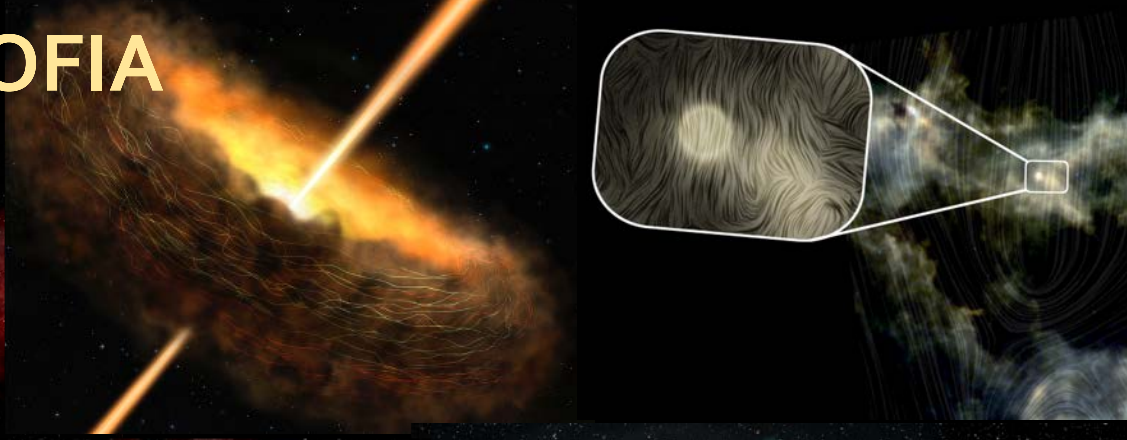
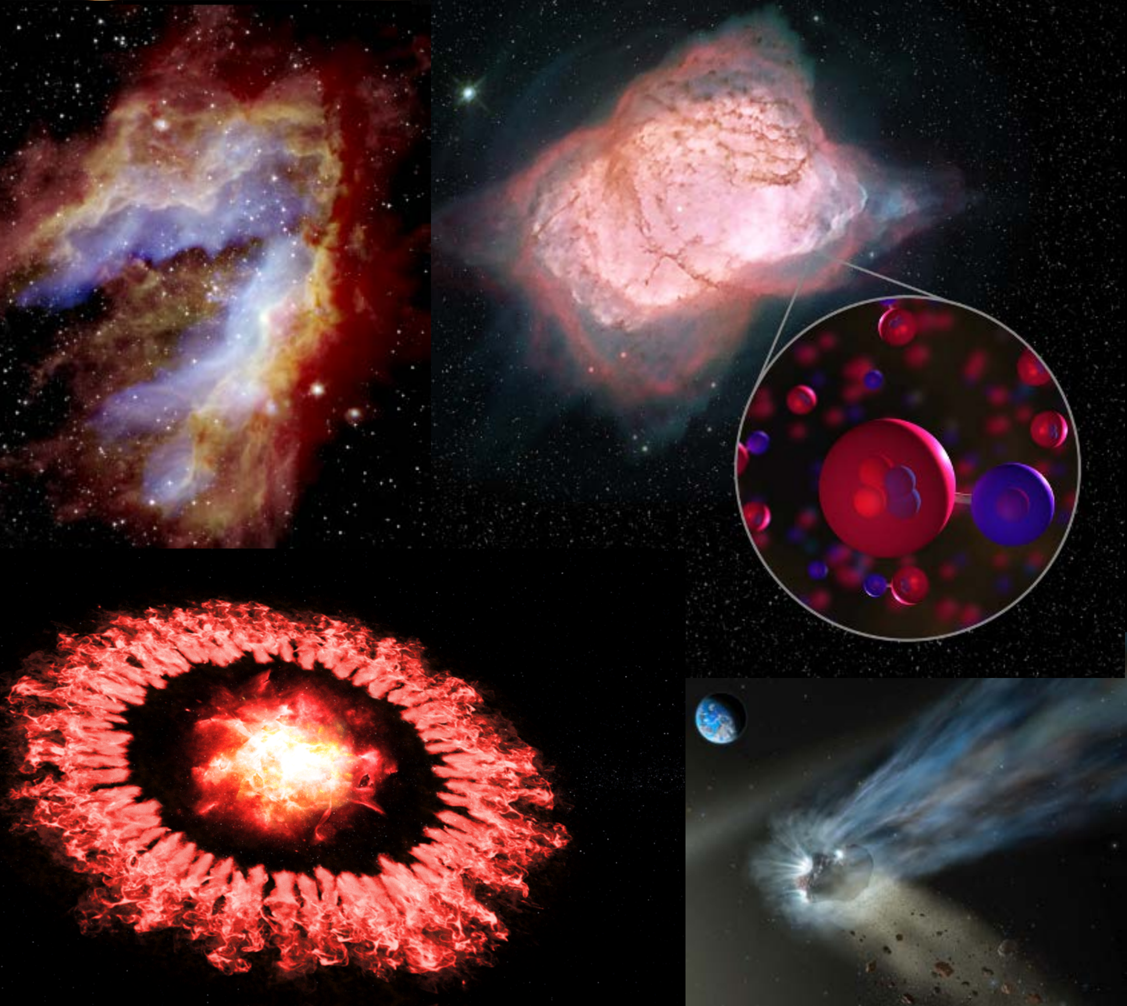
Exploring the Infrared Universe with SOFIA

Naseem Rangwala – SOFIA Project Scientist (NASA/Ames)





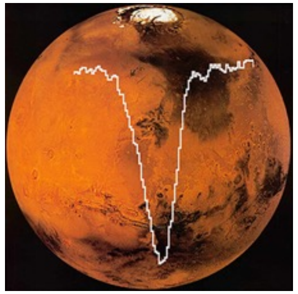
SOFIA Science Objectives

Birth of Stars and Planets

- Establish the role of magnetic fields at sub-parsec scales by mapping Galactic star-forming regions.
- Quantify the energetics of the interstellar medium that is the birthplace of stars and planets by measuring the dominant cooling lines, the radiative and stellar-wind feedback by stars, and the dynamics of the gas.

Path to Life: Water, Organics, and Ices

- Compile an inventory of water and organics in protostars to understand chemical pathways from simple molecules to prebiotic species.
- Monitor temporal and spatial changes of planetary atmospheres in our Solar System as analogs to exoplanets.
- Origins of water on the Moon: Map water in key regions on the Lunar surface.



Calibrating the Distant Universe

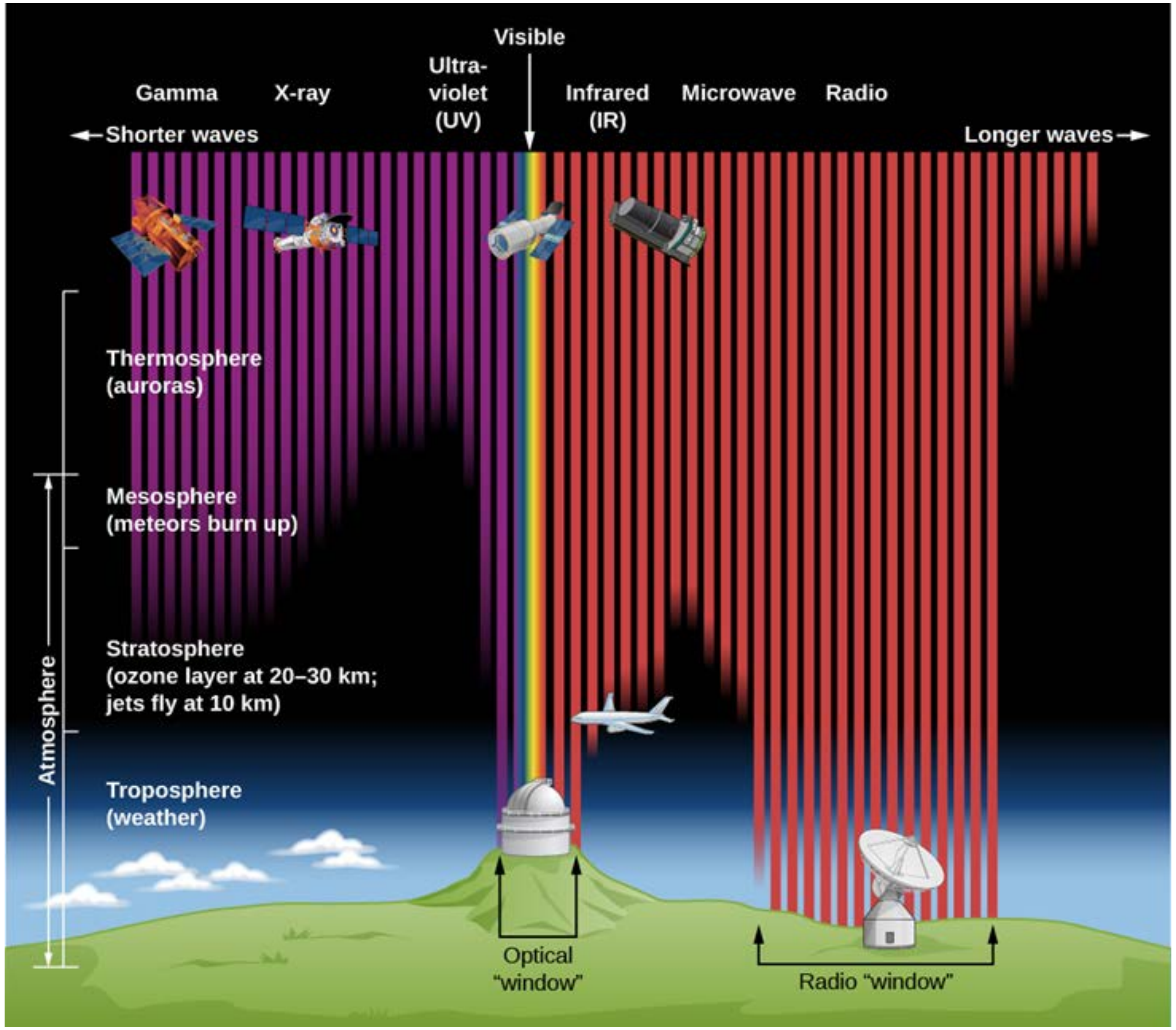
- Understand "single-pixel" (spatially unresolved) measurements of distant galaxies by measuring far-IR lines and magnetic fields investigating local analogs.

Exploring the Universe Requires Multi-Wavelength Observations

SOFIA provides community access to the mid- and far-infrared sky, impossible to observe from the ground or any current space-based telescopes.

It fills a critical spectral gap between JWST's longest wavelength (28 µm) and ALMA's shortest wavelength (320 µm), including gaps beyond 320 µm.

- Unique access to MIR and FIR wavelengths
- Large scale (faster) mapping (e.g., ~50x faster than Herschel in the [C II] line)
- High-resolution spectroscopy in the MIR and FIR
- Polarization capability at the peak of thermal emission; shape, direction and strength of magnetic fields



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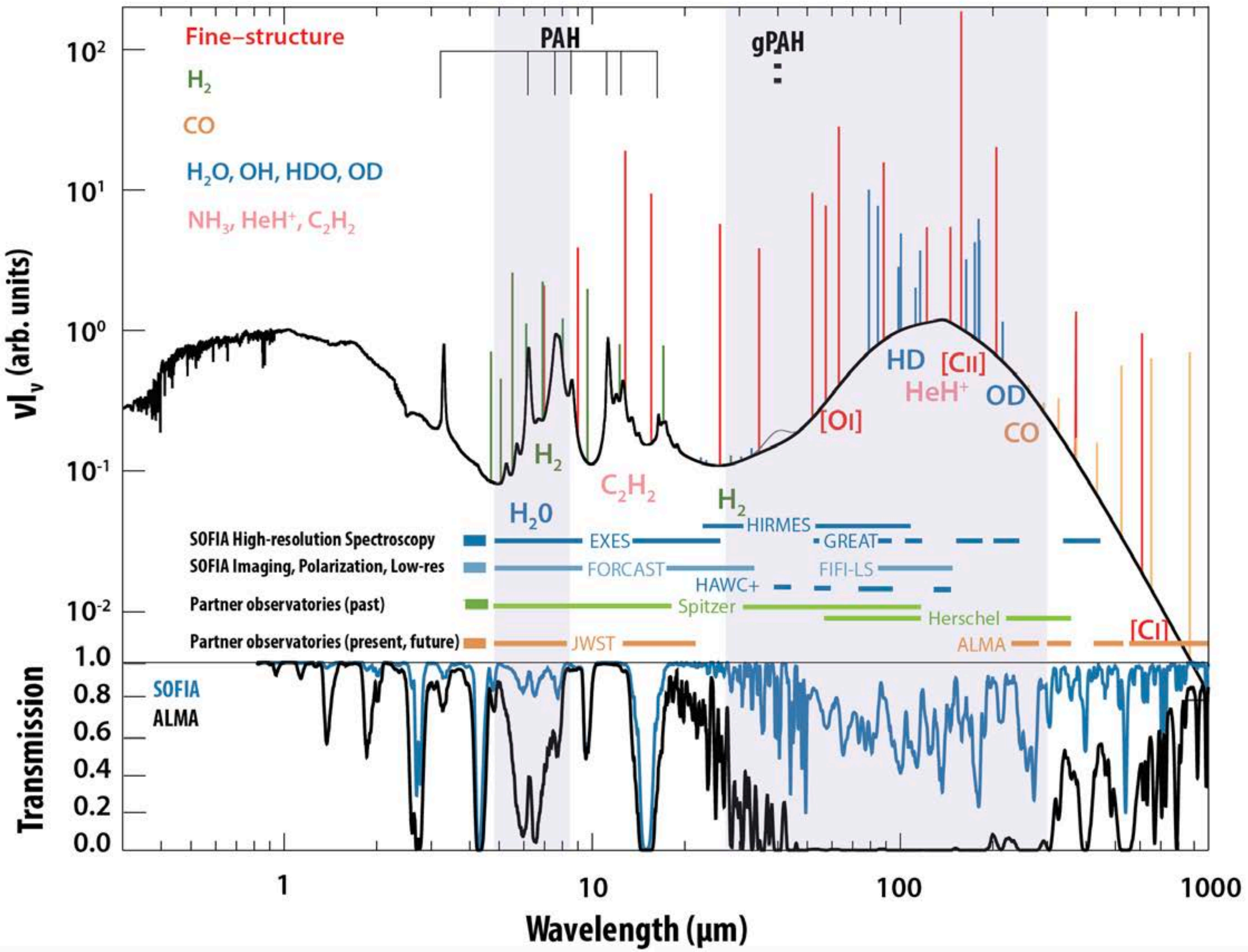

Magnetic 'Rivers' Feed Young Stars

Thushara Pillai
(Boston Univ.)

Pillai et al. (2020), Nature Astronomy

Composite image of the Serpens South Cluster.
Credits: NASA/SOFIA/T. Pillai; NASA/JPL-Caltech/L. Allen

SOFIA revealed a twist to the Planck story

- Finer resolution of SOFIA shows that in the most opaque parts (Av > 21mag), the magnetic field is once again aligned allowing gravitational collapse and star cluster formation to occur even in the presence of relatively strong magnetic fields

Background

Herschel and *Planck* unambiguously showed that stars form in filamentary gas clouds and that magnetic fields play a key role in formation of these dense filaments

SOFIA/HAWC+ confirmed the trend seen in the lower resolution *Planck* – that the magnetic field is parallel to low-density gaseous filaments and perpendicular at higher column densities.

