A talk the Marshall Space Flight Center
August 14, 2018

Magnifying Light by 100 Billion Times with the Solar Gravitational Lens for Direct Imaging of an Exoplanet

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Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

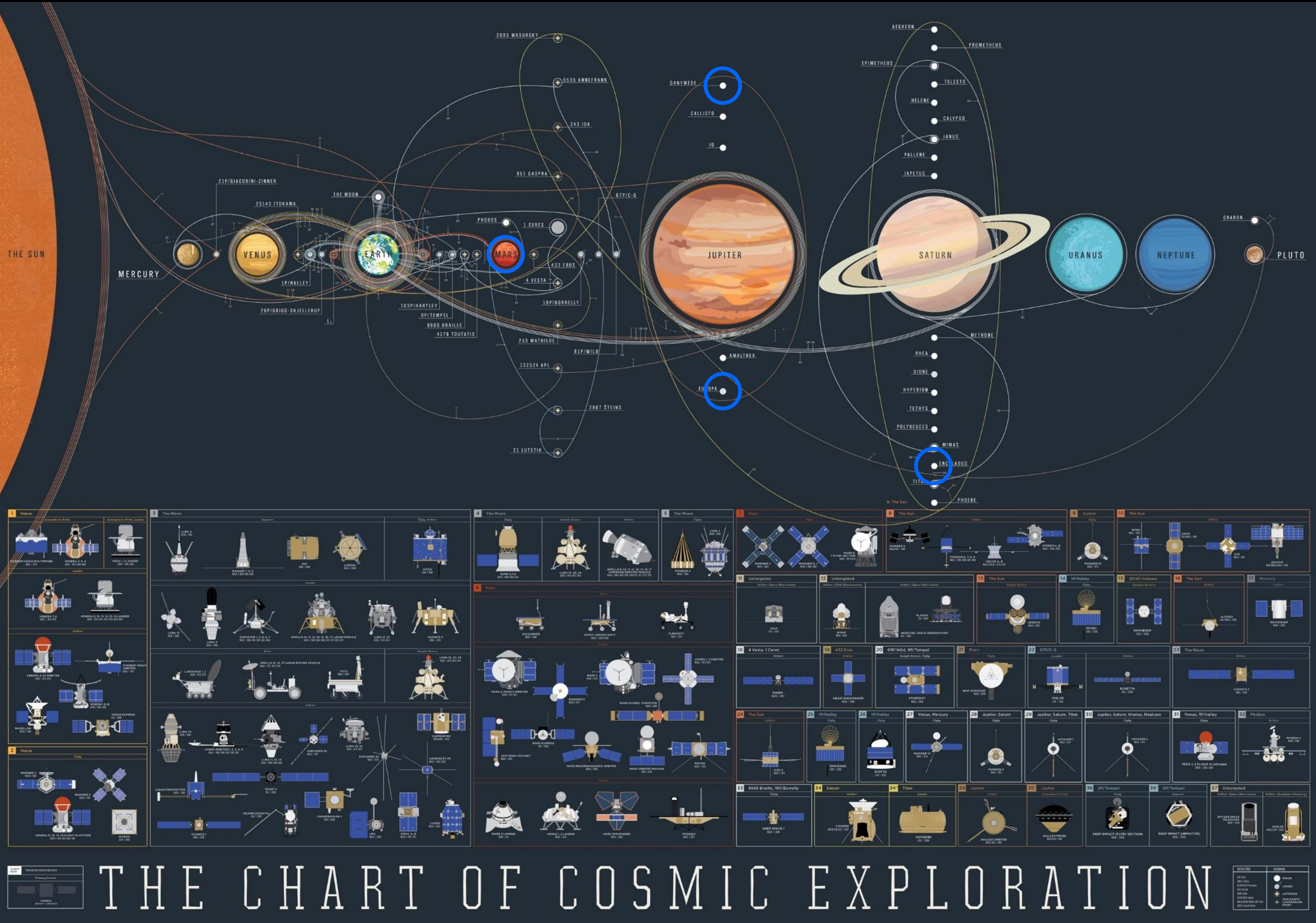
Presentation Presented to HAL5 on August. 14, 2018

… because we are all kids at heart…

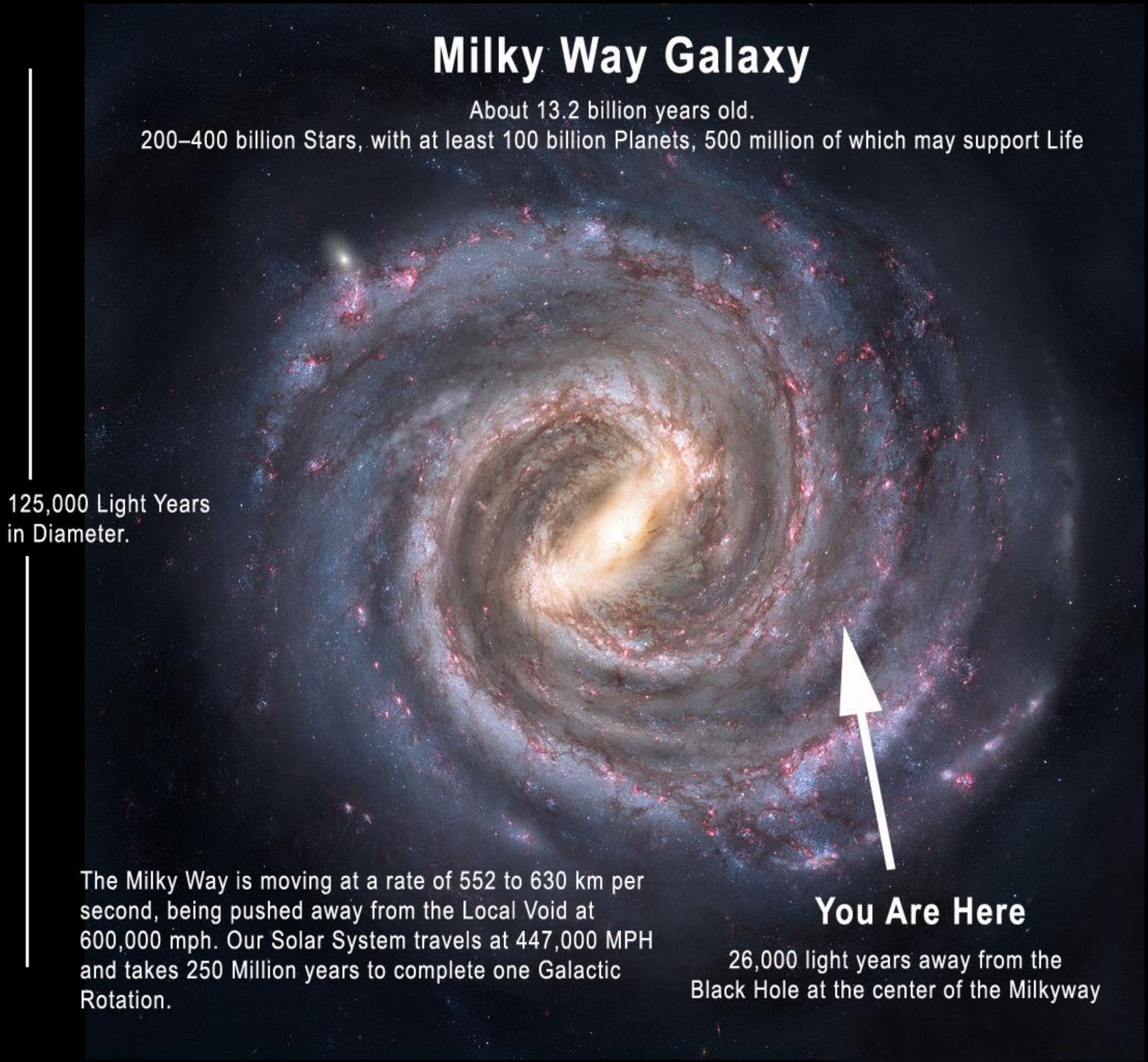
A nice family portrait…

"The Earth is the cradle of humanity, but mankind cannot stay in the cradle forever."
Konstantin Tsiolkovsky

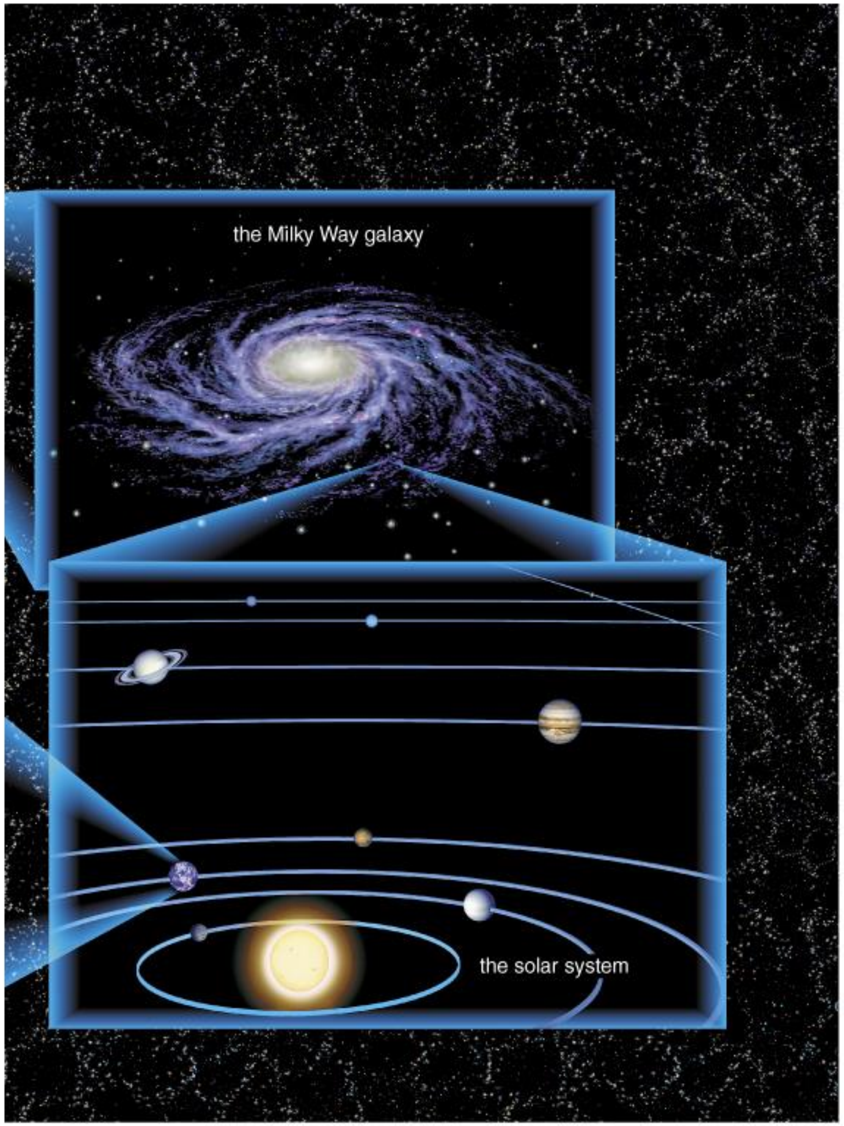
But…, is there anybody out there?



www.popchartlab.com


Milky Way Galaxy
About 13.2 billion years old.
200–400 billion Stars, with at least 100 billion Planets, 500 million of which may support Life
125,000 Light Years
in Diameter.
The Milky Way is moving at a rate of 552 to 630 km per second, being pushed away from the Local Void at 600,000 mph. Our Solar System travels at 447,000 MPH and takes 250 Million years to complete one Galactic Rotation.
You Are Here
26,000 light years away from the
Black Hole at the center of the Milkyway

Solar system is not alone!



Current estimates:

- ~50% of stars have planets;
- ~100 billion stars in our Galaxy, and 1-10 planets per star;
- 50 billion to 5 trillion planets in our Galaxy (alone);
- There are ~10 new stars forming each year in our Galaxy…
- ~5 new planetary systems/year…
- ~5-50 new planets/year.

Exoplanet census (Aug 2018):

- 3,725 – confirmed;
- 4,496 – candidates;
- 2,778 – solar systems;
- 929 – terrestrial.

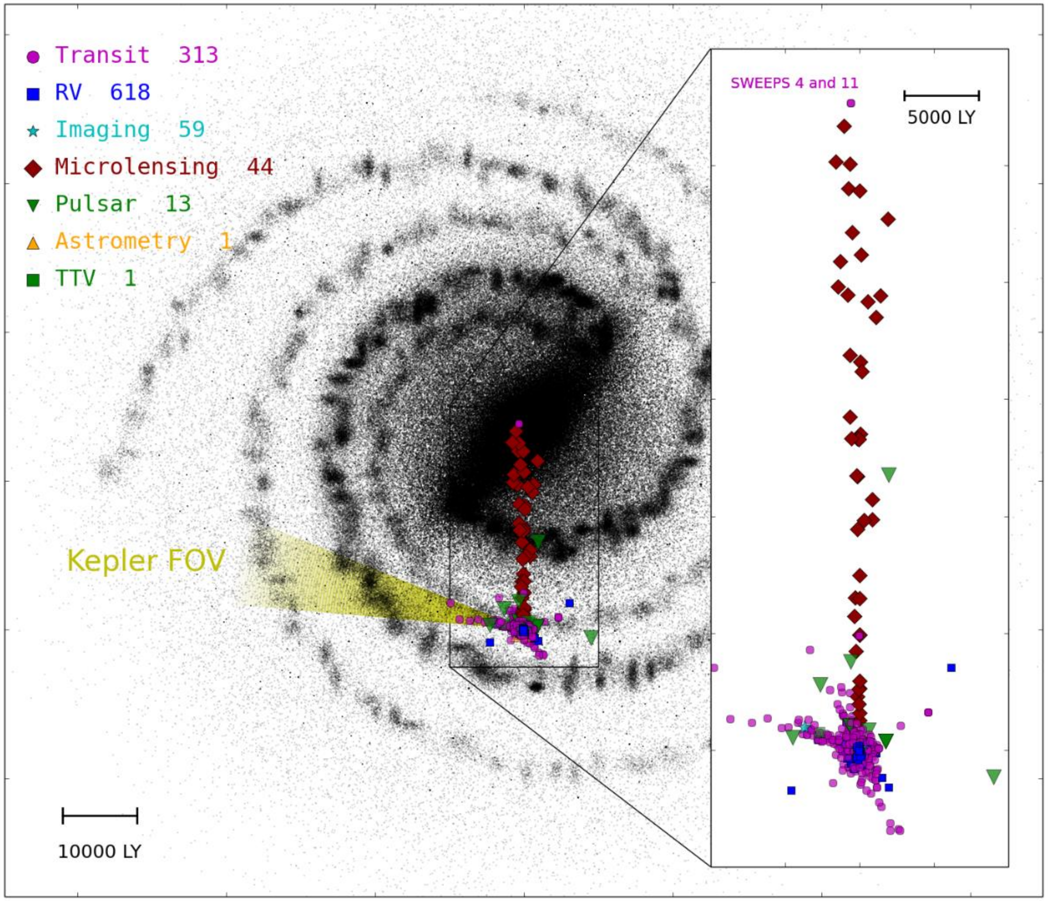
Finding Earth 2.0 is matter of time...

– but what will we do once we find it?

