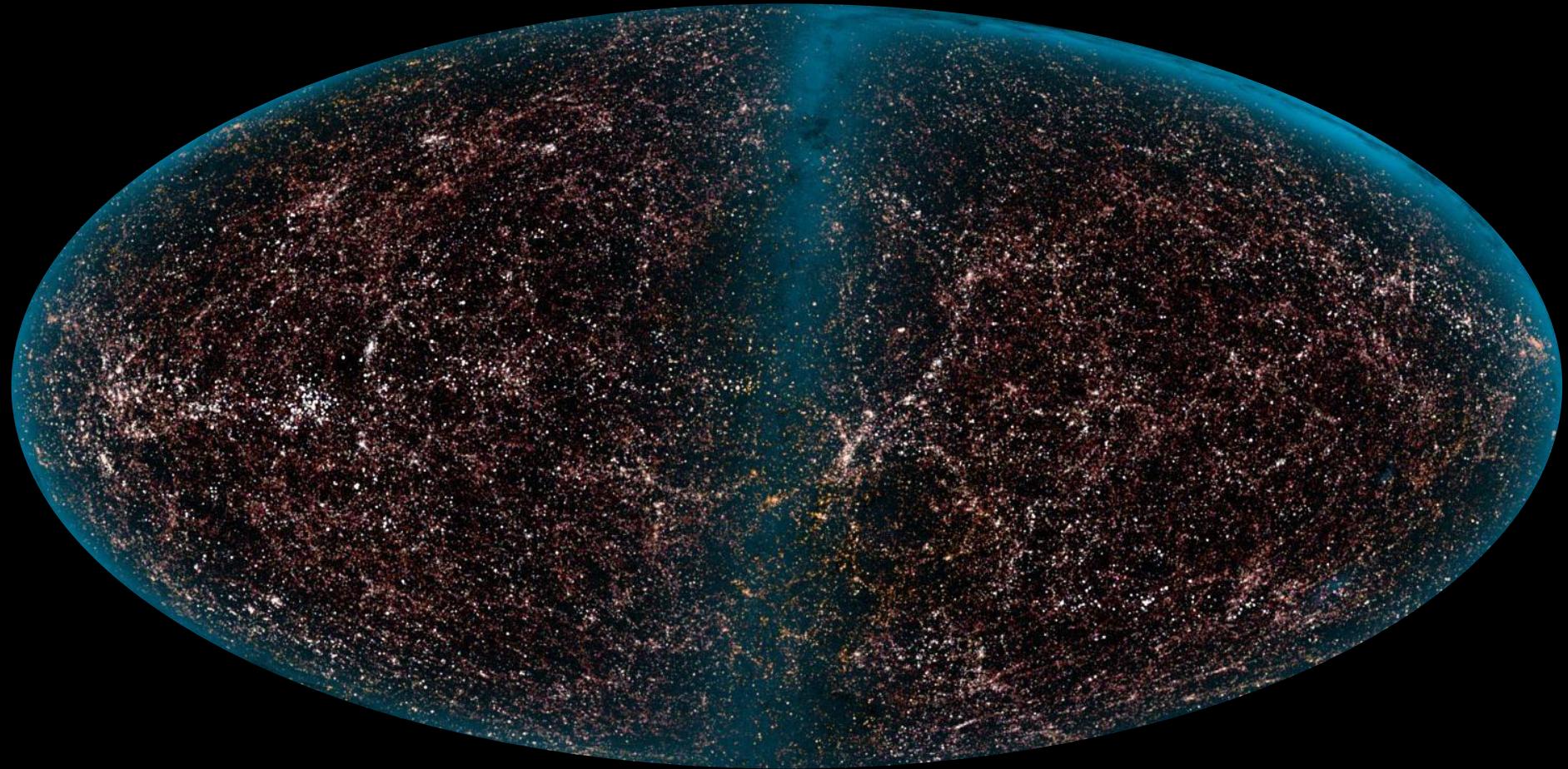


CLUSTERS OF GALAXIES



CAROLIN CRAWFORD
GRESHAM PROFESSOR IN ASTRONOMY



2MASS all-sky survey: Jarrett, Carpenter & Hurt



Robert Gendler



M Druckmuller



Manfred Konrad



Hubble Heritage AURA/STScI/NASA



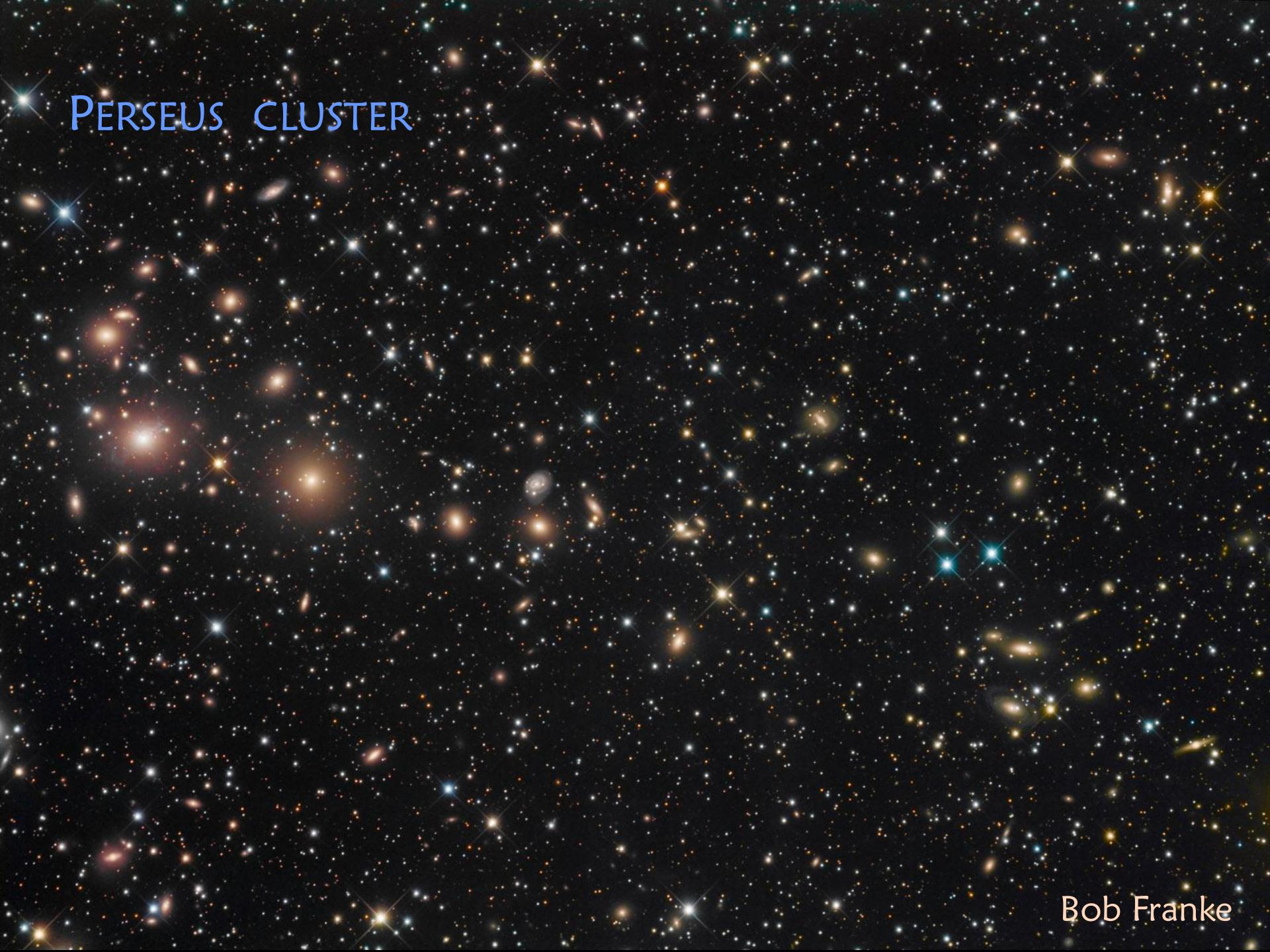
Stephen Leshin

COMA CLUSTER



Dean Rowe

PERSEUS CLUSTER

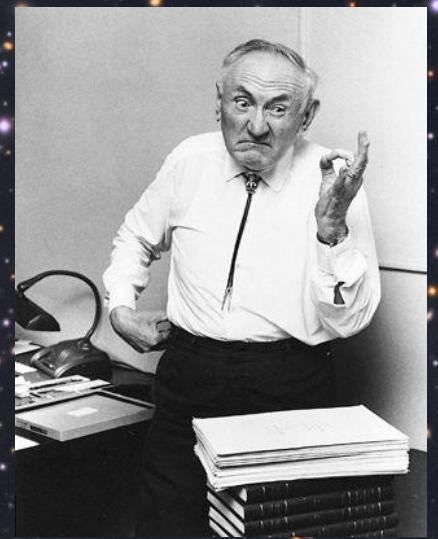


Bob Franke





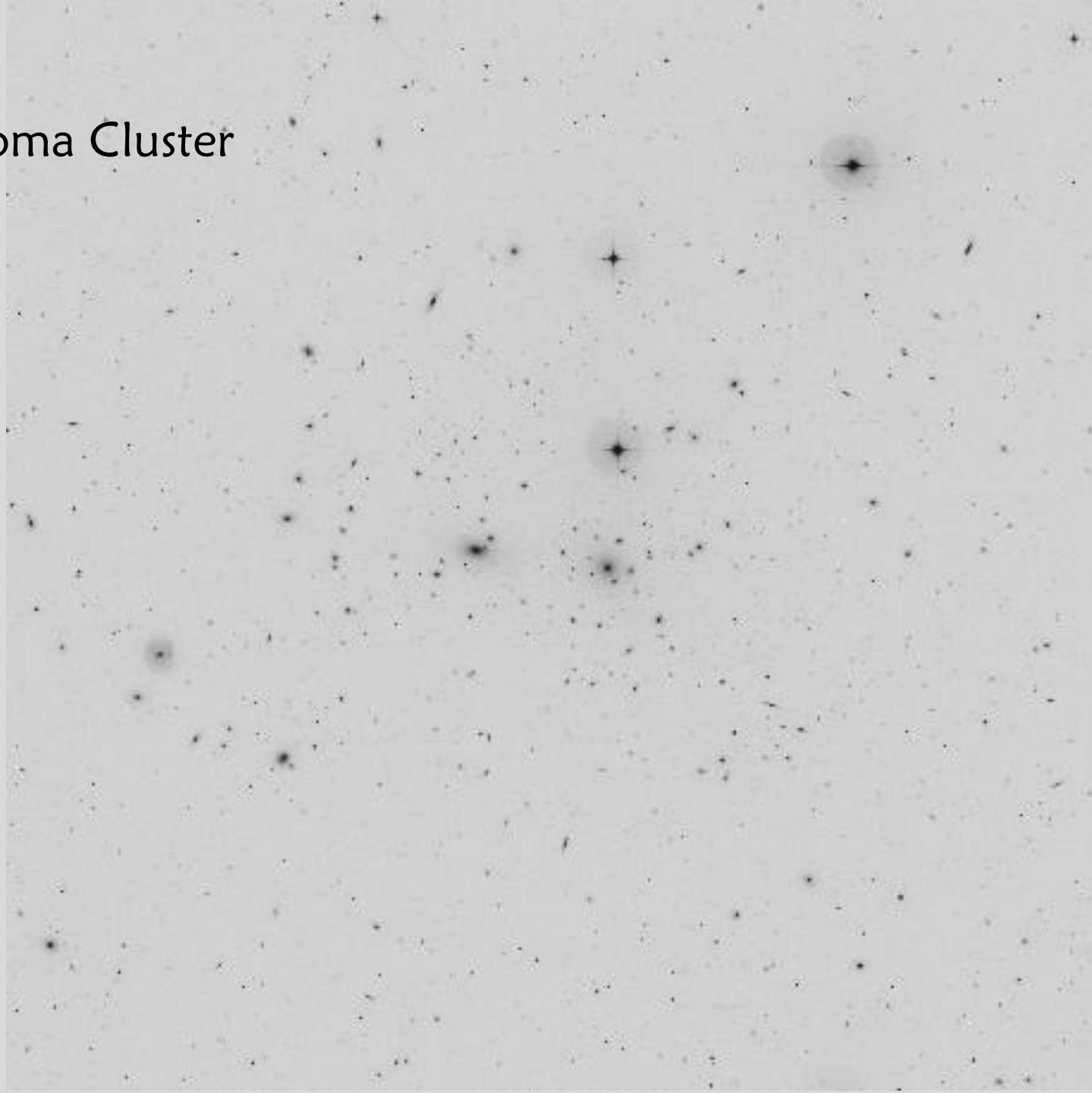
George Abell (1927-83)



