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Direct Multipixel Imaging and Spectroscopy of an Exoplanet with a Mission to the Focus of the Solar Gravitational Lens

Slava G. Turyshev[1], Michael Shao[1],
Hanying Zhou[1], Janice Chen[1], Viktor Toth[2], James DeLuca[3]

[1]Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91009 USA
[2]www.vttoth.com, [3]www.jimiticus.com,
[4]University of Arizona, Tucson AZ

BREAKTHROUGH INITIATIVES

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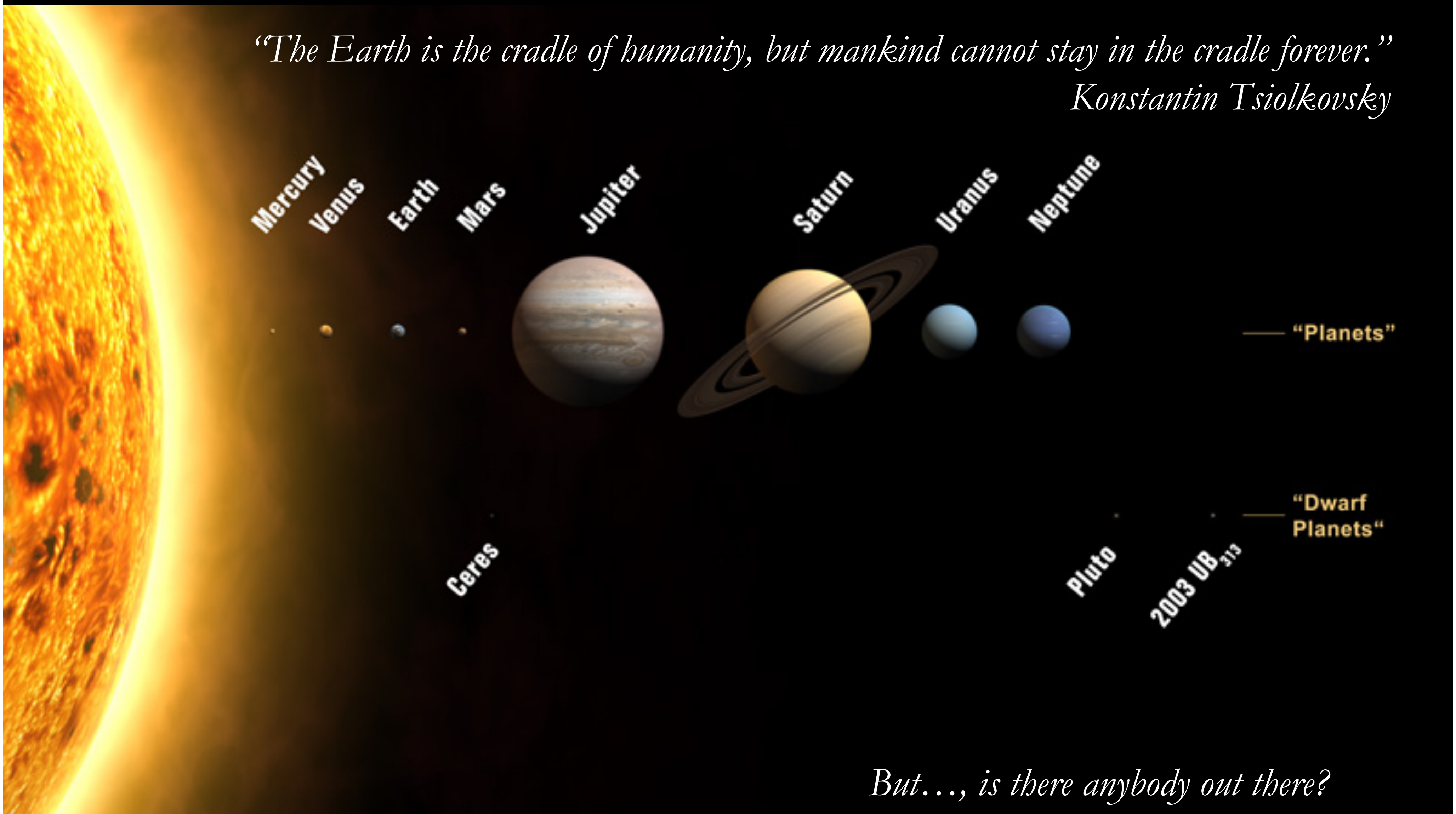
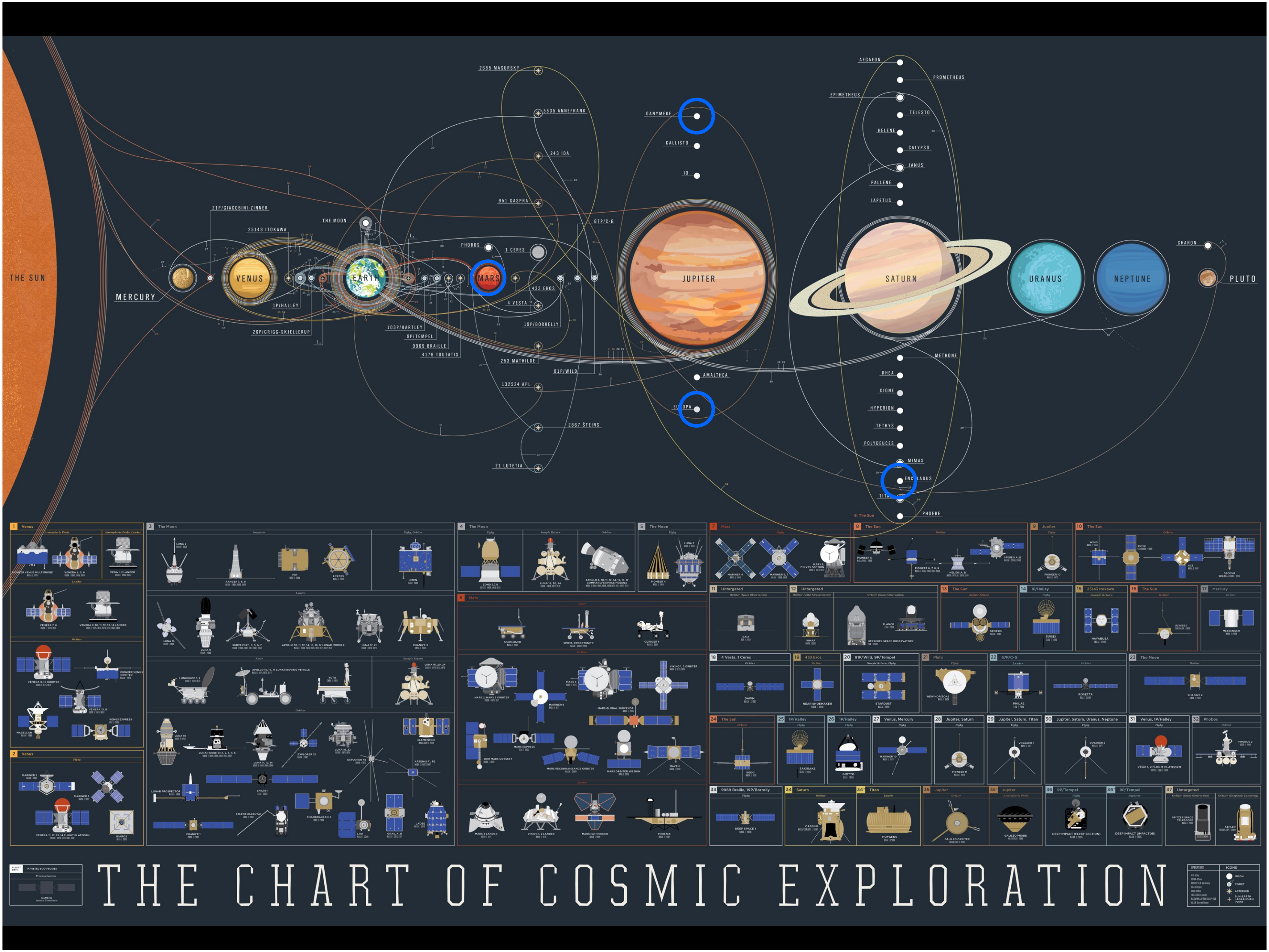
AEROSPACE

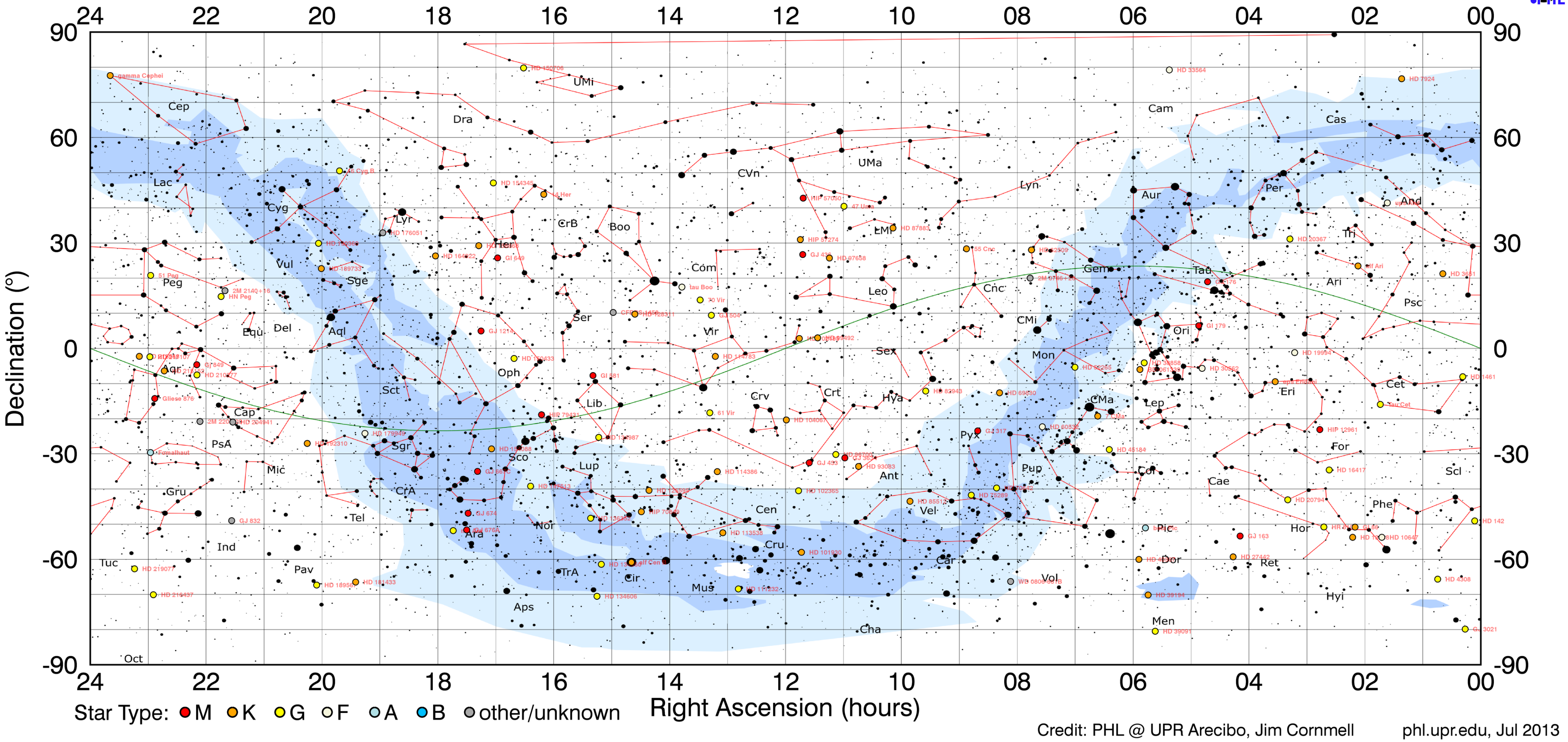
A nice family portrait…



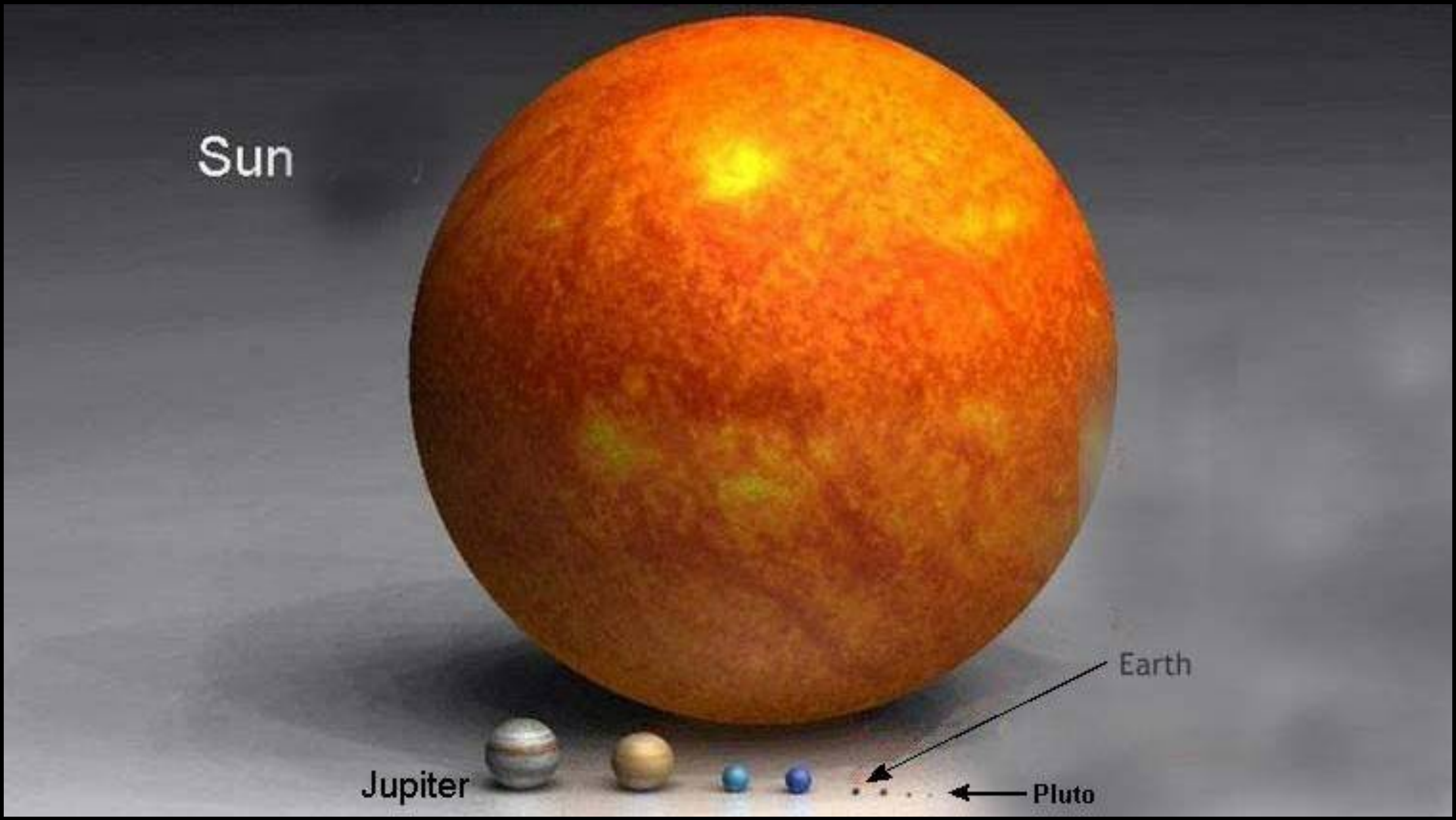

THE SUN
MERCURY
VENUS
EARTH
MARS
JUPITER
SATURN
URANUS
NEPTUNE
PLUTO
CHARON
THE MOON
PHOBOS
1 CERES
4 VESTA
433 EROS
2685 MASURSKY
5535 ANNEFRANK
243 IDA
951 GASPRA
67P/C-G
21P/GIACOBINI-ZINNER
25143 ITOKAWA
1P/HALLEY
26P/GRIGG-SKJELLERUP
103P/HARTLEY
9P/TEMPEL
9969 BRAILLE
4179 TOUTATIS
19P/BORRELLY
253 MATHILDE
81P/WILD
132524 APL
2867 ŠTEINS
21 LUTETIA
GANYMEDE
CALLISTO
IO
AMALTHEA
EUROPA
AEGAEON
PROMETHEUS
EPIMETHEUS
TELESTO
HELENE
CALYPSO
JANUS
PALLENE
IAPETUS
METHONE
RHEA
DIONE
HYPERION
TETHYS
POLYDEUCES
MIMAS
ENCELADUS
TITAN
PHOEBE
THE CHART OF COSMIC EXPLORATION