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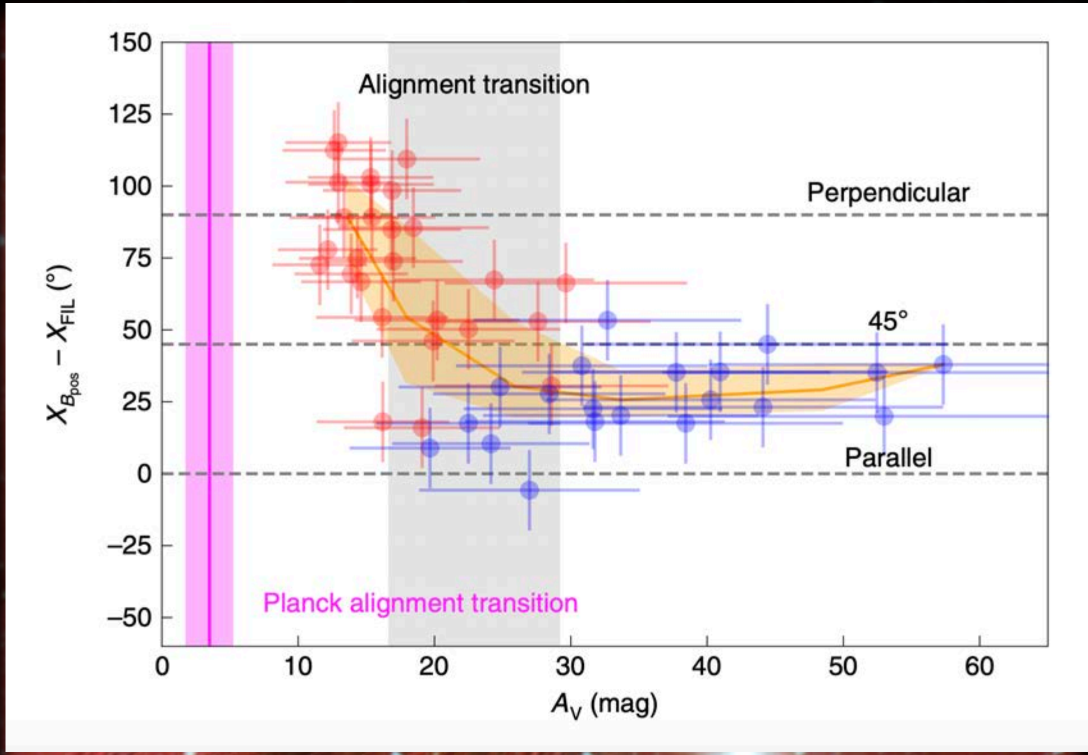

Distribution of relative orientations of the FIL2 gas filament with respect to *B*pos as a function of *A*V. The NIR *B*pos are shown as red filled circles and the FIR as blue filled circles. Their corresponding 1σ uncertainties are shown as error bars. The three dashed lines show parallel, 45° and perpendicular orientations of the magnetic field with the filament. The orange area captures the interquartile ranges for all data versus *A*V. The vertical grey rectangle highlights where the median relative orientation crosses 45°, with width related to the uncertainty of the crossing value. This indicates where the transition from a perpendicular to parallel field orientation occurs. The magenta bar represents the lower *A*V, first alignment transition suggested by Planck data, for the parallel-to-perpendicular transition near *A*V ≈ 3.5 mag

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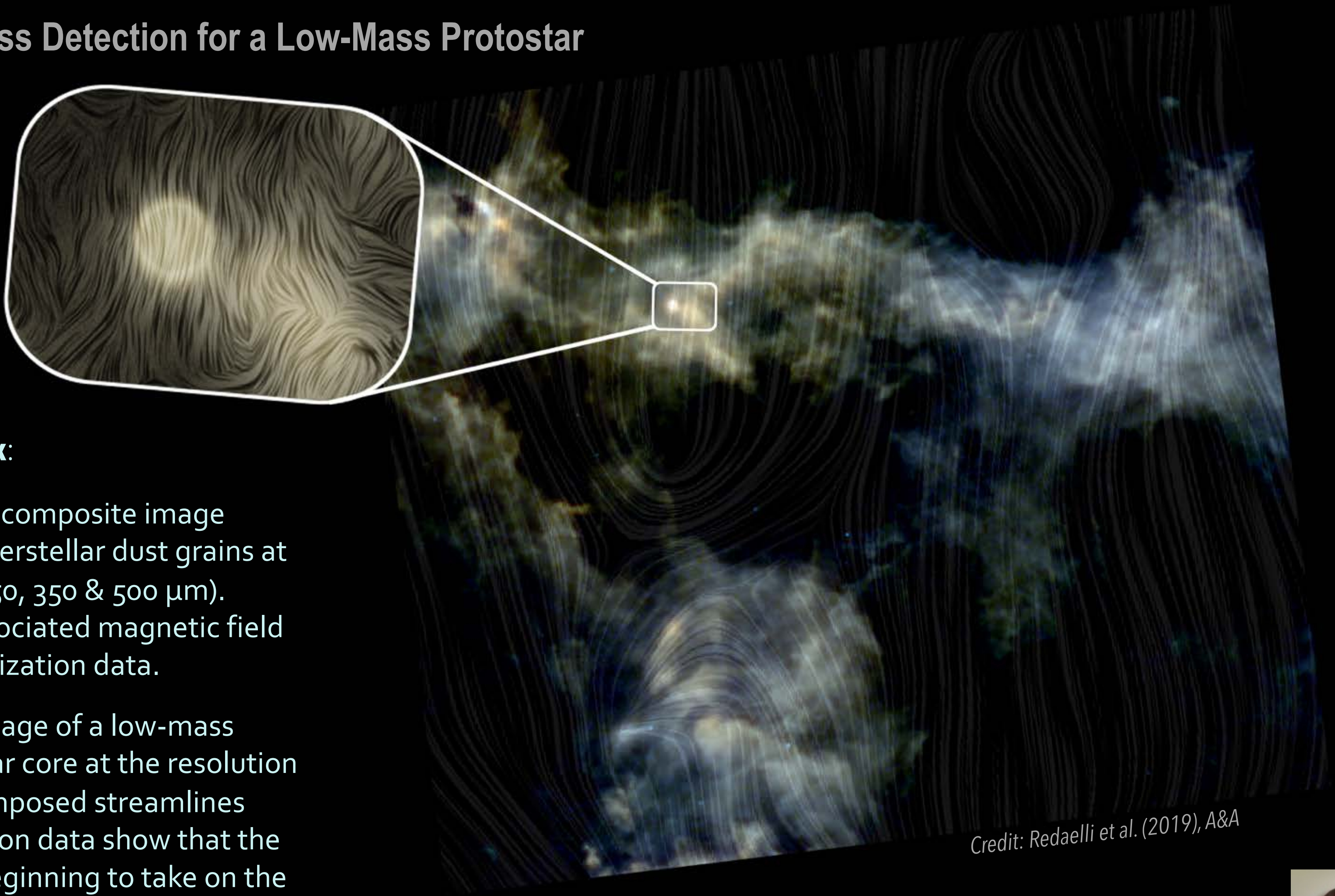
A Magnetic Hourglass Detection for a Low-Mass Protostar



Lupus I Cloud Complex:

Background *Herschel* composite image shows emission by interstellar dust grains at three wavelengths (250, 350 & 500 μm). Streamlines show associated magnetic field based on *Planck* Polarization data.

Inset shows SOFIA image of a low-mass embedded protostellar core at the resolution of 0.01pc. The superimposed streamlines from SOFIA polarization data show that the magnetic fields are beginning to take on the expected hourglass shape

Elena Redaelli
Max Planck Institute

Large Magellanic Cloud

30 Doradus (Tarantula Nebula)

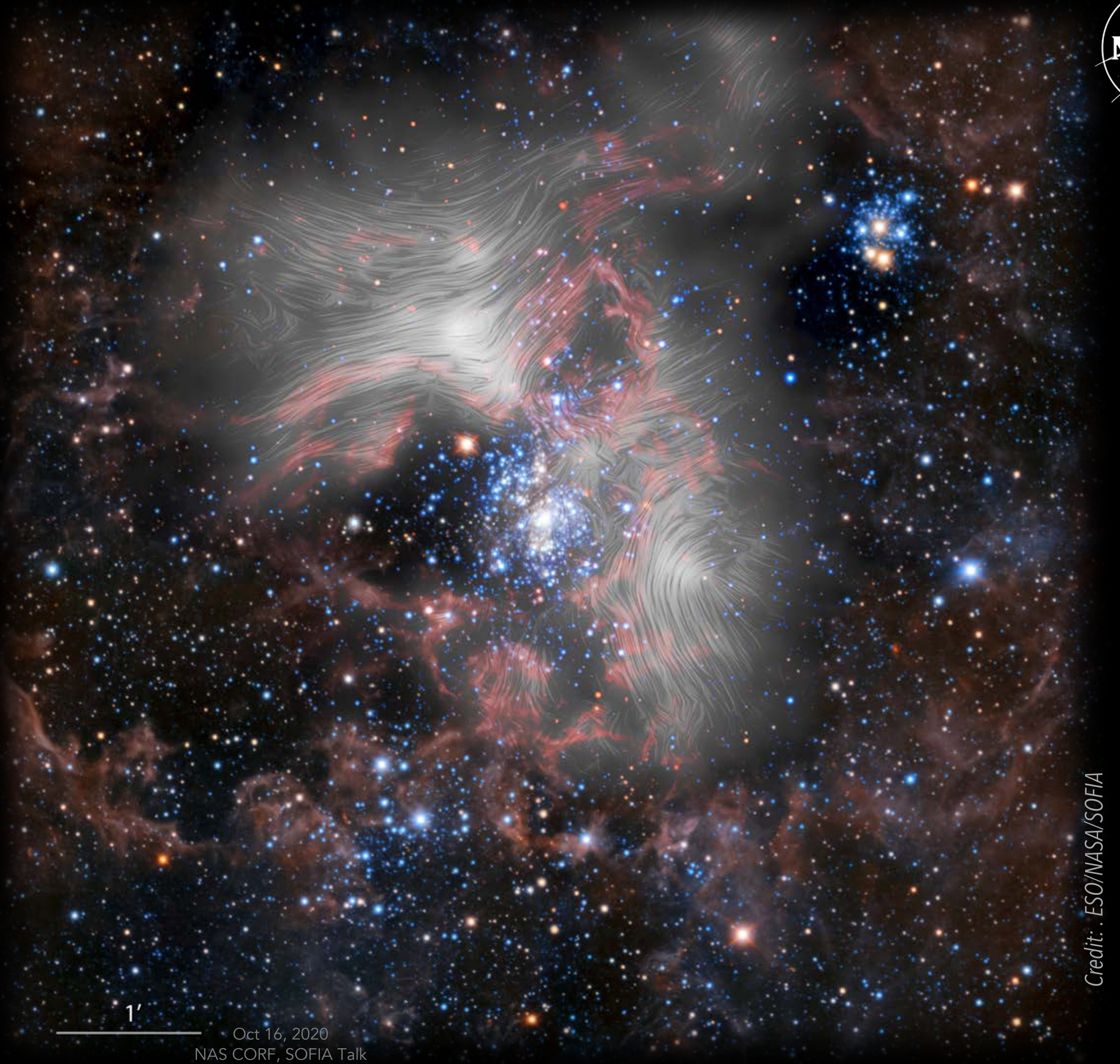
Magnetic field around this Super Star Cluster shows hourglass morphology on a very large scale

- SOFIA 154 μm intensity (gray) and magnetic field streamlines superposed on an ESO/HAWK Y (1.021 μm; blue & 2.146 μm; red) image of 30 Doradus .

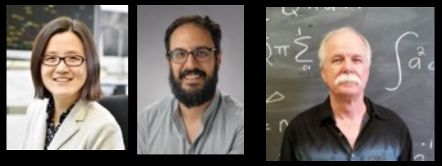
- This low-metallicity, high-luminosity cluster , a "mini-starburst" with hundreds of massive stars, is an excellent analog for a typical star-forming region in the early Universe.

- These data were immediately made available to the community as a Director's Discretionary Time observation.

Coude et al., in preparation



Magnetic fields in M82 and NGC 1068



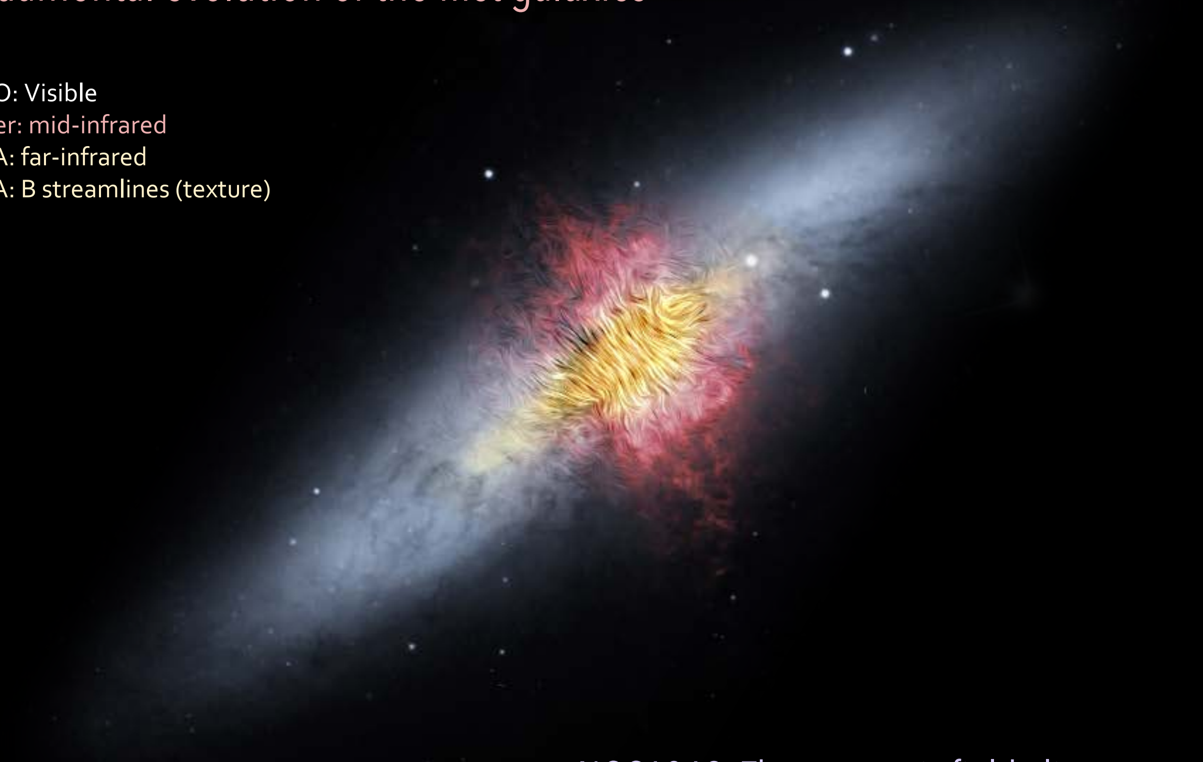
Sue Ann Mao
Max Planck

Enrique Lopez Rodriguez
SOFIA

Terry Jones
U. Minnesota

M82: SOFIA discovered that magnetic field is aligned with the supergalactic wind in this starburst galaxy over at least 700pc; dragging its magnetic field and injecting magnetic field into the intergalactic medium. Similar processes, if happened in the early universe would affect the fundamental evolution of the first galaxies

NOAO: Visible
Spitzer: mid-infrared
SOFIA: far-infrared
SOFIA: B streamlines (texture)



NGC1068: The magnetic field alignment stretches across the entire length of the massive, arms – approximately 24,000 light years across. This implies that the gravitational forces that created the galaxy's spiral shape are also compressing its magnetic field, supporting the density wave theory.

