

PHOENIX: A Photonics-Enabled Heterodyne Submillimeter/Far- Infrared Interferometer

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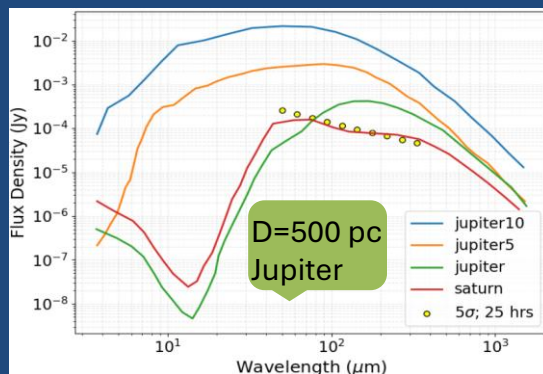
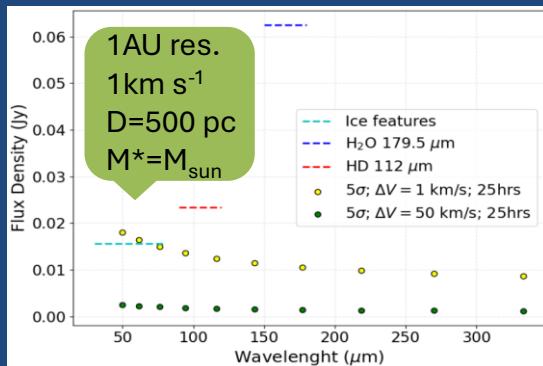
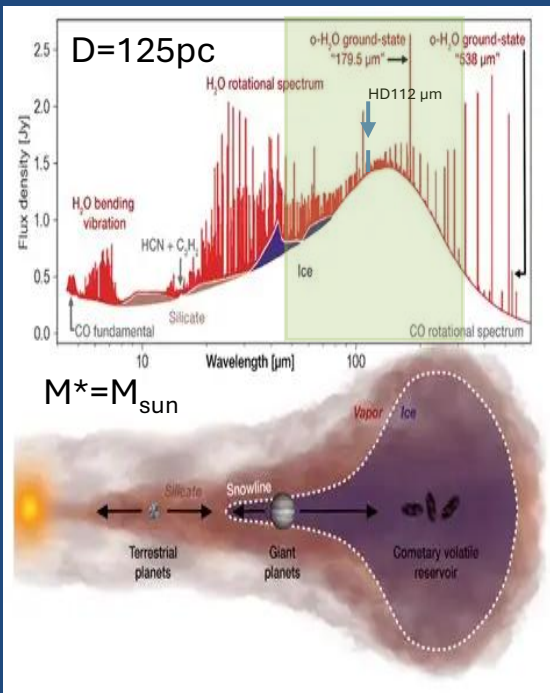


PHOENIX is a photonics-enabled interferometer designed to close the angular resolution gap between JWST and ALMA and to provide spectroscopic imaging with 1 km s^{-1} resolution.

Baseline Mission

Frequency	~1 - 6 THz
Wavelength	~300 - 50 μm
D_{ant}	6 m
N_{elements}	25
b_{max}	1.5 km
Beam @ 3 THz	~14 mas
T_{sys}	4 x QNL + 50 K
Cont. BW	100 GHz
Min spec. res.	1 km s^{-1}
Int. time	25 hrs.

Key Science Goals: Planet Formation and the Emergence of Habitable Environments



- Map the distribution of warm water vapor and water ice in protoplanetary disks (PPD)
 - Far-IR spectroscopy uniquely probes warm water ($T > 200\text{ K}$) and water ice.
- Measure disk gas masses using HD emission
 - Far-IR HD (112 μm) line provides a robust tracer of total gas mass, unlike CO, which can be depleted into CO ice.
- Observational Requirements
 - AU-scale angular resolution and $\sim 1\text{ km s}^{-1}$ spectral resolution.

