

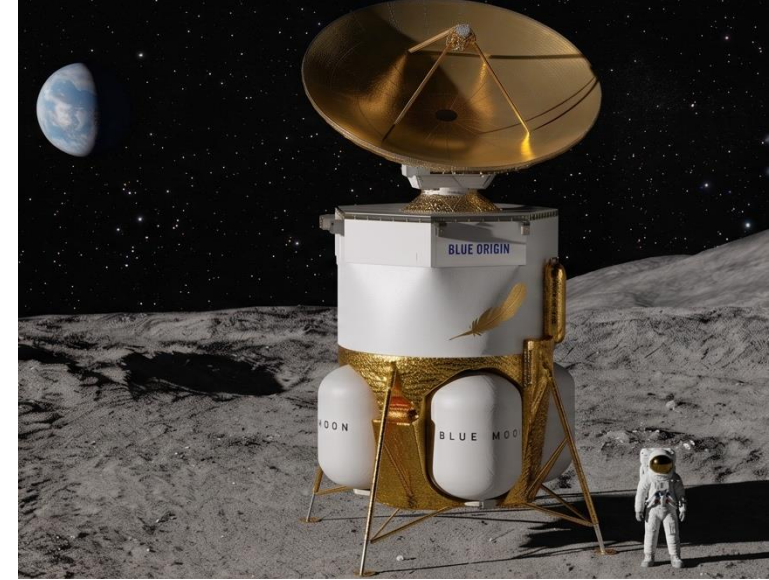
LunAr Submillimeter Survey Observatory (LASSO)

Addressing Key Science Questions in Star & Planetary System Formation **from the Moon**

Paul F. Goldsmith, Jorge L. Pineda, and Dariusz C. Lis

Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA

at ASTRA Community Science Workshop
California Institute of Technology
September 1, 2026



Jet Propulsion Laboratory
California Institute of Technology

The Far-Infrared Landscape

- Far-IR wavelengths are indispensable for addressing Astro2020 Science Questions related to the interstellar medium, star and planet formation:
 - How do star-forming structures form, evolve, and interact with the diffuse ISM?
 - What regulates the structure and motions within molecular clouds?
 - How does gas flow from parsec scales down to protostars and their disks?
- With the decommissioning of SOFIA, we have no current or planned Far-IR facilities for high-resolution spectroscopy, which are required to study gas motions in molecular clouds and galaxies
- This aspect can be addressed long before the future Far-IR Flagship, in a cost-effective way, by a **large aperture high spectral resolution Far-IR lunar telescope**, built in collaboration with industrial partners and taking full advantage of the Artemis infrastructure