Credits: NASA/SOFIA; NASA/JPL-Caltech/Roma Tre Univ
Jones et al. (2019), Lopez-rodriguez et al. (2020)

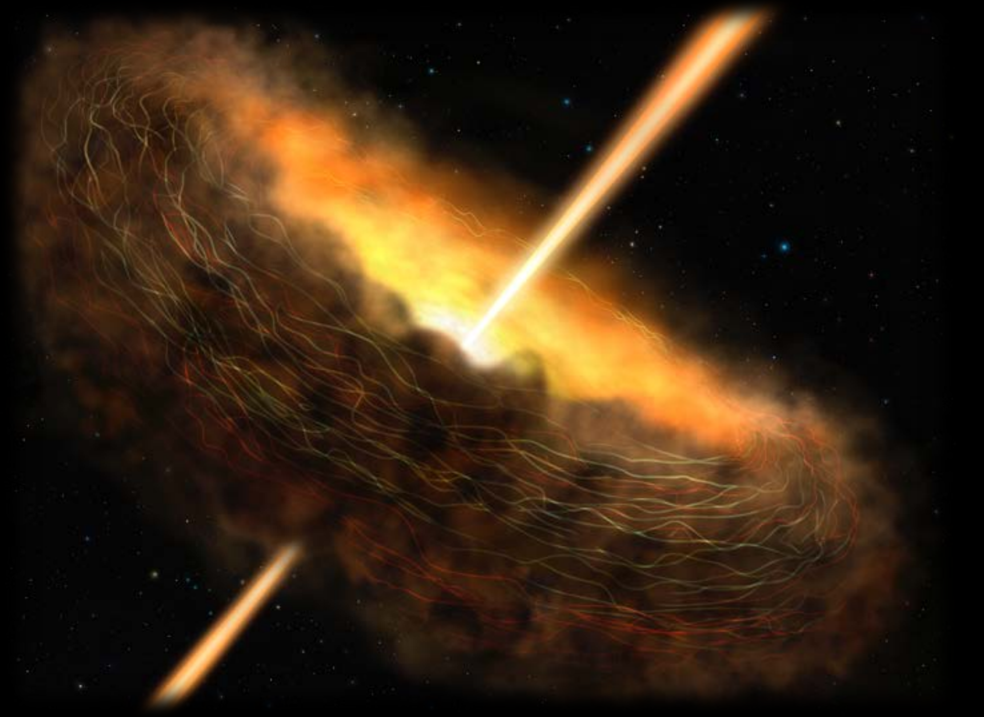
SOFIA Legacy Program
http://galmagfields.com

Role of Magnetic Fields in Feeding Black Holes

Credits: NASA/SOFIA/HST

Dowell et al. in preparation

Why is our central black hole quieter than other? The magnetic field is strong enough to constrain the turbulent motions of gas and channel the gas into an orbit around the black hole, thus preventing it from falling onto the black hole.



Lopez-Rodriguez et al. (2018), ApJ

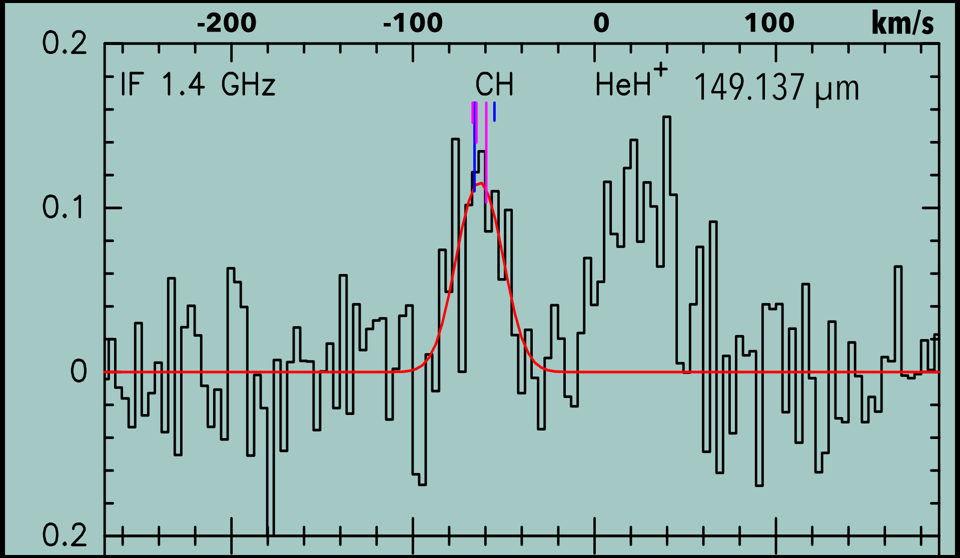
Cygnus A: A more dominant and strong magnetic field trapping the material that feeds the supermassive black hole in this active galaxy.

SOFIA 53 μm and 89 μm data with an angular resolution of 5″ and 9″. These observations are sensitive to temperatures of 30–50 K and show highly polarized infrared emission dominated by a well-aligned dusty structure

SOFIA Finds Helium Hydride: the Universe's First Molecule

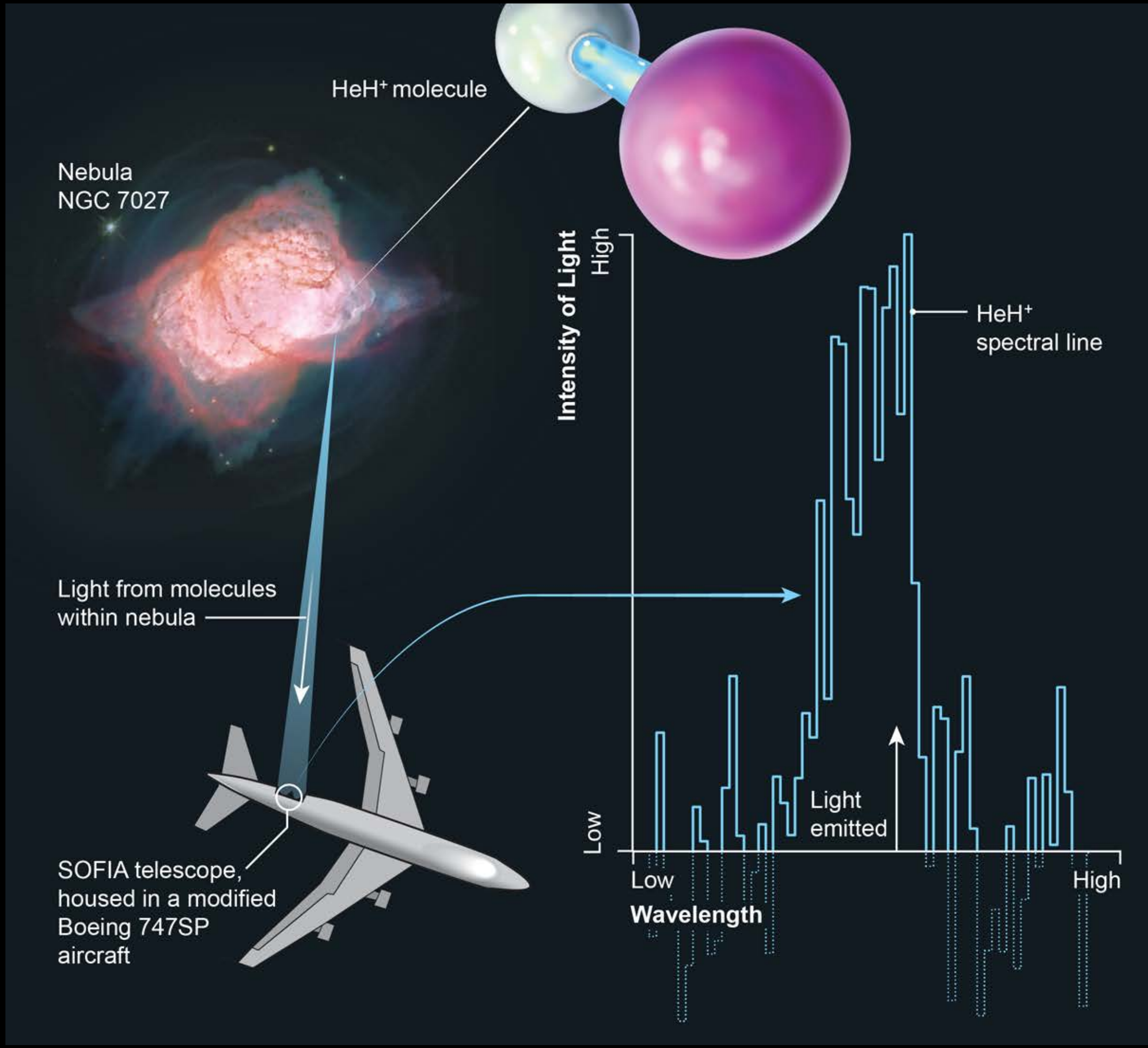
- When temperatures in the early Universe had fallen below ~4,000 K, ionized hydrogen interacting with neutral helium (radiative association) created the "Universe's first molecular bond" in the helium hydride ion (HeH^+).
- Destruction of HeH^+ created one of the earliest paths to forming H_2
- Decade long search for this molecule finally ended with a new upgrade on SOFIA's GREAT instrument that allowed tuning to the right frequency to detect this molecule
- The measured strength of this line exceeds model prediction by ~3x.

Rolf Gusten
MPIA



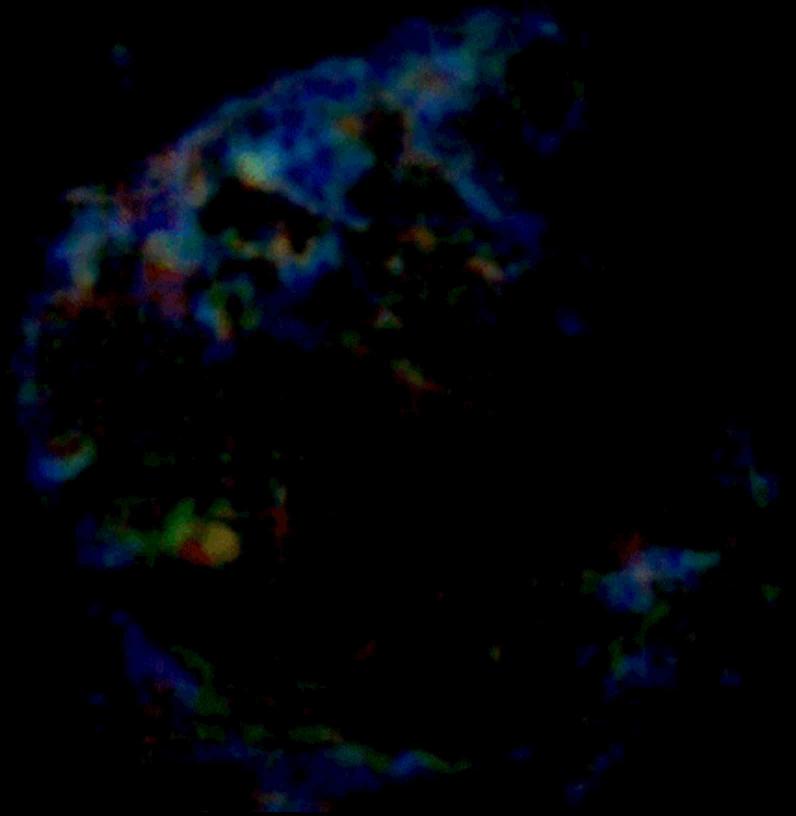
Gusten et al. (2019), Nature

Scientific American Feb 1, 2020

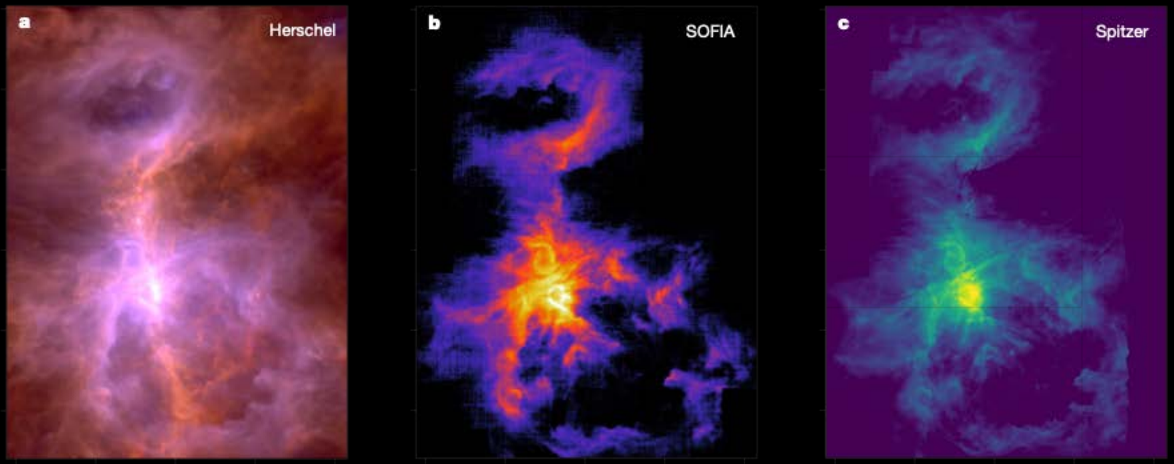


Credit: Elena Hartley (molecules) and Amanda Montañez (schematic) ; NASA/ESA/Hubble

Disruption of the Orion molecular core by stellar wind from a massive star



Pabst et al. (2019), Nature



FIR dust continuum emission measures the conversion of FUV radiation to dust emission in PDRs

[CII] spectral data cube; 2.2 million spectra; 0.03pc res measures the cooling and kinematics of the gas in PDR

