LOOK BEFORE YOU LEAP

Using the Solar Gravitational Lens to explore exoplanets

8th Interstellar Symposium, Montreal, July 10, 2023

The scale of the problem

Extrasolar scales

- Distance to the nearest star is almost 300,000 AU
- That is almost 100 million times the famous “one giant leap”
- If the Earth is a grape and the Moon is a peppercorn a foot away...
- ... the nearest star would be more than halfway around the Earth.
- It makes sense to look before we take such a giant leap

What does it entail to look?

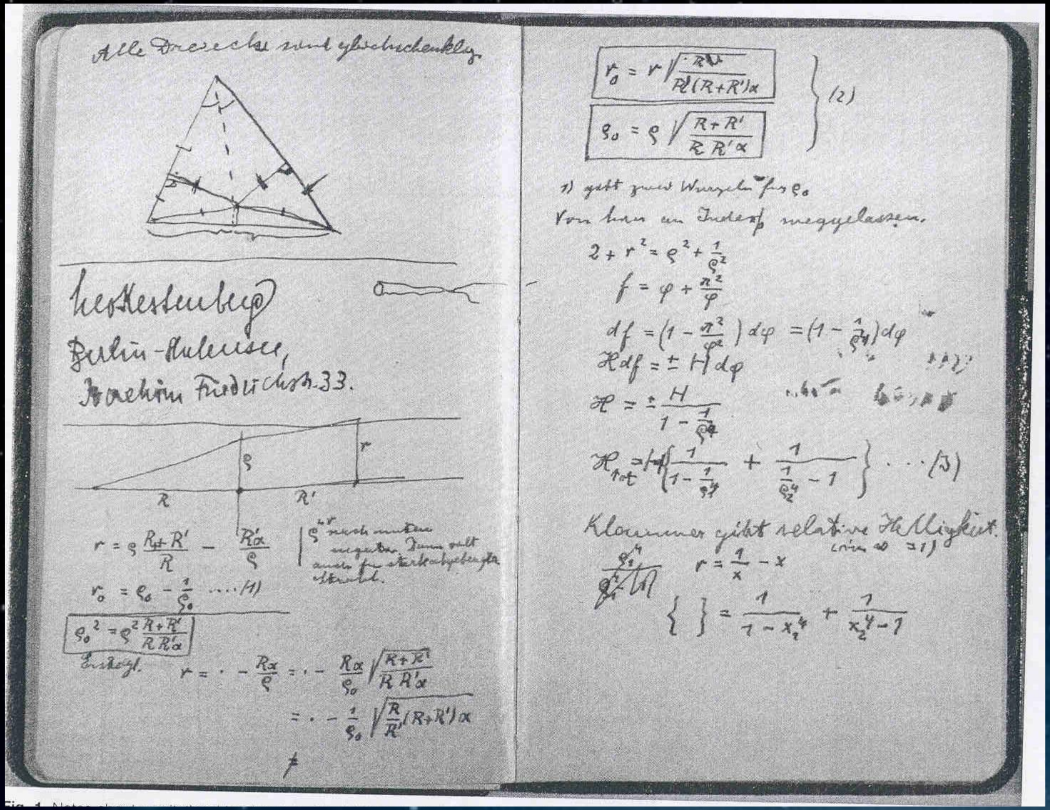
- Fundamentally, three issues:
  - Resolution: We want to be able to see details of a distant world. Diffraction
  - Brightness: We want enough light to form an image. Photons are scarce
  - Noise: There are many contaminating sources of light. Noise can get amplified