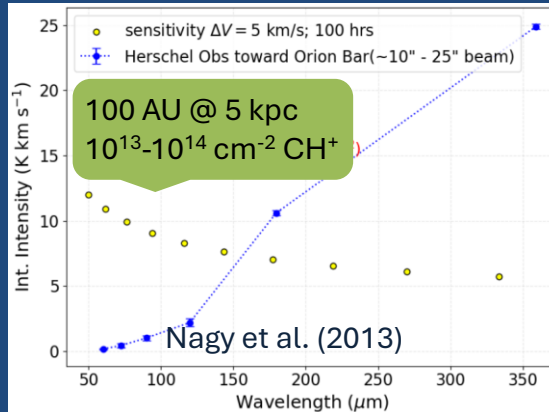
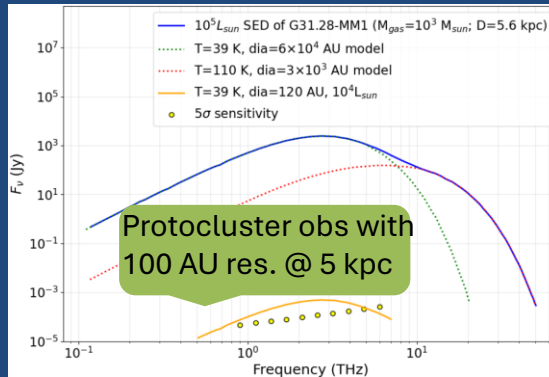
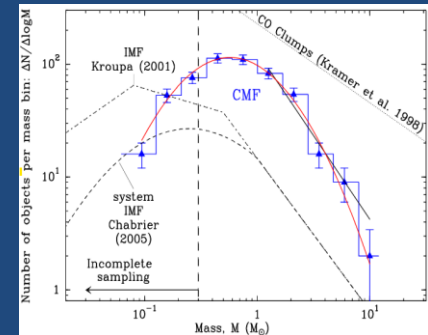
Pontoppidan et al. (2019)

Predicted Line and continuum sensitivity

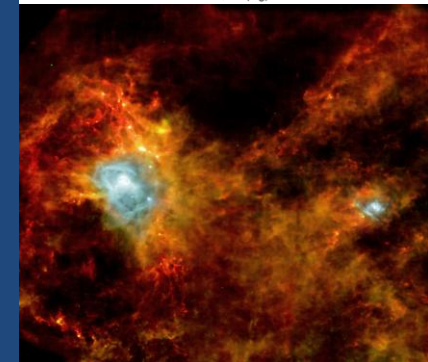
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Key Science Goals: Revealing the Origins of Massive Stars

Minier et al. (2005)



- Measuring the Core Mass Function of Massive Prestellar Cores in the OB-Star Regime ($M^* > 8 M_{\odot}$)
 - Deep FIR continuum imaging of the earliest, highly obscured prestellar cores near the SED peak, achieving 100 AU resolution at distances up to 5 kpc to resolve binary systems.
- Image turbulence dissipation in molecular clouds using CH^+ .
 - Require spectral resolution of $\sim 1 \text{ km s}^{-1}$ and spatial resolution $\sim 100 \text{ AU}$