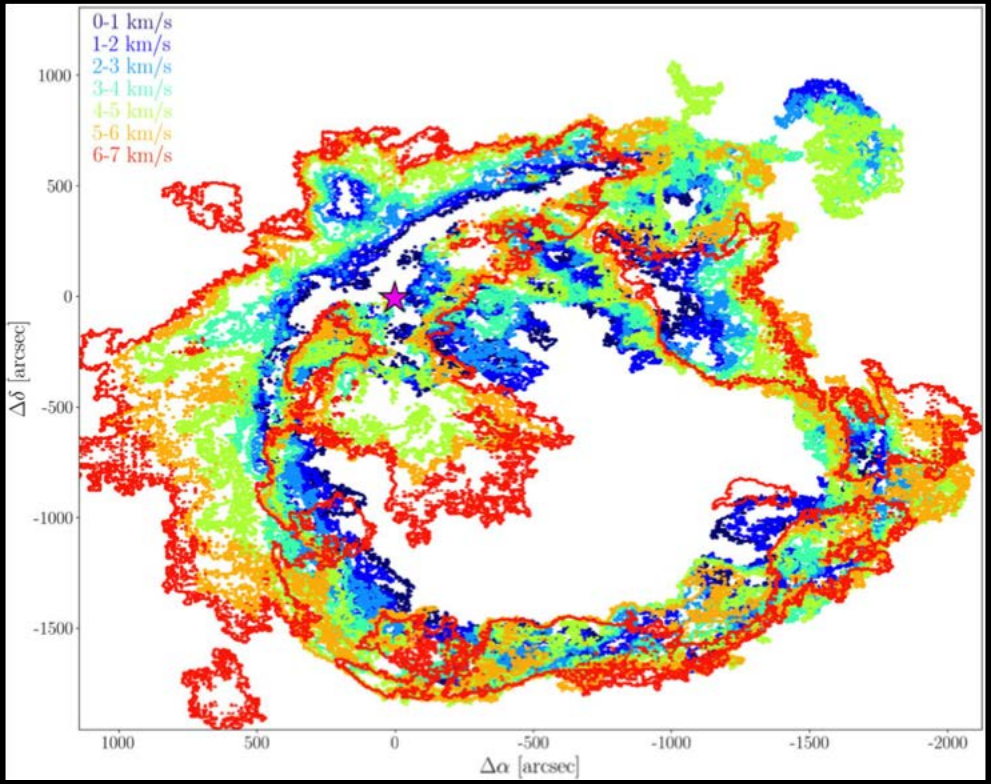
MIR PAH 8μm emission traces the FUV illuminated surface of PDR

Cornelia Pabst
(PhD Student, Leiden University)

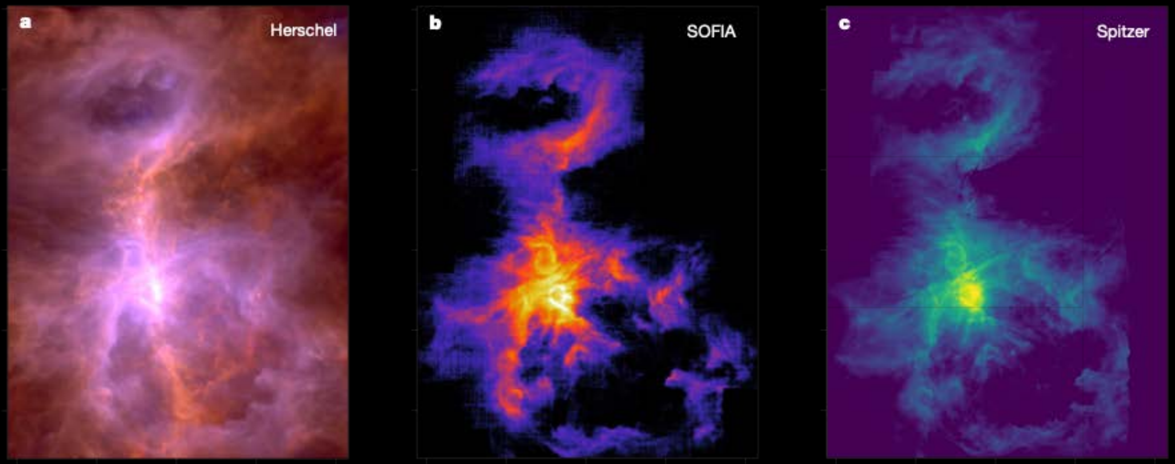
Contrary to the theoretical expectations, SOFIA found that the mechanical energy from stellar wind generated by the central massive star causes more disruption of the Orion molecular cloud core than do photo-ionization and evaporation
or future supernova explosions.

Disruption of the Orion molecular core by stellar wind from a massive star

Pabst et al. (2019), *Nature*



Composite figure showing the [C II] emission in different velocity channels. With increasing *Vlsr*, the shell is displaced outwards, away from the center of the bubble. This is the kinematic signature of an expanding half-shell. Each color outlines the emission boundaries of channels 1 km/s wide from *Vlsr* = 0-7 km/s



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<u>Total Kinetic energy (erg)</u>

Expanding shell: 4×10^{48}

Wind Mechanical: 5×10^{48}

Ionized Gas: 6×10^{46}

X-rays (hot gas): 10^{47}

Theory: 5/11 of mechanical energy will go into heat the gas

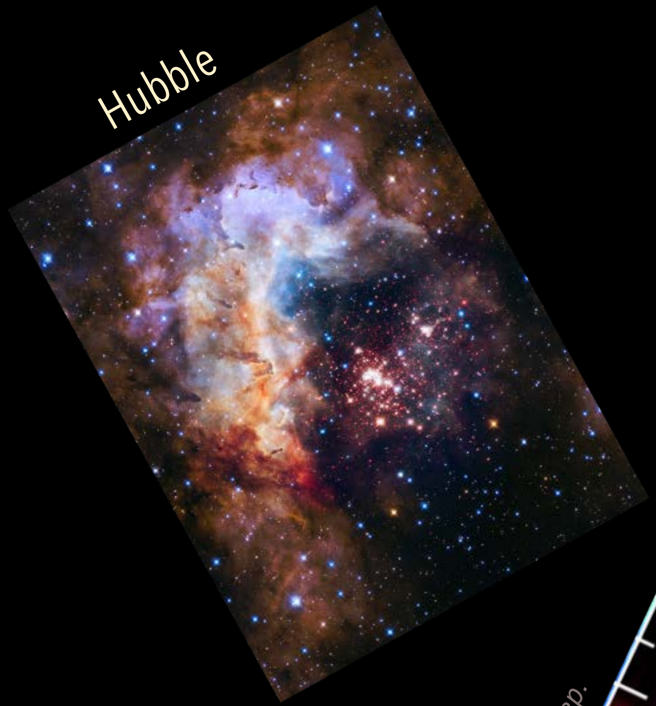
SOFIA observations: 4/5

SOFIA FEEDBACK Legacy Program

Alexander Tielens (Leiden)

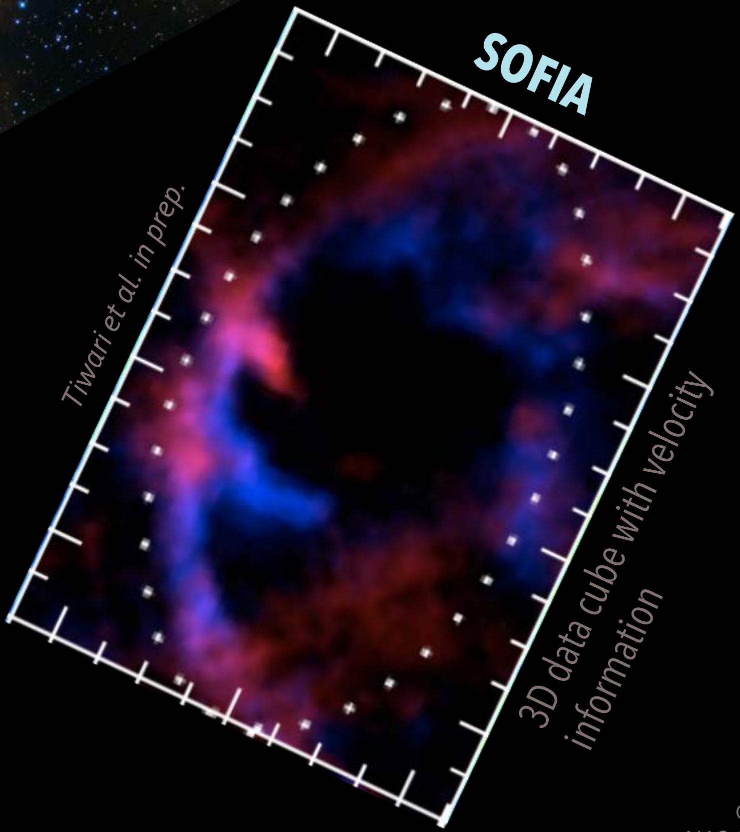
Nicola Schneider (U. Cologne)

Hubble



Spitzer

SOFIA



Tiwari et al. in prep.

3D data cube with velocity information

RCW 49
(HII region)

How do massive stars regulate star formation?

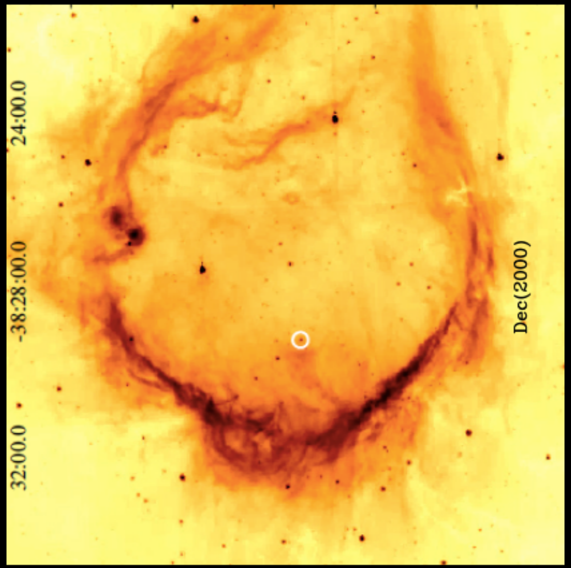
How do molecular clouds assemble and dissolve and how does this relate to star formation and nearby massive stars?

Radiative & kinematic interaction of massive stars with their environment drives the evolution of the Interstellar Medium and the evolution of galaxies.

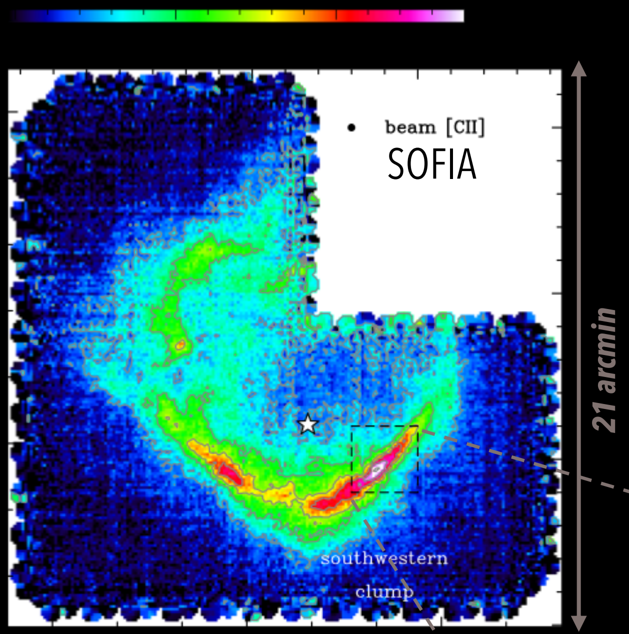
SOFIA GREAT [CII] survey of 11 regions of massive star formation to study feedback on scales of a single star, few stars, stellar groups & a mini starburst.

SOFIA FEEDBACK Legacy Program

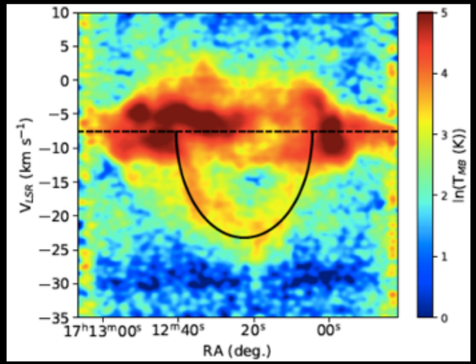
Spitzer (8 μm)



[CII] 158 μm 0 - 300 K km/s

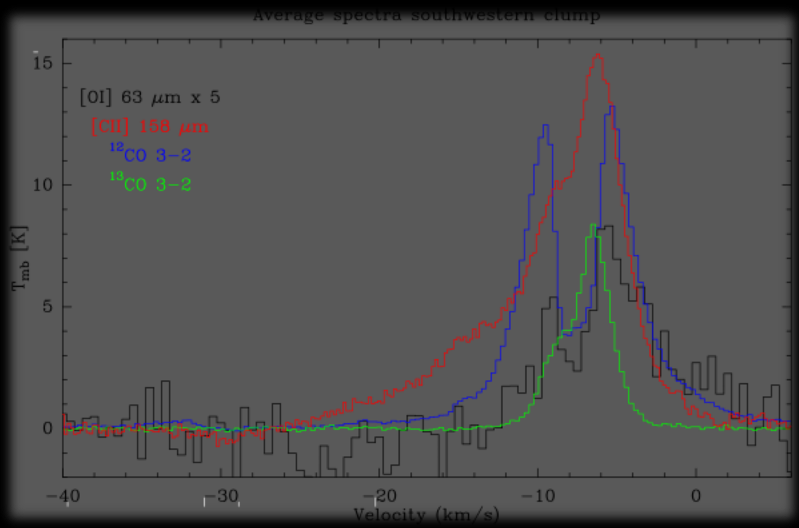


Schneider et al. (2020)



Luisi et al. 2020, in preparation

SOFIA reveals a few hundred $M_\odot$ shell expanding at ~15 km/s



Kabanovic et al. 2020, in preparation

RCW120 (emission nebula/HII region):
The stellar wind from the single O8 star (white star) has created a bubble filled with a million-degree plasma and photo-ionized gas

- [C II] spectrum has a prominent blue tail, reaching up to −30 km/s
- All tracers are showing various degrees of self absorption

SOFIA

Using [CII] as a star formation tracer: Calibrating the distant universe

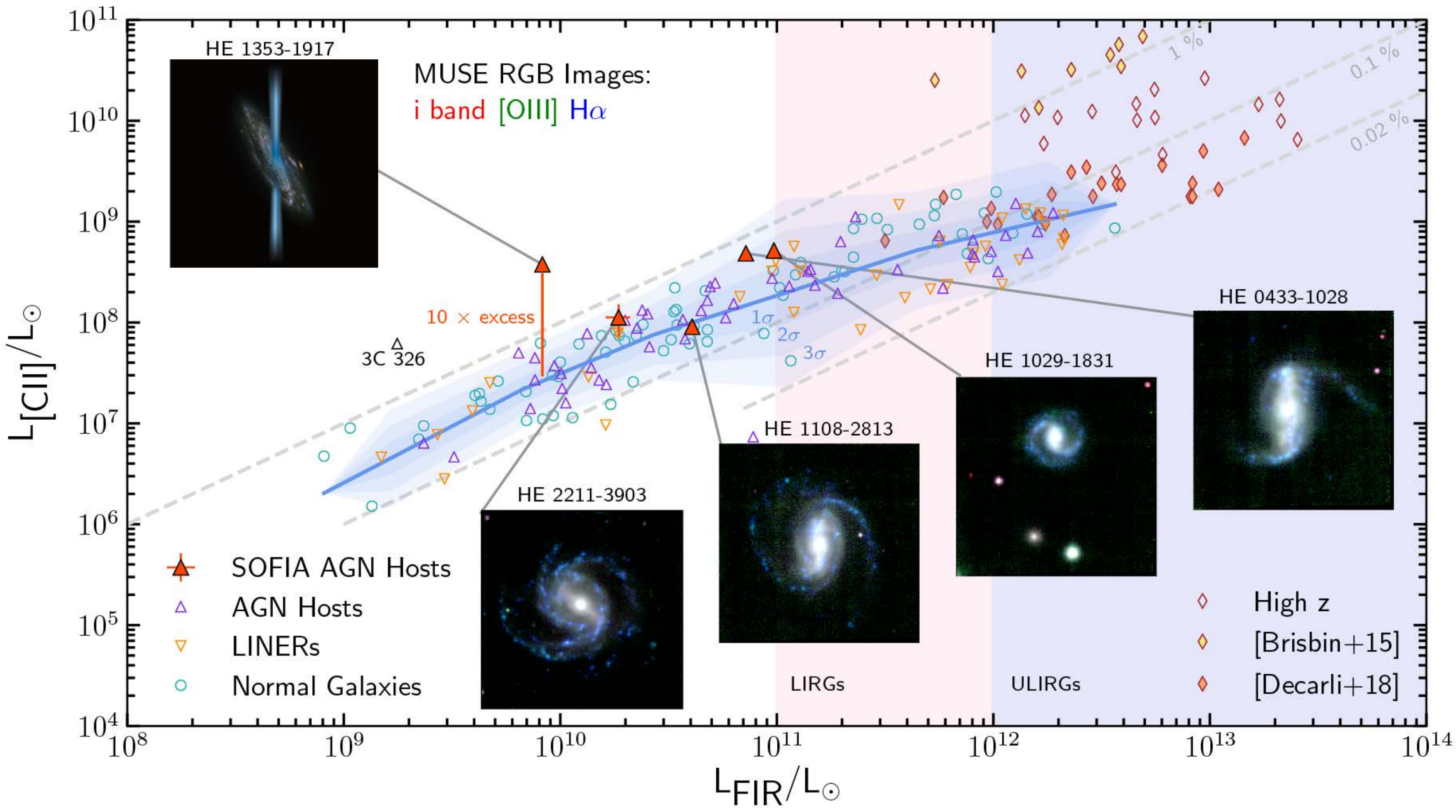
SOFIA observations of a galaxy known as HE1353-1917 revealed that [CII] emission is 10-times stronger than that observed in similar galaxies. The excess is from AGN ionization cone and radio jet directly intercept the cold galactic disk

Background

- [C II] 158 micron line is one of the brightest emission lines in the far-infrared; 0.1–0.3% to the FIR.

