
Image taken by Voyager 1 at 60 million km away from Earth (Feb. 14, 1990)

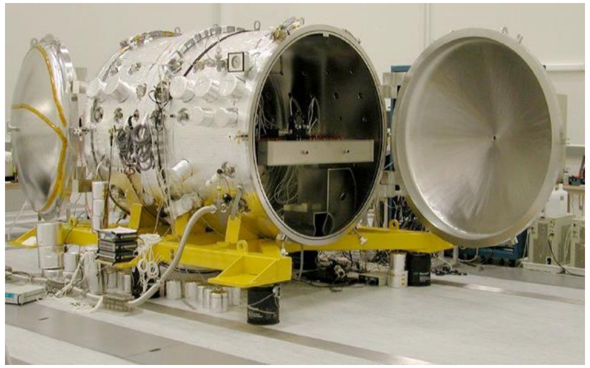
Pale Blue dot (1994):
From this distant vantage point, the Earth might not seem of any particular interest. But for us, it's different. Consider again that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives. - Carl Sagan

How to detect habitable candidates and advance this goal with CubeSat Missions

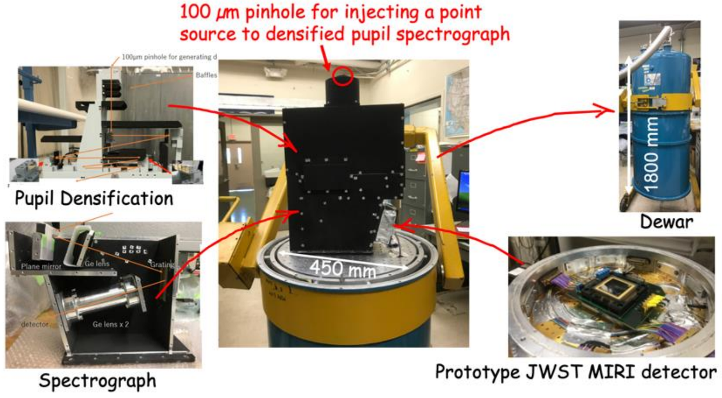
Taro Matsuo (The University of Osaka)

Self Introduction

Research Area: Astrobiology (Astronomical Instrumentation, Indicator of life for future space telescopes, Coevolution of Earth and life)



High-contrast imaging
at NASA JPL
(2008 – 2010)



New spectrograph
at NASA Ames
(2018 – 2021)

Formation Flying Interferometer
collaborating with space engineers
of U. of Tokyo (2019 -)

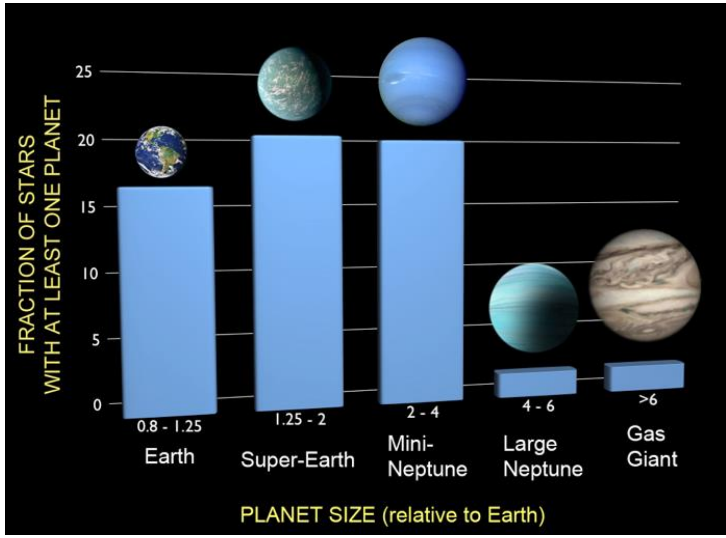
Technology development for search for life

Current landscape of exoplanets

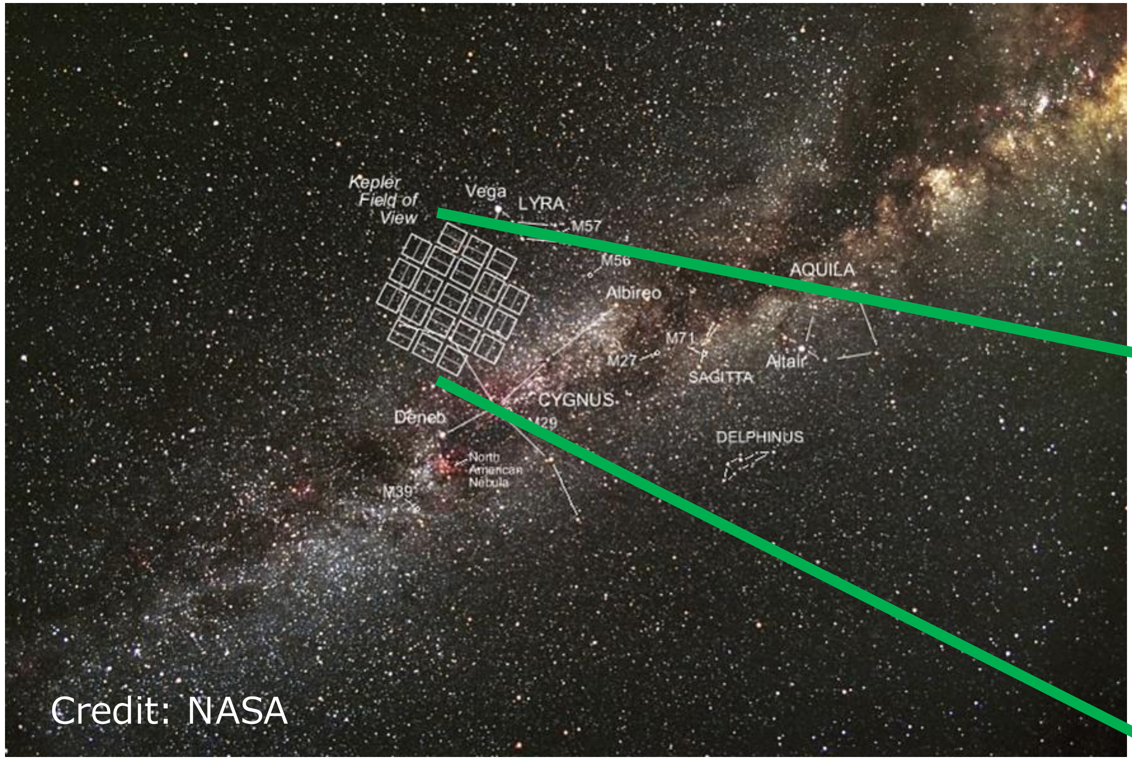
- Since the first planet was discovered in 1995, > 6000 exoplanets have been discovered.
- 30% of stars host Earth-sized or super-Earth (< 2Re) planets.

→ Habitable planet candidates are abundant in Universe

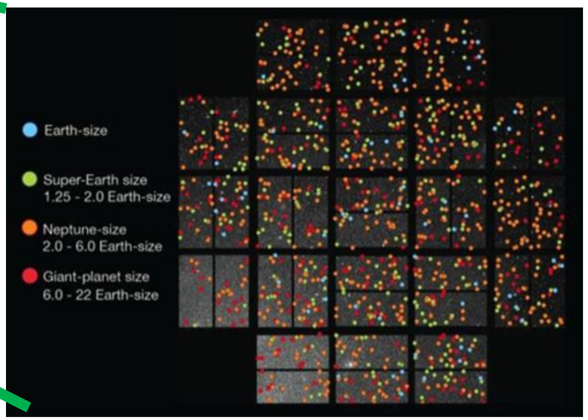
Statistical analysis



Frequency of Earth-sized planets

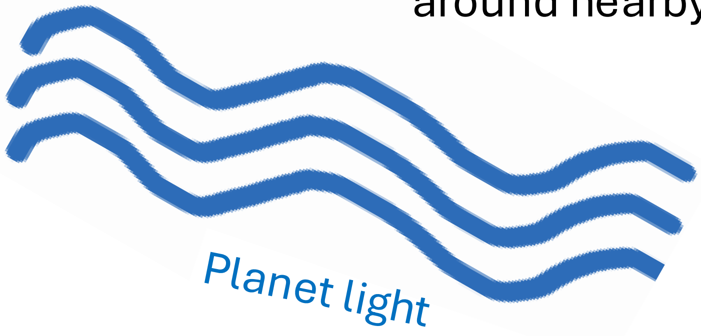


Field of view (FOV) of Kepler spacecraft

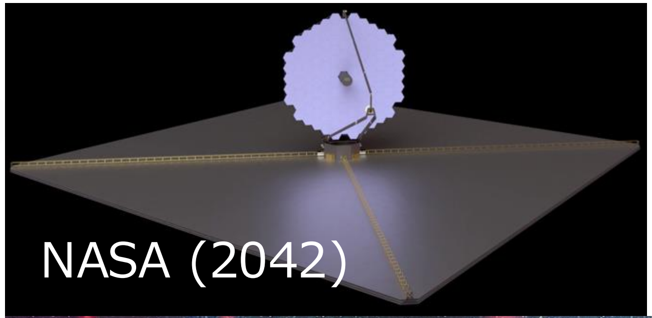


Planet detection within FOV

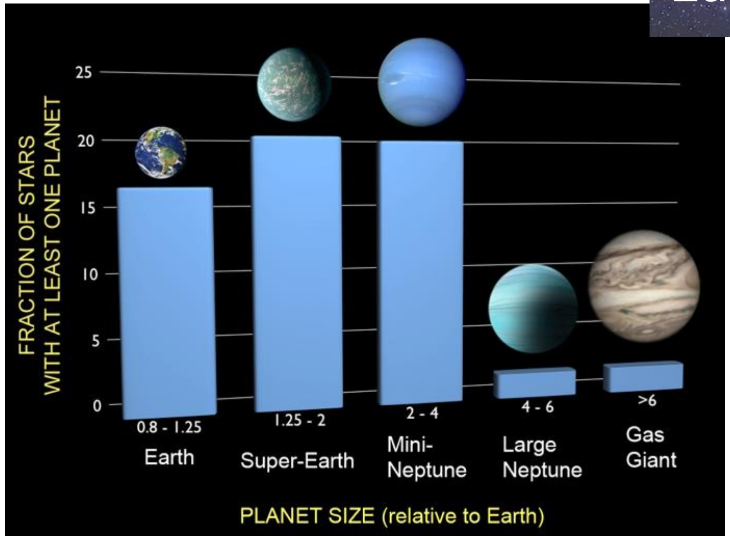
Next big milestone in Astronomy



- Search for life activity on habitable planet candidates around nearby stars



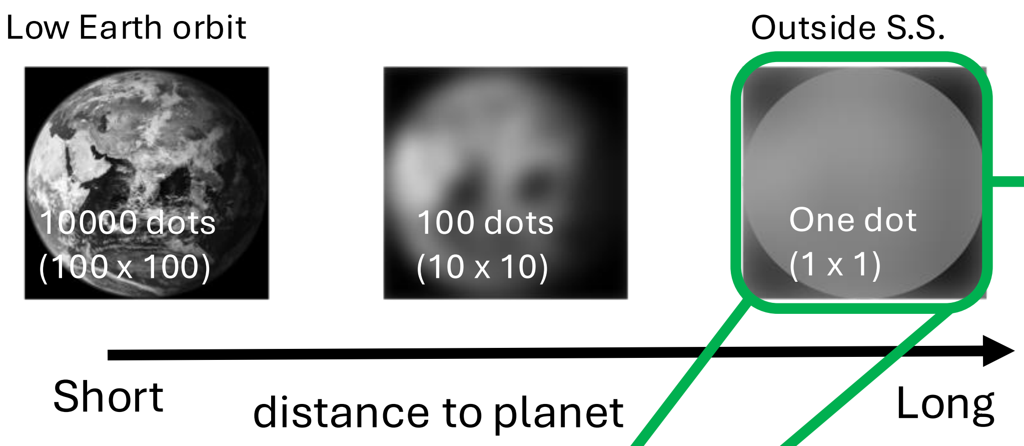
Field of view (FOV) of Kepler spacecraft

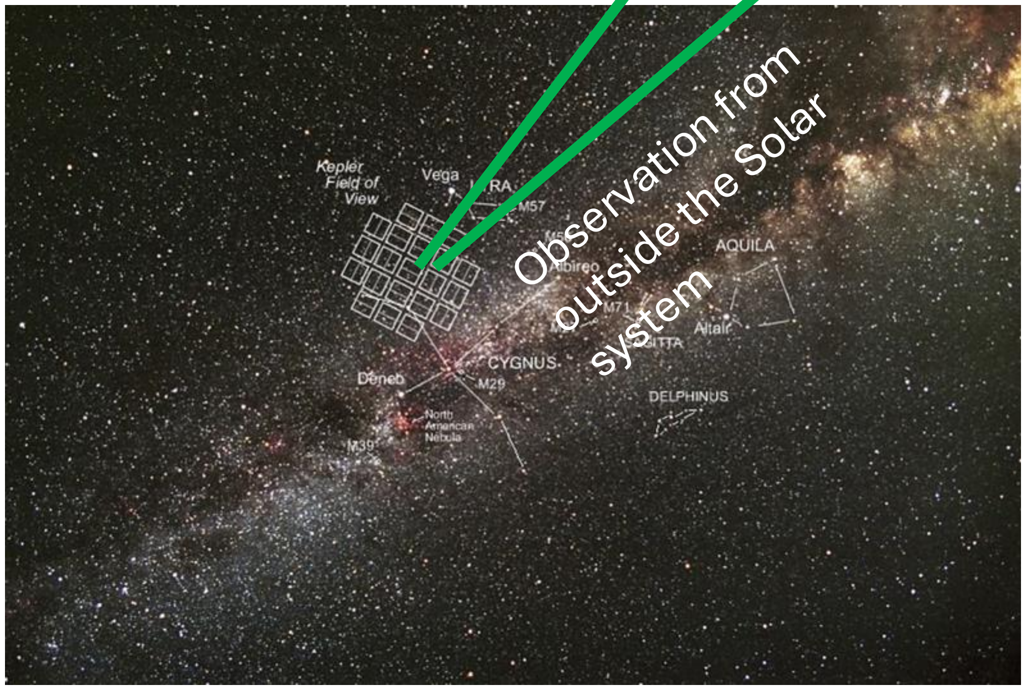


Frequency of Earth-sized planets

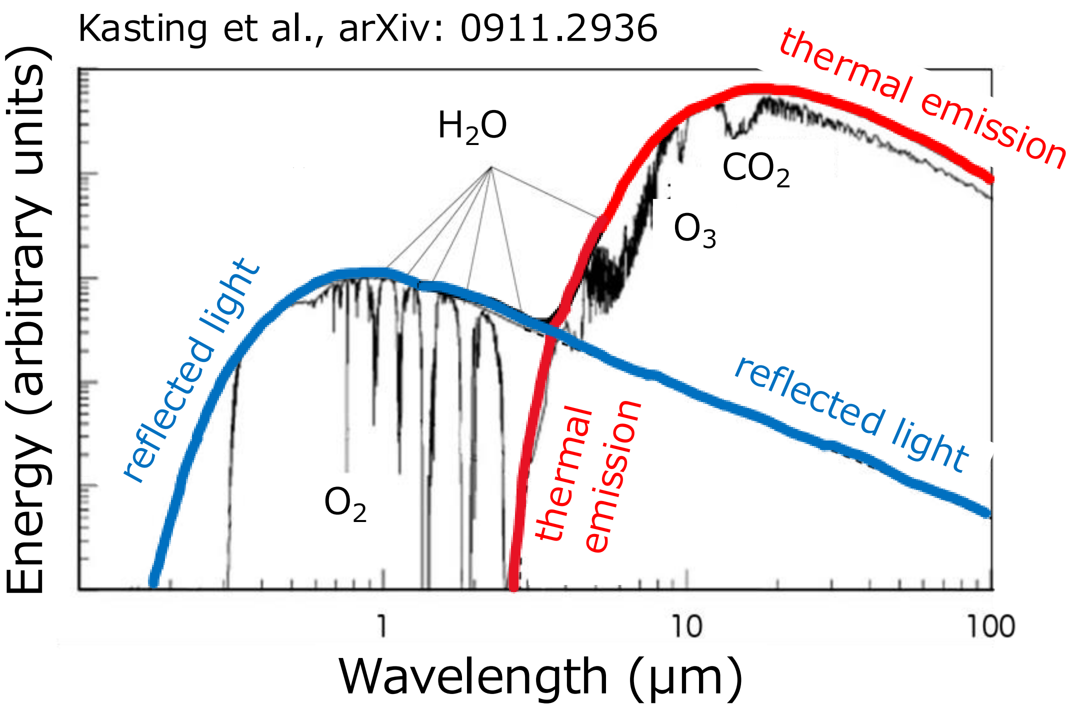
- ~ 30% of stars harbor Earth-sized planets

Difficulty of biosignature detection





Field of view (FOV) of Kepler spacecraft



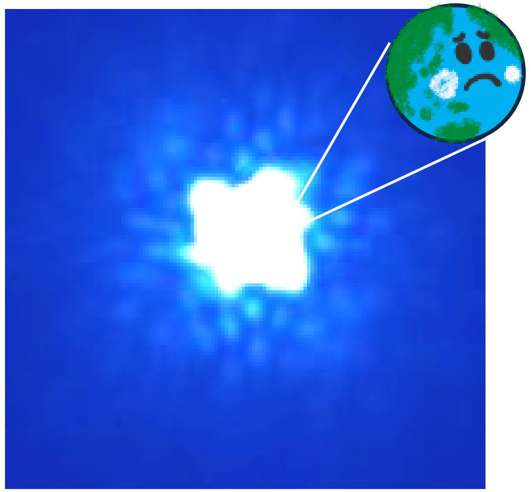
- How does Earth look like if we observe it from outside Solar system?
  - ➢ Observed as a point source (one dot)
- Earth shines through
  - ➢ Reflected light from Sun in visible.
  - ➢ Thermal emission in infrared.

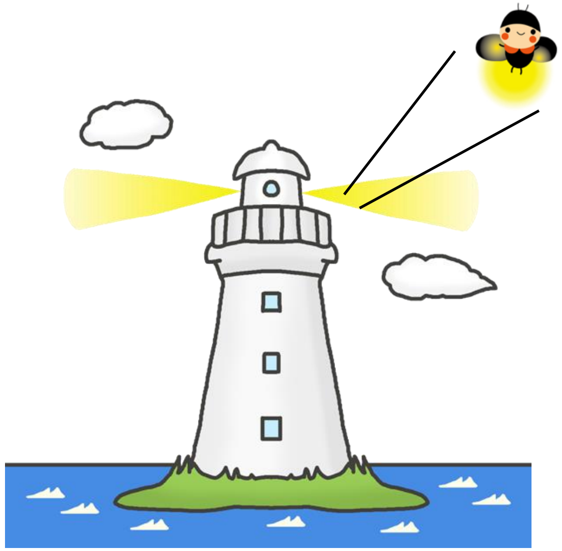
Big Question:
How can we identify life from a single unresolved point?