LASSO

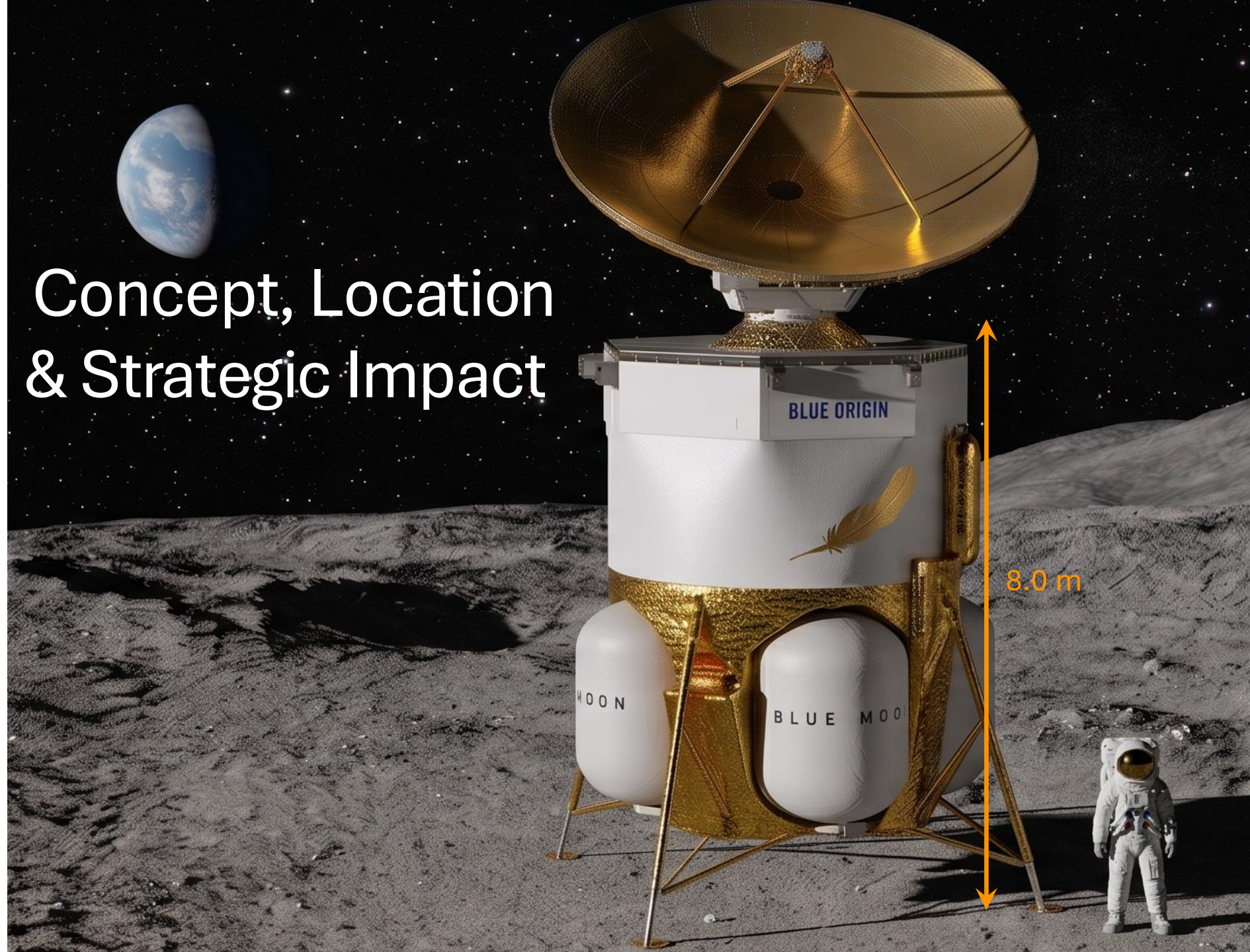
6.5m diameter
submillimeter
Antenna

Permanently
shadowed crater
near Lunar S. Pole

High resolution
heterodyne focal
plane array receivers
covering 1.2 - 5.8 THz
(300 μm – 52 μm)

High-impact science
on star-formation,
stellar feedback, the
water trail, and
galaxies

Concept, Location & Strategic Impact

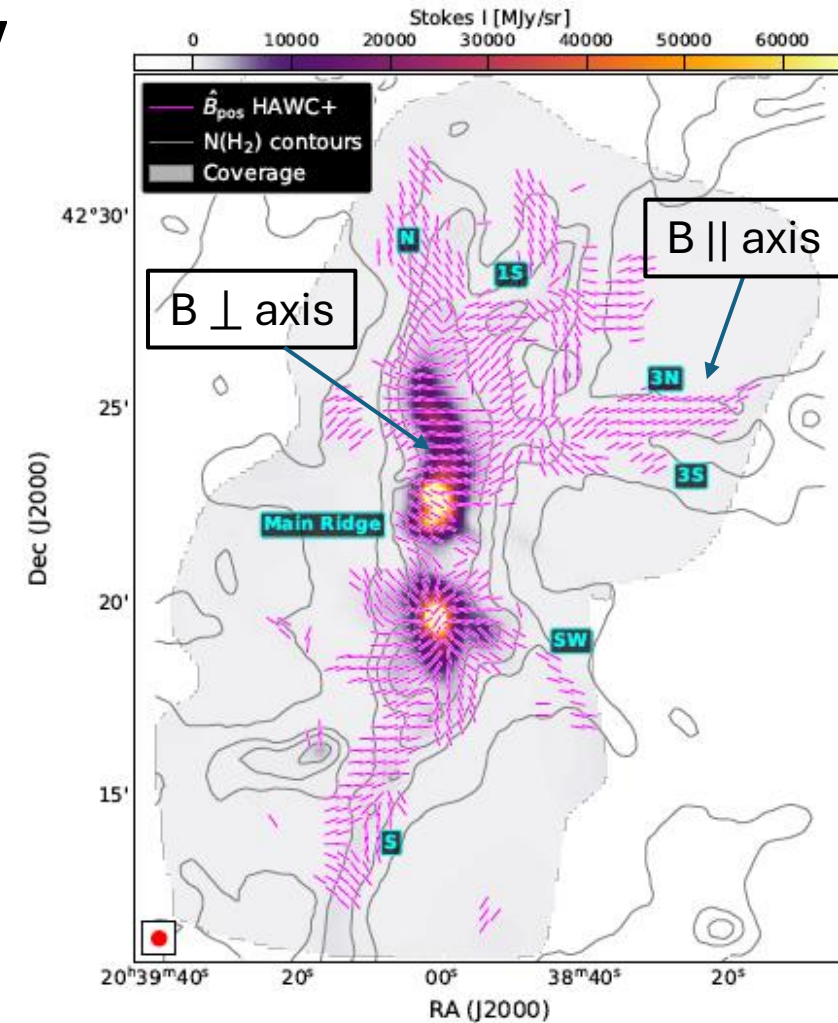


Why a Far-Infrared/Submillimeter Spectroscopic Observatory on the Moon?

