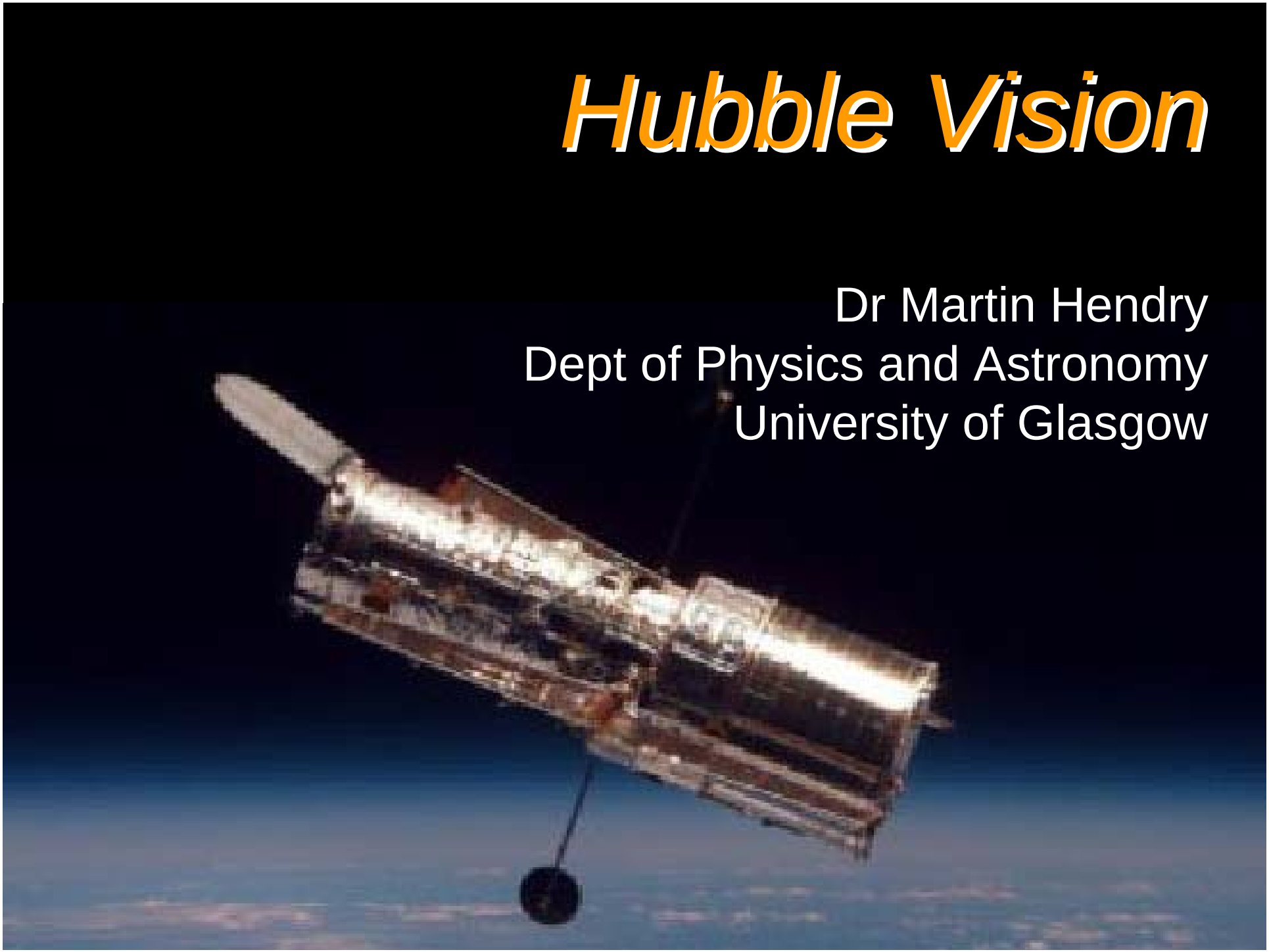
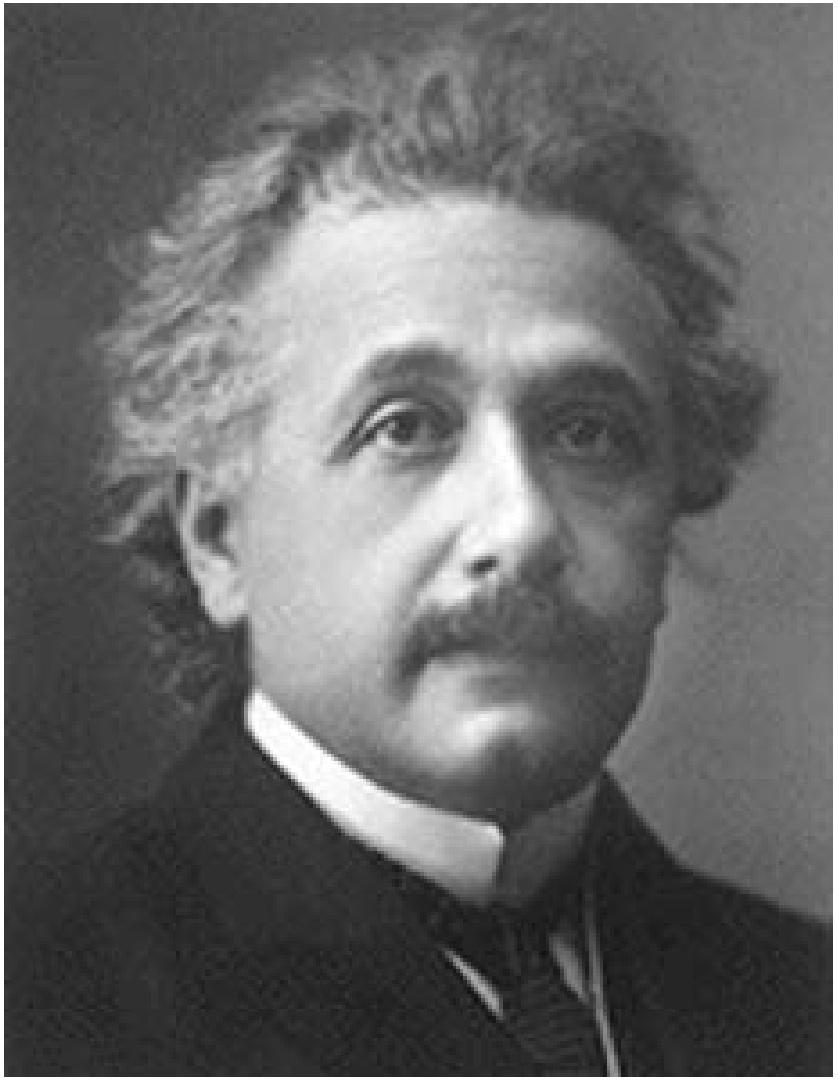
Hubble Vision

Dr Martin Hendry
Dept of Physics and Astronomy
University of Glasgow



"Einstein Cross" 2237+0305:
galaxy at z = 0.04, lensing quasar at z = 1.695



1916. № 7.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 49.

1. *Die Grundlage der allgemeinen Relativitätstheorie;* von *A. Einstein.*

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül", welcher auf den Forschungen von Gauss, Riemann und Christoffel über nichteuklidische Mannigfaltigkeiten ruht und von Ricci und Levi-Civita in ein System gebracht und bereits auf Probleme der theoretischen Physik angewendet wurde. Ich habe im Abschnitt B der vorliegenden Abhandlung alle für uns nötigen, bei dem Physiker nicht als bekannt vorauszusetzenden mathematischen Hilfsmittel in möglichst einfacher und durchsichtiger Weise entwickelt, so daß ein Studium mathematischer Literatur für das Verständnis der vorliegenden Abhandlung nicht erforderlich ist. Endlich sei an dieser Stelle dankbar meines Freundes, des Mathematikers Grossmann, gedacht, der mir durch seine Hilfe nicht nur das Studium der einschlägigen mathematischen Literatur ersparte, sondern mich auch beim Suchen nach den Feldgleichungen der Gravitation unterstützte.

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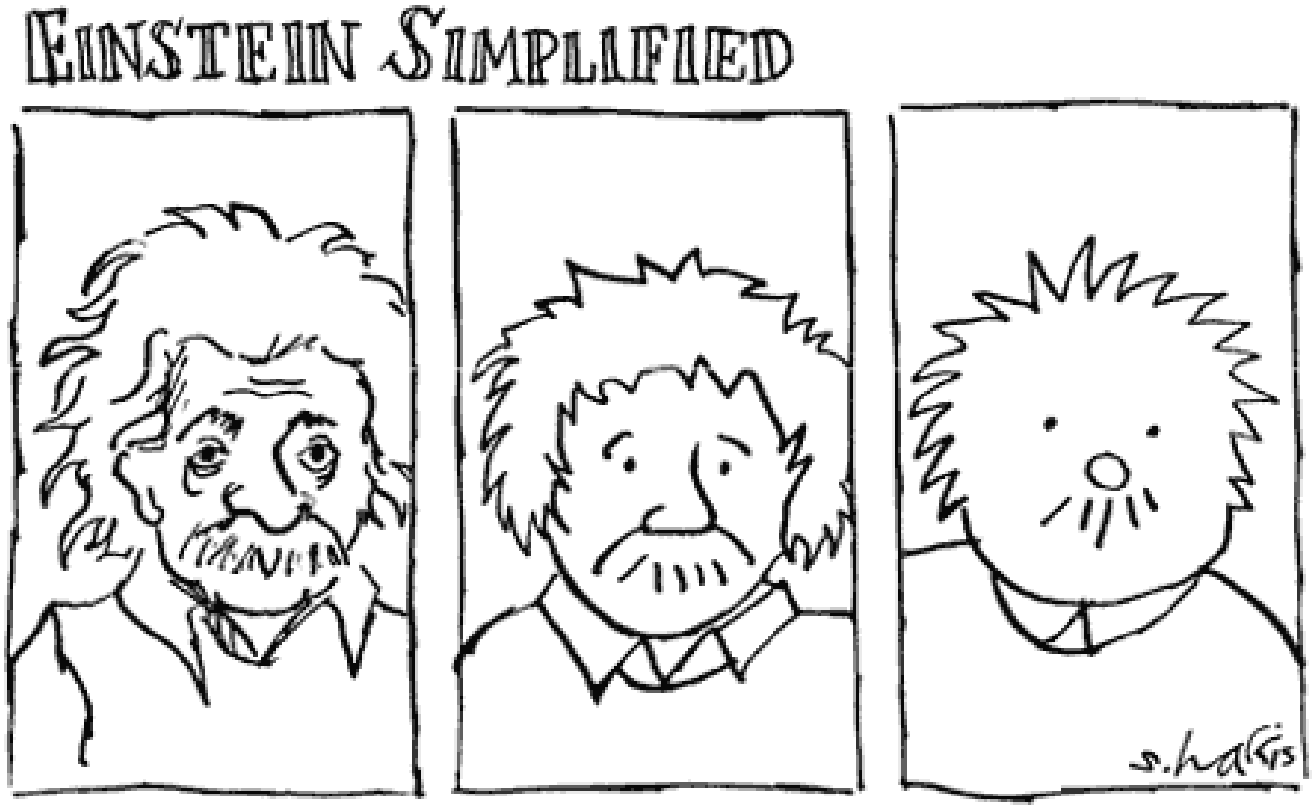
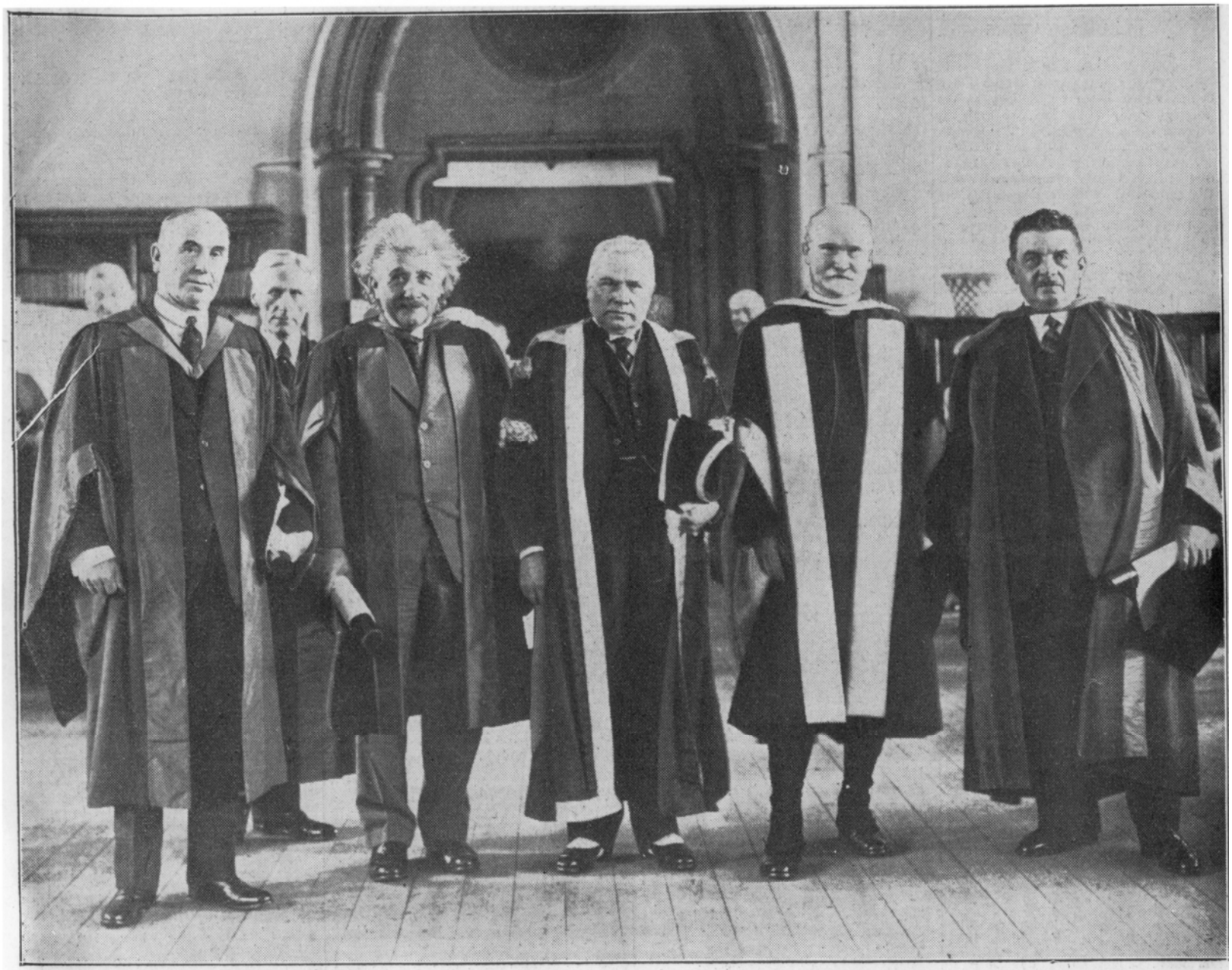
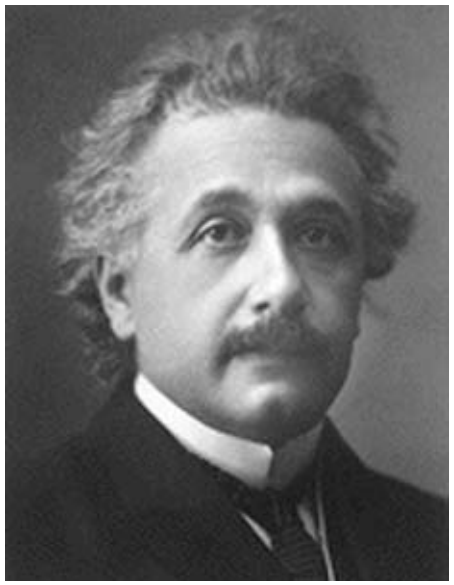
Einstein's general relativity has a reputation for being a very complex and highly mathematical theory



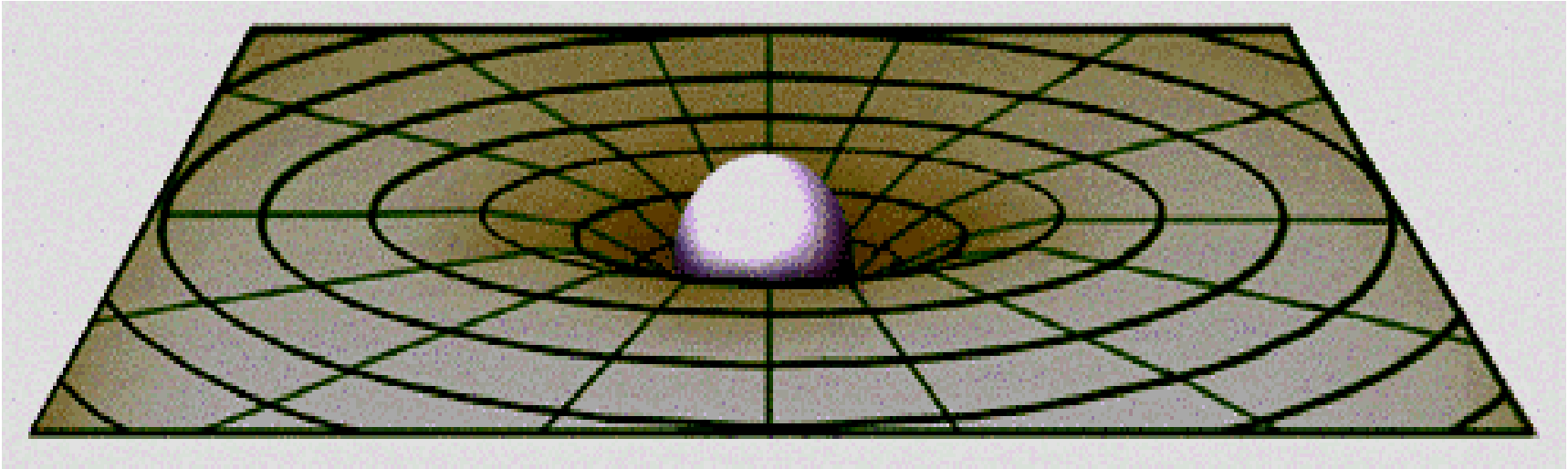


A group of some of the honorary graduates taken after the ceremony in the Bute Hall of Glasgow University yesterday. Left to right—The Right Hon. Sir Robert S. Horne; Emeritus Professor William Blair-Bell, University of Liverpool; Professor Albert Einstein; Principal Sir Robert S. Rait; the Archbishop of Armagh and Primate of All Ireland; and M. Edouard Herriot, former Prime Minister of France.