Our Stellar Neighborhood within 100 ly

Location of the Stars with Exoplanets within 100 light years

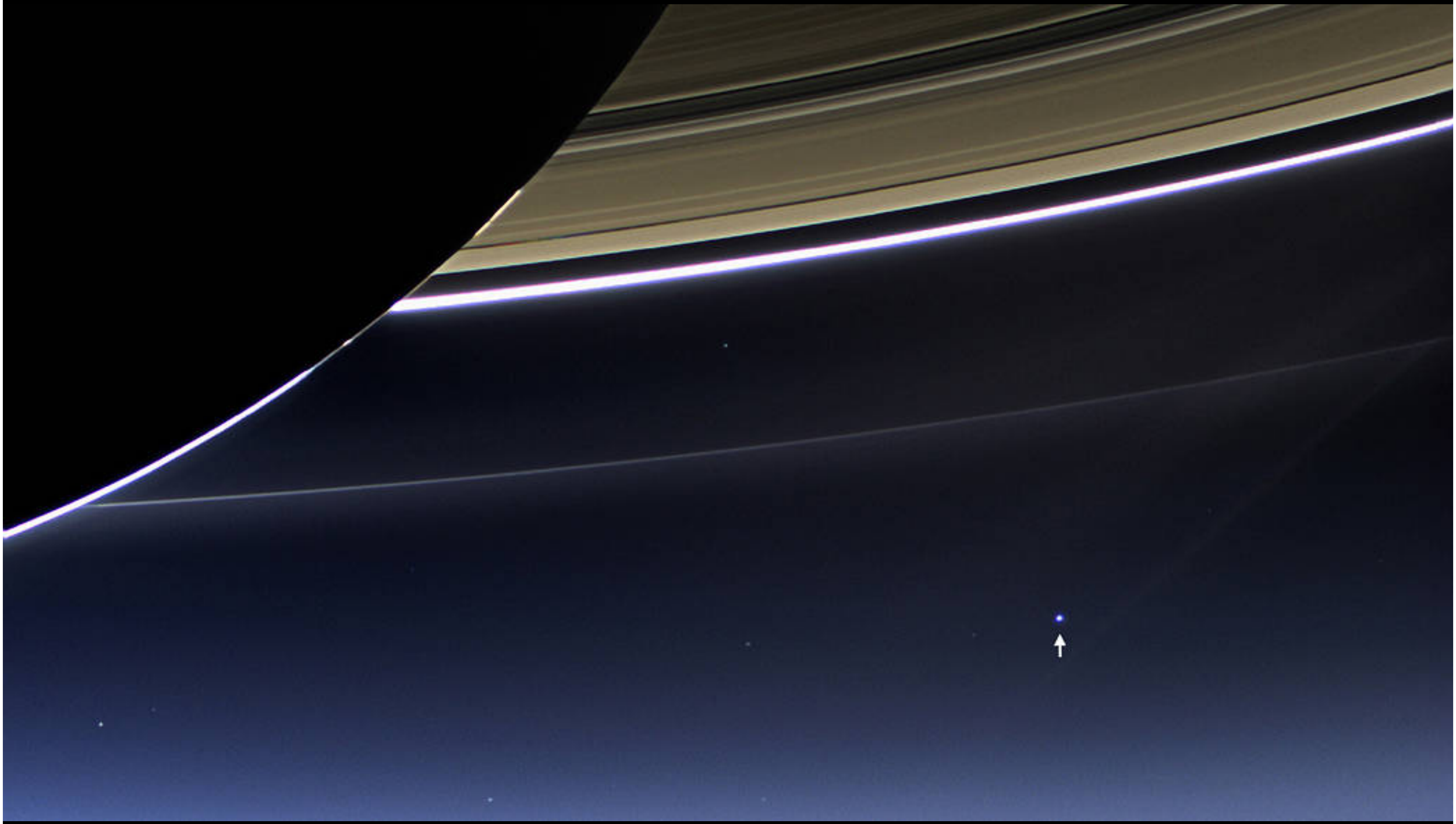


The size does matter…

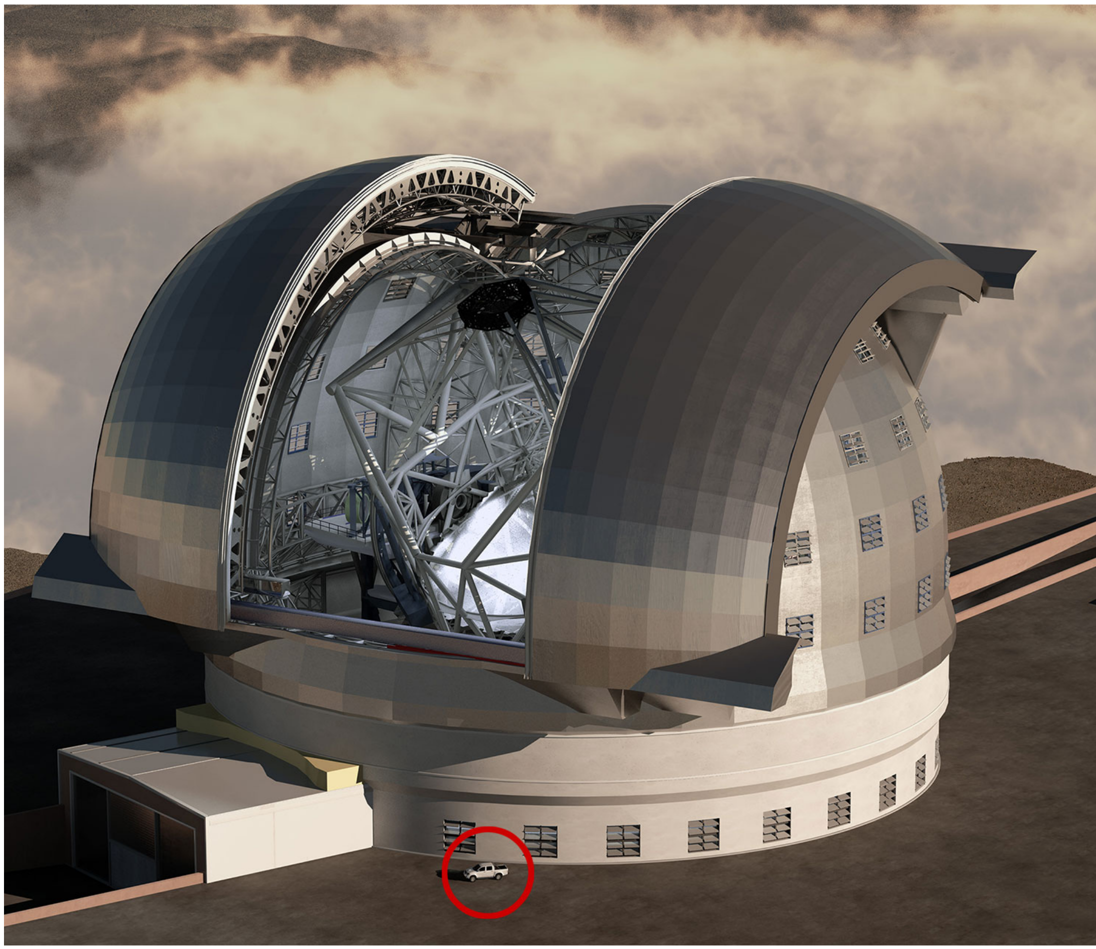


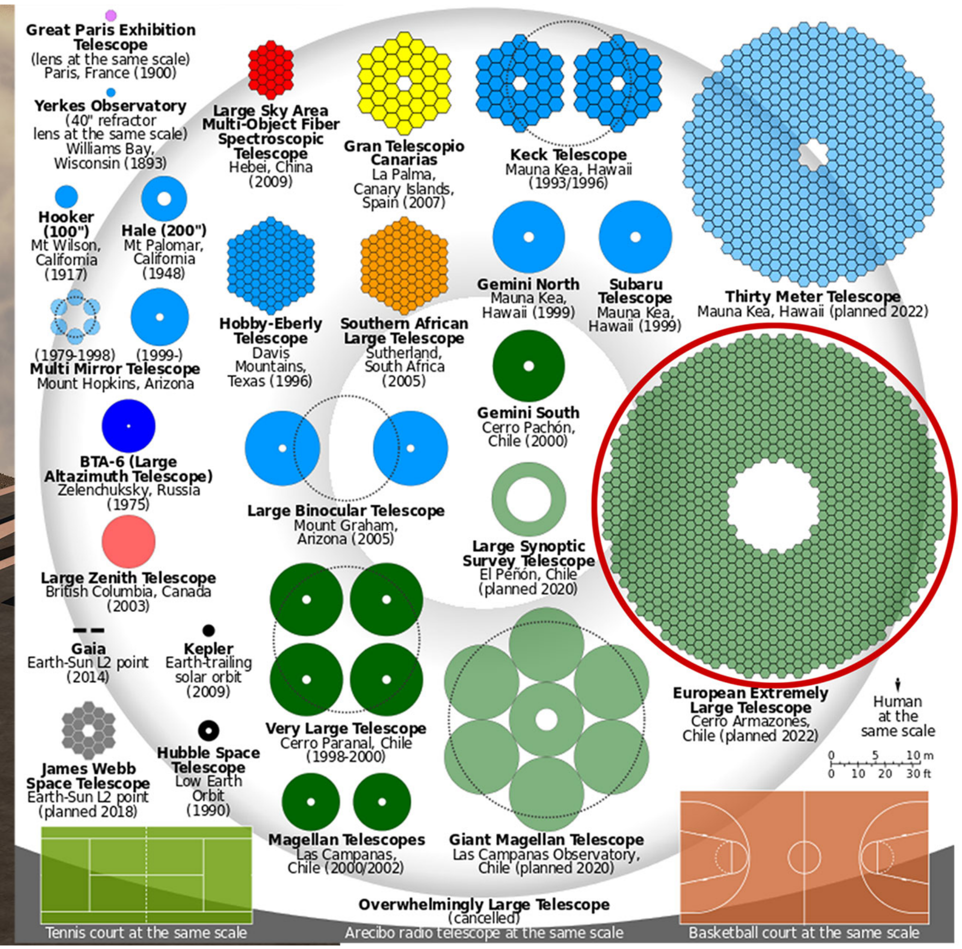
…and so does the distance: *the tyranny of the diffraction limit…*

Our Challenge



Largest telescopes to date…

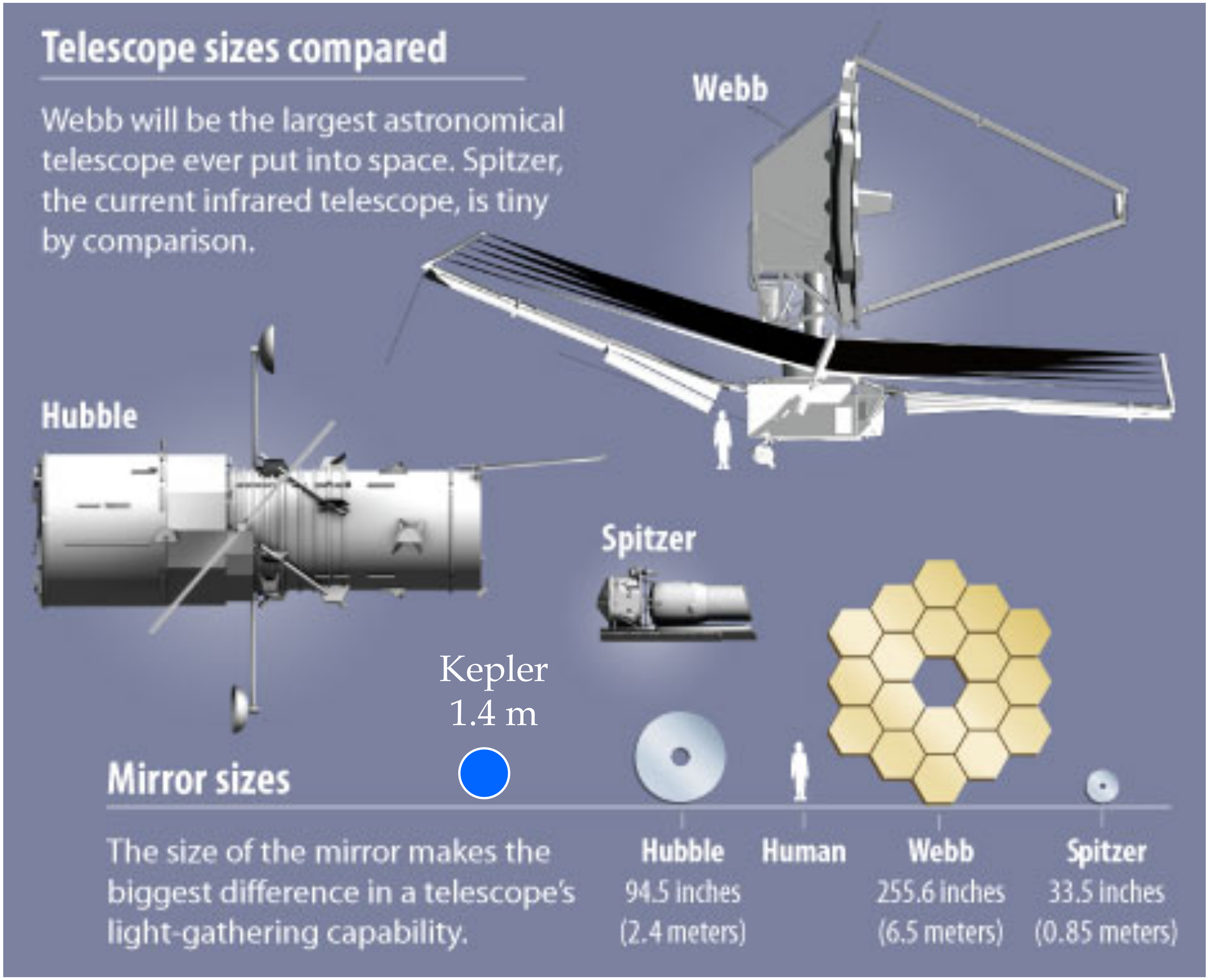




European Extremely Large Telescope
39 meters, Chile (est. 2022)

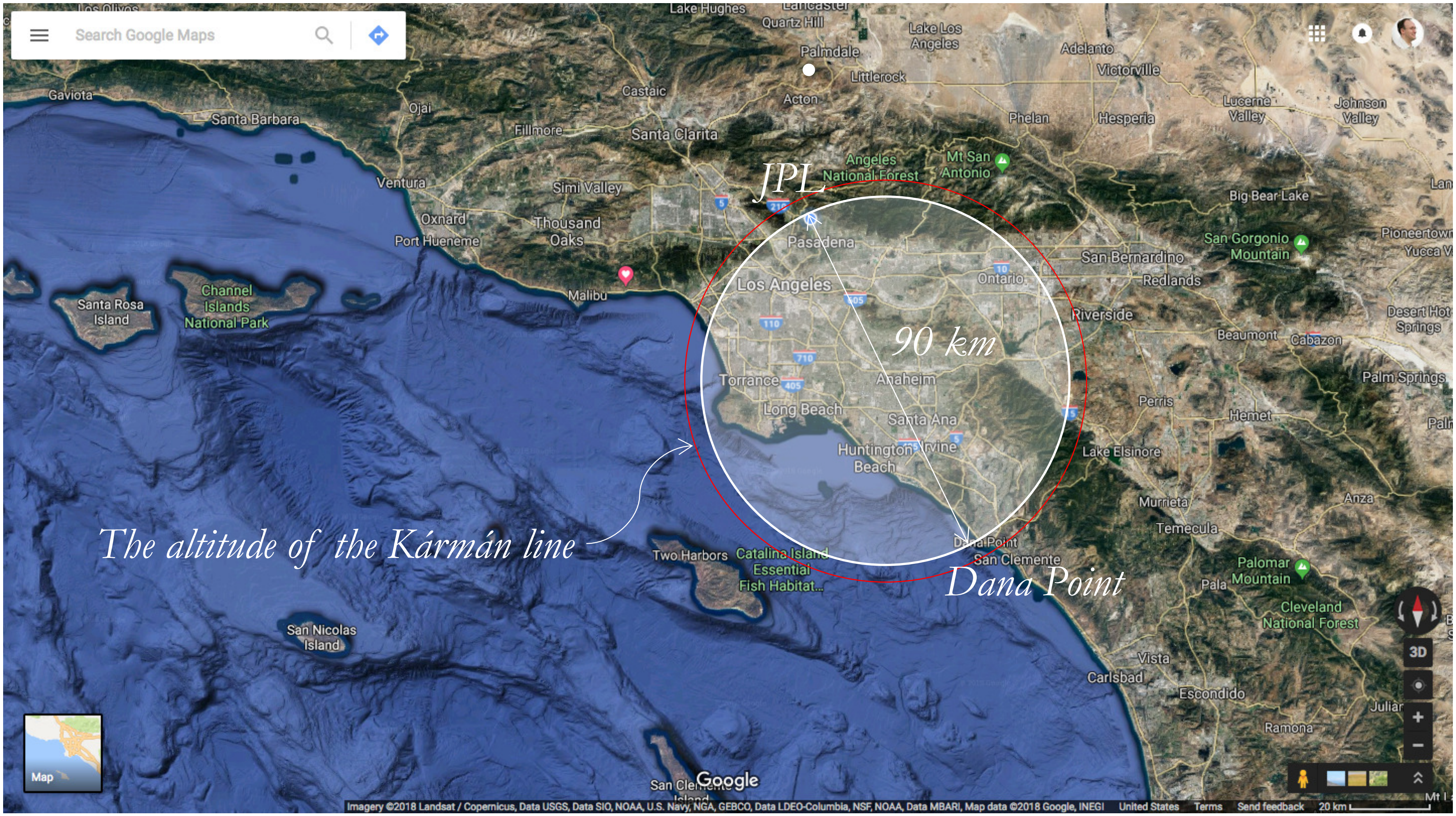
The largest telescopes for the last 125 years to date, both on the ground and in space

Largest telescopes in space



1-pixel direct image of an exo-Earth…

The tyranny of the diffraction limit: To make a 1-pixel image of an exo-Earth at 100 light years, a telescope with a diameter of ~90 km is needed…



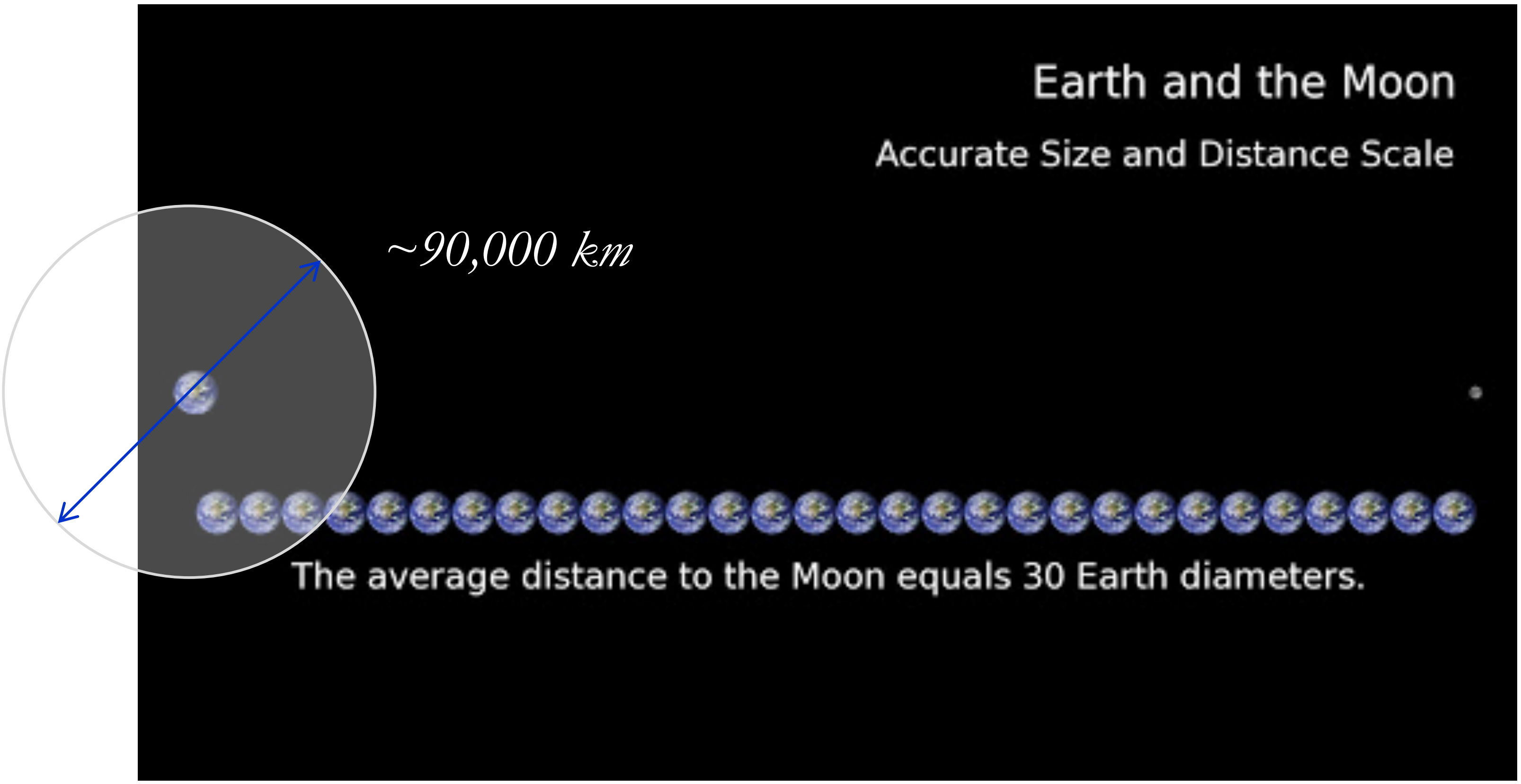
A (10k×10k)-pixels image of our Earth

This 2002 Blue Marble image features land surfaces, clouds, topography, and city lights at a maximal resolution of 1 km per pixel.