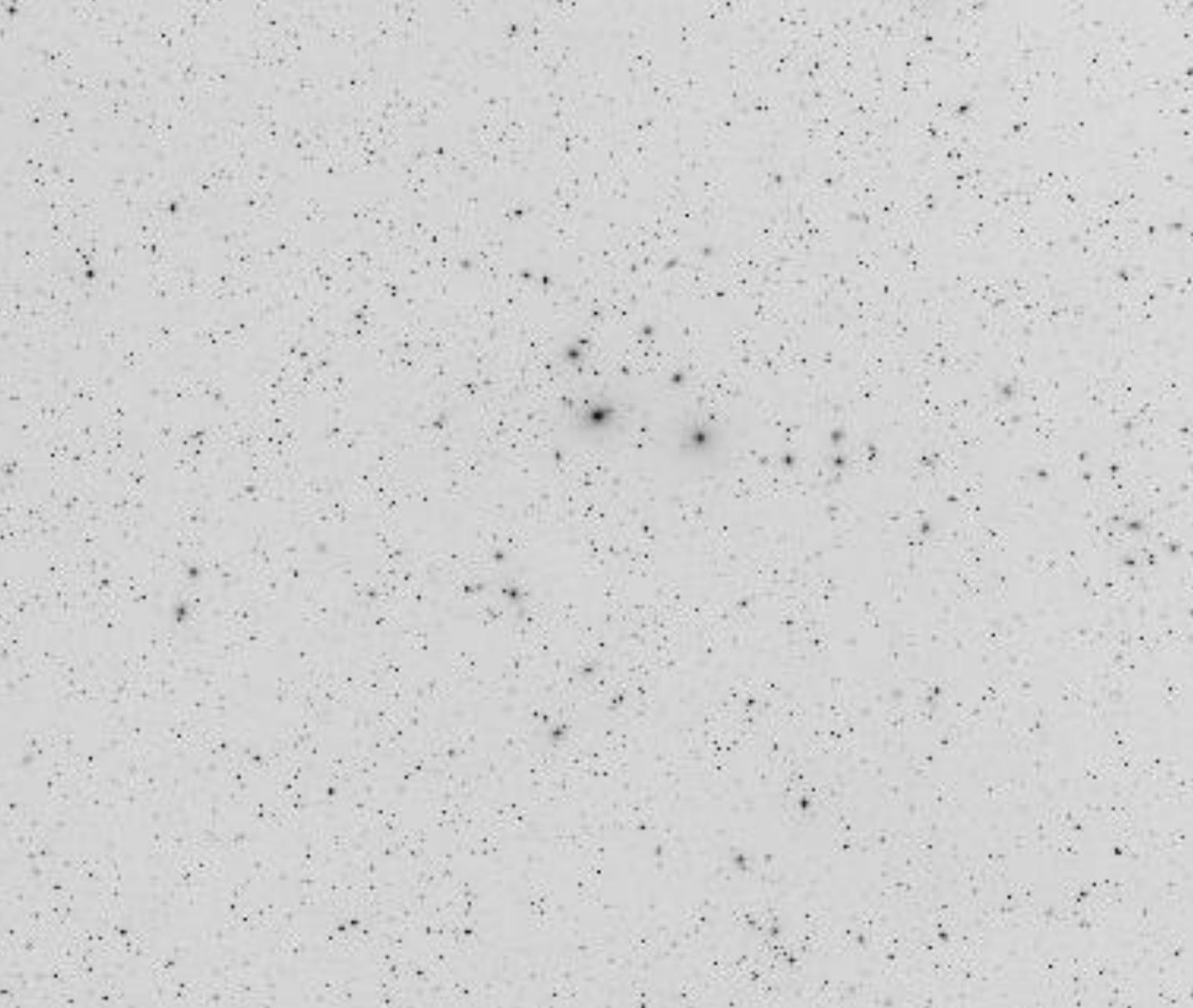
Fritz Zwicky (1889-1974)

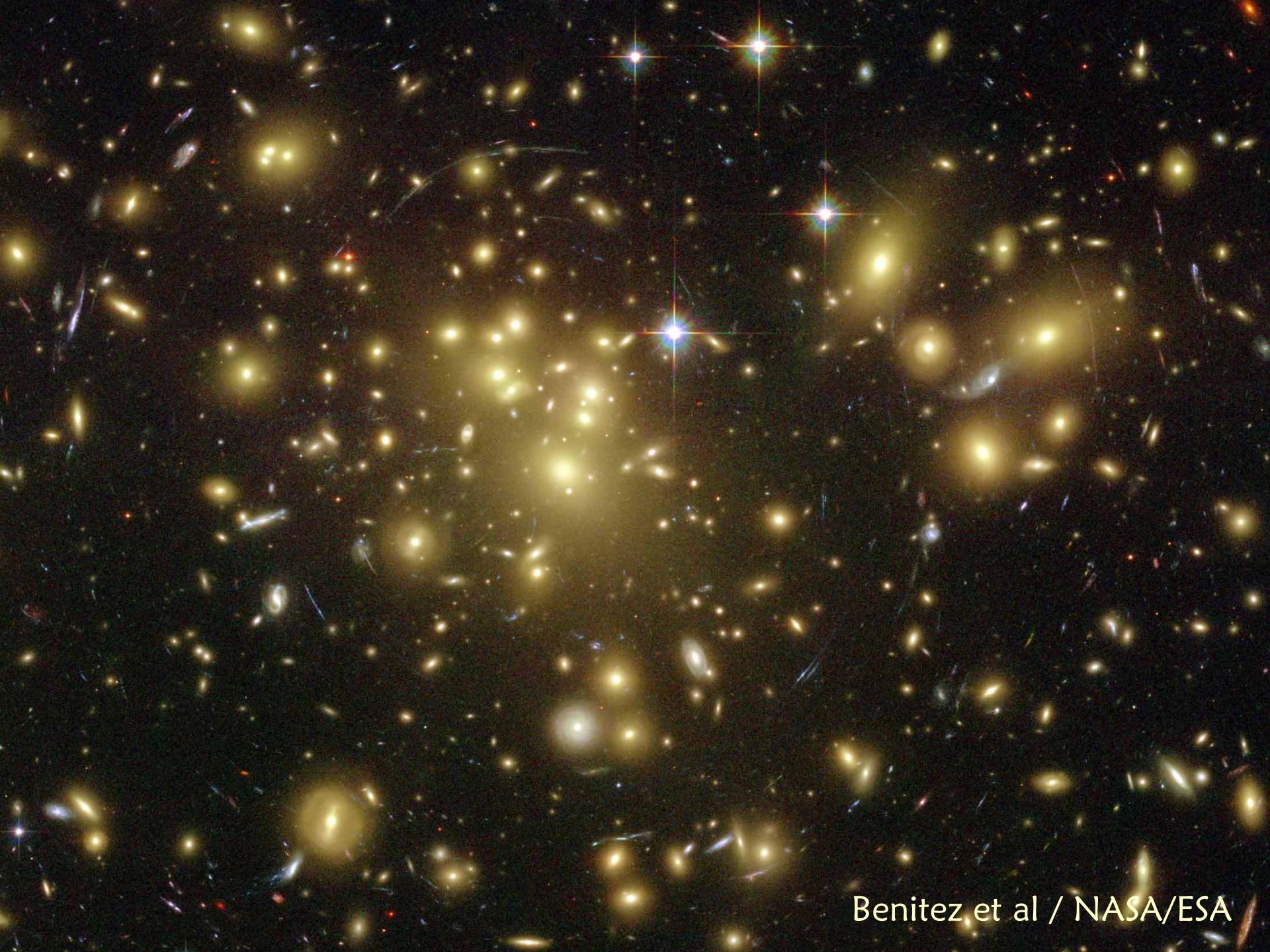
Tony Hallas

Coma Cluster

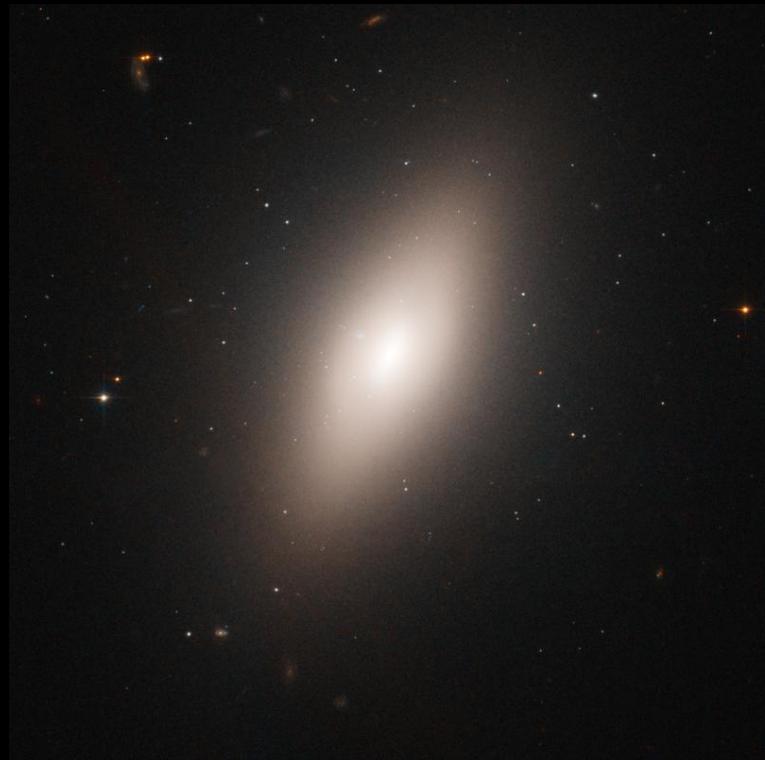
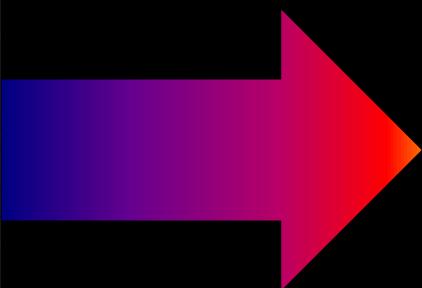