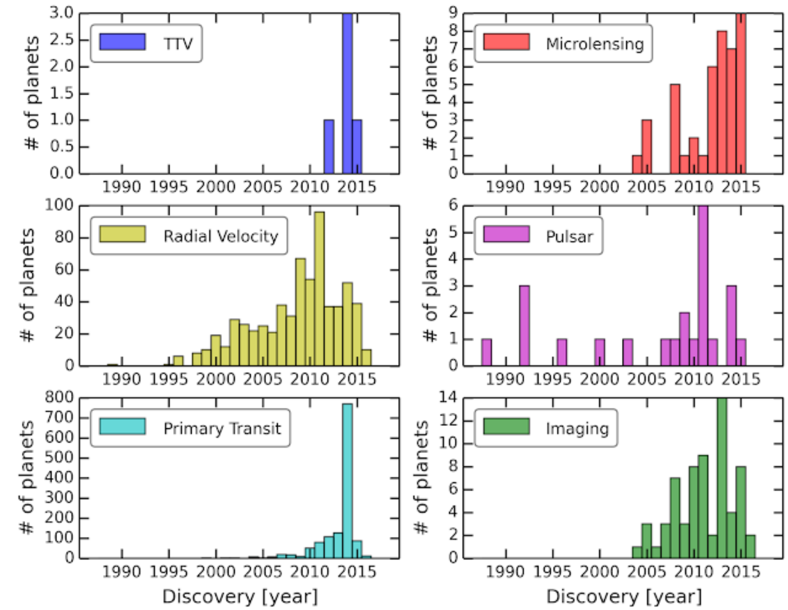
https://exoplanets.nasa.gov/

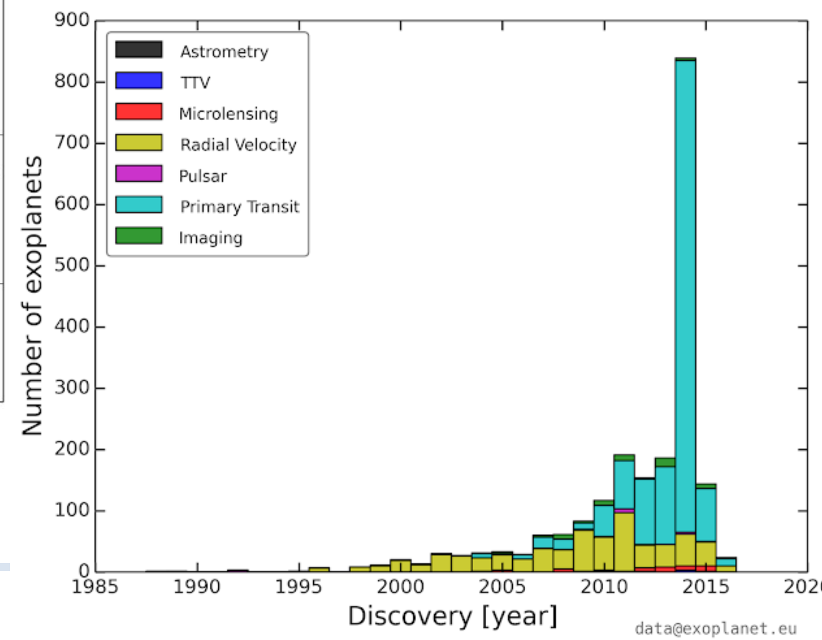
Exoplanet discoveries

Multiple techniques used to detect the presence of a planet

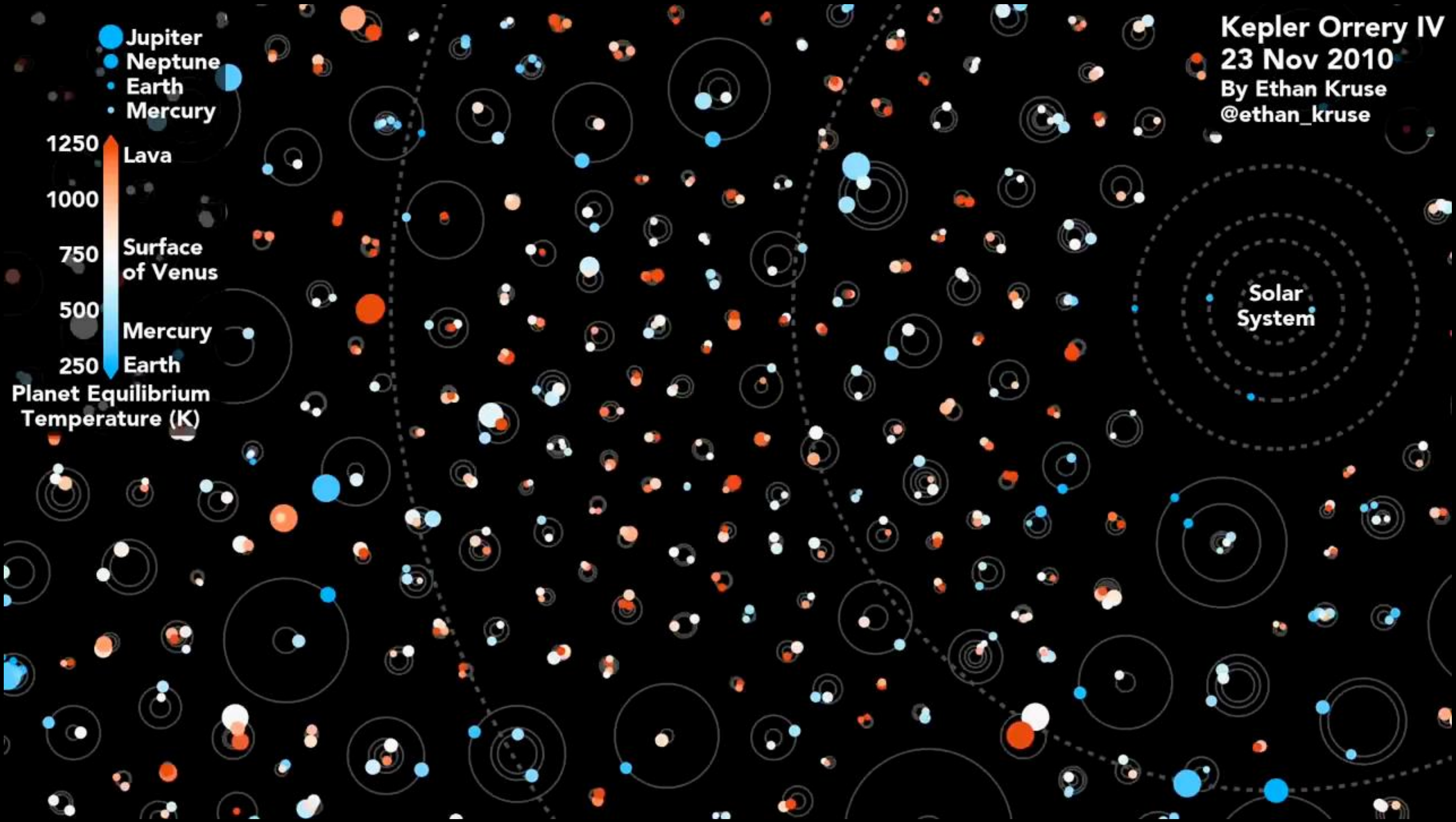


Exoplanet astronomy is poised for a major growth with detection of millions of exo-planets expected

