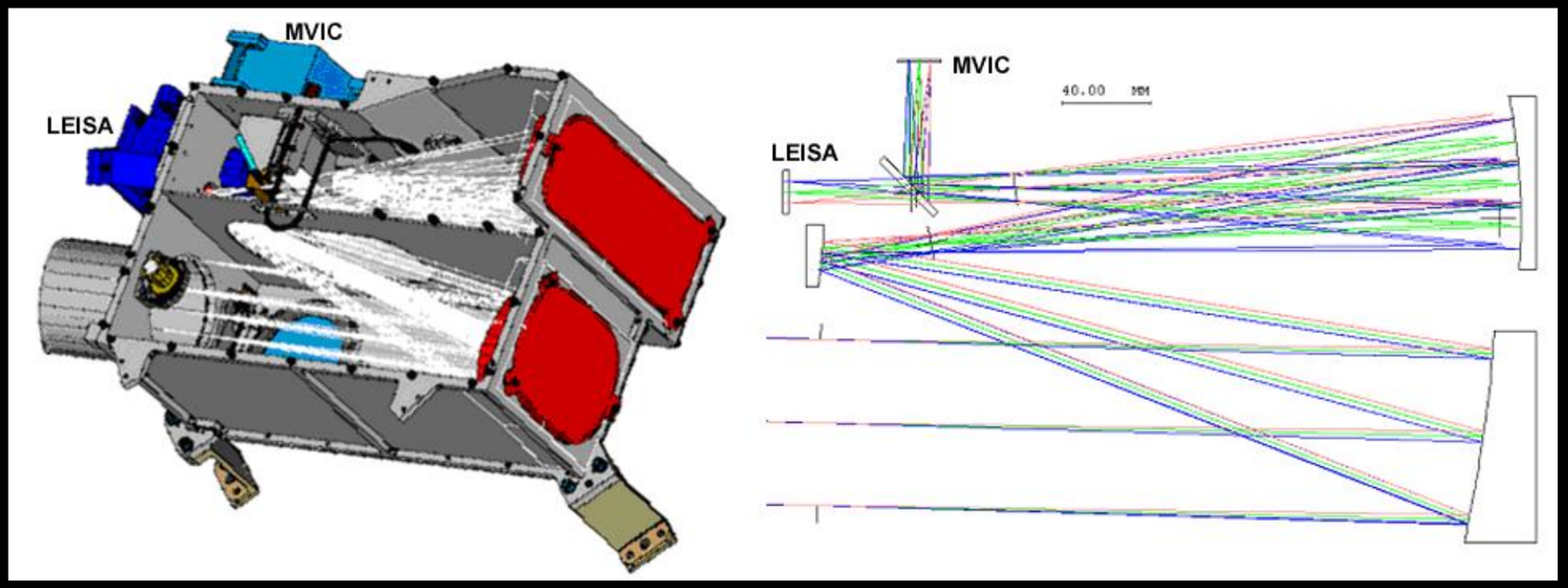
PEPSSI: High-Energy Charged Particle Detector: Search for Emitted Ions

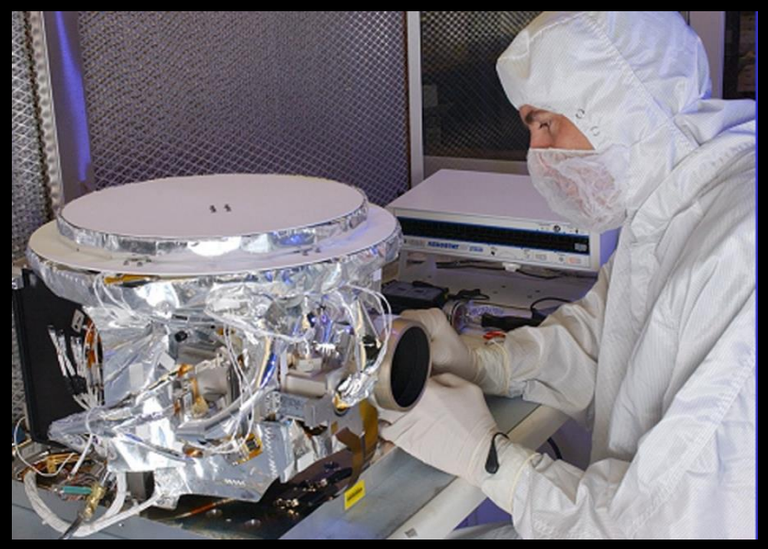
SDC: Dust Impact Detector

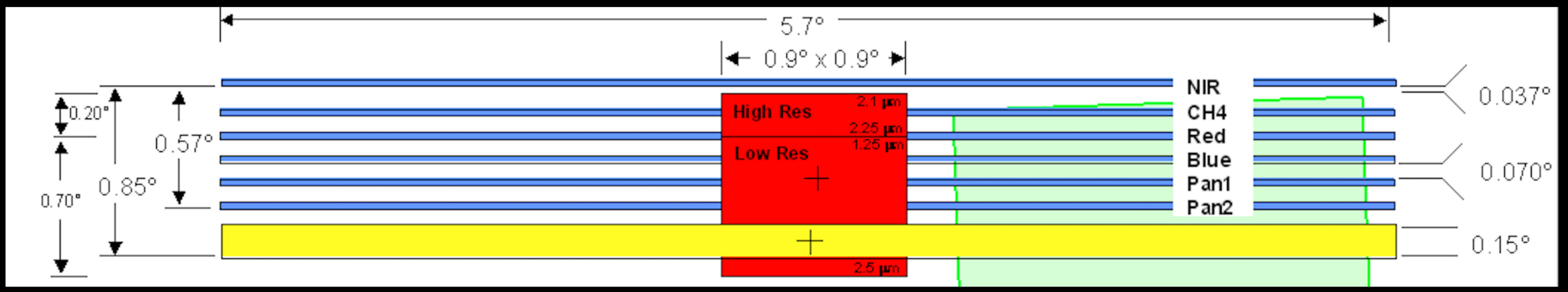
Eyes & Ears



Ralph: IR and Visible Camera in One Box







Ralph Provides Composition Information

- Ralph/MVIC – CCD detector with multi-band filters
  - Panchromatic Band
  - 4 visible/NIR colors including a methane band filter
- Ralph/LEISA – HgCdTe detector with wedged filter
  - 1.25 – 2.5 μm, $\lambda/\Delta\lambda$ = 240
  - 2.1 – 2.25 μm, $\lambda/\Delta\lambda$ = 560
    - N_2 feature at 2.15 μm useful for temperature

Interesting Effect

- During development there were the standard development situations
  - Unexpected noise sources, detector delivery concerns, thermal, mechanical and optical performance concerns
  - First Two TVAC rounds exposed problems that needed to be addressed
  - Everything looked good for third round and the instrument was loaded in the chamber, pumpdown went well and the cooling system to bring the optics box down to ~ 230 K was activated and temperatures were dropping
- Suddenly, at a bit below 0 C, the optics box cooling stopped and the flow of cold liquid cooling ceased

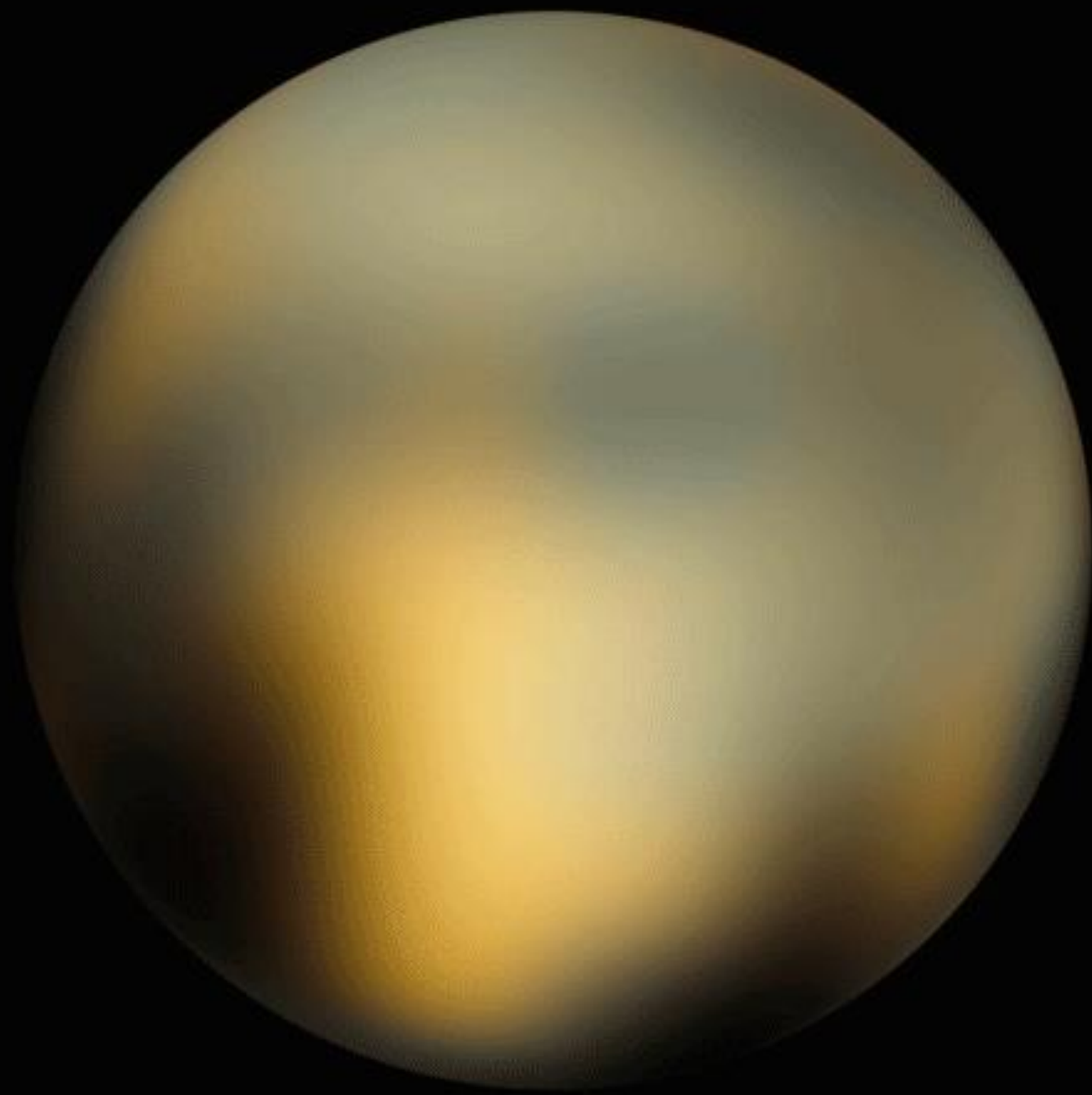
Interesting Cause

- Coolant liquid was a mixture of water and anti-freeze. Similar to that used in cars
- When topping off the system, a container that had the appropriate name and smelled appropriately was used.
- Turned out someone had filled a used container with water. This was not expected. Processes were changed
- After a couple of days of very controlled warm up to avoid stress from expanded ice, all was well and TVAC went as planned, as did Observatory Level testing

Exciting Circumstance

- Post launch, things were operating well
  - Constraints placed on pointing during observations due to an unexpected “light leak”, but these were not too problematic
  - Outstanding observations made during Jupiter Gravity Assist flyby
  - Closest Approach to Pluto was to be July 14, 2015
    - Fiftieth Anniversary of First Transmission of Pictures of Mars from a Spacecraft (Mariner 4)
- On about July 2, 2015 the spacecraft went into safehold
  - Cause was use of slightly untried operations change
  - Missed Fourth of July fireworks that year, but there were plenty on the program
- All was fixed in a few days and, as you’ll see, the Pluto System got to show its stuff

Our Best View of Pluto Prior to New Horizons w as only a few pixels across (from Hubble)



New Horizons has radically changed our view

Pluto and Charon in Color

Note: In the following charts, all Pluto system surface feature names are informal.

TOMBAUGH REGIO

Cthulhu Regio

Krun Regio

SPUTNIK PLANUM

1

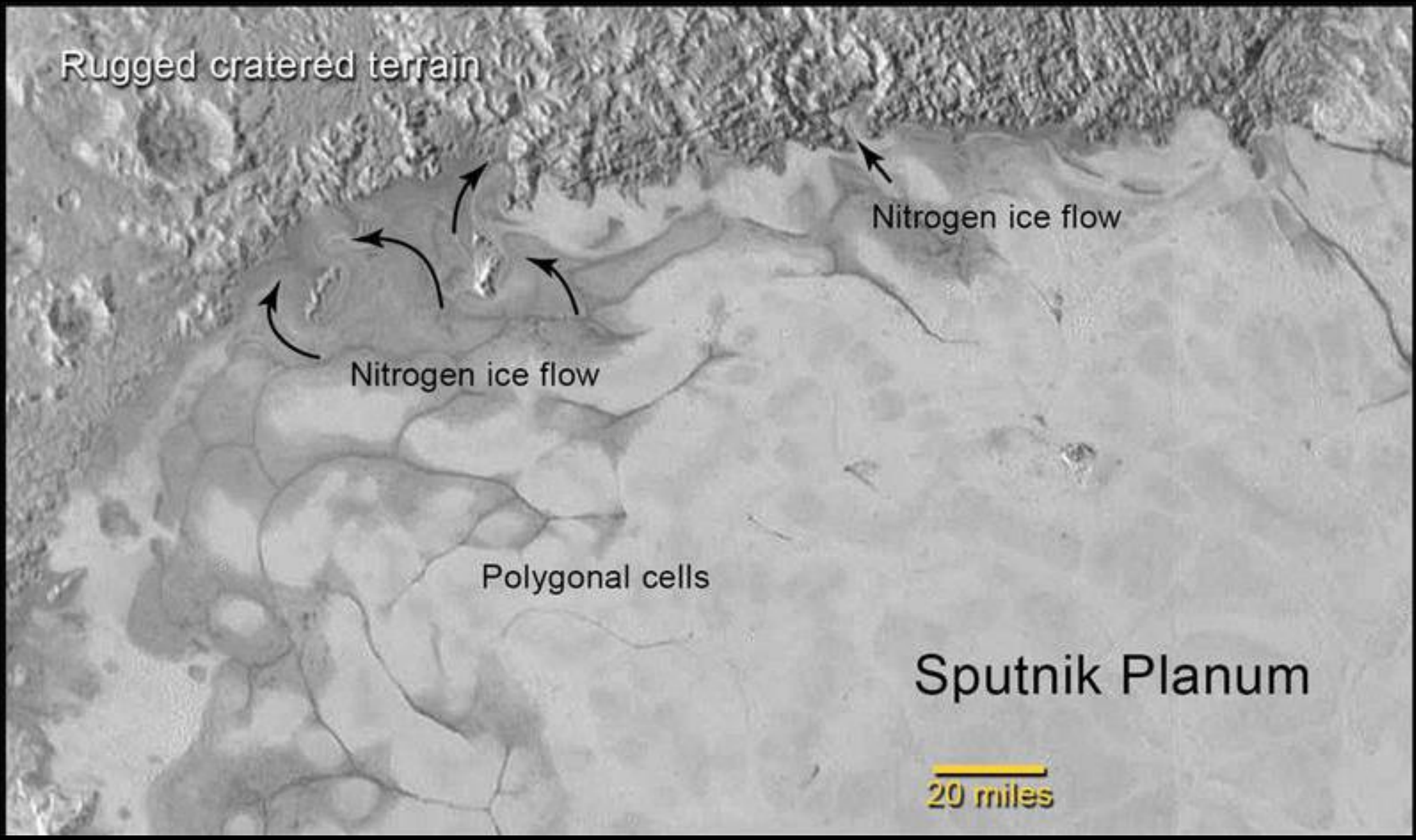
2

3

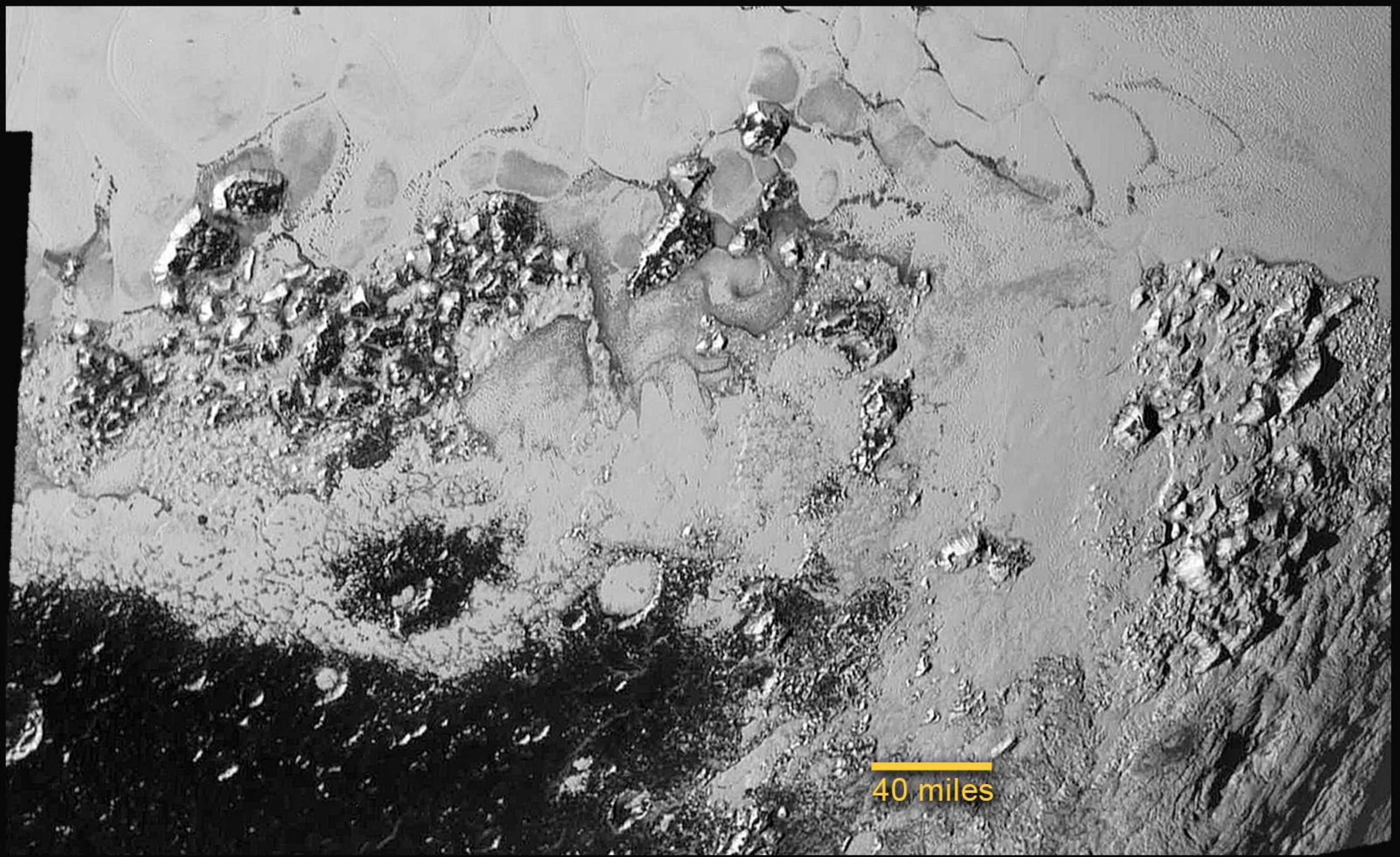
ALL NAMES ARE *INFORMAL*,
SUBJECT TO IAU APPROVAL.

150 miles

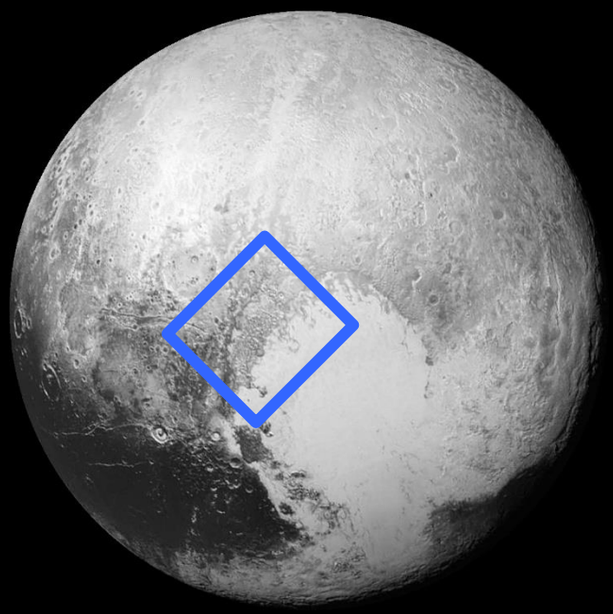
1) Nitrogen Ice Glacial Flows

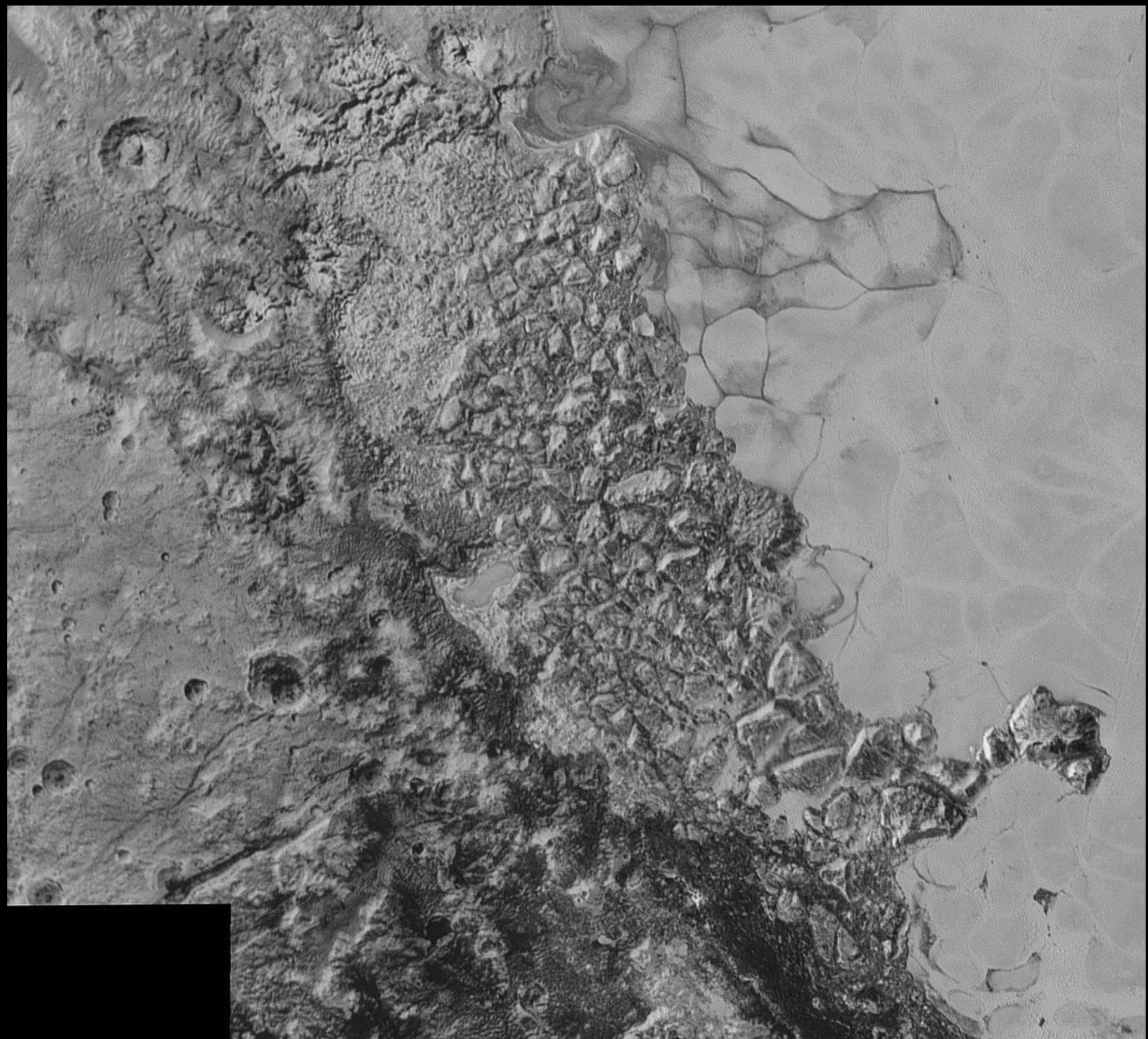


3) Boundary Between Glacial Flow and Older Surface



Region showing mountains of water-ice





Valley Glaciers on East Margin of Sputnik Planum

Sputnik Planum

Ridges and Pits

50 km

Valley Glaciers on East Margin of Sputnik Planum

Front of flow moving into SP

Ridges and pits here (origin unknown)