Perseus Cluster



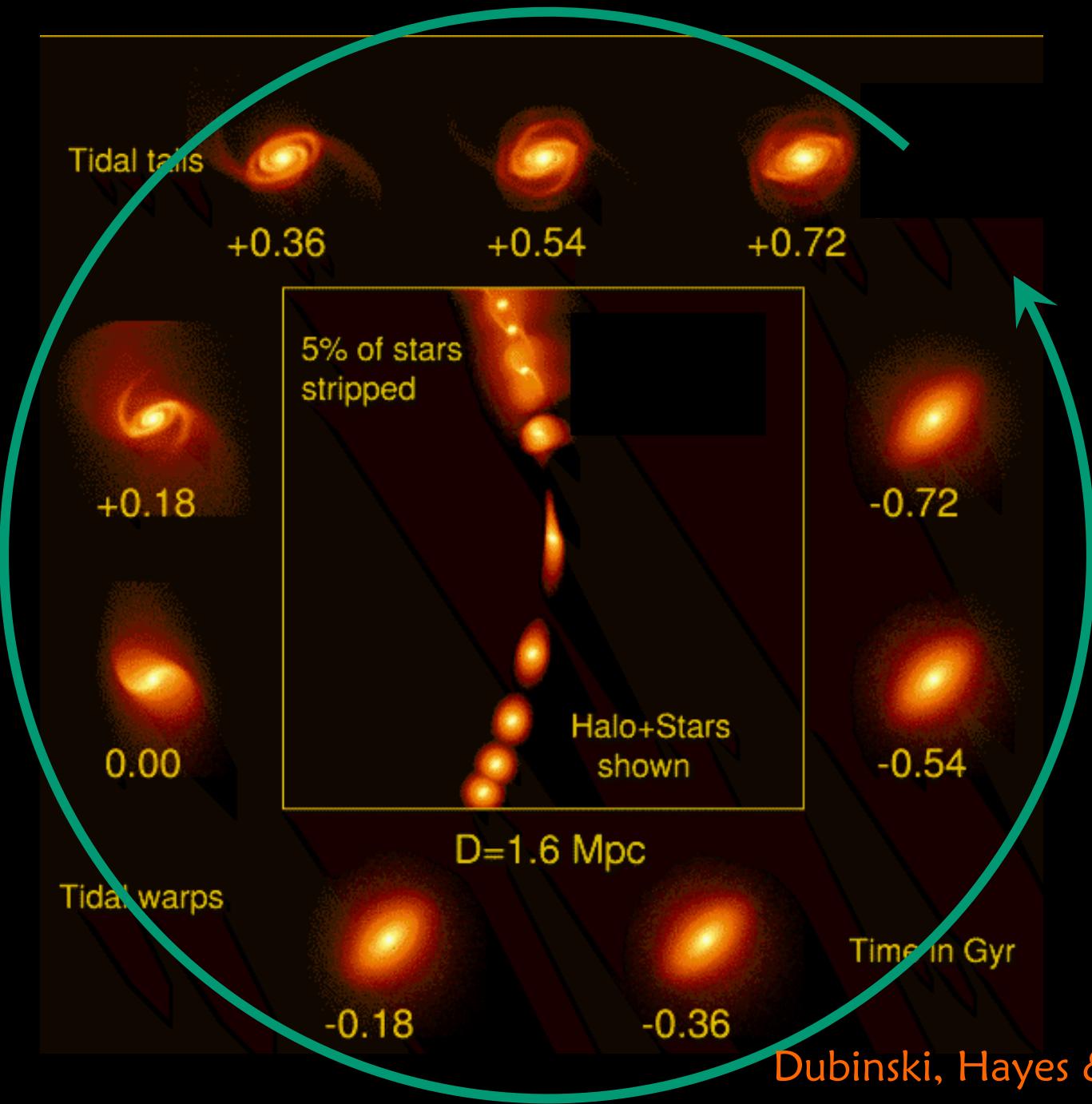


Benitez et al / NASA/ESA

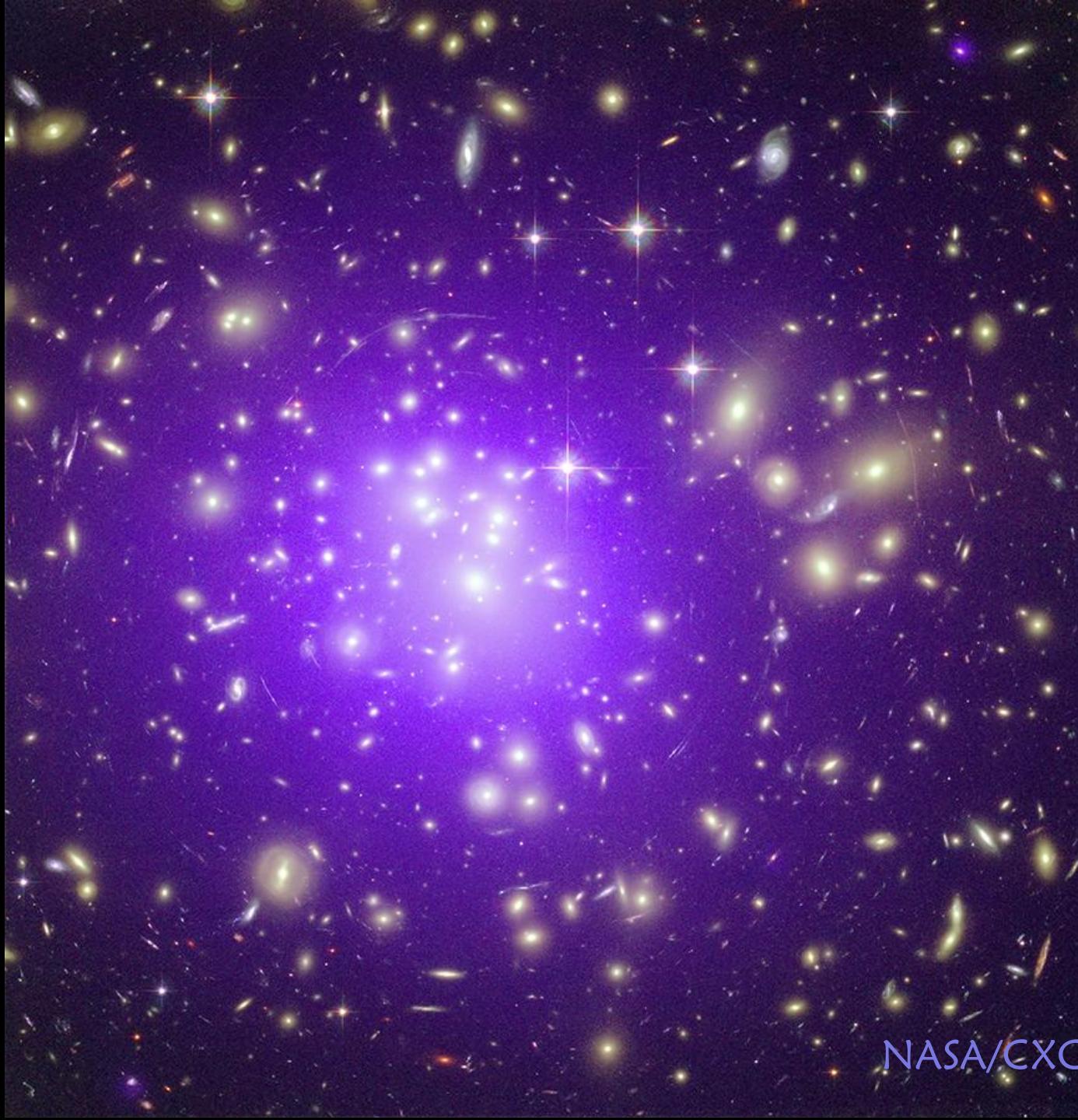


NASA/ESA/Riess et al

NASA/ESA/Peng



Dubinski, Hayes & Dieng



optical
X-rays

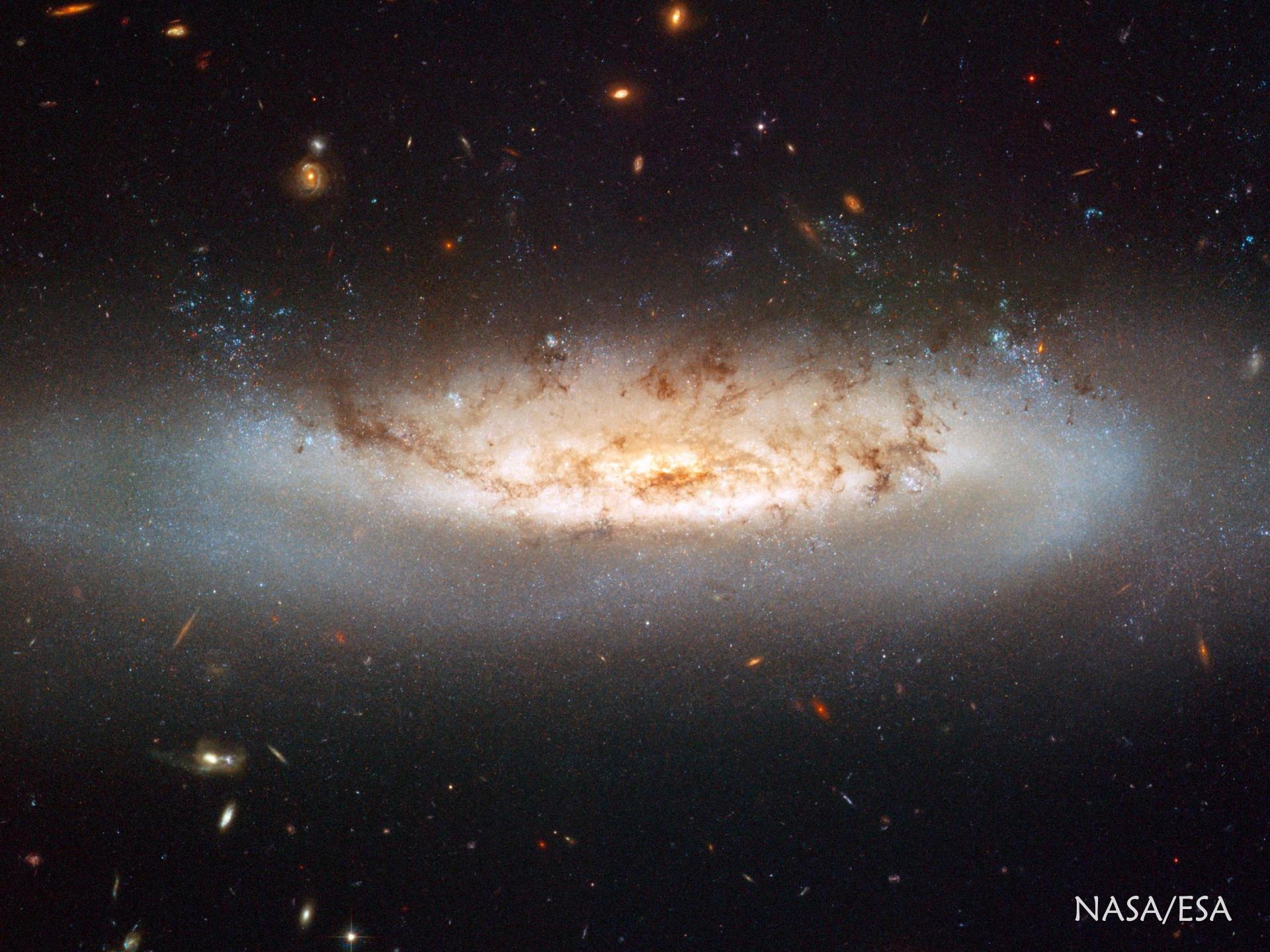
NASA/STScI
NASA/CXC/MIT/Peng et al



NASA/ESA/Kneib



NASA/ESA
Rogelio Bernal Andreo



NASA/ESA

This image is a wide-field astronomical photograph showing a dense cluster of galaxies and stars against a dark background. In the upper left, a bright, multi-pointed star is visible. A prominent, large elliptical galaxy is centered in the frame. To its right, another bright elliptical galaxy is visible. The background is filled with numerous smaller galaxies and stars of varying colors and magnitudes.

Adam Block (U Arizona)



1137

}

NASA/CXC/Allen et al

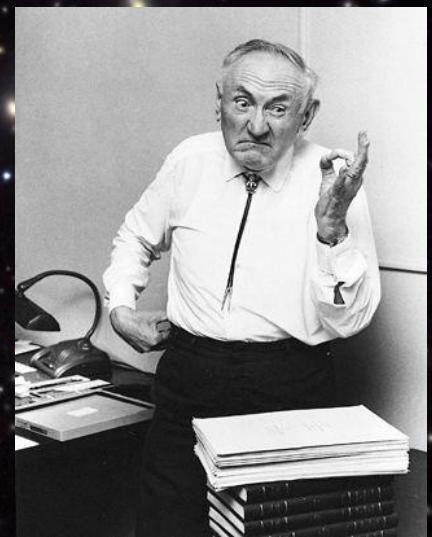
NASA/CXC/INAF/DSS/VLT

The mass of a cluster

Velocities of galaxies within a cluster are too high
gravitational mass is $\geq 10^{15} M_{\text{sun}}$ for a rich cluster

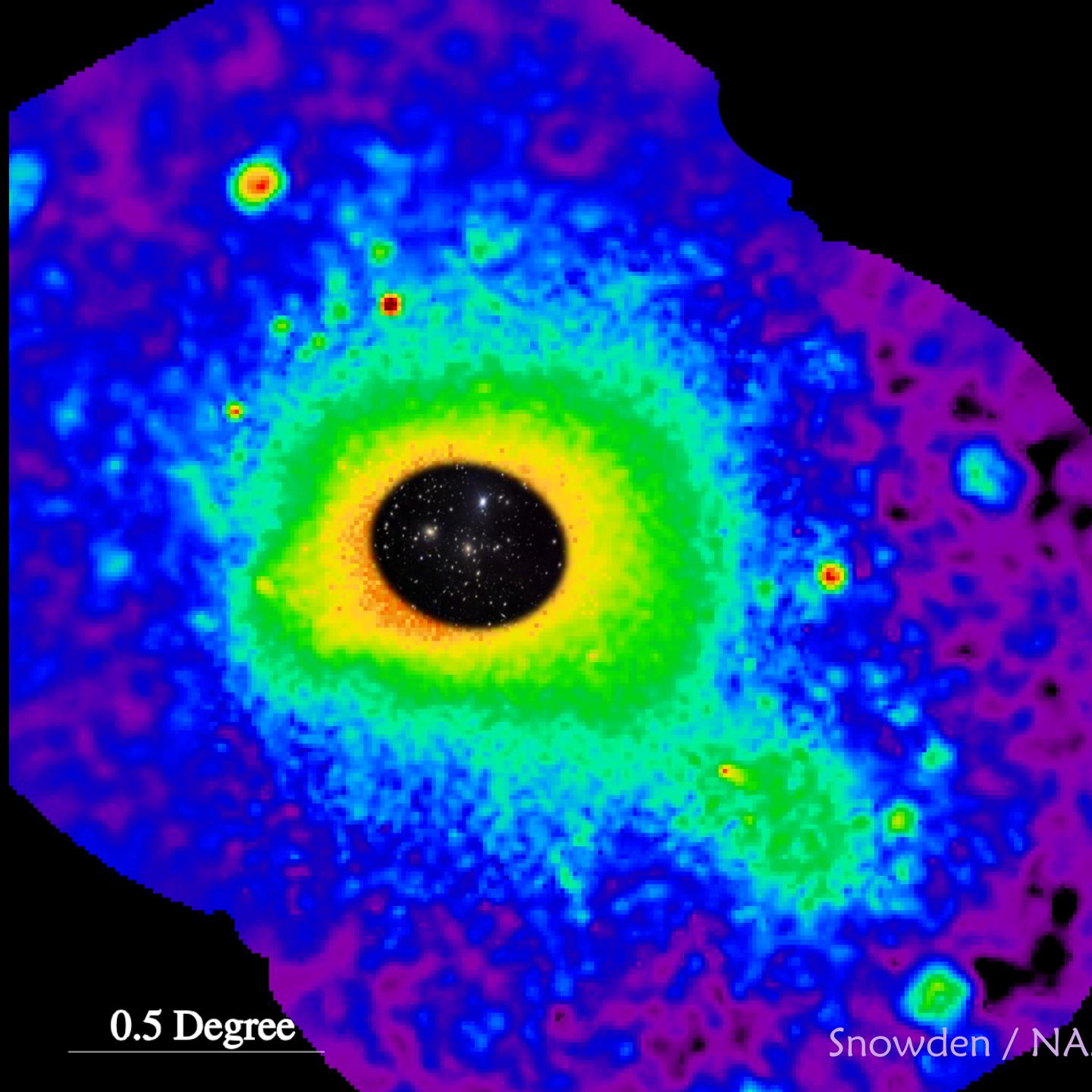
but $L_{\text{total}} \sim 10^{13} L_{\text{sun}}$ $\Rightarrow (M/L)_{\text{total}} \sim 300 M_{\text{sun}} / L_{\text{sun}}$

there is more mass in a cluster than we can see



Fritz Zwicky (1898-1974)

