Keck INSTITUTE FOR SPACE STUDIES

Exploring Exoplanets with Interferometry
November 28 - December 2, 2022

Overview of Caltech Keck Institute Workshop on Exploring Exoplanets with Interferometry

Bertrand Mennesson

Jet Propulsion Laboratory,
California Institute of Technology

Seattle ExoPAG 27 meeting
January 7, 2023

© 2023 California Institute of Technology, government sponsorship acknowledged. This work had its inception at the study funded by the W.M. Keck Institute for Space Studies

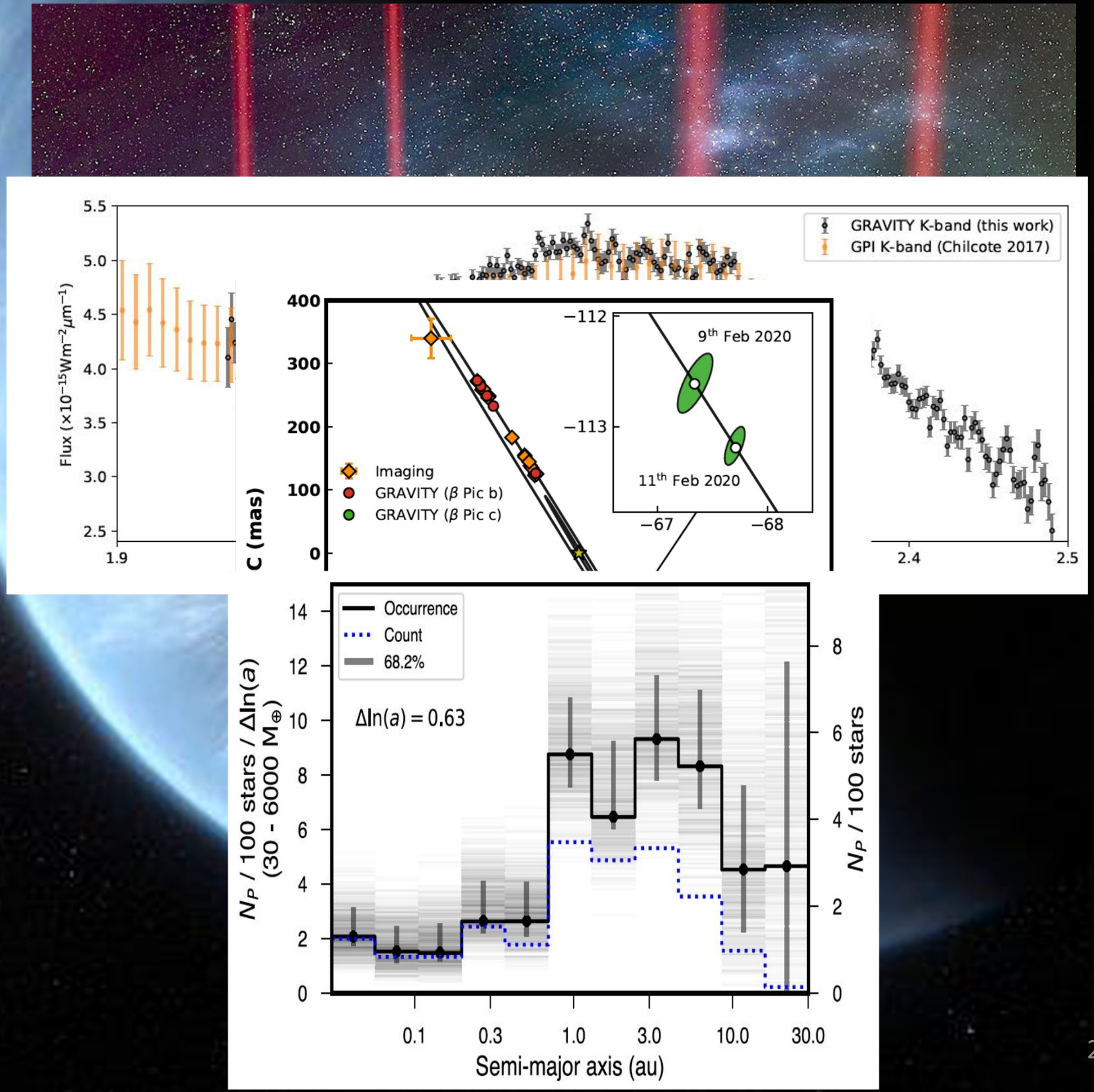
https://kiss.caltech.edu/workshops/Interferometry/Interferometry.html

Why an Infrared Interferometry Workshop now?