- The [C II] line is used as a star-formation indicator and is heavily used to estimate star formation rates formation at high-z

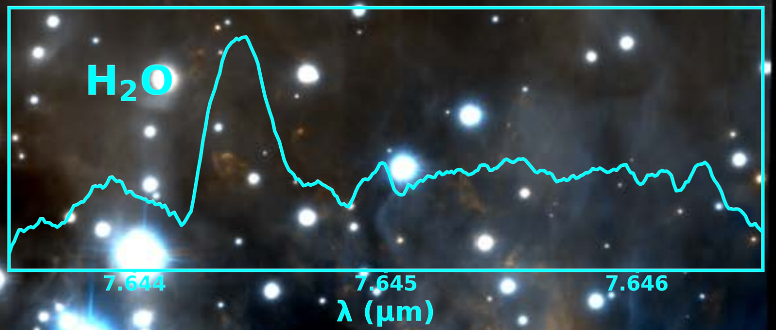
- Active galactic nuclei (AGN) can also affect the [CII] emission in several ways

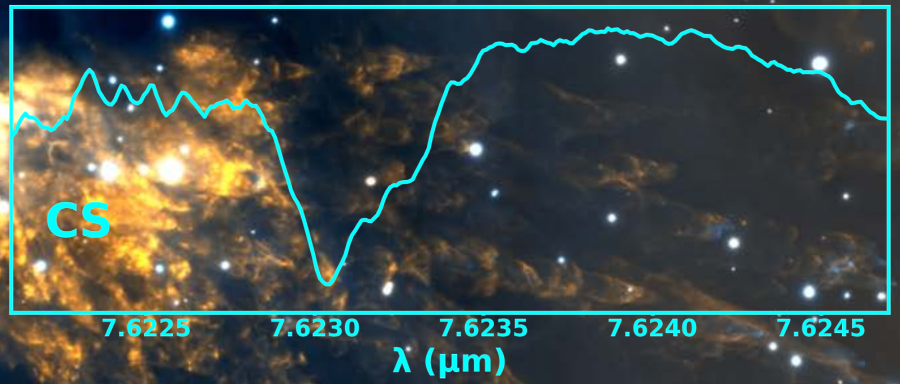


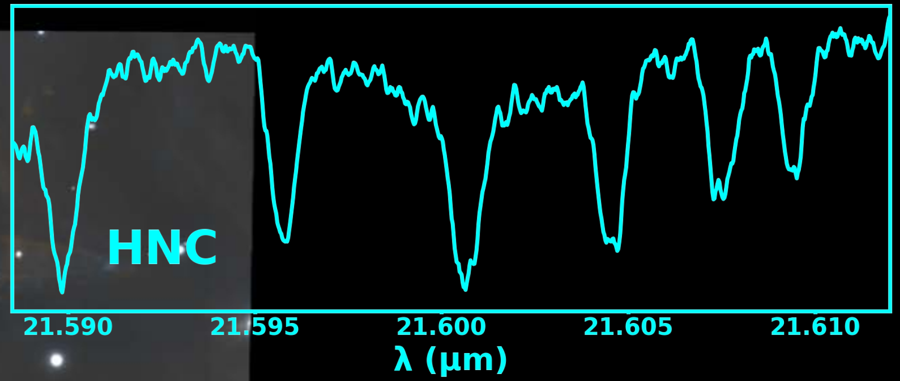
Irina Smirnova-Pinchukova
(PhD Student, MPIA)

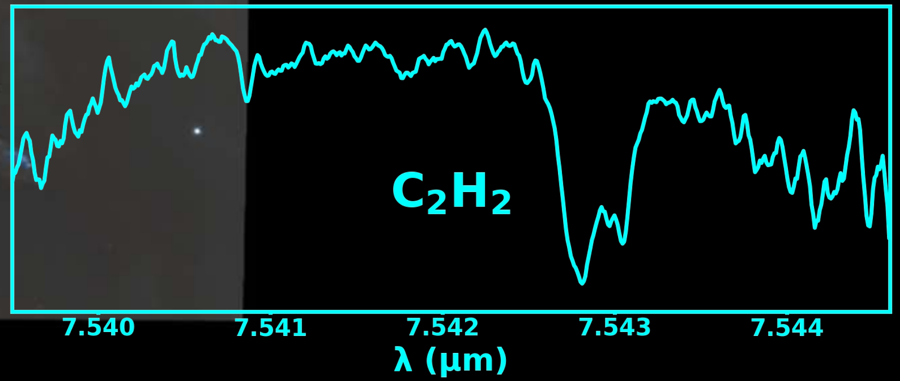
Towards Creating a Mid-Infrared Spectral Line Database

- What is the relationship between the molecules we see in the interstellar medium and the molecular inventory of Earth and other terrestrial planets?
- SOFIA is building high-resolution spectral inventory of molecular transitions in the mid-infrared (5-28 microns) for a sample of massive protostars that cannot be done any other way. Two line surveys are ongoing by PI Tielens and PI Rangwala.
- These data will serve as an essential reference for JWST MIRI lower resolution observations by providing inventory of bright transitions









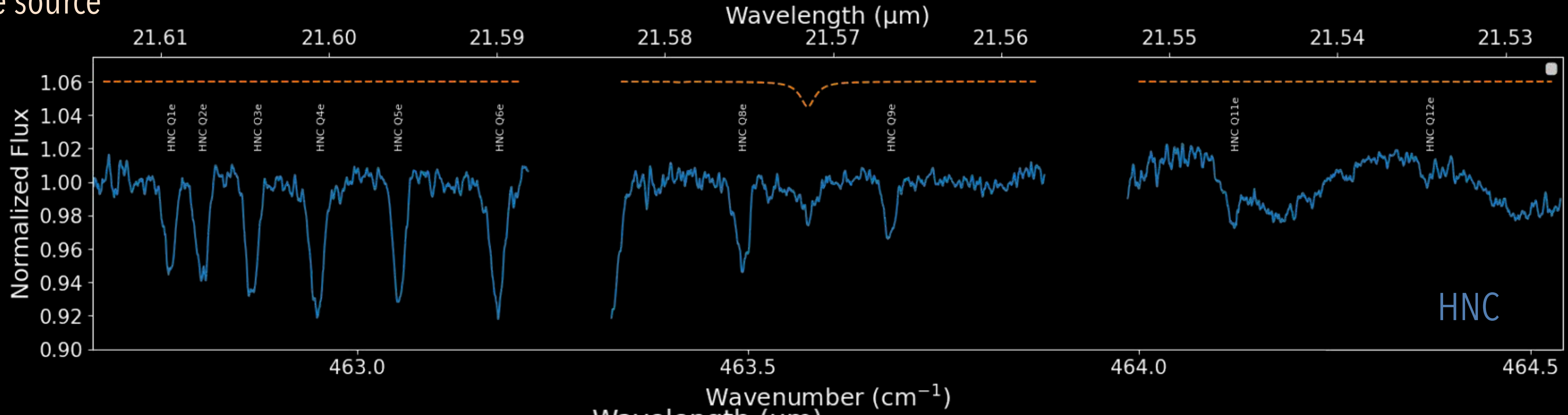
Explosion in the Orion BN-KL region 500 yrs ago

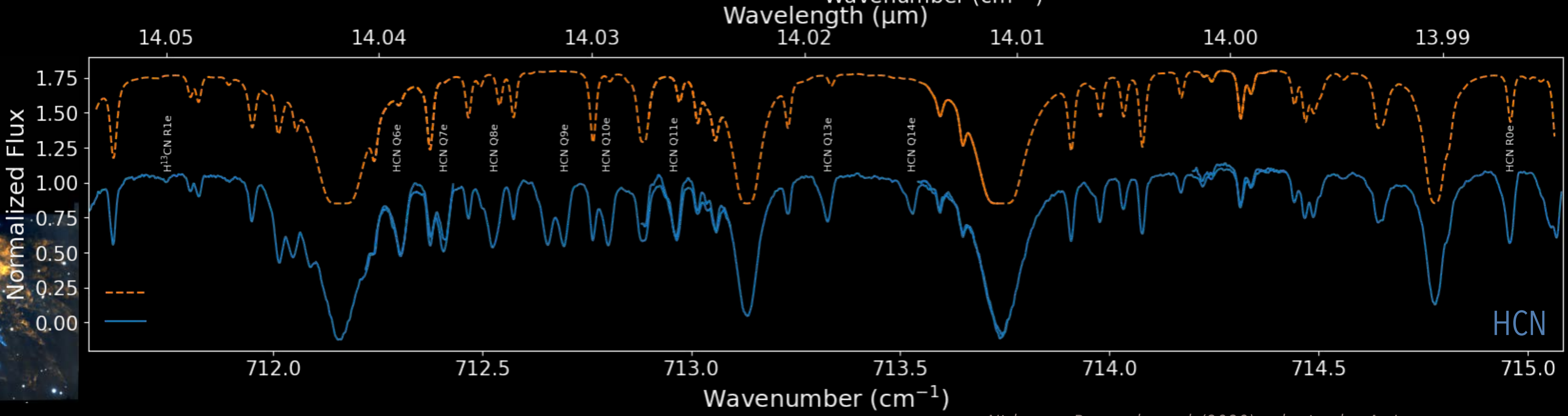
Left to right: Sarah Nickerson (Postdoc/Ames), Jose Monzon (Student/NASA intern), Naseem Rangwala (PI/Ames)

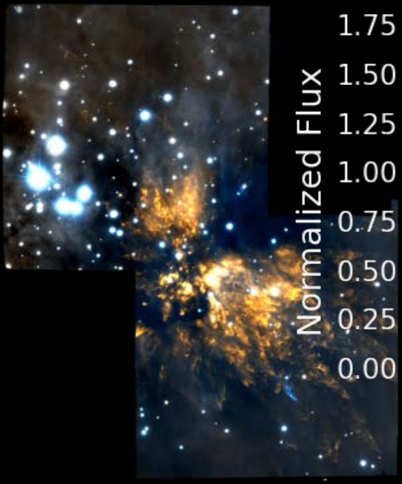
~300 unique spectral features measured towards the Orion hot core

New Chemical Fingerprints in the Vicinity of the Orion Hot Core

- First Mid-Infrared detection of HNC including isotopes
- Detect two distinct velocity component one of which is hottest measured HCN (> 300K) to date towards IRc2 and closest to the source
- MIR transitions are excellent at probing the physical conditions and chemistry closest to the infant massive star.

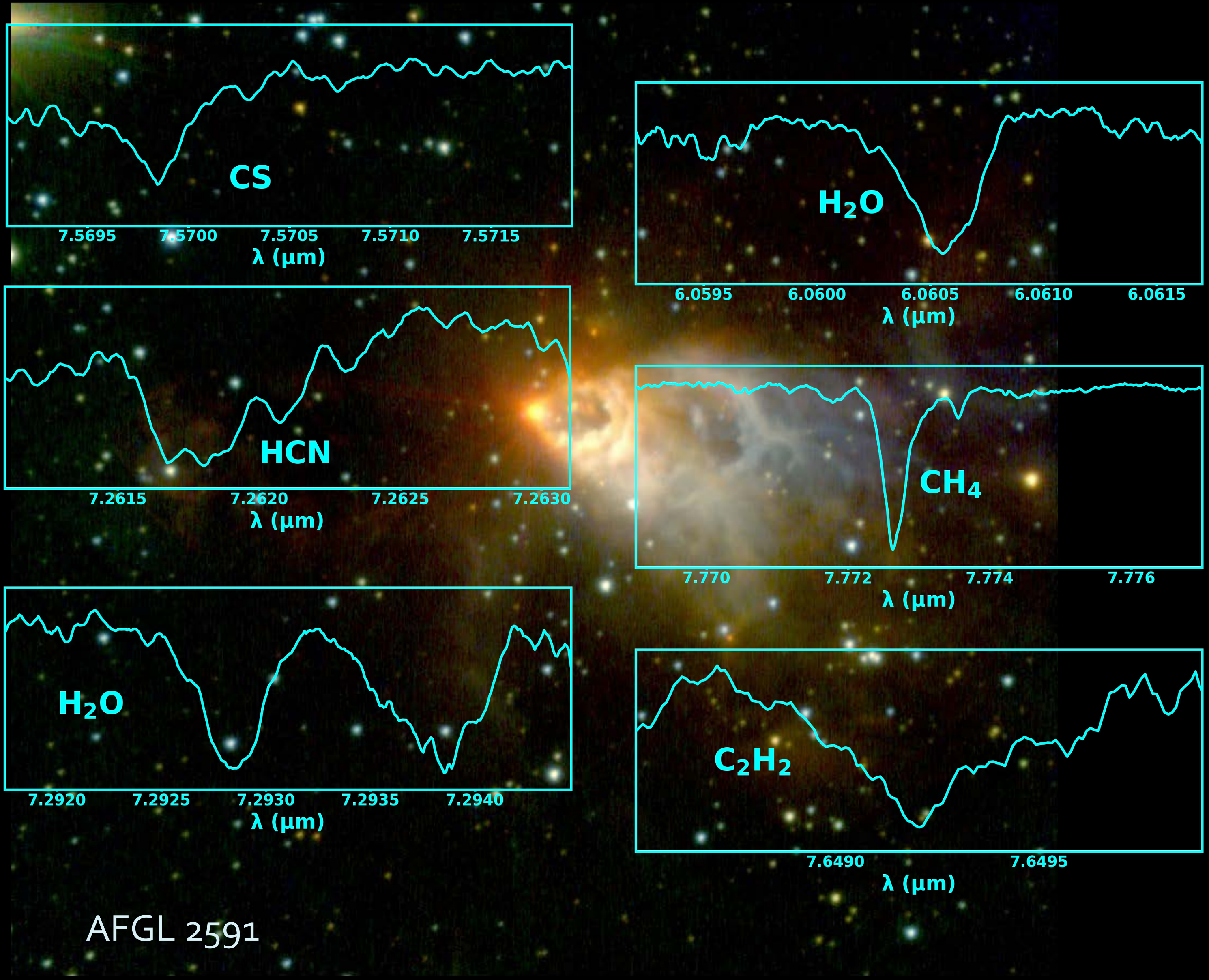






Nickerson, Rangwala, et al. (2020), submitted to ApJ

Massive Stars are Factories for Ingredients to Life



- Numerous molecular (water, organics) species were detected in their rovibrational transitions.
- The IR absorption lines probe high- temperature gas of the order of 600 K (versus 50K in submm).
- Line profiles show differences in line width and peak velocity when compared to the surrounding envelope, which is traced by sub-mm emission lines.
- IR absorption lines are broader and offset by several km/s with respect to sub-mm lines seen by single-dish telescopes.

