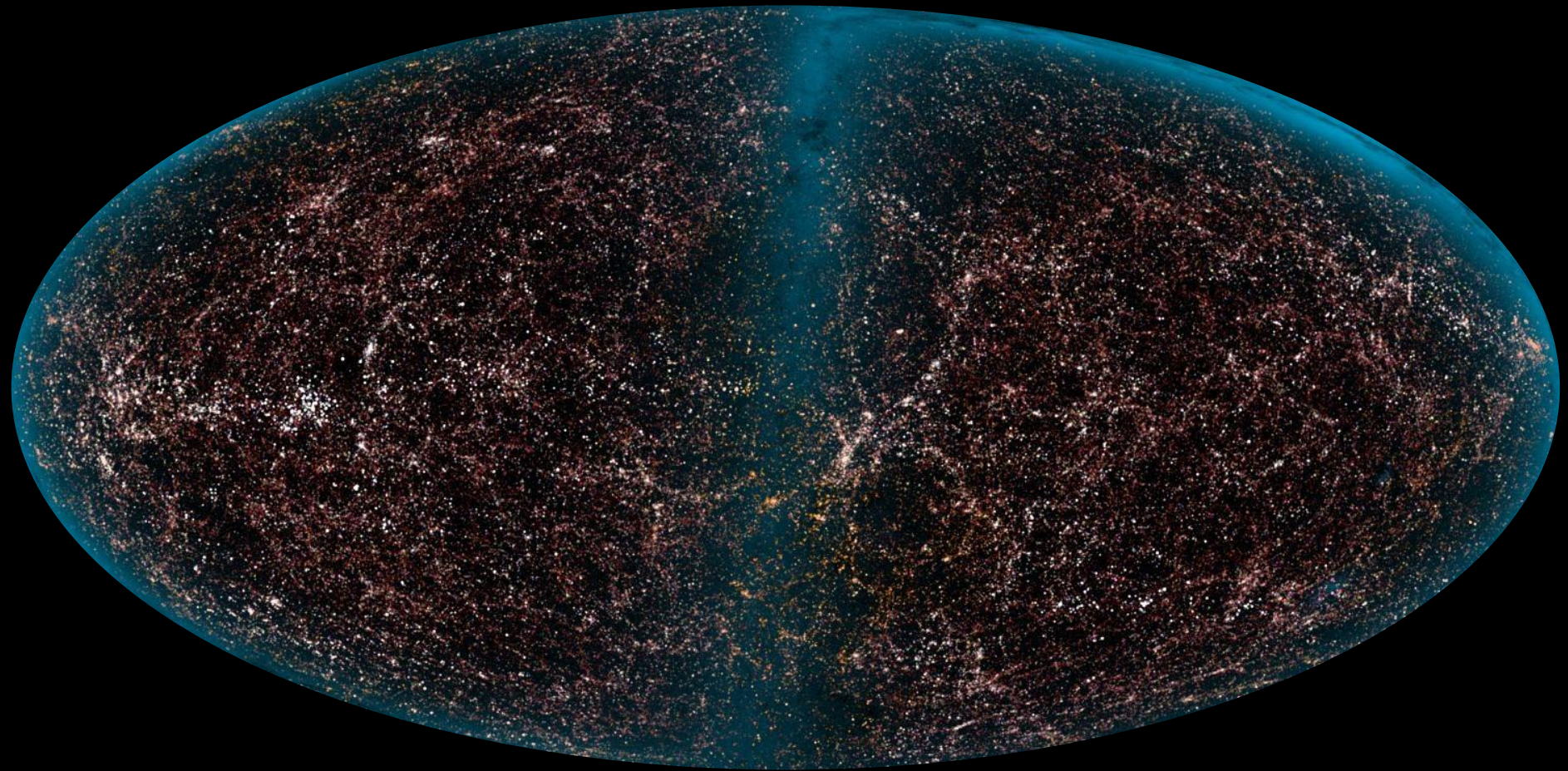


# CLUSTERS OF GALAXIES

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

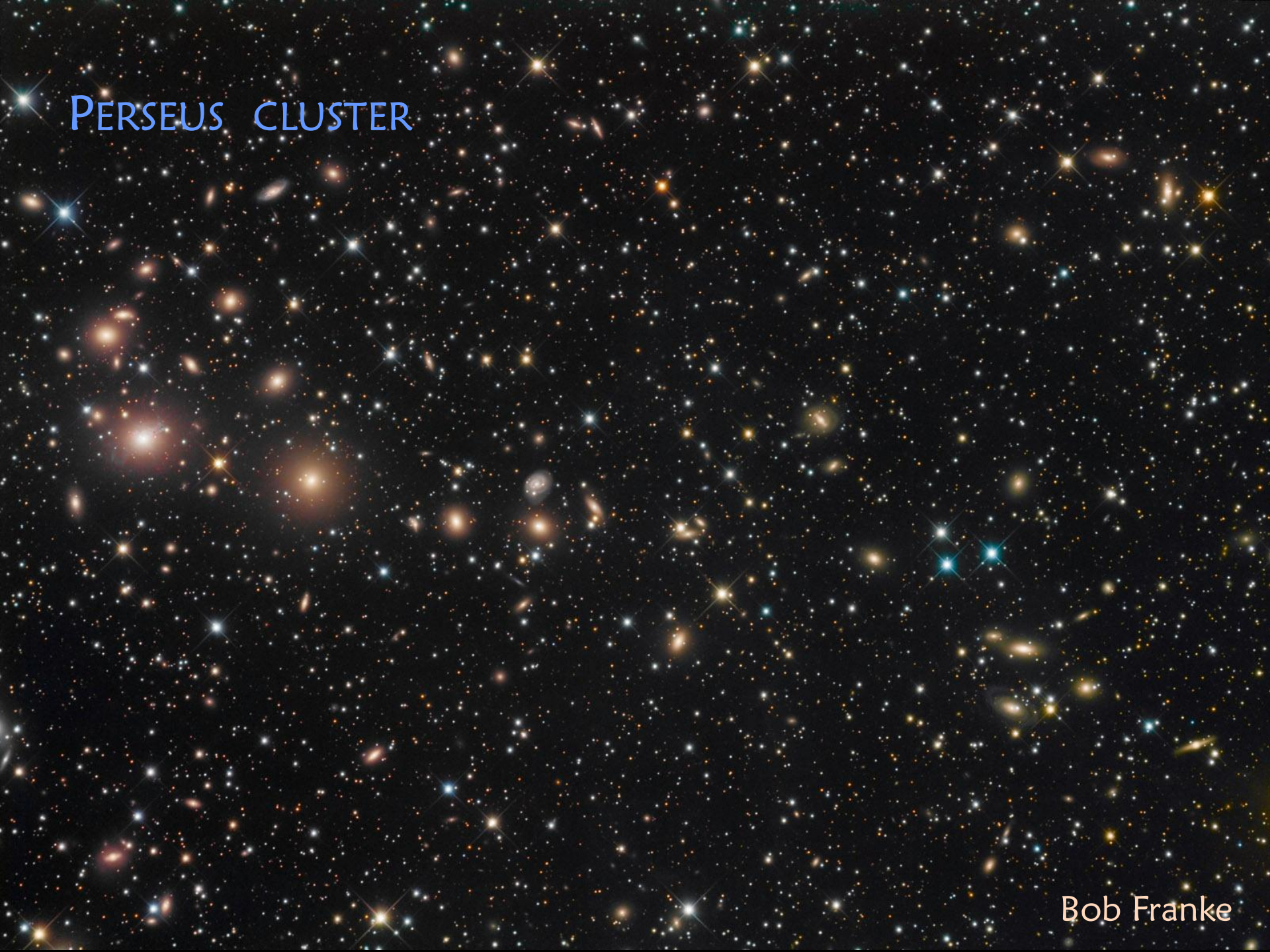
# COMA CLUSTER



Dean Rowe



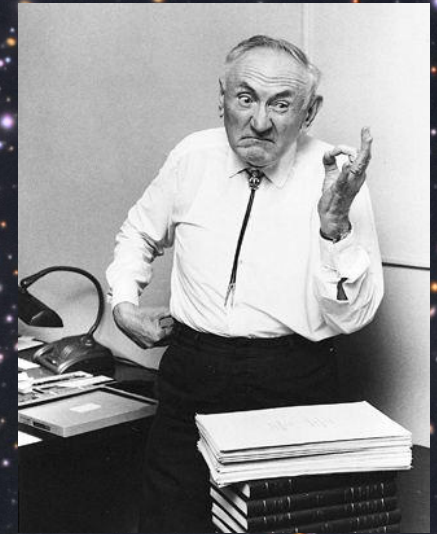
PERSEUS CLUSTER





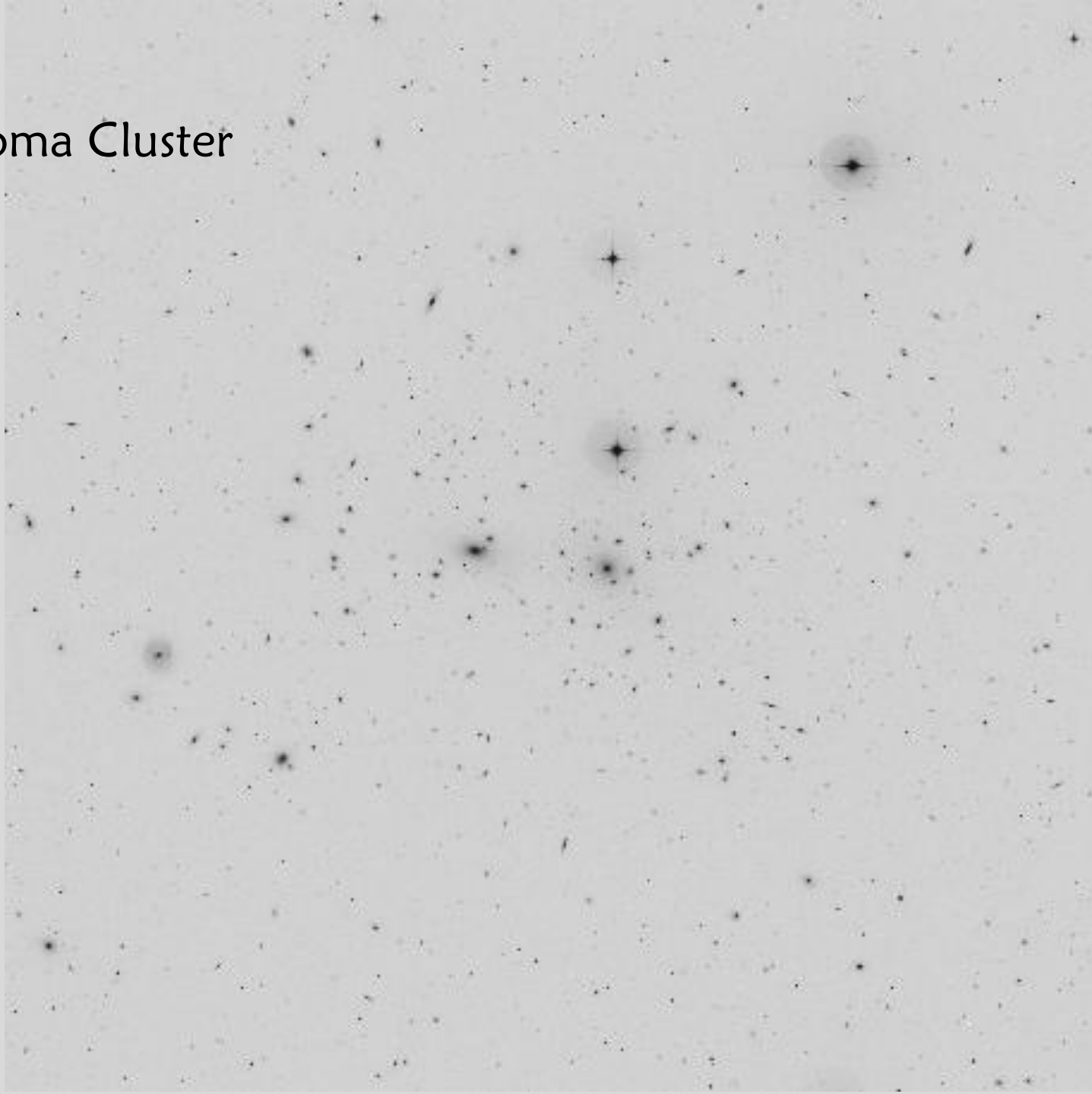


George Abell (1927-83)