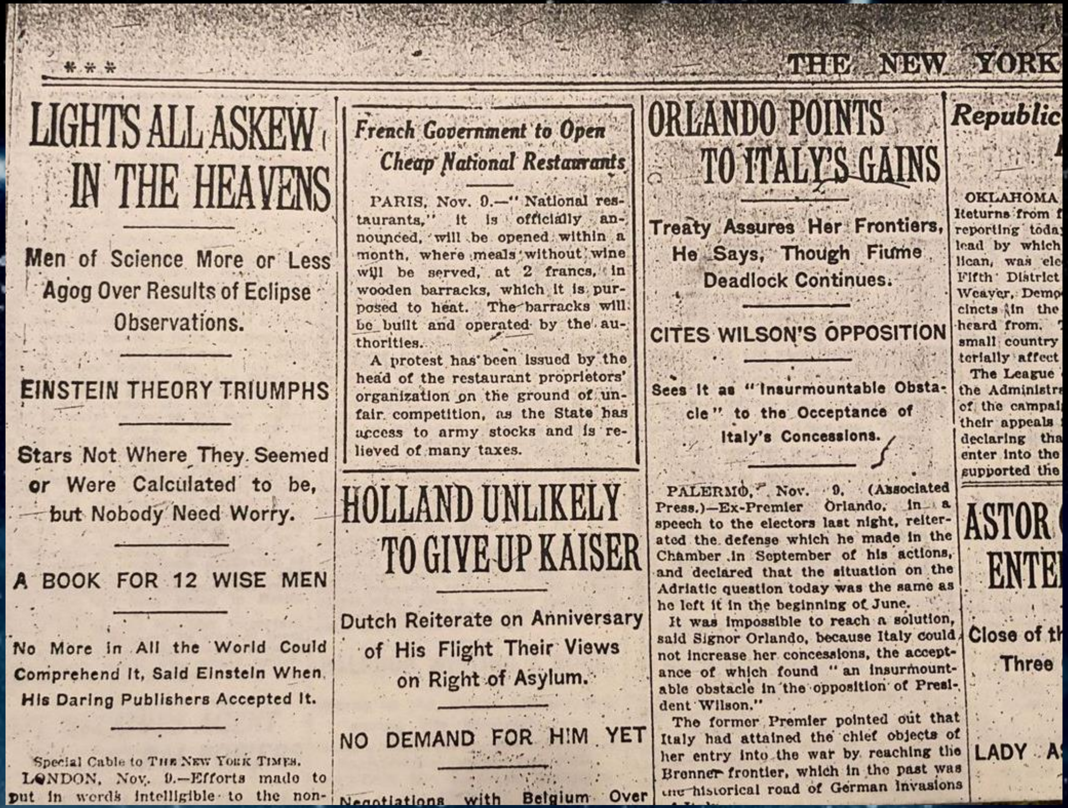
The tyranny of the diffraction limit

- Angular resolution is roughly proportional to λ/d
- Resolving features of 10 km at 10 light years implies d ~ 10,000 km
- Large baselines and interferometry may help but there's noise
  - Light contamination from host star
  - Exozodiacal noise
- Other techniques (e.g., rotational deconvolution) have limitations

The Sun to the rescue!

- The Sun bends rays of light and acts as an imperfect lens





THE NEW YORK

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Special Cable to THE NEW YORK TIMES.
LONDON, Nov. 9.—Efforts made to put in words intelligible to the non-

French Government to Open Cheap National Restaurants

PARIS, Nov. 9.—"National restaurants," it is officially announced, will be opened within a month, where meals without wine will be served, at 2 francs, in wooden barracks, which it is purposed to heat. The barracks will be built and operated by the authorities.

A protest has been issued by the head of the restaurant proprietors' organization on the ground of unfair competition, as the State has access to army stocks and is relieved of many taxes.

HOLLAND UNLIKELY TO GIVE UP KAISER

Dutch Reiterate on Anniversary of His Flight Their Views on Right of Asylum.

NO DEMAND FOR HIM YET

Negotiations with Belgium Over

ORLANDO POINTS TO ITALY'S GAINS

Treaty Assures Her Frontiers, He Says, Though Fiume Deadlock Continues.

CITES WILSON'S OPPOSITION

Sees It as "Insurmountable Obstacle" to the Occeptance of Italy's Concessions.

