Novel Instrumentation in Far-IR Astronomy

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On behalf of Karwan Rostem (NASA Goddard)

Addressing Decadal Science Goals

The far-IR community responded strongly to the NASA call for a Probe scale far-IR mission concept

PRIMA, with a 1.8m single-dish cold telescope, was selected for Phase A study and promises to answer key questions in astrophysics.

Future instruments in low-background environments could benefit from novel approaches that improve spectral recovery and mapping speed.

Demonstrations in air-borne (balloon) platforms are essential

- In specific areas, complementarity with Probe scale missions is possible

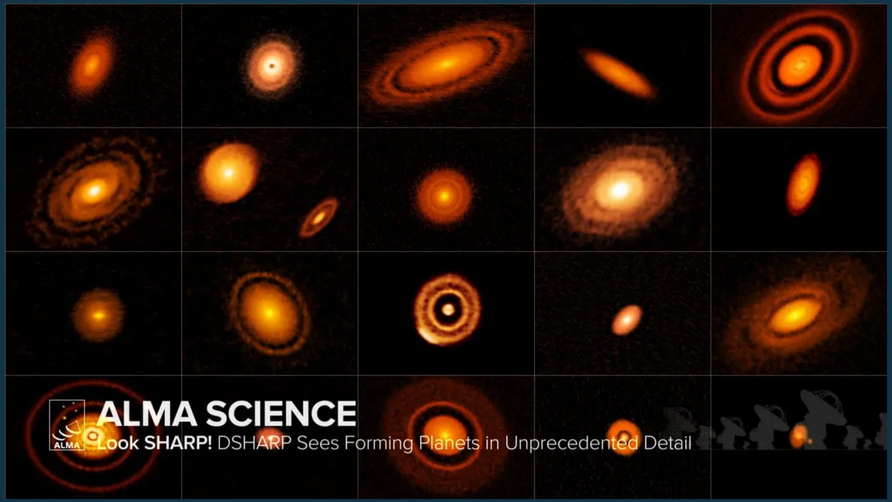
Planet Formation

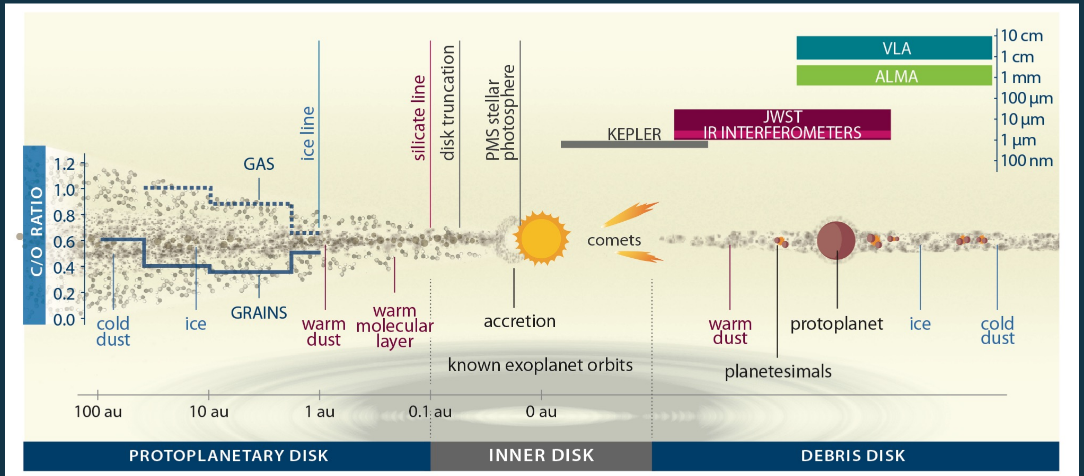
Protoplanetary disks (PPDs) are the birthplaces of planets. Understanding their evolution and composition is critical for explaining the size distribution and composition of exoplanet formation in the Galaxy.

Key questions remain in PPD science:

- What is the planet-forming mass of typical PPDs around solar-mass stars?
- Is water in PPDs inherited from the ISM or regenerated (sublimated) within the disk?
- Where is the water snowline?
- What is the cold ice mass beyond the snowline?

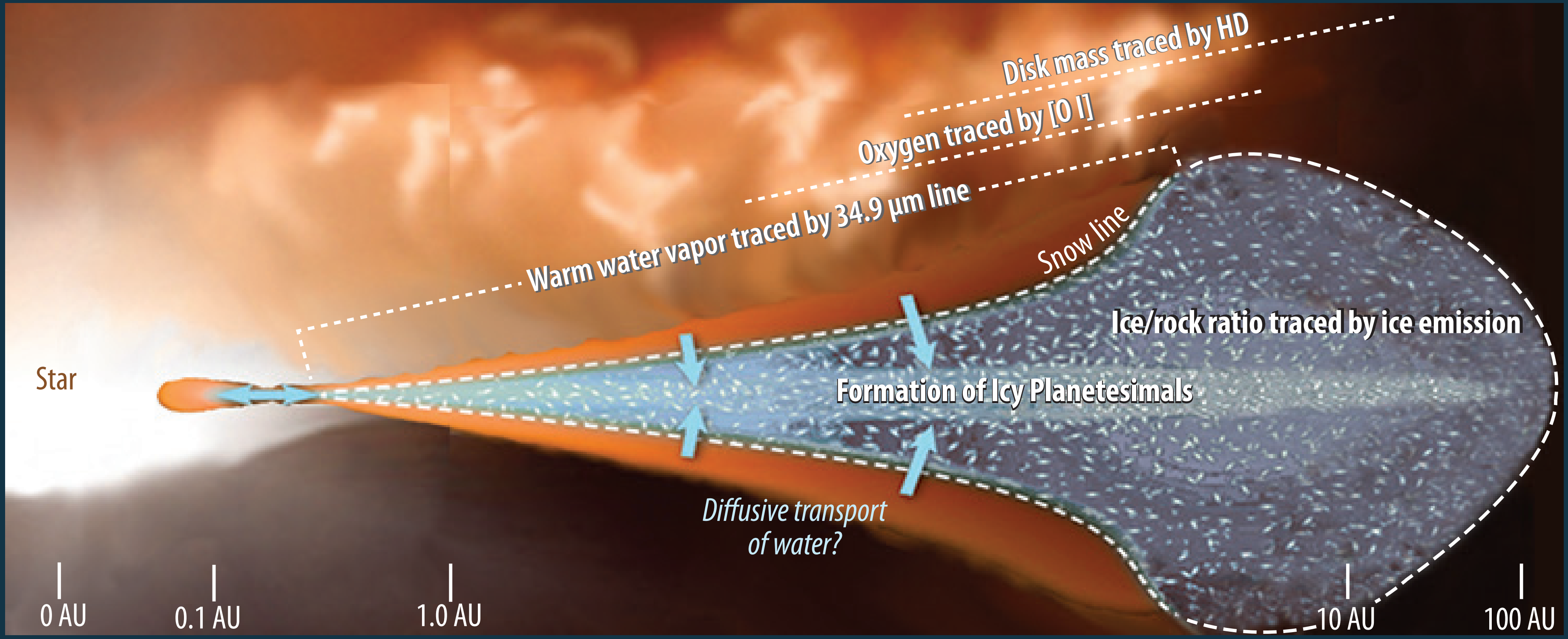
Size-scales ~ 0.1 to 10 AU are those at which the action occurs in PPDs