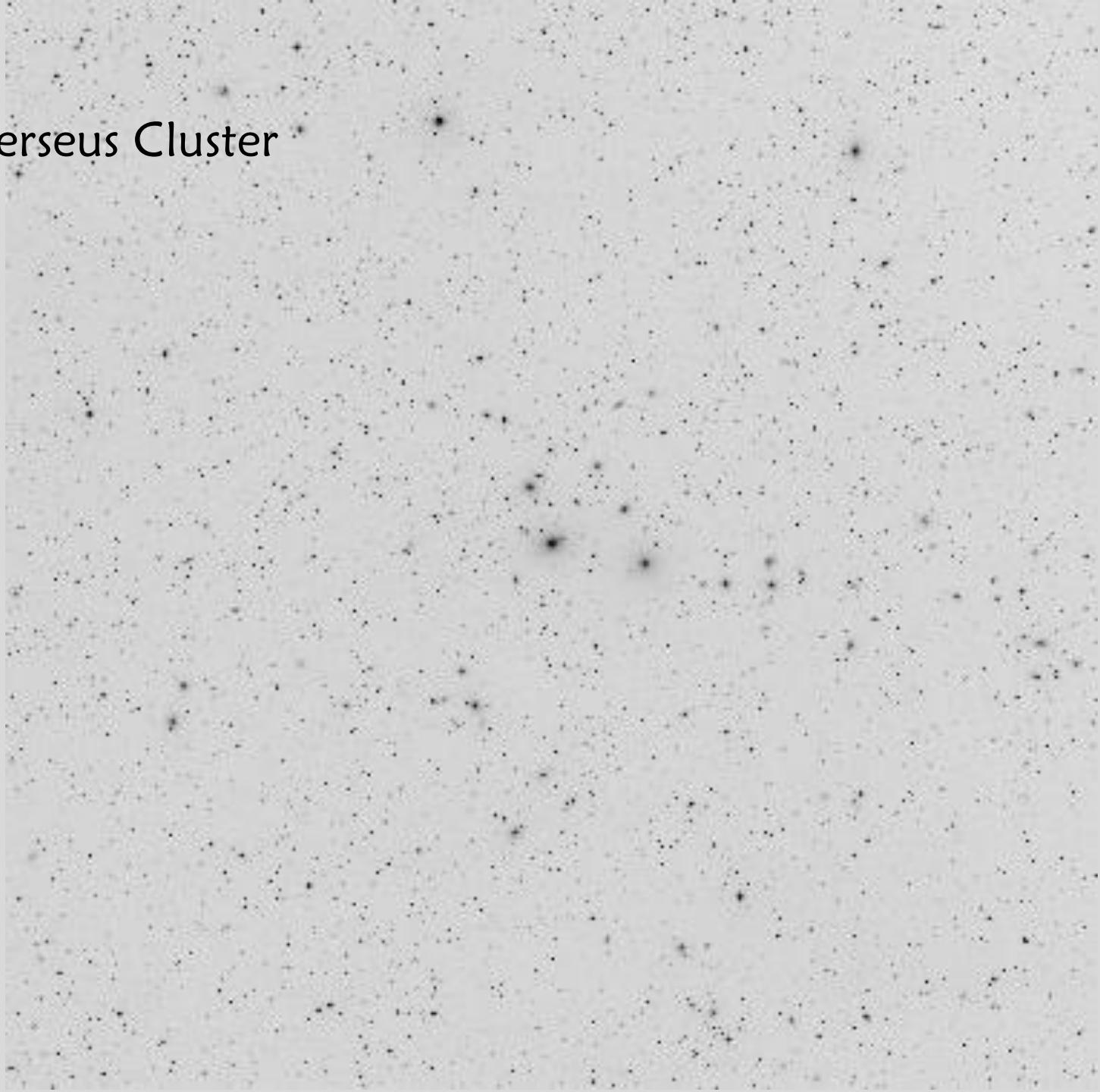


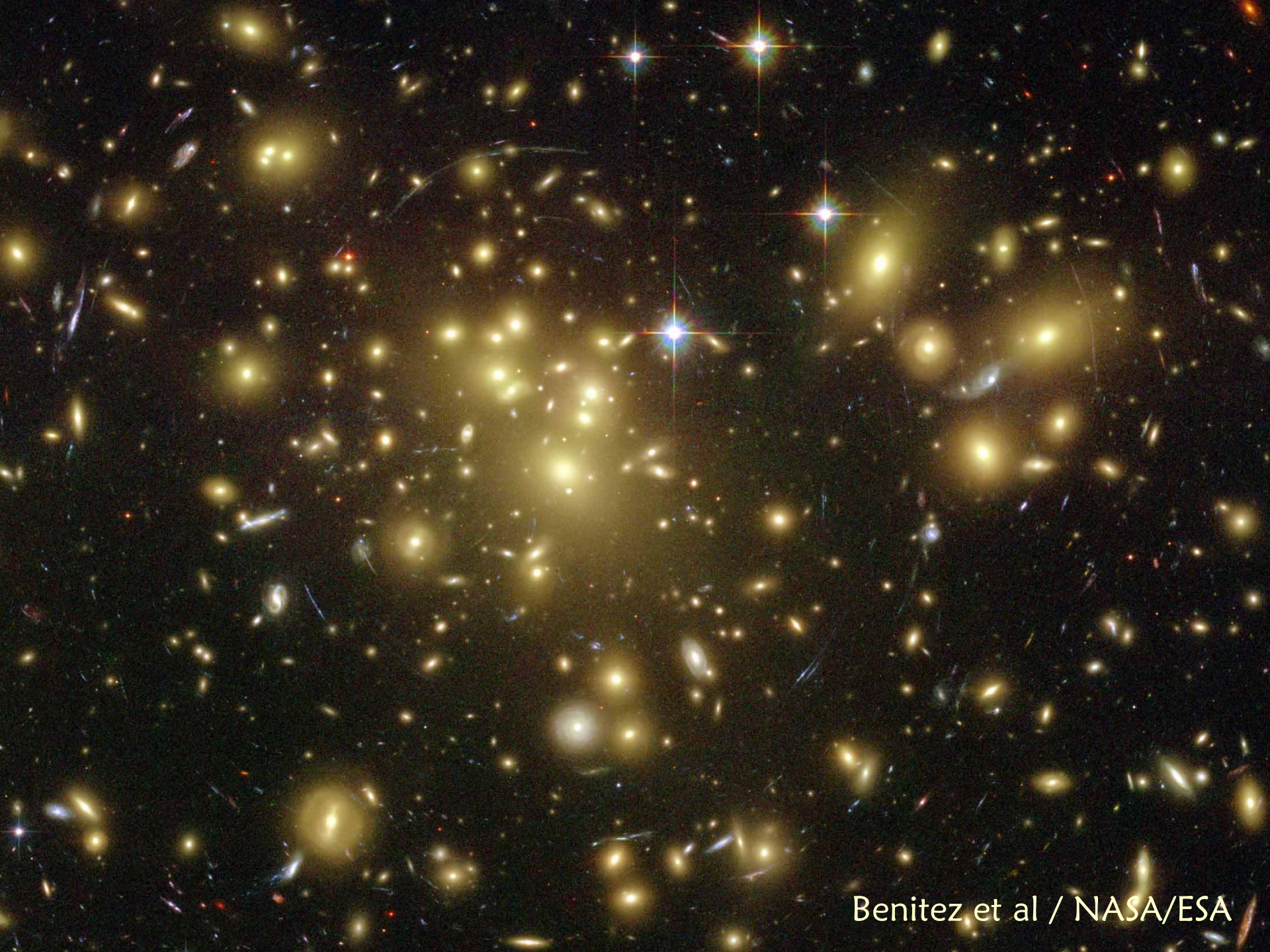
Fritz Zwicky (1889-1974)

# Coma Cluster

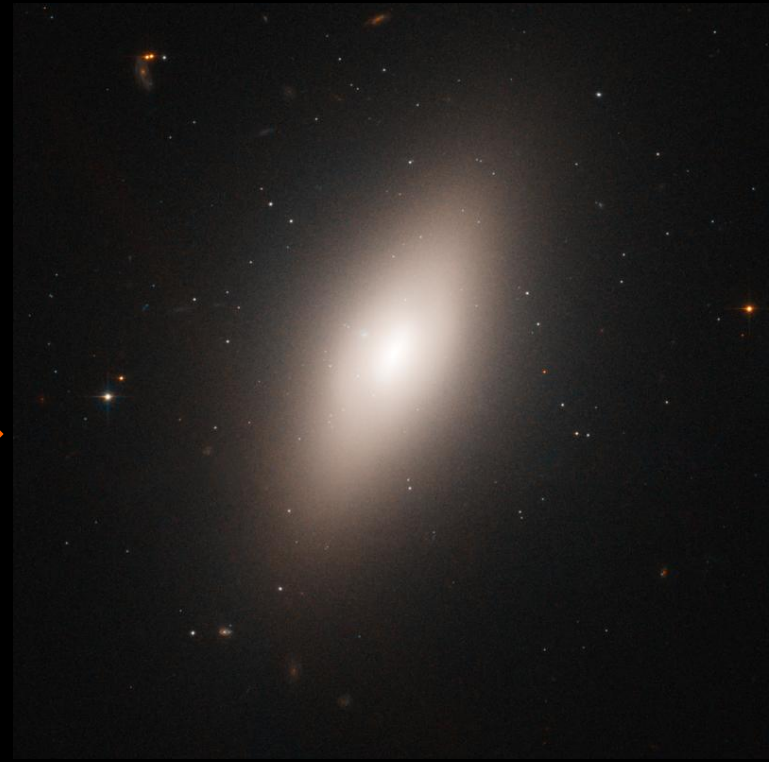
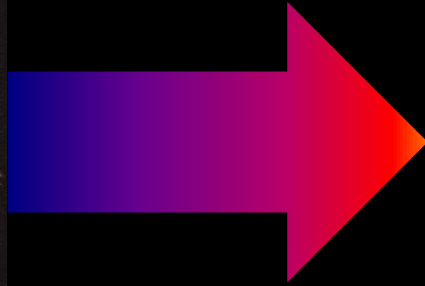


