The unexpected “flat rotation curves” of spiral galaxies were discovered in the 1960s

Vera Rubin,
discoverer of
dark matter in
galaxies


Vera Rubin at Lowell Observatory...


and at Palomar Observatory in 1965

# M31, the Andromeda galaxy

Image credit & copyright: Jason Ware

# M31, the Andromeda galaxy

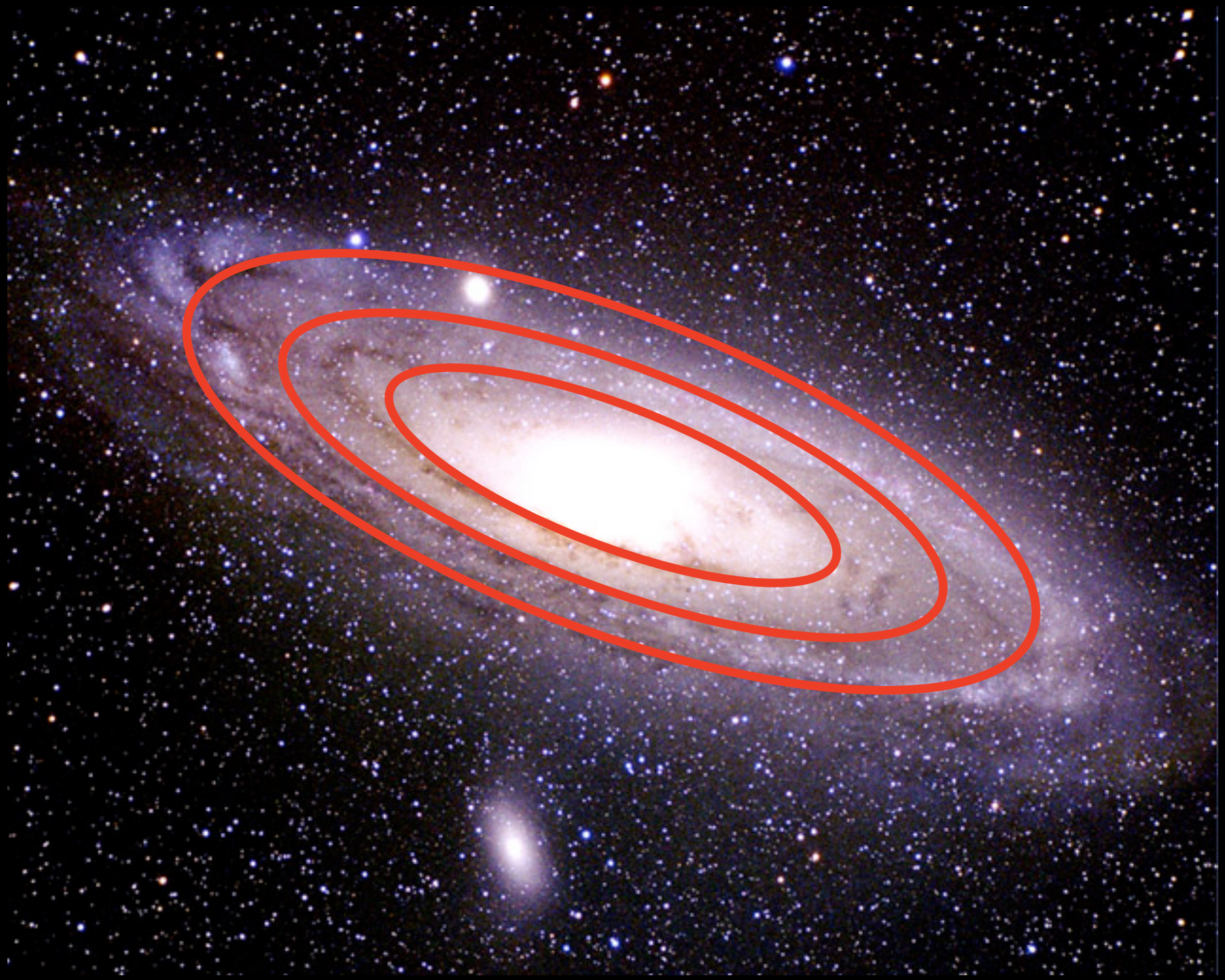
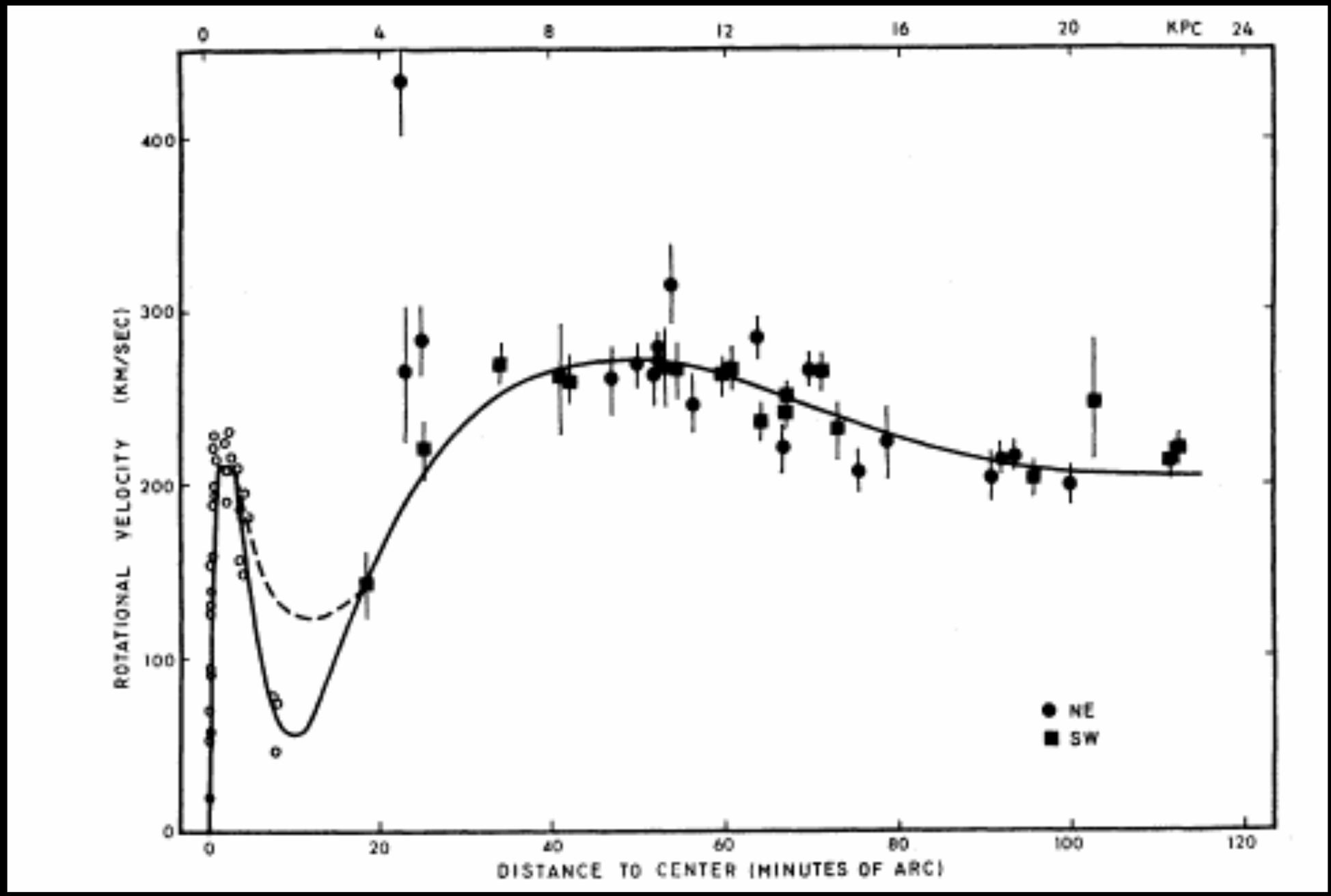


Image credit & copyright: Jason Ware

# The rotation speed of stars and gas in Andromeda, as a function of distance from the center

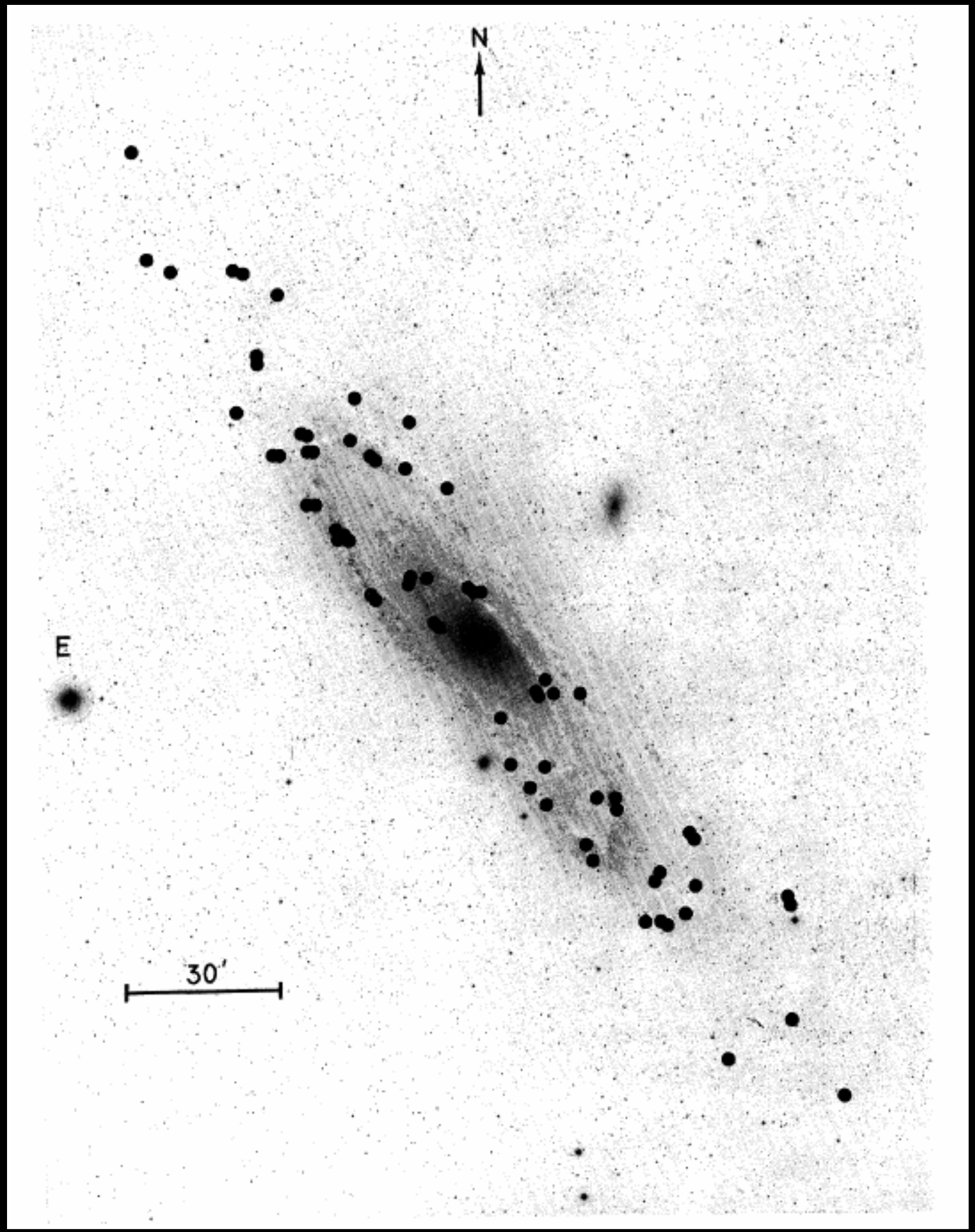
Rotation speed (km/s)