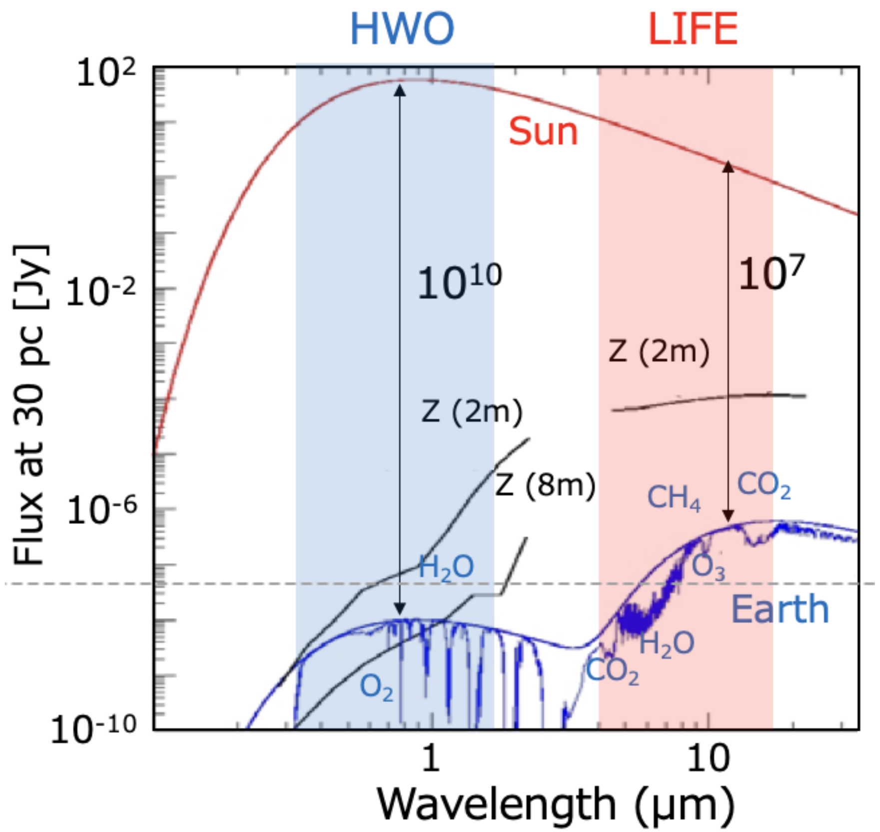
Another difficulty

Kasting et al., arXiv: 0911.2936, modified

Planet light
around bright stars → Firefly
around lighthouse

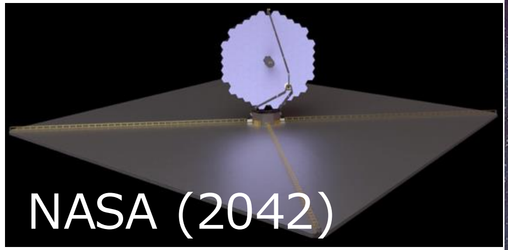






- Two technical barriers

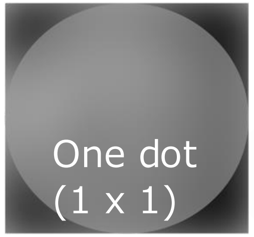
1. Small angular separation: 0.01 – 0.1 arcsec
2. High contrast: 10^{-10} in visible and 10^{-7} in infrared



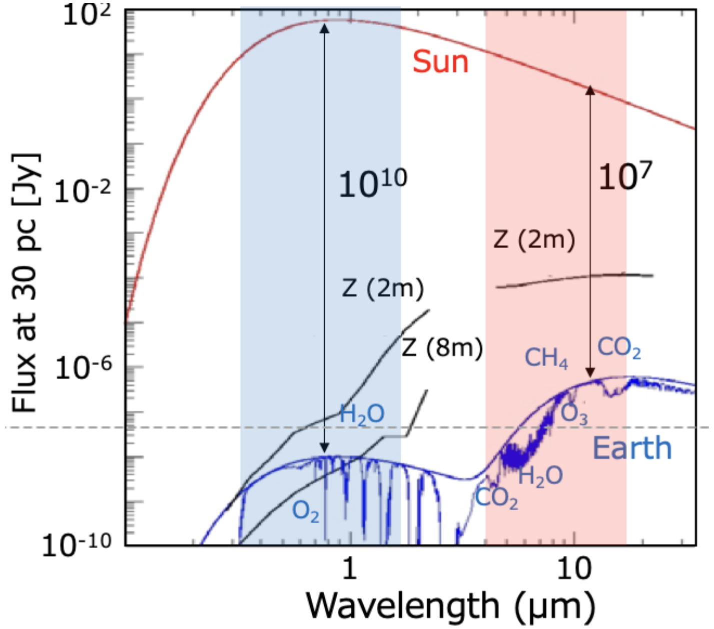
HWO

LIFE

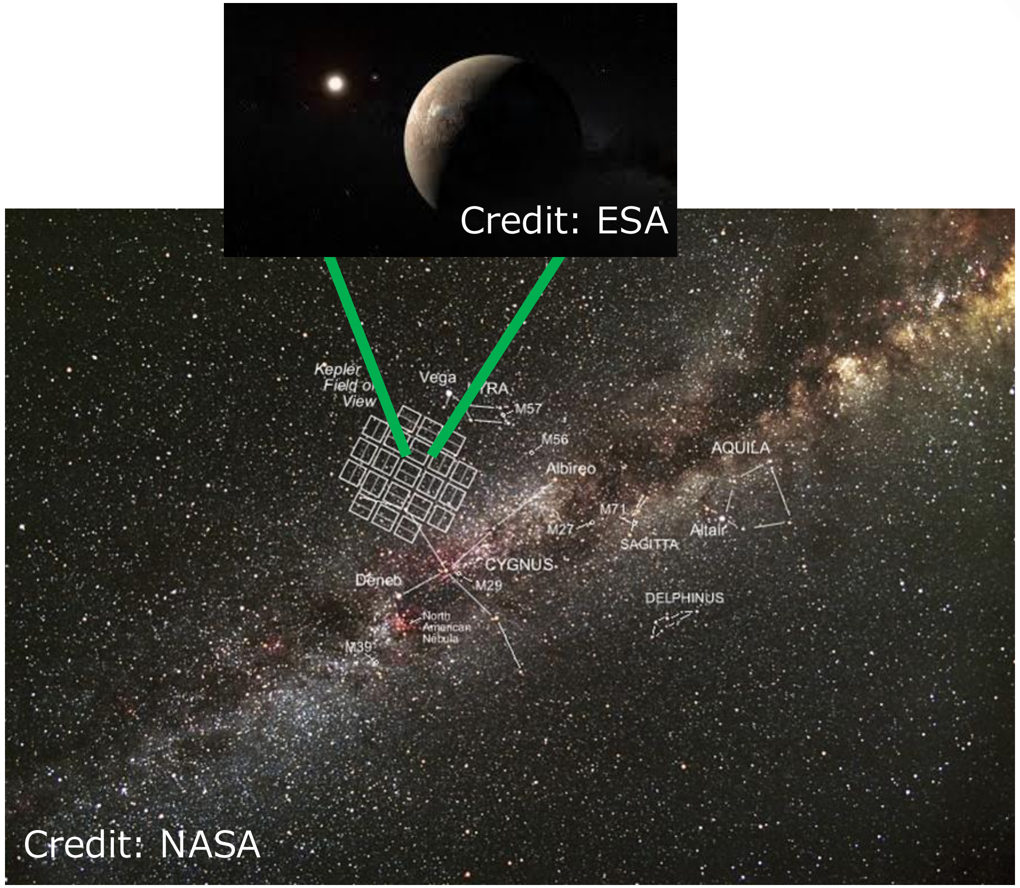
Search for life on distant planet



Kasting & Traub 2010, modified



Theoretical spectra of Sun and Eart



Field of view (FOV) of Kepler spacecraft

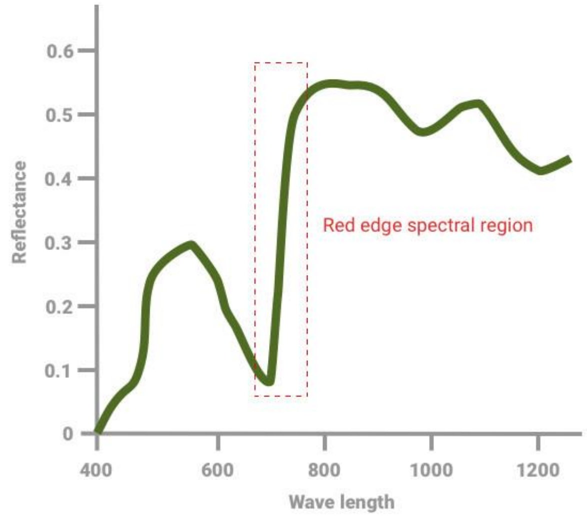
- How does Earth look like if we observe it from outside Solar system?
  - ➢ Observed as a point source (one dot)

  → How to identify life from a point source (covered by this talk)

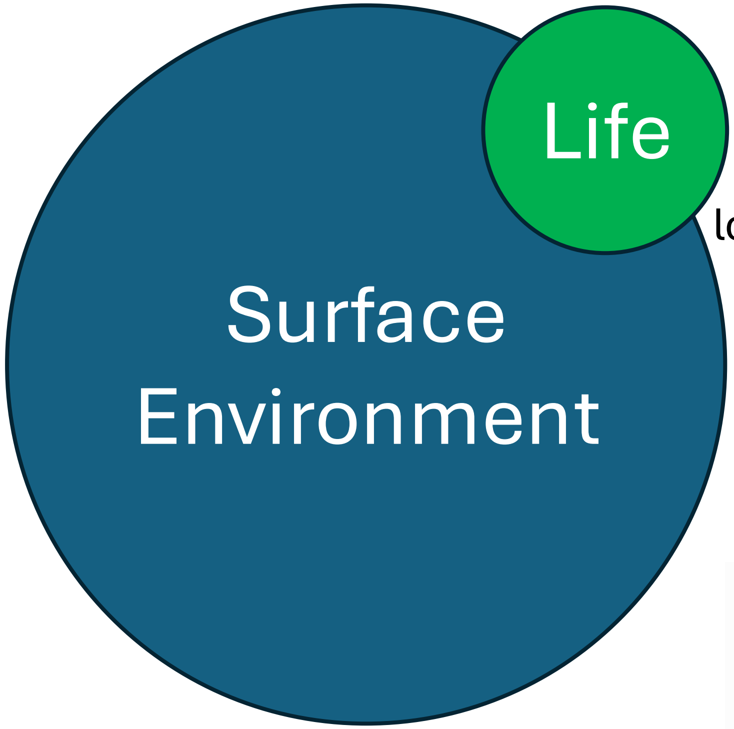
- Technical challenges of search for life:
  - ➢ High contrast and High angular resolution

  → How to overcome technical difficulties (mainly covered by Prof. Ikari)

Can we directly detect life itself on distant planets?

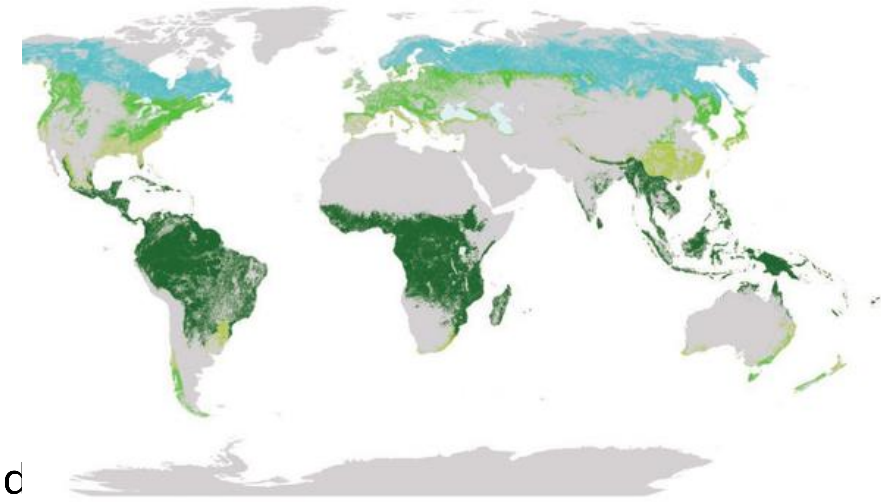


Reflectance of land plant



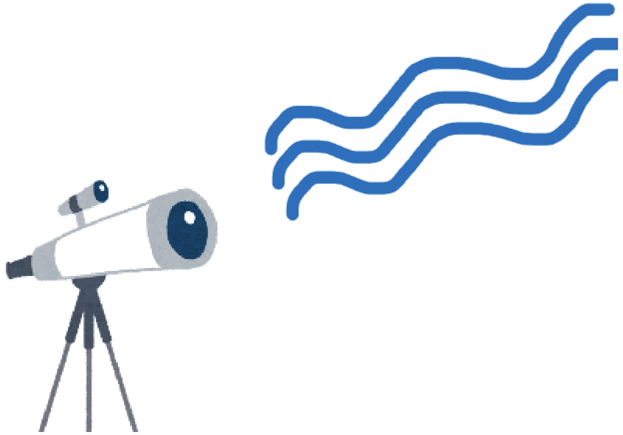
localized

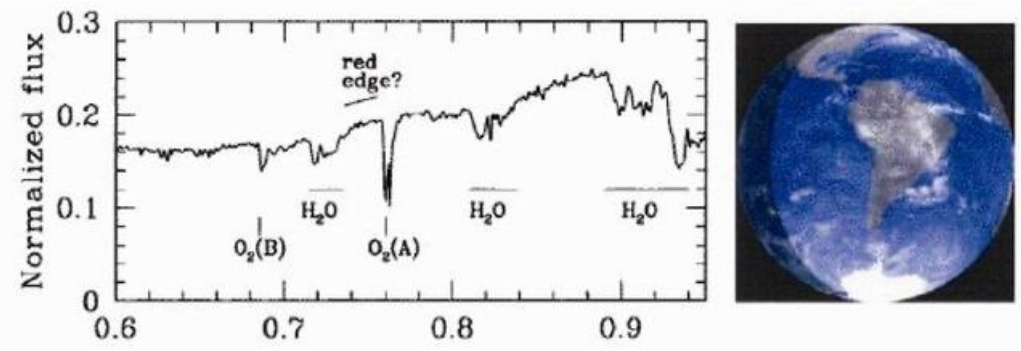
Globally distributed...



Tusa Thesis 2020

Only 8 % of surface is covered by plant...

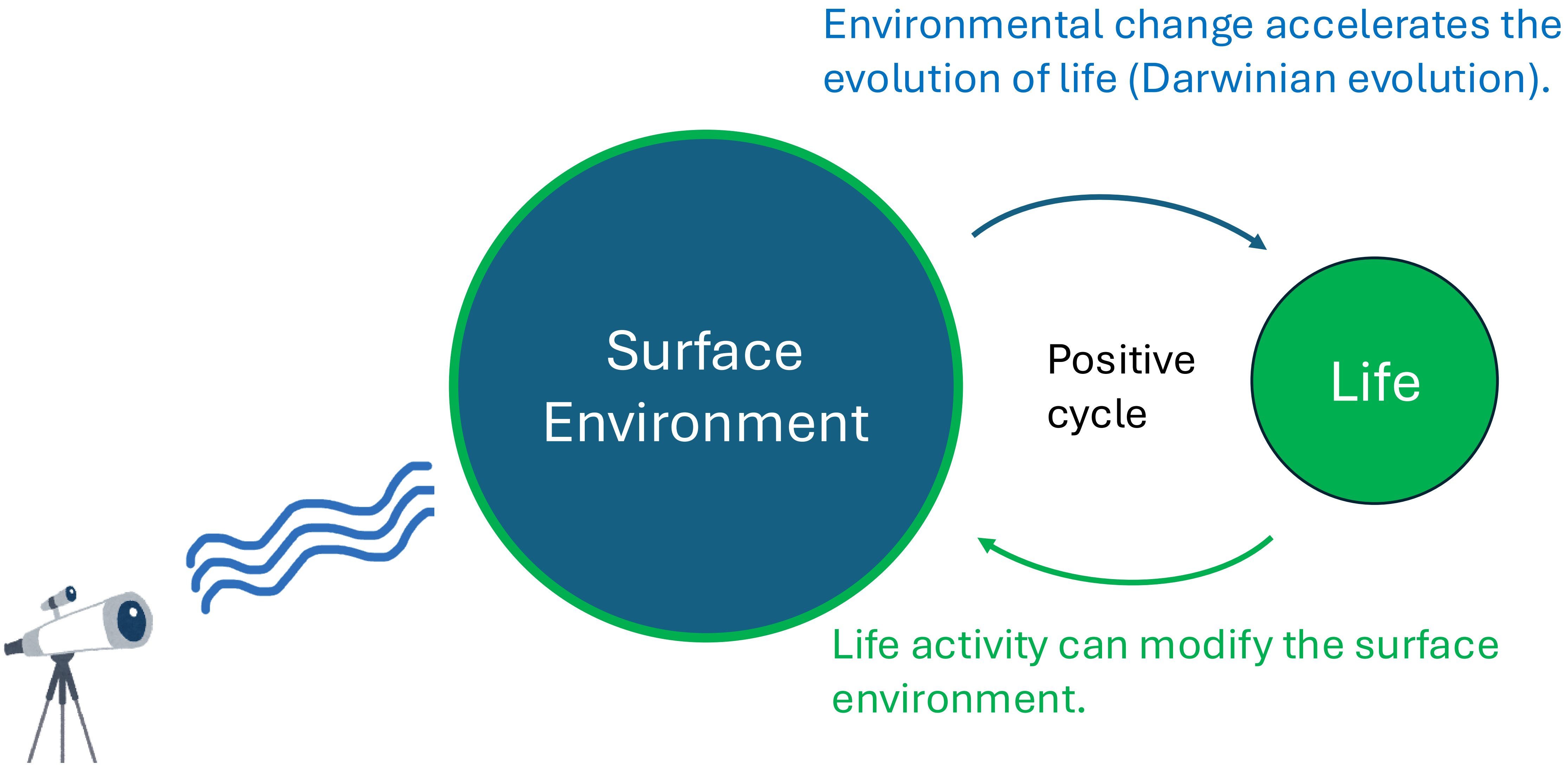




Bjorn et al. 2009

Detecting life itself is challenging due to localization of life

From the evolution of life to the coevolution of life and planet

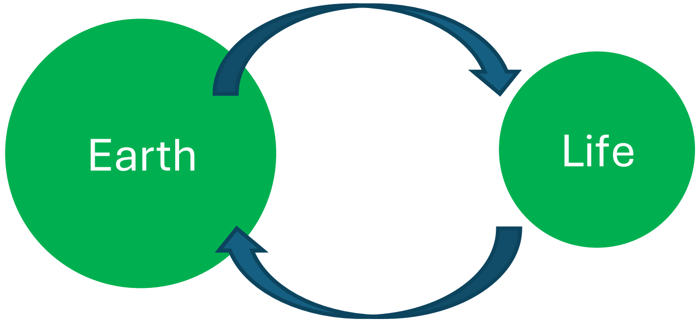


Global environmental changes caused by life on a planet are observable.

How did the surface environment change?

Coevolution

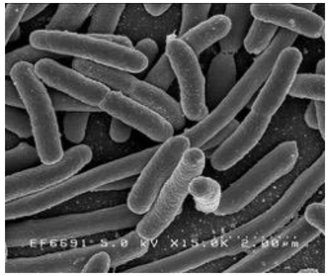
Environmental change accelerates the evolution of life (Darwinian evolution).



Metabolisms alter the surface environment.

Primitive Earth

4 billion years



bacteria

plant

Modern Earth

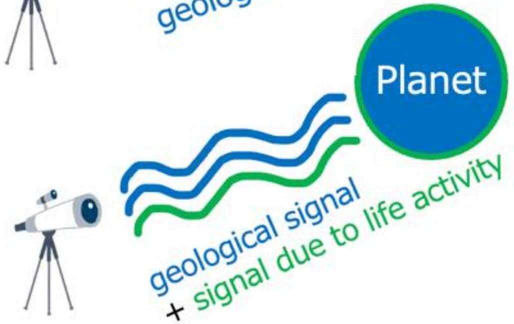
https://eco-word.jp/html/01_seitaikei/se-03.html

Why are cyanobacteria (as first oxygenic photosynthesis) important?

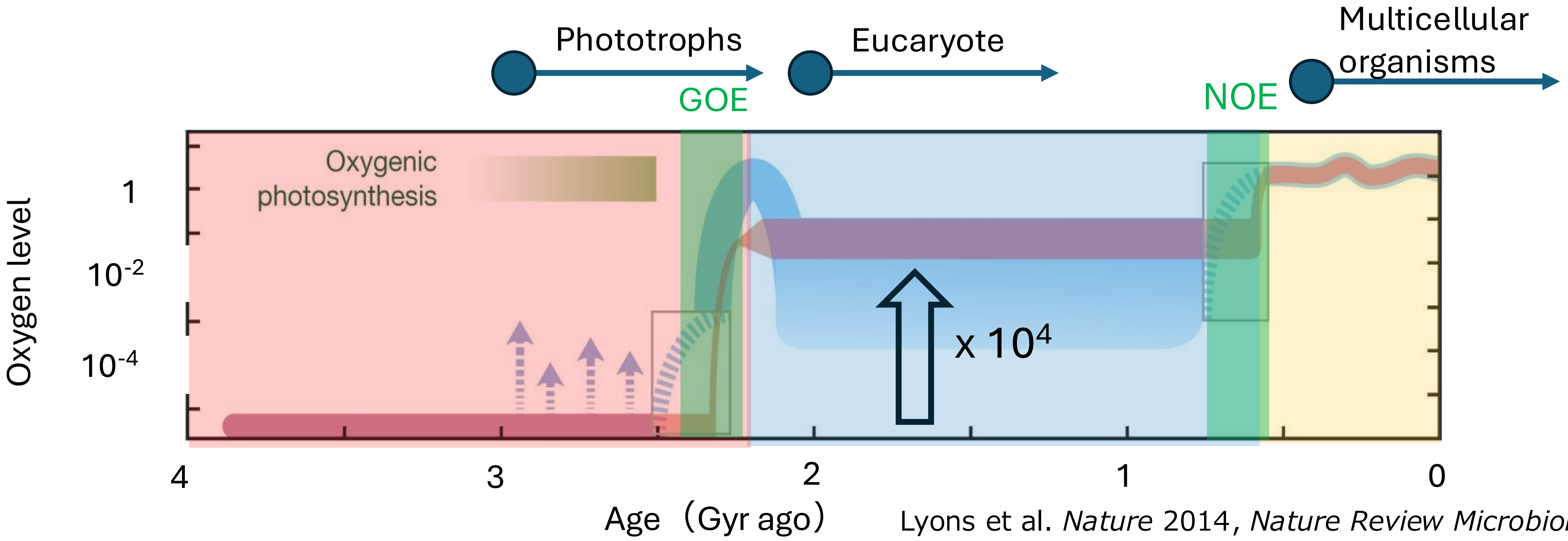
- (Ancestral) cyanobacteria induced **Global Oxidation Event (GOE)**

Astrobiology perspective: Global-scale change could be remotely detected even from a point source.

Life Evolution perspective: Aerobic environment promoted the birth of Eucaryote and multicellular organisms.