# Perseus Cluster



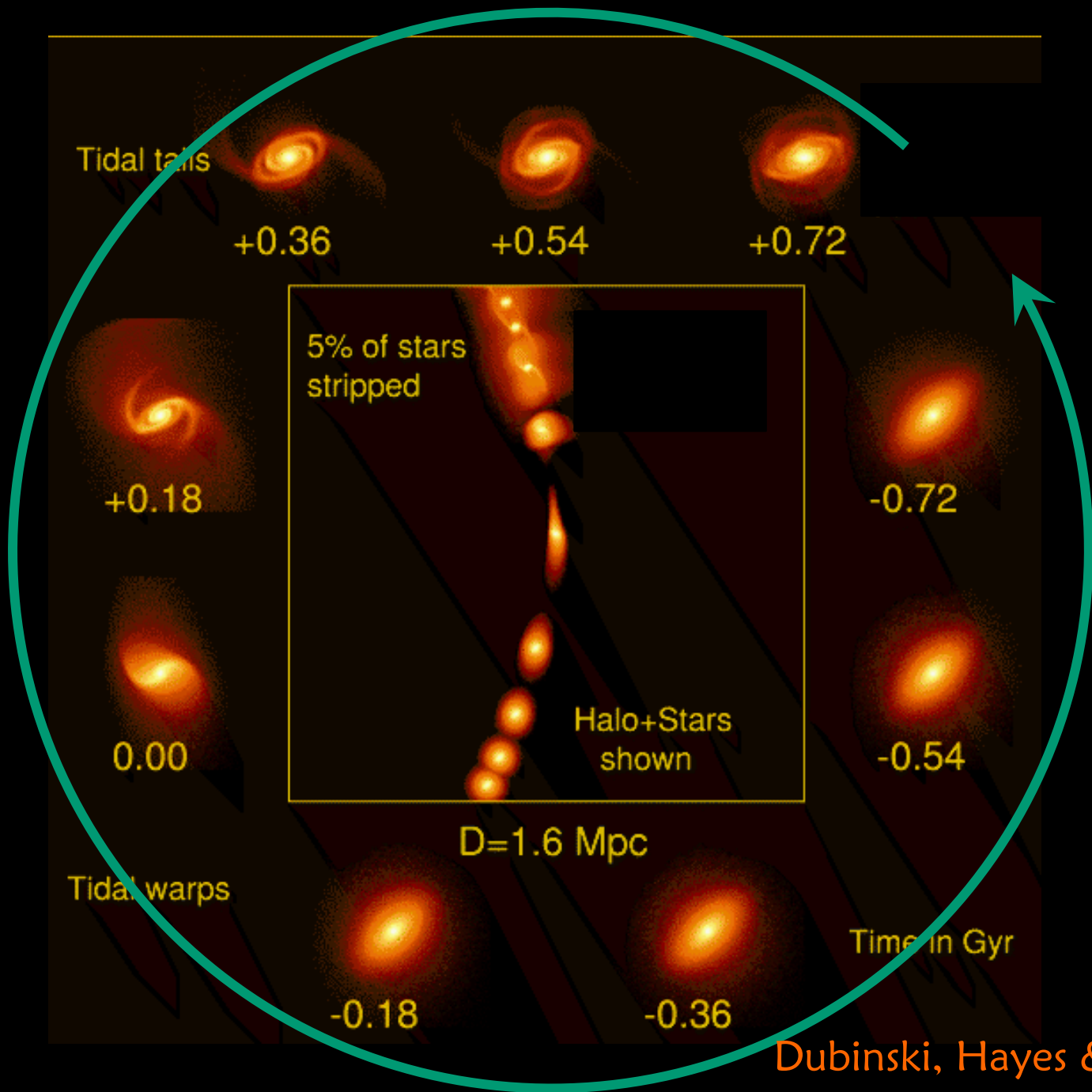


Benitez et al / NASA/ESA



NASA/ESA/Riess et al

NASA/ESA/Peng



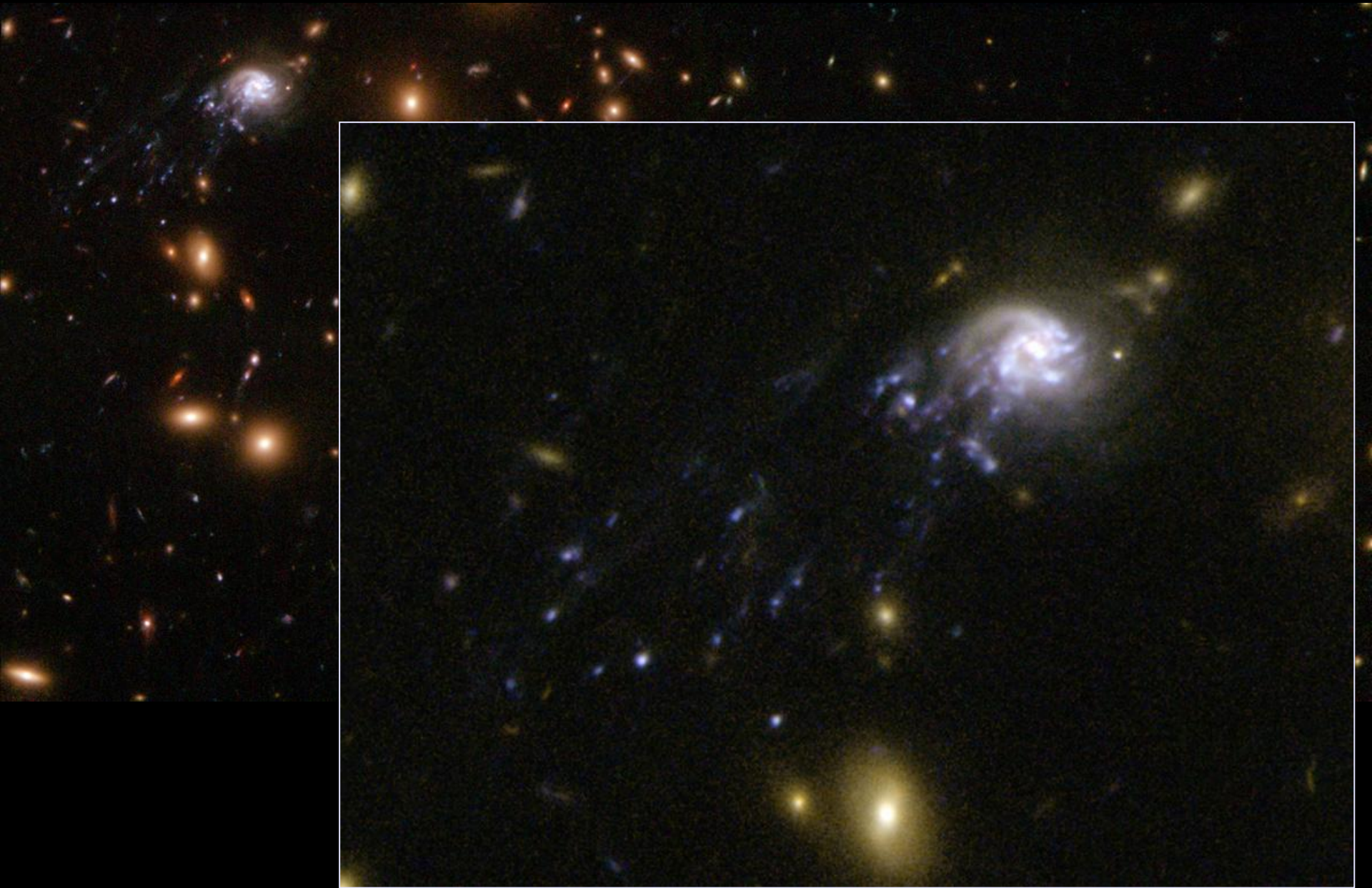
Dubinski, Hayes & Dieng





optical  
X-rays

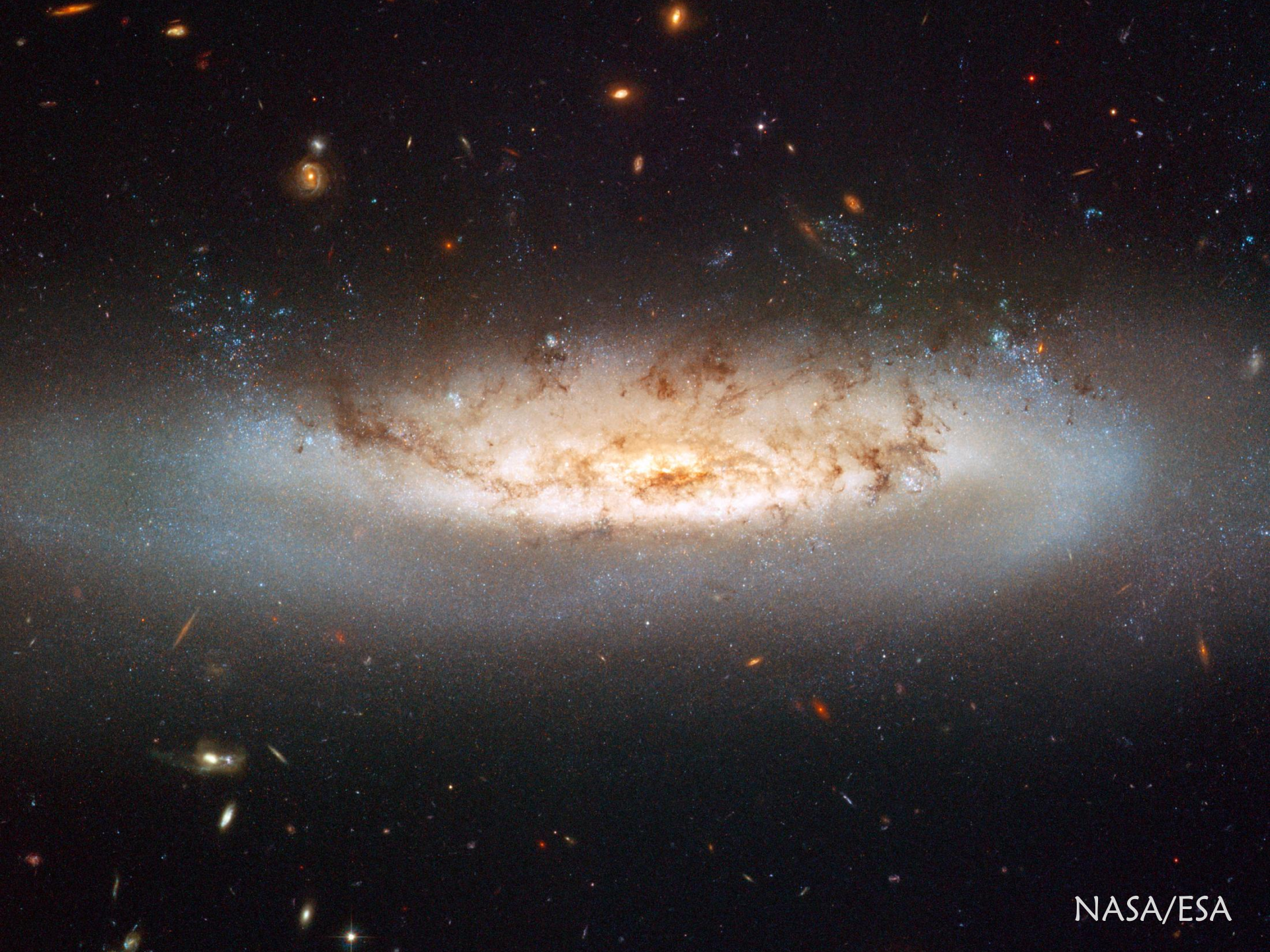
NASA/STScI  
NASA/CXC/MIT/Peng et al



NASA/ESA/Kneib



NASA/ESA  
Rogelio Bernal Andreo



NASA/ESA



Adam Block (U Arizona)



1137

}

NASA/CXC/Allen et al

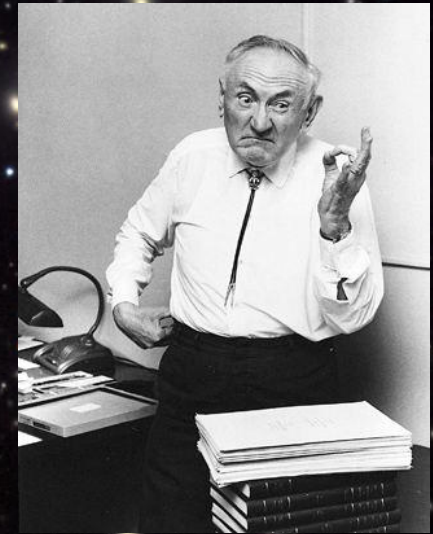
NASA/CXC/INAF/DSS/VLT

# 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

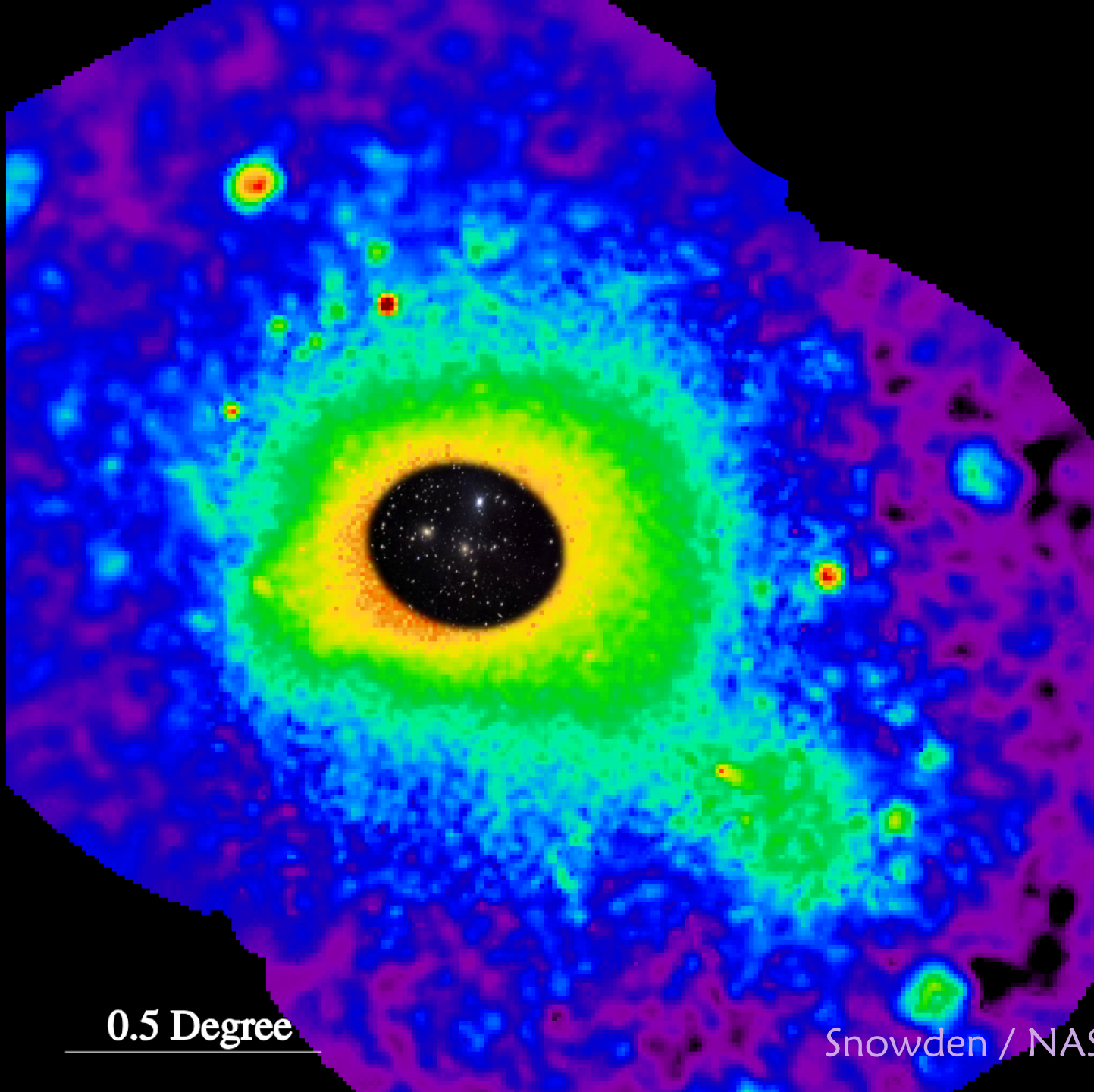
but  $L_{\text{total}} \sim 10^{13} L_{\text{sun}} \Rightarrow (M/L)_{\text{total}} \sim 300 M_{\text{sun}} / L_{\text{sun}}$

*there is more mass in a cluster than we can see*



Fritz Zwicky (1898-1974)