Distance from galaxy center

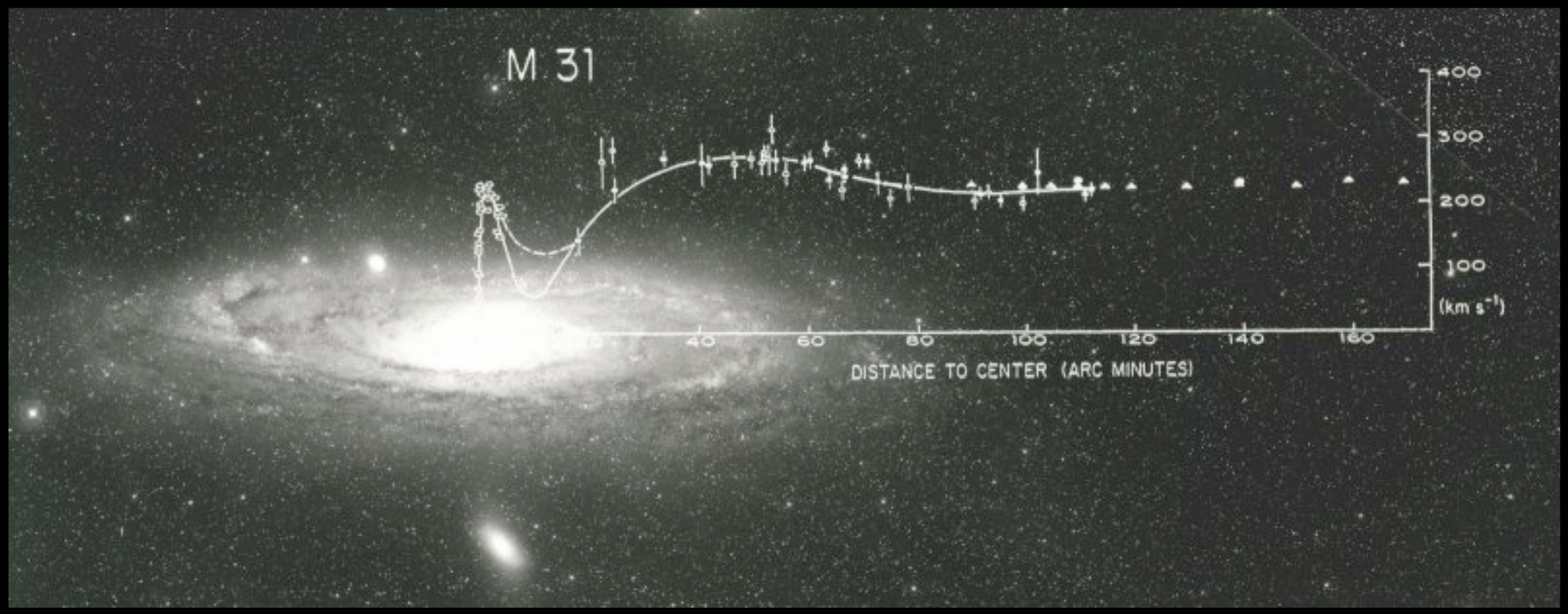
From Rubin & Ford, *Astrophysical Journal*, 159:379 (1970)

Positions of the rotational velocity measurements




From Rubin & Ford, *Astrophysical Journal*, 159:379 (1970)

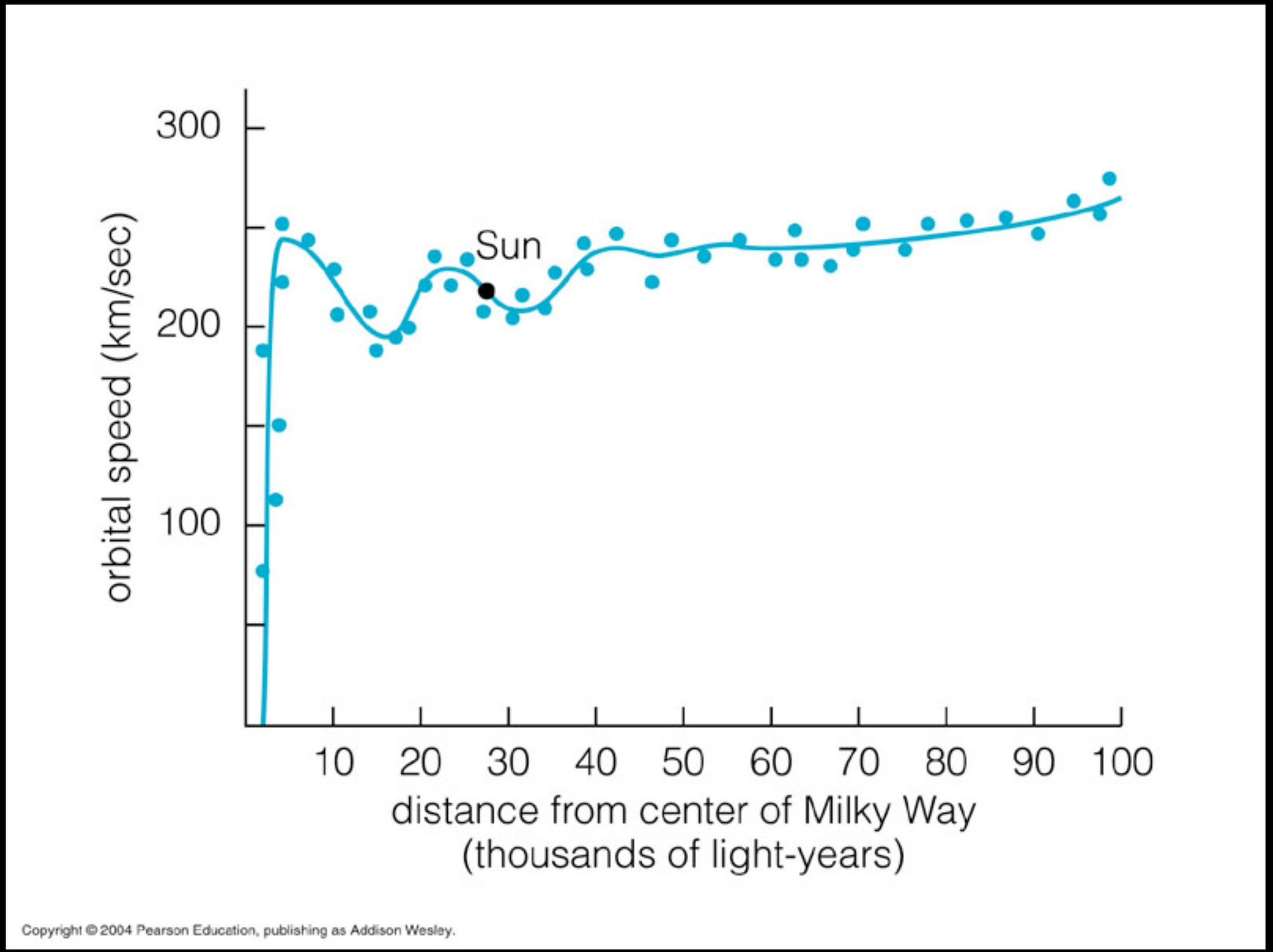
# The rotation speed is constant well beyond the visible edge of the galaxy!




This indicates a large amount of unseen mass, or *dark matter*

Image credit and copyright: V. Rubin and J. Dunlap, after M. Roberts

# The rotation curve for our Milky Way



# Rotation curves of other spiral galaxies, also showing the presence of dark matter

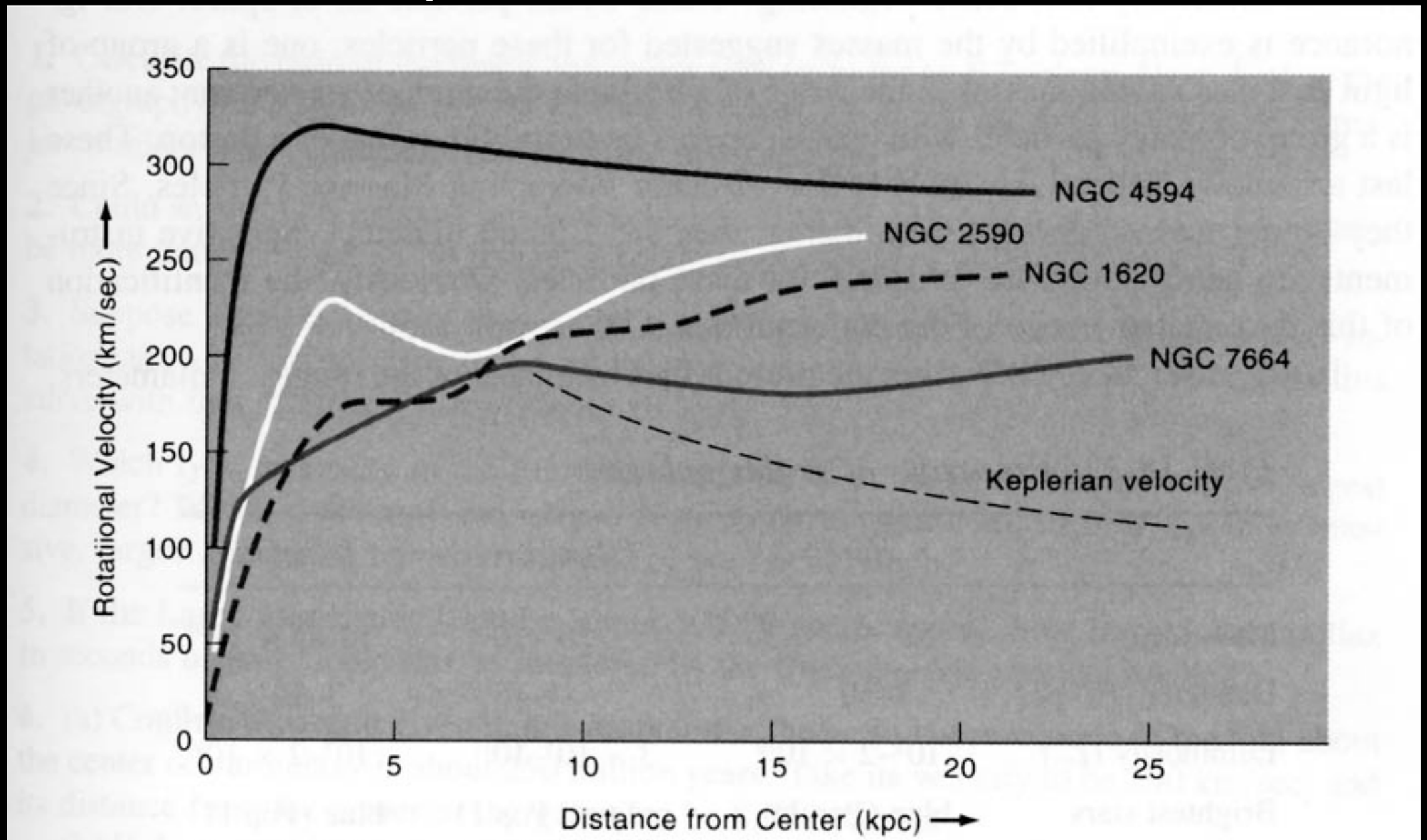
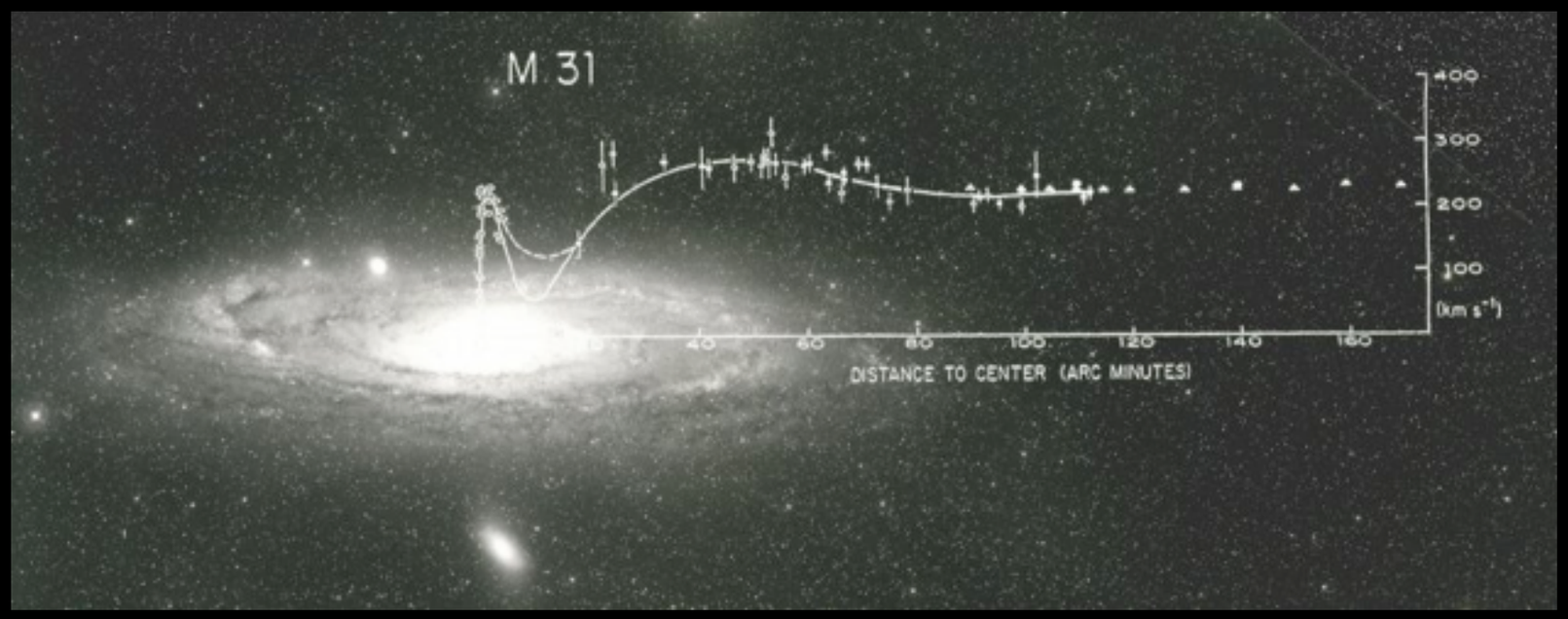


