SOFIA Instrument Planning

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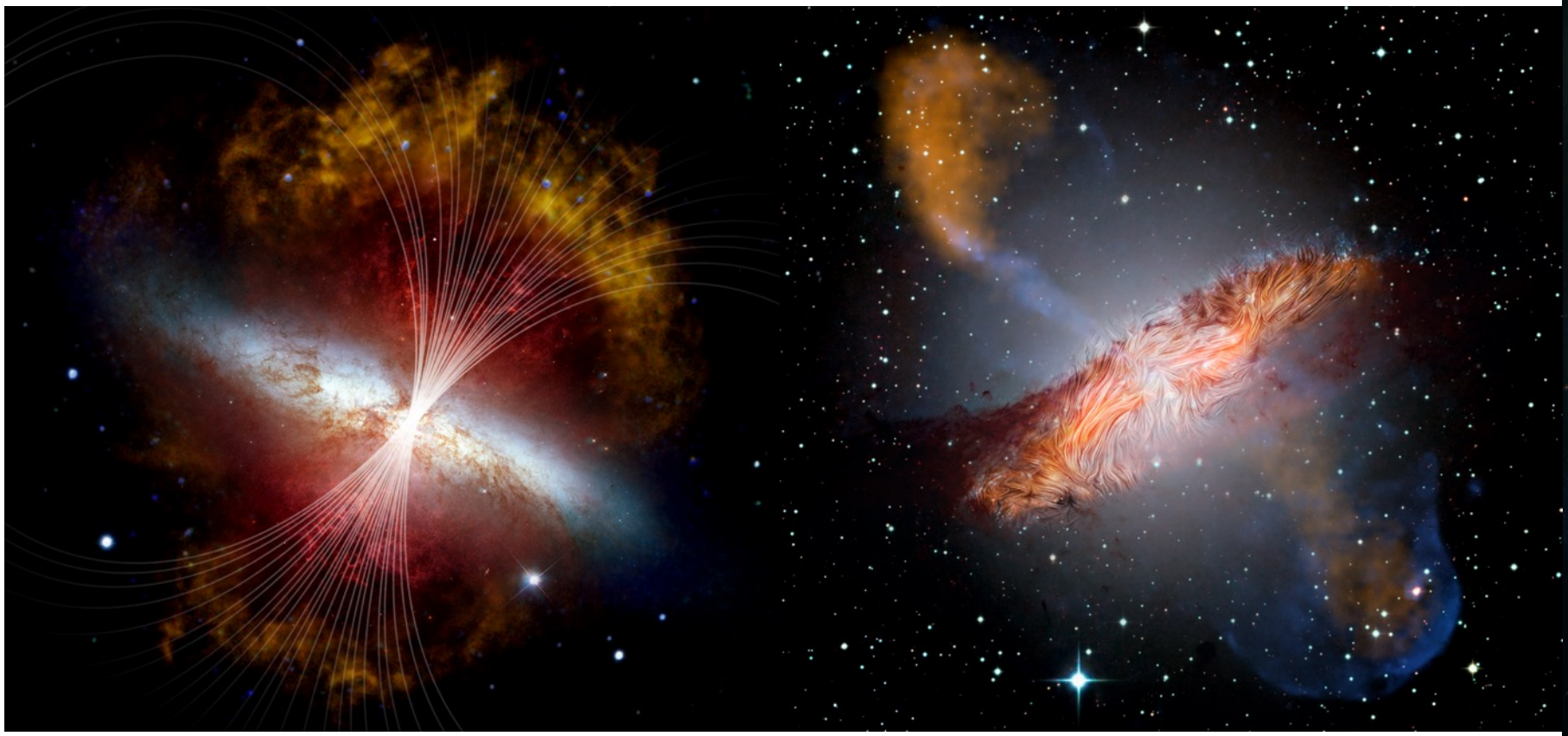
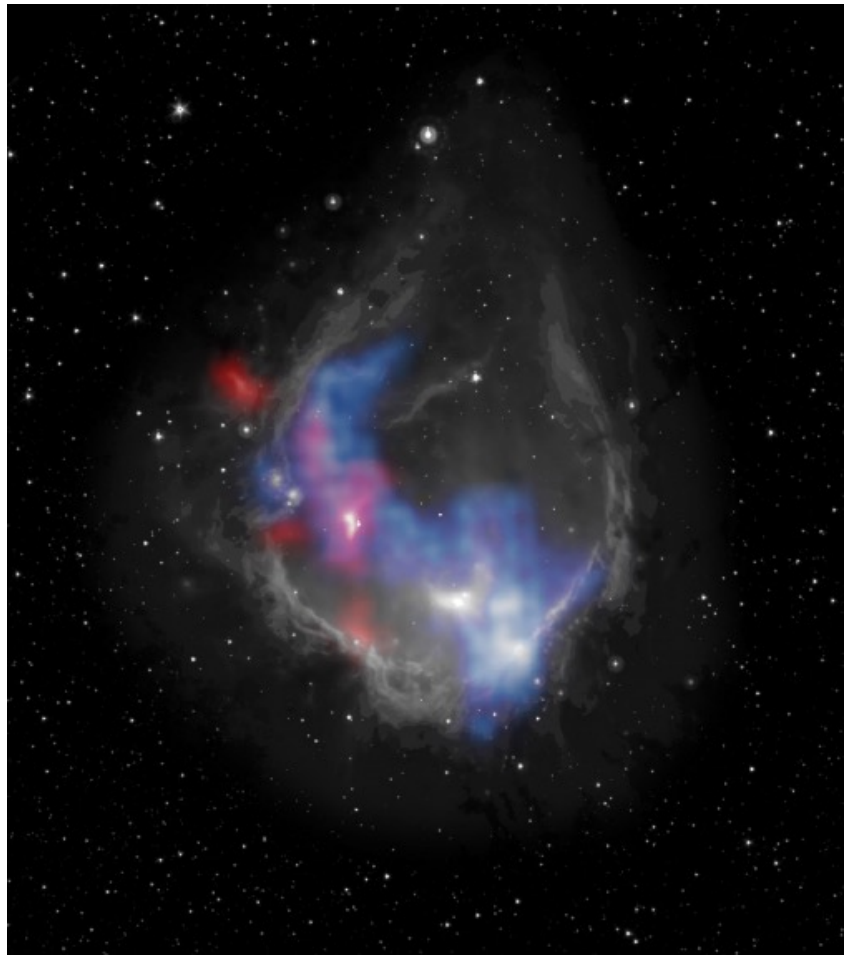
SOFIA Tele-Talk

HAWC+: Legacy: Magnetic Fields of Galaxies

PI: Lopez-Rodriguez, full legacy in progress

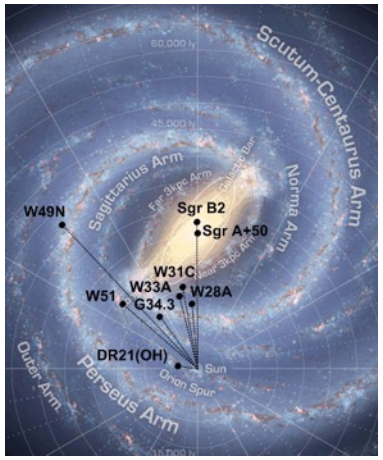


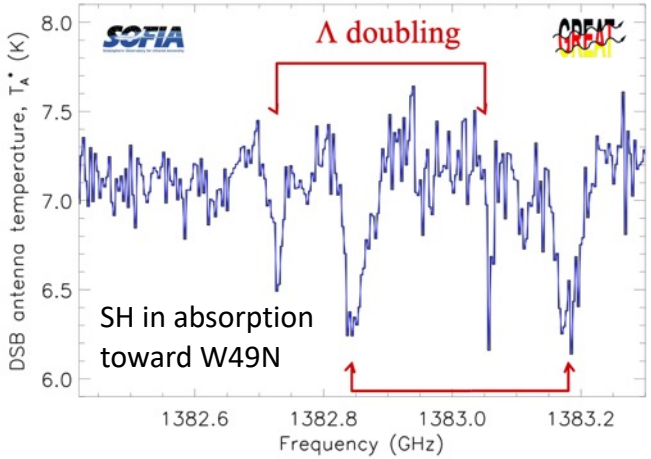
GREAT: [CII] Measuring Stellar Feedback



- Result from FEEDBACK Legacy Program, Pis: Tielens & Schneider
- RCW120, [CII] emission superposed on Spitzer image of expanding bubble (Luisi et a. 2021)
- Expansion speed of [CII] indicates a younger age for nebula
- indicates that triggered star formation happens on shorter timescale. <0.15 Myr