0.5 Degree

Snowden / NASA / GSFC

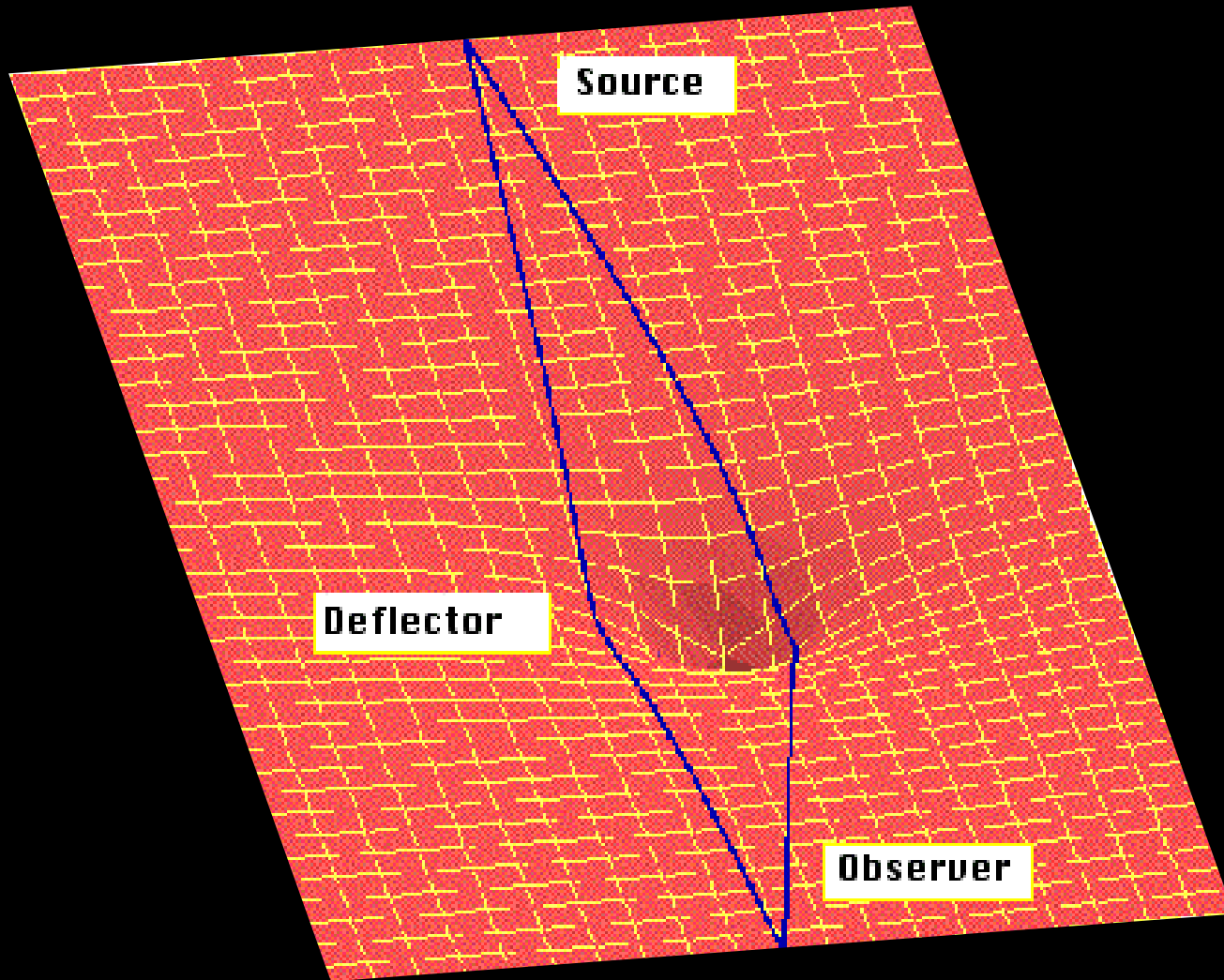


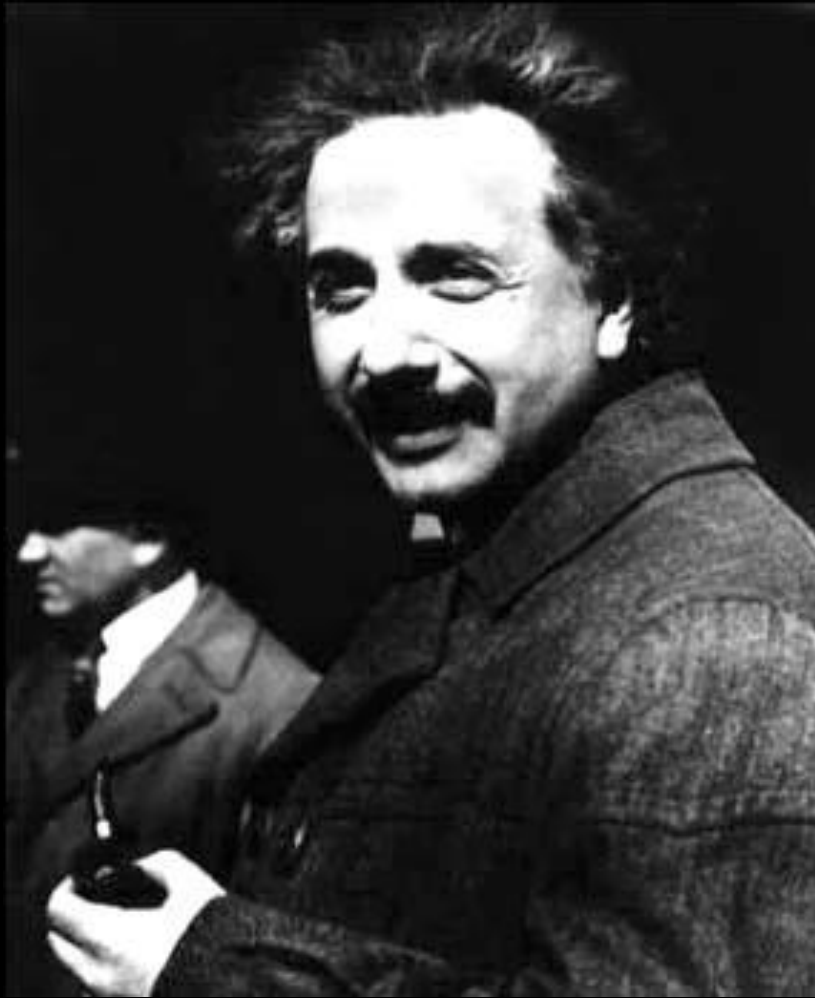
gravity



hot gas pressure

# Gravitational lensing in clusters





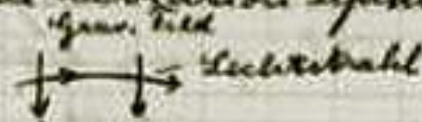
Albert Einstein (1879–1955)

Zürich. 14. I. 13.

Aus

Hoch geehrten Herr Kollege!

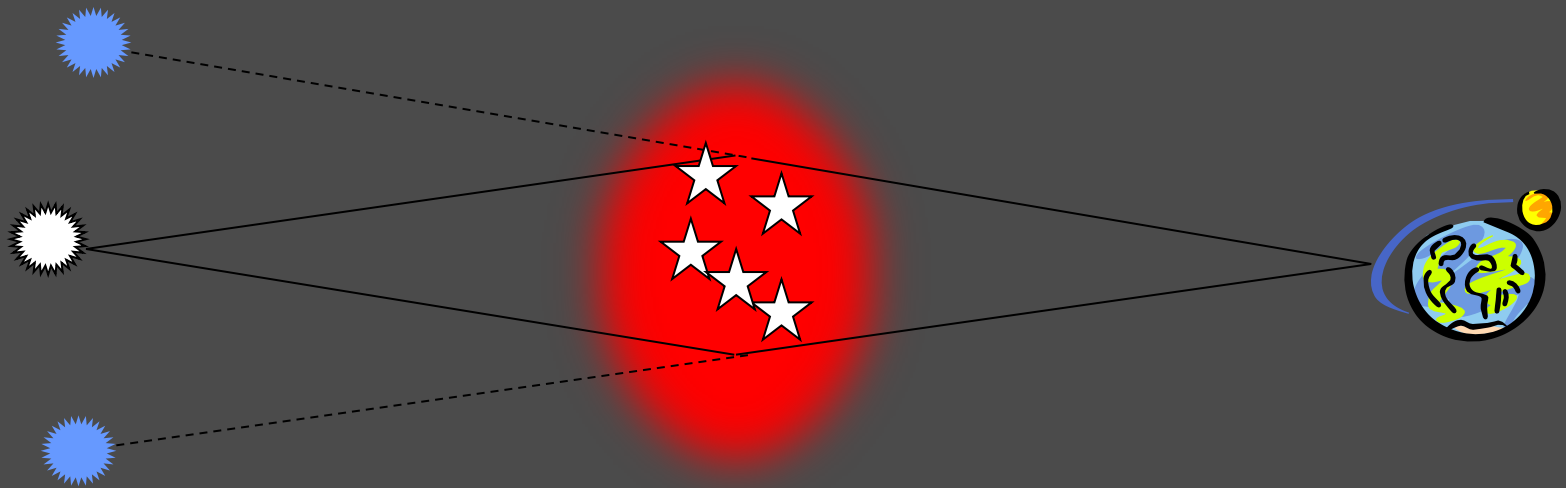
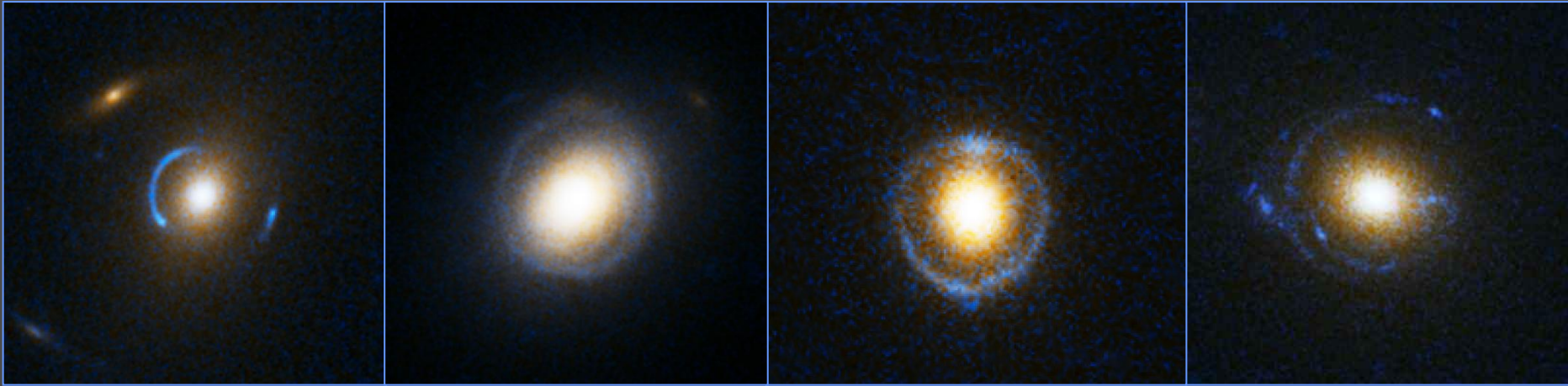
Eine einfache theoretische Überlegung macht die Annahme plausibel, dass Lichtstrahlen in einem Gravitationsfelde eine Deviation erfahren.

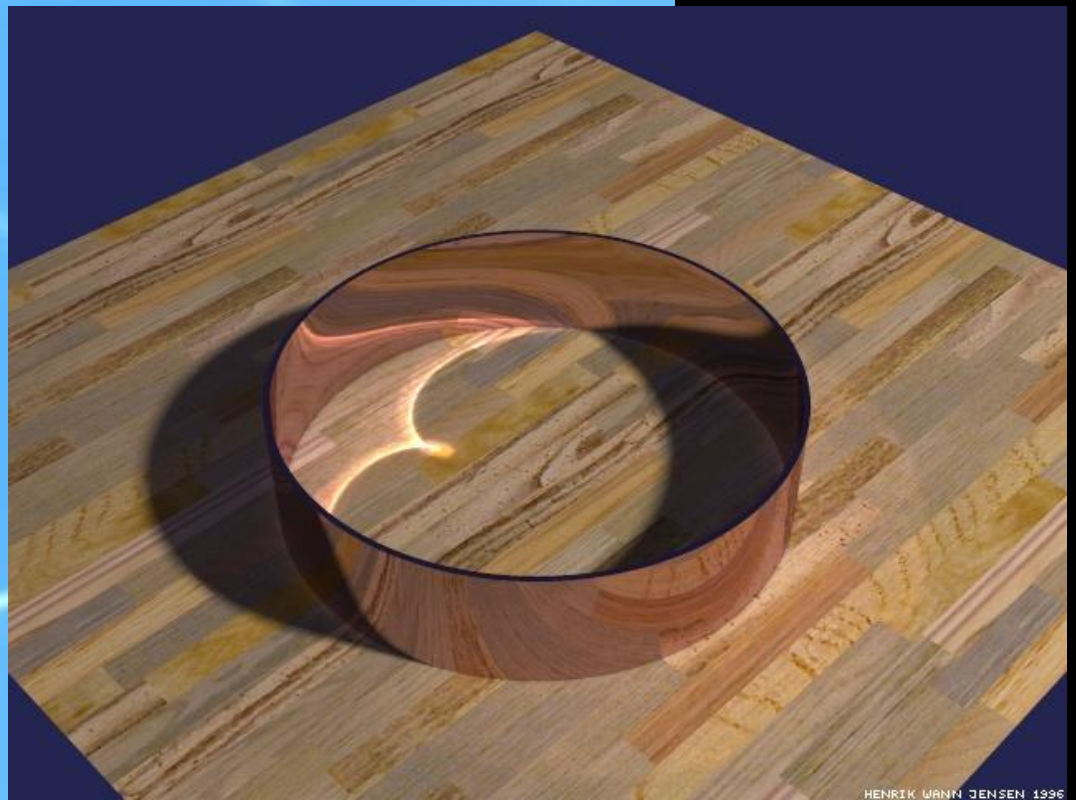
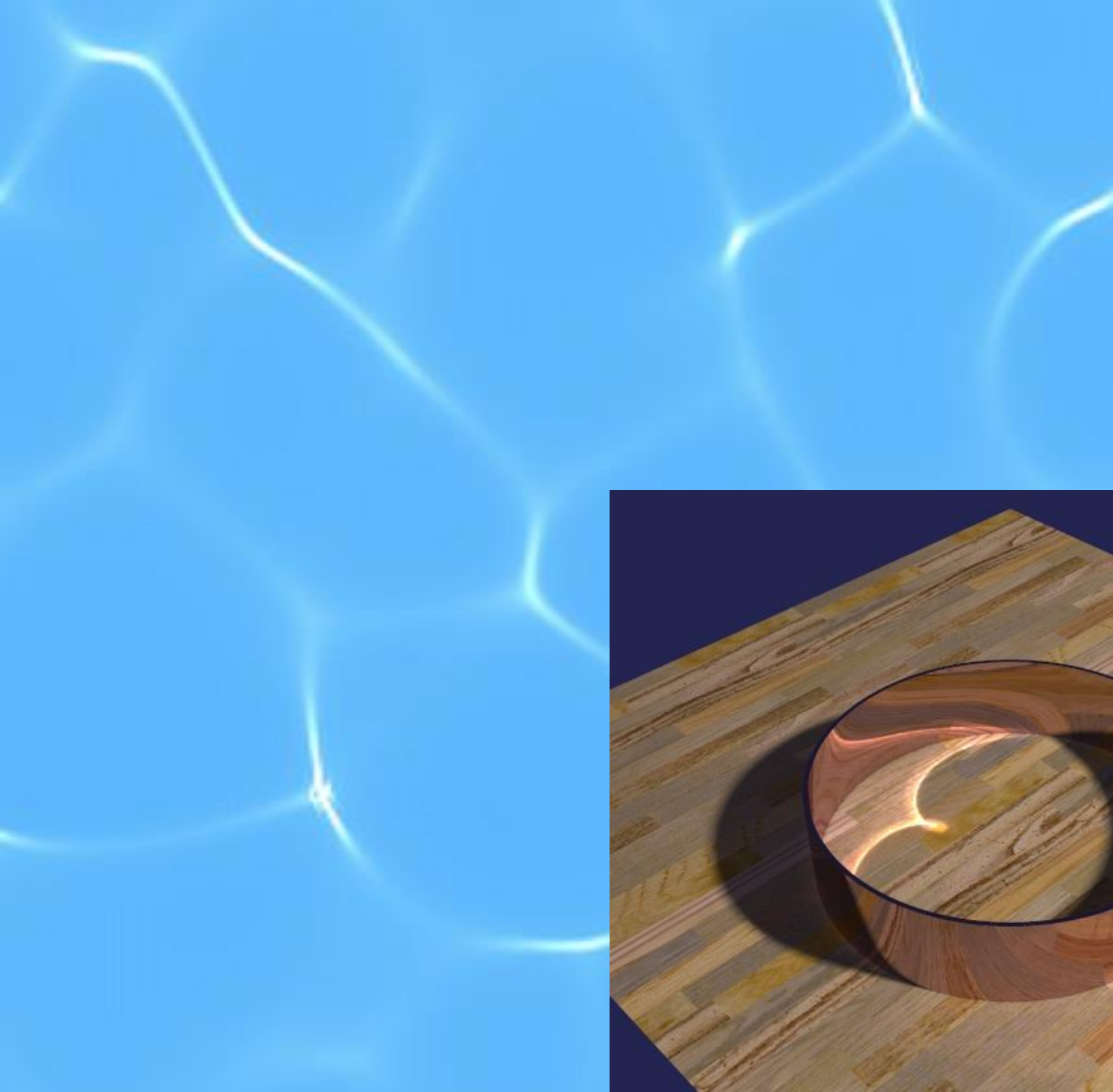


An Sonnensande müsste diese Ablenkung  $0,84^\circ$  betragen und wie  $\frac{1}{R}$  abnehmen ( $R =$  Sonnenradius).  
(Entfernung vom Sonnen-Mittelpunkt)



