The Solar Gravitational Lens
Imaging exoplanets

Viktor T. Toth

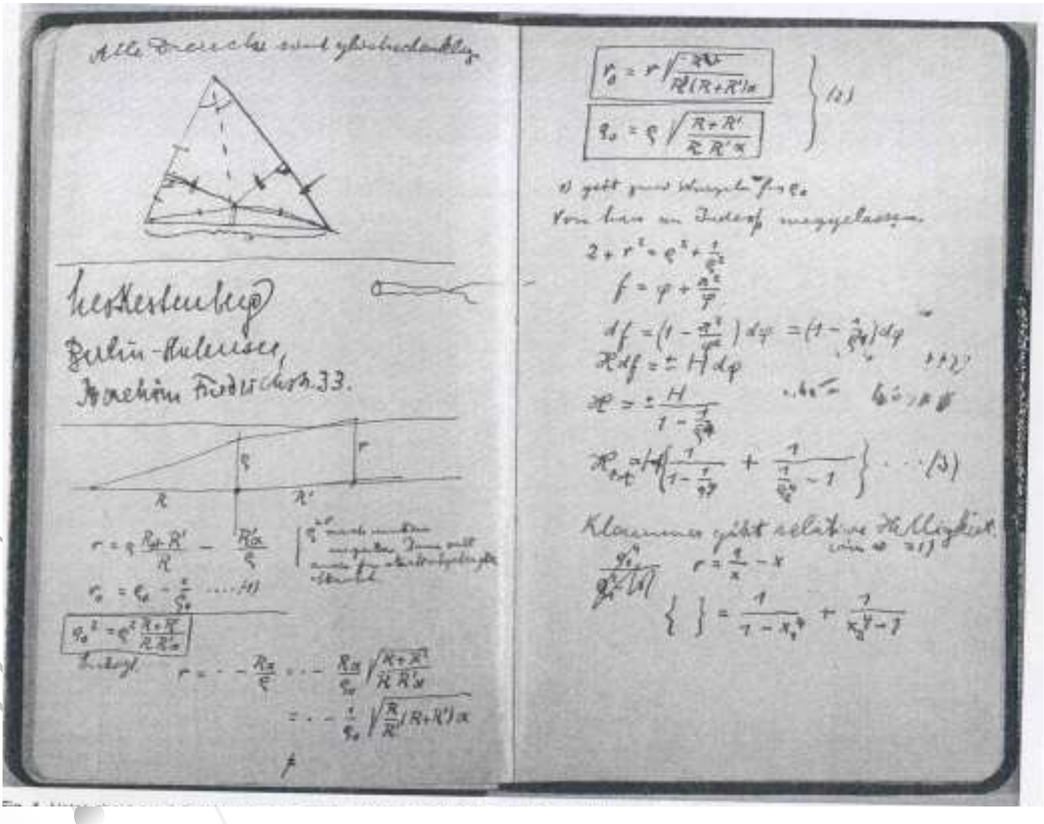
North Houston Astronomy Club
May 28, 2021

Gravitation and light

- Gravitation deflects light
- Newton considered corpuscular light
- In Newton's gravitation, a light corpuscle grazing the Sun would be deflected by 0.9"
- Einstein's theory applies to light
- The deflection angle doubles, to ~1.75"

First derivation

- **Einstein's notebook, c. 1911**



Einstein's success

- **1919: Eddington's eclipse expedition**

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.

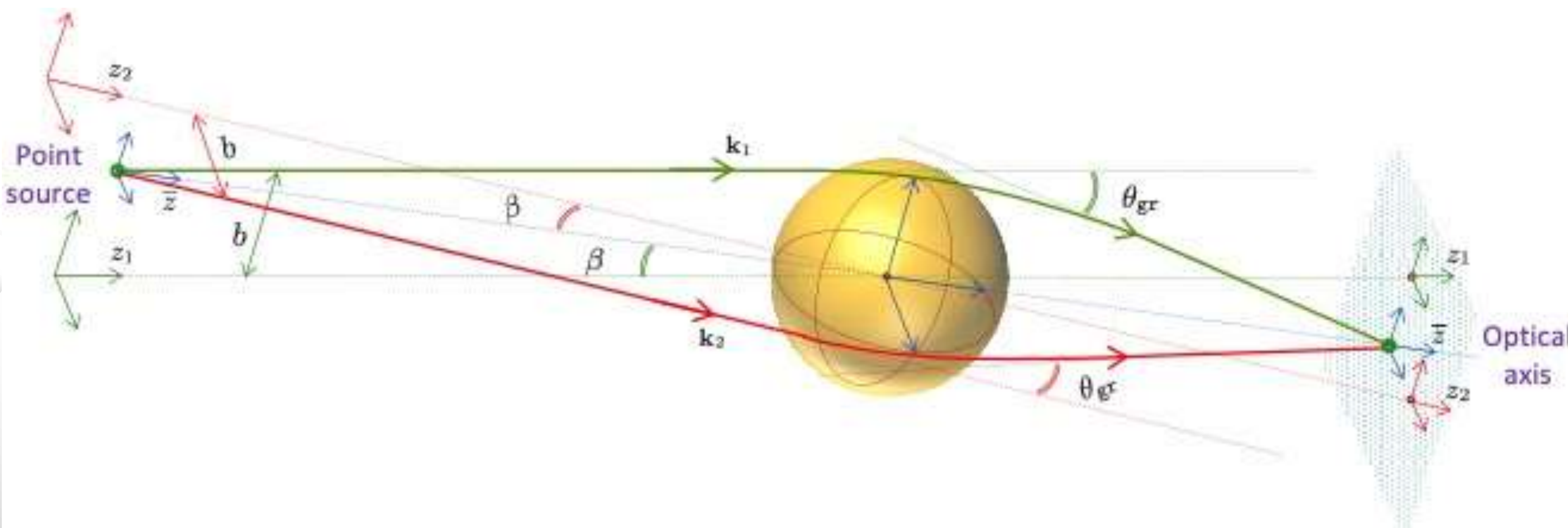
It was impossible to reach a solution, said Signor Orlando, because Italy could not increase her concessions, the acceptance of which found "an insurmountable obstacle in the opposition of President Wilson."

