

Connecting Planet Formation from the Solar System to Exoplanet Systems

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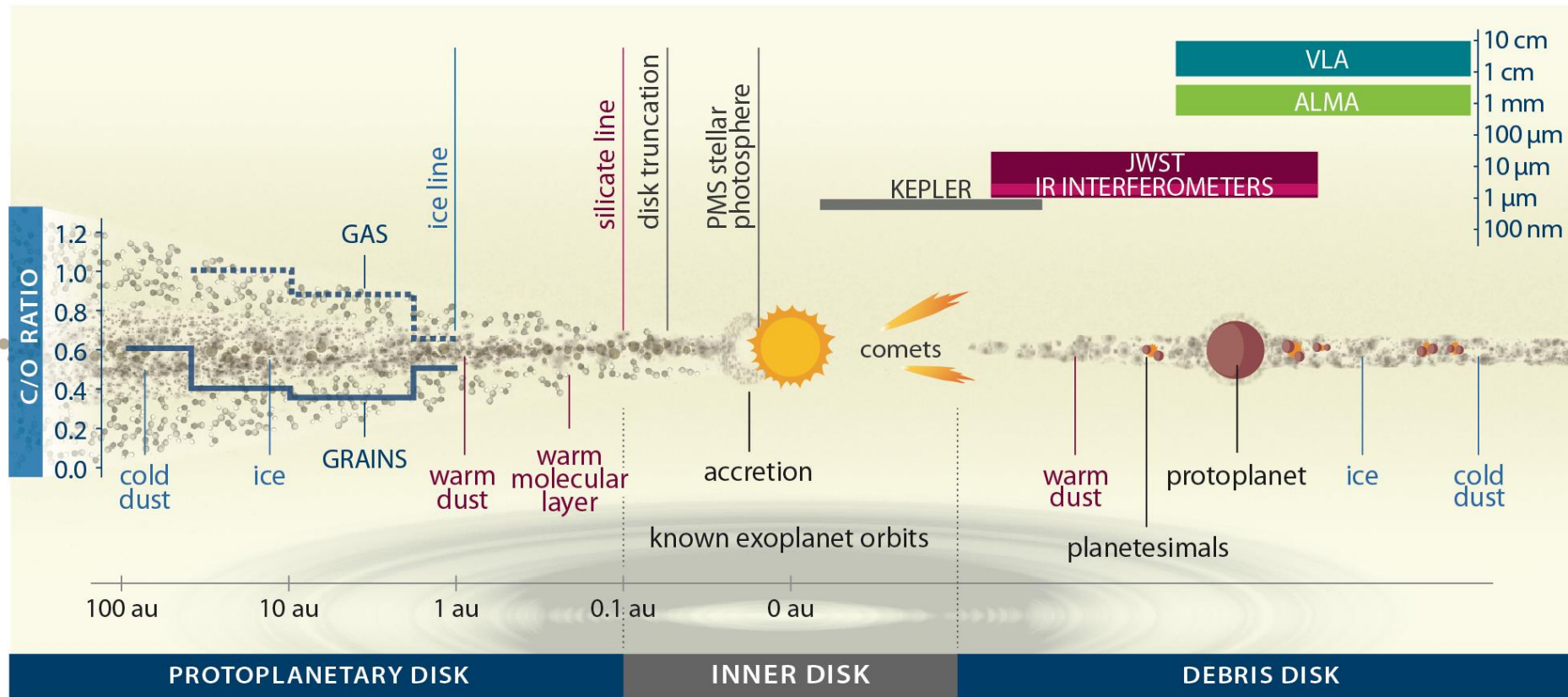