Question on biology: Why did cyanobacteria thrive in the Archean and Proterozoic eras?



Lyons et al. *Nature* 2014, *Nature Review Microbiology* 2024 modified

Pale Blue dot (1994):
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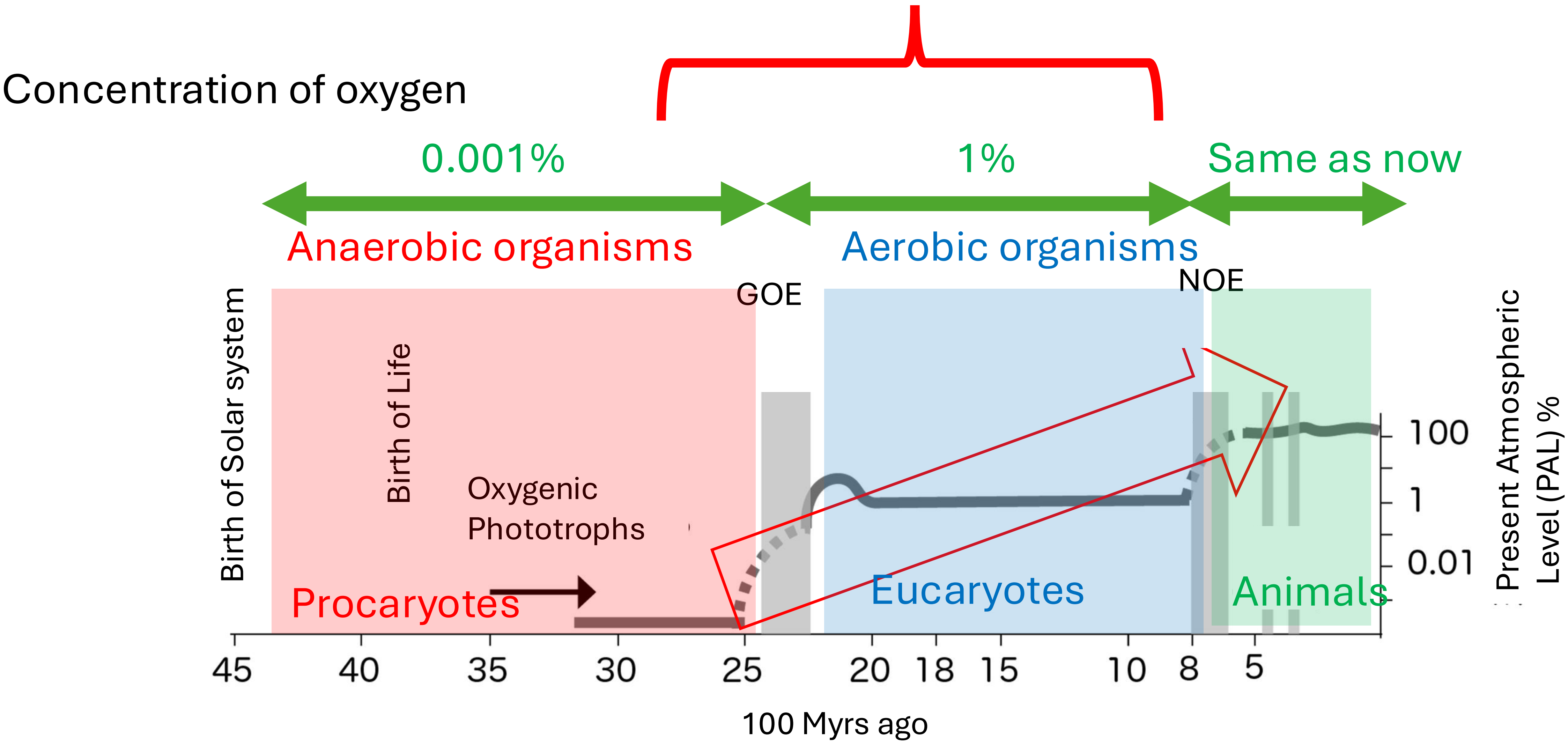
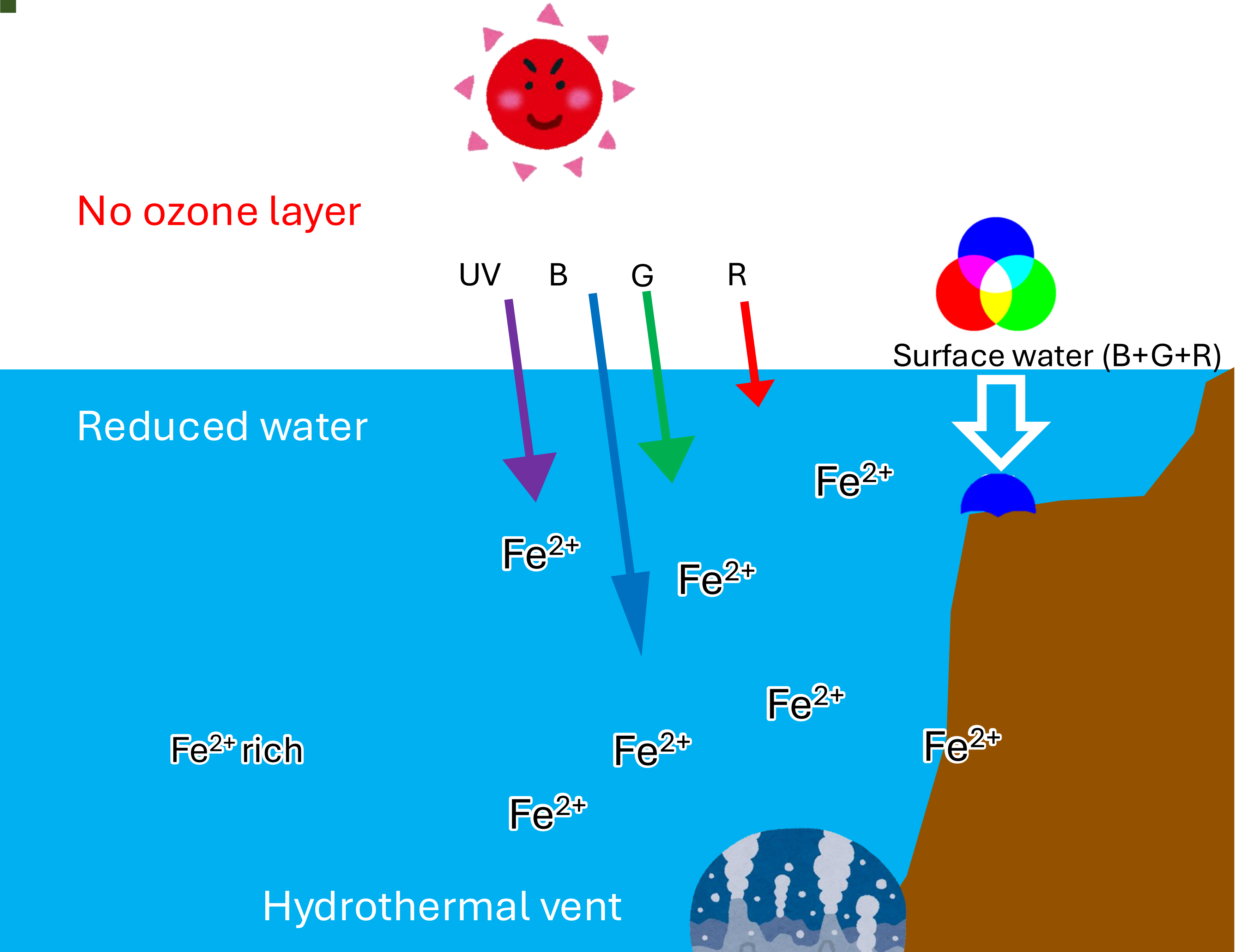
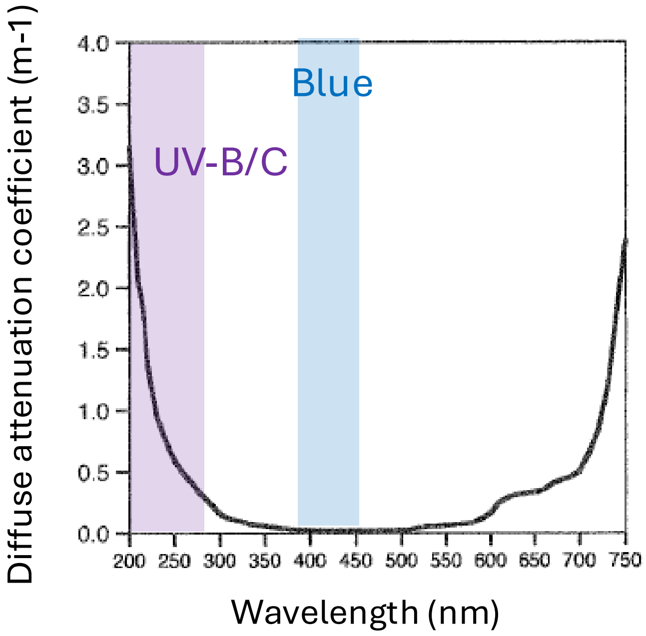
Various chemical compounds were created through oxidizing the surface (oceans, continents, and atmospheres)!



Blue tide is induced by one of life activities....

Before the birth of cyanobacteria

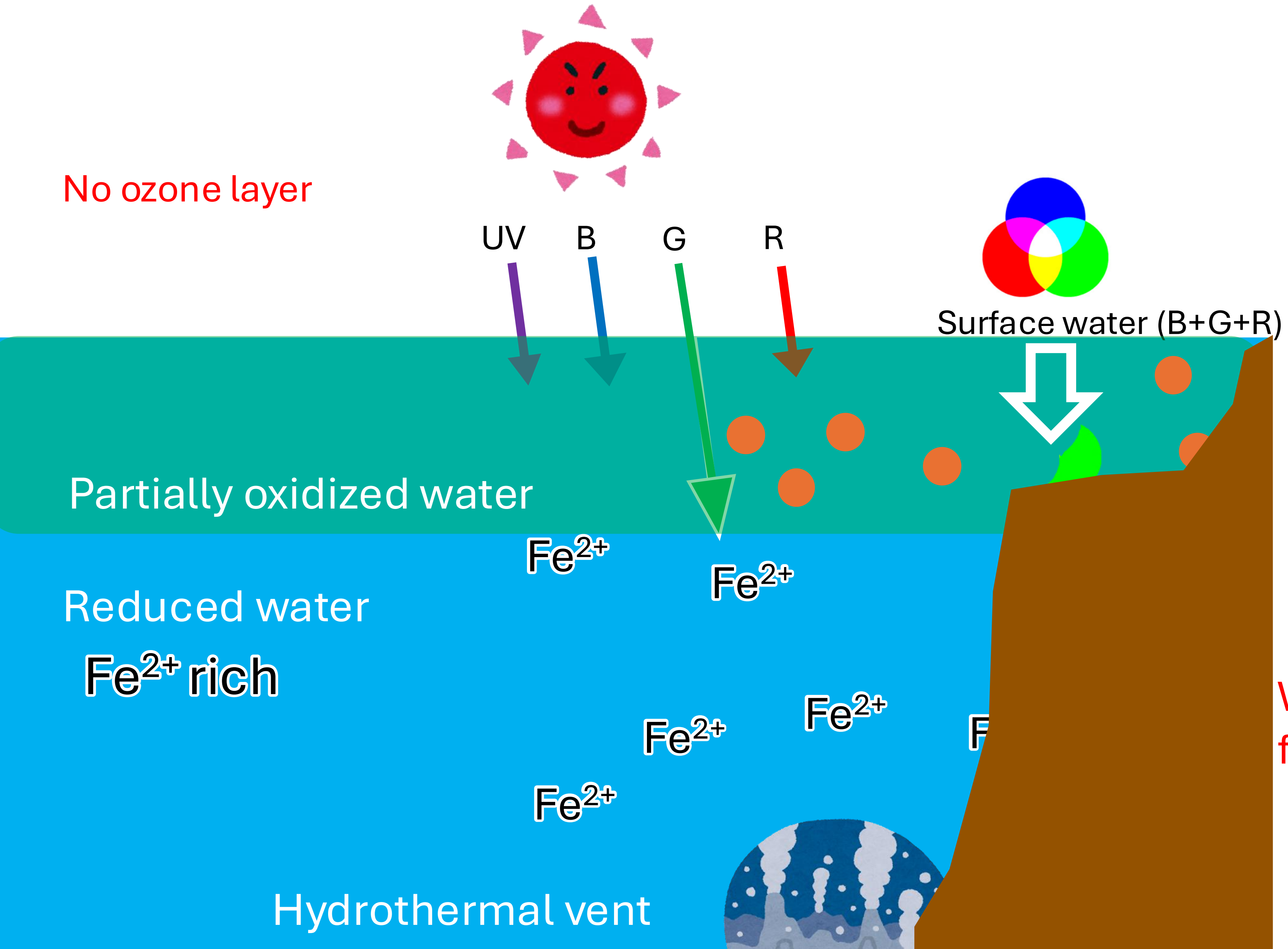


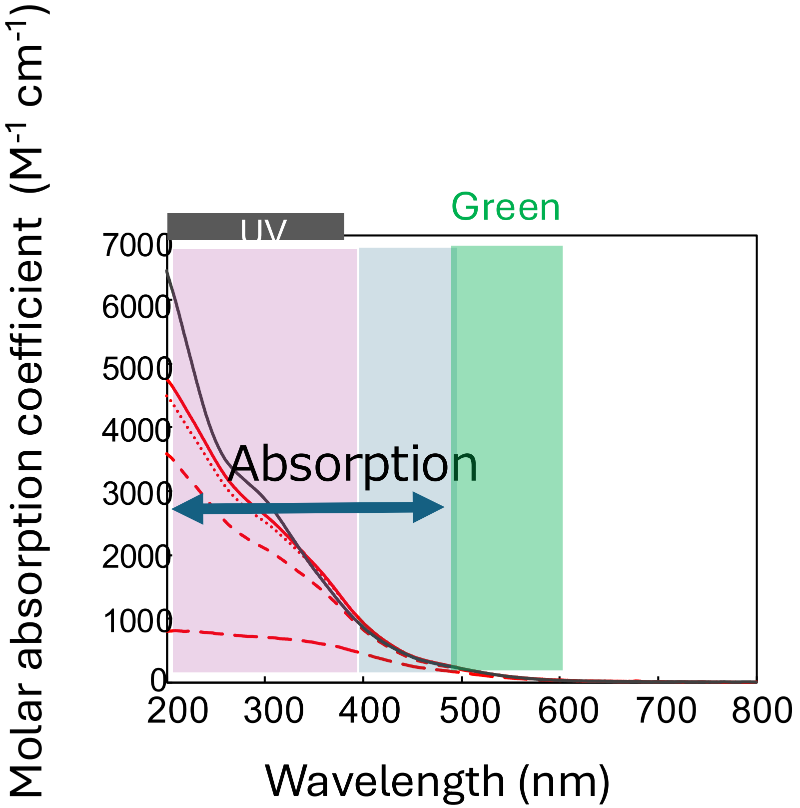


Water absorption coefficient

30 meters depth

After the birth of cyanobacteria



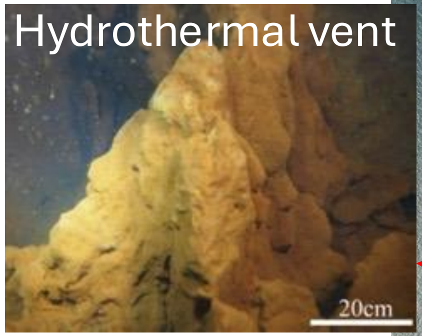


Absorption coefficient of Iron hydroxide

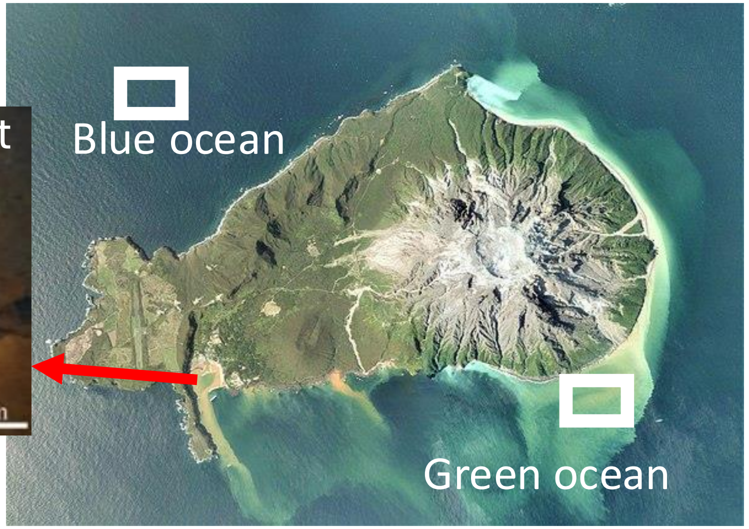
Were green light environments formed in the Archean era?

Green light environment around Iwo-island

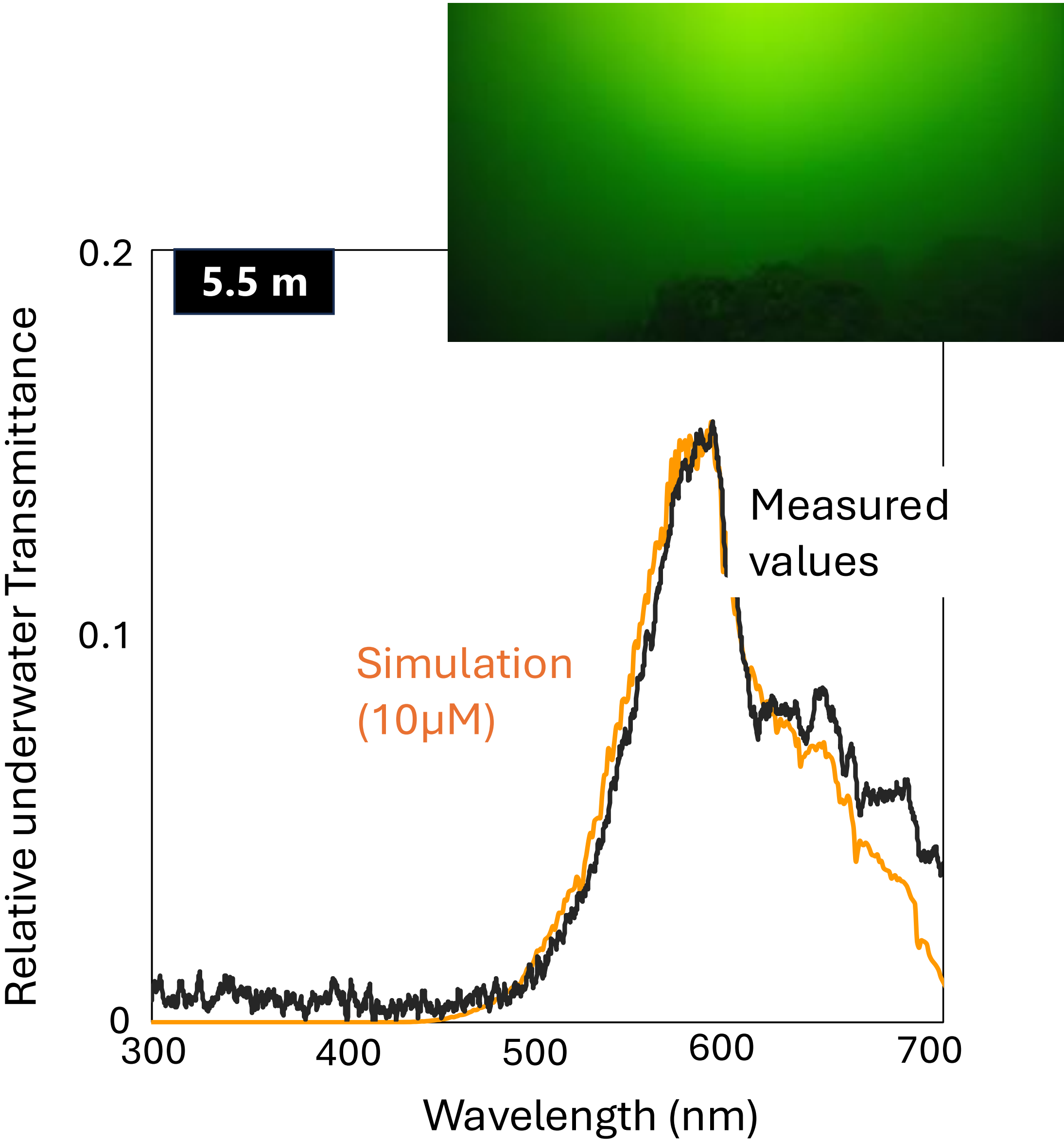
- Hydrothermal vents exist around Iwo Island.
- Fe^{2+} is rapidly oxidized to iron oxides, which absorb blue light and create a green-light underwater environment.
- This is well reproduced by an iron oxide concentration of ~10 μM.