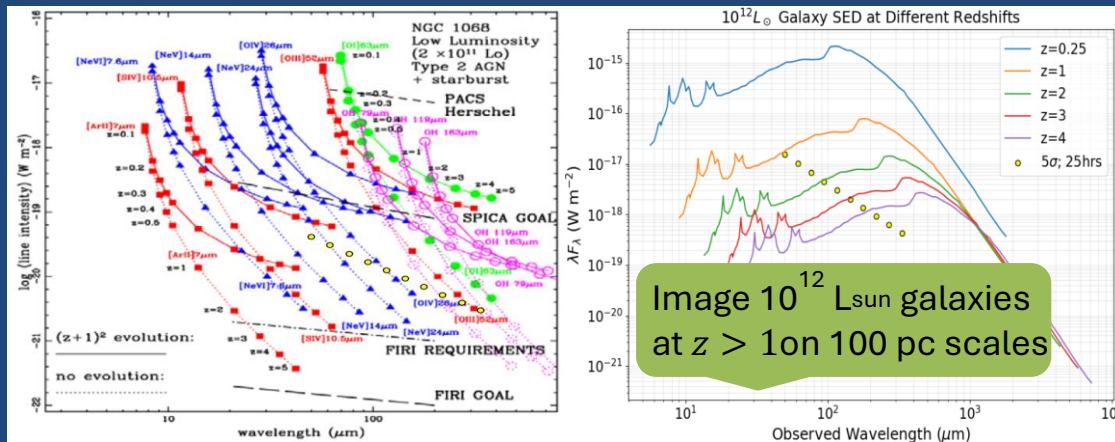


Composite 70, 160 & 500 μm
Herschel image of the $\sim 11 \text{ deg}^2$
Aquila field (Andre et al., 2010)

Predicted Line and continuum sensitivity

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Key Science Goals: Dust-Obscured Galaxy Evolution Across Cosmic Time



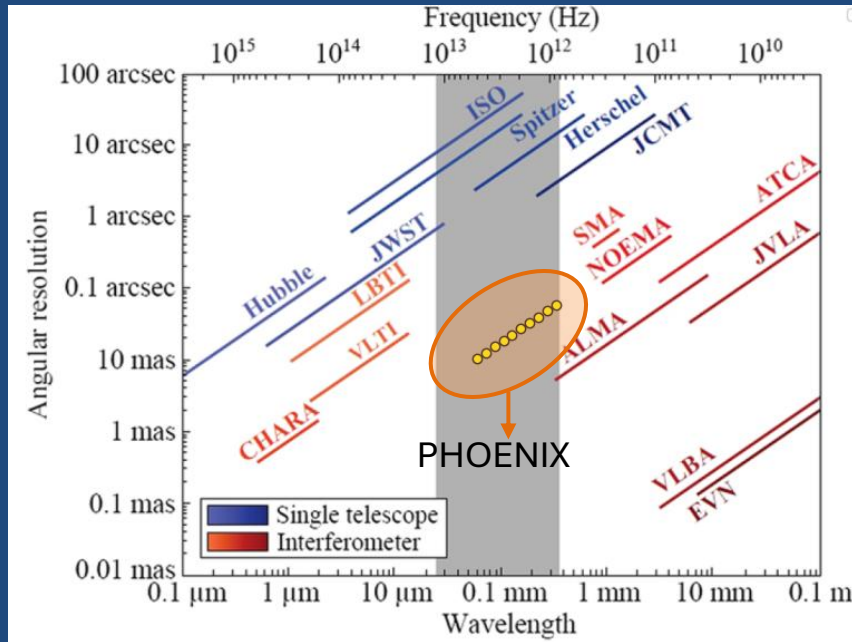
Predicted line and continuum sensitivity

- Uncover dust-obscured galaxy evolution by separating SMBH growth from star formation through high-resolution FIR observations.

Key Science Goals: FIR Transients

- Reveal the dust-obscured physics of short-lived transients through high-fidelity FIR imaging enabled by excellent instantaneous *uv* coverage.

Mission requirements



PHOENIX closes the FIR angular resolution gap.

Parameter	Value
Frequency	~1-6 THz
Wavelength	~300 - 50 μm
Angular resolution	10-20 mas
Field of view	> 2 arcsec
Min spectral resolution	1 km s ⁻¹
Spectral sensitivity @ 1km s ⁻¹ resolution	~5 mJy per beam (25 hrs)
Continuum sensitivity	~0.1 mJy per beam (25 hrs)
Image dynamic range	> 1000

These requirements can only be met with a heterodyne interferometer.