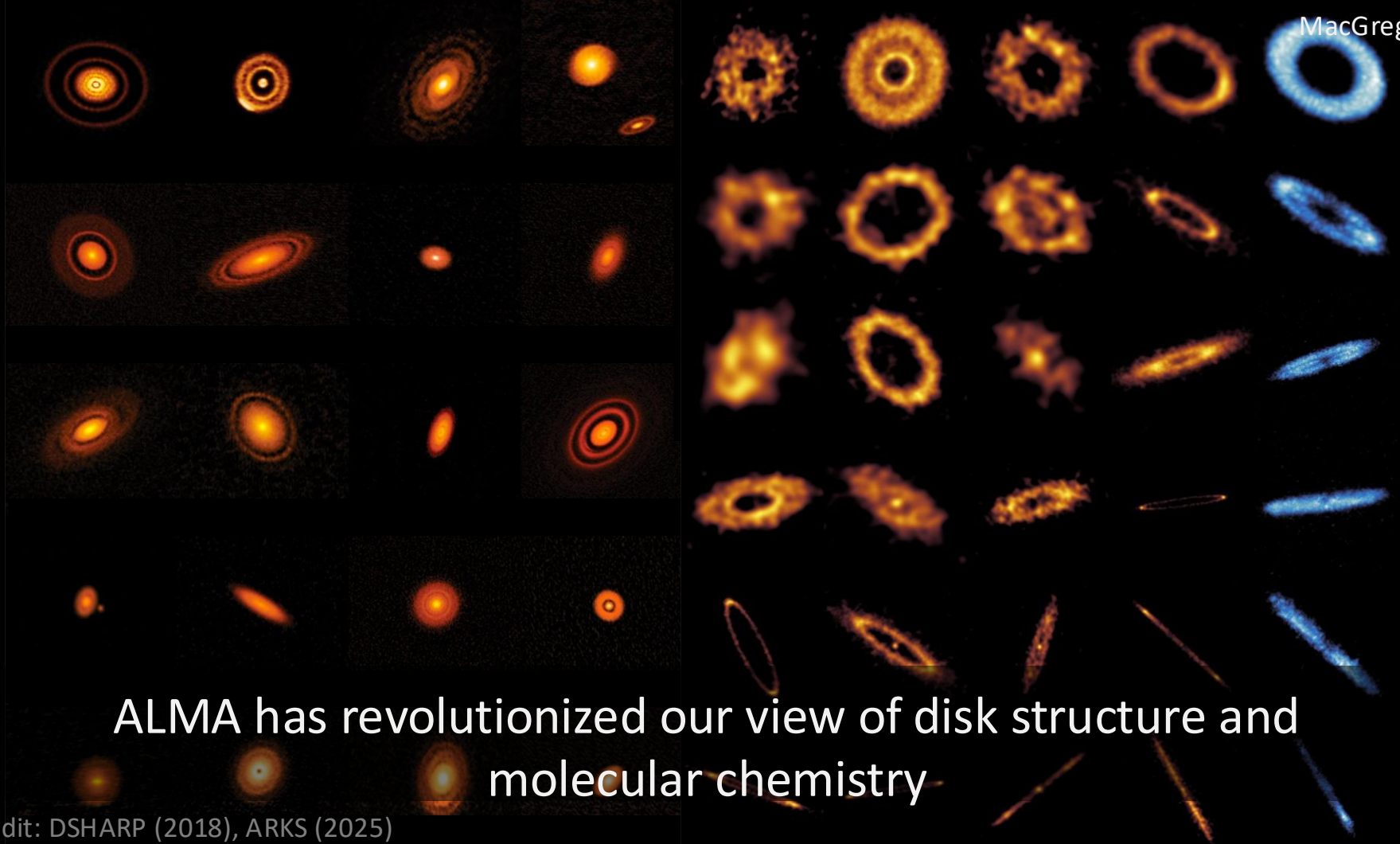
ASTRA Workshop
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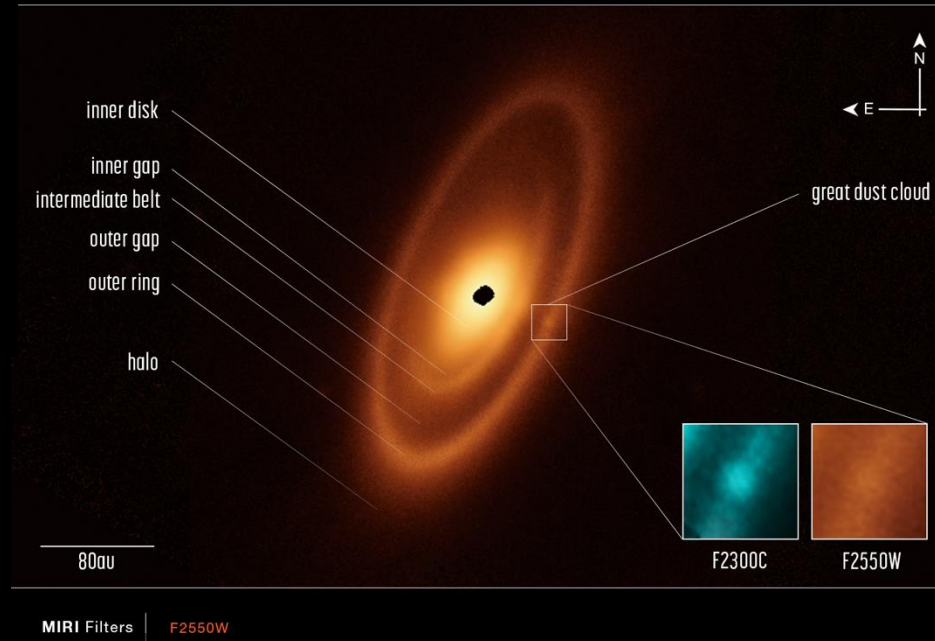