- 2021: Large Interferometer for Exoplanets (LIFE) Voyage 2050 mission proposal selected by ESA for further study

- Since 2018: spectacular VLTI Gravity results:
  - Direct detection, of young EGPs at smallest separations currently accessible (~100 mas)
  - "High" resolution high quality spectra of b Pic b (Nowak et al. 2020)
  - First direct detection of RV planets:
    - bep Pic c : 8.2 +/- 0.8 mJ at 2.7AU (Nowak et al. 2020)
    - HD 206893c at 3.5 AU (Hinkley et al. 2022)
  - Astrometric precision <~ 100 µas (>10x better than single ground-based telescopes

- Bulk of EGPs population likely within 10 AU (e.g. Fulton et al. 2021)
  - Majority of new direct detections before ELTs will come from interferometry



Workshop Key Questions

1. What are the Synergies between LIFE and HWO?

    Scientific complementarity

    Technical synergies

2. What are the immediate next steps to enable a LIFE-like interferometry mission?

    Toward a small space interferometry demo (or two)

    Gaining further science momentum: breaking the diffraction limit of direct exoplanet detection from the ground

3. What are the key technical trades ahead in prep for a LIFE-like mission?

1. How do we build a lasting international community around space IR interferometry?

Synergies and Complementarities between LIFE and HWO

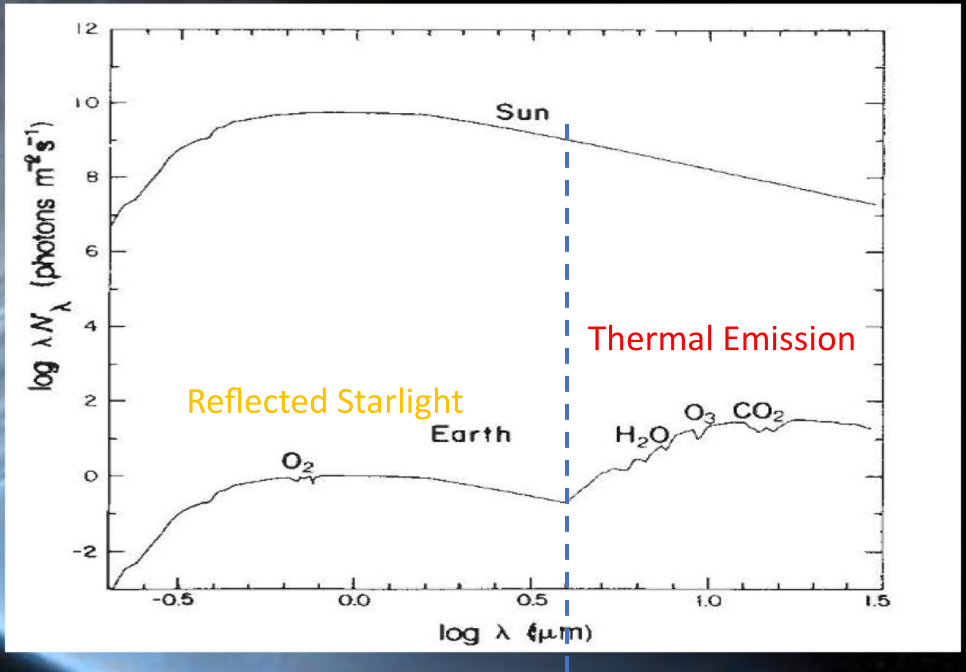
- Science

Precursor Science: both missions will benefit from:

- More accurate exoplanet occurrence rates
- Better estimates of exozodi levels and spatial distributions
- Better line opacity profiles

Complementary physical characterization of exo-Earths

- HWO atm. characterization: Rayleigh scattering, H_2O, O_2 (PAL), CH_4 (Archean), possibly O_3 in the UV (Proterozoic and PAL), and potential vegetation red edge
- LIFE ~5 to 20 um: O_3 (9.6 um) and CO_2 (~15 um) at PAL
- LIFE: estimates of planet radius and temperature