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

New York Times, 1919 november 10

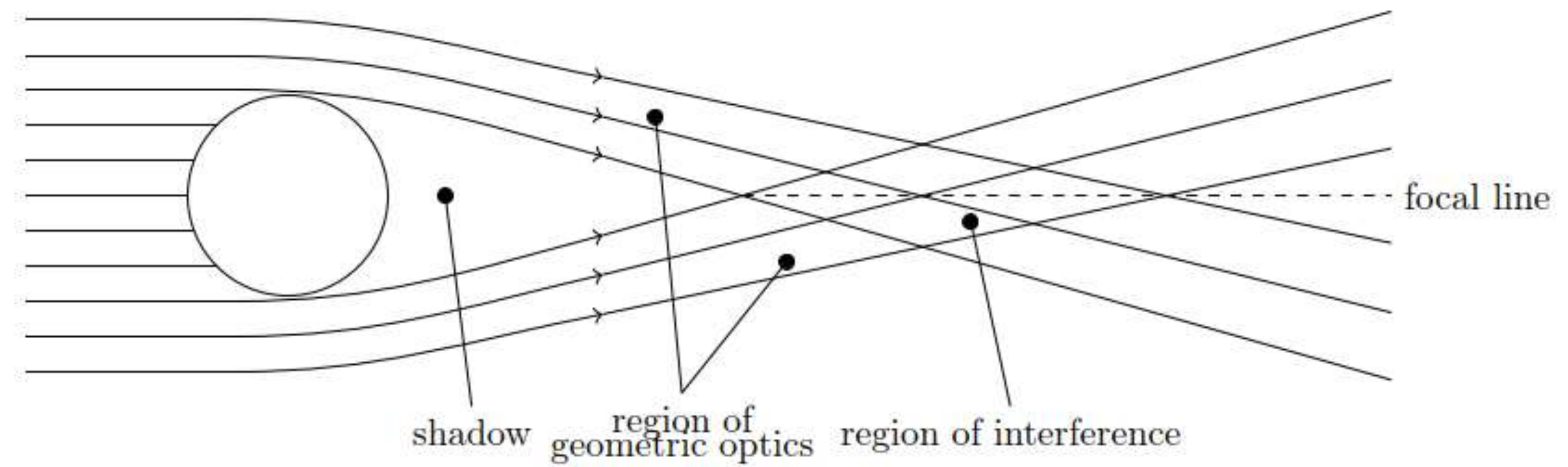
Focusing light

- **Light is deflected all around the Sun (not to scale):**



Focal distance

- Deflected rays converge
- Distance from the Sun is >~ 550 AU



Tremendous resolution and light amplification

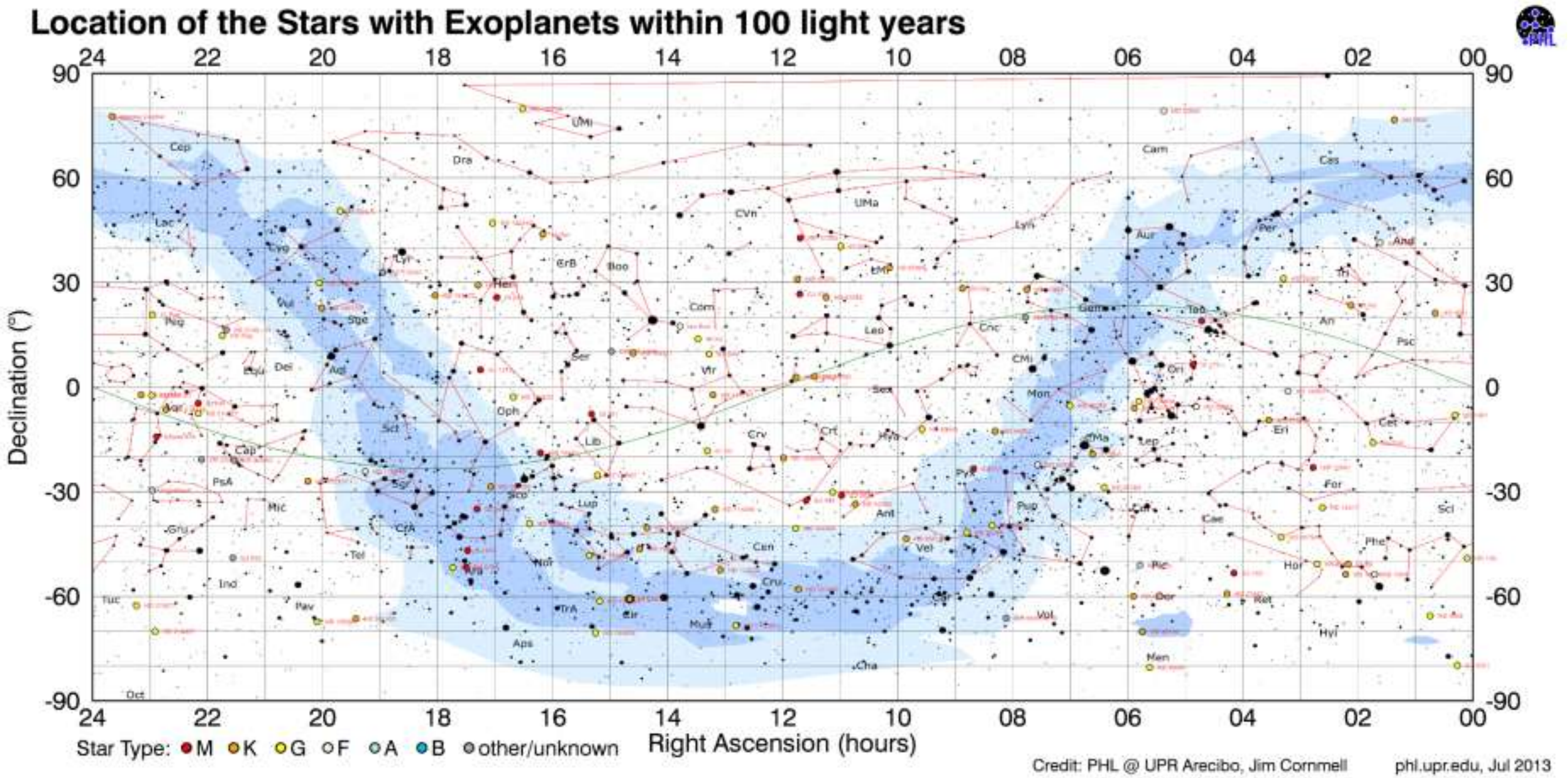
- If we could use it as a telescope, the Sun would have fantastic properties:
  - Maximum light amplification: 10^{11} (enough to see a candlelight on the Moon)
  - Resolution: 10^{-11} arc seconds (objects smaller than a centimeter could be resolved on the Moon)

Exoplanet research

- We're discovering thousands of exoplanets by indirect means
- None found yet, but there may be among these planets that harbor life
- Cannot observe: Even the best space telescope wouldn't provide more than a blurred, washed out partial pixel