The Snow Line

- Radial distribution of warm water – uniquely traced in the far-IR -- reveals *the location of the "snow line", outside of which gas giants can form*
- Ortho/para ratios of water lines are linked to its formation temperature



How to "resolve" the disk: Tomography

Nearest PPD is TW Hydra (56 pc) where 1 AU ⇔ 0.019"

⇒ *to spatially resolve this at 100 μm requires >1km aperture!*

Would require space-interferometry in the far-IR

Instead, observe lines at velocity resolution ~3 km/s

For a disk at inclination angle θ the circulation velocity is:

$$v_{circ} = v_{obs}/\sin\theta \cdot \sqrt{GM_*/r_e}$$

For a solar mass star at 1 AU, v_{circ}= 30 km/s

⇒ For the inner regions of the PPD one can place the region of emission to *sub-AU accuracy* modulo the stellar mass and disk inclination

- Geometry can be modeled, or…

Many PPD sources have been observed by ALMA in the mm-wave continuum and lines so that geometry and stellar mass are constrained

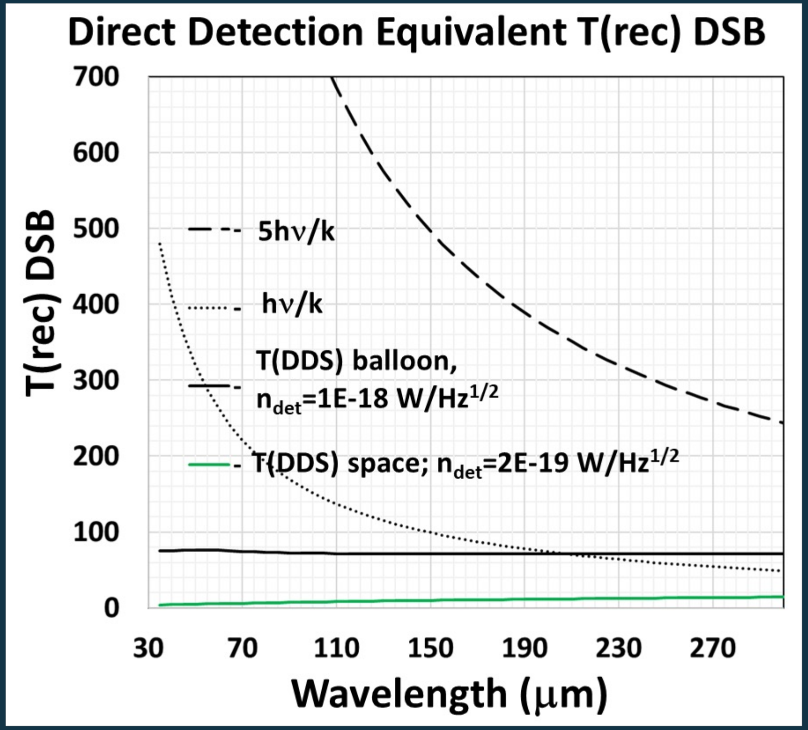
Direct Detection vs. Coherent Detection

Compare practical direct and heterodyne receiver sensitivities

Both subject to photon noise and detector noise

Heterodyne detection is limited by QM to $T_N > h\nu/k$. In practice, the best receivers have $T_N \sim 5h\nu/k$ (DSB)

In low background environments direct detection wins by large factors in the far-IR



From G. Stacey (Cornell)

Velocity Resolved Direct Detection

Direct detection and high resolving powers

- FPI, FTS, and gratings are used for both broad bandwidth and sensitivity
- *Velocity resolution limited by space constraints* for grating and FTS, e.g., R ~ $10^5 \Rightarrow$ delay path of 5 meters @ HD(1-0) 112 μm
- Multi-pass resonator (FPI) vastly reduces size: 5m $\rightarrow$ 10 cm
- *but* the FPI is not a spectral multiplexer: it must spectrally scan n resolution elements
  - penalty to sensitivity: $\sqrt{n}$
- Also, like the FTS, it requires moving parts.

For FIR science need to go to balloons or space $\Rightarrow$ a compact, no moving parts design is highly desirable!

The VIPA: A Marvelous Device

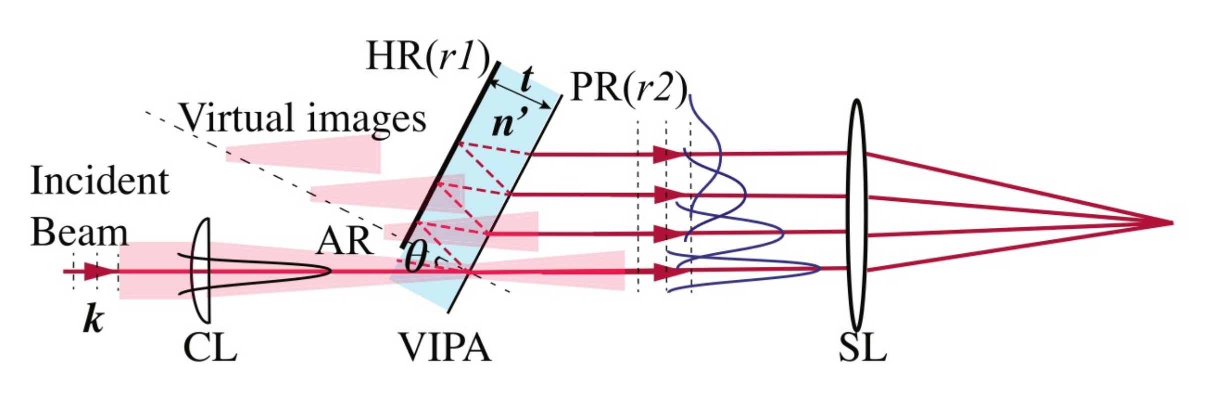
Virtually Imaged Phased Array

A piece of silicon for 112 µm HD line is 3 cm thick, 3 cm wide × 9 cm long for R ~ 100,000!

