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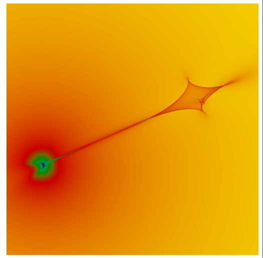
# Gravitational Lensing: Giant Luminous Arcs, Einstein Rings and Exoplanets

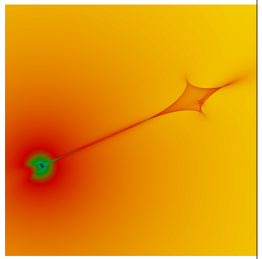
**Prof. Joachim Wambsganss**
**(Heidelberg University)**



## Relativity Seminar

28-30 Jan 2016, Prague

# Gravitational Lensing: Giant Luminous Arcs, Einstein Rings and Exoplanets



Prof. Joachim Wambsganss
(Heidelberg University)

- A short history of Light Deflection …
  ... and what Einstein contributed
- How a Gravitational Lens works …
  ... and why Einstein was so skeptical
- Exciting Gravitational Lens Phenomena …
  ... and very useful for astrophysical research
  - **Giant Luminous Arcs**
  - **Einstein Rings**
  - Searching for **Exoplanets**
- Summary …
  ... and why Einstein would be very pleased today

# What is General Relativity all about (GR)?

Space and Time are densely intertwined

Gravity and Acceleration are equivalent:
Equivalence Principle

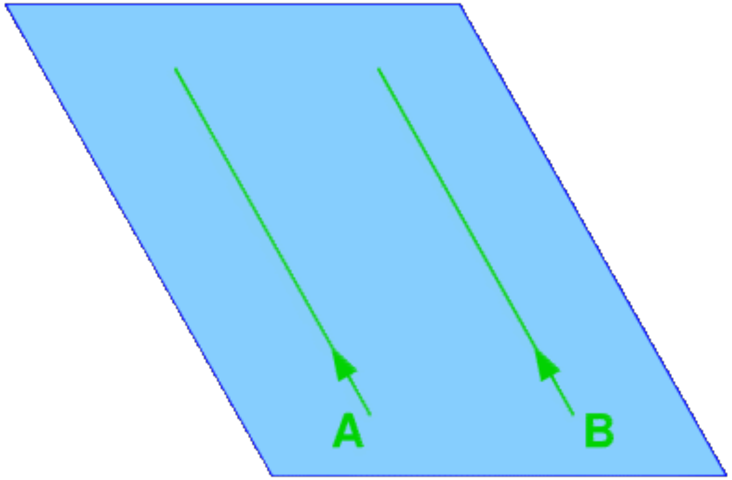
Objects/Masses affect („deform“) space

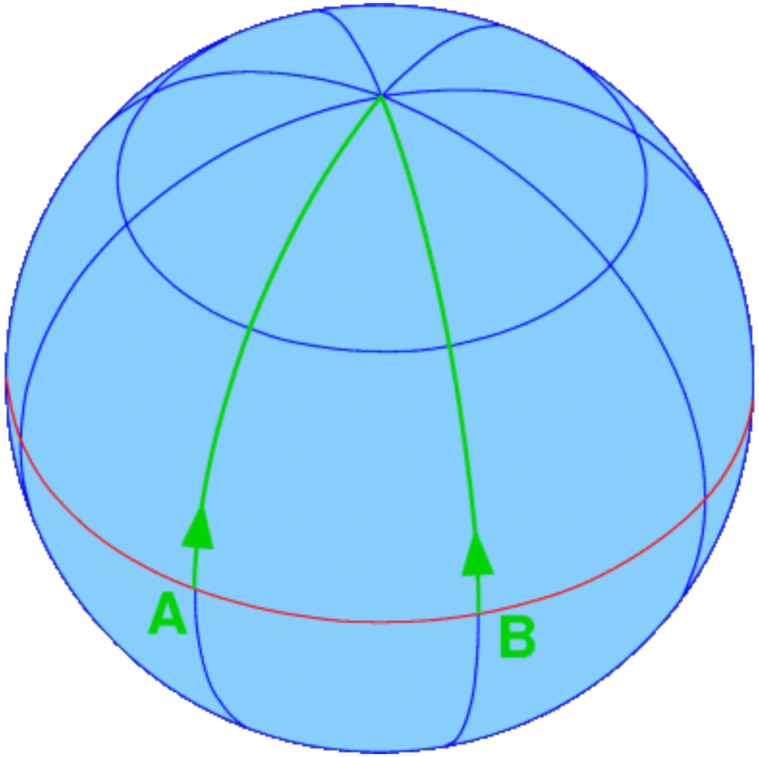
The „deformed“ space determines, how objects/masses have to move

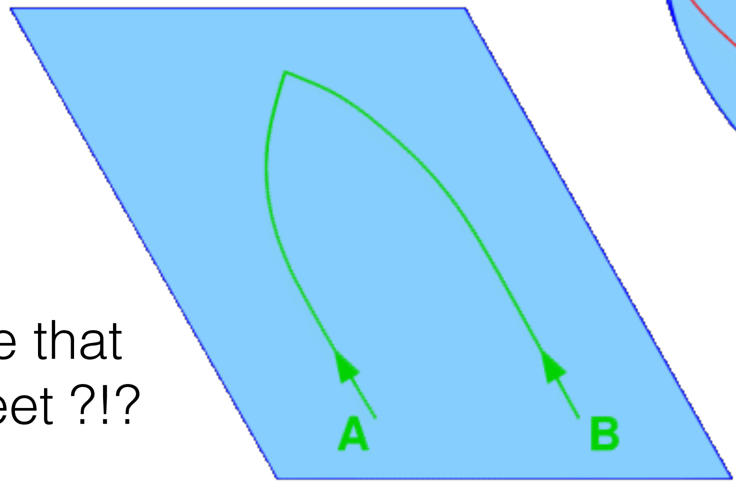
Gravity attracts light rays as well and forces them on „curved“ paths

Euclidian Geometry:
Parallels always stay parallel:

Yes !
In curved spaces parallel lines can meet !



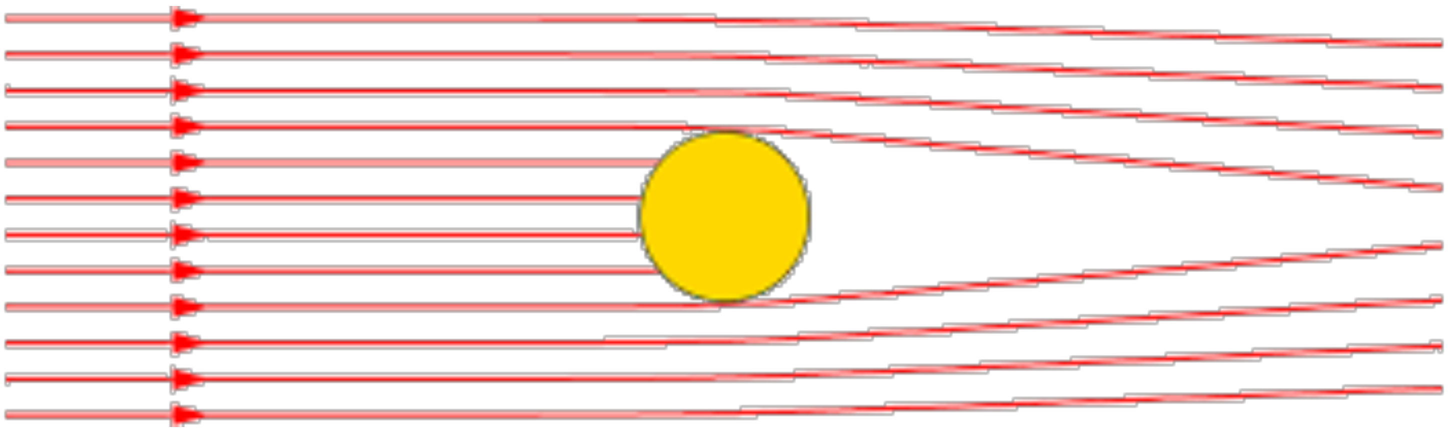




Or is it possible that
parallel rays meet ?!?

Website: http://www.einstein-online.info/

Einstein:
Sun „attracts light rays“ or „deflects light rays“!

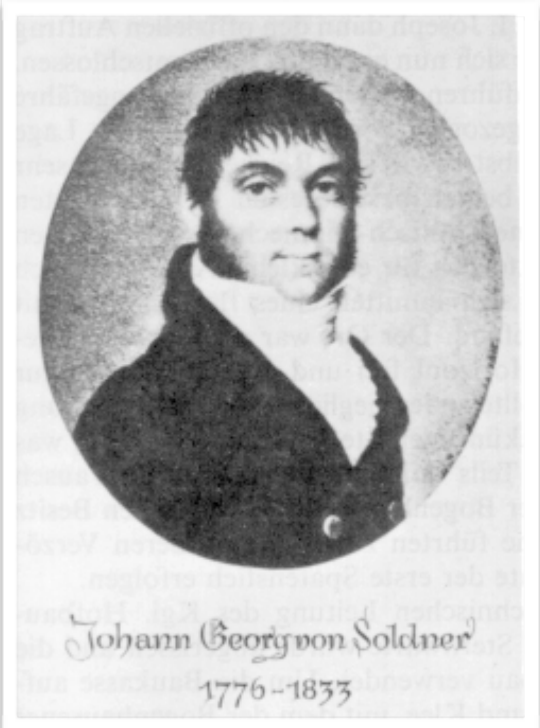


**Prediction** of General Relativity !

Can be tested during a solar eclipse !!

Von Webseite: http://www.einstein-online.info/

# Short History of Light De

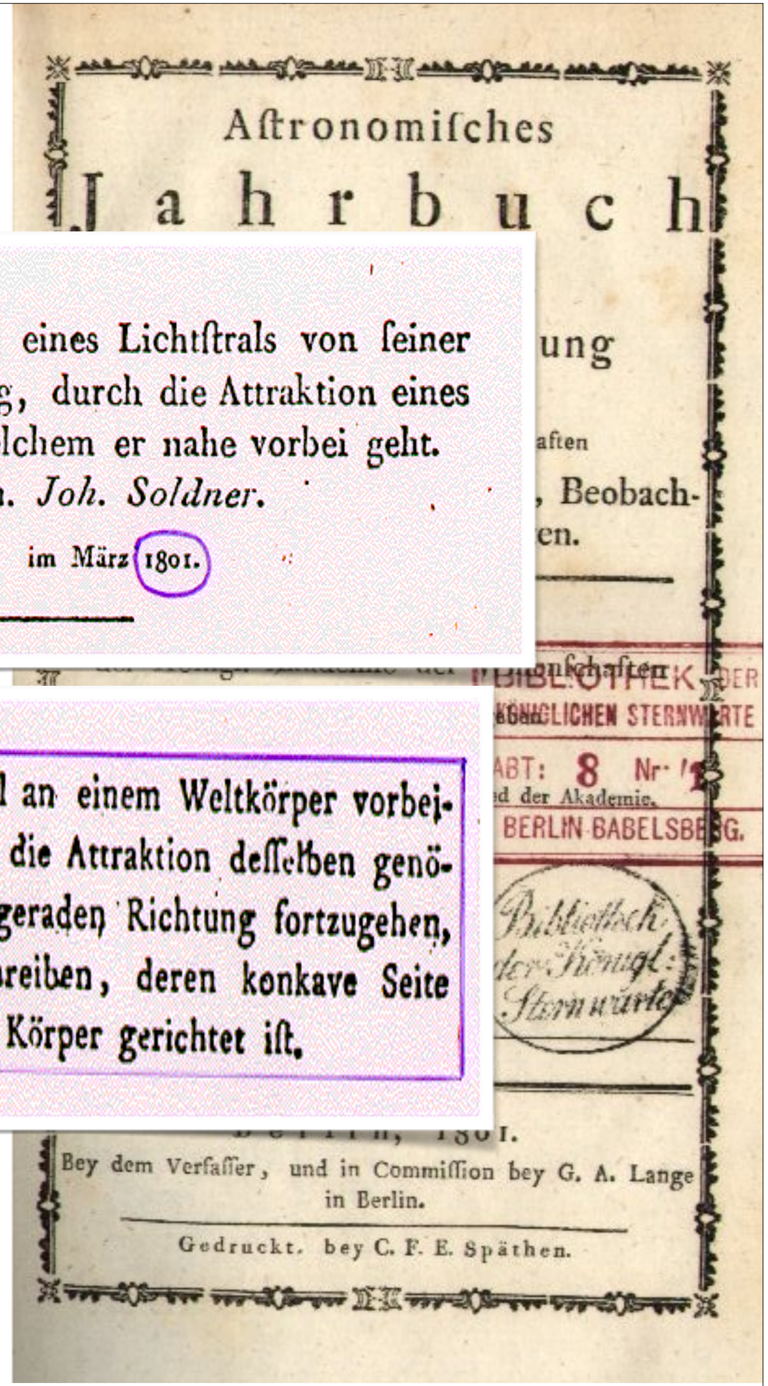



Ueber die Ablenkung eines Lichtstrals von seiner geradlinigen Bewegung, durch die Attraktion eines Weltkörpers, an welchem er nahe vorbei geht.

Von Hrn. *Joh. Soldner.*

Berlin, im März 1801.

Wenn also ein Lichtstral an einem Weltkörper vorbeigeht, so wird er durch die Attraktion desselben genöthiget, anstatt in der geraden Richtung fortzugehen, eine Hyperbel zu beschreiben, deren konkave Seite gegen den anziehenden Körper gerichtet ist.




For solar limb:

$$\alpha_{\odot,\mathrm{Soldner}} = 0.84''$$

# Short History of Light Deflection

Einstein 1911:

**4. *Über den Einfluß der Schwerkraft auf die Ausbreitung des Lichtes;* *von A. Einstein.***

$$\alpha_{\odot,\text{Einstein 1911}} = 0.84''$$

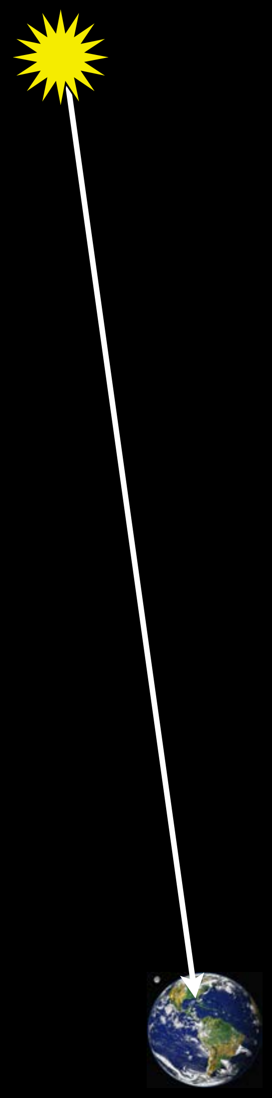
Da die Fixsterne der der Sonne zugewandten Himmelspartien bei totalen Sonnenfinsternissen sichtbar werden, ist diese Konsequenz der Theorie mit der Erfahrung vergleichbar.

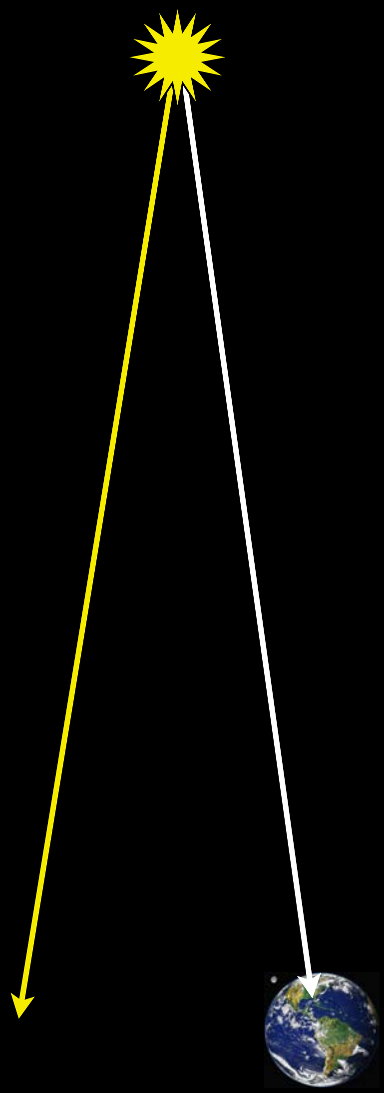
# Short History of Light Deflection

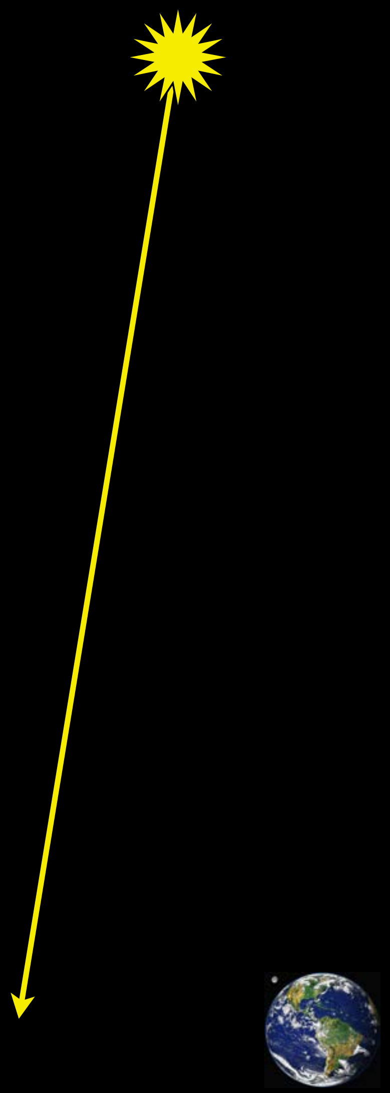
Idea to measure/verify Einstein's prediction:

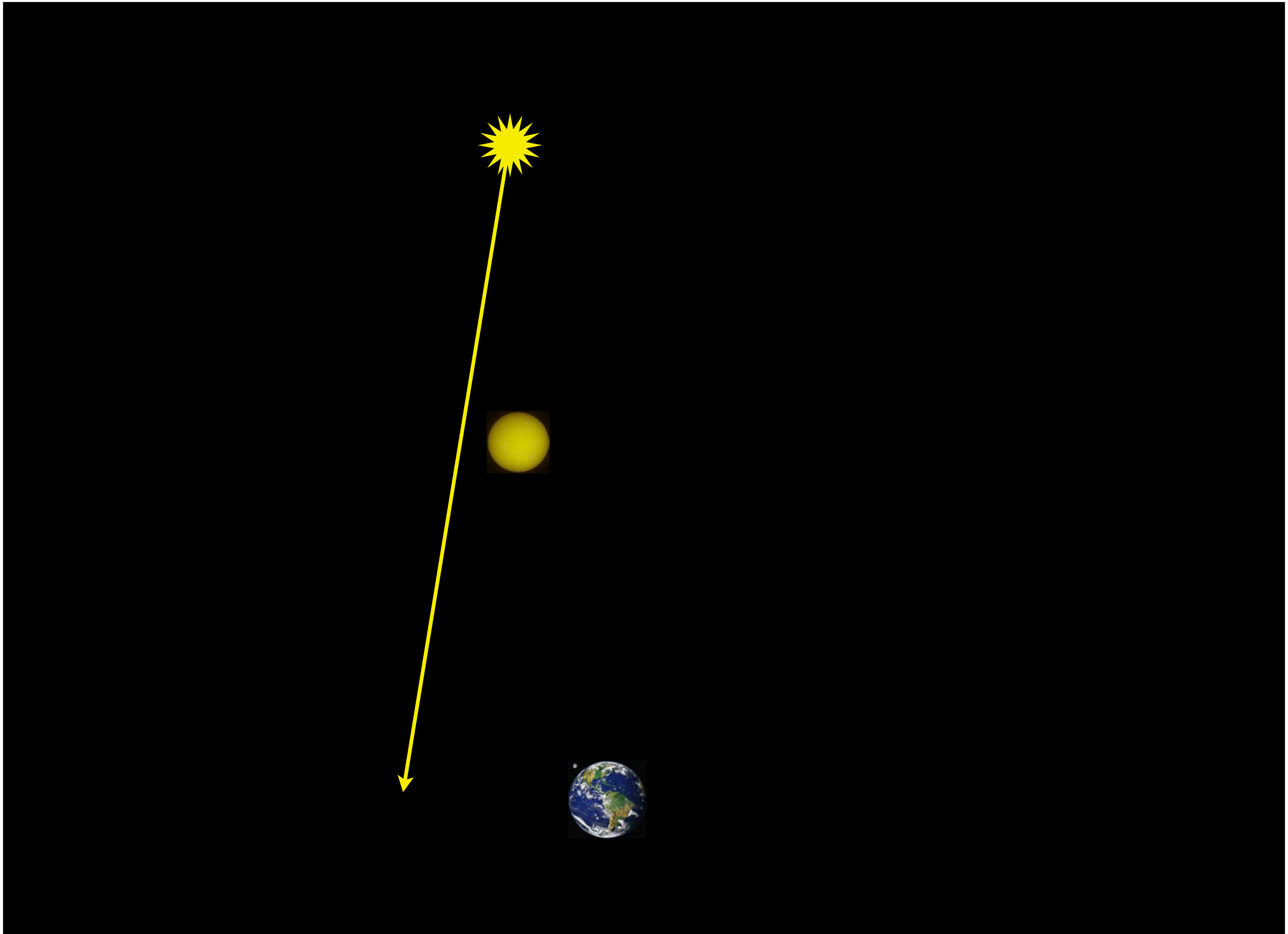
- How? During a solar eclipse!
- Who? Erwin Freundlich!
- When? August 21, 1914!
- Where?  Crimean Peninsula!

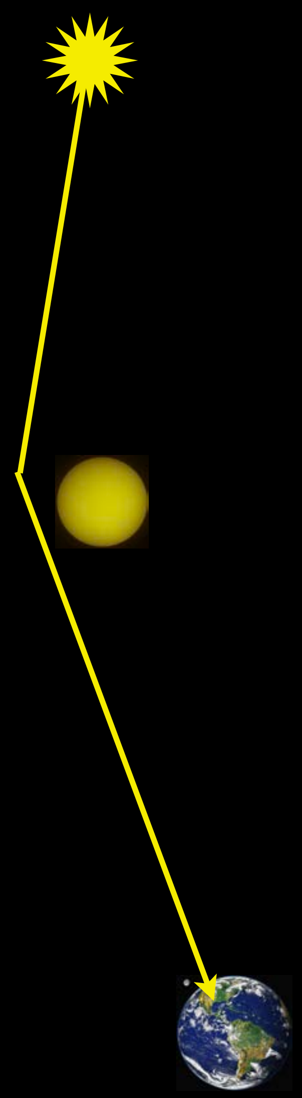
... and off they went, the  Potsdam Expedition  !