Exoplanet research

Plenty of potential targets

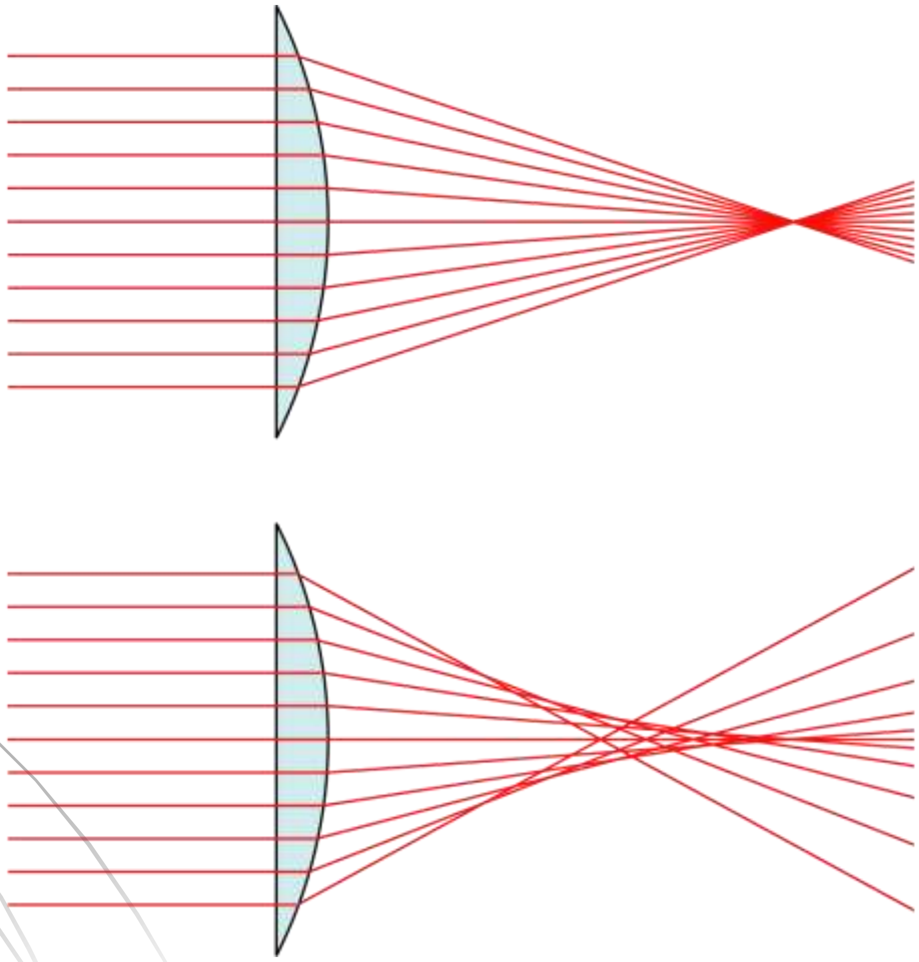


Conventional telescope

- To image an Earthlike planet at 100 light years as a sharply resolved single pixel, a telescope aperture or baseline of 90 km would be required
- Signal is so weak that light would need to be collected for millennia to deal with unwanted noise (host star, host system zodiacal light, background objects, shot noise, etc.)