Yields a free spectral range of spectral samples (= finesse)

VIPAs in the far-IR can have >50 spectral resolution elements and deliver > 6 spatial beams *with no moving parts*

A single VIPA can be used to observer multiple spectral lines, one at a time (detector array size limited) or all together with a cross-disperser and large detector array (already demonstrated at visible and near-IR).



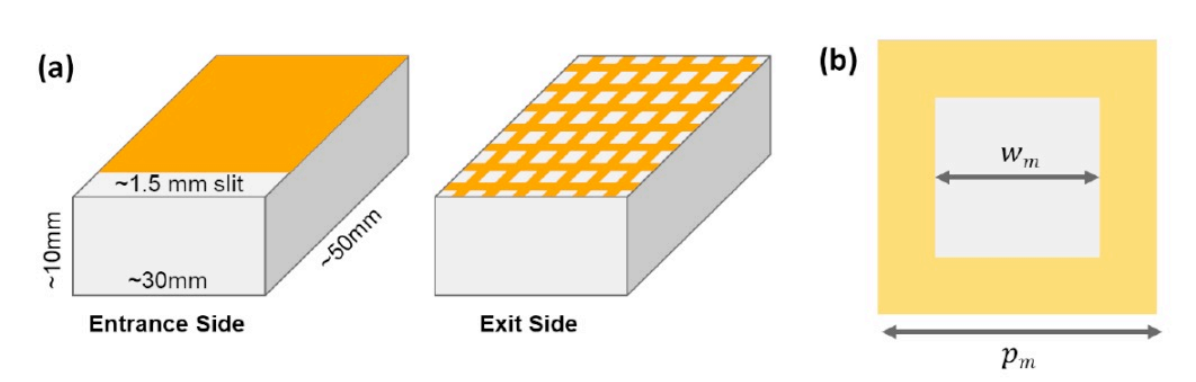
Zhu et al., The Astronomical Journal, 160:135 (8pp), 2020 September

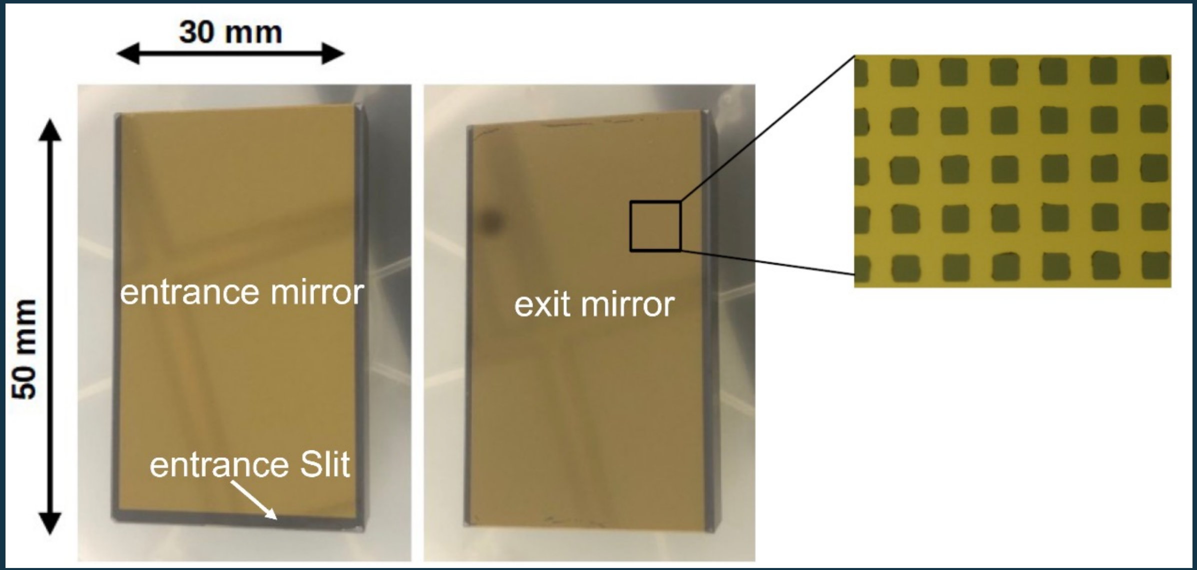
How to Make a far-IR VIPA

Cut a block of ultra pure silicon and coat it with appropriate reflective layers

First far-IR VIPA manufactured under small R&D effort (a collaboration between Cornell, Goddard, and SRON)