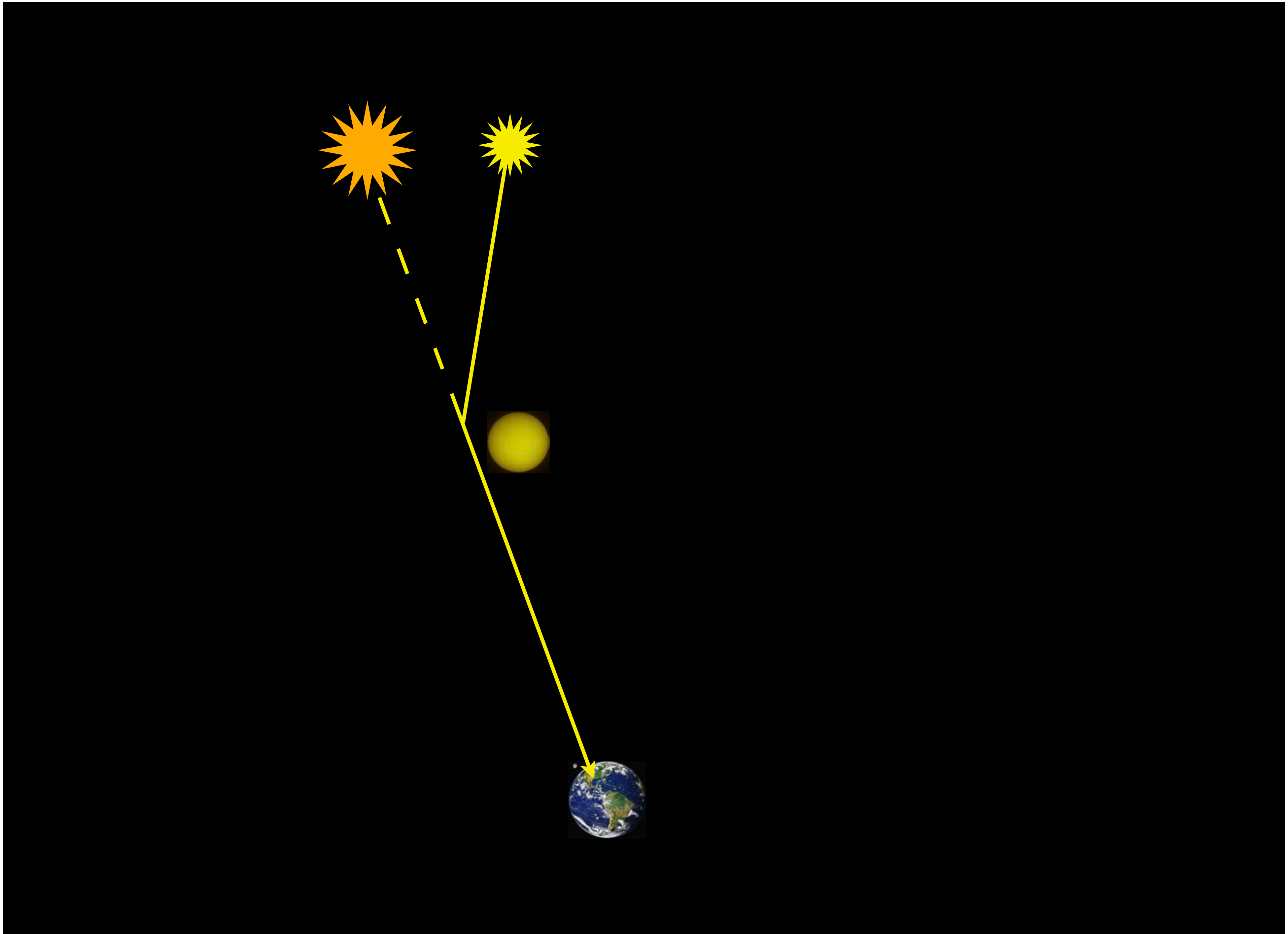




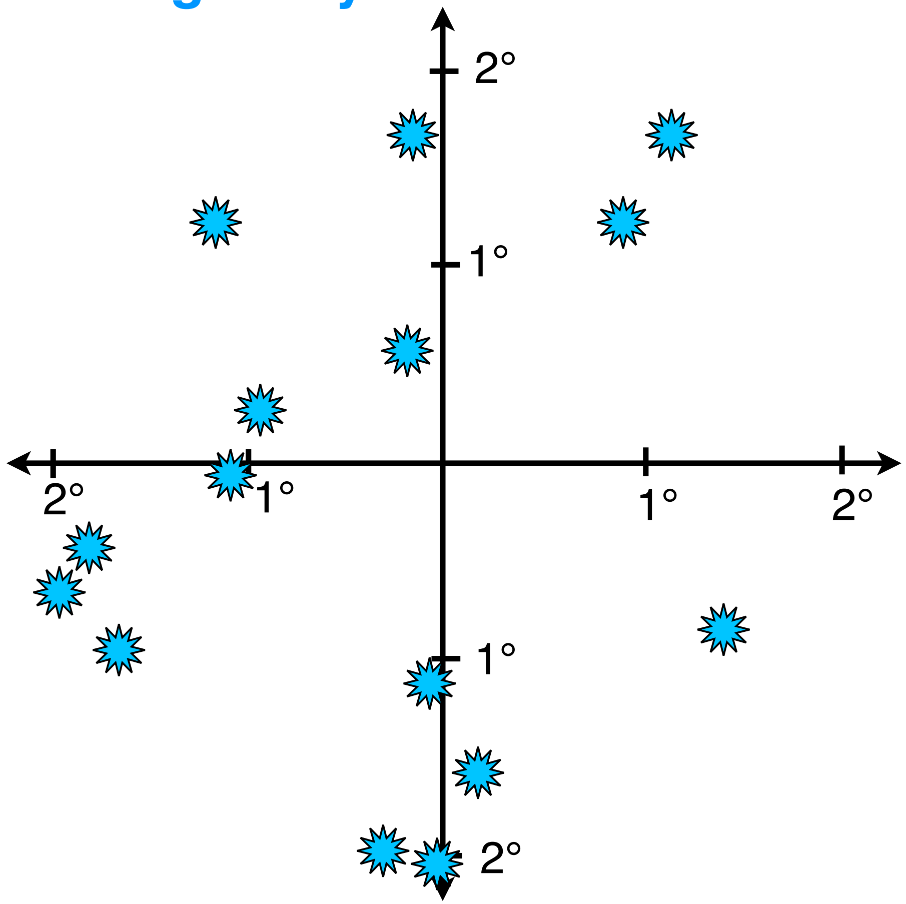


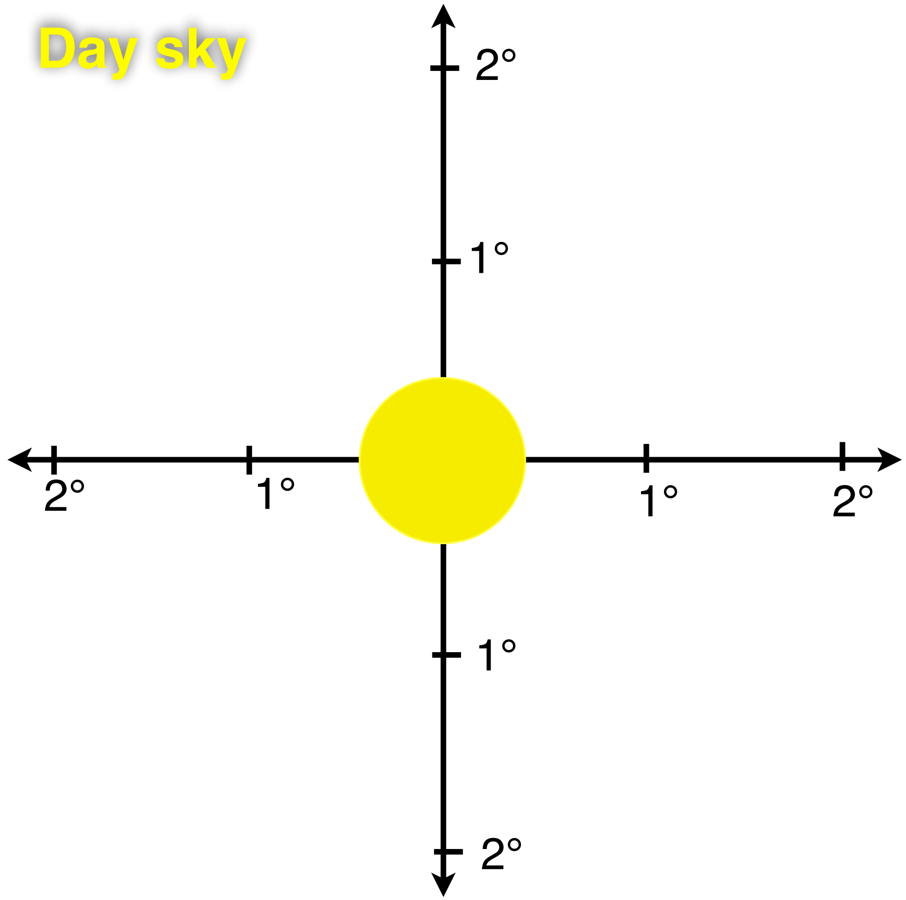






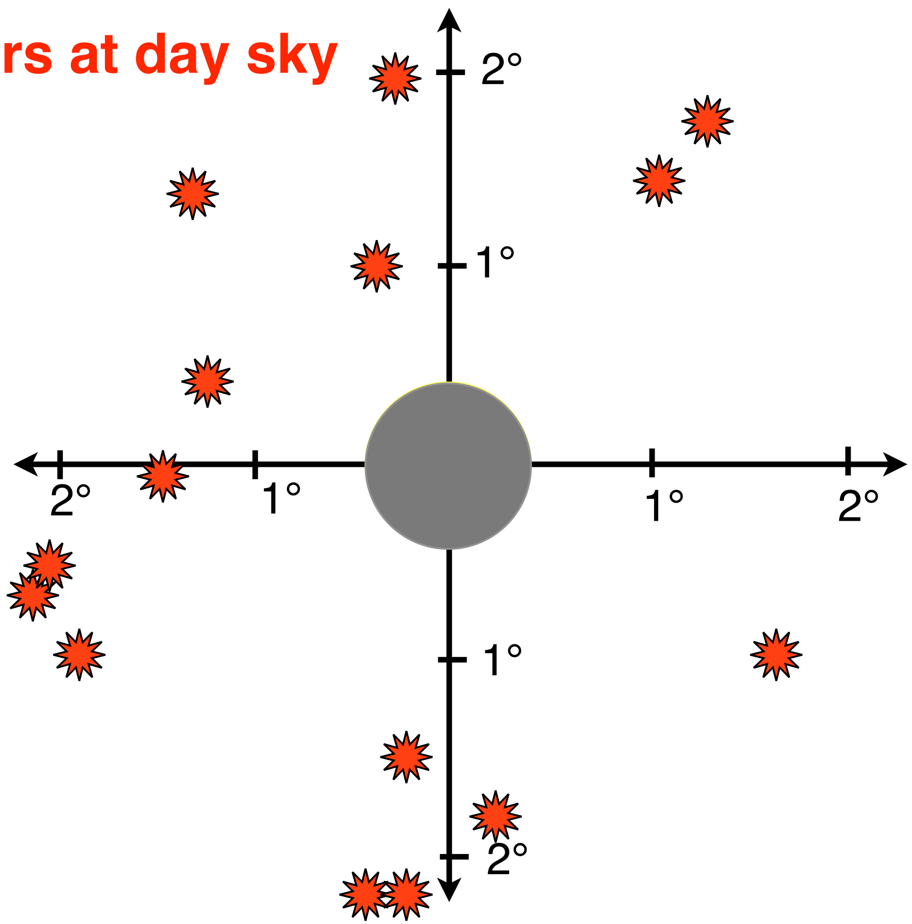
## Stars at night sky



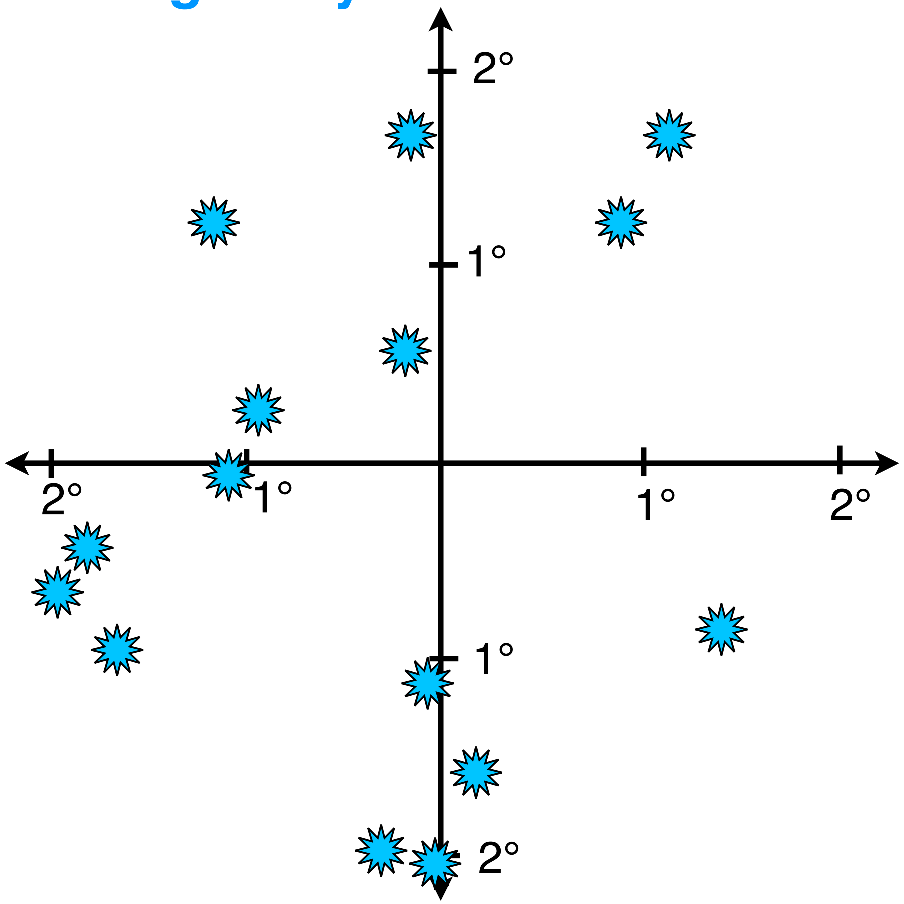


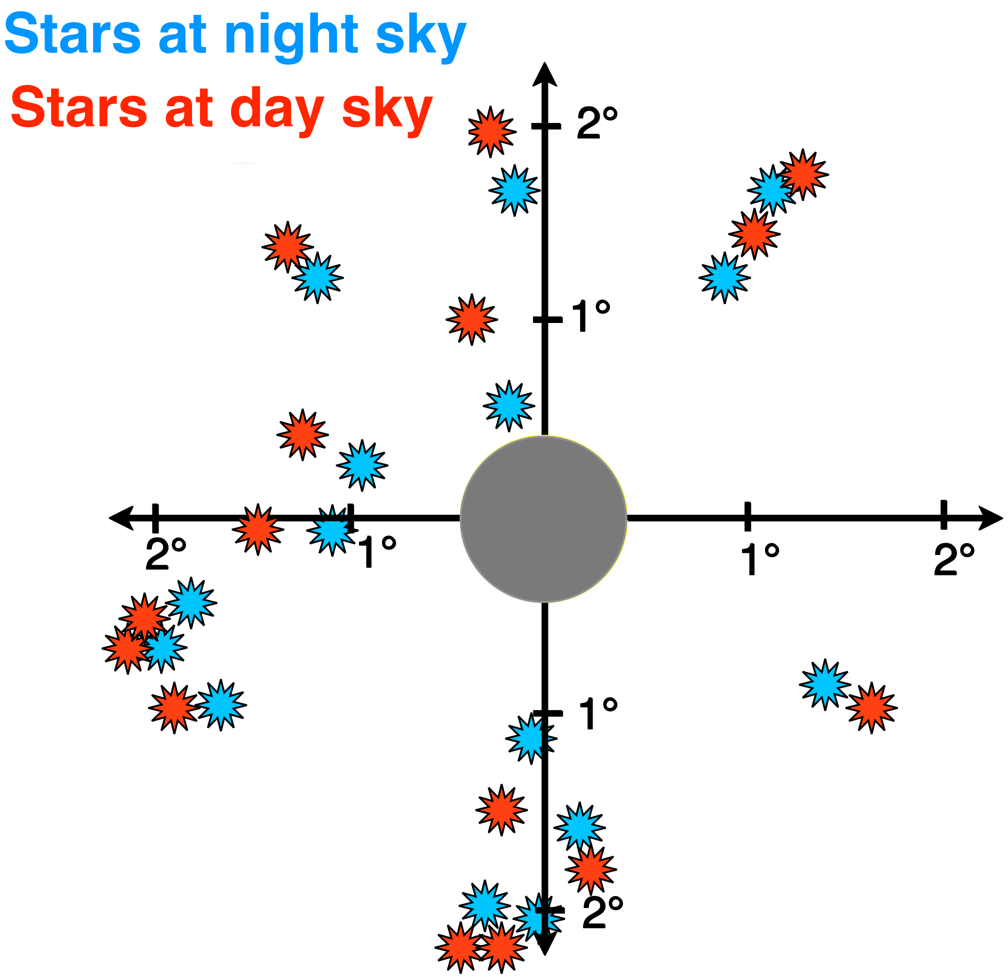
Day sky
2°
1°
2°
1°
1°
2°
1°
2°

## Stars at day sky

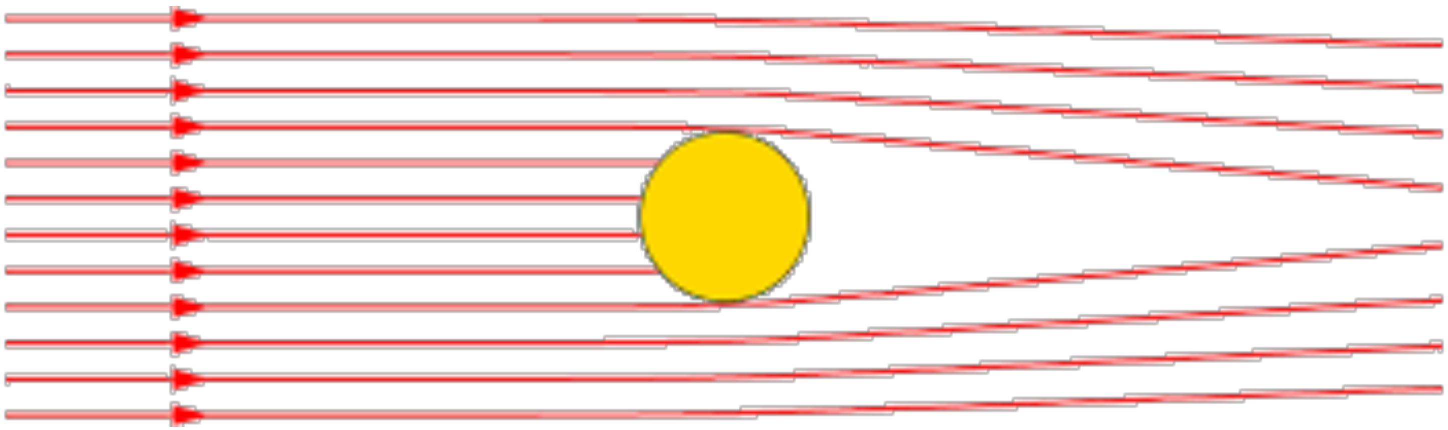


## Stars at night sky




Stars at night sky
Stars at day sky
2°
1°
2°
1°
1°
2°
1°
2°

Einstein says:
Sun „attracts light rays“ or „deflects light rays“!



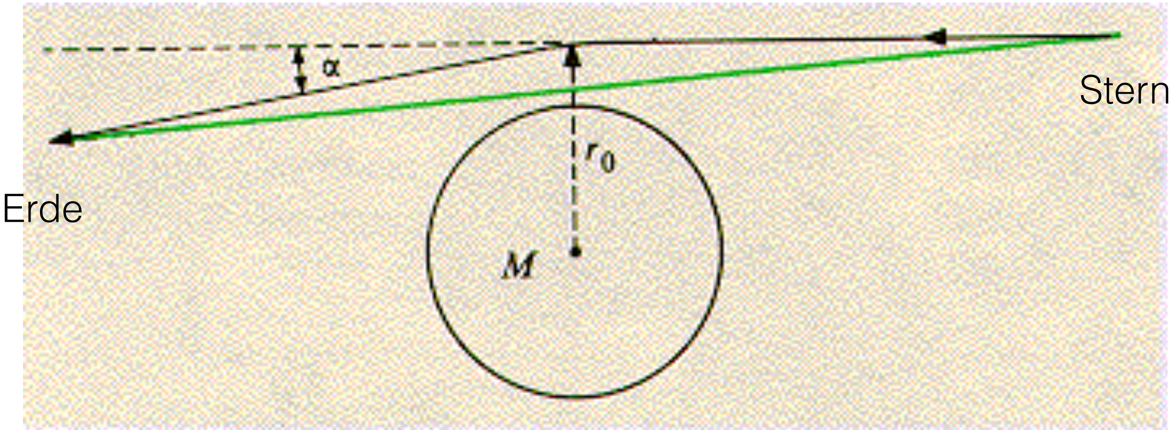
**Prediction** of General Relativity !

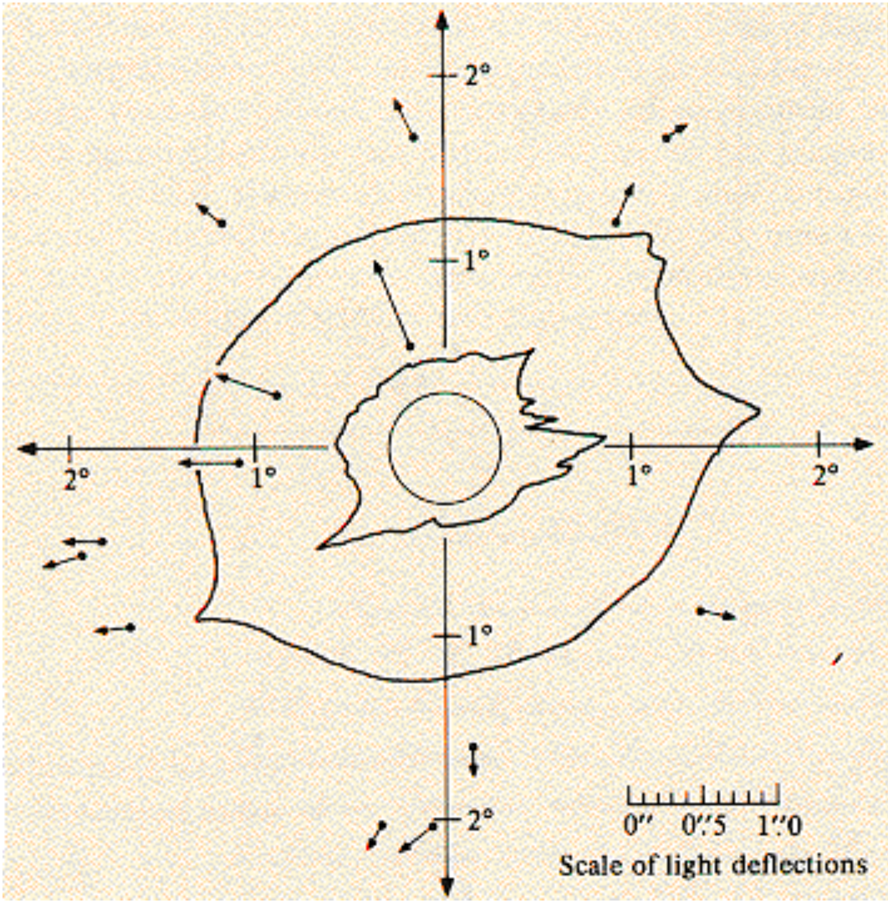
Can be tested during a solar eclipse !!

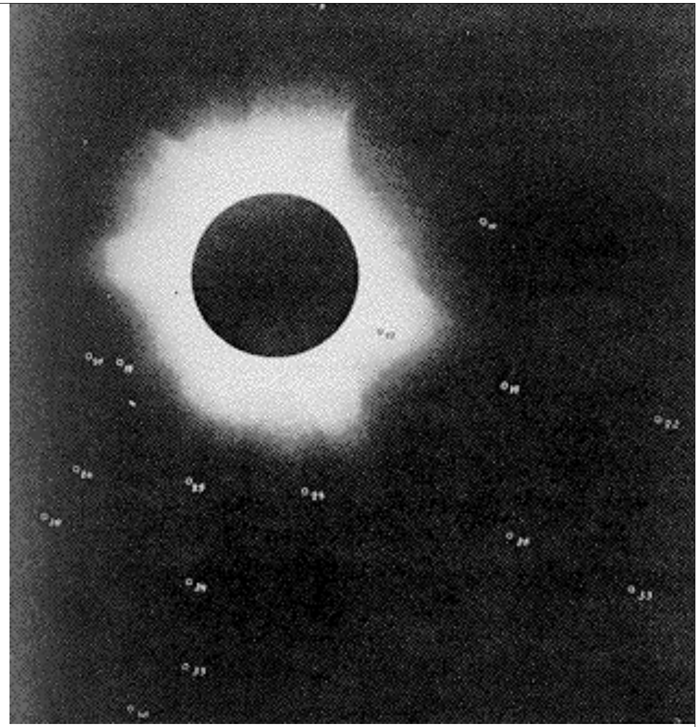
Light Deflection at solar limb confirmed during Eclipse Expedition
in May1919 by Sir Arthur Eddington and his team:

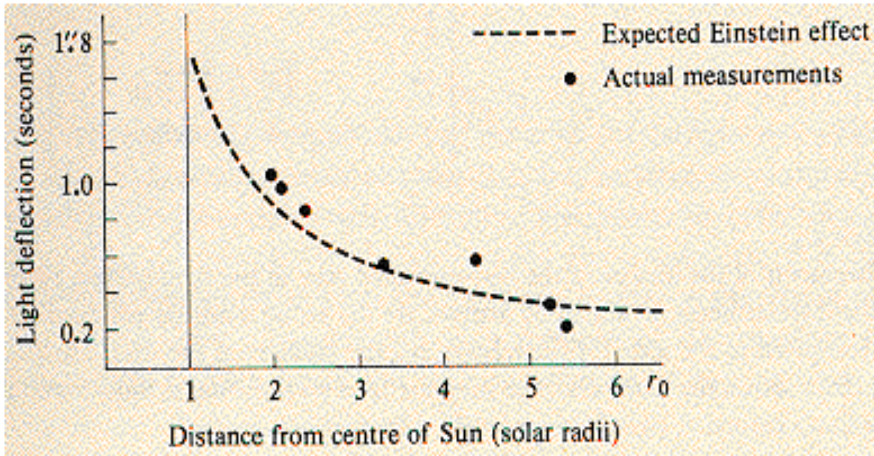
**Triumph for Einstein and General Relativity !!!**

Von Webseite: http://www.einstein-online.info/


α
Stern
$r_0$
Erde
M


2°
1°
1°
2°
1°
1°
2°
2°
0″ 0.″5 1.″0
Scale of light deflections




Expected Einstein effect
Actual measurements
1.″8
1.0
0.2
Light deflection (seconds)
1 2 3 4 5 6 $r_0$
Distance from centre of Sun (solar radii)

New York Times,
November 9, 1919

# ECLIPSE SHOWED GRAVITY VARIATION

Diversion of Light Rays Accepted as Affecting Newton's Principles.

## HAILED AS EPOCHMAKING

British Scientist Calls the Discovery One of the Greatest of Human Achievements.



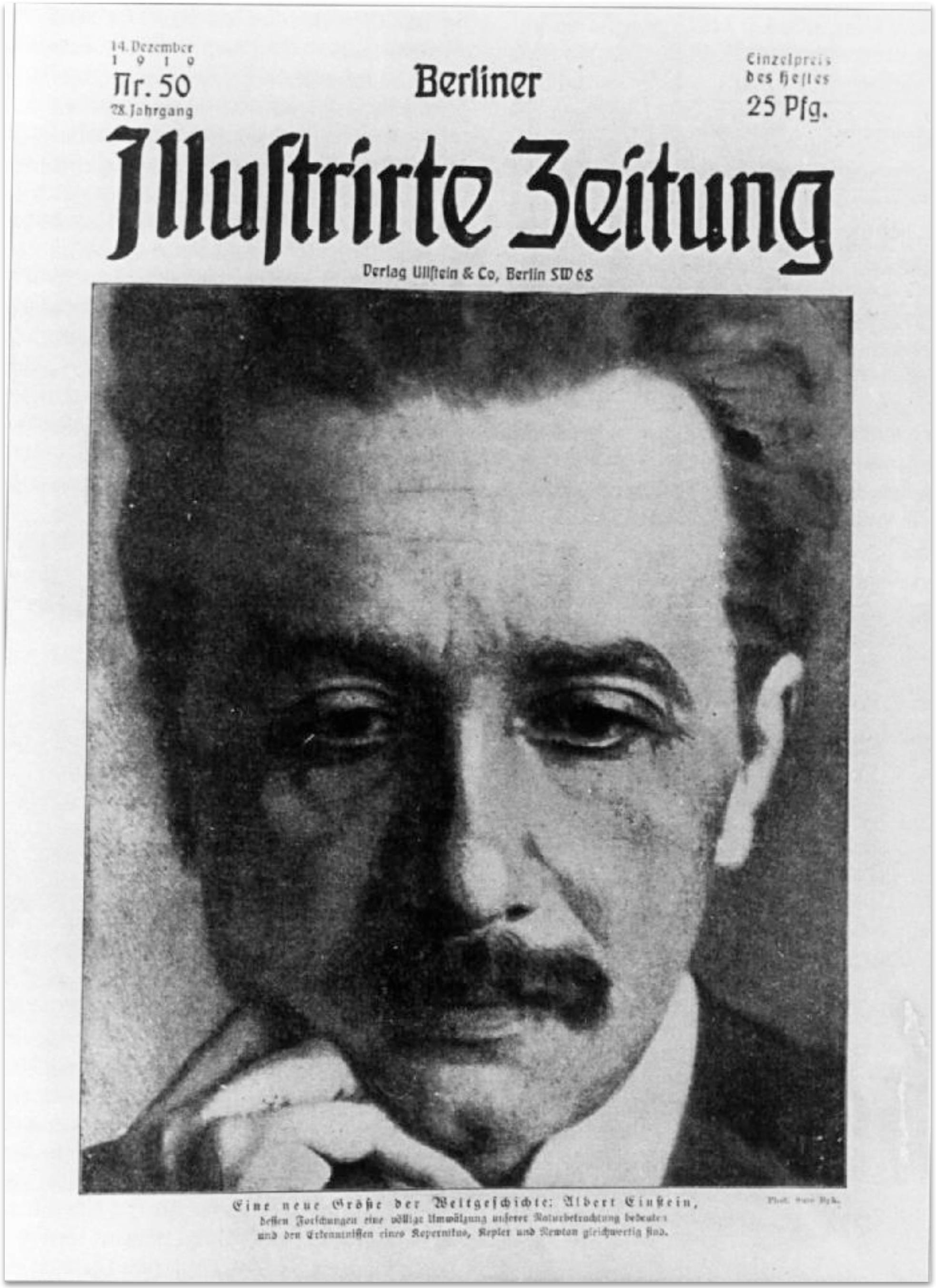
November 10, 1919

# 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.




# Dezember 14, 1919

**A new big name in world history:**

**Albert Einstein**,

whose research means a complete change of our view of Nature, equal to the discoveries of Copernicus, Kepler and Newton.

# A short history of Light Deflection

Einstein 1936:

DECEMBER 4, 1936

LENS-LIKE ACTION OF A STAR BY THE DEVIATION OF LIGHT IN THE GRAVITATIONAL FIELD

SOME time ago, R. W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request. This note complies with his wish.