Mission Concept

PHOENIX: Submm/Far-IR INTERFEROMETER

25 Antenna Spacecraft, 6 m Reflector Antennas, Central Processing Spacecraft
Located at Earth-Sun L2 point



25 Antenna Spacecraft

4-8m size Antenna

1 Central Processing Spacecraft

1-2 km Maximum baseline

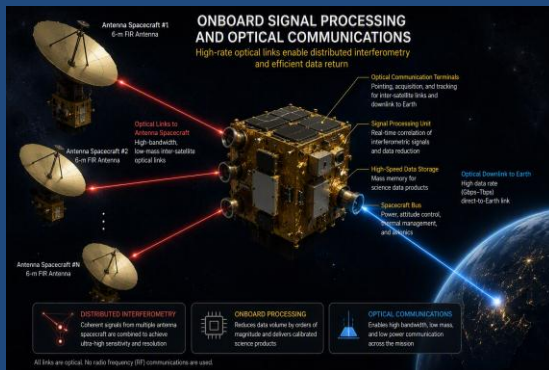
Earth-Sun L2 location

6 m HIGH-PERFORMANCE ANTENNA

Deployed for high-sensitivity observations



Antenna spacecraft

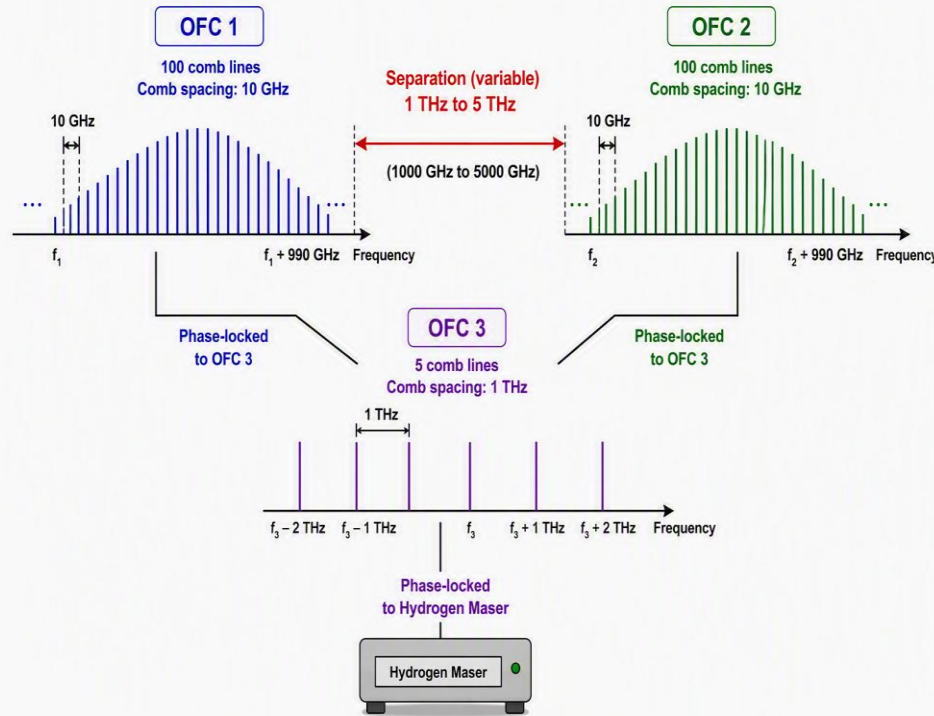


Central processing spacecraft
Red: analog link
Blue: digital link to earth

Photonic Integrated Architecture

NIAC 2026
concept study

Three Optical Frequency Combs (OFCs) Phase-Locked to a Hydrogen Maser



- Three-OFC master architecture phase-locked to a hydrogen maser reference
- OFC signals transmitted from the CPS to AS and coherently returned to CPS
- Provides local oscillator (LO) generation
- Provides a THz calibration comb for complex gain calibration
- Enables 100 GHz bandwidth signal transport from AS to CPS
- Supports high-precision ($\sim 5 \mu\text{m}$) metrology and ranging
- Provides command, control, and synchronization links for the AS