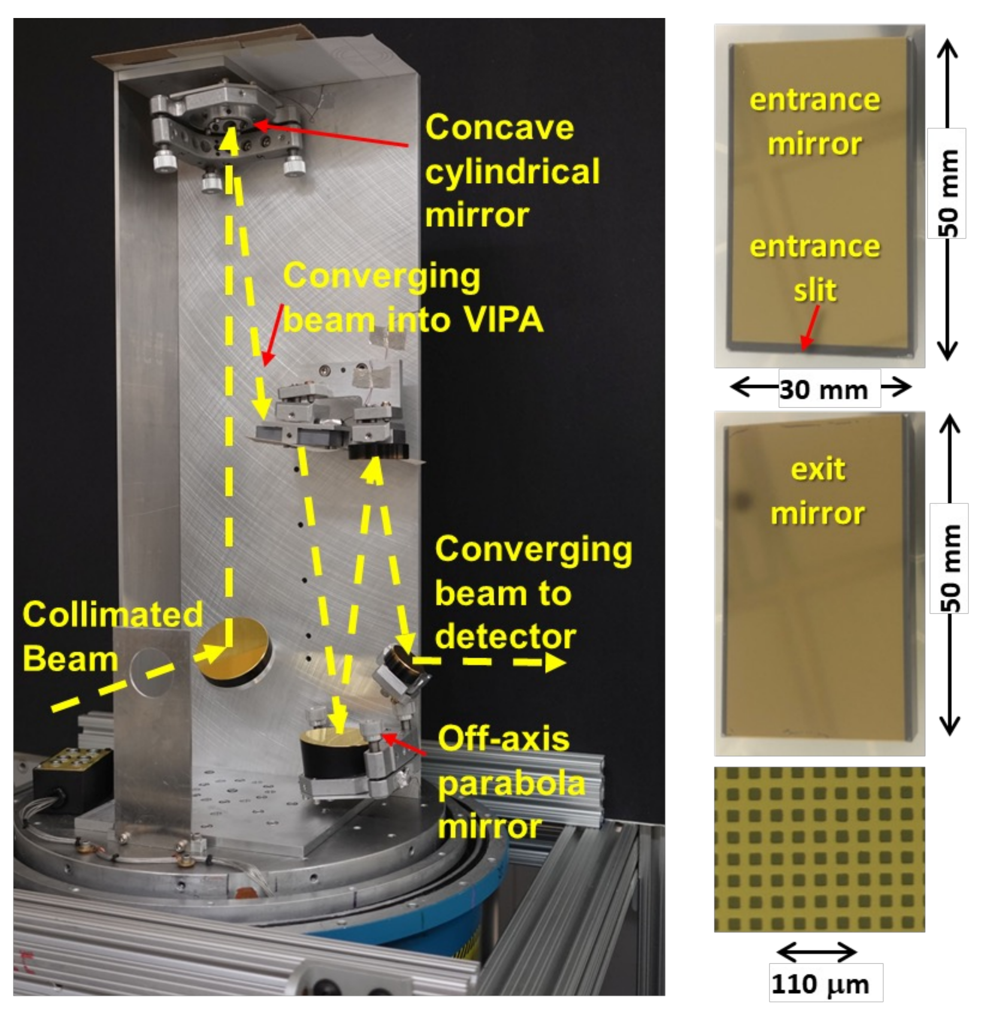
Zou et al. 2025, Applied Optics, Accepted





Far-IR VIPA Demonstration

Collaboration between Cornell, Goddard, and SRON.



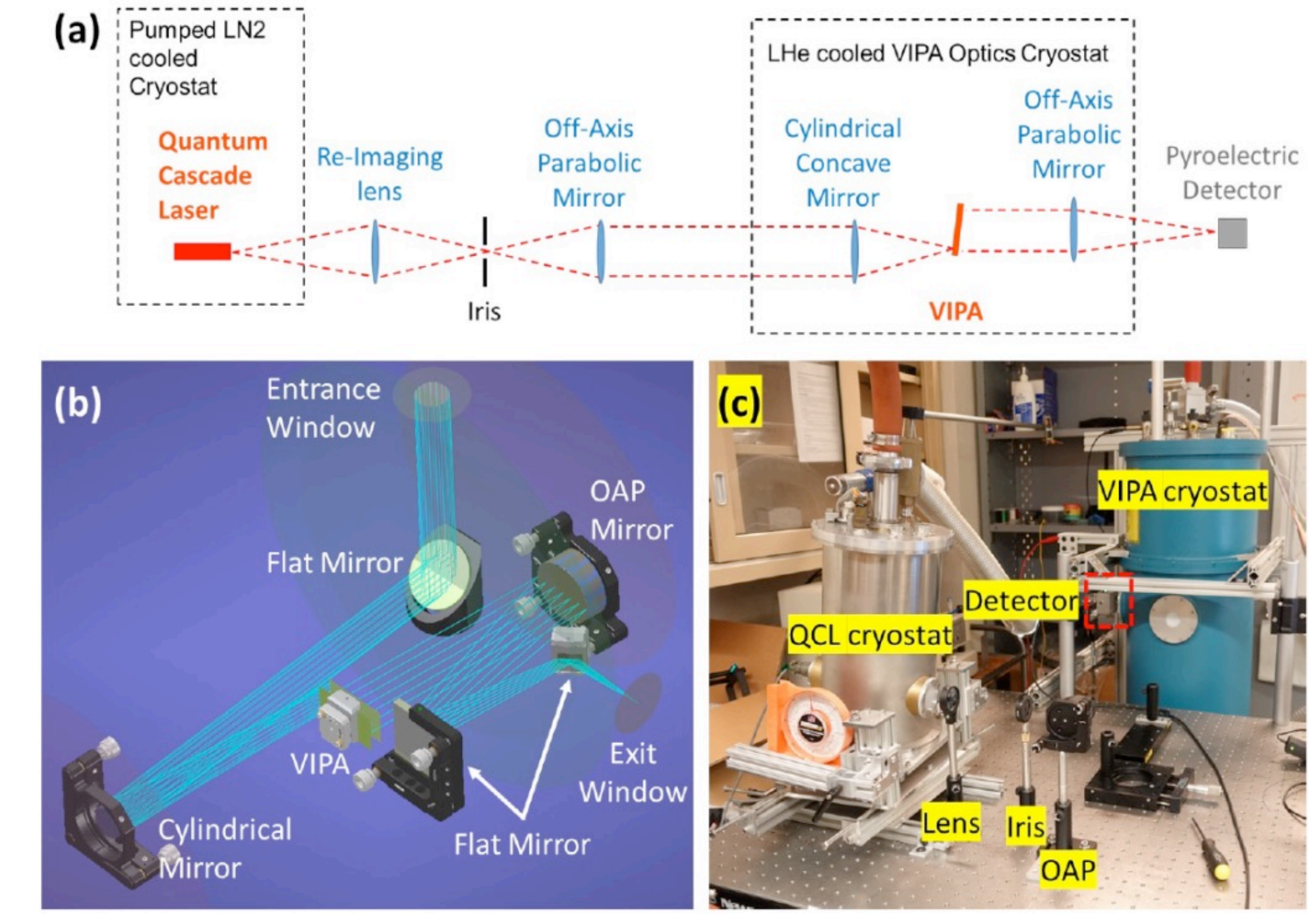
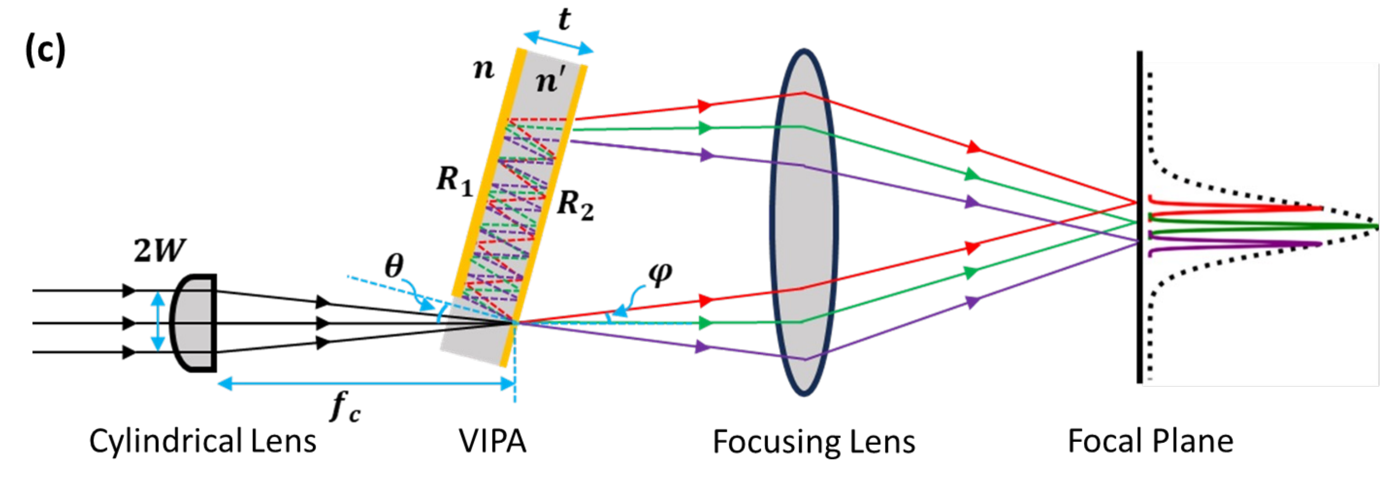
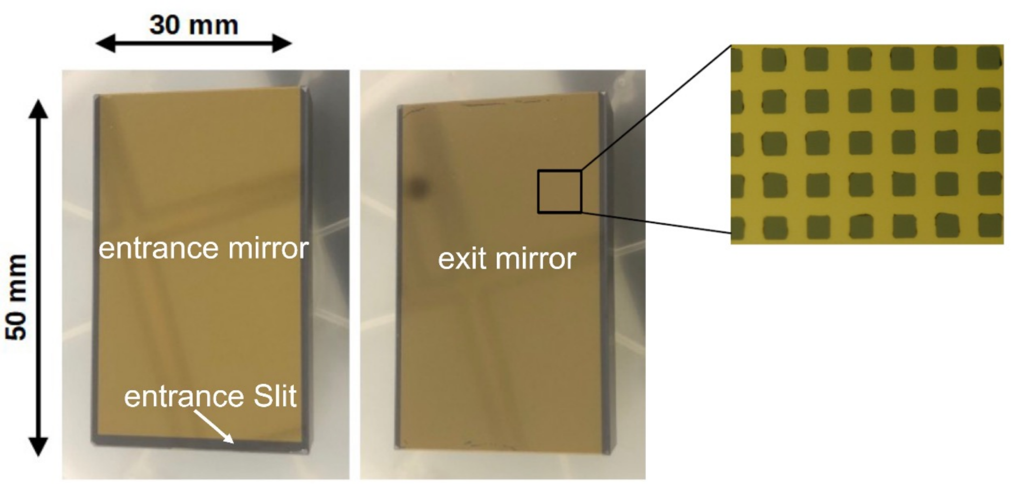