- The thermal environment in a permanently shadowed crater on the lunar surface is ideal for a pointable precision structure – extremely cold ($\sim 30\text{K}$) giving lower emission, very stable temperature, and no variations of thermal input due to changes in pointing
- Low temperature facilitates cryogenic cooling of detectors; active cooling of the telescope is not required
- Power and communications should be provided by national agency or commercial source
- Telescope diameter can exceed that taken to L2
- The cost could be lower than free-flyer, depending on development of lunar infrastructure
- Blue Origin Blue Moon Mk 1 Lander will deliver 3000 kg mission payload

S1 – High Resolution CII Spectroscopy & Magnetic Field in the Diffuse ISM

- The formation of dense molecular clouds from the diffuse interstellar medium (ISM) incorporates formation of highly nonuniform filamentary structures that are fundamental for future star formation
- Their morphology is affected and likely dominated by the magnetic field. The limited observations to date suggest that $\mathbf{B} \parallel$ axes of subfilaments that appear to be feeding mass to larger filaments for which long axes $\perp \mathbf{B}$
- Figure illustrates this in DR21 region



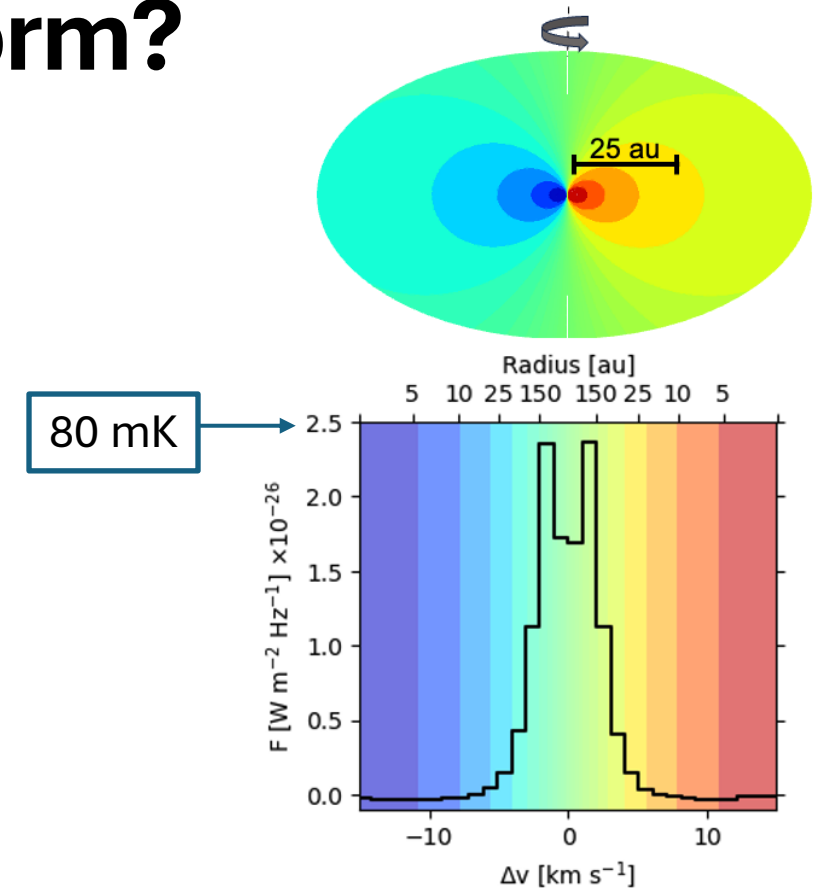
From Pillai et al. (2026) using data obtained with HAWC+ polarimeter on SOFIA

S1- Magnetic Fields (2)

- We need to trace **B** throughout lower column density portions of clouds that are NOT molecular. The dust emission can be measured with FIR continuum polarimetry as done by SOFIA and will be spectacularly with PRIMA
- To obtain the MAGNITUDE of the POS component of **B** (in addition to direction, which is what you get from polarimetry) you need a measurement of the velocity dispersion in the region. You must **spectrally** resolve an appropriate tracer and thus have $R > 10^5$. In low- A_V regions, this can best be determined by observing C^+ via $158\ \mu\text{m}$ [CII] fine structure line, an excellent tracer of the CO-dark molecular gas
- LASSO will carry out large-scale surveys of [CII] to complement e.g. PRIMA polarimetric observations. This will reveal the behavior of a critical step in star formation. The beam size will be $\sim 6''$, which is close to that of ground-based telescopes that will be doing dust polarimetry of limited regions and also good for comparison with data from PRIMA

S2 - How Do Planetary Systems Form?

- A critical question is the **MASS** of the protoplanetary disk that condenses from the ISM along with the material forming the central protostar
- The HD molecule is the best method for measuring disk mass, especially if the J=2-1 (56 μm) line is available along with J=1-0 (112 μm) line to break temperature degeneracy
- LASSO's **large collecting area** (3.5 x *Herschel*) and **high spectral resolution** will enable Doppler disk tomography revealing the radial mass distribution of a large sample of disks



HD J=1-0 spectrum of min. mass disk around solar mass star at $D = 140 \text{ pc}$ with $i = 60^\circ$