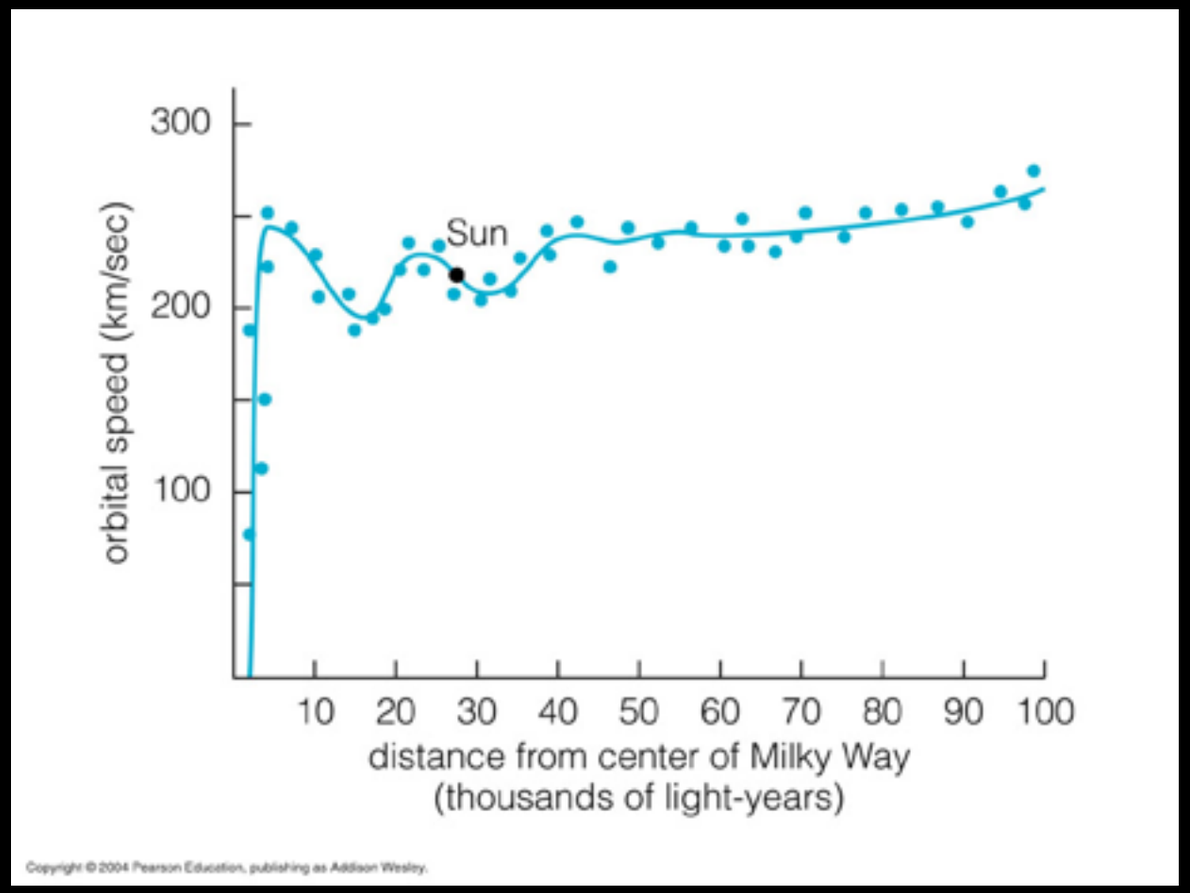

***Figure 18.12.*** Curves of rotational velocity at increasing distances from the centers of four spiral galaxies. The velocities remain roughly flat instead of becoming smaller with greater distances from the center, as would be expected if most of the mass were located in and near the central bulge. The expected decrease, labeled "Keplerian velocity," is shown for NGC 7664. Contrast this with the observed velocity.

Stars and gas on the edges of spiral galaxies orbit much faster than they would if they only felt the gravity of the other stars in the galaxy

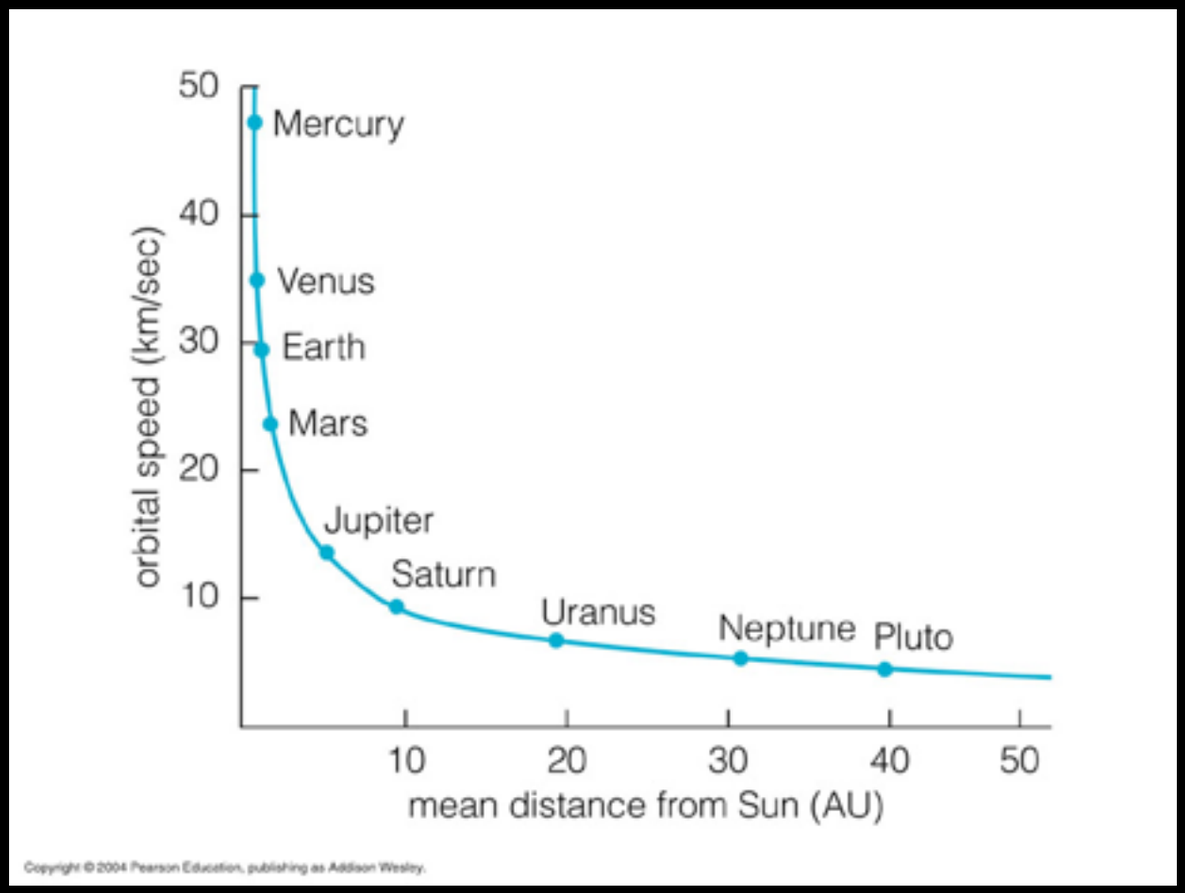
There isn't just more mass than the starlight we see can account for, but that mass is distributed differently than the stars