Iron hydroxide



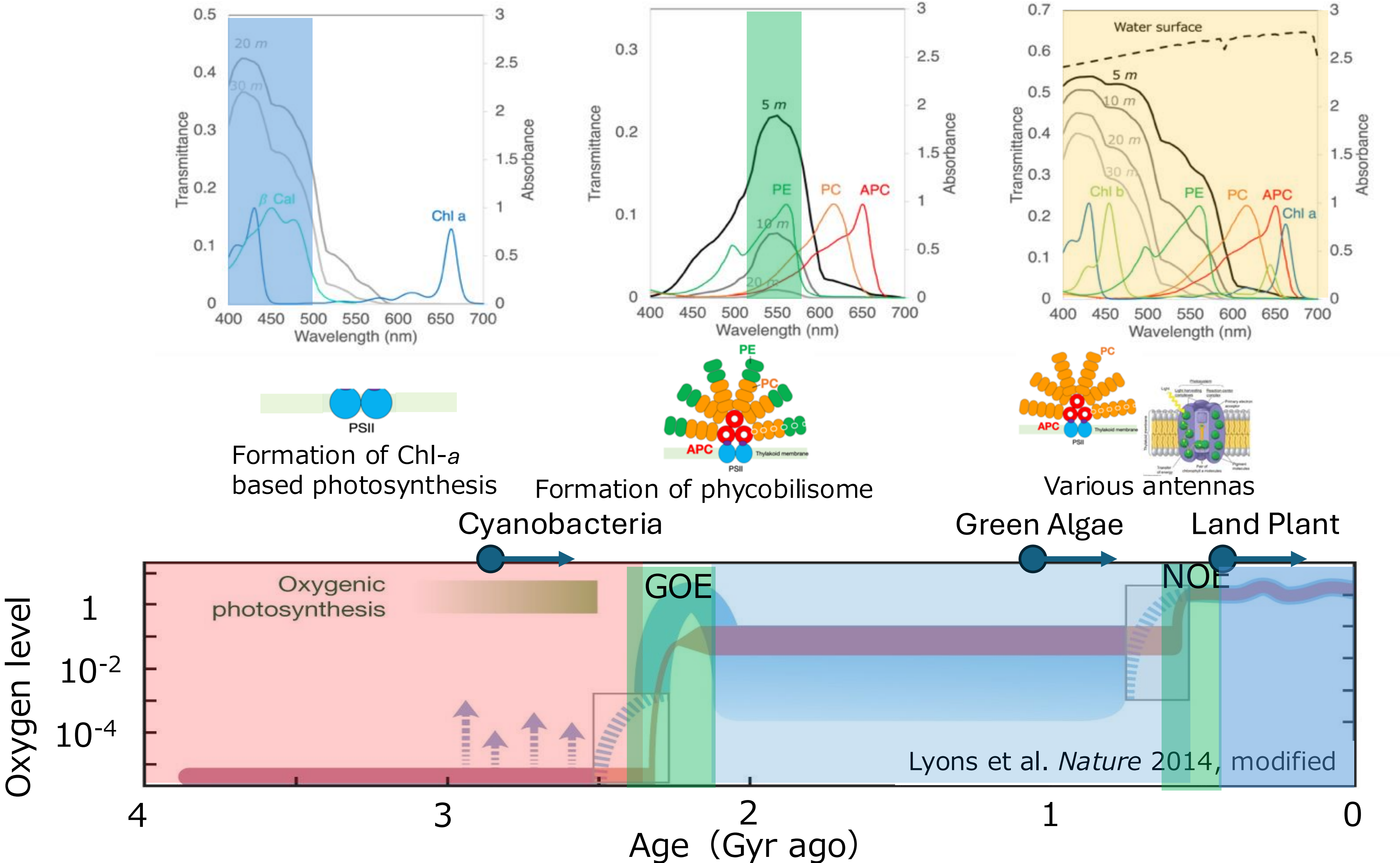
Iwo Island, Kyusyu, Japan



Measured underwater transmission spectrum at depth of 5.5 meters

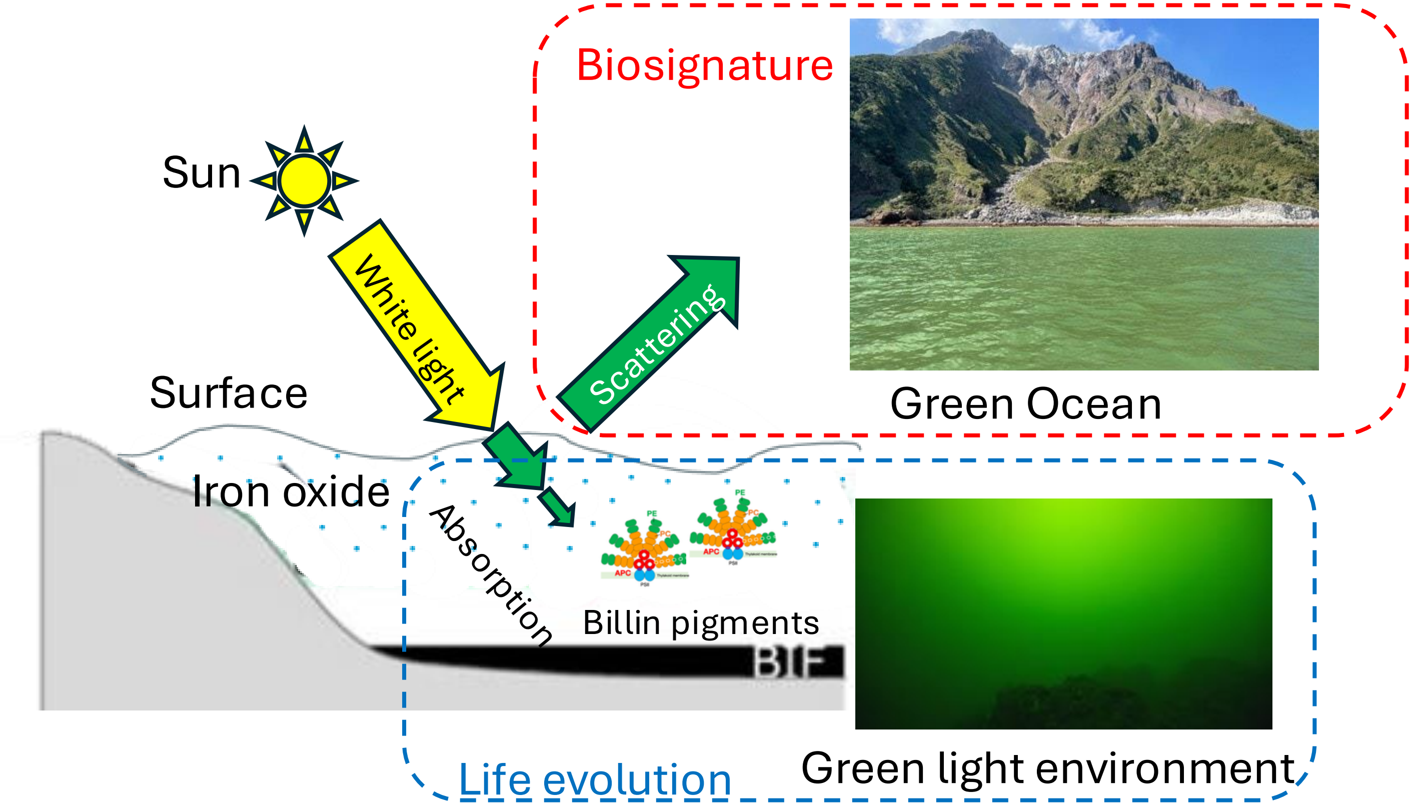
Three light environments over 3.0 Gyr

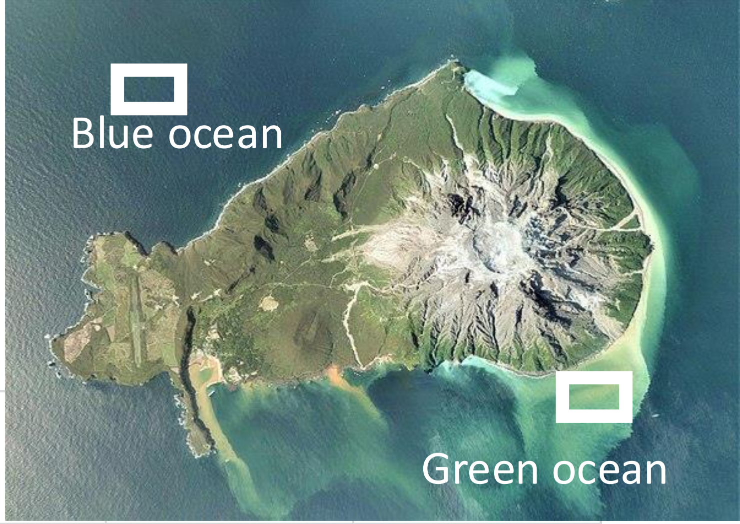
Matsuo et al. *Nat. Eco. Evo.* 2025

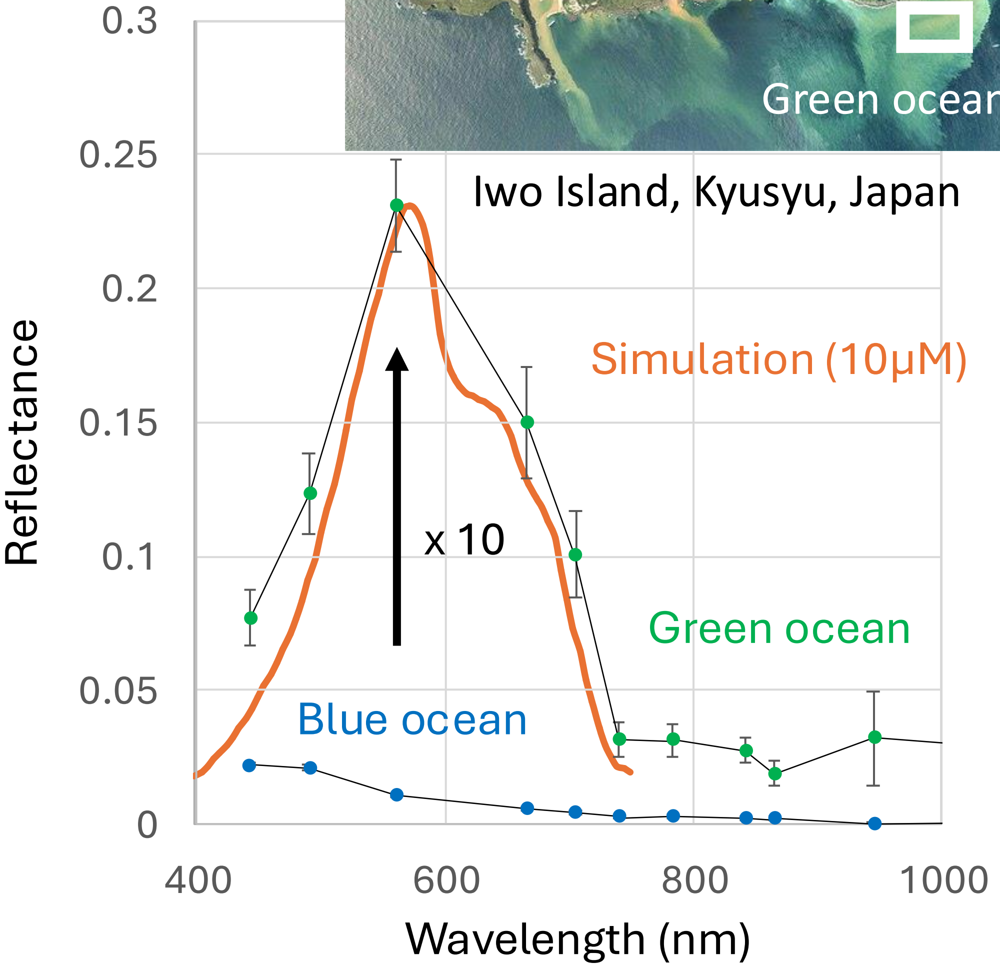


Green Oceans in the Archean era?

- Iron oxides effectively scatter green light, producing ~10× higher albedo than typical blue oceans.
- They create a distinct spectral edge at 550 nm.
- Iron oxide concentration of ~10 μM explains the observed remote sensing data.

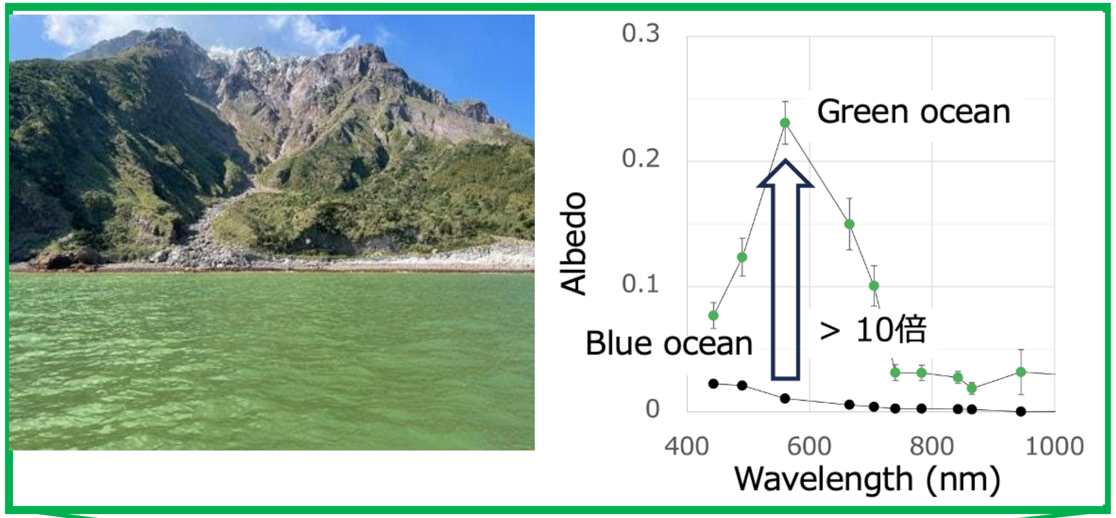


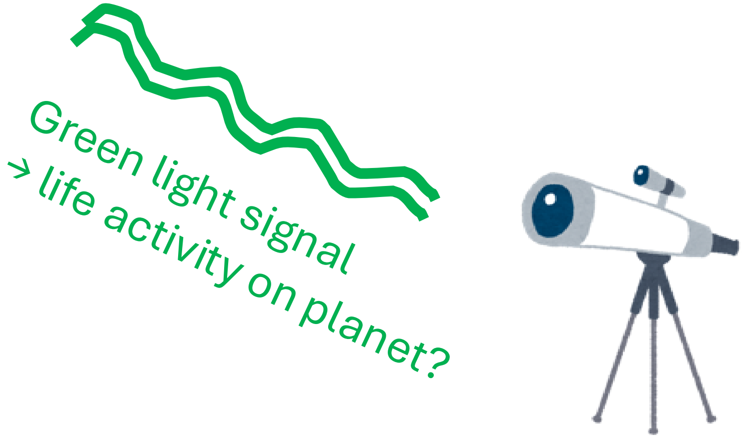




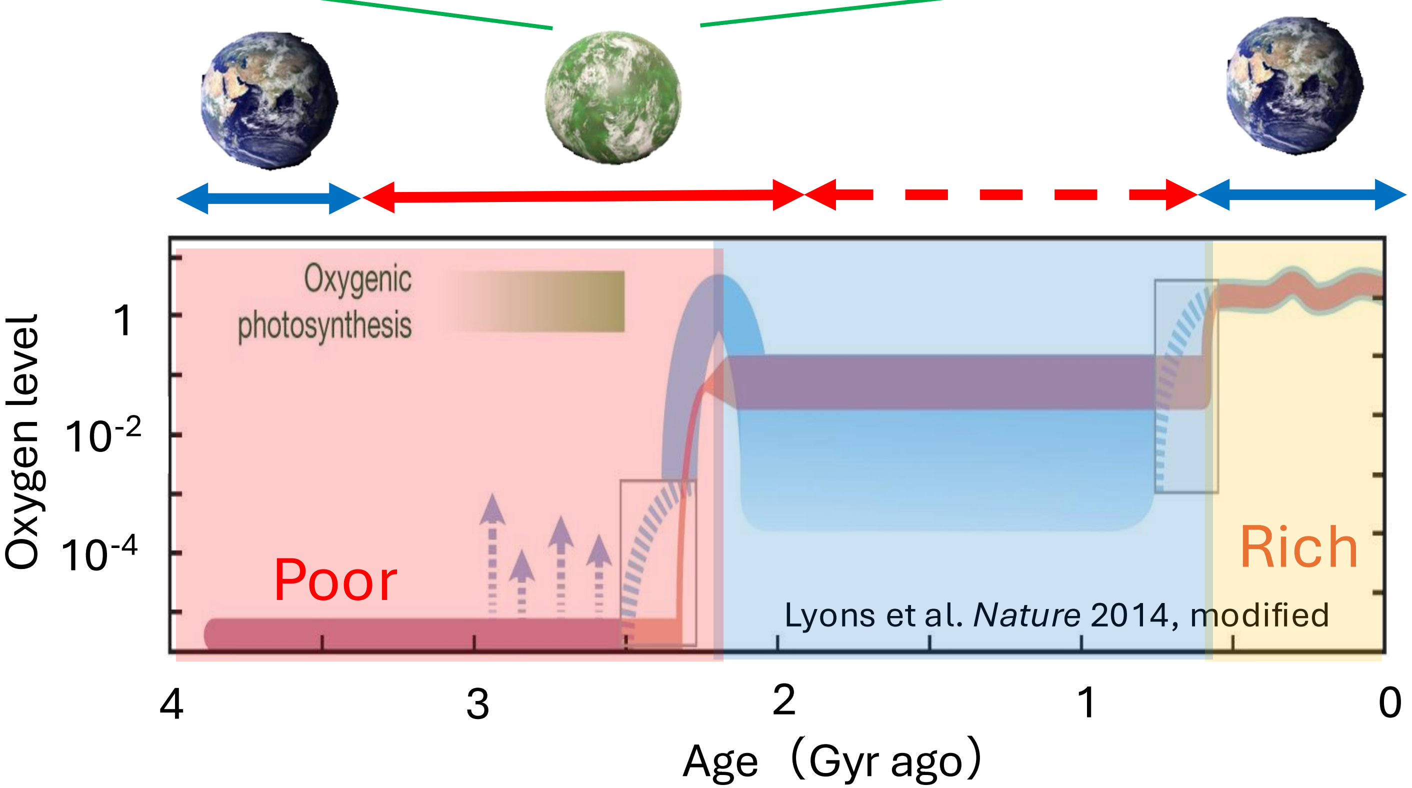
Reflectance spectrum

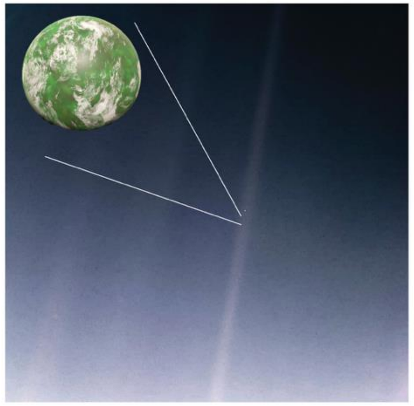
Pale green dot?