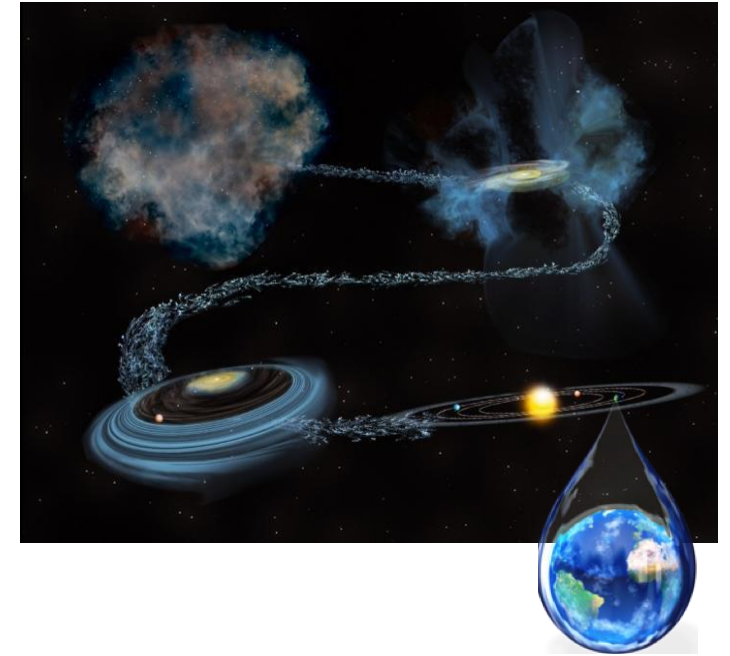
S2 – The Role of Water

Water is a key ingredient for planetary habitability

- Low-lying water transitions are all in the FIR regime
- LASSO will map the water vapor distribution in disks with a range of ages and stellar spectral types using Doppler tomographic mapping
- LASSO will investigate the **inheritance of water** through HDO/H₂O and the ortho/para ratios in star forming regions and disks of different ages
- LASSO can search for water in interstellar “objects”

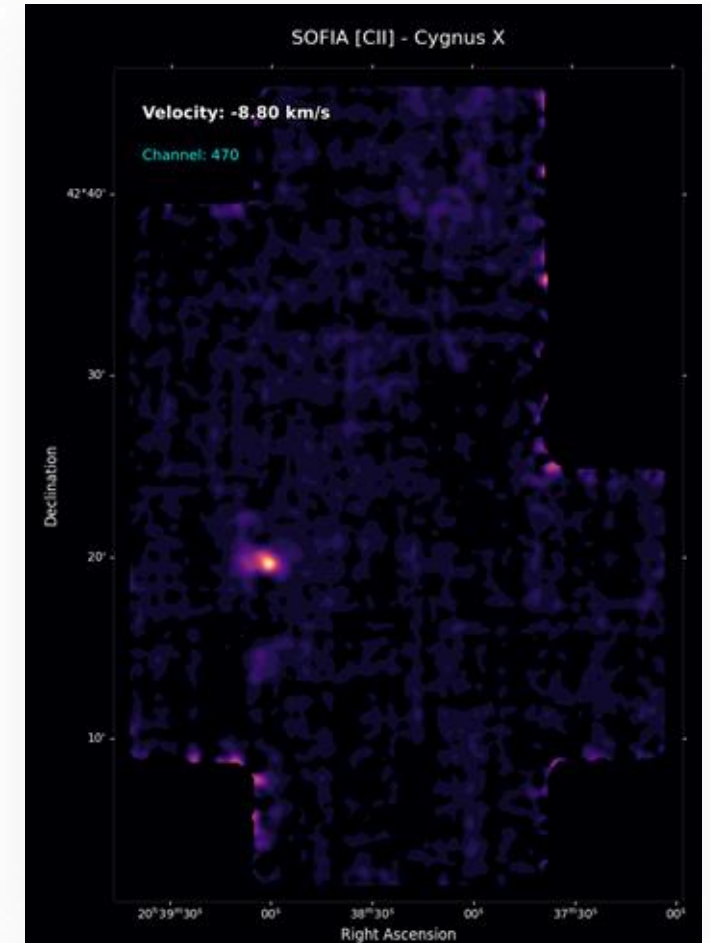
On the scale of galaxies

- Many IR luminous galaxies have vast reservoirs of water that provide key insights into their evolution and nature of the buried AGN
- LASSO will detect for the first time water emission in nearby dwarf galaxies