Gravity in Einstein's Universe



"Spacetime tells matter how to move, and matter tells spacetime how to curve"



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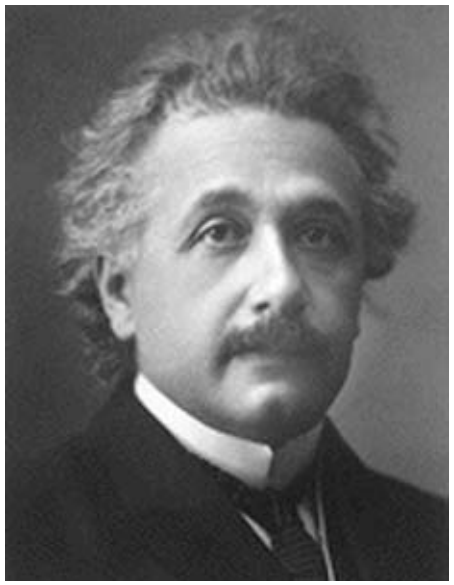
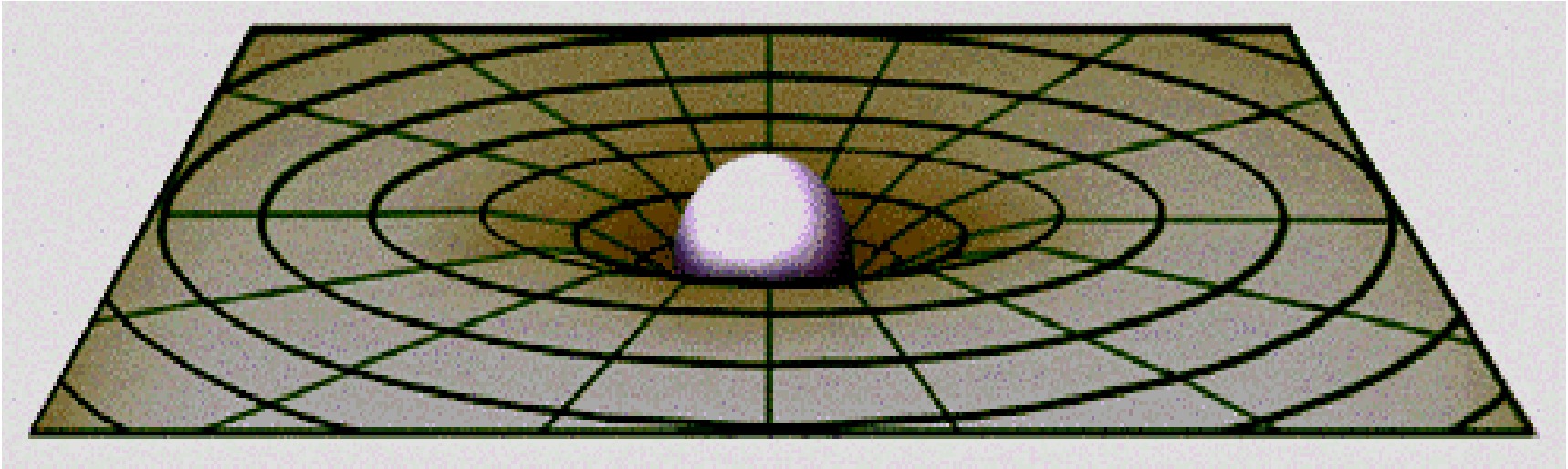


As light passes close to a star its path is bent by the curved spacetime

Gravitational Lensing



Three regimes:

- Strong gravitational lensing
  - Easily visible distortion of background objects: arcs, rings and multiple images
- Weak gravitational lensing
  - Distortions much smaller: can only be detected statistically, analysing large numbers of galaxies
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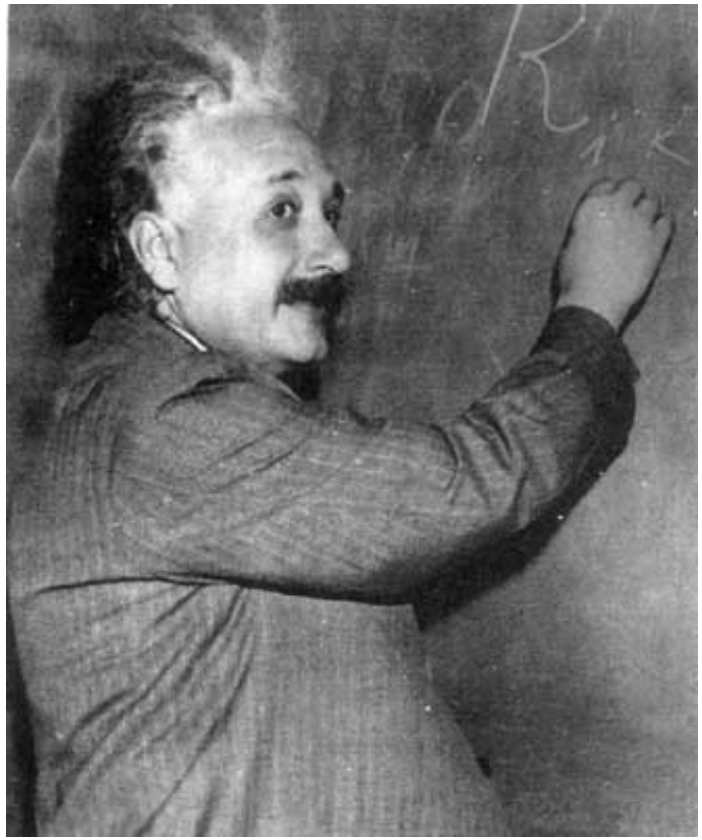
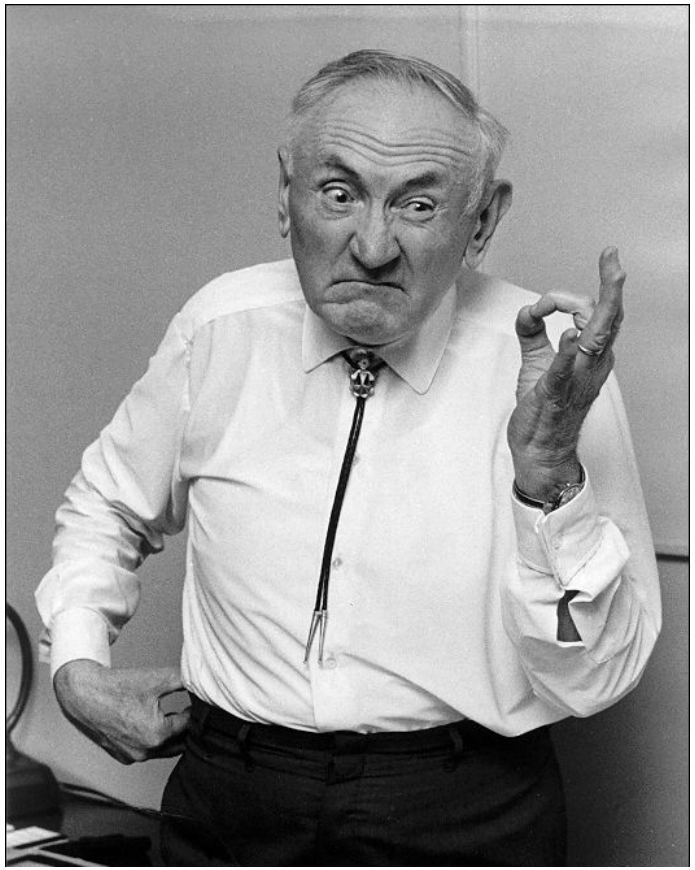
If the observer, lens and source are exactly aligned, images form an **Einstein Ring**





Chwolson (1924), Einstein (1936), Zwicky (1937)

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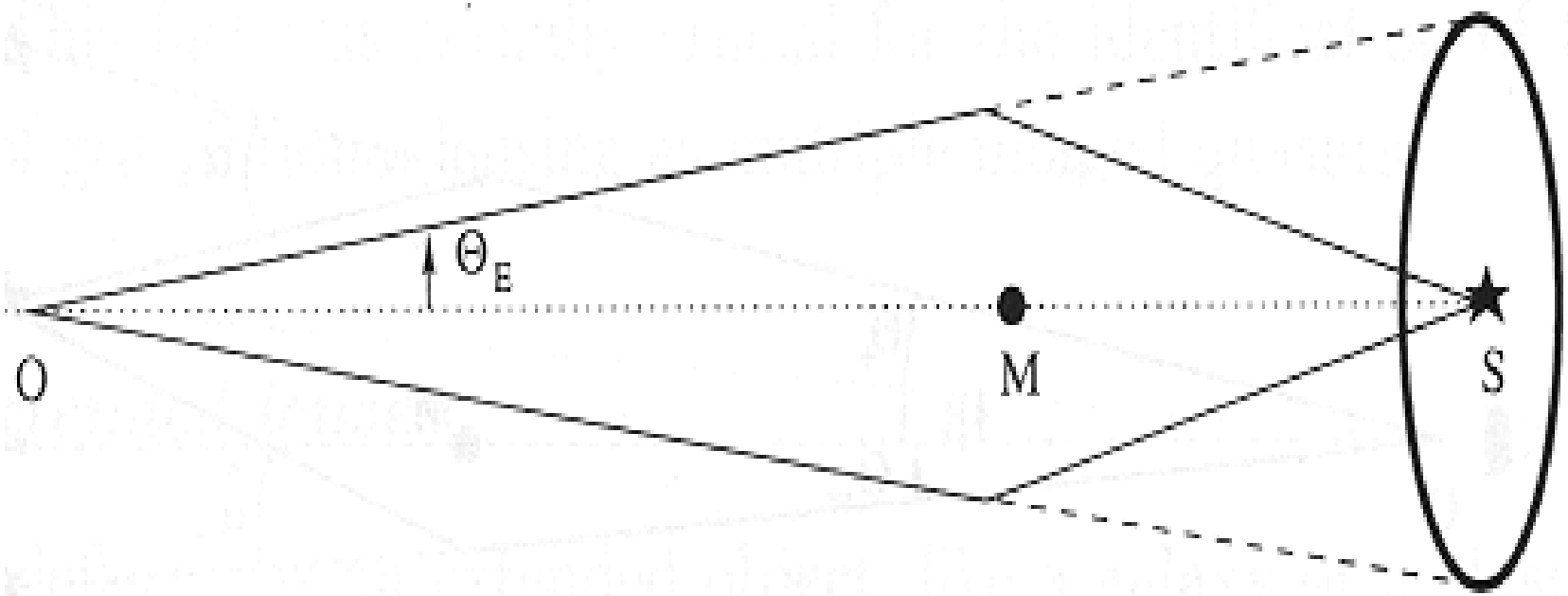

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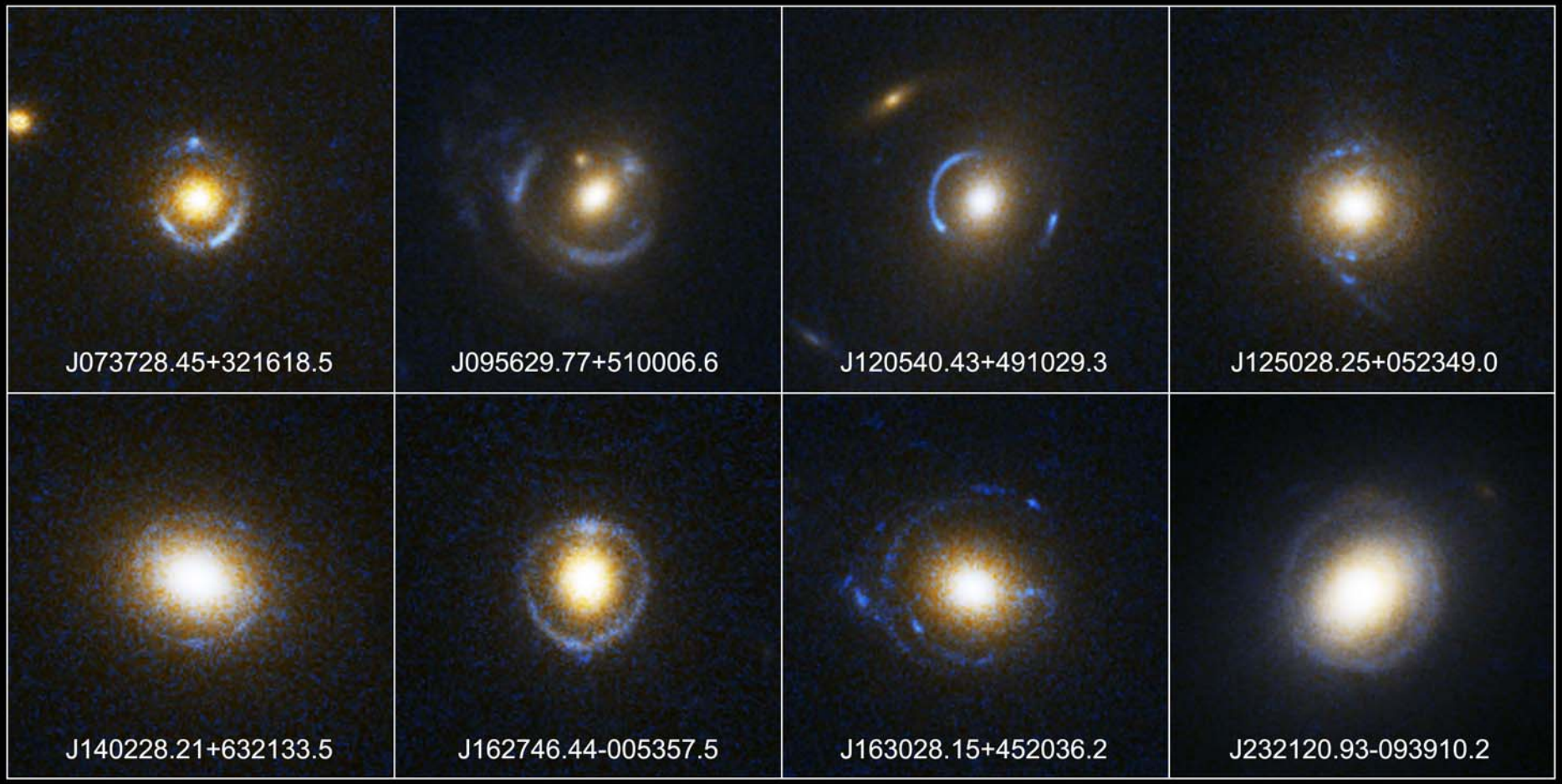
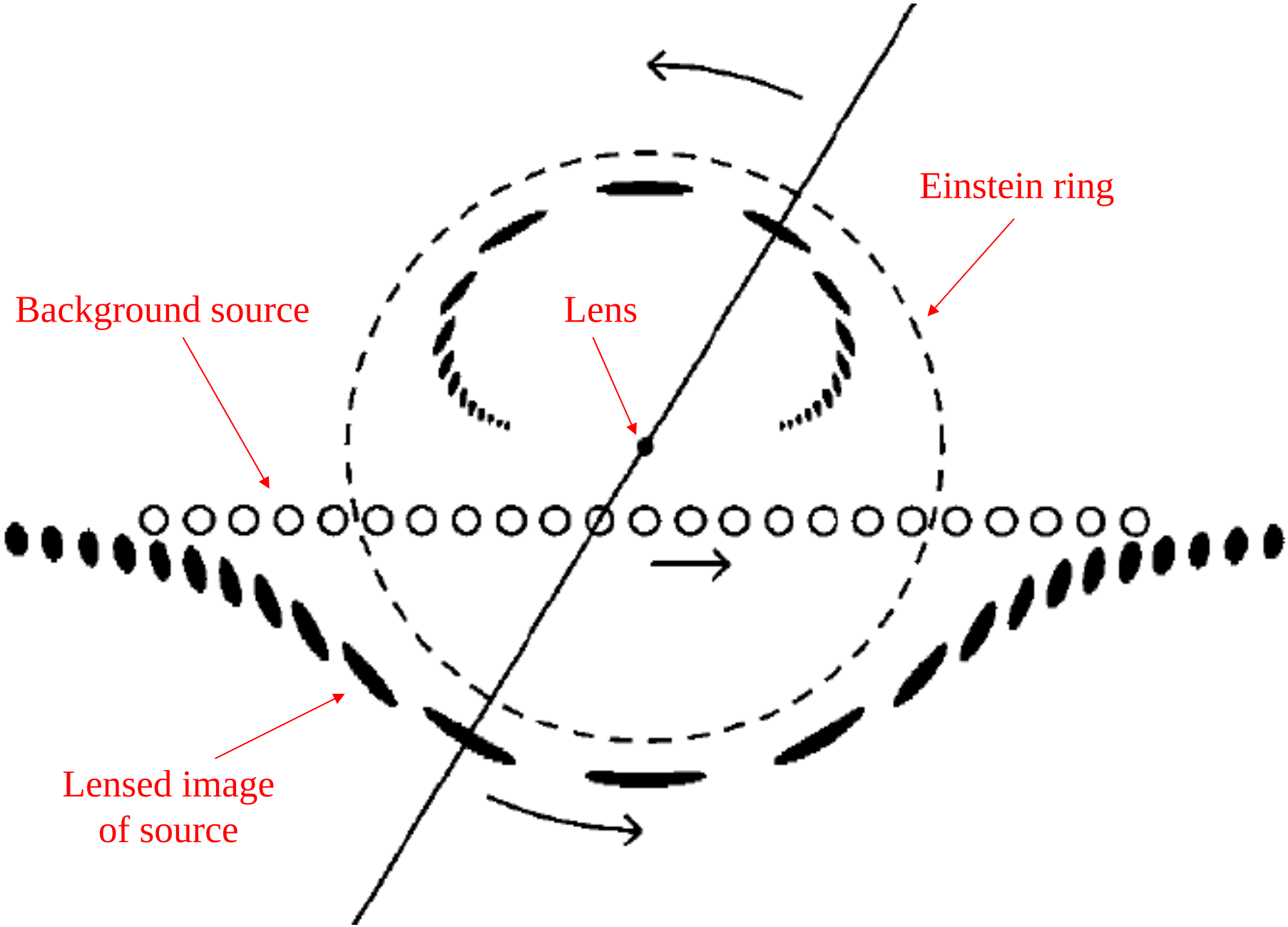


Einstein Ring Gravitational Lenses

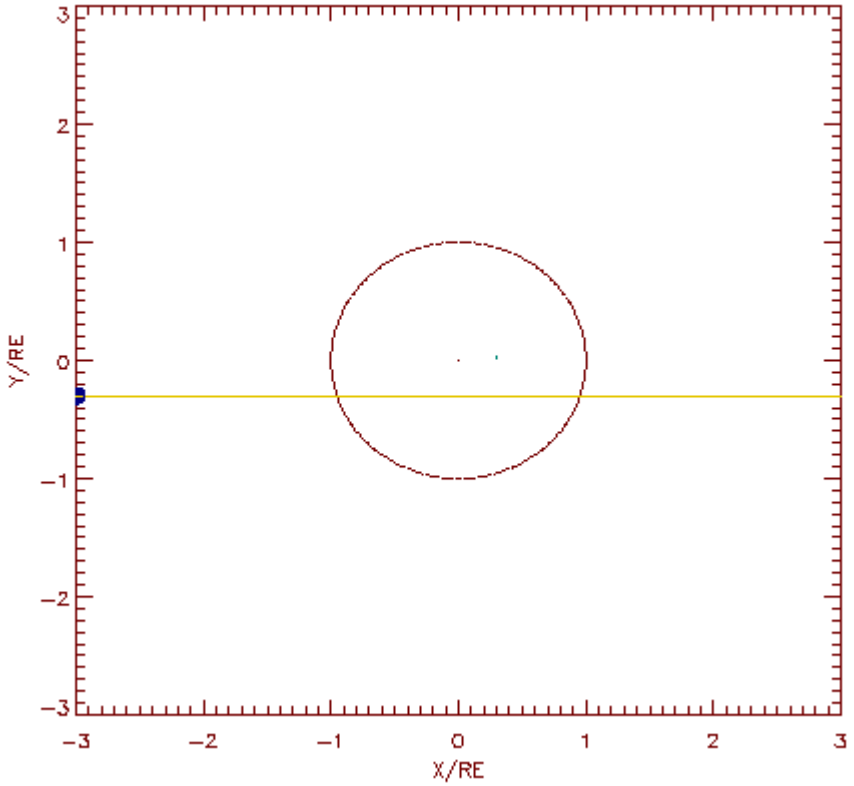
Hubble Space Telescope • Advanced Camera for Surveys