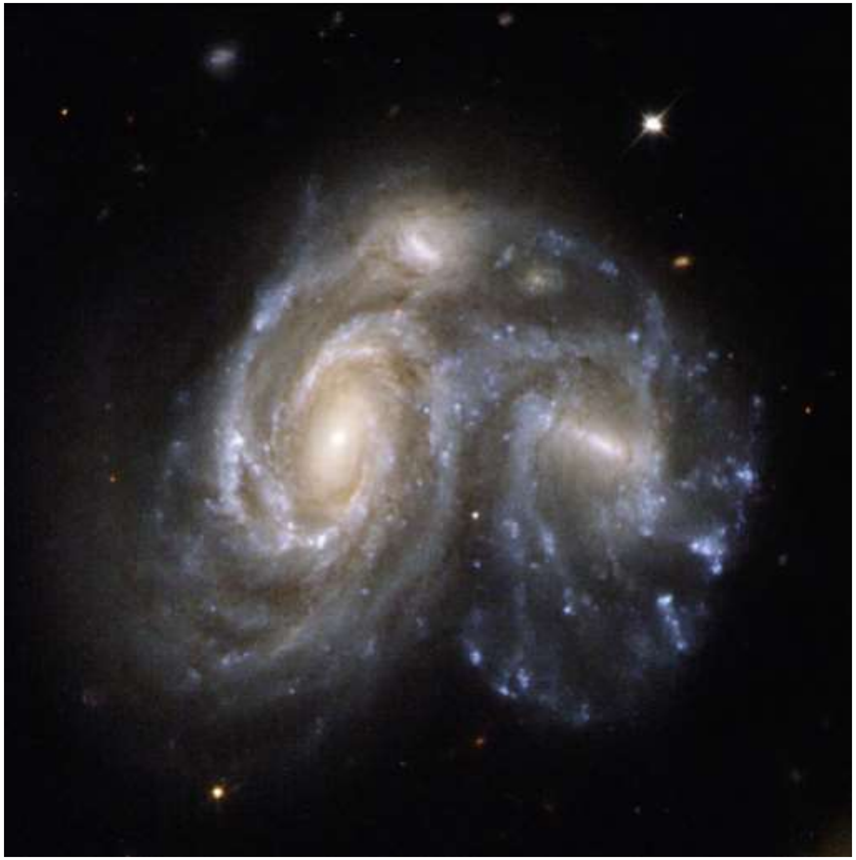
But the Sun is an imperfect lens

Spherical aberration



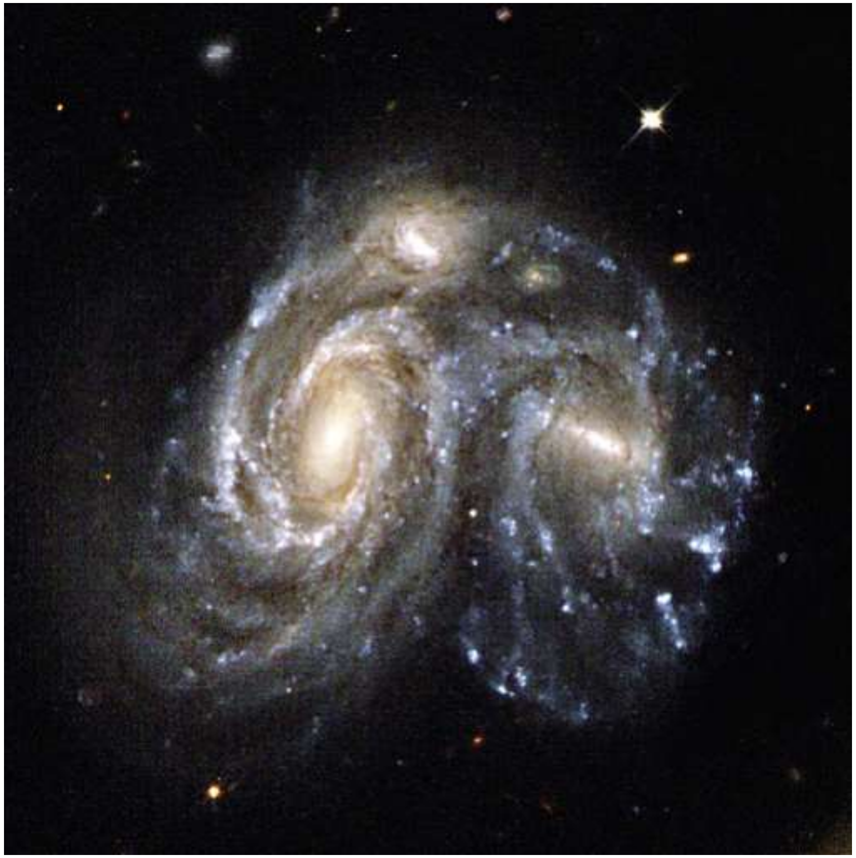
Remember Hubble

- Was launched in 1990 with a faulty primary mirror
- Produced washed out, blurred images



Deconvolution

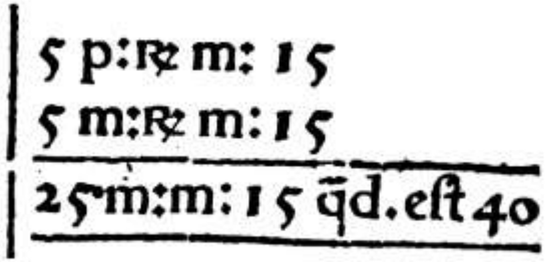
- If optical properties are known accurately, the original image can be reconstructed



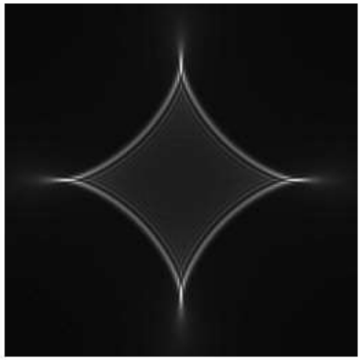
Characterizing the lens

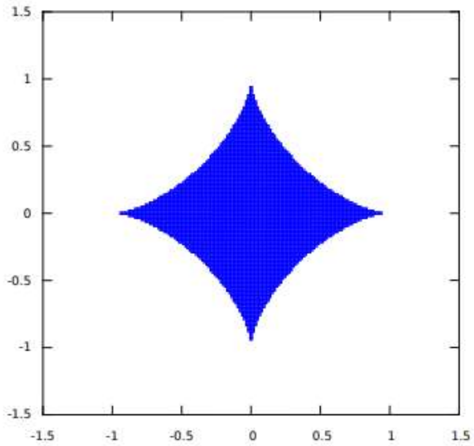
- Spherical aberration
- Astigmatism
- The point-spread function (PSF) is known
- The operation can be inverted in principle

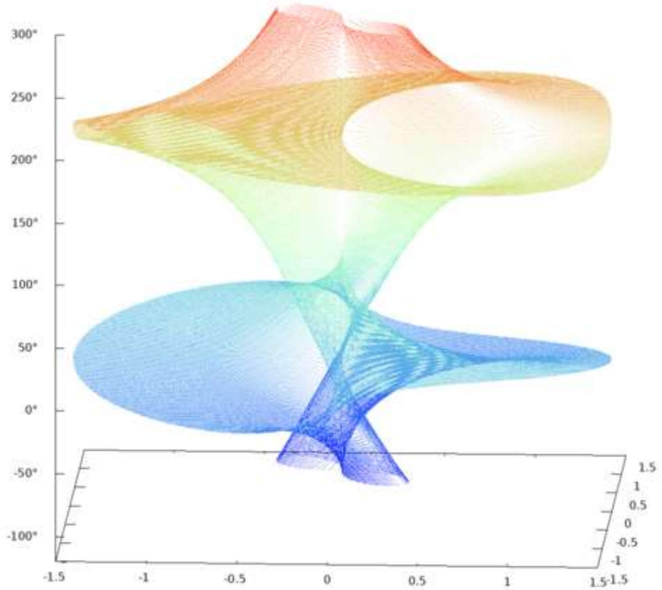
Sixteenth century algebra


5 p:R m:15
5 m:R m:15
25 m:m:15 q̃d. eſt 40

$$x^4 - 2\eta\sin\mu\, x^3 + (\eta^2 - 1)x^2 + \eta\sin\mu\, x + \tfrac{1}{4}\sin^2\mu = 0.$$