Therefore, there is no great chance of observing this phenomenon, even if dazzling by the light of the much nearer star $B$ is disregarded. This apparent amplification of $q$ by the lens-like action of the star $B$ is a most curious effect, not so much for its becoming infinite, with $x$ vanishing, but since with increasing distance $D$ of the observer not only does it not decrease, but even increases proportionally to $\sqrt{D}$.

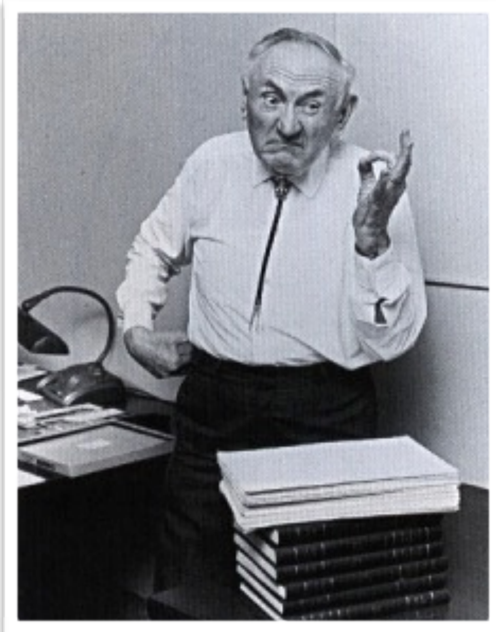
ALBERT EINSTEIN

INSTITUTE FOR ADVANCED STUDY,
PRINCETON, N. J.

# A short history of Light Deflection

Zwicky 1937: "Nebulae as gravitational lenses"

> As a consequence I made some calculations which show that extragalactic *nebulae* offer a much better chance than *stars* for the observation of gravitational lens effects.
>
> In the first place some of the massive and more concentrated nebulae may be expected to deflect light by as much as half a minute of arc. In the second place nebulae, in contradistinction to stars, possess apparent dimensions which are resolvable to very great distances.



1) additional test for General Relativity

2) "Telescope": fainter objects visible

3) determine masses: confirmation of [high!] masses of "nebu
(”dark matter”)

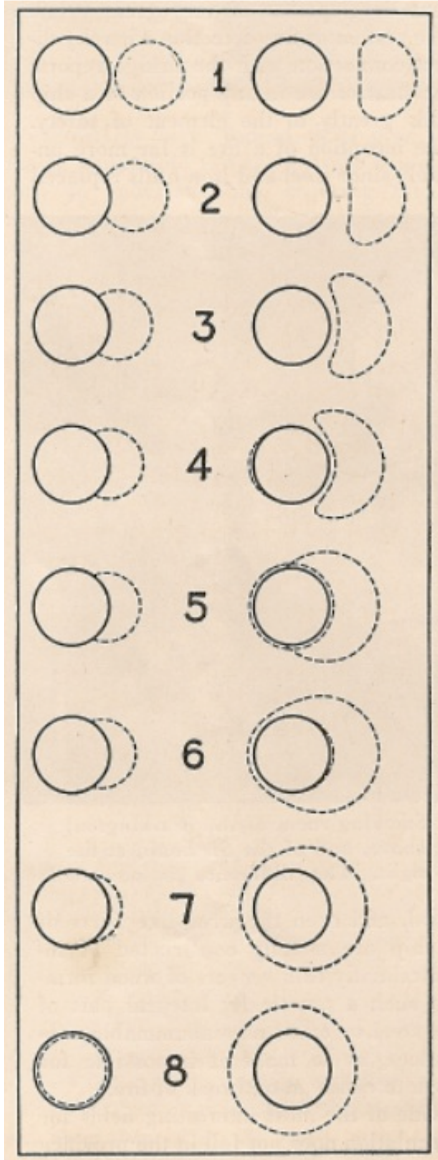
**Henry Norris Russell,** Scientific American, Feb 1937

# A RELATIVISTIC ECLIPSE

**What Might be Seen from a Planet Conveniently Placed Near the Companion of Sirius . . . Perfect Tests of General Relativity that are Unavailable**


By HENRY NORRIS RUSSELL, Ph. D.

Chairman of the Department of Astronomy and Director of the Observatory at Princeton University. Research Associate of the Mount Wilson Observatory of the Carnegie Institution of Washington. President of the American Astronomical Society.


My hearty thanks are due to Professor Einstein, who permitted me to see the manuscript of his note before its publication.—*Princeton University Observatory, December 2, 1936.*

1) "Einstein effect" is perfect (but unavailable) test for GR: "effects conspicuous to the immediate gaze"

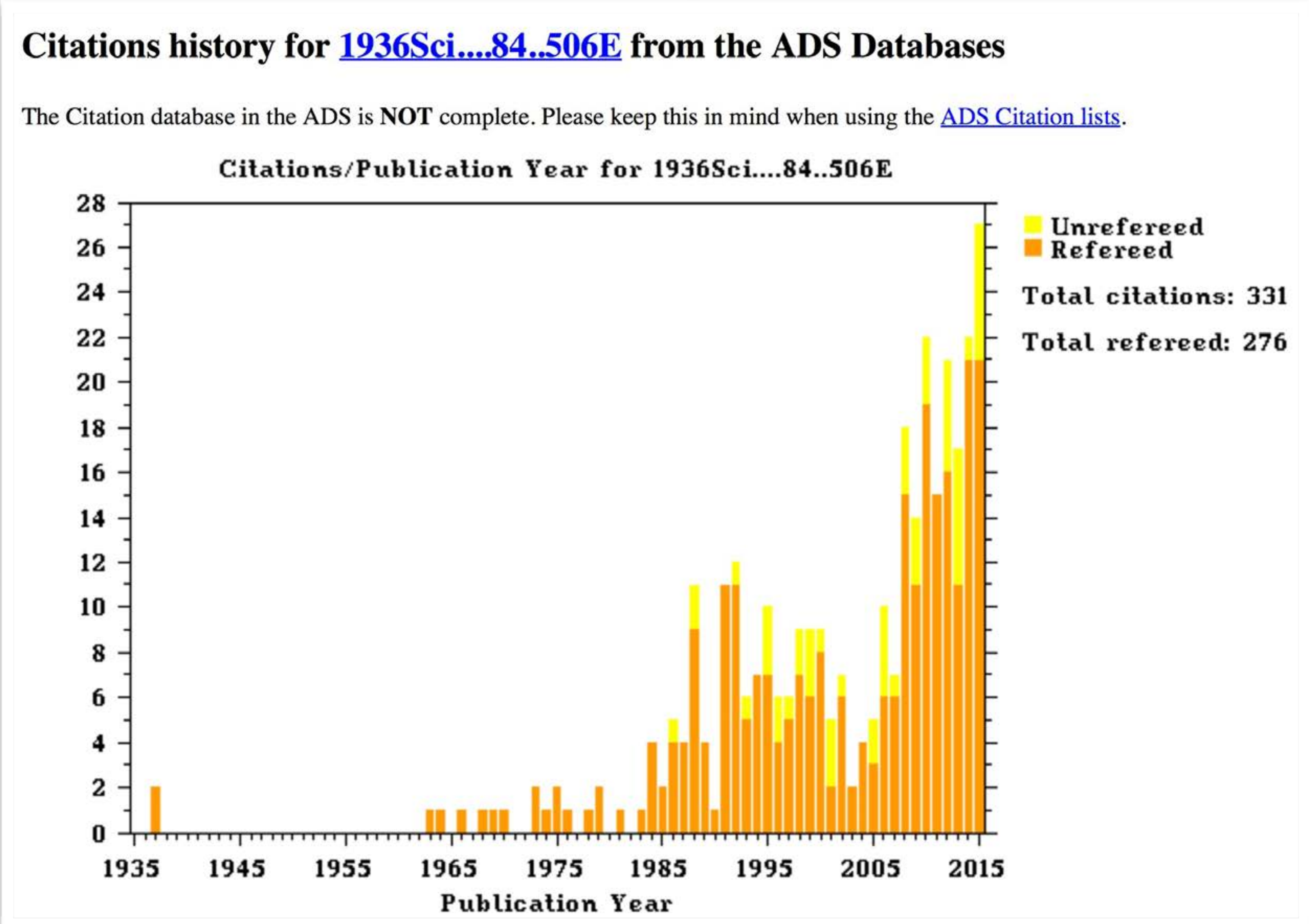
2) source is not point-like: "finite angular size"

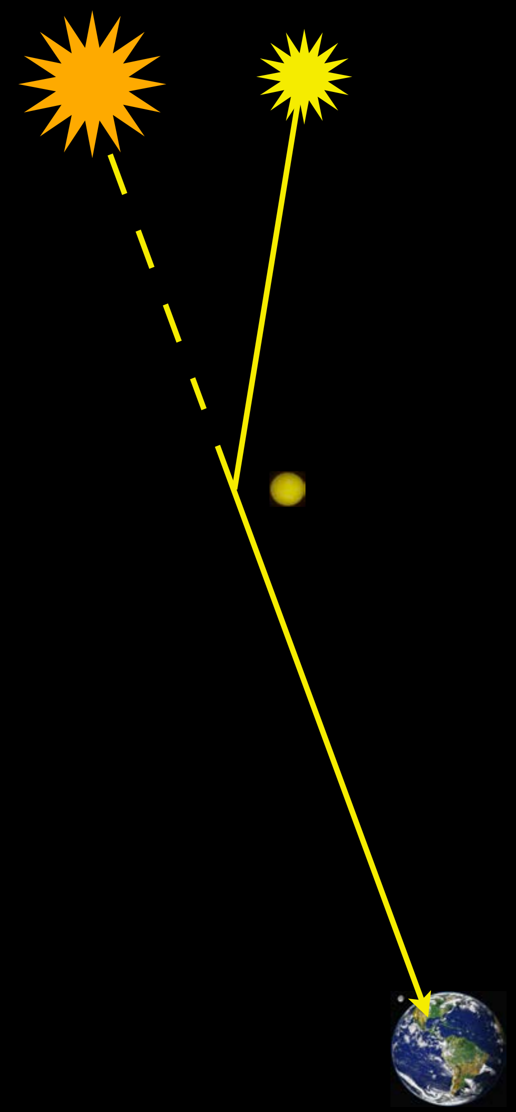
3) image "appears to be enlarged vertically", "bright crescent", "image has developed pointed horns"

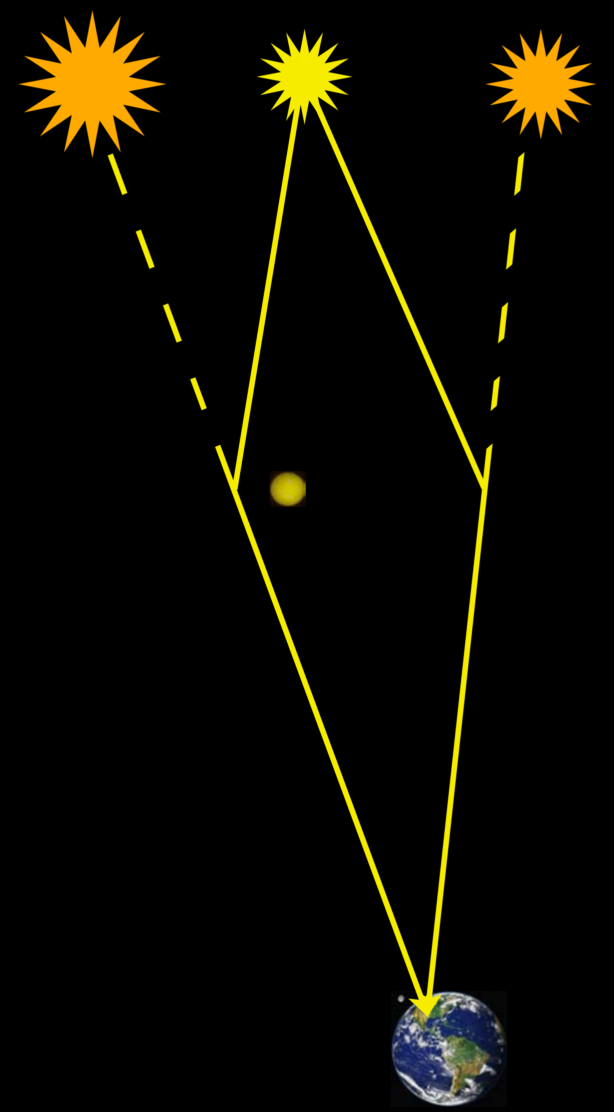
4) "most spectacular phenomena of the heavens"

# A short history of Light Deflection

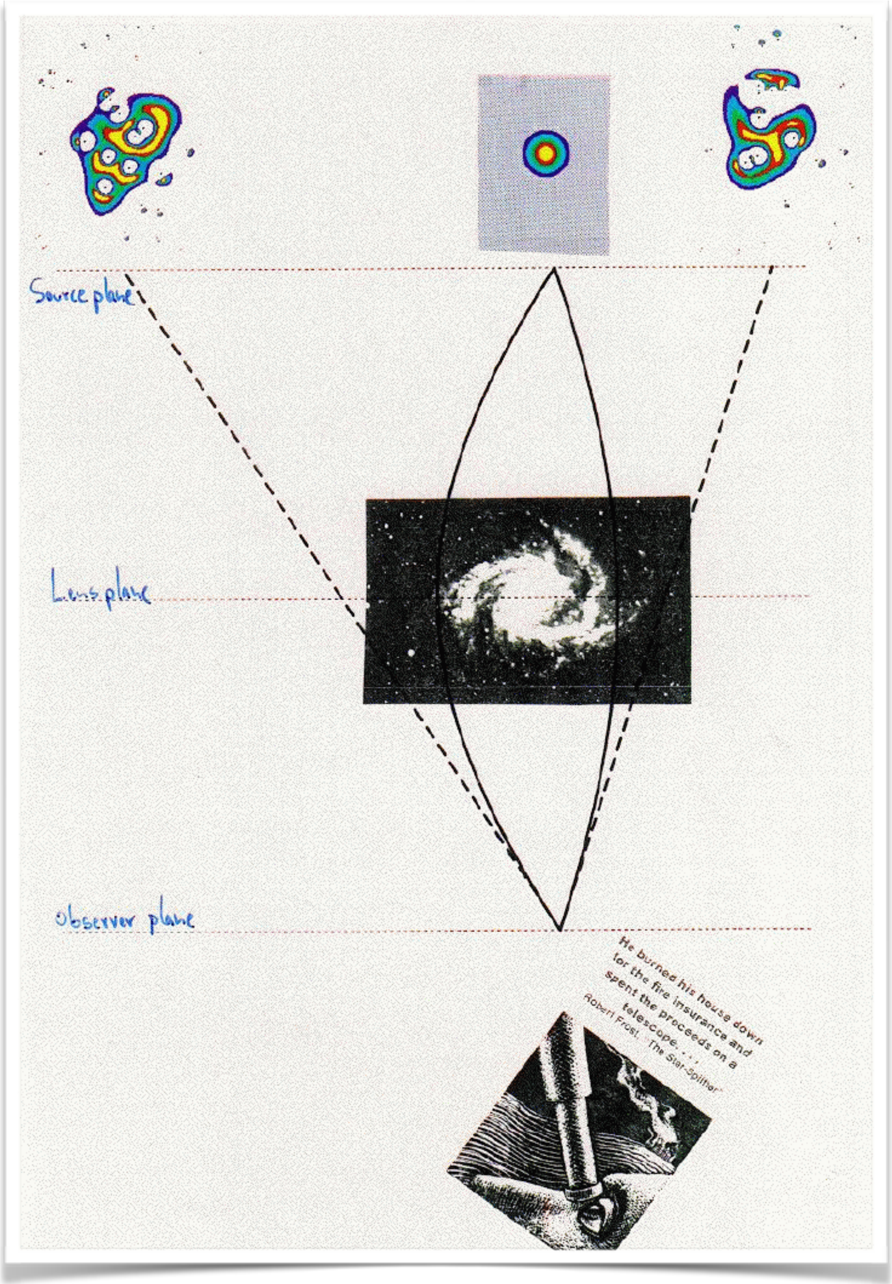
Einstein 1936:



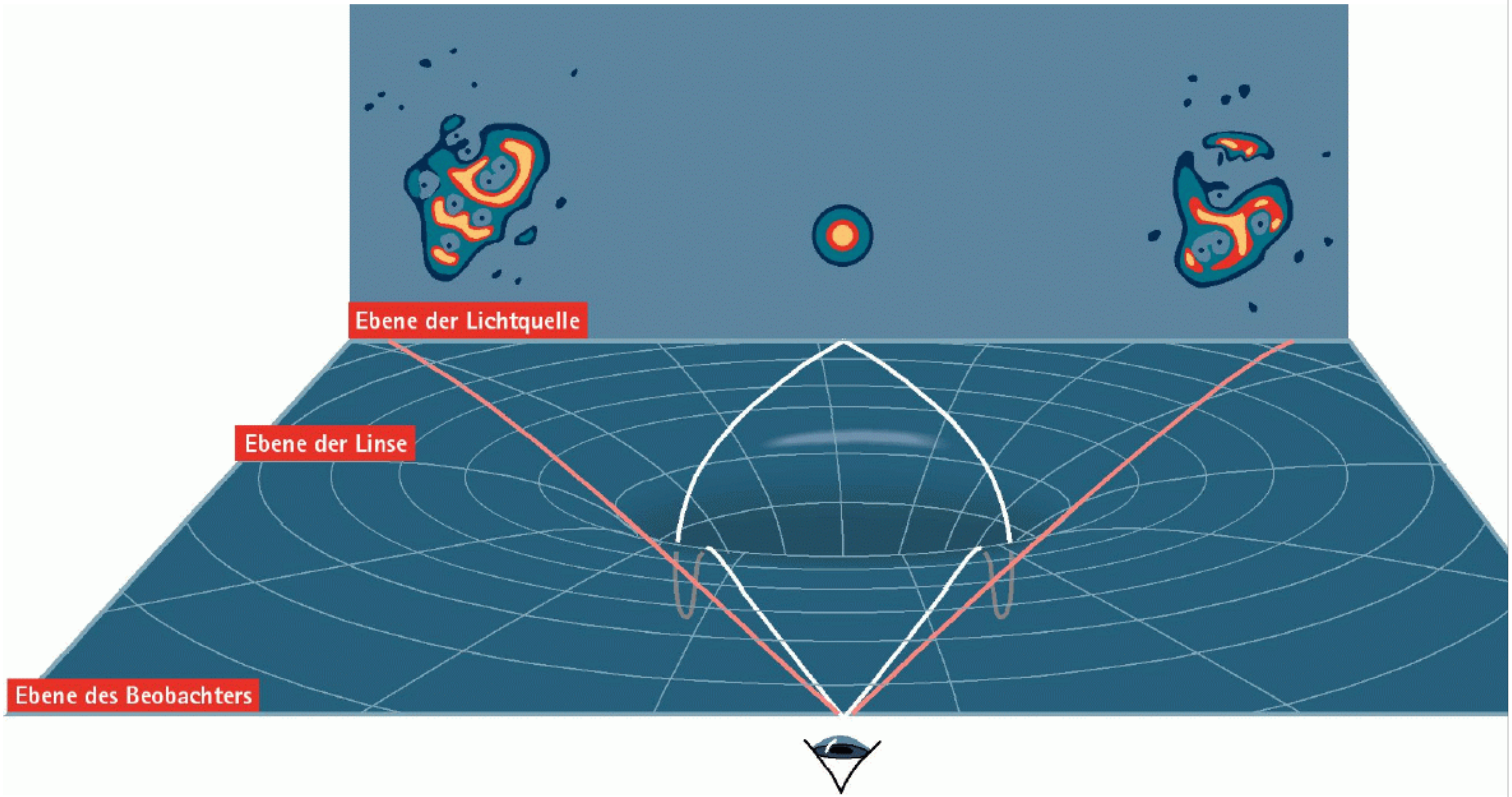




# Geometry of Gravitational Lensing Effect



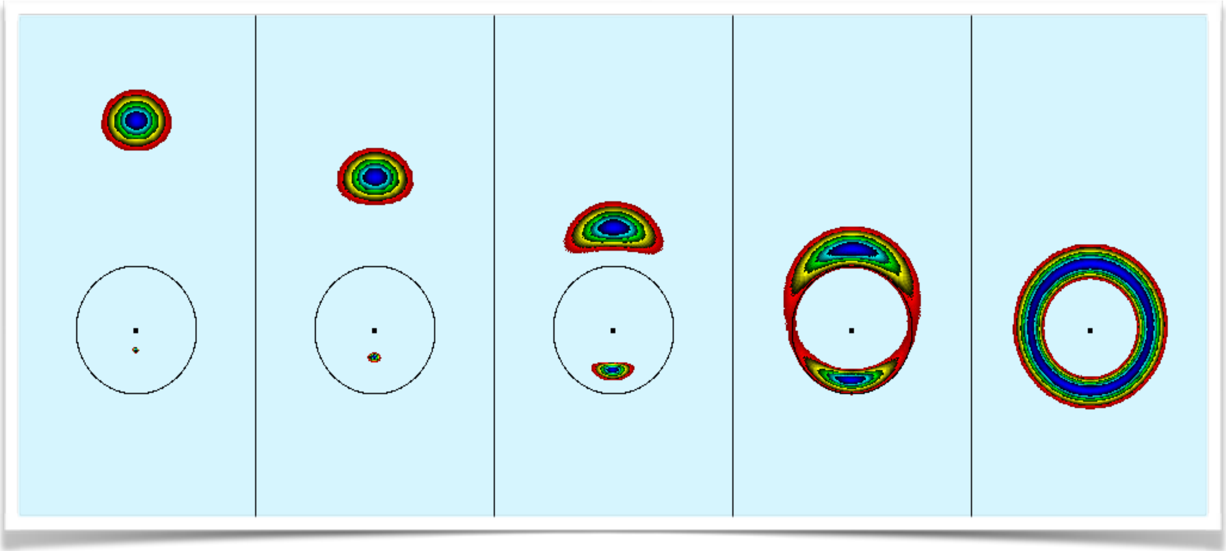
# Geometry of Gravitational Lensing Effect

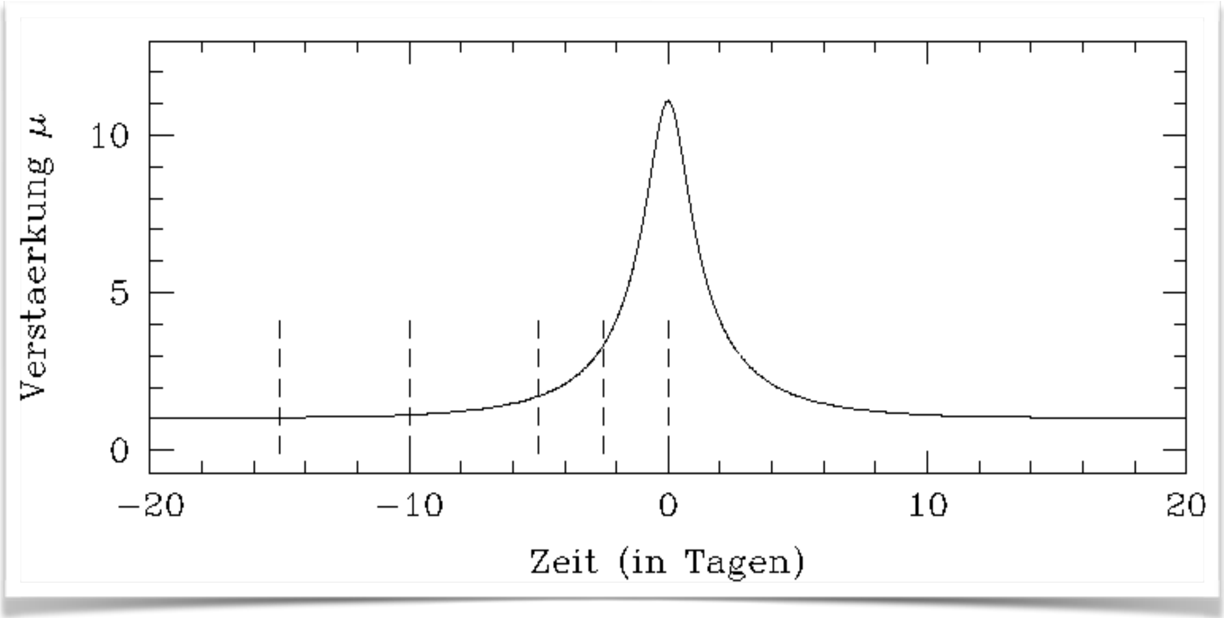


# Effects of Gravitational Lensing

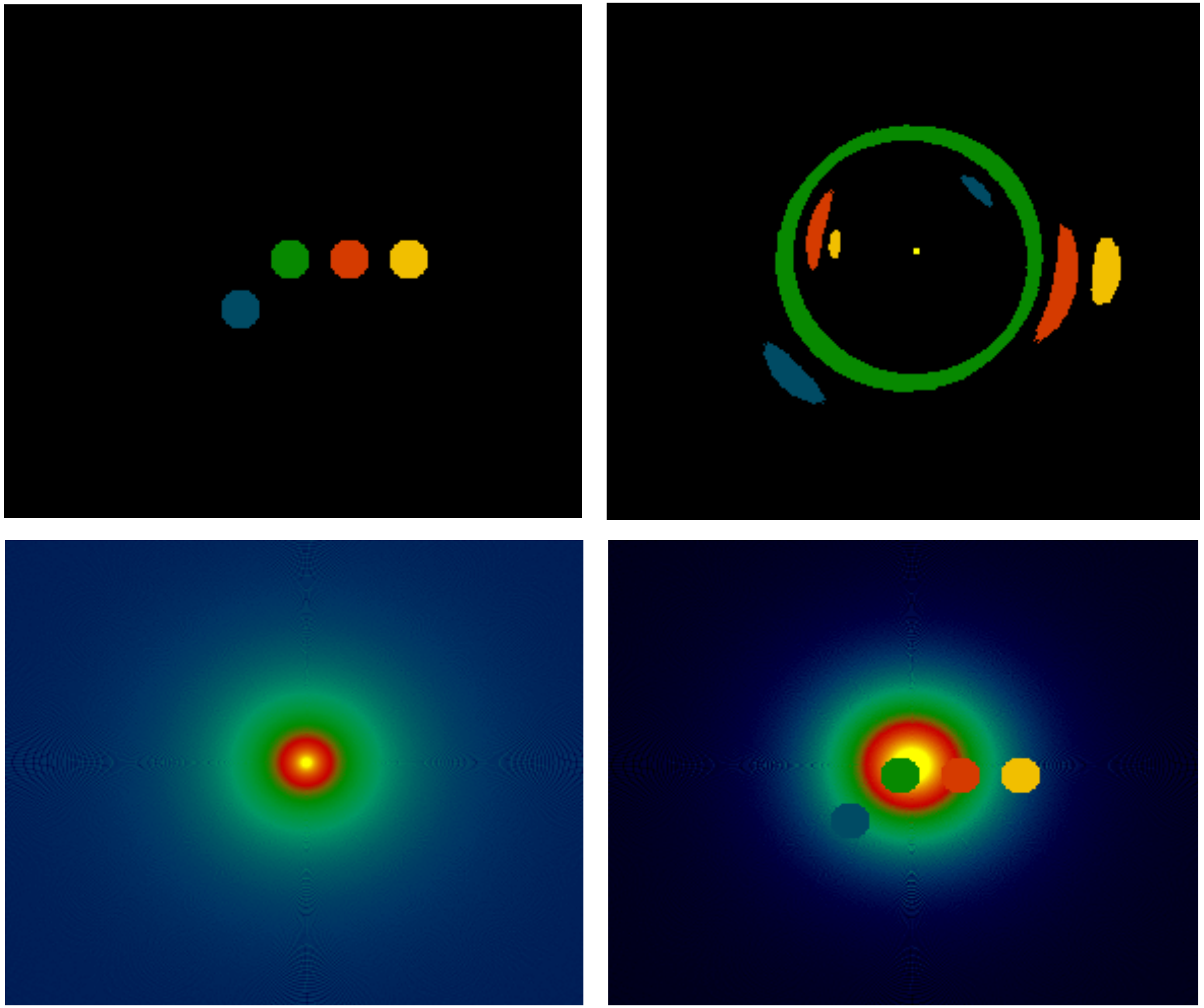
- Change of Position
  - first confirmation of light deflection (1919!)
  - »normally« not observable
- Distortion
  - extended sources: Galaxies
- Magnification/Demagnification
  - Stars: may appear brigher/dimmer
  - Galaxies: may appear larger/smaller
- Multiple Images
  - most dramatic effect

# Effects of Gravitational Lensing: Point lens and extended source

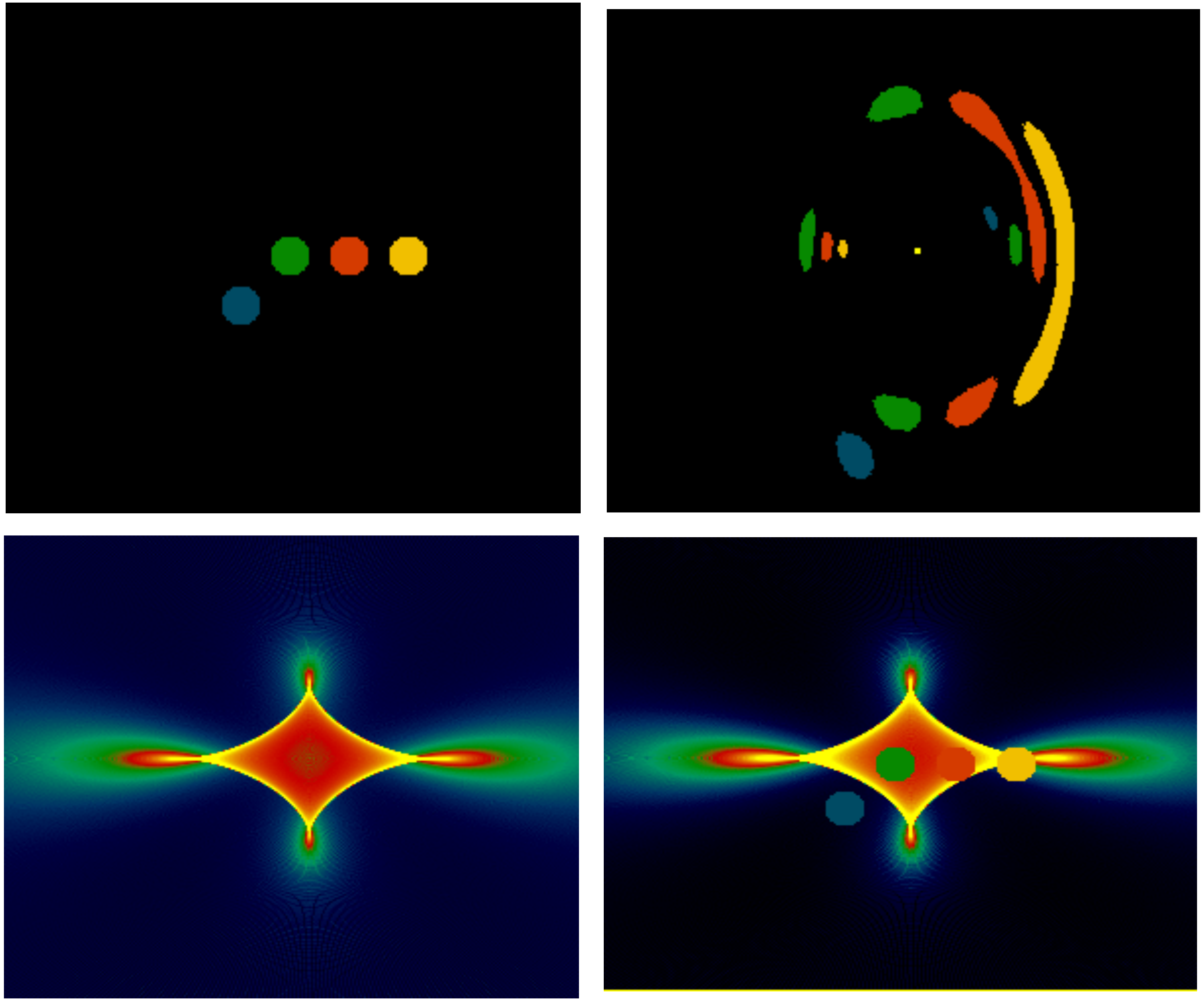




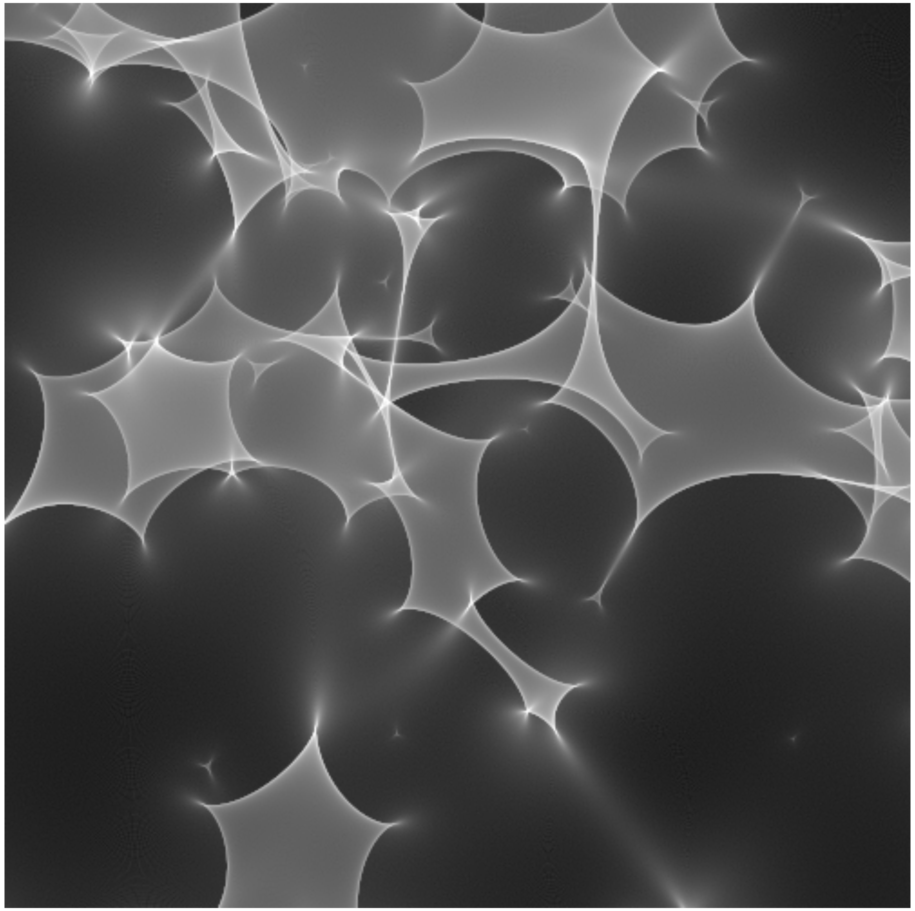
# Effects of Gravitational Lensing: Point lens and extended source