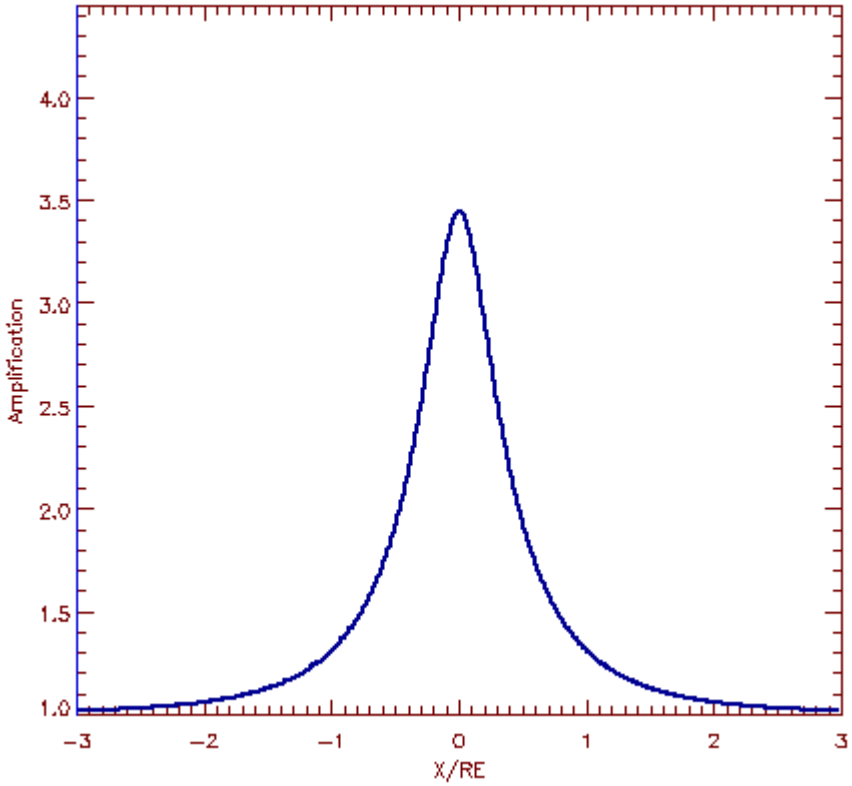
NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

STScI-PRC05-32


Einstein ring
Background source
Lens
Lensed image
of source

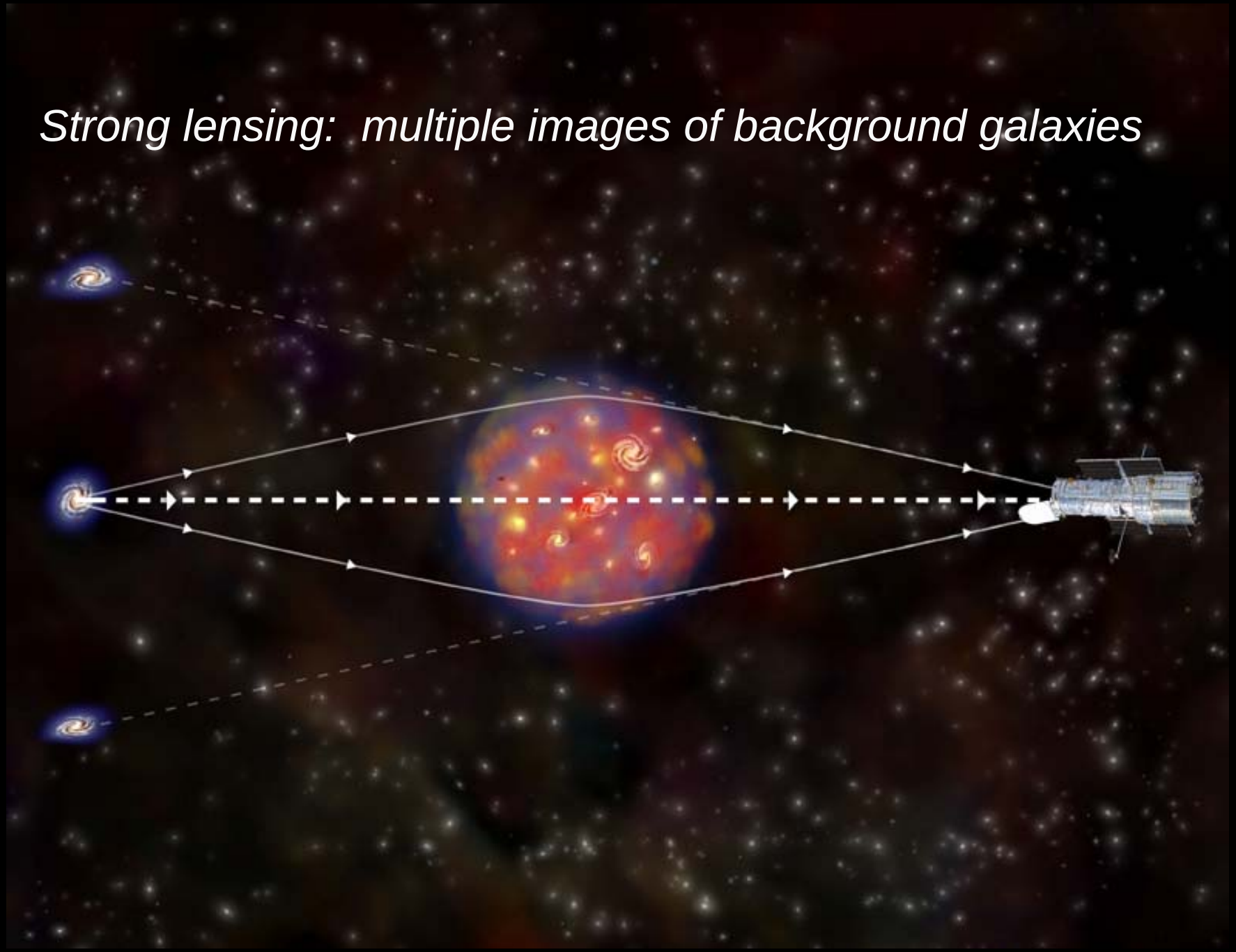
Courtesy: B.S. Gaudi

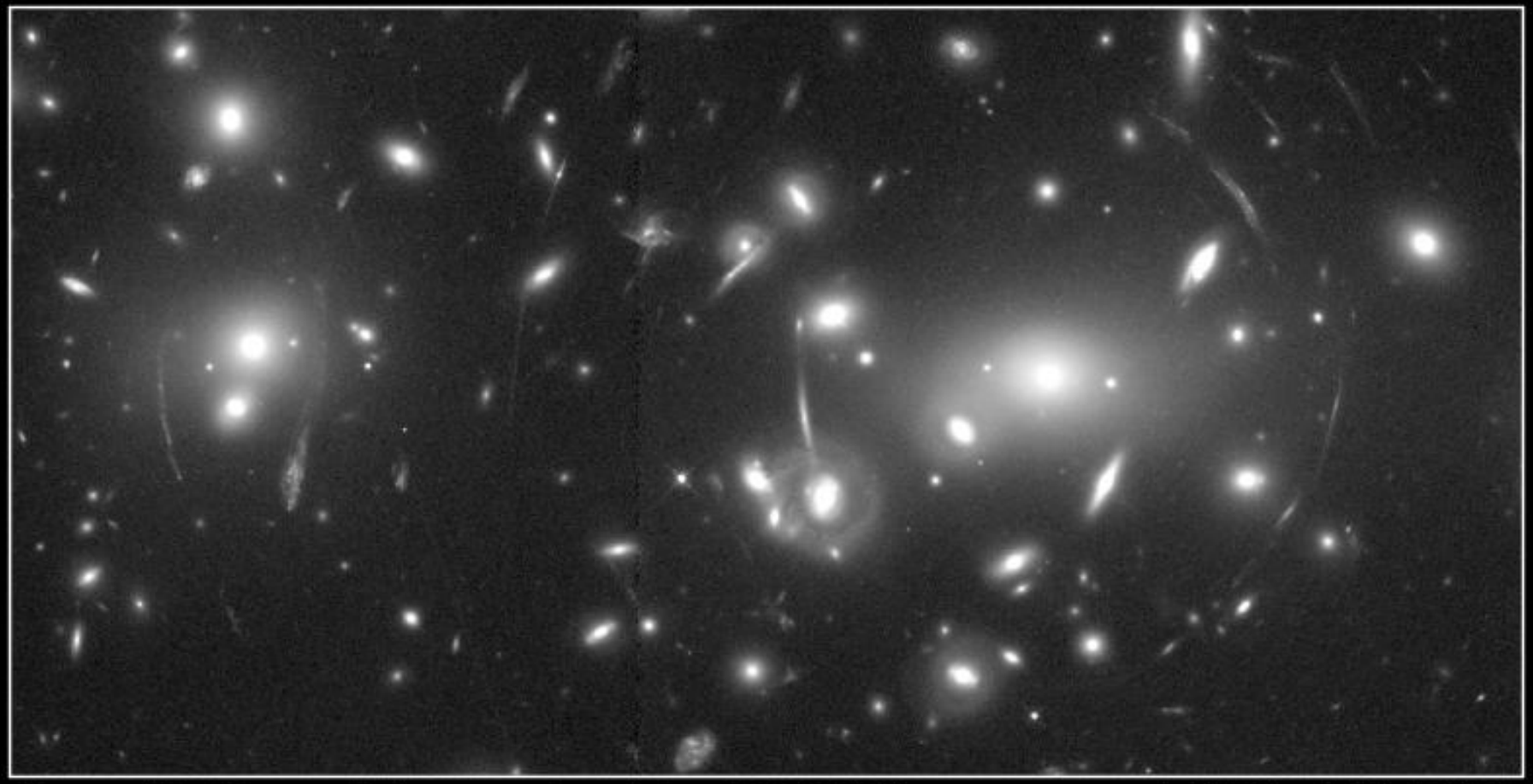




As the lens crosses in front of the source, the brightness of the source increases by a significant factor, then decreases again.

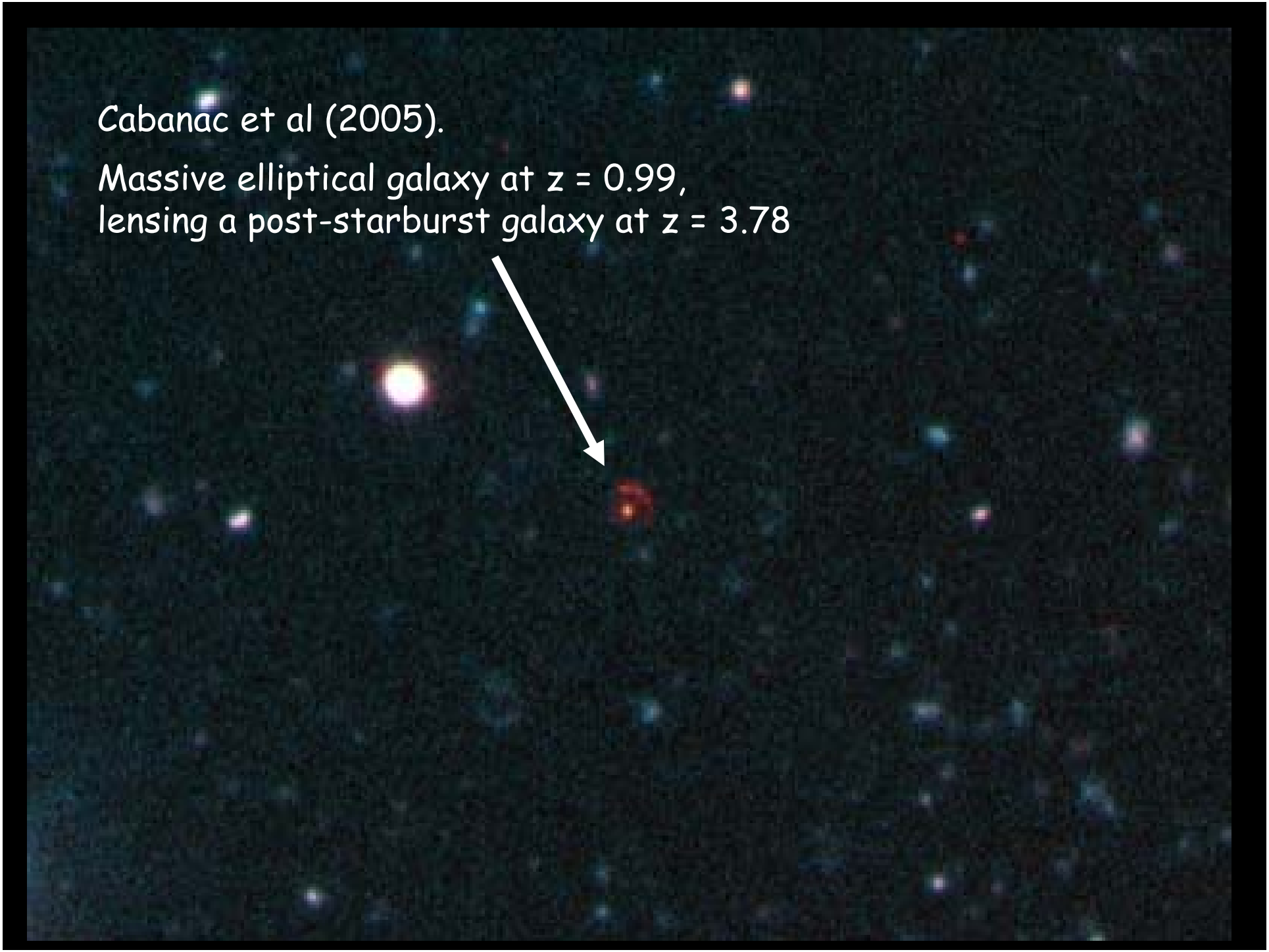
Strong lensing: multiple images of background galaxies



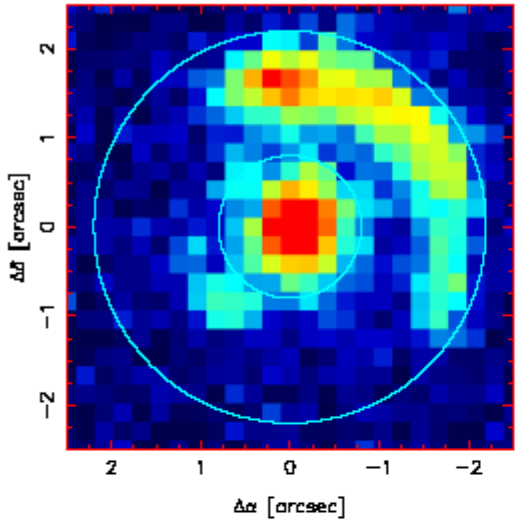


Gravitational Lens in Abell 2218 HST • WFPC2

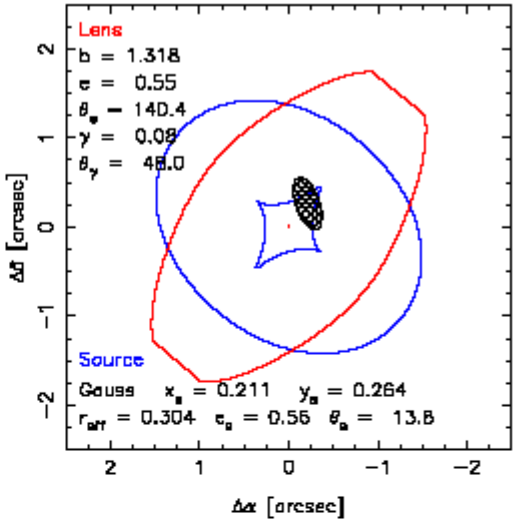
PF95-14 · ST ScI OPO · April 5, 1995 · W. Couch (UNSW), NASA


Cabanac et al (2005).
Massive elliptical galaxy at z = 0.99,
lensing a post-starburst galaxy at z = 3.78

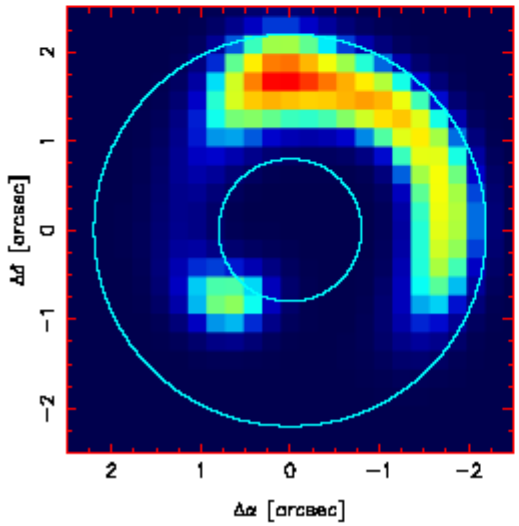
(a) VLT R_E image with 0.5'' resolution



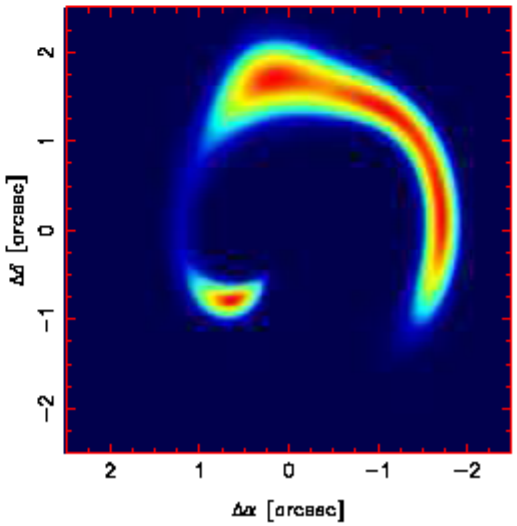
(b) Best lens + source model configuration