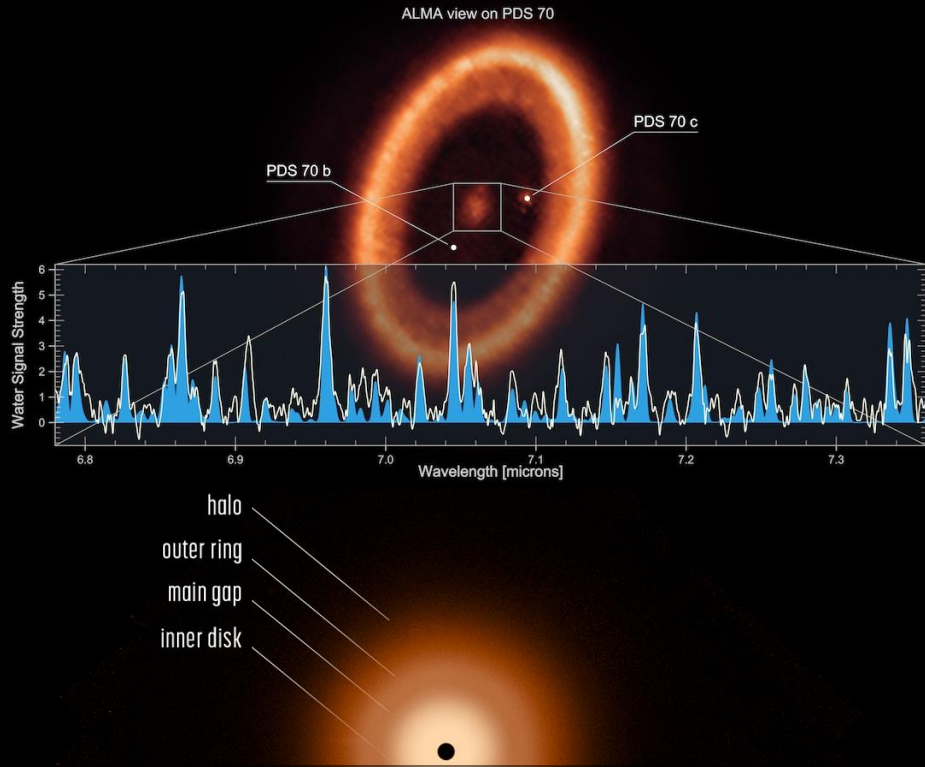
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Different wavelengths trace different physical locations and chemistry