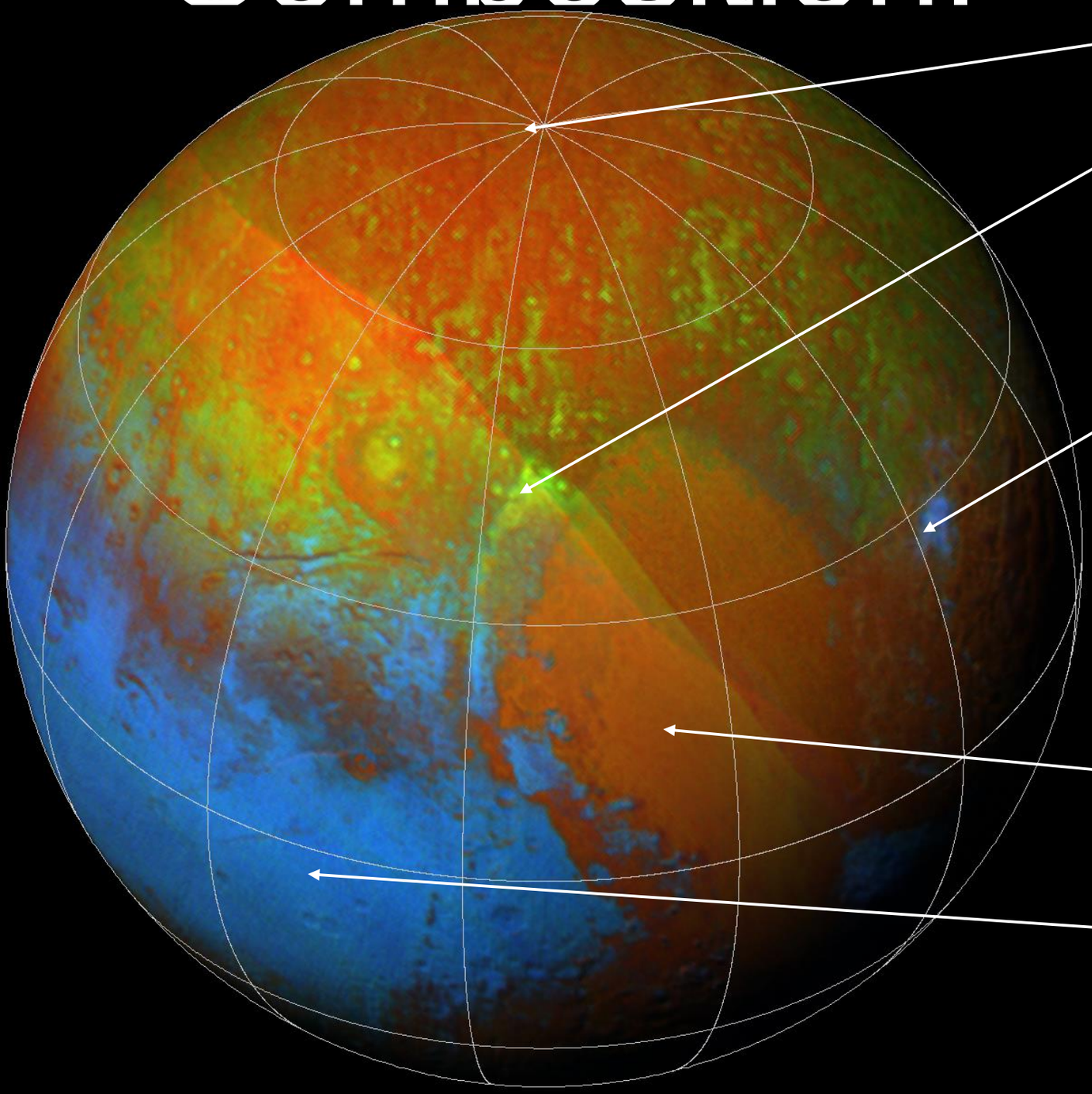
50 km

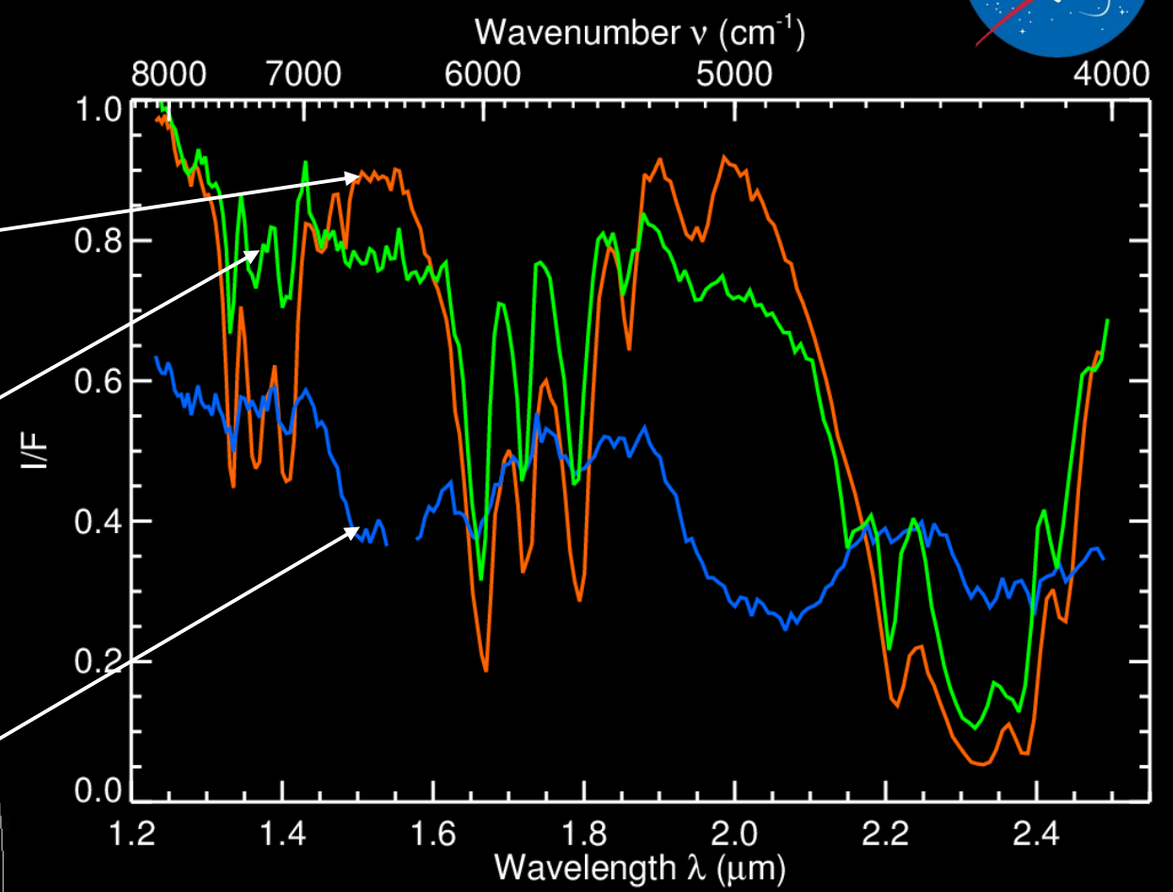
147.2°

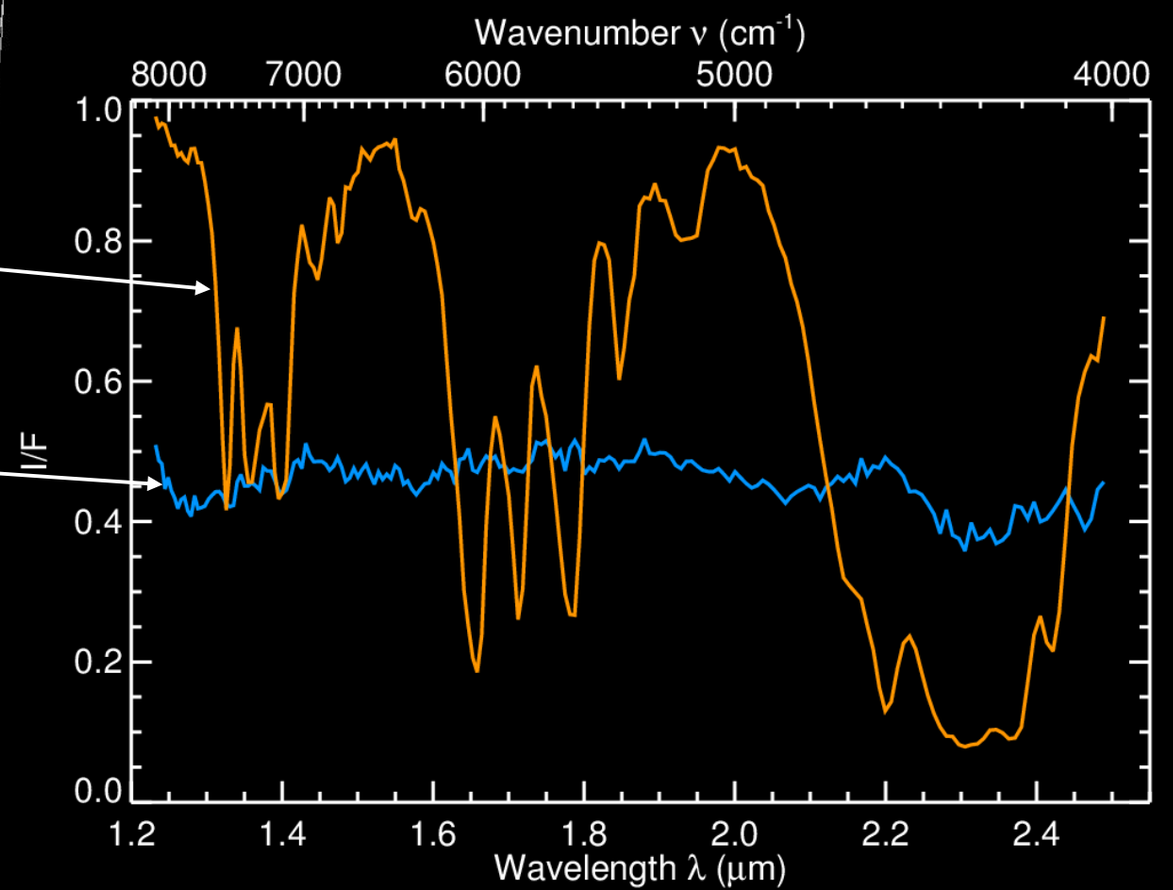
LAYERS IN AL-IDRISI MONTES

MVIC COLOR IMAGES SHOW SURFACE COMPOSITION VARIETY

Pluto Composition:

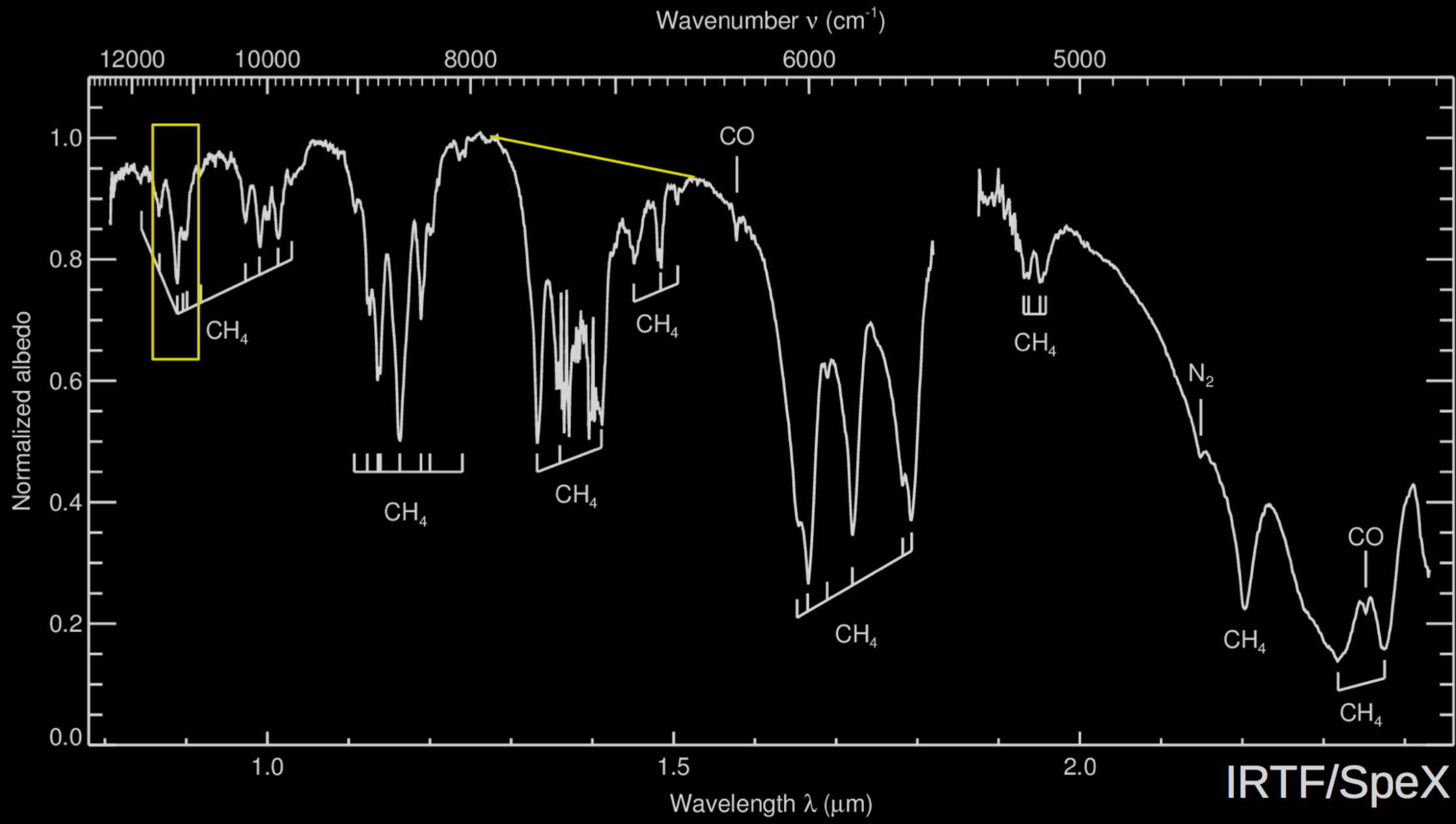


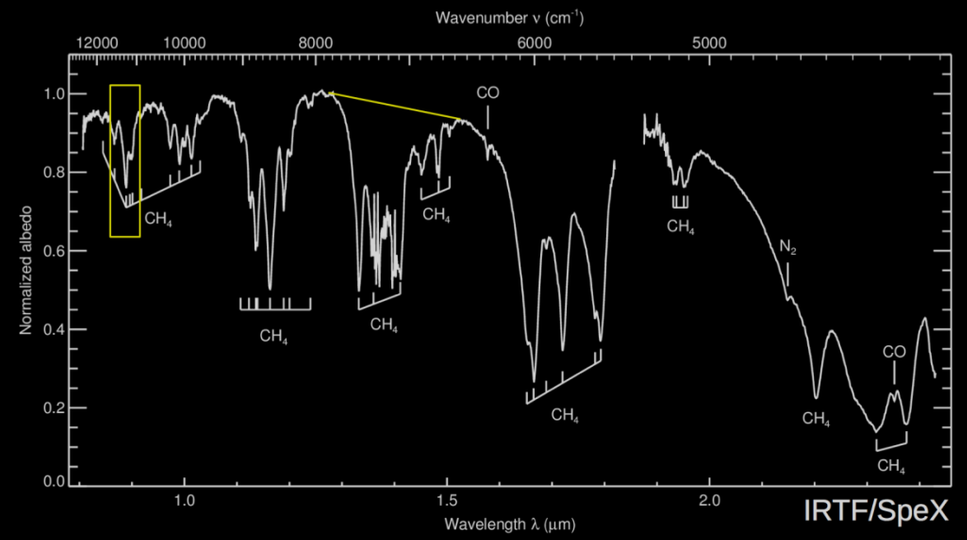




All Pluto system names are informal at this time

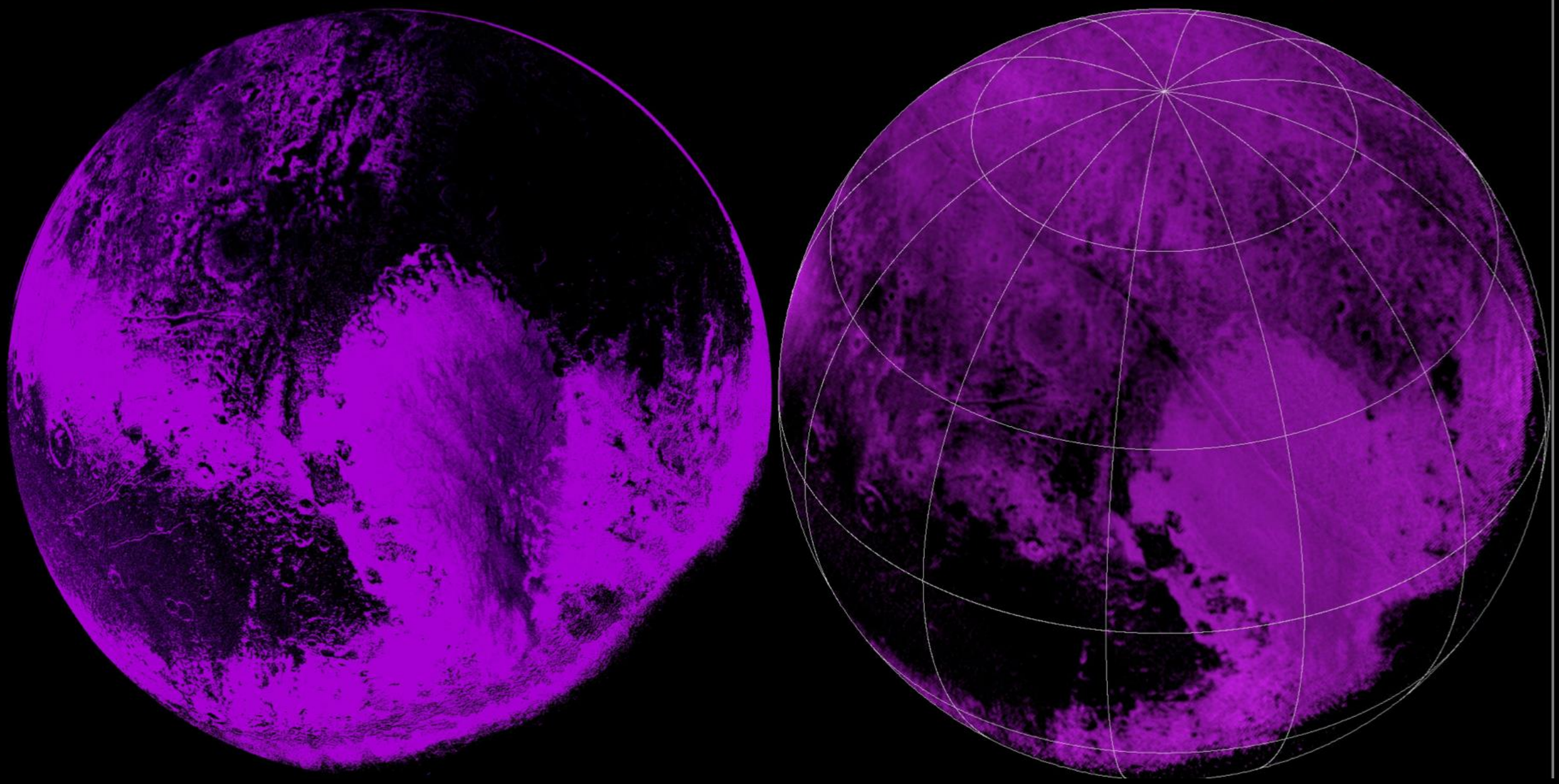
Comparing two bands…



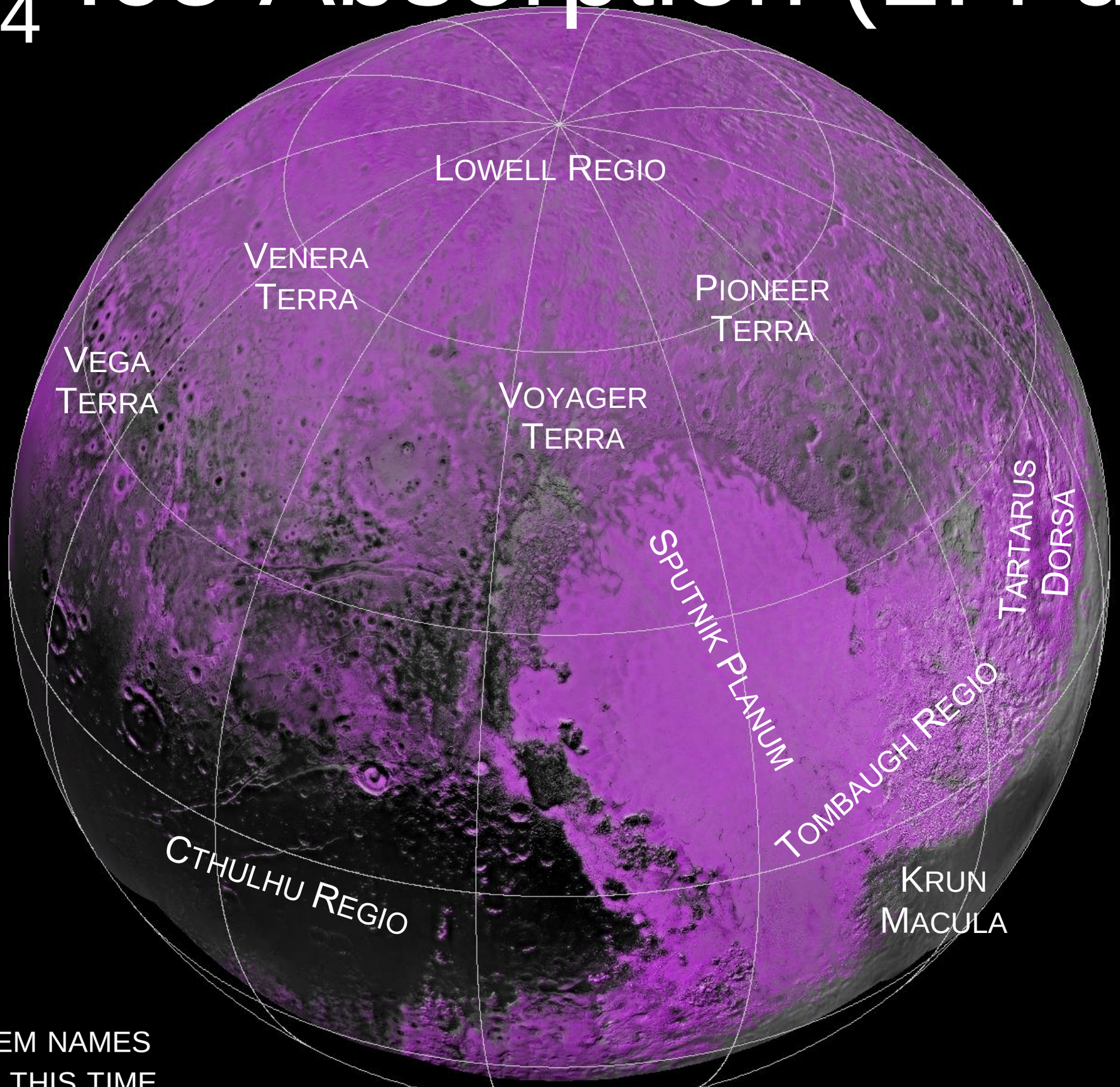


MVIC 0.89 μm

LEISA 1.3-1.4 μm

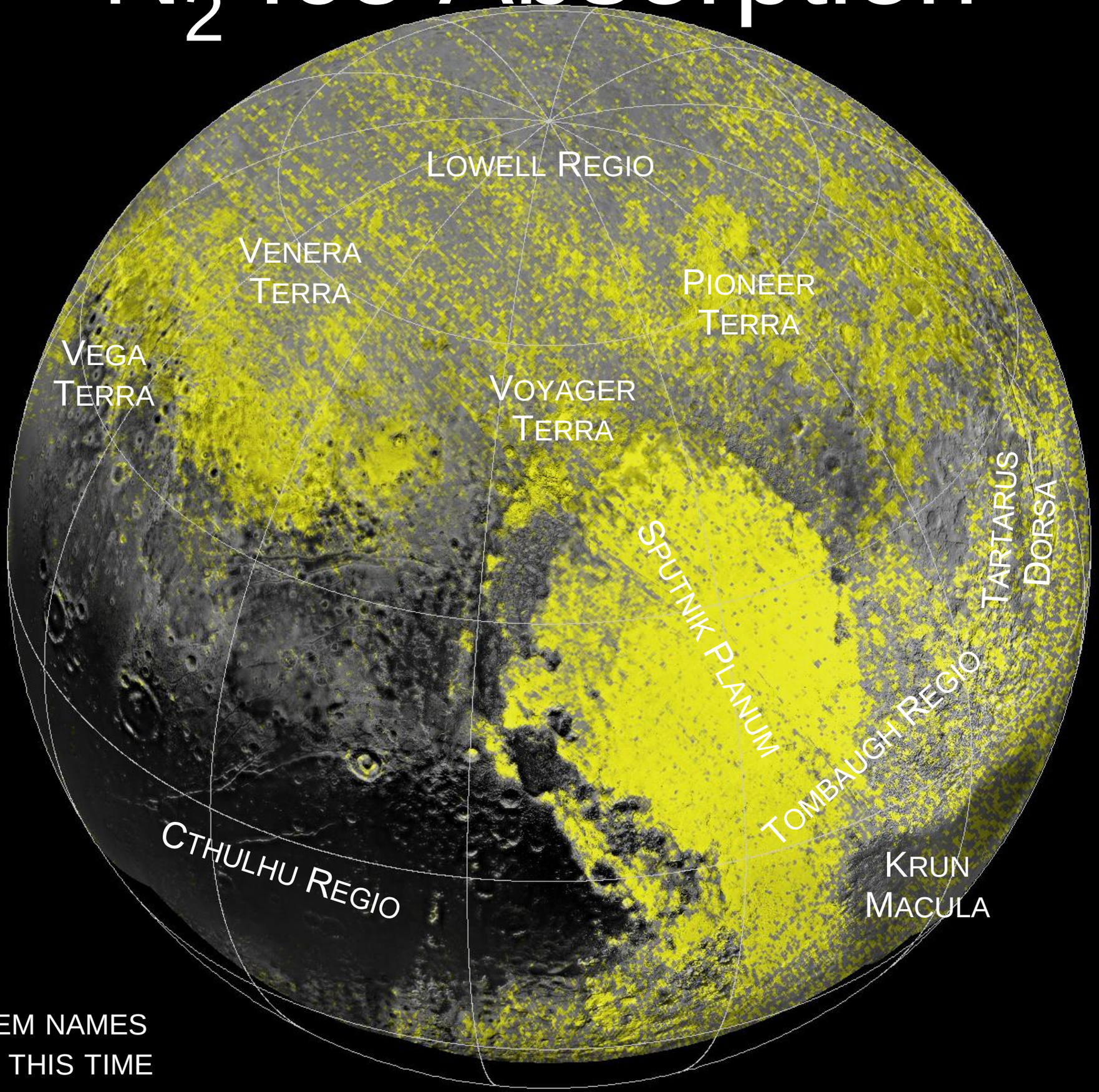


CH_4 Ice Absorption (1.4 um)