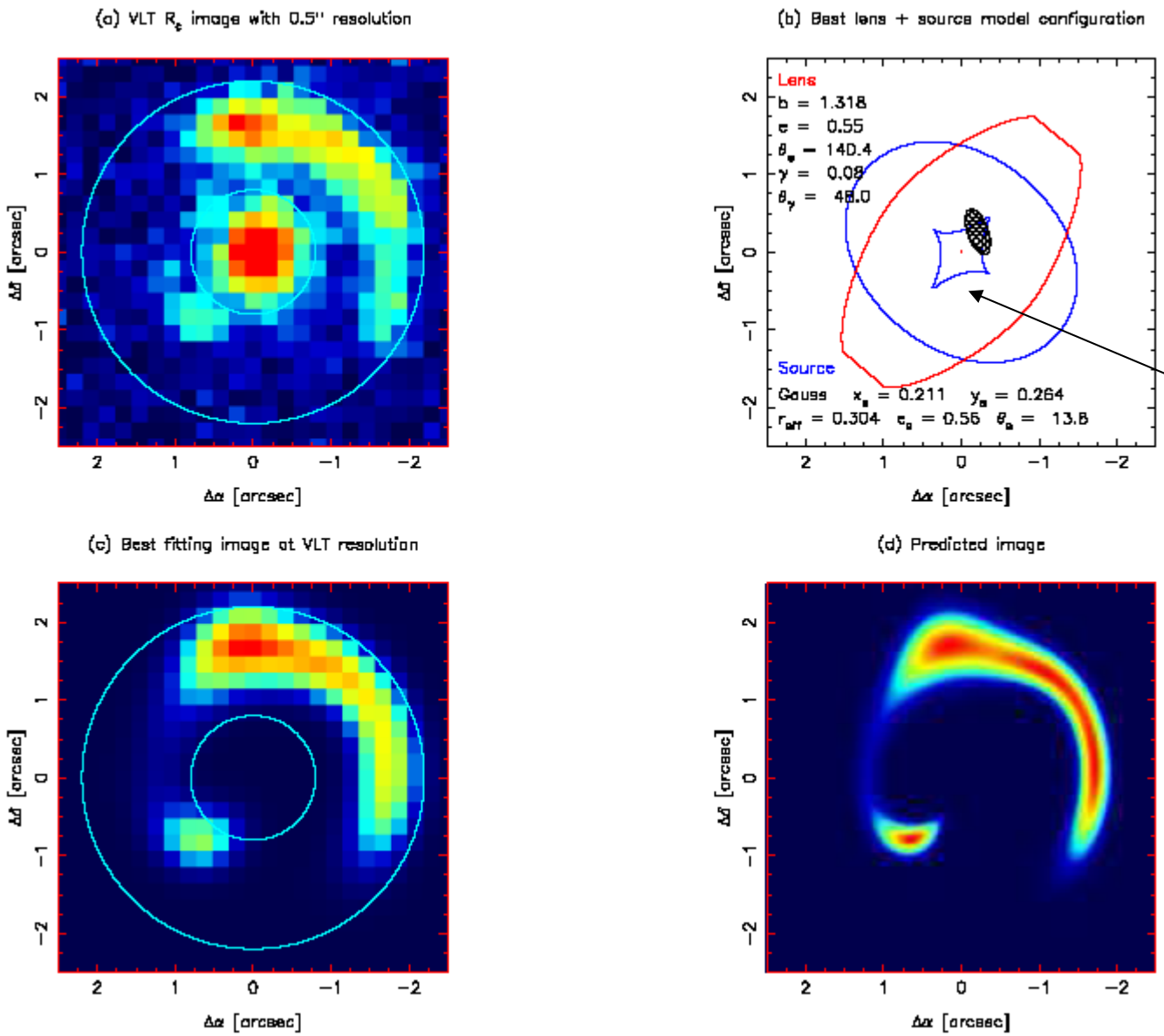


(c) Best fitting image at VLT resolution



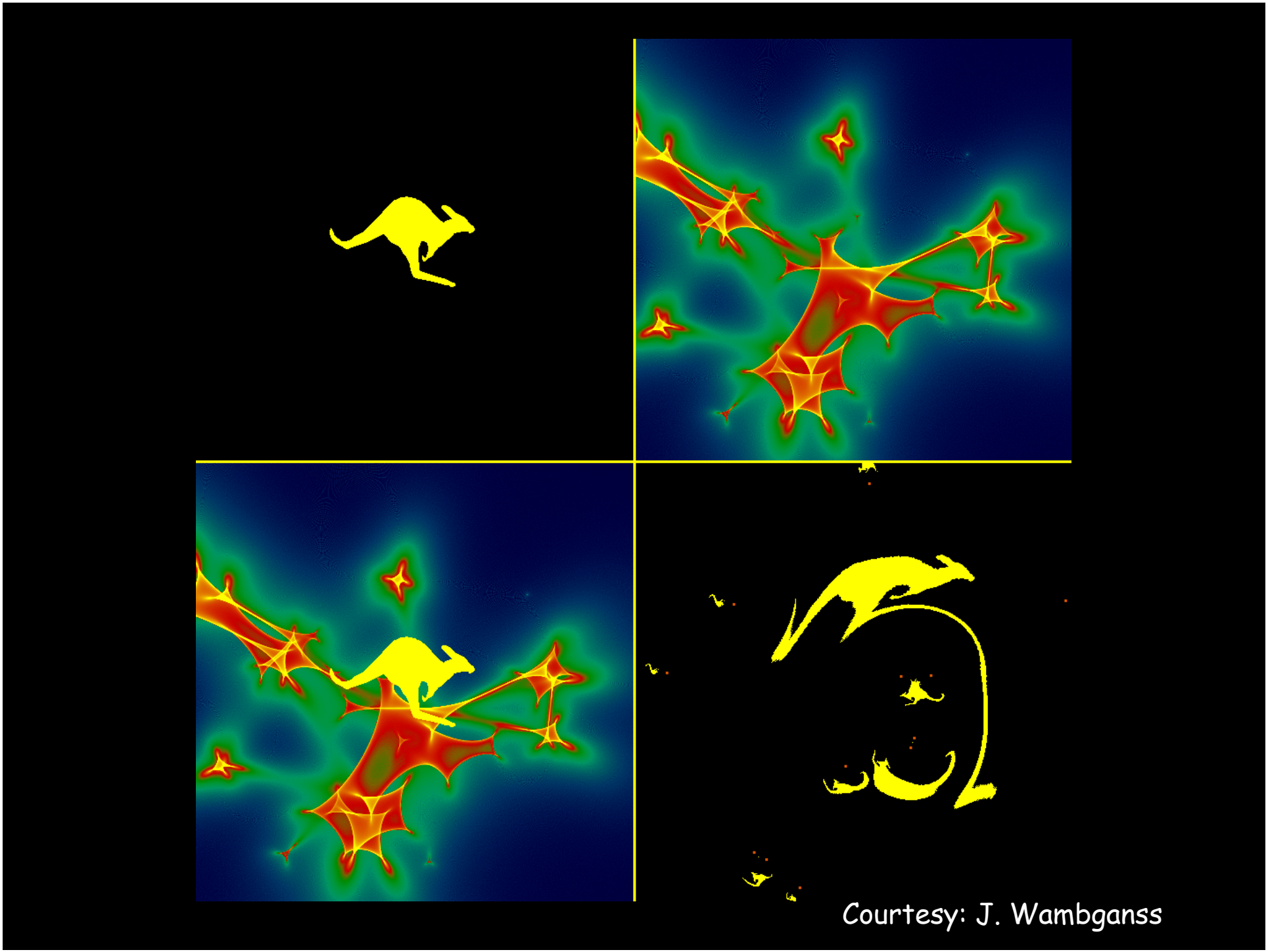
(d) Predicted image

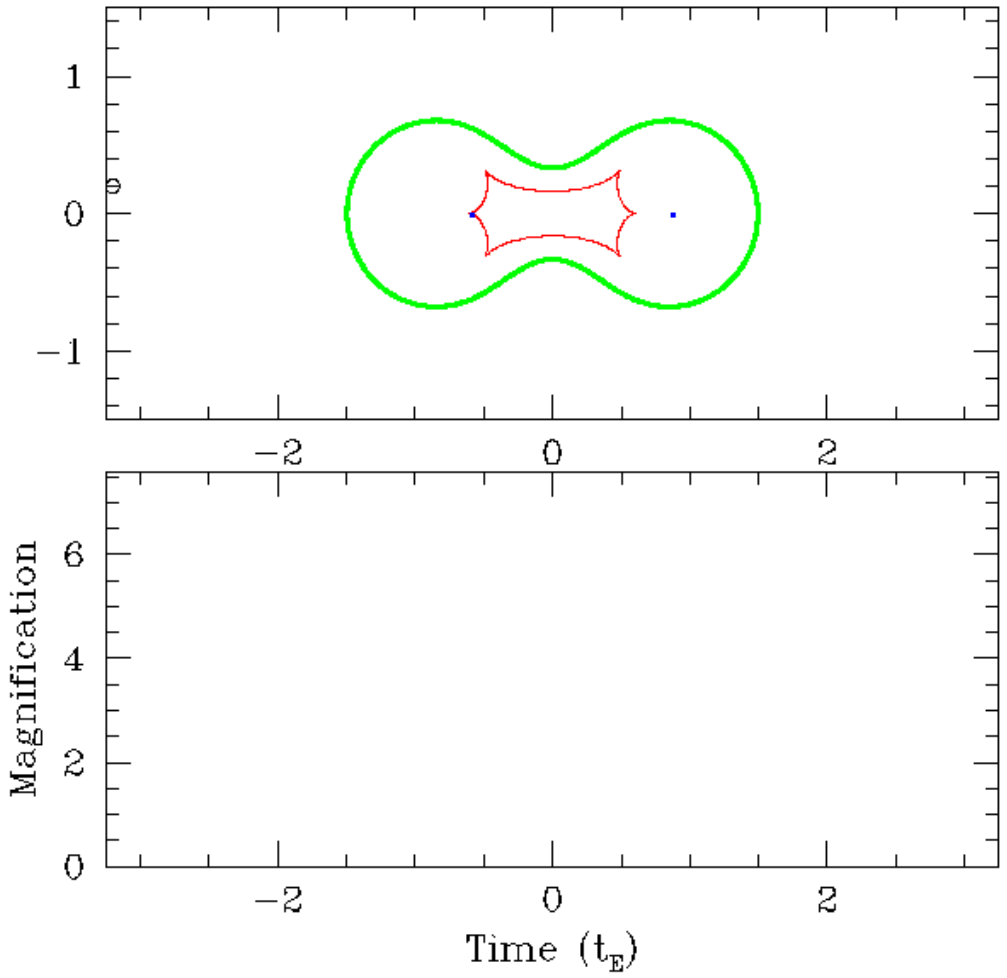




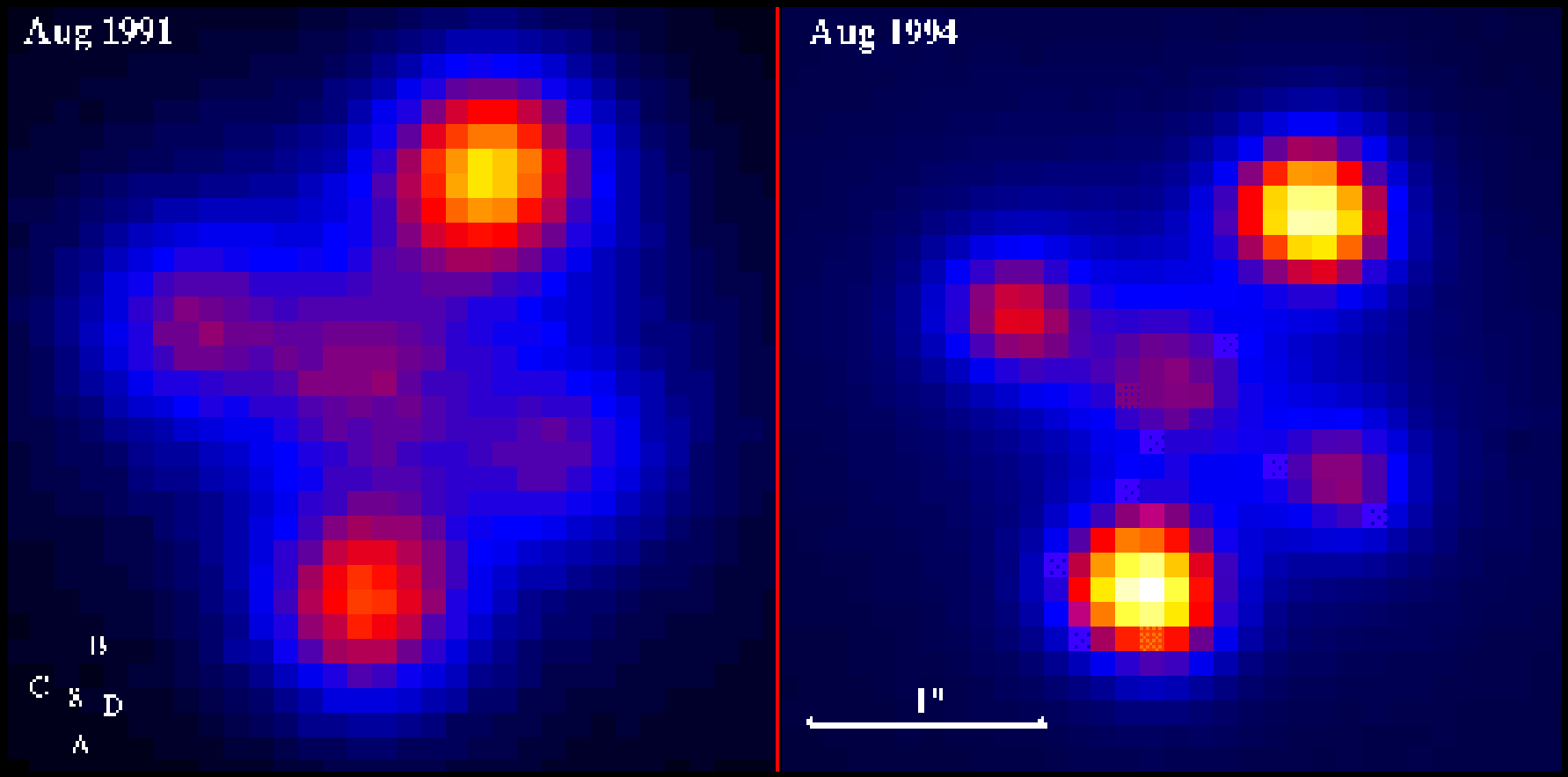
Complex *caustic* structure due to extended mass distrib. of lens

Can produce very complicated image structure.


Courtesy: J. Wambganss


1
0
−1
−2
0
2
Magnification
6
4
2
0
−2
0
2
Time (t_E)

"Einstein Cross" 2237+0305:
galaxy at z = 0.04, lensing quasar at z = 1.695



Gravitational microlensing of the Einstein Cross:

The individual images of the quasar change in brightness as they are microlensed by individual stars in the lensing galaxy

Lewis & Irwin (1994)

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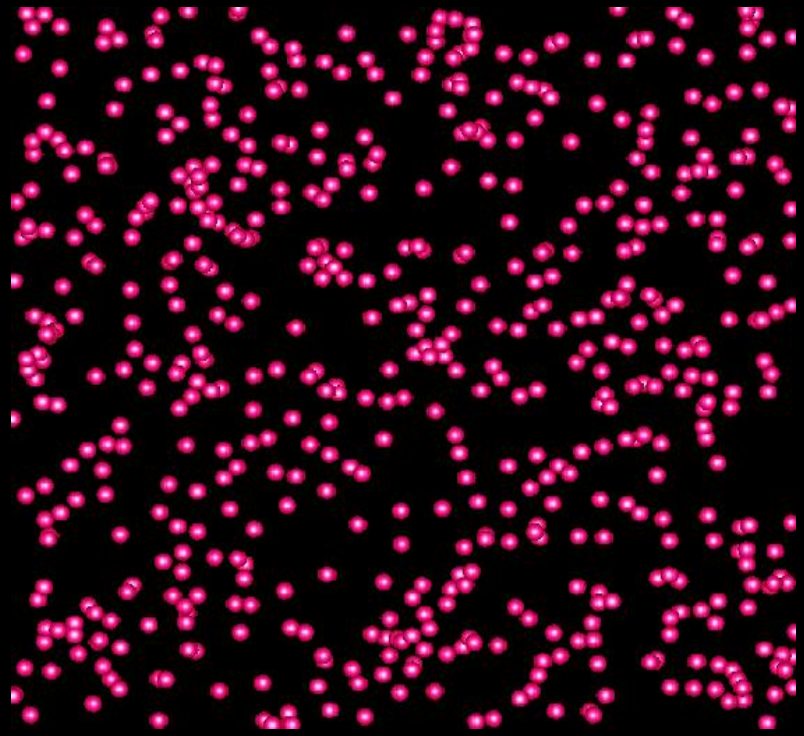
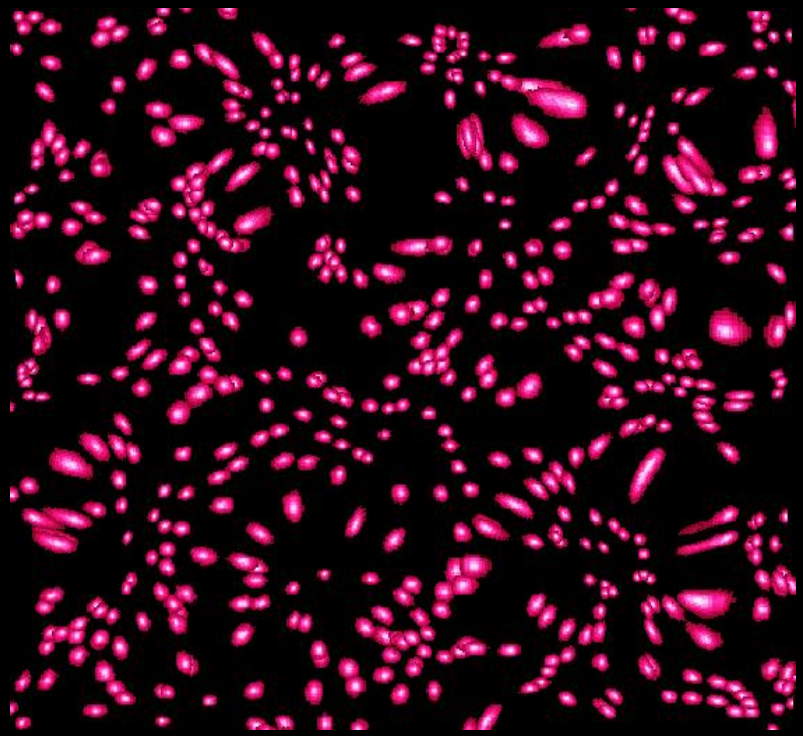
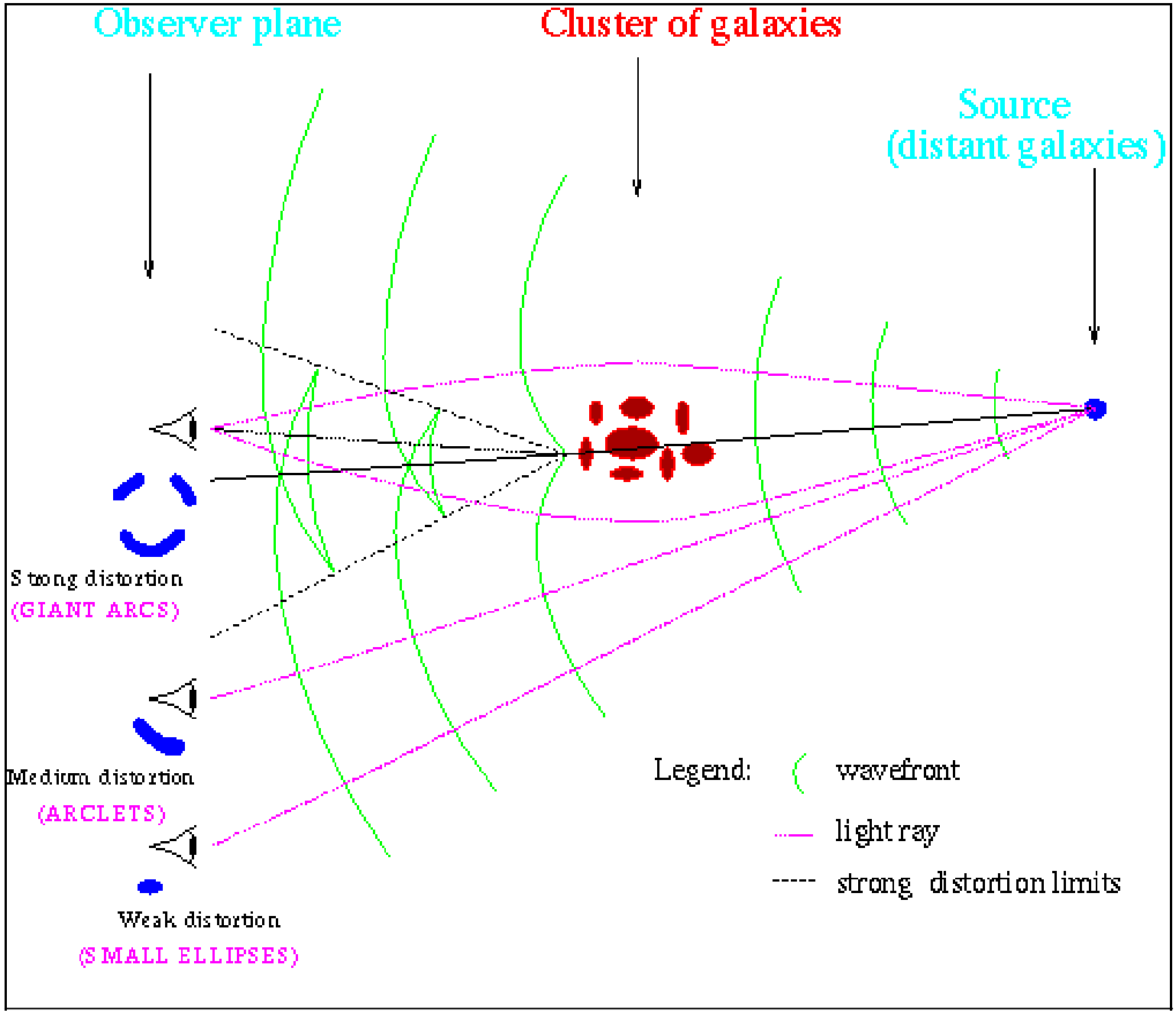
Weak lensing: distorted images of background galaxies