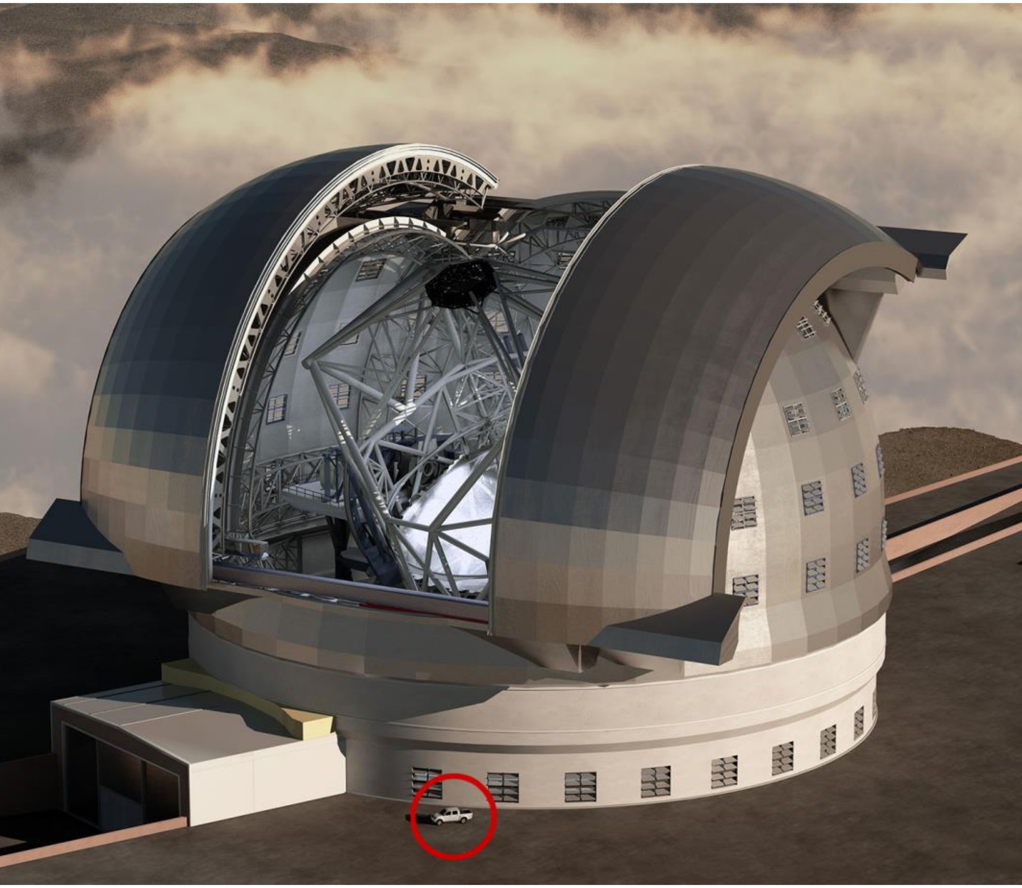


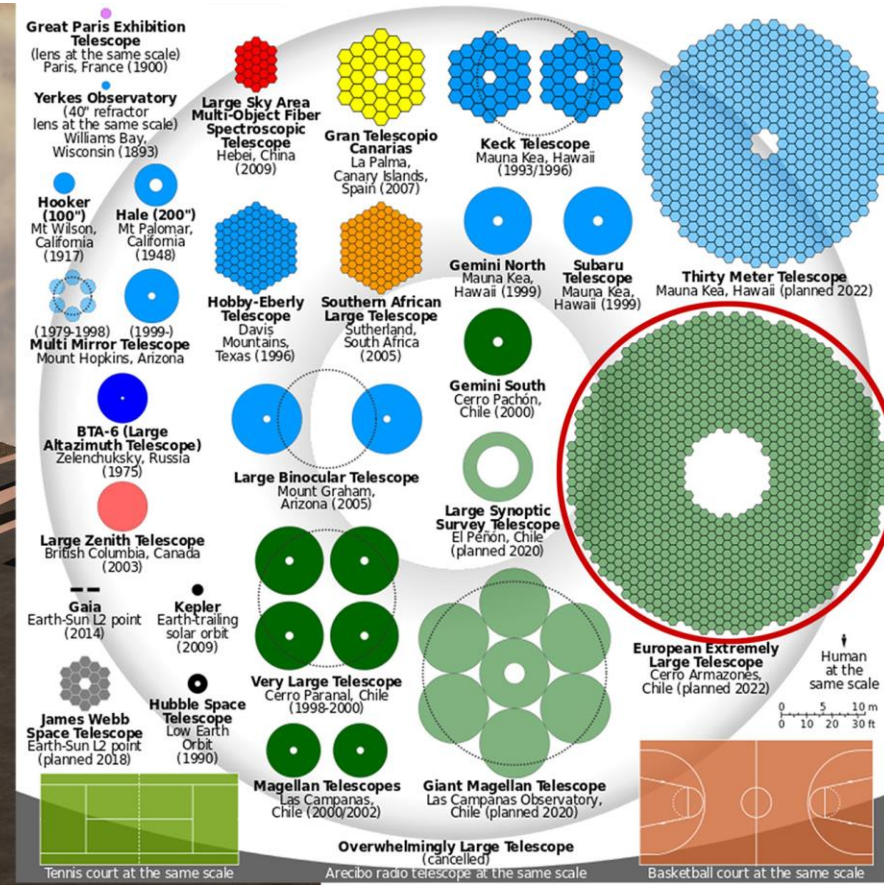


The Kepler planets



Largest telescopes to date…

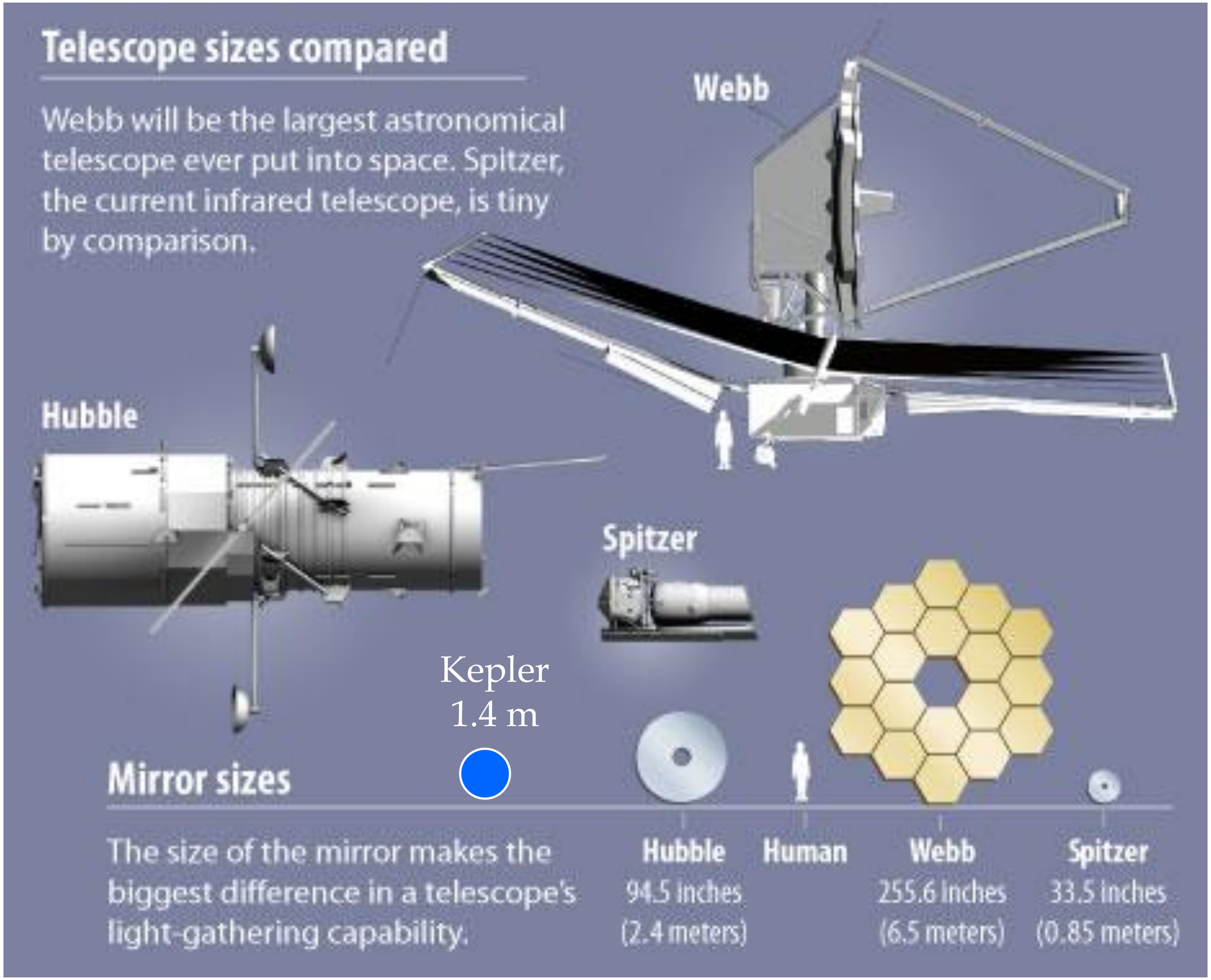


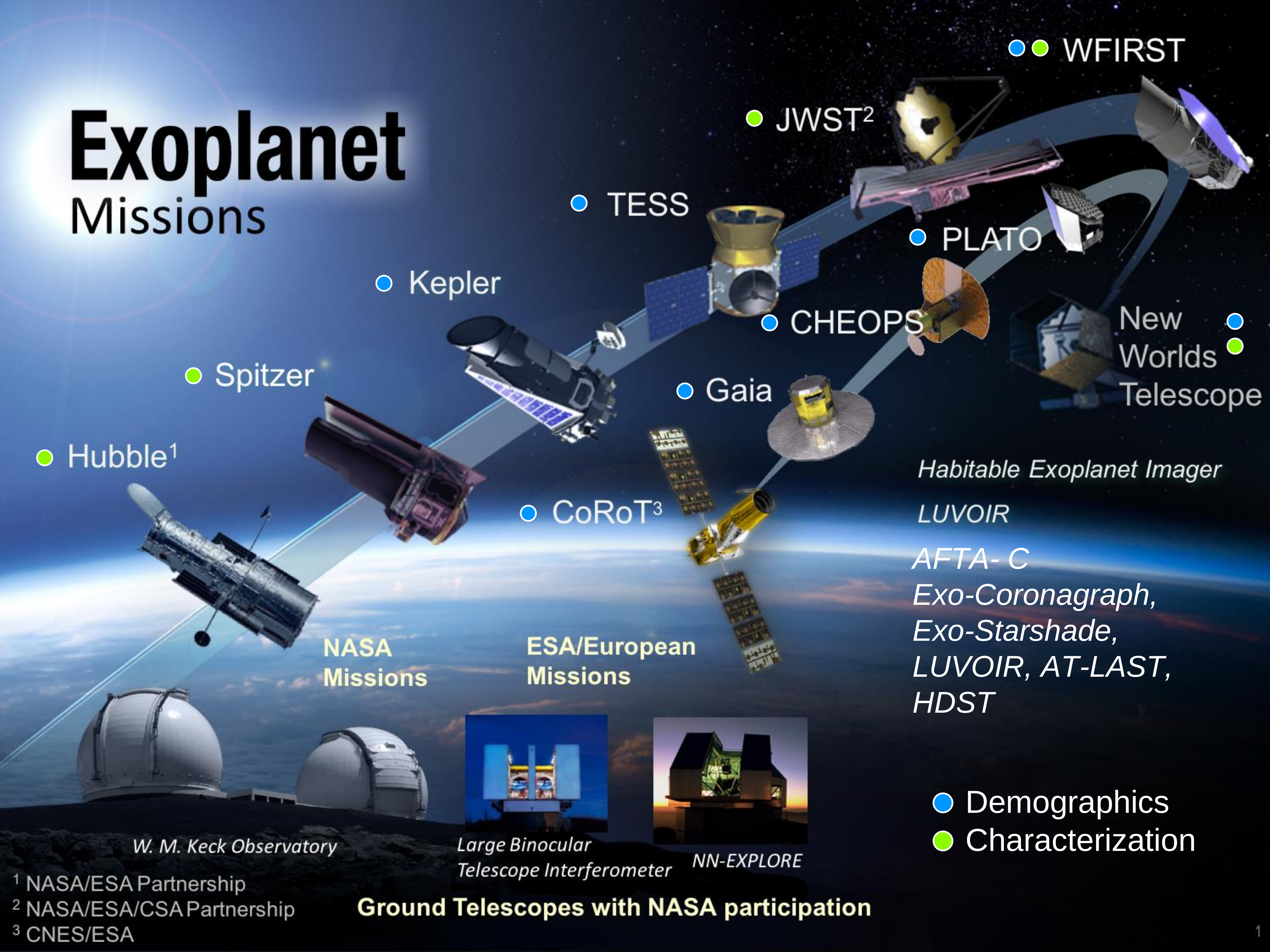


European Extremely Large Telescope
39 meters, Chile (est. 2022)

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

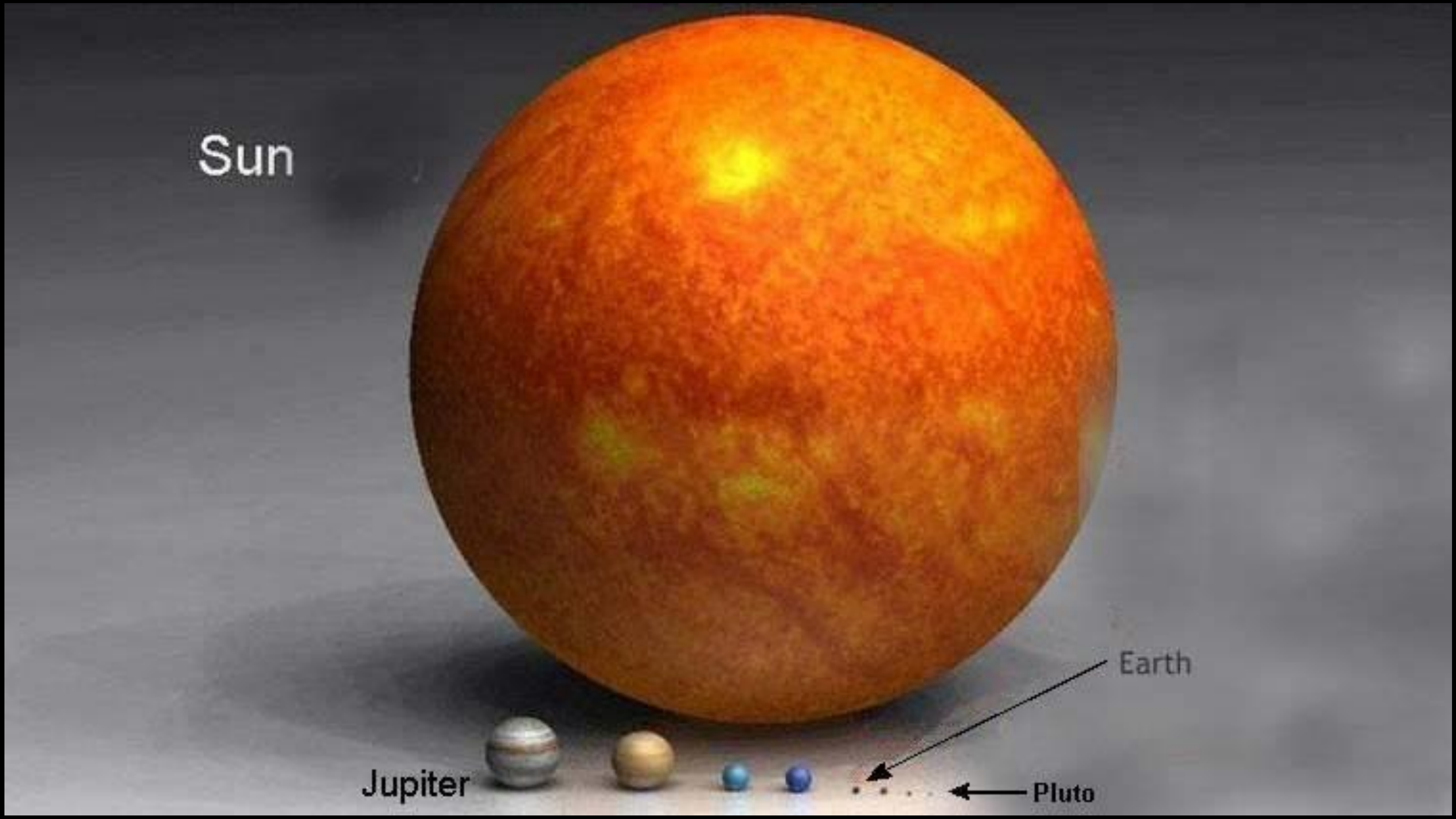
Largest telescopes in space





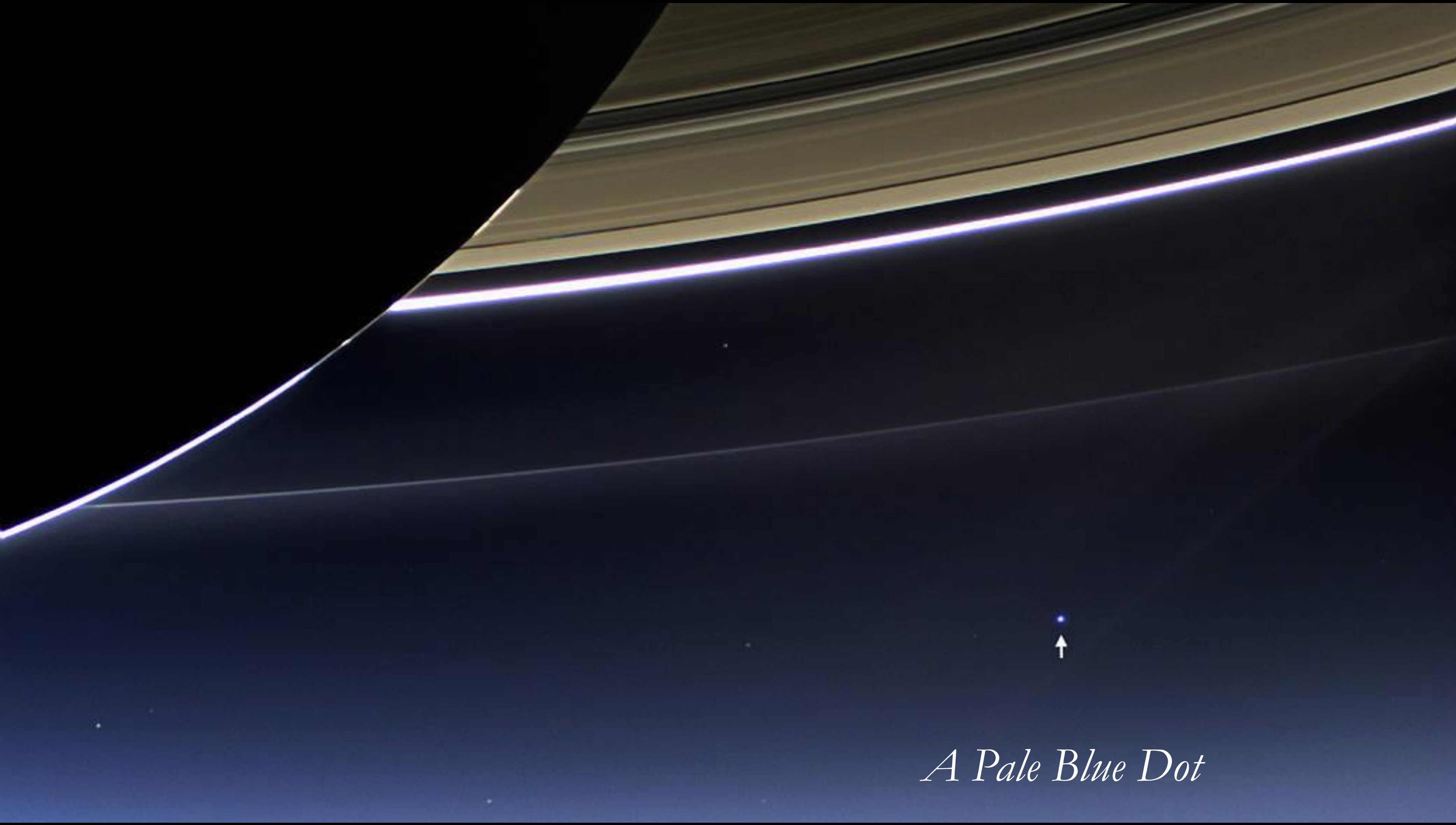
Exoplanet
Missions
WFIRST
JWST[2]
TESS
PLATO
Kepler
CHEOPS
New
Worlds
Telescope
Spitzer
Gaia
Hubble[1]
Habitable Exoplanet Imager
LUVOIR
CoRoT[3]
AFTA- C
Exo-Coronagraph,
Exo-Starshade,
LUVOIR, AT-LAST,
HDST
NASA
Missions
ESA/European
Missions
Demographics
Characterization
W. M. Keck Observatory
Large Binocular
Telescope Interferometer
NN-EXPLORE
[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
Ground Telescopes with NASA participation
1