JWST has revealed new inner dust populations and probes water in terrestrial regions of disks.

What is the past and current landscape of FIR mission concepts?



Telescope

1.8-m
all aluminum
4.5 Kelvin

PRIMAger Imager and Polarimeter

R = 10 hyperspectral imaging (25-80 μm)
R = 4 imaging and polarimetry (91-261 μm)

FIRES Spectrometer

R > 85 spectroscopy
24-235 μm
High-Res mode
R = $4400 \times (\lambda/112\mu\text{m})$

Detectors

100 mK KID arrays (~12k total)

Data

IPAC

Orbit

Earth-Sun L2

Instantaneous Field of Regard

26% of sky

Launch

2032



ORIGINS
Space Telescope

From
first stars
to life

Origin Space Telescope Instruments

Instrument	Wavelengths (μm)	Instantaneous Field of View	Observing Modes
MISC Mid-Infrared Spectrometer	2.8 - 20	5" (2.8 - 10.5 μm) 3."4 (10.5 - 20 μm) set by field stop	Transiting exoplanet spectrometer
OSS Origins Survey Spectrometer	25 - 590	14' slit (grating mode); single beam (high-resolution modes)	R = 300 grating spectroscopy with wide-field survey capability R = 43,000(112 $\mu\text{m}/\lambda$) FTS R = 325,000(112 $\mu\text{m}/\lambda$) Etalon
FIP Far-Infrared Imager and Polarimeter	50 and 250	3.'6 x 2.'5 (50 μm) 13.'5 x 9' (250 μm)	Broadband imaging, pointed observations or wide-field survey; polarimetry.

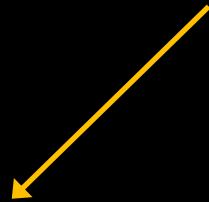
Where do we go next?

Where is the biggest scientific advance to be had?

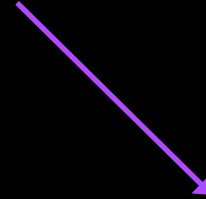
How do habitable planetary systems form?

→ disk and exoplanet characterization, solar system small bodies

Spectral or spatial resolution



Single aperture
telescope with high
spectral resolution



Large single aperture or
interferometer

The Closest Protoplanetary Disks

Disk	Distance (pc)	Stellar Mass (M _☉)	Inner Radius (AU)	Outer Radius (AU)	Spectrometer Res. (AU)*	Interferometer Res. (AU)**
TW Hya	60	0.8	0.1	60	0.64	13.9
PDS 70	112	0.76	65	140	0.65	25.9
DG Tau	121	0.7	0.1	75	0.68	28.0
DN Tau	128	0.65	0.1	125	0.71	29.6
RY Tau	128	2.04	0.2	115	0.40	29.6
CY Tau	129	0.3	0.1	230	1.04	29.8
BP Tau	129	0.7	0.083	105	0.68	29.8
UZ Tau E	131	1.2	10	160	0.52	30.3
DoAr 25	138	0.95	80	165	0.58	31.9
GM Aur	140	0.95	28	220	0.58	32.3

*Assuming R = 10⁵ and orbital radius of 2 AU

**Assuming 100 m baseline



ORACLE – Observatory for Resolving Atmospheric Chemistry in the Lifecycle of Exoplanetary systems

A cryogenic space telescope at L2 studying exoplanet atmospheres and the protoplanetary disks that form them.

3.6 m
primary
diameter



Compact. Cold. Optimized for Discovery.

Operating at L2 provides a thermally stable environment and an unobstructed view of the universe.

SUN

EARTH

1.5 million km

L2

TWO POWERFUL INSTRUMENTS

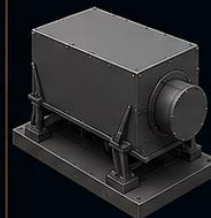


1. A MIR Coronagraph and High Resolution Spectrograph

Wavelength: 4 – 25 μm

Resolution: 5,000 – 50,000

Suppresses starlight to directly image young exoplanets and characterize their atmospheres; maps the structure of protoplanetary disks and disk winds.