Synergies and Complementarities between LIFE and HWO

- Technology

High dispersion (R> 10,000) options for both optical coronagraphs and mid-IR nullers

- E.g. explore approach analogous to Keck Vortex Fiber Nuller Coronagraph coupled to high res spectrograph

Cross-aperture nulling techniques could reach smaller separations and benefit HWO

- May access Earth-sized planets around M stars

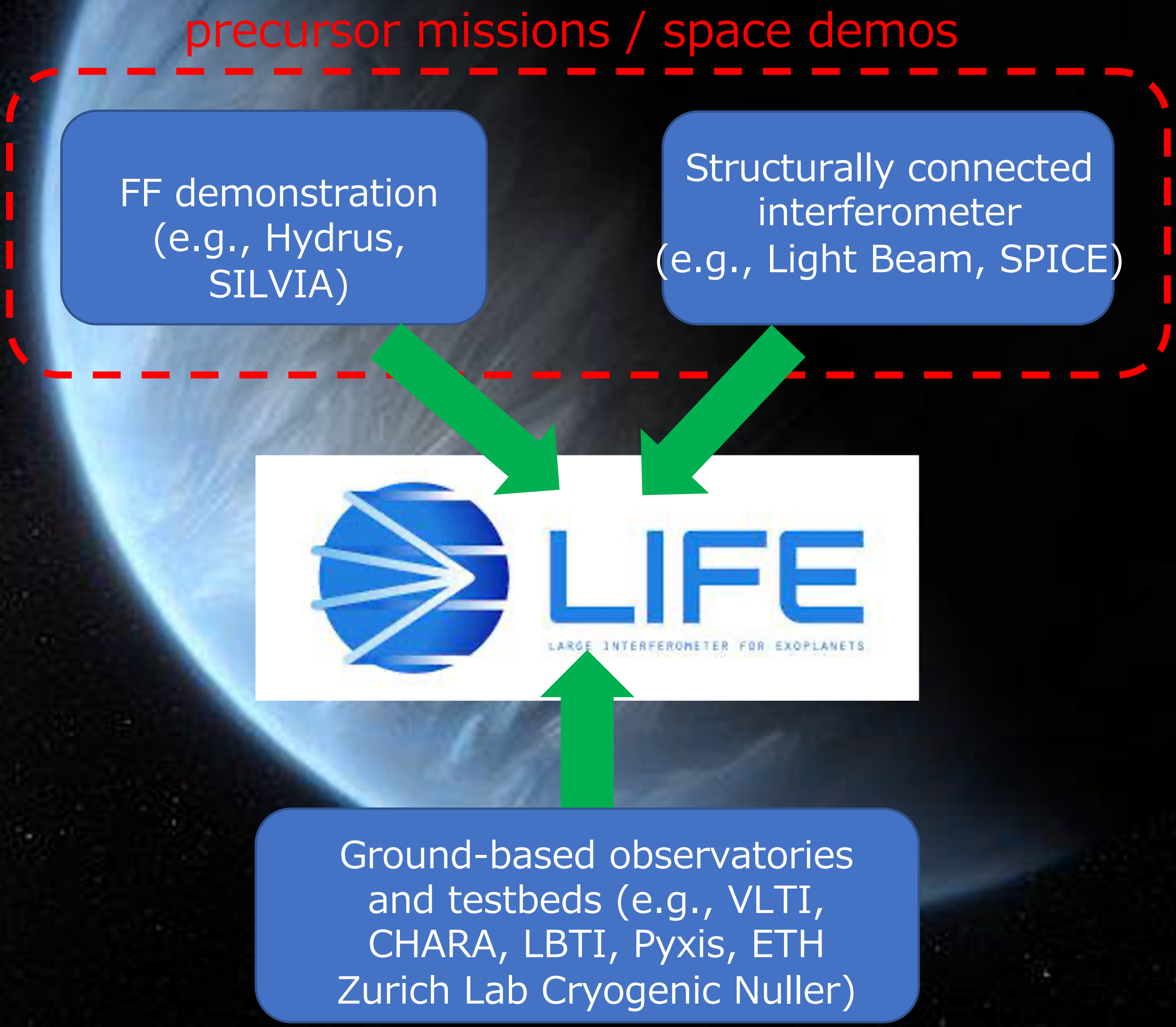
Low noise infrared detectors

- Fringe tracking wavelength for LIFE = HWO red science channel

LIFE Free flying technology may be applicable to a possible starshade on HWO

Next Steps to enable and support a LIFE-like Mission

- Formation Flying Space Interferometry
- Structurally-connected Space Interferometry
- Ground-based facilities