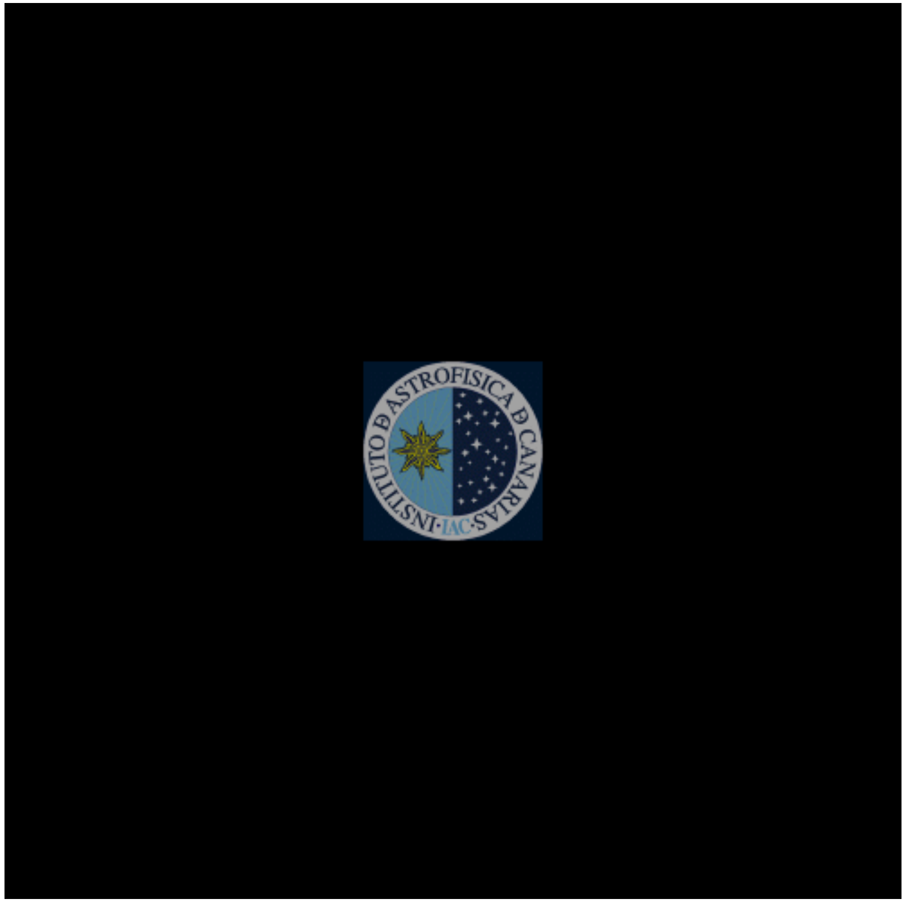


# Effects of Gravitational Lensing: Point lens and more

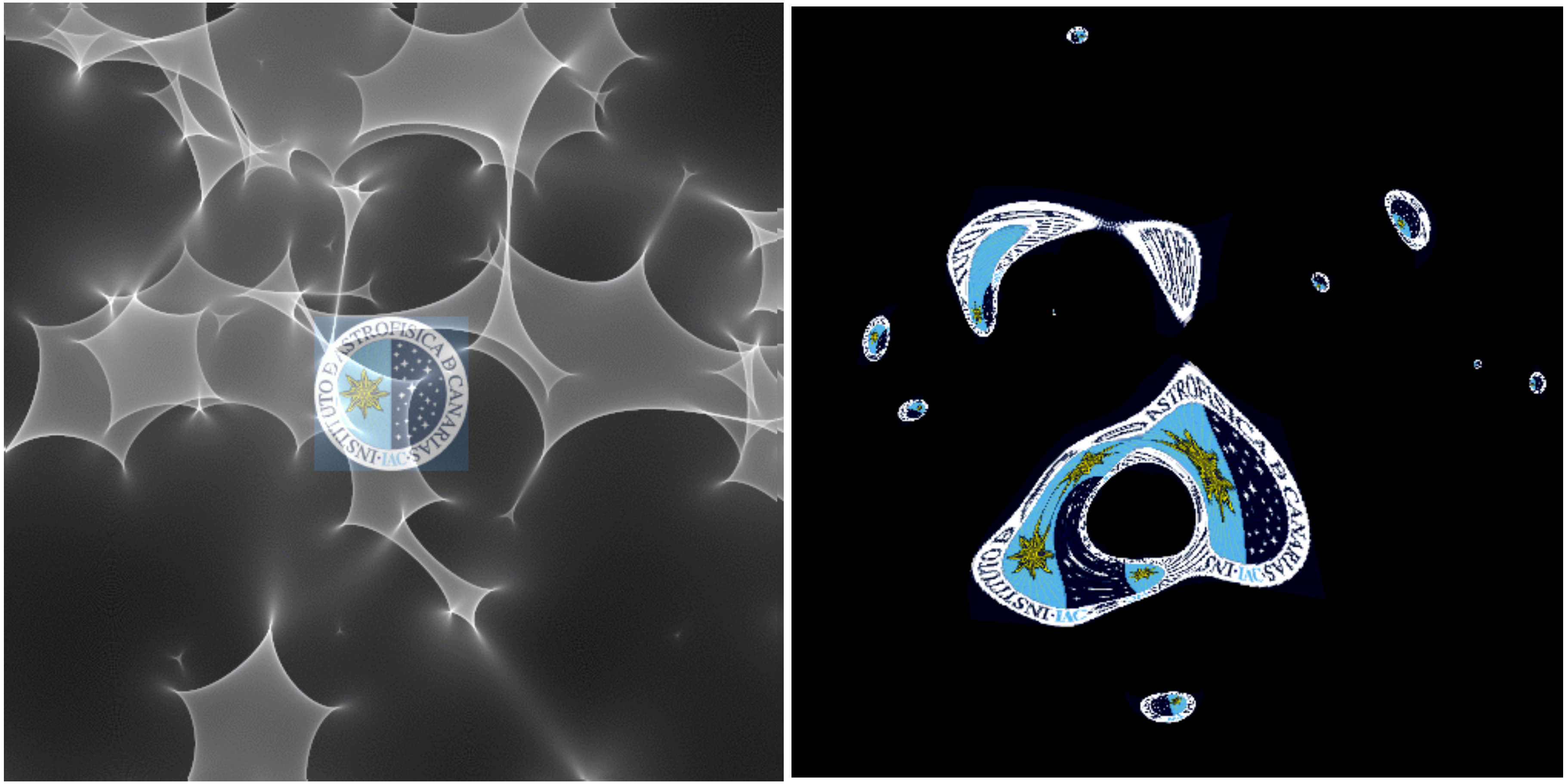


# Wirkungen des Gravitationslinseneffekts: Viele Punkt-Linsen





# Wirkungen des Gravitationslinseneffekts: Viele Punkt-Linsen



# Effects of Gravitational Lensing: Experiment with one point lens

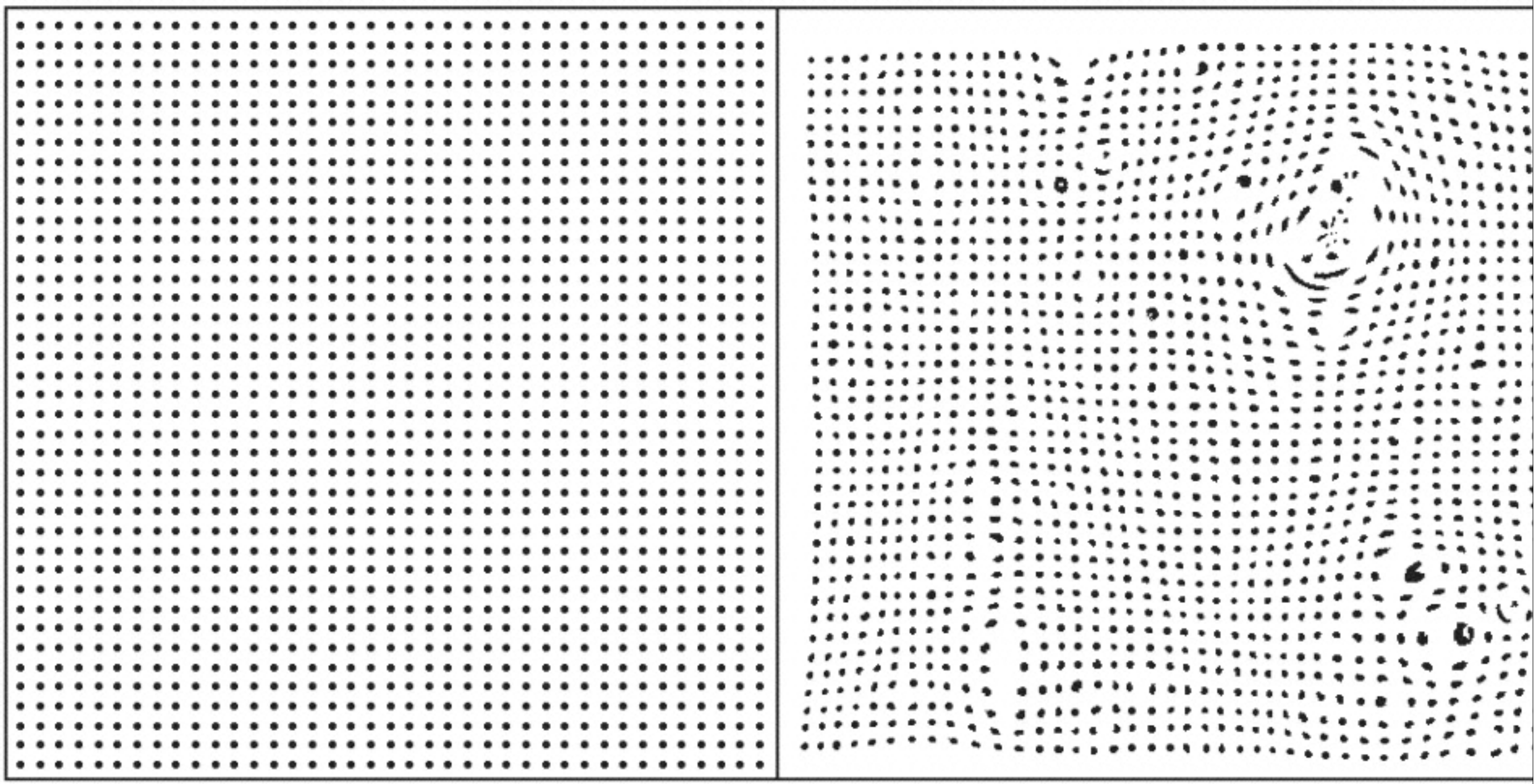

(from Phil Yock)

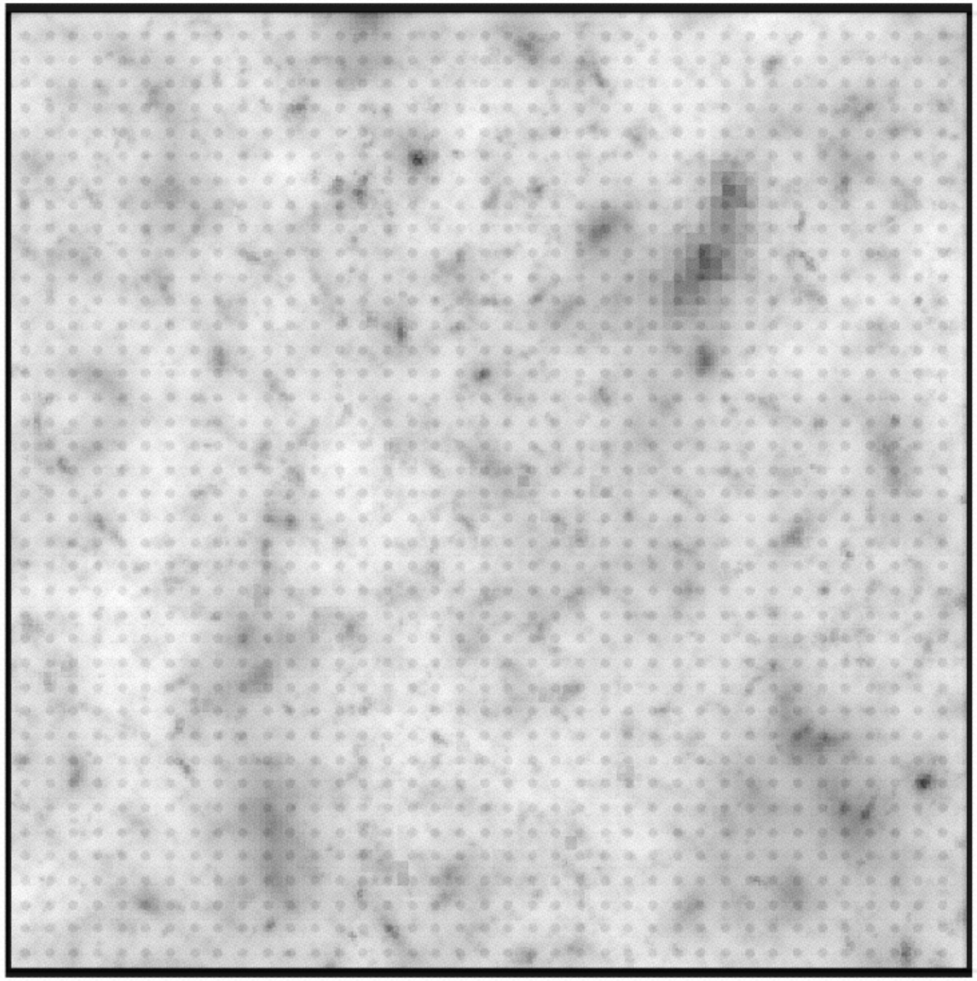
(from Phil Yock)

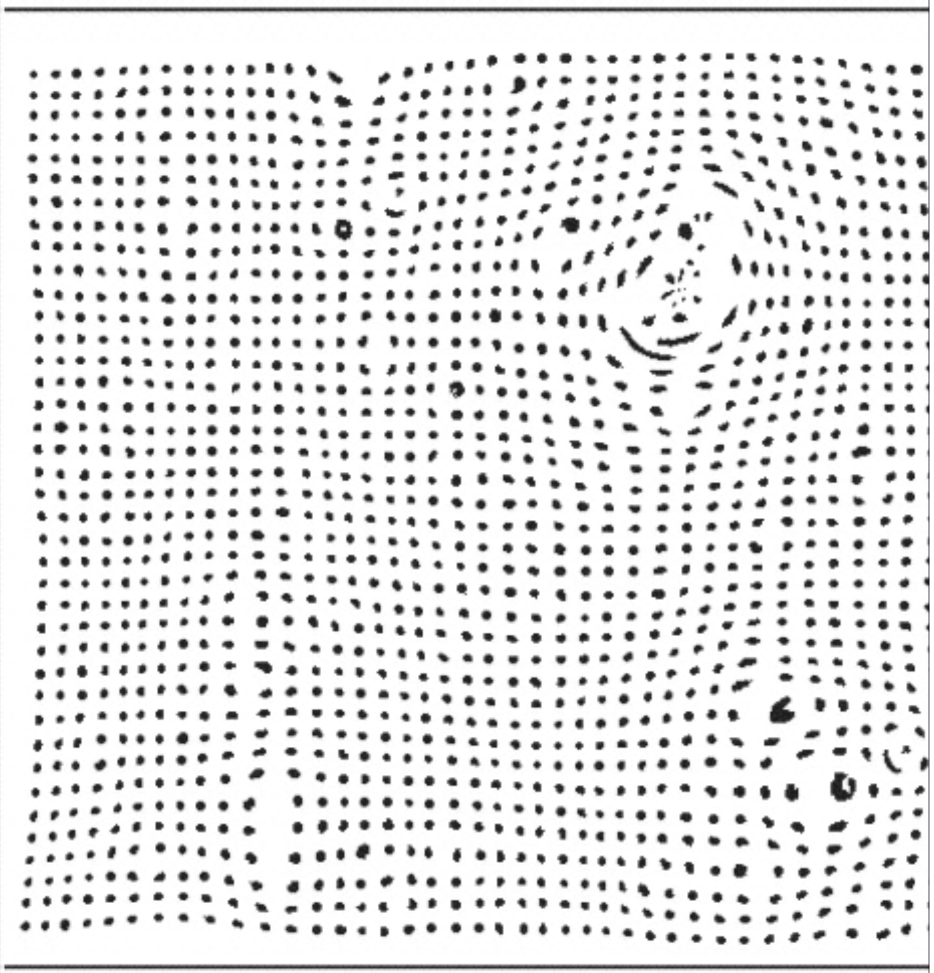
# Gravitational Lens Phenomena

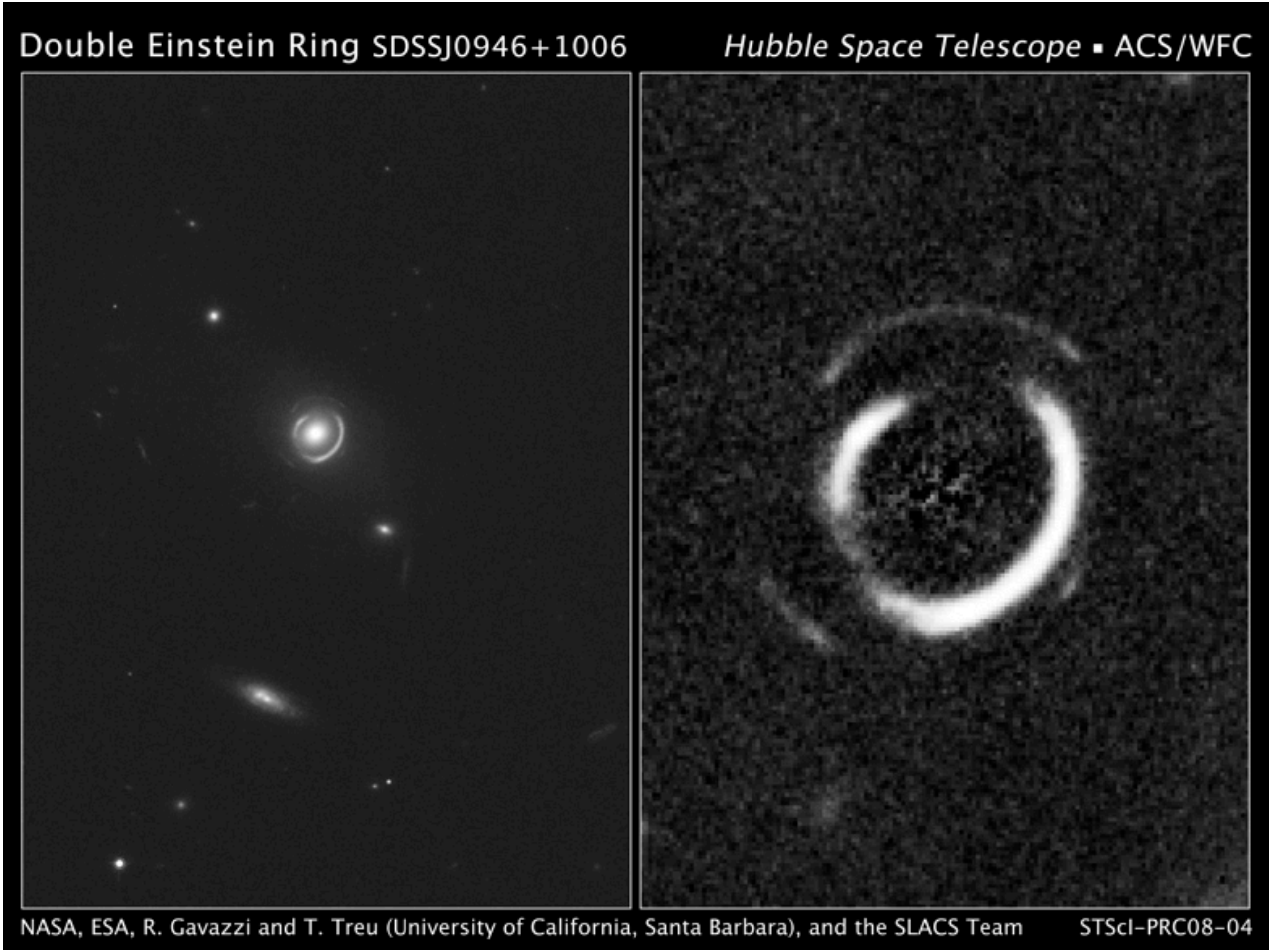
- Giant Luminous Arcs
- Einstein Rings
- Microlensing by Exoplanets