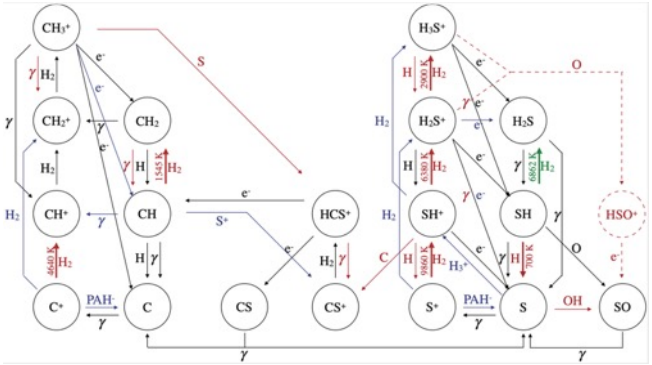
GREAT: Legacy, HyGAL: Characterizing the Galactic ISM with observations of hydrides, PI: Neufeld, started

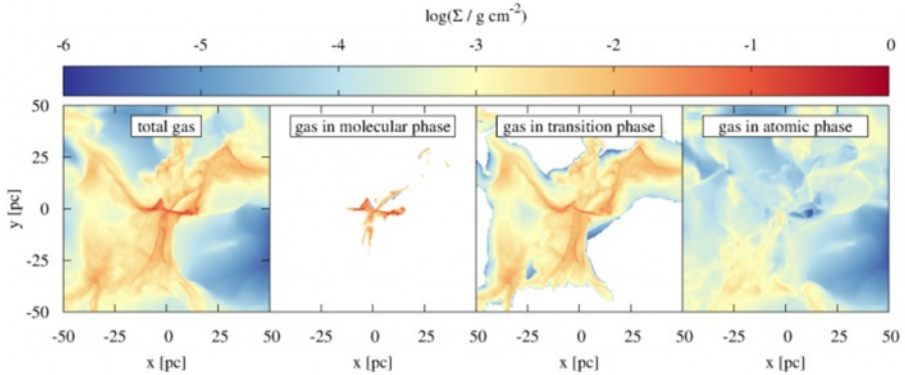




Absorption line spectroscopy ……. of multiple hydride molecules

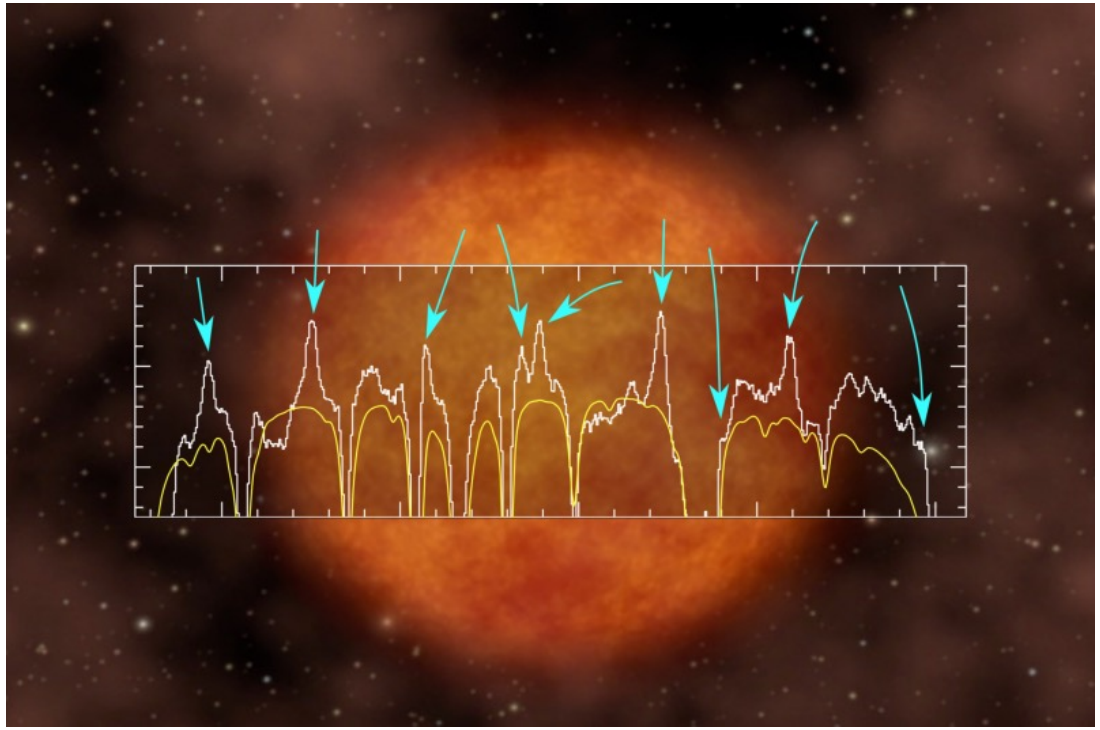
to constrain astrochemical models ……. of the turbulent interstellar medium