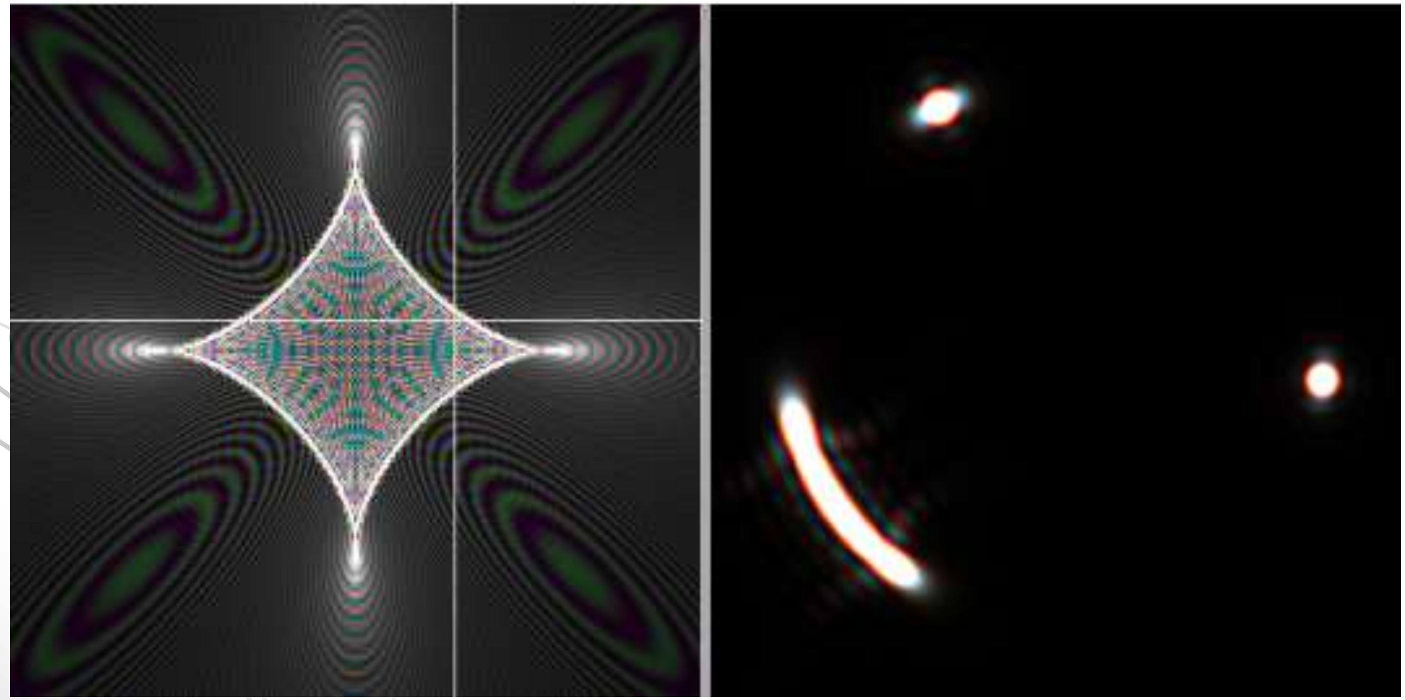






Wave-optical description

- Geometric optics (raytracing) will not tell us this:

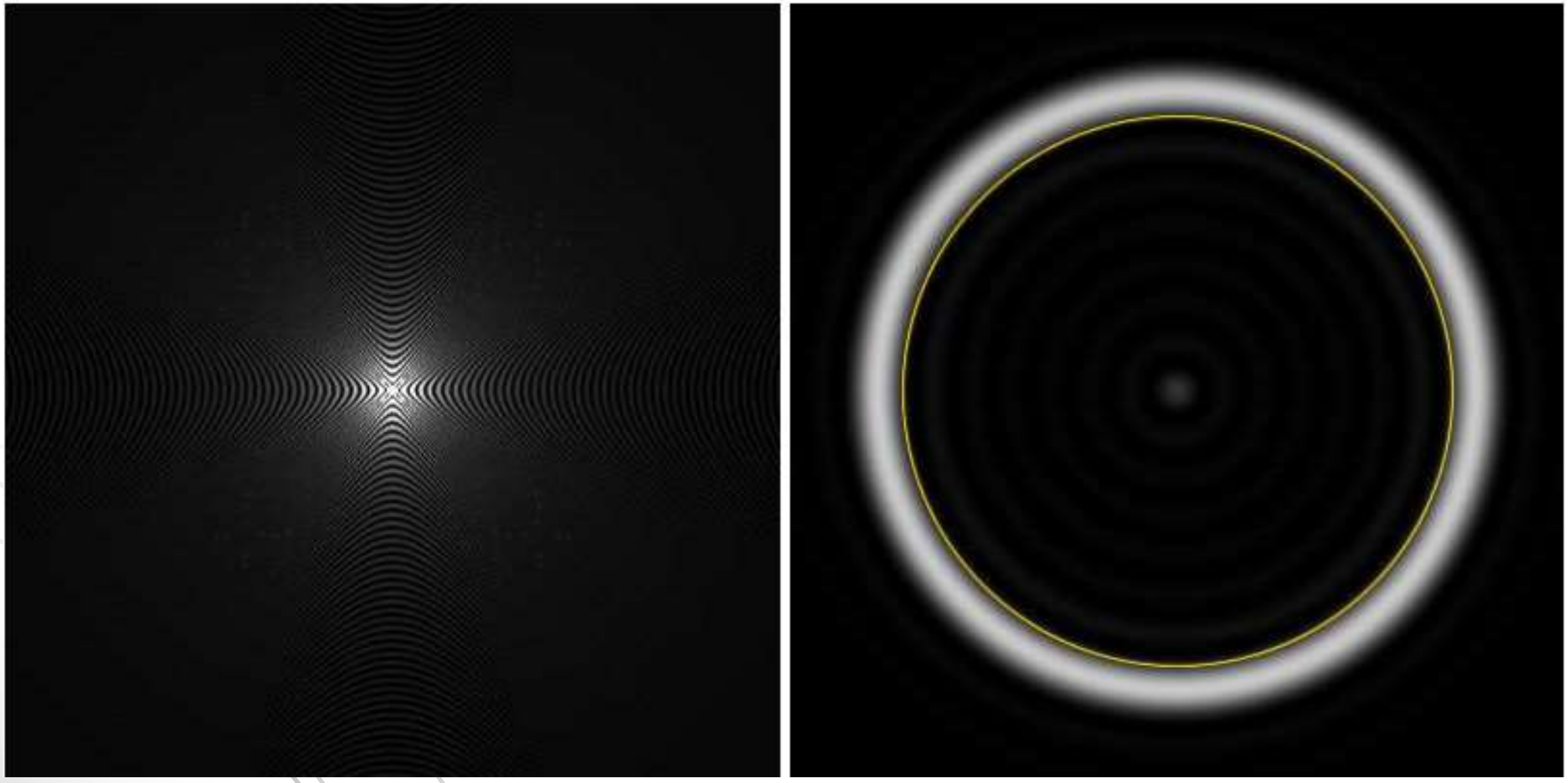


Seen vs. projected image

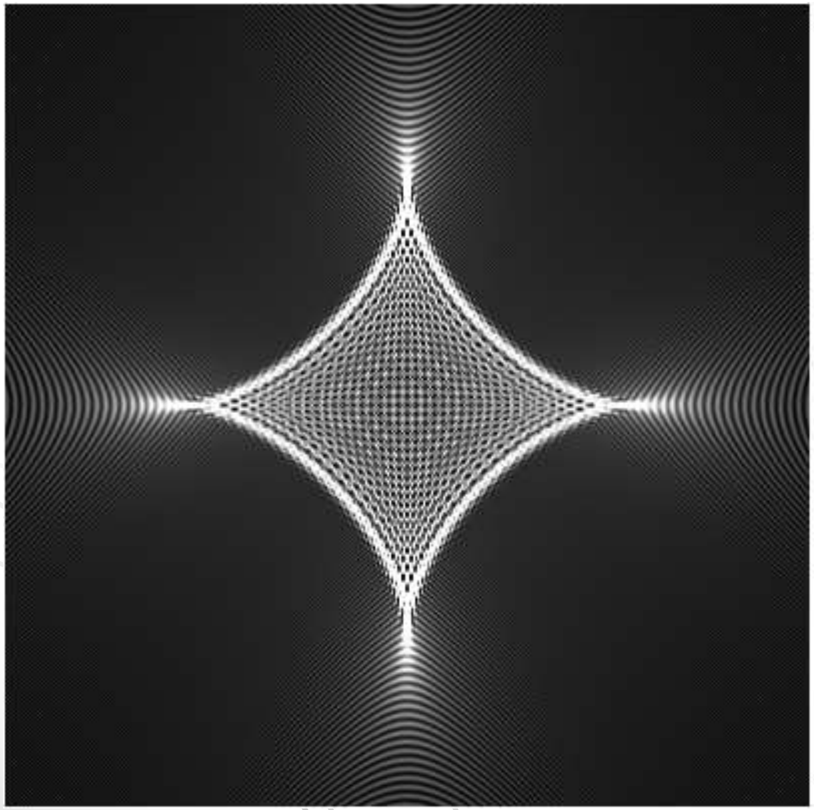
- What a telescope looking in the direction of the Sun “sees” is not what’s projected
- In a cinema the projector projects an image but standing in front of the screen, looking back, we just see the sharp light of the projector
- In the case of the Sun, we see an Einstein ring; the Sun projects a blurred image of the exoplanet