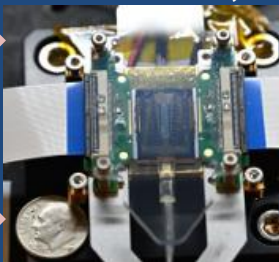
Correlator Architecture

NIAC 2026
concept study

Photonic channelizer

(Roshi et al. 2026, Gambini et al. 2024)

100 GHz
analog
optical
link



OFC

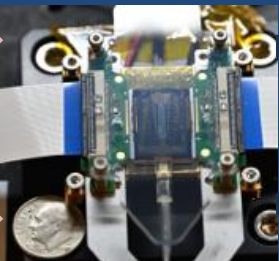
Low-power
ASIC-Based
Digital
Correlator

- The correlator is the dominant power consumer, particularly for ultra-wideband operation.

- Hybrid Optical-Digital Signal Processing Architecture



100 GHz
analog
optical
link



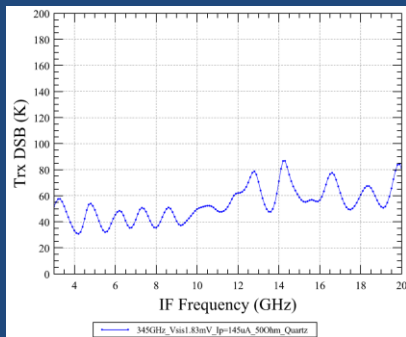
Photonic
Correlator

- A fully photonic correlator



Quantum Noise-Limited Receiver Technology

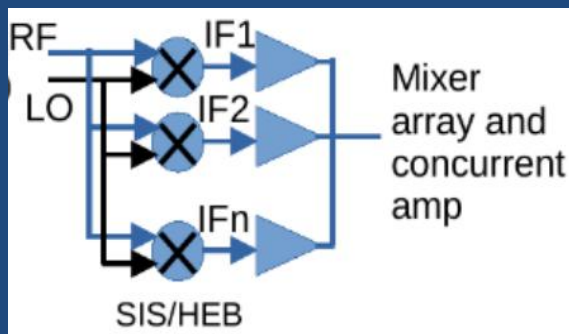
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MgB₂ based SIS mixers (Kooi et al., 2025)

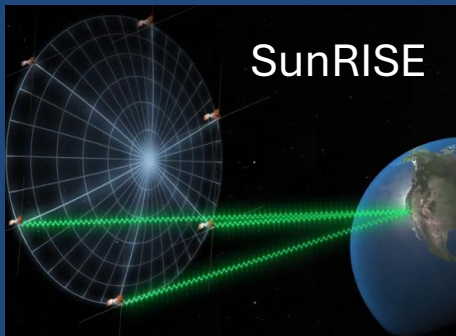


- Achieve quantum noise-limited sensitivity ($\sim 48 f_{\text{THz}} \text{ K}$)
- Broad RF Coverage to reduce the number of receivers
- Ultra-Wide IF bandwidth ($\sim 100 \text{ GHz}$) for increased continuum survey efficiency



Tong et al. (2013)

Spacecraft Constellation Architecture



A constellation of 6 CubeSats

- Near-uniform uv coverage for high-fidelity imaging across the sky
- Providing 1-2 km baselines
- Design to operate with minimal formation-flying constraints
- Propulsion-efficient architecture leveraging passive orbital geometry
- Extended mission lifetime through reduced station-keeping requirements

Other Enabling Technology Breakthroughs

- Cost-Effective Deployable Antennas
 - Surface RMS $\sim 2\text{-}3\ \mu\text{m}$; Multi-Spacecraft Deployment per Launch to Reduce Mission Cost
- Wide-Field Observation Capability
 - Heterodyne feed array, Nyquist-sampled focal plane arrays, distributed small-aperture arrays
- Cooling the Telescope Aperture
 - Quantum noise-limited sensitivity requires passive cooling the reflector to temperatures 70 - 20 K.