Jim Misti



0.5 Degree

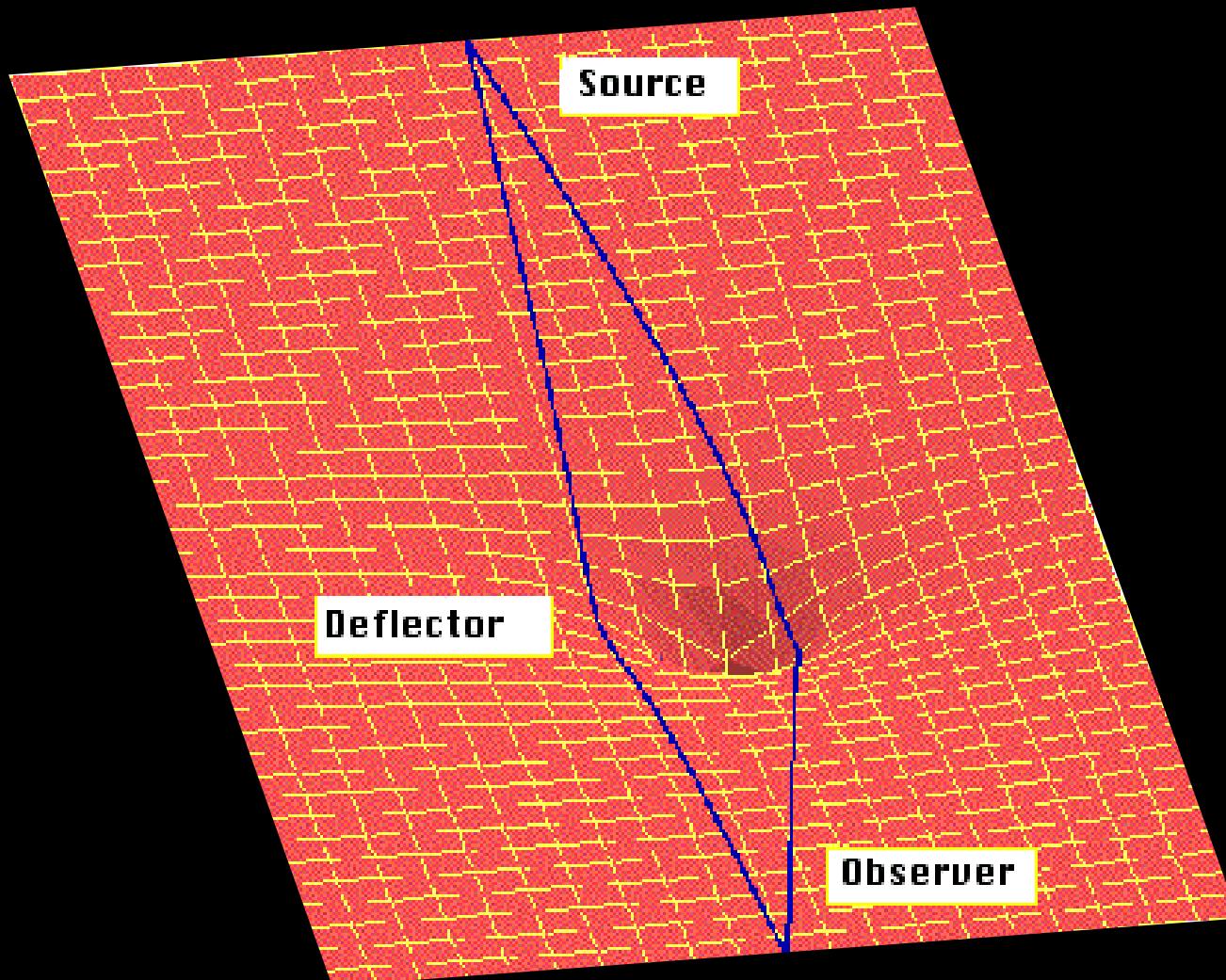
Snowden / NASA / GSFC

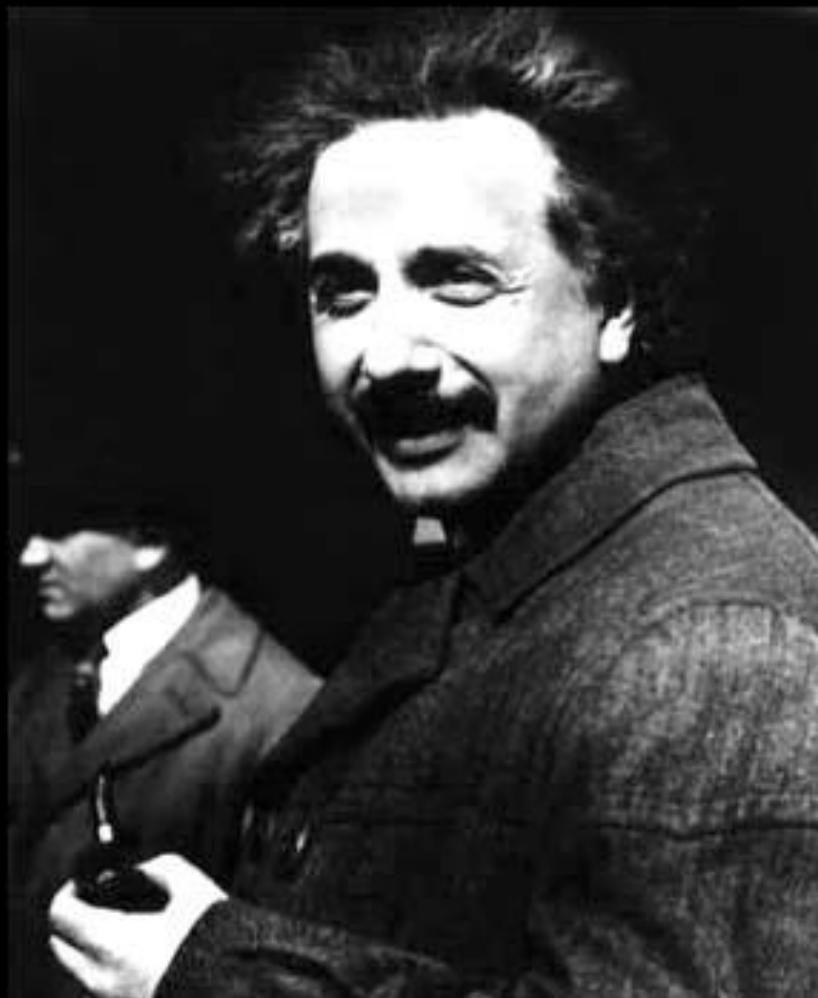


gravity

hot gas pressure

Gravitational lensing in clusters





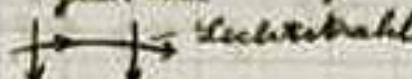
Albert Einstein (1879–1955)

Zürich 14. X. 13.

Aus

Hoch geachteter Herr Kollege!

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

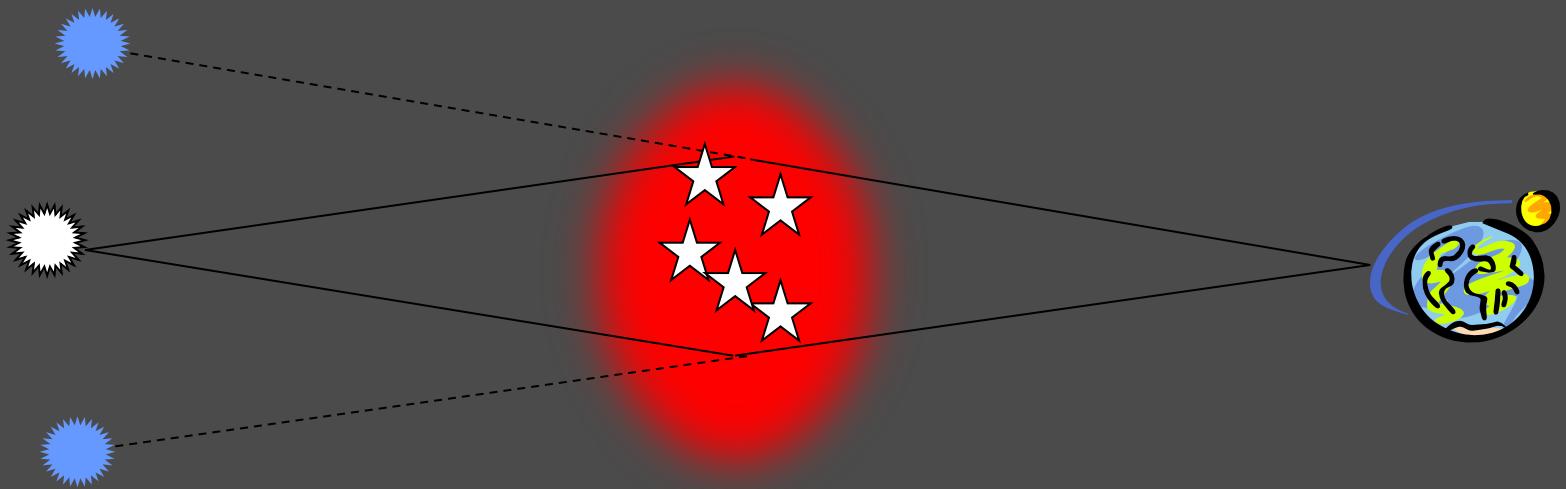
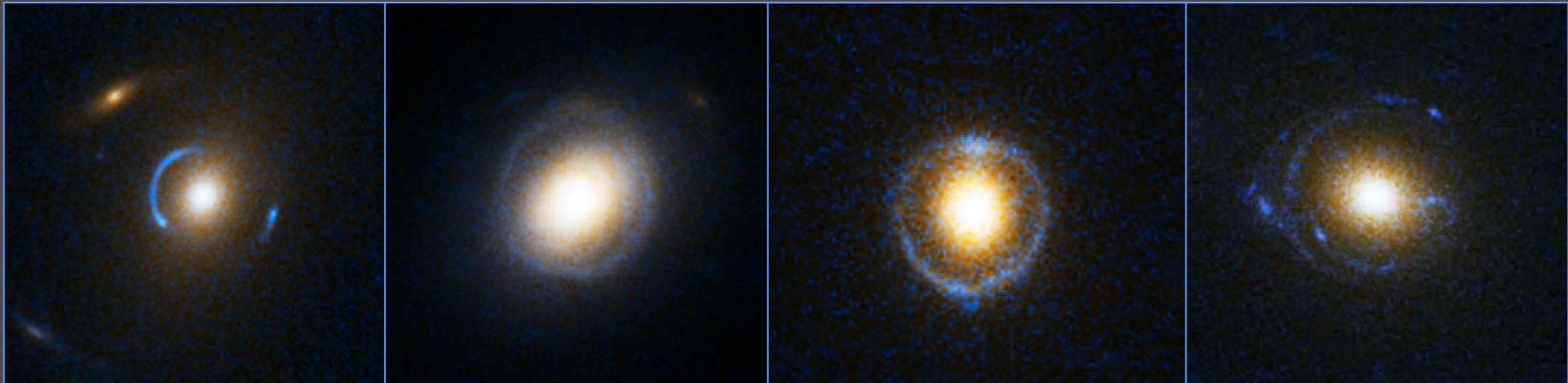


An Sonnenrands müsste diese Ablenkung $0,84^\circ$ betragen und wir $\frac{1}{R}$ abnehmen
~~(Abstand von Sonne - Beobachtungspunkt)~~

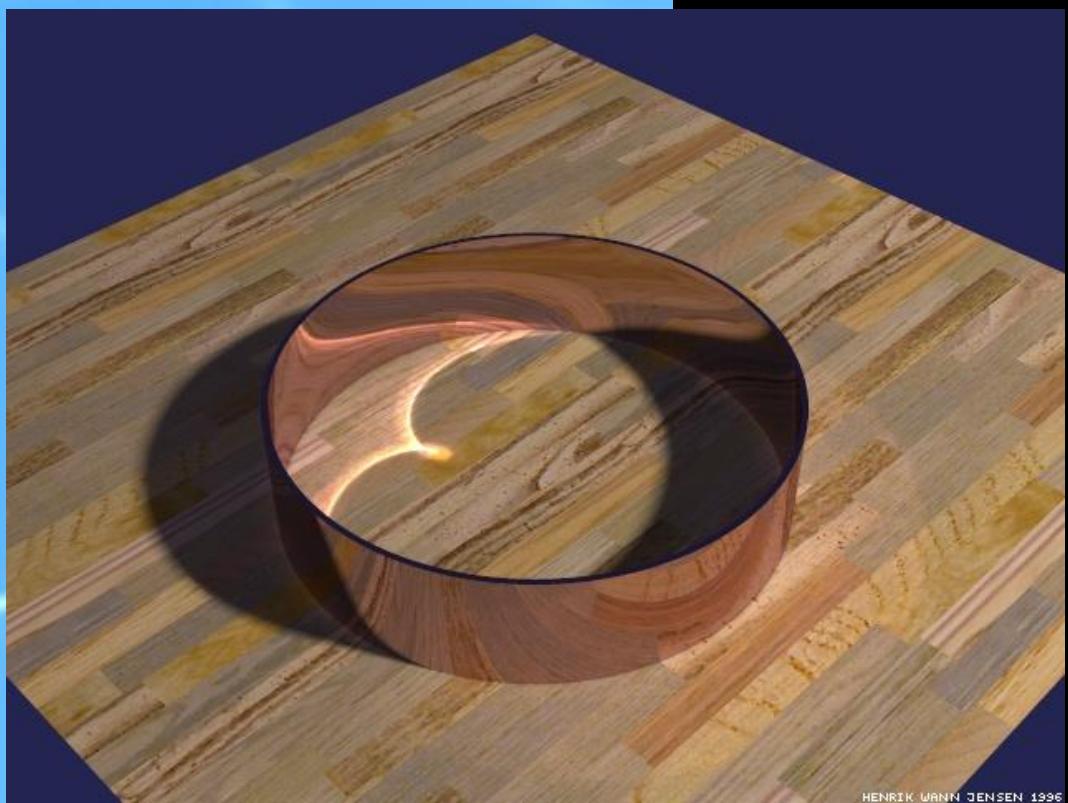
$- 0,84^\circ$



Es wäre deshalb von grösster Interesse, bis zu wie grosser Sonnen-nähe ~~helle~~ Sterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.