Unlensed view of background galaxies

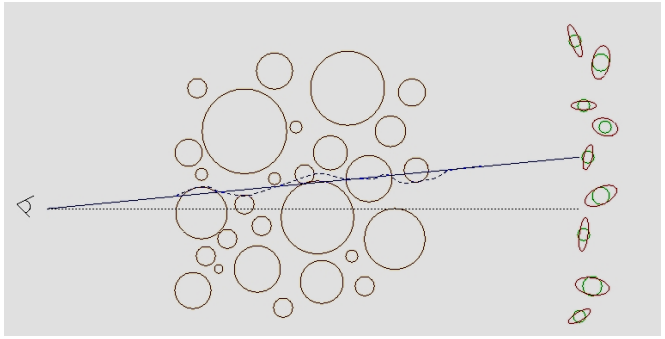


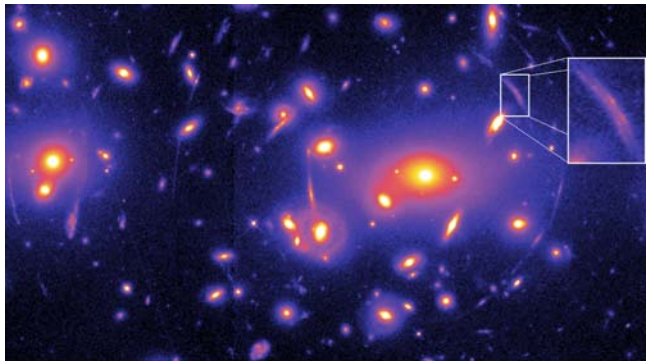
Lensed view of background galaxies



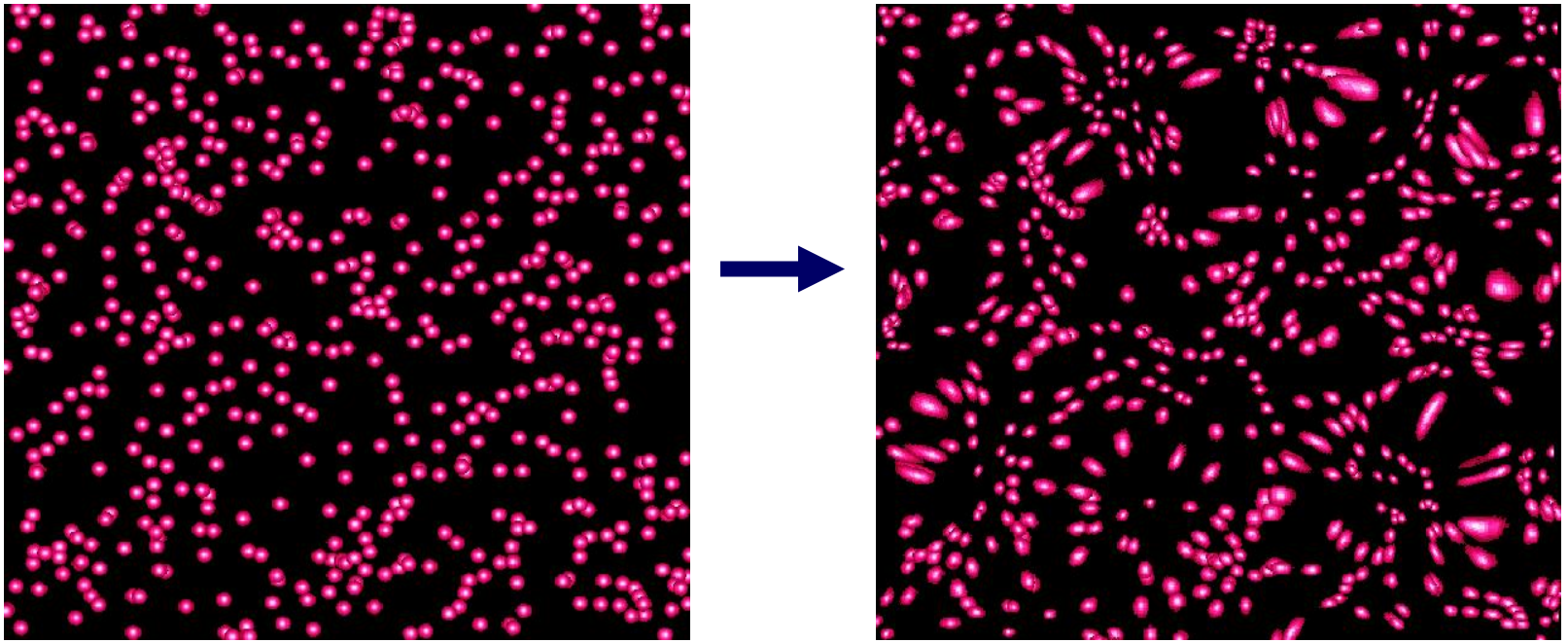
Courtesy: Y. Mellier

Mapping dark matter with weak gravitational lensing

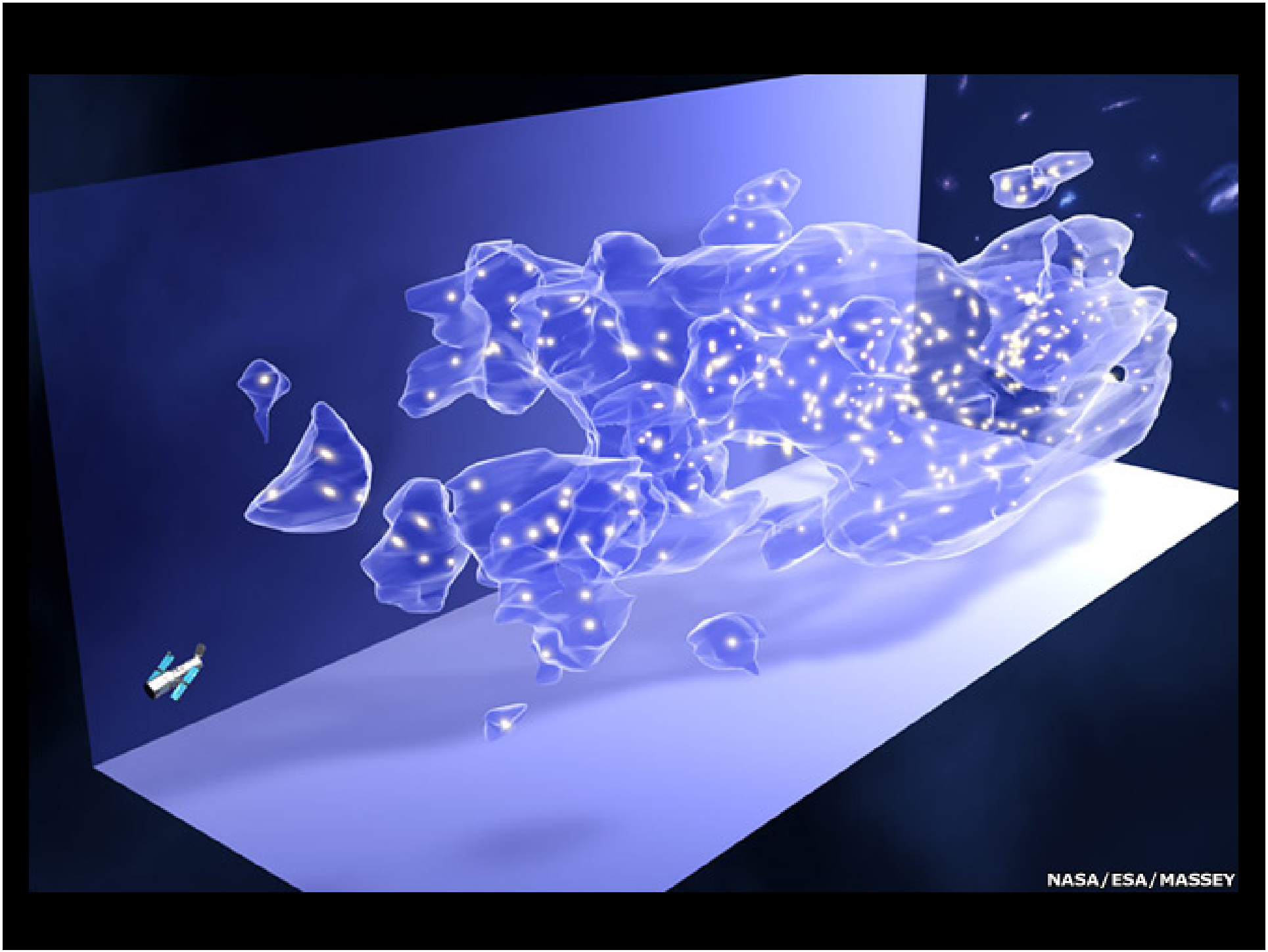


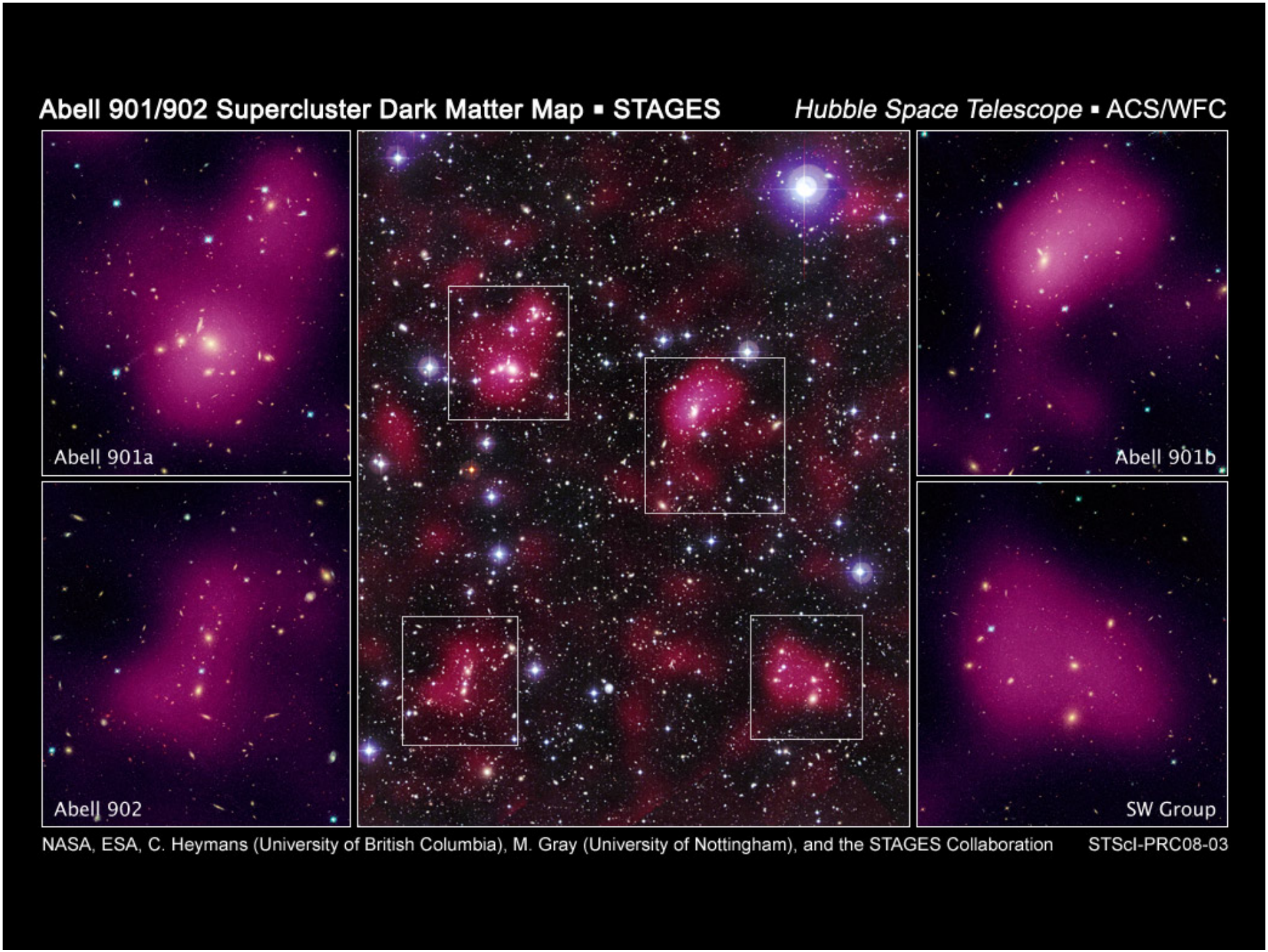


Distortion of background images by foreground matter



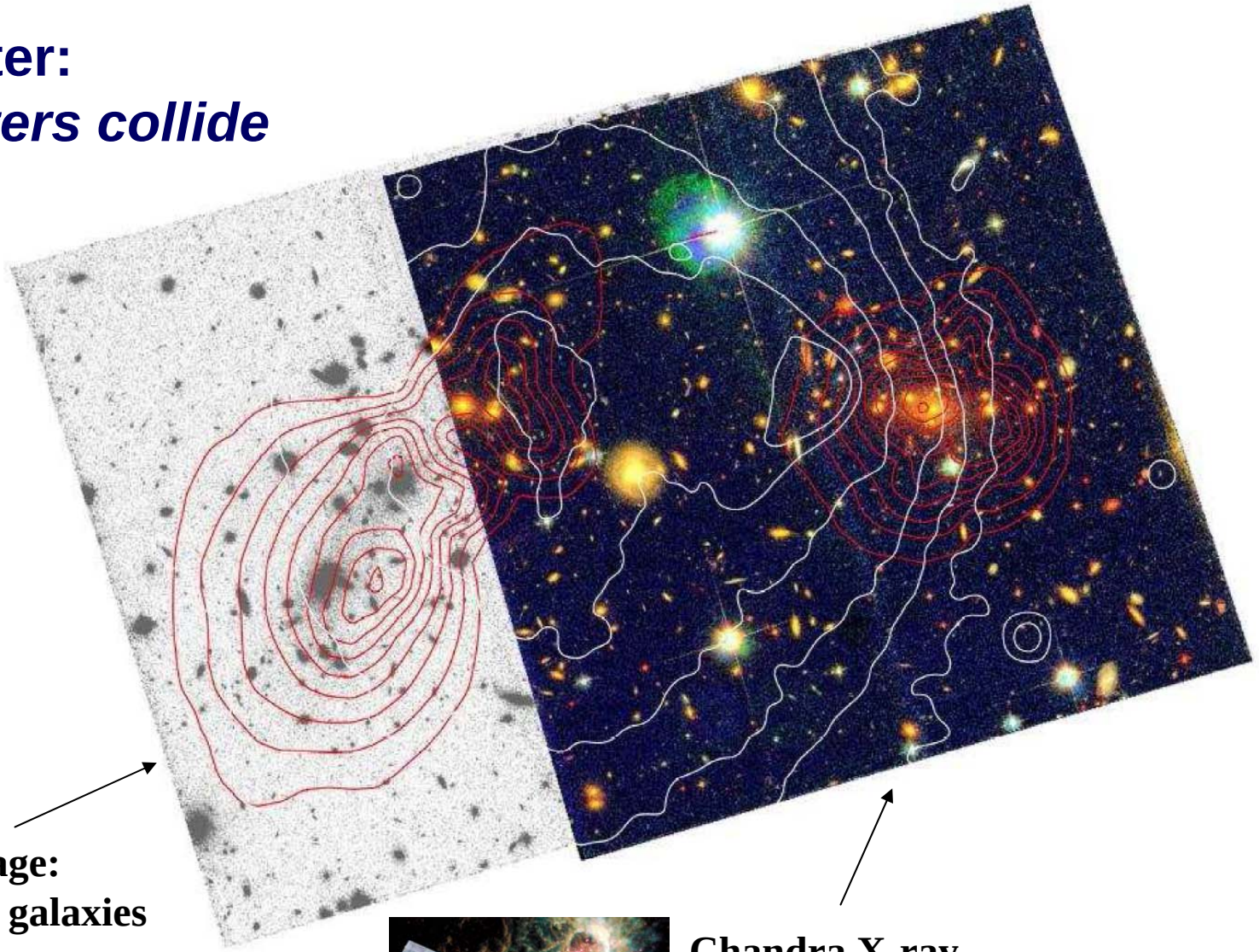
Unlensed **Lensed**


NASA/ESA/MASSEY


Abell 901/902 Supercluster Dark Matter Map ▪ STAGES
Hubble Space Telescope ▪ ACS/WFC
Abell 901a
Abell 901b
Abell 902
SW Group
NASA, ESA, C. Heymans (University of British Columbia), M. Gray (University of Nottingham), and the STAGES Collaboration
STScI-PRC08-03