Future space telescopes





Past

Pale green dot

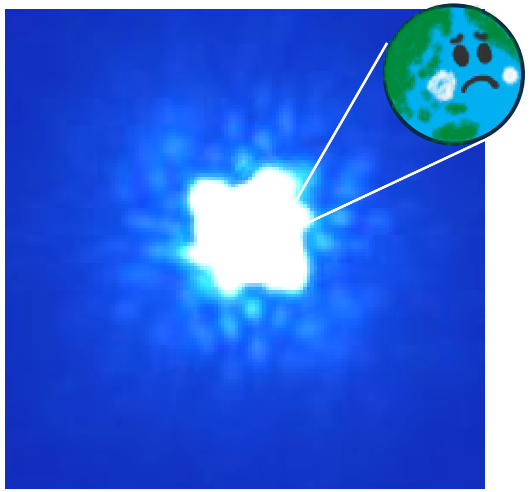
Evolution

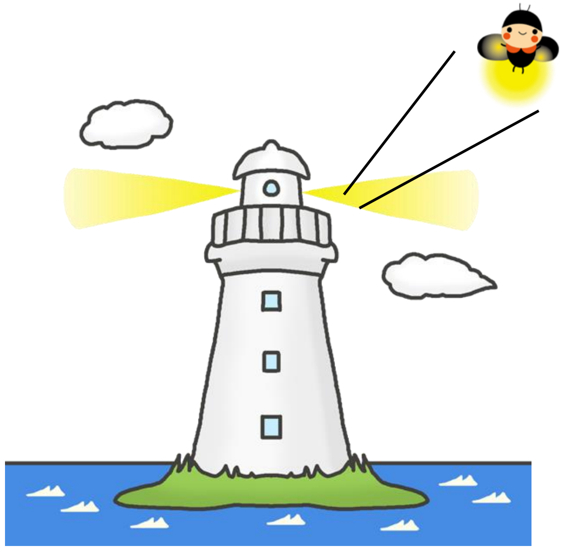
Current

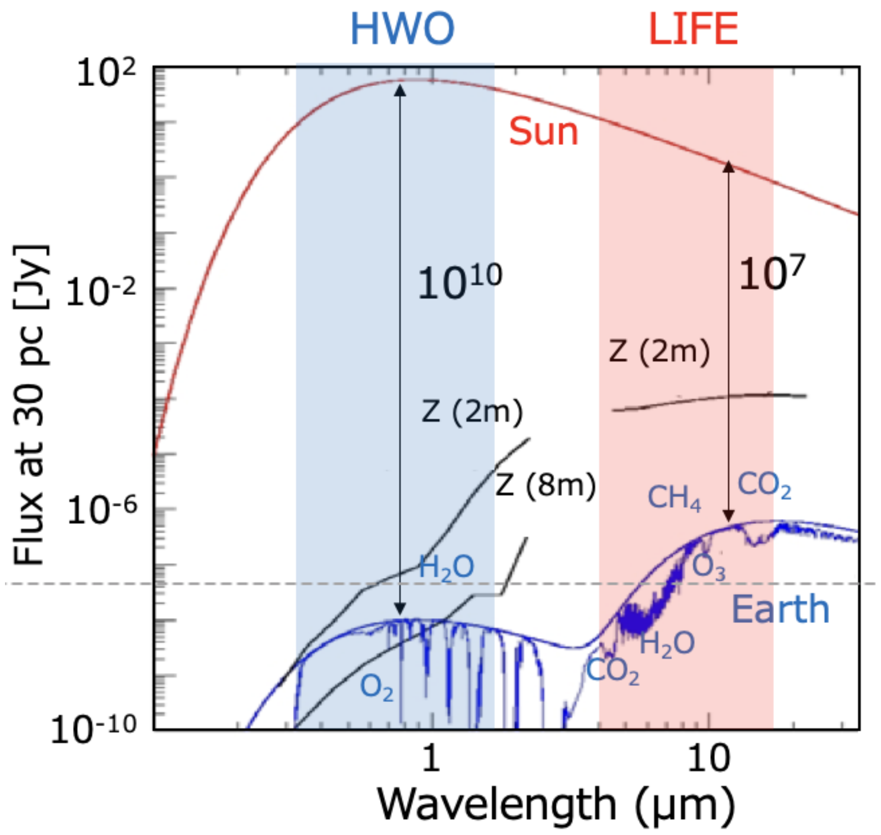
Pale blue dot

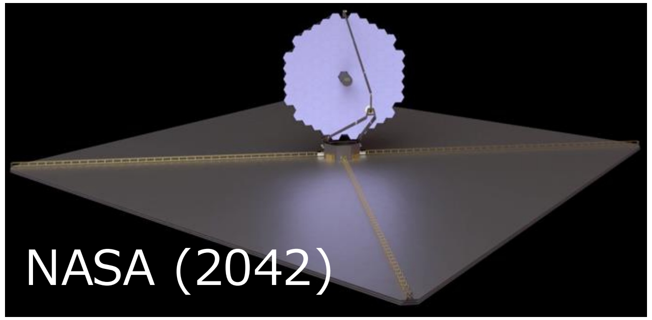
Two telescope concepts

Kasting et al., arXiv: 0911.2936, modified









HWO: Reflected light

Habitable Worlds Observatory

LIFE: Thermal emission

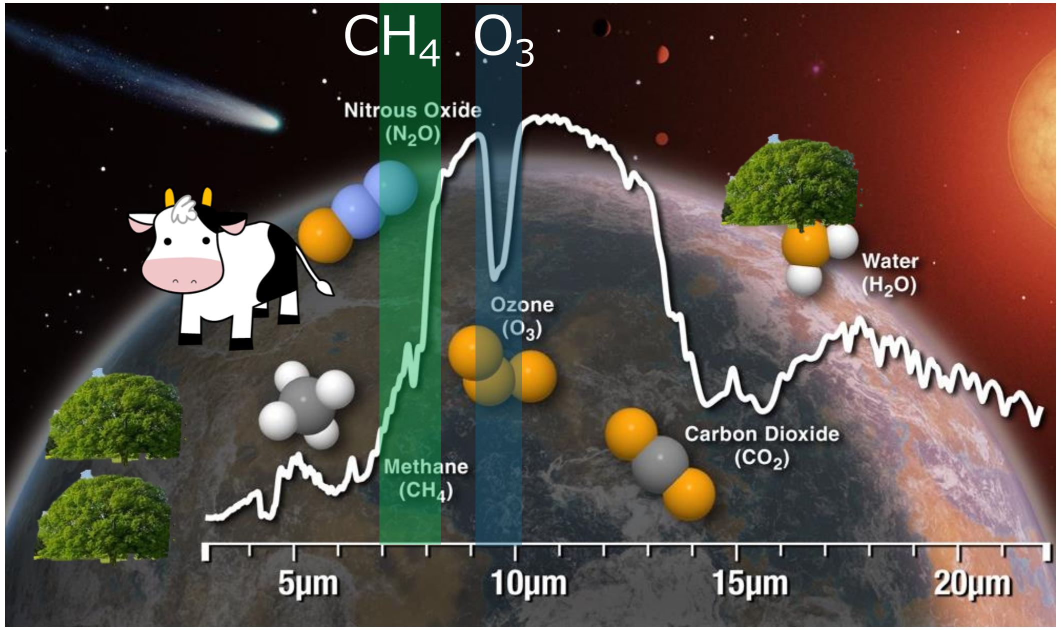
Large Interferometer for Exoplanets

LIFE: Large Interferometer for Exoplanets

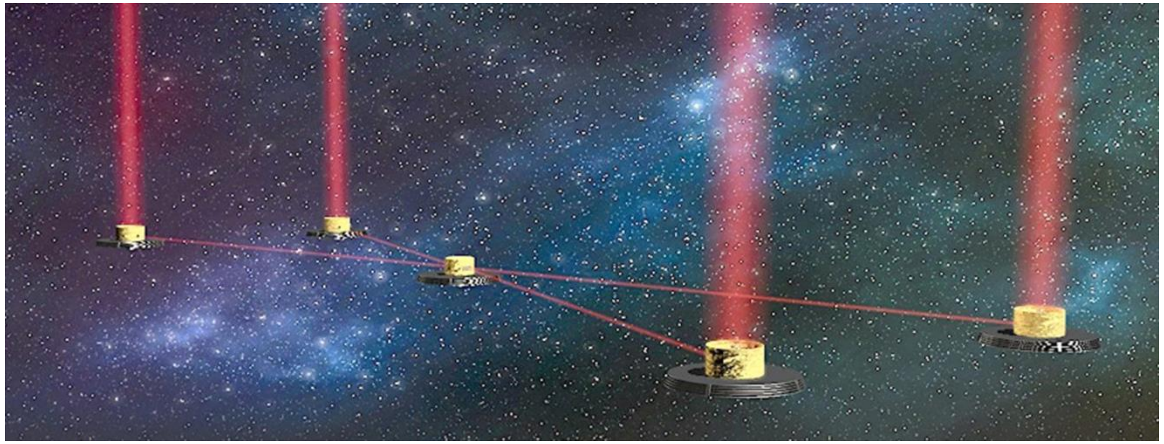
Quanz et al. A&A 2022; Matsuo et al. A&A 2023

- Characterization of thermal emissions from temperate planets
  - ~ 50 habitable candidates
  - Search for biosignature gases (O_3 and CH_4) due to biological activity

- Specifications:
  - Baseline length: 80 – 300 m (fixed for each celestial body)
  - Wavelength: 4.5 – 18 μm
  - Nulling + Stellar interferometry
  - 4 telescopes + 1 beam coupling

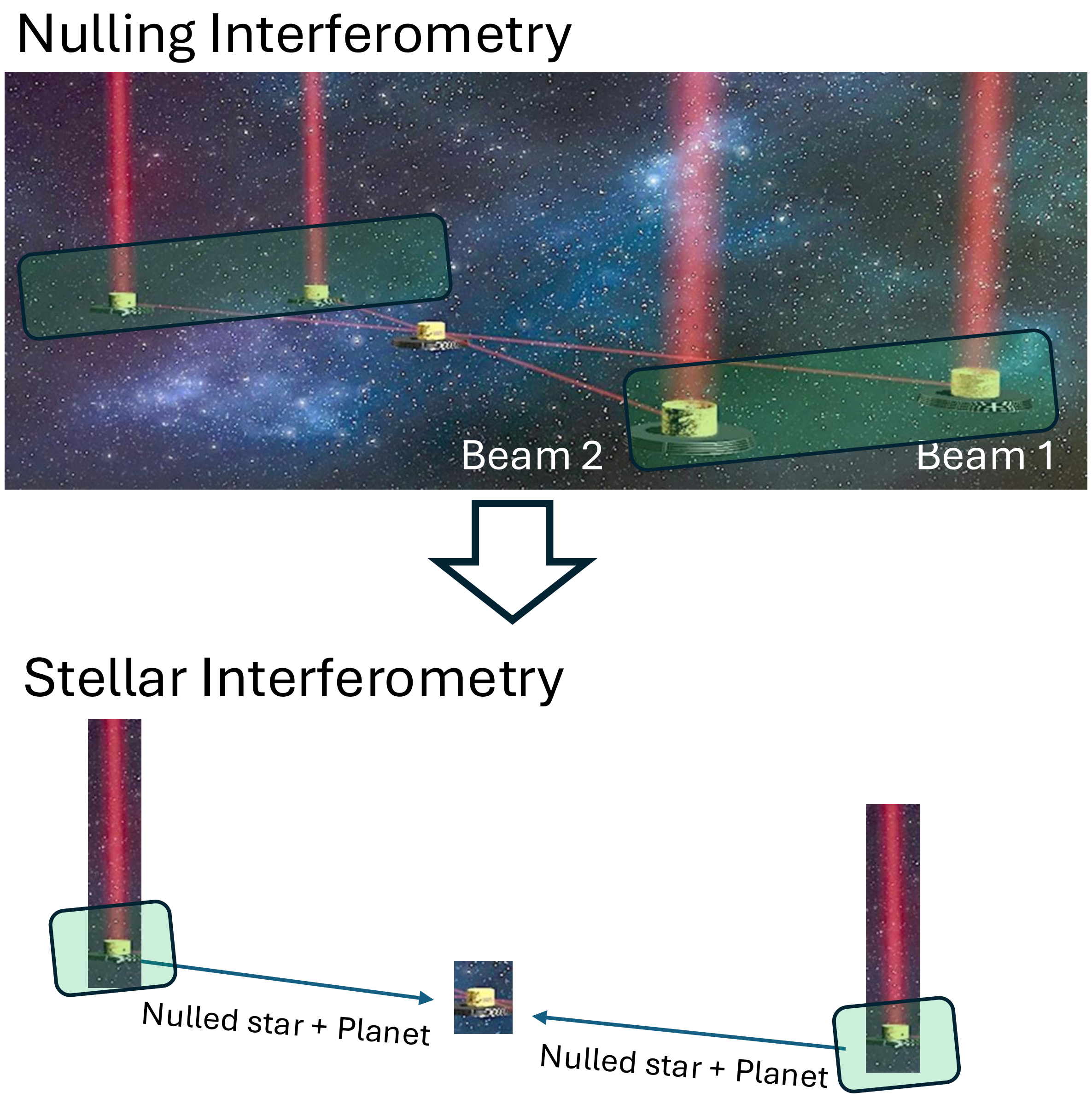


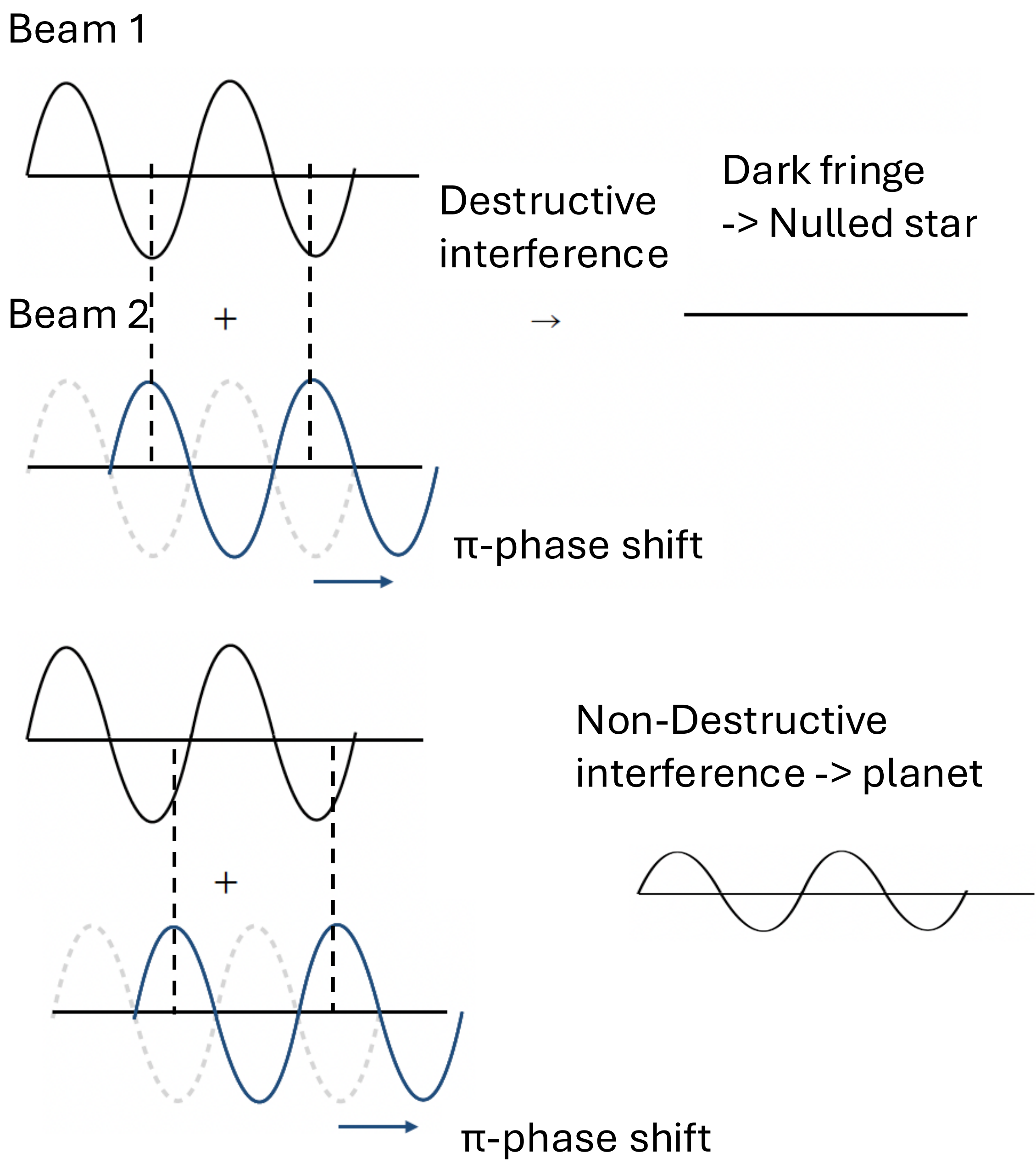
Planet Spectrum



LIFE

Why are four telescopes needed? -> Nulling + Stellar Interferometry



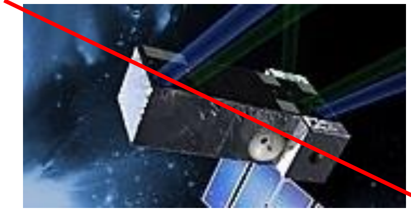


History and Status of Space Interferometry

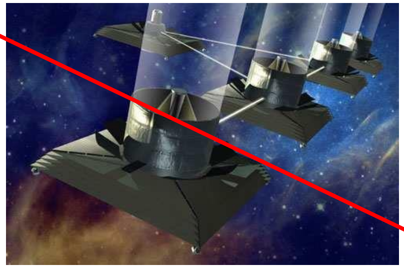
1921

Michelson stellar interferometer

1990s – 2000s



Space Interferometry Mission (SIM)

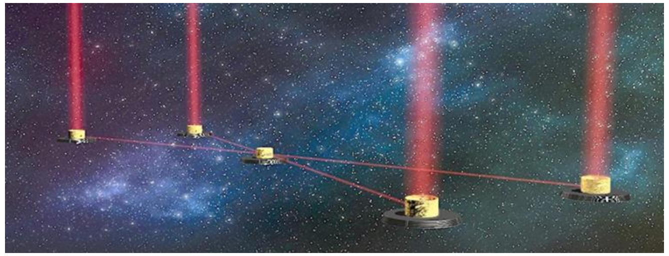


Terrestrial Planet Finder-Interferometer

Canceled

?

2040s



Large Interferometer for Exoplanets

- > 10 space interferometry concepts have been **canceled**.
  “mission proposed → indefinite postponement.”

- Key issues discussed at Caltech (2022–23).
  ➤ **Move stepwise** toward large missions (LIFE-like mission).
  ➤ A white paper identified several critical technologies.

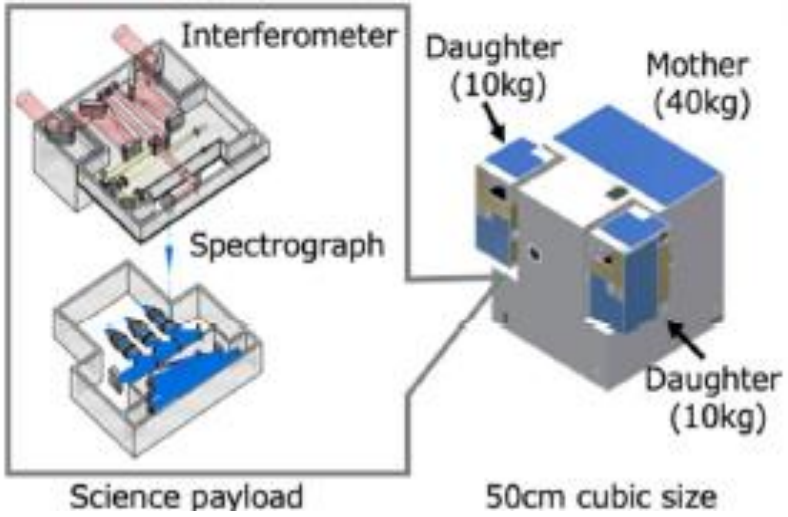
SEIRIOS

This will be introduced in detail.

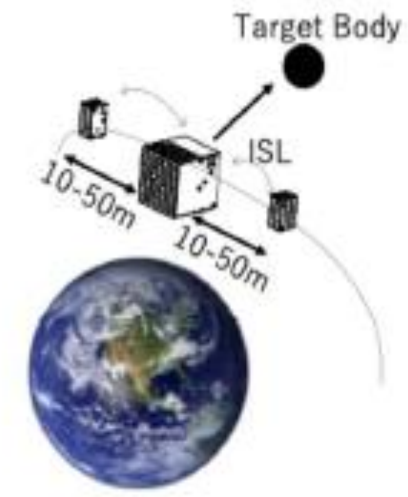
Matsuo, Ikari et al. JATIS 2022

- A formation-flying stellar interferometer was **approved by JAXA in Dec. 2024**.
- SEIRIOS is planned to be launched in Jan. 2031 after passing two critical design reviews.
- **Technology-focused mission: main technical objectives**

1. Demonstrate **millimeter-level formation-flying control** of small satellites in low Earth orbit.
2. Realize a formation-flying interferometer capable of **measuring and controlling the optical path difference (OPD)** between beams from two 6U CubeSats **with a precision of a few tens of nanometers**.



