Galaxy rotation curves

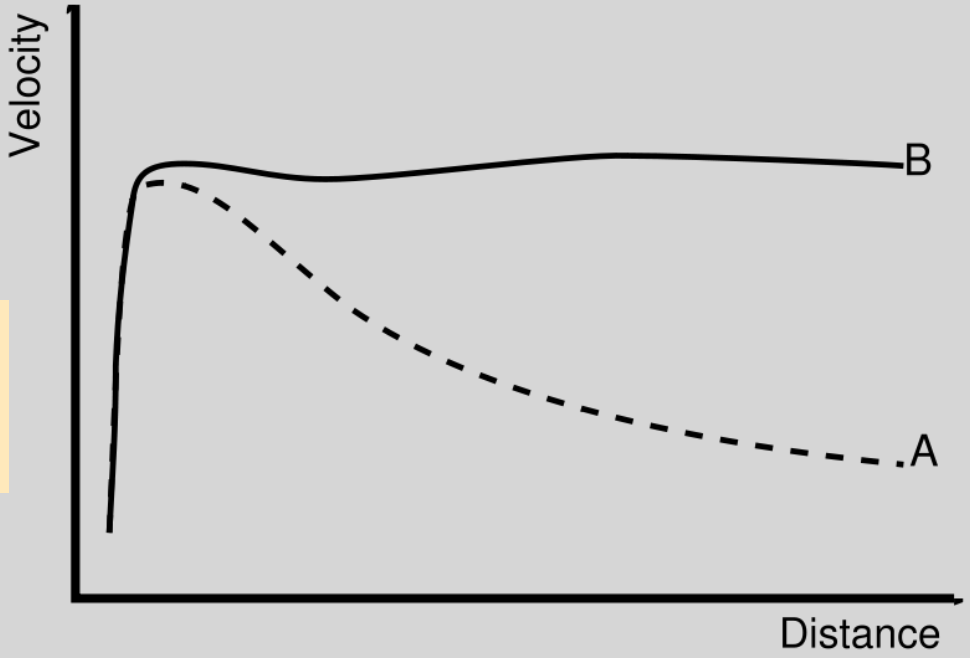
$$\frac{v^2(r)}{r} = \frac{GM(r)}{r^2} \rightarrow v(r) = \sqrt{\frac{GM(r)}{r}}$$

At large distances, where the galaxy runs out of light, the rotation speed should decrease as $r^{-1/2}$

Galaxy rotation curves

Instead, it stays flat.

$$v(r) = const \rightarrow M(r) = \frac{v^2}{G} r$$



There must therefore be lots of mass that is not visible, out to very large distances. ---> Dark matter

Modified gravity?

Alternatively, our theory of gravity is wrong, and gravitational accelerations are stronger than Newton on very large scales.

Newton: $\vec{F} = m\vec{a}$

MOND: $$\vec{F} = m\mu\left(\frac{a}{a_0}\right)\vec{a} = \begin{cases} m\vec{a}, & a \gg a_0 \\ m\left(\frac{a}{a_0}\right)\vec{a}, & a \ll a_0 \end{cases}$$

How does MOND work?

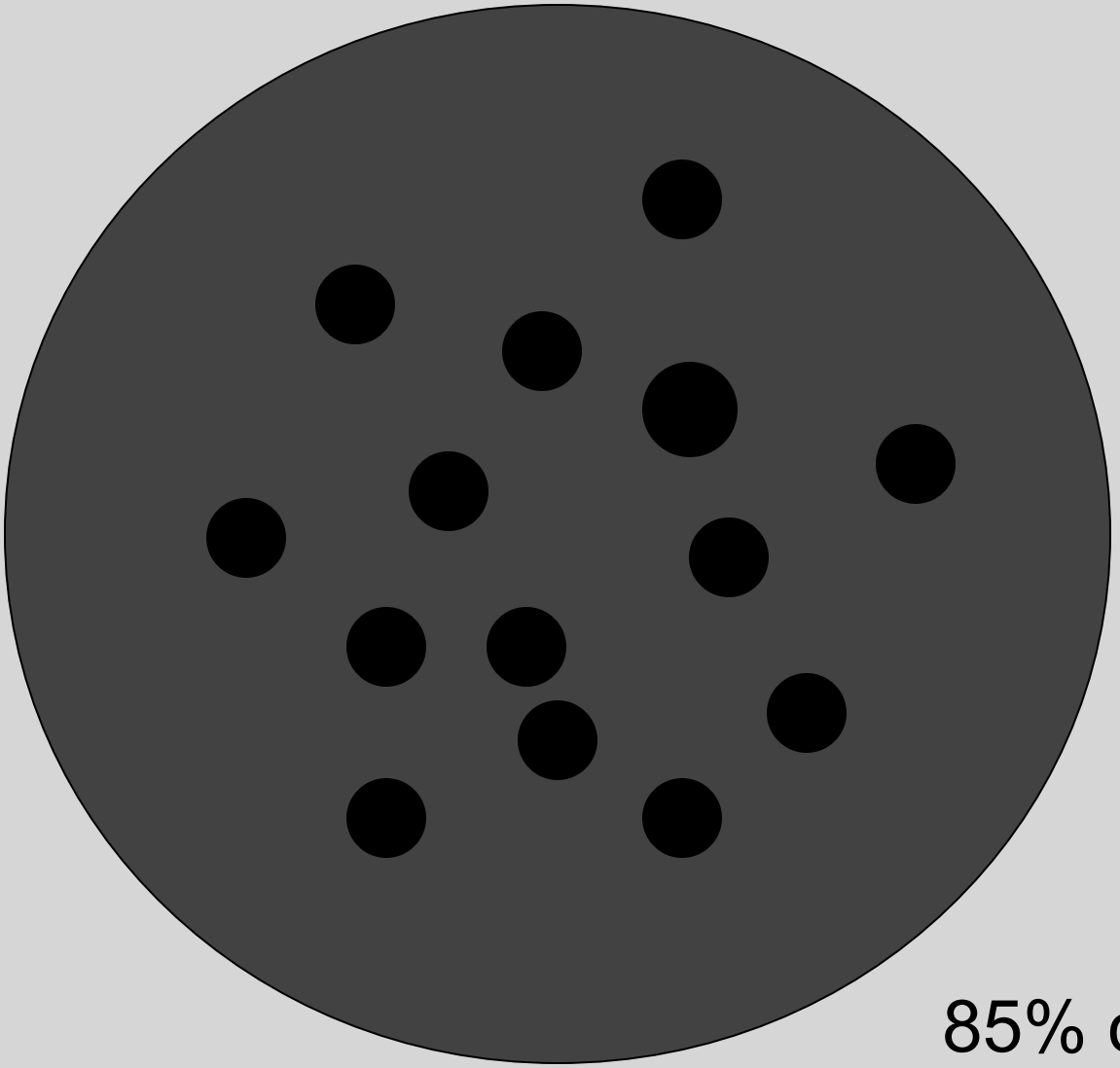
$$F = \frac{GMm}{r^2} = \frac{ma^2}{a_0} \rightarrow a^2 = \frac{GMa_0}{r^2}$$