The size does matter…

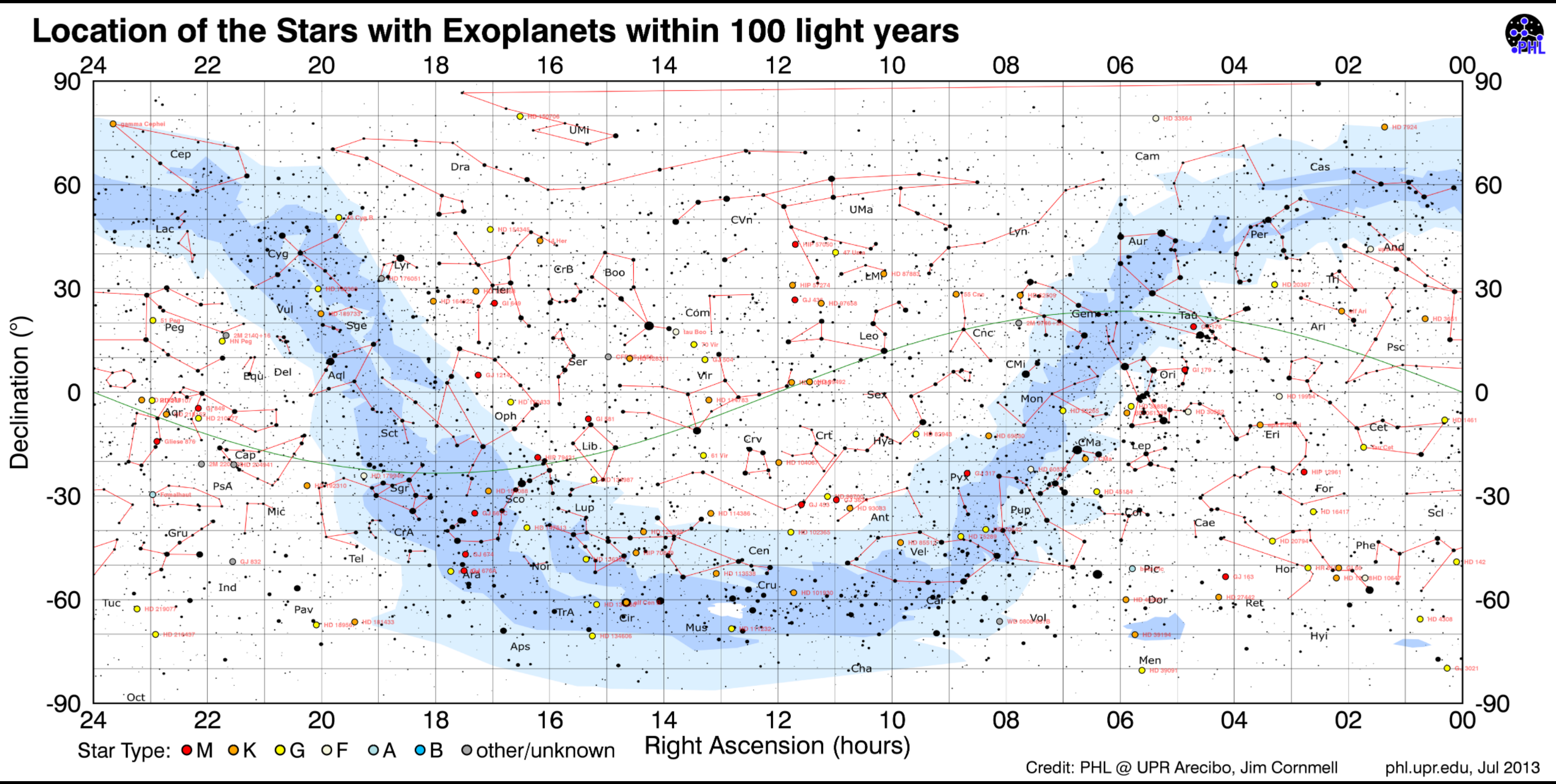


…and so does the distance: *the tyranny of the diffraction limit…*

Our Challenge

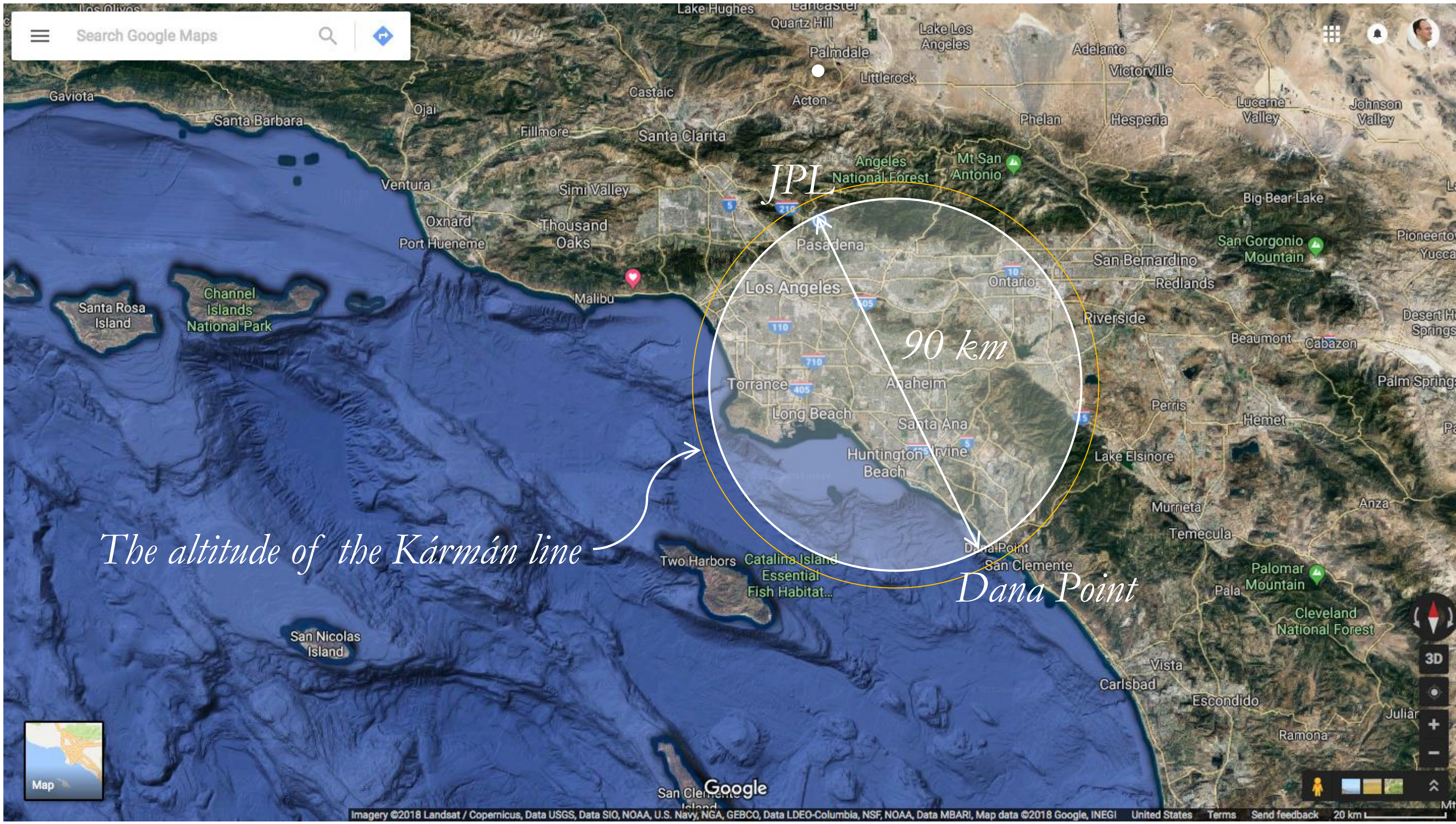


Our Stellar Neighborhood within 100 ly



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, one needs a telescope with a diameter of ~90 km…



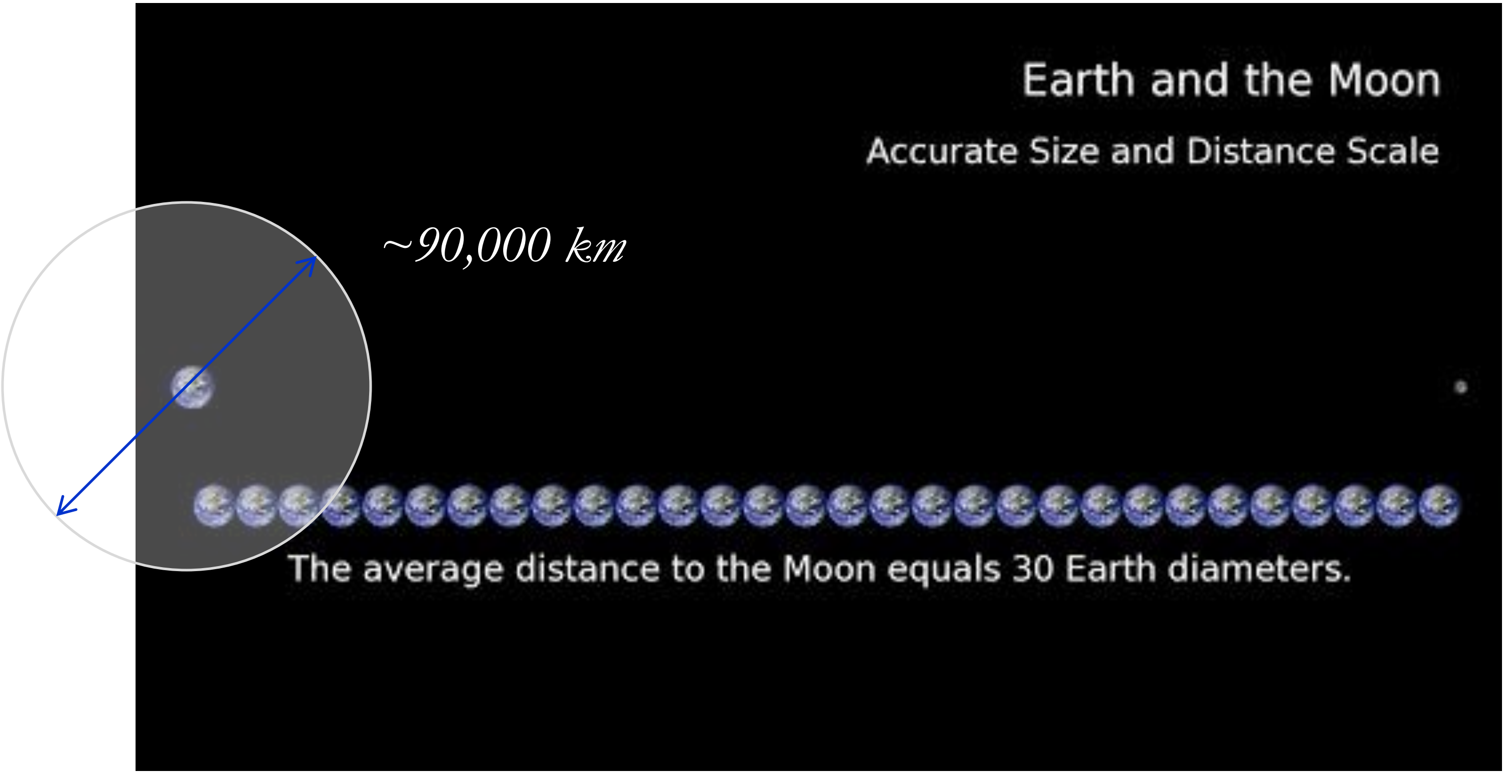
A (10k×10k)-pixels image of our Earth

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

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

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

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-

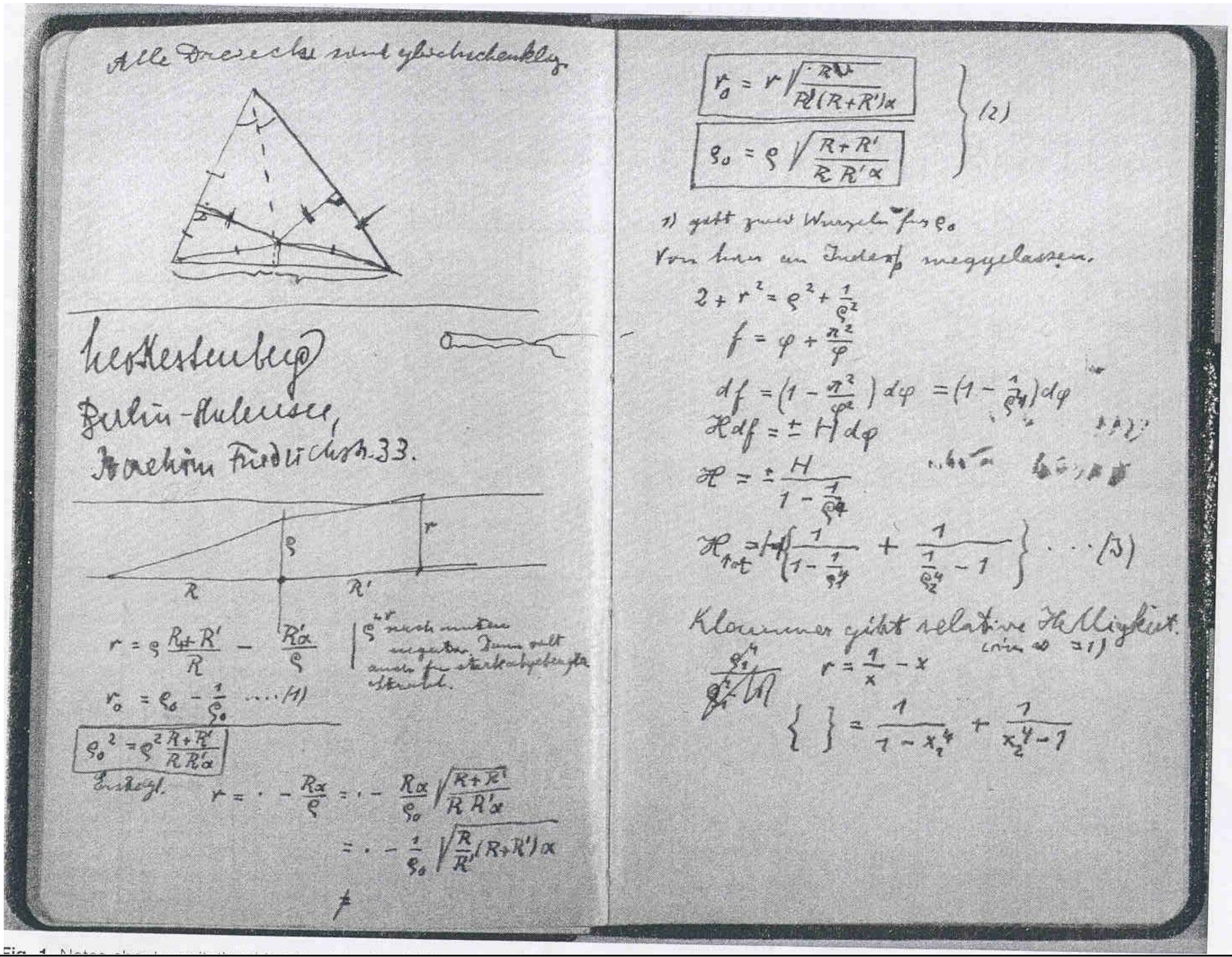
Optical wavelengths magnification
~10^{11}

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)

Original gravity lens derivation (Einstein c.1911)



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

Gravitational deflection of light before GR

$$\alpha_{\texttt{Newton}}(b) = \frac{2GM_\odot}{c^2 b} = 0.877\left(\frac{R_\odot}{b}\right)\ \mathrm{arcsec}$$

Zürich. 14.X.13.

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 $\frac{1}{R}$ abnehmen (R = ~~Sonnenradius~~ Entfernung vom Sonnen-Mittelpunkt).

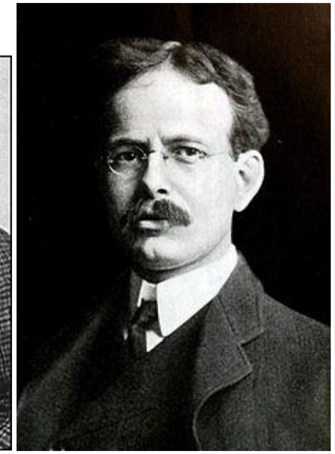
0,84"

Sonne

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

The Huntington Library, Pasadena, CA

Albert Einstein
c.1913

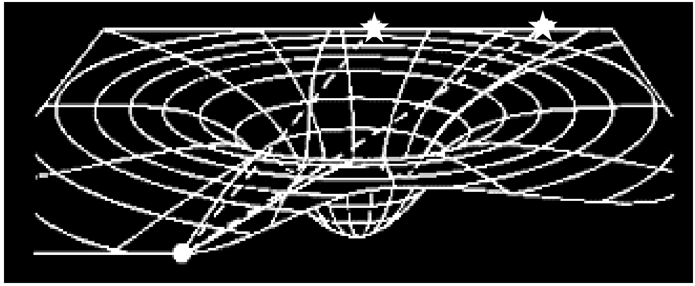


George Ellery Hale
(1868-1938)

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

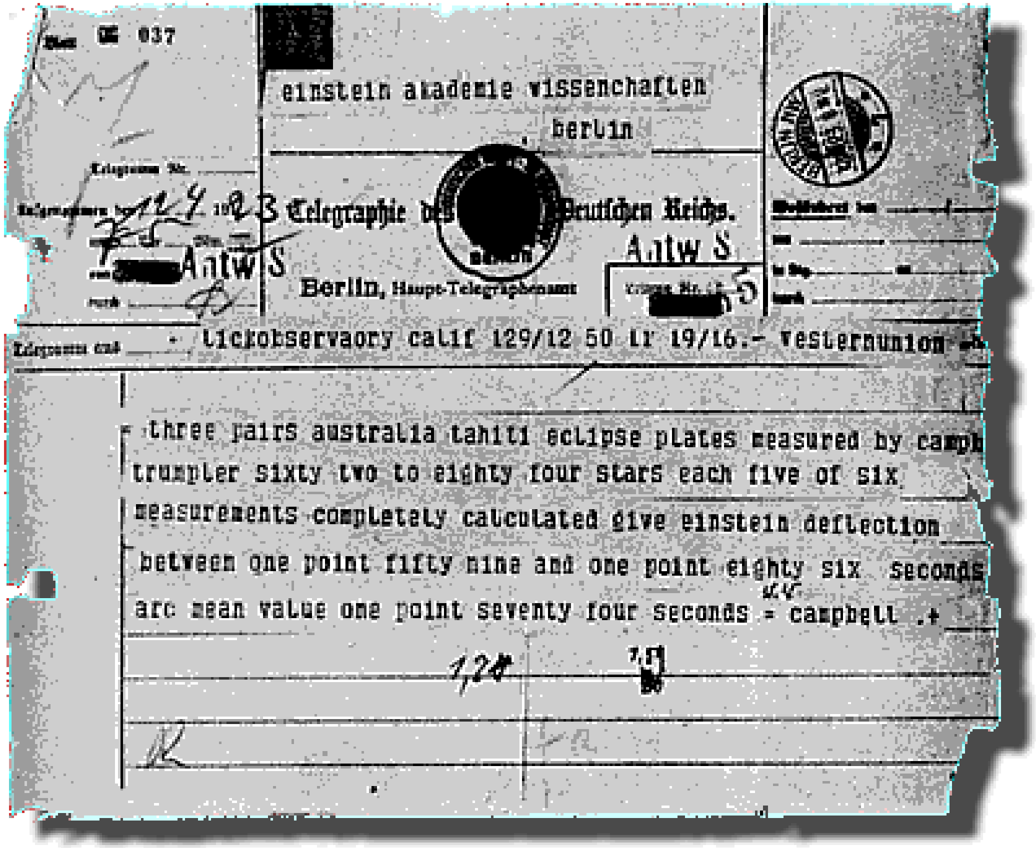


Gravitational Deflection of Light:

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

Solar Eclipse 1919: possible outcomes

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



einstein akademie wissenchaften
berlin

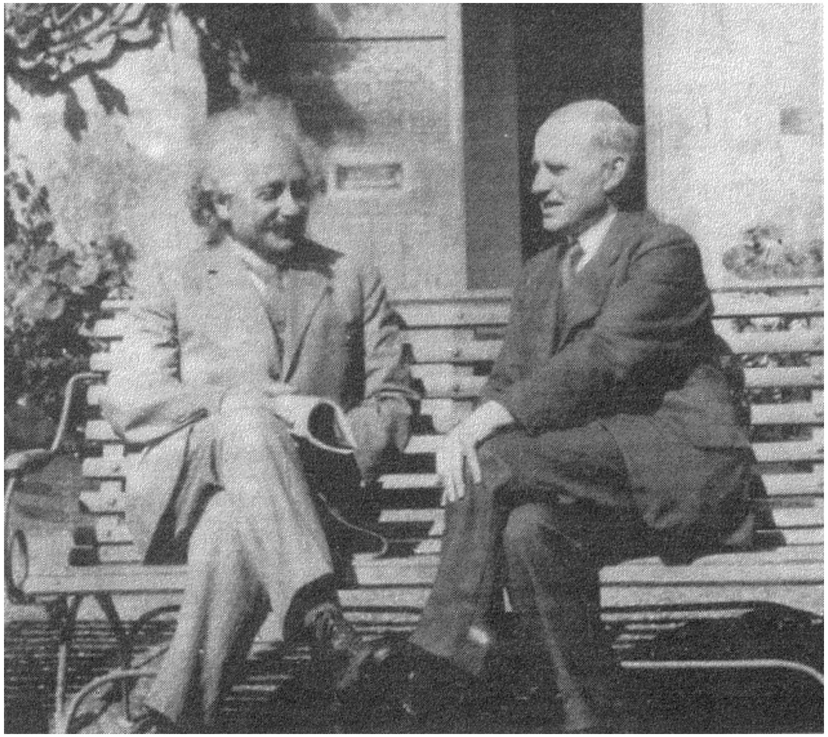
Telegraphie des Deutschen Reichs.