Minimum Success

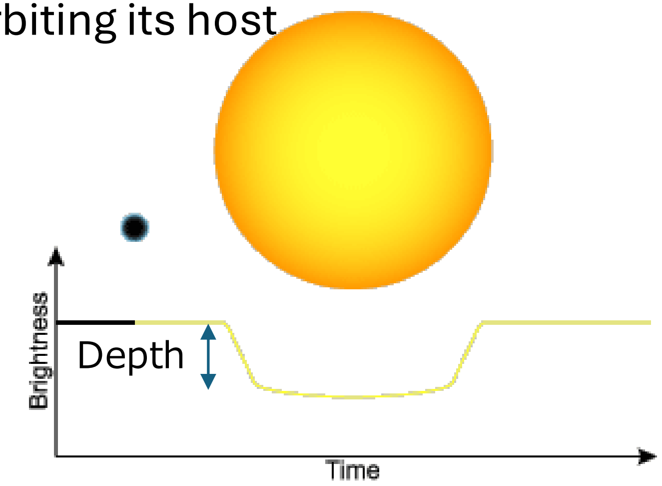


Full Success

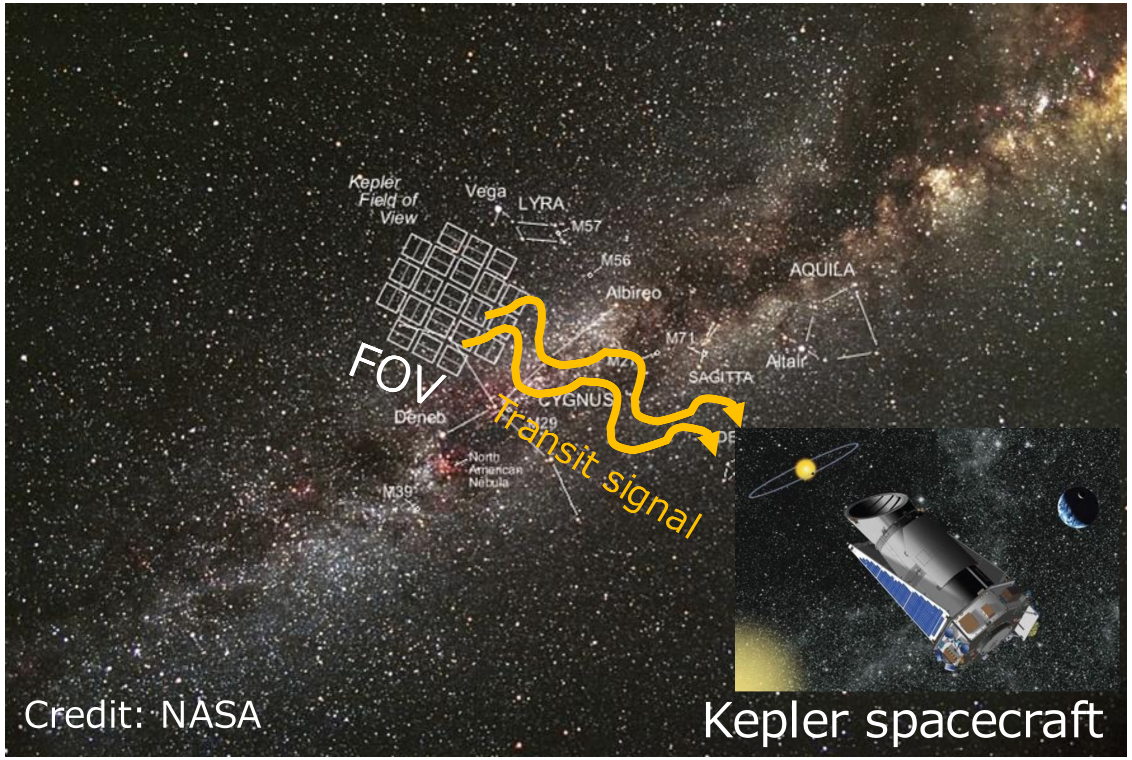
Extra Success

Current landscape of exoplanets

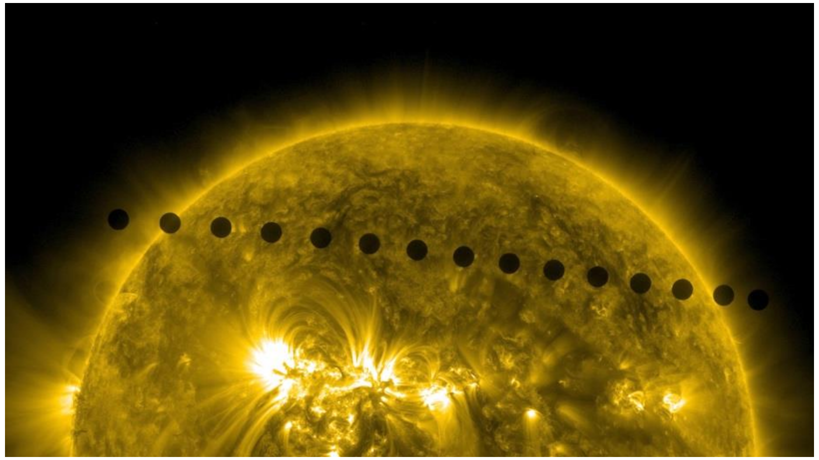
- 6000 planets outside solar system (exoplanets) have been discovered since 1995.
- Kepler spacecraft (launched in 2009) measured light curves of stars within FOV.
- If an eclipse is observed, Kepler confirms the existence of an (unseen) planet orbiting its host star and the diameter of planet.



Light curve during planetary transit



Field of view (FOV) of Kepler spacecraft

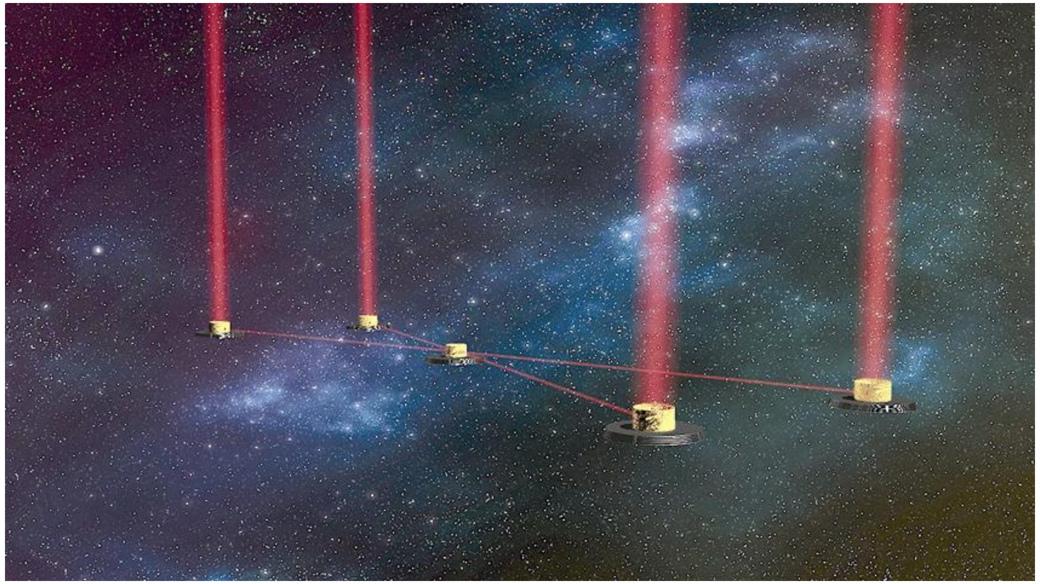


Transit signal

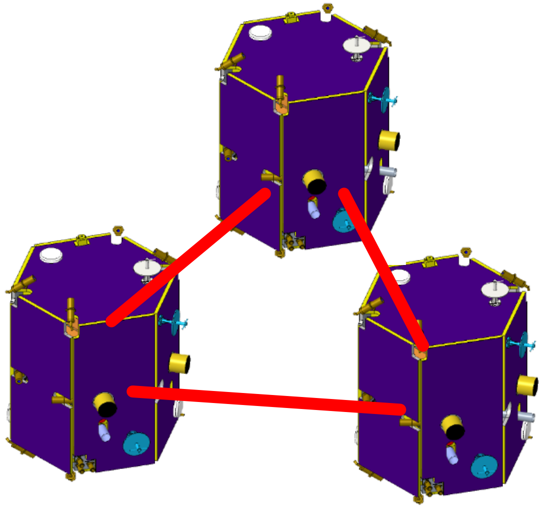
Revival of space interferometer

- All space interferometers were cancelled around 2010 due to the technical difficulty.

- Many small planets in nearby universe found by Kepler space telescope.
- Mid-infrared space interferometer (LIFE) selected in ESA Voyage 2050.
- Demonstration of high-precision formation flight (FF) under review by JAXA/ISAS
  -> A new path from SILVIA to LIFE



LIFE: large infrared for exoplanets



SILVIA:

Space Interferometer Laboratory Voyaging towards Innovative Applications

Mission Configuration & Key Specifications

- **Configuration:** One 50-kg-class microsatellite and two 6U CubeSats
  - Launched in a docked configuration and initially operated as single spacecraft
  - Two daughter satellites are separated from the mother satellite after in-orbit calibration
- Orbit: **Dawn–dusk** low Earth orbit at ~600 km altitude
- Baseline length: **10 – 100 m**
- Fringe tracking wavelength: **550 – 950 nm (potentially extended to 1.7 μm)**
- OPD control: Real-time measurement and correction at **>100 Hz**

Team Structure/Experience

SEIRIOS is a **University-led** space program. A **close collaboration between science and engineering** has been developed over the past five years to prepare this mission concept.

Space Engineering Team
led by Satoshi Ikari (U. of Tokyo)

Members: ~ 40

Science Team
led by Taro Matsuo (U. of Osaka)

Members: ~ 20
(inc. international partners)

Close communication

> 20 CubeSats / MicroSatellites successfully launched !

Bringing together technologies and expertise from international partners

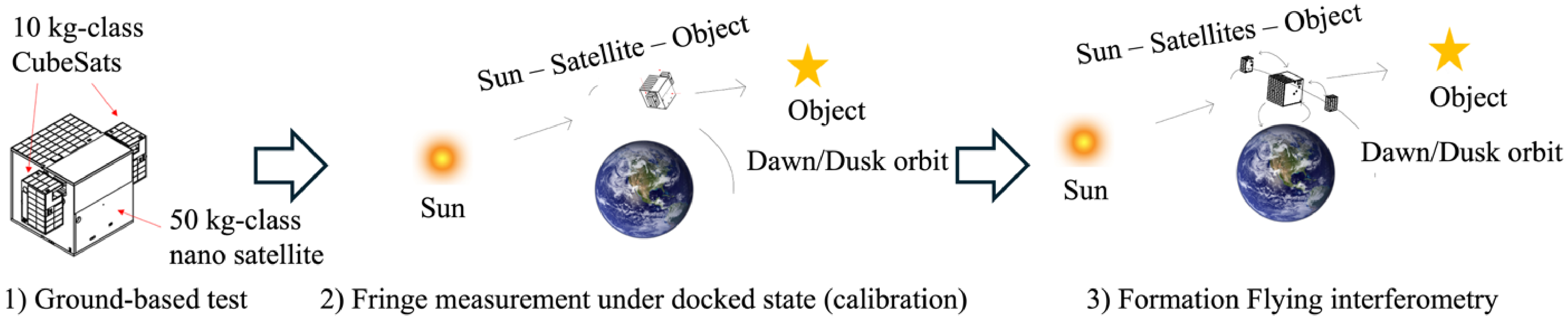
Three Step Realization of FF interferometry

1. **Ground Calibration & Fringe Test:**

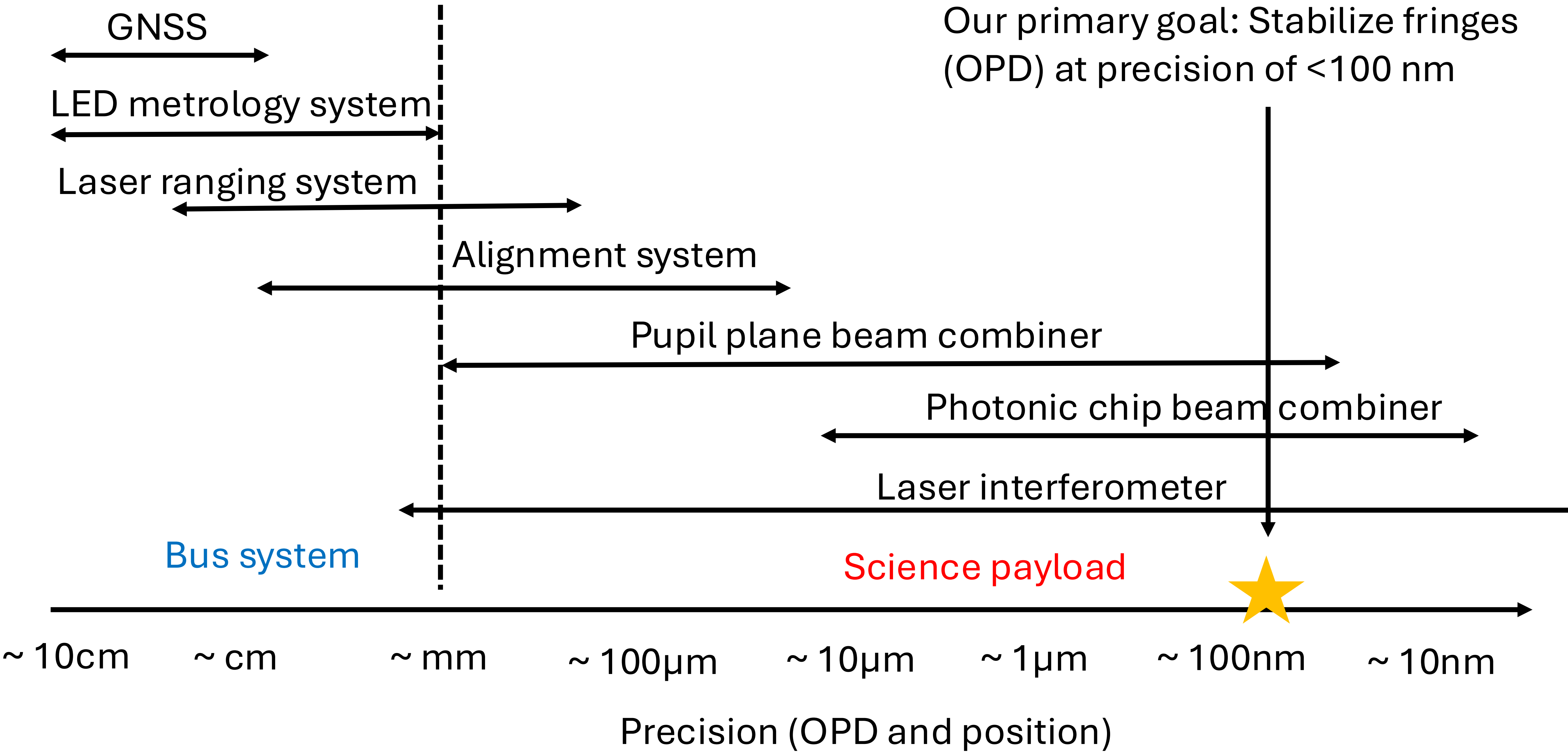
   All three satellites are docked together, and fringe measurement is performed in a ground-based test.

2. **On-Orbit Fringe Measurement While Docked**
   SEIRIOS is launched in the docked configuration. The alignment system is calibrated, and interference fringes are measured while docked.

3. **Formation-Flying Interferometry**
   After successful on-orbit fringe verification, the satellites are separated. Initial formation at ~10 m separation relaxes metrology requirements; finally expanded to ~100 m baselines.



Metrology systems



Science Payload Overview

- **Measurement subsystems:**

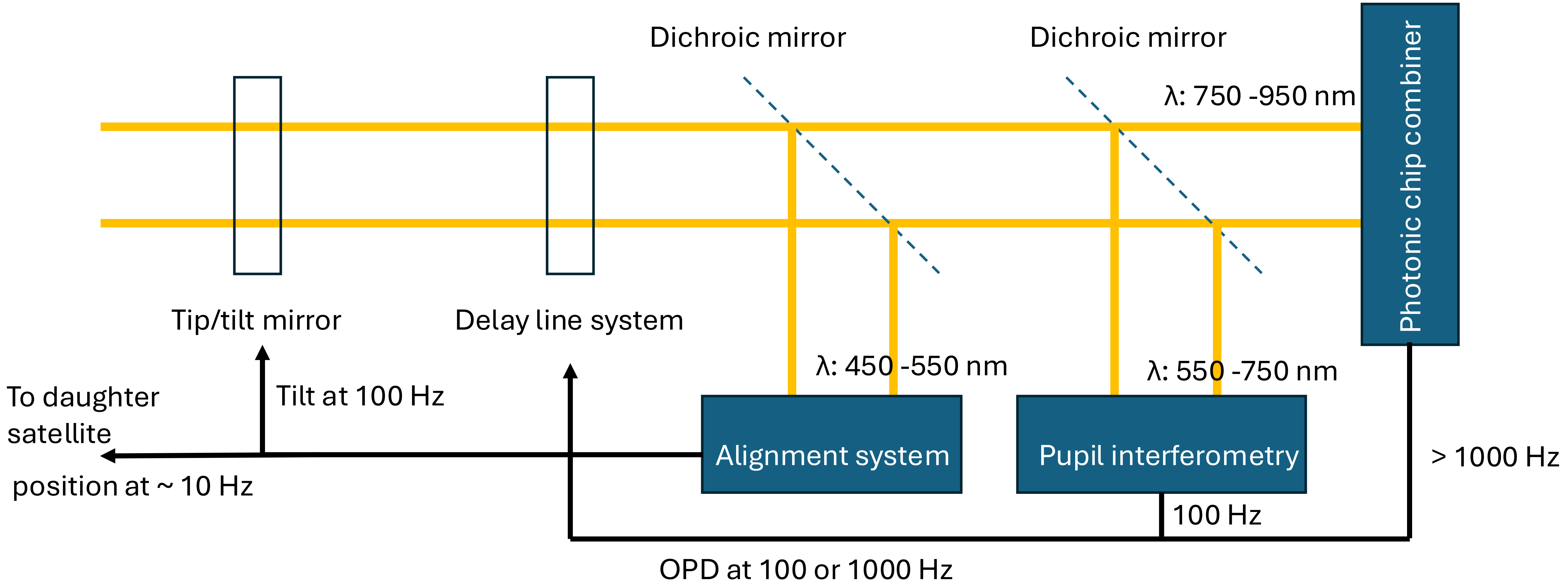
1. Alignment system to measure beam tilt and position (450–550 nm)
2. Two (three) beam combiners for fringe measurement
   - **Pupil-based** beam combiner, R ~ 1000 (550–750 nm)
   - **Photonic chip** beam combiner, R ~ 50 (750–950 nm)
     → Long coherence length (~1 mm) and high precision (~tens of nm)

     (Near-infrared beam combiner towards LIFE)
3. External laser interferometer for precise relative displacement and velocity measurements between spacecraft *(see Anika Chan's presentation)*

- **Control subsystems:**

1. Tip-tilt mirror (Precision: **0.2"**, Range: **~ 3'**)
2. Delay line system (Precision: **1 nm**, Range: **2 cm** in optical path length)

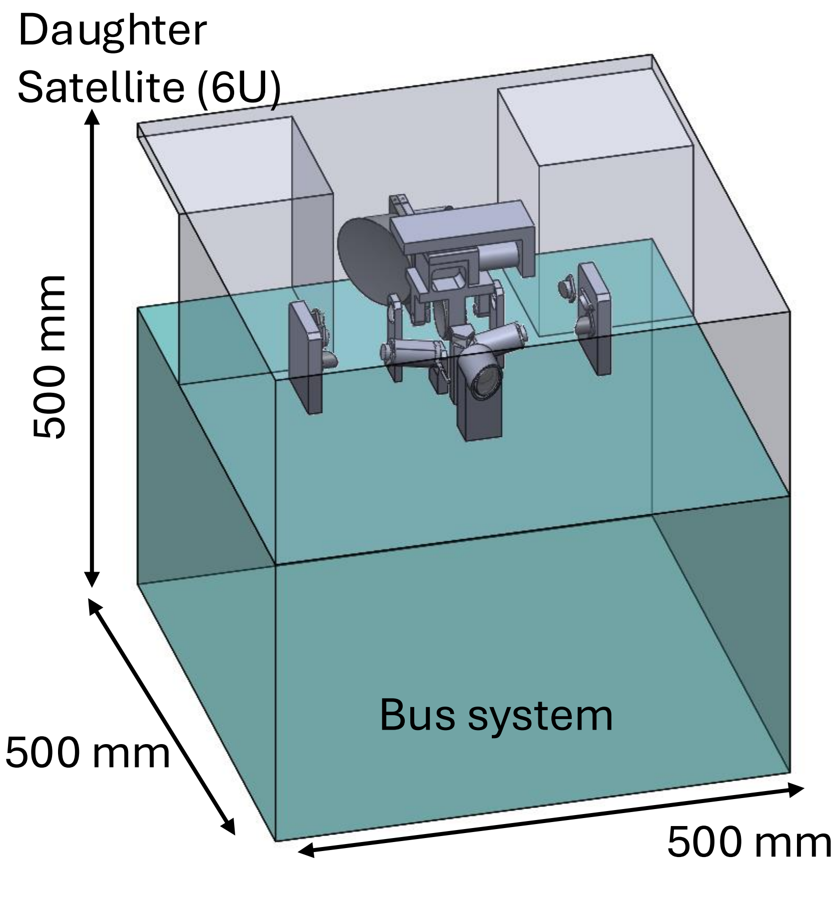
Science mission payload



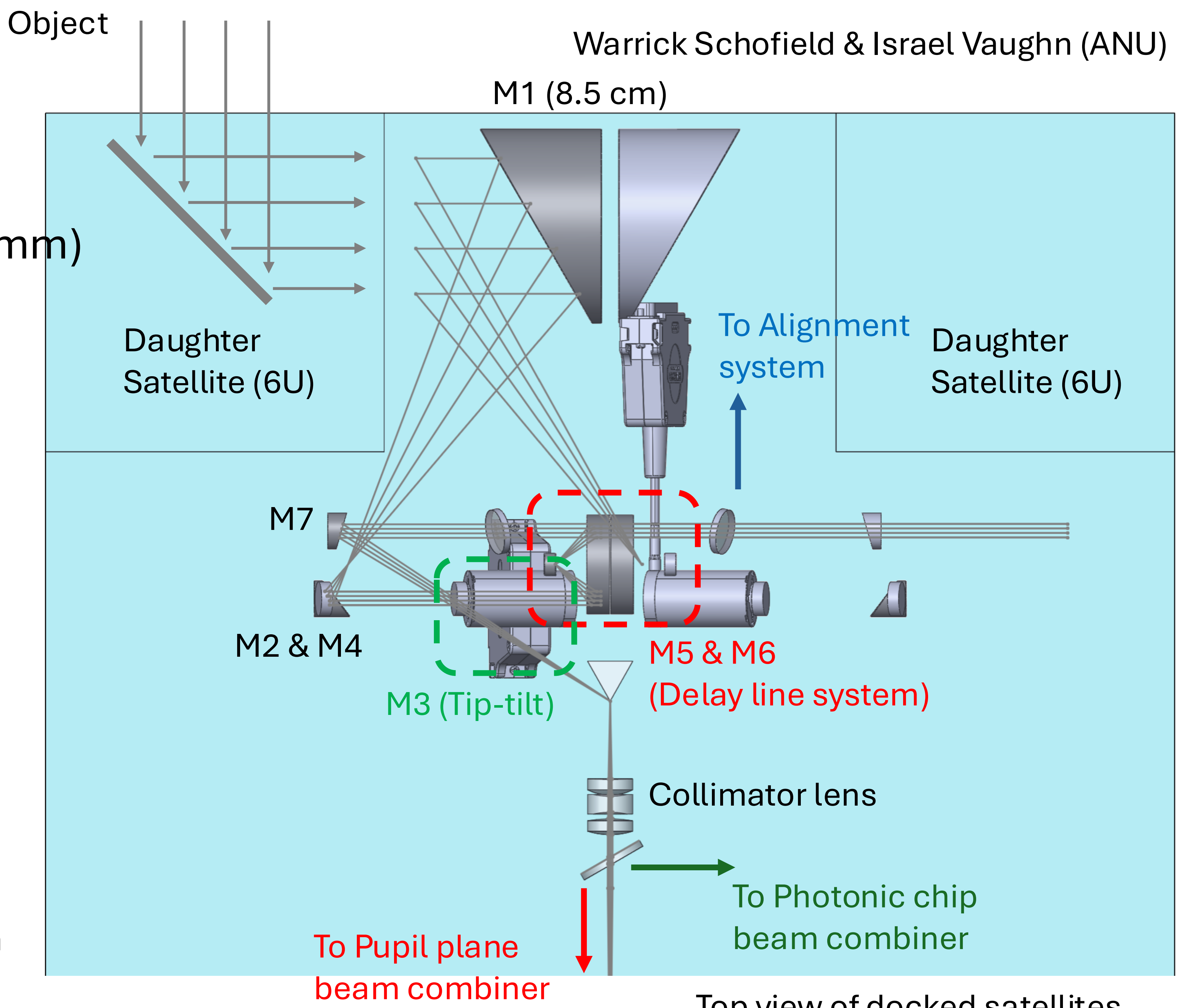
Optical system

- Total mass: < 10 kg,
  Dimensions: 450 x 400 x 200 mm)