$$a = \frac{v^2}{r} \rightarrow v^2 = \left(\frac{GMa_0}{r^2} \right)^{1/2} r \rightarrow v = \sqrt[4]{GMa_0} = const!$$

Plugging in measured rotation speeds and visible masses of galaxies:

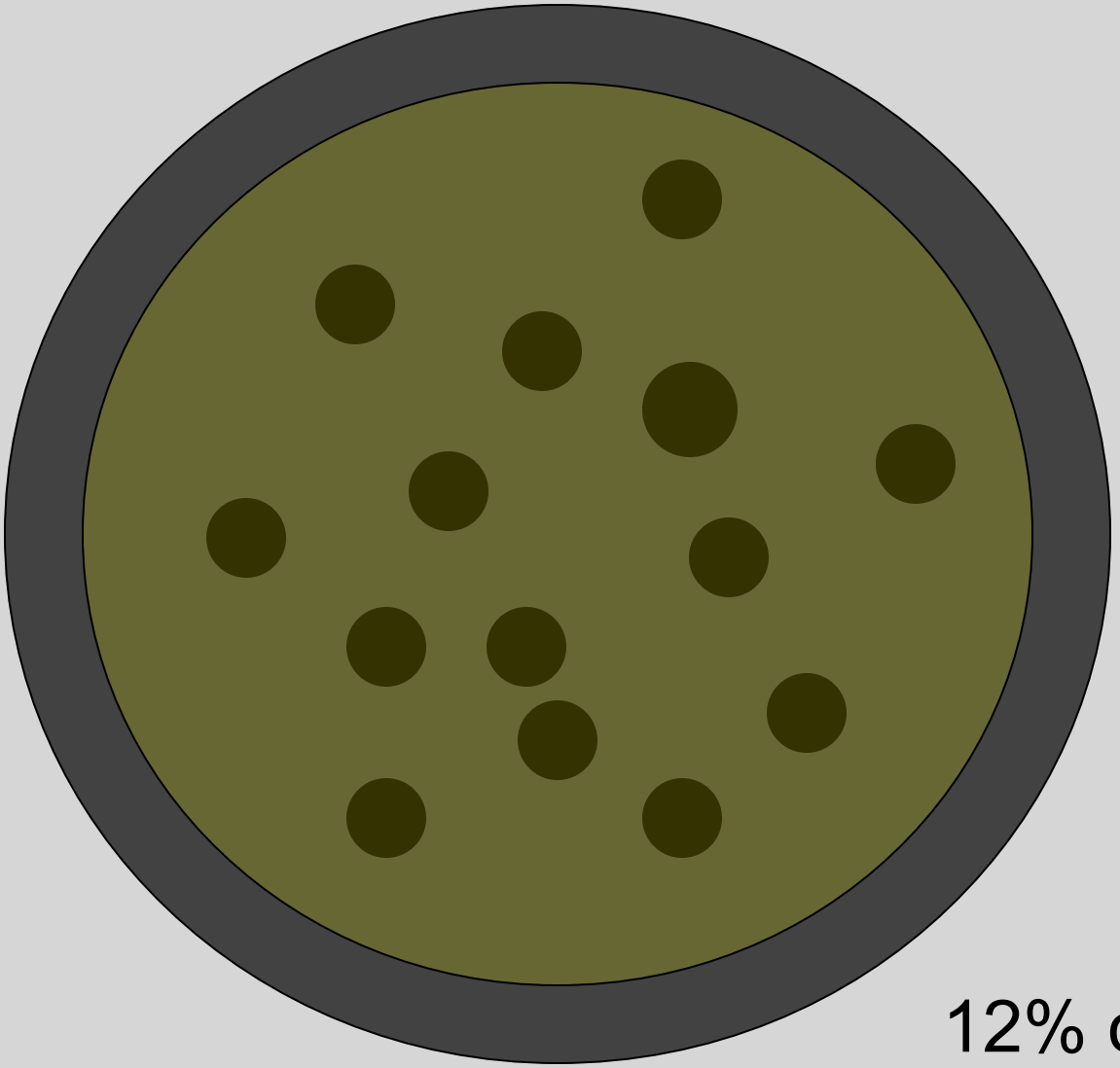