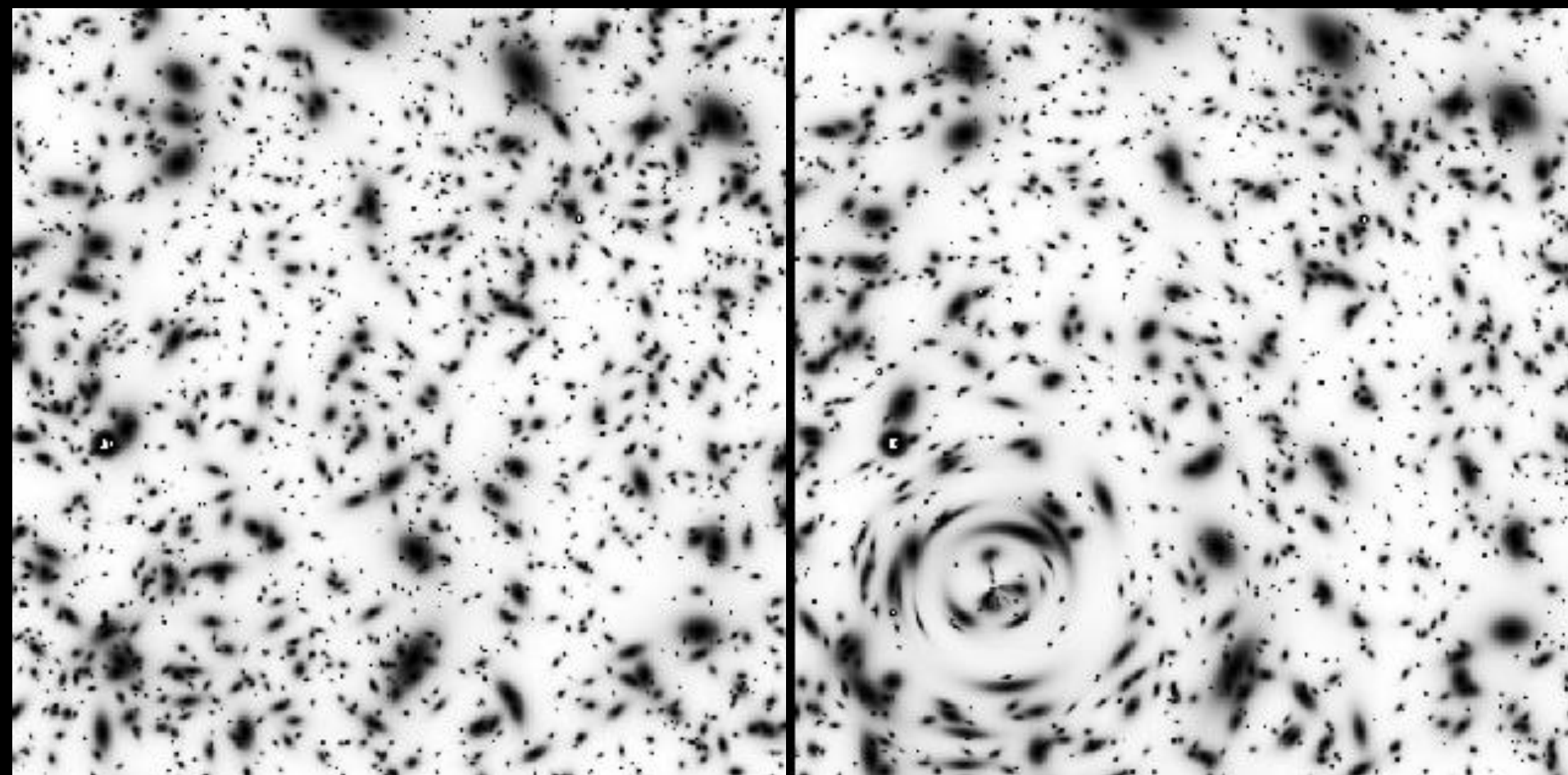
Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnen-nähe <sup>helle</sup> Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.





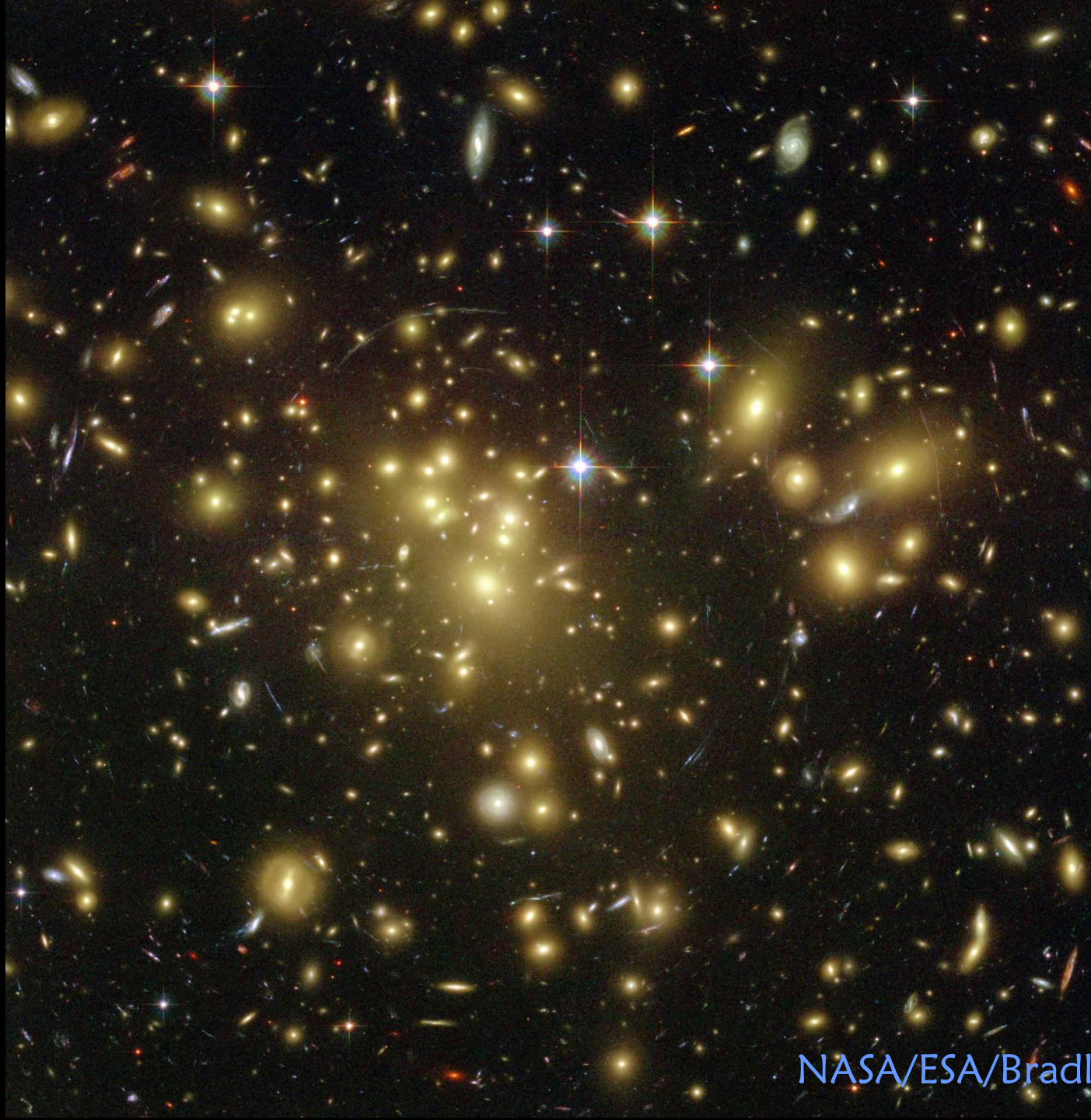


NASA/ESA/Beckwith et al

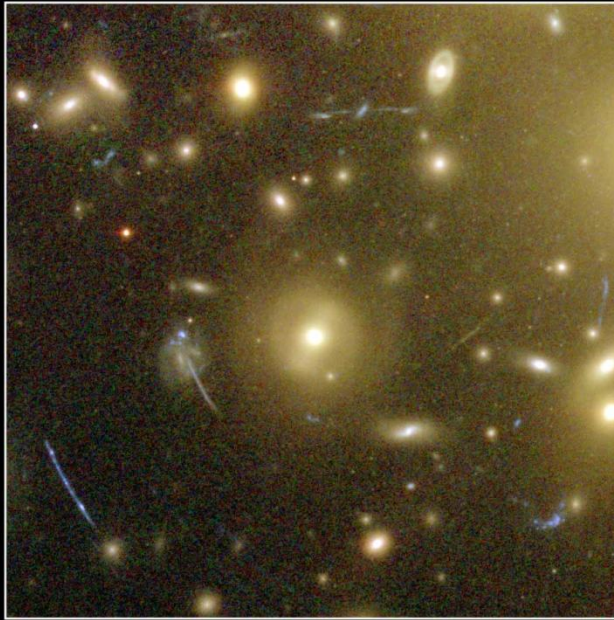
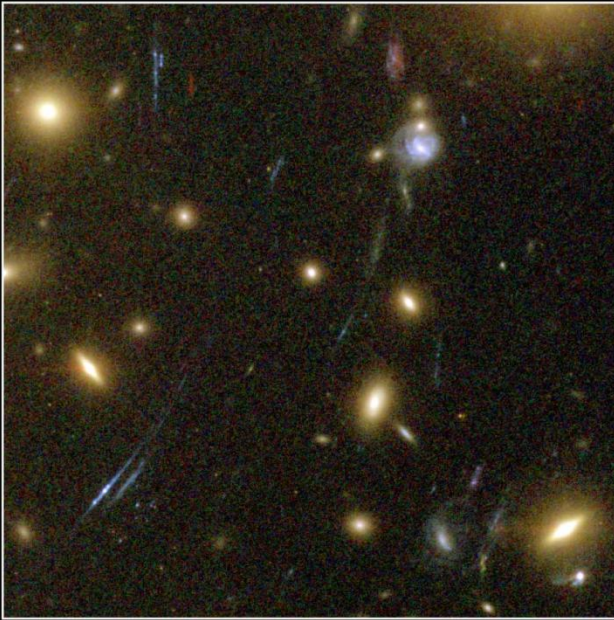
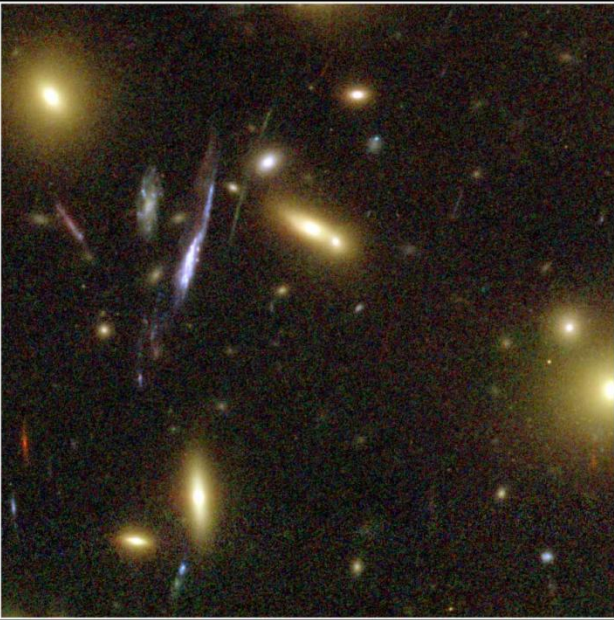
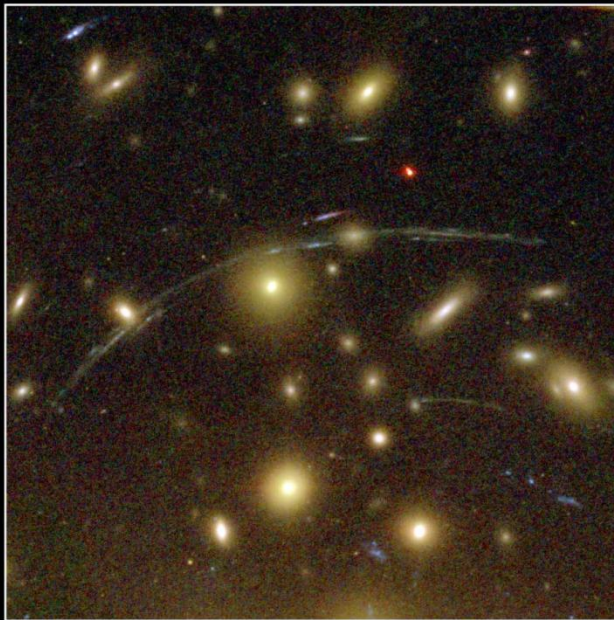
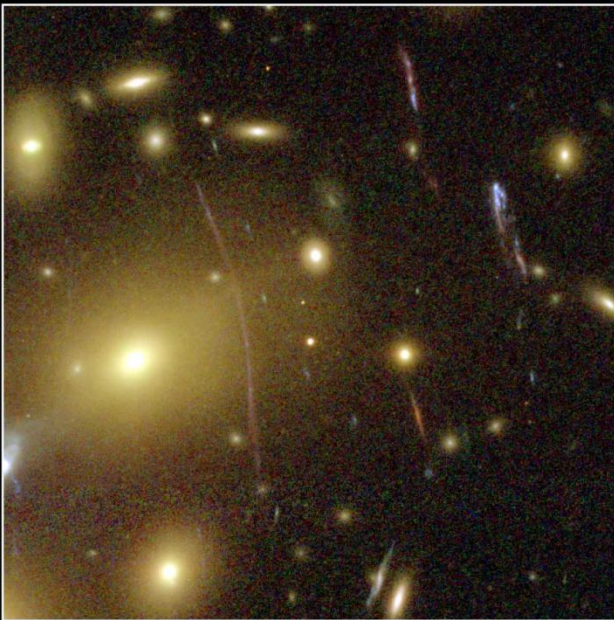
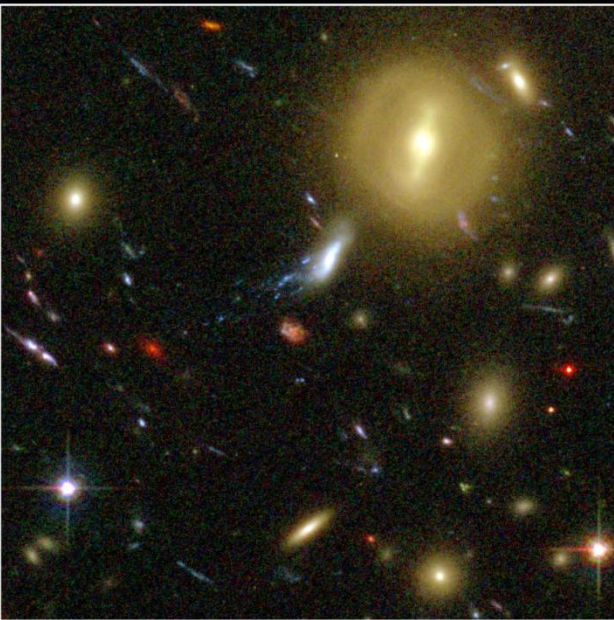