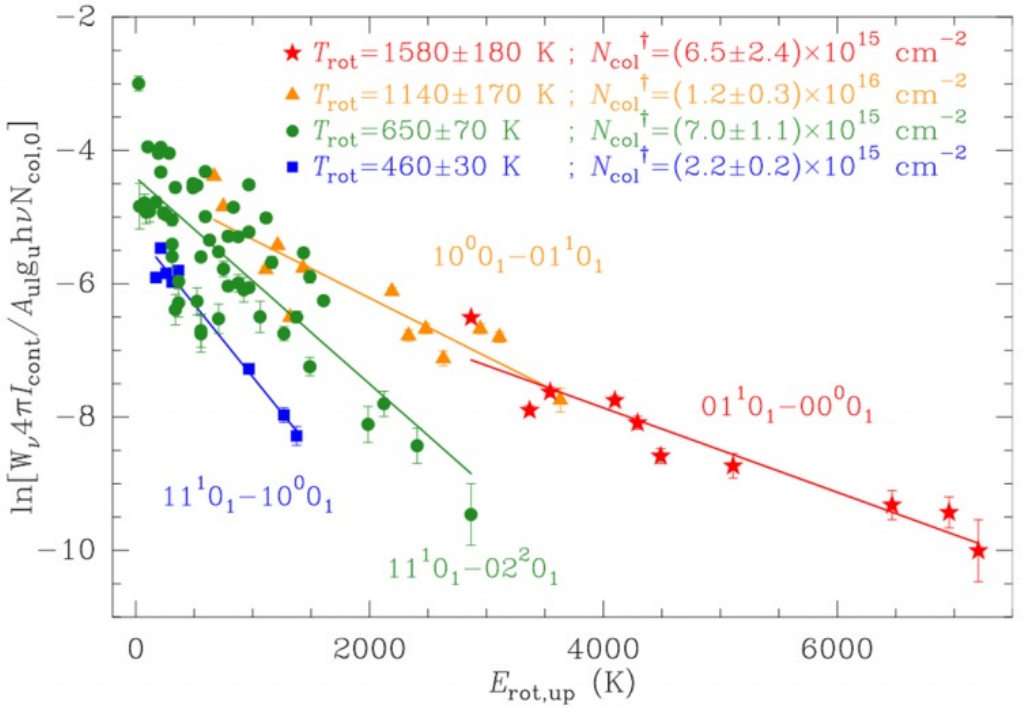




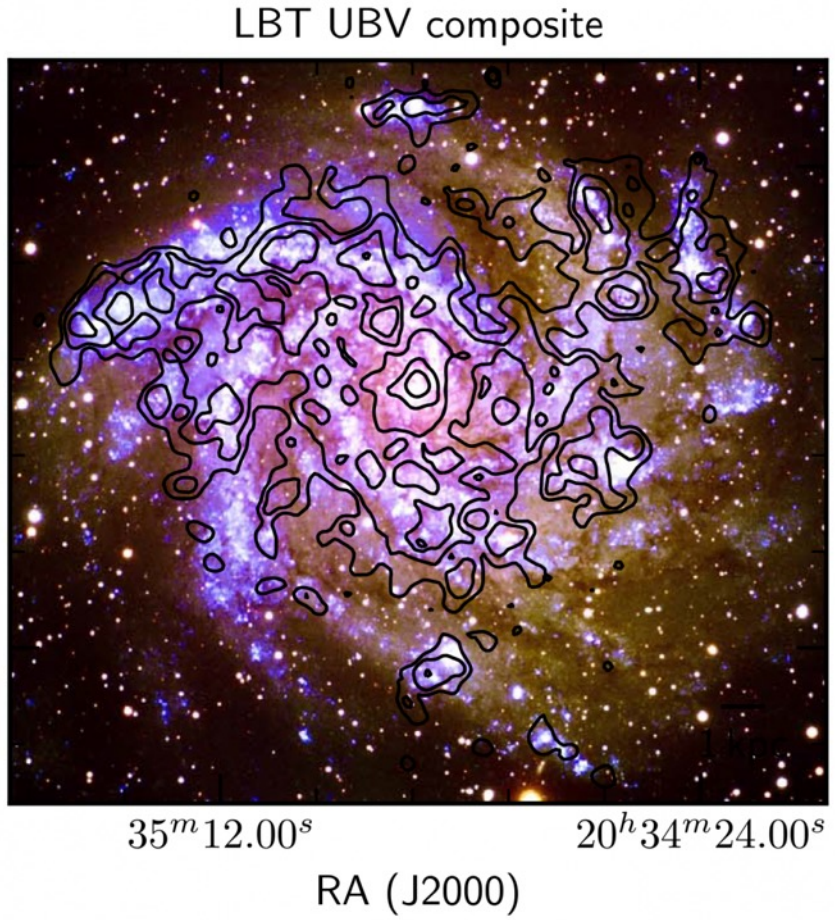
EXES: Carbon Dioxide in R Leonis

Fonfria et al. 2020, Detection and analysis of 240 individual lines of CO_2, analysis shows 3 regions with temperatures of 550, 1150 and 1600K



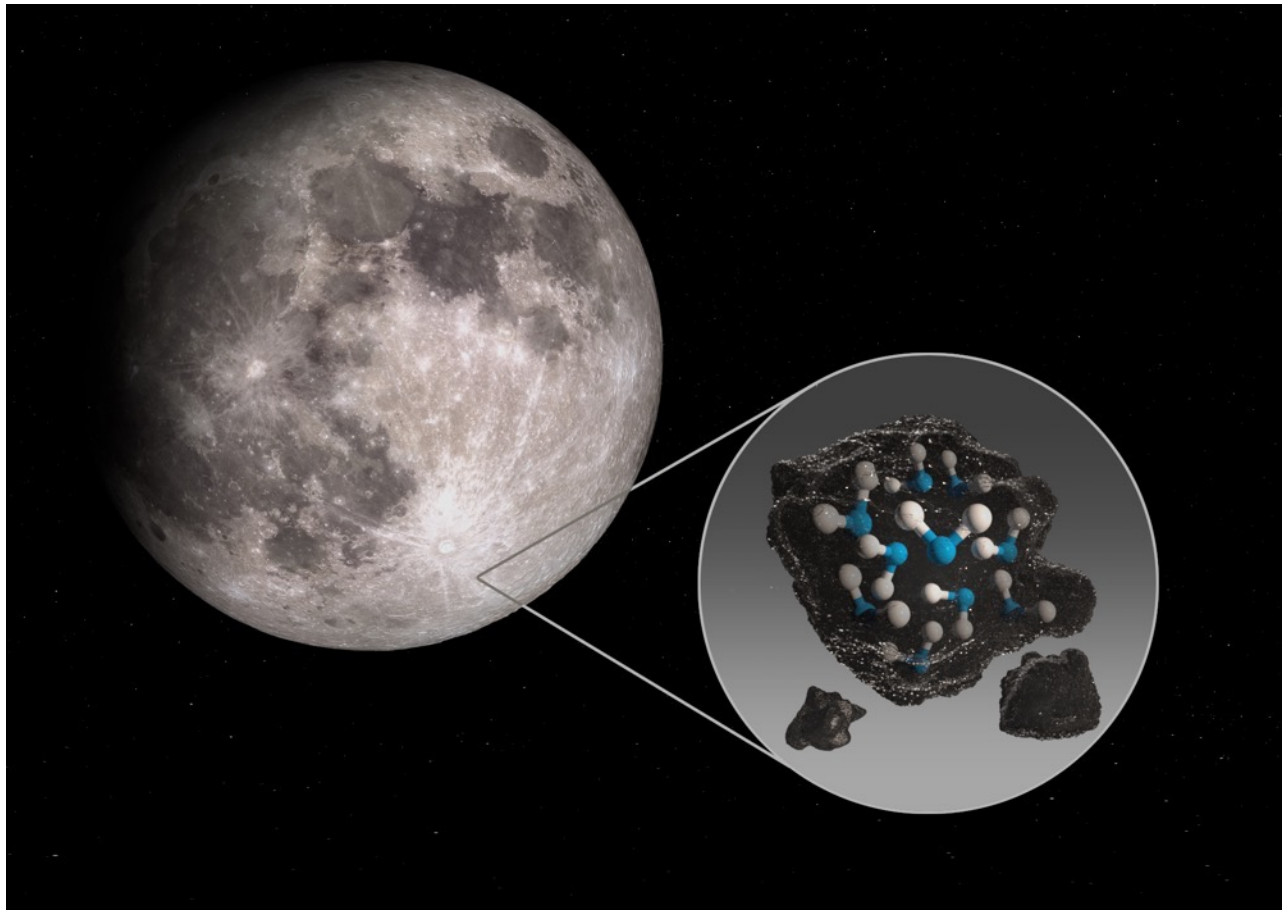


FIFI-LS: Star Formation



- [CII] 158 micron line is the dominant cooling line of Photodissociation regions surrounding newly formed stars
  -samples stellar feedback
- Up to 2% of a galaxy's light is emitted in the [CII] line
- Fireworks galaxy, NGC 6946 (Bigiel et al. 2020) at left, shows excellent correlation between [CII] and star formation
- Is [CII] a Universal Star Formation Tracer?
- ~20 nearby galaxies being investigated through GO in [CII] and other far-IR lines
- LMC+, pilot legacy for LMC+ south molecular ridge, PI: Madden