Galaxy Cluster Abell 1689

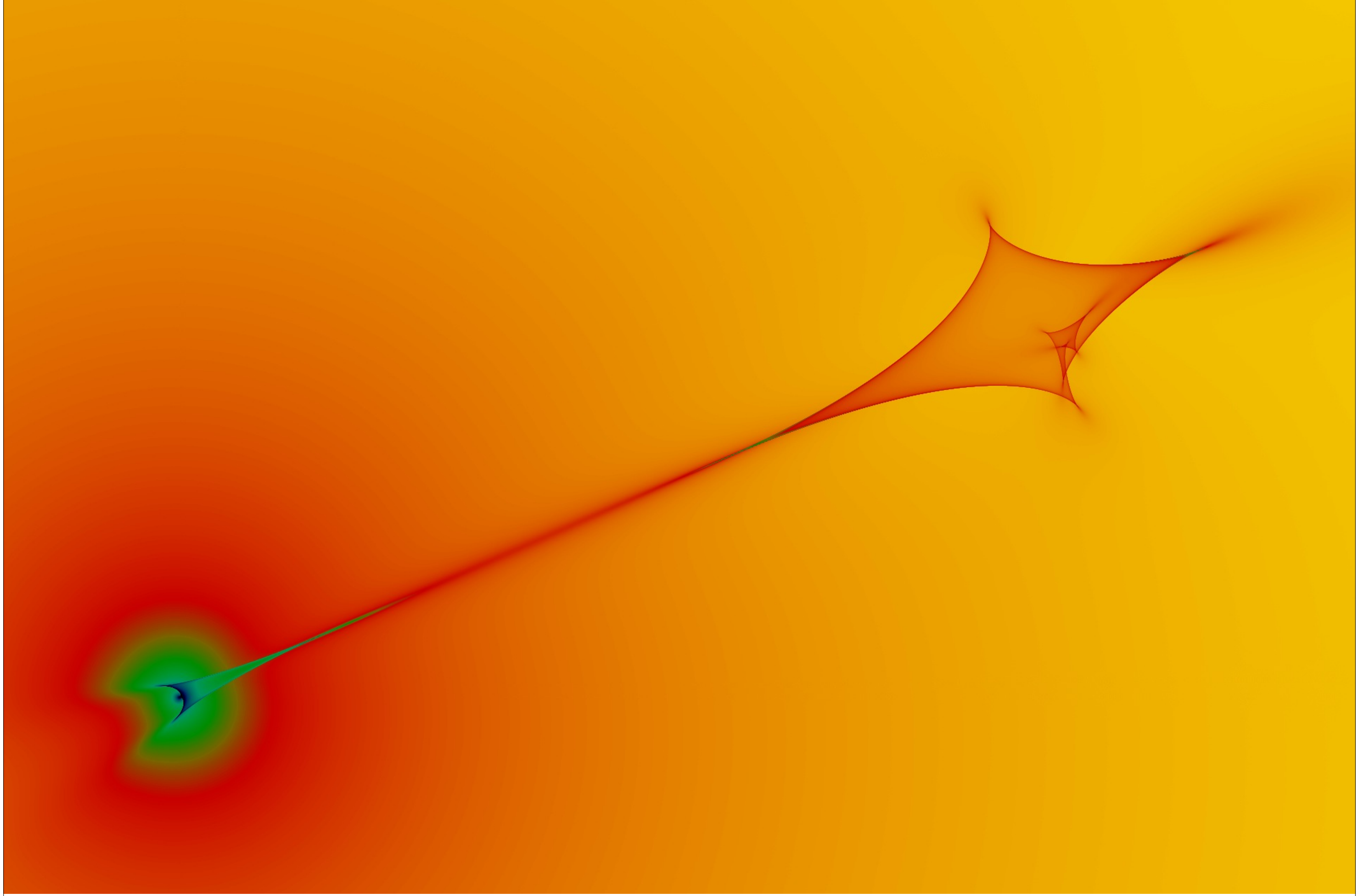


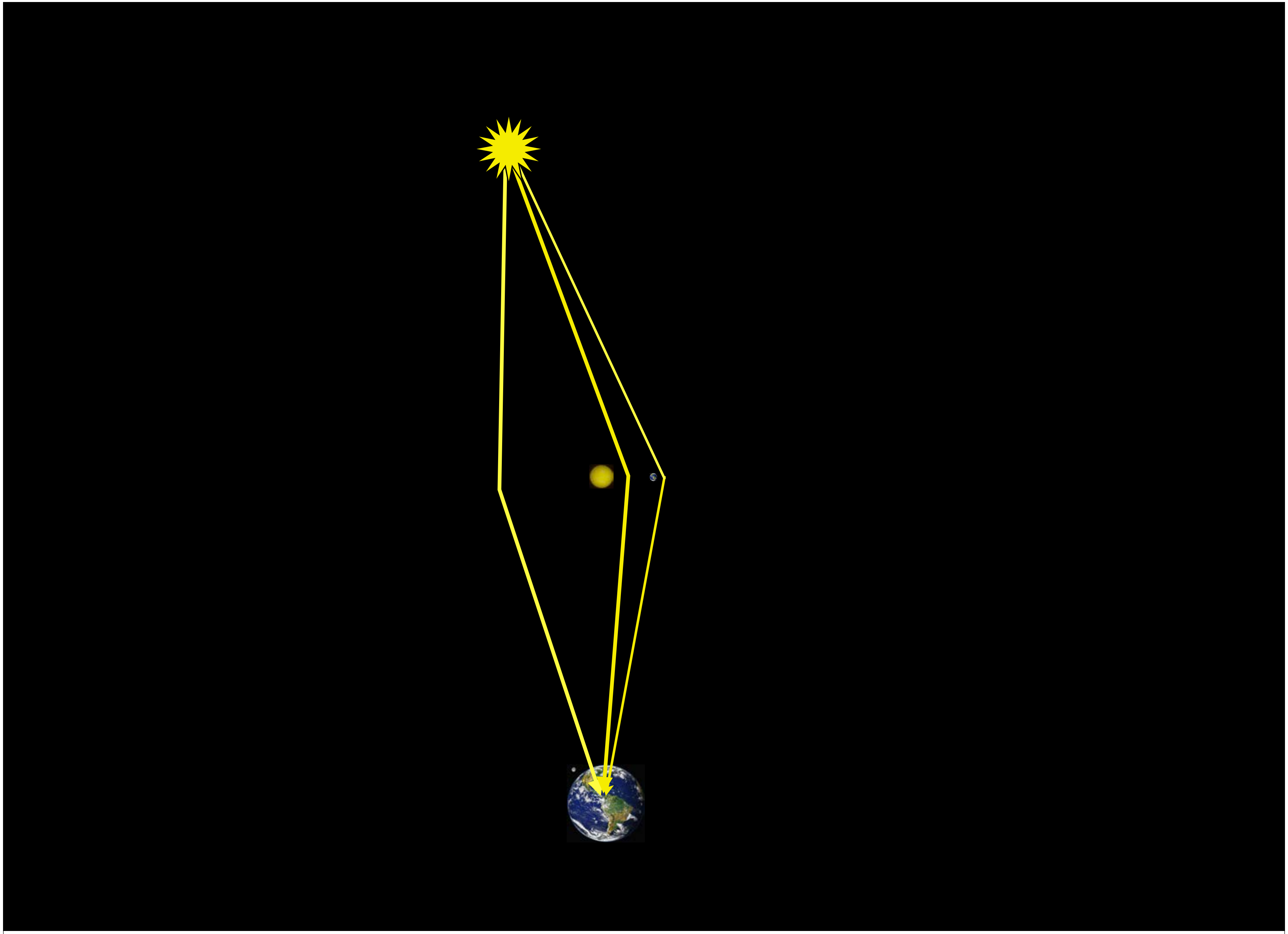




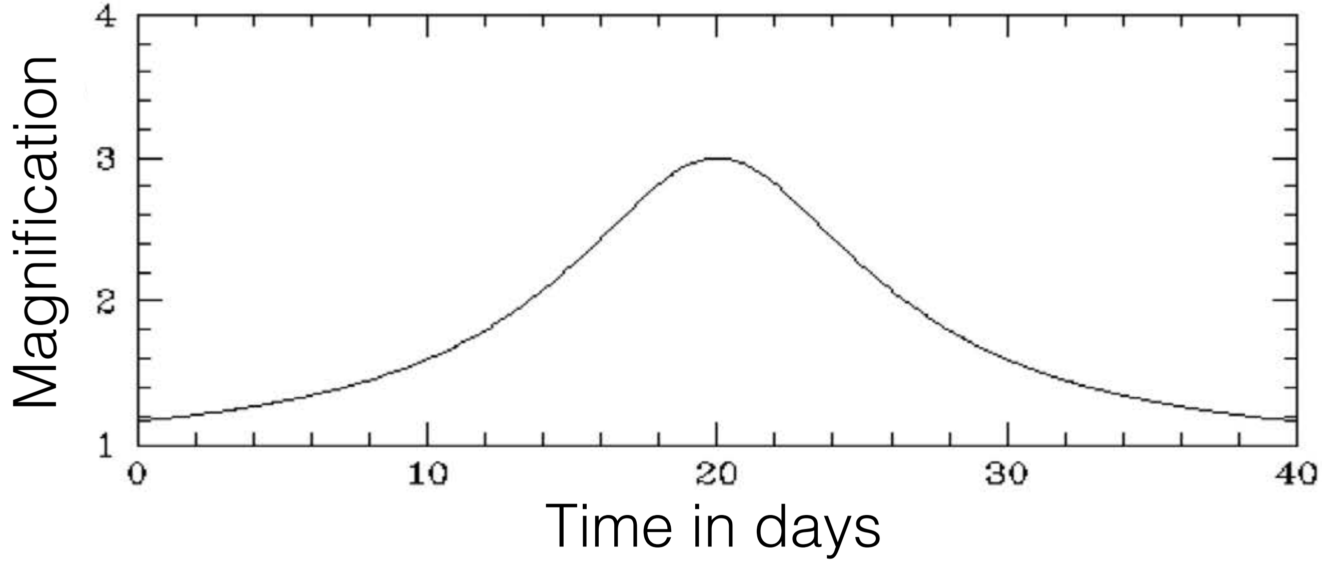

Double Einstein Ring SDSSJ0946+1006
Hubble Space Telescope ▪ ACS/WFC
NASA, ESA, R. Gavazzi and T. Treu (University of California, Santa Barbara), and the SLACS Team
STScI-PRC08-04

# Microlensing by Exoplanets

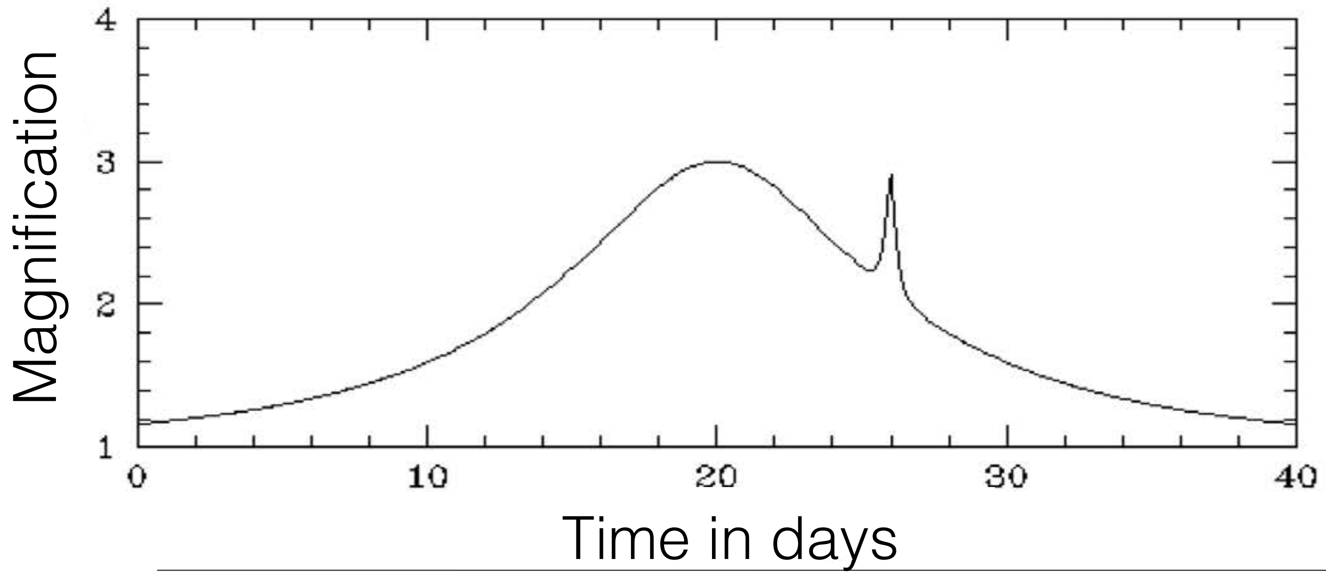




# Astrophysical Application of Gravitational Lensing:
## Searching for planets around other stars



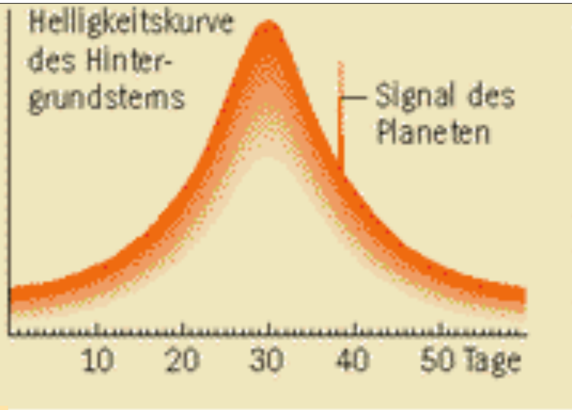

Background star magnified by single lens star




Background star magnified by single lens star **plus planet**

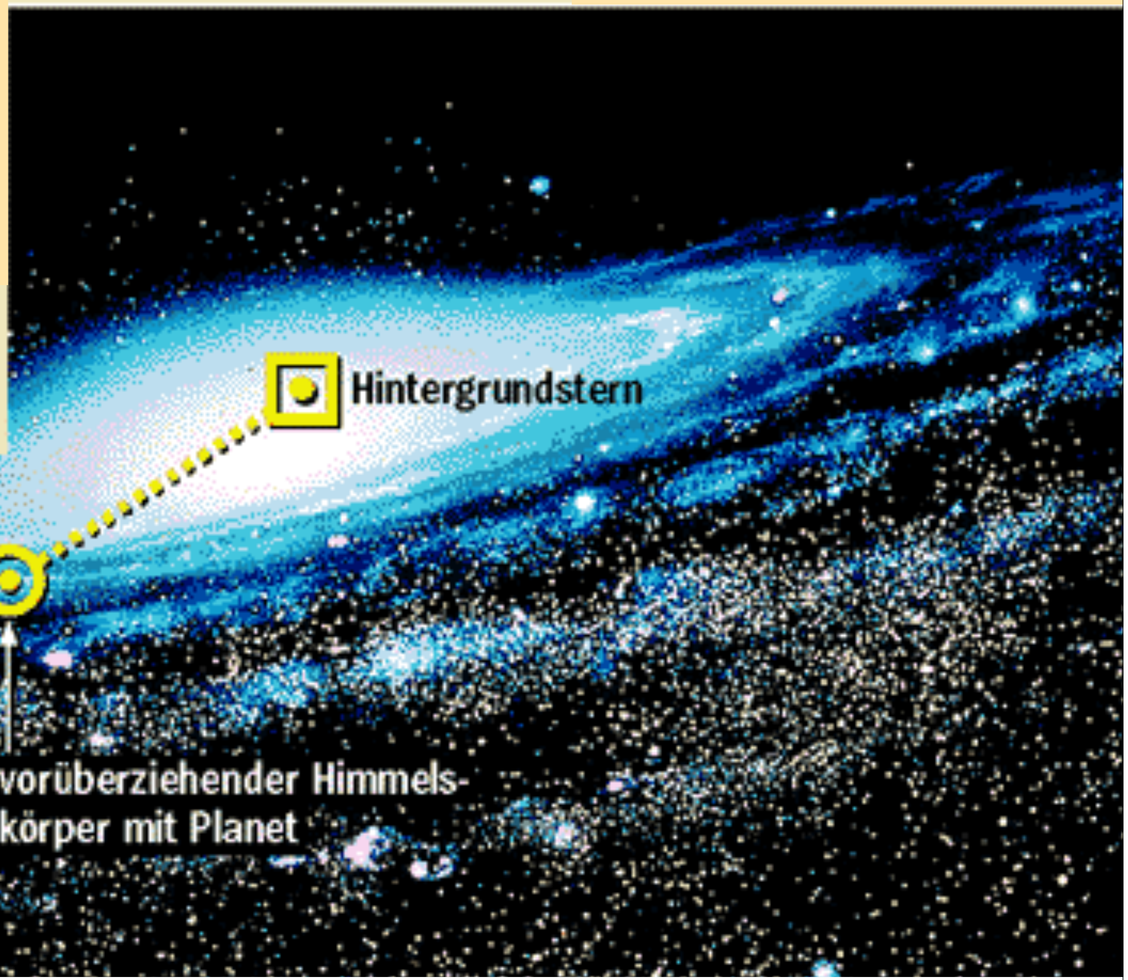
## Principle of a gravitational lens:

Unperturbed light rays: A relatively small fraction of the stellar light reaches Earth.