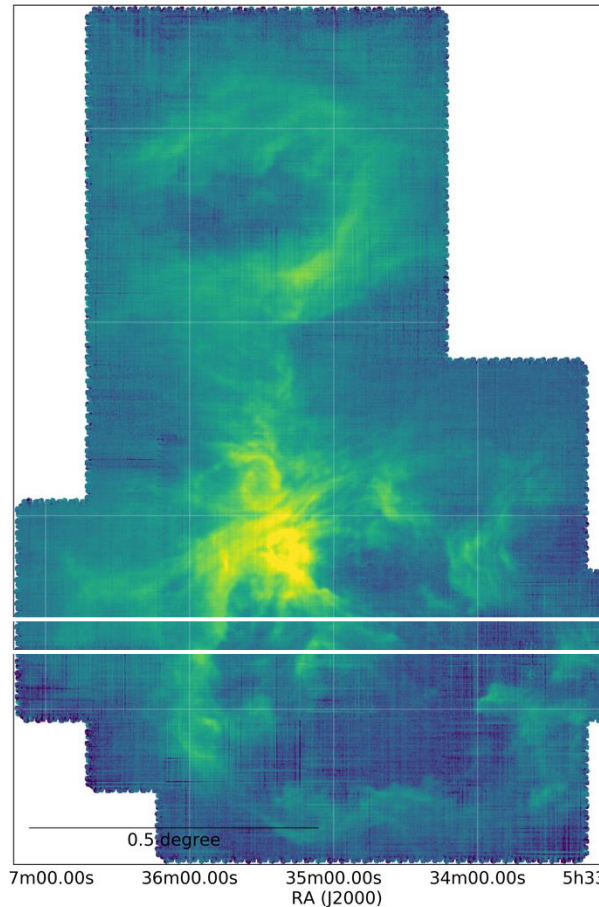
S3: Measuring Stellar Feedback

- Galaxy growth is a complex, non-linear, multi-scale process in which **gas accretion, outflows, molecular cloud formation, and stellar feedback** together determine how gas is transformed into stars
- The influence of **feedback (Stellar and AGN)** is the **most important systematic uncertainty** in galaxy-formation modelling and is a **key limiting factor** in our understanding of galaxy growth and evolution
- **Direct measurements of the coupling of energy and momentum** from feedback to the interstellar medium in galaxies and transfer to the circumgalactic medium will have a profound impact on our understanding of galaxy evolution.
- These measurements require velocity-resolved spectroscopy to determine energy and momentum of affected gas

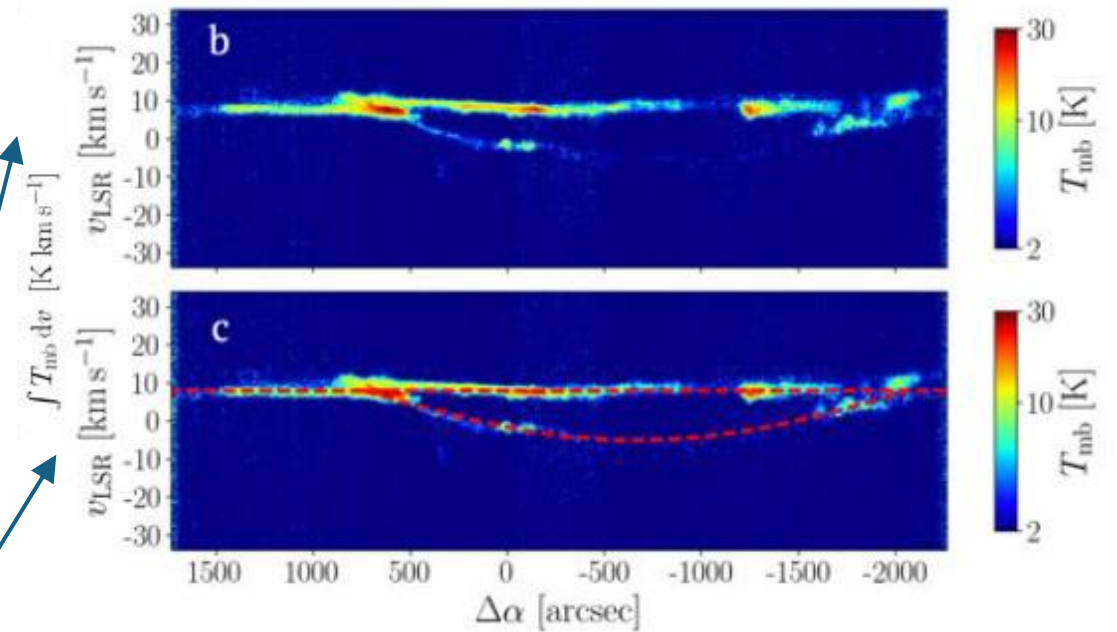


Velocity channels of [CII] line observed by SOFIA showing intricate velocity structure in Cygnus X

Feedback from Massive Young Stars: Expanding Shell in Orion



Pabst et al. (2019); SOFIA



Expanding spherical half shell with constant expansion velocity $v = 13 \text{ km s}^{-1}$
 Mass of shell $\sim 1500\text{-}2500 M_{\text{sun}}$
 Age $\sim 2 \times 10^5 \text{ yr}$
 Kinetic energy $= 2.5\text{-}4.0 \times 10^{48} \text{ ergs}$
 [CII] luminosity $= 0.001 \times \text{luminosity of } \theta^1 \text{C Ori}$

S4: **LASSO** Extragalactic Science

Part 1: Studies of Galaxies in the Local Universe

- Star formation drives the evolution of galaxies -a critical driver and measure of the process is **cooling of the interstellar medium (ISM)**
- ISM cooling of different phases requires imaging of galaxies in a selection of fine structure and molecular lines including [NII] (ionized phase), [OIII], [OI] (high and medium temperature PDR regions), [CI] and CO (warm cloud envelopes and interiors)
- All of these are blocked by the Earth's atmosphere but can be imaged nicely by LASSO in Magellanic Clouds and nearby galaxies. High angular resolution (2.4" @ 63 μm) is a significant advantage
- We envision a large survey of ~ 100 local galaxies spanning orders of magnitude in star formation rate



JWST image of galaxy showing large-scale bubbles

LASSO Extragalactic Science Part 2: Study of Galaxies at Cosmic Noon

Redshifts around $z = 2$ encompass peak in the star formation rate; referred to as **Cosmic Noon**

Understanding how star formation took place at that epoch is fundamental for understanding the big picture chemical and physical evolution of galaxies