$$a_0 = 1.2 \times 10^{-10}\, ms^{-2}$$

A galaxy cluster: Dark matter



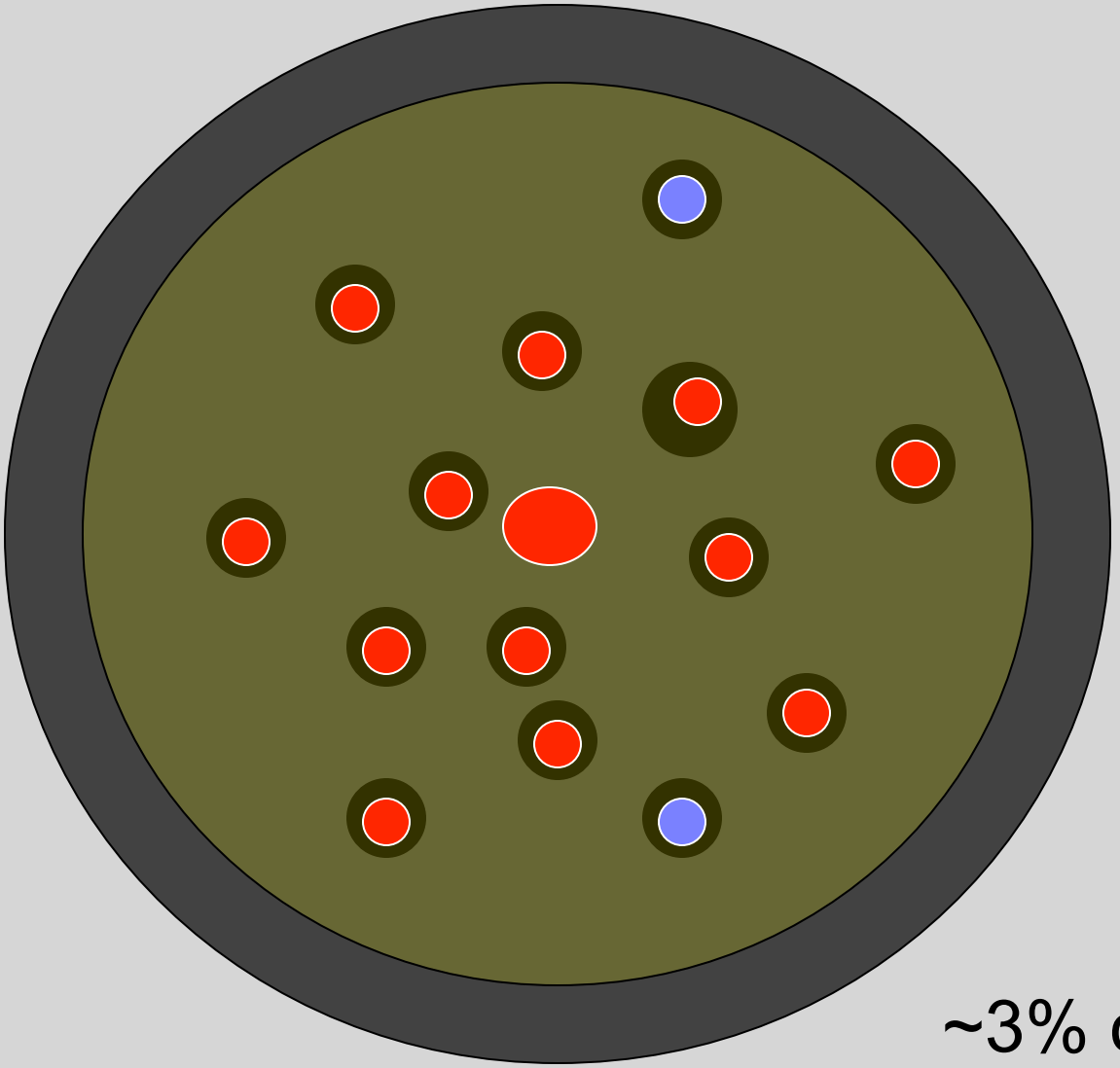
85% of mass

A galaxy cluster: Hot X-ray gas



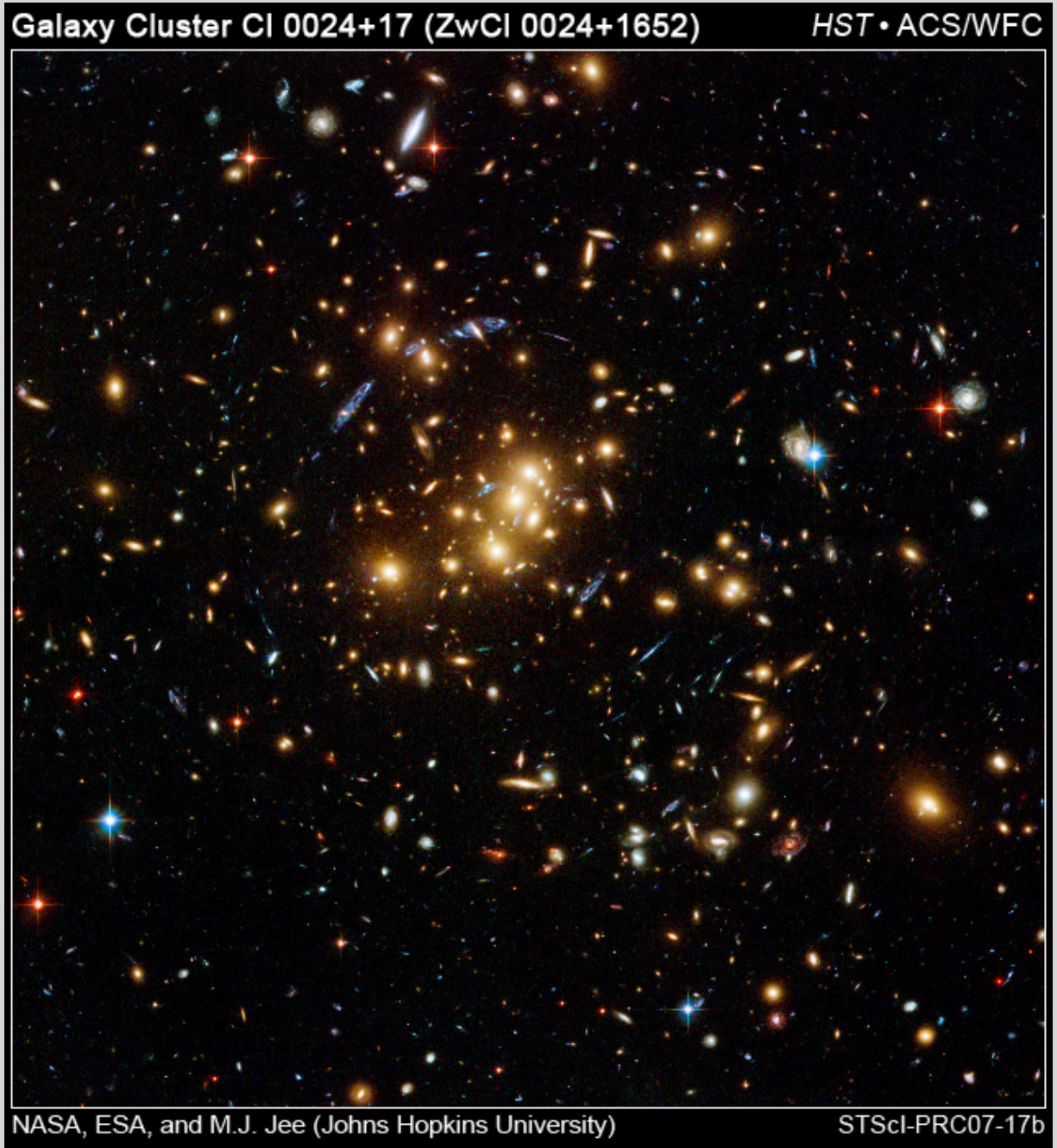
12% of mass

A galaxy cluster: Galaxies (stars + cold gas)