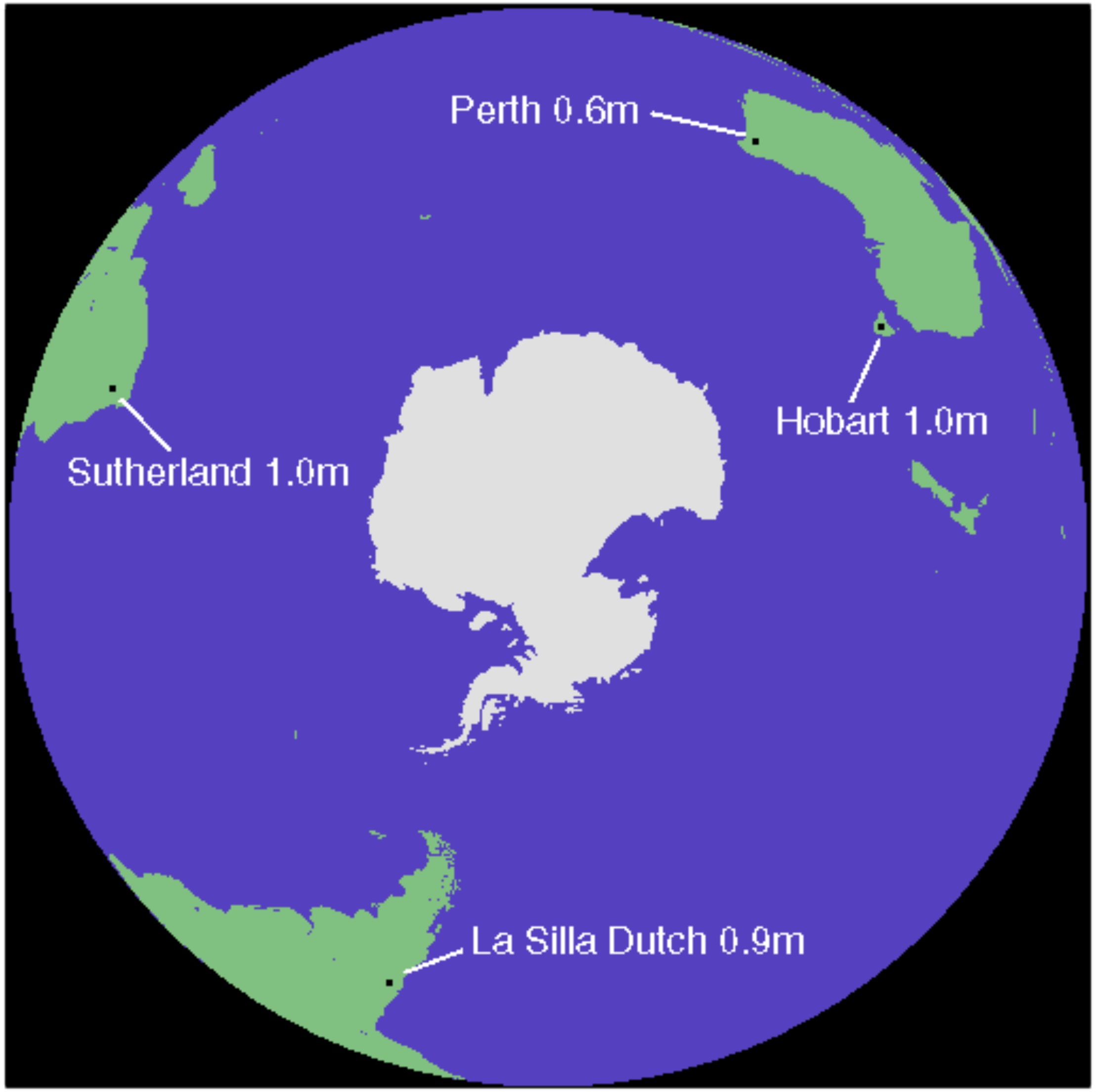

Astronomers register the temporary increase of brightness of the background star as a symmetric light curve. If the lensing star is accompanied by a planet, an additional peak can occur.

If a massive object passes between background star and Earth, its gravity attracts and focusses the light rays like a lens: More light reaches Earth, the **background star appears brighter**.

Searching for exoplanets with microlensing:

The 24-hour night shift: The Telescopes



Searching for exoplanets with microlensing:

Vol 439|26 January 2006|**doi:10.1038/nature04441** nature

LETTERS

# Discovery of a cool planet of 5.5 Earth masses through gravitational microlensing

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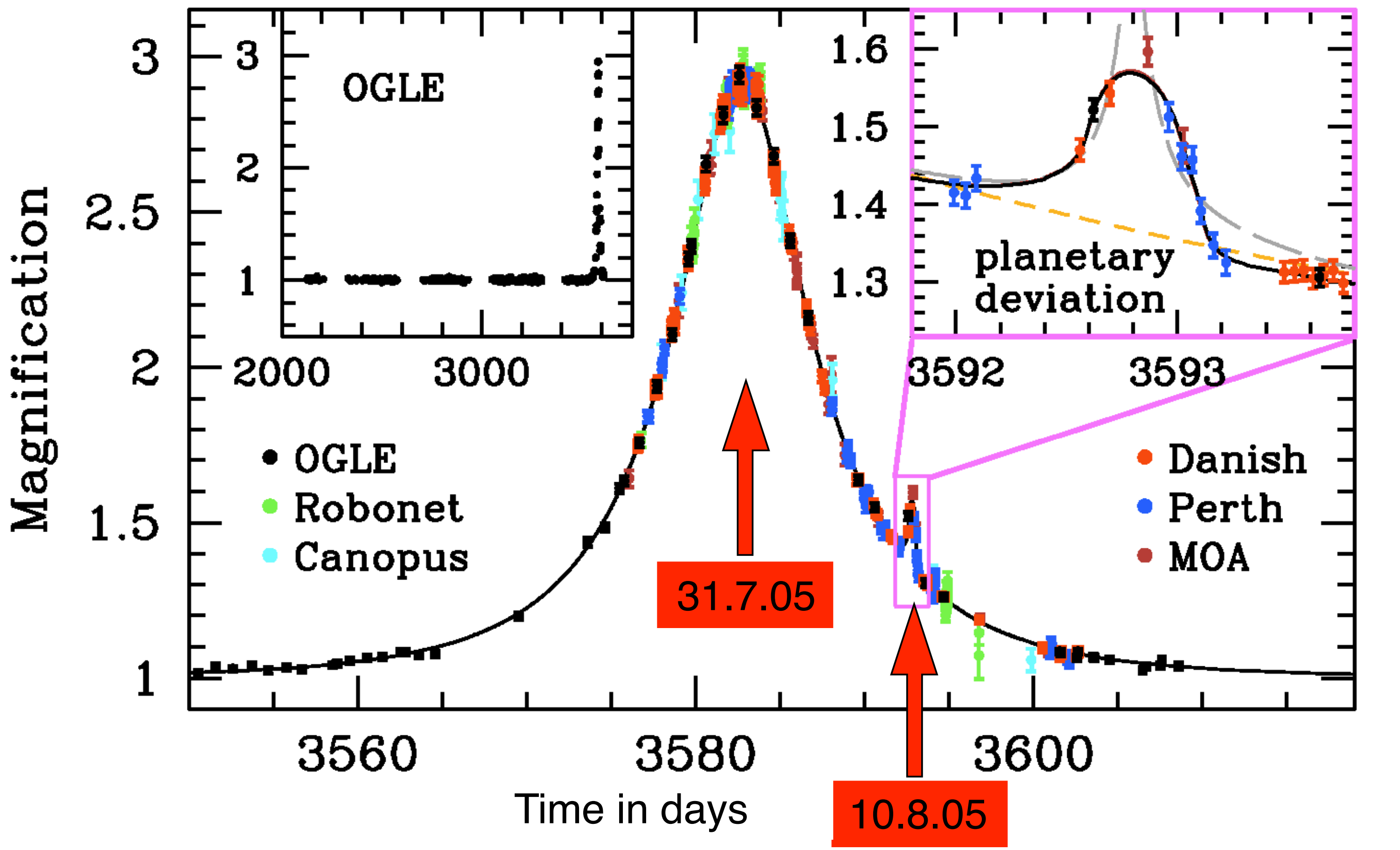
# Searching for exoplanets with microlensing:

Detection of a planet with 5.5 times the mass of Earth



# Planets are the rule, not the exception:

# All stars in the Milky Way have on average at least one planet!

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## One or more bound planets per Milky Way star from microlensing observations

A. Cassan[1,2,3], D. Kubas[1,2,4], J.-P. Beaulieu[1,2,25], M. Dominik[1,5], K. Horne[1,5], J. Greenhill[1,6], J. Wambsganss[1,3], J. Menzies[1,7], A. Williams[1,8], U. G. Jørgensen[1,9], A. Udalski[10,11], D. P. Bennett[1,12], M. D. Albrow[1,13], V. Batista[1,2], S. Brillant[1,4], J. A. R. Caldwell[1,14], A. Cole[1,6], Ch. Coutures[1,2], K. H. Cook[1,15], S. Dieters[1,6], D. Dominis Prester[1,16], J. Donatowicz[1,17], P. Fouqué[1,18], K. Hill[1,6], N. Kains[1,19], S. Kane[1,20], J.-B. Marquette[1,2], R. Martin[1,8], K. R. Pollard[1,13], K. C. Sahu[1,14], C. Vinter[1,9], D. Warren[1,6], B. Watson[1,6], M. Zub[1,3], T. Sumi[21,22], M. K. Szymański[10,11], M. Kubiak[10,11], R. Poleski[10,11], I. Soszynski[10,11], K. Ulaczyk[10,11], G. Pietrzyński[10,11,23] & Ł. Wyrzykowski[10,11,24]

nature

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# Free floating planets ?!?

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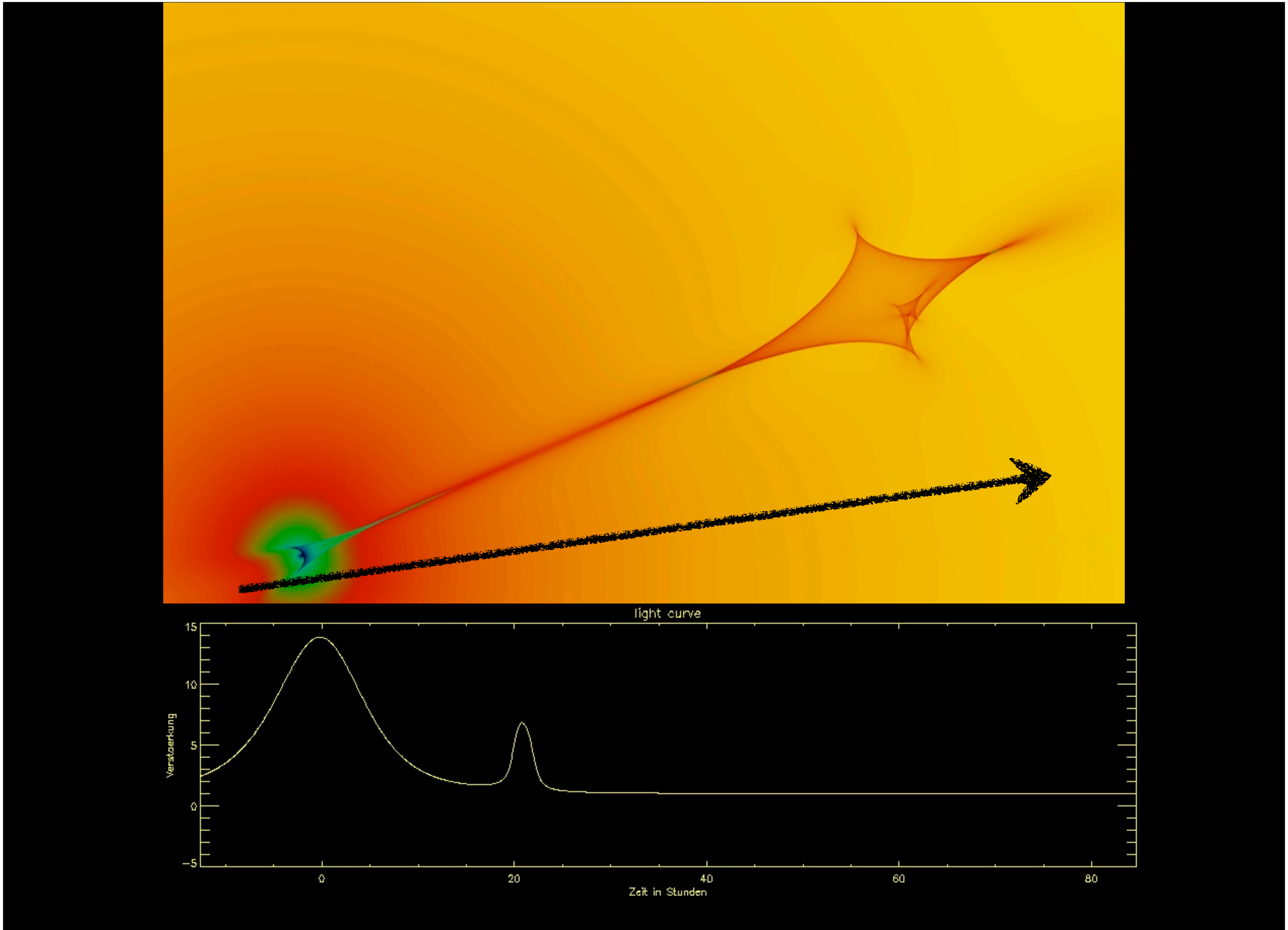
## Unbound or distant planetary mass population detected by gravitational microlensing

The Microlensing Observations in Astrophysics (MOA) Collaboration & The Optical Gravitational Lensing Experiment (OGLE) Collaboration*

nature

Sumi et al., Nature 473, 349 (May 19, 2011)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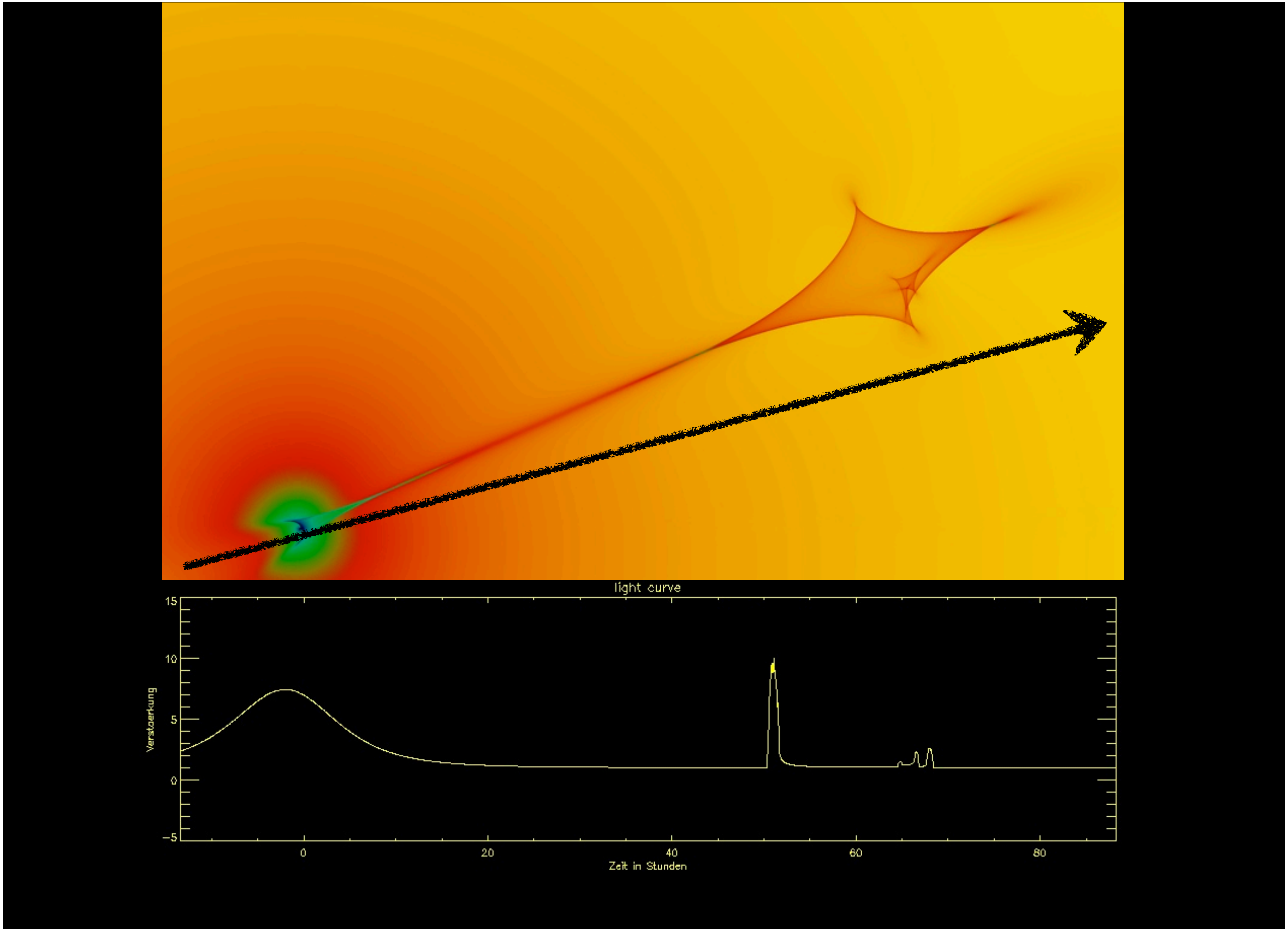
10
5
0
−5
Verstaerkung
0
20
40
60
80
Zeit in Stunden


light curve
15
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Verstaerkung
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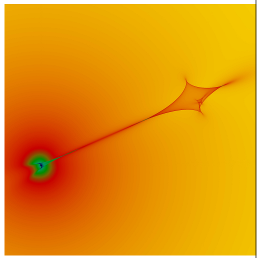
Zeit in Stunden

# Gravitational Lensing: Giant Luminous Arcs, Einstein Rings and Exoplanets

Prof. Joachim Wambsganss
(Heidelberg University)



Gravitational Lensing is an extremely useful tool in modern astrophysics:

- **Giant Luminous Arcs** are highly magnified background galaxies which can be studied in great detail; using them we can determine mass/mass distributions of galaxy clusters
- **Einstein Rings** can be used to determine the mass of the lensing galaxy very accurately
- Gravitational Microlensing is a very efficient method for the detection of **extrasolar planets**: sensitive to low masses and well suited for statistical analyses

… so 80 years after Einstein's original paper in 1936:
**Yes, we can** detect this effect and make great use of it in astrophysics !