Bullet cluster:
When clusters collide

HST optical image: shows luminous galaxies

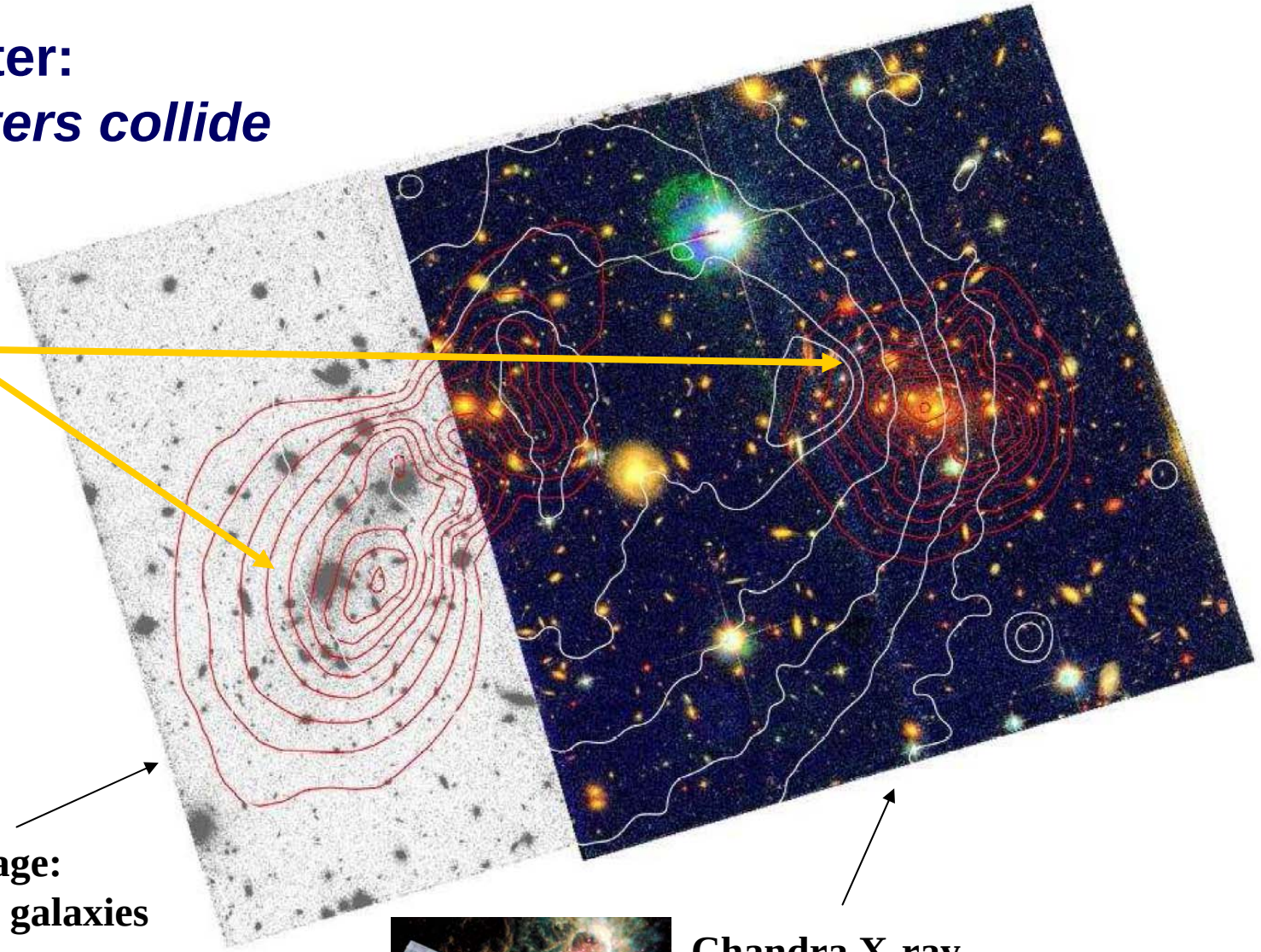


Chandra X-ray image: also shows ‘dark’ cluster gas

Bullet cluster:
When clusters collide

Dark matter, reconstructed from strong and weak lensing

HST optical image: shows luminous galaxies



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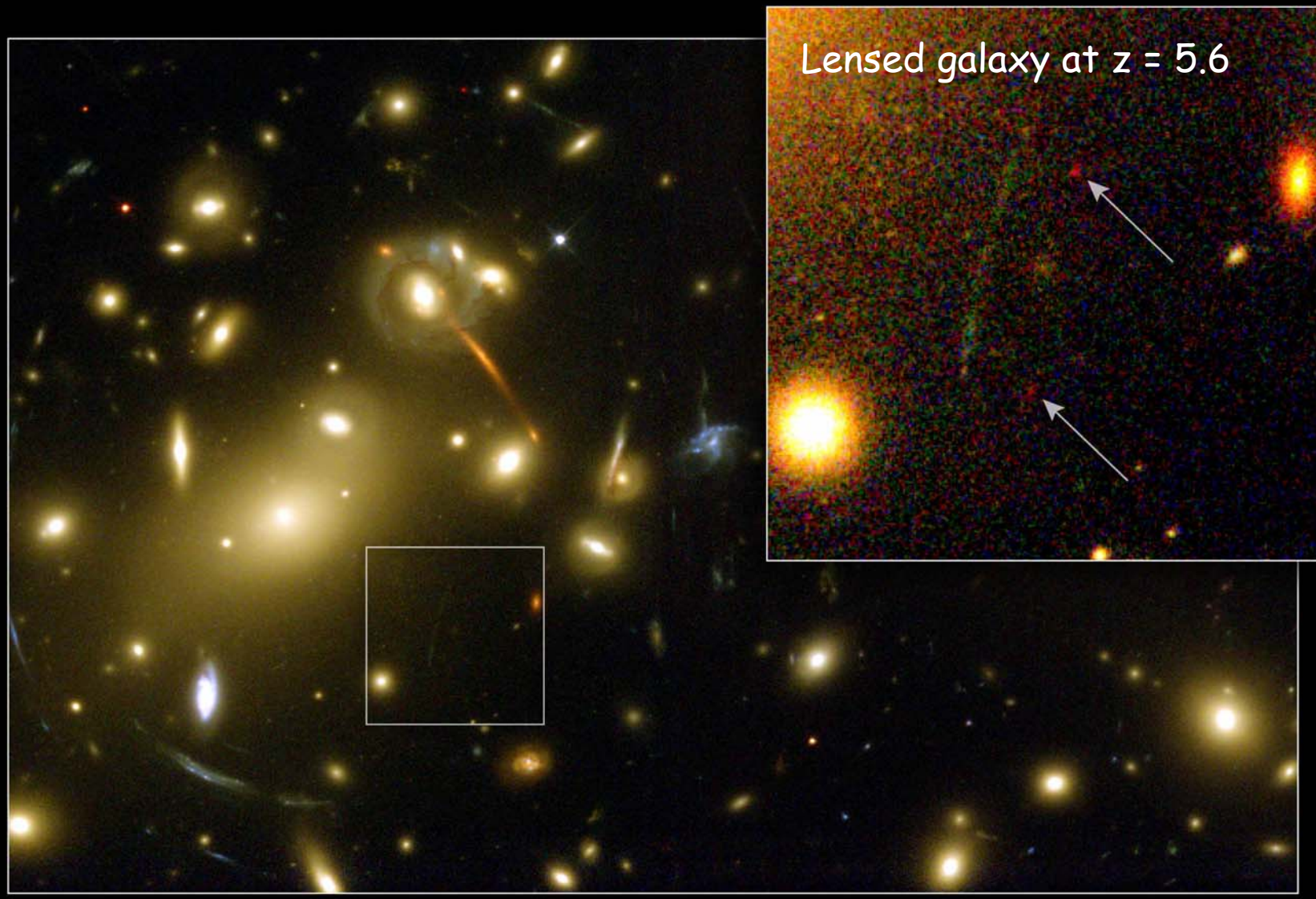
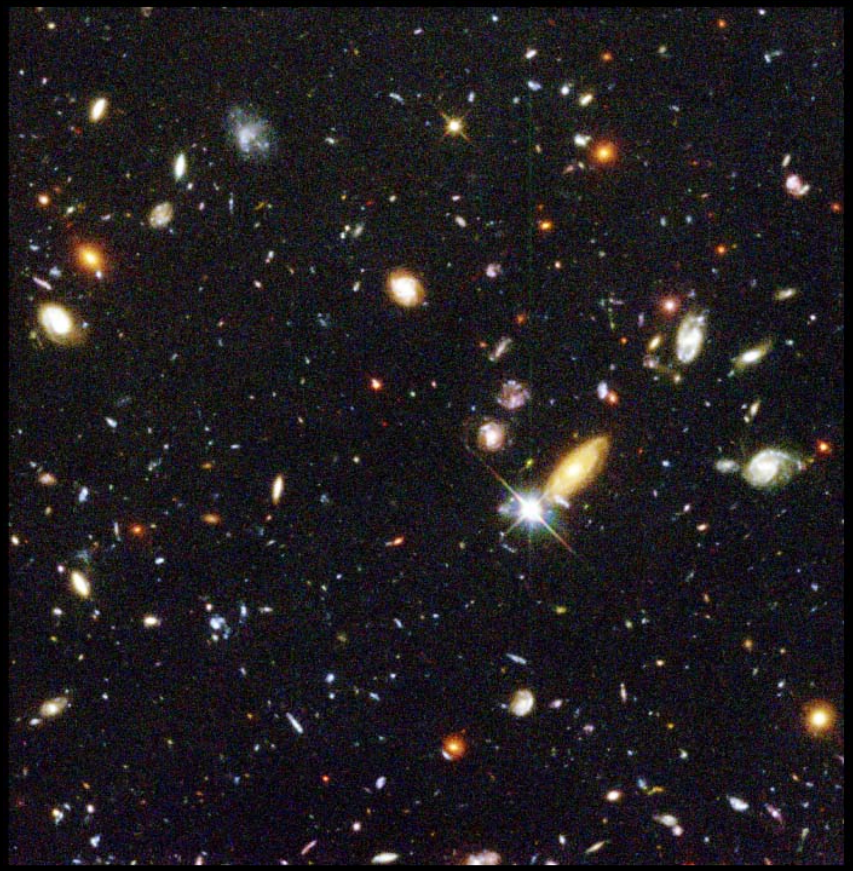


Distant Object Gravitationally Lensed by Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

NASA, ESA, R. Ellis (Caltech) and J.-P. Kneib (Observatoire Midi-Pyrenees) • STScI-PRC01-32

Cosmology – the study of the Universe as a whole:

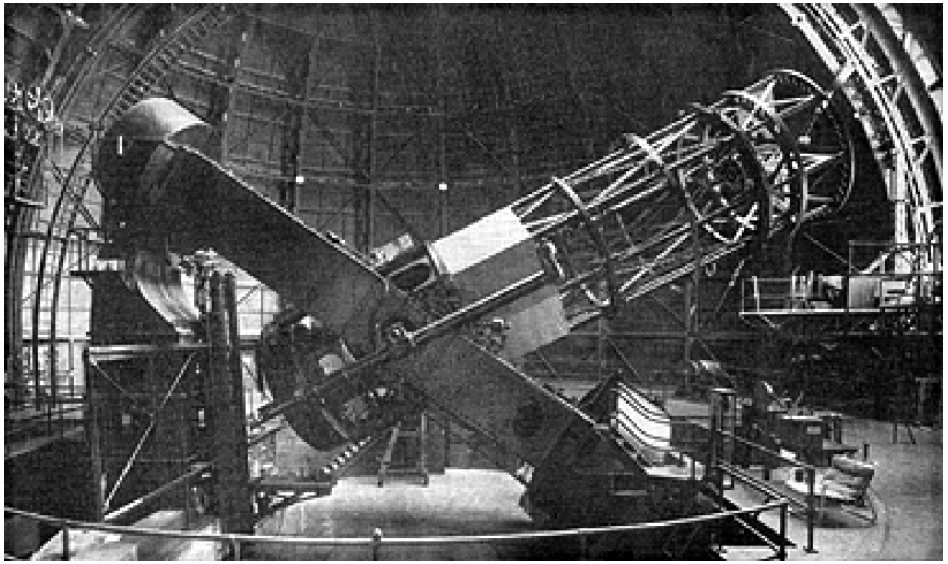
- Origin
- Evolution
- Eventual Fate

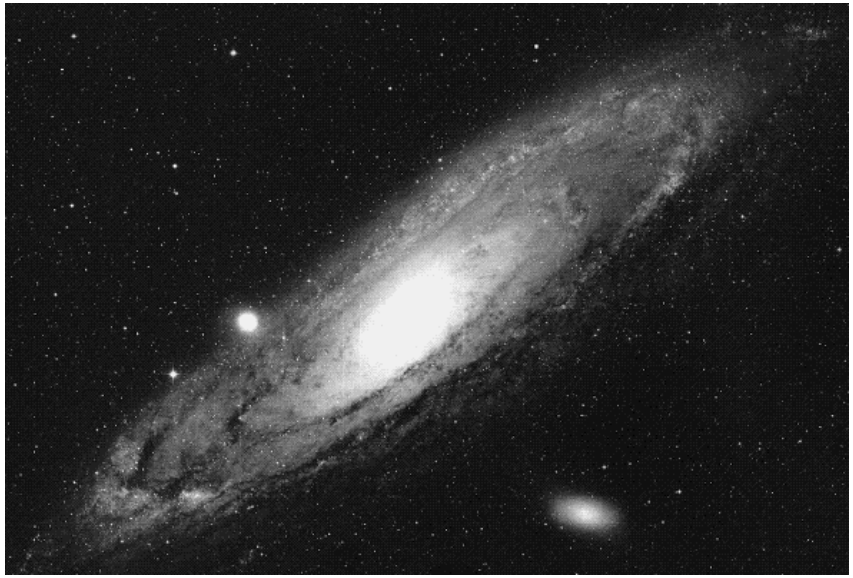


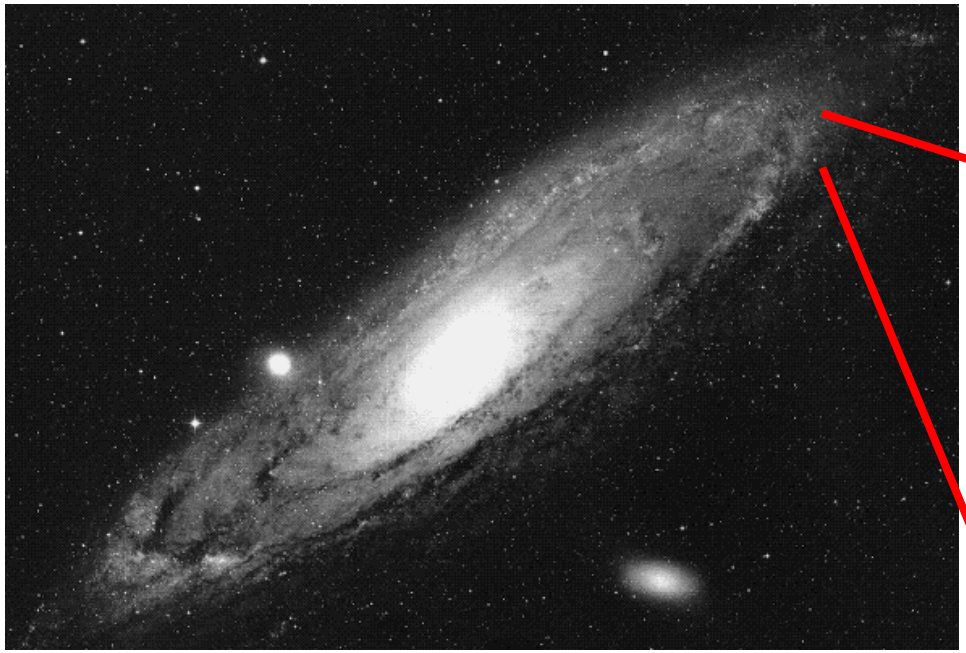
A long time ago,

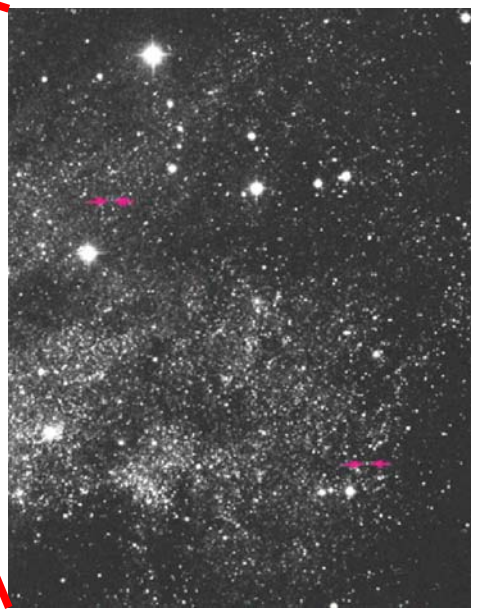
in a galaxy far, far away…

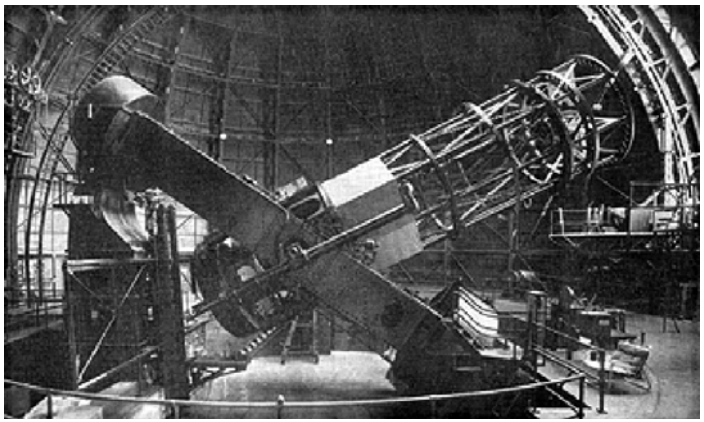
Edwin Hubble





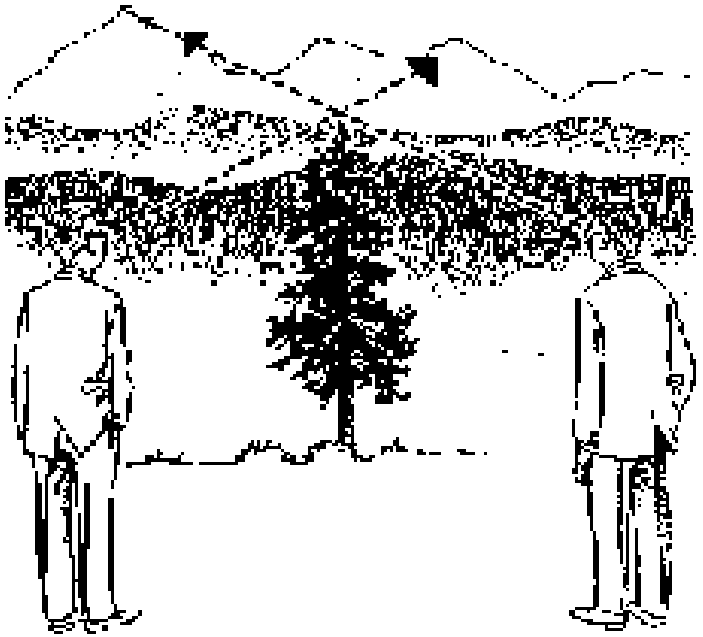


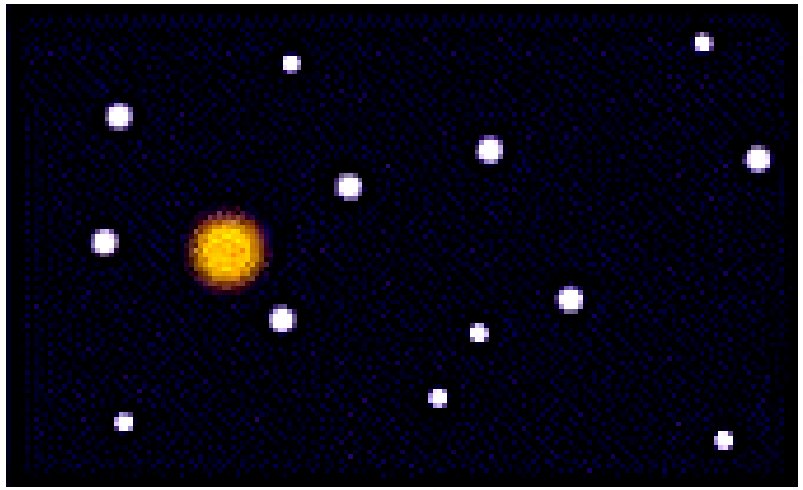




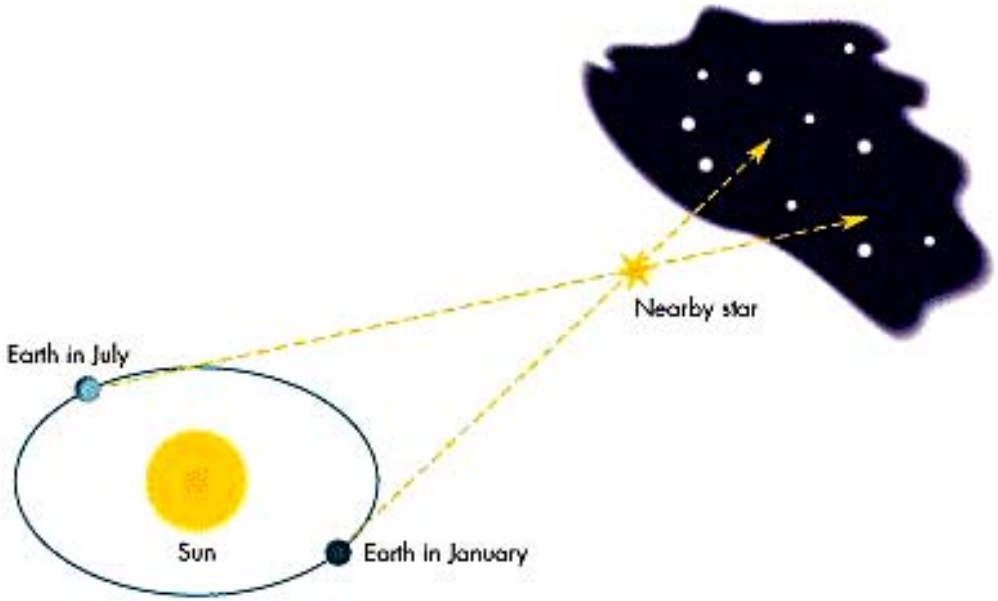
1922: Hubble finds Cepheids in the Great Nebula in Andromeda