Toward a Space Interferometry Demo (I)

A zoo of small Sats (100-250 kg) + cube sats (<15kg) demonstrations planned

we are rapidly accumulating expertise in FF!

Funded conceptual studies: mDoT (500km starshade + 9cm CubeSat Telescope, NASA, Stanford), VTXO (NASA, Xray, Cubesat)

Funded formation flying missions to be launched soon:

- Pure tech demo: Starling (NASA, 4 CubeSats, 2023?), Rendezvous autonomous 2 Cubesats experiment (RACE, ESA, launch 2024)
- Solar and Plasma Science: Swarm-Ex (NSF, 2023), Helio SWARM (NASA, 2028), VISORS (NSF, UV, 2 Cubesats, 2024), Proba-3 (ESA, 2 small Sats, 2024)
- First formation flying interferometers: Aero-VISTA (NASA, Sun, 2CubeSats, Radio 2023?), Sunrise (NASA, Sun, Radio, 6 CubeSats, 2024)

Unfunded Formation Flying missions

- Laser Guided Stellar Interferometer (LGSI, MIT, several Cubesats LEO), JUStIInE (NSA APRA), Optimast, SPICE, SEIRIOS, SYLVIA (JAXA), STARI (U Mich), IRASSI (Germany, infrared), HYDRUS (Cubesats in LEO, NAU), Lunar Sited Interferometer (Artemis “suitcase”)?

Light Beam concept

Unfunded structurally connected 2T interferometer mission concepts:

- Optimast/ Light Beam (NASA/Lowell SBIR), SPICE Probe (25-400 um)

Toward a Space Interferometry Demo (II)

- Workshop Recommendation #1: demonstrate nm level FT capability in space on bright star while rotating baseline between 2 FF cubesats