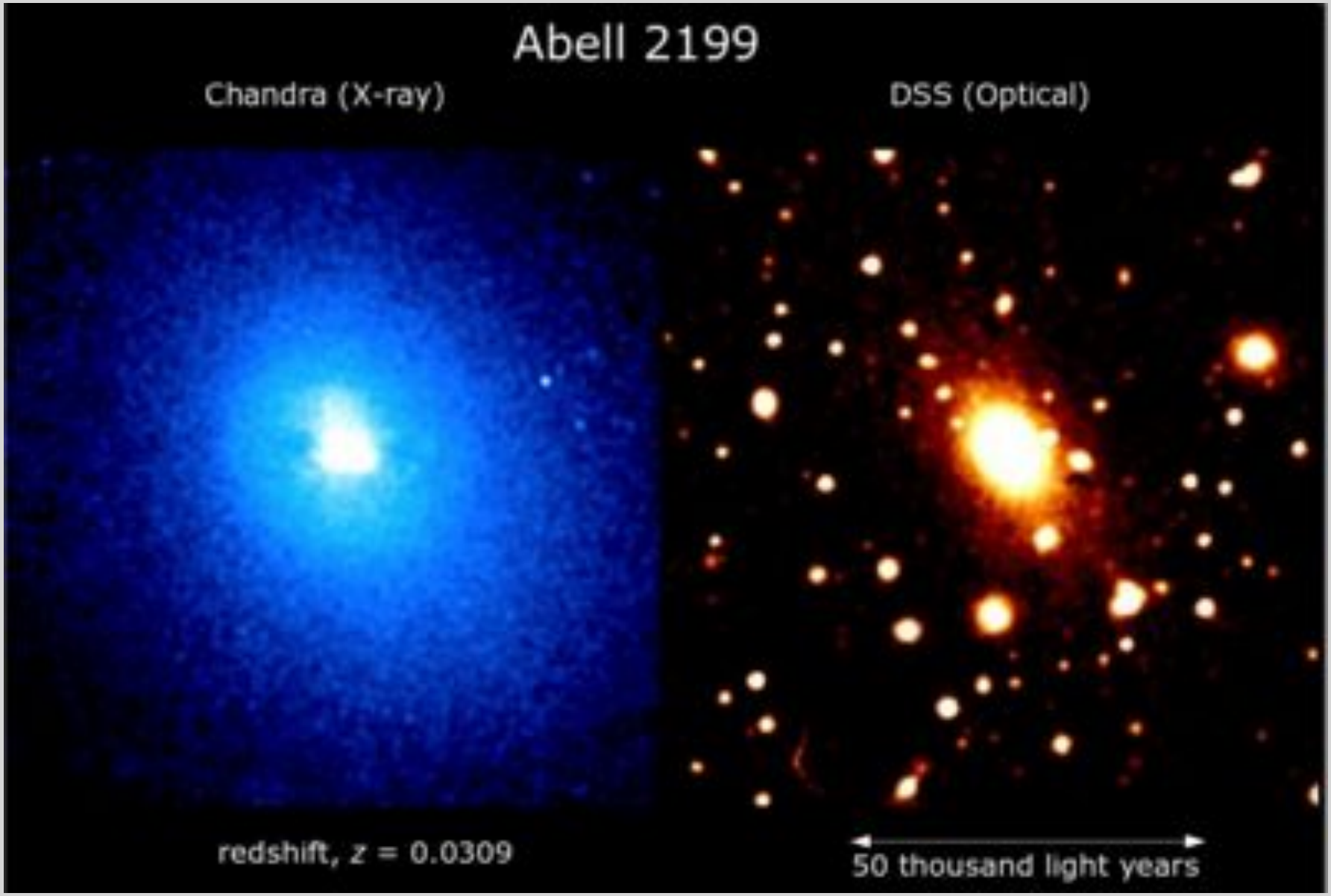


~3% of mass

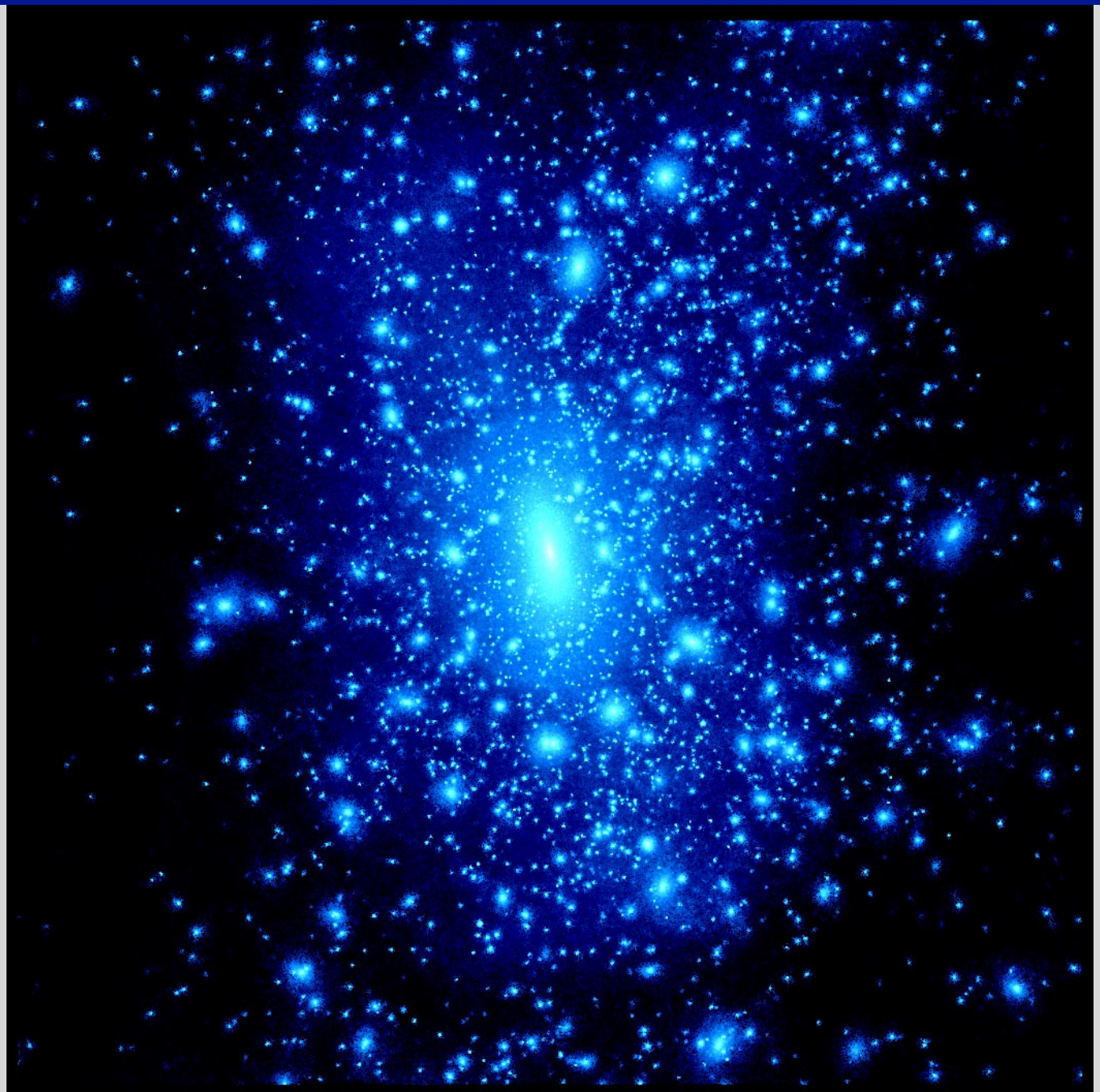
Galaxies


Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)
HST • ACS/WFC