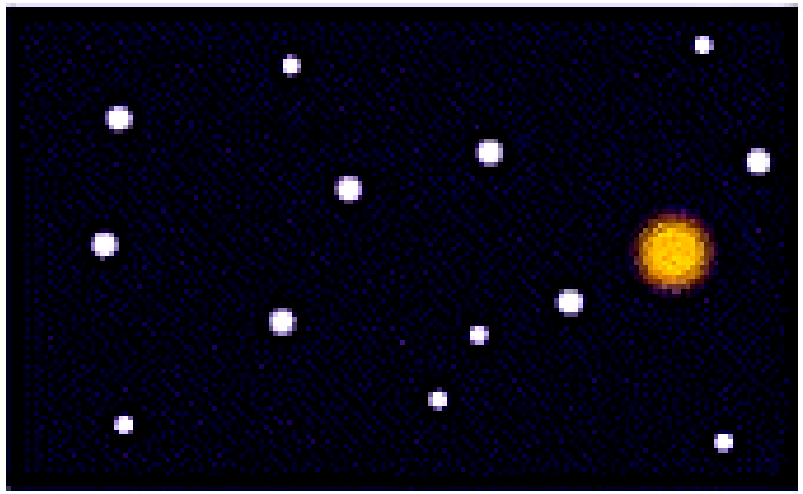
Measuring Astronomical Distances: Parallax





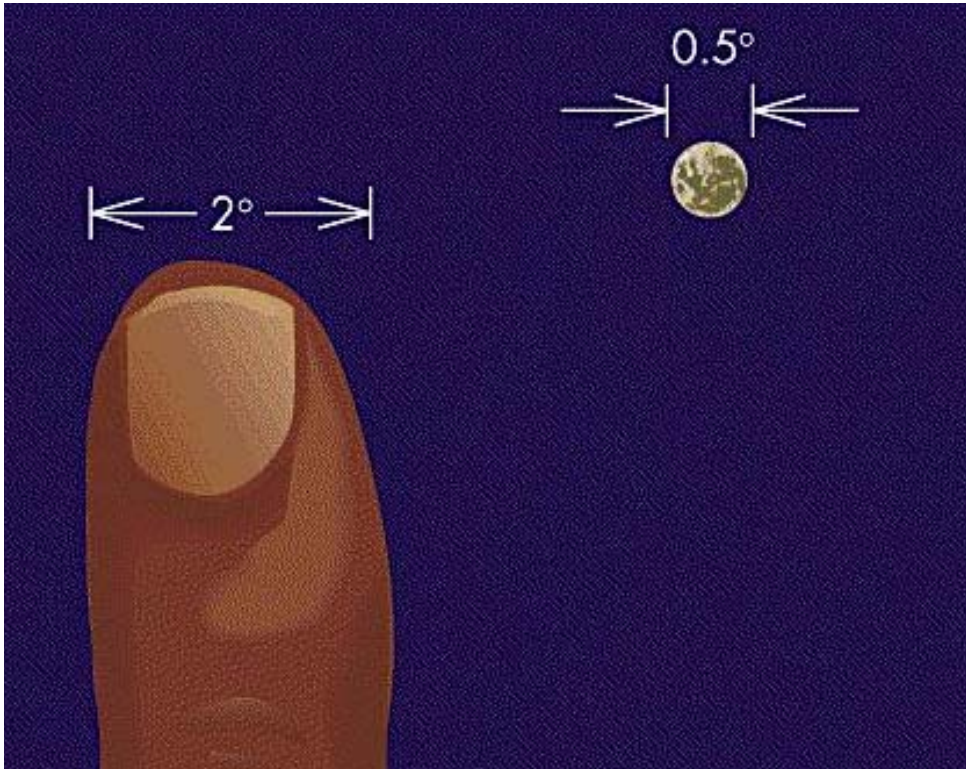
View from the Earth in January

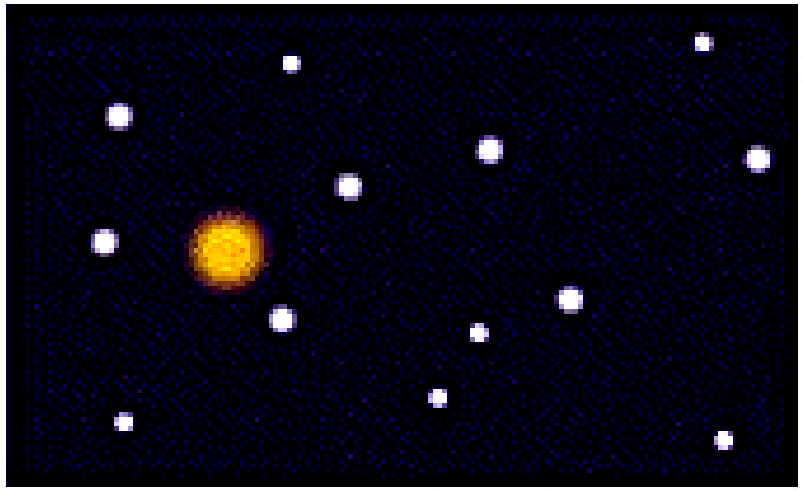




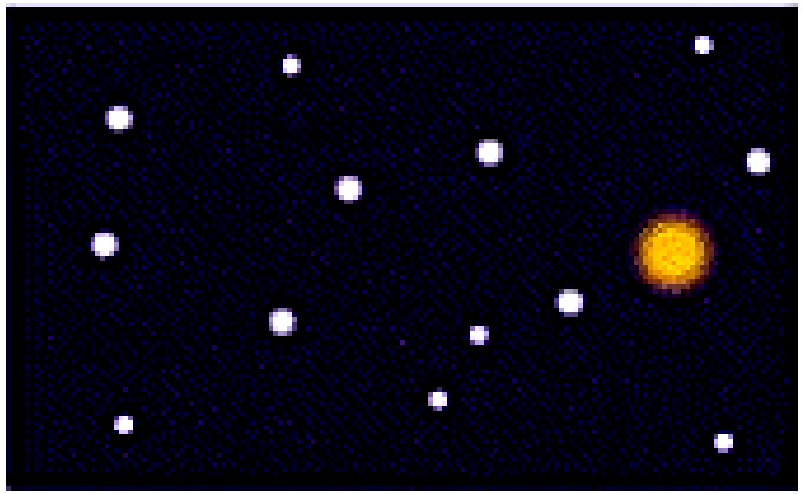
View from the Earth in July

Measuring Astronomical Distances: Parallax





View from the Earth in January

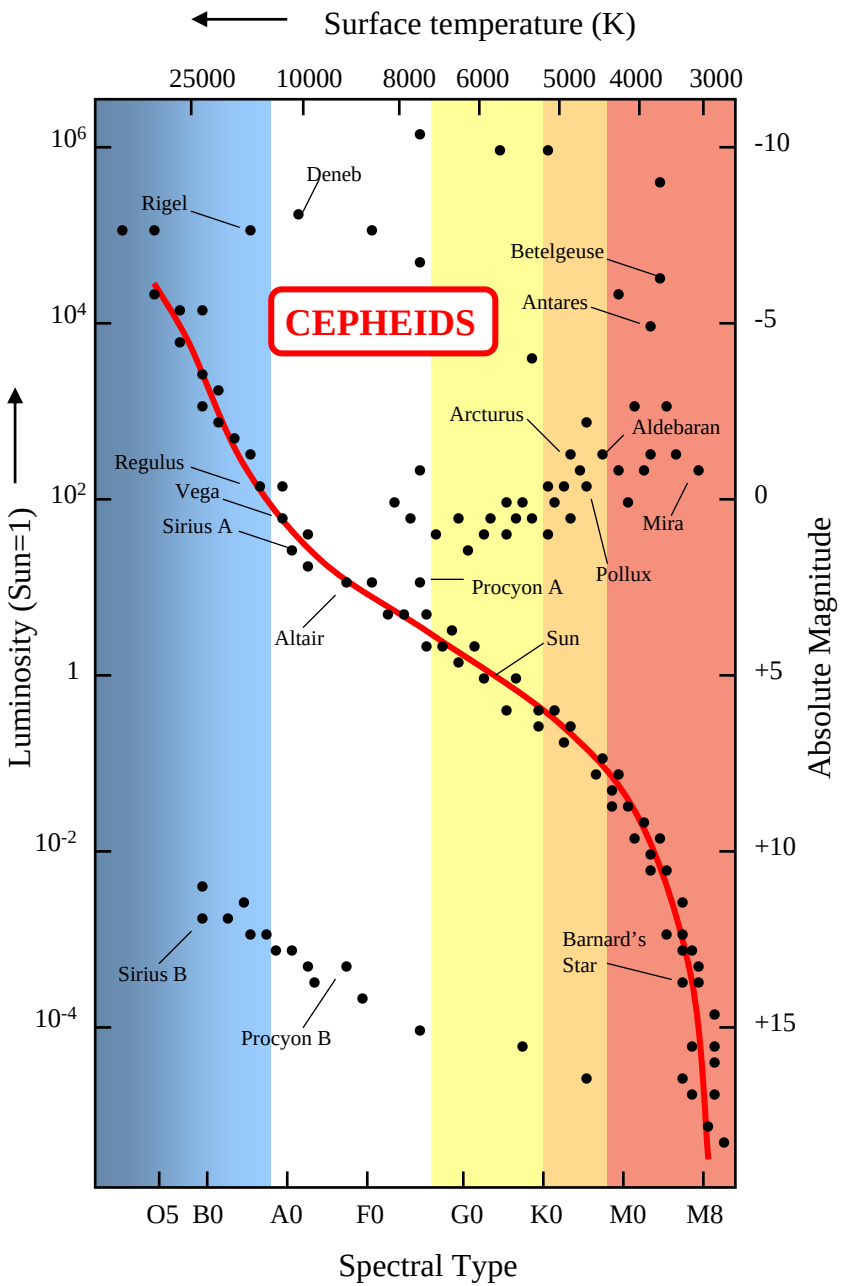


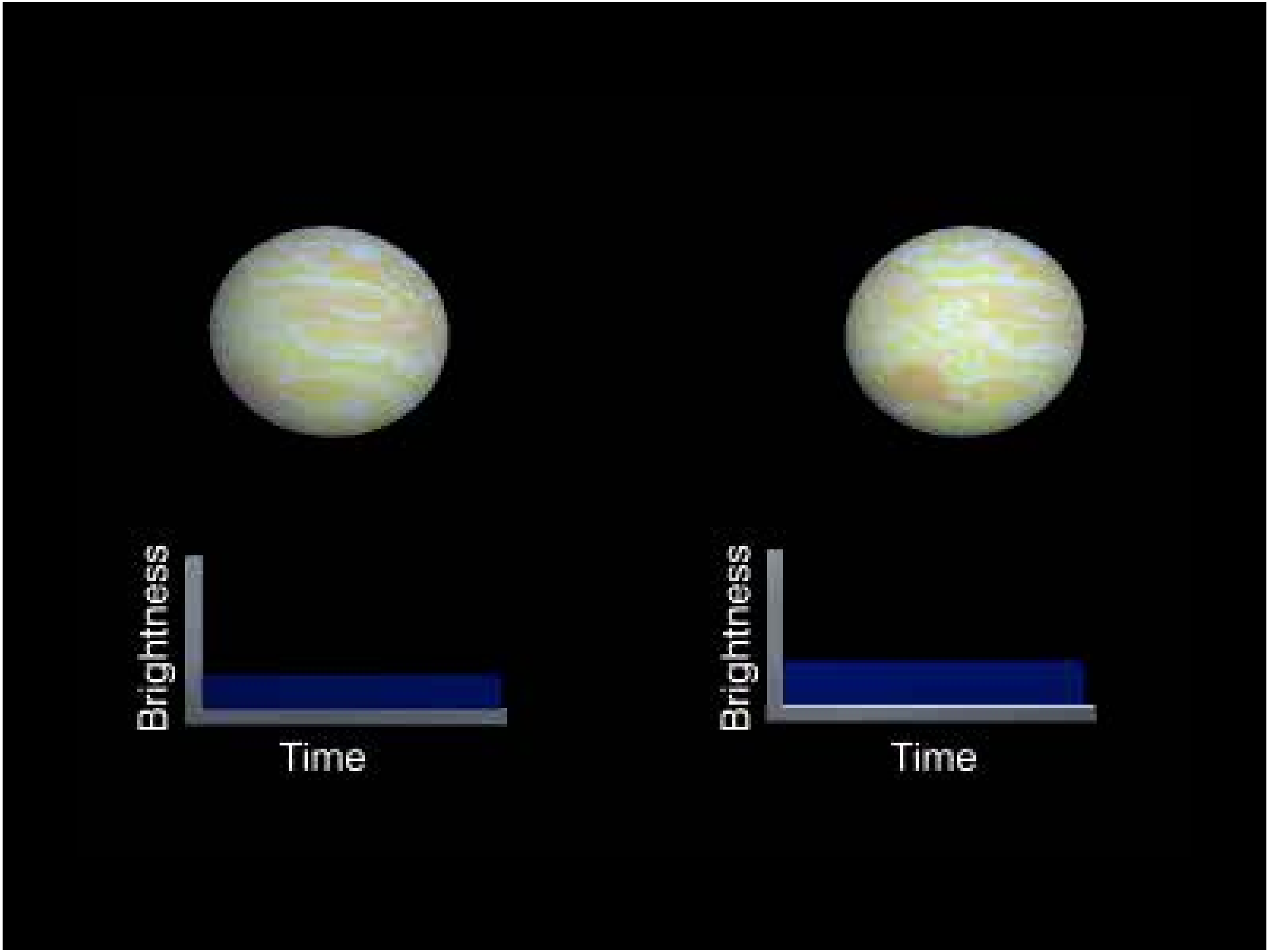
View from the Earth in July

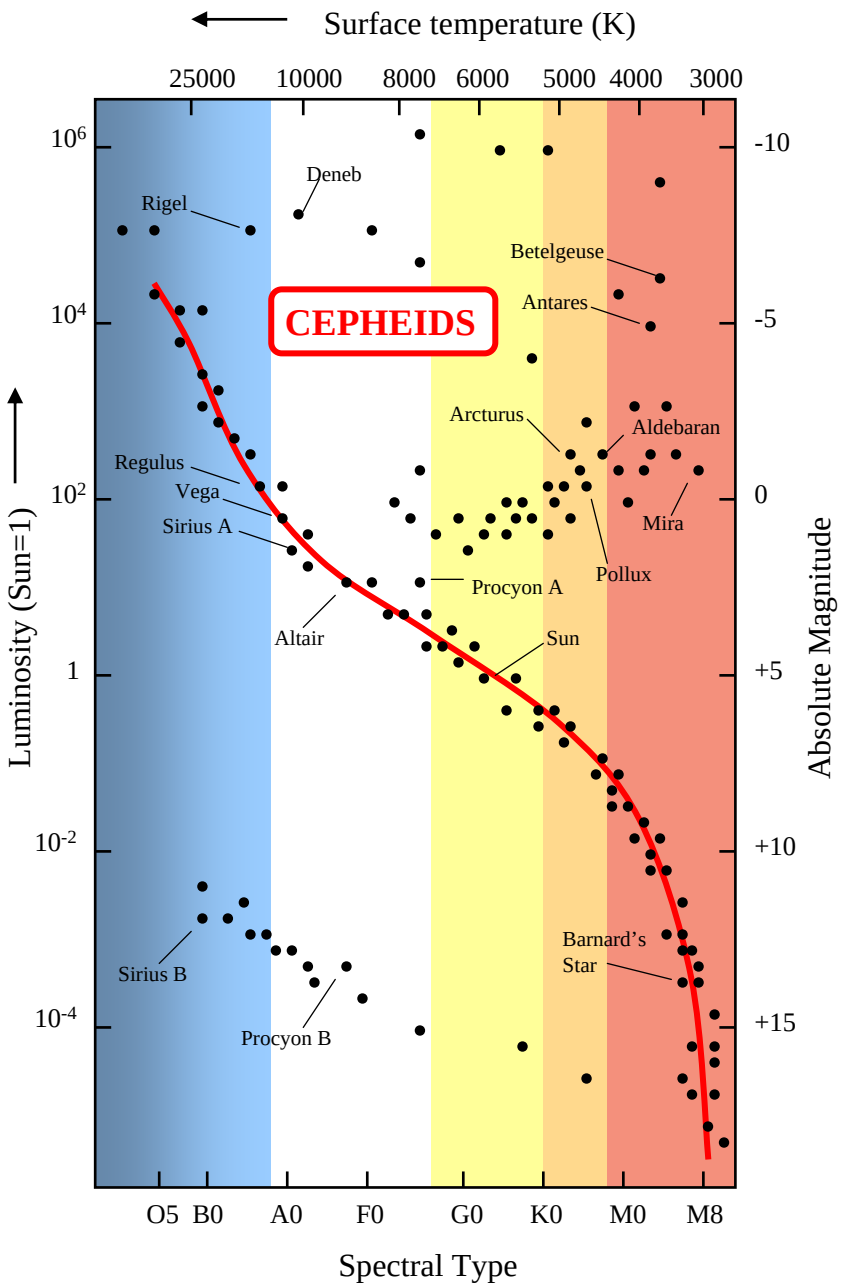
Even the nearest star shows a parallax shift of only 1/2000th the width of the full Moon

John Goodricke (1764-1786)

(photo from *Sky & Telescope*)


Surface temperature (K)
25000
10000
8000
6000
5000
4000
3000
10^6
10^4
10^2
1
10^{-2}
10^{-4}
Luminosity (Sun=1)
-10
-5
0
+5
+10
+15
Absolute Magnitude
CEPHEIDS
Deneb
Rigel
Betelgeuse
Antares
Arcturus
Aldebaran
Regulus
Vega
Sirius A
Mira
Pollux
Procyon A
Altair
Sun
Barnard's Star
Sirius B
Procyon B
O5
B0
A0
F0
G0
K0
M0
M8
Spectral Type