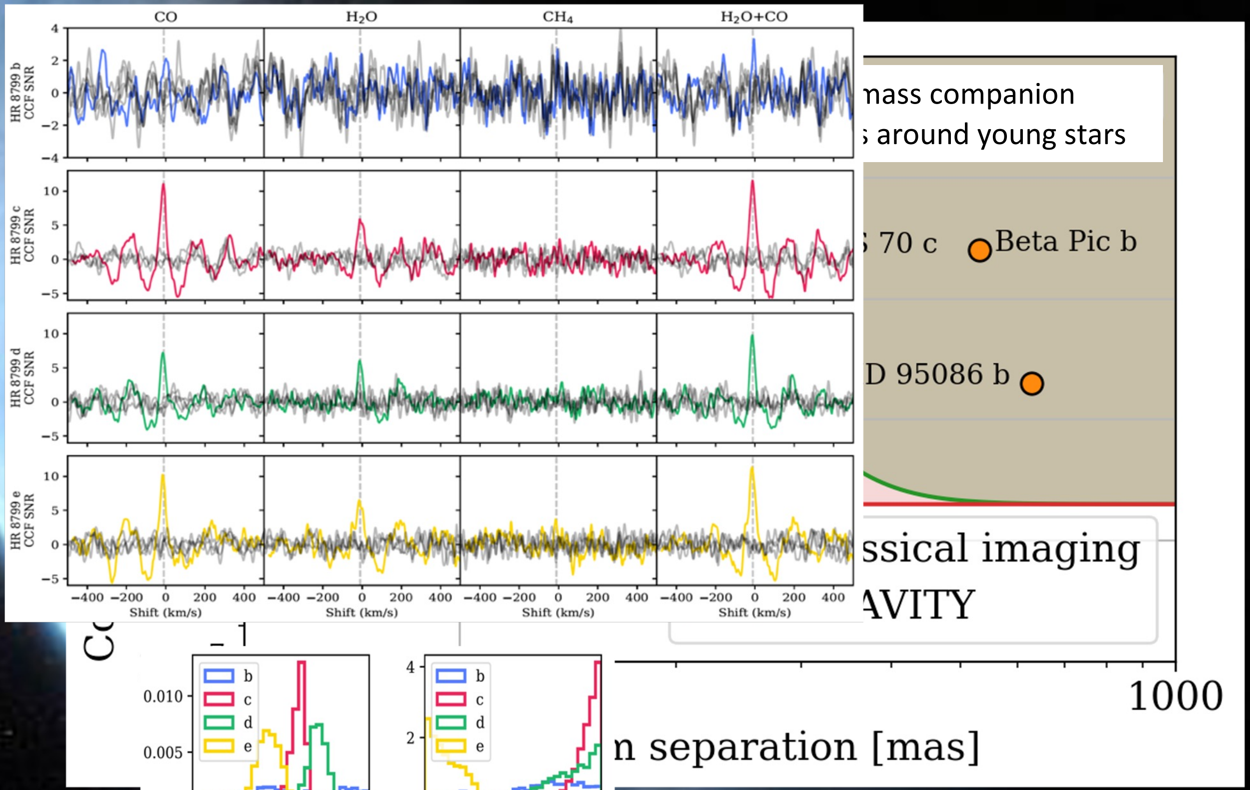
  Pure Tech Demo

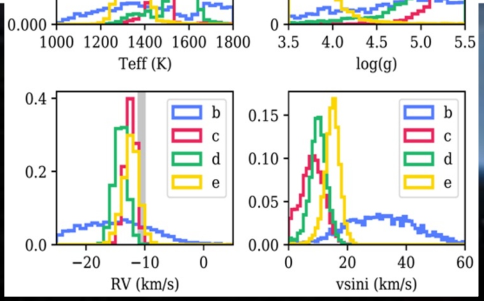
- Workshop Recommendation # 2 (lower priority): demonstrate IR nulling interferometry in space with structurally connected interferometer

  Possibly some Science

Science Momentum: breaking the diffraction limit for direct exoplanet detection using ground-based interferometry

- VLTI / Gravity already detects young EGPs down to ~100 mas ~ 2λ/D
- Pushing down to < λ/D (50 mas for Gravity) to access the bulk of young EGPs (e.g. GAIA)?
  - High precision phase closure measurements (CHARA / VLTI)
  - Gravity+ (2024 throughput ⬆️, vibrations ⬇️)
  - VLTI L-band 4-beam nuller (2025)
  - Keck R=37,000 KPIC /Vortex Fiber Nuller obs
  - New data reduction strategies (spectral NSC for 2T, Kernel Nulling for > 2T)