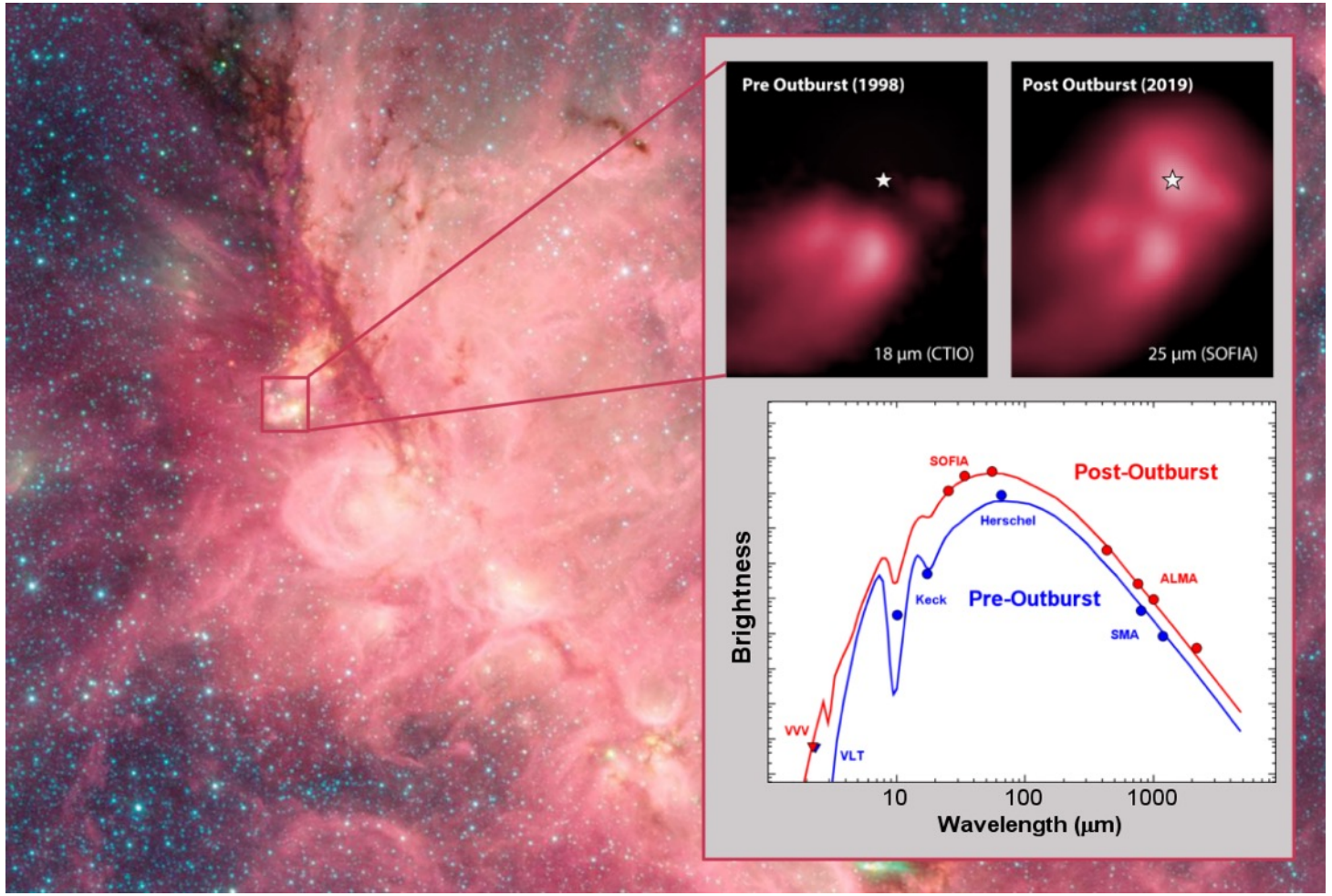
FORCAST: Water on the Moon



- SOFIA/FORCAST measured water on the sunlit surface of the Moon.
- A pilot legacy program has started with the plan to map water on a larger surface of the Moon

Time Domain Studies: FORCAST, HAWC+, FIFI-LS

- Opens up FIR time variable studies
- Temporal Variations on Multi-Cycle Timescales
- Accretion Bursts in High-Mass Protostars
- New Cycle 10 category



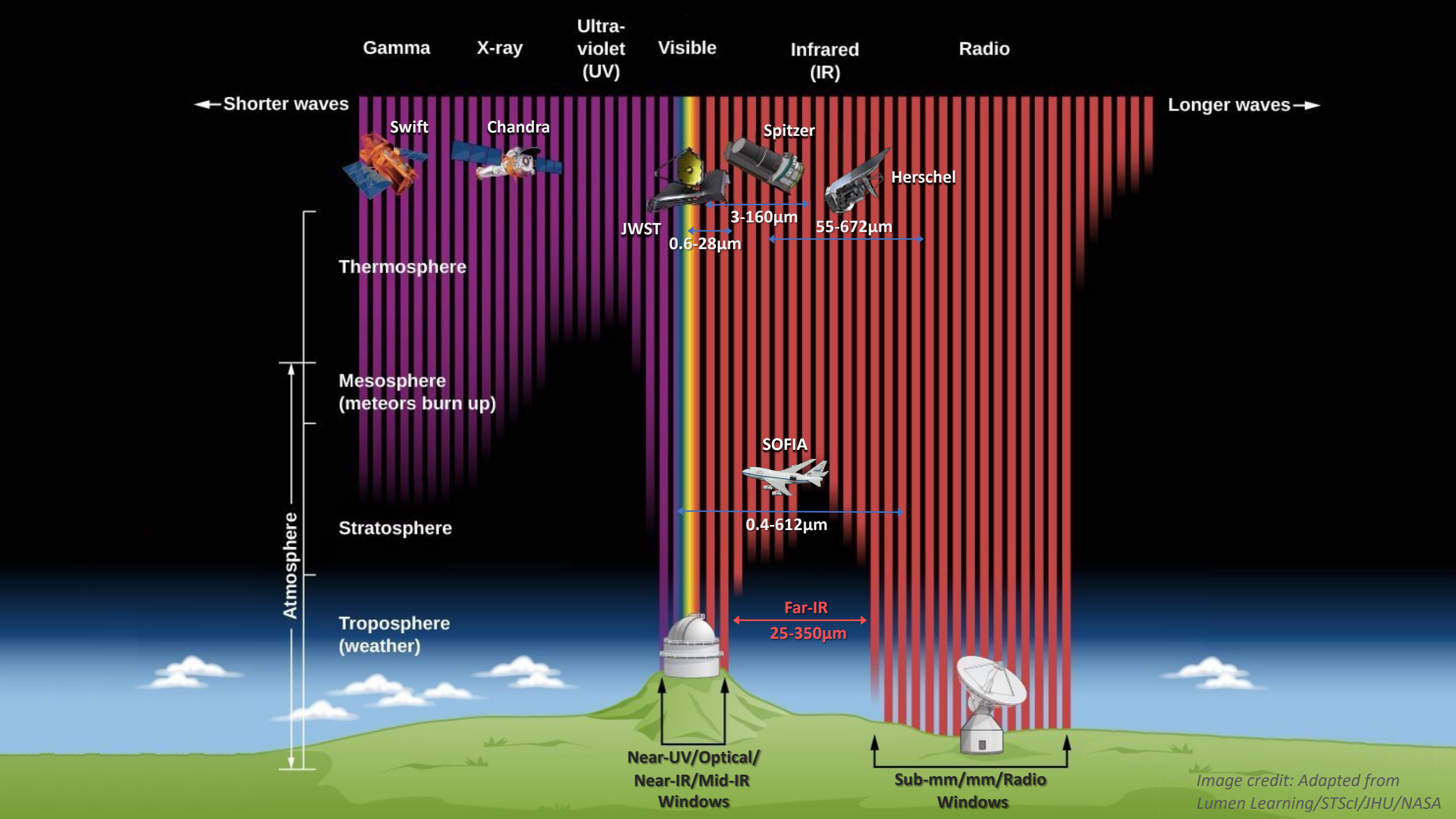
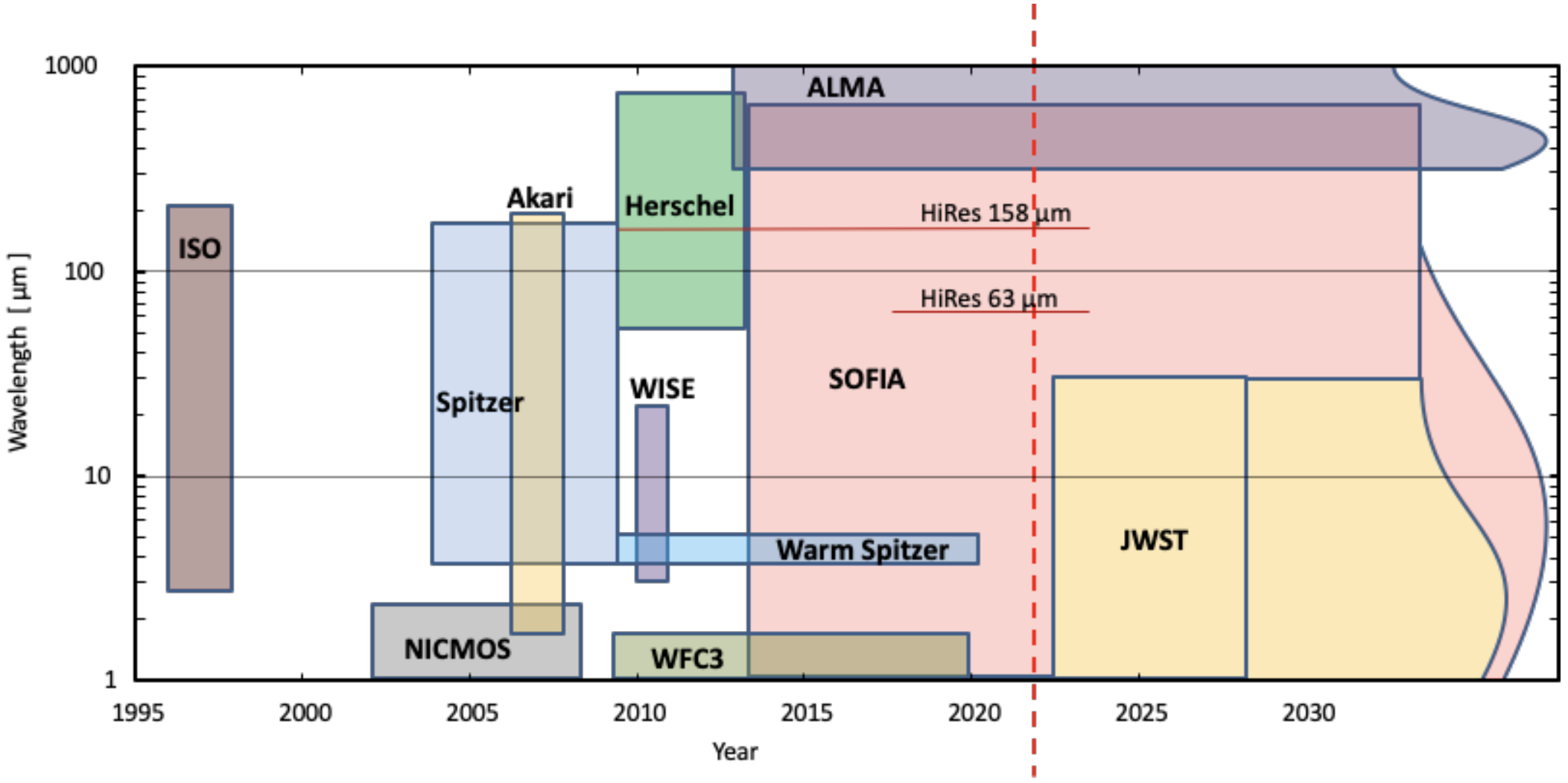