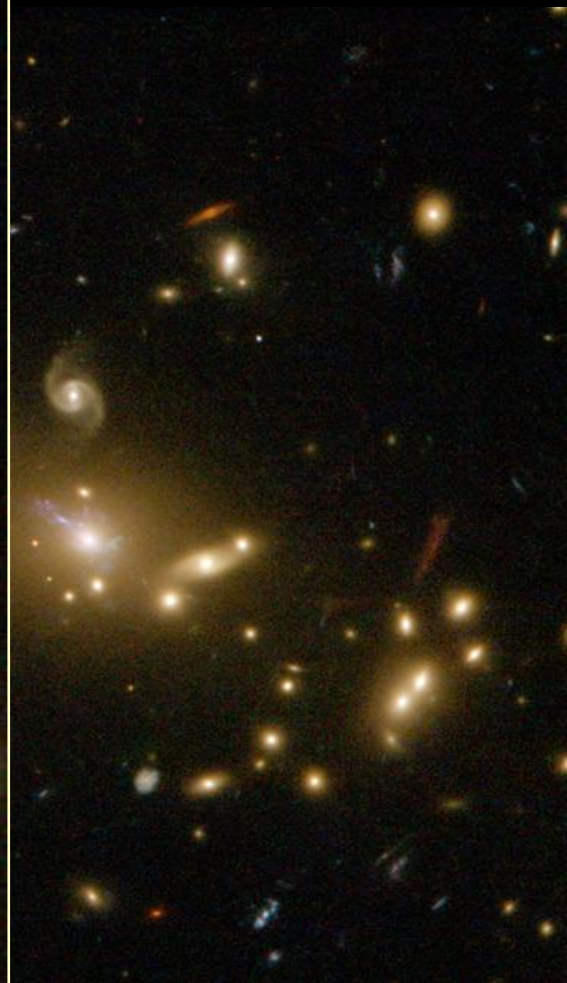
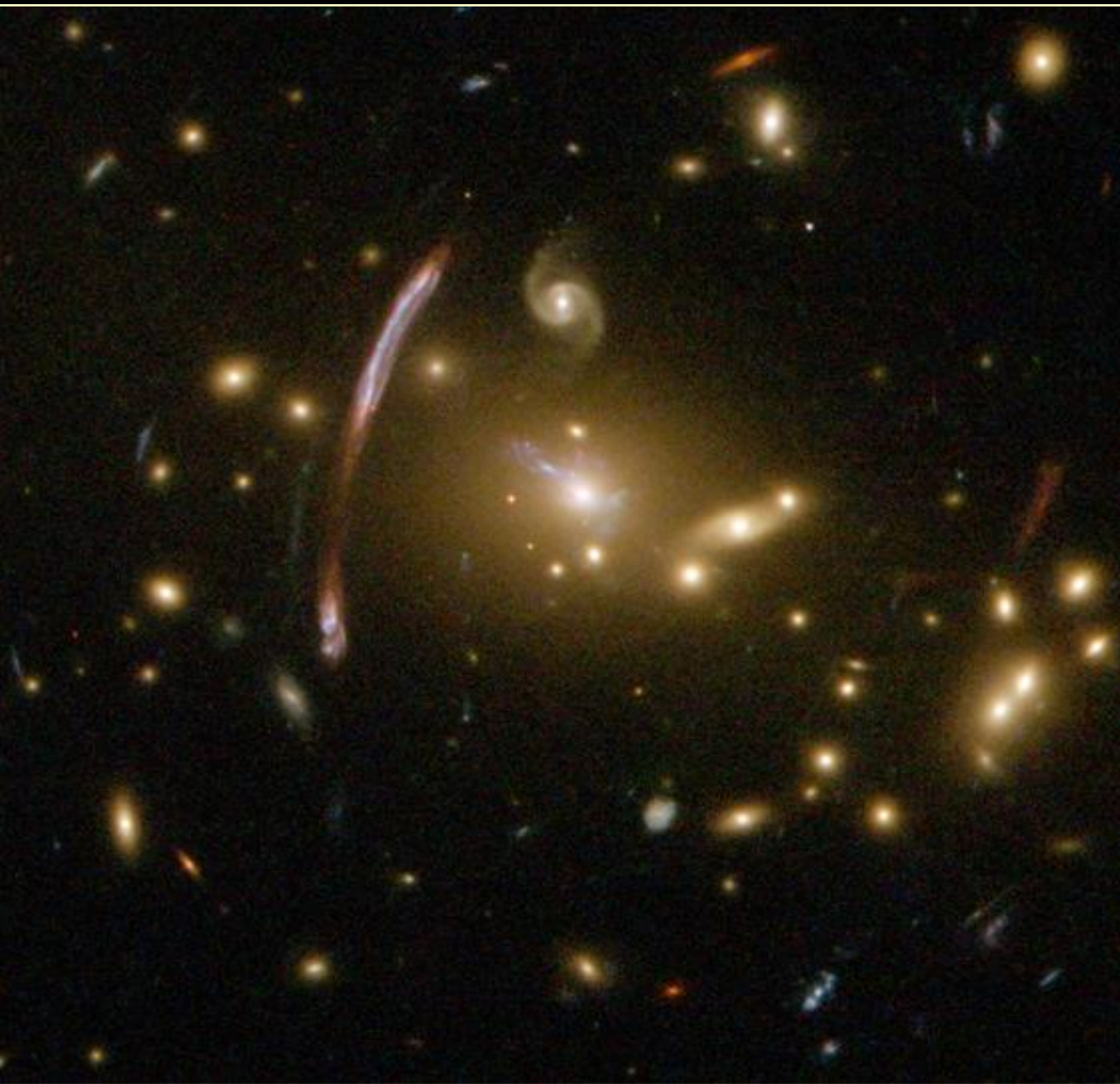
Yannick Mellier