Composed from 4 months data from NASA's Terra satellite by R.Simmon, R.Stöckli.

1,000-pixel direct image of an exo-Earth…

The tyranny of the diffraction limit: To make a 1,000-pixel image of an exo-Earth at 100 light years, a telescope with a diameter of ~90,000 km is needed…

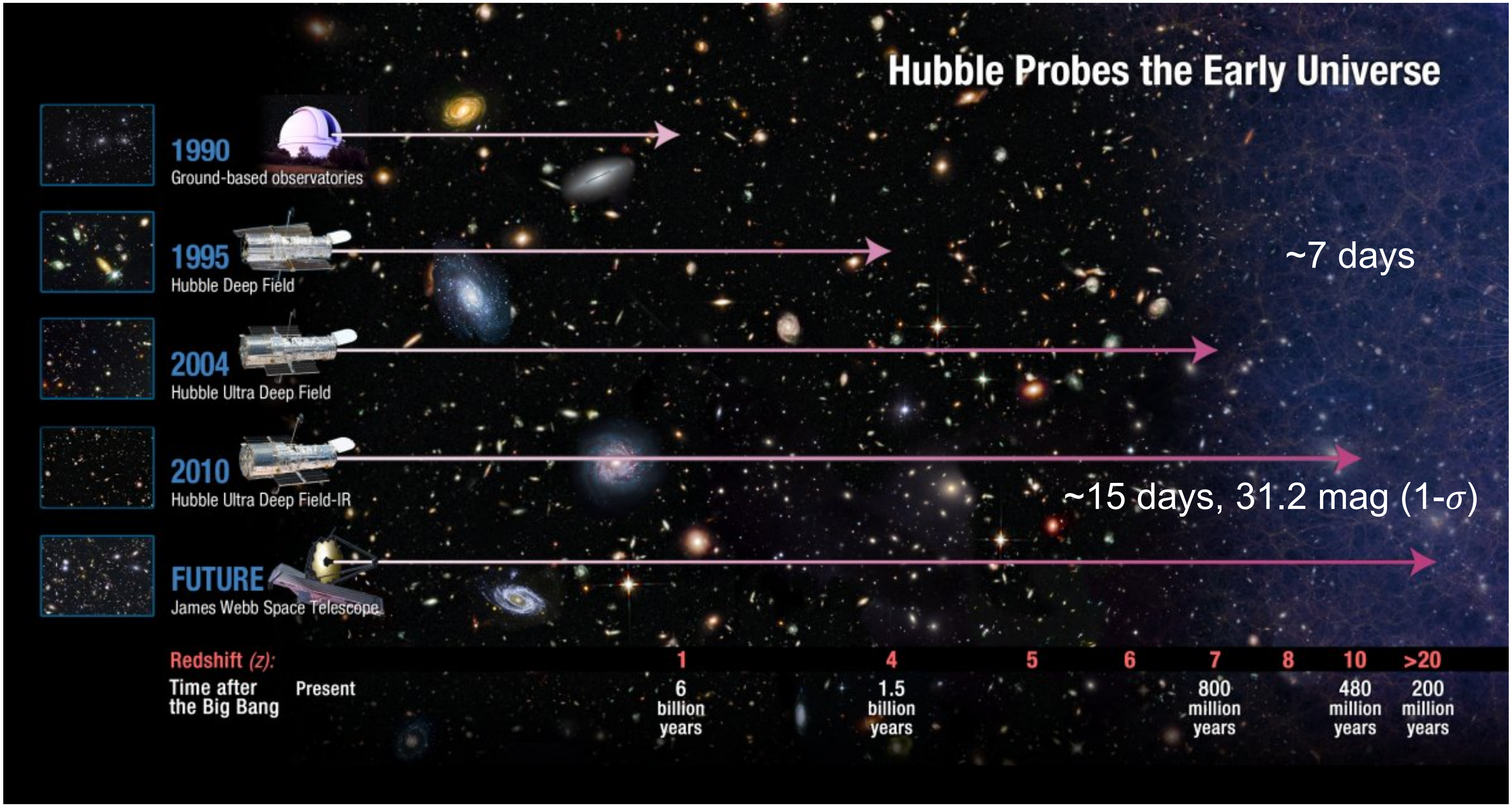


Diameter of 90,000 km is ~7 diameters of the Earth

SGL enables direct multipixel imaging

- Solar gravitational lens (SGL) offers:
  - Magnification (at 1 um) ~2×10^{-11} & angular resolution: ~0.5 nanoarsec
- Overcoming the issue of a small target size:
  - Consider an exo-Earth @ 30pc (100 l.y.) is ~1.4×10^{-11} rad;
  - A diffraction-limited telescope needed to resolve an object with this size at such distance must have a diameter of ~90 km;
  - To resolve the planet with 1,000 pixels one needs a telescope with a diameter of 90×10^4 km (or ~14 $R_\oplus$), which is impractical...
  - Even more challenging is the integration time needed to reach SNR=10:
    - a 50 m telescope would need an integration time of $t \sim 10^6$ years (zodi);
    - with SGL's light amplification (~2×10^9) we could do the job in ~3 month.
- Solving the parent start light contamination issue:
  - Current exoplanet-imaging concepts detect light of a planet as a single pixel. Contamination from the parent star (~0.1" off the planet) is a major problem;
    - Due to the high angular resolution of the SGL (~0.5 nas), the parent star is resolved from the planet with its light amplified 0.01 AU away from the optical axis, making the parent star contamination issue negligible.

Observing faint targets…

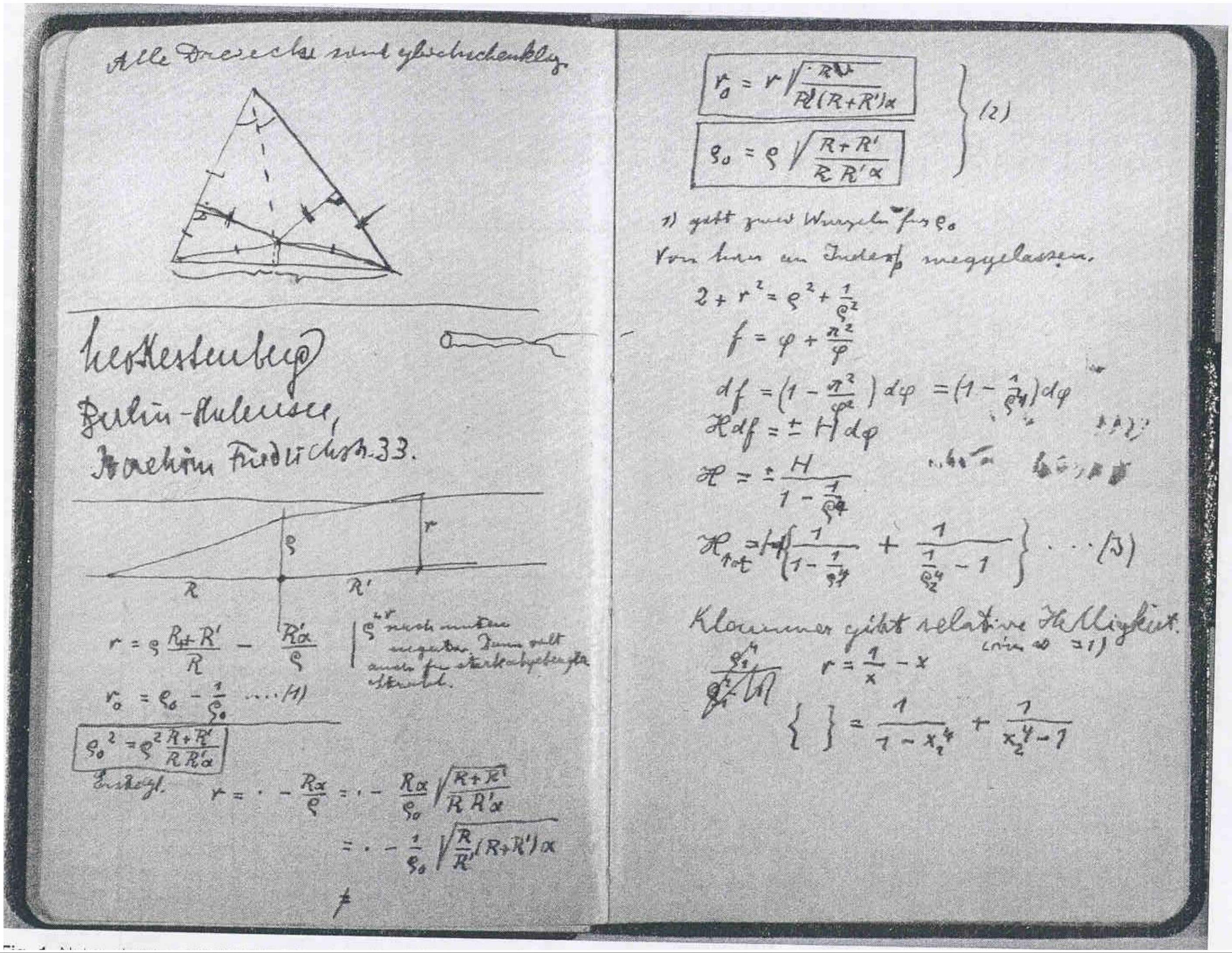


Conventional techniques?

- Overcoming the issue of the long integration times:
  - Let’s calculate integration time to get SNR = 10 on the longest baseline for an interferometer that resolved an object with 1,000 pixels across:
    - exo-Earth @ 30pc is an object of 32.4 mag;
    - background is 1 exo-zodi of 22 mag/arcsec^2;
    - 10m space telescope(s) with perfect coronagraphs;
    - max baseline ~45,000 km;
    - integration time is t_0 ~400 million years…
  - Assume the interferometer is phased to < λ/20 during the integration and the coronagraph suppresses the parent star to below the exo-zodi level:
    - To image with 1,000 pixels (pixel = 47 mag), a million baselines are needed;
    - If only 2 of 10m telescopes are available, multiply the above t_0 by a million to get integration time of t ~ 4e14 years;
    - If more telescopes added, decrease integration time by # telescopes…
    - Integration time decreases rapidly with D > 10m as ~ D^4;
  - Array of 10^3 of 100 m telescopes would take t = 4e14/1e7 ~40 million years

1-m telescope at SGL (zodi & solar corona brightness): SNR = 10 in ~ few months

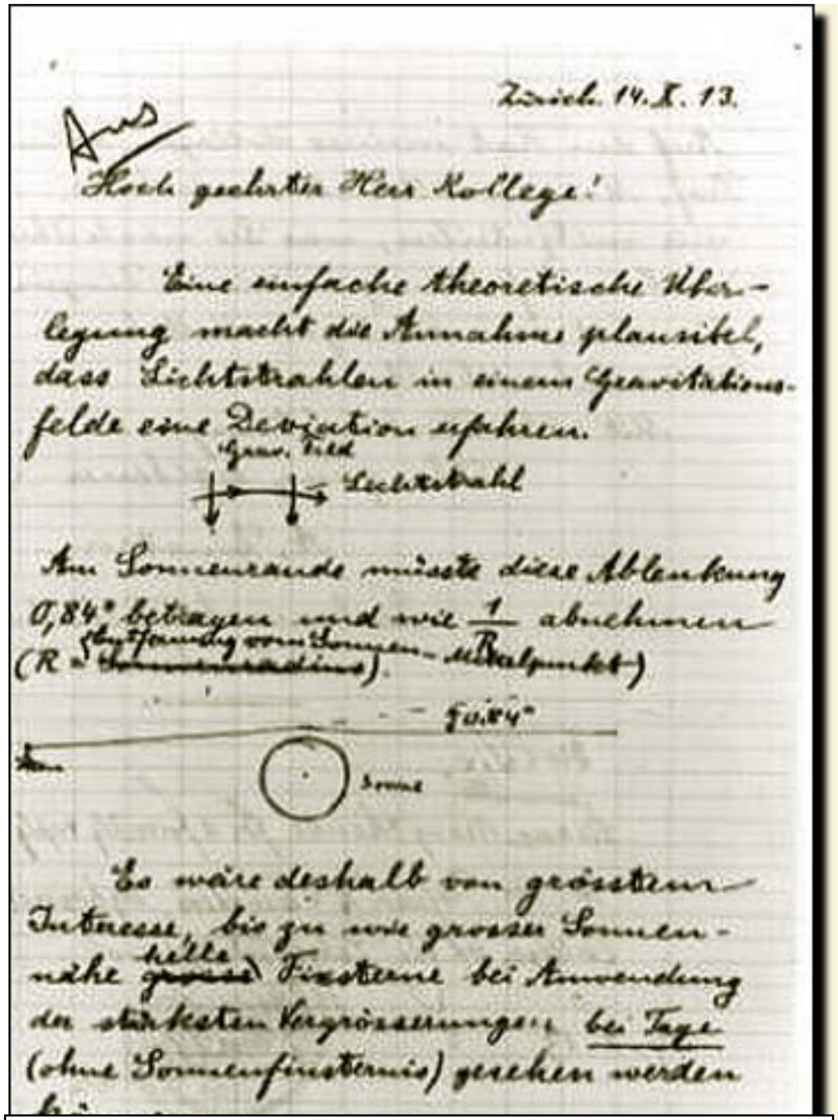
Original gravity lens derivation (Einstein c.1911)



Precision alignment between a Lens and the Earth is very unlikely…

Gravitational deflection of light before GR

$$\alpha_{\texttt{Newton}}(b) = \frac{2GM_\odot}{c^2 b} = 0.877\left(\frac{\mathcal{R}_\odot}{b}\right) \text{ arcsec}$$


Zürich. 14. X. 13.

Ans

Hoch geehrter Herr Kollege!

Eine einfache theoretische Überlegung macht die Annahme plausibel, dass Lichtstrahlen in einem Gravitationsfelde eine Deviation erfahren.

Grav. feld

Lichtstrahl

Am Sonnenrande müsste diese Ablenkung 0,84" betragen und wie 1/R abnehmen (R = Abstand des Strahles vom Sonnen-Mittelpunkt).

0.84"

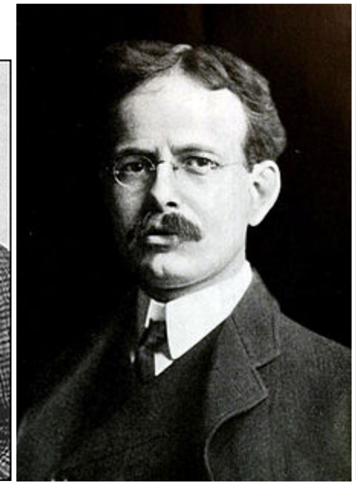
Erde

Sonne

Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnennähe helle Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden kön-

The Huntington Library, Pasadena, CA

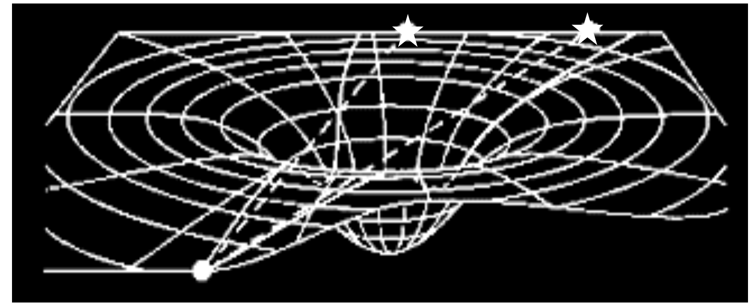

Albert Einstein c.1913


George Ellery Hale (1868-1938)


Erwin Finlay-Freundlich (1885-1964)

- In 1913 Einstein wrote to Hale:
  - "Is eclipse necessary to test this prediction?"
  - Hale replied: "Yes, an eclipse is necessary, as stars near the Sun would then be visible, and the bending of light from them would show up as an apparent displacement of the stars from their normal positions."
- In 1914, the first attempt - a German expedition
  - A German astronomer Finley-Freundlich led an expedition to test the Einstein's prediction during a total solar eclipse on Aug. 21, 1914 (in Russia);
  - However, the First World War (July 28, 1914) intervened, and no observations could be made.