NASA, ESA, and M.J. Jee (Johns Hopkins University)
STScI-PRC07-17b

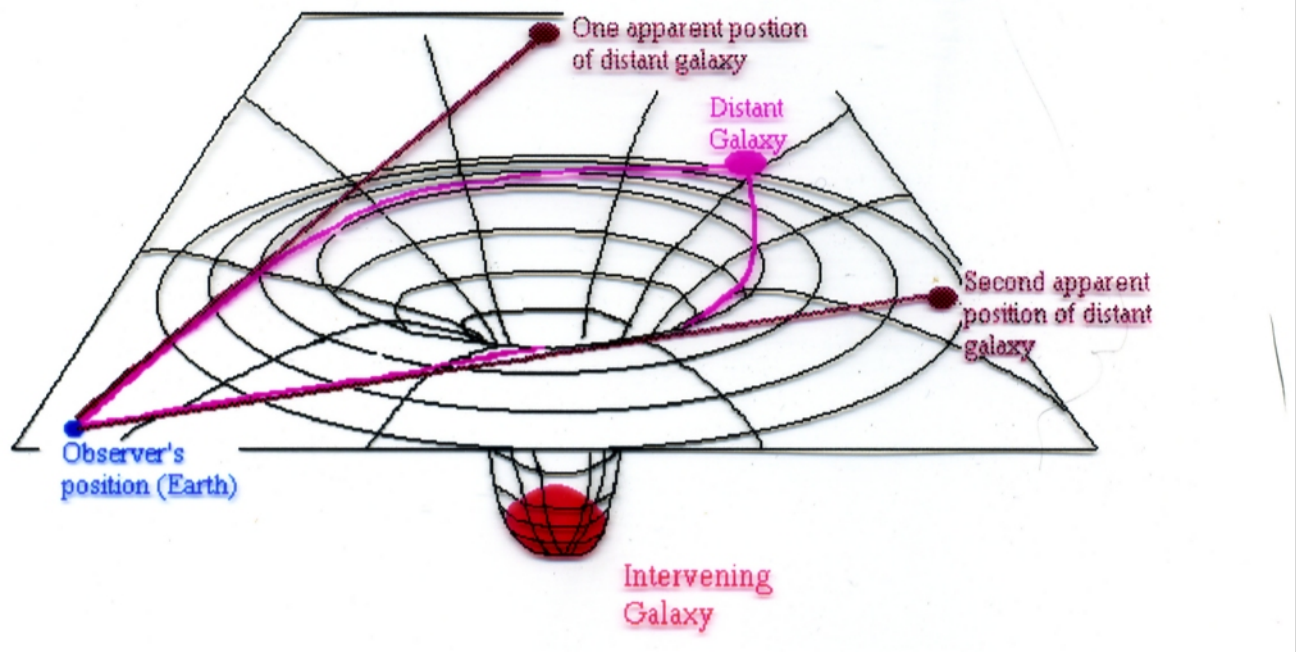
X-ray gas


Abell 2199
Chandra (X-ray)
DSS (Optical)
redshift, z = 0.0309
50 thousand light years