Berlin, Haupt-Telegraphenamt

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

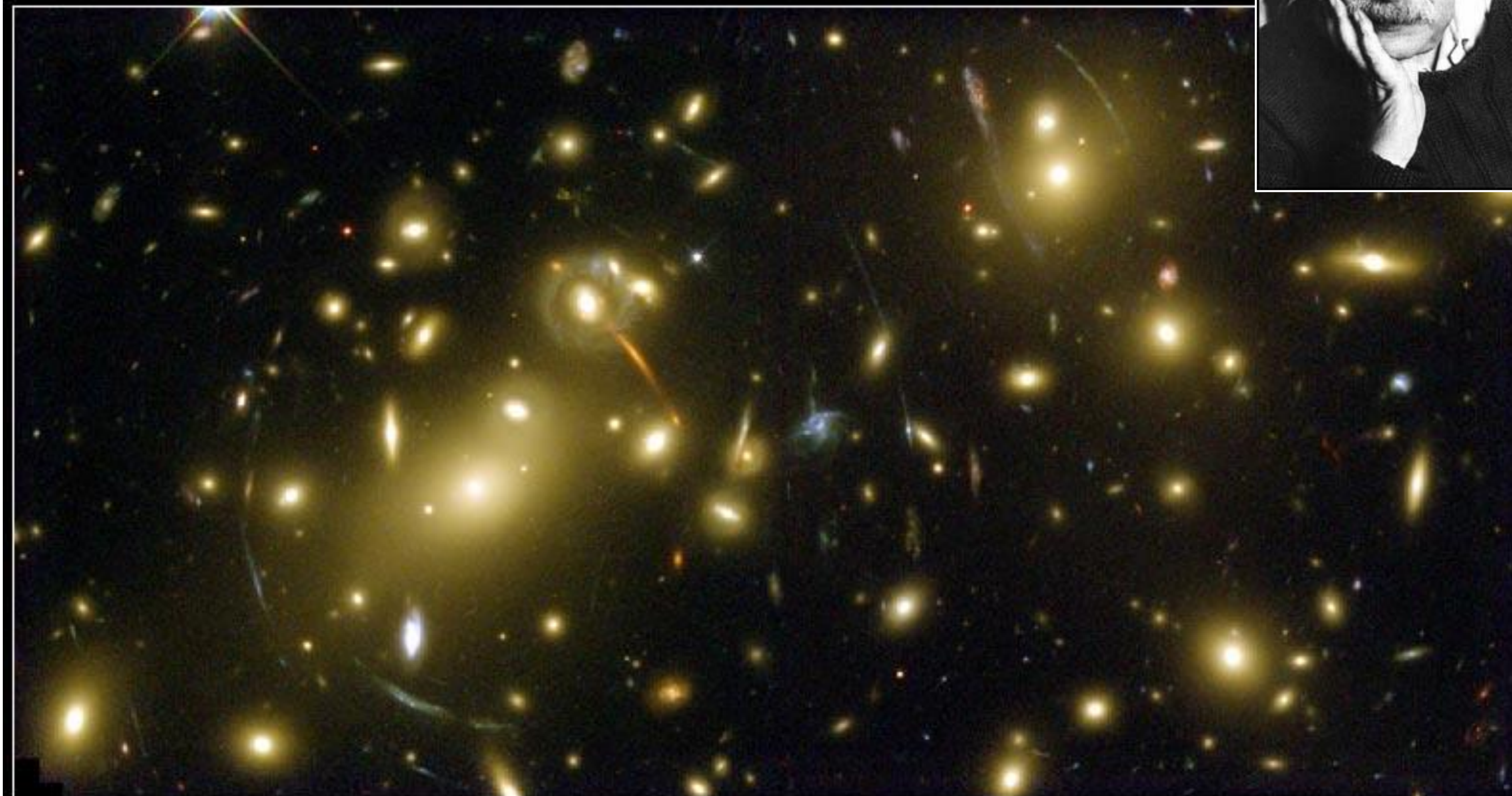
three pairs australia tahiti eclipse plates measured by campb
trumpler sixty two to eighty four stars each five of six
measurements completely calculated give einstein deflection
between one point fifty nine and one point eighty six seconds
arc mean value one point seventy four seconds = campbell .+

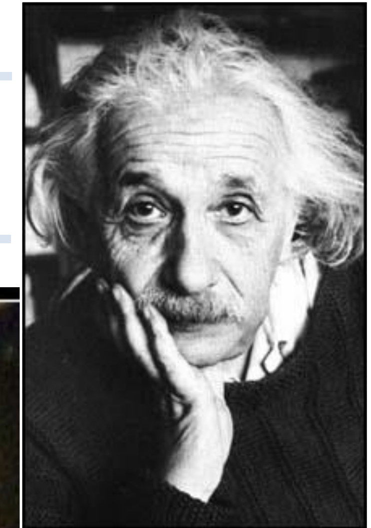
Campbell's telegram to Einstein, 1923



Einstein and Eddington, Cambridge, 1930

Gravitational Deflection of Light is a Well-Known Effect Today

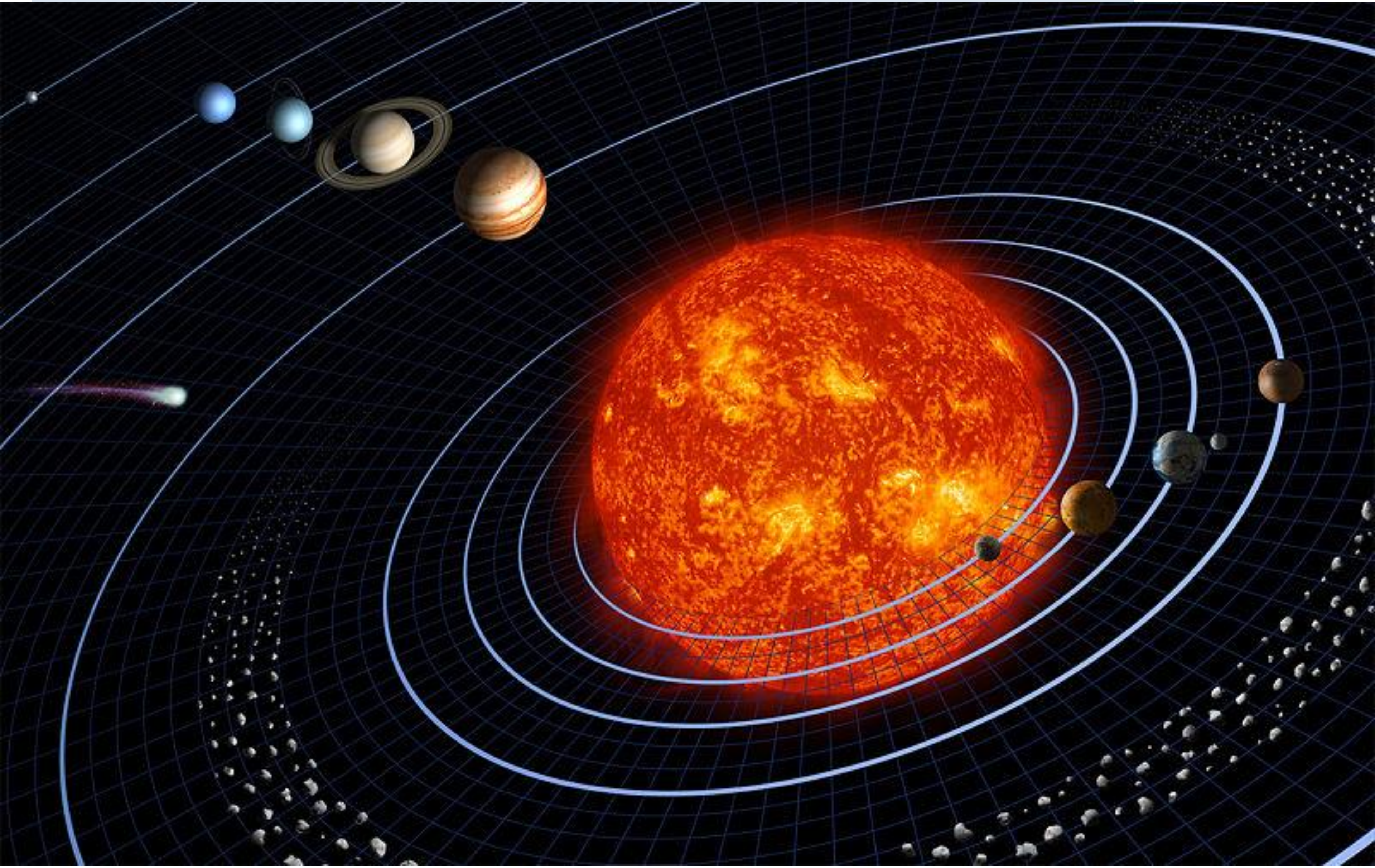




Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Our solar system and tests of gravity



40+ Years of Solar System Gravity Tests

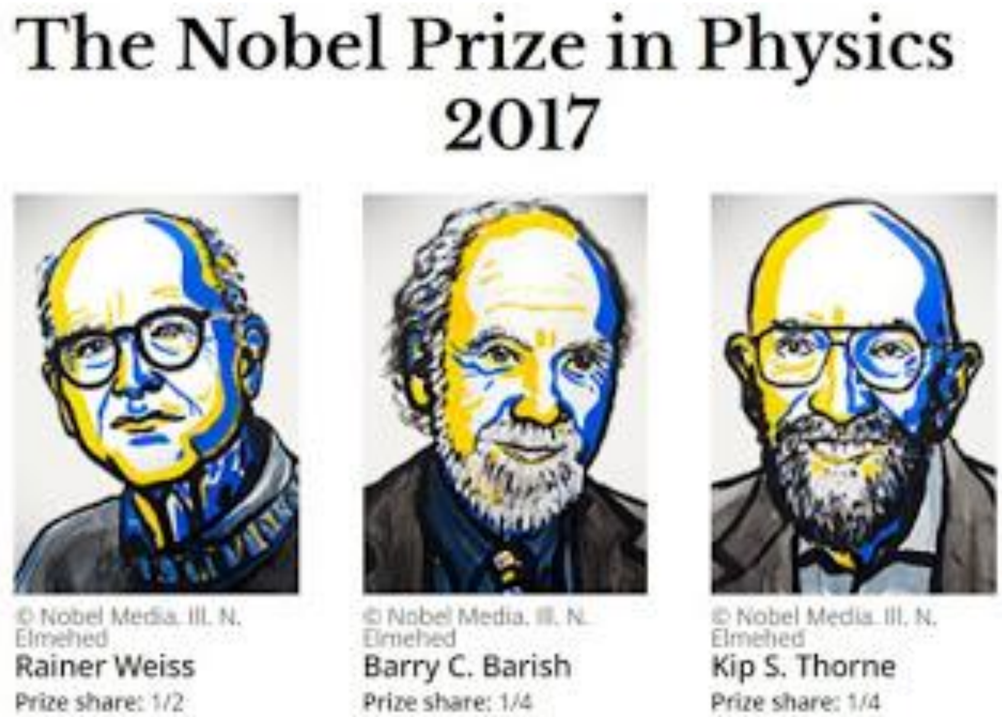
Techniques for Gravity Tests:

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+(?)



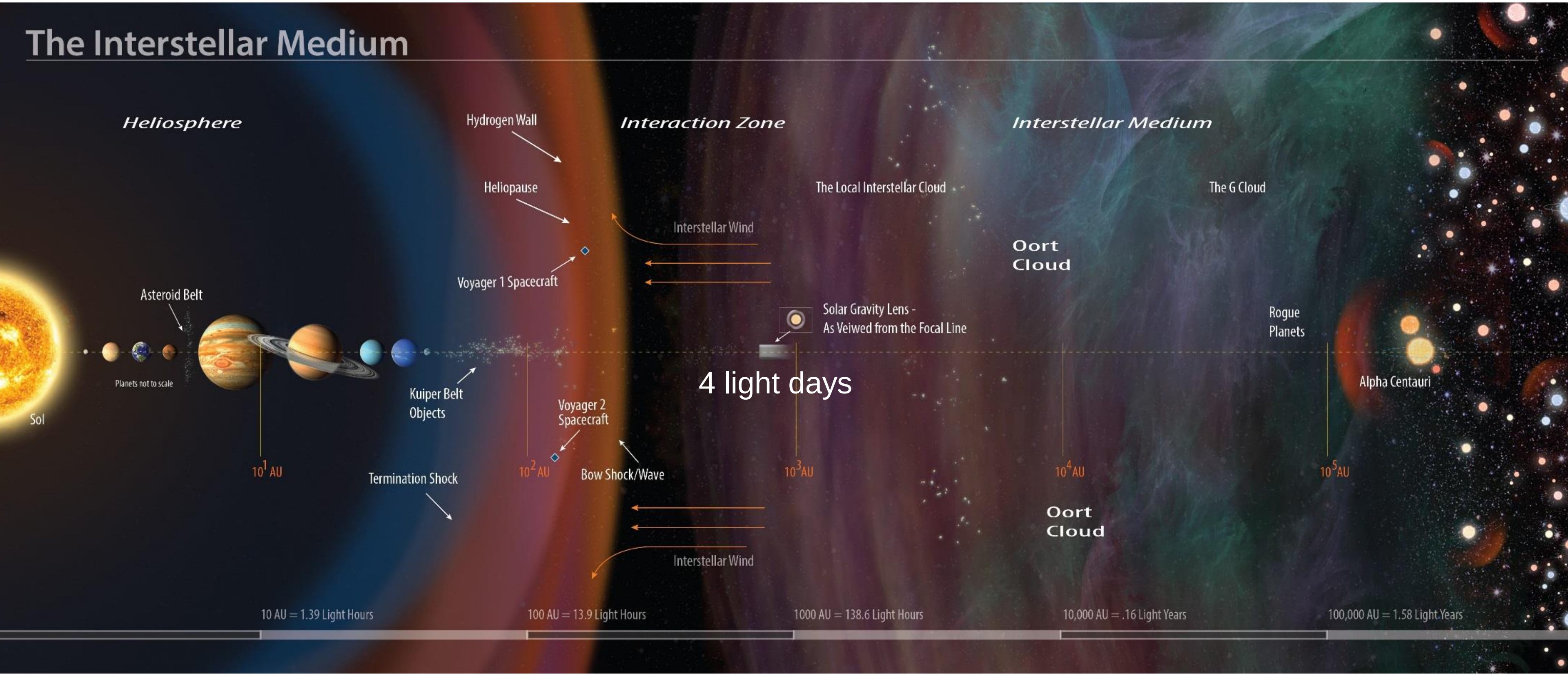
"for decisive contributions to the LIGO detector and the observation of