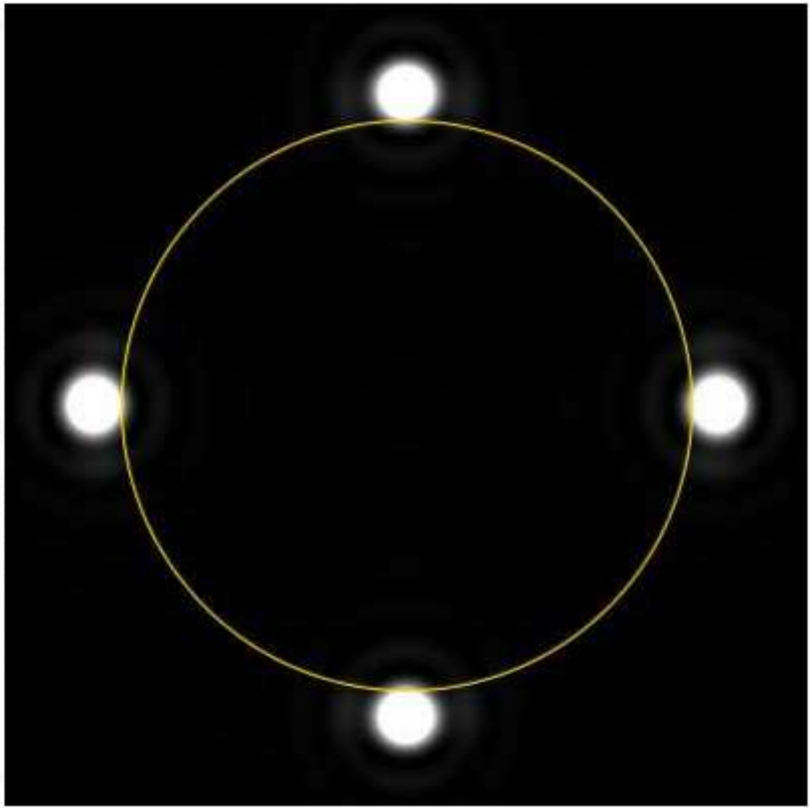
In a cinema

Point source, no astigmatism



Point source, quadrupole moment

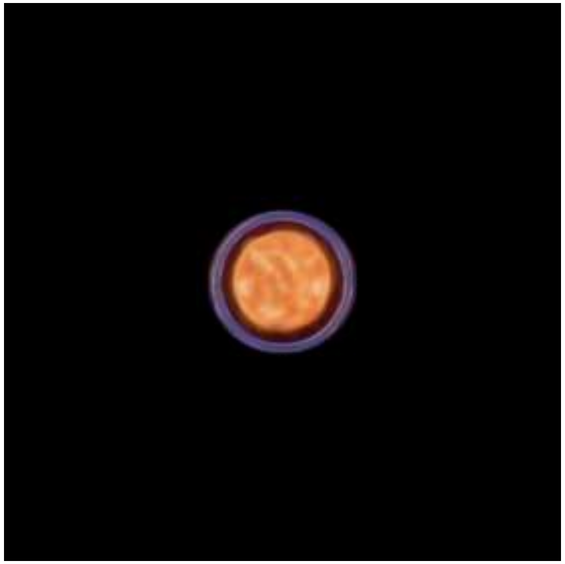




What do we see?

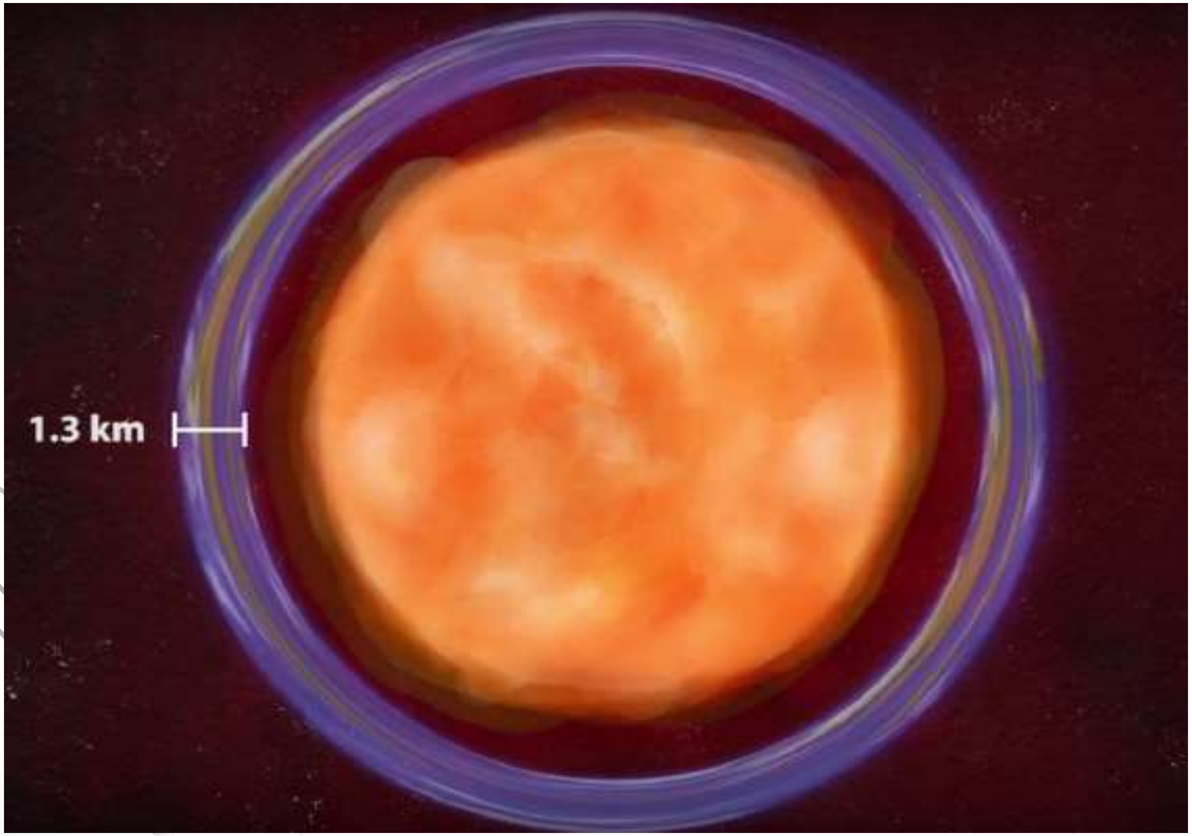
- Projected image (~km^2 area):