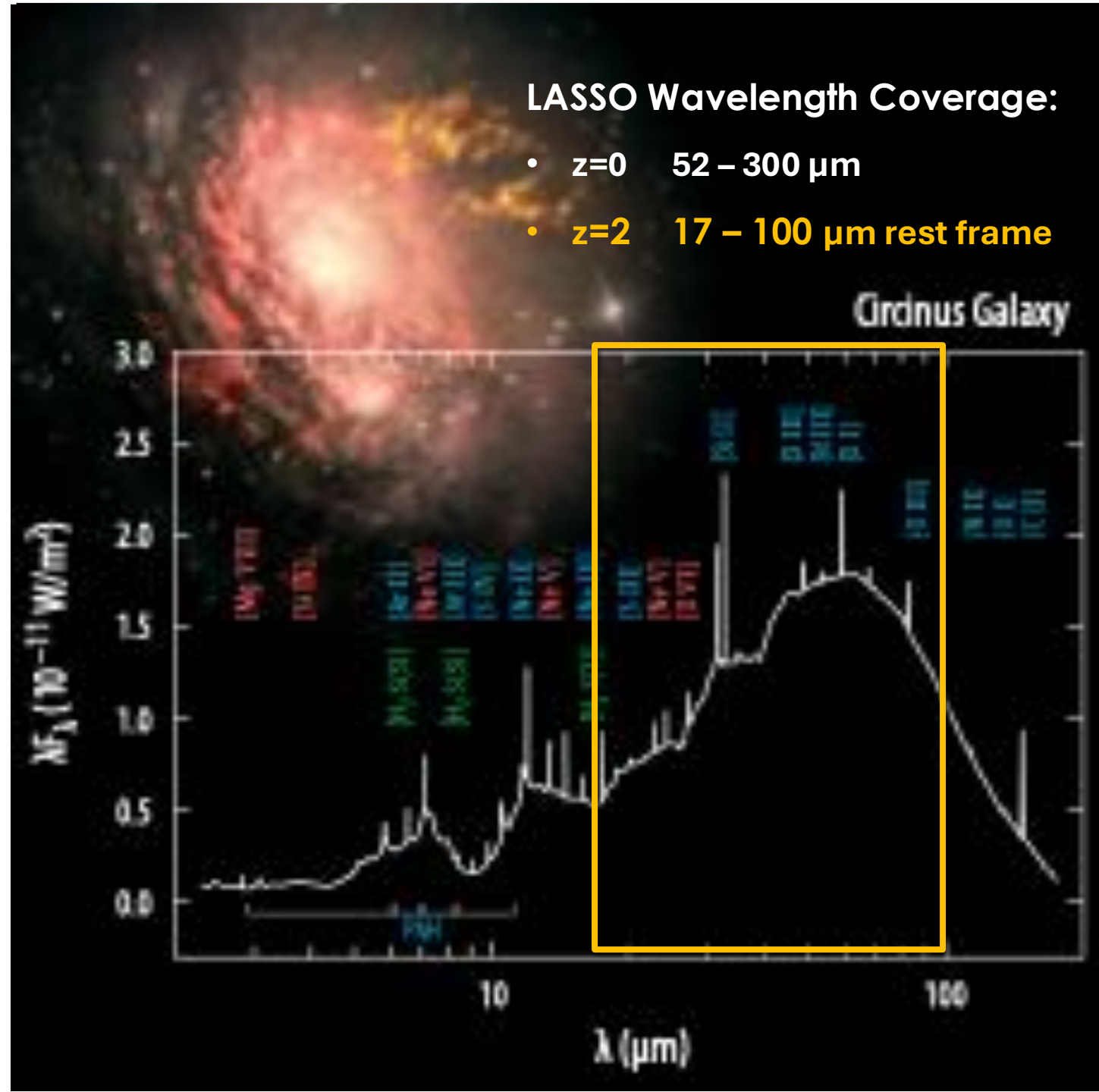
Several key tracers in these galaxies **remain beyond the reach of ALMA** (and other ground-based facilities) and will be important targets for LASSO

[OIII] (52 μm) $\rightarrow$ 156 μm (1920 GHz)

[OIII] (88 μm) $\rightarrow$ 264 μm (1120 GHz)

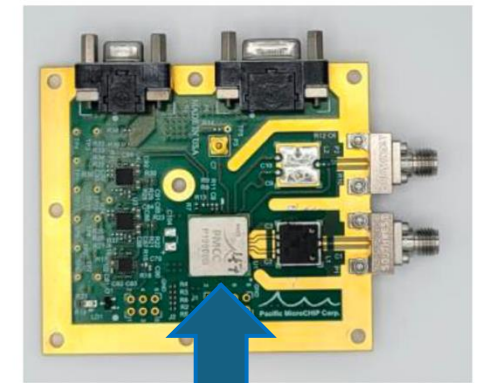
[OI] (63 μm) $\rightarrow$ 190 μm (1590 GHz)

[NIII] (57 μm) $\rightarrow$ 171 μm (1750 GHz)