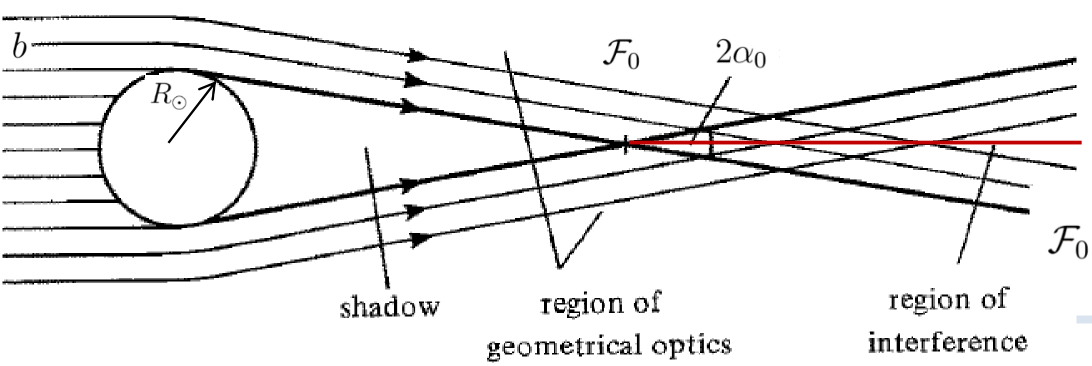
New Engineering Discipline – Applied General Relativity:

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

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

The Solar Gravitational Lens (KISS study, 2015)

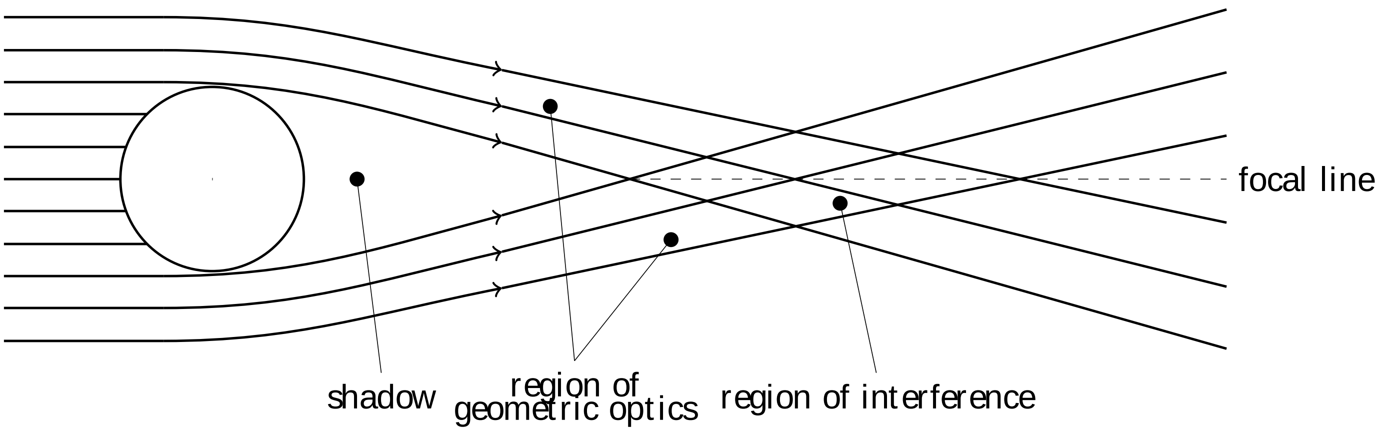




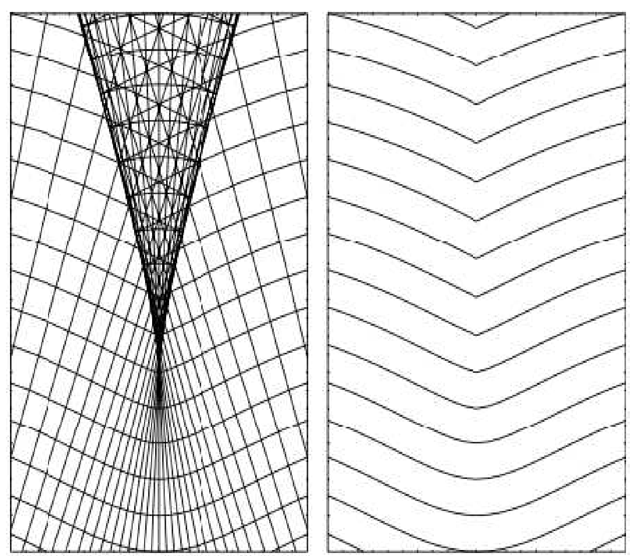
$$\alpha_0 = \frac{2r_g}{R_\odot} \approx 8.5\ \mu\text{rad} \quad \rightarrow \quad \alpha(b) = \alpha_0 \frac{R_\odot}{b}$$

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

Optical properties of the SGL: caustic



Different regions of the SGL



Caustic formed behand the Sun

Focal beam of extreme intensity

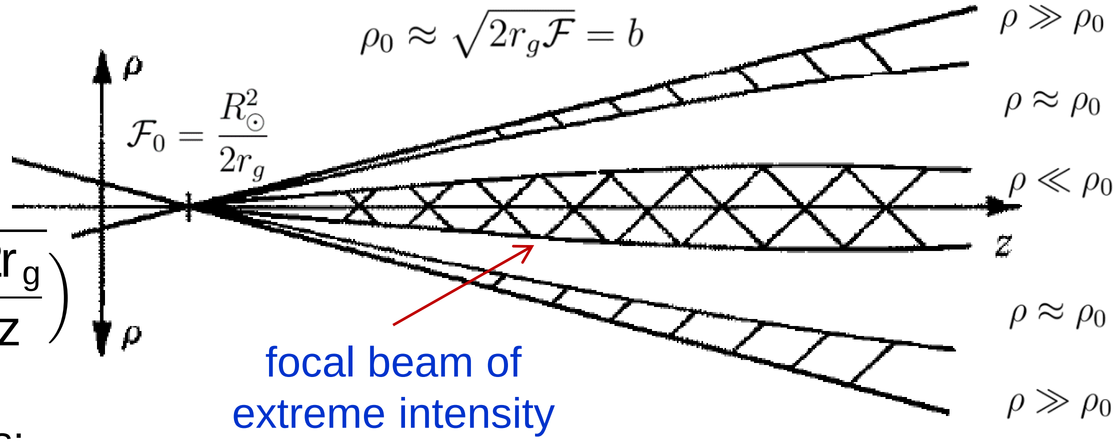
Herlt & Stephani, IJMP 15, 45 (1976)

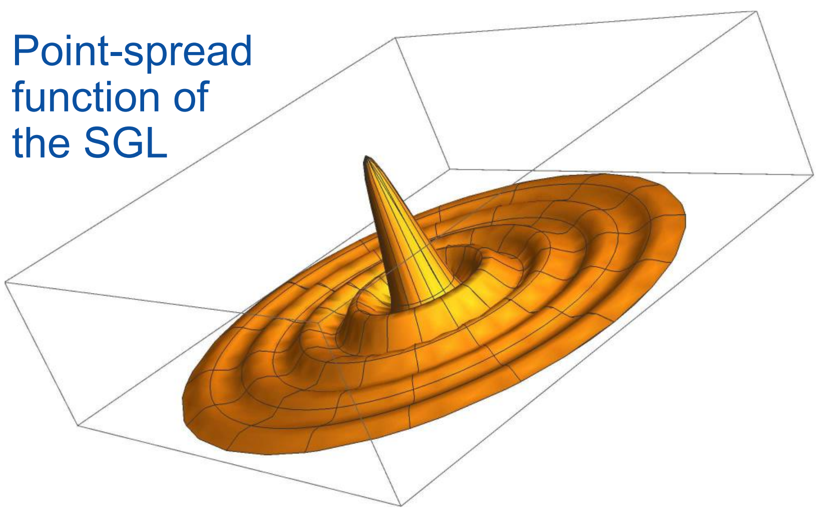
- Major brightness increase:
  - For small departures from the optical axis, ρ, magnification of the SGL is:

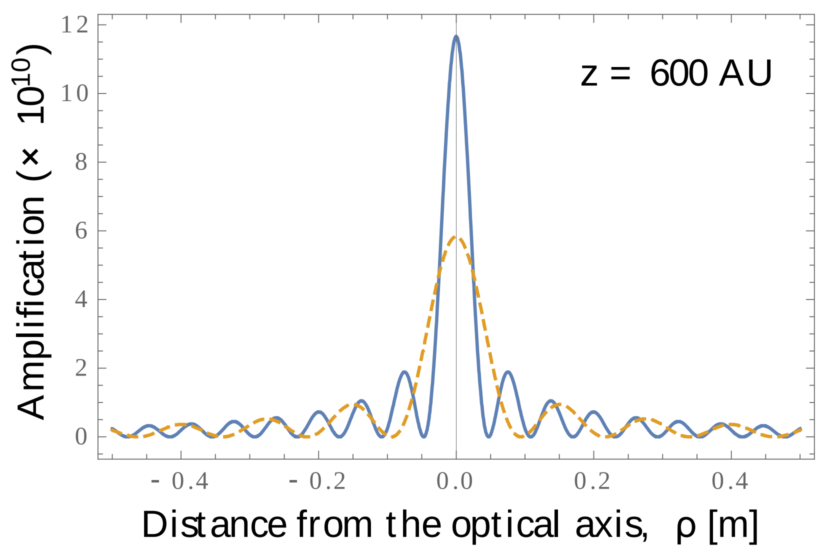
$$\mu_z(\rho, z, \lambda) \;\simeq\; 4\pi^2 \frac{r_g}{\lambda} J_0^2\left(2\pi \frac{\rho}{\lambda}\sqrt{\frac{2r_g}{z}}\right)$$

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

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



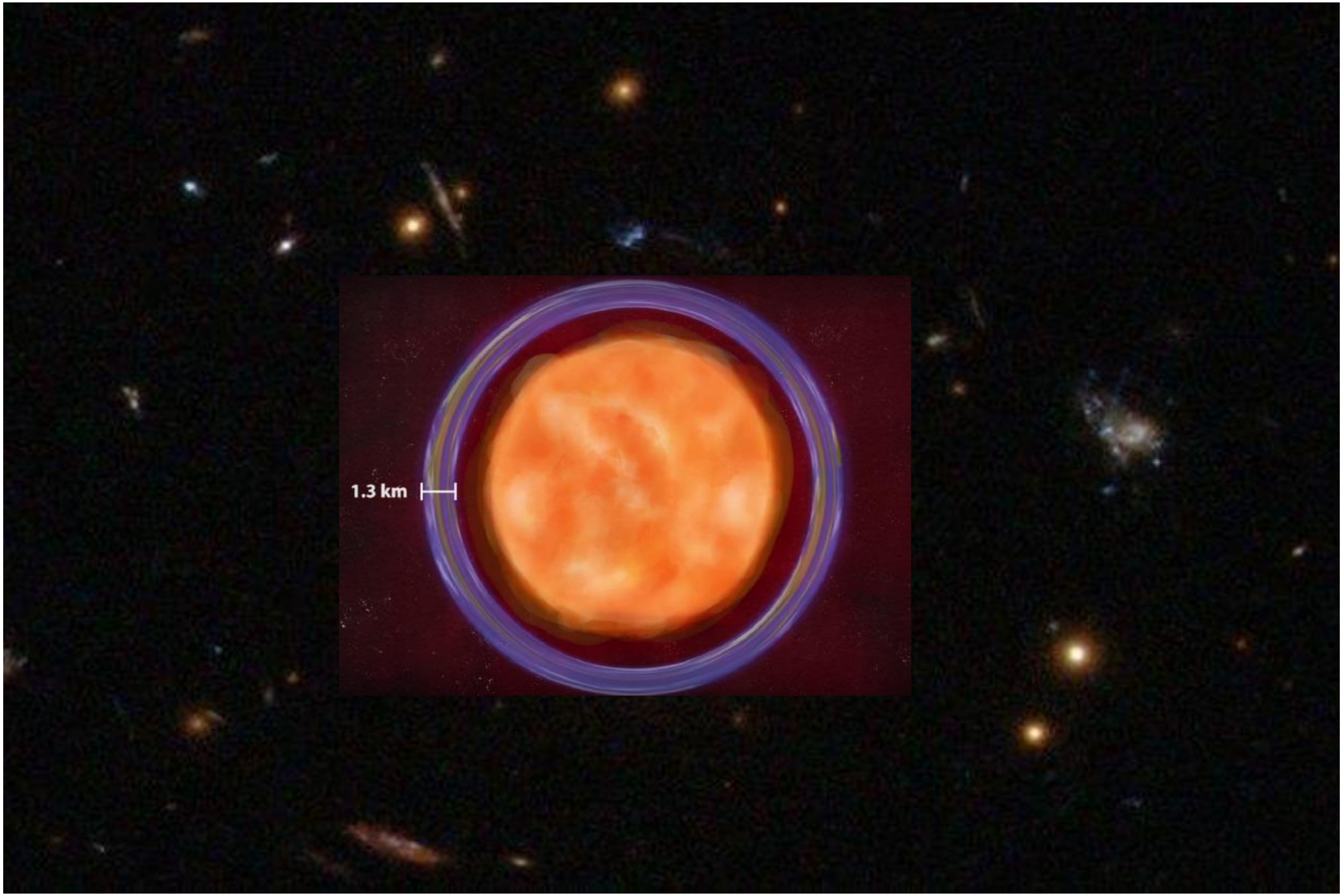




Turyshev & Toth, Phys. Rev. D 96, 024008 (2017)

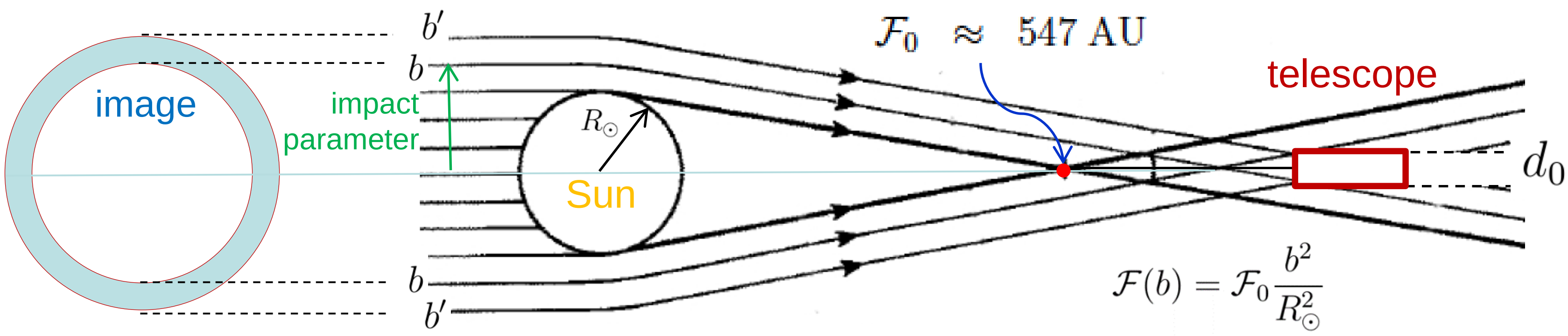
Gain of the SGL as seen in the image plane as a function of possible observational wavelength

The image within 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…

Imaging Exoplanets with the Solar Gravitational Lens

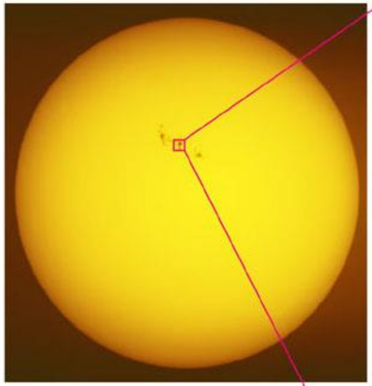
Video Not Embedded in the PDF

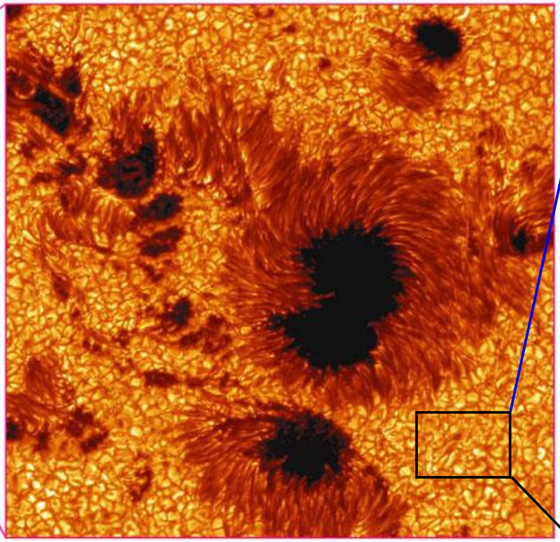
https://www.youtube.com/watch?v=Hjaj-Ig9jBs

Or see HAL5 website (www.HAL5.org look for August 14, 2018 program page for video

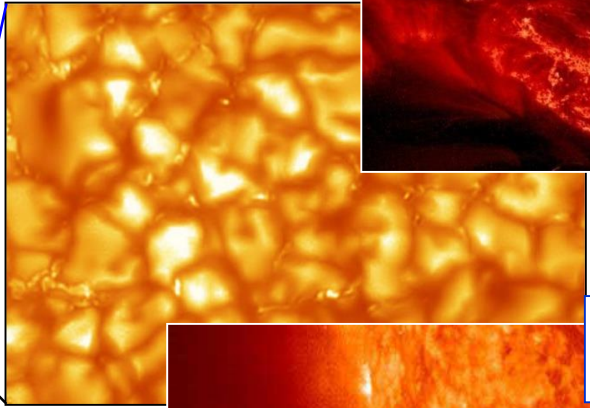
Credit: J. DeLuca

Do not point at the Sun!!!!