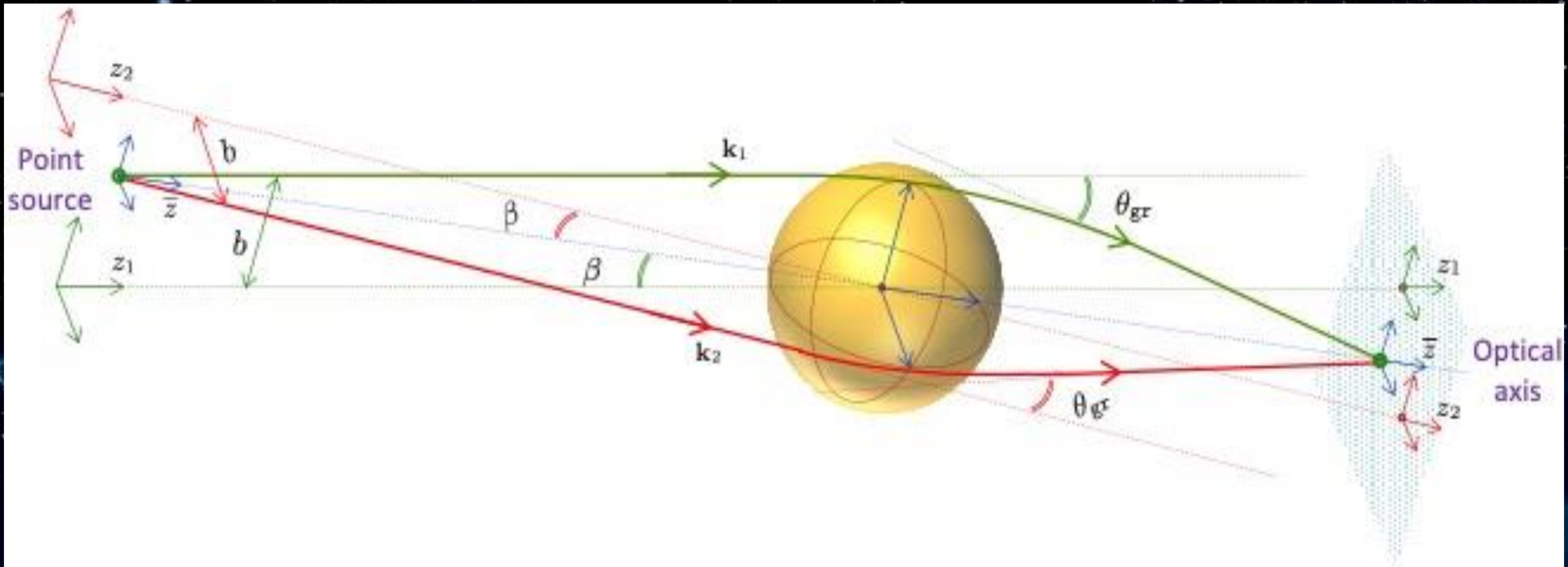
PALERMO, Nov. 9. (Associated Press.)—Ex-Premier Orlando, in a speech to the electors last night, reiterated the defense which he made in the Chamber in September of his actions, and declared that the situation on the Adriatic question today was the same as he left it in the beginning of June.

It was impossible to reach a solution, said Signor Orlando, because Italy could not increase her concessions, the acceptance of which found "an insurmountable obstacle in the opposition of President Wilson."

The former Premier pointed out that Italy had attained the chief objects of her entry into the war by reaching the Brenner frontier, which in the past was the historical road of German invasions