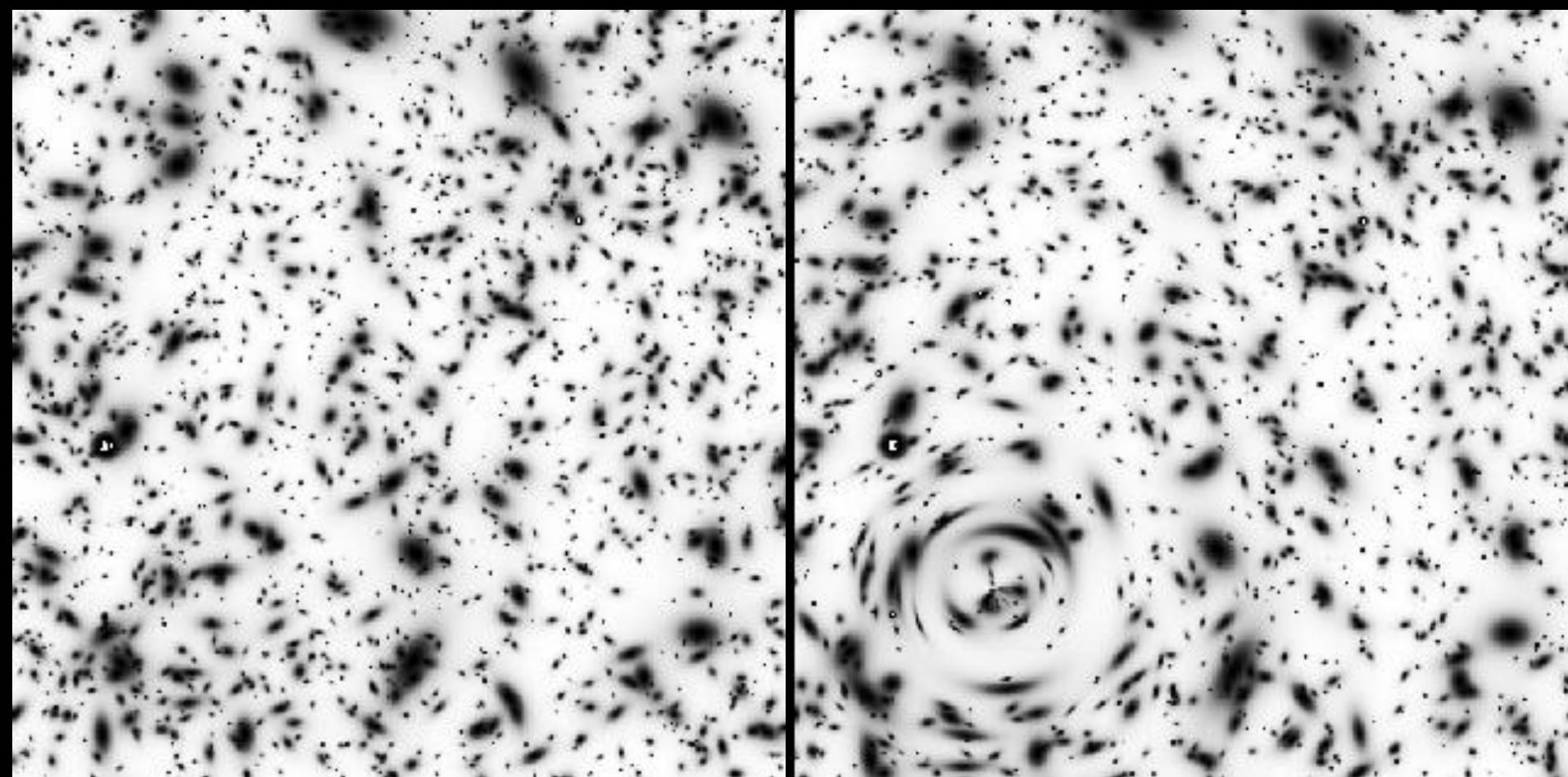
NASA/ESA/Bolton et al



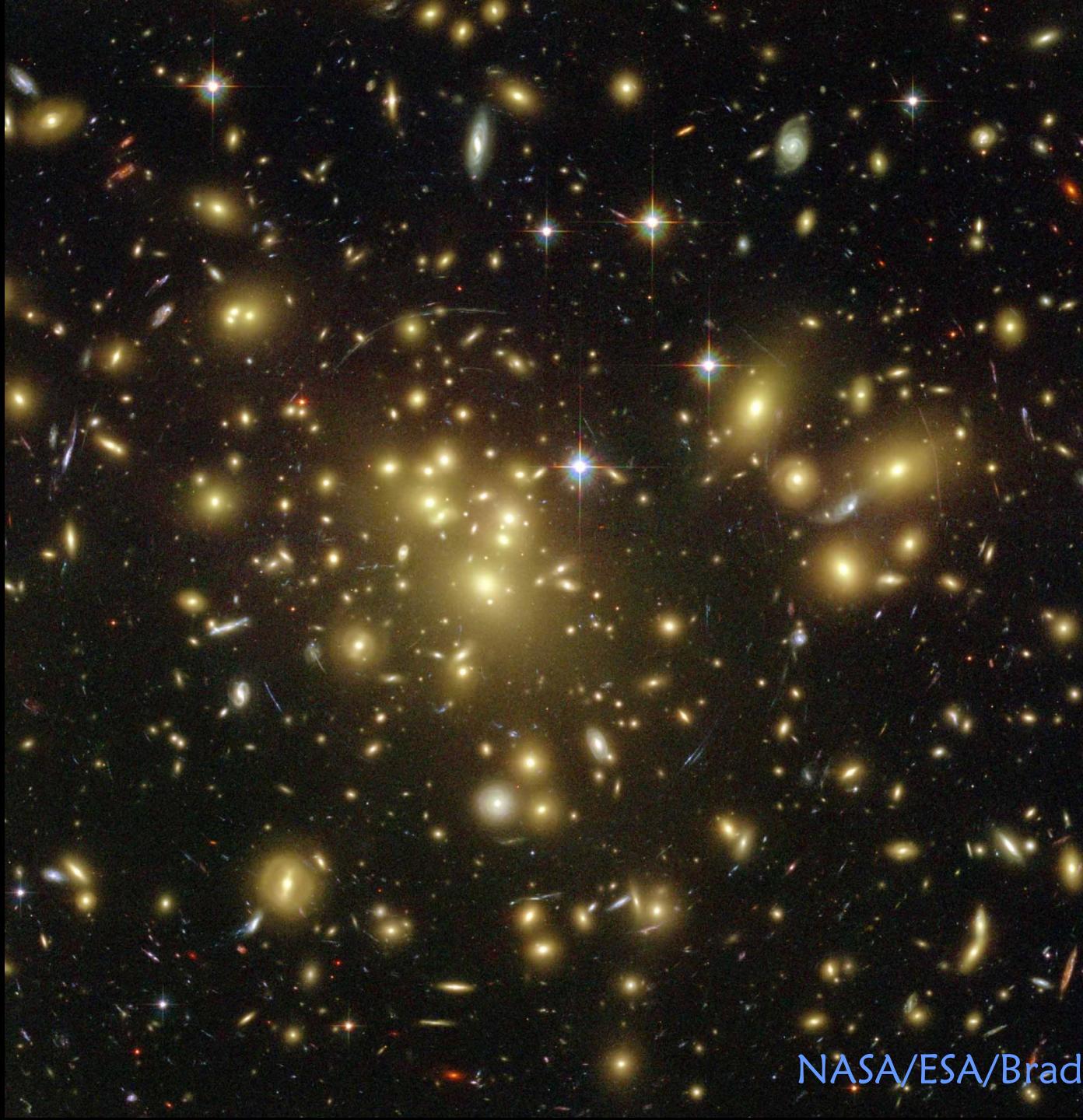
HENRIK WANN JENSEN 1996



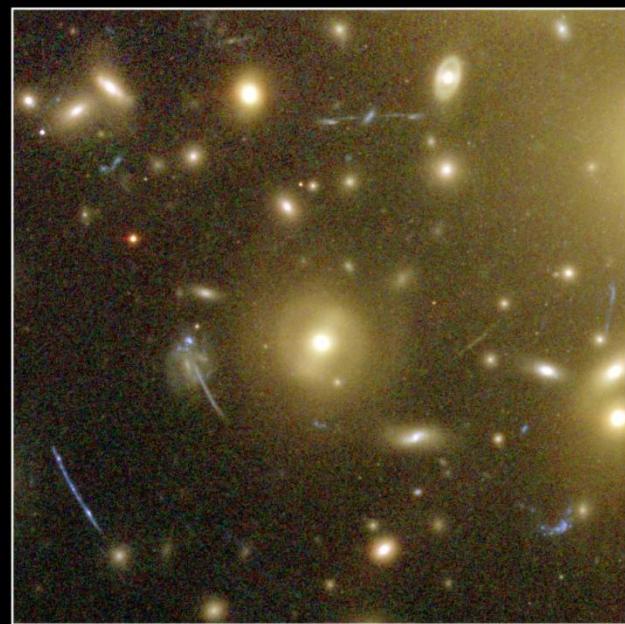
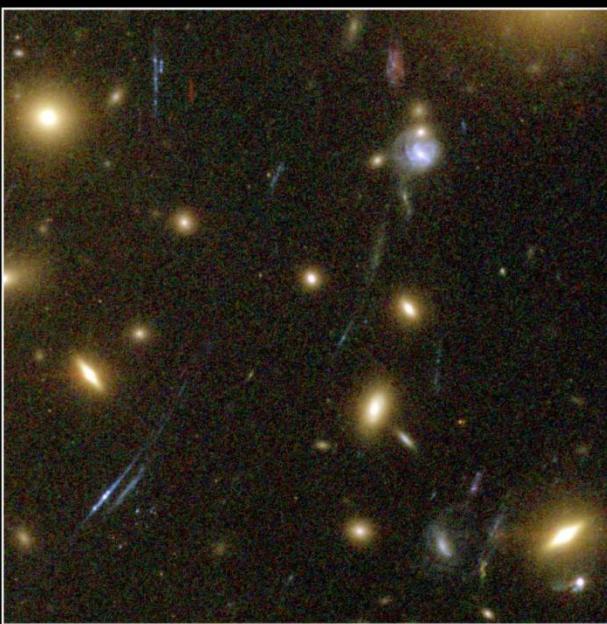
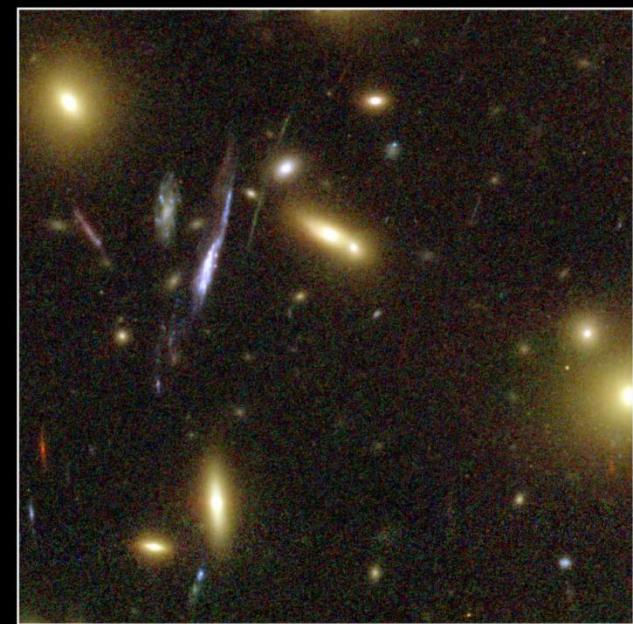
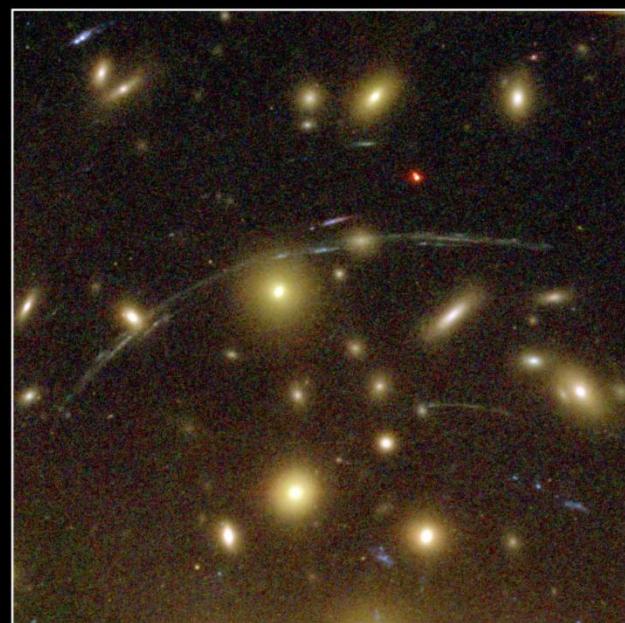
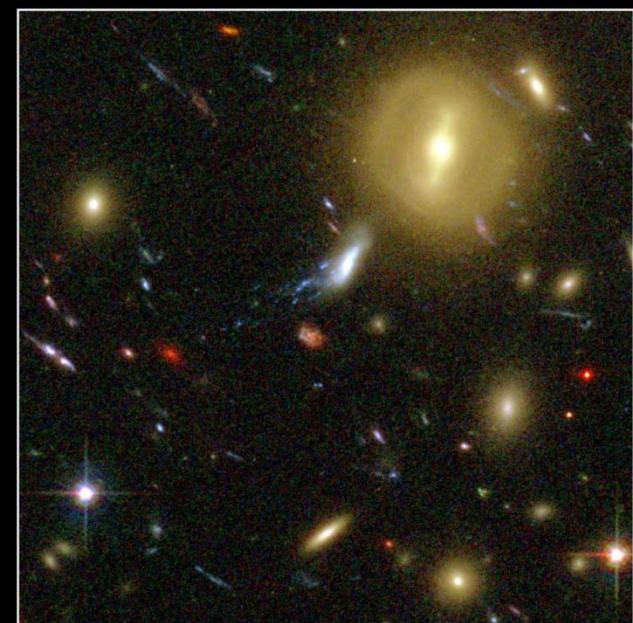
NASA/ESA/Beckwith et al