Dark matter



Gravitational lensing



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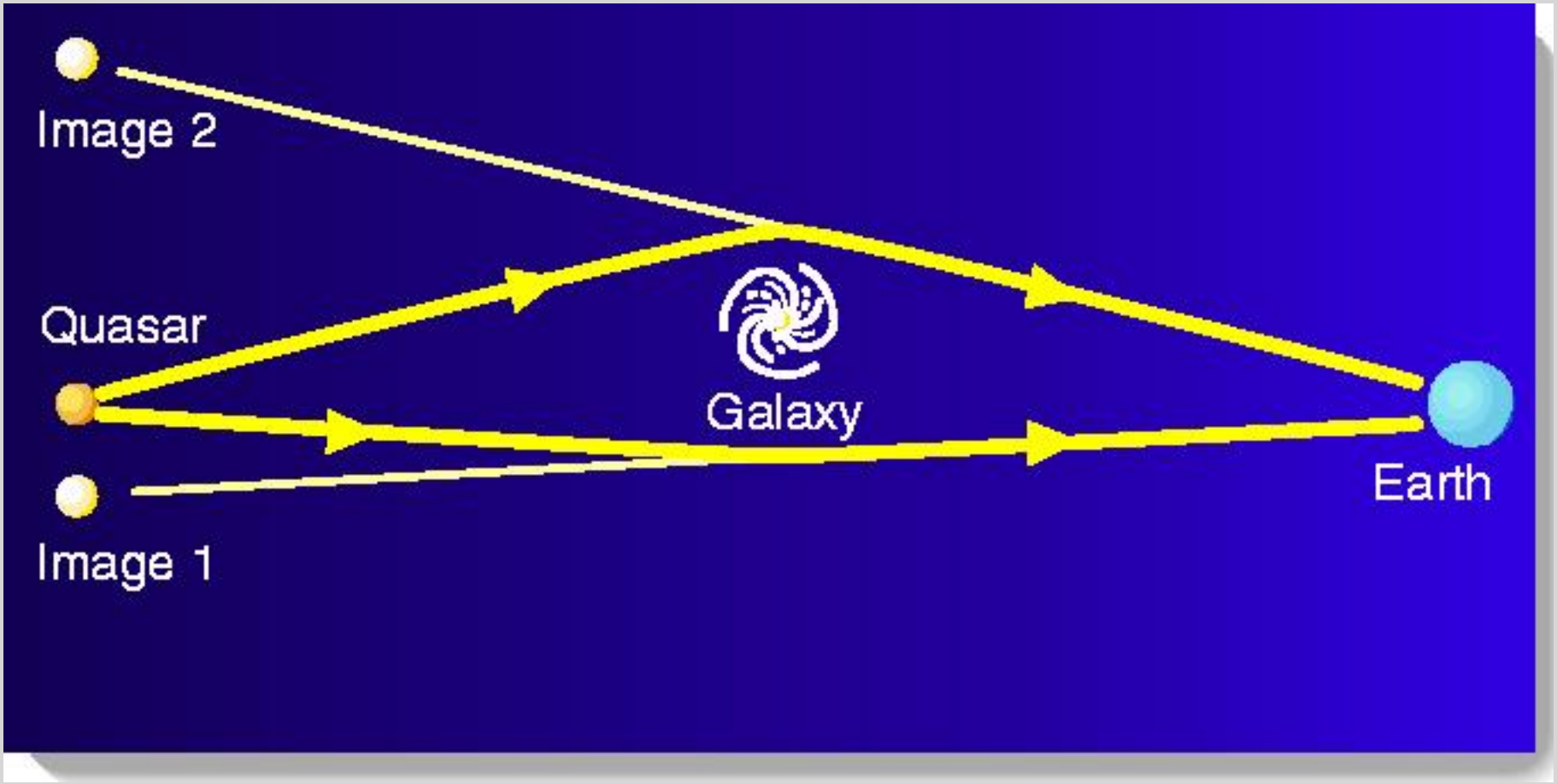
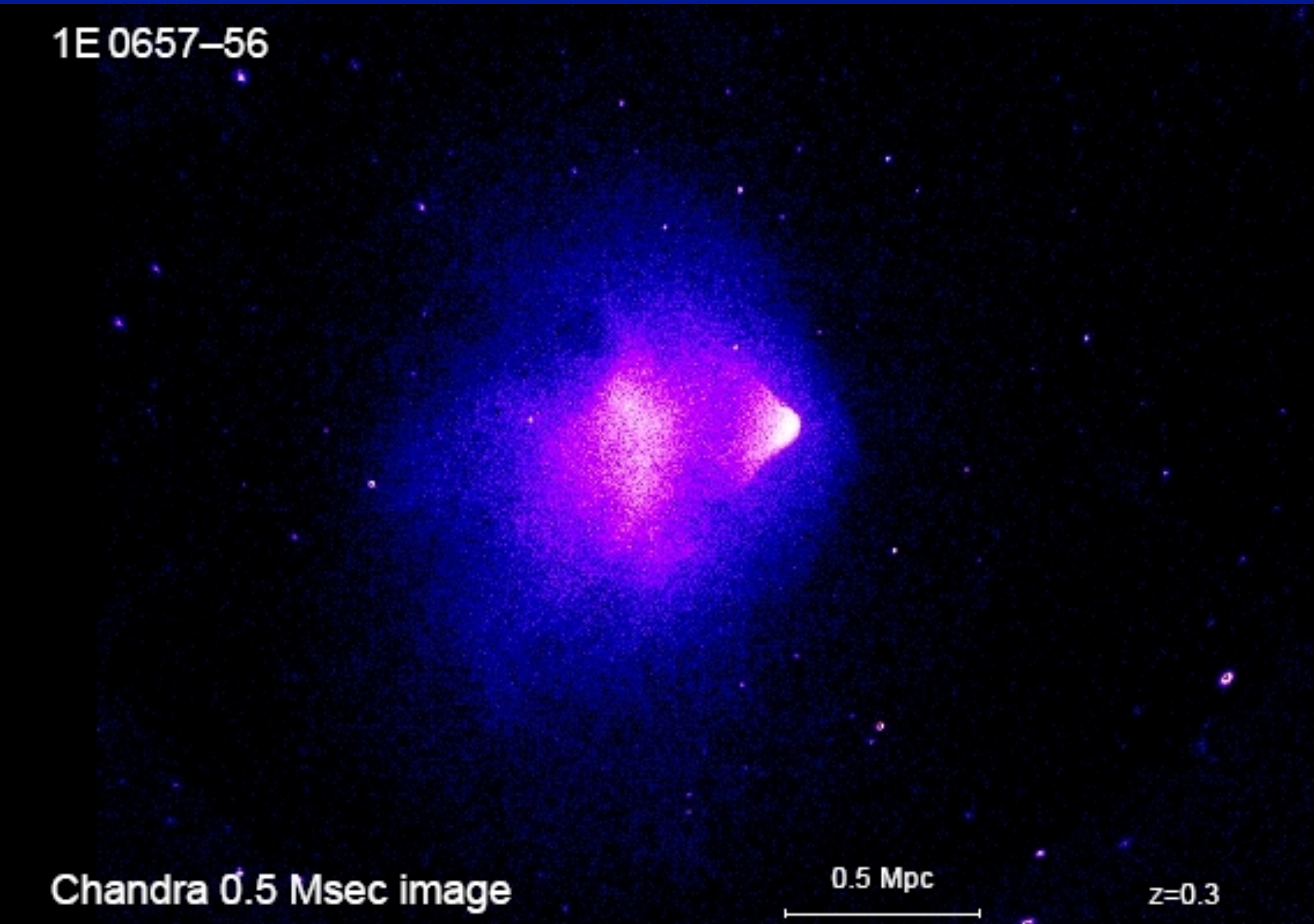