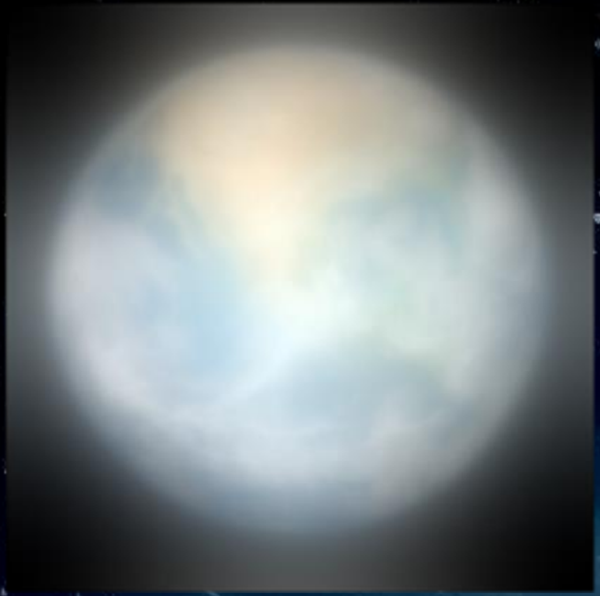
The focal region

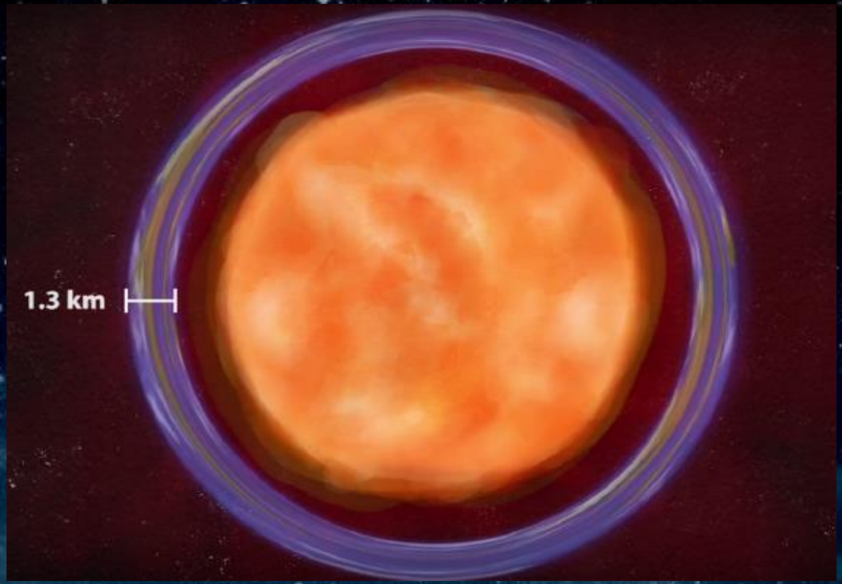
- Parallel rays of light are deflected, meeting at 550+ AU



Projection vs. view

- The Sun projects a km-scale blurry image of a distant object
- A telescope in the focal region only sees a thin Einstein-ring





Images must be reconstructed

- Multiple observations needed
- Each observation captures 1 “pixel”
- What is imaged is a moving target
- Long exposure times are required
- Precise stationkeeping, location tracking essential

Why not go there today?

- Target must be known in advance to pick focal region
- Imaging has many challenges
- Distance is enormous

The imaging challenge: signal-to-noise

- From any one vantage point in the image plane, all we see is a very faint Einstein ring through the very bright solar corona
- Corona is $10^4 - 10^5$ times brighter than the Einstein ring
- Even if the corona background is removed, we have to deal with shot noise due to the very low signal photon count
- We must also block light from the Sun
- There will be light from the host star, brightening the Einstein ring in specific places
- Light from interlopers must be known

The imaging challenge: collecting light

- Low SNR and stochastic (shot) noise has one solution: increased integration times
- Prolongs mission duration
- Represents added navigational challenge
- Must deal with a temporally changing target