# Orbital speed as a function of distance (a "rotation curve")




Milky Way Galaxy




Solar System

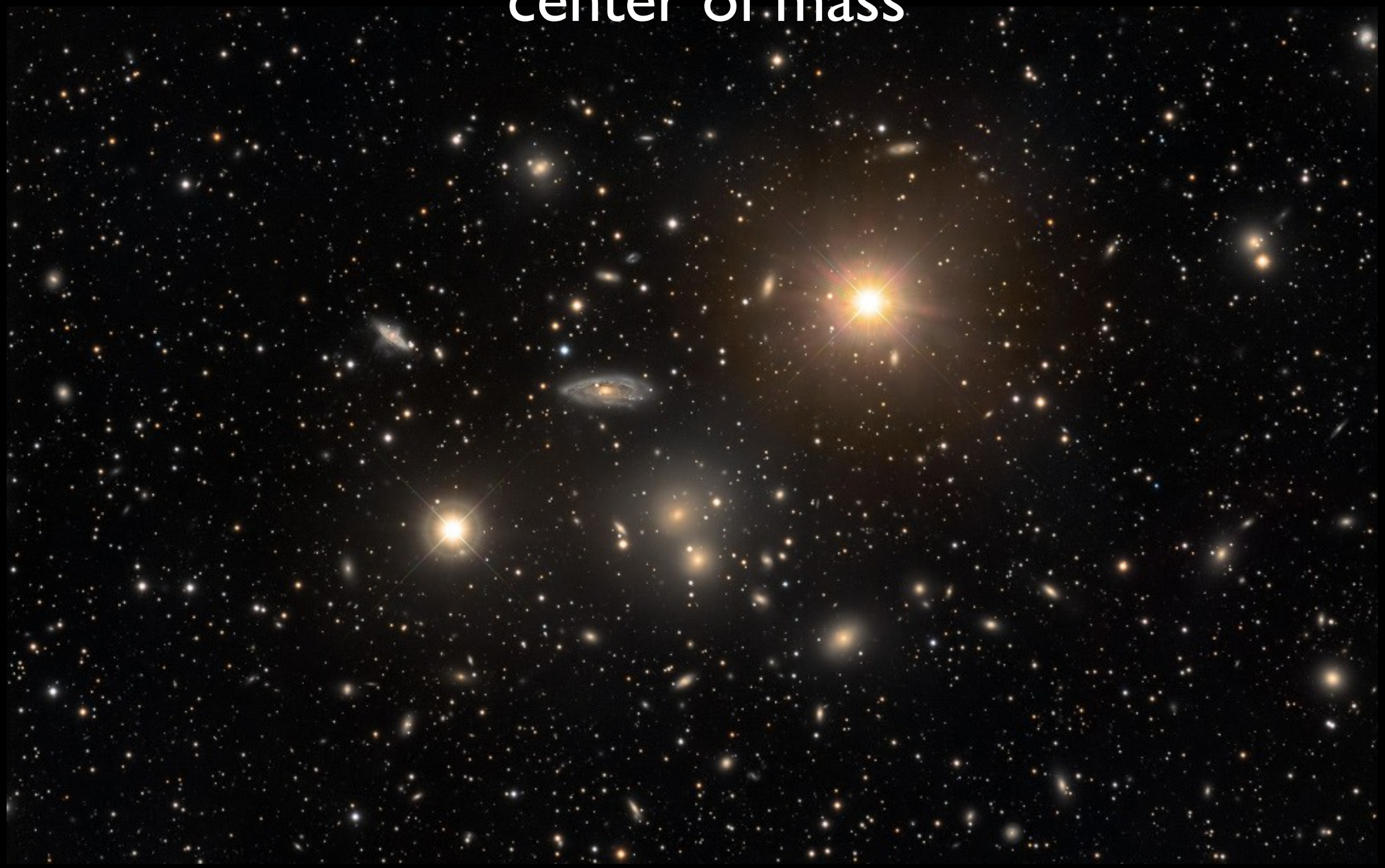
Most of the mass in spiral galaxies is not stars (or gas, dust)

It is 80 to 90% dark matter

and that dark matter is much less centrally concentrated than the stars (and starlight) are

In another, even larger context

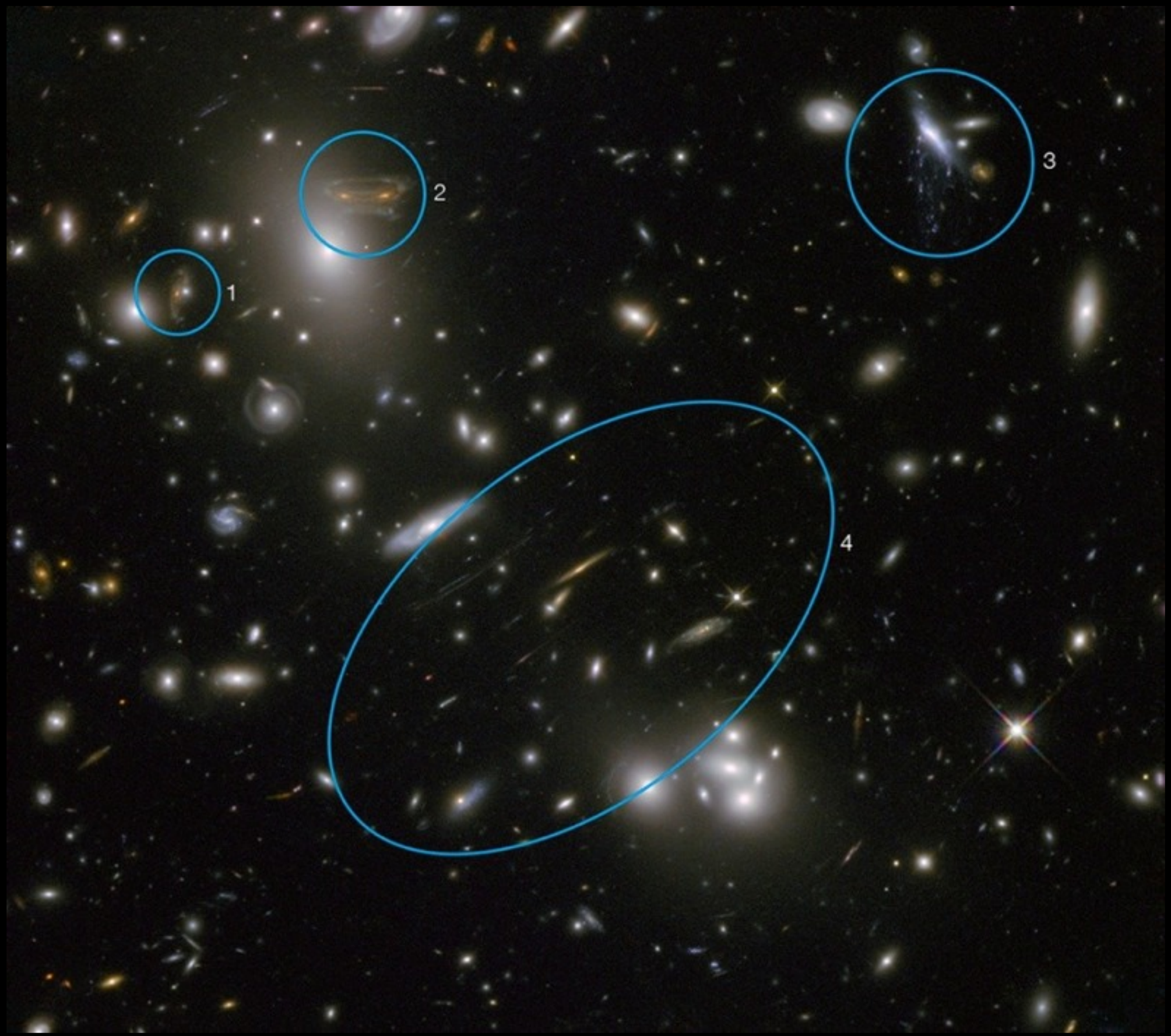
galaxy clusters: all galaxies orbit common center of mass



# Coma cluster

# Hercules cluster

# Abell 68 cluster



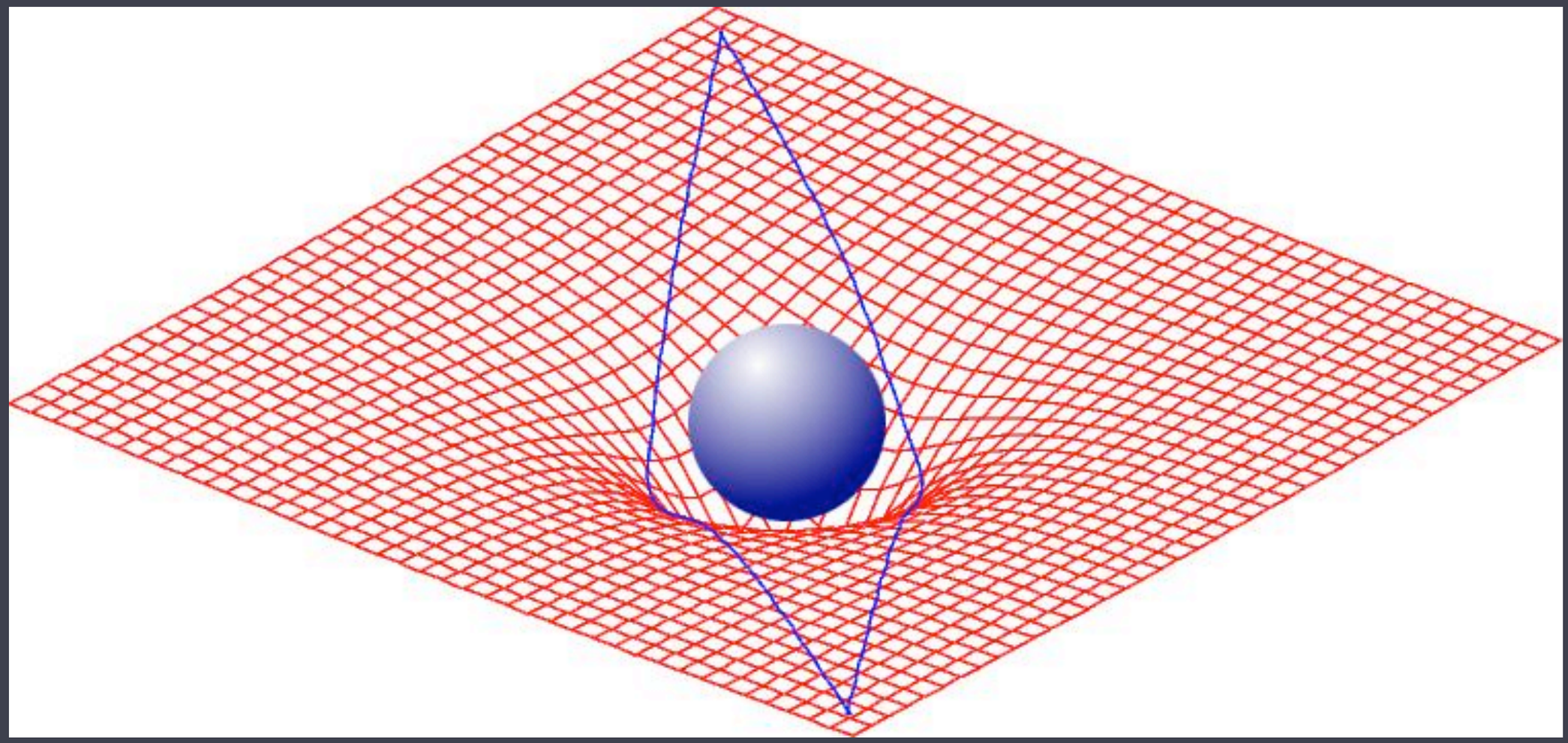
galaxies are moving faster than expected

80 to 90% of the mass is “missing”