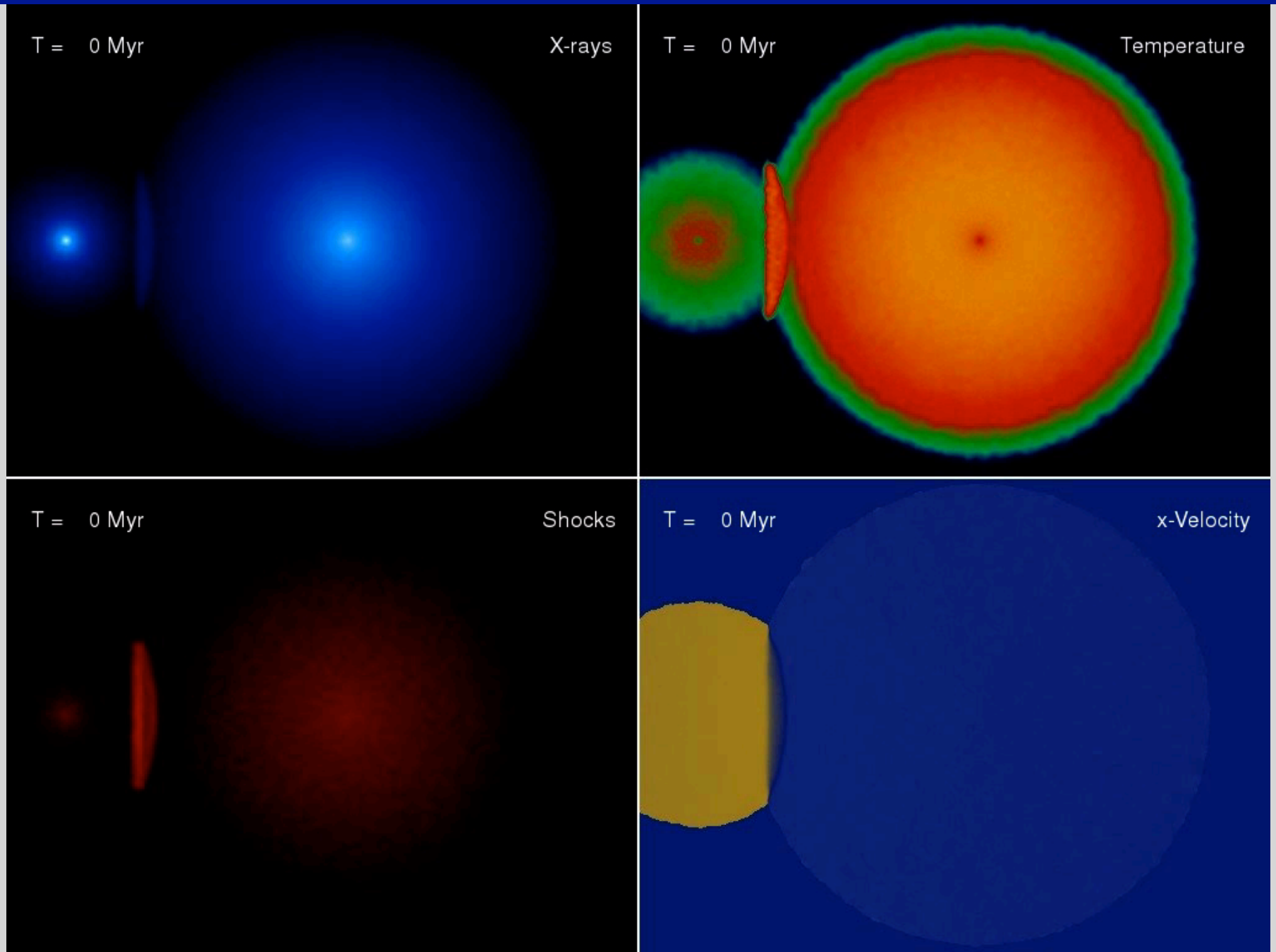
Gravitational lensing

Optical image

X-ray image



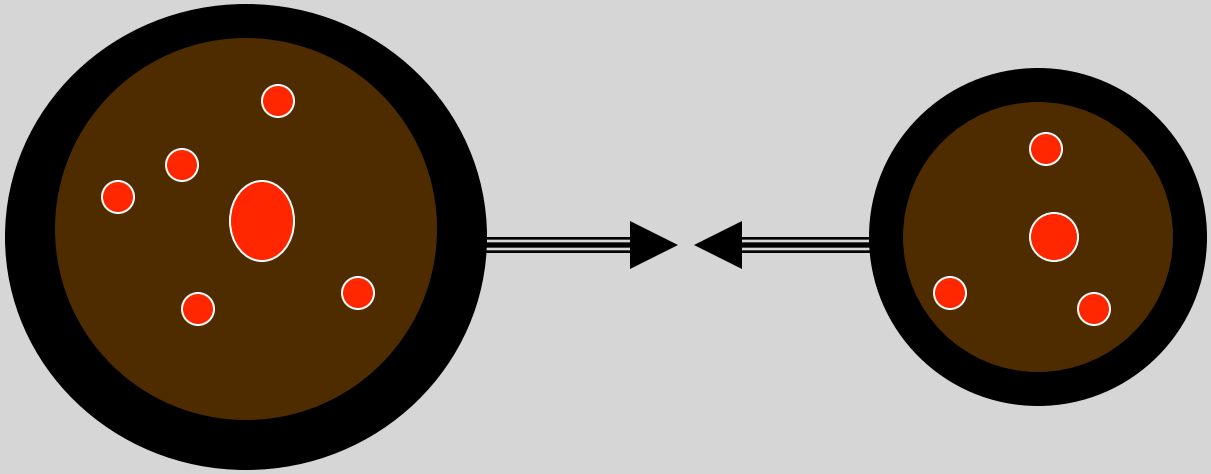
Modelling


T = 0 Myr
X-rays
T = 0 Myr
Temperature
T = 0 Myr
Shocks
T = 0 Myr
x-Velocity

What happens in a cluster collision?