Image credit: Adapted from Lumen Learning/STScI/JHU/NASA

Infrared/Submm Observatories in Time

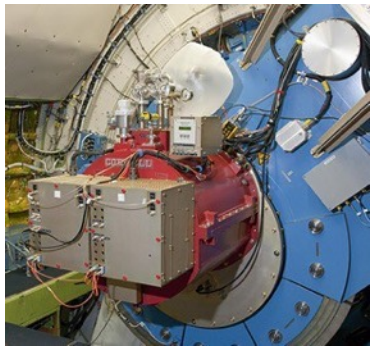


SOFIA Scientific Instruments: Current

FPI+ Focal Plane Imager Plus

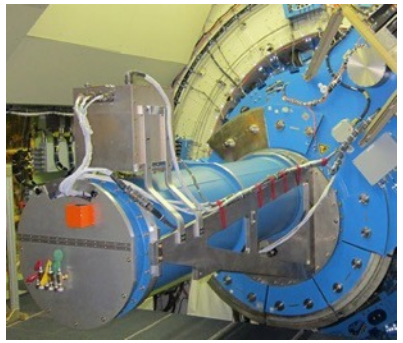
λ = 0.36–1.10 µm Optical Camera,
R = 0.9–29.0 always running!

FORCAST Faint Object Infrared Camera for the SOFIA Telescope



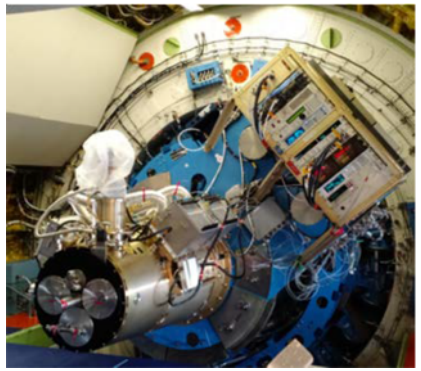
λ = 5–40 µm Grism Spectrometer
R = 100–300

EXES Echelon-Cross-Echelle Spectrometer



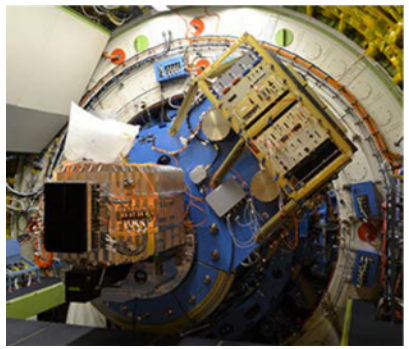
λ = 4.5–28.3 µm High Resolution Spectrometer
R = 1,000–10^5