All Pluto system names are informal at this time

N_2 Ice Absorption



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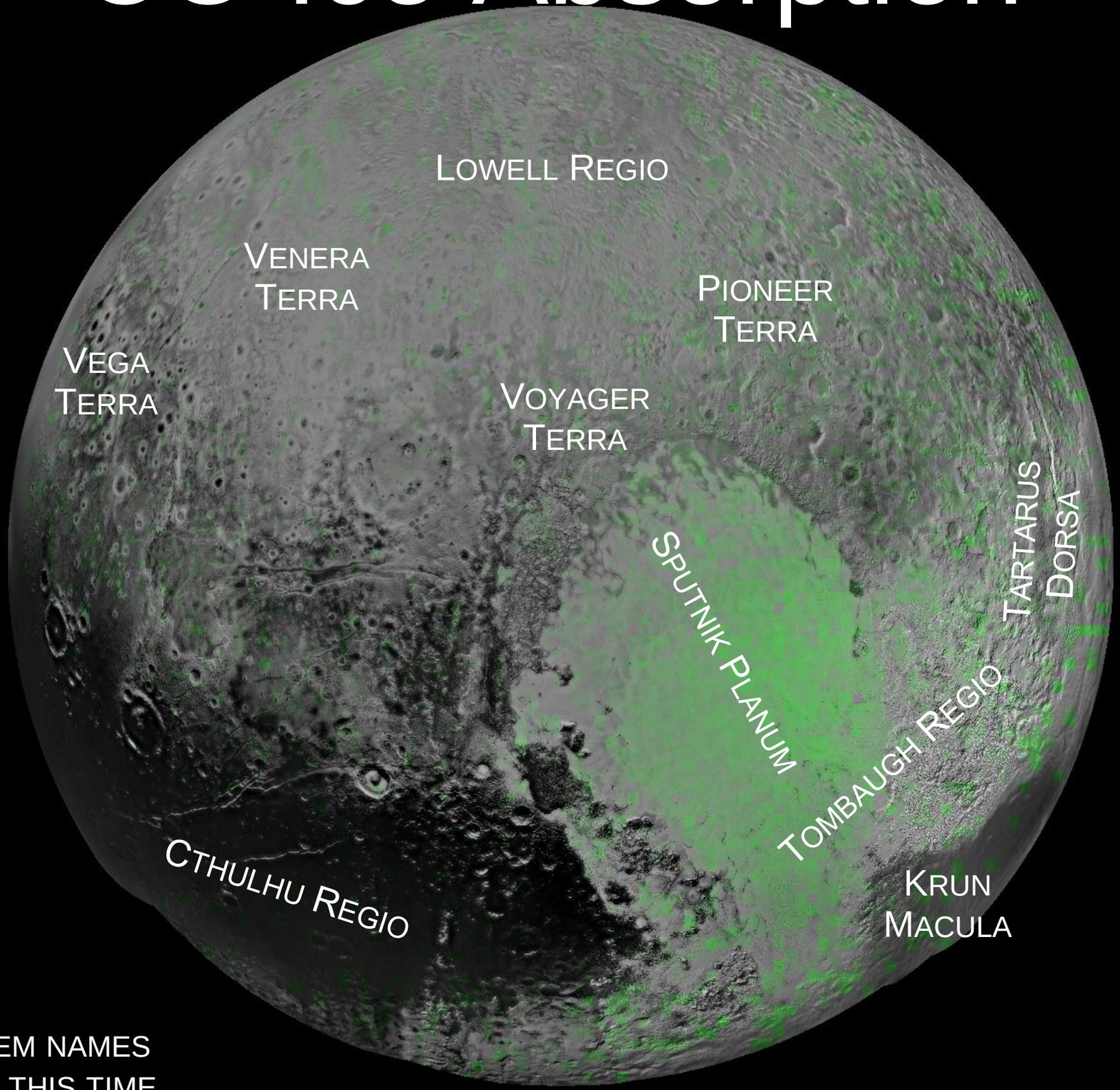
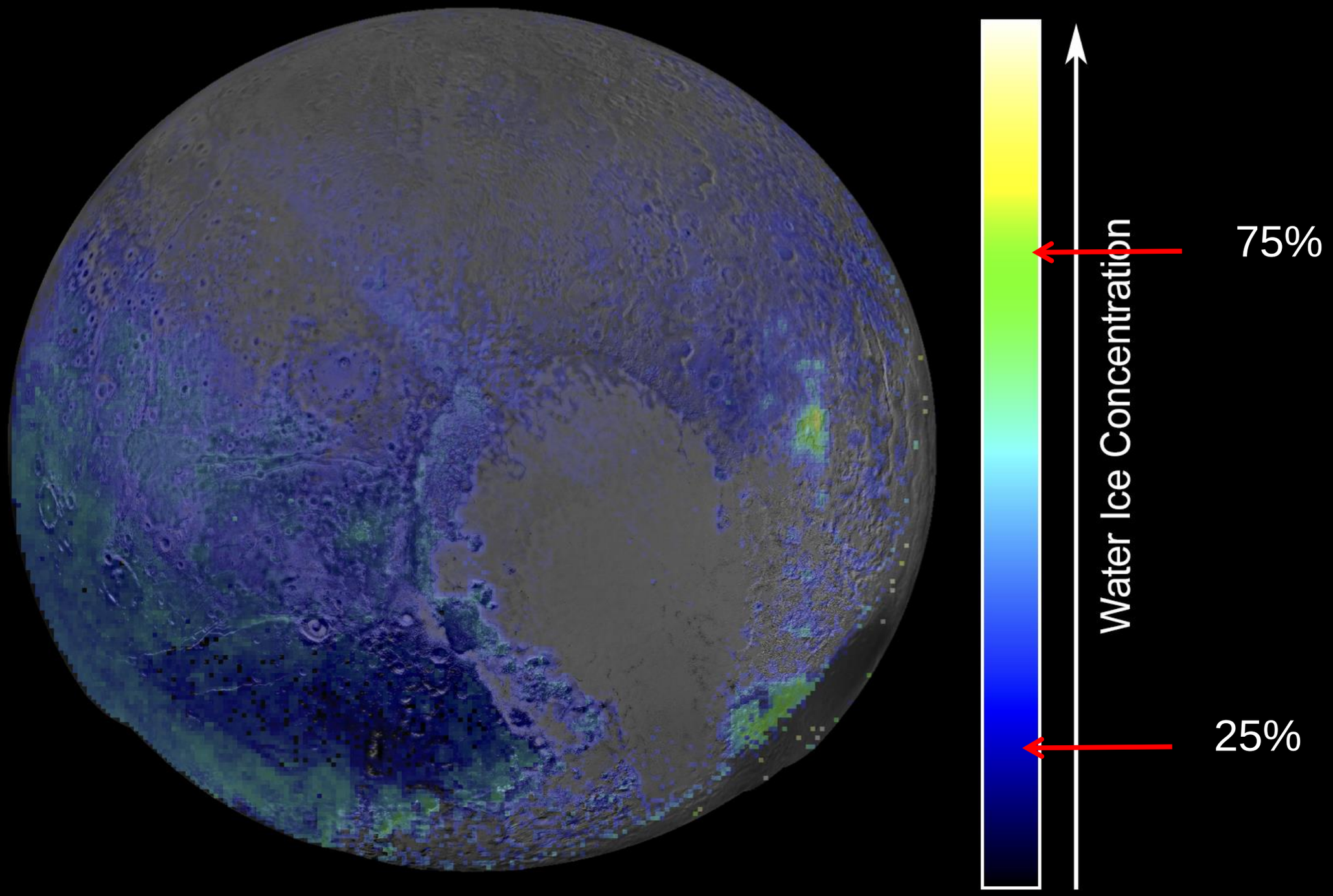
CO Ice Absorption

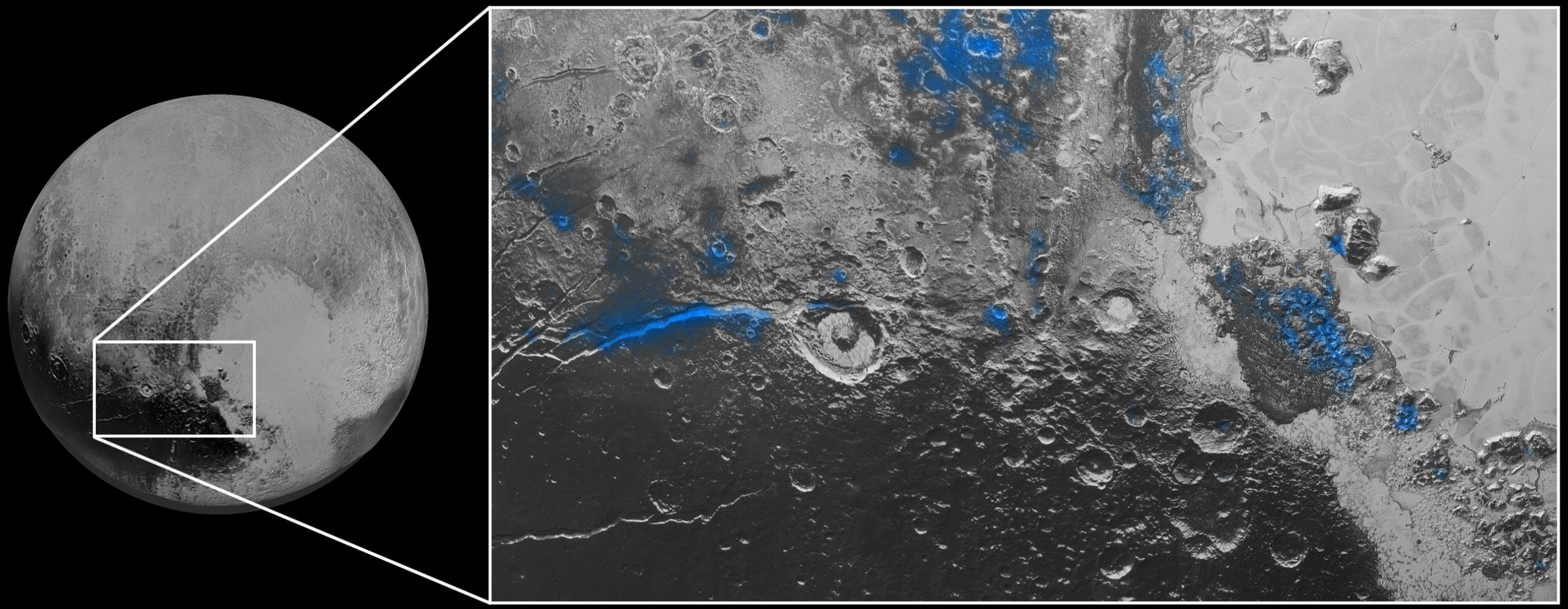


All Pluto system names are informal at this time

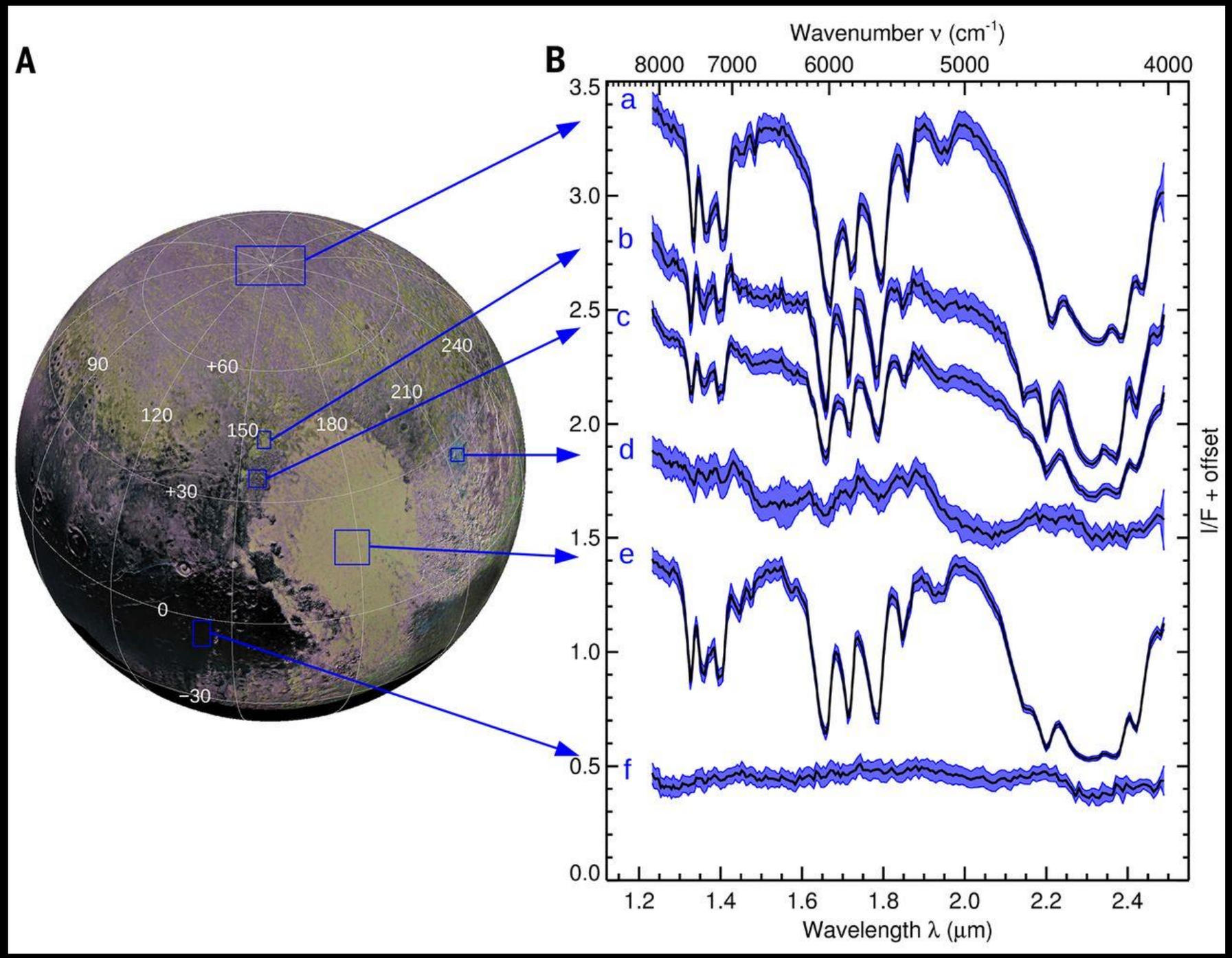
H_2O Ice Absorption from detailed modeling



LEISA Spectra Show isolated areas nearly "pure" (i.e. Charon-like) water ice

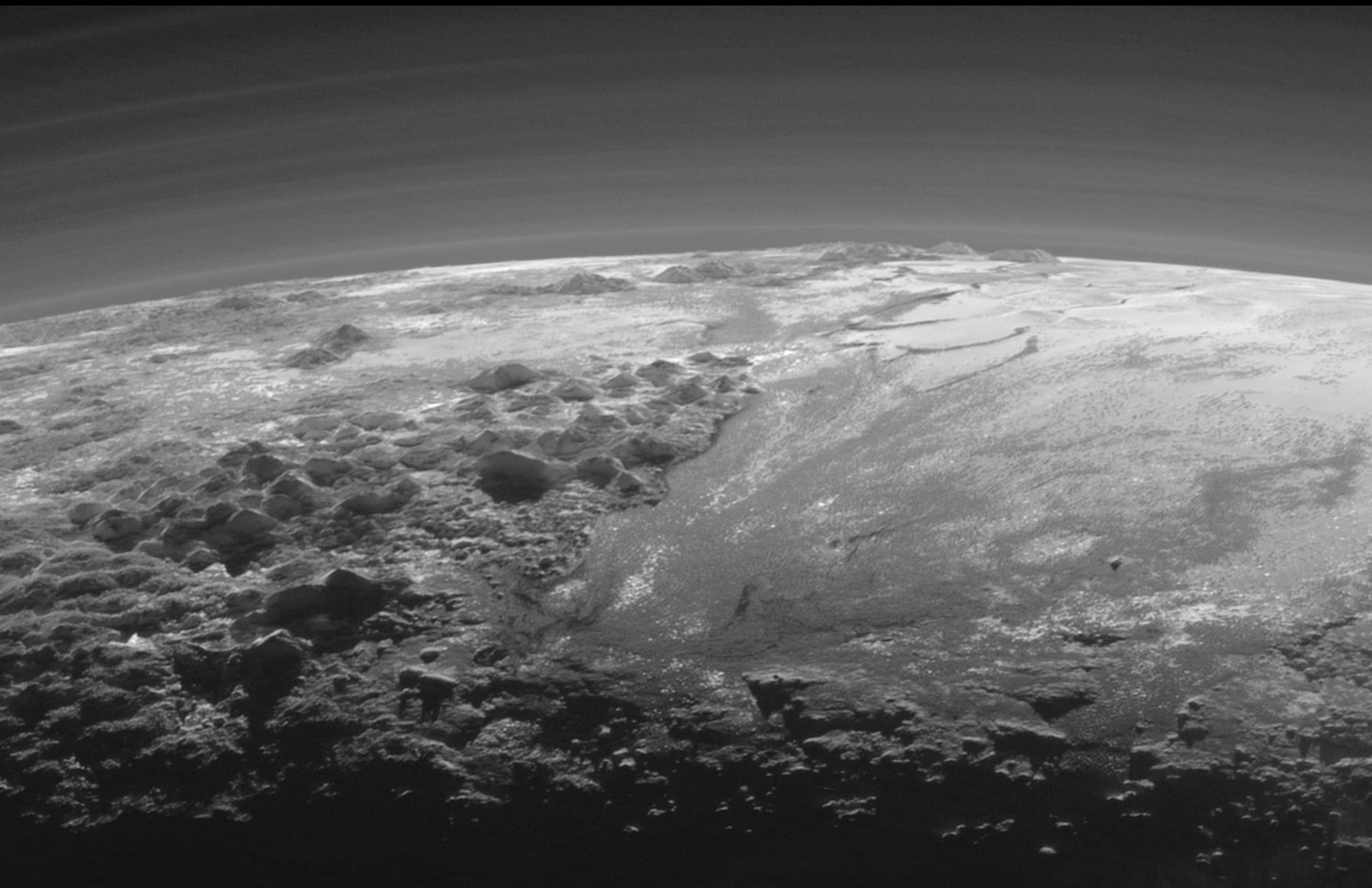


- Blue areas are regions with Charon-like water ice spectra
- This does not mean there is no water in the non-blue areas
  - Water ice could be mixed with other species (e.g. CH_4) or covered by a surface layer of other absorbers

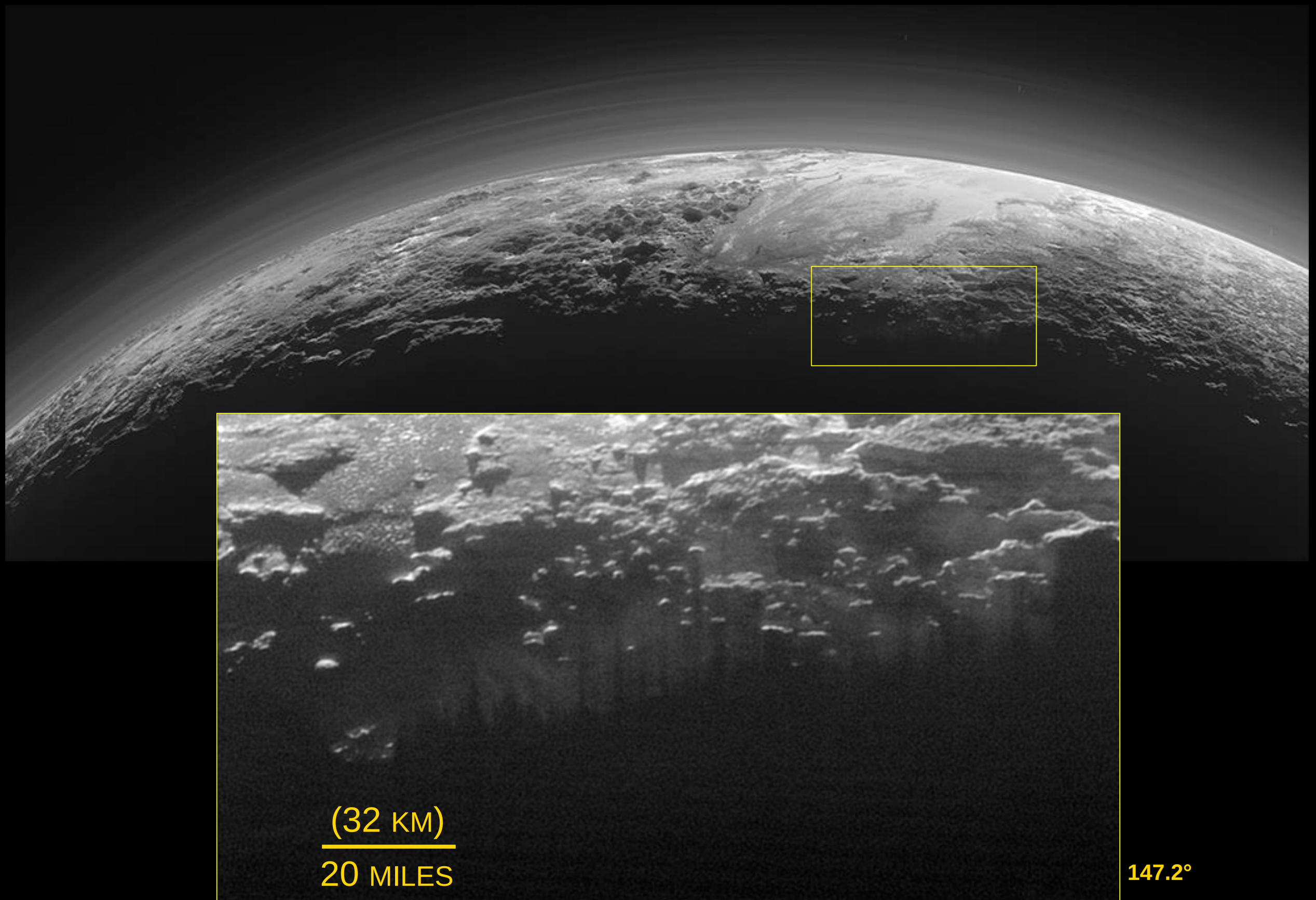


MVIC pan Image taken soon after closest approach

You are there!



Crepuscular Rays show Mountainous Terrain

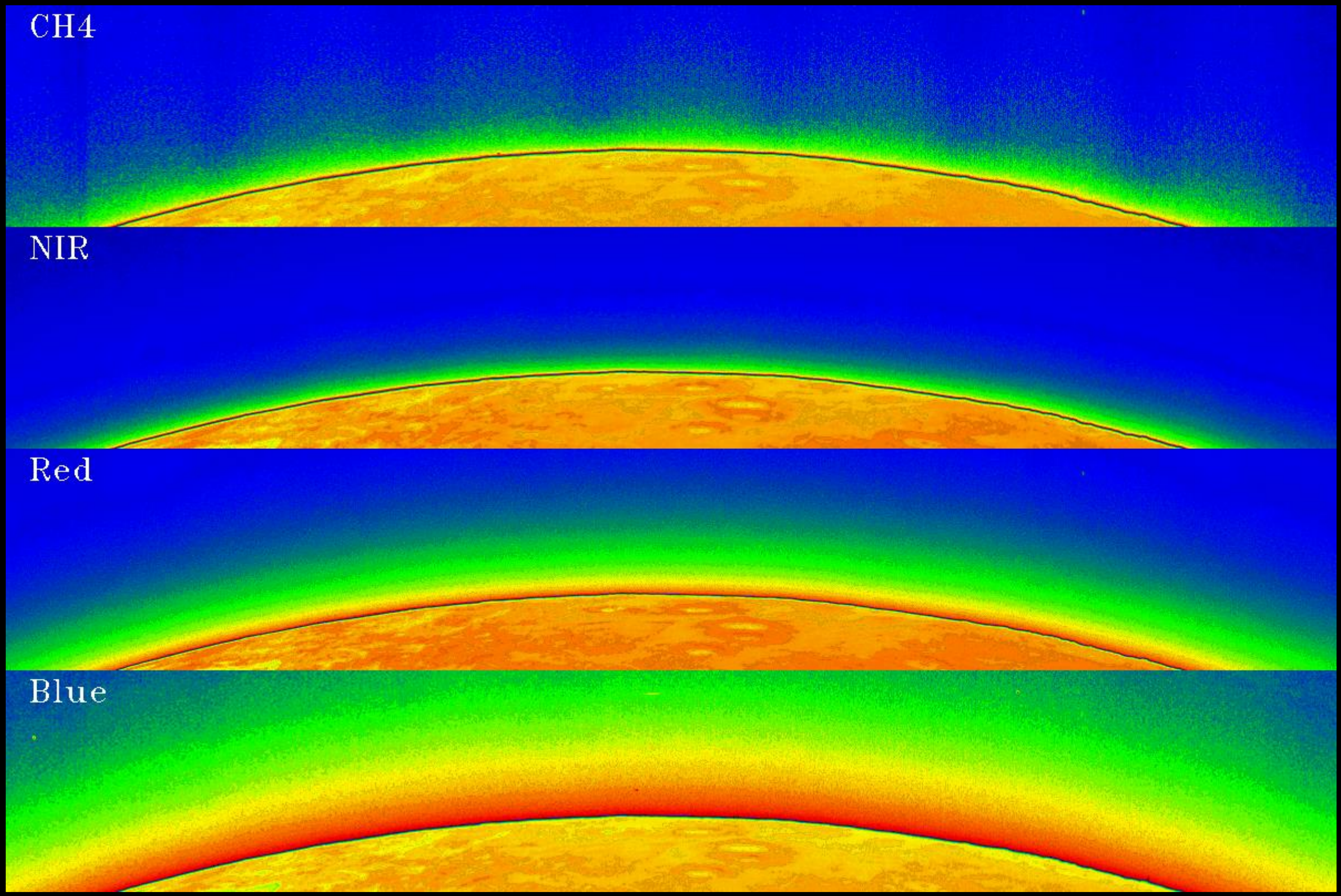


MVIC color Image of Pluto's haze layers on departure

HAZES PROBABLY INVOLVE SUNLIGHT INITIATED CHEMICAL REACTIONS OF NITROGEN AND METHANE, LEADING TO RELATIVELY SMALL, SOOT-LIKE PARTICLES THAT GROW AS THEY SETTLE TOWARD THE SURFACE.