Warrick Schofield & Israel Vaughn (ANU)



Entire view of docked satellites

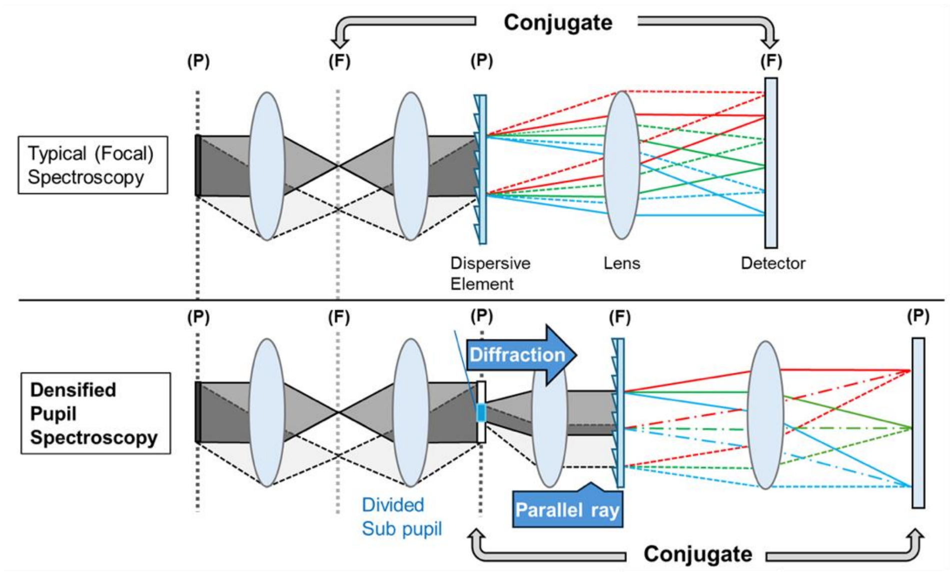


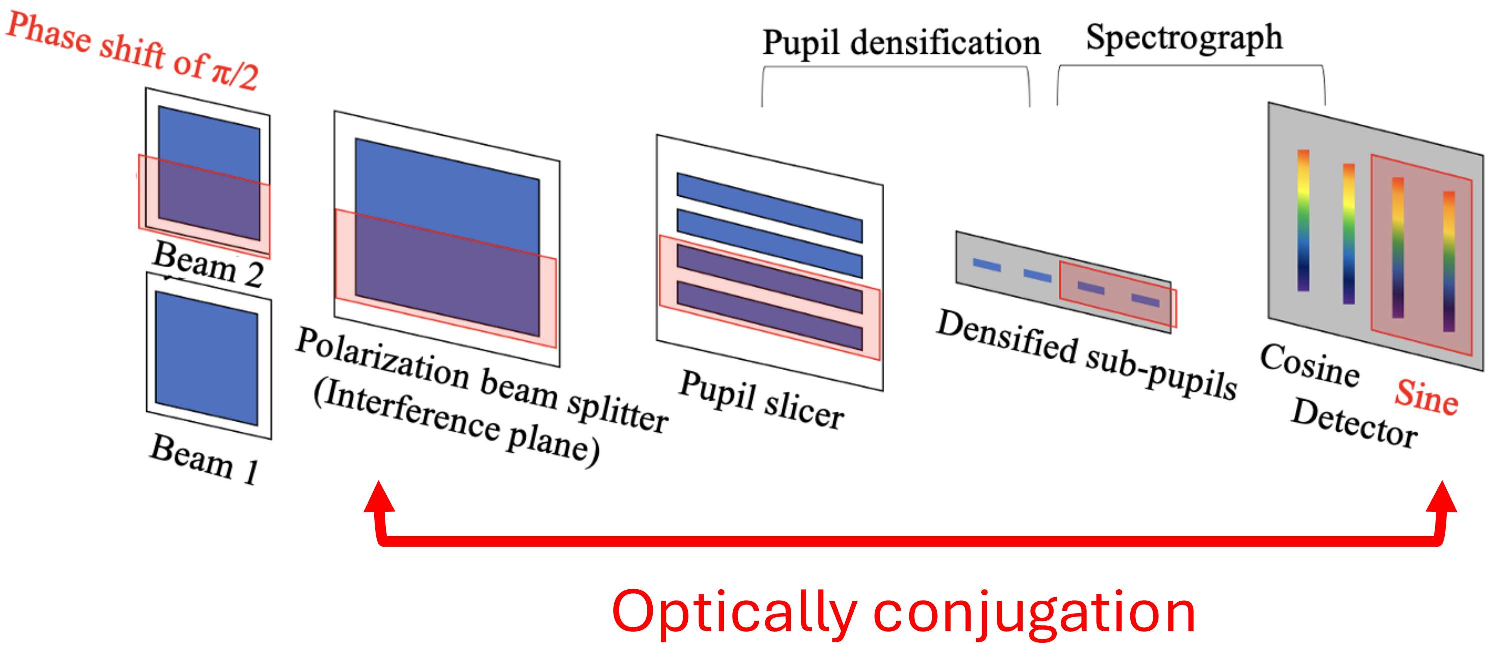
Top view of docked satellites

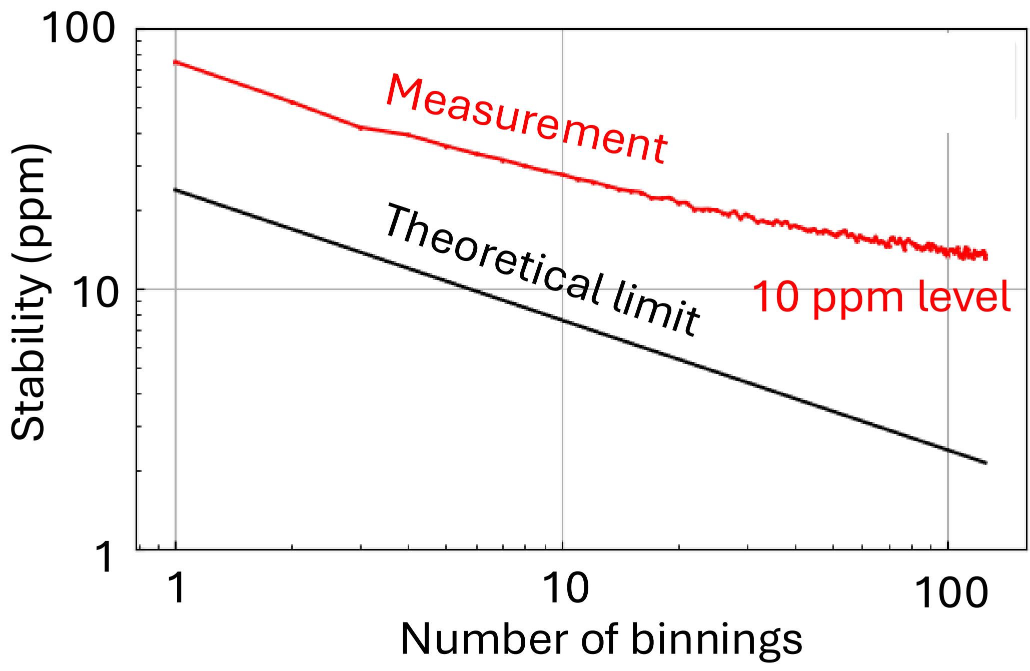
Matsuo et al. ApJ 2016; Matsuo et al. JATIS 2022
Yoshida et al. in prep.

Pupil-based beam combiner

- Pupil spectroscopy offers robustness against a large pointing error: **~ 10 ppm stability** was achieved under **5 λ/D**
- Pupil spectroscopy is applied to beam combiner: optical conjugation between beam combiner and detector:
  -> Complex visibility can be formed by adding π/2 phase to one of the two beams before interference.



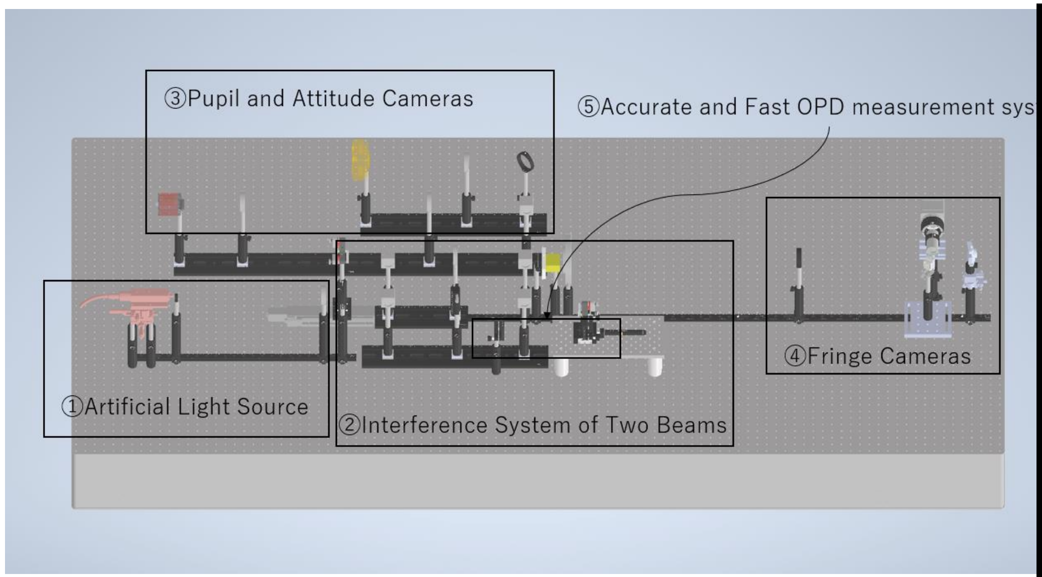


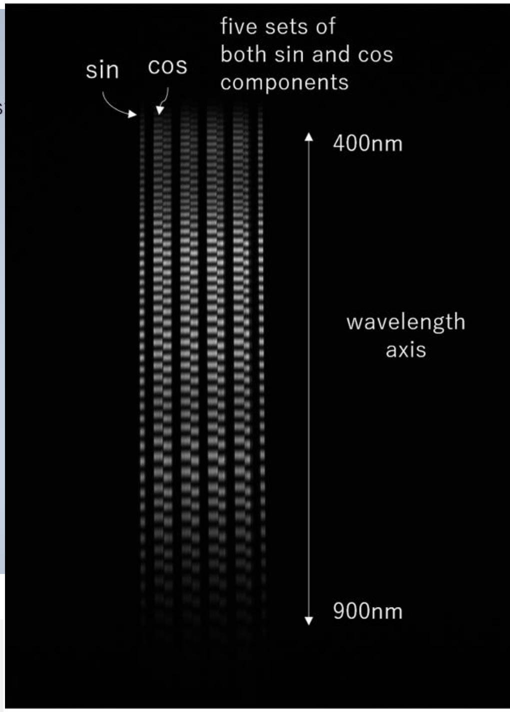


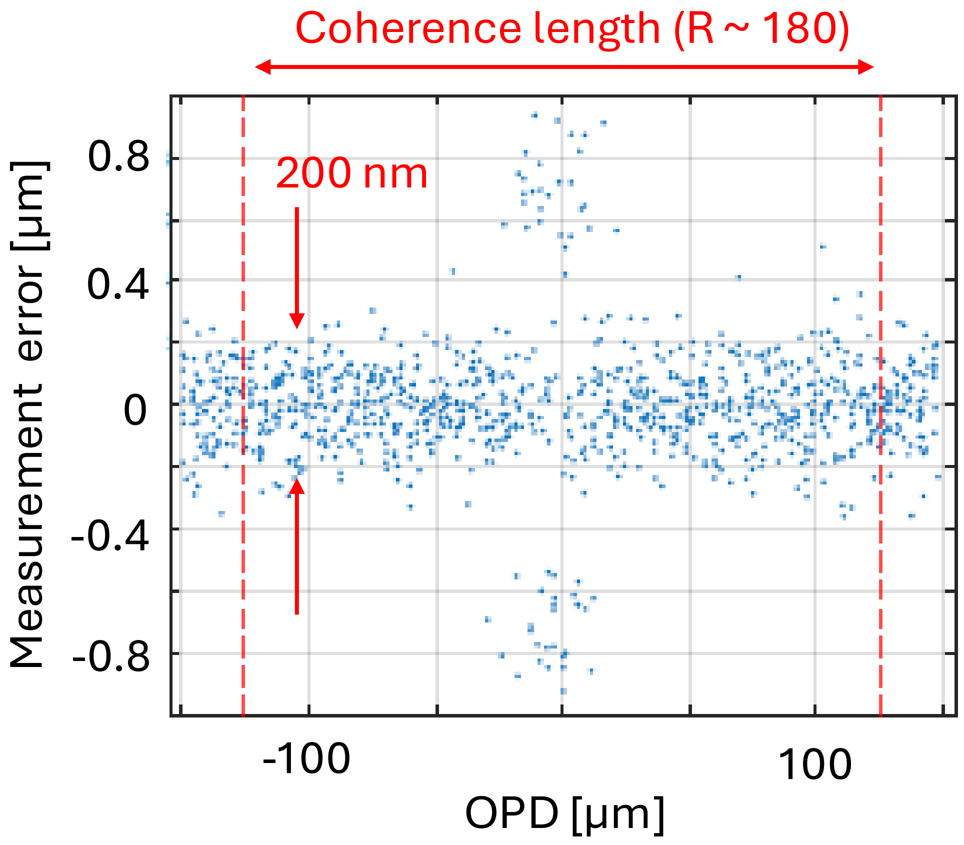
Verification

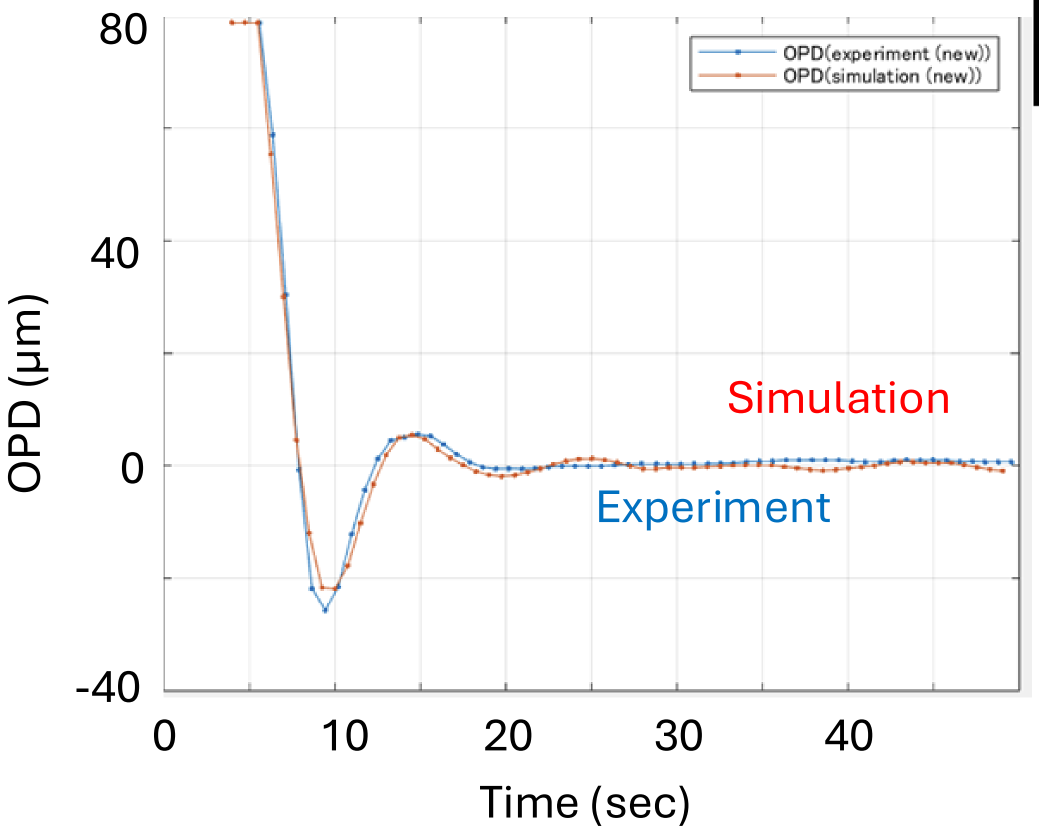
Kondo et al. in prep.

- Complex visibility reconstructed from one exposure.
- Measurement error of ~ 140 nm over the coherence length (+/- 300 μm).
- Control of OPD w/ delay line



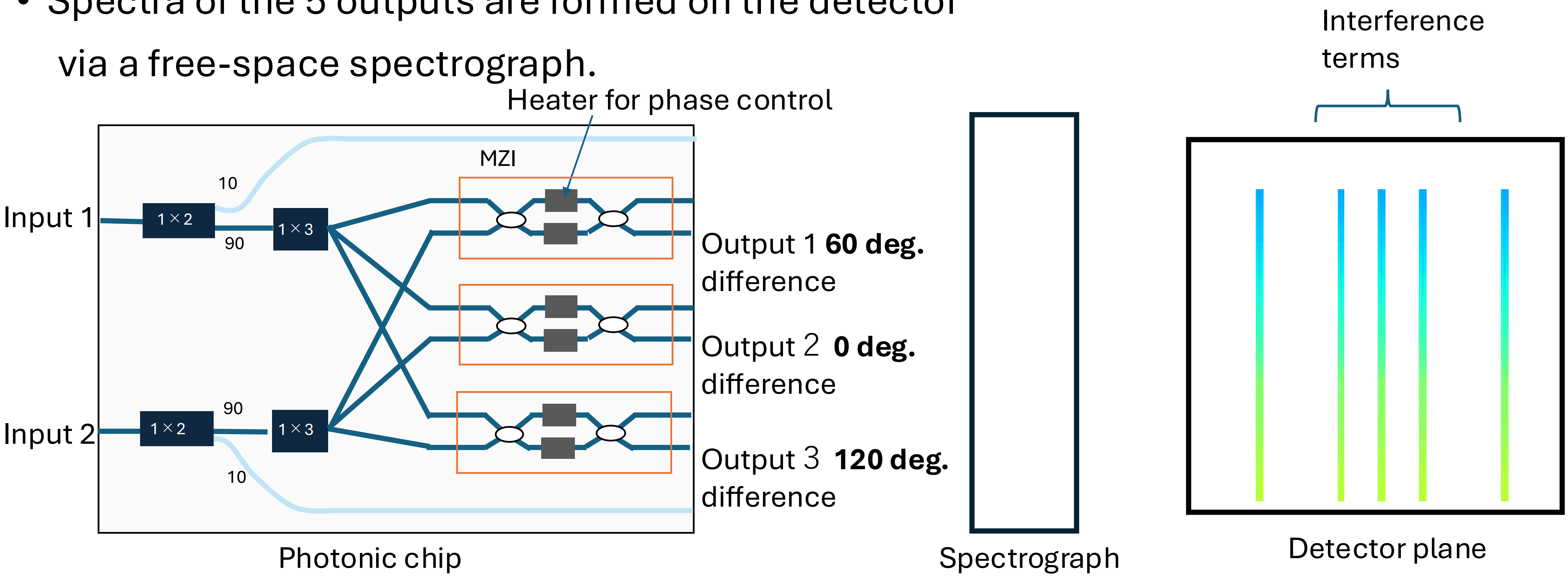






Photonic chip beam combiner

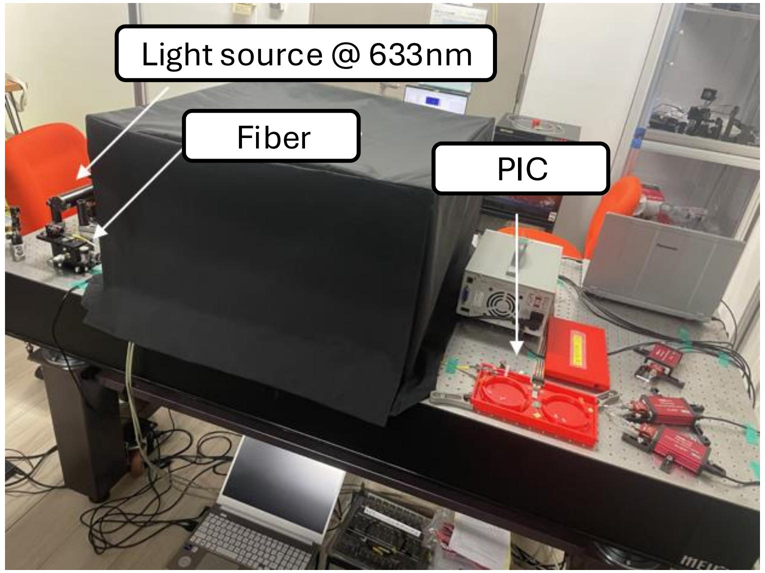
- 2 input beams, **5 outputs** to reconstruct complex visibility from a single exposure
  - 3 interference terms with phase offsets of 0°, 60°, and 120°
  - 2 photometric taps for flux monitoring
- Spectra of the 5 outputs are formed on the detector via a free-space spectrograph.