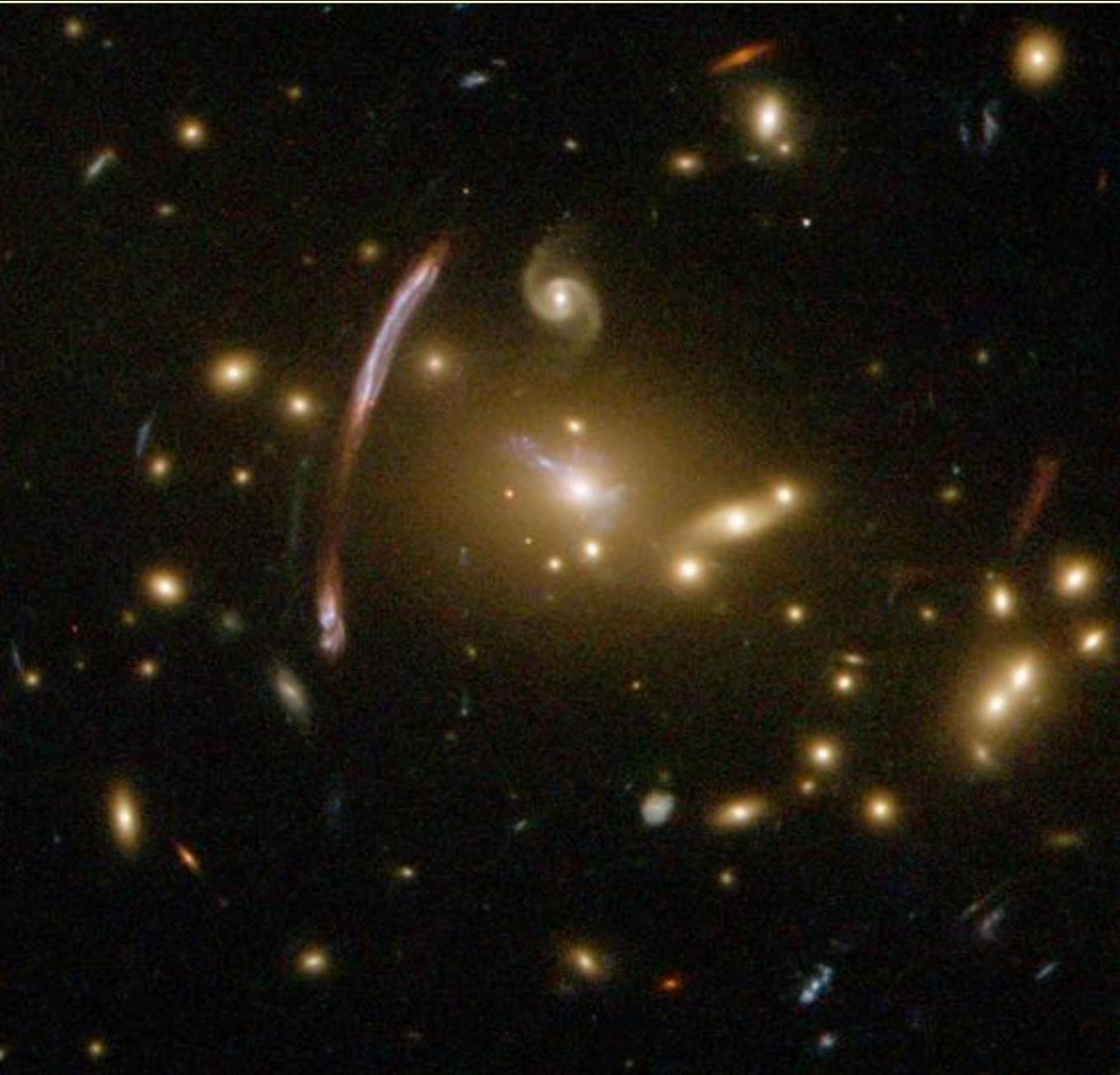
Yannick Mellier



NASA/ESA/Bradley et al



NASA/ESA/Bradley et al



NASA/ESA/Kneib



A Fruchter (STSci) et al

constituents of mass in clusters

galaxies	< 10 %
X-ray intra-cluster gas	10 – 25 %
dark matter	70 – 90 %

What is the dark matter?

Unlikely to be *baryonic*...

Appeal to *exotic* particles:

- massive neutrinos
- stable weakly-interacting massive particles



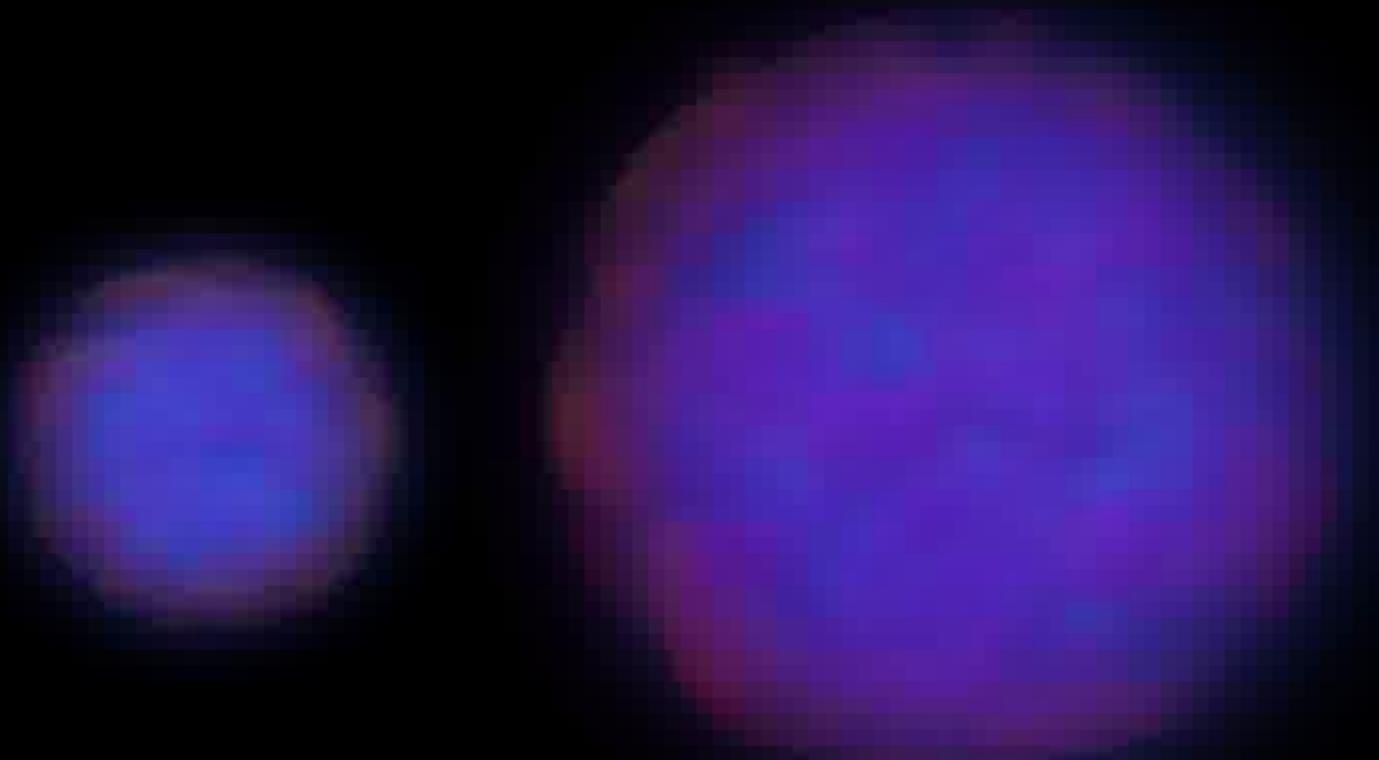
NASA/STScI/ESO/Clowe et al

NASA/CXC/Markevitch et al

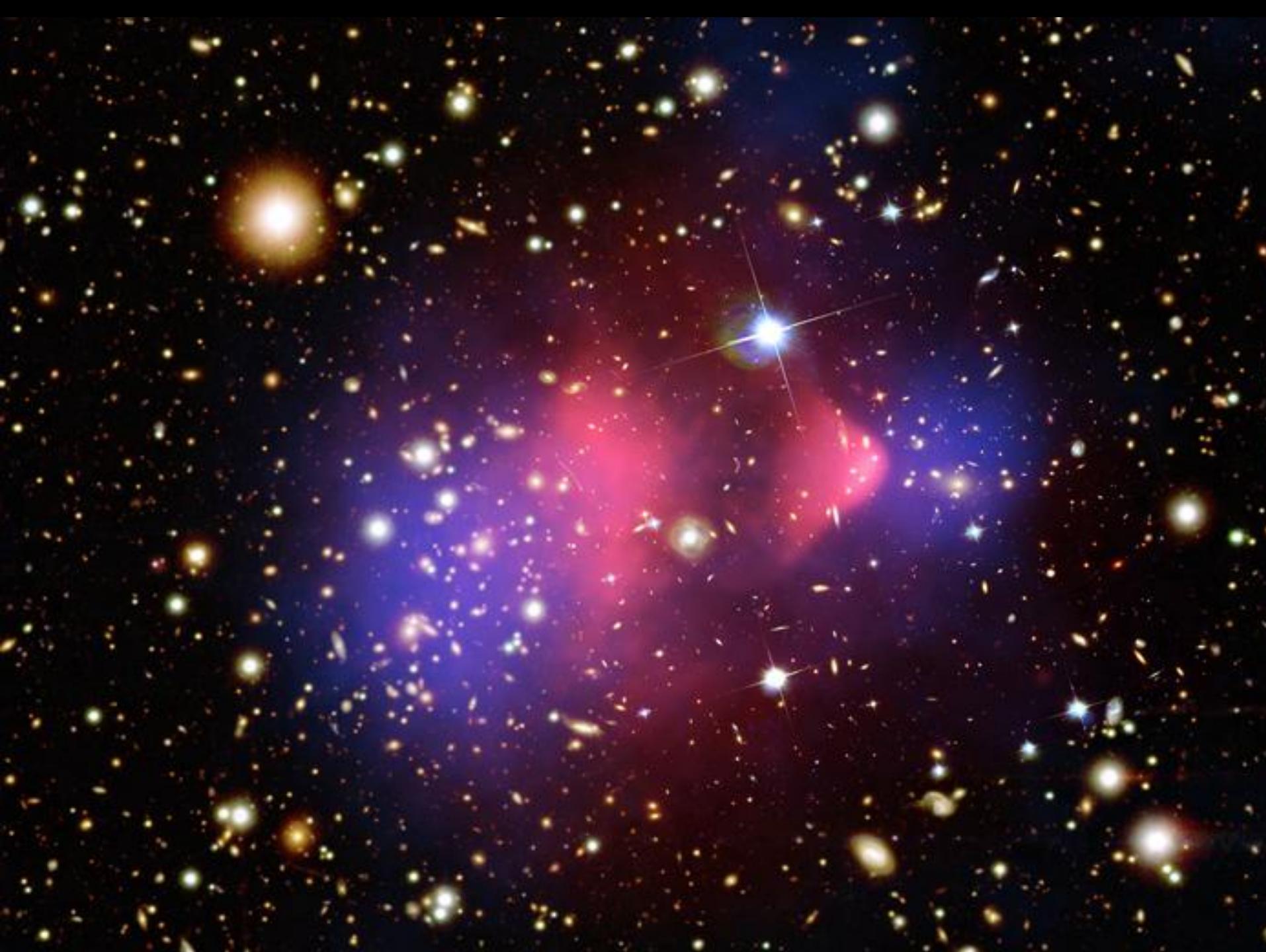


A composite image of a galaxy cluster. The background is dark space filled with numerous small, glowing points representing distant galaxies. In the center, there is a large, diffuse emission of red and blue light, representing X-ray emission from hot gas. A bright, white, multi-pointed star-like object is positioned in the upper right quadrant, with two thin lines extending from it towards the center, illustrating gravitational lensing by dark matter. The overall image shows the complex interplay between visible light, dark matter, and X-ray radiation in a massive celestial object.