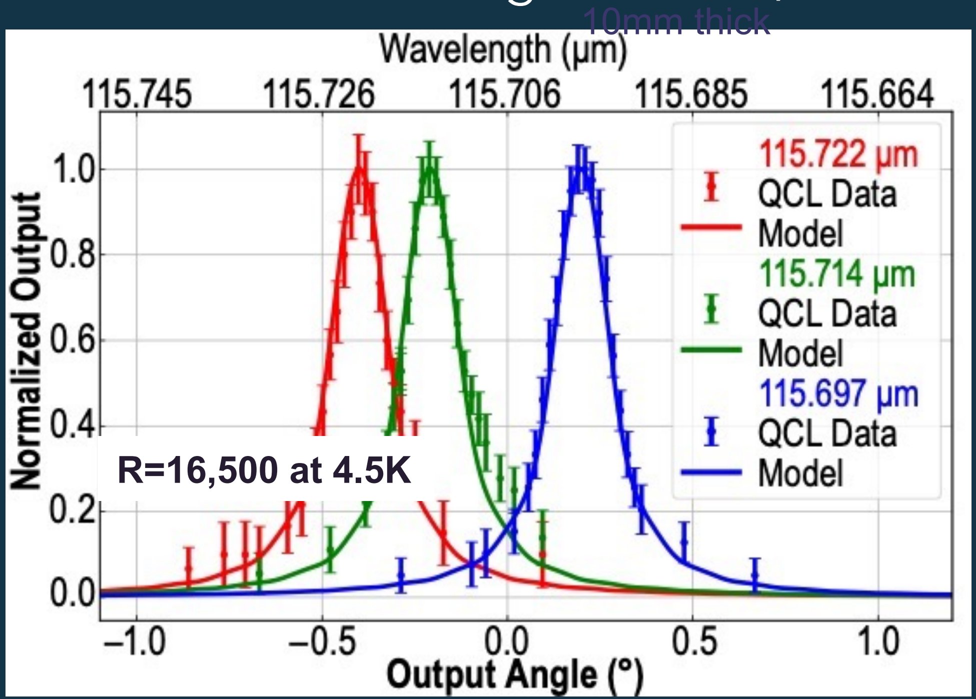
Fig. 5. (a) Simplified schematic of the main components of the testbed. (b) Detailed optical layout of the VIPA cryostat. (c) Photograph of the experimental setup in lab.