LASSO Mission Concept

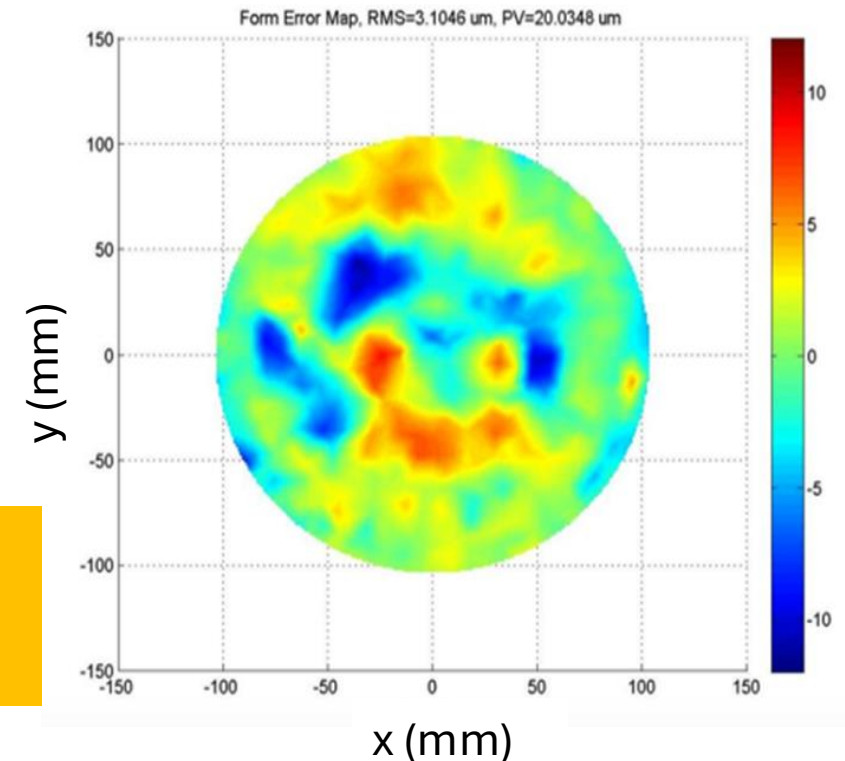
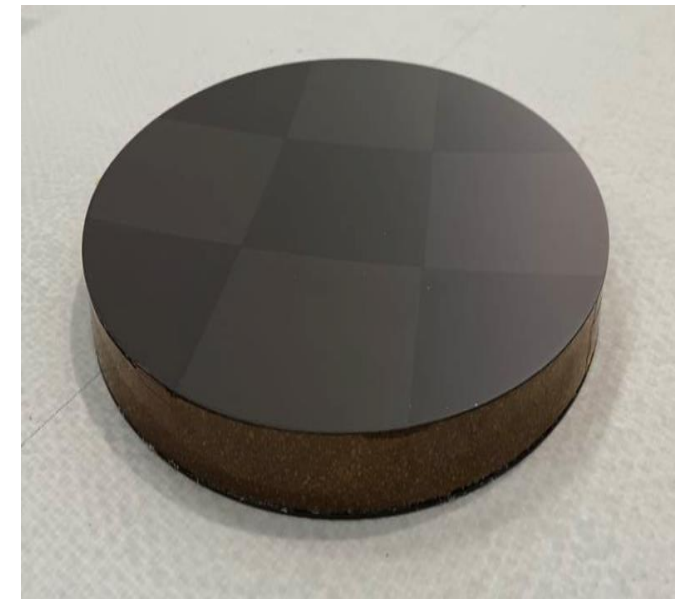
- Utilize Blue Origin's Blue Moon lander to place largest submillimeter telescope sited above Earth's atmosphere in a permanently-shadowed lunar crater
- Equip the telescope with heterodyne array receivers covering key fine structure lines and molecular lines – CII (158 μm), NII (205 μm , 122 μm) OI (146 μm , 63 μm), OIII (88 μm , 52 μm), HD (112 μm , 56.2 μm), H₂O (269.5 μm , 180.6 μm , 179.6 μm , & others), HDO, CO, ¹³CO, C¹⁸O (many lines)
- Resolving power $R \geq 10^6$ (0.3 km/s). ASIC spectrometers cover 4 GHz bandwidth w/ 8192 channels $\leq 2\text{W}$ power consumption each
- The array receivers will allow accelerated spectra imaging of large areas and observations of small sources in multiple lines simultaneously
- The cryogenic cooling requirements are drastically mitigated by having thermal reservoir at $\leq 30\text{ K}$



13 x 13 mm ASIC

LASSO Mission Concept (2)