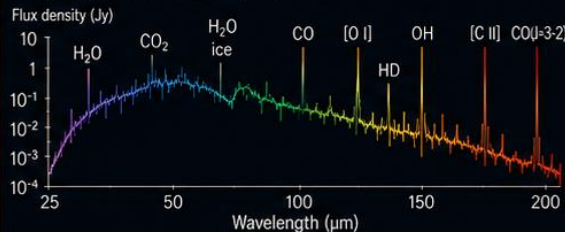
2. A FIR High Resolution Spectrograph

Wavelength: 25 – 200 μm

Resolution: >100,000

Measures the chemical composition, temperature, pressure, and dynamics of exoplanet atmospheres and the gas in protoplanetary disks.

SIMULATED MID- TO FAR-INFRARED SPECTRUM OF A PROTOPLANETARY DISK

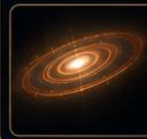


Spectrum generated from a physical-chemical model of a protoplanetary disk.

SCIENCE GOALS



CHARACTERIZE EXOPLANET ATMOSPHERES
Identify molecules (H_2O , CO_2 , CH_4 , O_3 , etc.), measure thermal structure, clouds, and winds to understand planet formation and atmospheric chemistry.



EXPLORE BIRTHPLACES OF PLANETS
Probe the gas and dust in protoplanetary disks, measure composition, temperature, and kinematics, and uncover how planets form and evolve.



CRYOGENIC OBSERVATORY

Passive cooling enables ultra-low temperatures for infrared sensitivity.



STABLE AT L2

Provides a stable thermal environment and continuous, unobstructed cosmic view.



HIGH CONTRAST

Precision wavefront control and coronagraphy enable direct imaging of faint planets.



MOLECULES TO PLANETS

From molecules to worlds—unlocking the origins and diversity of planetary systems.

Observing the Lifecycle of Planetary Systems from Formation to Atmospheres.

Answering Decadal Priority Questions

Science Objectives	Physical Parameters	Observables	Potential Challenges
Determine the volatile mass and composition for a sample of 300 protoplanetary disks and 100 debris disks	Disk gas mass, temperature, and geometry for a range of stellar types and ages	Emission lines of HD (56 and 112 μm), C II (158 μm), O I (63 μm), H ₂ O (both gas and ice)	R>100,000 to tomographically map lines; PRIMA lacks resolution; POEMM but can only study a small sample
Determine the composition of comets in the Solar System and exoplanet systems	Abundances of molecules in Solar System comets, exocomets, and interstellar objects (ISOs)	Multiple emission lines of molecules like H ₂ O, HDO, CO ₂ , CO, and CH ₄	Fast-tracking capability and solar avoidance angle
Determine the properties of disk winds and their role in disk dissipation for a sample of 1000 protoplanetary disks	Abundances of disk wind tracers for a range of stellar types and ages	Emission lines of forbidden lines Ne II (12.8 μm), Ne III (15.6 μm), Ar II (7.0 μm), O I (63 μm), and N III (57 μm)	R>100,000 to tomographically map lines