Far-IR VIPA Demonstration



First far-IR VIPA demonstration
R~16,500 (limited by VIPA length and loss in metal mesh Au layer)
Current effort leading to R~100,000





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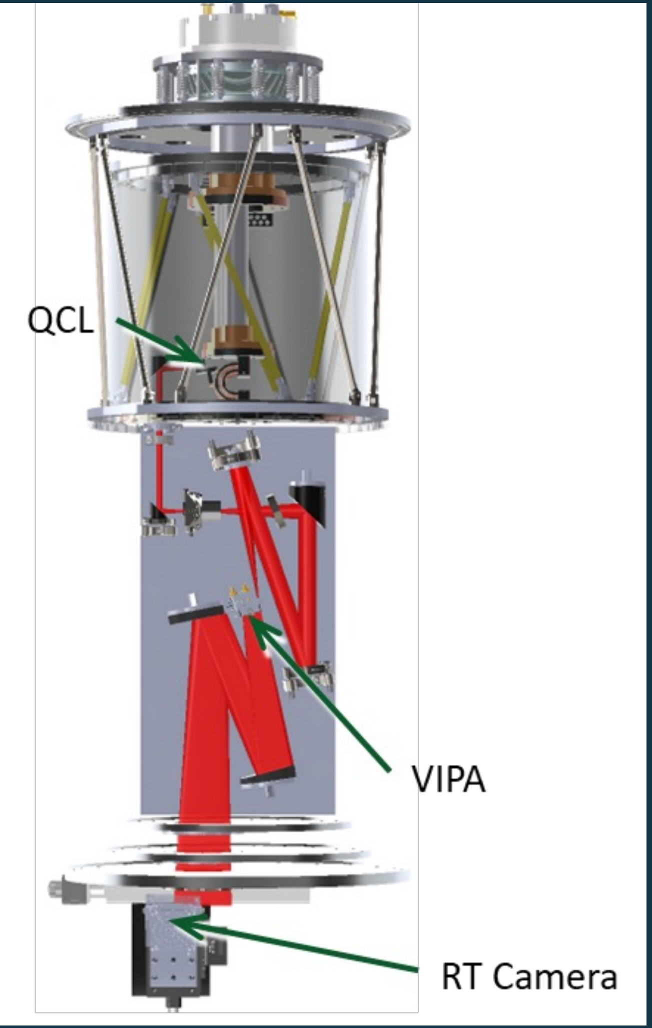
VIPA Testbed at Goddard



- Goddard designing a 60 and 80 μm VIPA testbed
- Up to 1.5 FSR of the VIPA can be detected, enabling full characterization of the VIPA dispersion and optical efficiency
- Quantum Cascade Laser (QCL) source is used for single frequency and high optical beam power
- A spatial filter cleans the QCL beam before injection into the VIPA

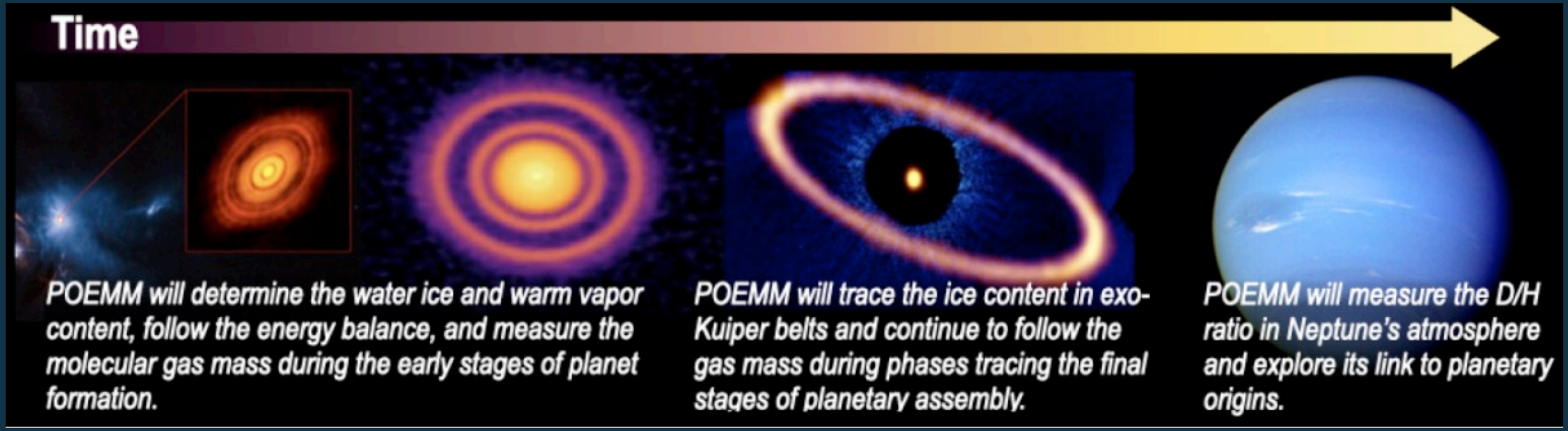
POEMM

POEMM (Planetary Origins and Evolution Multispectral Monochromator) is the latest selection in NASA's Astrophysics Explorer Pioneers line

POEMM is a 1.8-meter balloon-born telescope dedicated to exploring planet formation through far-IR spectroscopy

POEMM contains VIPA spectrometers, a low-resolution grating spectrometer, and 3 MKID arrays from SRON

⇒ POEMM provides complementary capability to PRIMA in PPD science!



POEMM Team

POEMM Science Team

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Planet Formation: Disk Mass

- H_2 rotational line emission is highly forbidden, and the lowest level lies 510 K above ground ⇒ quadrupole line emission is very weak and temperature dependent.
- CO is often used as a proxy but the "conversion factor" is highly dependent on physical properties of the gas.
- In contrast, the HD lines (1-0 @ 112 μm & 2-1 @ 56 μm) are *low-lying and permitted* ⇒ they trace molecular gas mass, and their ratio constrains T_{gas}.