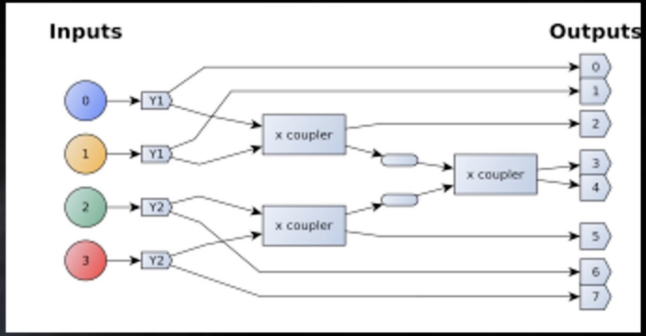


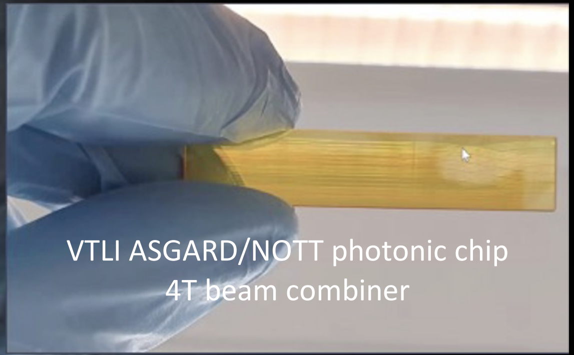


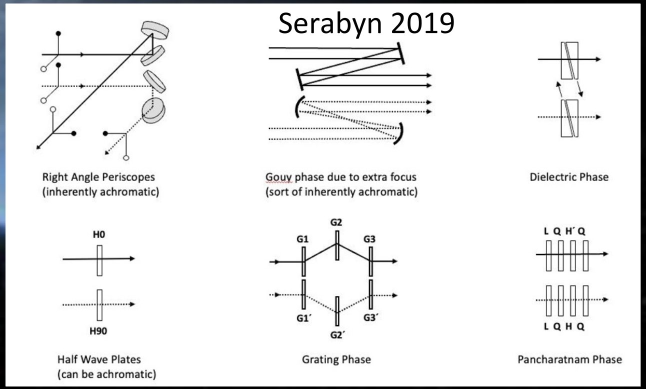
High Res spectroscopic Observations of HR8799 planets with KPIC (J.J. Wang et al. 2021)

What are the Key Technical Trades ahead in prep for a LIFE-like Mission?

- Nulling front-end architecture / entrance pupil:
  - Number of apertures (2 to 5) and relative phase shifts
  - Phase modulation scheme: temporal and/or different beam combiner outputs
- Nulling back-end / beam combination
  - Bulk optics vs Integrated optics vs Hybrid
  - Multi-axial (Fizeau) into SM waveguide vs Michelson (co-axial)
  - Nulling approach: periscopes vs rooftops vs dielectric plates vs adaptive nuller
  - Spectral resolution: low res (< 100) vs high res (> 10,000)
  - Passive WF correction via SM waveguides vs cold DMs







How do we Build a Lasting International Community around a LIFE-like Mission?

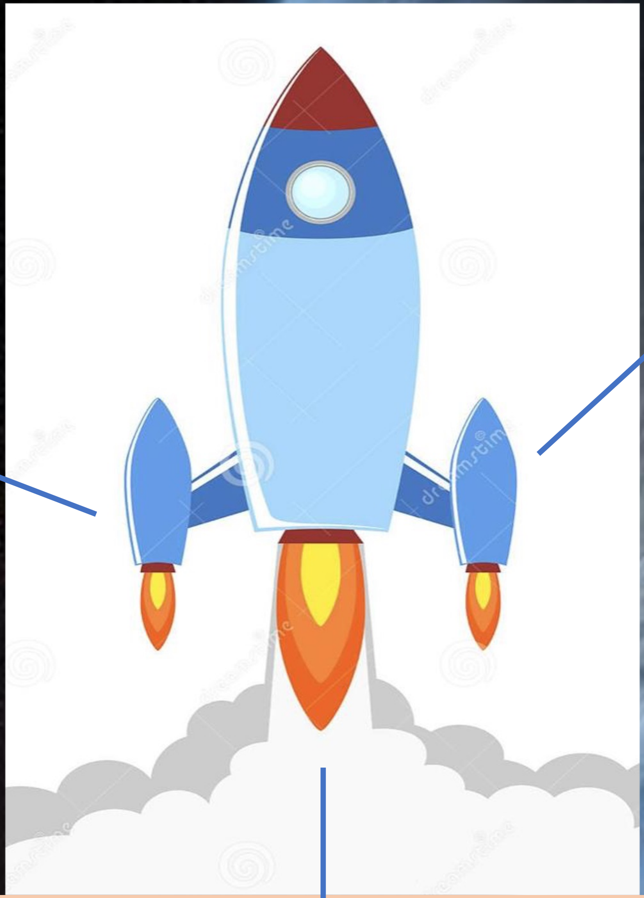
- Lessons learned from TPF-I/ Darwin studies:
  - A vigorous General Astrophysics (non-exoplanet science) is essential for community support
  - Leverage the large multidisciplinary interest in the quest for Life outside Earth
- Capitalize on current science momentum: interferometry has unique potential for new EGP direct characterization before high contrast imaging with ELTs in ~ 10 years
- Keep regular interaction using and expanding workshop working groups. Submit joint papers and research proposals
- Repeat such international meetings / workshops once a year to foster scientist-to-scientist collaborations
- Build a single international community for exoplanet direct imaging, that highlights complementarity and is *not* split by wavelength
- Ideal world and objective: NASA flies HWO with international collaboration (incl. ESA) and ESA flies LIFE with international collaboration (incl. NASA)
- Workshop report available this summer at *https://kiss.caltech.edu/workshops/Interferometry/Interferometry.html*