NASA/ESA/Bradley et al







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

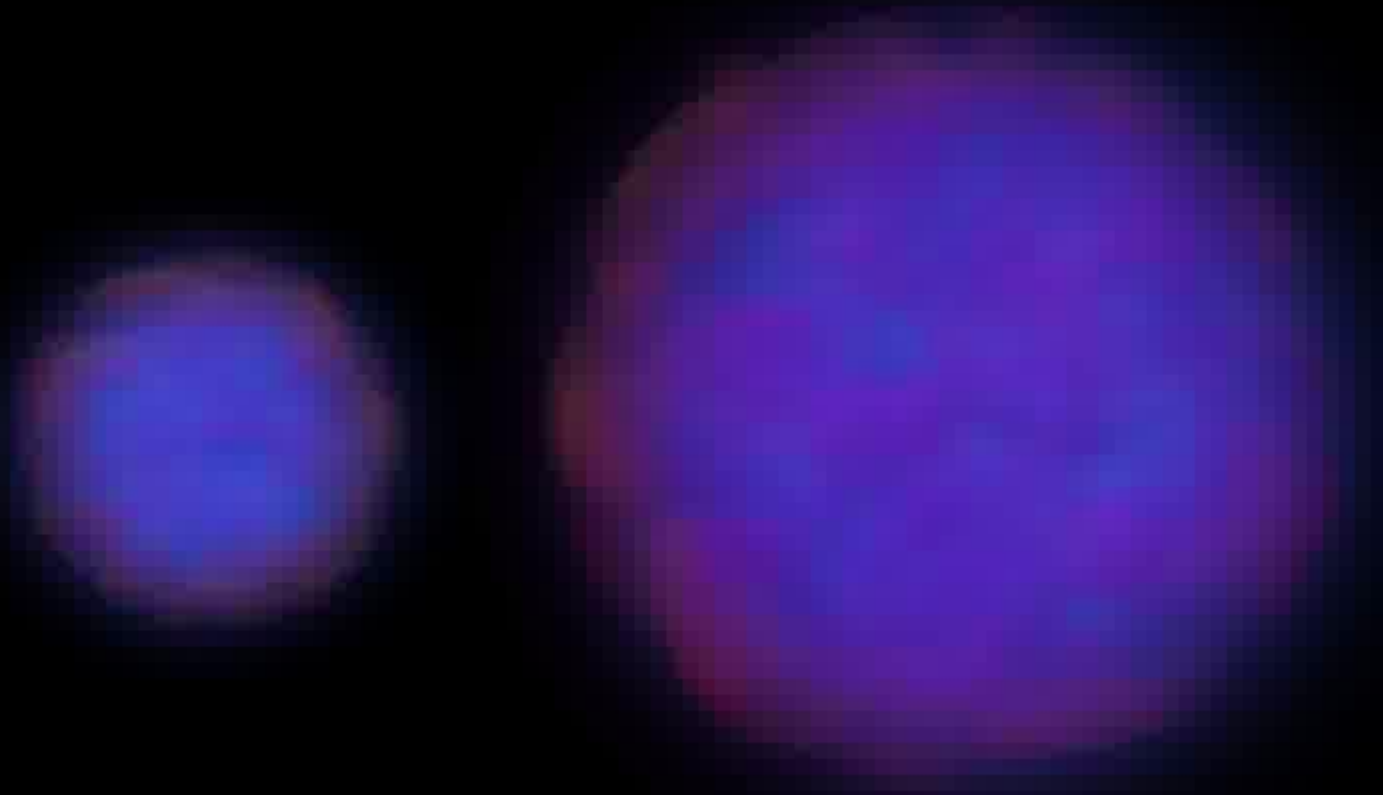


NASA/STScI/ESO/Clowe et al

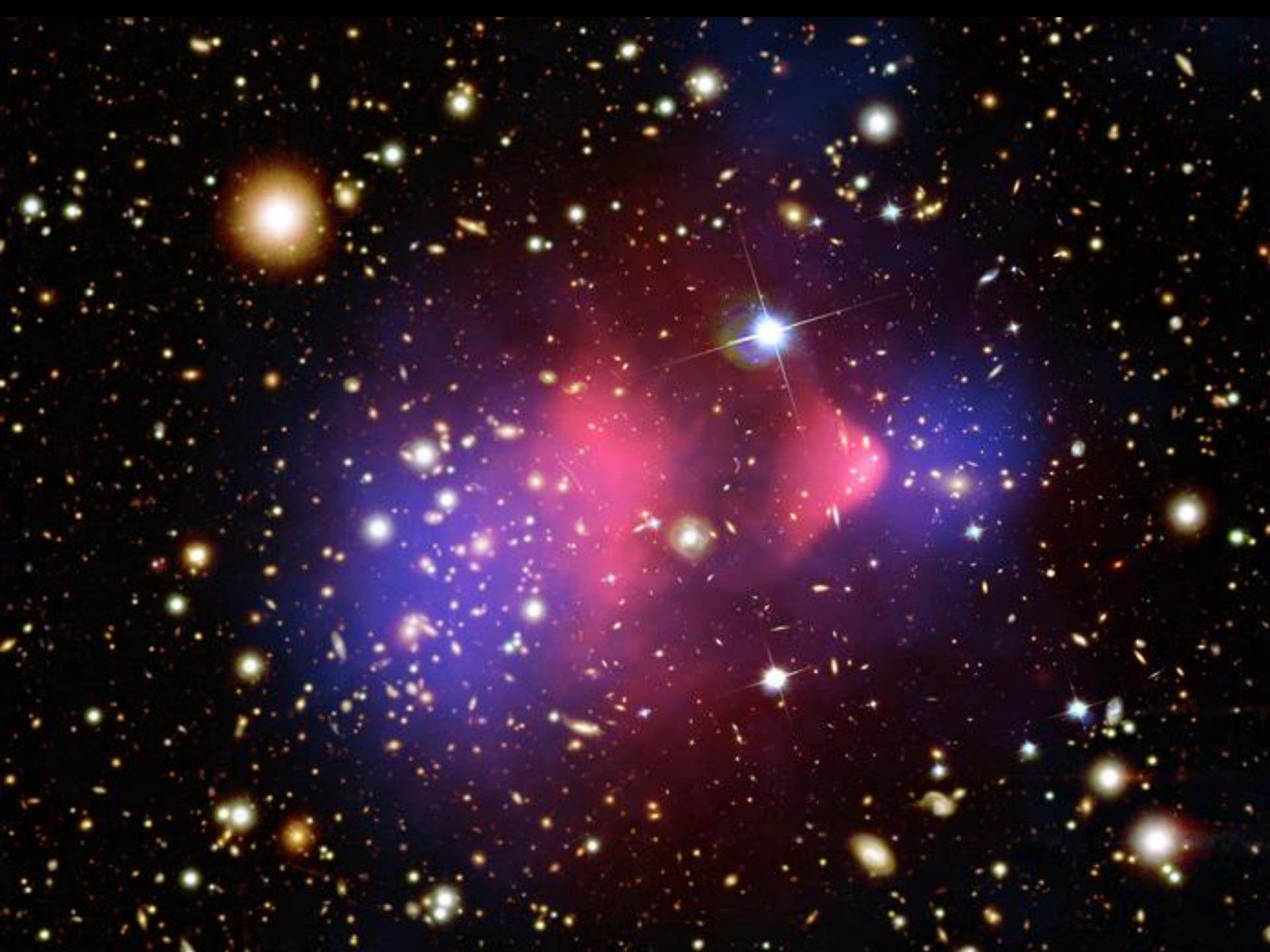
NASA/CXC/Markevitch et al



Lensing (dark matter)  
X-rays





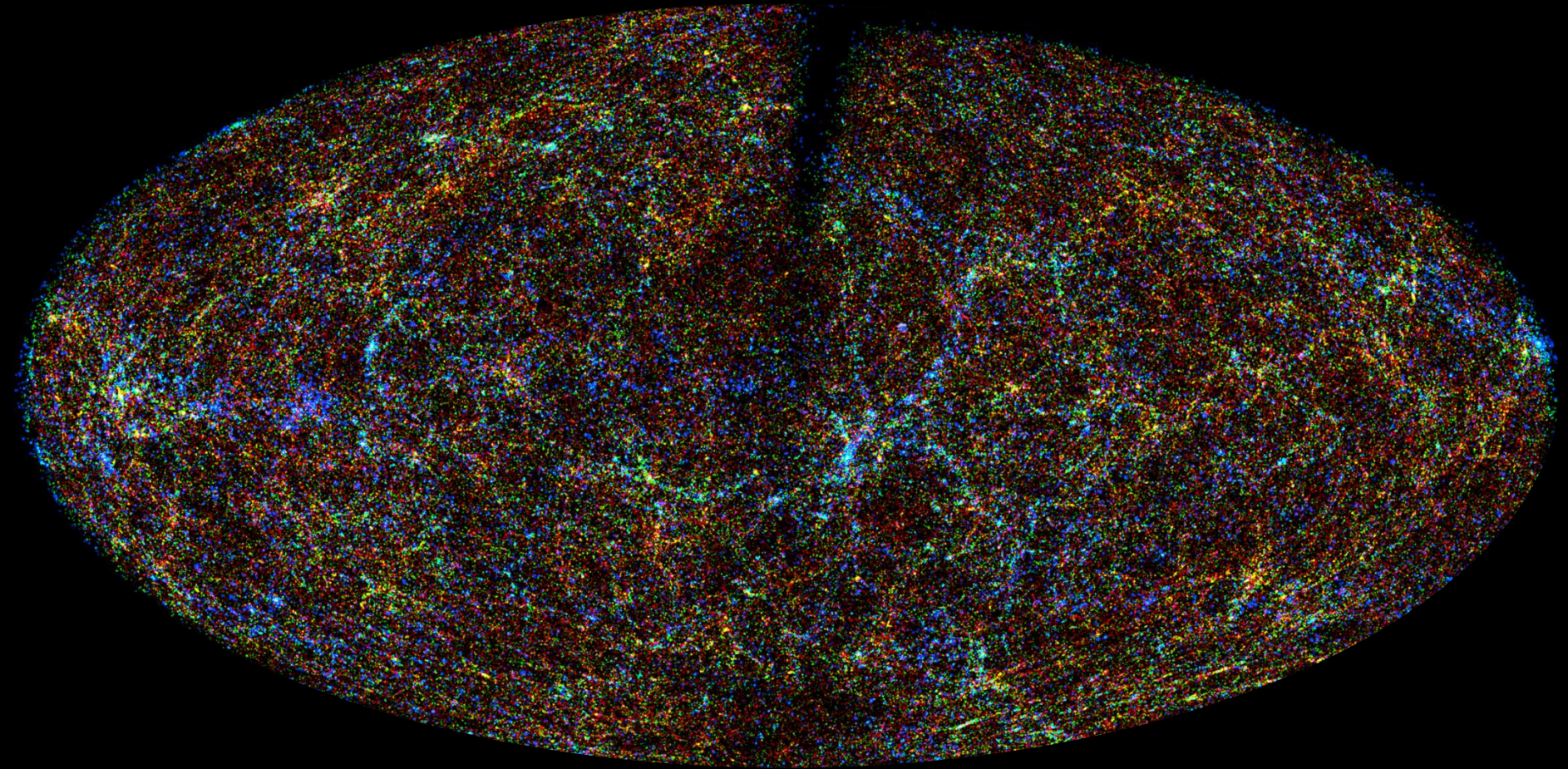


galaxy distribution dark matter (lensing) X-rays

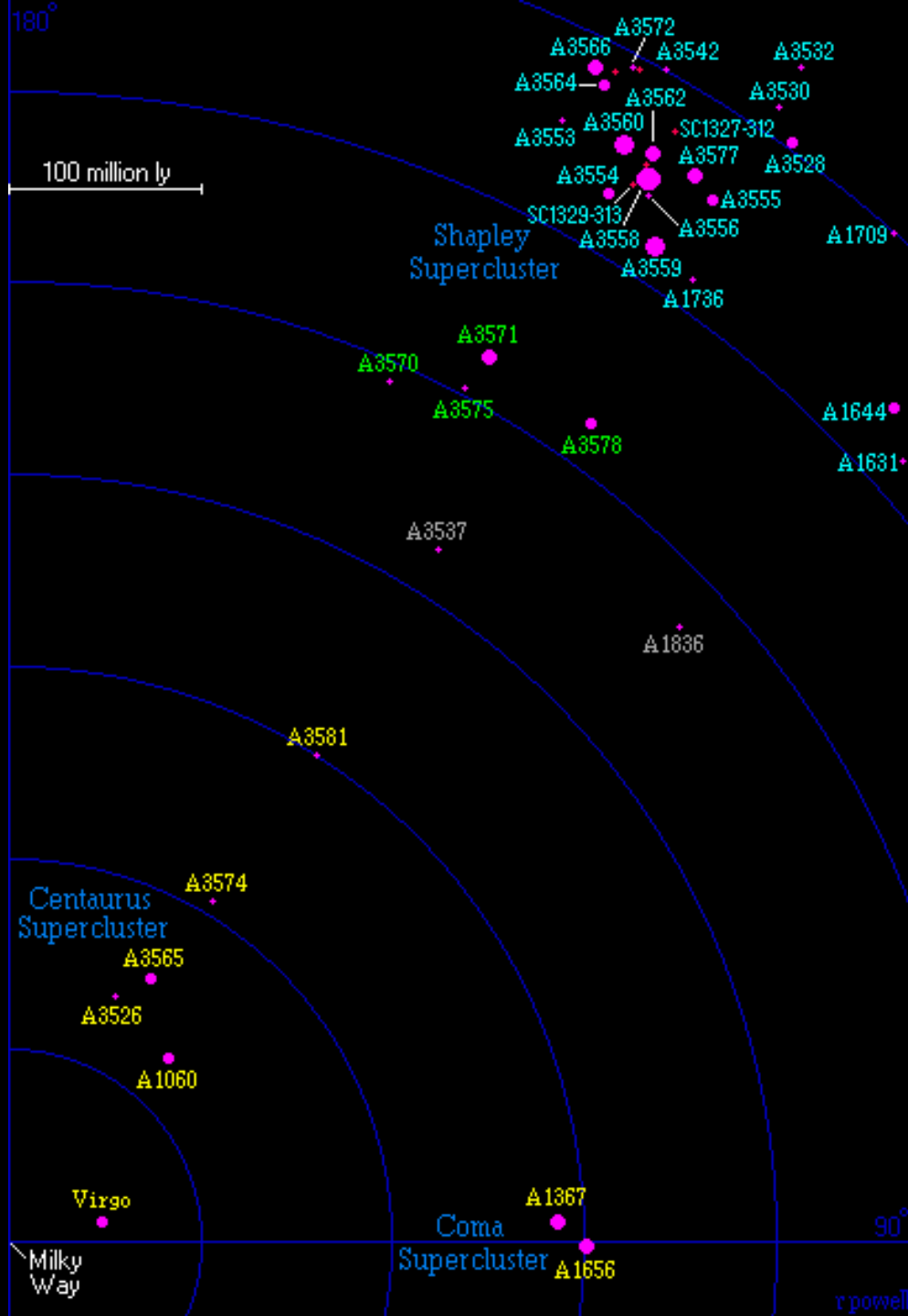


NASA/ESA/CFHT/CXO/Jee & Mahdavi

nearby galaxies  
next nearby galaxies  
more distant galaxies

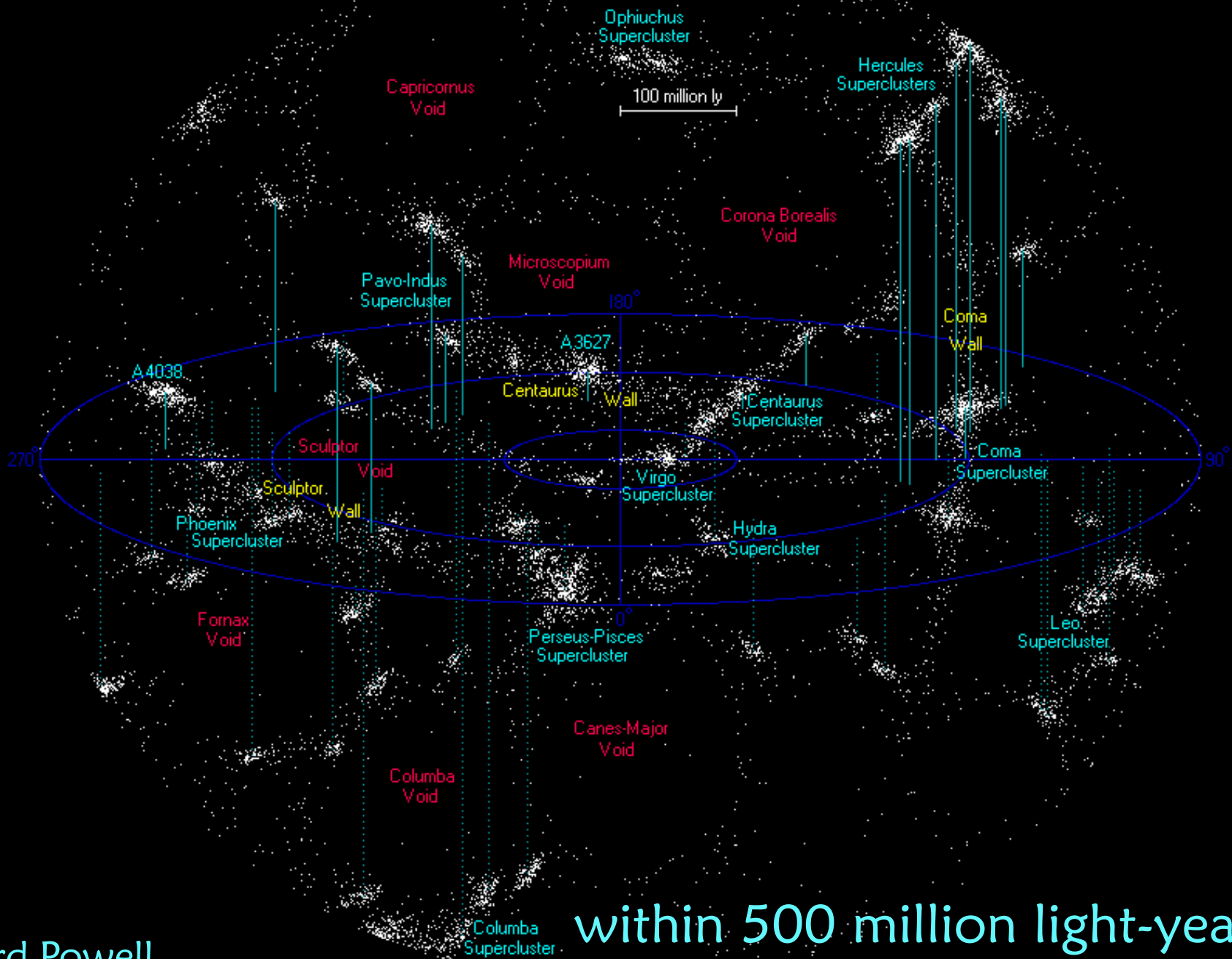


2MASS all-sky survey: Jarrett, Carpenter & Hurt

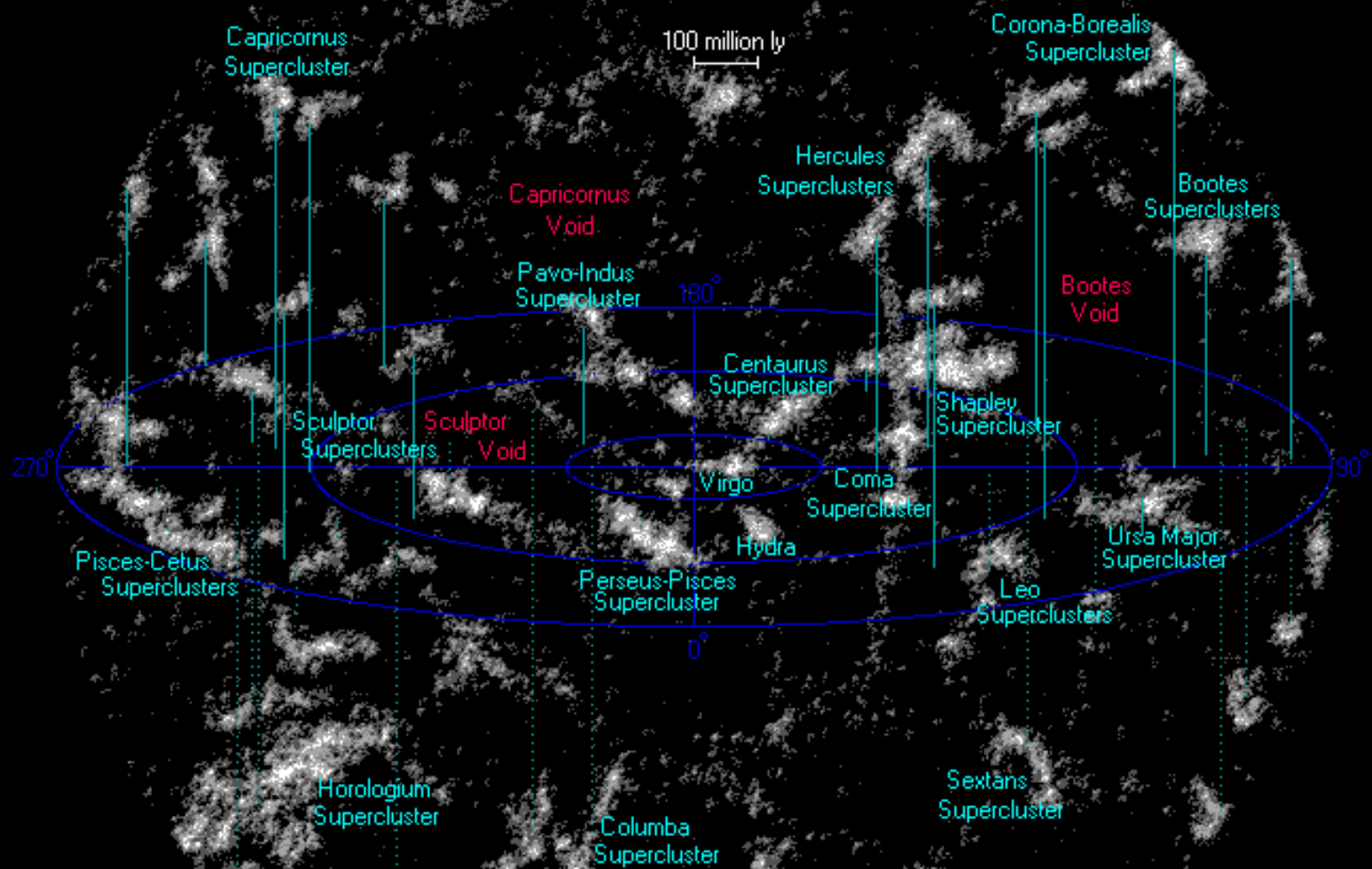


Richard Powell

r powell

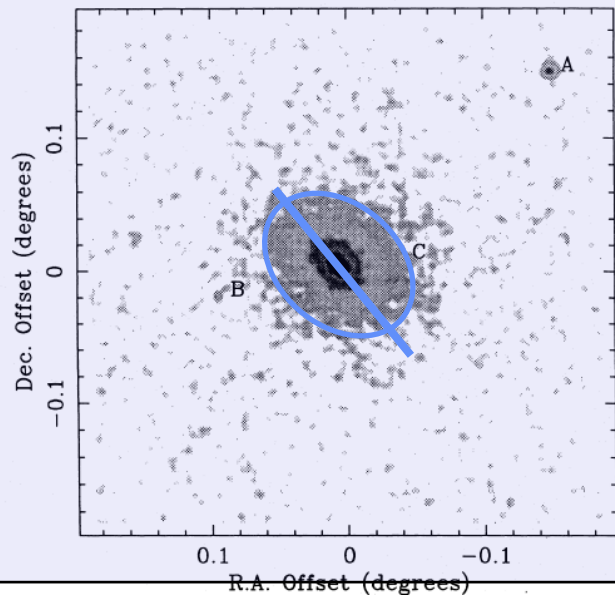


within 500 million light-years