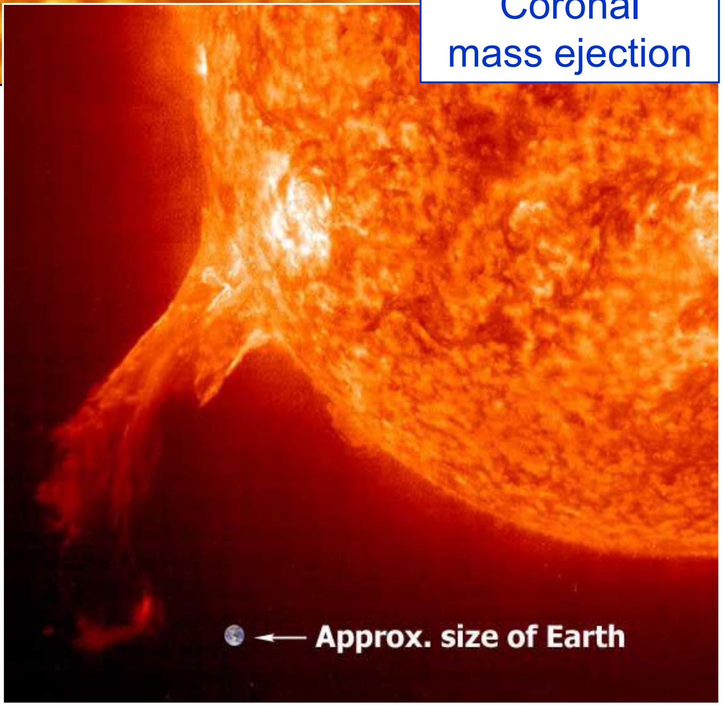


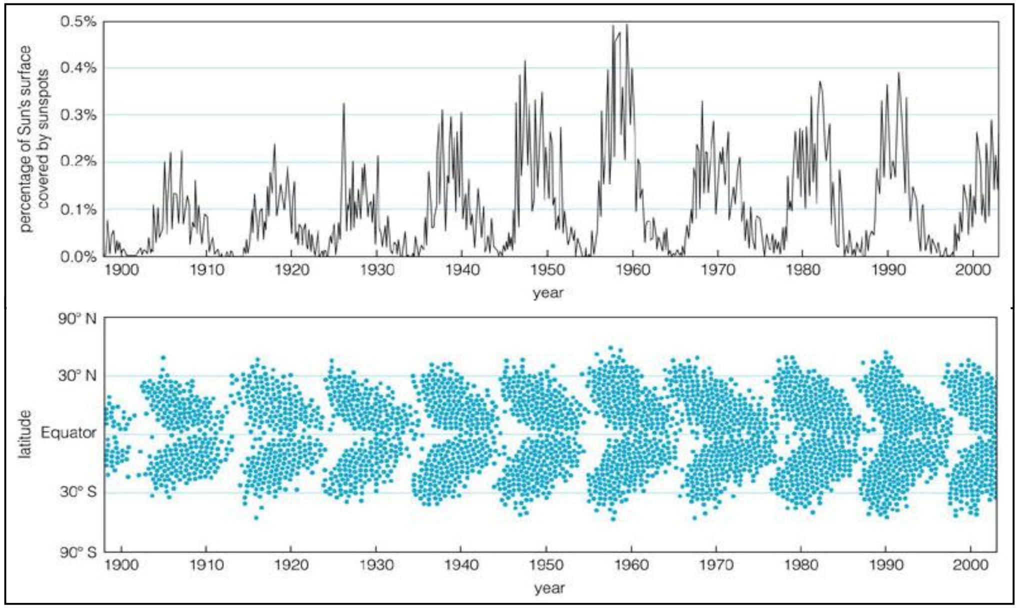
Granulation of solar surface



A solar flare

Coronal mass ejection



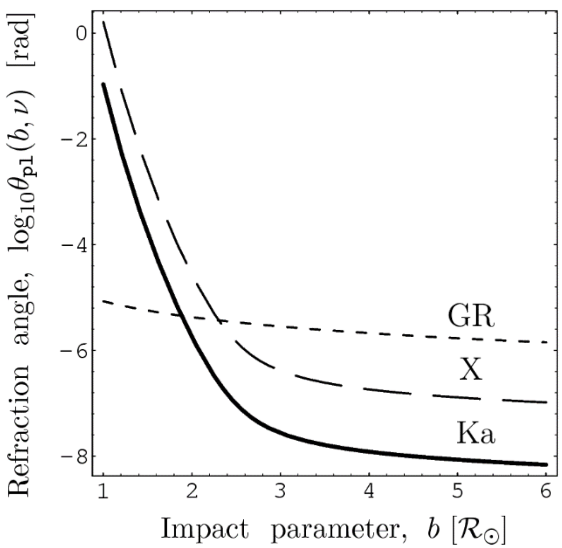


Effects of plasma on the Solar Lens

- Total deflection: gravity & plasma

$$\alpha_{\rm tot}=\alpha_{\rm GR}-\alpha_{\rm pl}=\frac{2r_g}{b}-\alpha_{\rm pl}$$

  – Note the opposite sign. For observer: gravity bends the ray outwards, plasma inwards, and the different dependence on b, plasma being steeper.



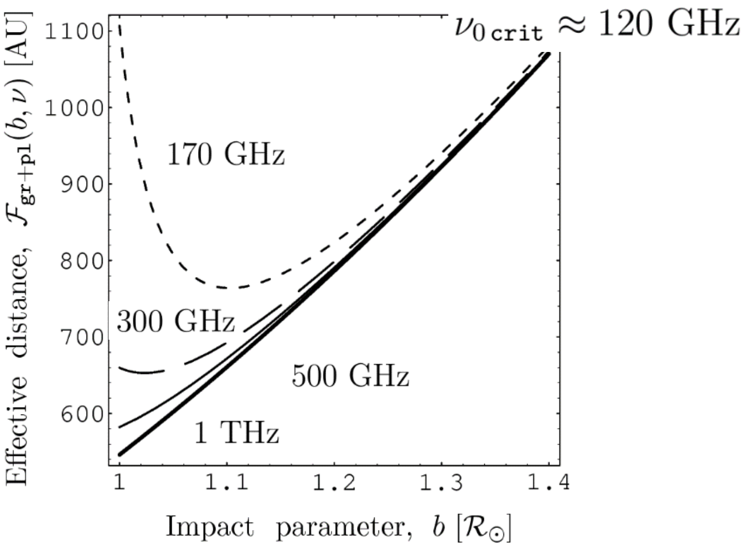
Refraction of radio-waves in the solar atmosphere: the steady-state model, and X- and K-bands radio freqs. The absolute value for GR is also shown.

- Moving the interference zone out:

$$\frac{b}{\mathcal{F}_{\tt gr+pl}}=\alpha_{\tt tot}=\frac{2r_g}{b}-\alpha_{\tt pl}$$

  – For impact parameters $b/\mathcal{R}_\odot\in\Big[1.05,\ 1.35\Big]$

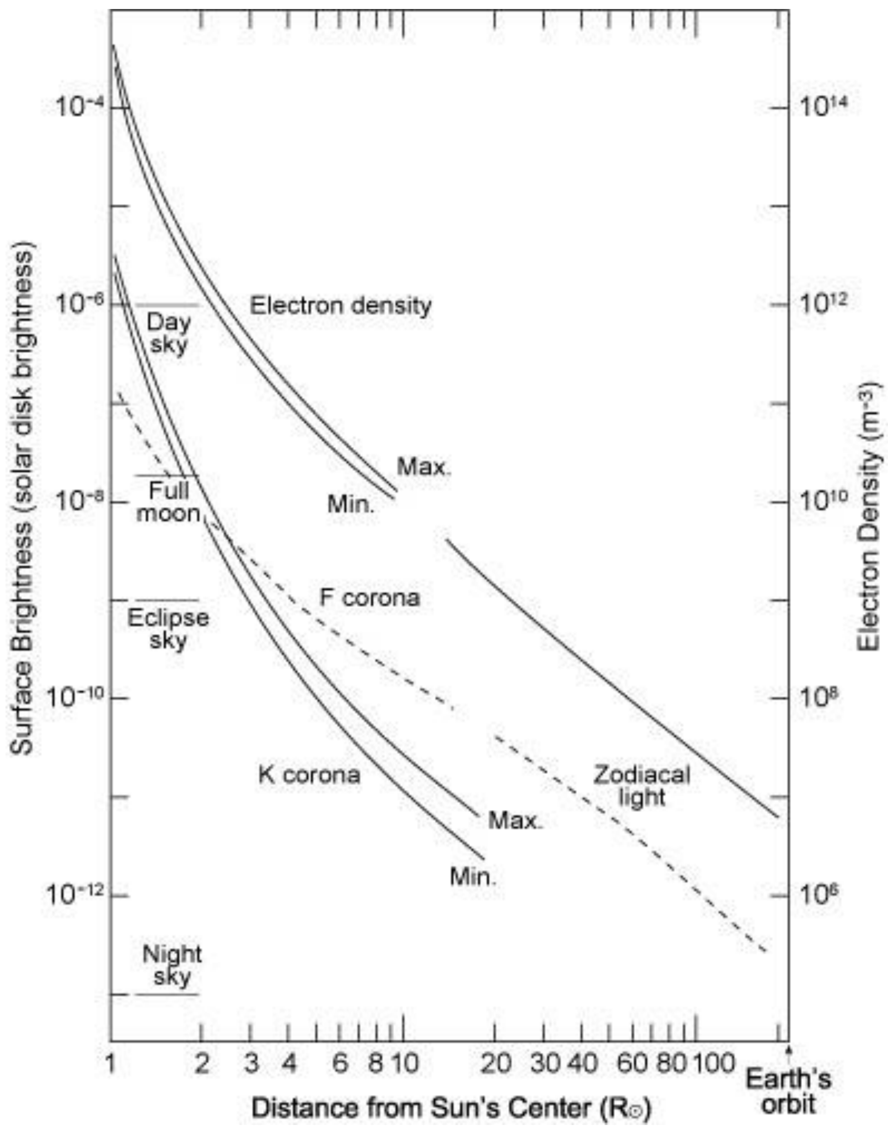
$$\mathcal{F}_{\tt gr+pl}(b,\nu)=546\Big(\frac{b}{\mathcal{R}_\odot}\Big)^2\Big[1-\frac{\nu^2_{\tt 0\,crit}}{\nu^2}\Big(\frac{\mathcal{R}_\odot}{b}\Big)^{15}\Big]^{-1}\ \ \text{AU}$$



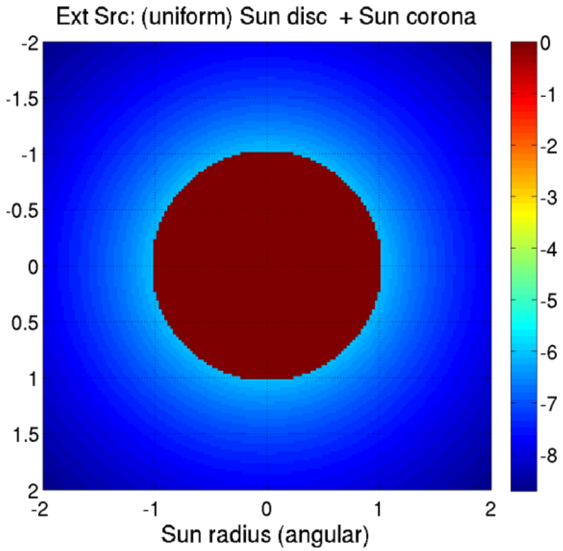
Effective optical distances for different freqs and impact parameters. From top to bottom: 170 GHz, 300 GHz, 500 GHz, and last 1 THz.