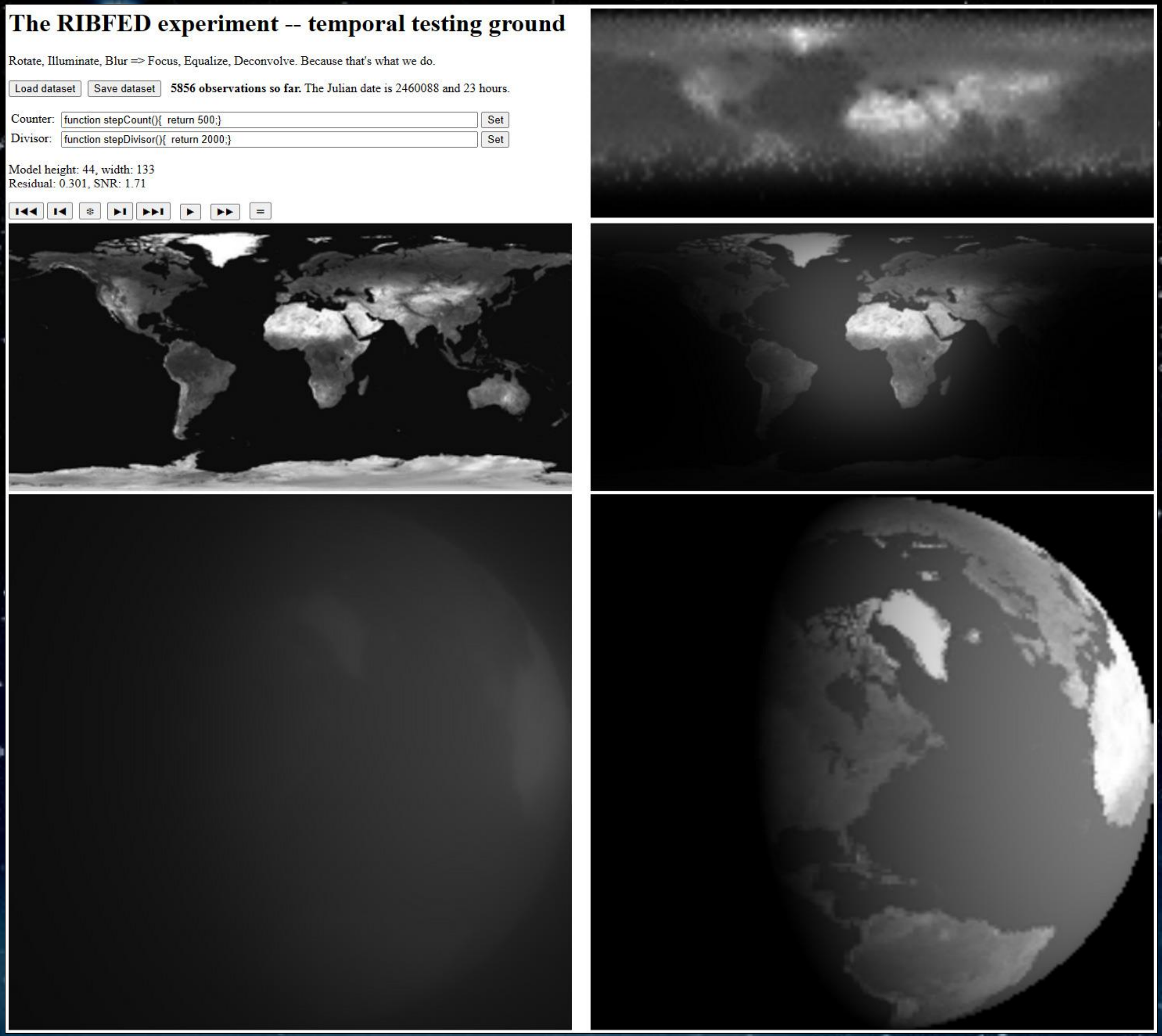
The imaging challenge: imperfect lens

- The monopole SGL is a lens with significant spherical aberration
- Quadrupole contributes significant astigmatism
- Reconstruction (deconvolution) is possible but it substantially amplifies noise
- Without deconvolution, a less noisy but blurry image results
- Trade-off between noise, resolution and sharpness must be considered