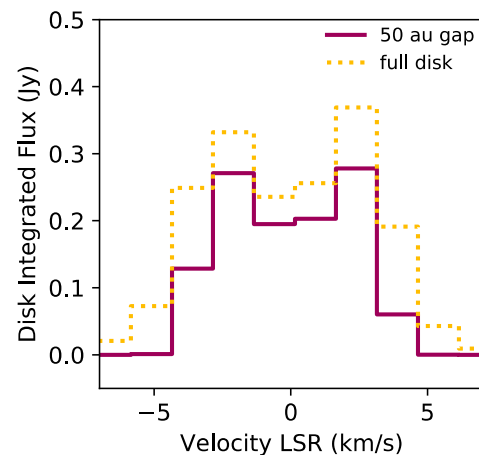
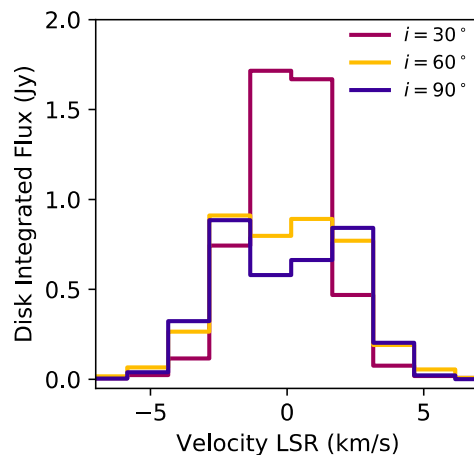
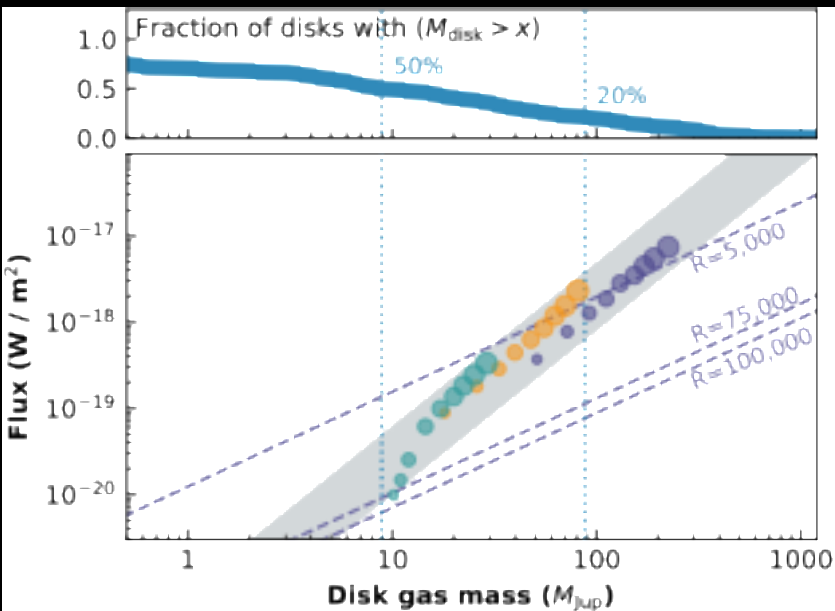
Answering Decadal Priority Questions

Science Objectives	Physical Parameters	Observables	Potential Challenges
Determine how photochemistry shapes atmospheric composition and haze production for a sample of 50 gas and ice giant planets	Abundances of key tracers of atmospheric photochemistry	Emission lines of photochemical products SiO_2 (8.6 μm and SO_2 (4 μm)	Inner working angle and sensitivity of coronagraph
Determine the level of atmospheric heating in a sample of 50 gas and ice giant planets	Atmospheric temperature- pressure profile	Broadband spectra and phase curves (measured both in and out of transit)	Inner working angle and sensitivity of coronagraph
Determine the frequency of inner dust belts and exomoons for all Main Sequence stars within 15 pc	Disk geometry, Exomoon size	Coronagraphic imaging of warm dust grains in the MIR (< 20 μm)	Inner working angle and sensitivity of coronagraph