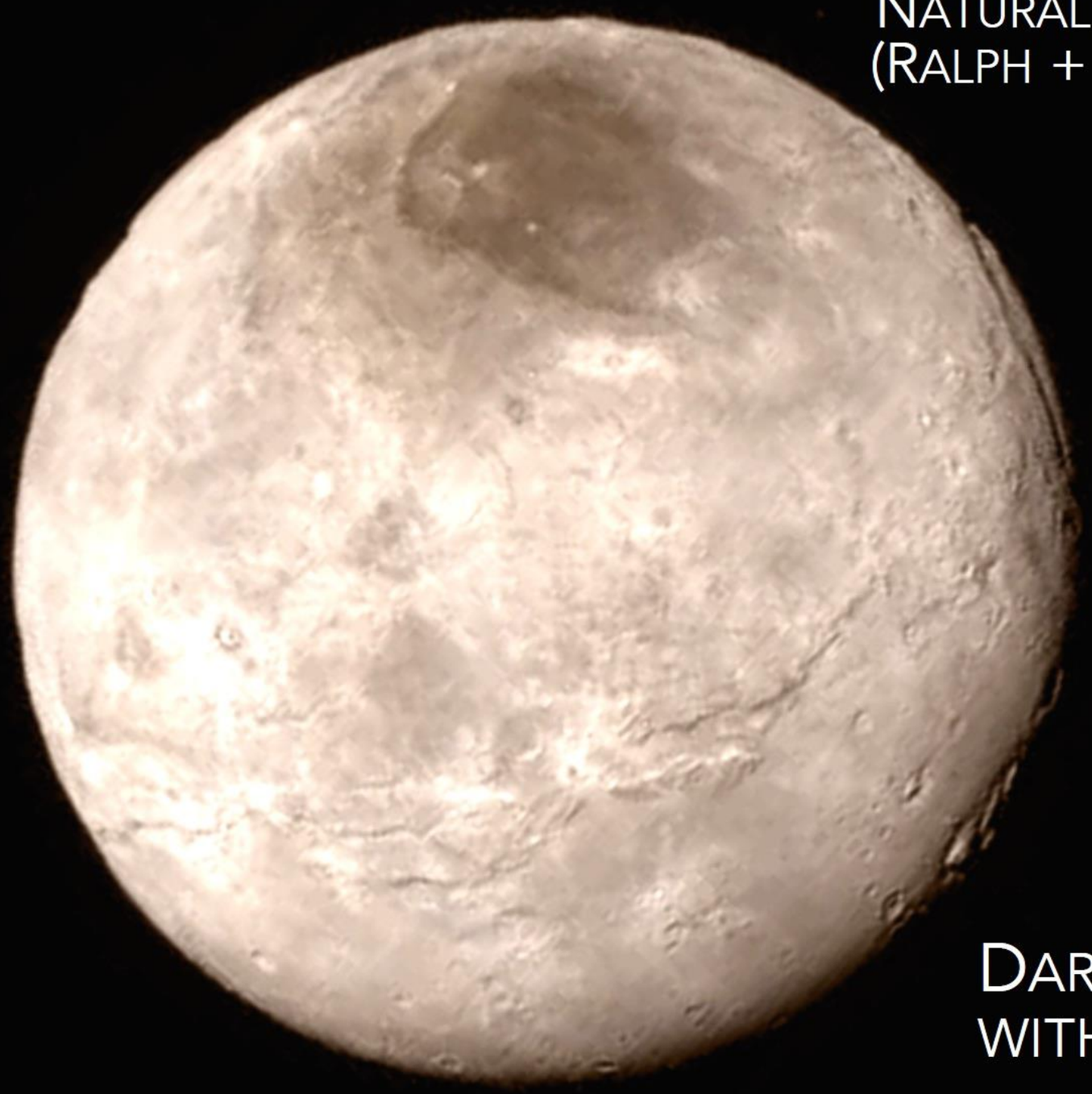
The particles extend several hundred km above the surface and are strongly forward scattering in the MVIC blue channel

MVIC Haze I/F On Approach



CHARON'S RED *ZUCHETTO*
"SKULL CAP"

NATURAL COLOR
(RALPH + LORRI)



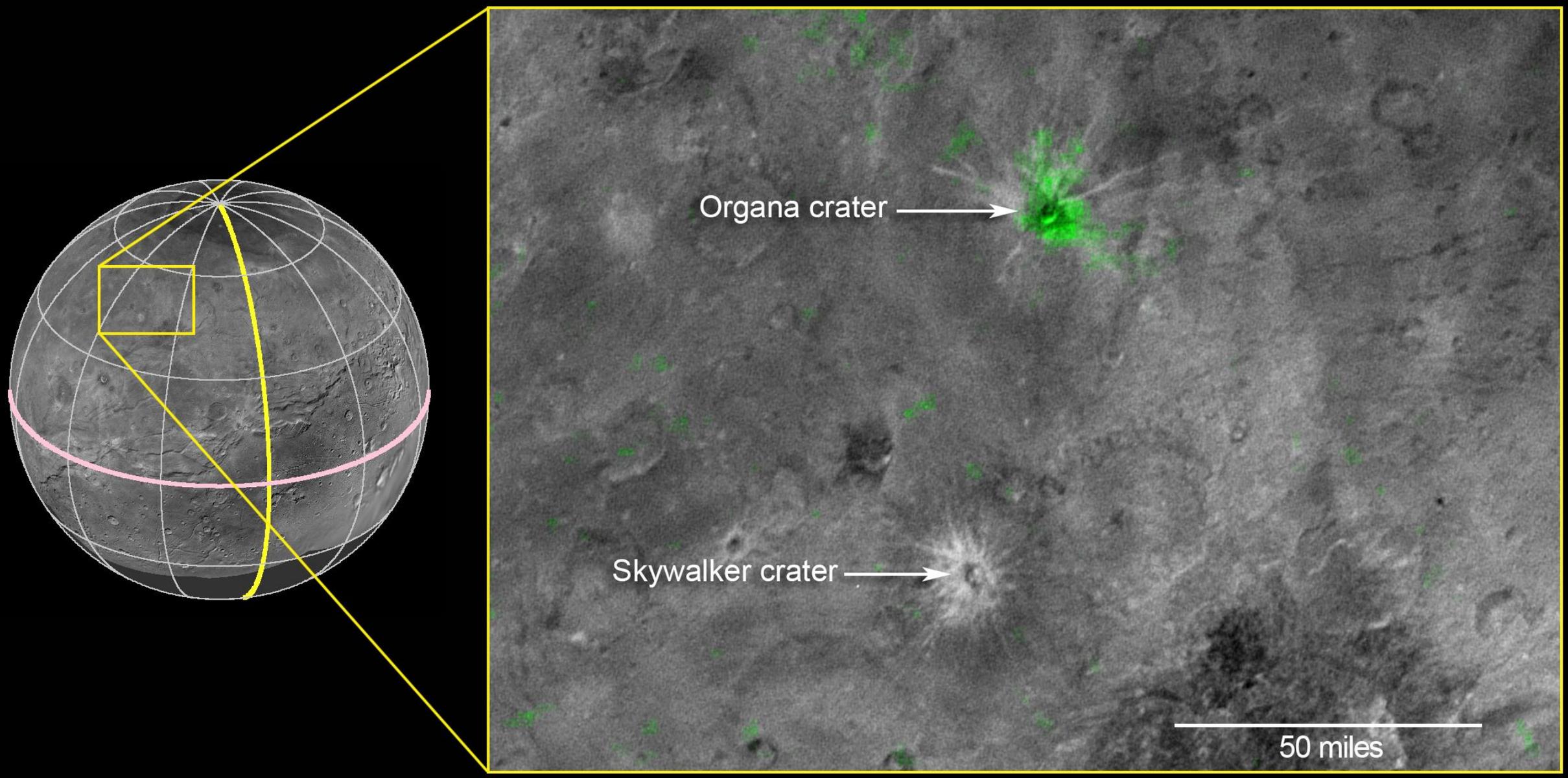
ENHANCED COLOR
(RALPH)

DARK POLAR SPOT IS REDDER THAN CHARON AVERAGE

RED TERRAIN EXTENDS BEYOND DARK CORE OF SPOT

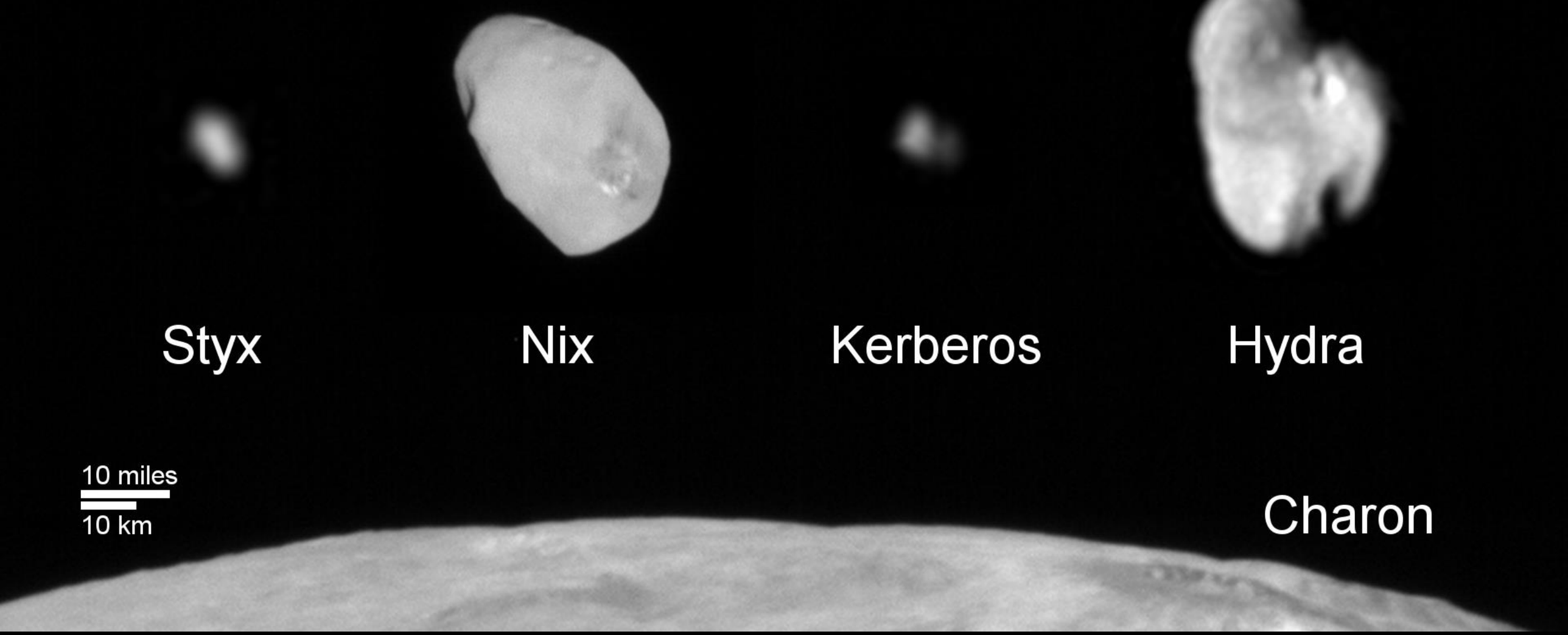
DARK CORE MAY BE CORRELATED WITH GEOLOGIC STRUCTURES

Charon Composition: NH_3 rich regions may indicate newer features



All Pluto system names are informal at this time

Charon and the Small Moons of Pluto

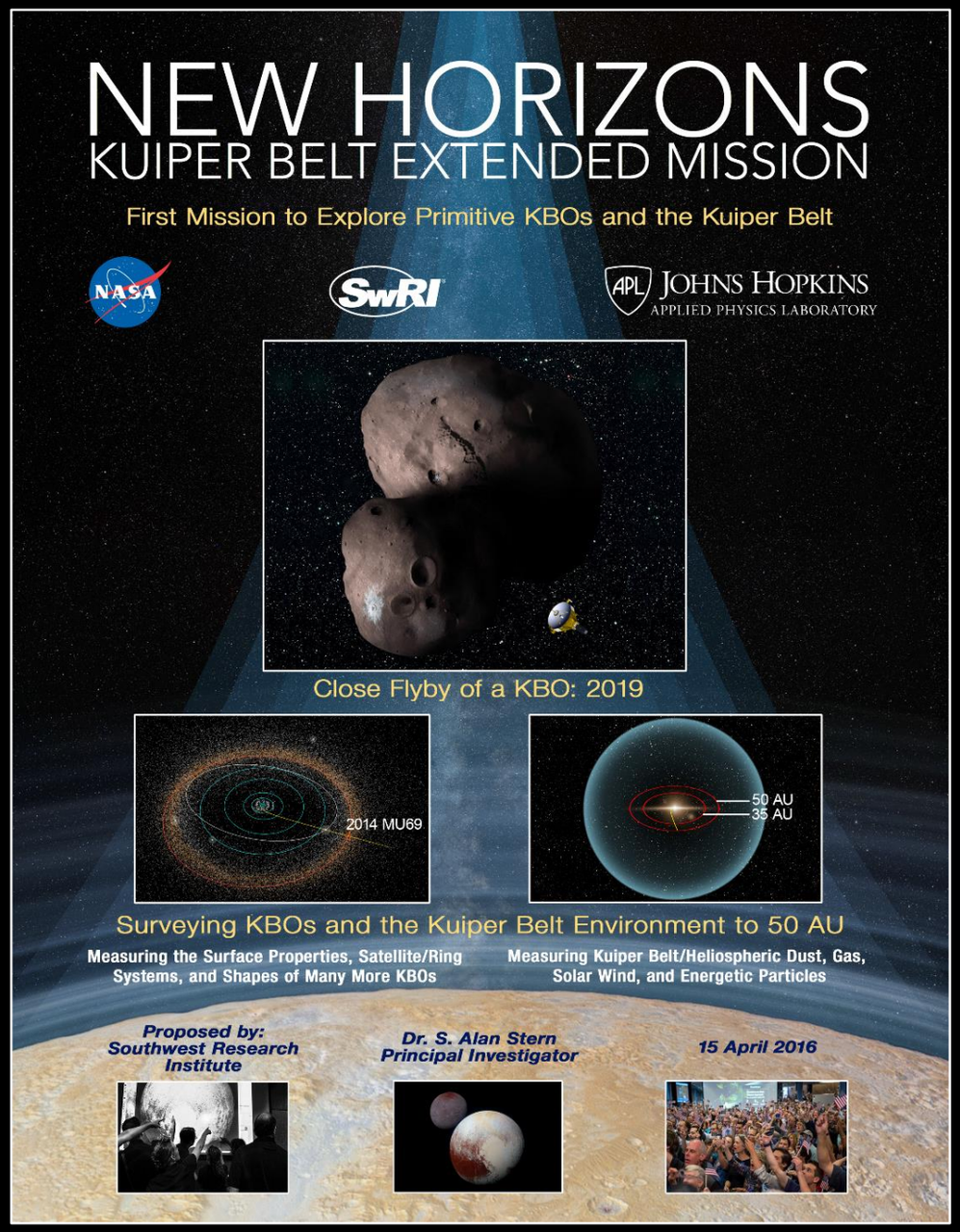


We are still looking at and Learning about the Pluto Syst em

But wait - There's more

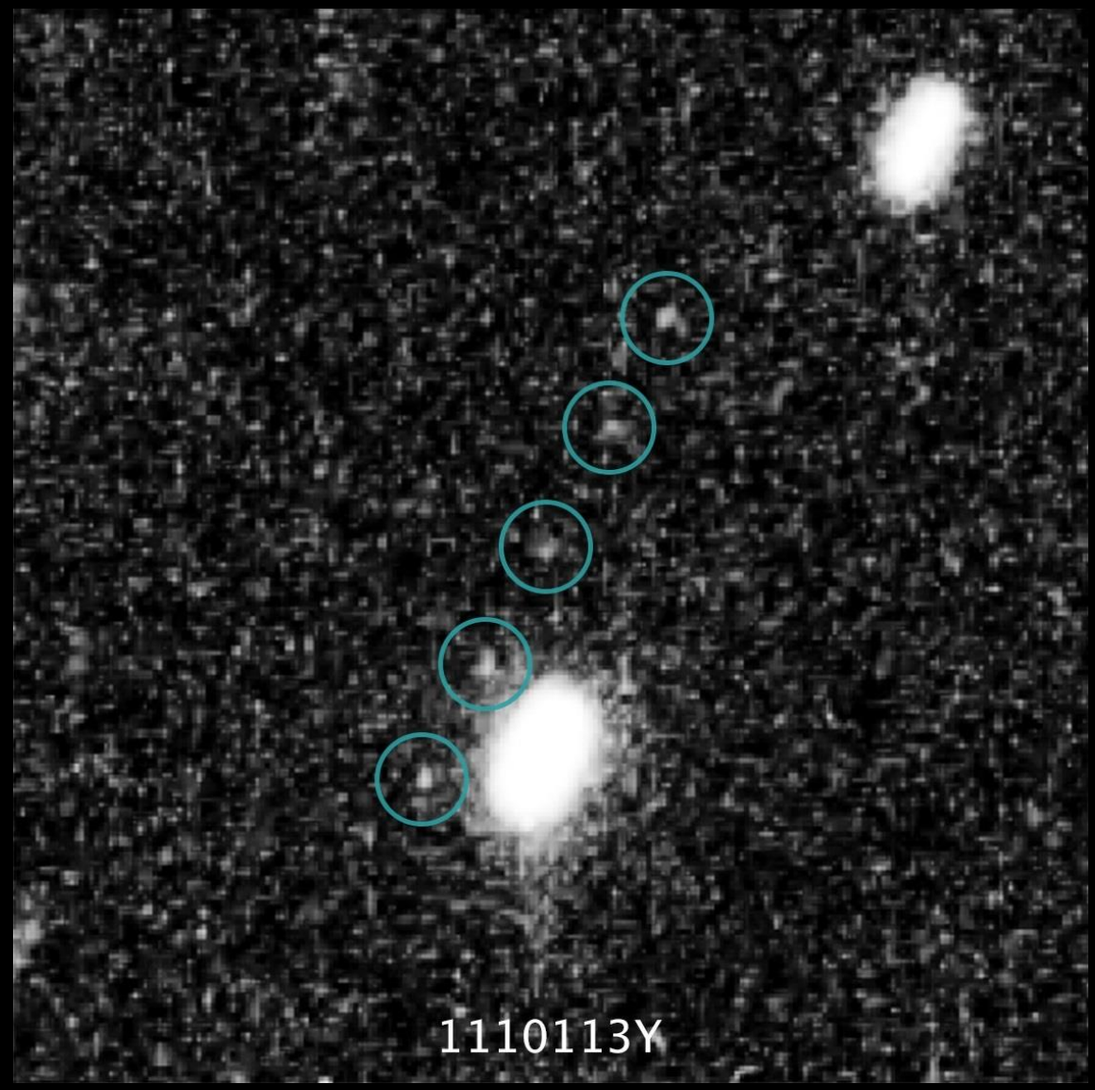
New Horizons Extended Mission

Flyby of *MU69* on New Year's Day 2019
Flyby distance = 3500 km (2170 miles)



The Discovery of MU69

- Searched with HST in 2014…
- Found three potential targets
- Chose 2014 MU69
  - Required little delta-v
  - Cold classical

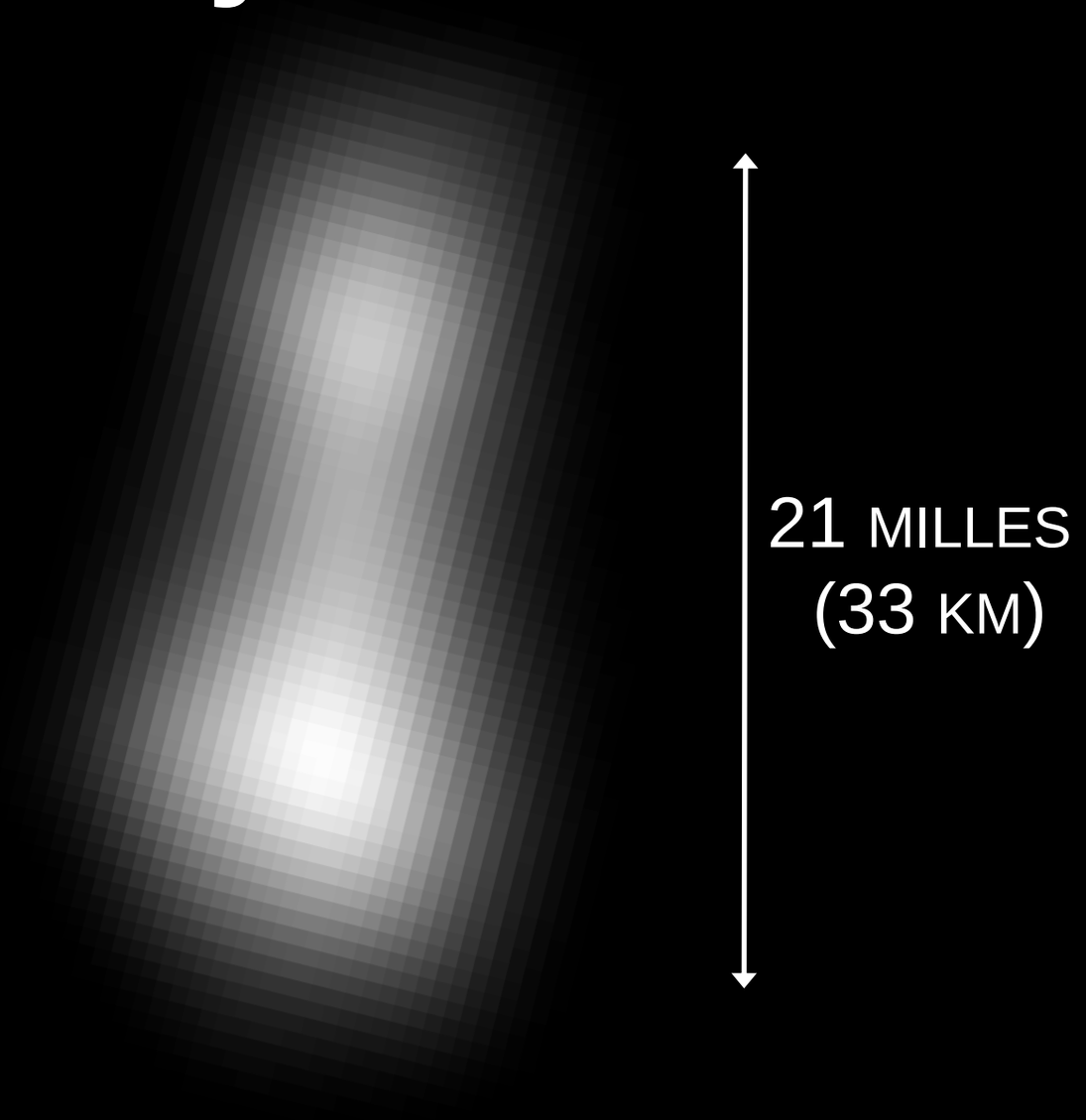


2014: HST Discovery image(s)

MU69: A More Challenging Flyby

- Target is 80× smaller in diameter than Pluto
- ~4× closer flyby, requiring more navigational precision
- Unknown environment
- ~4× darker target, lower light levels
- Reduced spacecraft power
- 12.25 hour round-trip light time
- **Uncertain target location** (discovered 2014, P=293 yr)

One object or two?



DEC 31, 2018

What a Difference a Day Makes

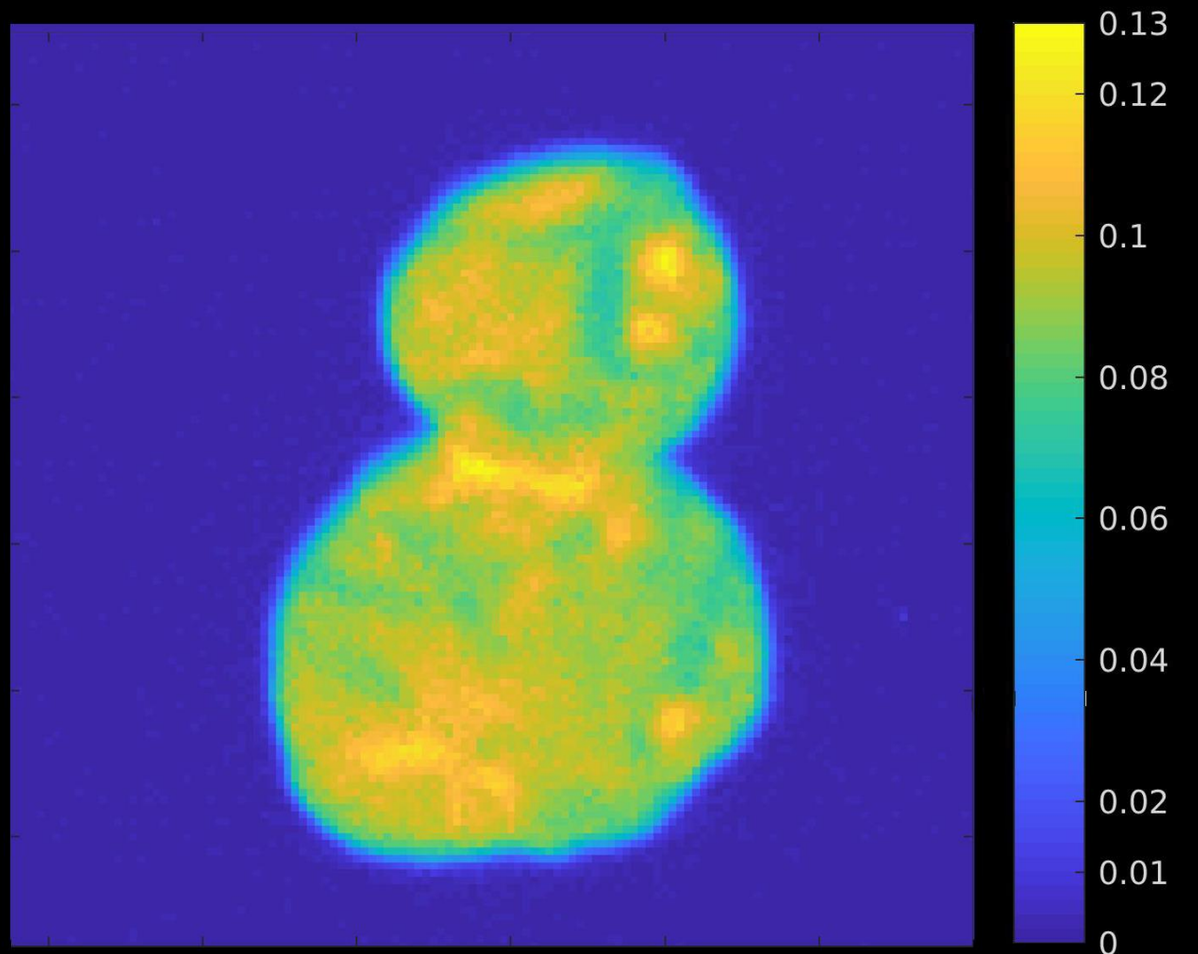
- MU69 is clearly bilobed
- Likely a merger of two planetesimals
  - Binary systems are common in the KB.
  - Maybe bilobed objects are too (at smaller scales than we can image from Earth)
- Low impact
- High albedo at ‘neck’
- Streaming instability would predict low velocity impacts because objects would have formed in vicinity of each other.