- What we see from any specific pixel:

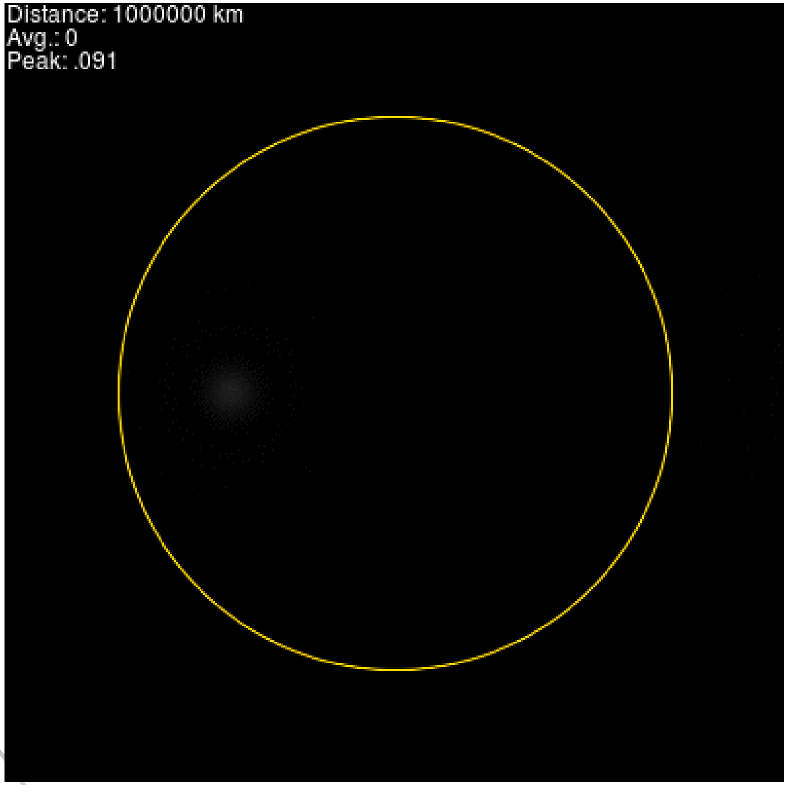


Einstein ring of exoplanet

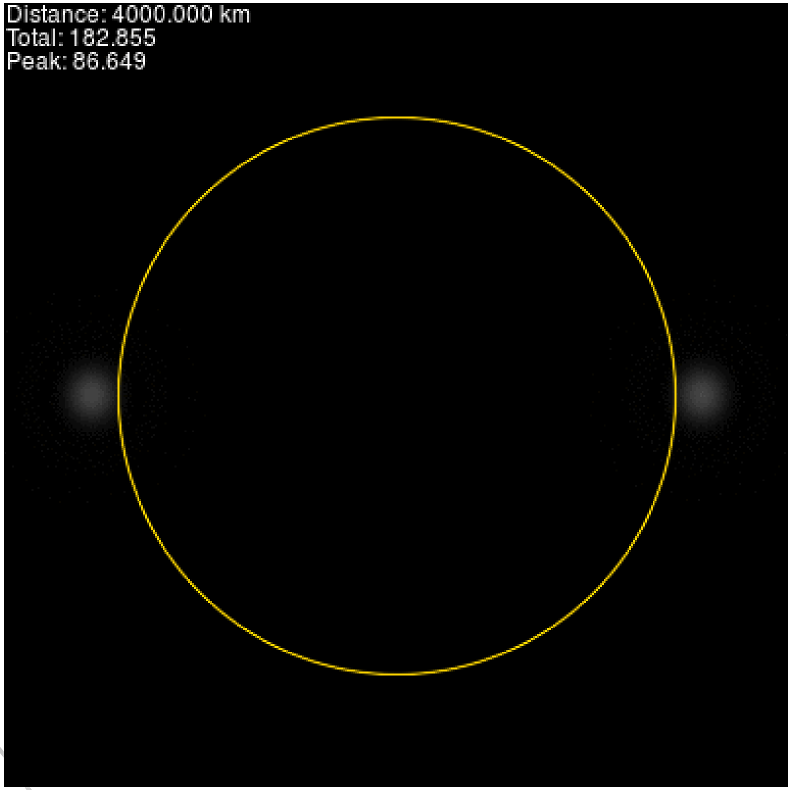
- **We see a ring around the Sun!**



Approaching the focal line



Final approach



Convolution theorem

- In practice, the convolution matrix is gigantic (megapixel image: 10^{12} matrix elements!)
- The convolution theorem helps: After a Fourier-transform, deconvolution becomes simple division

Deconvolution and noise

- Deconvolution restores an image if the PSF is known
- It significantly increases noise, reducing the signal-to-noise ratio (SNR) substantially

The Sun and its corona

- The Sun is bright, its light must be blocked (coronagraph)
- At a distance beyond 550 AU, this requires a telescope
- Background of the Einstein-ring is the bright solar corona