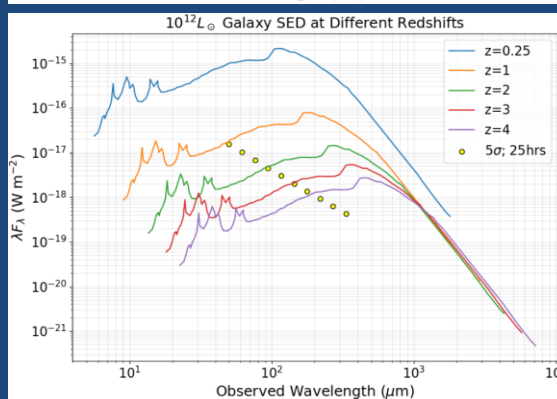
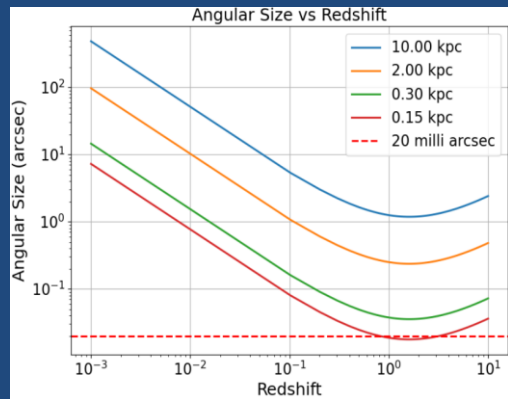
Path to PHOENIX

- Validate the OFC-enabled interferometric architecture
- Demonstrate low-power photonic signal processing and correlation
- Fly a photonics-enabled Solar THz interferometer pathfinder with ambient-temperature receiver technology
- Enable PHOENIX: milliarcsecond FIR imaging and spectroscopy Following SIS/HEB Technology Maturation

Thank you

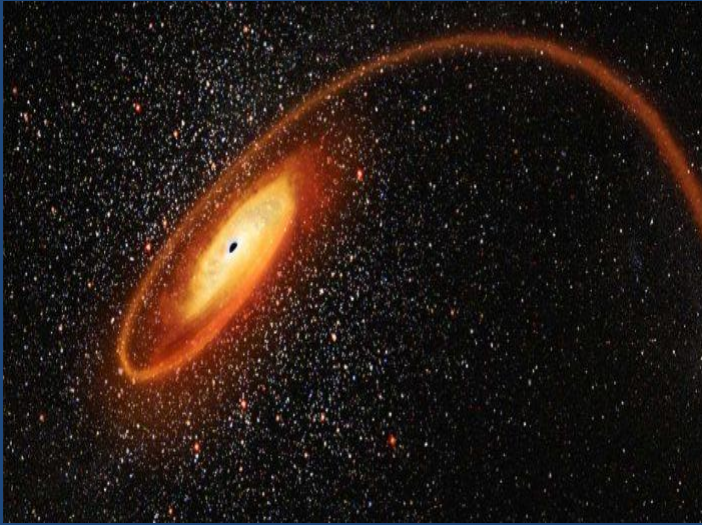
Co-Authors of the whitepaper: Anderson, Loren (West Virginia University); Benford, Dominic J. (NASA Headquarters); Brisset, Julie (University of Central Florida); Chen, Bin (New Jersey Institute of Technology); Cooray, Asantha (University of California, Irvine); Cox, Elbert L. (NASA Headquarters); Delfyett, Peter (CREOL, University of Central Florida); Dey, Saikat (University of Central Florida); Dwek, Eli (GSFC; University of Maryland, College Park); Eikenberry, Stephen (CREOL, University of Central Florida); Elvis, Martin (Center for Astrophysics | Harvard & Smithsonian); Emig, Kimberly (NRAO); Fernandez, Yan (University of Central Florida); Fischer, Jacqueline (Naval Research Laboratory); Ford, Alyson (University of Arizona); Goldsmith, Paul F. (JPL); Gopalswamy, Natchimuthuk (GSFC); Harwit, Martin (Cornell University); Iannello, Chris (University of Central Florida); Kashlinsky, Alexander (GSFC; University of Maryland, College Park); Kasdin, Jeremy (Princeton University); Kawamura, Jonathan H. (JPL); Kogut, Alan J. (GSFC); Kooi, Jacob W. (JPL); Leisawitz, David (GSFC); Li, Guifang (CREOL, University of Central Florida); Mather, John C. (GSFC); Melnick, Gary (CfA, Harvard & Smithsonian); Mundy, Lee G. (University of Maryland, College Park); Pineda, Jorge L. (JPL); Quadrelli, Marco B. (JPL); Rajagopal, Jayadev (NOIRLab); Rieke, George (University of Arizona); Salas, Pedro (NRAO); Sandell, Göran (University of Hawaii); Smith, Howard (CfA | Harvard & Smithsonian); Spergel, David N. (Princeton University); Swain, Mark R. (JPL); Weinberger, Alycia (Carnegie Institution for Science); Wright, Edward L. (UCLA); Hacking, Perry B. (El Camino College).