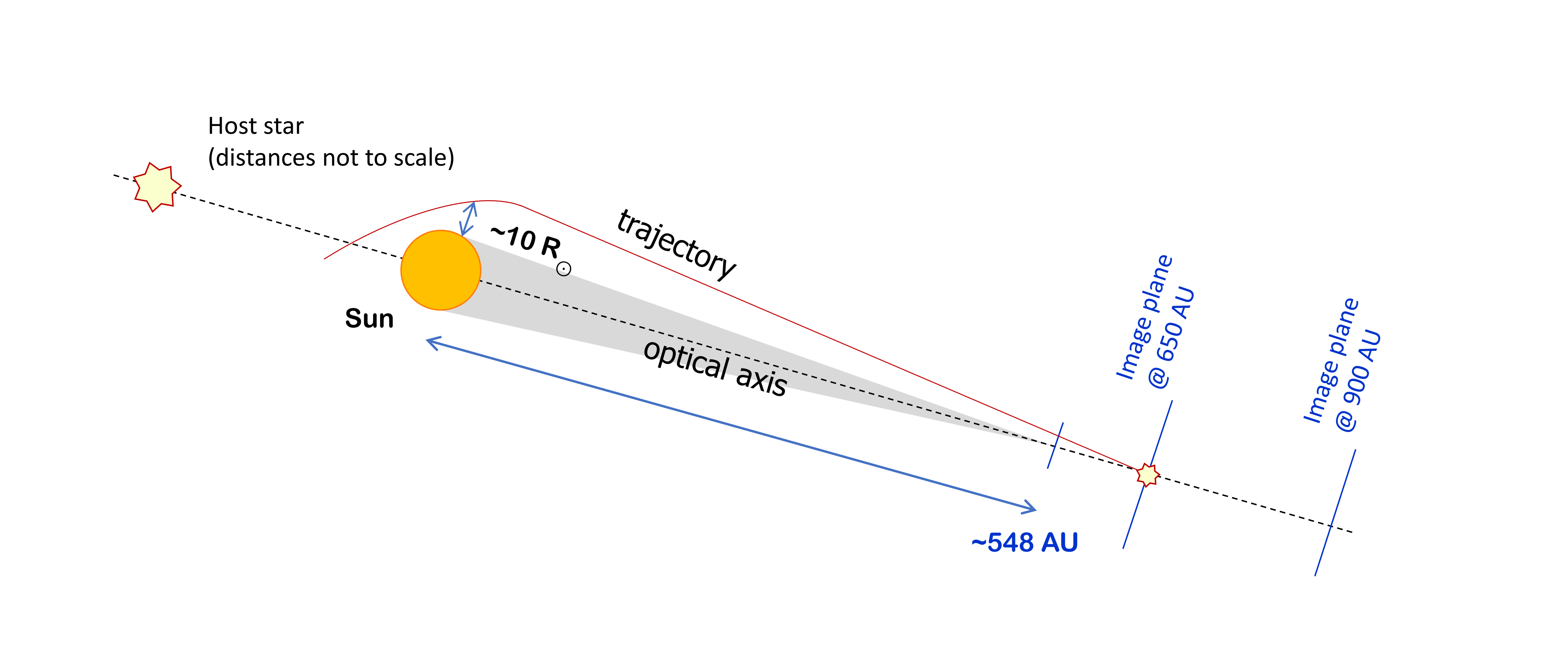
The imaging challenge: moving target

- An Earth-like planet rotates, changes significantly over the scale of minutes
- Its illumination changes with the seasons
- Its appearance changes: short-term stochastic changes (weather) and periodic changes (e.g., ice cover, vegetation)

Recovering a moving target

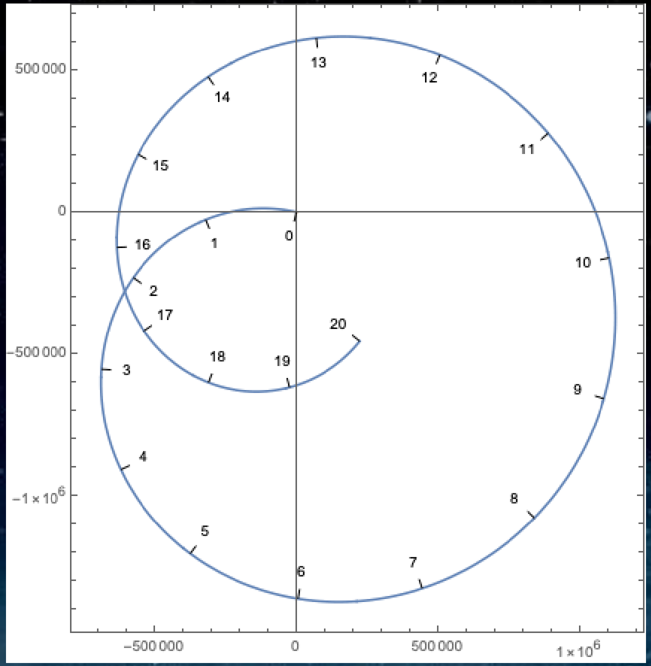


How to get there?