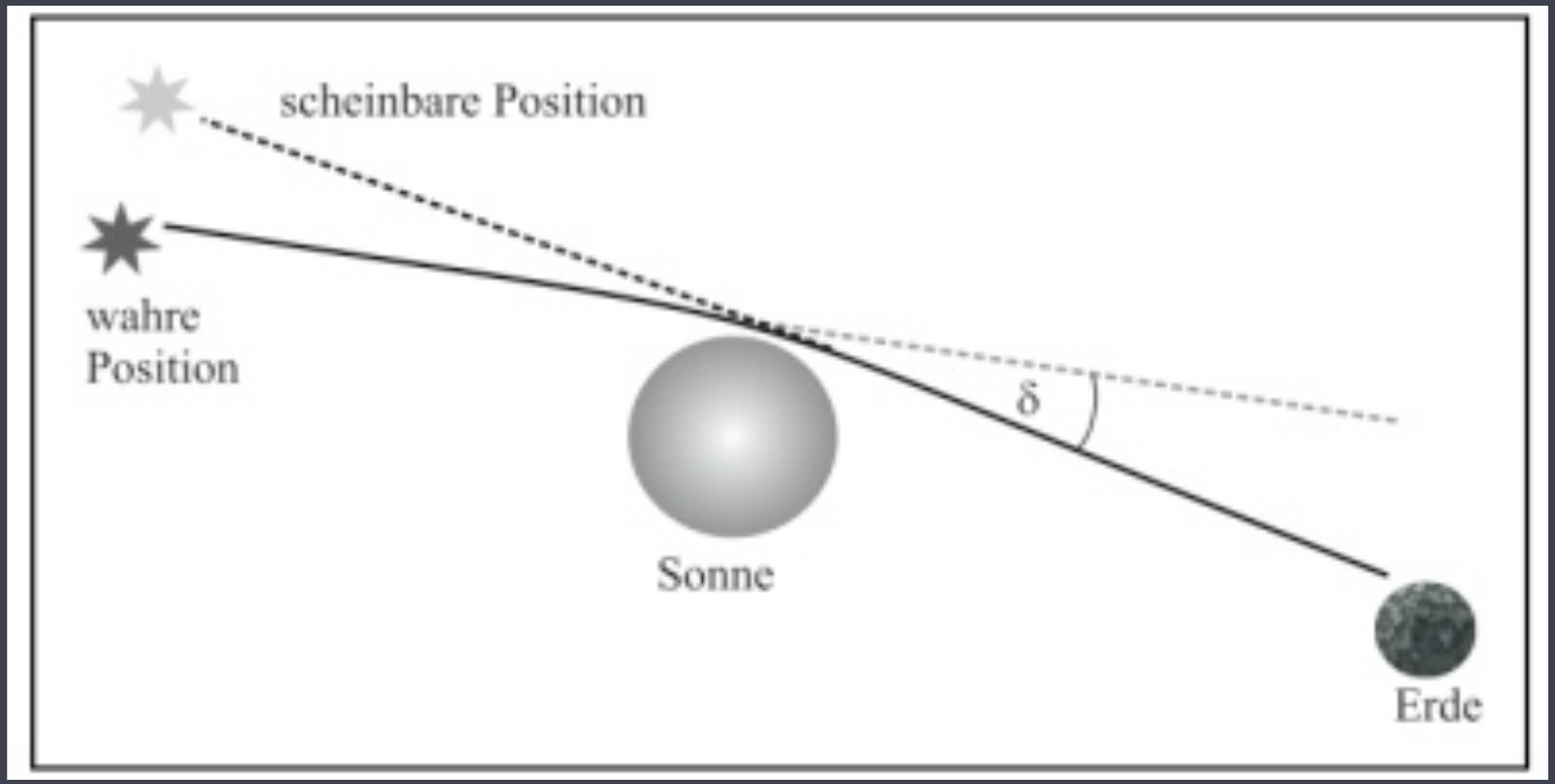
1930s

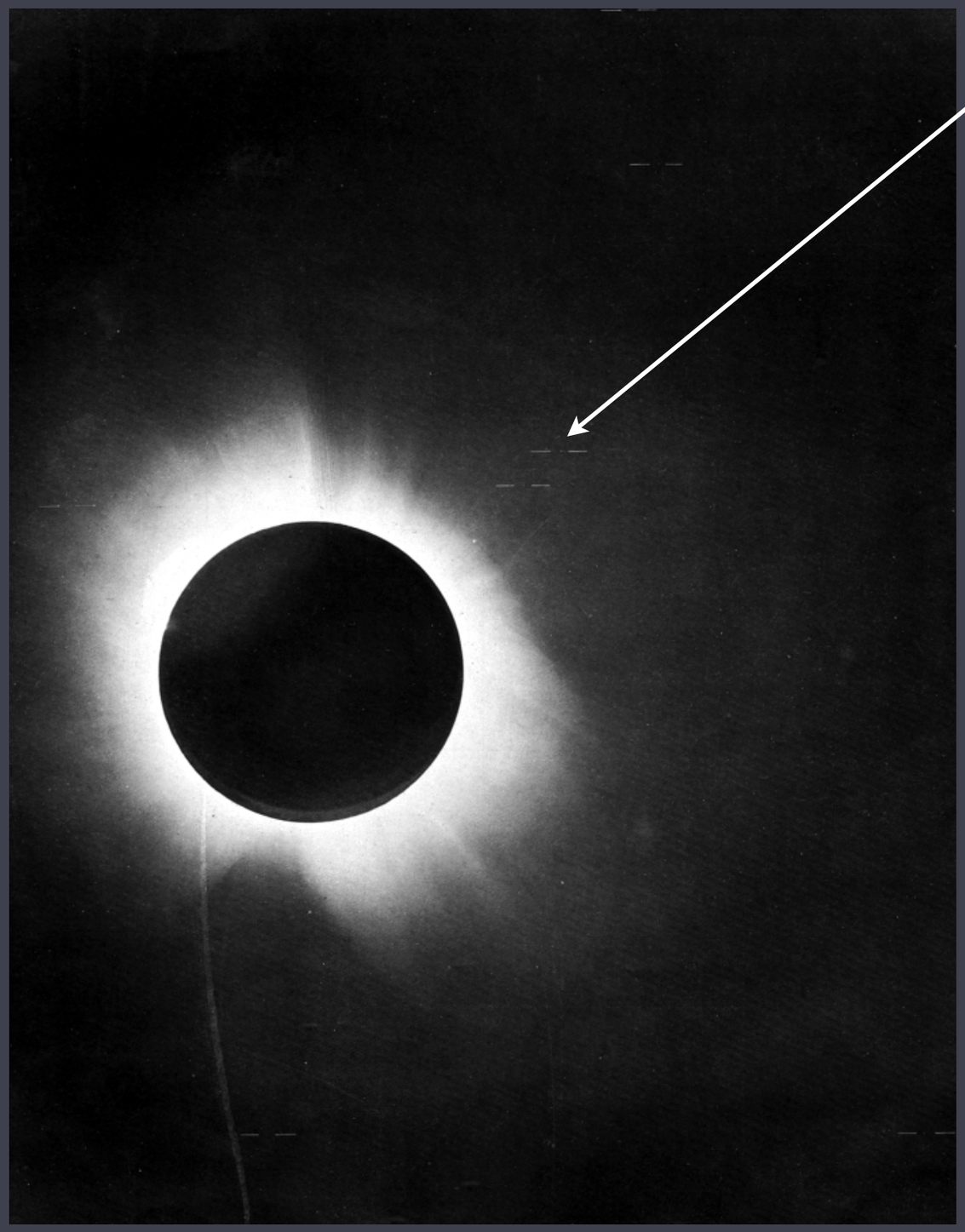
Fritz Zwicky

# Shifting gears… gravity as the curvature of space



# *Prediction*: the Sun bends starlight that passes near it





1919 eclipse expedition confirms the bending of starlight by the Sun…

Actual Position of the Star

Apparent Position of the Star

Distance from the Earth to the Stella Background is more than 93,000,000,000,000 miles.

THE SUN

Distance from the Earth 93,000,000 miles

This Diagram shows the proportional Displacement of the Stars in relation to the distance from the Sun.

The amount of Displacement is exaggerated about 600 times

Apparent Position: ↑
Actual Position: *

THE SUN

AFRICA

Principe I.

Sobral

SOUTH AMERICA

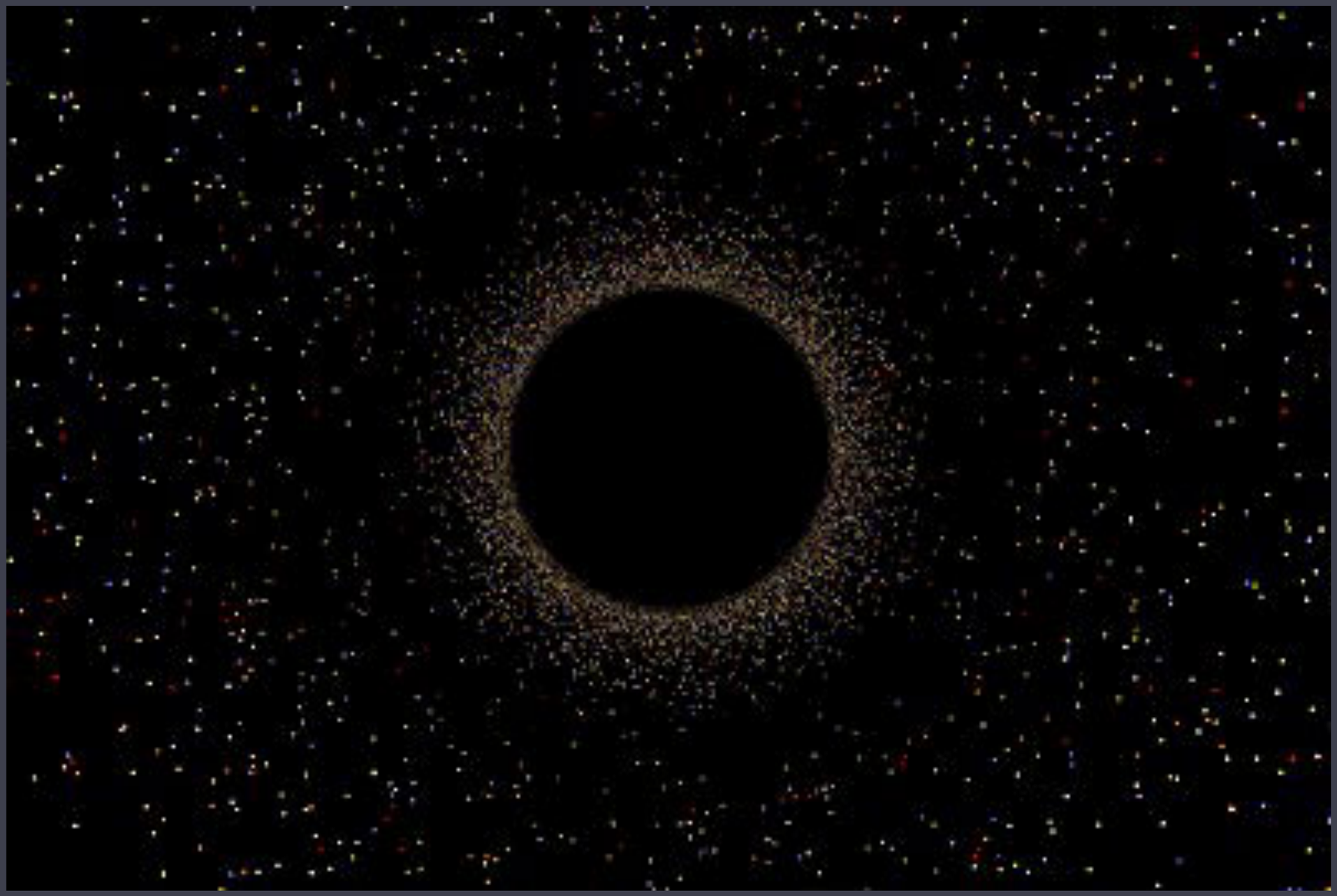
ATLANTIC OCEAN

Showing Path of Total Eclipse of May 28-29, 1919, and positions of the two Observation Stations.