HAWC+ High-resolution Airborne Wideband Camera Plus



λ = 50–240 µm Bolometer Camera & Polarimeter
R = 2.3–8.8

FIFI-LS Far Infrared Field-Imaging Line Spectrometer



λ = 51–203 µm Grating Spectrometer
R = 600–2,000

GREAT German Receiver for Astronomy at Terahertz Frequencies

λ = 63–612 µm Heterodyne Spectrometer
R = 10^6–10^8

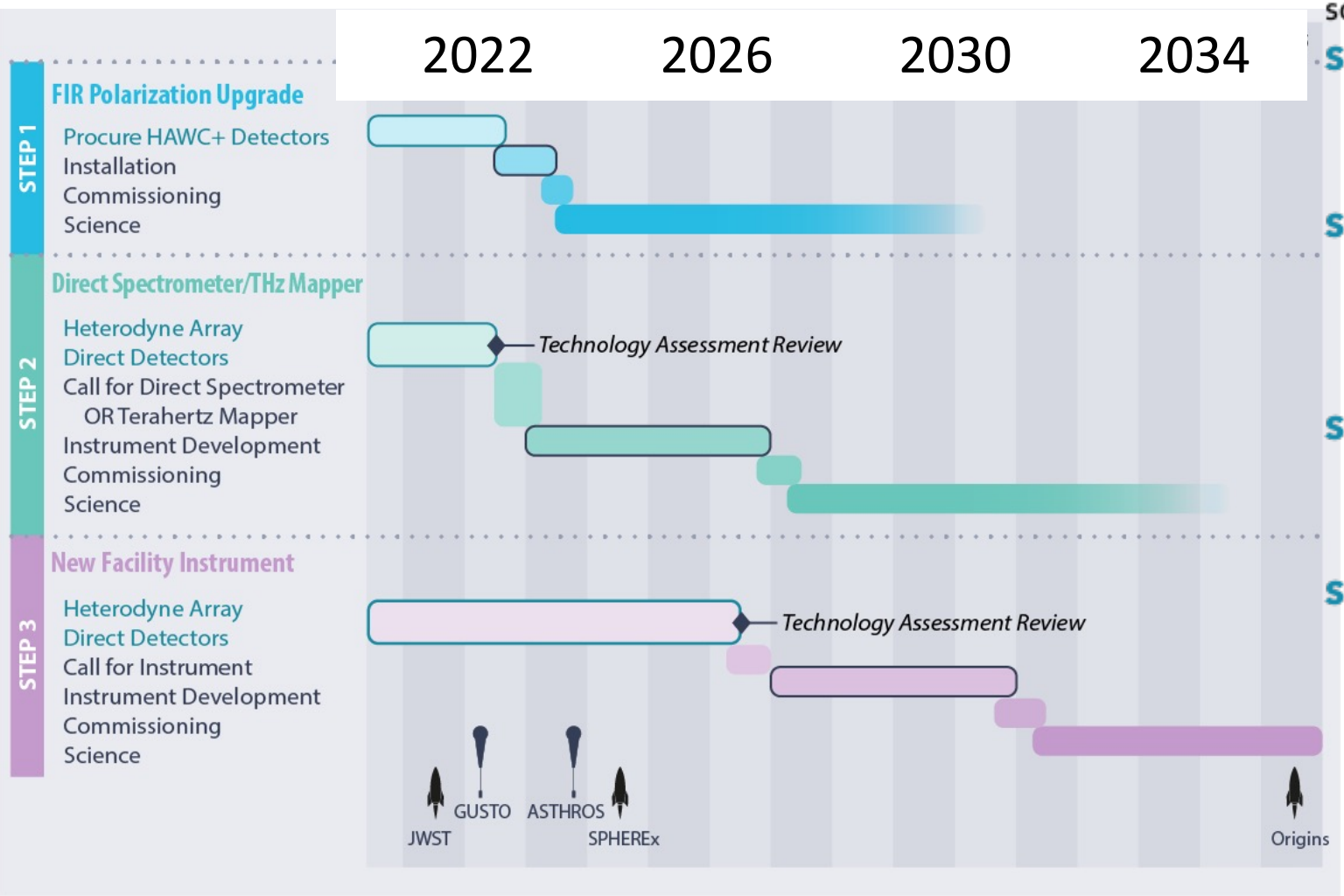
- A plan for future scientific instrumentation on SOFIA

- Public report available for download:
https://www.sofia.usra.edu/sites/default/files/Other/Documents/instrument-roadmap-public.pdf

Instrument Roadmap: Science Cases

	Science Case	Required Measurement	New Instrument Capability
Star and Planet Formation	Protoplanetary disk gas masses	Velocity-resolved HD line at 112 μm	High-resolution direct-detection FIR spectrometer
	Star formation feedback	Entire star-forming-region (>deg^2), velocity resolved maps of FIR lines (C II, O I, O III, CO)	Wide-field FIR heterodyne mapper
	Role of magnetic fields in star formation	Polarization from entire molecular filaments (>deg^2)	FIR polarimeter with improved mapping speed
Path to Life	Astrochemistry and disk chemistry	Velocity-resolved spectroscopy (H_2 pure rotations, light hydrides, H_2O, O I)	High-resolution MIR & FIR spectrometer, improved wavelength coverage and sensitivity
	Comets, asteroid, protoplanetary disk minerals & ices	5-70 mm ice, mineral, PAH feature strengths	MIR moderate to low-res spectrometer with improved sensitivity
	Planets and cometary gas	Med-res and high-res spectroscopy	Improved sensitivity
Calibrating the Distant Universe	Role of magnetic fields in spiral arms	Map entire nearby galaxies in FIR polarimetry	FIR polarimeter with improved mapping speed
	Evolution of galaxies with metallicity and size	Wide-field spectroscopy of entire nearby galaxies in FIR lines (C II, O I, O III)	Moderate resolution FIR spectrometer with wide field of view, improved mapping speed
	Transient phenomena	Monitoring of stellar eruptions, mergers, novae, and supernovae	Sensitive, rapid-response MIR/FIR photometer

Notional Timeline



Two orthogonal inputs are combined to create this roadmap: science priorities and technology readiness.

Step 1: Upgrade HAWC+

- Enables 2 out of 9 science cases
- Upgrade can be made using current technology
- Enables large (legacy) programs efficiently

Step 2: Direct-detection 30-120 μm spectrometer

- Enables ~5 out of 9 science cases
- New science, expands SOFIA's discovery space, expands/broaden SOFIA's community
- Strong synergies with Webb and SPHEREx

Step 2: Terahertz Mapper

- Preserves and expands SOFIA's core capability
- In high demand by current SOFIA users
- Heterodyne arrays are further along technologically

Step 3: Instrument Call

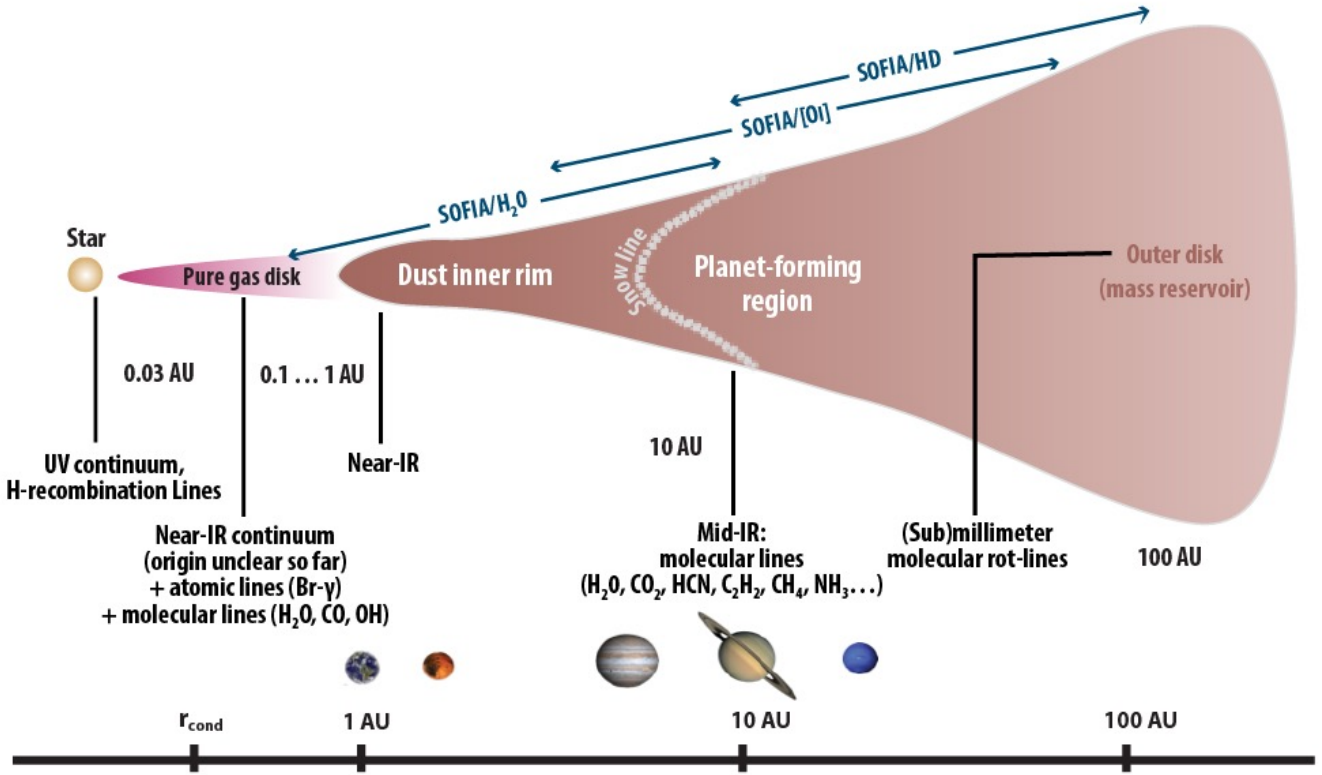
- Discoveries from SOFIA and other missions/observatories (e.g., Webb, GUSTO, ALMA, SPHEREx, VIPER) will change the scientific landscape/priorities of the community in the next 5 years
- Additional community input will be needed around 2024-25 to better define Step 3