Andrew Barr
(PhD Student, Leiden University)

Barr et al. 2020. ApJ
Credit: Sarah Nickerson

Exoplanet Collision: SOFIA find unusually warm dust signature

- BD +20 307 is an older planetary system (1 billion years old) that is not expected to have warm dust
- Decade ago Spitzer found a sigatures of warm debris hinting at a collision event
- Decade later SOFIA found 10% (+/- 2%) increase in the infrared brightness indicating there is now even more warm dust (Thompson et al 2019).
- To increase the IR brightness in just 10 yrs further supports recent collision between two rocky planets may have occurred
- Follow up observations are being analyzed

Maggie Thompson
PhD student, UC Santa Cruz

It is believed that a similar catastrophic collision between a Mars-sized body and the Earth 4.5 billion years ago created debris that eventually formed the Moon.

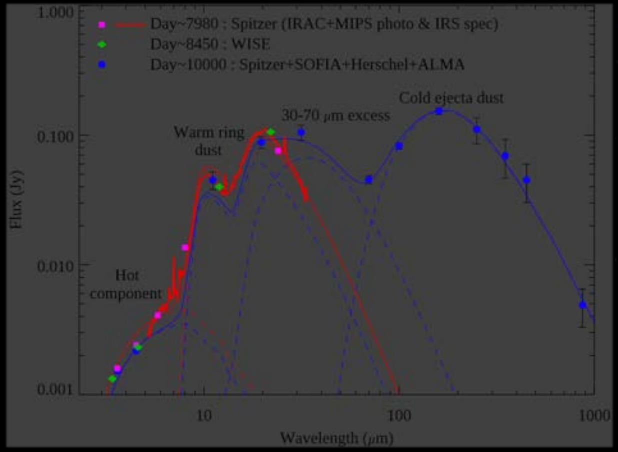
Artist's concept illustrating a catastrophic collision between two rocky exoplanets in the planetary system BD +20 307, turning both into dusty debris

Credit: NASA/SOFIA/Lynete Cook

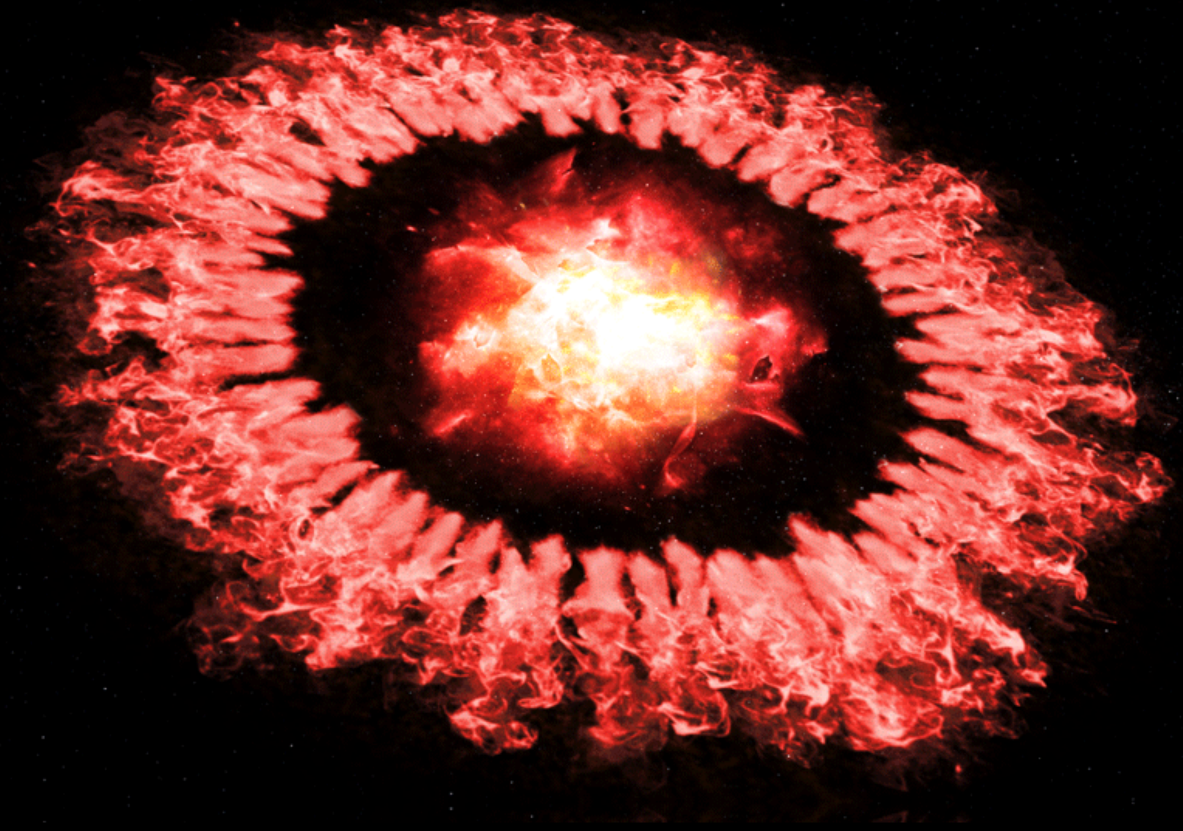
Dust Survives Obliteration in Supernova 1987 A

- SOFIA detects excess flux at 31.5 μm, significantly higher than Spitzer 10 yrs earlier and appears to be related to the Herschel 70 μm excess, which was detected 5 years earlier.
- The dust mass needed to account for this excess is ten times larger than the ring dust mass estimate from the data10-years earlier.
- Dust grains are re-formed or grown in the post-shock regions in the ring after forward shocks have destroyed pre-existing dust

Mikako Matsuura
Cardiff University



Matsuura et al. (2019)



Artist's concept illustrating Supernova 1987A as the powerful blast wave passes through its outer ring and destroys most of its dust, before the dust re-forms or grows rapidly.

SOFIA is Community's Observatory

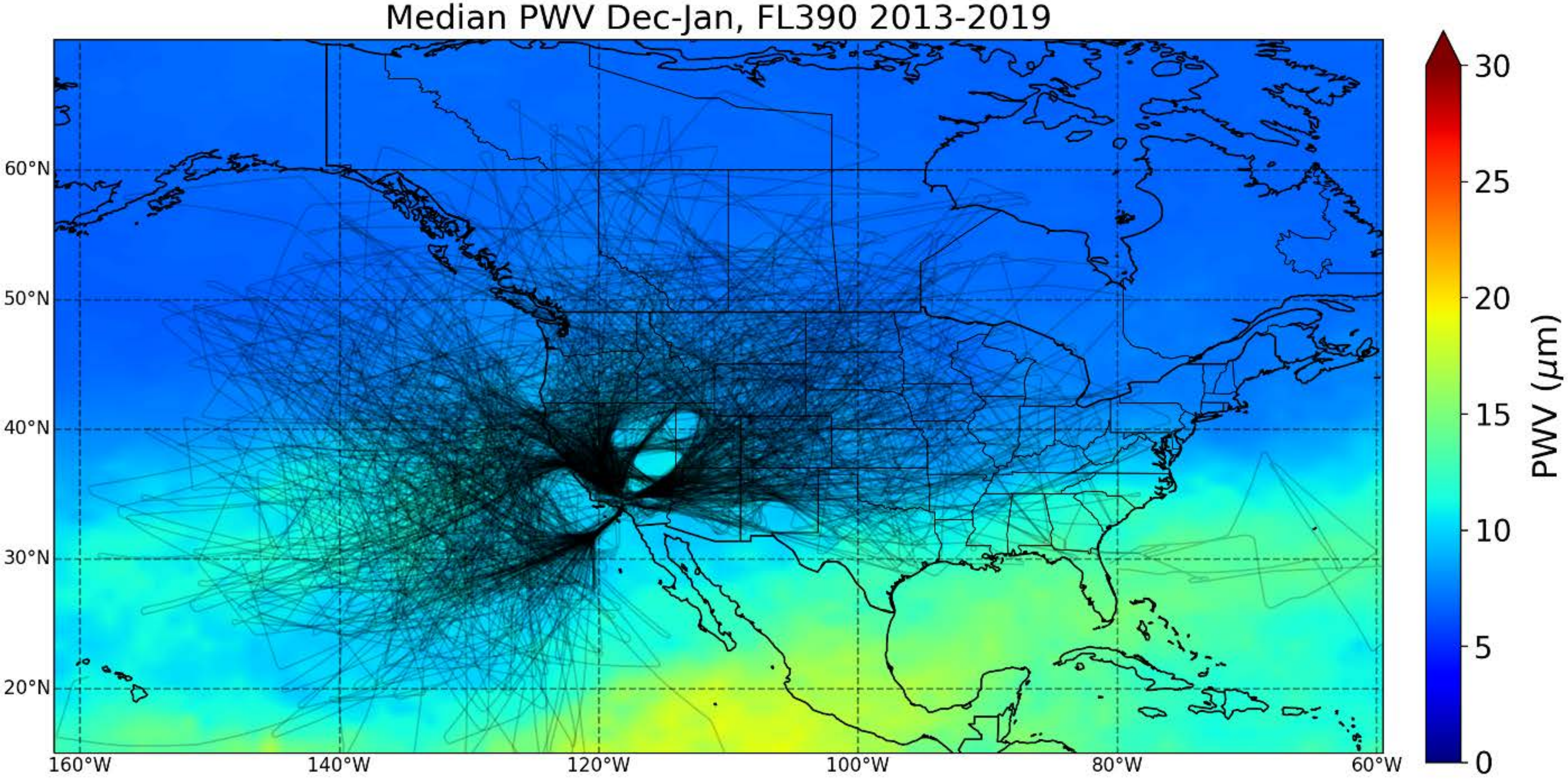
- SOFIA solicits new ideas & proposals from the community every year. Cycle-9 call recently closed.
- Best proposals are selected through a competitive peer-review process.
- These proposals are observed by SOFIA, and the principal investigator of the proposing team is invited to fly on SOFIA.
- Proposing teams are funded by NASA to carry out their research and publish results. Graduate students, interns & postdocs are often part of these teams and can be funded to work on SOFIA data.

Professor Emily Levesque
(University of Washington)
On board SOFIA during the 2019 Southern Hemisphere Deployment.

Spectacular Aurora over Antarctica was captured by an atmospheric scientist on SOFIA during the 2019 Southern Hemisphere deployment. These Auroral data also are being used for research.

SOFIA Water Vapor Estimates and Forecasting from NASA GEOS Weather Database

Flight Level 39,000 feet



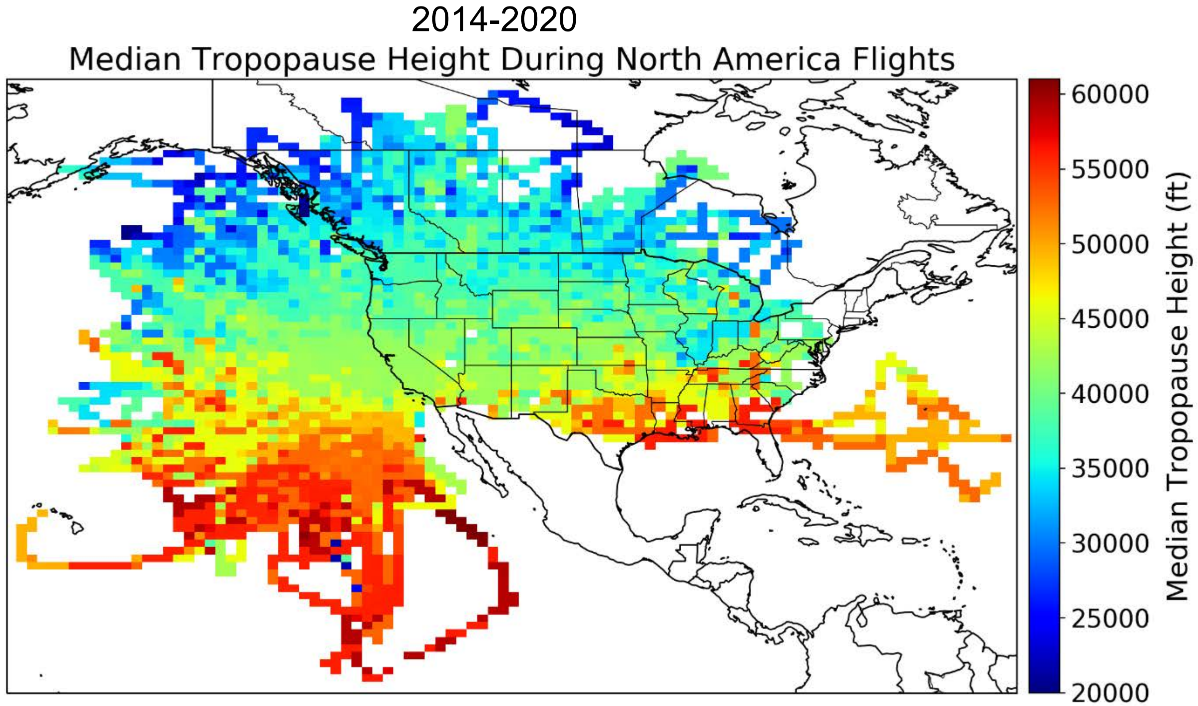
Precipitable Water Vapor

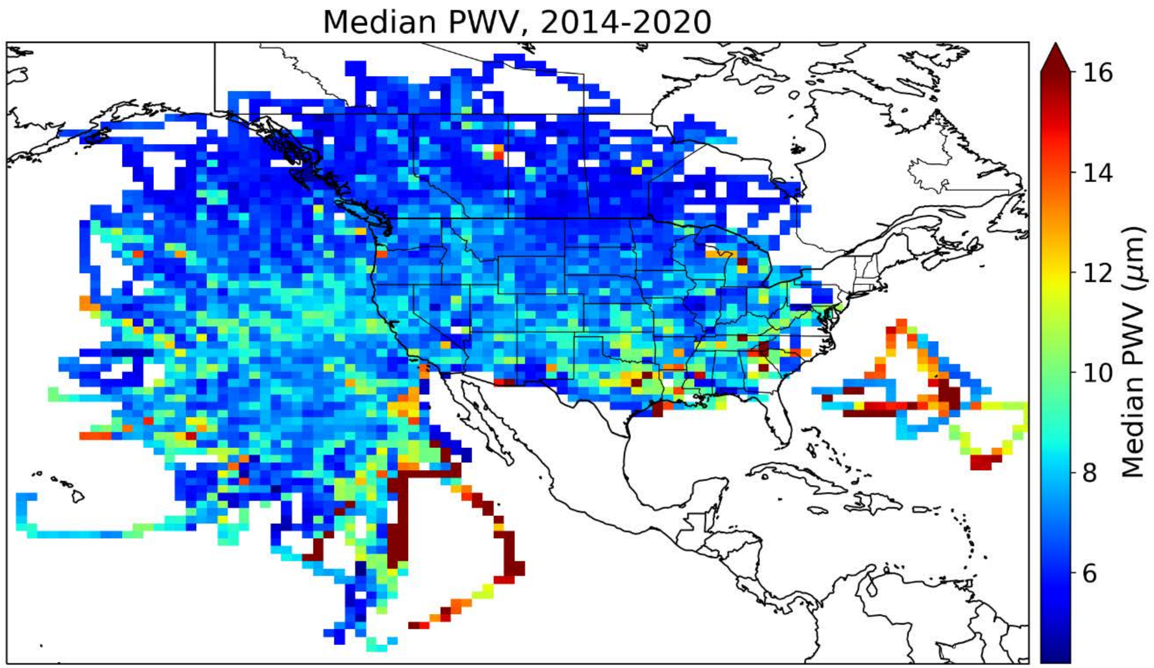
All SOFIA North American Flight Paths since 2013