Impellizzeri et al. 2019



- Reveal how dust-obscured star formation and SMBH growth shape galaxy evolution through high-resolution FIR imaging and spectroscopy.
 - FIR fine-structure lines ([CII], [OI], [NII], [OIII], OH) and continuum emission provide powerful diagnostics for distinguishing star formation from AGN activity.
 - At $z > 1$, milliarcsecond-scale angular resolution is required to resolve AGN narrow-line regions and separate them from circumnuclear star formation.

Key Science Goal IV: FIR Transients

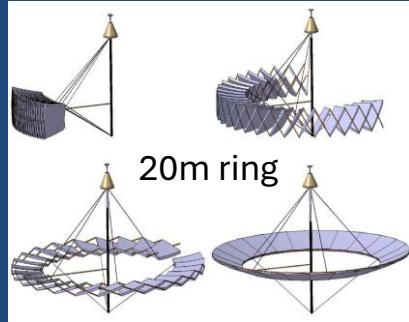


Artist's illustration of a tidal disruption event, in which a black hole tears apart a passing star and lights up as it accretes the stellar material.
<https://science.nasa.gov/missions/hubble/hubble-finds-best-evidence-for-elusive-mid-sized-black-hole/>

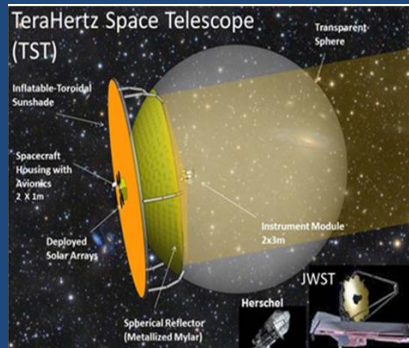
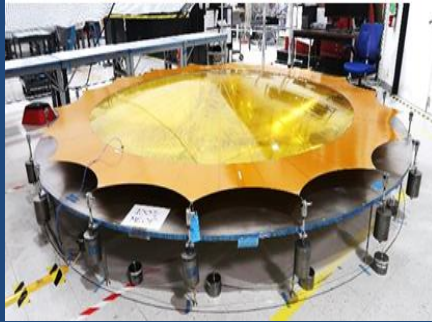
- Rubin Observatory and next-generation CMB surveys will revolutionize the discovery of transient astrophysical phenomena.
- FIR observations reveal the dust-obscured physics and energetics inaccessible at optical wavelengths.
- Short-lived transients (e.g., tidal disruption of stars) require high-fidelity imaging enabled by excellent instantaneous *uv* coverage.