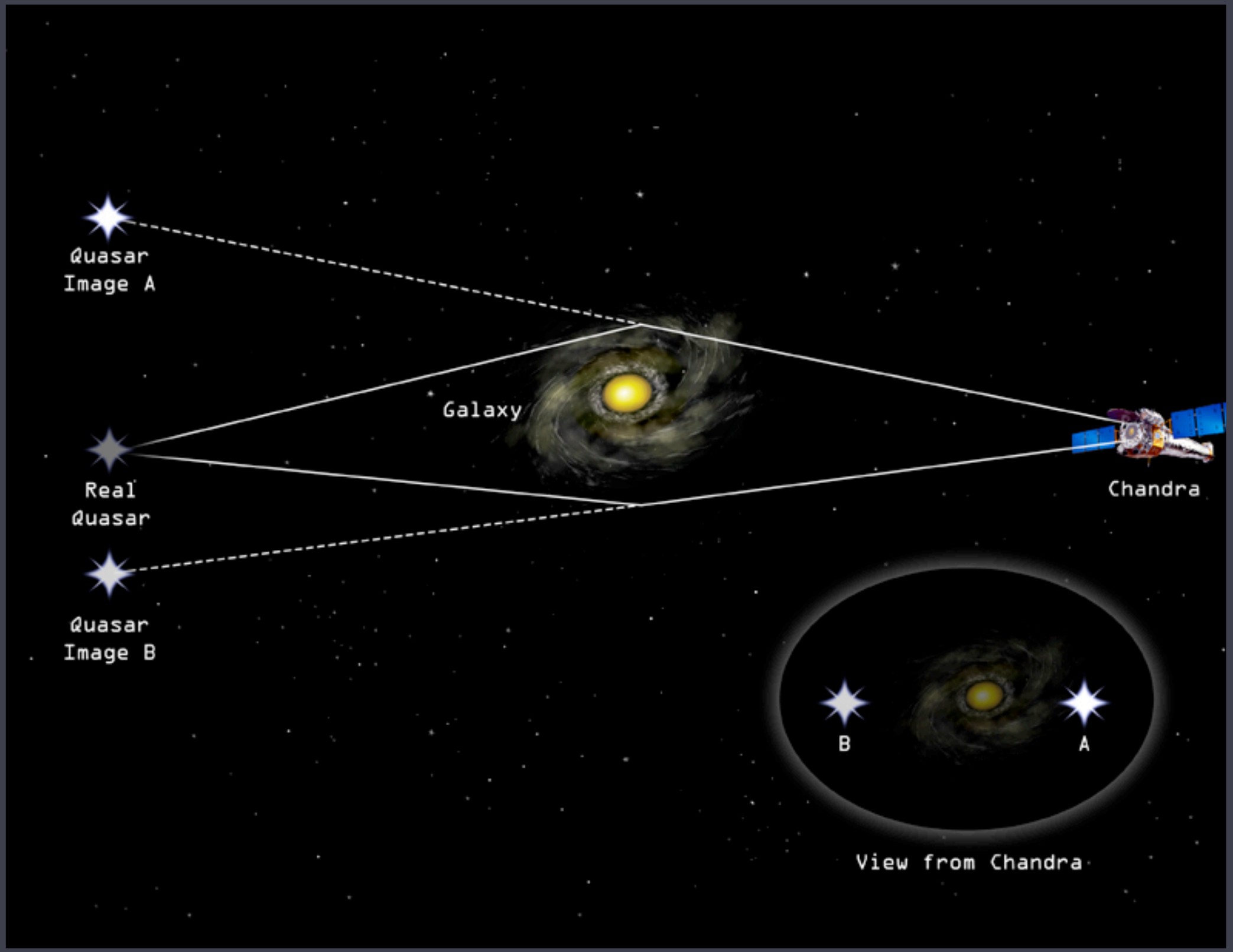
THE OBSERVATION STATION AT SOBRAL, IN BRAZIL

The Corona

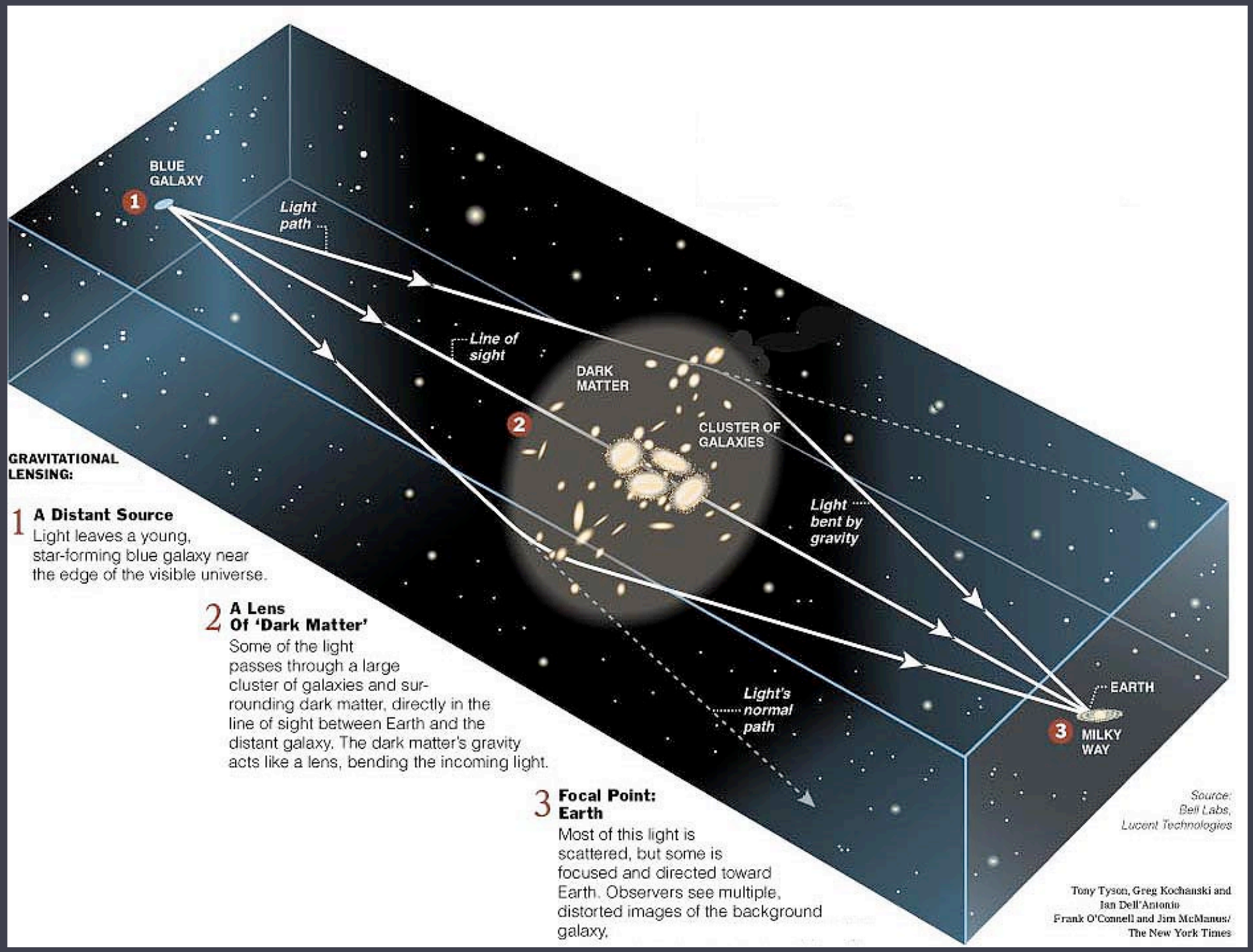
*simulation* of a black hole distorting the stars behind it



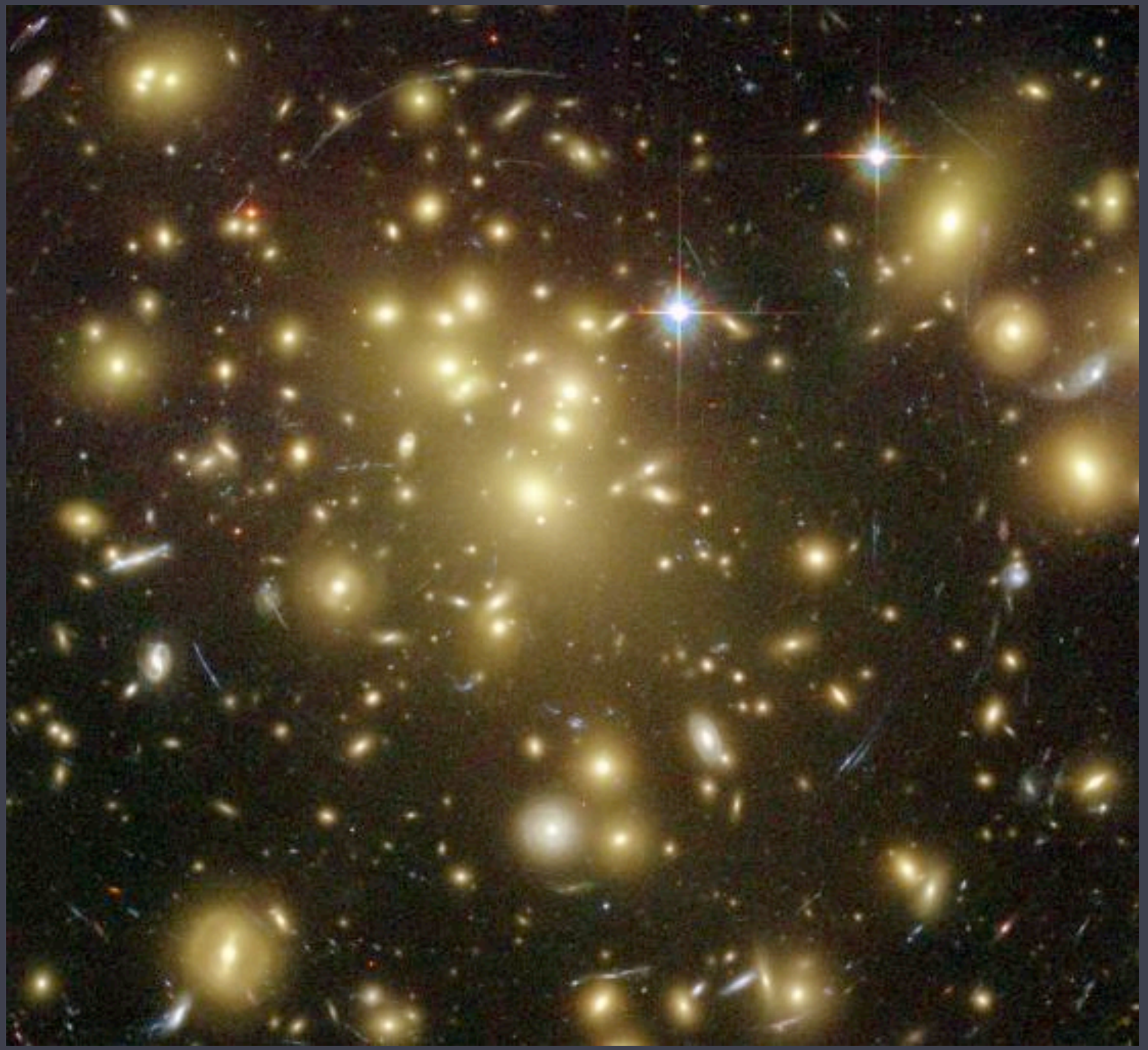
# Smithsonian building on the Washington Mall, with a Saturn-mass black hole halfway between the building and the observer