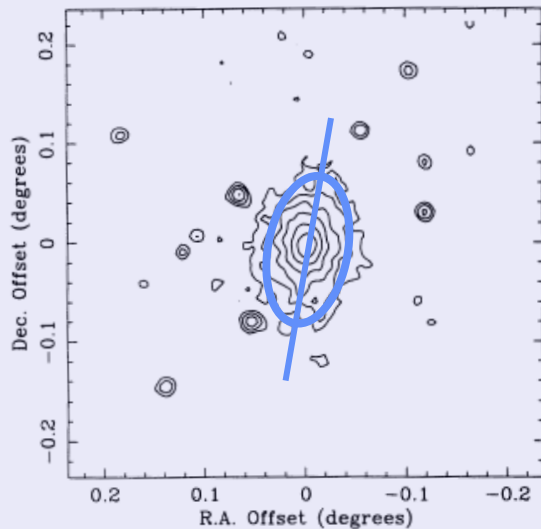


within 1 billion light-years

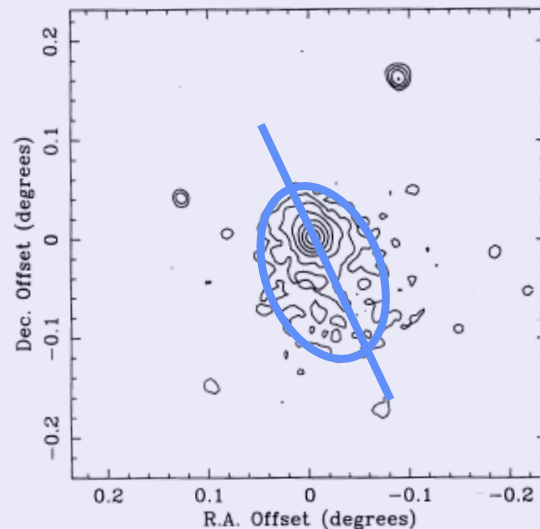
# Cluster X-ray emission



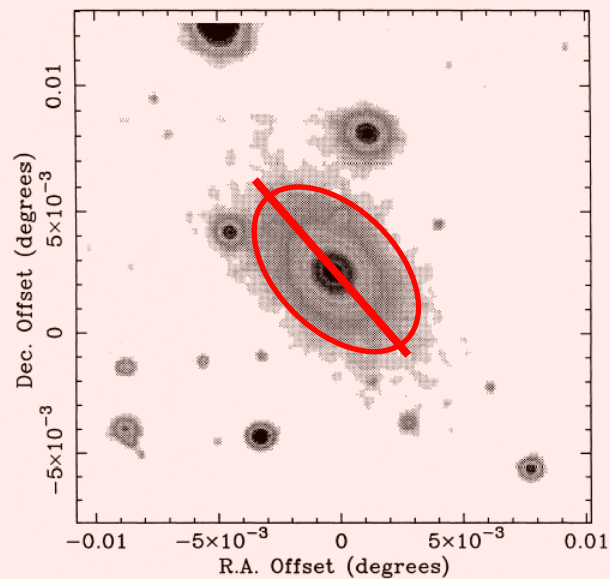
(a) Abell 1413



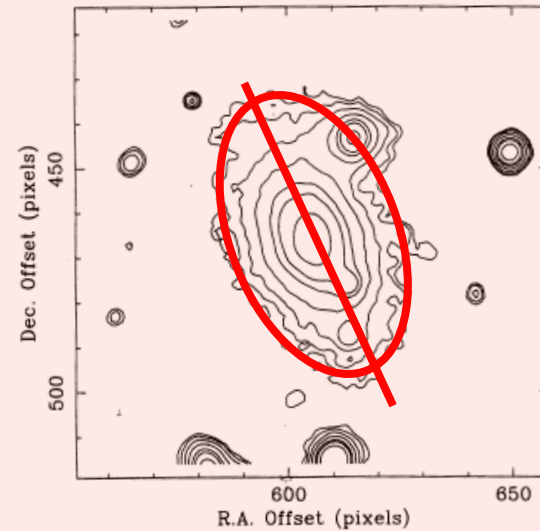
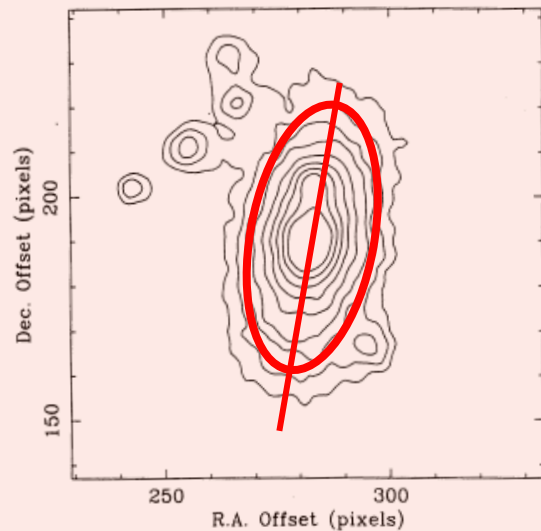
(a) Abell 1664



(b) Abell 1413 CCG



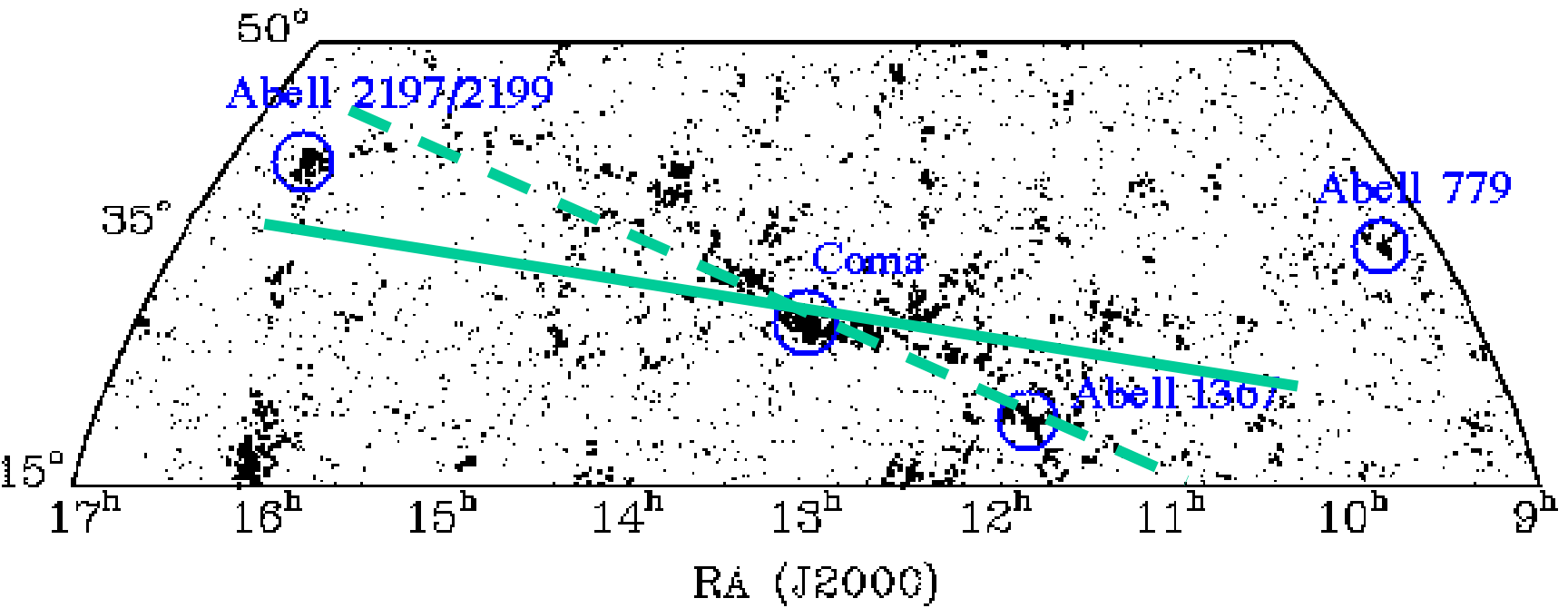
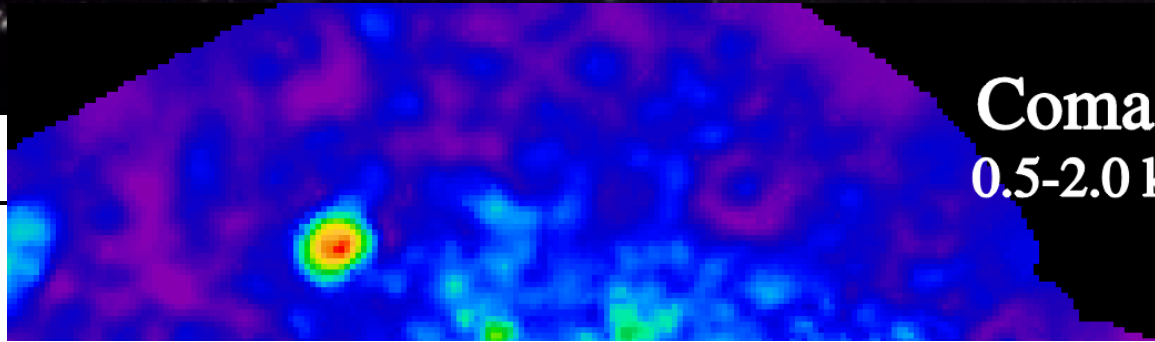
(b) Abell 1664 CCG



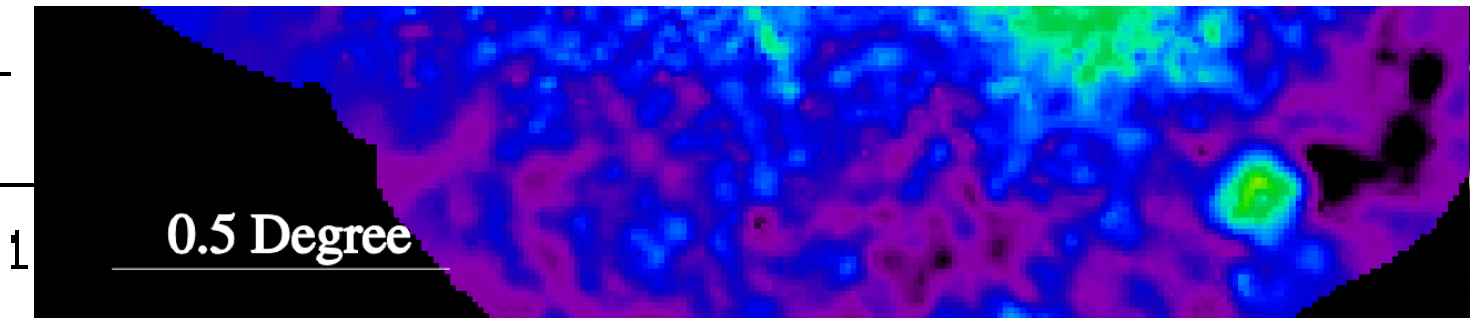
Central dominant galaxy

# Coma Cluster 0.5-2.0 keV

+32°



+34°

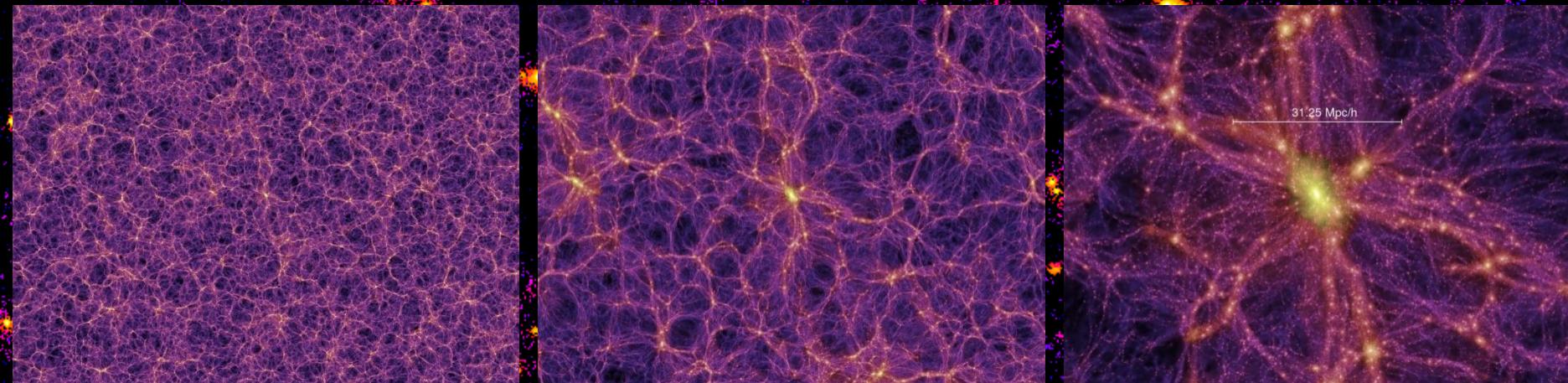






Clusters of galaxies are often strongly elongated

- 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 9<sup>TH</sup> MAY 2012 1PM