Lensing (dark matter)
X-rays



NASA/CXC/M Weiss

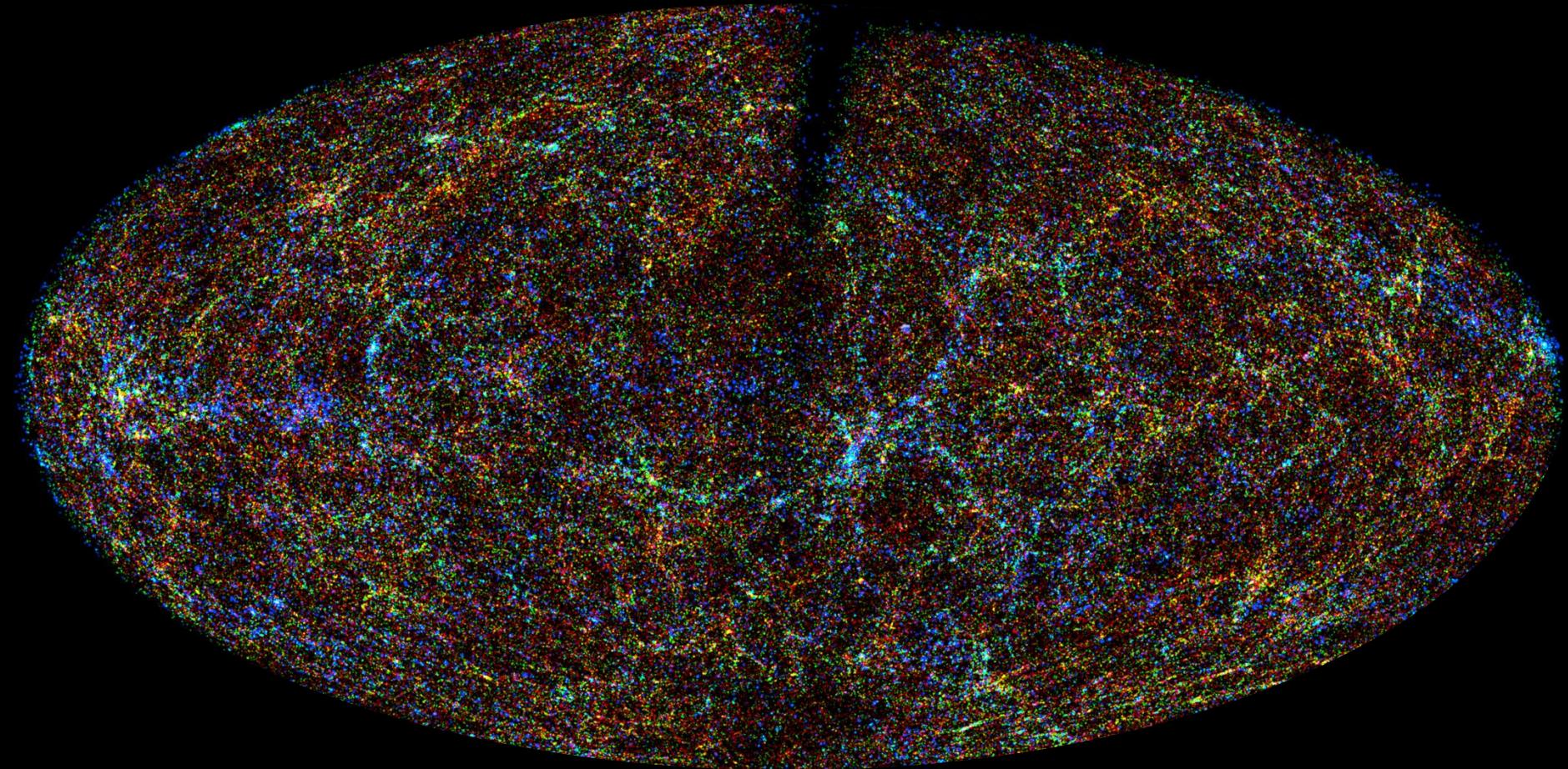


galaxy distribution dark matter (lensing) X-rays

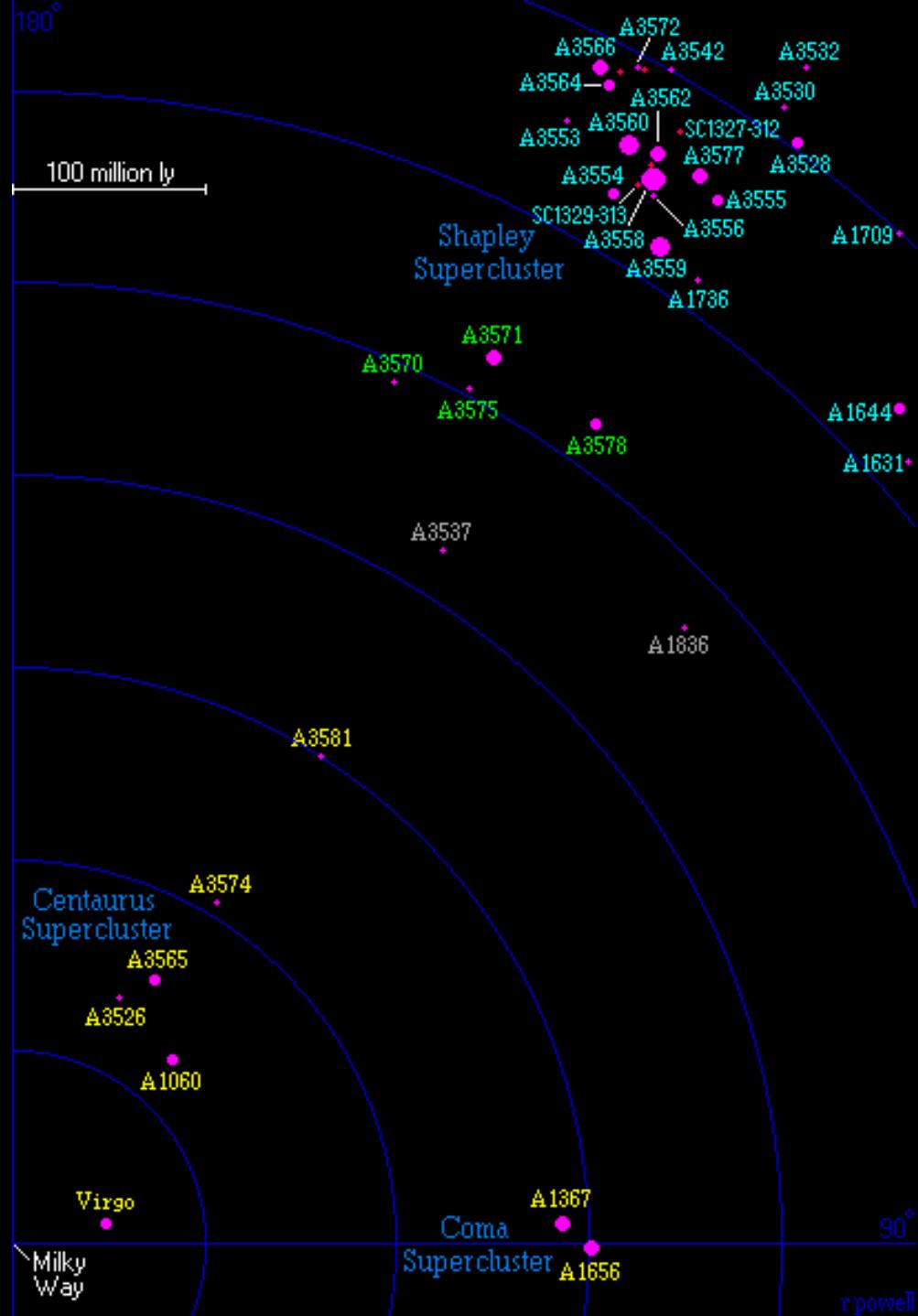


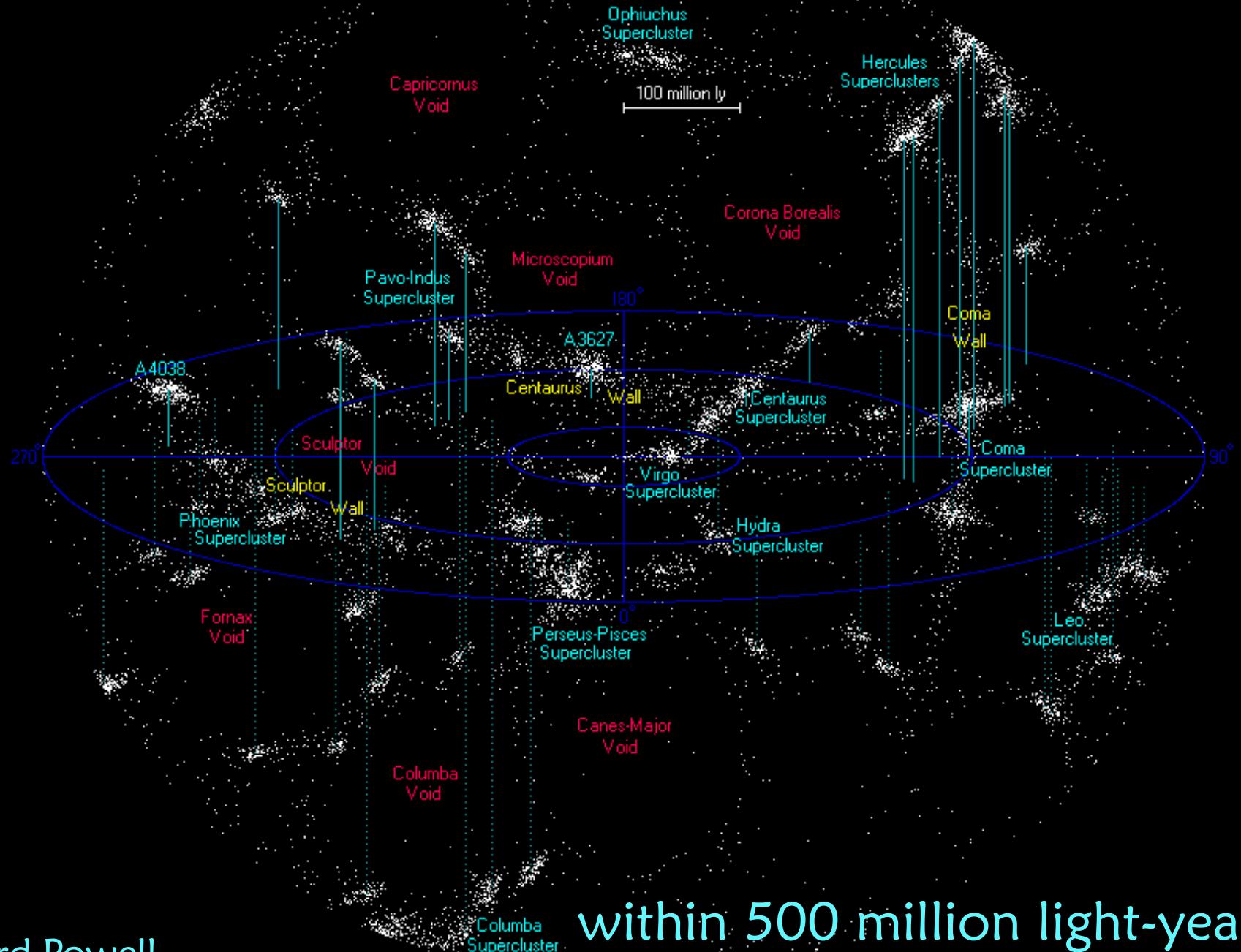
NASA/ESA/CFHT/CXO/Jee & Mahdavi

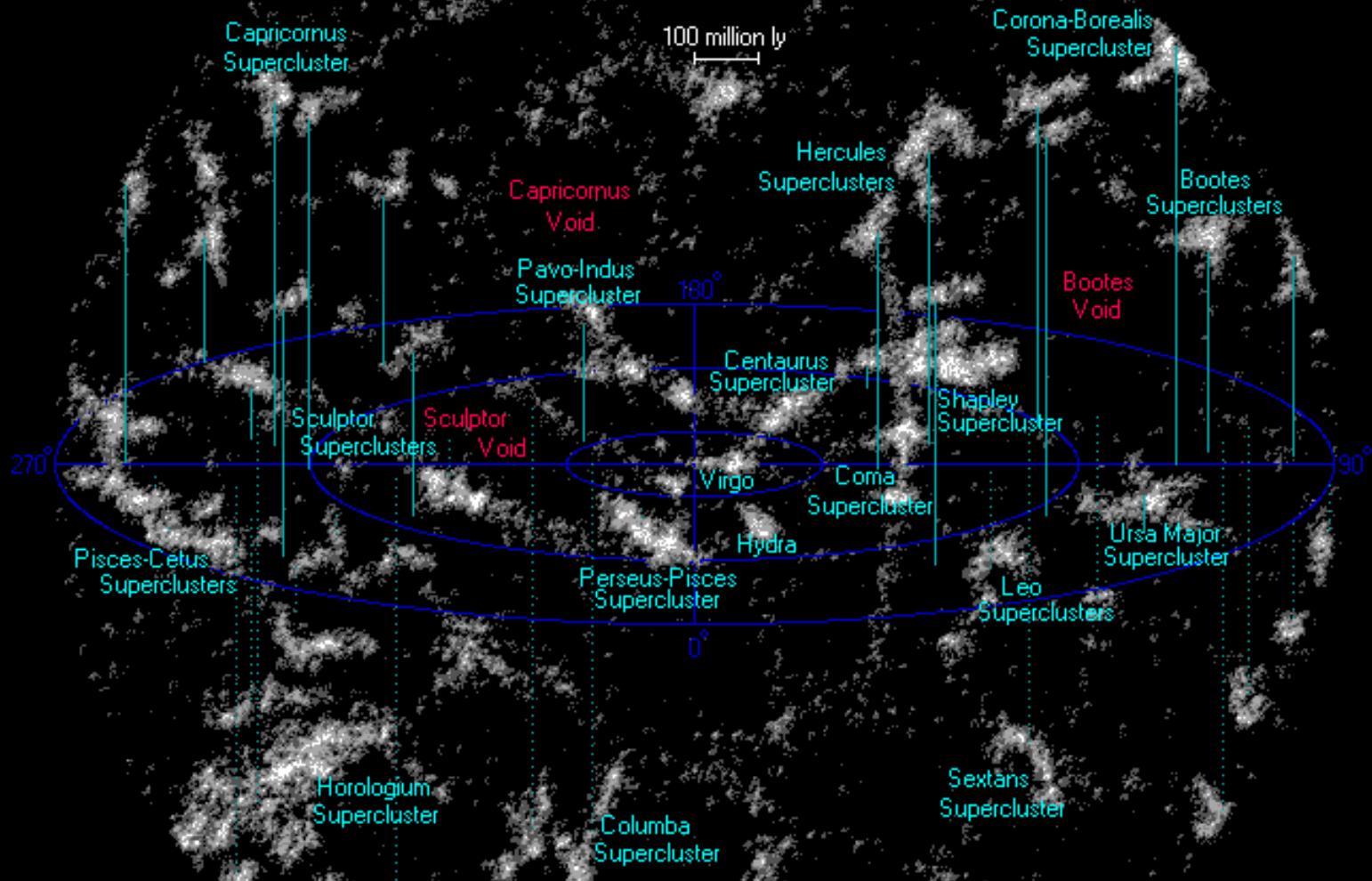
nearby galaxies
next nearby galaxies
more distant galaxies