The First Test of General Theory of Relativity

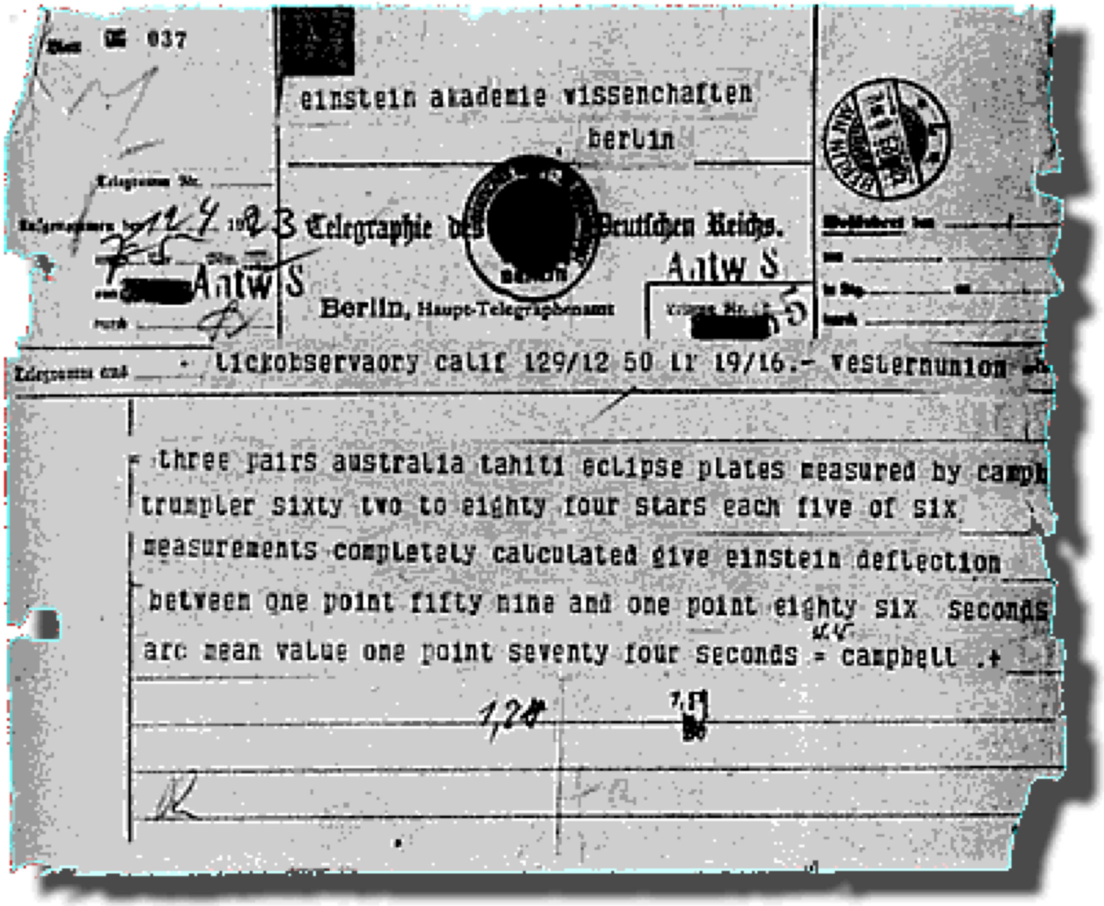


Gravitational Deflection of Light:

$$\alpha_{\mathrm{GR}}(b) = \frac{2(1+\gamma)GM_\odot}{c^2 b} \simeq 1.75\left(\frac{1+\gamma}{2}\right)\left(\frac{\mathcal{R}_\odot}{b}\right) \text{ arcsec}$$

Solar Eclipse 1919: possible outcomes

Deflection = 0;
Newton = 0.87 arcsec;
Einstein = 2 x Newton = 1.75 arcsec



einstein akademie vissenchaften berlin

Telegraphie des Deutschen Reichs. Berlin, Haupt-Telegraphenamt

[redacted] Antw S

Antw S

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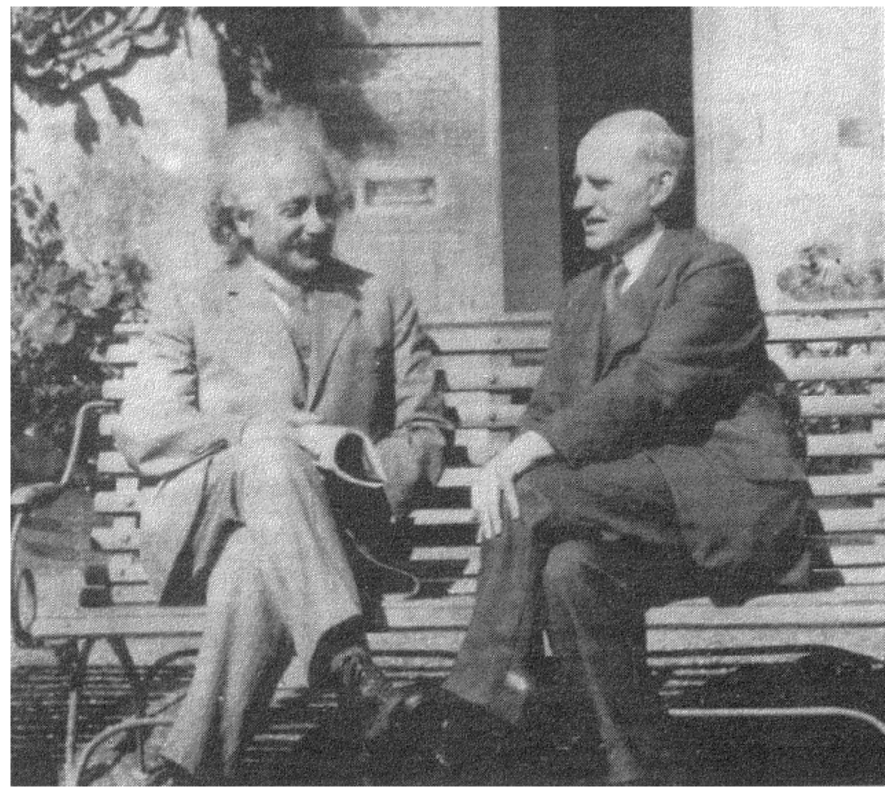
lickobservaory calif 129/12 50 lr 19/16.- vesternunion

three pairs australia tahiti eclipse plates measured by campb trumpler sixty two to eighty four stars each five of six measurements completely calculated give einstein deflection between one point fifty nine and one point eighty six seconds arc mean value one point seventy four seconds = campbell .+

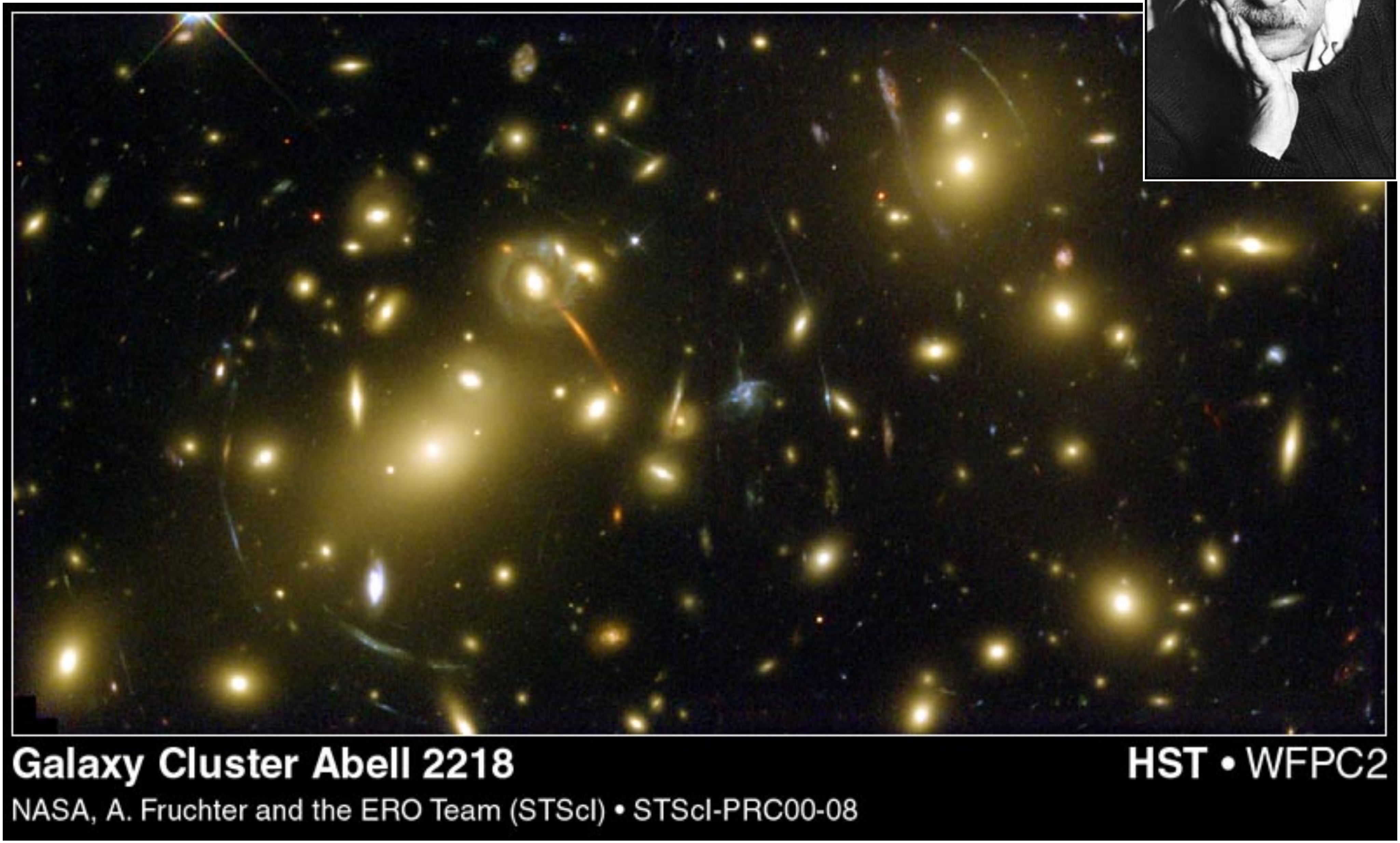
1,24 7,5

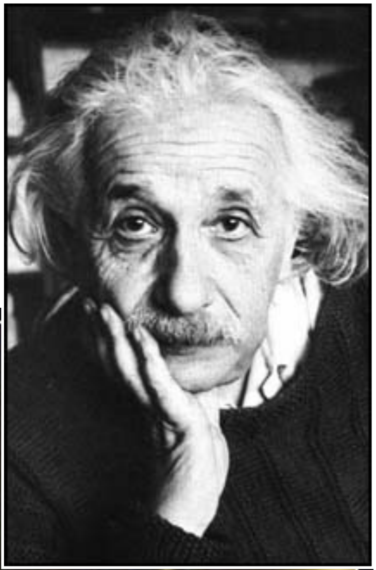
Campbell's telegram to Einstein, 1923



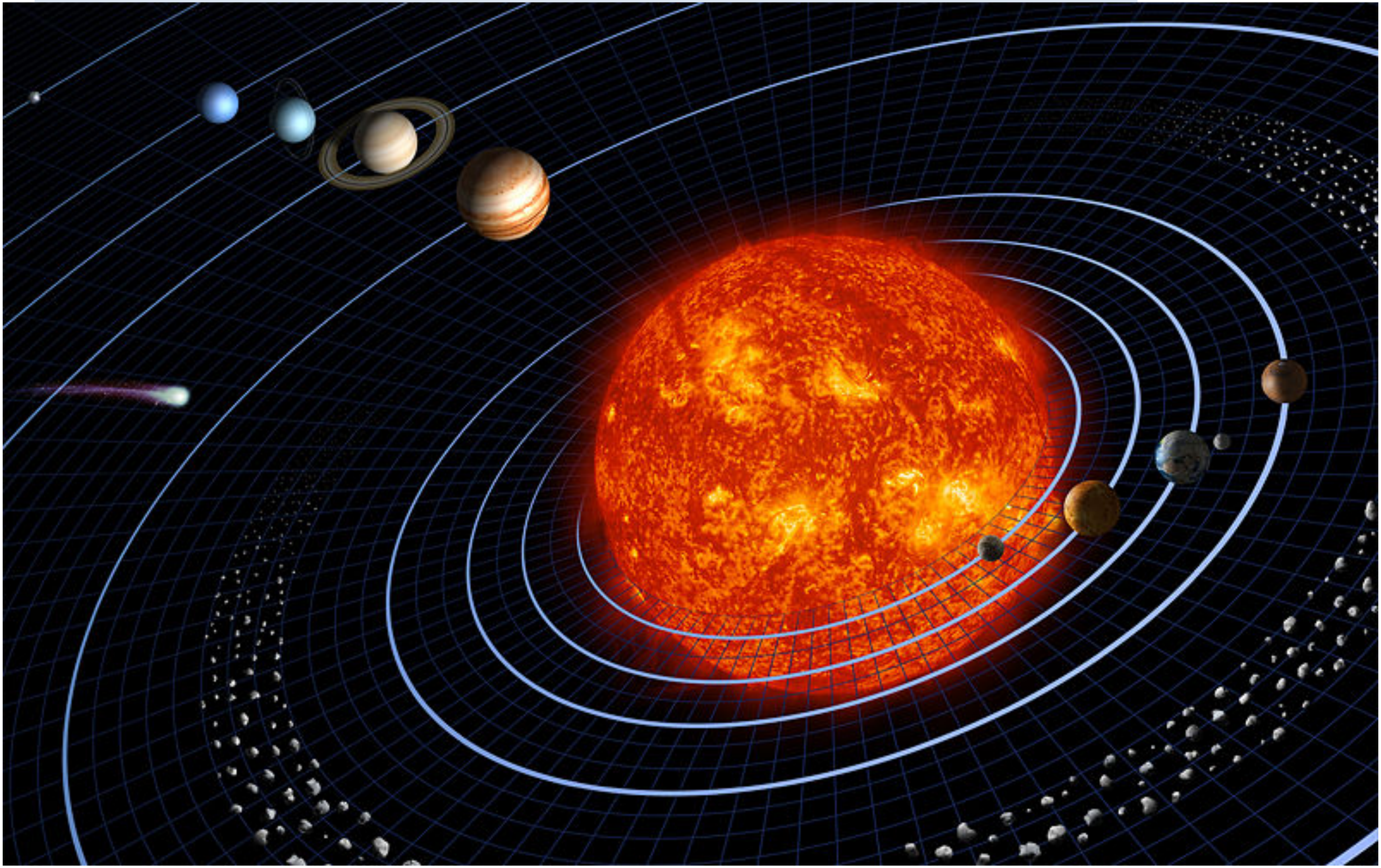
Einstein and Eddington, Cambridge, 1930

Gravitational Deflection of Light is a Well-Known Effect Today





Our solar system and tests of gravity



40+ Years of Solar System Gravity Tests

Techniques for Gravity Tests:

Radar Ranging:
- Planets: Mercury, Venus, Mars
- s/c: Mariners, Vikings, Pioneers, Cassini, Mars Global Surveyor, Mars Orbiter, etc.
- VLBI, GPS, etc.

Laser:
- SLR, LLR, interplanetary, etc.

Dedicated Gravity Missions:

- **LLR (1969 - on-going!!)**
- GP-A,'76; LAGEOS,'76,'92; GP-B,'04; LARES,'12; MicroSCOPE,'16, ACES, '18; LIGO,'16; eLISA, 2030+(?)

New Engineering Discipline – Applied General Relativity:

- Daily life: GPS, geodesy, time transfer;
- Precision measurements, deep-space navigation & μas-astrometry (Gaia)

The Nobel Prize in Physics 2017

© Nobel Media. Ill. N. Elmehed
Rainer Weiss
Prize share: 1/2

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Barry C. Barish
Prize share: 1/4

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Kip S. Thorne
Prize share: 1/4

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

General relativity is now well tested. Can we use it to build something?

Mission to the Gravity Lens of the Sun

Eshleman V.R., Science **205**, 1133 (1979)

Gravitational Lens of the Sun: Its Potential for Observations and Communications over Interstellar Distances

Abstract. *The gravitational field of the sun acts as a spherical lens to magnify the intensity of radiation from a distant source along a semi-infinite focal line. A spacecraft anywhere on that line in principle could observe, eavesdrop, and communicate over interstellar distances, using equipment comparable in size and power with what is now used for interplanetary distances. If one neglects coronal effects, the maximum magnification factor for coherent radiation is inversely proportional to the wavelength, being 100 million at 1 millimeter. The principal difficulties are that the nearest point on the focal half-line is about 550 times the sun-earth distance, separate spacecraft would be needed to work with each stellar system of interest, and the solar corona would severely limit the intensity of coherent radiation while also restricting operations to relatively short wavelengths.*

About 40 years ago, Einstein (*1*) published a short note in *Science* on the focusing of starlight by the gravitational field of another star. He emphasized the improbability of observing this phenomenon by the chance alignment of two stars and the earth. From concepts based on current technology and trends, however, it appears that gravitational focusing of electromagnetic radiation might be employed, by design, for highly directional observations and communications over interstellar distances.