POEMM traces the mass distribution in PPDs constraining models of planet formation

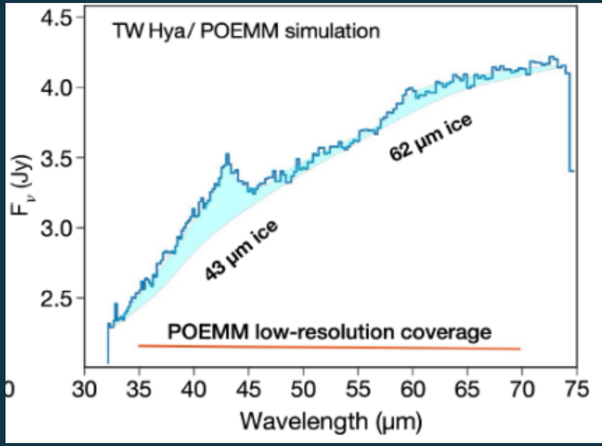
The Origins of Oceans

- How is water delivered to terrestrial planets?
- Are icy Kuiper Belt and Ort Clouds common in exoplanetary systems or are exoplanetary debris disks dry?

- Collisions of minor bodies release ice

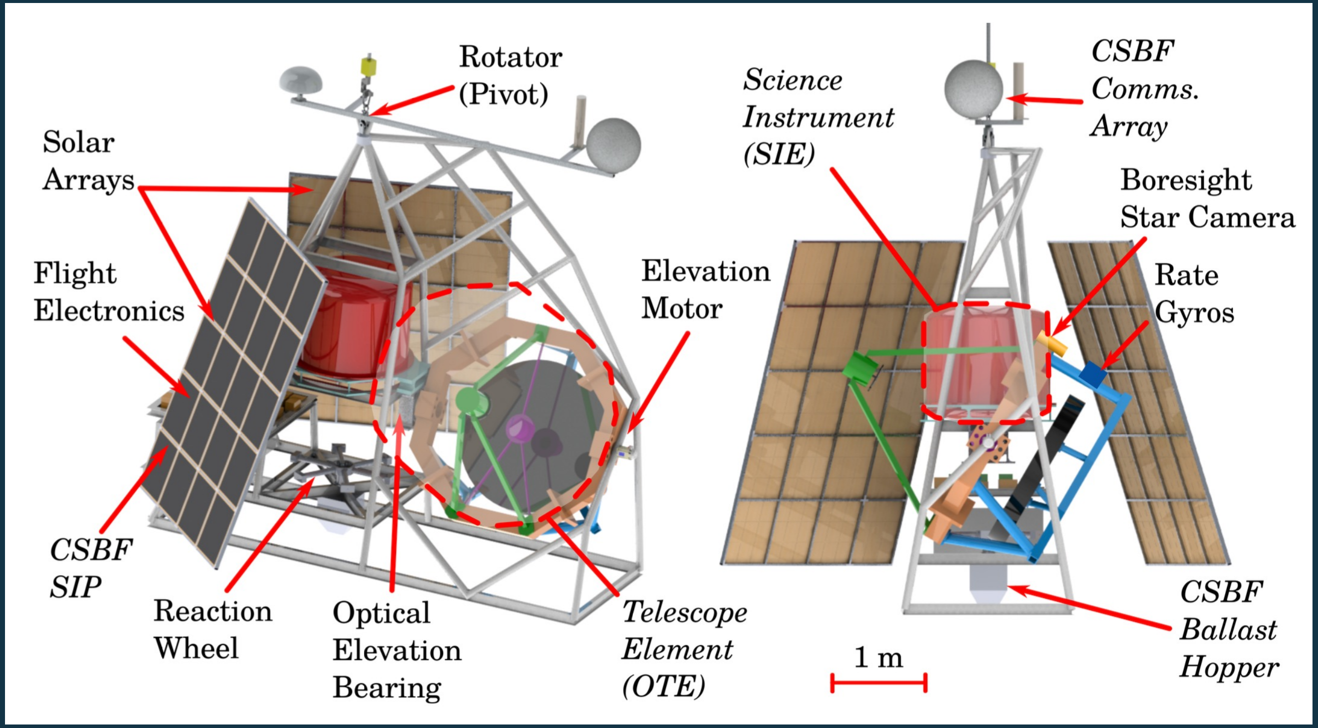
⇒ ice emission at 43, 47 & 63 μm

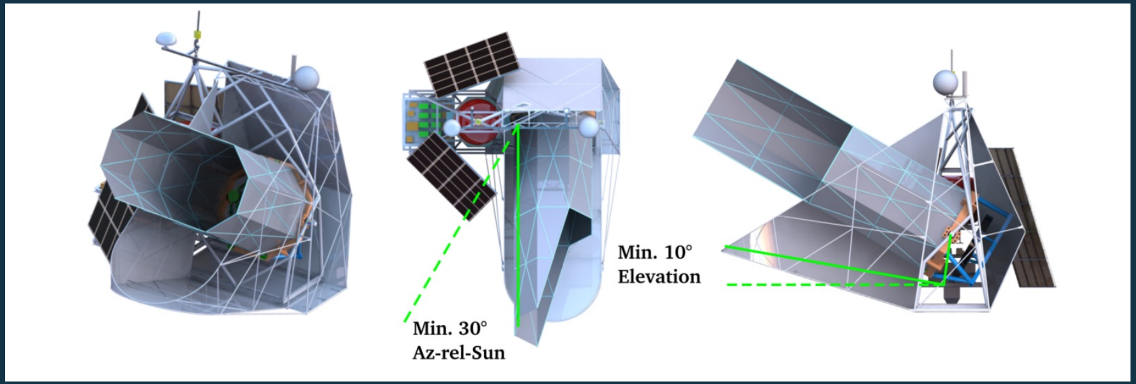
⇒ a source for oceans in terrestrial planets.