Instrument Roadmap: Step 1 has started

- Replacing the HAWC+ detectors will increase the mapping speed for magnetic fields by a factor of up to 4
- Currently in 6 months funded formulation phase to assess new detector technology options
- Decision point to proceed depends on cost and schedule

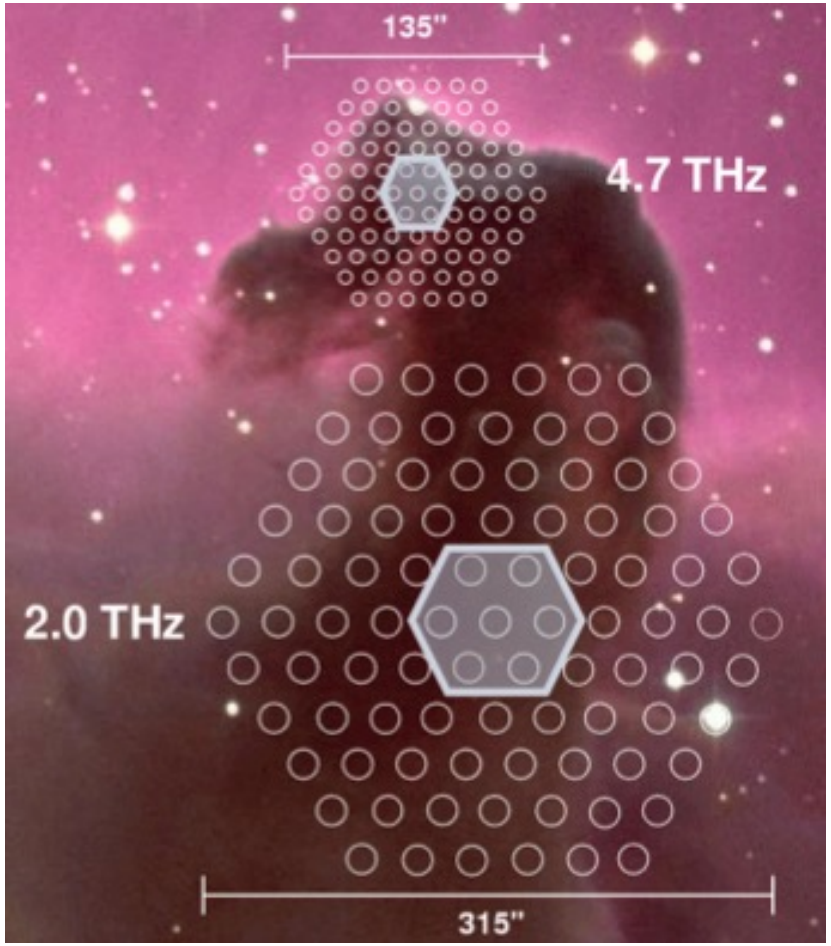
Step 2 Instrument: Concept 1

- Direct-detection 30-120 micron spectrometer
- Measure mass of protoplanetary disks using HD as a proxy for H_2



- Concepts at the workshops included:
  - Transition Edge Sensor (TES) detectors
  - Kinetic Inductance Detectors (KIDs).

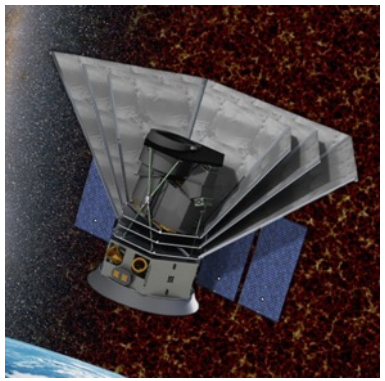
Step 2 Instrument: Concept 2

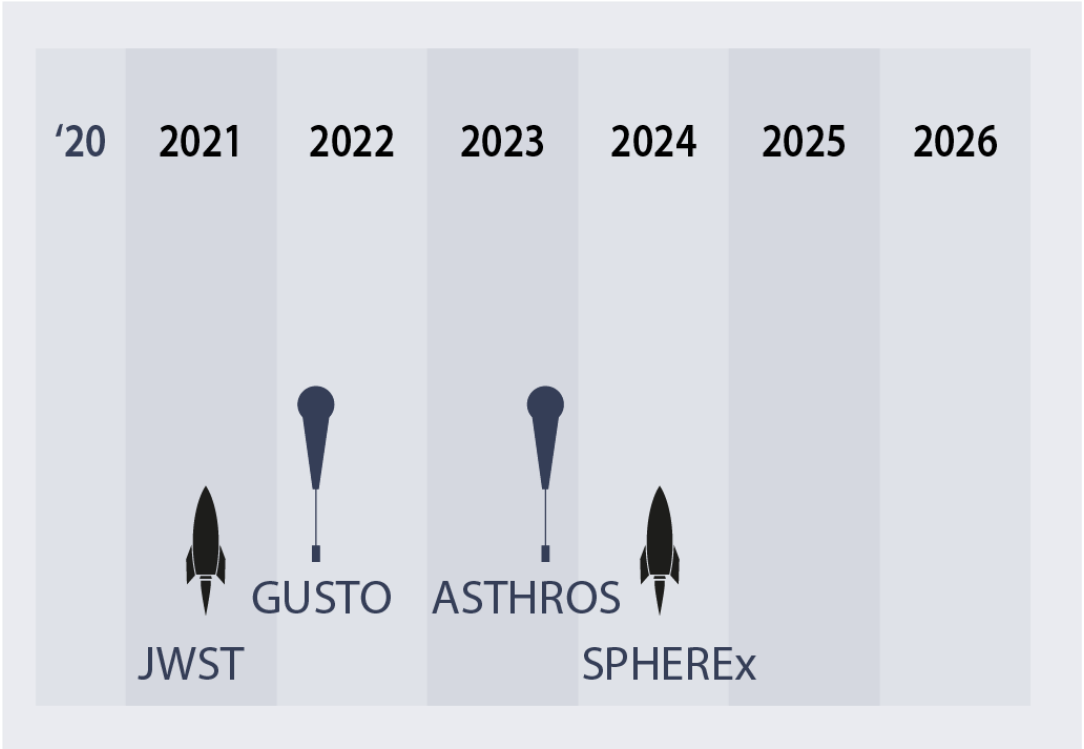


- Terahertz Mapper: 100-pixel Heterodyne Array
- Build on the success of the GREAT instrument
  - 14x faster mapping speed
- Utilize SOFIA's large focal plane
- Complementary to GUSTO
- Heterodyne technology development is farther along

Step 3: New Facility Instrument

- Discoveries from SOFIA and other observatories will change the scientific landscape and priorities
- Additional community input will be needed around 2024-25 to better define this step





Plan for Germany/Europe

- Use the opportunity to change the SOFIA paradigm
  - NASA does senior reviews but that is a normal process
  - No serious alternatives for Infrared/Submm on the 10 year horizon
  - Long term NASA vision makes termination less likely!