In such use, the gravitational field of the sun could play several roles. First, it might be used to reduce fuel and time re-

$1 + \nu$, where the refractivity $\nu = g/r$ at radius r. A ray is deflected through the angle $\alpha = 2g/a$, where a is the ray impact parameter and g is the gravitational radius ($g = 2Gm/c^2$, where G is the gravitational constant, m is the mass of the central body, and c is the speed of light). It is assumed throughout that $\alpha << 1$. An observer at position z behind the lens and x from the center line, as illustrated, would see an energy density lessened by defocusing in the plane of propagation, but increased by focusing due to the curved limb normal to this plane. The relative single-ray intensity $I = F_h^2 F_v^2$, where in ray optics F_h^2 =

nel scales along the circumference of a circle at the ray-impact radius. Using also the wave number $k = 2\pi/\lambda$, the maximum intensification of the coherent signal is simply

$$I_{max} = 2\pi kg \quad (2)$$

As an approximation, let the focal "spot" radius x_s be the value of x where I falls to $I_{max}/4$, so that $x_s = (2/\pi k)(z/2g)^{1/2}$. Thus the angular resolution for distinguishing two adjacent coherent sources by a corresponding change in intensity is x_s/z radians. (The first null off the center line is at $x = \pi^2 x_s/2$, and the first sidelobe is twice this distance with intensity I_{max}/π^2.) The periapsis or minimum radius of the ray relative to the center of mass is $a - g$, or essentially a, and this must be greater than r_0, the physical radius of the spherical mass. Thus $\alpha_{max} = 2g/r_0$ and the focal line begins at $z_{min} = r_0^2/2g$.

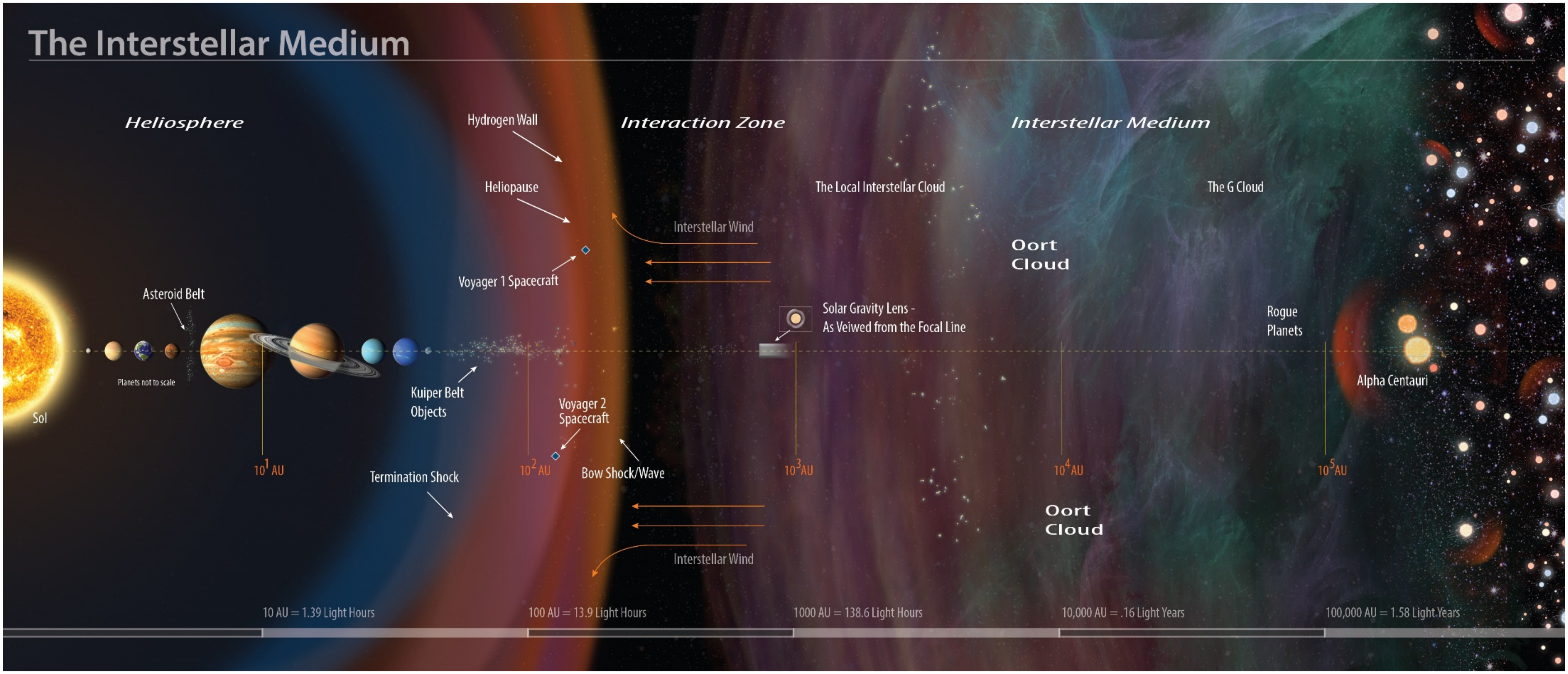
Now consider the focusing at $z > z_{min}$ of incoherent radiation from a uniformly bright, circular, extended source of radius r_p and distance $z_p >> z$. This is the problem considered by Einstein (*1*) and more completely by others, notably Liebes (*4*). The gain factor A of the gravitational lens for the intensity observed from the two individual image com-

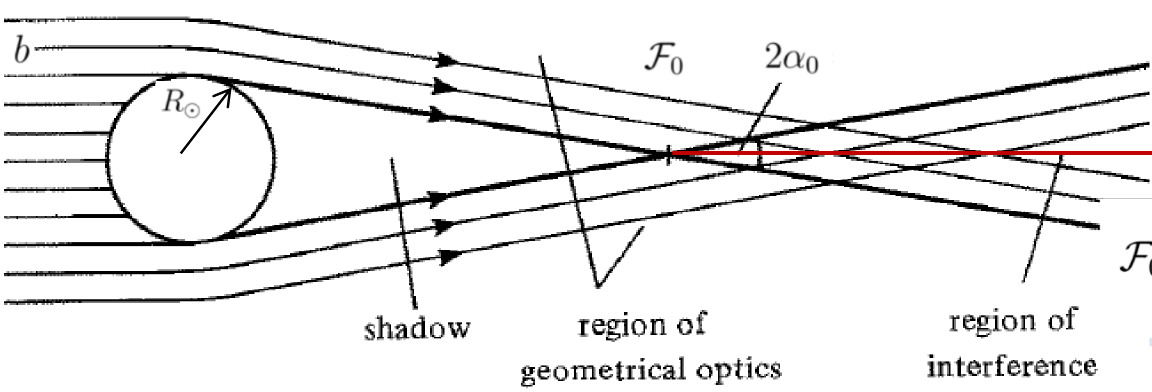
Kraus J.D., Radio Astronomy, Cygnus-Quasar Books, Powell, Ohio, 6-115 (1986)

Maccone C., many papers, 1999-present

Turyshev & Andersson, MNRAS **341**, 577 (2003)

The Solar Gravitational Lens (KISS study, 2015)

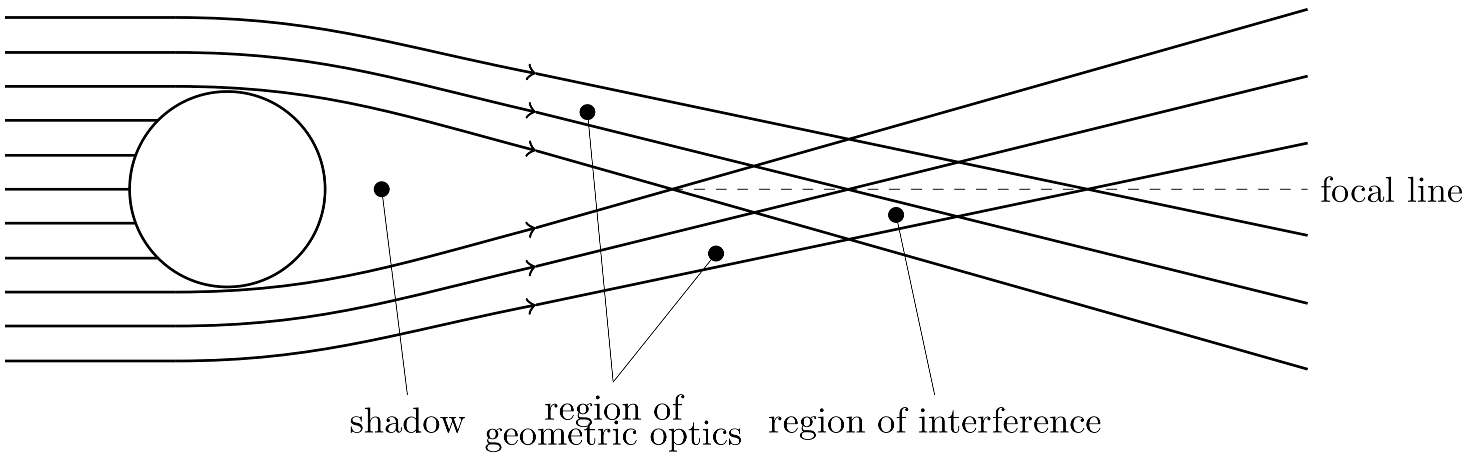




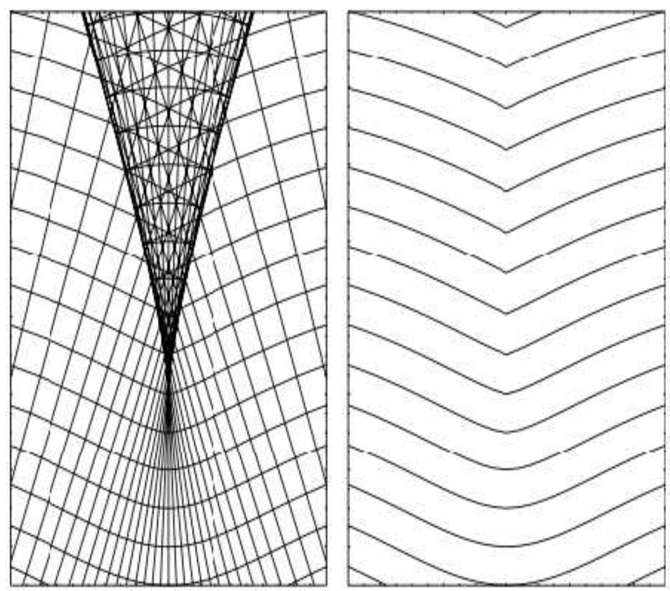
$$\alpha_0 = \frac{2r_g}{R_\odot} \approx 8.5\ \mu\text{rad} \quad \rightarrow \quad \alpha(b) = \alpha_0 \frac{R_\odot}{b}$$

$$\mathcal{F}_0 = \frac{R_\odot}{\alpha_0} = \frac{R_\odot^2}{2r_g} \approx 547\ \text{AU} \quad \rightarrow \quad \mathcal{F}(b) = \mathcal{F}_0 \frac{b^2}{R_\odot^2}$$

Optical properties of the SGL: caustic



Different regions of the SGL



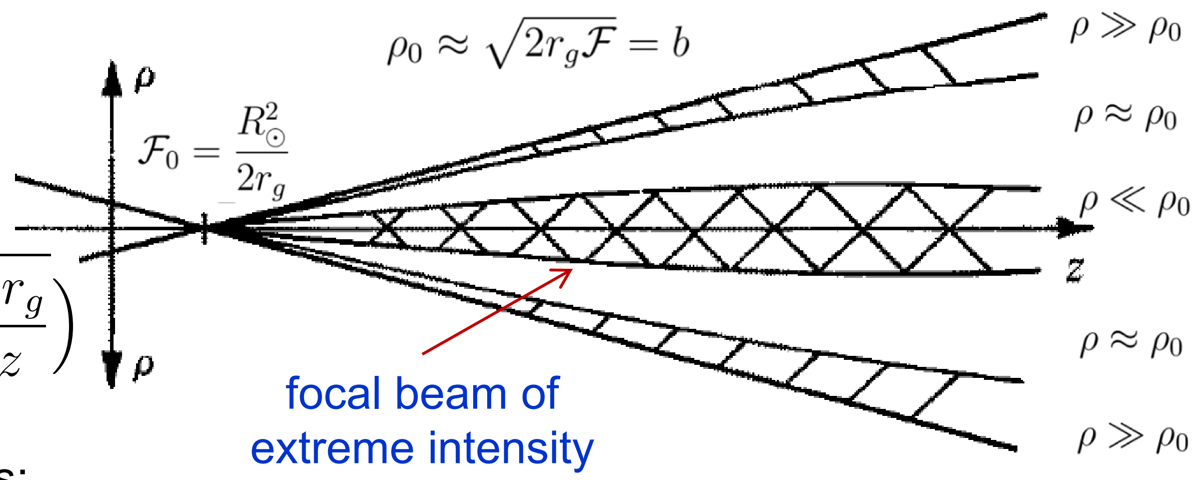
Caustic formed behand the Sun

Focal beam of extreme intensity

Herlt & Stephani, IJMP 15, 45 (1976)

- Major brightness increase:
  - For small departures from the optical axis, ρ, magnification of the SGL is:

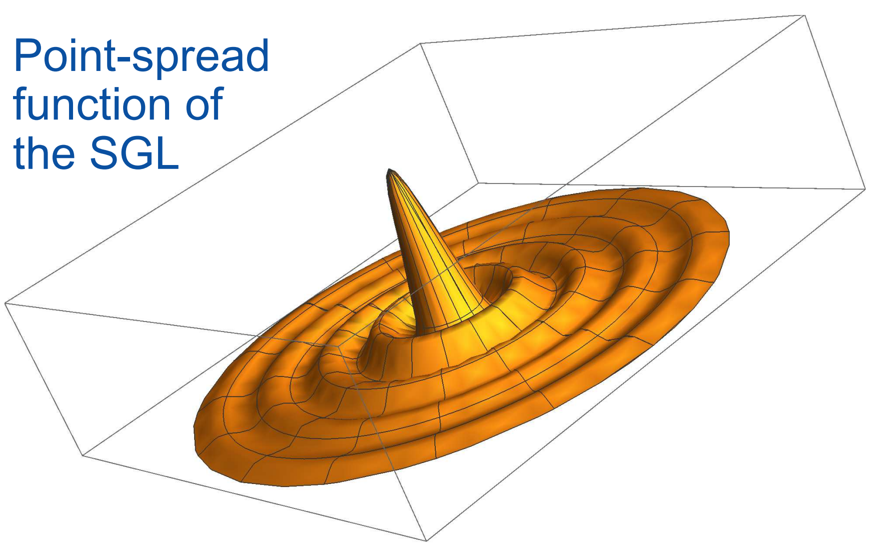
$$\mu_z(\rho, z, \lambda) \;\cong\; 4\pi^2\frac{r_g}{\lambda}\, J_0^2\Big(2\pi\frac{\rho}{\lambda}\sqrt{\frac{2r_g}{z}}\Big)$$

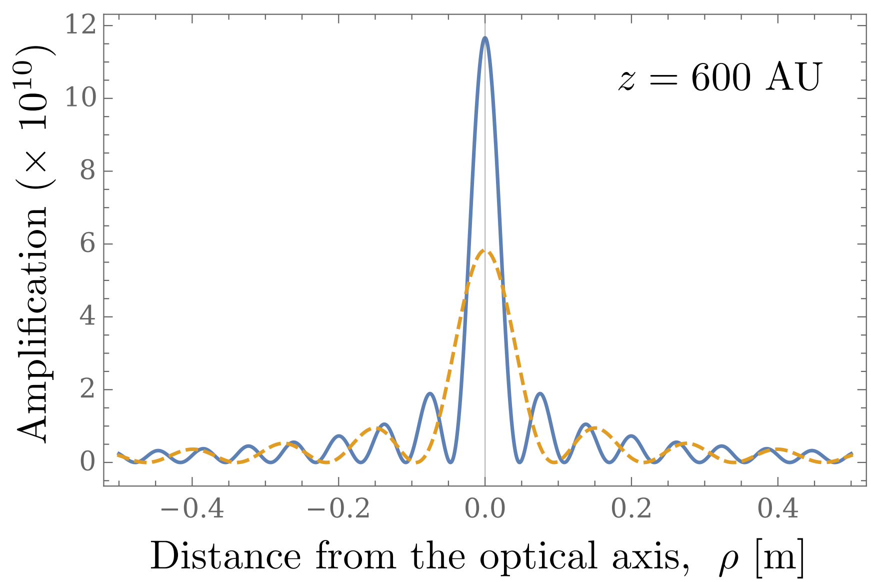


  - Max value of $G(\rho, \lambda)$ is on axis:

$$\mu_z(0, z, \lambda) \;\cong\; 4\pi^2\frac{r_g}{\lambda}$$

Point-spread function of the SGL

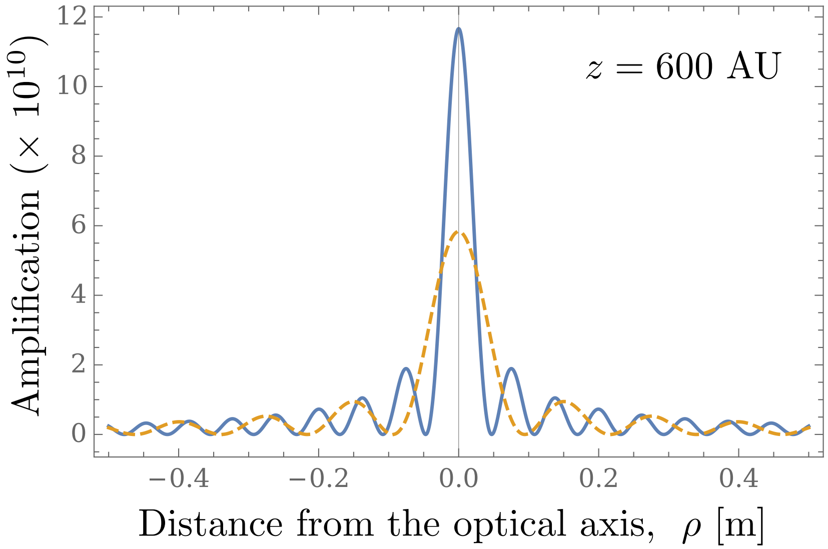


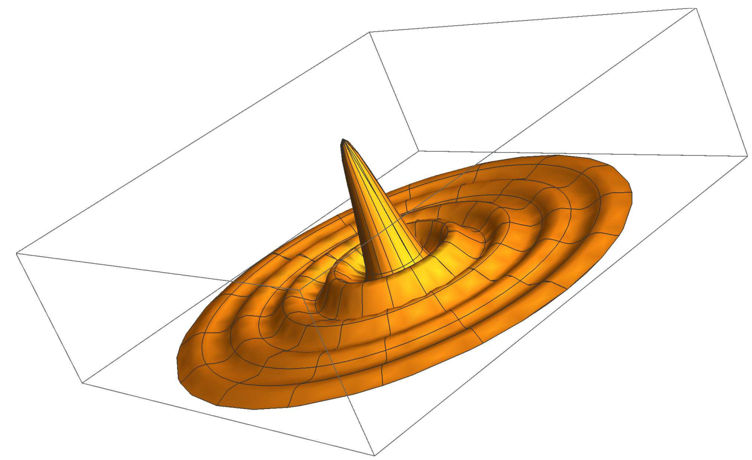


Turyshev & Toth, Phys. Rev. D 96, 024008 (2017)