Highest Resolution MVIC Image

- Small pits on terminator
  - Craters? "Collapse Pits"? Sublimation remnants?
  - Linear pattern would not be expected if they were a result of impacts.
- Depression on small lobe
- Bright features:
  - Collar between lobes
  - Inside depression on bright lobe
  - Circular small albedo features
  - +others

135 m/pix
Range 6,640 km
7 min before

Albedo Variations



Highest Resolution: ~33m/pix

Composite of 9 LORRI images
Each 0.025 sec exposures
Range 6,628 km

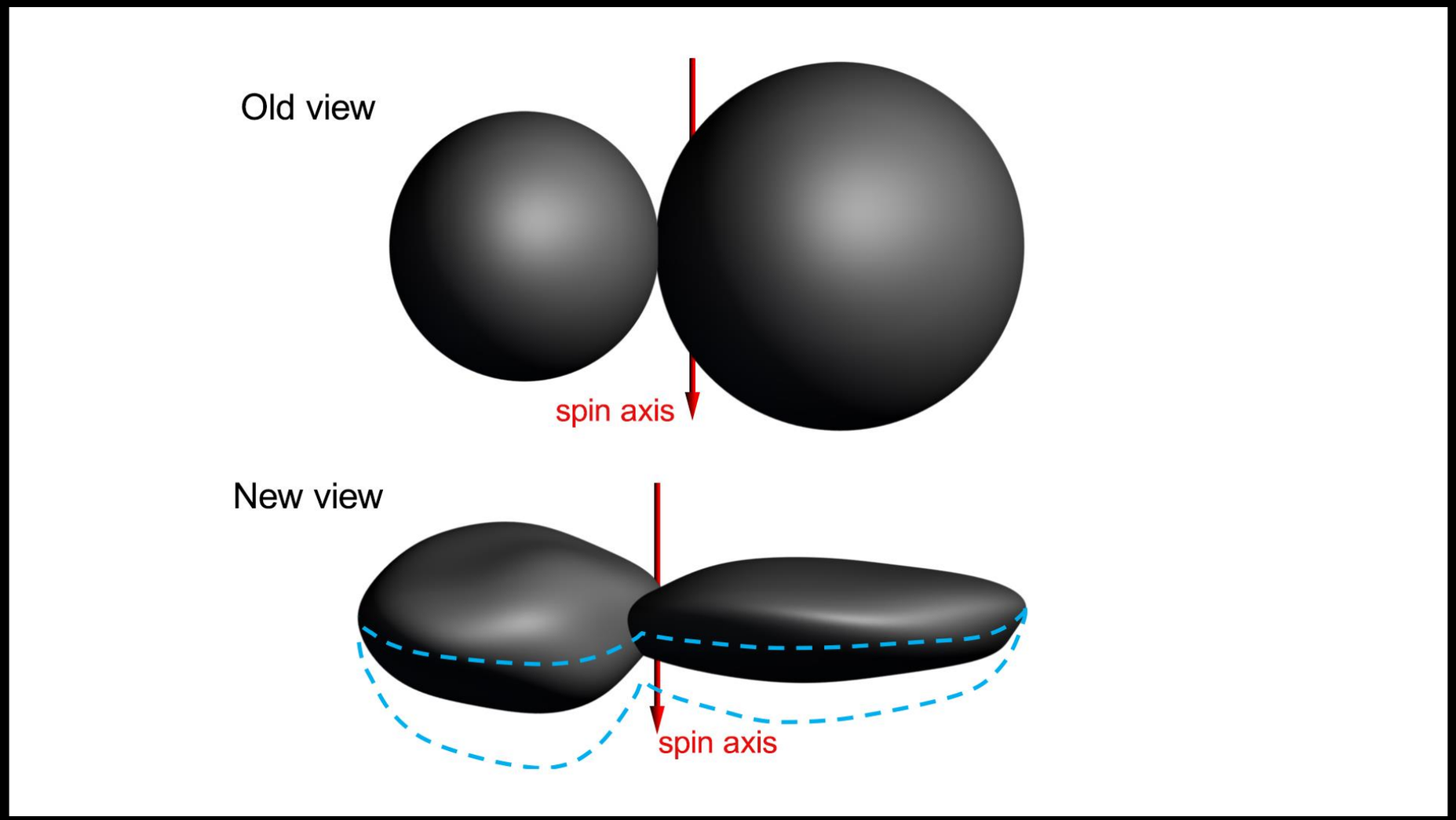
Spectral Slope: ~20-30%/100nm

MVIC Enhanced Color
1.5 km/pixel

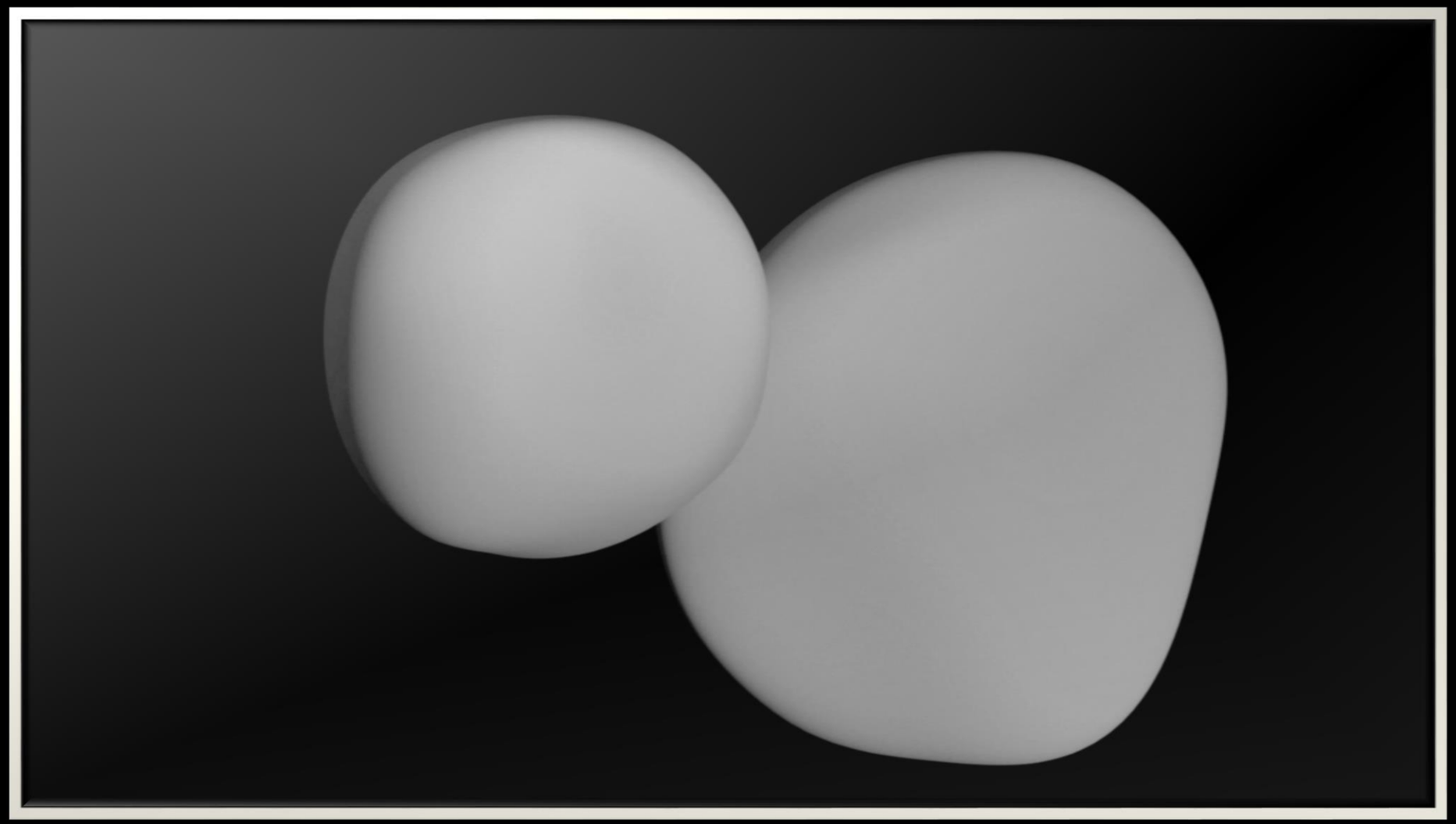
LORRI
0.14 km/pix

MVIC + LORRI

MU69's True Shape

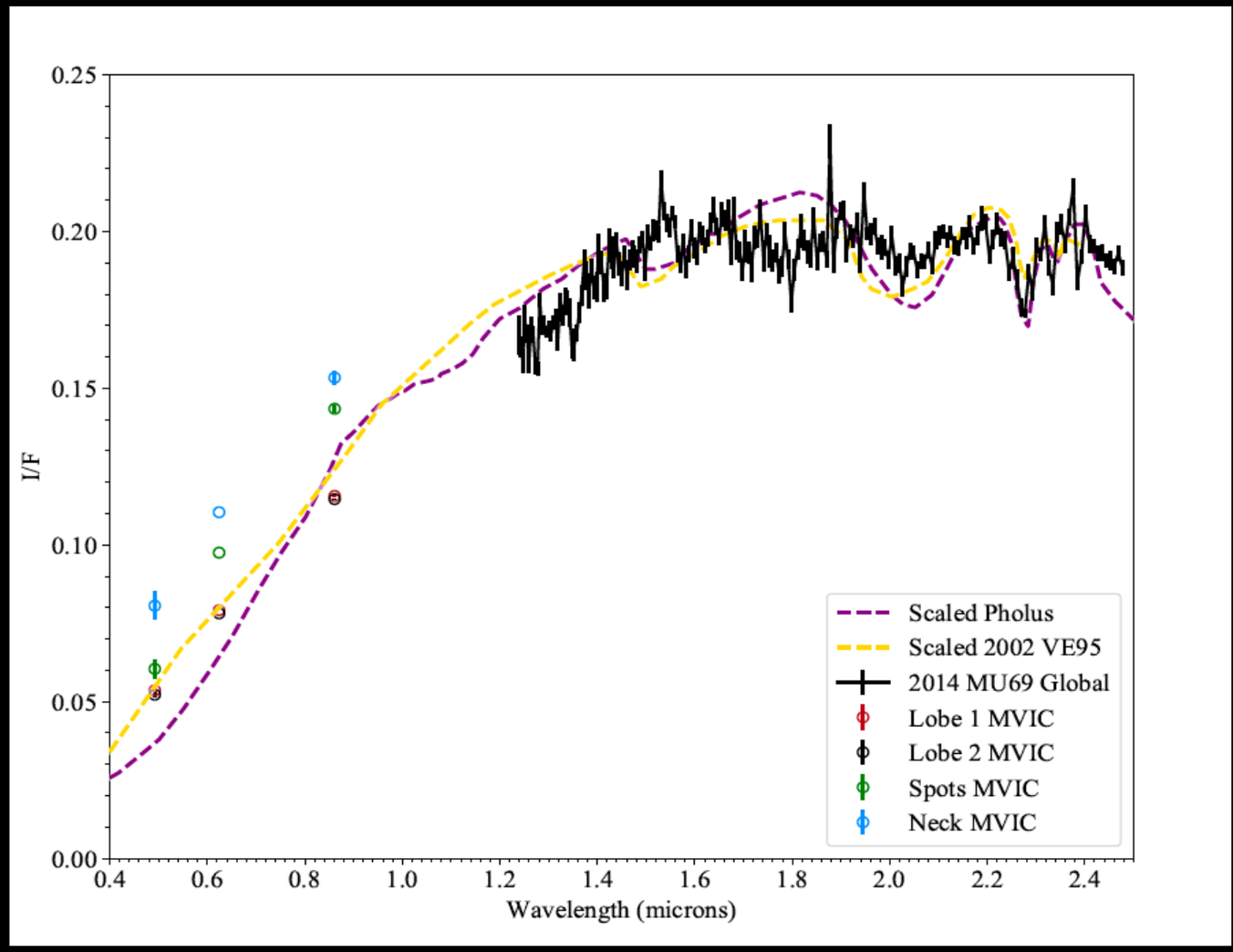


Face-On vs Edge-On Views



Composition Results: MVIC + LEISA

- Red spectrum typical of Cold Classical KBOs
- But MU69 spectrum looks similar to spectra of the Centaur Pholus and the Plutino VE95
- Possible detection of H_2O ice?
- Possible detection of CH_3OH ice?



What We've Learned

- Pluto has a very diverse surface with what appears to be both old and new regimes
  - Evidence of dynamic processes including N_2 ice flow and convective overflow
  - Variety of surface compositions evident
  - Atmosphere with multiple haze layers
  - Etc. etc.
- Mu69 is a contact binary most consistent with formation in a cold collisional environment
  - Flattened and non-spherical lobes are unusual
  - Even this small object has much surface detail
- None of this was expected before the encounters

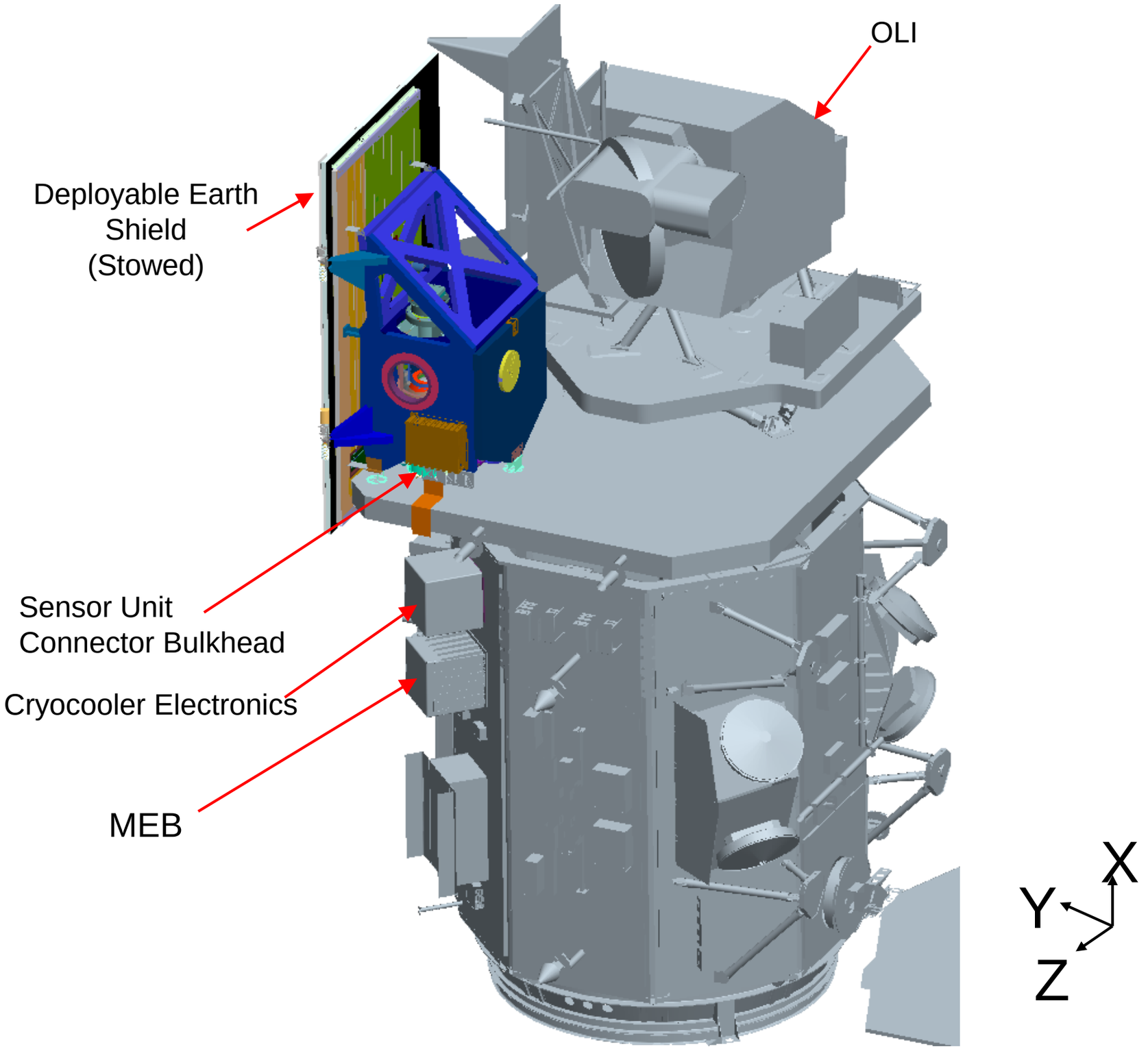
Turning Now to TIRS on Landsat 8

- TIRS (the Thermal Infrared Sensor) and OLI (the Operational Land Imager) make up the payload of Landsat 8
- TIRS produces radiometrically calibrated, geo-located thermal image data
- TIRS operates in concert with, but independent of, OLI
- They are at a ~ 97 degree orbit so provide a 16 day revisit cycle
- TIRS was not originally on the Landsat 8 payload manifest and its development was very schedule driven
- As you will see, TIRS has provided very useful data since the L8 launch om Feb. 11, 2013
- But there were certainly some hiccups before and after launch

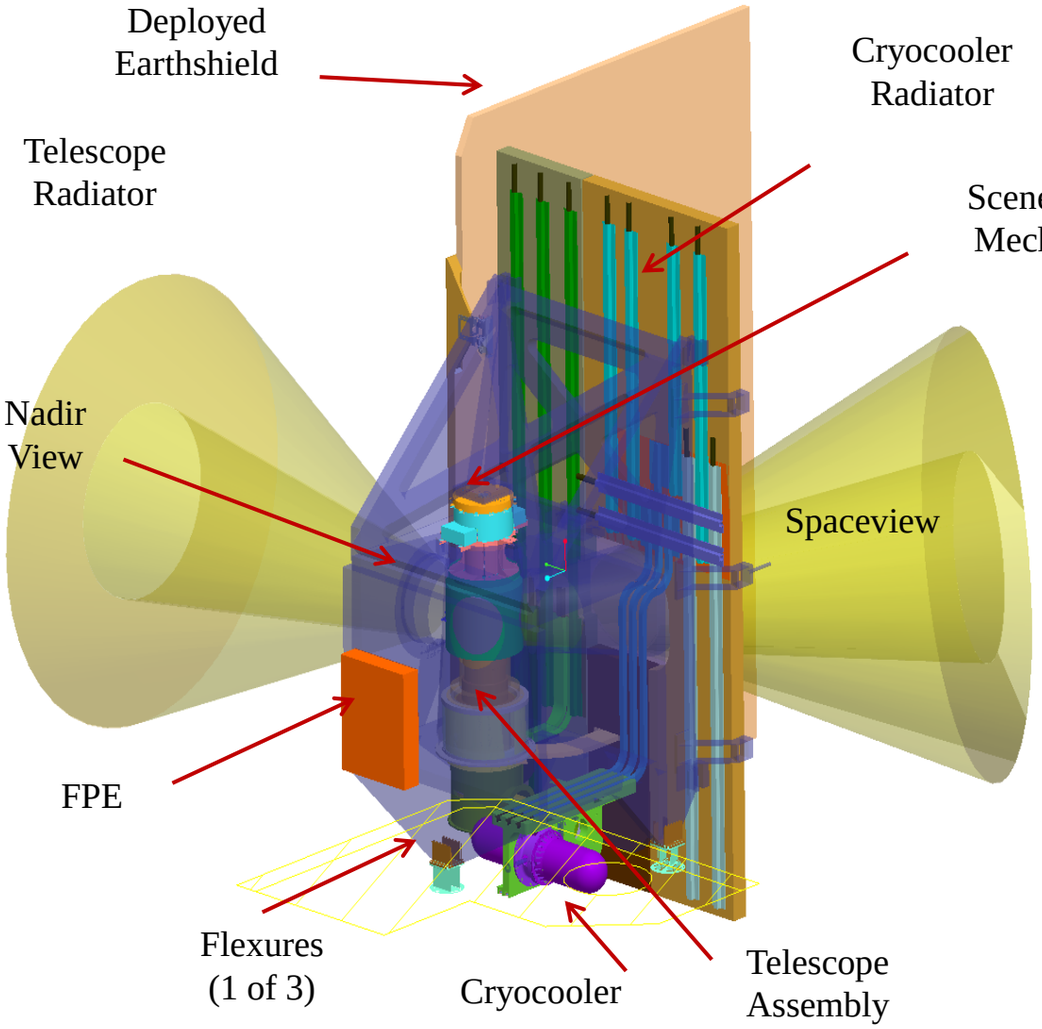
TIRS Instrument Overview

- Instrument Characteristics
  - 2 channel (10.6-11.2 um and 11.5-12.5 um) thermal imaging instrument
  - Quantum Well Infrared Photodetector (QWIP) detector/FPA
    - First flight use of GSFC developed QWIPs
  - 100 m Ground Sample Distance
  - 185 km ground swath (15º field of view)
  - Operating cadence: 70 frames per second
  - Precision scene select mirror (SSM) to select between nadir view, onboard variable temperature blackbody and space view
    - Repeatability better than 10 microradians
  - Passively cooled telescope assembly operating at ~185K (nominal)
  - Actively cooled (He cryocooler) FPA operating at ~38 K
  - Thermal stability key to radiometric stability
  - NEΔT < 0.1 K @ 300 K

TIRS and OLI on Landsat 8 Spacecraft



TIRS Sensor Unit Design Overview



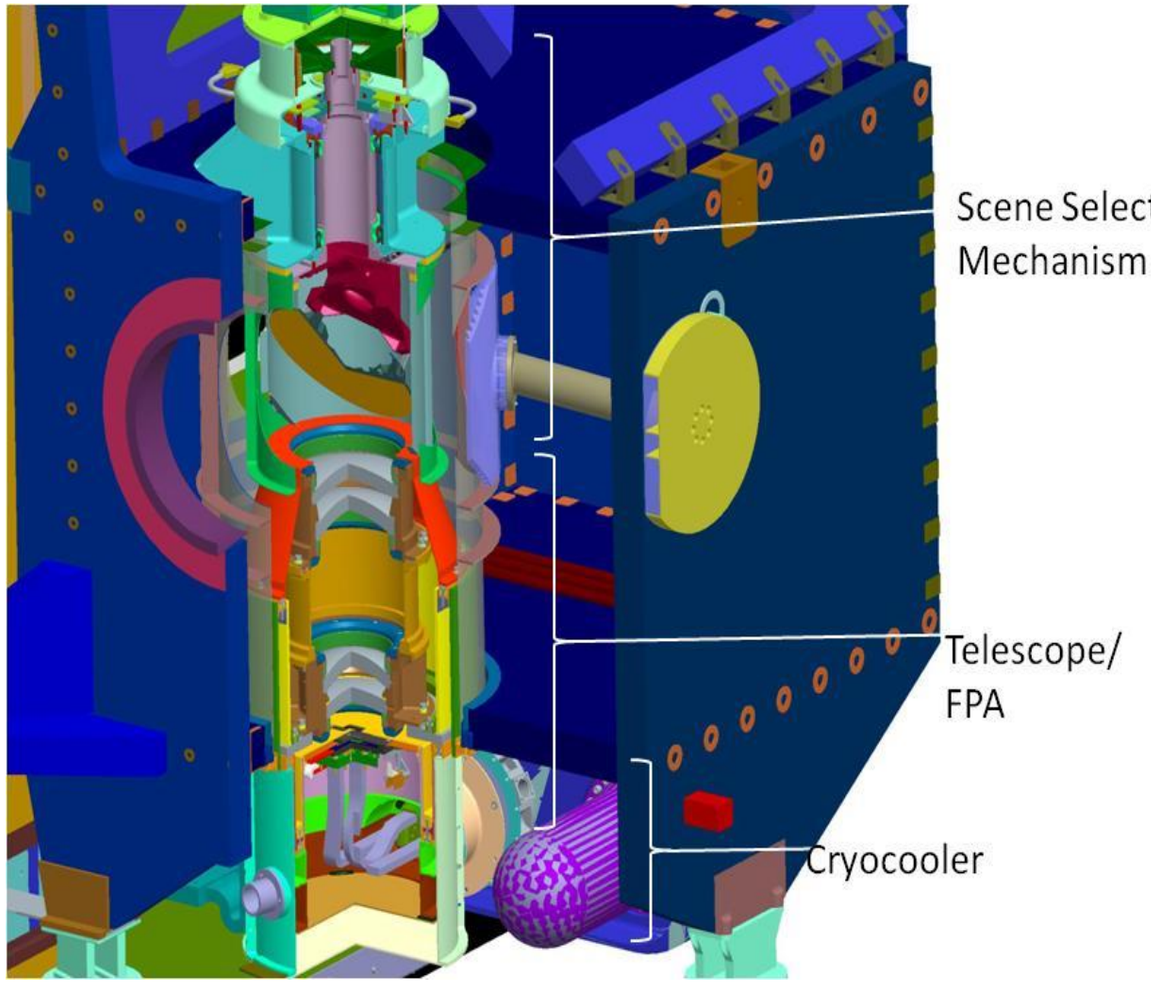
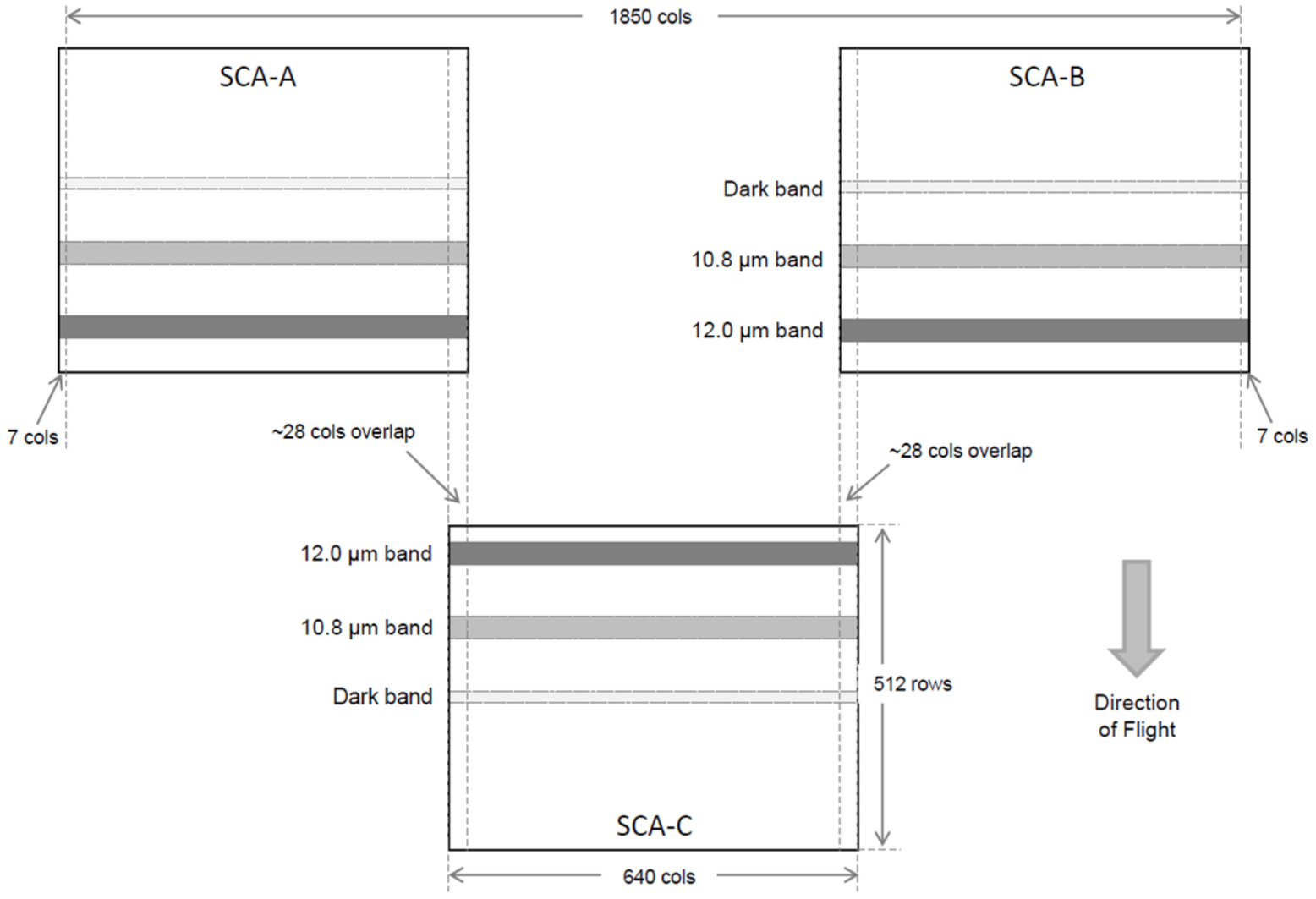


Image Formed on QWIP Focal Plane Assembly



FPA has 1850 unique pixel columns
Corresponds to 185 km swath width
In-track FOV < 5.4 degrees