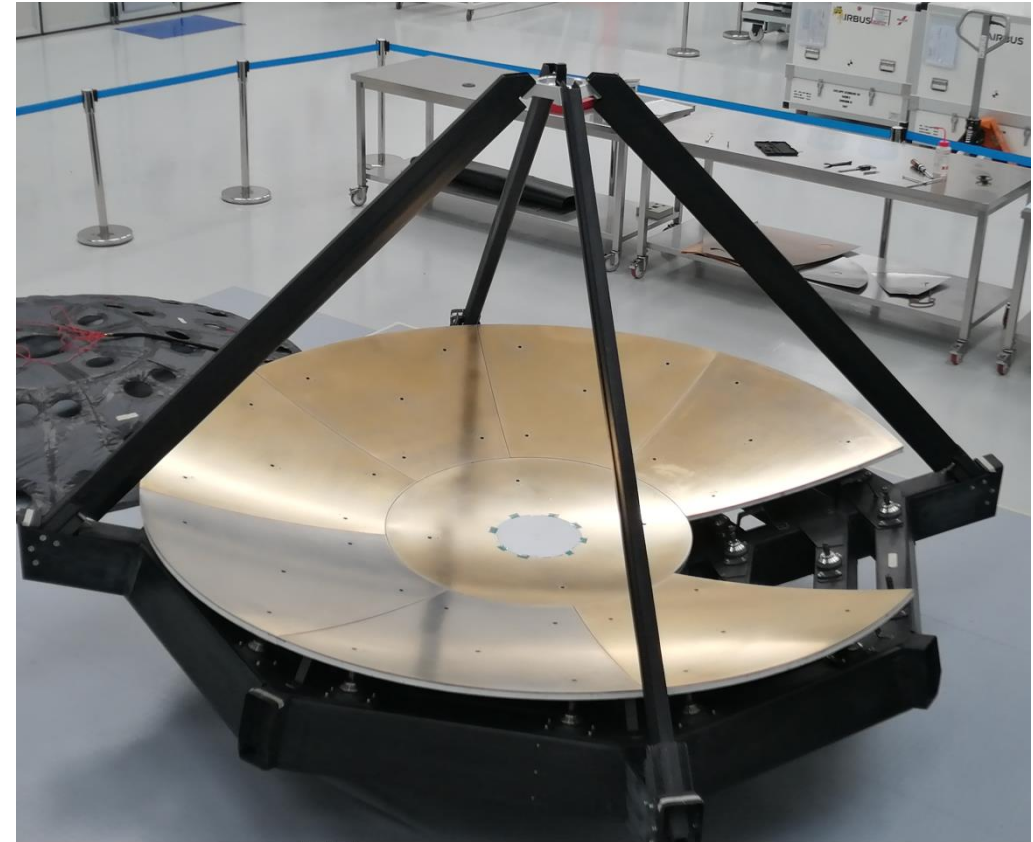
- Telescope design in very early stage, with support having been received by Media Lario (Italy) who made European ALMA antennas
- They envision a completely carbon fiber back structure. The surface panels will be carbon fiber sandwich (carbon fiber foam core & solid surface layers)
- Very early models achieved surface error of 3 μm rms with improvement anticipated. This is already $\lambda/17$ at shortest wavelength for LASSO
- No deployment envisioned given capacity of New Glenn shroud, but simple segmentation would allow even larger telescope diameter



20 cm CFRP-carbon foam -
CFRP sandwich panel
(Media Lario)
NOW 45 cm and 2 μm rms

LASSO Mission Concept (3)

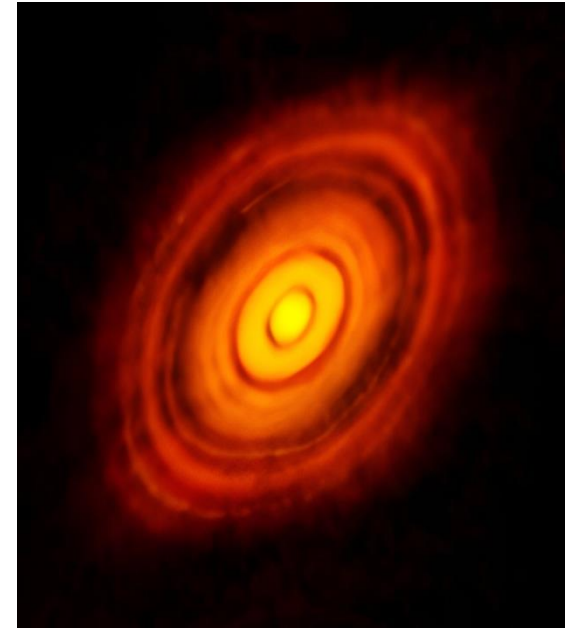
- Telescope motion will be achieved by standard elevation over azimuth axis configuration
- A star tracker will be used to ensure $< 1''$ pointing and tracking, especially important for observing protoplanetary disks
- Power consumption is key question being studied, but is estimated to be ~ 450 W, not including communications



ASTHROS 2.5m antenna CFRP structure
 $7 \mu\text{m}$ rms surface accuracy (Media Lario)

LASSO: Summary and Conclusions

- As a submillimeter spectroscopic observatory in a permanently shadowed lunar crater, LASSO has the potential for major scientific advances and strategic impact including the following:
 - Broadband access to key submillimeter lines will allow studies of the impact of stellar feedback and the magnetic field on star formation, the structure and role of the ISM in galaxies ranging from the local universe to cosmic noon, and the inheritance of material from the ISM to planetary systems via the water trail
 - Demonstration of an autonomous and impactful astronomical facility in this location will highlight cooperation with industry, be a pathfinder for future missions, and demonstrate the financial advantage of doing science on the lunar surface.



LASSO will study the gas mass distribution across planet forming disks pinpointing the location where planets like the earth form.