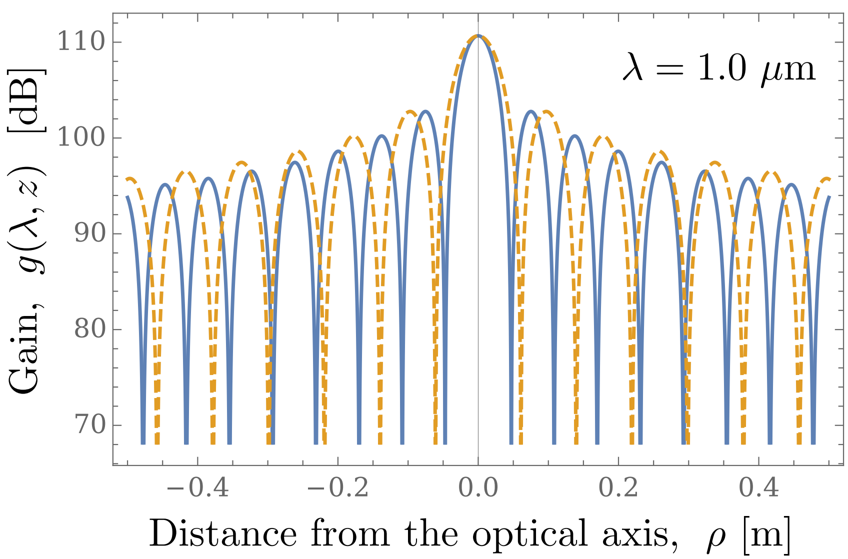
Gain of the SGL as seen in the image plane as a function of possible observational wavelength

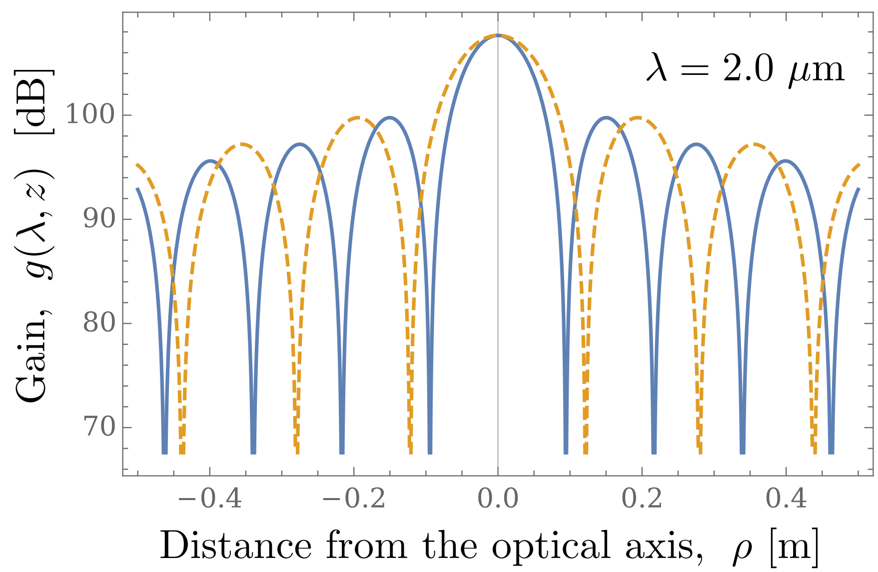
Point spread function & gain of the SGL





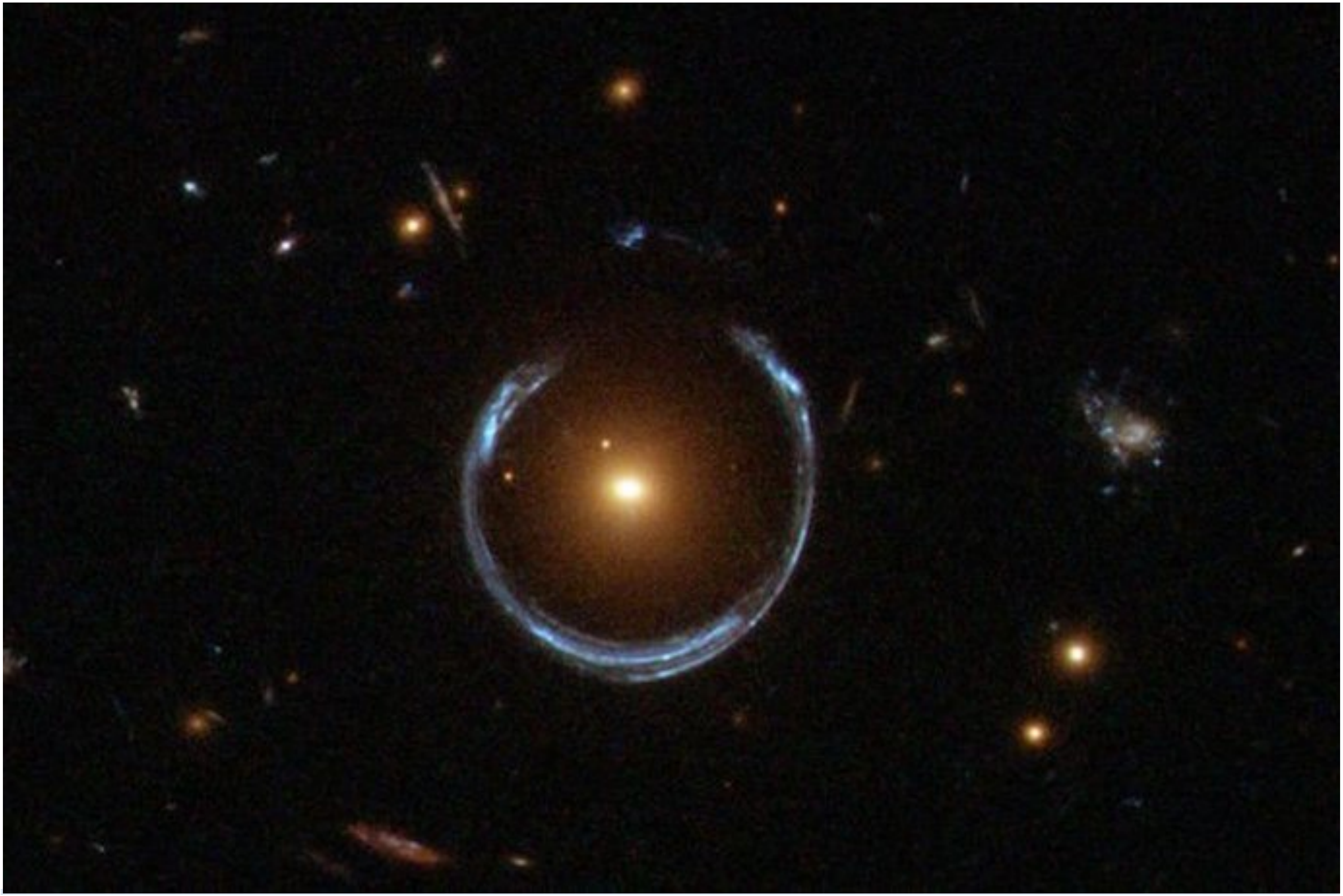
3-D Airy pattern of the SGL





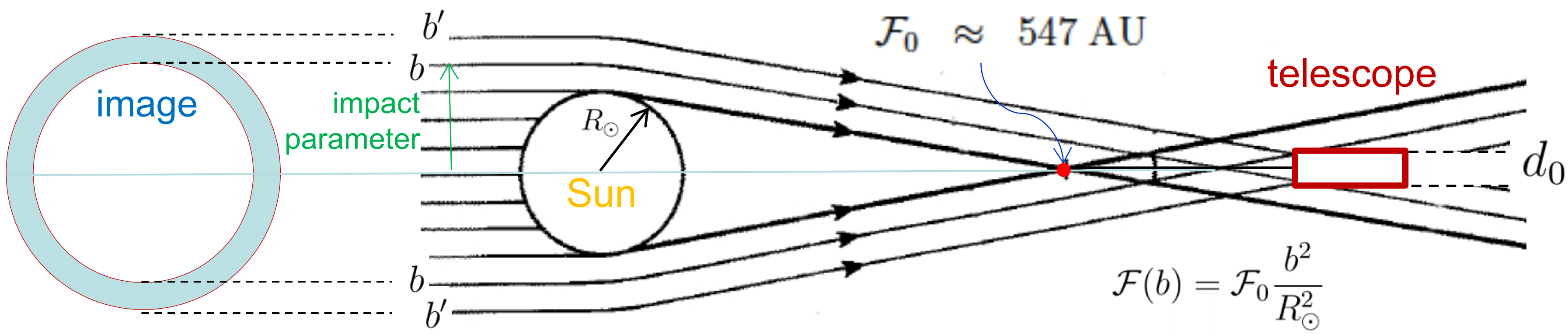
Turyshev & Toth, Phys. Rev. D 96, 024008 (2017)

The image in a form of the Einstein ring



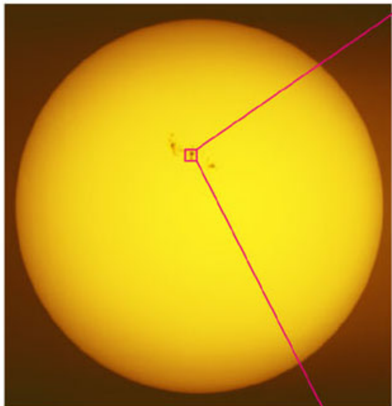
Credit: ESA, Hubble & NASA Wikimedia

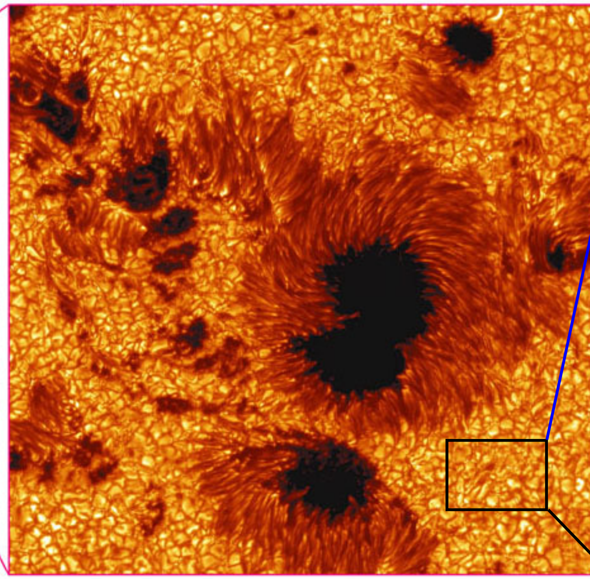
Properties of the Solar Gravity Lens



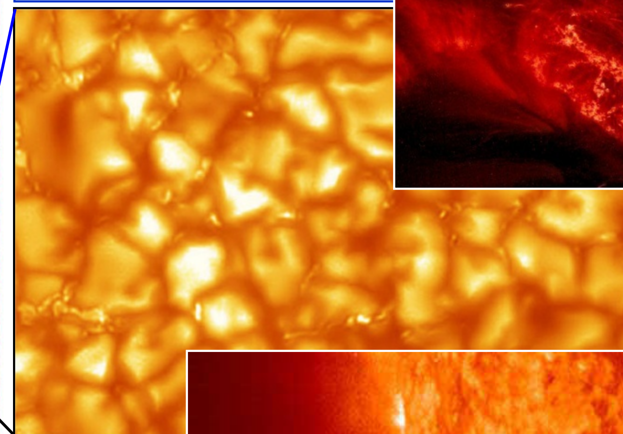
- Important features of the SGL (for λ = 1 μm):
  - Major brightness magnification: a factor of 10^{11} (on the optical axis);
  - High angular resolution: ~0.5 nano-arcsec. A 1-m telescope at the SGL collects light from a ~(10km × 10km) spot on the surface of the planet, bringing this light to one 1-m size pixel in the image plane of the SGL;
  - Extremely narrow "pencil" beam: entire image of an exo-Earth (~13,000 km) at 100 l.y. is included within a cylinder with a diameter of ~1.3 km.
- Collecting area of a 1-m telescope at the SGL's focus:
  - Telescope with diameter d_0 collects light with impact parameters $\delta b \simeq d_0$;
  - For a 1-m telescope at 750AU, the total collecting area is: 4.37×10^9 m^2, which is equivalent to a telescope with a diameter of ~80 km…

Do not point at the Sun!!!!