Preliminary test at 633 nm

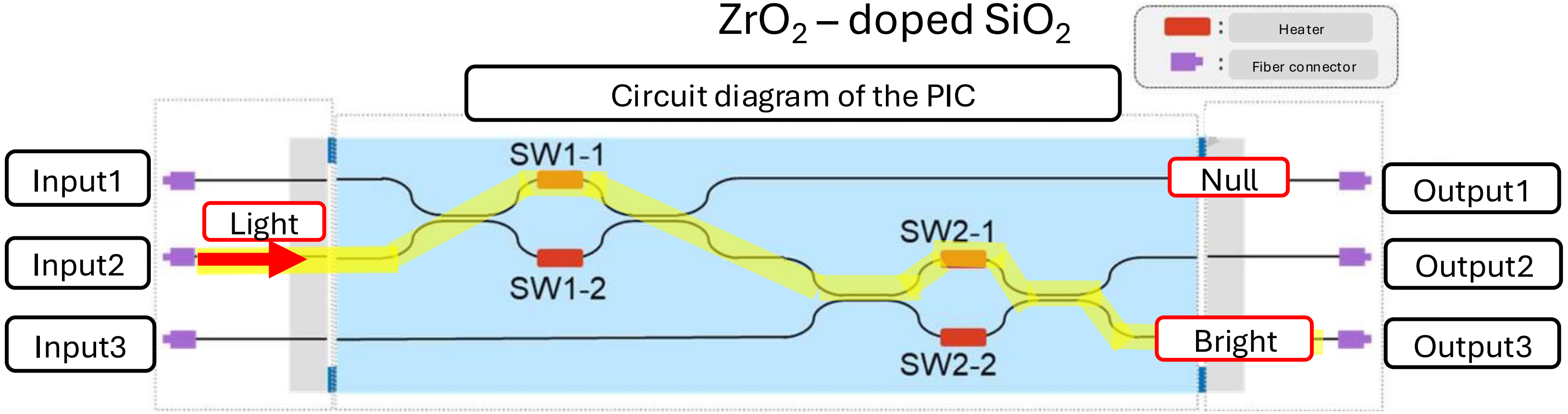
- **Achieved Contrast of 4 x 10^{-4}** achieved with a single MZI
- **Only 5% loss of light** through the PIC

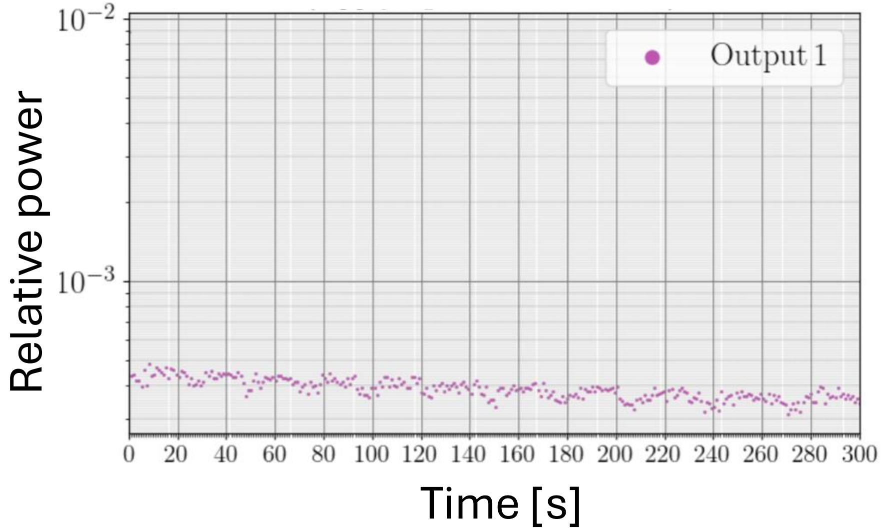
- Future work:
  - Design incident optical system for **robust against a large tilt error**
  - Design PIC for **minimum phase difference over a large bandwidth**



Experimental setup for the PIC

ZrO_2 – doped SiO_2





Other Critical Technologies

- **High-precision (< 1 nm) and low power consumption (< 0.1 W) delay line system** based on Space Interferometry Mission (SIM) heritage in a collaboration with JPL.

- Space-qualified **sCMOS** with **high-speed (~ 120 Hz)**, **low read noise (< 0.5 e-/s) and low-power consumption (< 1W)** under development with Hamamatsu.

- **High-speed laser interferometer** for high-precision measurement of relative velocity between spacecraft.

- **Calibration unit** to define zero OPD and zero Tip/tilt using internal source.

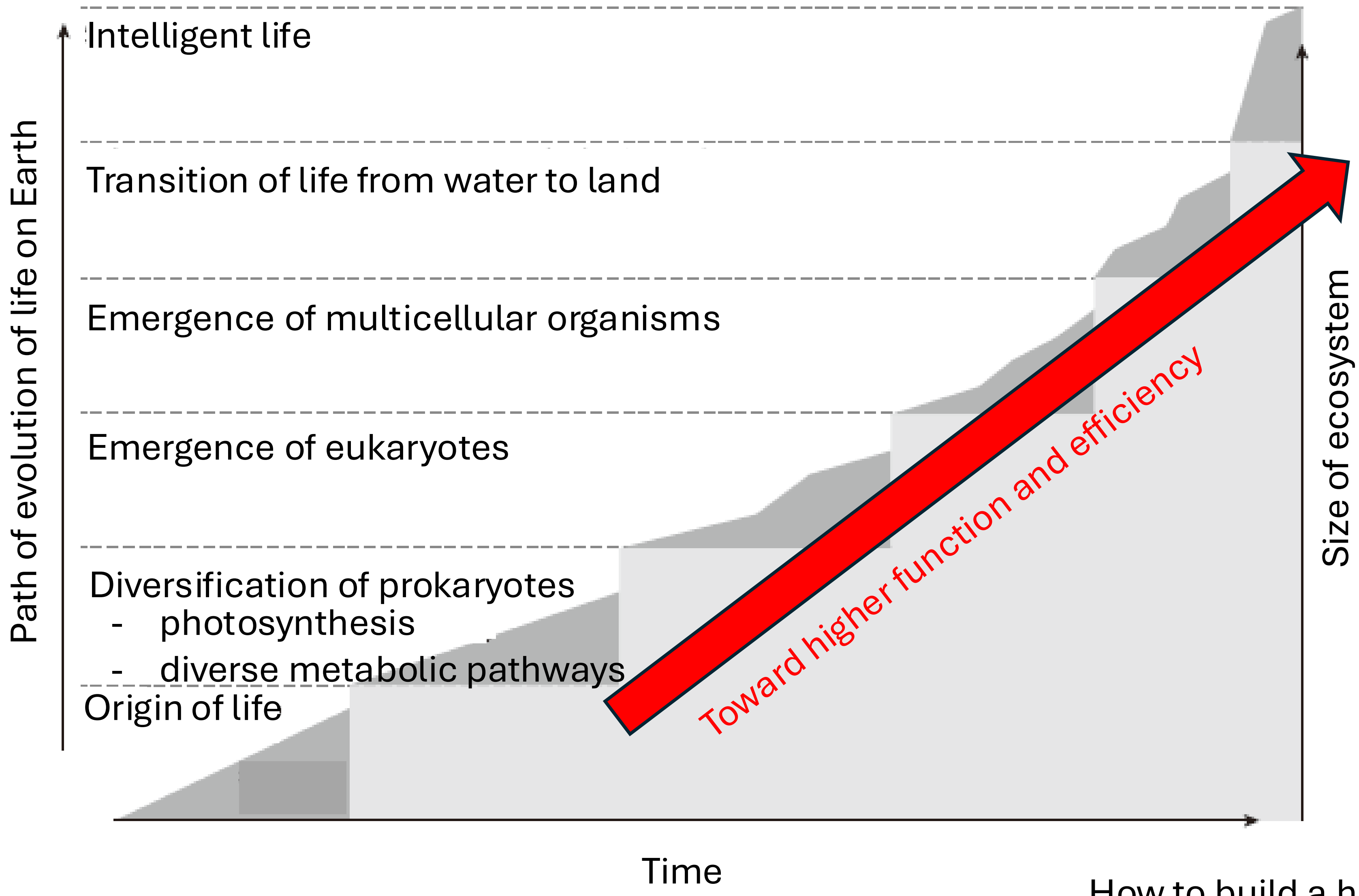
Plan

- Mar. 2025: SEIRIOS formally approved.
- Apr. 2025 – Mar. 2027: Design and verification of critical components
- Jan. – Mar. 2027: Preliminary Design Review (PDR)
- Apr. 2027 - Mar. 2029: Engineering model fabrication and environmental tests
- Mar. 2029: Critical Design Review (CDR)
- Apr. 2029 – Mar. 2030: Flight model integration and testing
- **Jan. 2031: Launch of SEIRIOS**
- Jul. 2031: Completion of operations

Summary

- The baseline configuration has been almost defined.
- SEIRIOS will provide a unique opportunity to demonstrate
  1. **mm-level formation flight**
  2. **fringe tracker/stability with a precision of 100 nm**
- Critical subsystems will be also verified in orbit:
  - Photonic chip beam combiner
  - Laser interferometer system
  - High-precision delay line system
- Core international partners include ANU, NASA/JPL, and ETH Zurich. We welcome discussion and information exchange on formation flying interferometer.

How did life evolve on Earth?



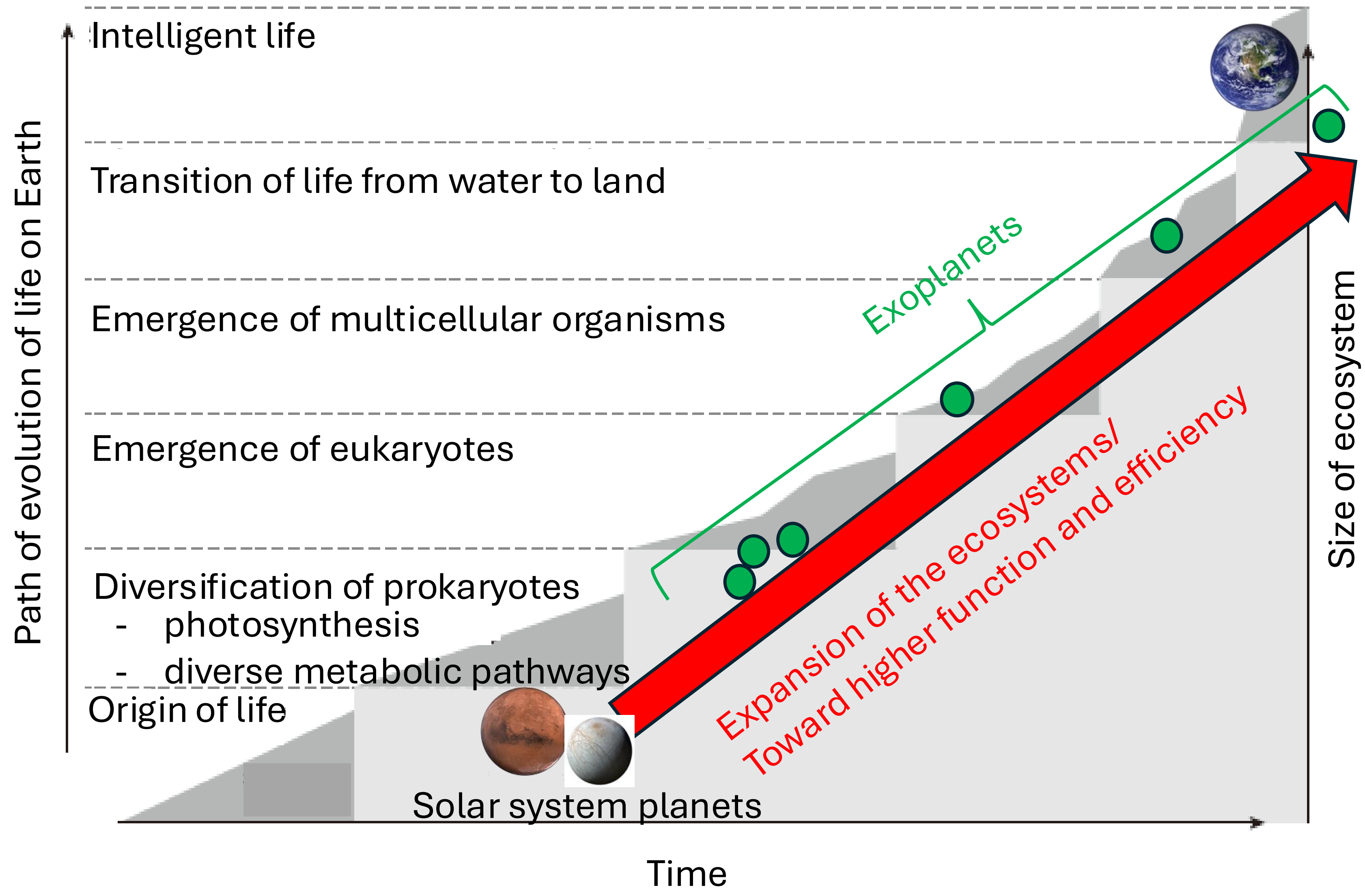
- Evolution through random mutation in DNA

➔ Increased energy use efficiency

➔ Expansion of ecosystems

How to build a habitable planet (C. H. Lagmuir et al.)

Various evolutionary stages of life in the universe



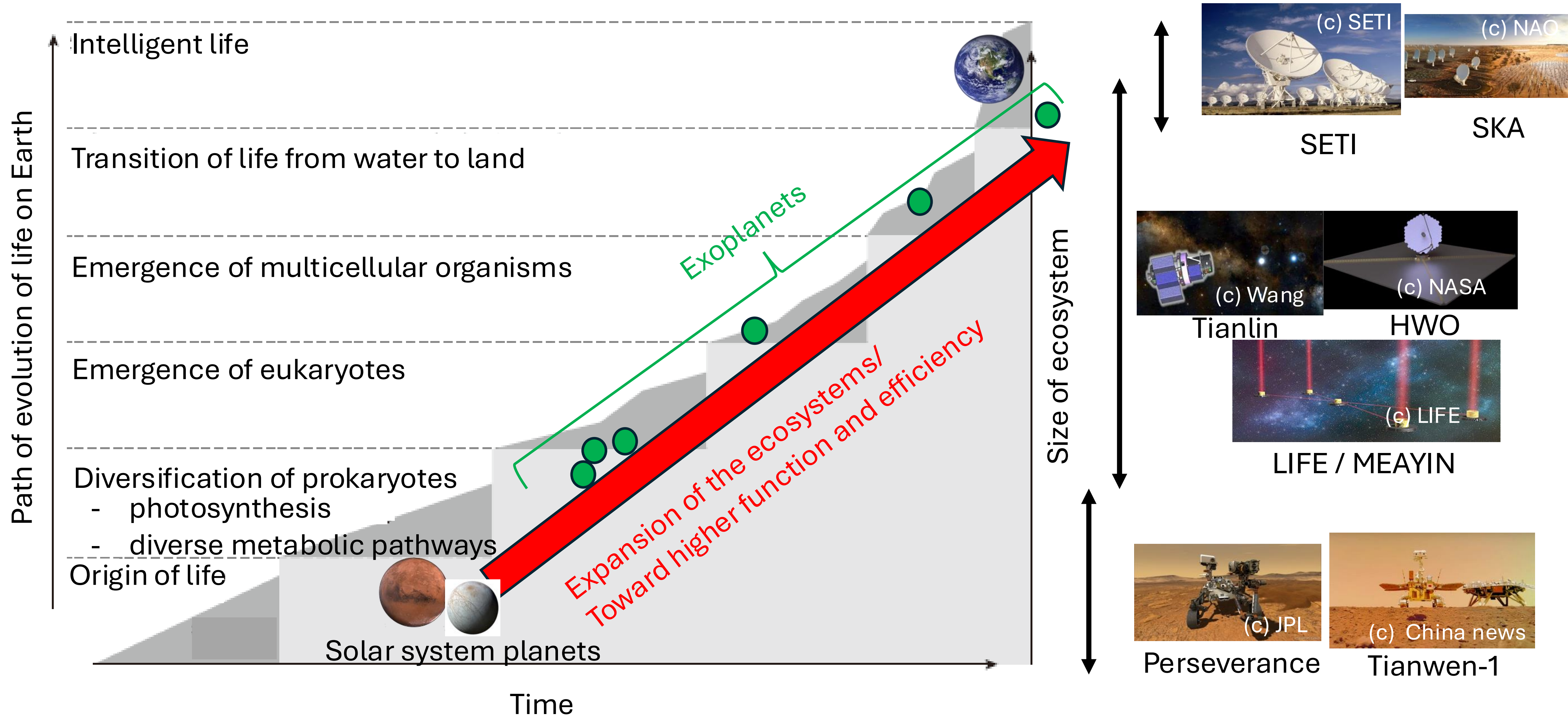
- Evolution through random mutation in DNA

  ➔ Toward higher function and efficiency

  ➔ Expansion of ecosystems

- Life on exoplanet is at various evolutionary stages

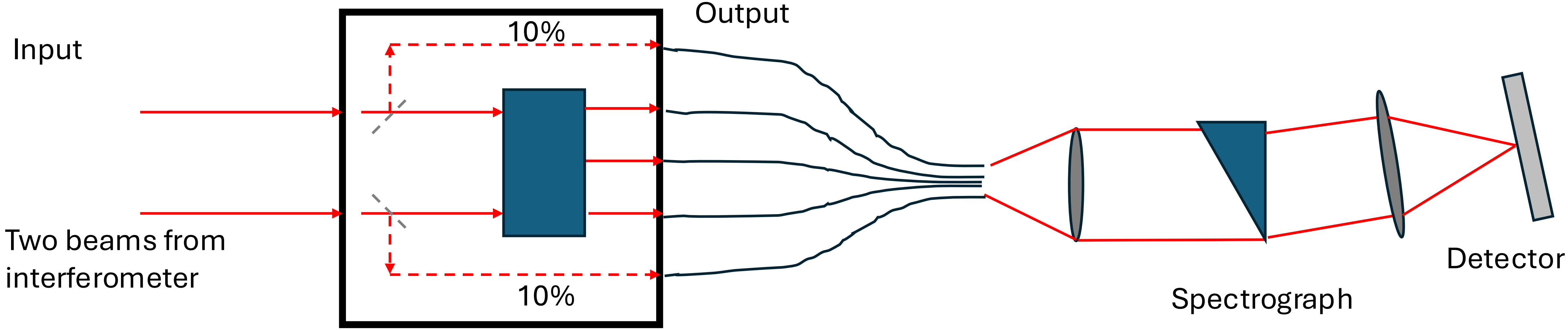
Various evolutionary stages of life in the universe



Photonic integration device for space interferometer

- Spectral range: 750–950 nm
- 2 inputs, 5 outputs
- 3 phase-stepped fringes (0°, 60°, 120°) + 2 photometric taps

-> Reconstruction of complex visibility from one exposure



Five spectra:
Three fringes + Two intensities

Photonic integration device for space interferometer

- Interferometer calibration with an internal LED.
- Two beams from the internal source map the PIC input location on the focal plane.