Filter band locations based on FPA selection . Optimized to be in best region on FPA

- Up to 140 rows between channels on a single detector
- 700 rows before data produced by SCA C aligns with SCAs A and B

- Read 2 rows from the central 30 rows for each filter on each array and for dark region (far from filters)
- Dark region is an area covered by the filter holder
- Combine data on ground to get single best row
- Row selection can be changed in flight

TIRS Build and Test

- As with Ralph, during development there were the standard development problems
  - Unexpected noise sources, thermal, mechanical and optical performance concerns
  - Since the QWIPs were being used for the first time, there were some additional challenges, but these could be addressed quickly
- There were some more unusual problems, but they were taken care of
  - For example, a noticeable earthquake (in Maryland!) during TVAC – no damage done
  - The capacitors in the cryocooler power supply exploded
- In the end, though, the instrument was built, tested in TVAC and delivered for spacecraft integration
- However, when first tested at the spacecraft facility, the cryocooler was not cooling the system
- This was an exciting circumstance
  - Initially thought to be an electronic issue

Addressing the Problem

- Electrical tests were performed and all was good
- Initial He leak tests showed no evidence of a leak
  - TIRS was taken off the spacecraft for further analysis, but the inability to find a cause was very concerning. As class C TIRS could have been replaced by a mass model
- One of the better days in my professional career occurred when the He fill tube was exposed

- With the cause determined the problem could be fixed
- Initial seal was provided by crimping fill tube – only 100 μm seal
- Replaced with valve system – He refilled – performed fine
- In a twist of fate, while TIRS was off the spacecraft, there was an electrical problem that damaged many of the electrical systems
- Had TIRS been on the spacecraft it would have been affected

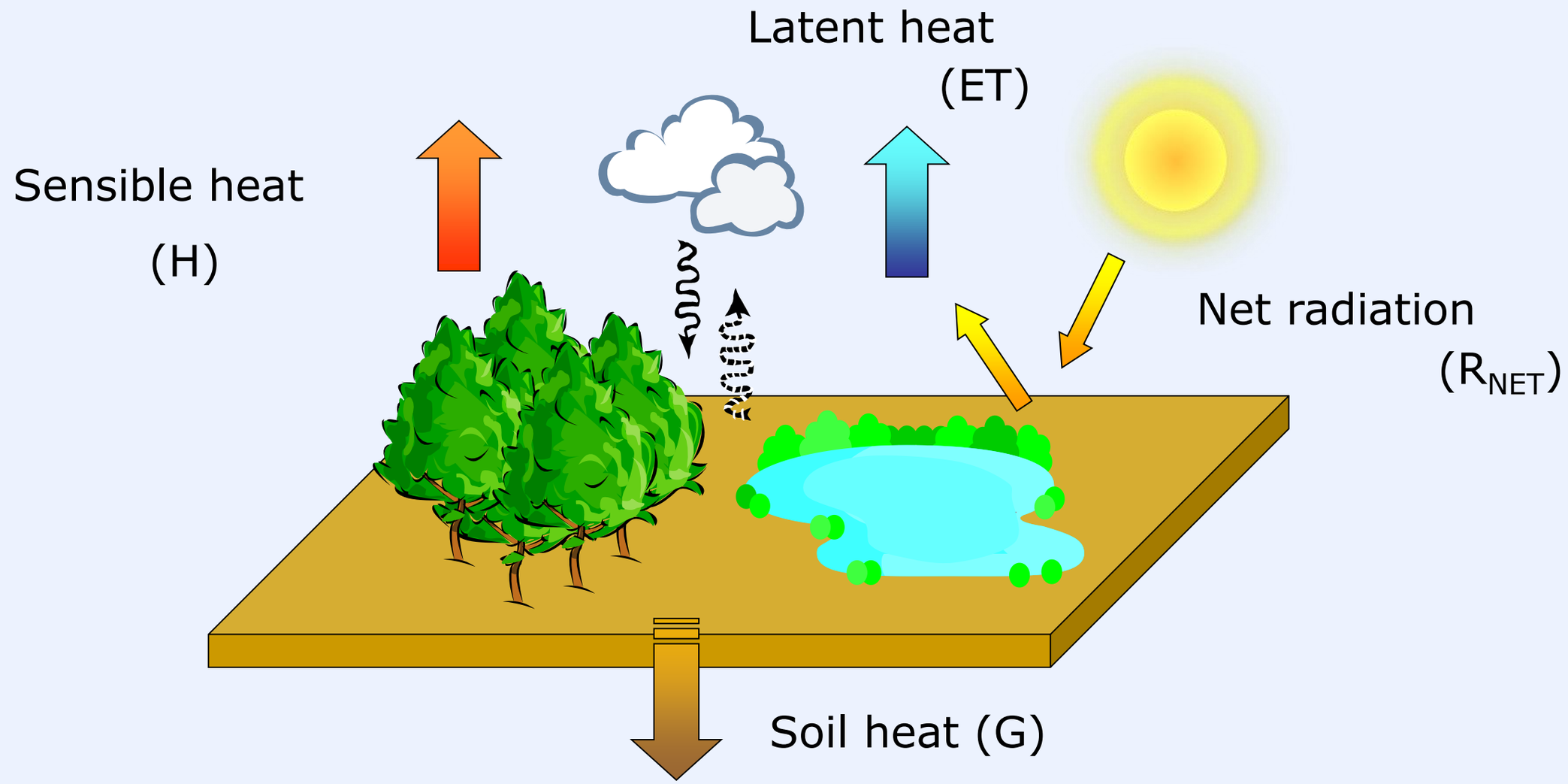
TIRS is a Cooled Instrument Producing Cool Science

- Landsat thermal data are now used operationally to monitor water consumption on a field-by-field basis in the U.S. West and internationally
- Evapotranspiration cools vegetation
- Analysis allowed by development of operational energy balanced-based evapotranspiration models
- Parametric models use measured vis/NIR and thermal radiation, surface classification and estimates of soil thermal transport
- Other products as well

Water Management Using Surface Energy Balance

$$R_{NET} = G + ET + H$$

$$R_{NET} = (SW_{dn} - SW_{up}) + (LW_{dn} - LW_{up})$$



- Net Radiation is the balance between incoming minus outgoing radiation
  - OLI required to calculate the SWup (short wave albedo)
  - TIRS data required to calculate the LWup from surface temperature

Satellite Evapotranspiration

- Monitoring water use at field to continental scales
- Land-surface temperature conveys early warning of vegetation stress
- Independent check on precipitation- and vegetation index-based drought indices
- Applications in global water and food security

hrsl.arsusda.gov/drought

TIRS Goal is to ……

Upscaling ET Measurements from Local to Regional Scales using Remote Sensing

Martha C. Anderson, Feng Gao, Yun Yang, Liang Sun, Yang Yang, Wayne Dulaney

USDA-Agricultural Research Service
Hydrology and Remote Sensing Laboratory
Beltsville, MD

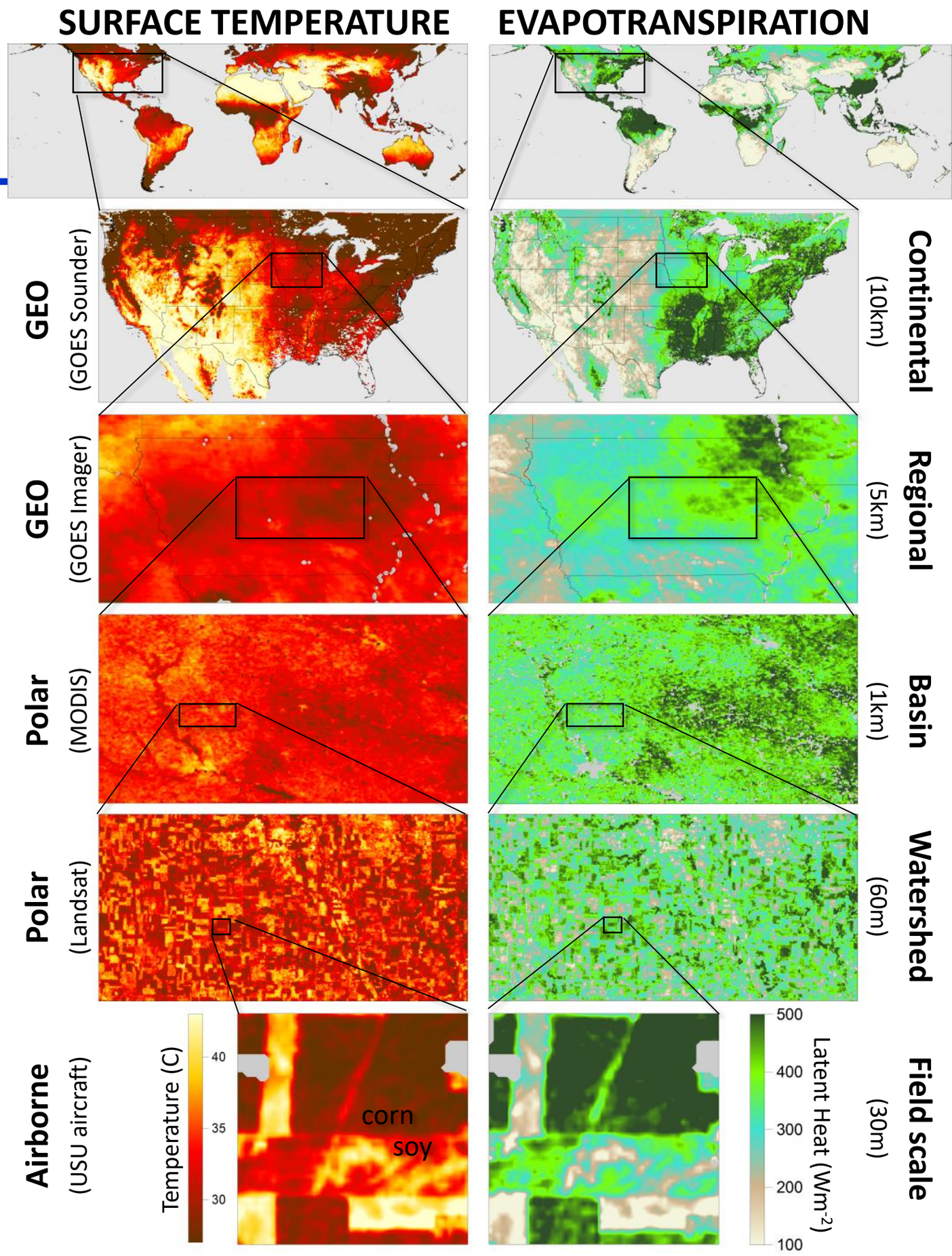
Chris Hain

Earth System Science Interdisciplinary Center,
University of Maryland, NOAA-NESDIS

DATA FUSION:

daily ET at field scale

(F. Gao)



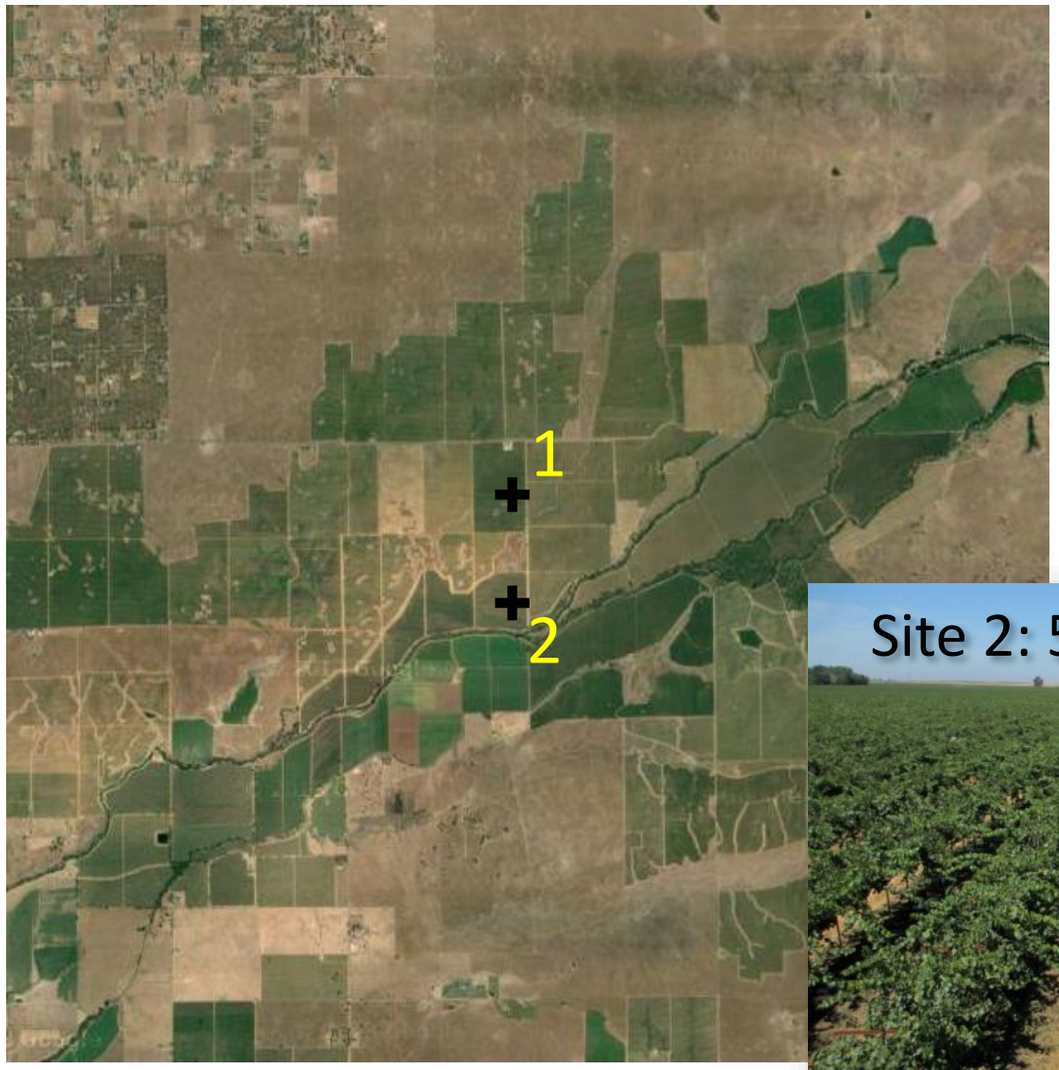
Hourly

Daily

1 LS – 16 day

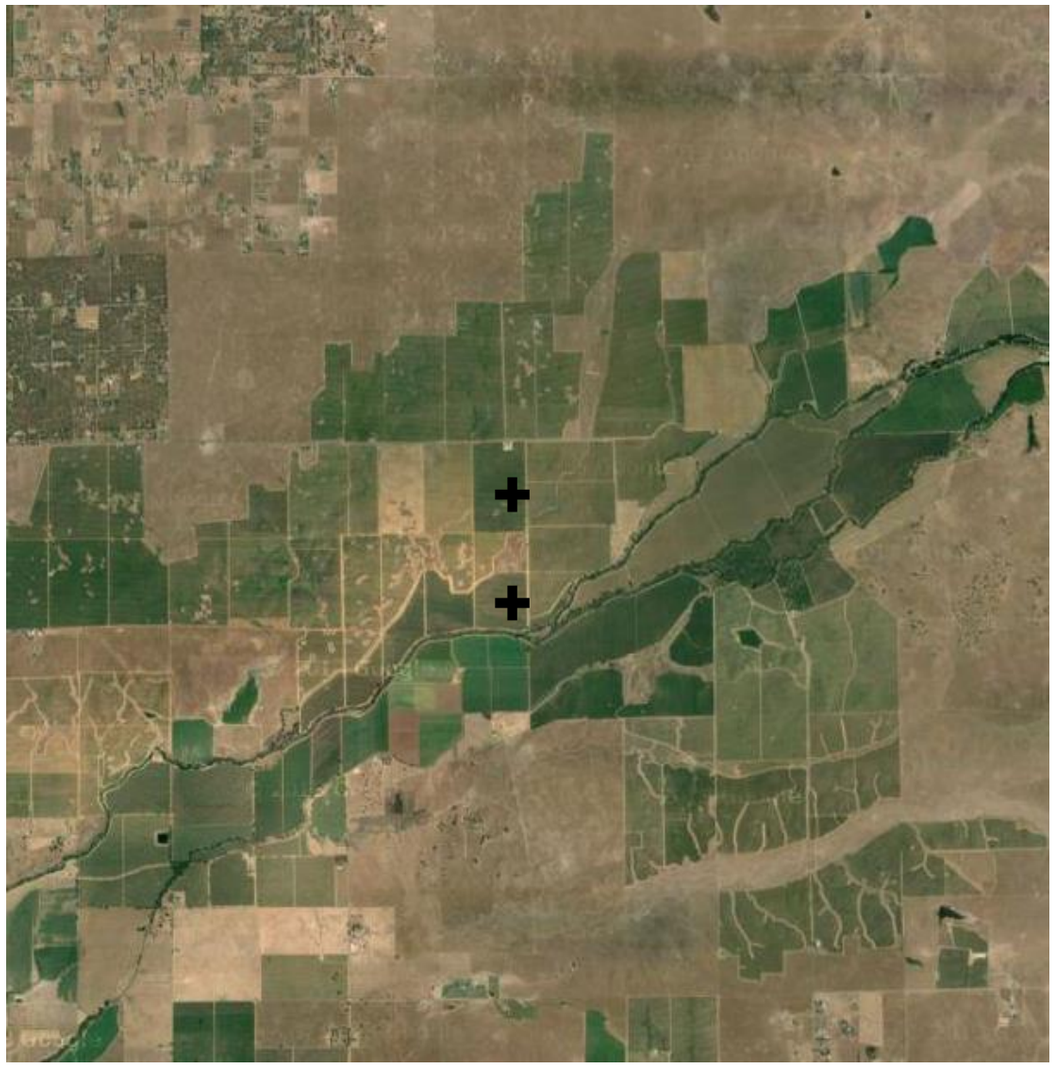
2 LS – 8 day

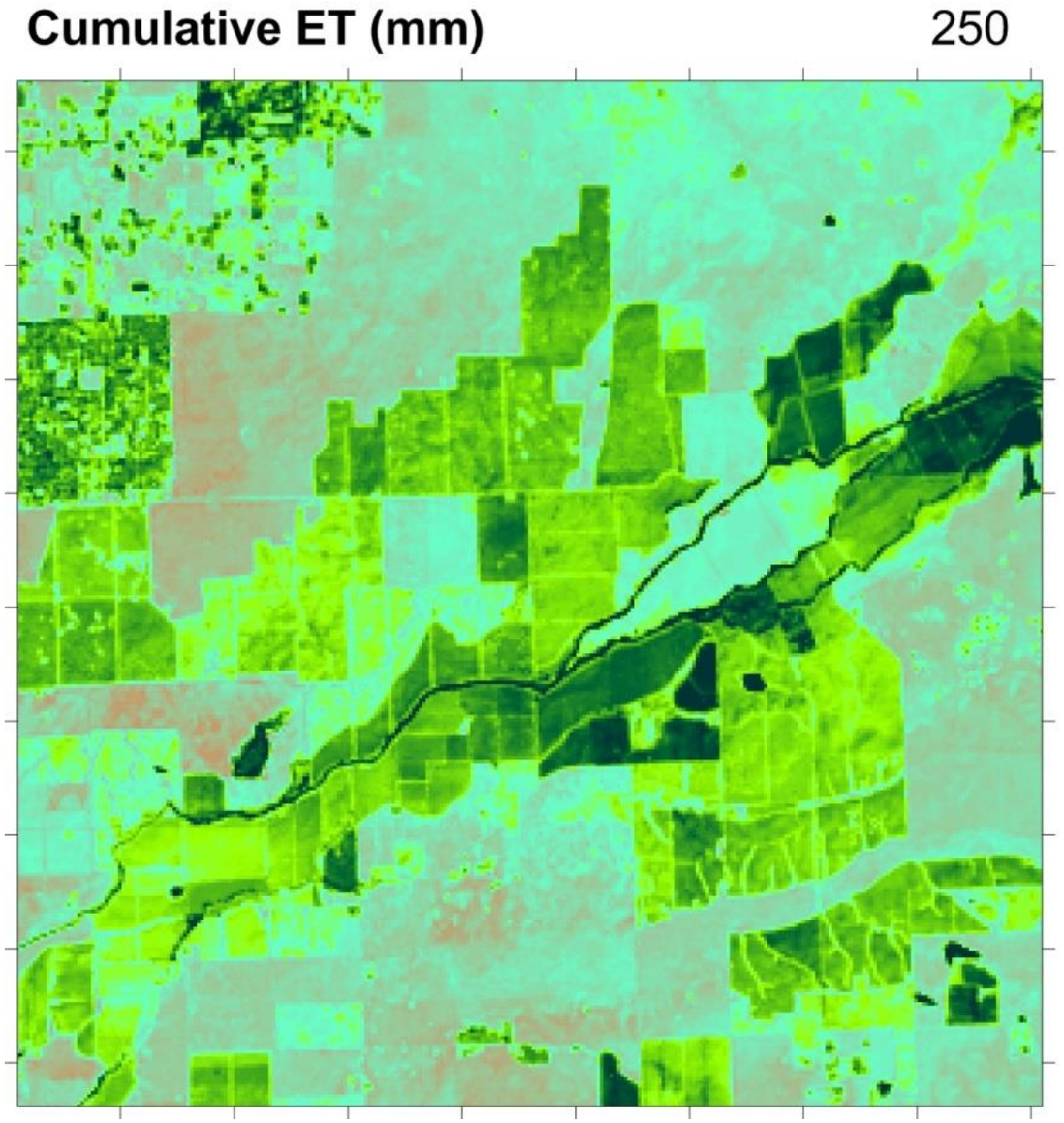
Gallo Vineyards, Lodi CA



GRAPEX2013, 14, 15

Gallo Vineyards, Lodi CA

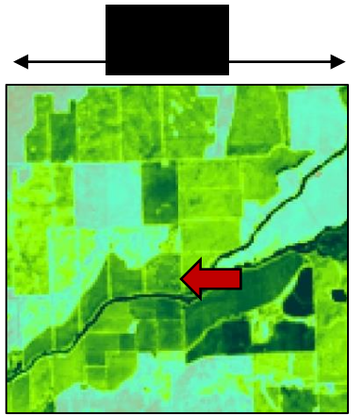




Landsat 8 - 2013

Semmens, K.A., et al.(2015). Monitoring daily evapotranspiration over two California vineyards using Landsat 8 in a multi-sensor data fusion approach. *Remote Sens. Environ.*, *doi:10.1016/j.rse.2015.1010.1025*

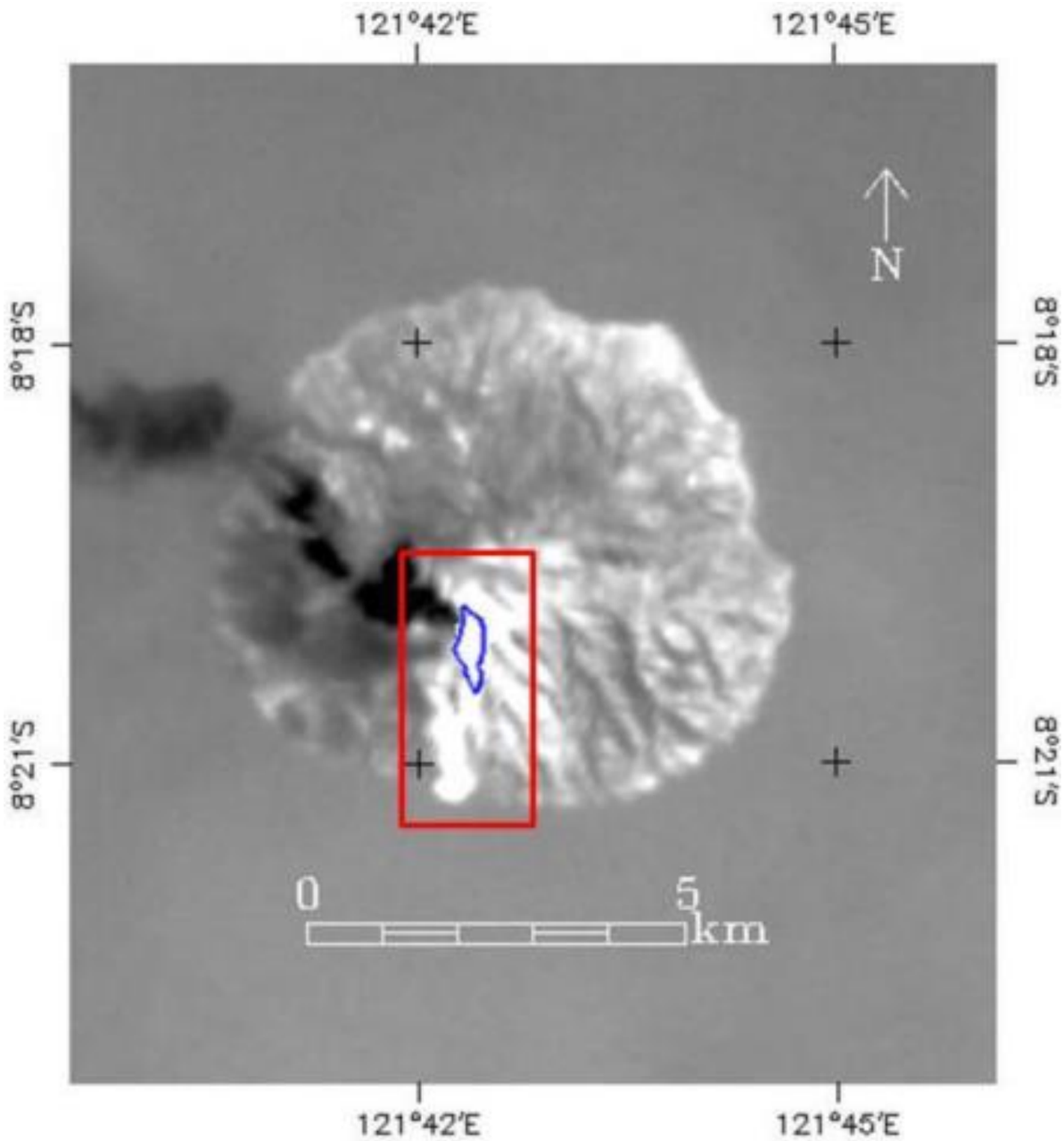
Comparisons with flux tower data



SITE 2:

Pinot Noir – 5 YR (2013)