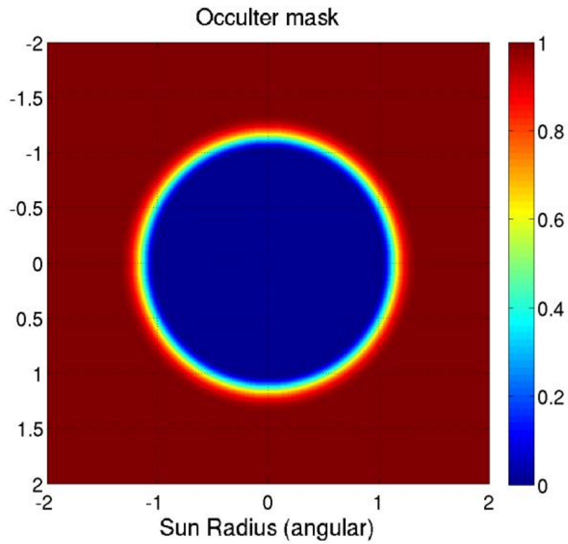
For 1 um refraction in the solar corona is not an issue, but brightness needs to be addressed

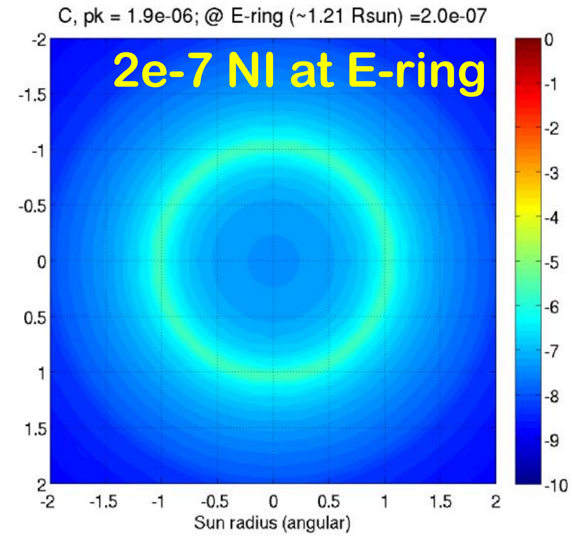
Solar corona brightness



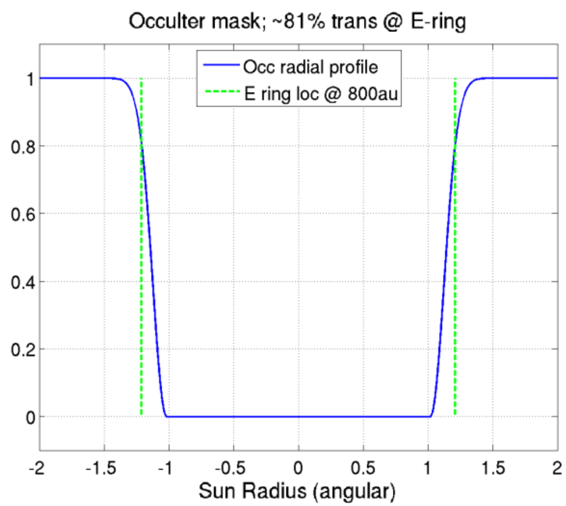
Coronagraph study: sun disc & solar corona

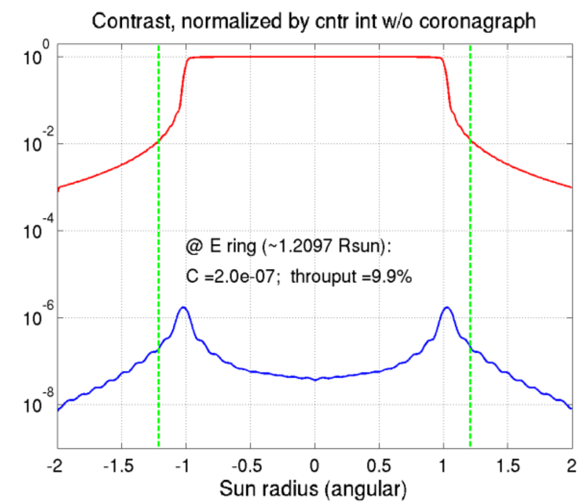






- Contrast @ E-ring: 2e-7
  - w/o corona: 1.4e-7
- E-ring planet core PSF throughput: ~ 10%
  - Lyot + Occulter over +/- λ/D

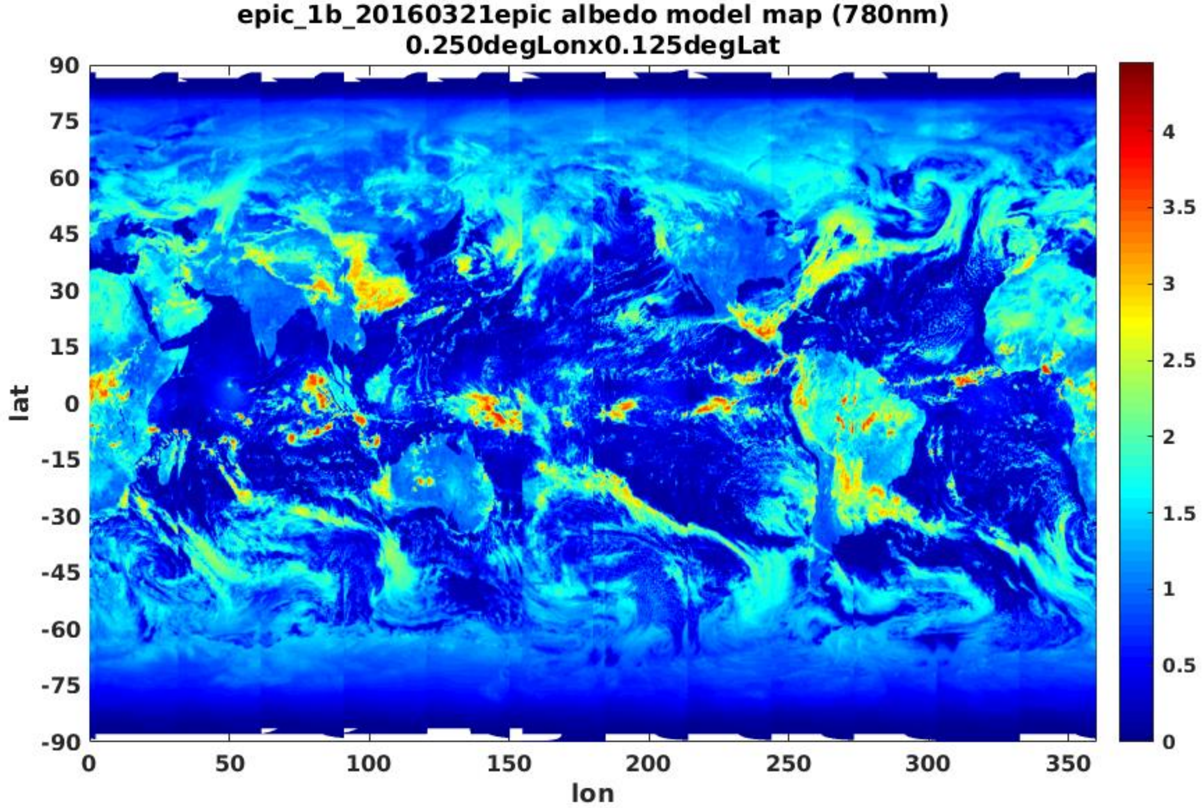




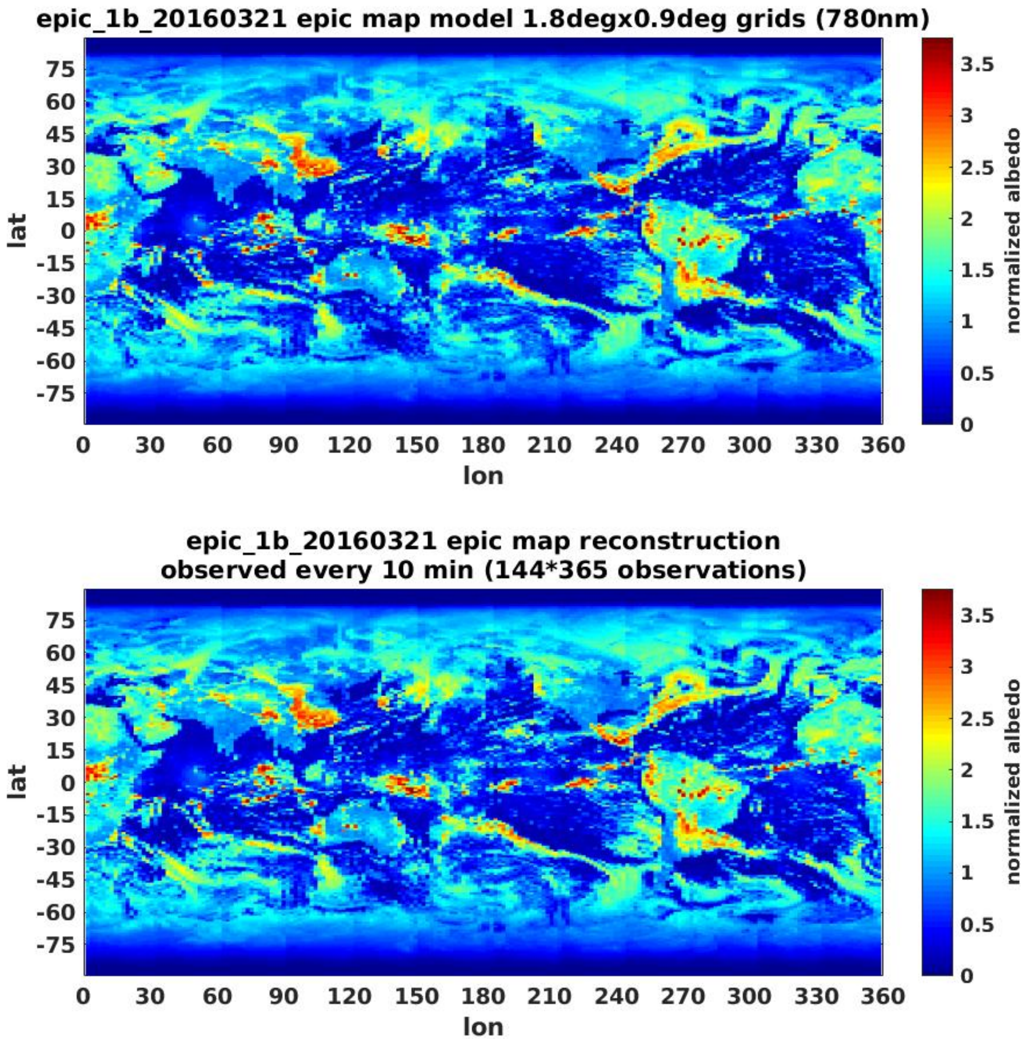
Albedo model high resolution map

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

Earth Polychromatic Imaging Camera (EPIC)



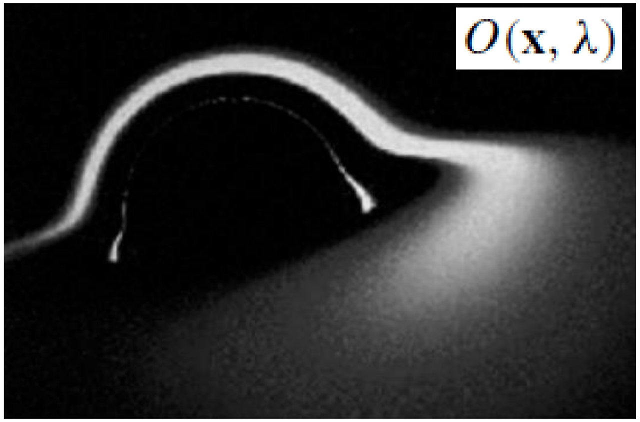
Rotational deconvolution



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.

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

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

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

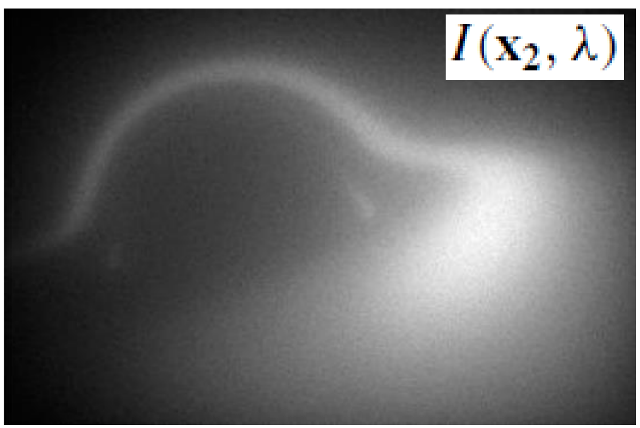
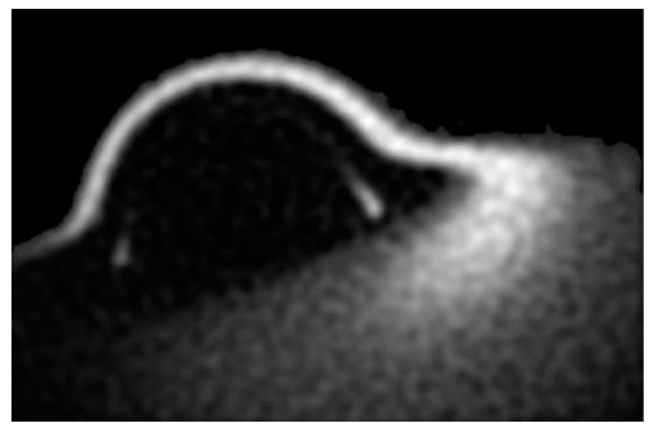


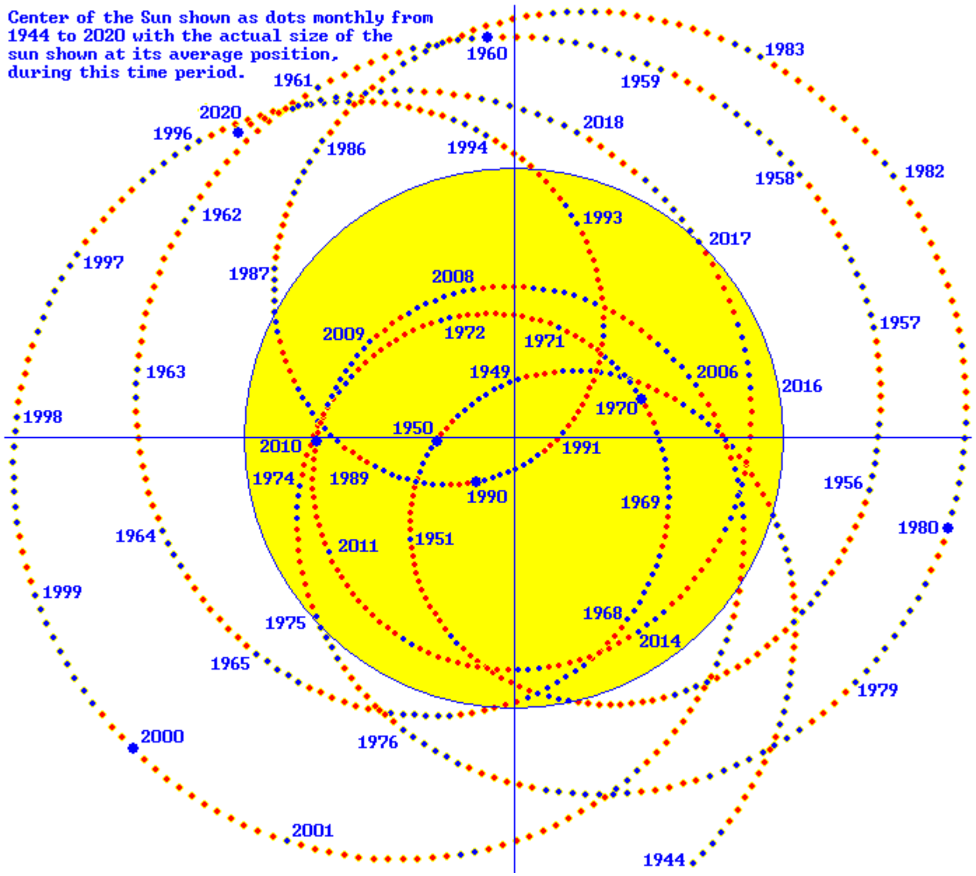
Image obtained after convolution. Photon noise is added, corresponding to 100 ph/pixel

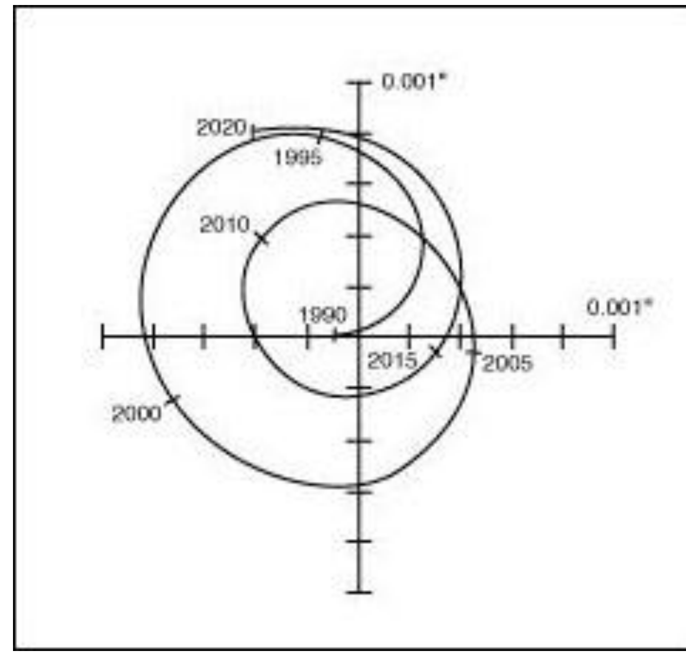


De-convolved image using the SGL' PSF. Low-pass filtering in spatial frequencies is applied

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

The 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.

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.

Image of Our Earth in Physical Colors