Brightness
Time
Brightness
Time



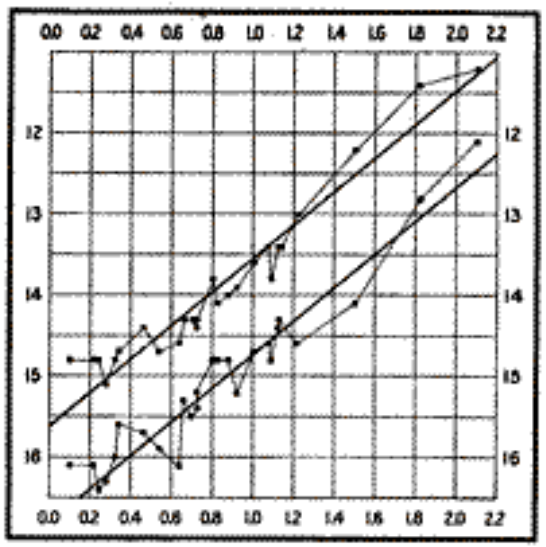
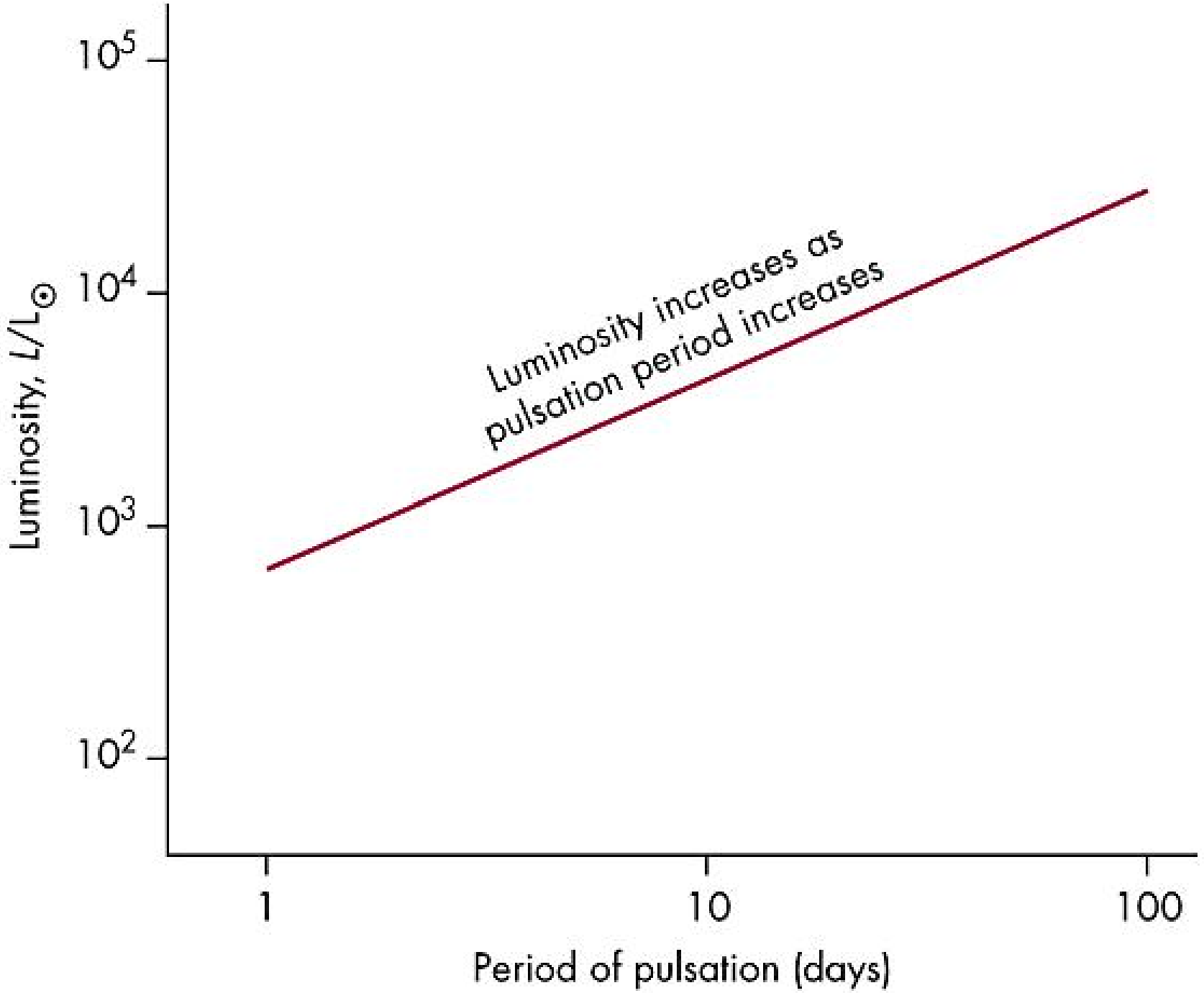


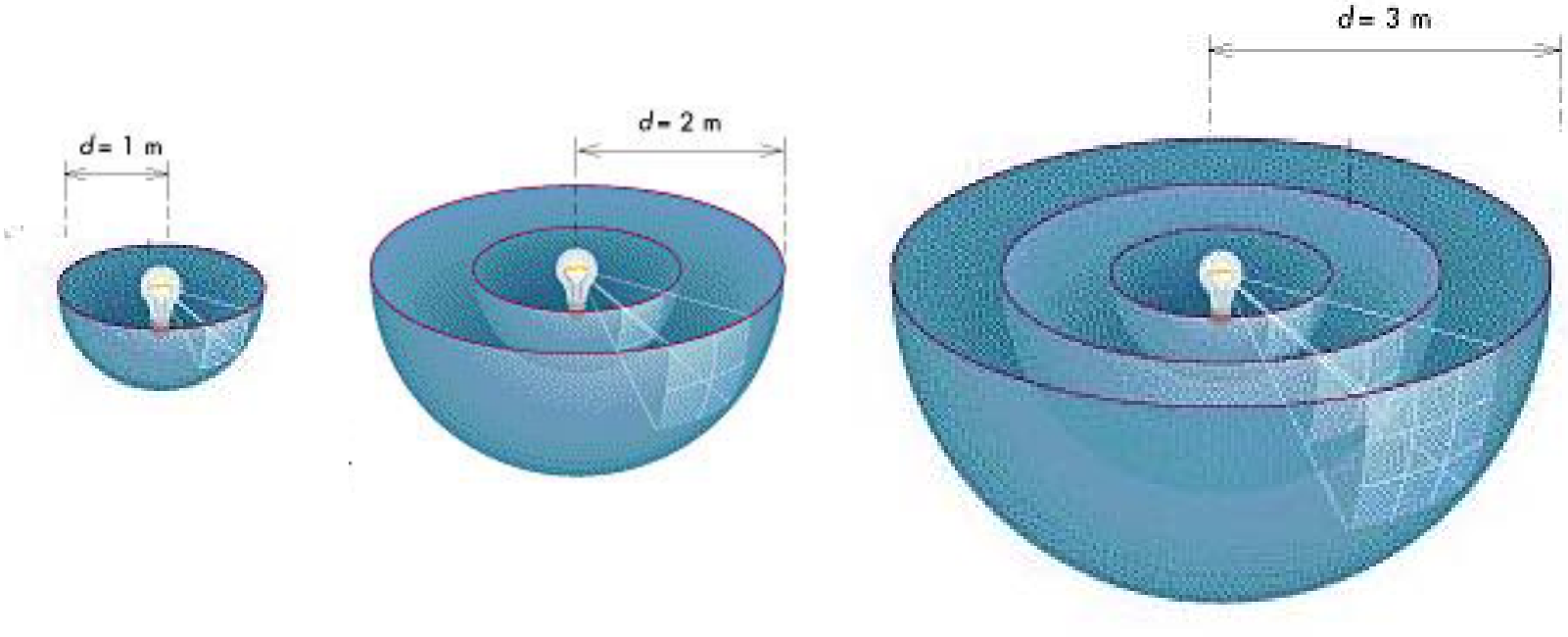
FIG. 2.

Pickering 1912

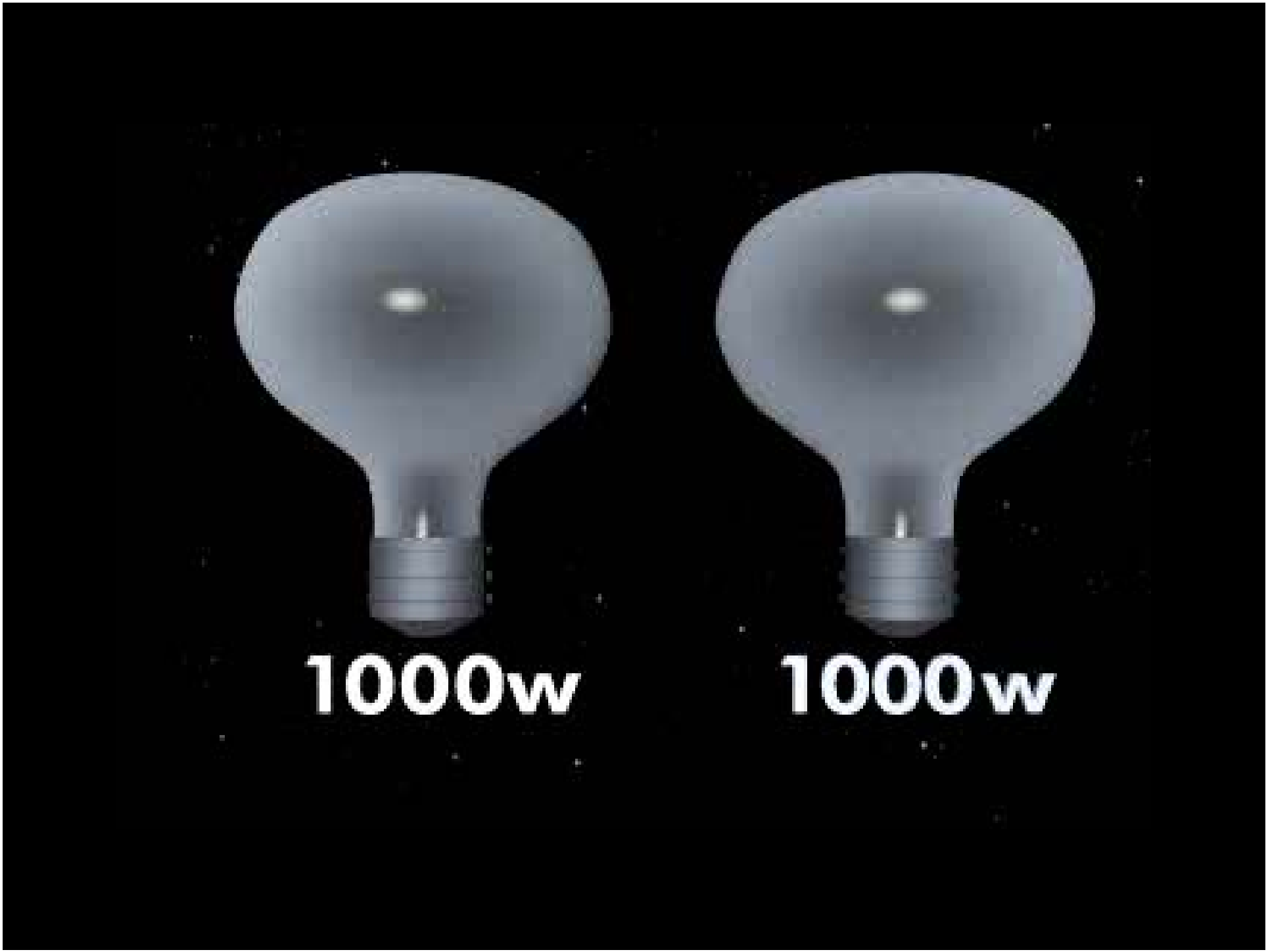

10^5
10^4
10^3
10^2
Luminosity, $L/L_\odot$
Luminosity increases as
pulsation period increases
1
10
100
Period of pulsation (days)

Measuring Astronomical Distances:

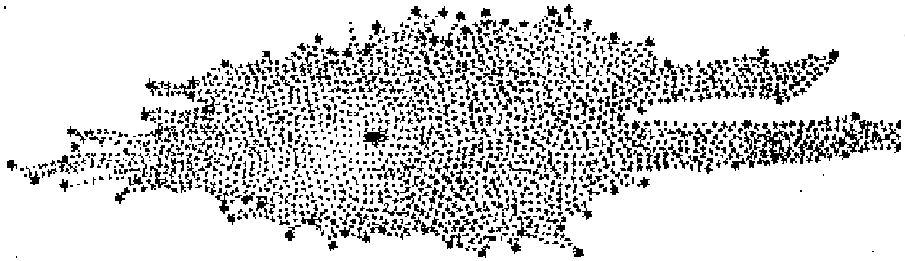
Inverse Square Law

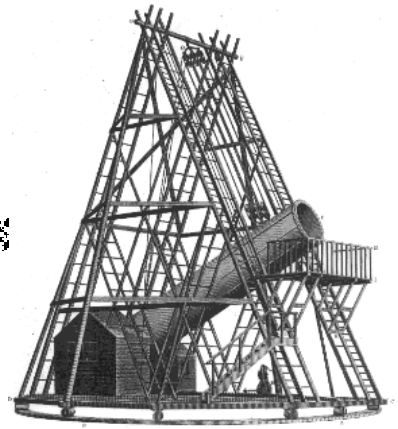


Brightness falls off with the square of the distance, because surface area of a sphere increases with the square of the radius

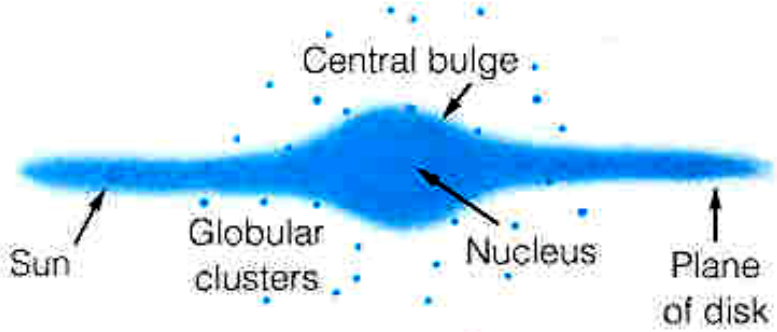

1000w
1000w

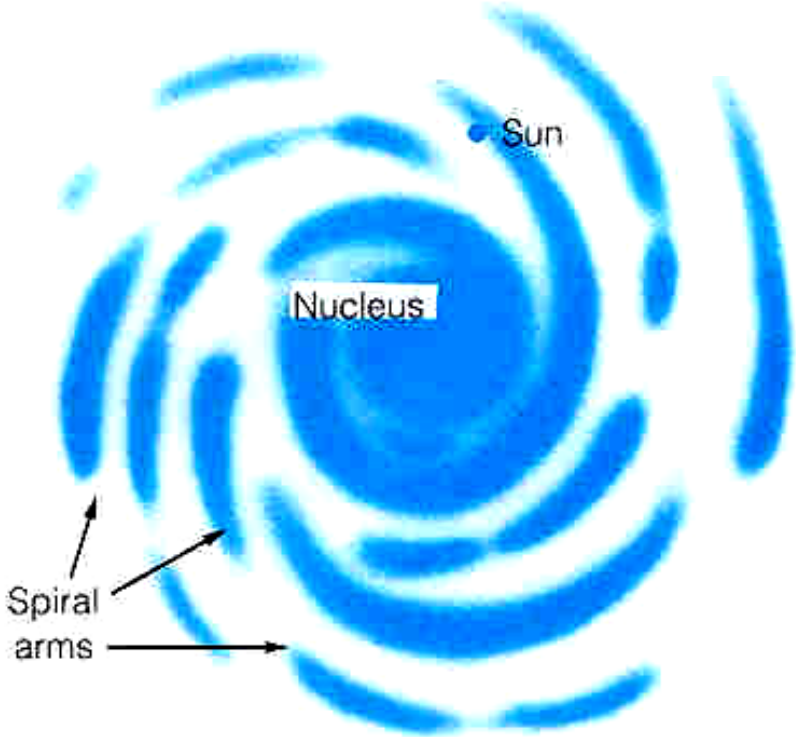
Herschel's Milky Way (1790)





Shapley's Model (1915)

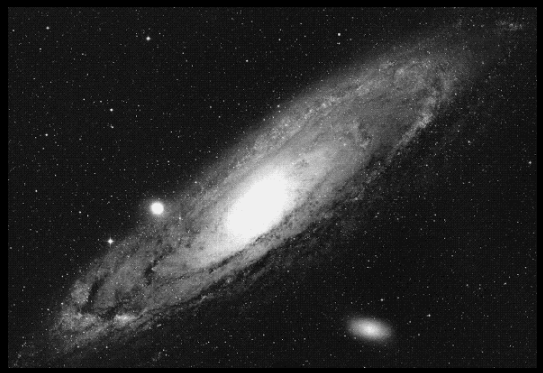
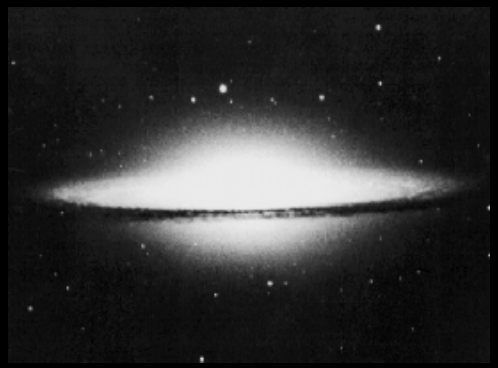




Early 20th Century

The nature of the nebulae?…



Gas clouds within the Milky Way,
or Island Universes?….

The Great Debate, 1920

Shapley vs Curtis

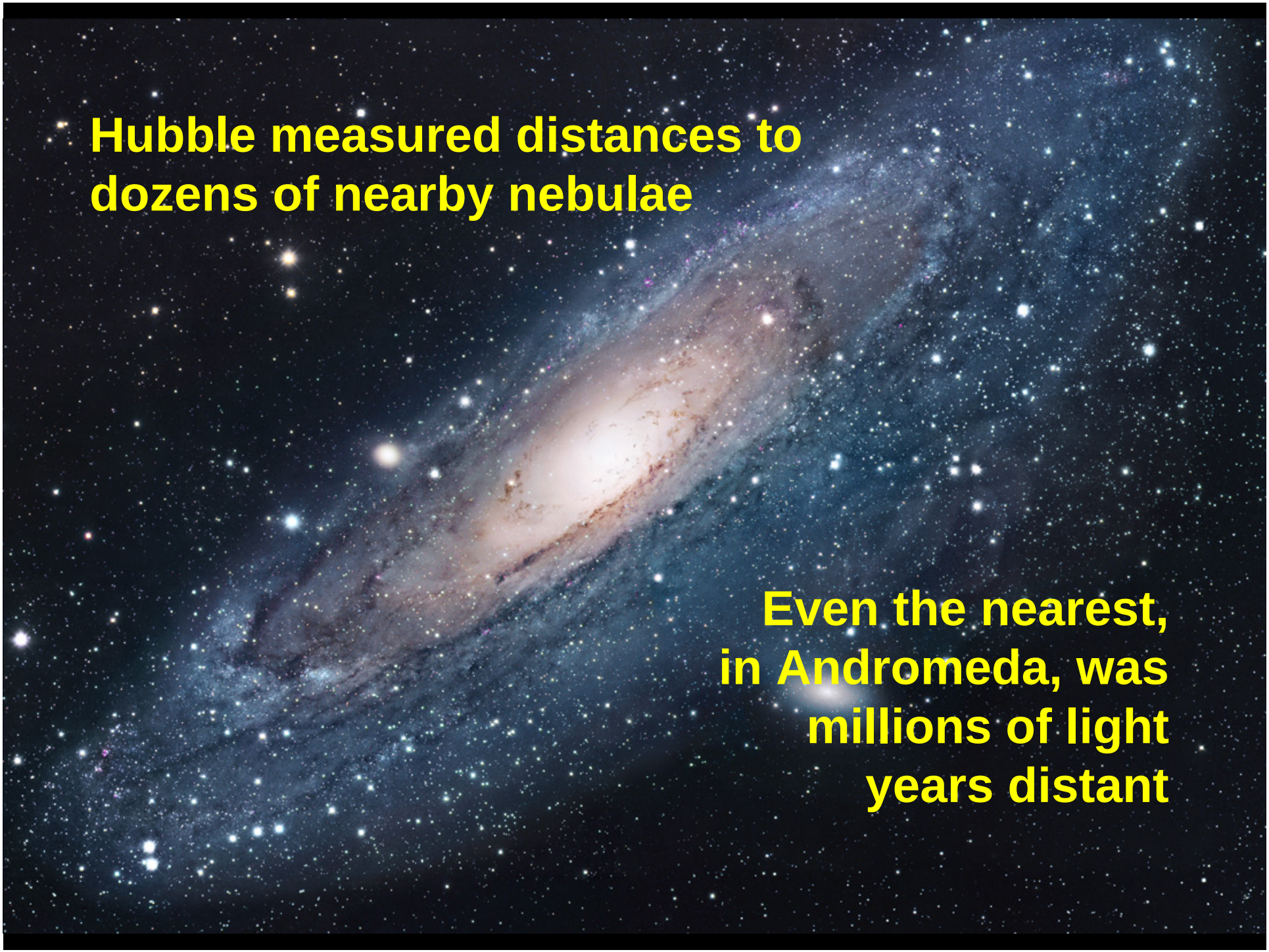
at the National Academy of Sciences

The Great Debate, 1920

Shapley vs Curtis

at the National Academy of Sciences

Shapley argues successfully
that the nebulae are *within*
the Milky Way


Hubble measured distances to dozens of nearby nebulae
Even the nearest, in Andromeda, was millions of light years distant