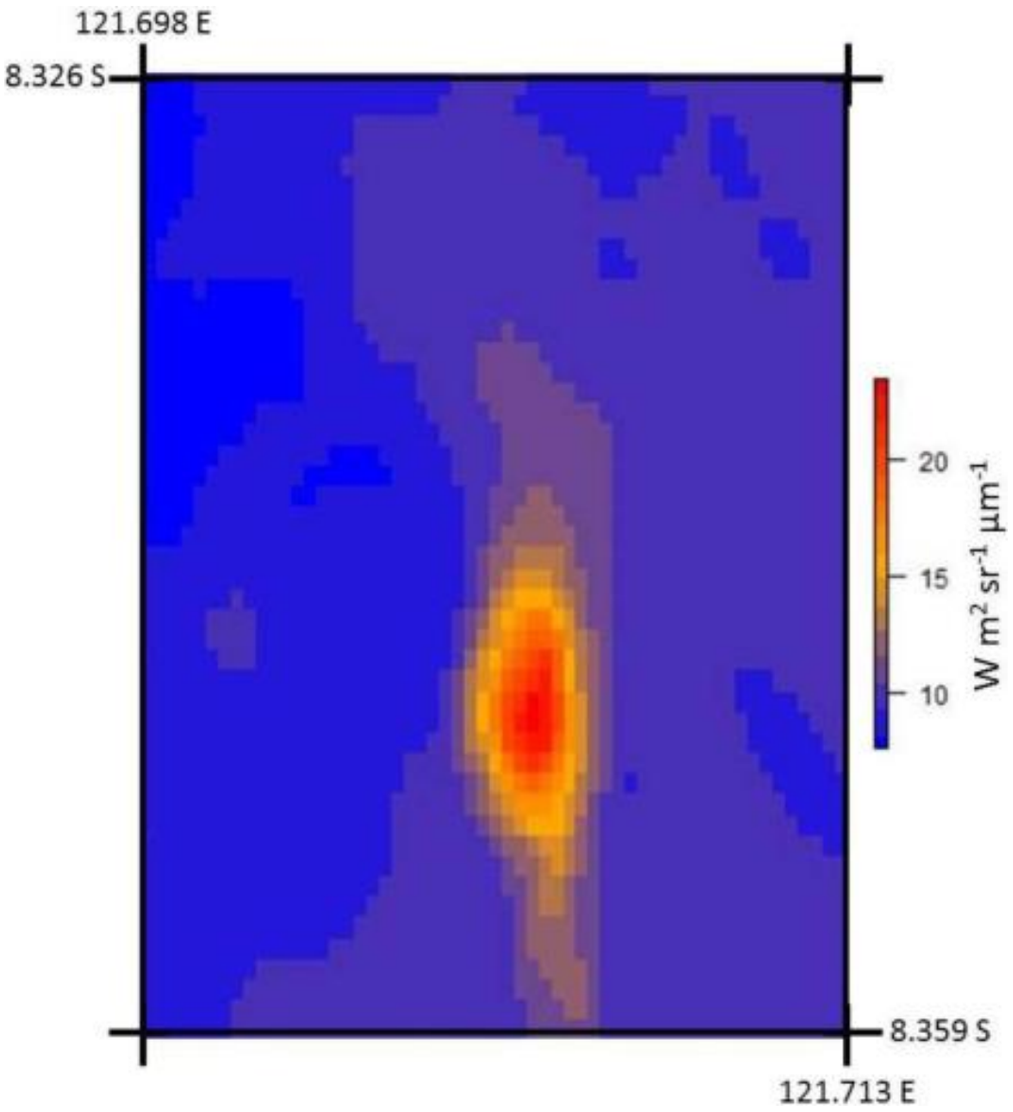
Another Use: Studies of Volcanic Activity



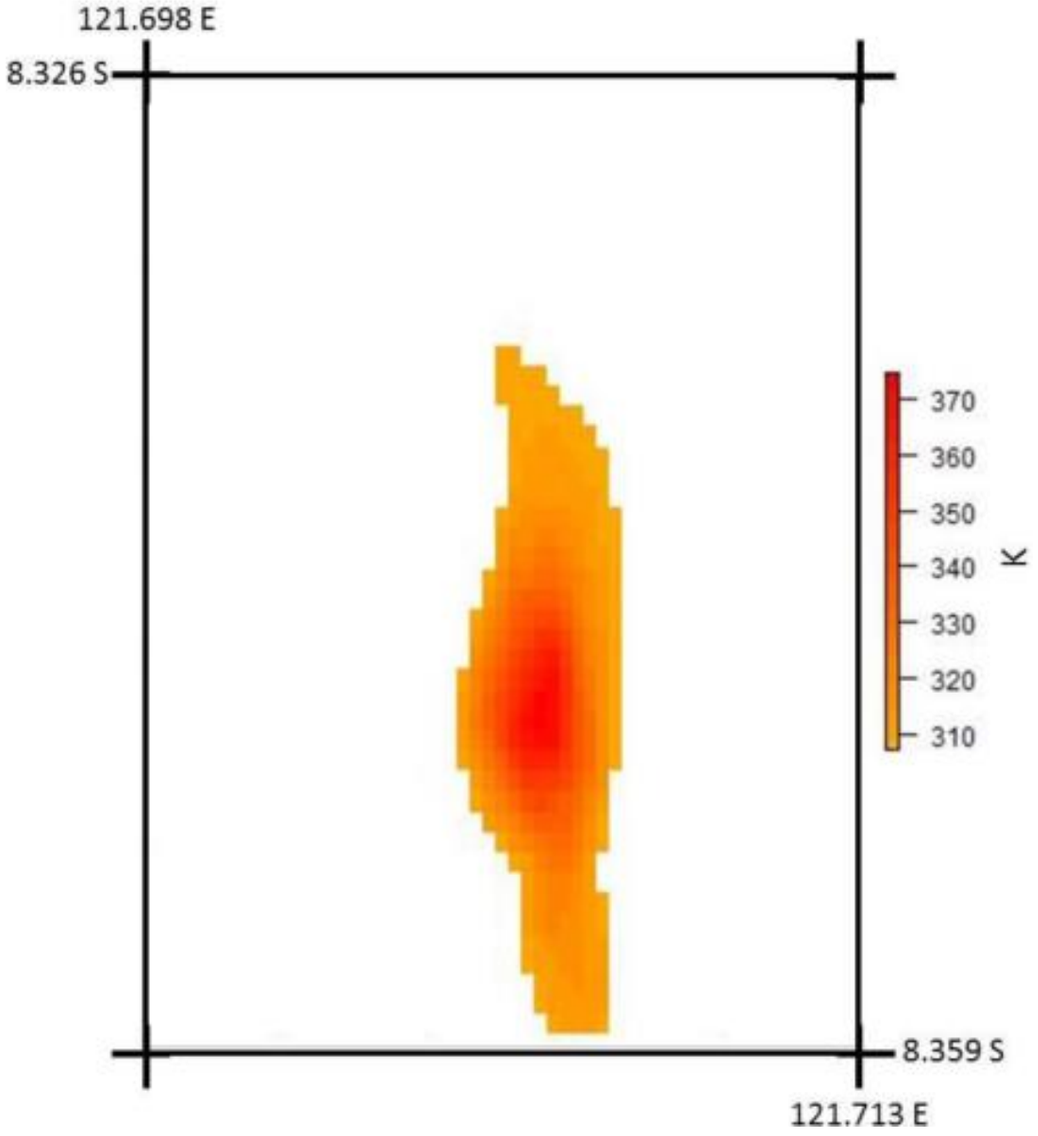
Landsat-8 band 10 image of Paluweh Volcano on 29 April 2013. The volcano forms an island in the Flores Sea to the north of the Indonesia island of Flores. Evident here are bright regions to the center and south of the landform which constitute the thermally anomalous activity at the volcano. To the west, the plume emanating from the volcano can be seen as a darker (cooler) region. The rectangular region outlined in red is that which was extracted for analysis. It encompasses the anomalous volcanic radiant signals, here outlined in blue, and also a portion of the non-volcanically active surroundings and a small part of the associated ash plume. Source : Matthew Blackett "Early Analysis of Landsat-8 Thermal Infrared Sensor Imagery of Volcanic Activity ",*Remote Sens.* **2014**, *6*, 2282-2295; doi:10.3390/rs6032282

Anomalously High Temperatures Show Areas of Subsurface Lava

Top of atmosphere radiant signals in TIRS-1 band 10 near the blue area in the previous figure

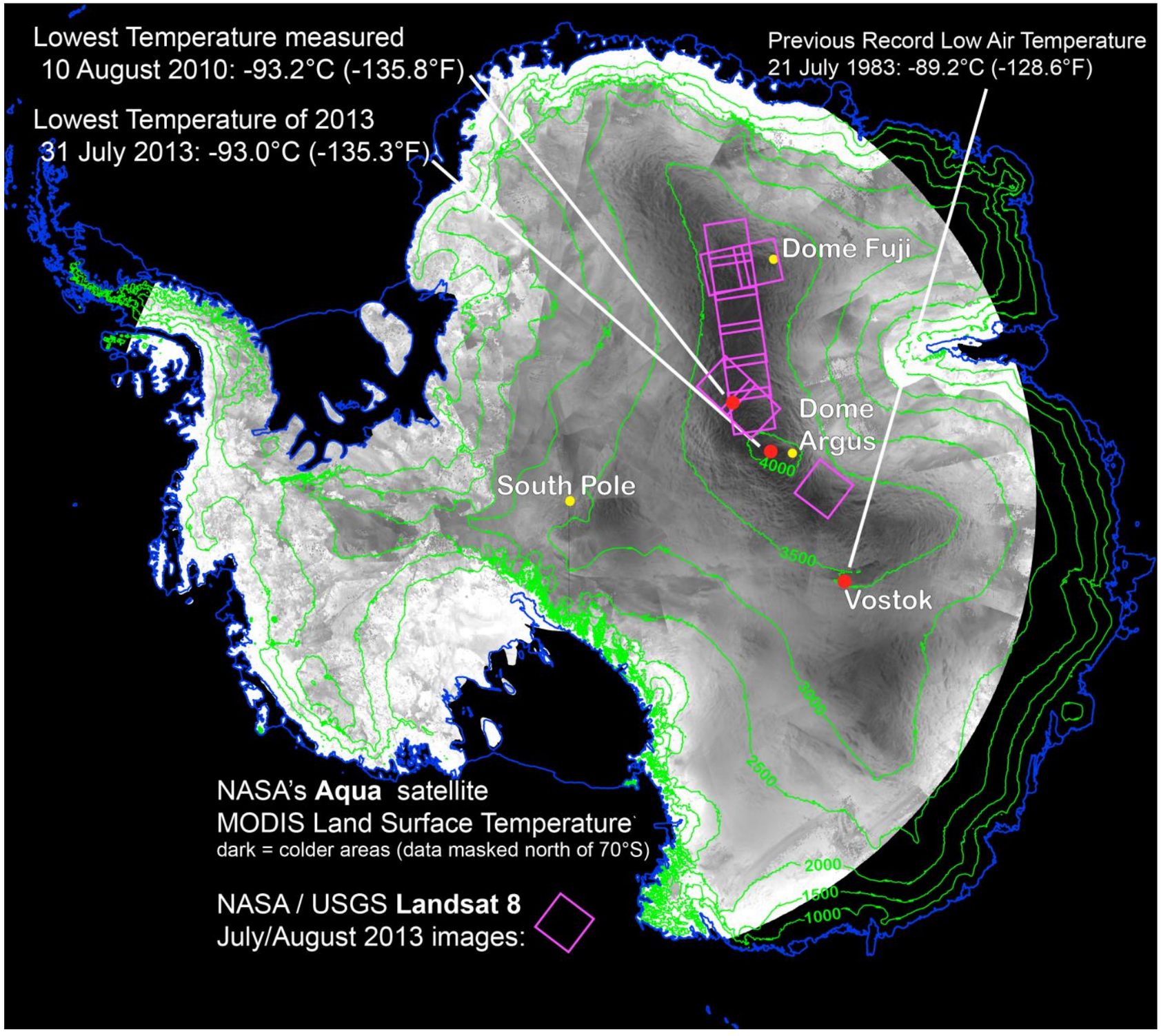


Brightness Temperatures for areas of high radiance. The region shown corresponds to the blue area



- **Studies such as these contribute to the understanding of volcanic structure and activity and possibly can provide early warnings of dangerous events**

At the Other End of the Spectrum (in More Ways Than 1) – The Coldest Spot on the Earth



Ted Scambos, Allen Pope, Garrett Campbell, Terry Haran

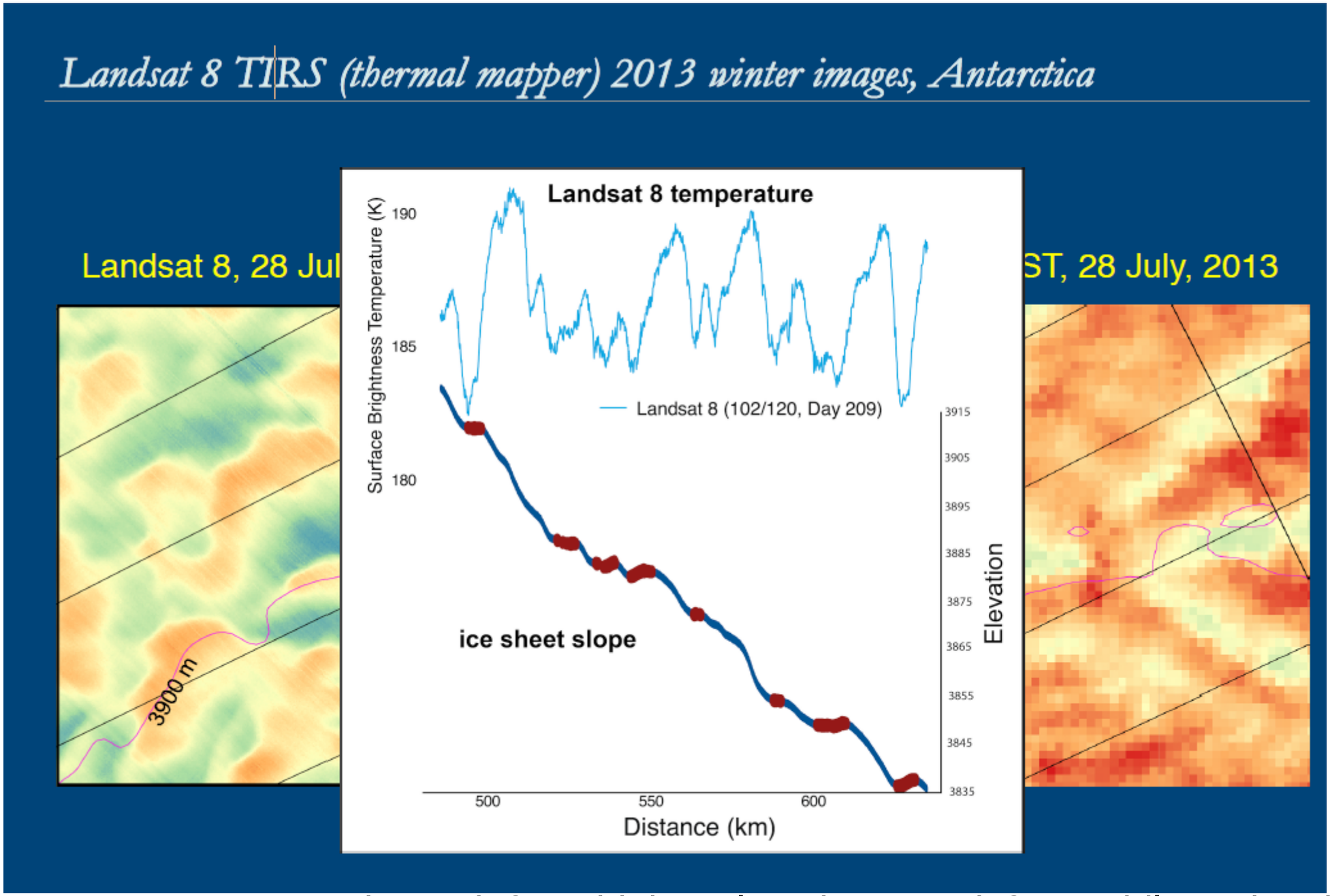
National Snow and Ice Data Center, University of Colorado, Boulder

Matt Lazzara

Antarctic Meteorology Research Center, University of Wisconsin, Madison

Ultra-low surface temperatures (90ºC and lower) occur in local topographic lows (pockets) just south of a long ice ridge. These areas routinely surpass the record temperature of the previous lowest temperature on record, at Vostok Station, Antarctica.

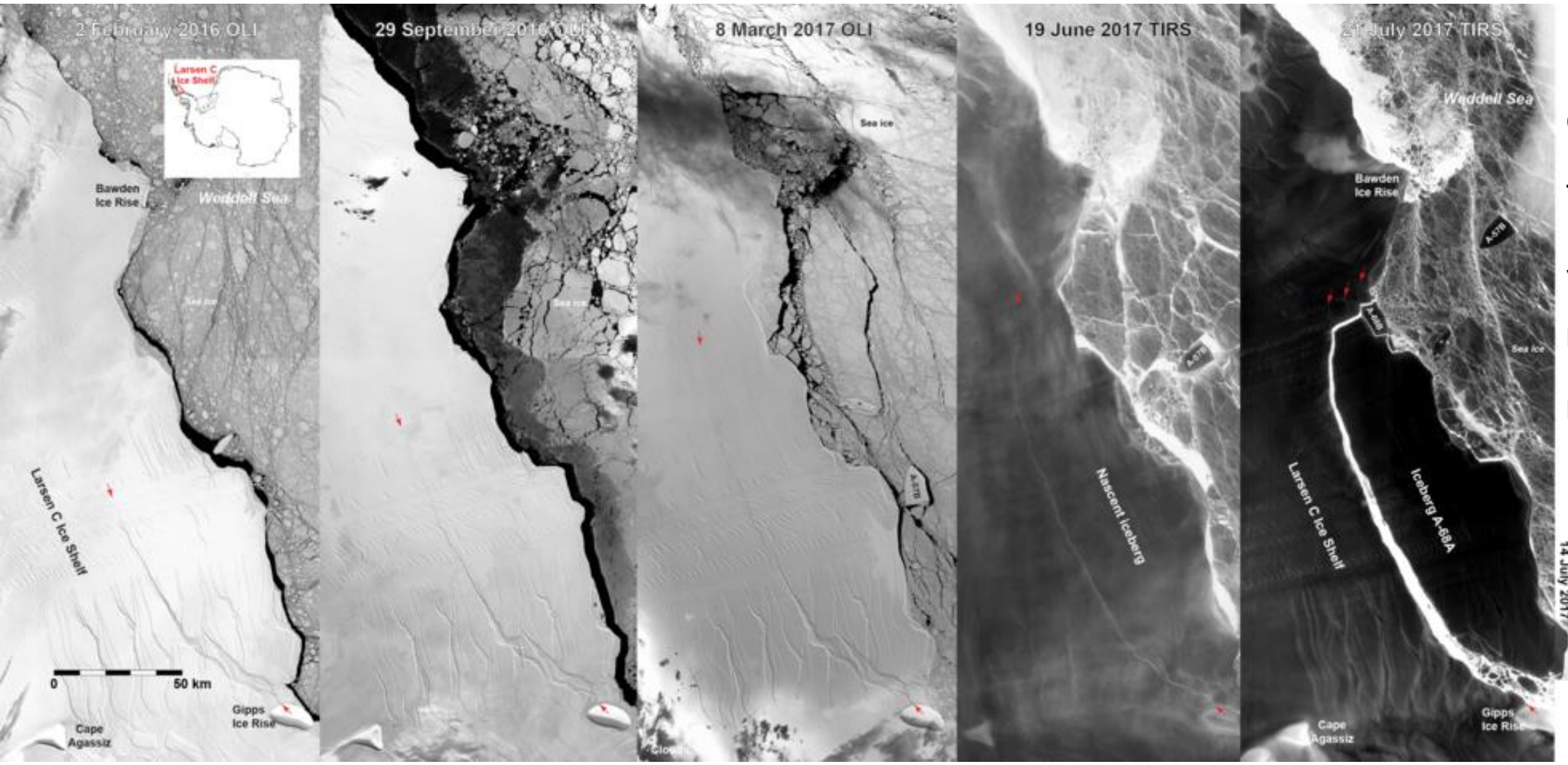
TIRS Data Point to the Physics of the Distribution



Coldest temperatures occur where air from higher elevation can sit for a while and emit radiation

Science directions: What climate and weather conditions lead to the ultra-cold events? Is there a physical limit to how cold it can get?

Large Iceberg Formation Seen in Antarctic Night



Christopher A. Shuman
UMBC JCET at NASA GSFC

Ted A Scambos
University of Colorado, Boulder

Jeffrey E Schmaltz
NASA GSFC

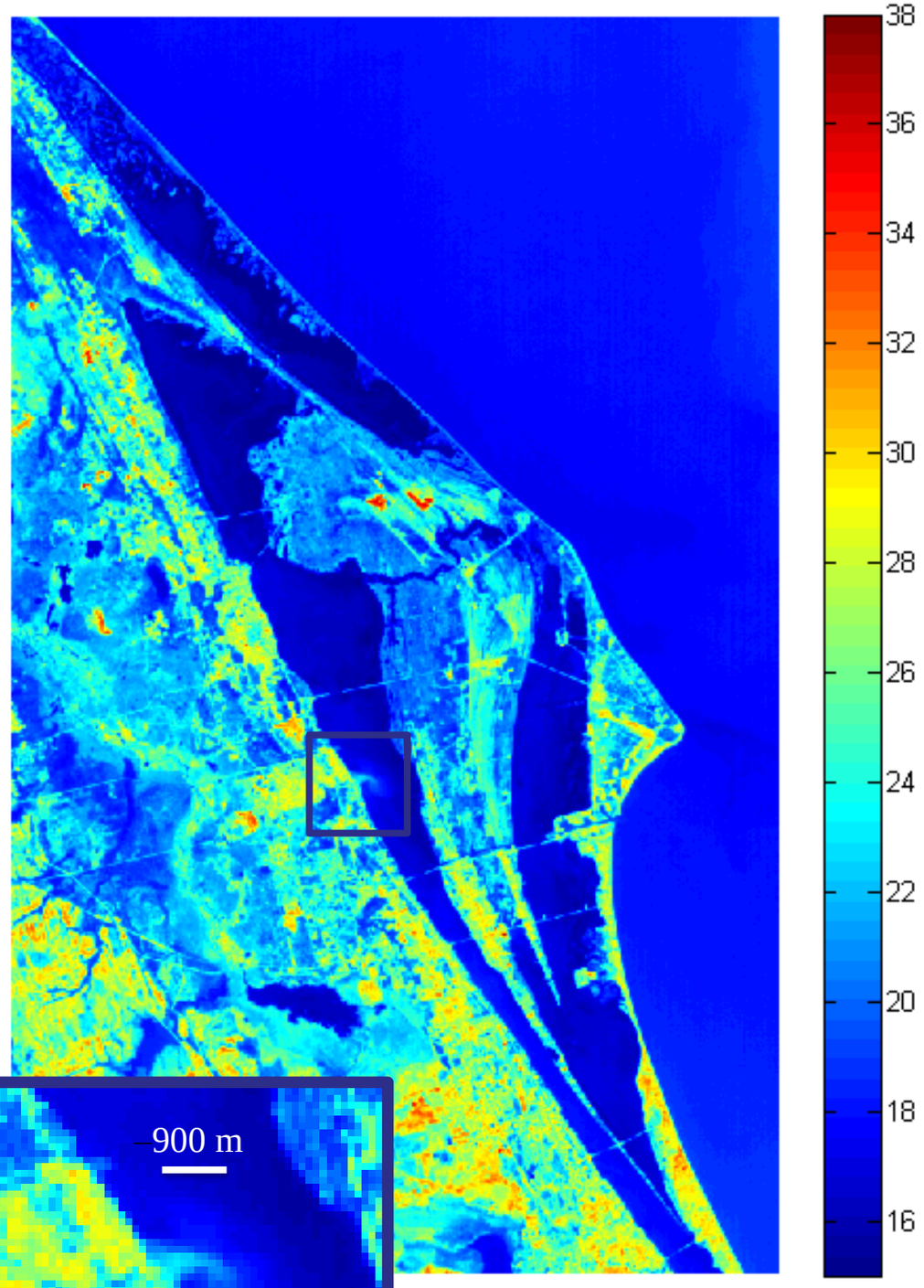
Katherine A Melocik
NASA GSFC

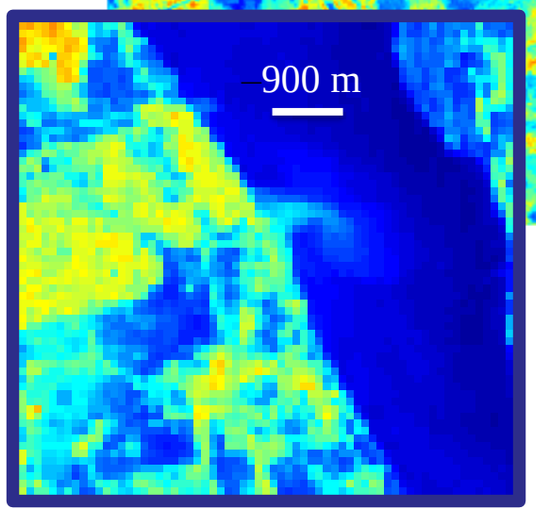
Marin J Klinger
University of Colorado, Boulder

Images from OLI and TIRS showing the fragmentation of the Antarctic ice sheet to form the iceberg A-68. The three images to the left are from OLI and show the intersection of the Larsen C Ice Sheet and the Weddell Sea. They are using reflected solar radiation and white is higher reflectance (ice) than the darker water (with sea ice). The 2 images to the right are from TIRS and are taken during the Antarctic winter when there is no reflected light. In these images white corresponds to the warmer ocean water that is viewed through the cold (black) ice. They clearly show the iceberg breaking off from the ice shelf. This appears to be the first time that thermal imagery has been extensively used to study both an advancing rift as well as the characteristics of the iceberg and its environs. TIRS high SNR made this particularly useful.