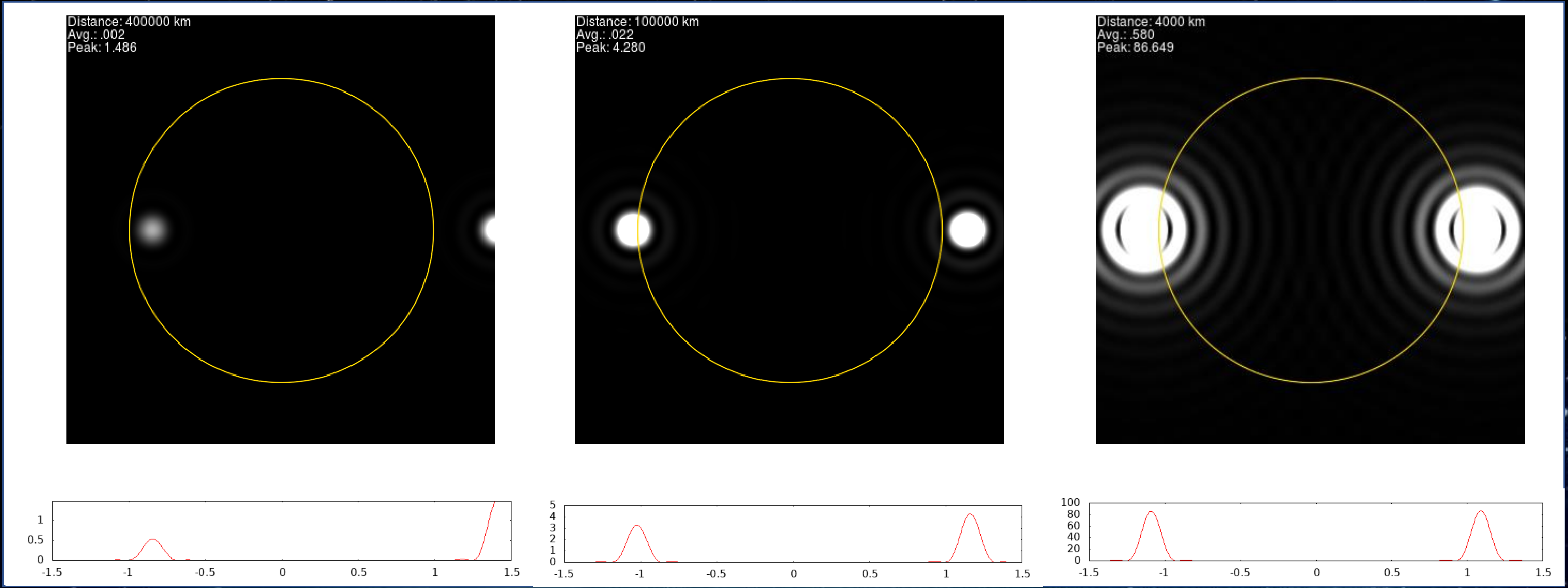
Navigation is a serious challenge

- Host star is visible throughout the cruise
- Focal region wobbles by as much as a million km