Quasar
Image A
Galaxy
Real
Quasar
Chandra
Quasar
Image B
B
A
View from Chandra

# “Einstein Cross” - quadruply lensed galaxy


BLUE GALAXY
1
Light path
Line of sight
DARK MATTER
2
CLUSTER OF GALAXIES
Light bent by gravity
Light's normal path
EARTH
3
MILKY WAY
GRAVITATIONAL LENSING:
1 A Distant Source
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.
2 A Lens Of 'Dark Matter'
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.
3 Focal Point: Earth
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.
Source: Bell Labs, Lucent Technologies
Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/ The New York Times

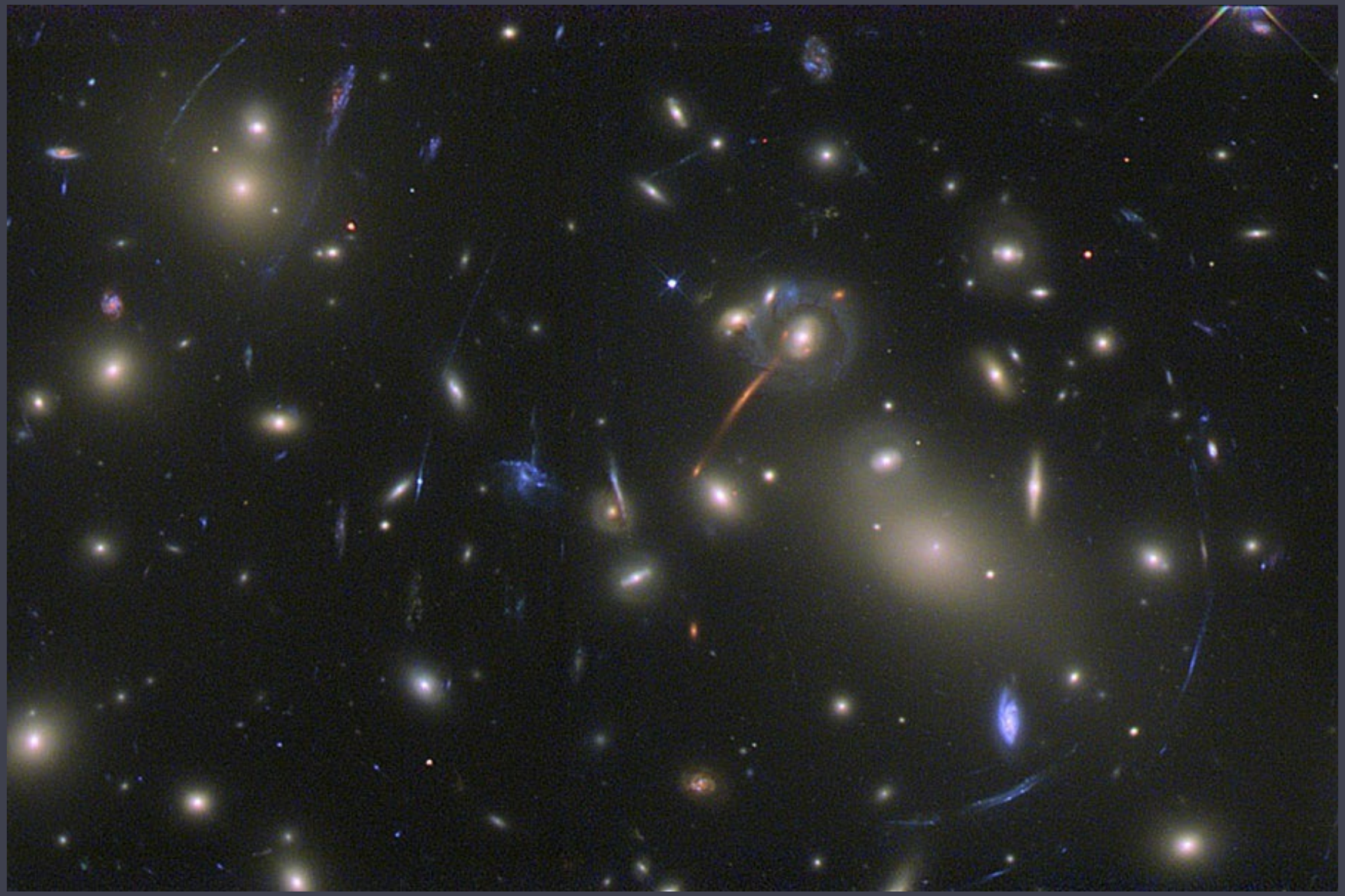
# foreground galaxy cluster lensing background galaxies