Gondola

Provided by StarSpec Technologies Inc. based on their extensive experience, including BLAST

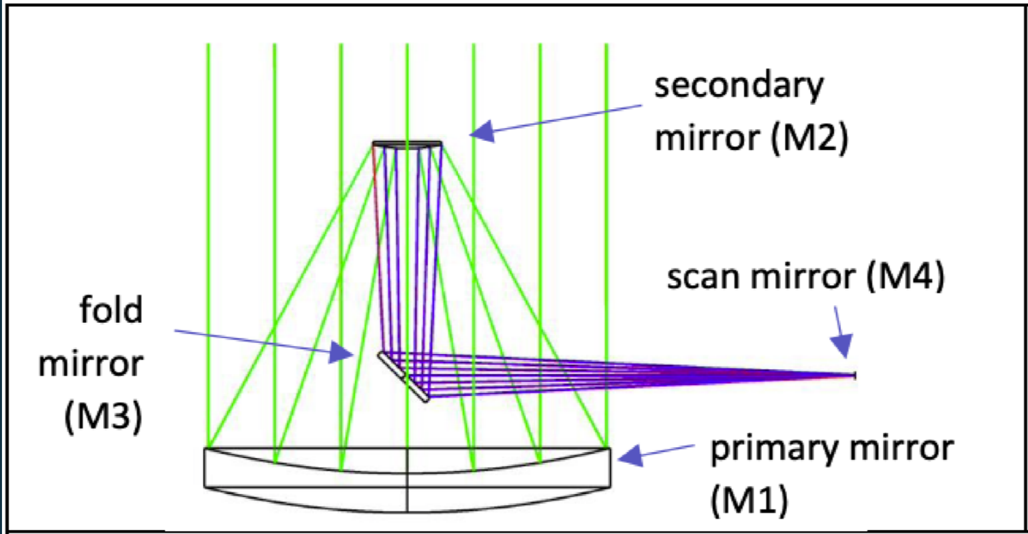




Telescope

1.8 m Nasmyth-Cassegrain that delivers an f/10 beam to the instrument focal plane

The 1.8-m diameter primary mirror will be manufactured at MSFC - based on technologies successfully demonstrated on a 1.2-m prototype.



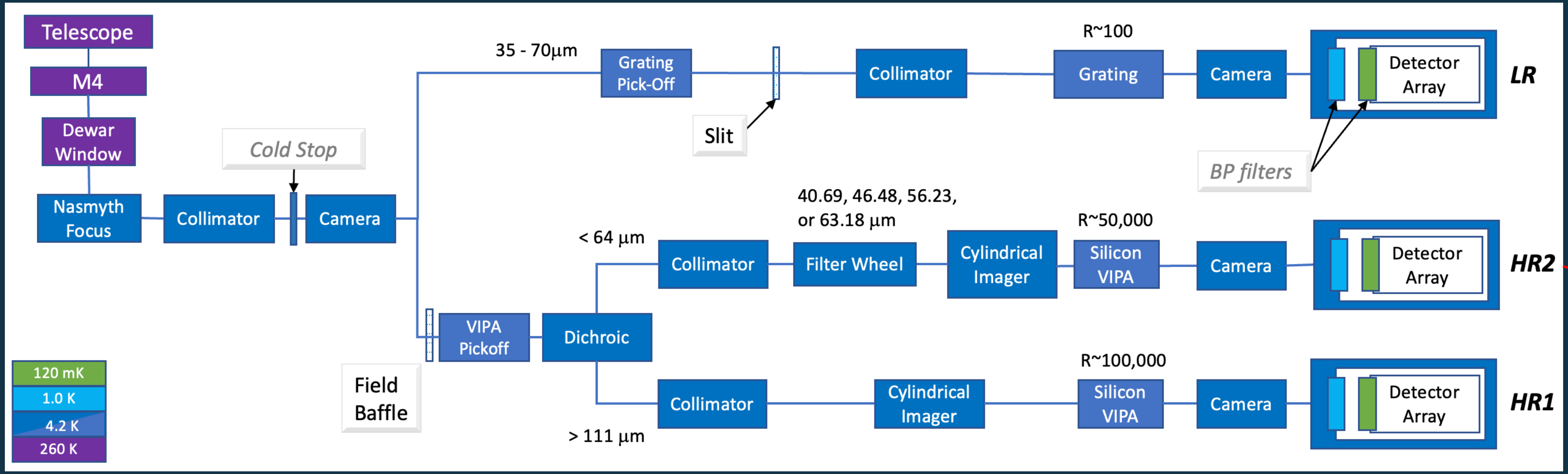
Key parameter characteristic:

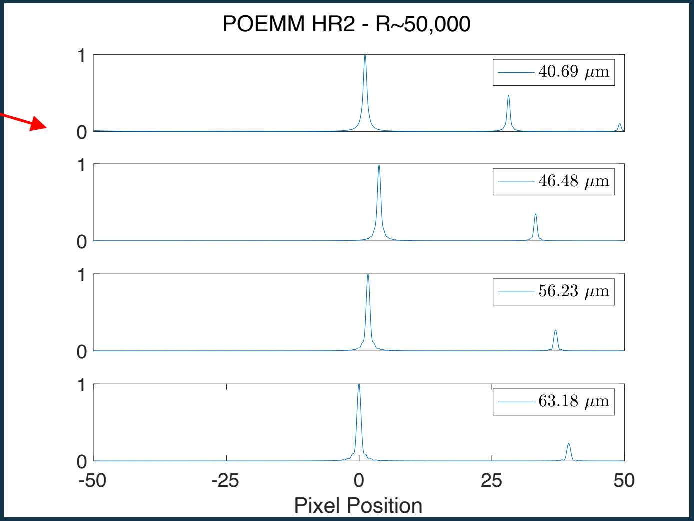
- Operating Wavelength: 35 to 112 µm
- Focal length: 18 m
- Aperture Diameter: 1.8 m
- Diffraction limiting wavelength: <70 µm (goal of 40 µm)
- Elevation range: 10 to 65 deg.
- Weight: 550 kg
- Operating Temperature: -10 °C
- 1st Resonant Mode: >25 Hz

Instrument Implementation

Telescope provides 1 DOF scanning at ~1 Hz for scanning source along slit in each channel

Selection between LR and HR modes is achieved by placing the source in the appropriate field position at the Nasmyth Focus





Further optimization underway

POEMM Schedule

Official approval June 27, 2024

Concept Study Report (CSR) due August 2025

System Readiness Review 6 months after CSR

Test flight in Texas Fall 2028

Antarctic flight Austral 2029-2030 summer for a 20-day flight

Summary

There is exciting progress in far-IR instrumentation and detection

The vast improvement in far-IR detector sensitivity coupled with novel approaches will lead to breakthrough science with air-borne and ambitious future space missions

An example is the VIPA spectrometer described here, enabling far-IR spectral line tomography across a free spectral range with no moving parts

POEMM, a balloon-borne instrument, will use VIPAs to resolve the 112 μm HD line and a host of other important diagnostic lines across 40 to 63 μm to study protoplanetary disks

POEMM is currently in a concept study phase, with an Antarctic flight expected in Austral 2029-2030 summer