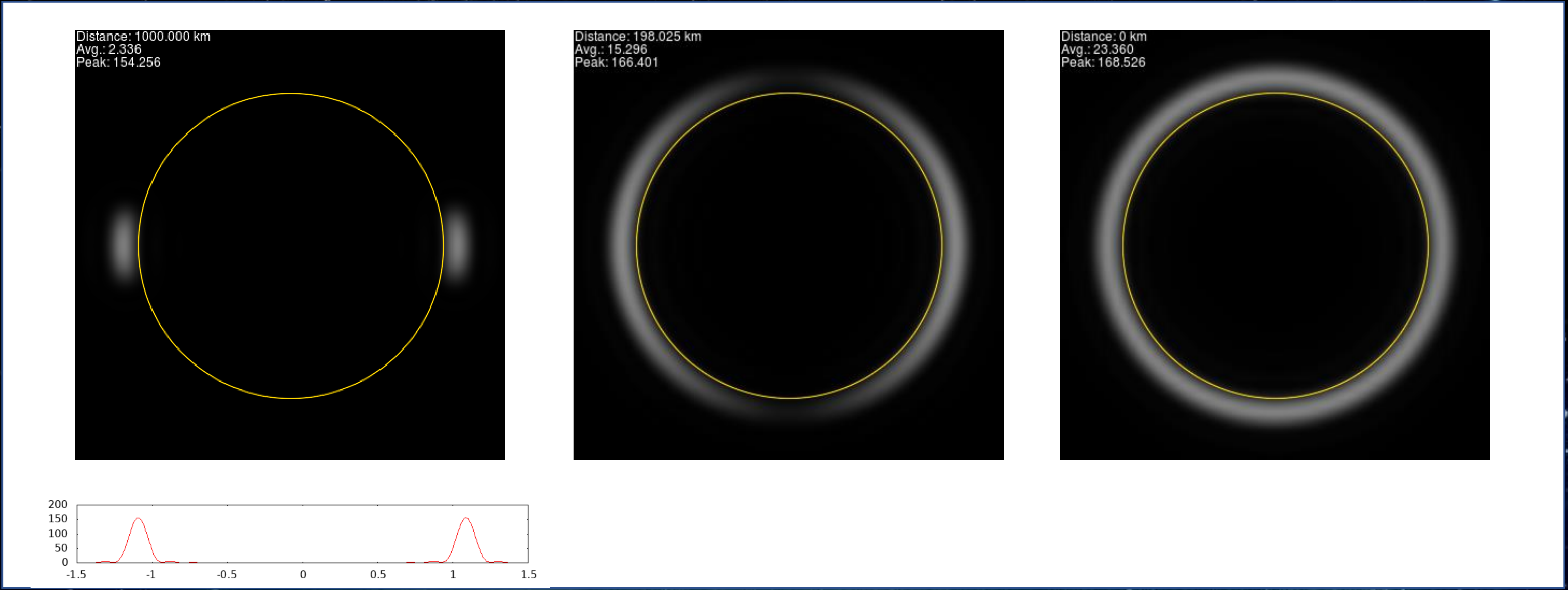
Navigating from 400,000 to 4,000 km

- Light amplification by O(100)



Zeroing in on the host star

- From 1,000 km to the exostar optical axis



Fine-grained navigation

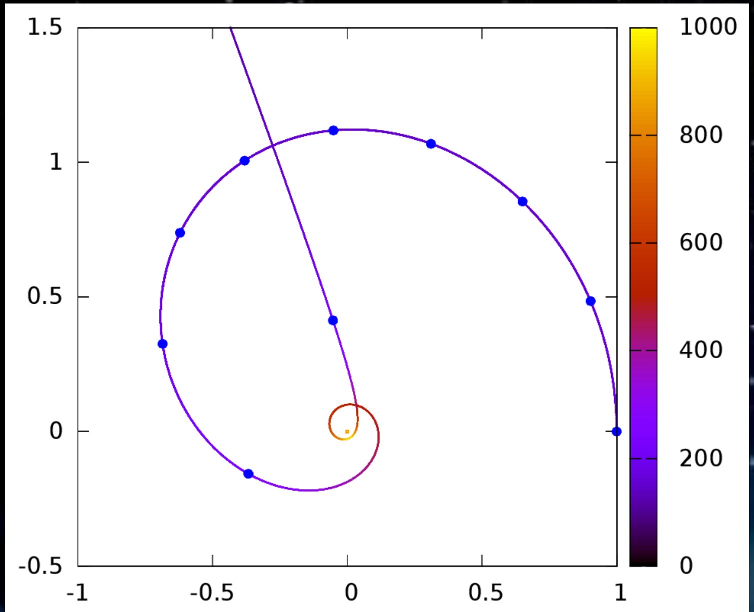
- Exoplanet image located O(10,000 km) from host star image in the image plane
- Approximate direction known
- Approaching the exoplanet image is a repeat of the host star approach but on a smaller and fainter scale, on the host star light background
- Exoplanet image size is of O(1 km)

Need for a local reference frame

- Projected image motion is known but it is noninertial
- Absolute navigation at that accuracy is unrealistic
- Once the exoplanet image is located, two or more telescopes could establish its precise boundary
- These telescopes establish and maintain a local reference frame
- Observing telescope can move from pixel to pixel on a meter-scale grid with respect to this frame
- Primary observable: Total amount of light collected from the Einstein-ring at each pixel location

The means to get there

- Sundivers!



Technical challenges

- Large spacecraft vs. in-flight assembly
- Systems to survive 25-30 years cruise plus up to 10 years science
- Autonomous constellation (required for navigation, corona light suppression)
- Coronagraph (possible use of discarded sails as external sunshades?)
- Power (40+ years)
- Communication (650 – 900 AU)

Thank you

- Questions?