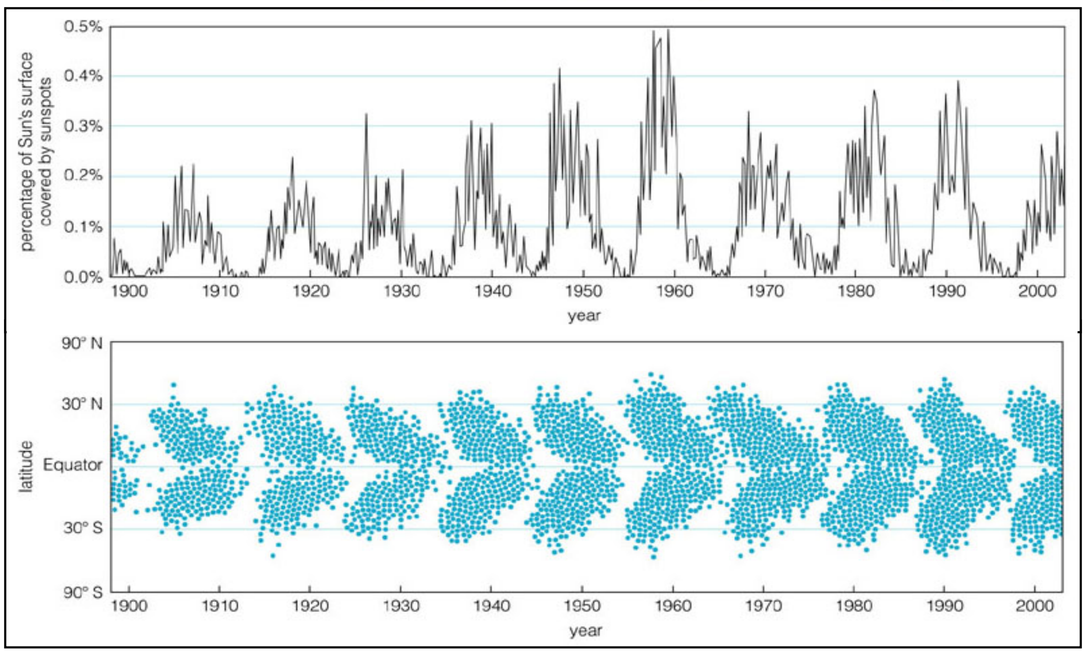




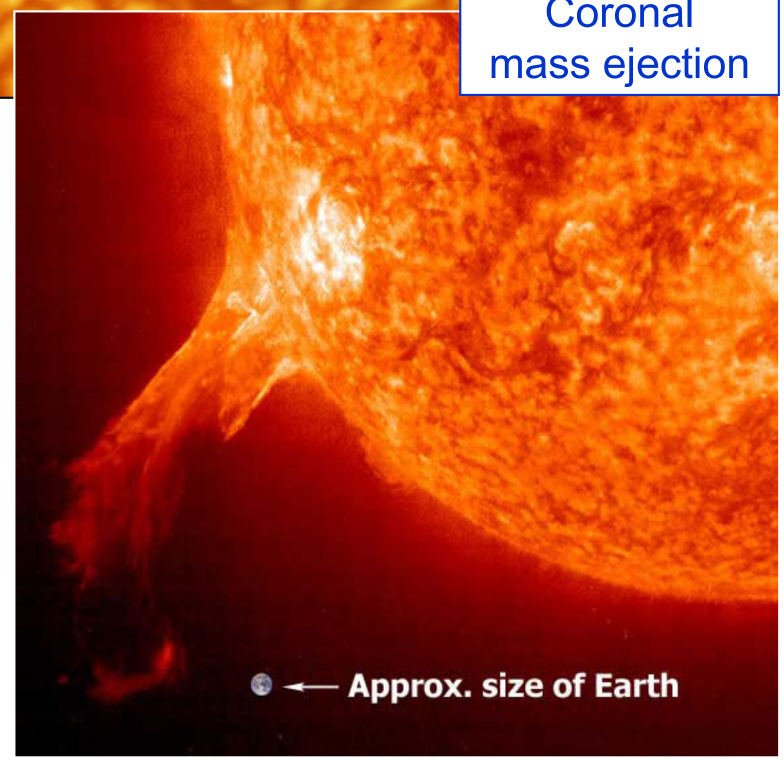
Granulation of solar surface



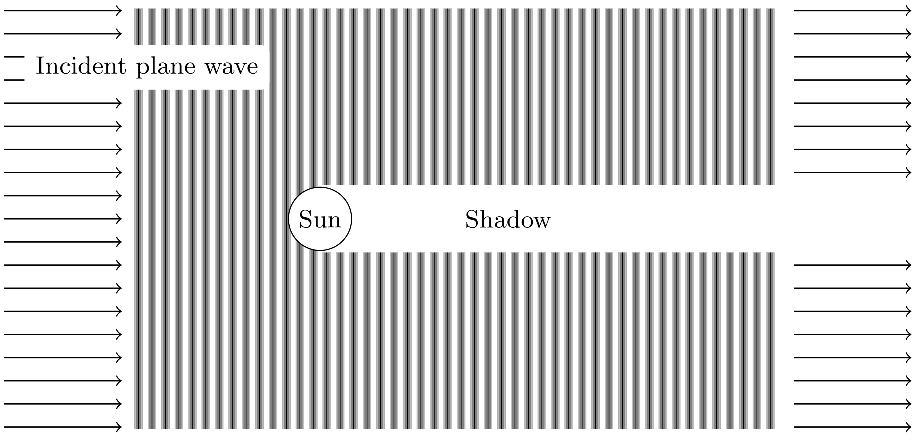
A solar flare



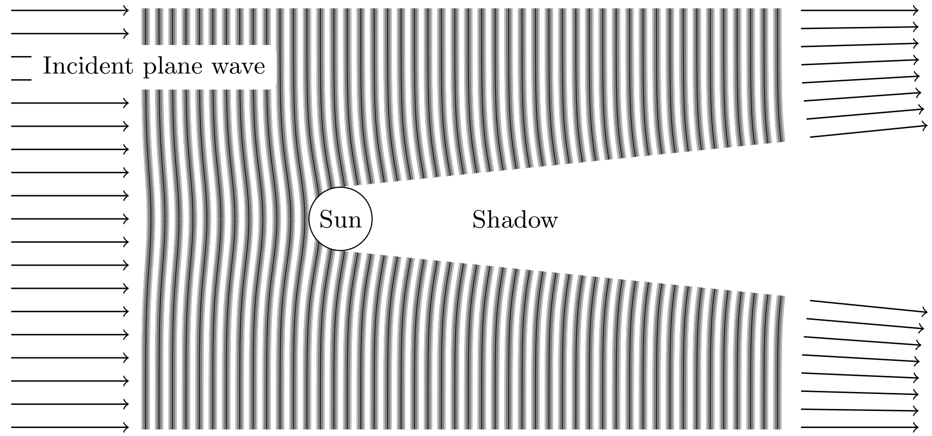
Coronal mass ejection



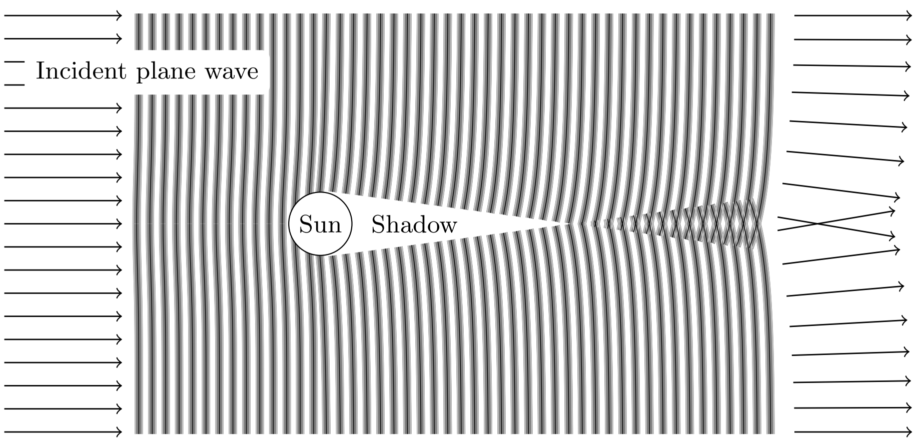
Effects of gravity & solar plasma



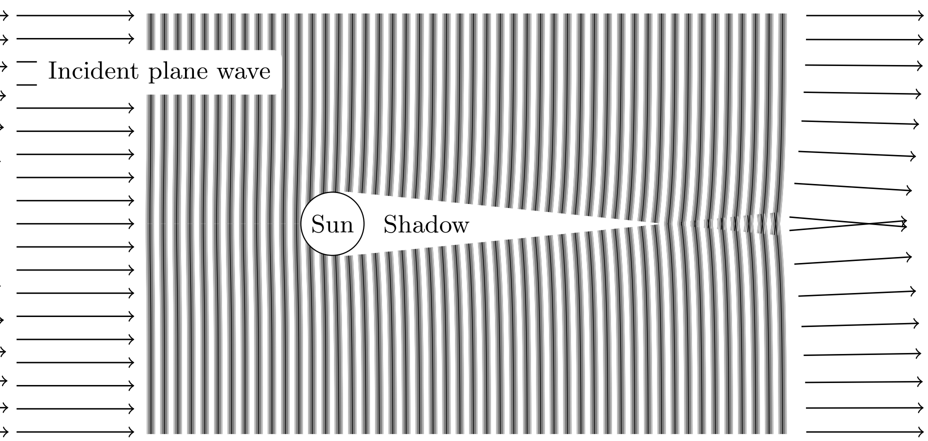
No gravity, no plasma



Plasma, no gravity

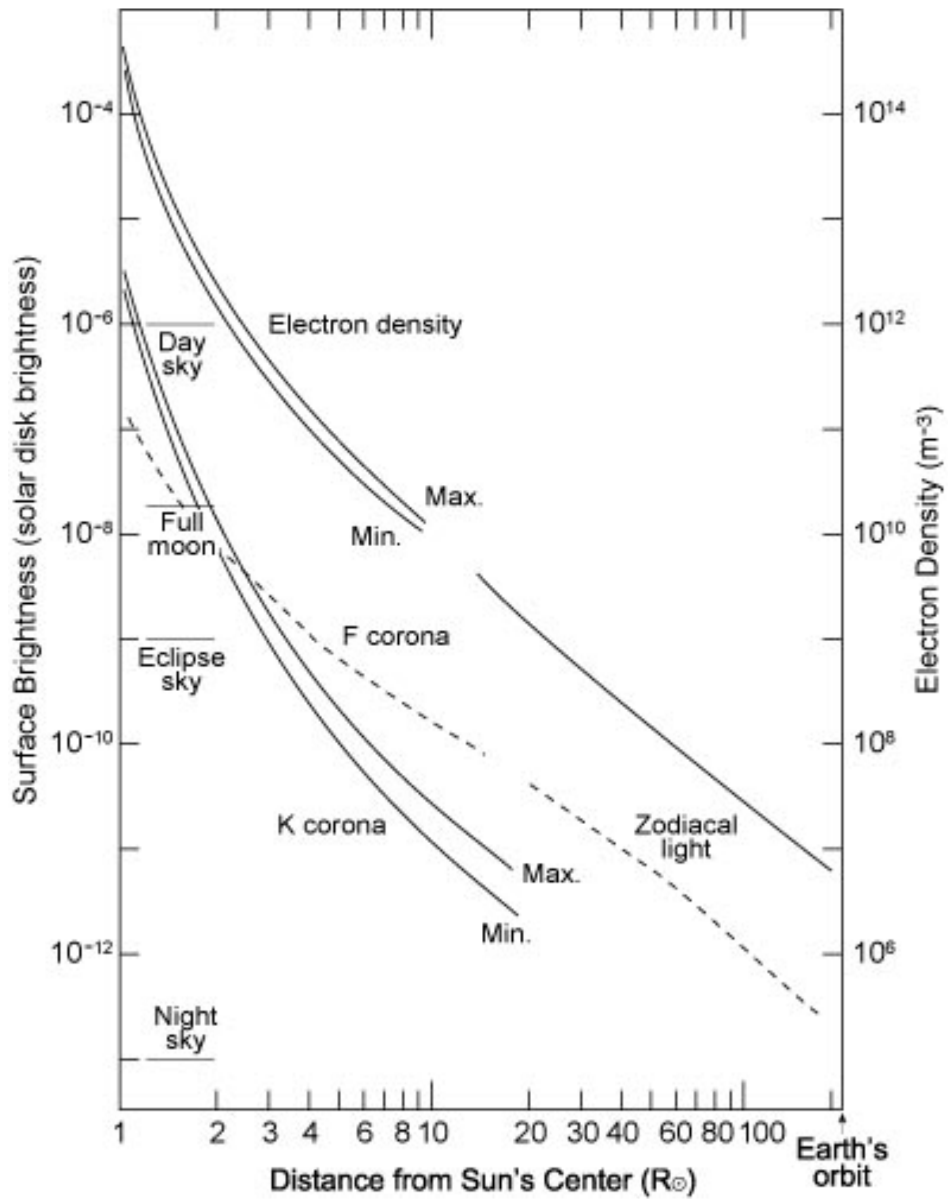


Gravity, no plasma



Gravity and plasma

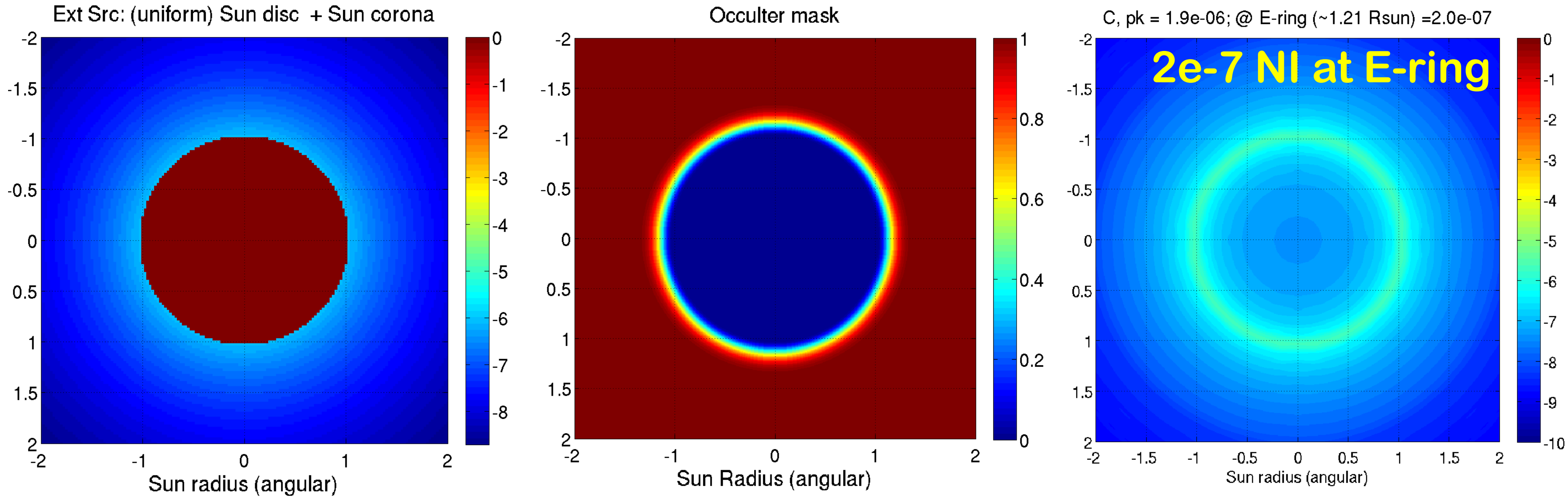
Solar corona brightness



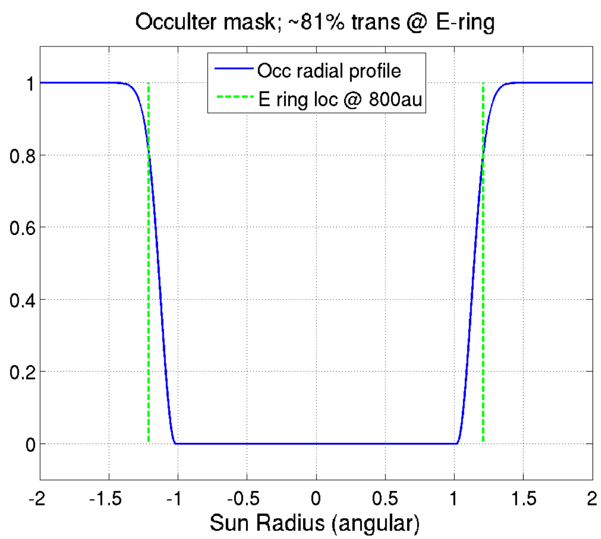
The instrumental design

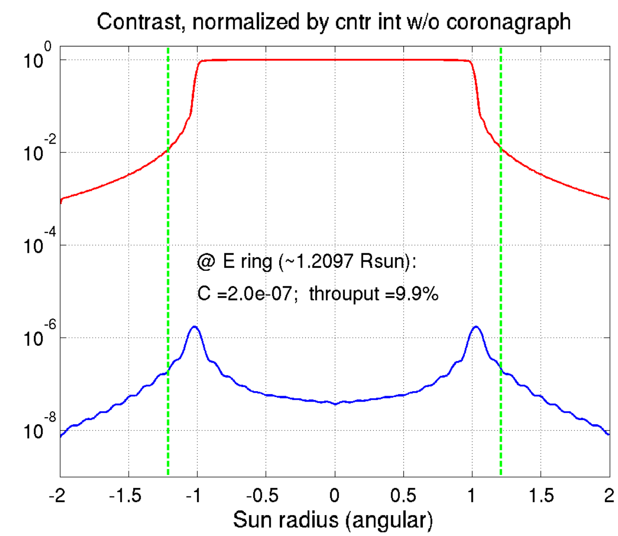
- The instrument:
  - A diffraction-limited high-resolution spectrograph, enabling Doppler imaging techniques;
- The SGLF telescope needs a coronagraph to block the Sun's light:
  - To block the solar light to the level of solar corona;
  - At 1 μm, the gain of the SGL is ~110dB (27.5 mag), so an exoplanet, which is 32.4 mag object, will become a ~4.9 mag object;
  - When averaged over a 1m telescope (the gain is $\sim 2\times 10^9$), it would be 9.2 mag, which is sufficiently bright (even on the solar background);
  - To derive an image with the SGLF, including solar corona brightness (the parent star will be resolved), zodiacal light, instrument, and s/c systematics;
- Perhaps several small spacecraft?
  - We could rely on a swarm of small spacecraft, lunched together each moving at a slightly different trajectory parallel to the optical axis.

Coronagraph study: sun disc & solar corona



- Contrast @ E-ring: 2e-7
  - w/o corona: 1.4e-7
- E-ring planet core PSF throughput: ~ 10%
  - Lyot + Occulter over +/- λ/D