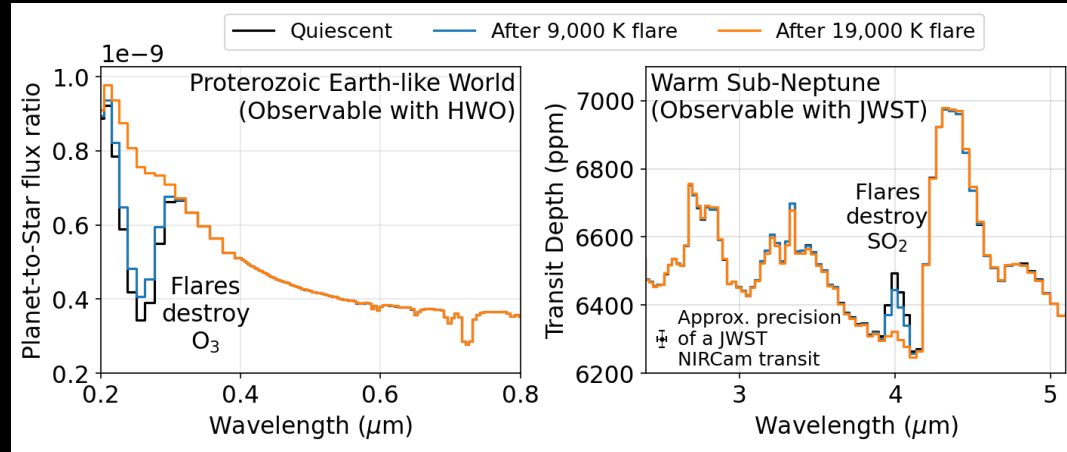
Doppler Tomography

High spectral resolution increases the fraction of disks that can be detected
($R \sim 10^5$ to detect >50% of ALMA disks)