Comparing Stratospheric Heights with Zenith Water Vapor

- Water vapor is the key parameter in determining observing conditions
- Water vapor can vary with weather and location

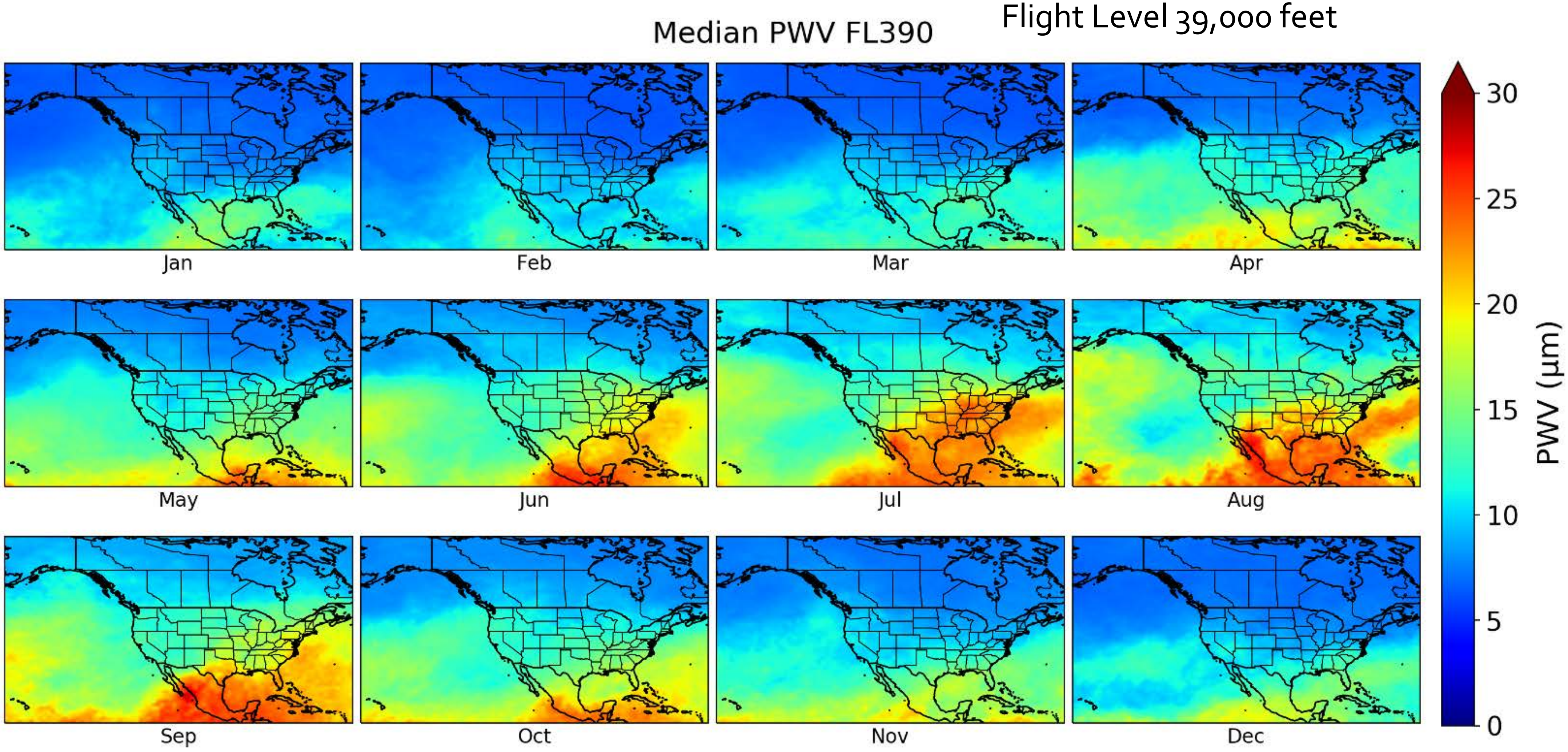
Water vapor map shows that zenith water vapor is low even when SOFIA is not in the Stratosphere



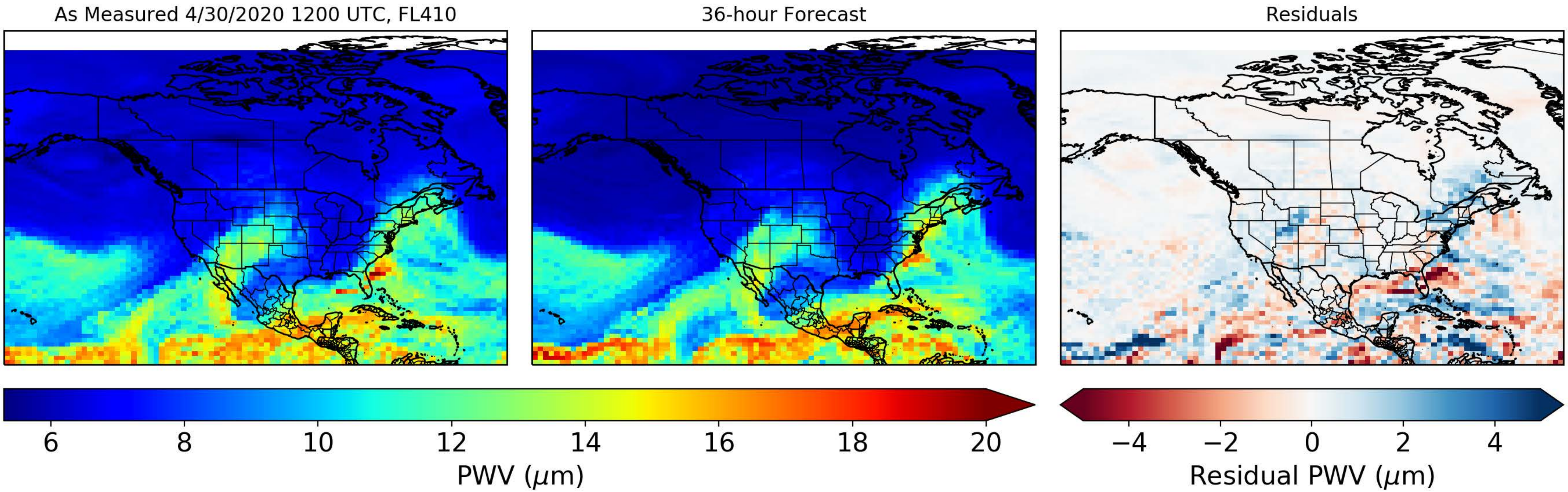


Water Vapor Seasonal Variations

Flight Level 39,000 feet



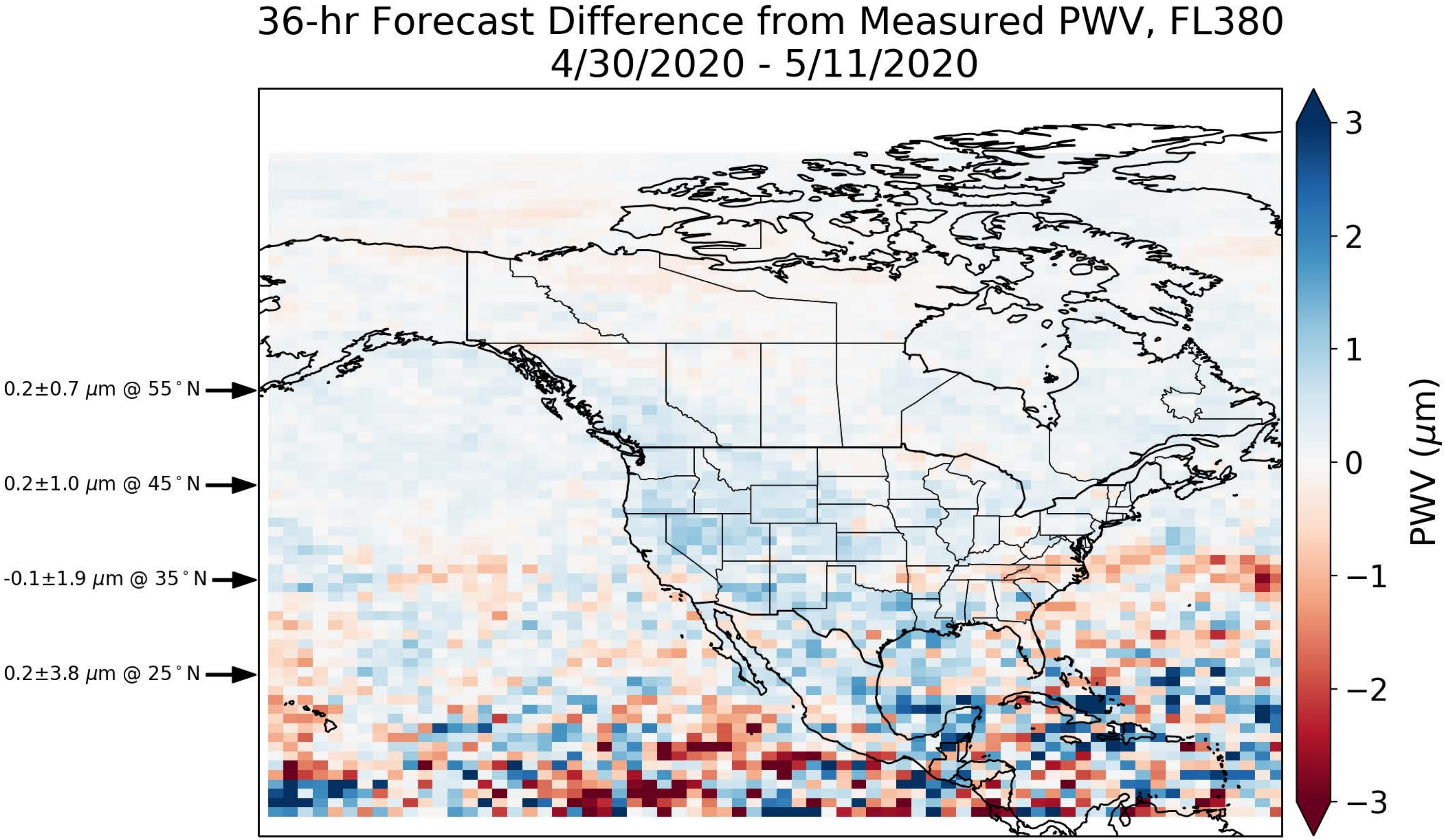
Water Vapor Forecast Analysis



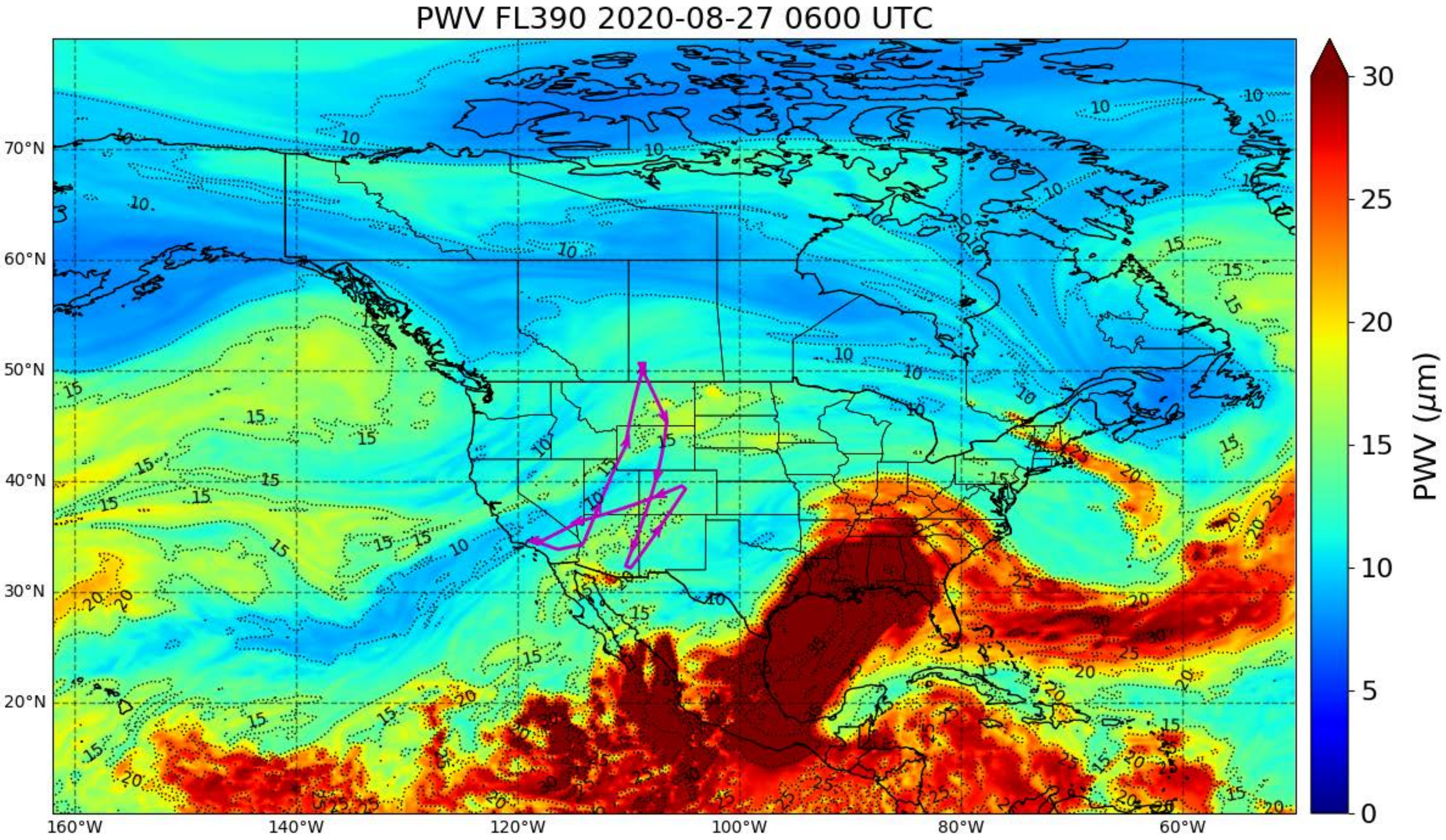
36-hour weather forecast before the mission from NASA GEOS is very accurate