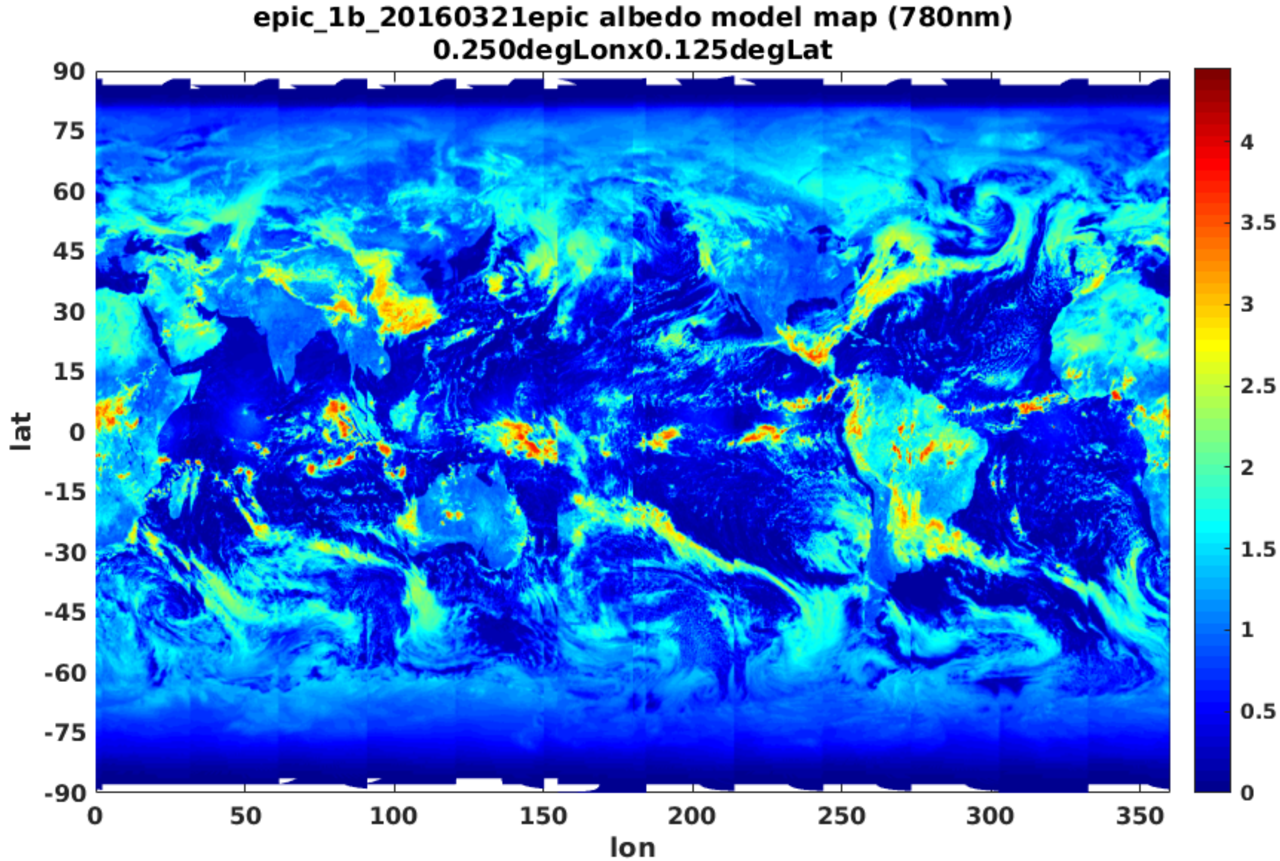




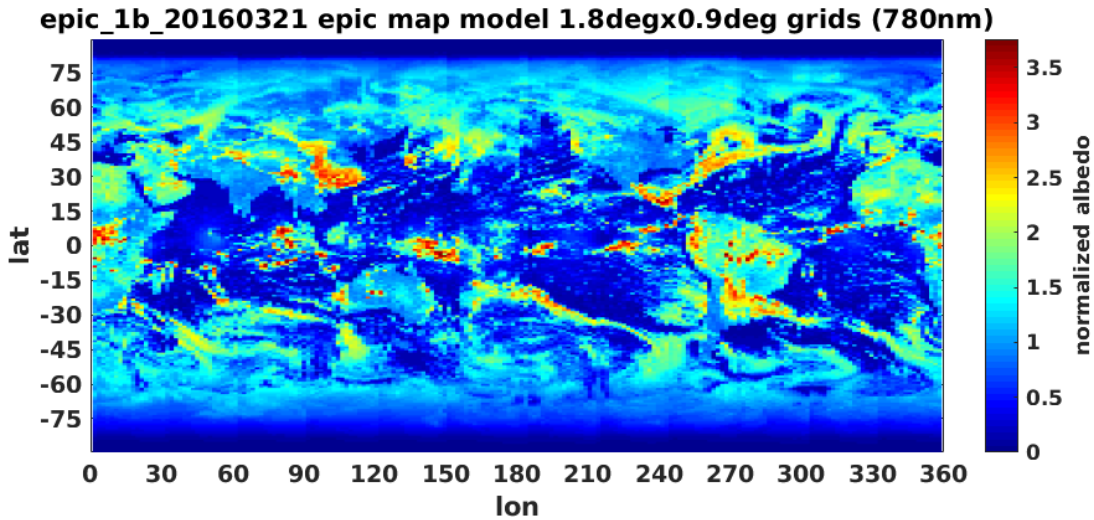
Albedo model high resolution map

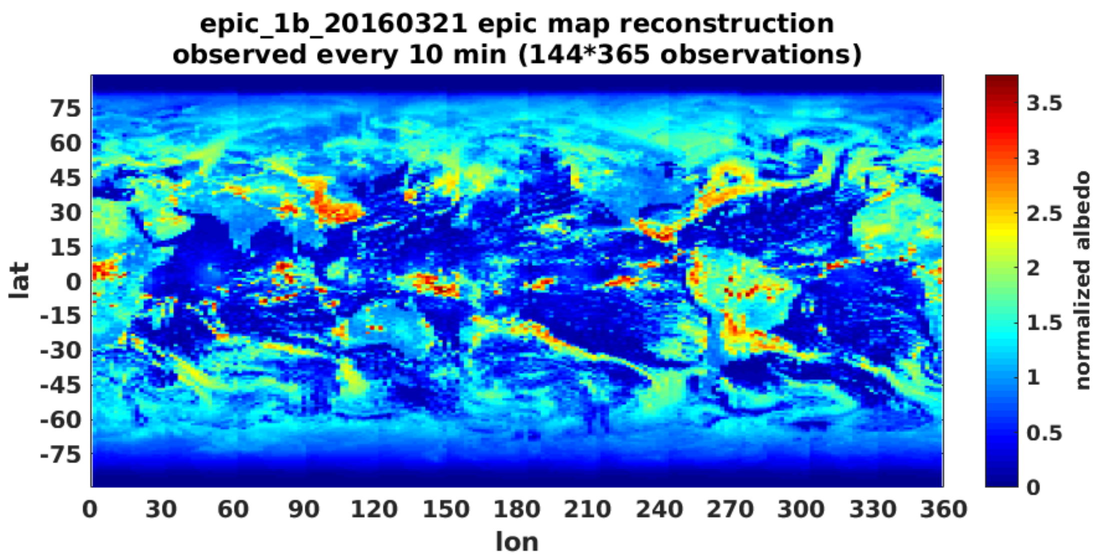
Deep Space Climate Observatory (NOAA, Feb. 11, 2015):

Earth Polychromatic Imaging Camera (EPIC)



Rotational deconvolution

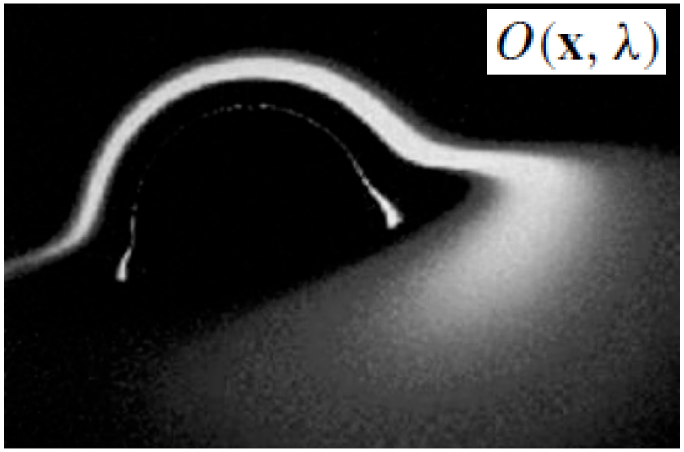




High SNR allows for

- High-resolution spectroscopy
- Allows reconstruction of a 2-D albedo map from annual variation of the disk-integrated scattered light using technique of spin-orbit tomography (i.e., rotational deconvolution)
- Next step is a direct deconvolution

Image formation by the SGL



Accretion disk around a black hole as a test object for convolution by the PSF of the SGL.

$$I(\mathbf{x}_2, \lambda) = O(\mathbf{x}, \lambda) \otimes PSF_{\rm diff}(\mathbf{x}_2, \lambda)$$

$$PSF_{\rm diff}(\mathbf{x}_2, \lambda) \simeq J_0\left(\frac{\pi|\mathbf{x}|r_0}{\lambda f}\right) \otimes \frac{r_0}{|\mathbf{x}_2|}$$

- r_0 – impact parameter,
- $|\mathbf{x}_2|$ – distance in the image plane,
- $\otimes$ – 2D convolution operator.

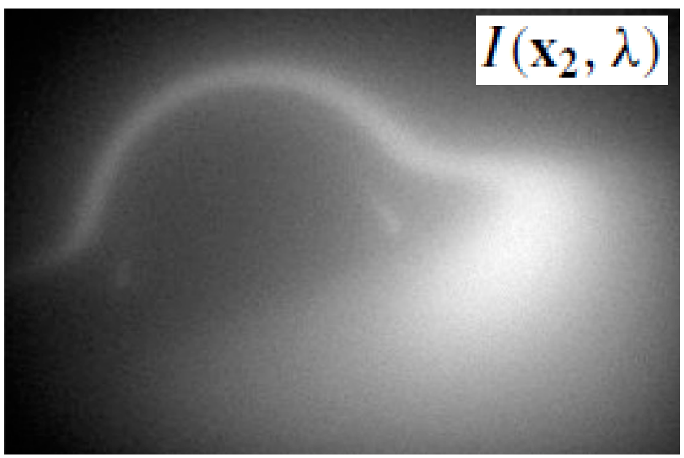
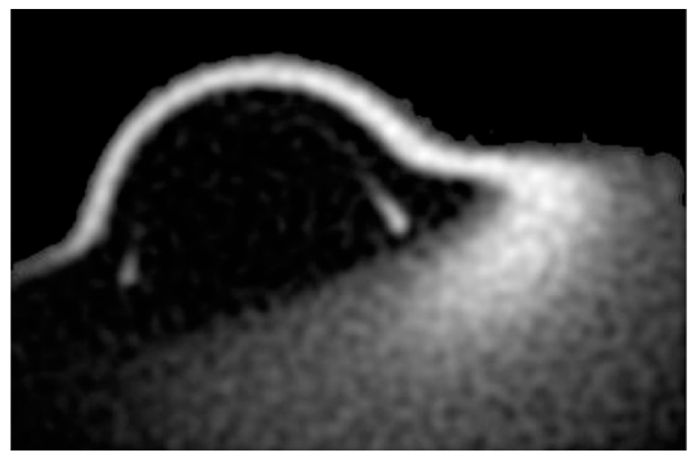


Image obtained after convolution. Photon noise is added, corresponding to 100 ph/pixel



De-convolved image using the SGL' PSF. Low-pass filtering in spatial frequencies is applied

L. Koechlin et al., Exp Astron (2005) 20:307–315

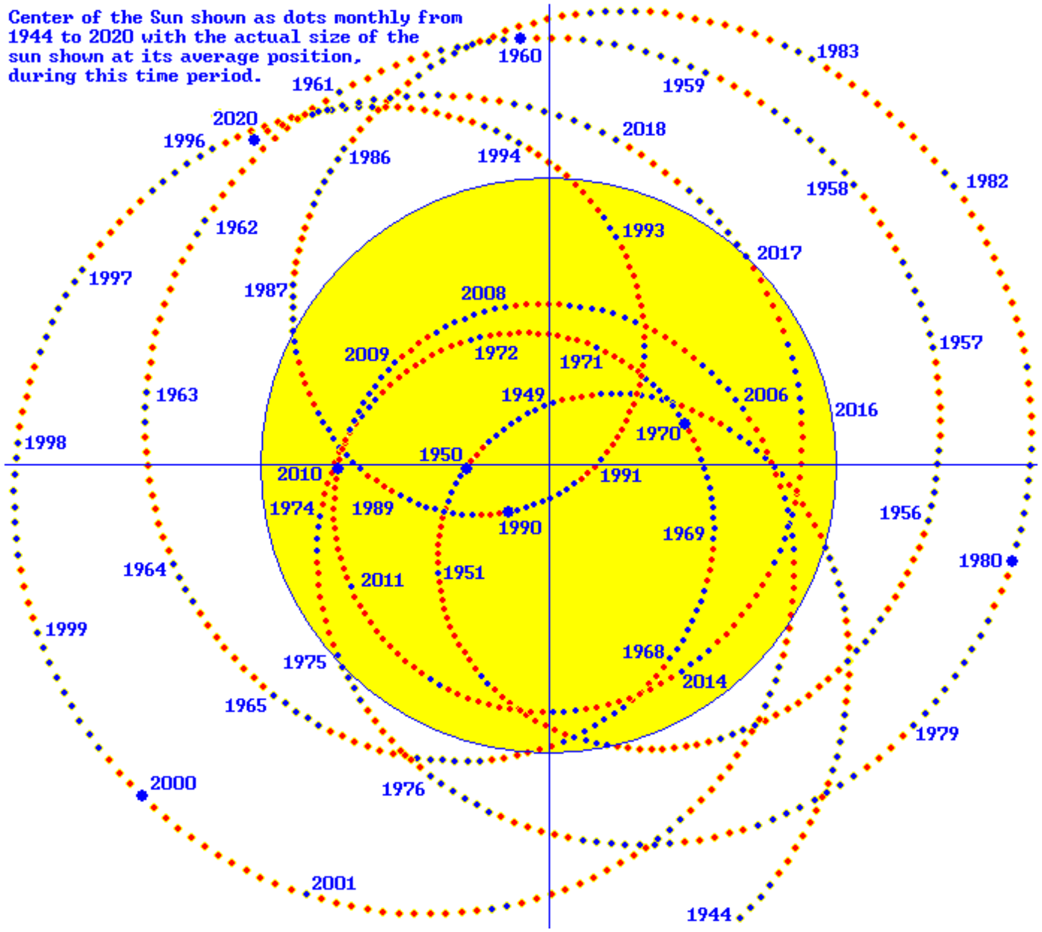
The *a priori* properties of the target

- We want to image Earth 2.0, around a G star, which is not transiting:
  - Once habitability is confirmed (“big TPF” for spectra), the next step is to image it.
- We will rely on astrometry, RV, spectroscopy, and direct imaging to obtain:
  - orbital ephemeris: to ~mas accuracy and precision;
  - rotation: from temporal monitoring of the spectroscopy;
  - atmosphere: temperature, structure, chemical composition, and albedo, from non-spatially-resolved spectroscopy;
  - understanding of cloud & surface properties from Doppler imaging.
- This information will help us to point the s/c:
  - Time to reach 550 AU ~10 years, enough to observe the parent star’s location ~100 times with 1 μas precision, so that its position would be known to 0.1 μas;
  - The parent star’s position would be known to ~45 km at a distance of 30 pc;
  - Orbital period to <1% $\Rightarrow$ the semi-major axis is known to ~0.7% (~1 million km);
  - If face-on, the radial distance to ~1 million km, with tangential error ~6 larger;
  - Earth’s diameter is 13,000 km, so we will search the (80 × 500) grid on the sky;
  - Once SGLFM detects the planet $\Rightarrow$ scan a smaller area to define the “edges”.

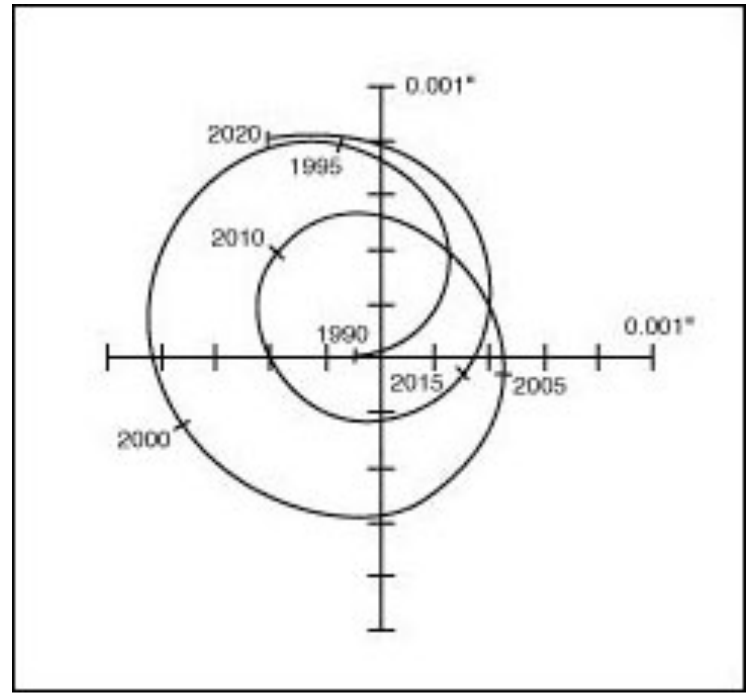
Imaging with SGL

- Imaging is done on a pixel-by-pixel basis:
  - The image of an exo-Earth occupies ~(1.3km×1.3km) area from the optical axis.
  - Each pointing corresponds to a different impact parameter: 1 image ⇔ 1 pixel.
  - Between the adjacent pixels the impact parameter changes, brings light from adjacent surface areas on the planet ⇒ a raster scan moving the spacecraft;
  - To build a ($10^3 \times 10^3$) pixels image, we would need to sample the image pixel-by-pixel, while moving in the image plane with steps of ~1 km/10^3 = 1 m:
    - Pointing: Inertial navigation and 3 laser beacon spacecraft in heliocentric orbit in the plane of the Einstein's ring (for precision pointing & comm).
  - Contamination from the parent star is negligible for an SGL scenario.
- Exoplanet imaging requires several key technologies that are challenging:
  - determination of an exoplanet astrometric orbit at ~10 nas,
  - motion & stabilization of the s/c over millions of pointings with limited power.
- Perhaps even spectroscopy or even spectro-polarimetry of the exoplanet?
  - Potentially a spectrally resolved image over a broad range of wavelengths: atmosphere, surface material characterization, biological processes.

The solar wobble



Center of the Sun shown as dots monthly from 1944 to 2020 with actual size of the sun shown at its average position, during this time period



Astrometric displacement of the Sun due to Jupiter as at it would be observed from 10 parsecs, or about 33 light-years.

Trajectories (Measure vs Control)

- Pointing precision (between three objects):
  - Needs to be maintained to ~ few μas for proper operation of the SGL.
  - Knowledge is needed at 1 μas level, control is at the ~100 μas.
  - The motion is unfortunately complex (1-m of motion at 600 AU ~ 1 μas of angle seen from Earth)
- Simple motions (straight lines):
  - Motion of the target star around the galaxy; the Sun around the galaxy
- More complex motions:
  - Motion of the exoplanet around its host star (Keplerian)
  - Motion of our Sun around the solar system barycenter.
    - Dominated by the orbits of Jupiter, Saturn.
    - Jupiter ⇒ 75 million m motion of the Sun (12yr orbit)
    - Saturn ⇒ 50 million m of motion of the Sun (29 yr)
    - Earth ⇒ 450,000 m (1 yr)
- Propulsion system must compensate for the reflex motion of the Sun
  - Due to most of the planets in the solar system. (perhaps many of the big asteroids in the main belt) Uranus and Neptune’s motion over a short time may be just a straight line (need to calculate for sure).

Direct Multipixel Imaging and Spectroscopy of an Exoplanet with a Solar Gravity Lens Focus (SGLF) Mission

An imaging mission to SGLF appears to be feasible, but needs further study

Concept

- SGLF provides a major gain (~10^{11} at 1um), resolution of 10^{-9} arcsec in a narrow FOV;
- A 1-m telescope at ~750AU has a collecting area equivalent ~80 km aperture in space;
- A mission to the SGLF could image Earth 2.0 up to 30pc away with resolution to ~10km to see surface features;
- A small s/c with electric propulsion (or solar sails) can reach the SGLF in <35-40 yrs.

Proposed Study and Approach

- Define baseline design, sub-syst components;
- Define mission science goals & requirements;
- Develop system and subsystem requirements;
- Study mission architecture and con-ops;
- Assessment of feasibility (cluster) small-sats;
- Identify technology development needs;
- Study instruments & systems: power, comm, pointing, s/c, autonomy, coronagraph, nav, propulsion, raster scan in the image plane, etc.

Benefits

- A breakthrough mission concept to resolve a habitable exoplanet at modest cost/time;
- Could find seasonal changes, oceans, continents, life signatures on an exo-Earth;
- Small-sat & fast exit from the solar system;
- Electric propulsion for raster-scanning the image using tethered s/c (or cluster);
- SLGF is valuable for other astrophysics and cosmology targets.

Earth with resolution of (1000 × 1000) pixels.

Comments on NLAC Phase II proposal (March 2018):

The concept continues to demonstrate unexplored and exciting aspects of value to investigate over the Phase I study. Analysis completed in Phase I is credible. However, unknowns remain that are not readily determined, thereby warranting further study.

If successful, the concept will enable wholly new missions, offer a significant advantage to previously studied work, or provide a great leap in capabilities for NASA or the greater aerospace community. Based on results from the Phase I study, the concept continues to generate enthusiasm for a mission and potential to build advocacy to support it within NASA or in the greater aerospace community.