Determine disk geometry through topographic mapping

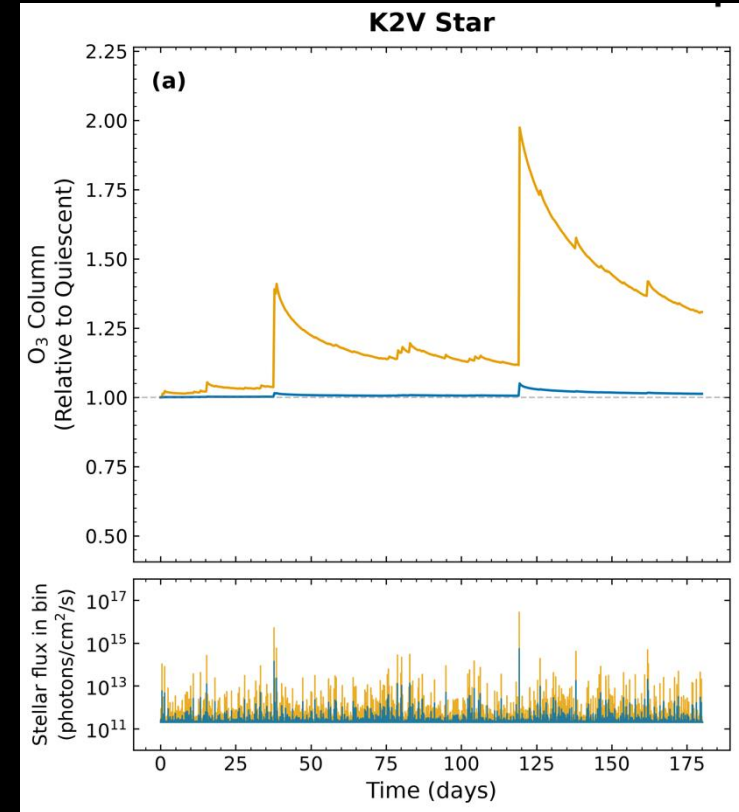


Photochemistry



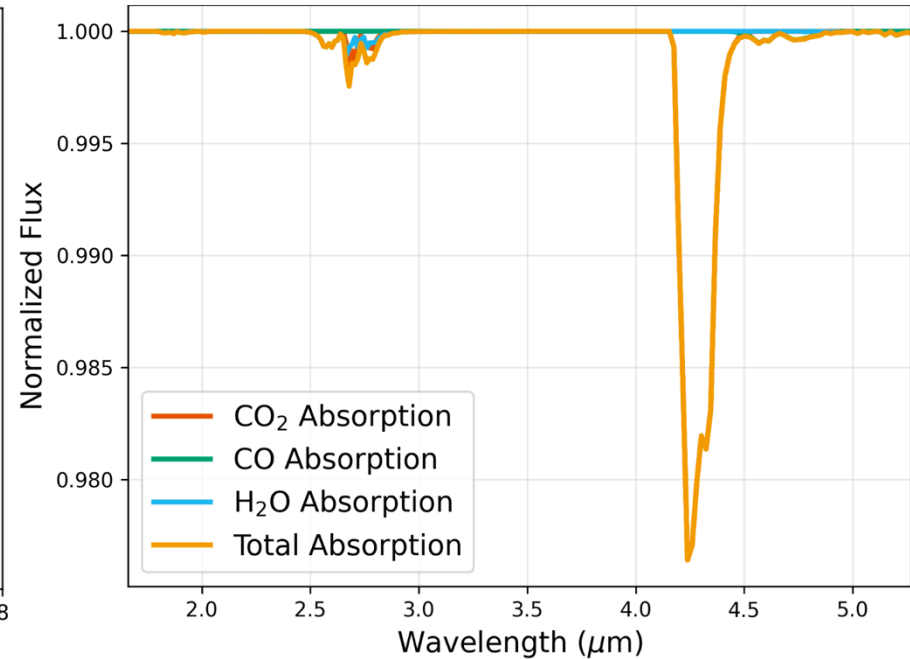
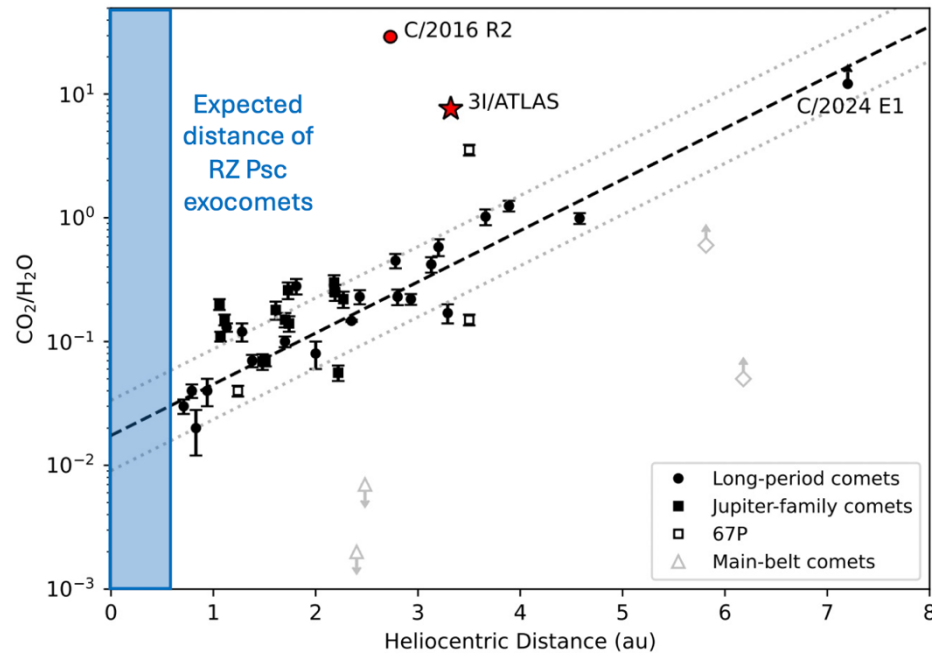
Energetic flares can dramatically alter
atmospheric chemistry

Quasi-steady state elevated O_3 column depth?



Comet Composition

Relative volatile abundances measured for Solar System comets, exocomets, and Interstellar Objects (ISOs) probe formation location and composition



Take-Away Messages

- (1) The mid- and far-infrared (MIR and FIR) spectrum provides unique access to critical tracers of planetary systems. Transitions for numerous atomic and molecular species (e.g., O_3 at $9.6\ \mu\text{m}$, CO_2 at $15\ \mu\text{m}$, OI at $63\ \mu\text{m}$, HD at 56 and $112\ \mu\text{m}$, and H_2O) lie in this bandpass that play a role in the formation of planets through to their atmospheric chemistry and ultimately the habitability of their surfaces.
- (2) High-resolution spectroscopy and coronagraphy require similar cooling, detectors, etc. and thus combine well onto a single space platform. Given current technological development, such an observatory is more readily achievable and could be a stepping-stone to a future FIR interferometer.