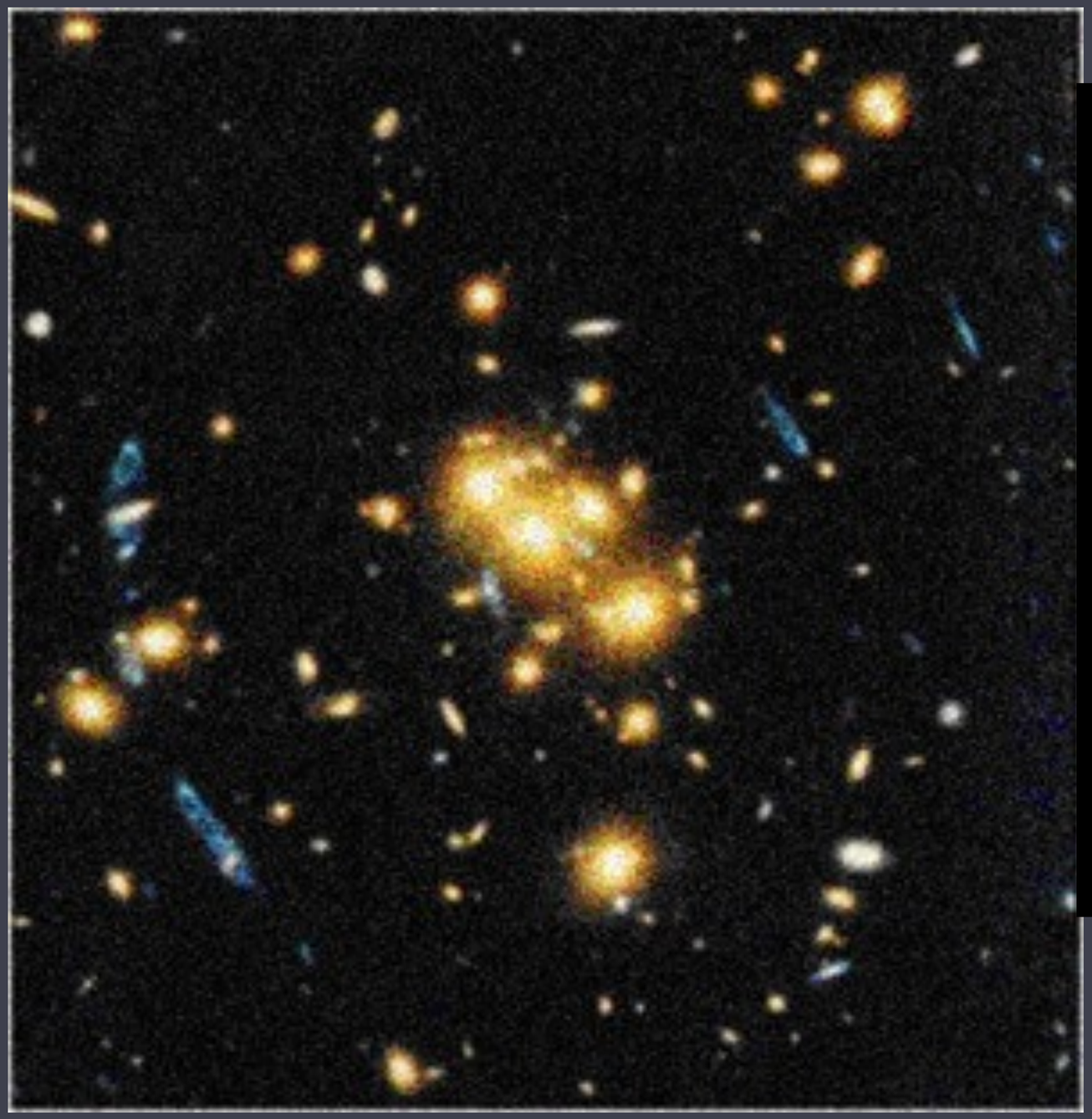
# Gravitational Lens in Abell 2218

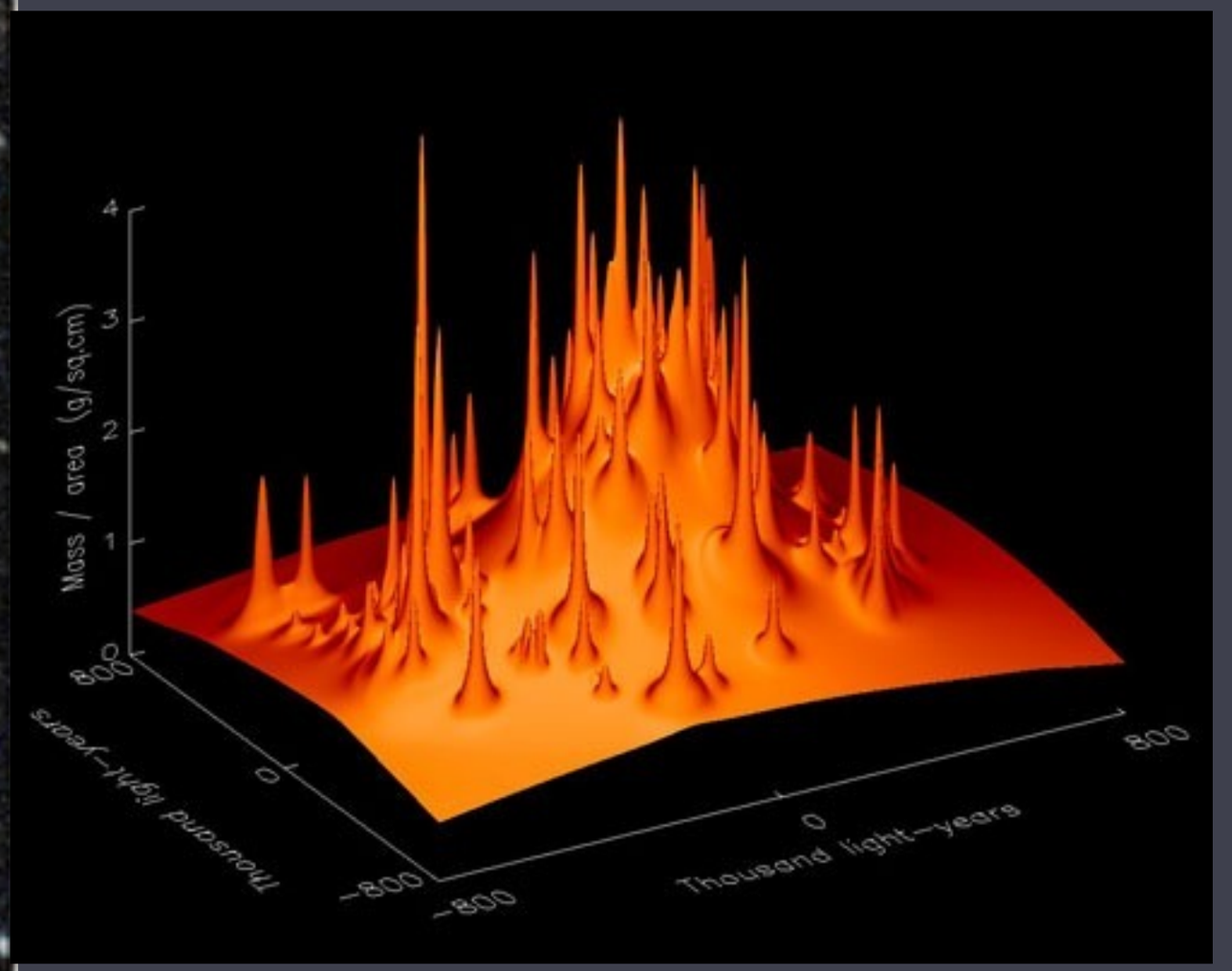
HST • WFPC2

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

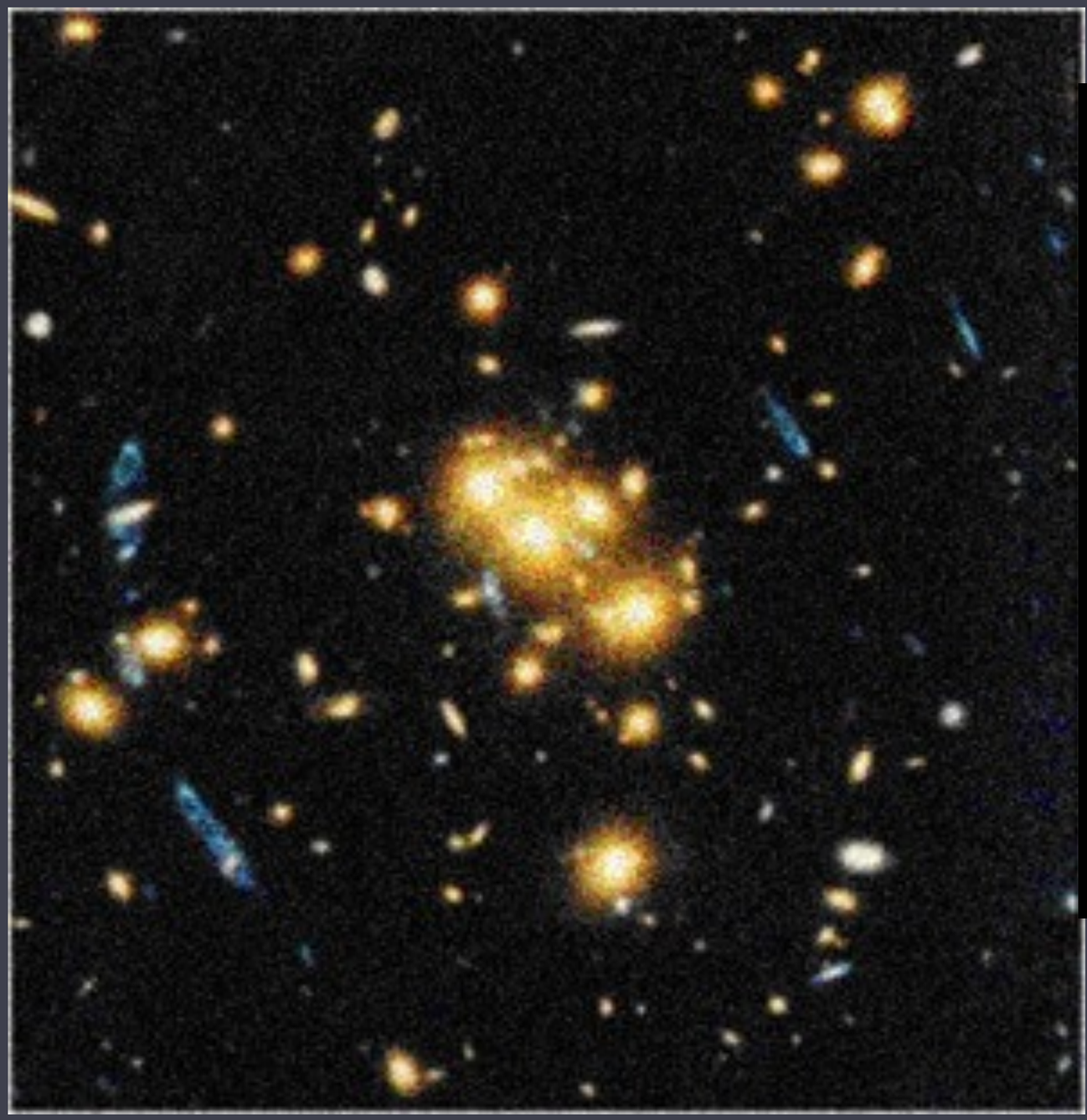


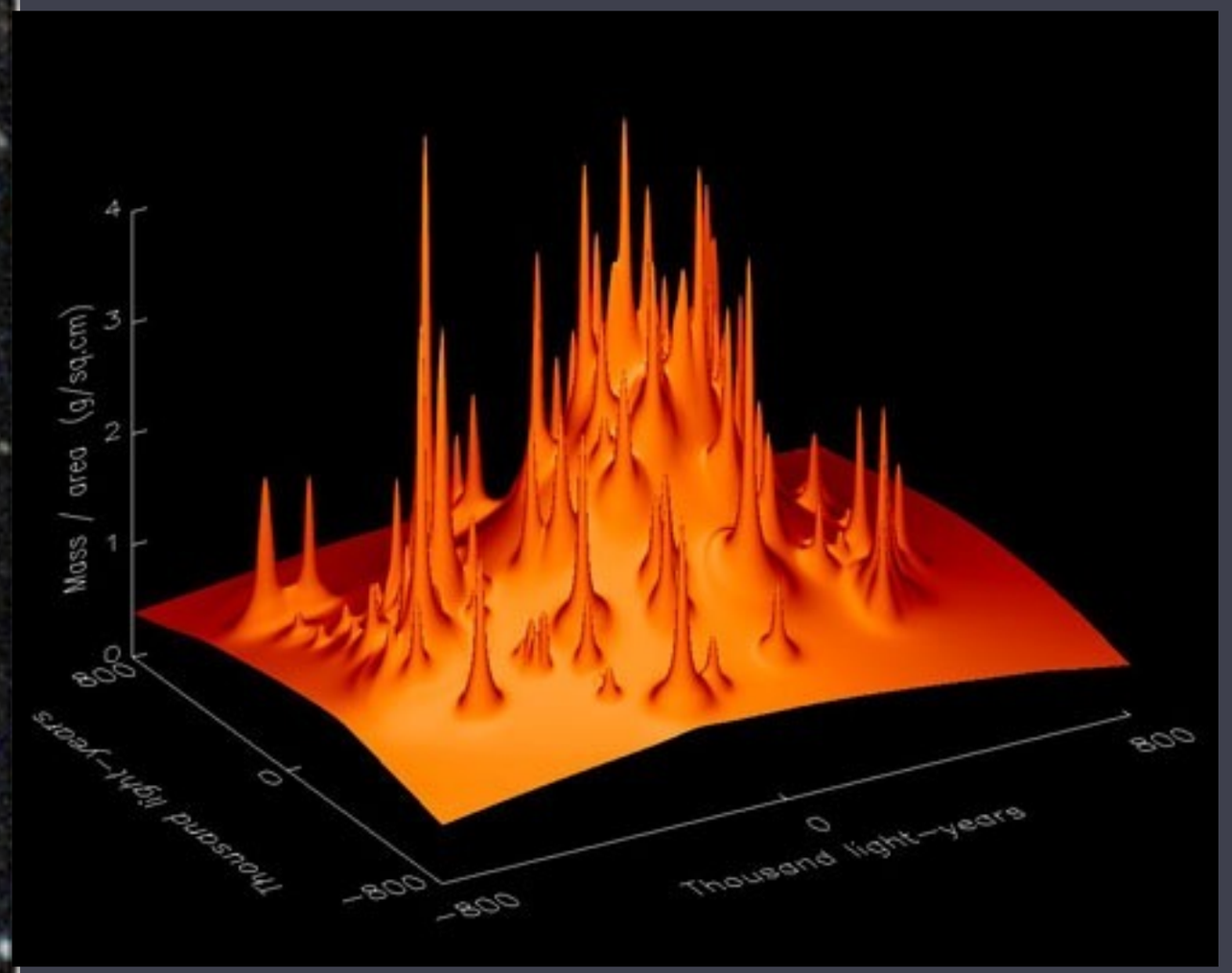
# The observed lensing (left) is used to reconstruct the matter distribution (right)





# This mass is much more than expected from just the observed light

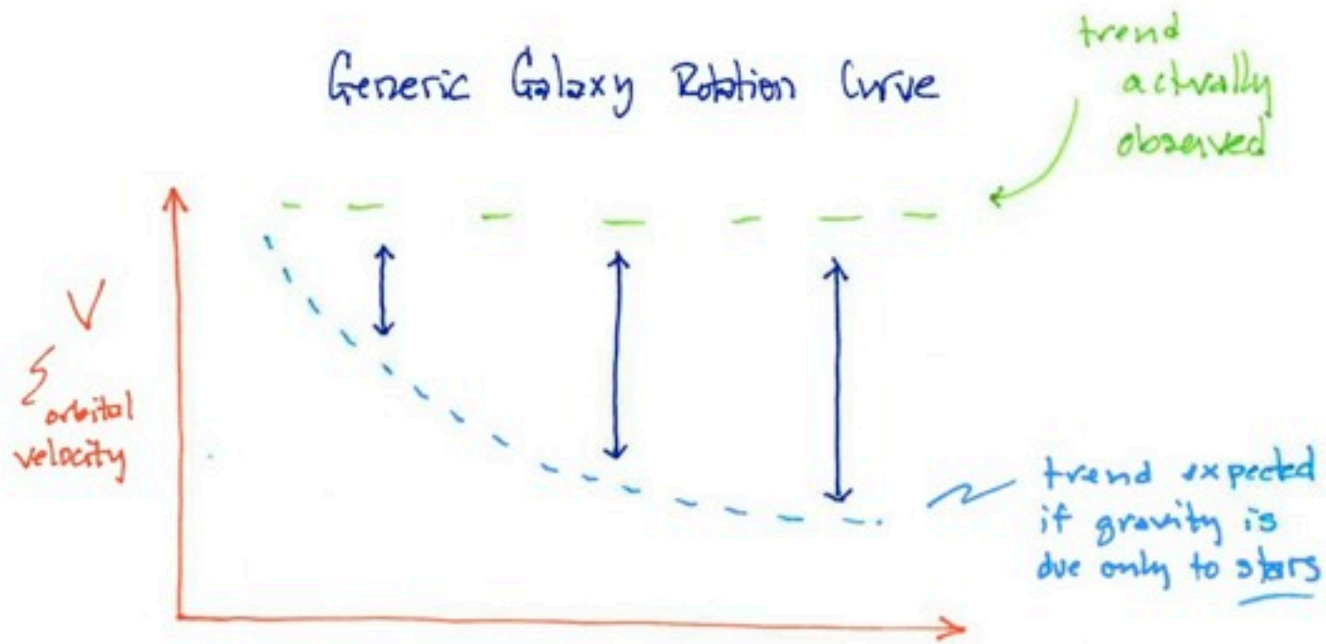




*key result Dec. 3

dark matter & galaxy rotation curves

Generic Galaxy Rotation Curve




* fact that velocities are higher than expected → more mass than just stars (∴ gravity from matter that's not emitting light)

* fact that discrepancy is larger at bigger distances from the galactic center means → the dark matter is distributed differently than the stars (it is not as centrally concentrated)