Cape Canaveral & Merritt Island, Florida, USA

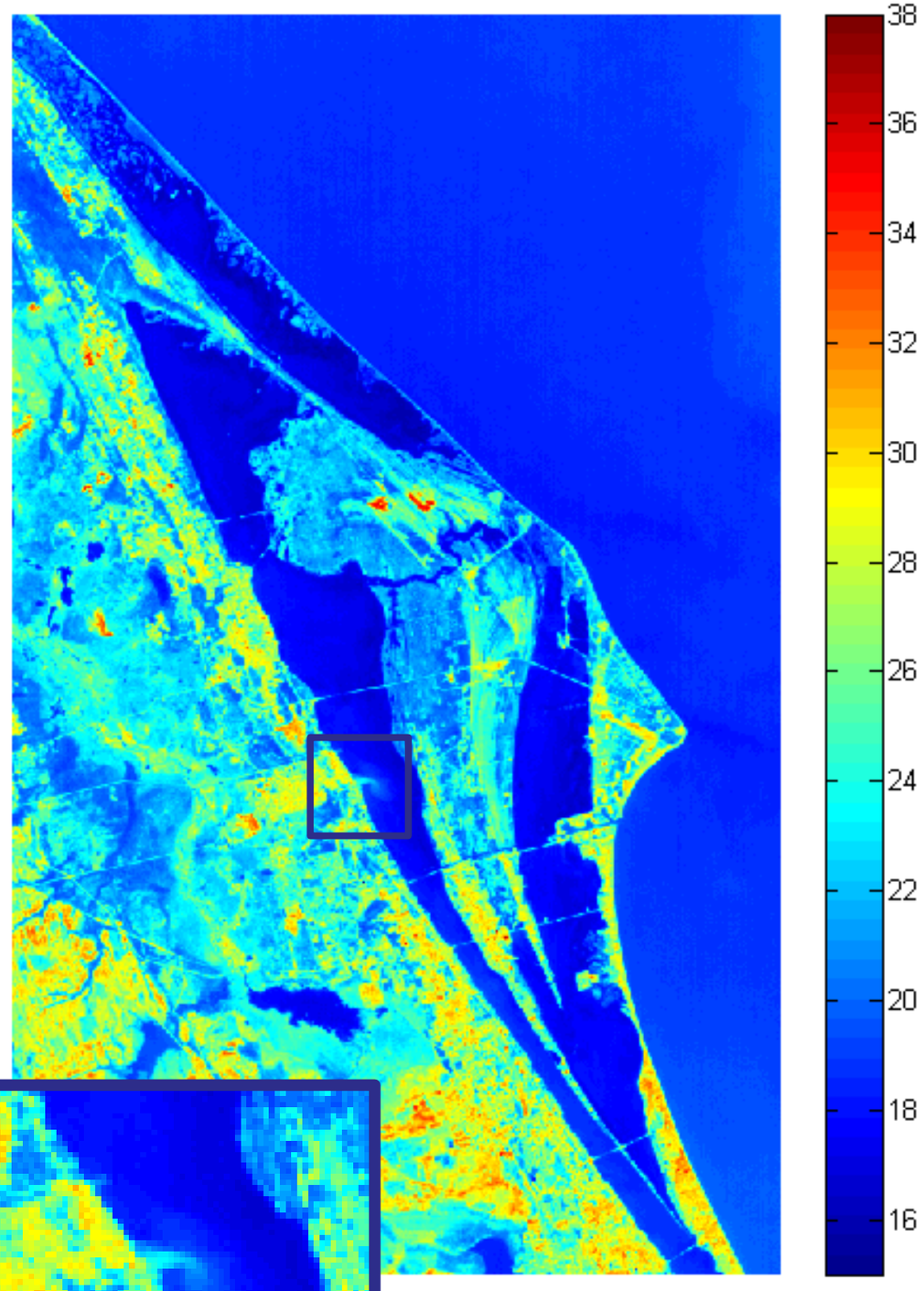
–10.8 µm Brightness Temperature [C]

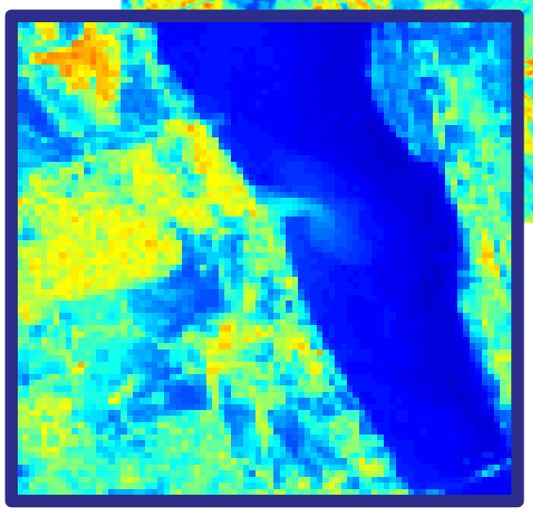




–Close-up of power plant water discharge

–12.0 µm Brightness Temperature [C]





–(~60km width)

Vector Borne Diseases

- Landsat Data have been used to track and identify disease sources
  - Studies in Benin, Nigeria, Florida, New York, Kenya etc.

- Soil moisture maps have been used to identify:
  - Worm habitat (Helminthiases)
  - Tick habitat (Lyme disease)
  - Vector breeding habitat (Malaria)
  - Snail habitat (Schistosomiasis)

Conclusion

- TIRS on Landsat 8 is Providing Crucial Information Over a Broad Range of Subjects
  - The evapotranspiration measurements determined from TIRS data are very much in line with ground measurements

- As those who use TIRS data know, TIRS has a scattered light problem that primarily affects the radiometric accuracy but also the relative error
  - This interesting effect was originally observed in the mismatch between the TIRS radiances and ground based measurements
  - Scattering was verified as the cause by lunar calibration scans
  - An operational application has been developed to account for this and it has brought the radiometry and relative response back in line with requirement
  - However, using the two channels to do atmospheric correction is still not recommended

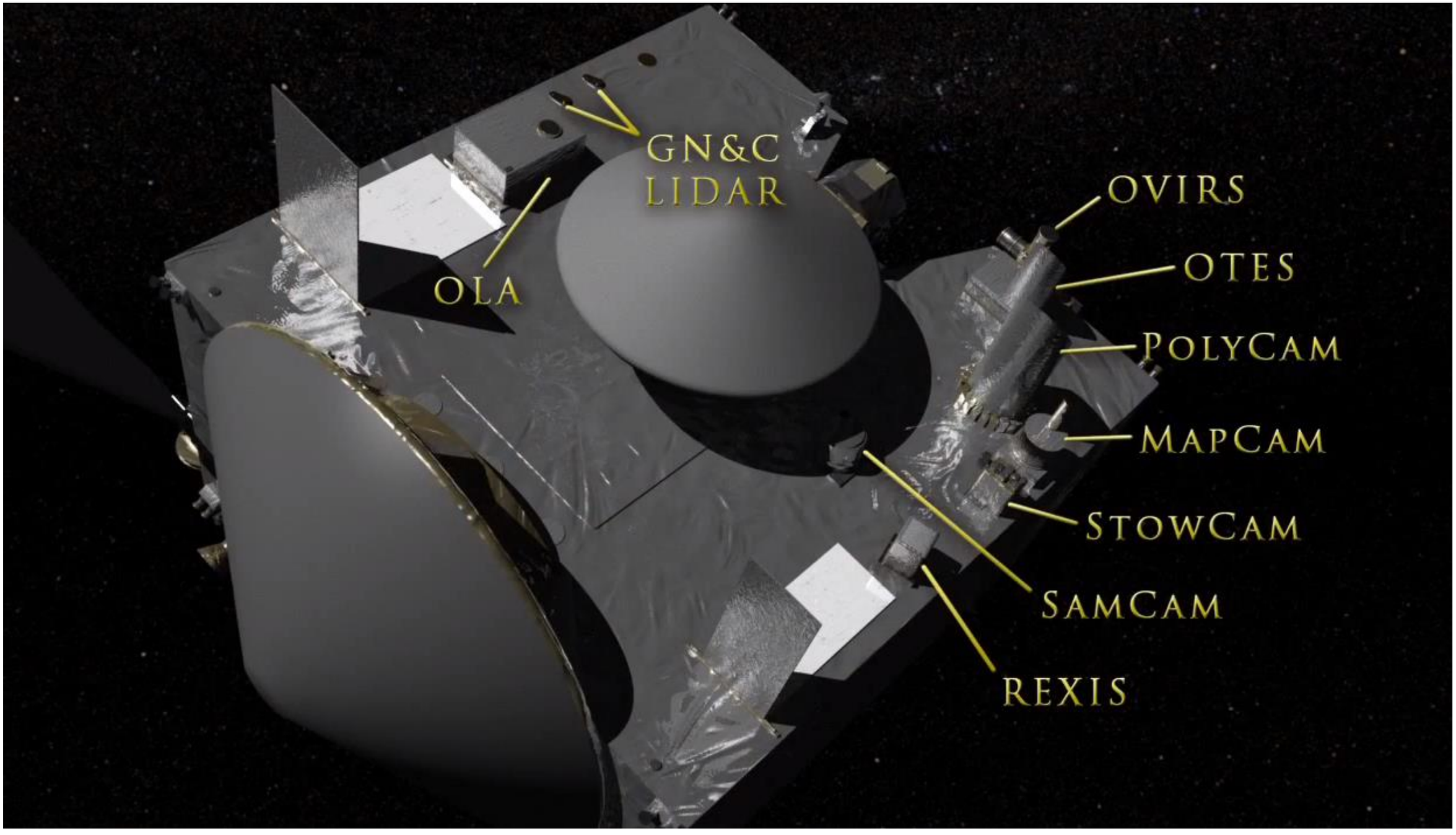
- TIRS-2, the follow-on to TIRS for Landsat 9 is currently finishing its TVAC testing

- TIRS-2 *Does Not* have the TIRS scattering problem

Finally OVIRS on OSIRIS-REx

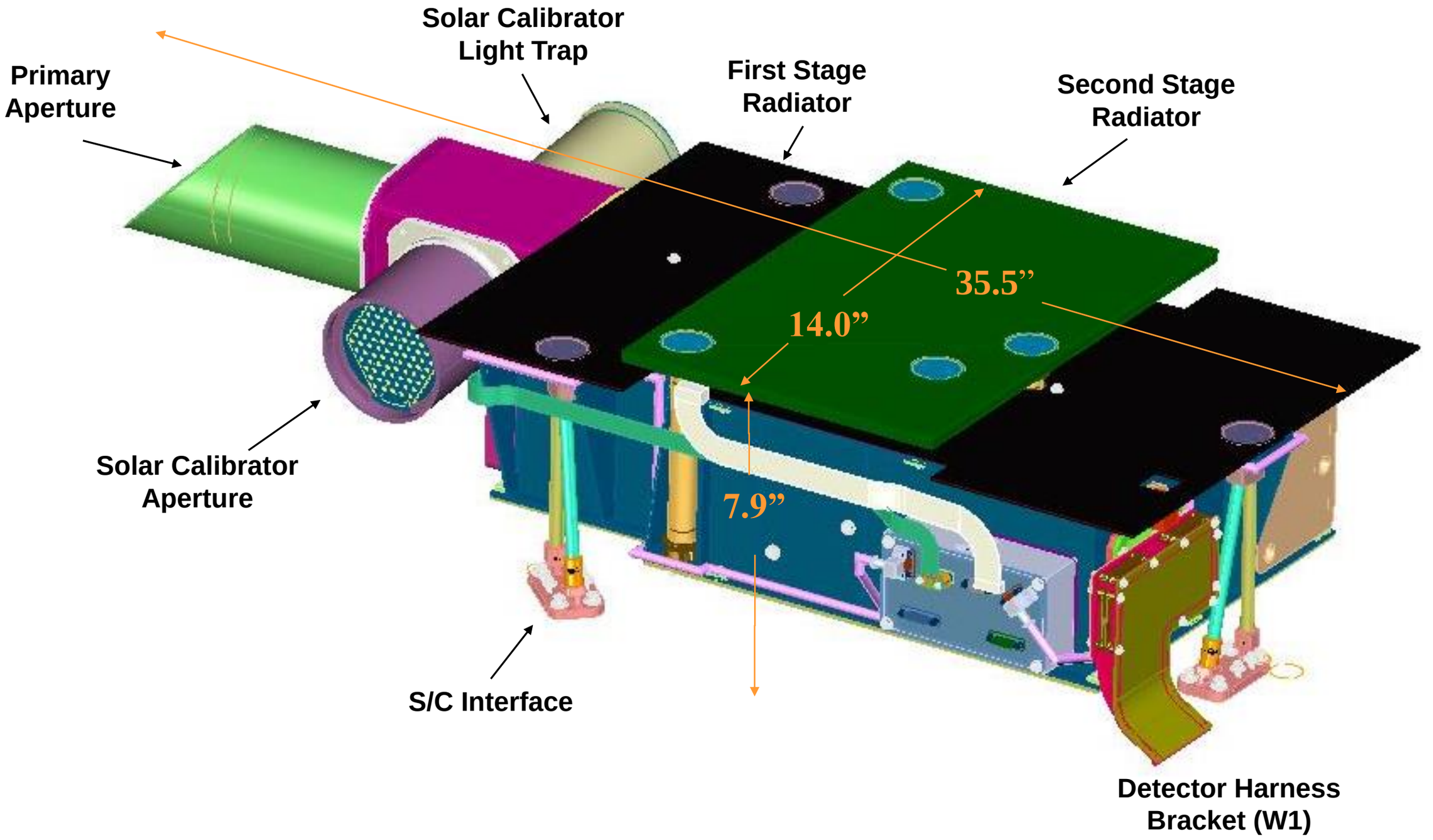
- OVIRS (OSIRIS-REx Visible and IR Spectrometer) is a spectrometer that samples light in visible and infrared wavelengths
- It is part of the OSIRIS-REx instrument suite that also includes
  - OCAMS (OSIRIS-REx Camera Suite): A package of 3 instruments (POLYCAM, MAPCAM, SAMCAM) that provide high resolution (POLYCAM) and color images (MAPCAM) of Bennu's surface and observe sample collection (SAMCAM) – Univ. of AZ
  - OLA (OSIRIS-REx Laser Altimeter): A laser ranging instrument (LIDAR) that will provide maps of the surface heights – Canadian Space Agency
  - OTES (OSIRIS-REx Thermal Emission Spectrometer): A spectrometer that samples even longer infrared wavelengths than OVIRS – AZ State Univ.
  - REXIS (Regolith X-ray Imaging Spectrometer): An instrument that measures X-rays to determine the elements in Bennu – student instrument Harvard/MIT
- This remarkably comprehensive set of instruments is providing outstanding information about the shape and composition of Bennu. It is guiding the selection of the sample site.

OSIRIS-REx Instrument Layout

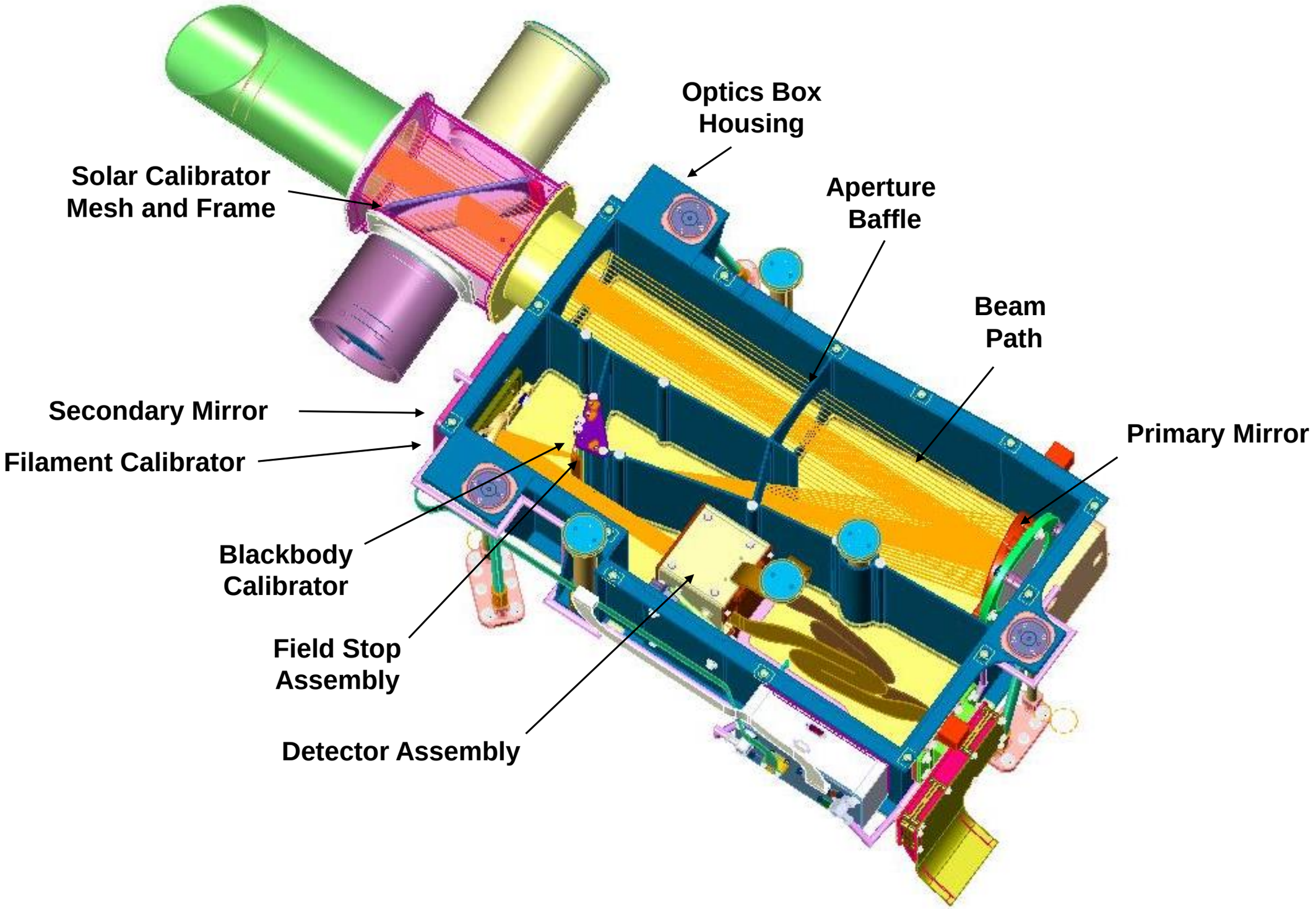


OSIRIS-REx was launched in September, 2016 and has been carrying out approach and orbital phase observations of Bennu since November, 2018

OVIRS Optics Box External View

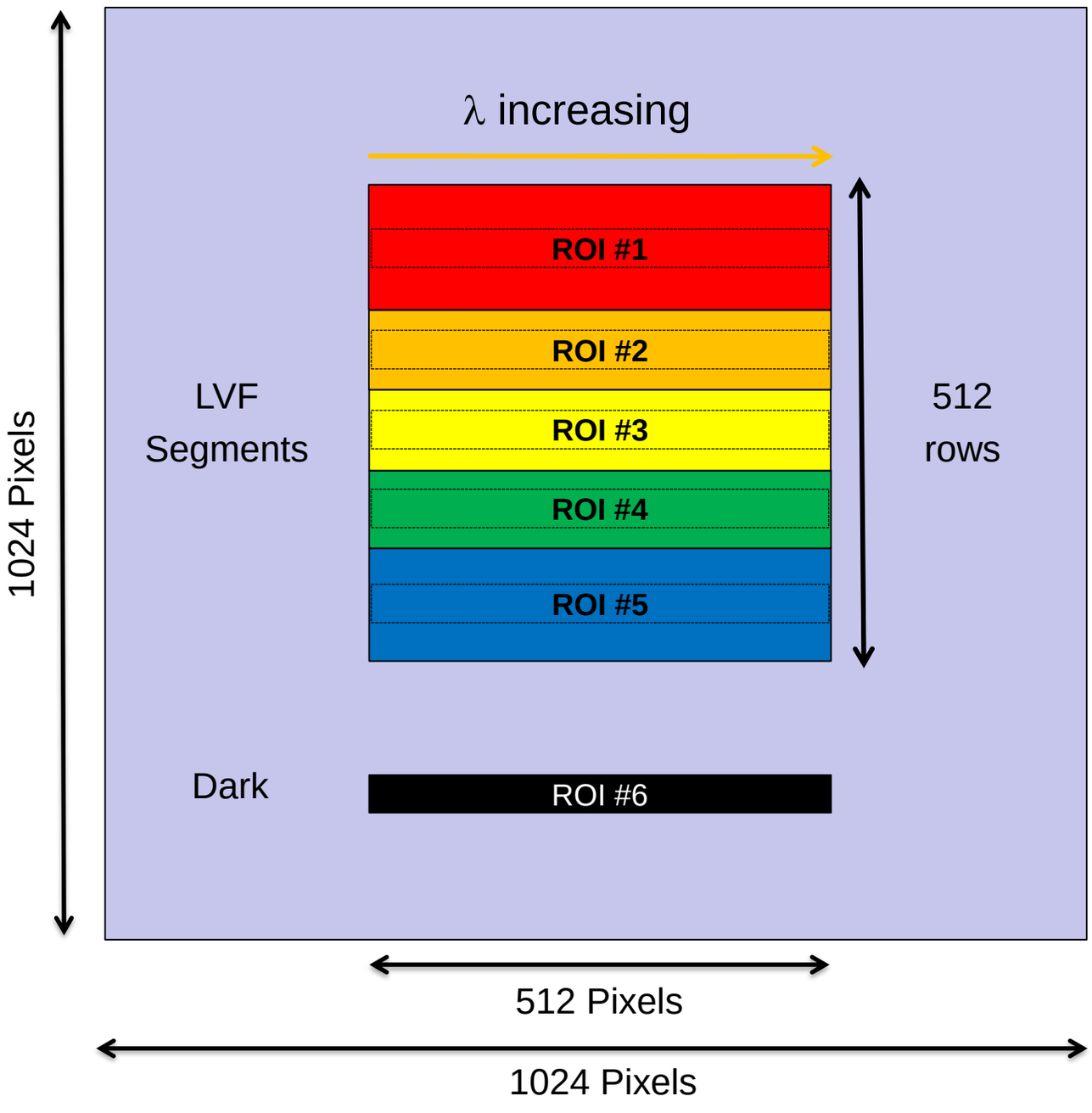


OVIRS Optics Box Internal View



Full Spectrum of Each FOV Obtained Each Frame

Optics collimate light from the 4-mrad FOV, all 512 x 512 pixels illuminated



- **5 LVF segments** define spectral regions
  - Resolution and central wavelength will be determined on a pixel-by-pixel basis
    - 389 to 668 nm: resolving power ($\lambda/\Delta\lambda$) = 220 to 140
    - 658 to 1102 nm with resolving power = 160 to 140
    - 1080 to 1814 nm with resolving power = 200 to 185
    - 1773 to 3006 nm with resolving power = 250 to 240
    - 2880 to 4323 nm with resolving power = 410 to 370
- Nominally read 30 rows **(ROI)** within each filter band to improve SNR
- Dark current sampled from **dark region** to allow correction for temperature shifts
  - Eliminates need for T-control of array or box

An Exciting Circumstance

- One day an OVIRS team member was having trouble getting ahold of the plating vendor, so he went online to see if there was another contact number
- Here is what he saw
- There was a major fire at the vendor that, fortunately caused no injuries, destroyed the plant. The OVIRS flight and flight spare optics boxes were at the facility

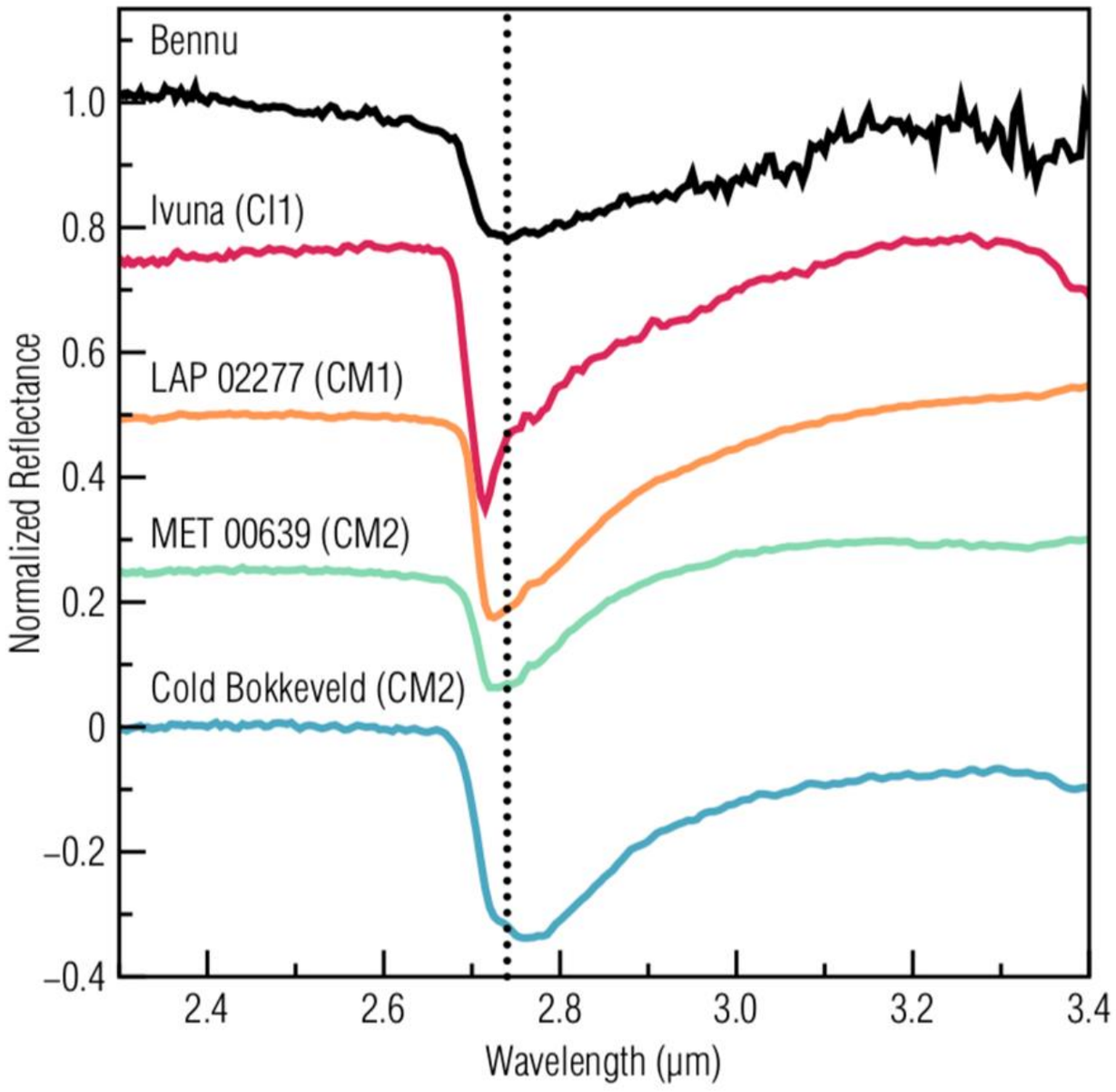
View of housing w/o Optics taken 2 days later when CSO was allowed in

View of Optical Box Lower Cover

Completed Optics Box Housing with Plating – 4 months after fire

New box had to be cut-out, thermal cycled and plated – The plating was done by the original vendor

OVIRS Data is Helping us Understand Bennu



–Spectral observations of Bennu using OVIRS in the approach phase of OSIRIS-REx have shown the presence of hydrated clays over the entire surface. Looks similar to CM/CI type meteorite spectra which bodes well for the sample collection. Indicate that Bennu's parent had abundant water in its interior

In addition to these results, data taken during later orbit phases when Bennu is much larger than the OVIRS FOV are looking very interesting – Additional analysis is needed – Stay tuned

TAKE AWAY

- In this talk, I've tried to show that what would seem to be unbelievable things can occur during instrument development
  - I've only shown a small fraction of these type of situations
  - I'm sure that experience is shared by all here who have worked on spacecraft instruments
- The way to handle these situations is to assess the situation and develop a path forward. Lessons learned are important. Placing blame is irrelevant and useless
- As I hope I've also shown, what matters is the value of the data returned in flight
- Thank you for inviting me