Cost-Effective Deployable Antennas

Durand et al. (2014)



Kim et al. (2022) 14m

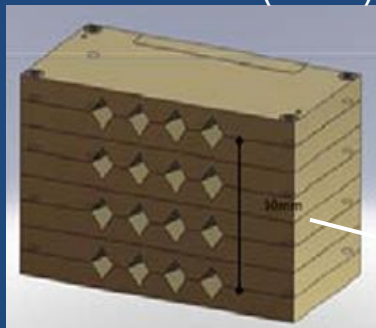


- Large Deployable Antennas (4-8 m Diameter)
- Surface RMS $\sim 2-3 \mu\text{m}$
- Multi-Spacecraft Deployment per Launch to Reduce Mission Cost

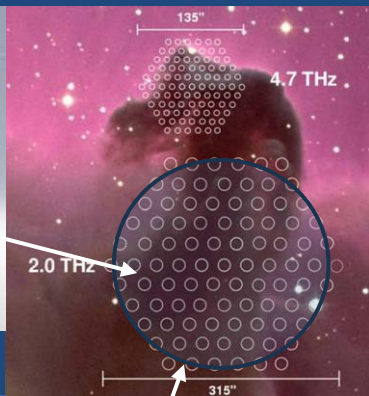
Walker et al. 2017 (10+ m) Array of small reflectors

Wide-Field Observation Capability

Walker et al. (2010)



Feed array



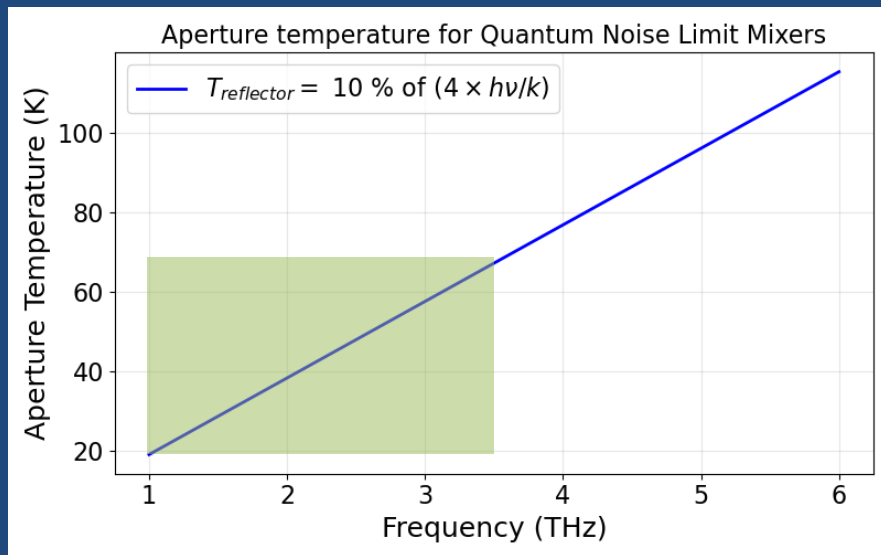
Phased
array feeds



Array of small reflectors

- Scalable heterodyne feed array architectures
- Nyquist-sampled focal plane arrays for wide-field imaging
- Distributed small-aperture arrays for enhanced sky coverage

Cooling the Telescope Aperture



- Quantum noise-limited sensitivity requires **(passive)** cooling the reflector to temperatures below approximately 70 K.

Receiver temperature is assumed to be four times the quantum limit.

Content

- Key Science Goals
- Mission Concept
- Enabling Technology Breakthroughs
 - Spacecraft Constellation Architecture
 - Low-Cost Deployable Apertures
 - Wide-Field Imaging and Enhanced Field of View
 - Quantum Noise-Limited Receiver Technology
 - Photonic Integrated Architecture for Array Synchronization, Calibration, LO Distribution, and Precision Metrology
 - Low-SWaP Correlator Architecture

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Baseline Mission

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D_{ant}	6 m
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Int. time	25 hrs.

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 - Revealing the Origins of Massive Stars
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