2MASS all-sky survey: Jarrett, Carpenter & Hurt

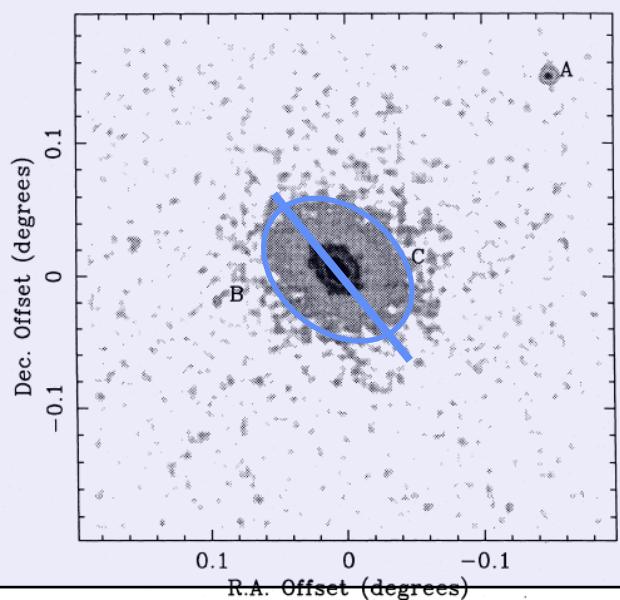




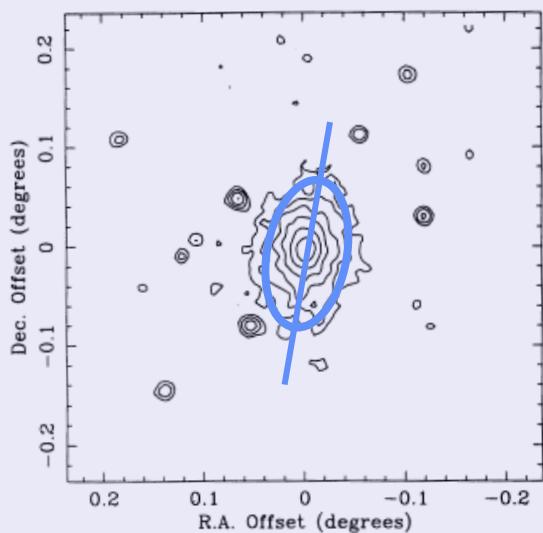


within 1 billion light-years

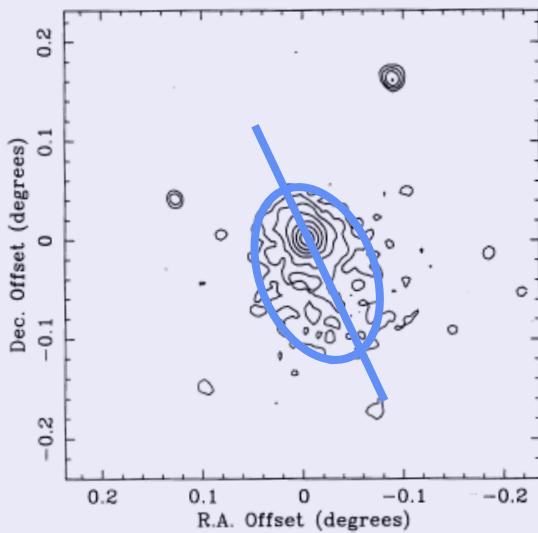
Cluster X-ray emission



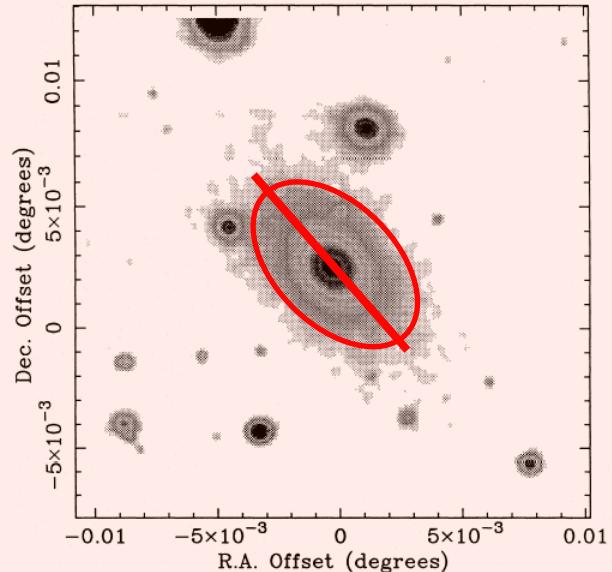
(a) Abell 1413



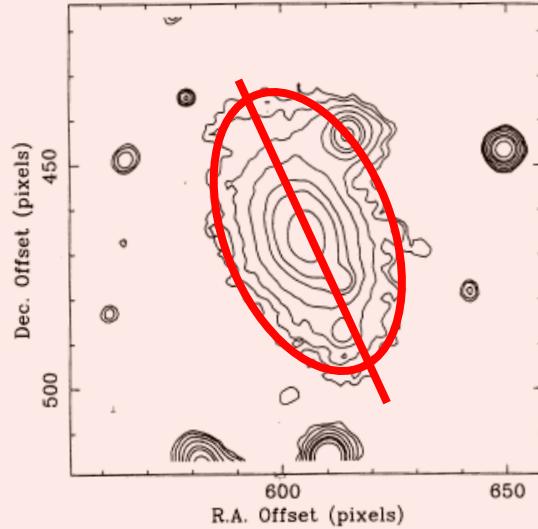
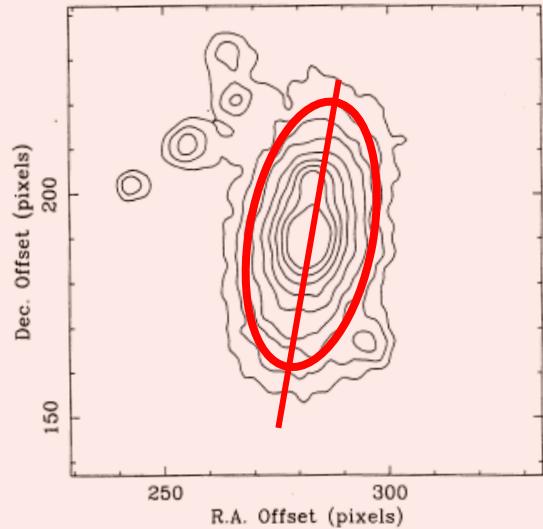
(b) Abell 1413 CCG



(a) Abell 1664



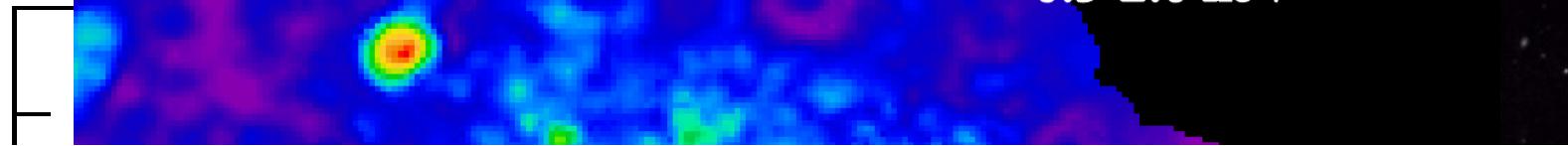
(b) Abell 1664 CCG



Central dominant galaxy

Coma Cluster
0.5-2.0 keV

+32°



50°

Abell 2197/2199

35°

Coma

Abell 779

17^h
16^h

15^h

14^h

13^h

12^h

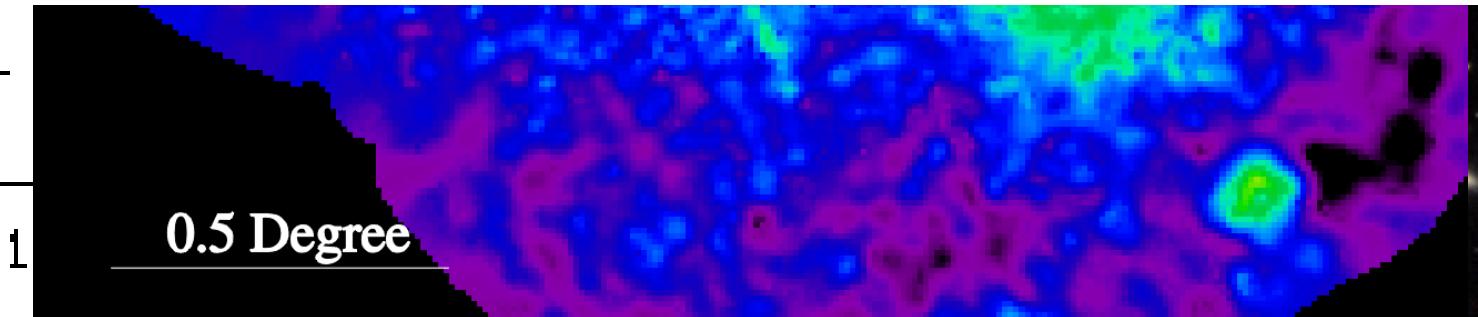
11^h

10^h

9^h

RA (J2000)

+34°

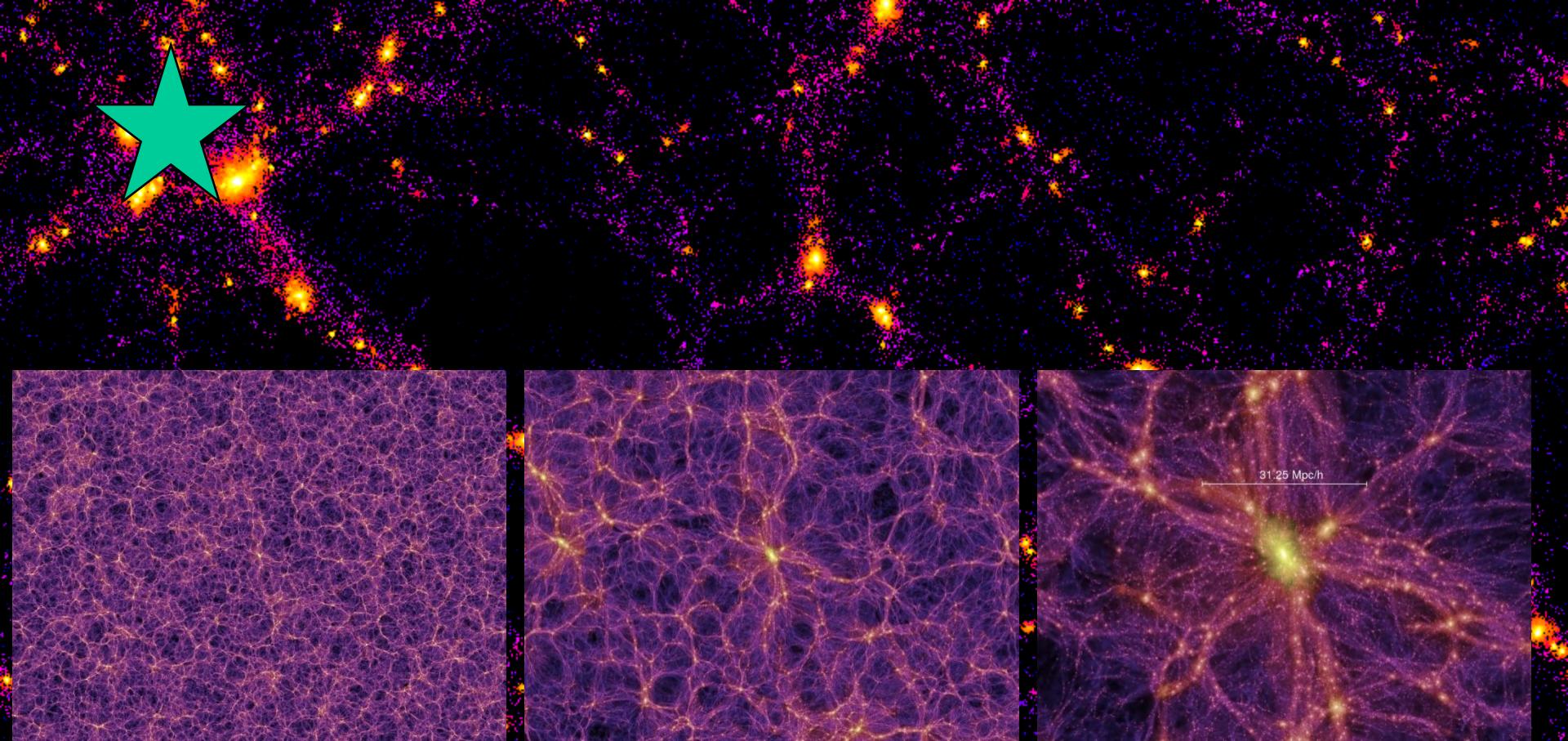


1

0.5 Degree

Clusters of galaxies are often strongly elongated

- dominant galaxy tends to be aligned with ...
- ...the cluster principal axis which aligns with...
- ...the orientation of the local supercluster structure



$T = 13.6$ billion years
 $T = 4.7$ billion years
 $T = 1$ billion years
 $T = 200$ million years

LARGE TELESCOPES... ...AND WHY WE NEED THEM

WEDNESDAY 9TH MAY 2012 1PM