- The German/European community can create a complementary 10 year vision for Infrared/Submm astronomy
  - SOFIA is a working observatory
  - Future lighter-than-air observatories are good additional options

- First determine science interests and requirements (July 26-28, 2021) ✓
  - Get German and European Infrared Astronomy together and determine scientific interests
- Second discuss instrumentation and funding (Nov 17-19, 2021) ✓
  - Talk about how to make this science happen
  - New SOFIA instruments, new and planned balloon missions, instrument/detector development, funding opportunities
- Write white paper summary (by end Jan 2022)
  - Reference for proposals to build new instrumentation.

Science Workshop 26-28 Jul 2021

- 231 registered participants
- 3 days @ ~4.5h per day
- typical online attendance 80-90
- 56 Presenters
  - 10 invited speakers
  - 32 Contributed talks
  - 14 Poster presentations
- Summary presentation by Karl Menten
- Main Themes: ISM, PDRs, shocks, star formation, astrochemistry

Science Workshop 26-28 Jul 2021

- **Main Themes:** ISM, PDRs, shocks, star formation, astrochemistry
- 1/3 of presentations extragalactic
- High resolution spectroscopy MIR and FIR
- Trade spectral resolution for sensitivity
  - extra galactic work
  - large scale line mapping
- Polarimetry in FIR
- MIR/FIR broadband photometry
- Specific lines
- Time sampling

Specific requests:

- Fine structure lines, HD, CO ladder, oxygen compounds
- large scale mapping of [NII] 122μm / 205μm
- 350μm filter
- NIR capabilities for occultation obs.

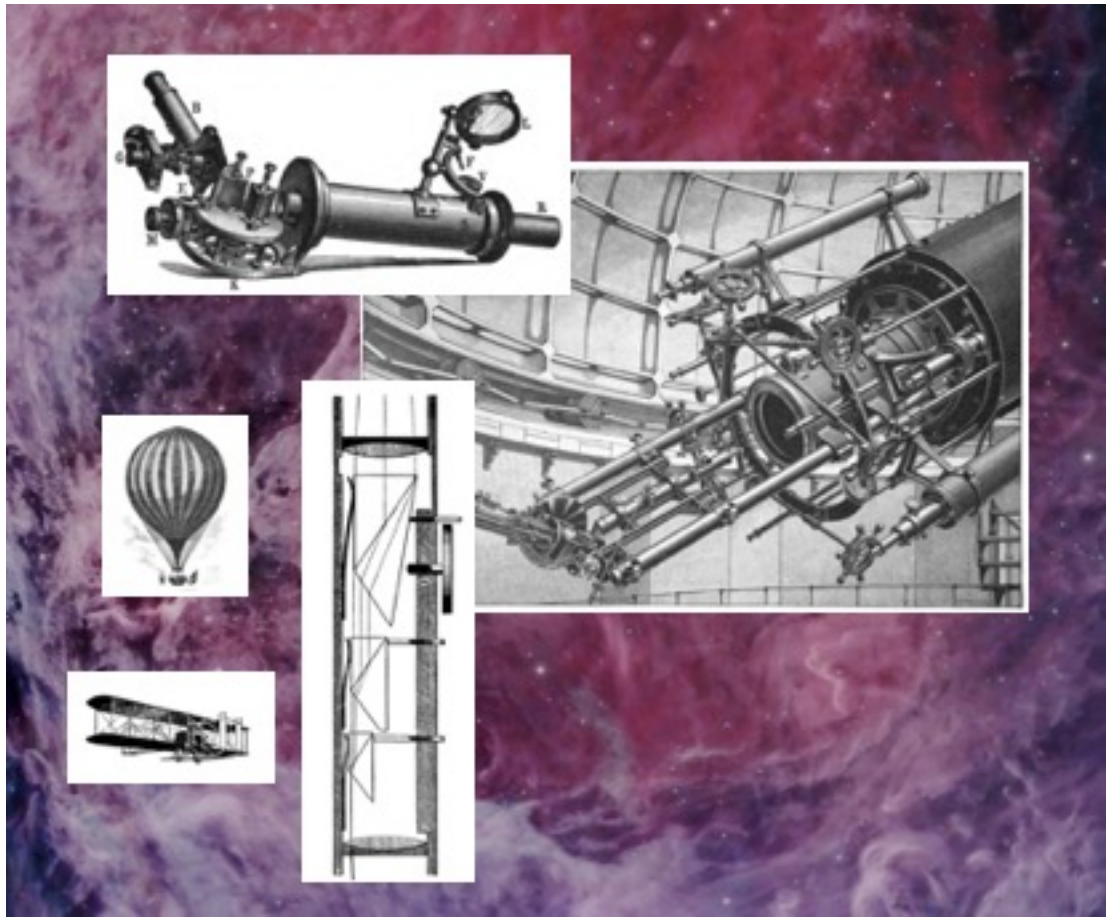
Session	Talks	Posters
Solar System	5	
Star & Planet Formation	6	
Interstellar Medium	15	8
Late Stellar Evolution	2	
Nearby Galaxies	8	3
High-Redshift Galaxies	3	4

Instrumental Requirements

Spectrometer	46	73%
Photometer	15	24%
Heterodyn	32	51%
R=5000 FIFI	13	21%
FIFI-LS	19	30%
EXES	4	6%
FIR camera	12	19%
MIR camera	2	3%
NIR camera	3	5%
Pol.	7	11%
Time sampling	5	8%
balloon	6	10%
single pointing	21	33%
maps	37	59%
Total Science Cases	63	100%

Version: 14-Oct-2021

Instrument Workshop 17-19 Nov 2021



- 156 registered participants
- 3 days @ ~5h per day
- typical online attendance 50-80
- 31 Presenters
  - 21 invited speakers
  - 6 Contributed talks
  - 2 Poster presentations
- Final discussion
  - Short summaries (Heinz Wilhelm Hübers and Leslie Looney)
  - Including representatives of DLR, DFG, DESY
- Main Themes: Heterodyne- and direct detection systems, balloon platforms, funding opportunities

Instrument Workshop 17-19 Nov 2021

First impressions:

Very Preliminary!!!

- Balloon options look promising for specific programs
  - Scalable gondola developments
  - Survivability of payload remains a big issue
  - Low flight cadence
  - France has a dedicated balloon budget line
- SOFIA is the only regular platform for at least the next 10 years
  - Roadmap first step is in a 6 months formulation phase now
- Heterodyne HEB mixers, SIS mixers, Schottky diode mixers discussed
  - HEB mixers mature
  - High frequencies still hard to reach because no space missions
  - 100 pixels in focal plane considered very ambitious

Instrument Workshop 17-19 Nov 2021

Very Preliminary!!!

First impressions:

- Direct Detectors: Kinetic Inductance Detectors (KID), Transition edge detectors (TES), polarimetric Si-bolometers, Cold-electron bolometers
  - Expertise in UK, France, The Netherlands, Germany
- Instrument presentations: upGREAT, FIFI+LS, HERO, Millimetron, HIRMES, pHD, SOFIA Chopper, FPI++, ArTeMis/CoPilot/B-BOP
- Heterodyne:
  - 100 pixels array hard --> better modular approach
  - spectrometer power issue
- Direct Detection:
  - Many solutions exist, pushing to blue side no easy quick solutions, complex instruments will delay the next instrument
- Funding opportunities in Germany and Europe exist but managers need more awareness of researcher's needs

Conclusions

- SOFIA is a unique and important asset for astronomy
- The observatory is operating with increasing efficiency and scientific impact
- A major advantage is its ability to upgrade instrumentation
- The next major Infrared/Submm space mission comes not earlier than in 10 years from now
- SOFIA's 20 year design lifetime isn't quite over yet