Possible results

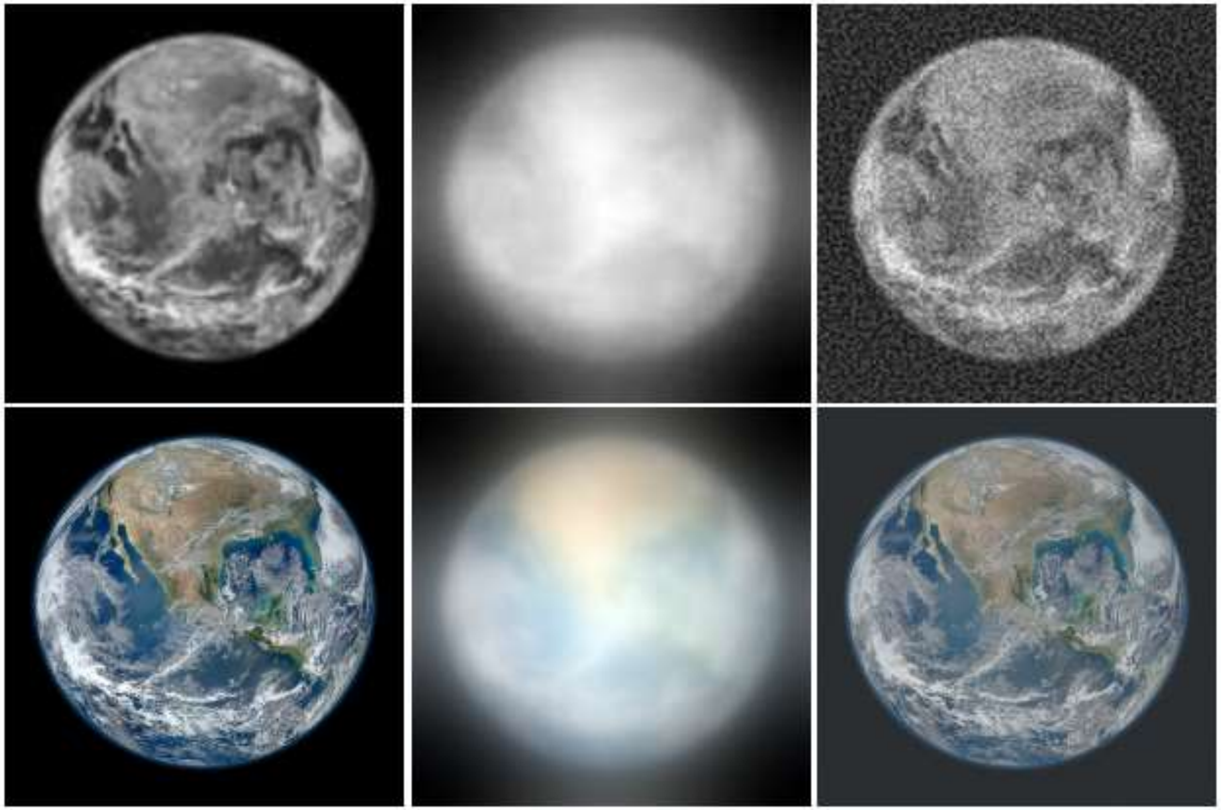


FIG. 11: A simulation of the effects of the monopole solar gravitational lens on an Earth-like exoplanet image. Top row, left: a monochrome image, sampled at 128×128 pixels; center: blurred image; right: deconvolution at SNR ∼ 4.5. From [27]. Bottom row, left: original RGB color image with a 1024×1024 pixel resolution; center: image blurred by the SGL; right: the result of image deconvolution at an SNR of ∼5.2 per color channel, or combined SNR of ∼9.

SGL expedition

- Delivering one or more meter-class telescopes to a distance four-six times greater than Voyager 1's in decades, not centuries
- Finding the focal line of an exoplanet with meter-scale accuracy
- Data collection over the course of several years, with sufficient integration time for successful deconvolution

More challenges

- SGL an imperfect lens
- Moving, temporally changing target
- Background objects
- Shot noise
- Navigational accuracy
- Communications bandwidth

Possible technologies

- Solar sail
- Multiprobe constellation (swarm)
- Multiple waves of probes (string-of-pearls)
- Nuclear power supply, long life batteries
- Electronics operating for decades
- High level autonomy
- Ultraprecise autonomous navigation
- Extreme communications efficiency

Other targets

- QSOs
- SMBH accretion disks (e.g., M87*)

Thank you for your attention

- Questions?

References

- *Algebraic wave-optical description of a quadrupole gravitational lens*, Slava G. Turyshev and Viktor T. Toth, arXiv:2105.07295 [gr-qc]
- *Imaging point sources with the gravitational lens of an extended Sun*, Slava G. Turyshev and Viktor T. Toth, arXiv:2104.08442 [gr-qc]
- *Optical properties of an extended gravitational lens*, Slava G. Turyshev and Viktor T. Toth, arXiv:2103.06955 [gr-qc]
- *Diffraction of electromagnetic waves by an extended gravitational lens*, Slava G. Turyshev and Viktor T. Toth, arXiv:2102.03891 [gr-qc], Phys. Rev. D 103, 064076, DOI: 10.1103/PhysRevD.103.064076
- *Image recovery with the solar gravitational lens*, Viktor T. Toth and Slava G. Turyshev, arXiv:2012.05477 [gr-qc], Phys. Rev. D (accepted for publication)
- *Exploring the Outer Solar System with Solar Sailing Smallsats on Fast-Transit Trajectories and In-Flight Autonomous Assembly of Advanced Science Payloads*, Slava G. Turyshev, Henry Helvajian, Louis D. Friedman, Tom Heinsheimer, Darren Garber, Artur Davoyan, Viktor T. Toth, arXiv:2007.05623 [astro-ph.IM]
- *Direct Multipixel Imaging and Spectroscopy of an Exoplanet with a Solar Gravity Lens Mission*, Slava G. Turyshev, Michael Shao, Viktor T. Toth, Leon Alkalai, Janice Shen, Mark R. Swain, Hanying Zhou, Henry Helvajian, Tom Heinsheimer, Siegfried Janson, Zigmond Leszczynski, John McVey, Darren Garber, Artur Davoyan, Seth Redfield, Jared R. Males, arXiv:2002.11871 [astro-ph.IM]
- *Image formation for extended sources with the solar gravitational lens*, Slava G. Turyshev and Viktor T. Toth, arXiv:2002.06492 [astro-ph.IM]
- *Image formation process with the solar gravitational lens*, Slava G. Turyshev and Viktor T. Toth, Phys. Rev. D 101, 044048 (2020)
- *Photometric imaging with the solar gravitational lens*, Slava G. Turyshev and Viktor T. Toth, Phys. Rev. D 101, 044025 (2020)
- *Recognizing the Value of the Solar Gravitational Lens for Direct Multipixel Imaging and Spectroscopy of an Exoplanet*, Slava G. Turyshev et al., (A White Paper to the National Academy of Sciences Committee on an Exoplanet Science Strategy Call for Papers) arXiv:1803.04319 [astro-ph.IM]
- *Direct Multipixel Imaging and Spectroscopy of an Exoplanet with a Solar Gravity Lens Mission*, Slava G. Turyshev et al., (Final Report for the NASA's Innovative Advanced Concepts (NIAC) Phase I proposal) arXiv:1802.08421 [astro-ph.IM]
- *Diffraction of electromagnetic waves in the gravitational field of the Sun*, Slava G. Turyshev and Viktor T. Toth, Phys. Rev. D 96, 024008 (2017)
- *Introduction to Fourier optics*, J. W. Goodman (W.H. Freeman and Company, New York, 2017), 2nd ed.