Back-up

The 3 Pillars of a Successful Mission

Science

- Exoplanet Science Motivation for a mid-IR mission (Short Course 1, Day 1)
- Precursor Science Investigations: Theory (Day 1, WG #1)
- Precursor Science Observations (Day 2, WG #2)



Technology

- Nulling Architecture and Approach (Day 2, WG #4)
- Free Fliers & Metrology (Day 3, WG #3)
- Space Demo (Day 4, WG #3)
- Integrated Optics (Day 3, WG #5)
- Nulling Data Reduction and Design Impact (Day 4, WG #6)
- High Contrast Ground-Based Interferometry* (Day 4, WG #7)

Funding 💵 💶 💴 …

- General Astrophysics (Day 5, WG #10)
- Building a lasting community (Day 5, WG #11)
- Leveraging the large multidisciplinary interest in the quest for Life outside Earth (Day 5)

WG: workshop Working Groups

Space Interferometer Laboratory Voyaging towards Innovative Applications

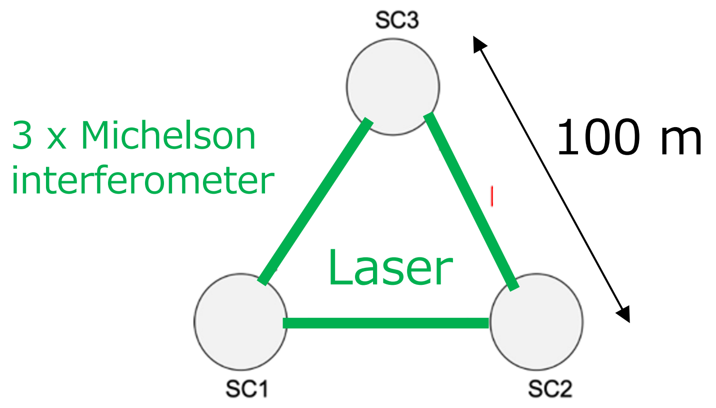
SILVIA

confidentially proceeded under JAXA/ISAS
(To be officially announced after successfully moving to the pre-project phase)

- Space engineering program for future space interferometry missions
- High-precision formation flight experiment using three satellites

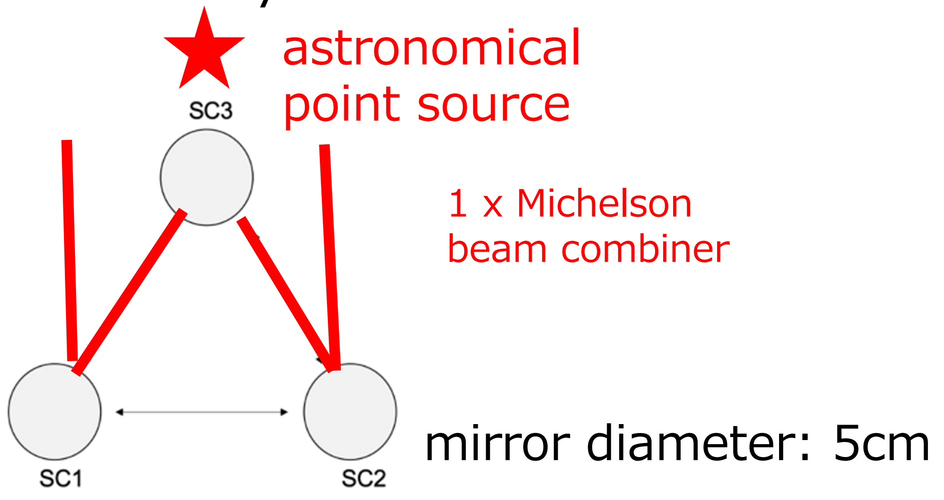
  Stability: < 1 μm for a minute, Absolute: < 1 mm (TBD), Tilt: < 0.3 arcsec (TBD)

- Two measurement systems to be mounted:
  1. Michelson interferometer to measure stability of each of 3 distances between satellites
  2. Stellar interferometer to independently measure the stability for one of them



+

Measurement of distance between satellites



Measurement of fringes using a star