- Can be used to fine tune or change flight/observing plan to preserve the quality of observations

Water Vapor Forecast Analysis

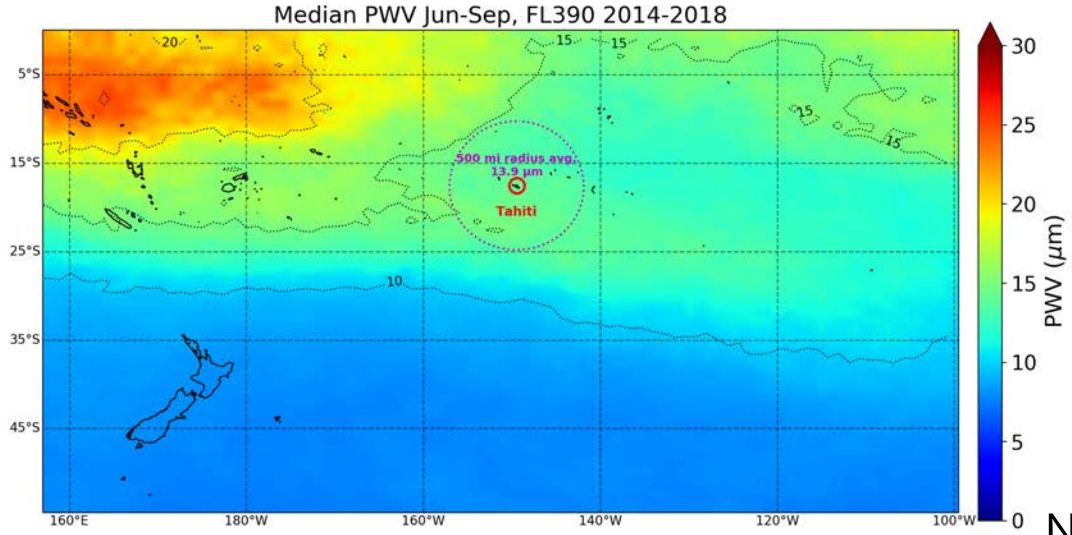


Recent SOFIA flight and Water Vapor Forecasting

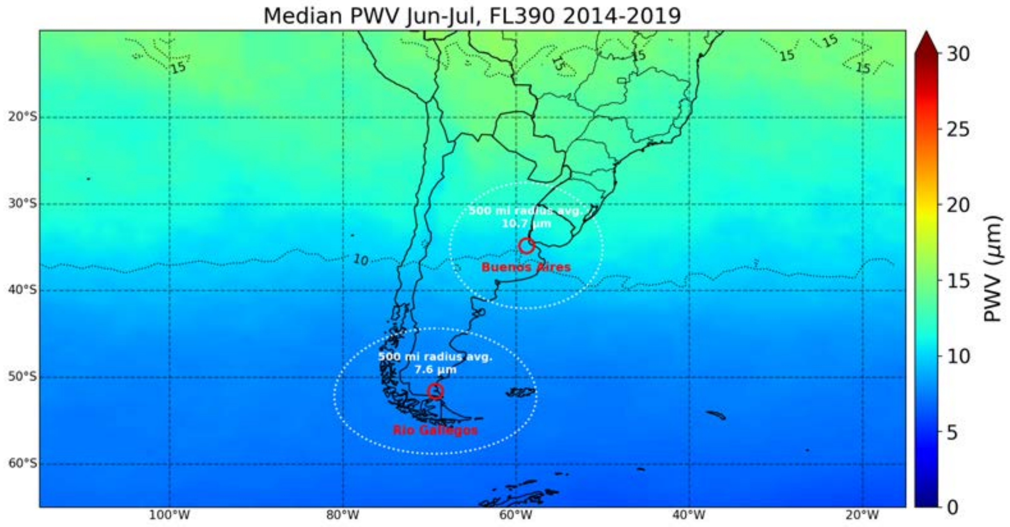


Water Vapor Forecasting at any Site in the World

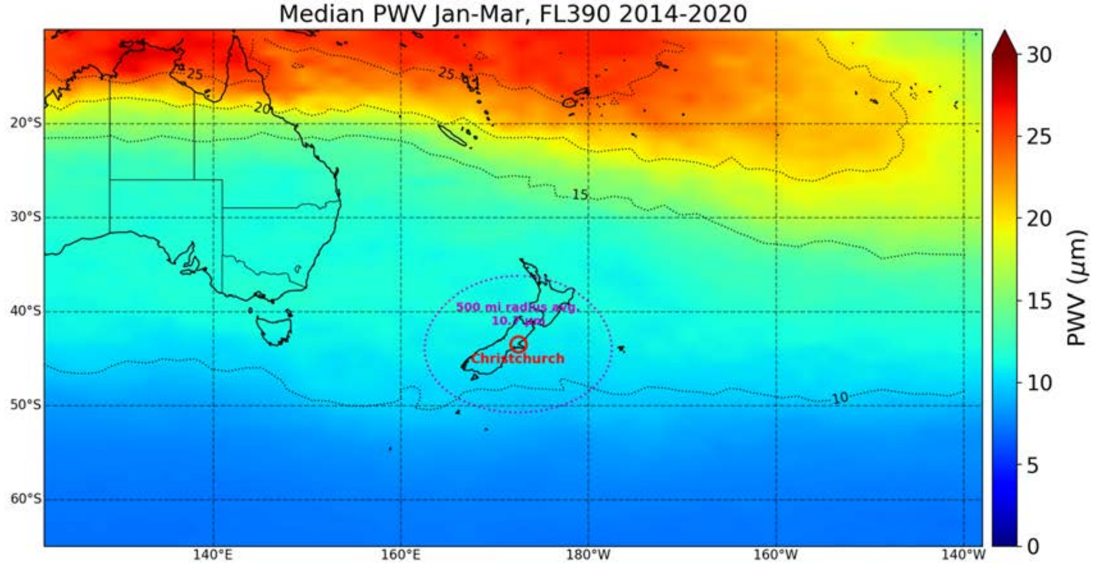
Tahiti (French Polynesia)



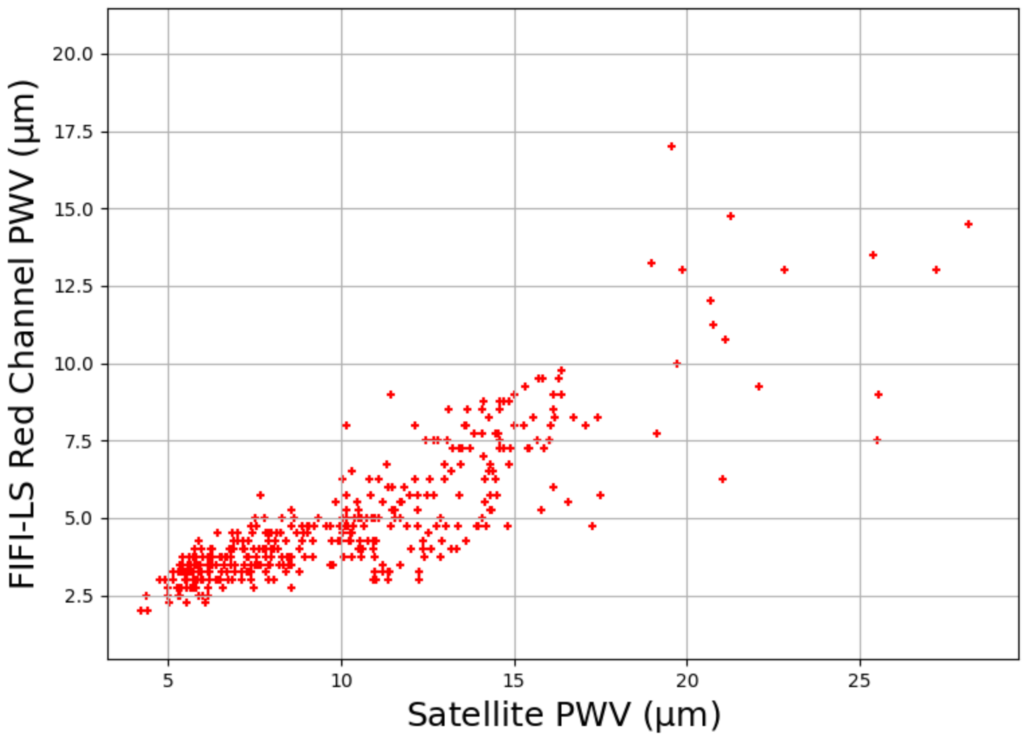
Argentina

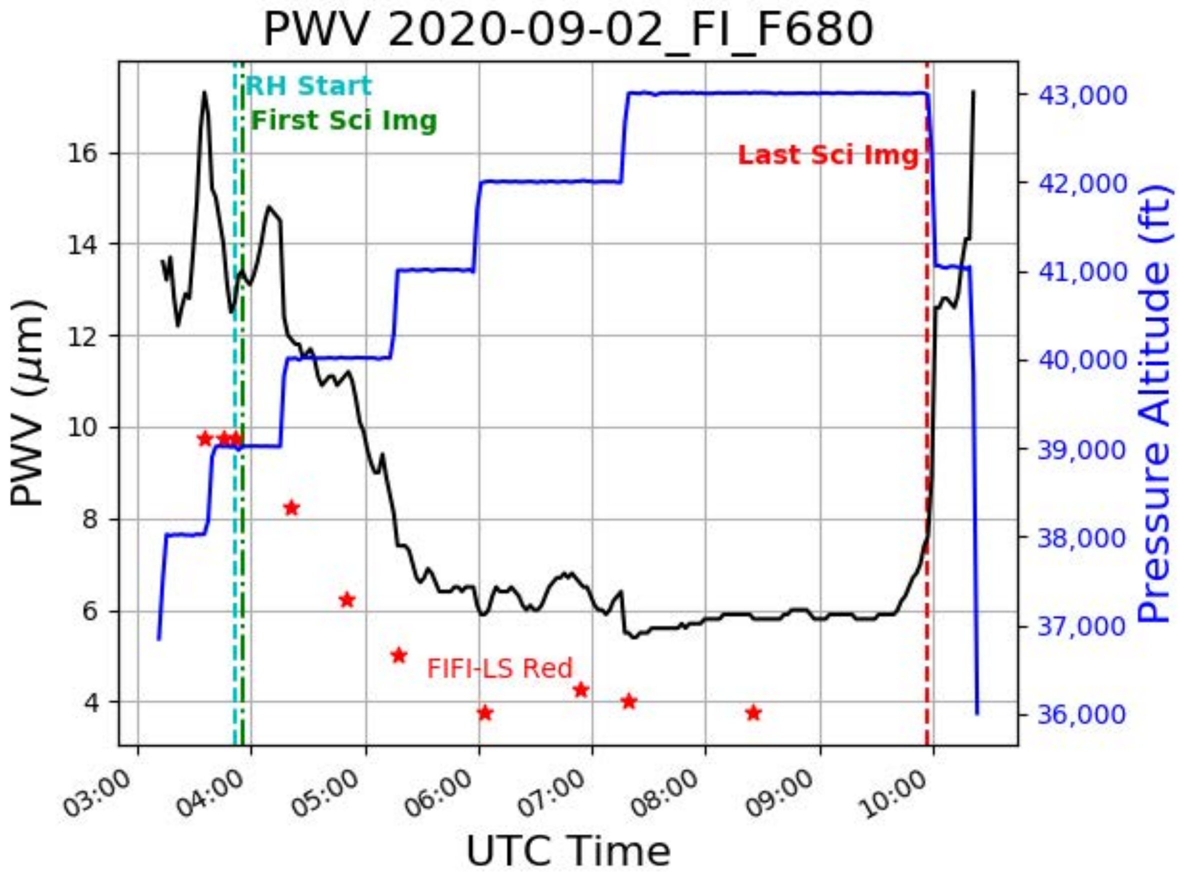


New Zealand



Comparing NASA GEOS Water Vapor to SOFIA instruments





Discoveries are made possible by a multi-disciplinary and talented SOFIA team

(Pre-COVID photos)

Mission Director

Safety Technicians

Telescope Operators

Mission Briefing before take-off

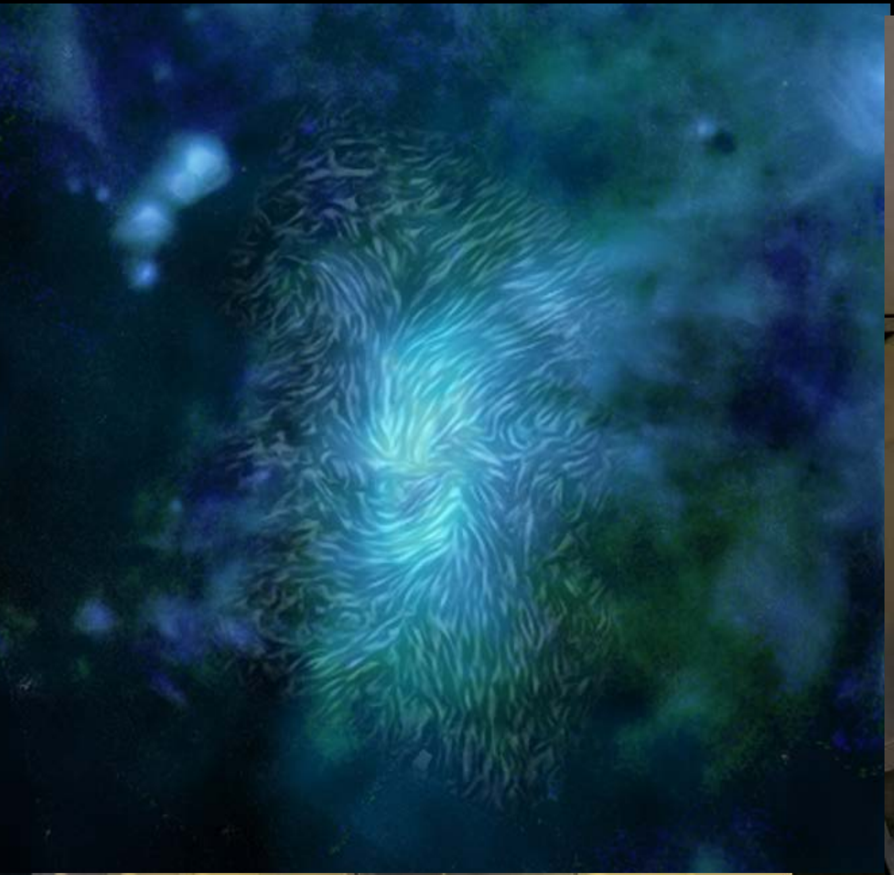
Airborne Ambassadors / Teachers

SOFIA

Instrument Scientists/Operators

Mission Directors/ Guest Observers

SOFIA: Operating Under COVID-19 Protocols



In-Flight Science Mission Execution & Data Acquisition

SOFIA

Mission Briefing

“Great aurora northeast of us as we fly through Saskatchewan.”

SOFIA Flash Report
Date: 2020-09-12 UT

SOFIA


HELIUM

In Flight on SOFIA

"The pilots were able to get us up to 44,000 ft and then 45,000 ft on the last two legs of the flight – so that helped out quite a bit."

SOFIA Flash Report
Date: 2020-09-11 UT

SOFIA

Successfully Resumed Science Operations on August 17th

SOFIA Flight Paths

Image depicts paths of science flights since August 17