- Dark matter does not collide
- Hot gas collides and gets shock-heated
- Galaxies do not collide.

So, galaxies and dark matter should move through each other whereas gas should stay behind.



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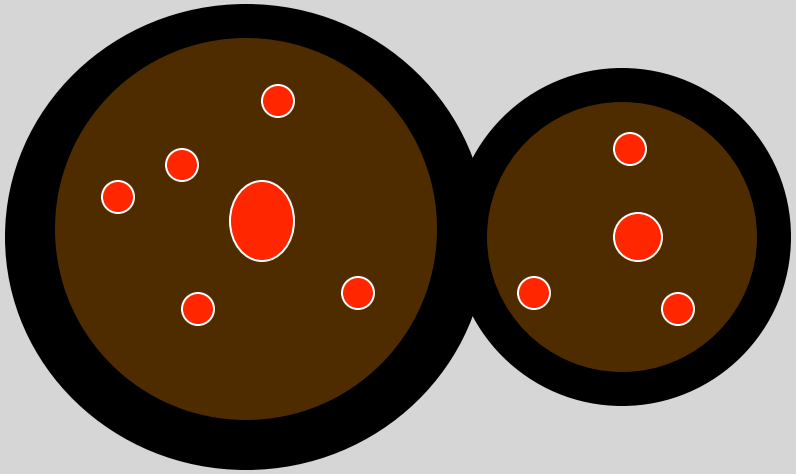

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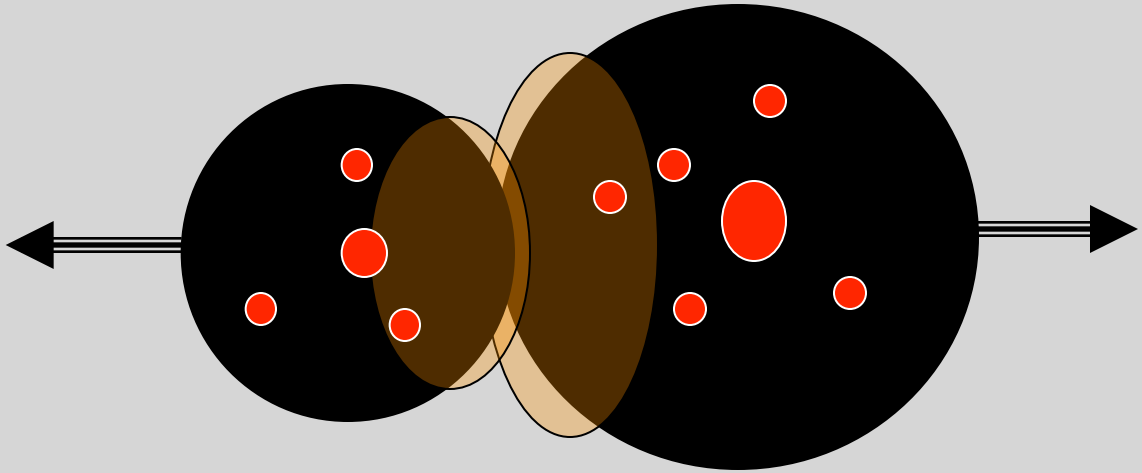

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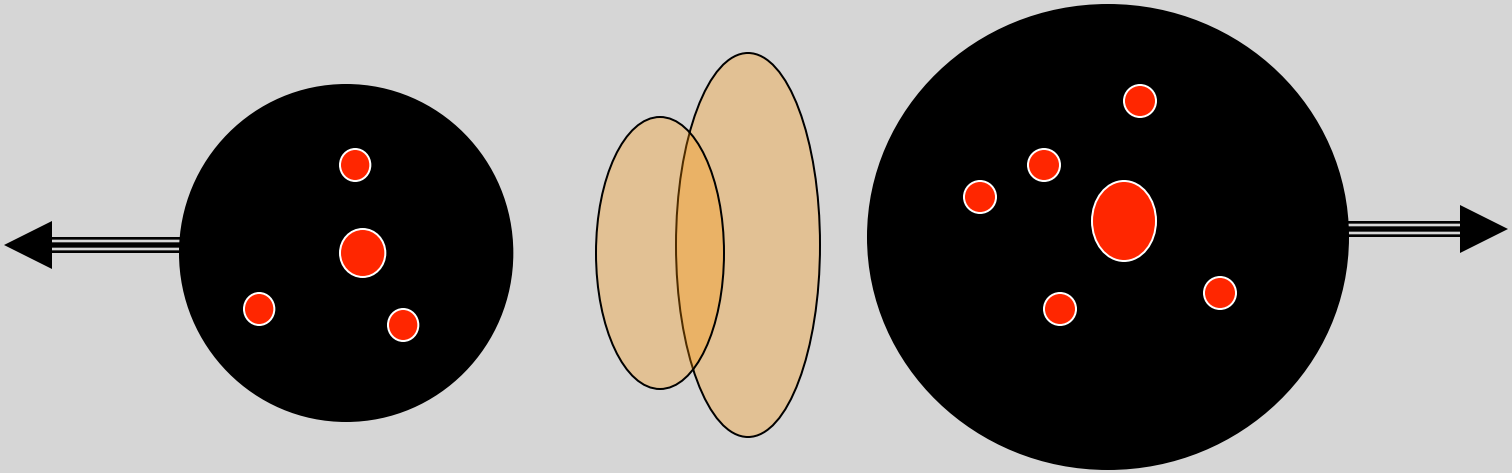
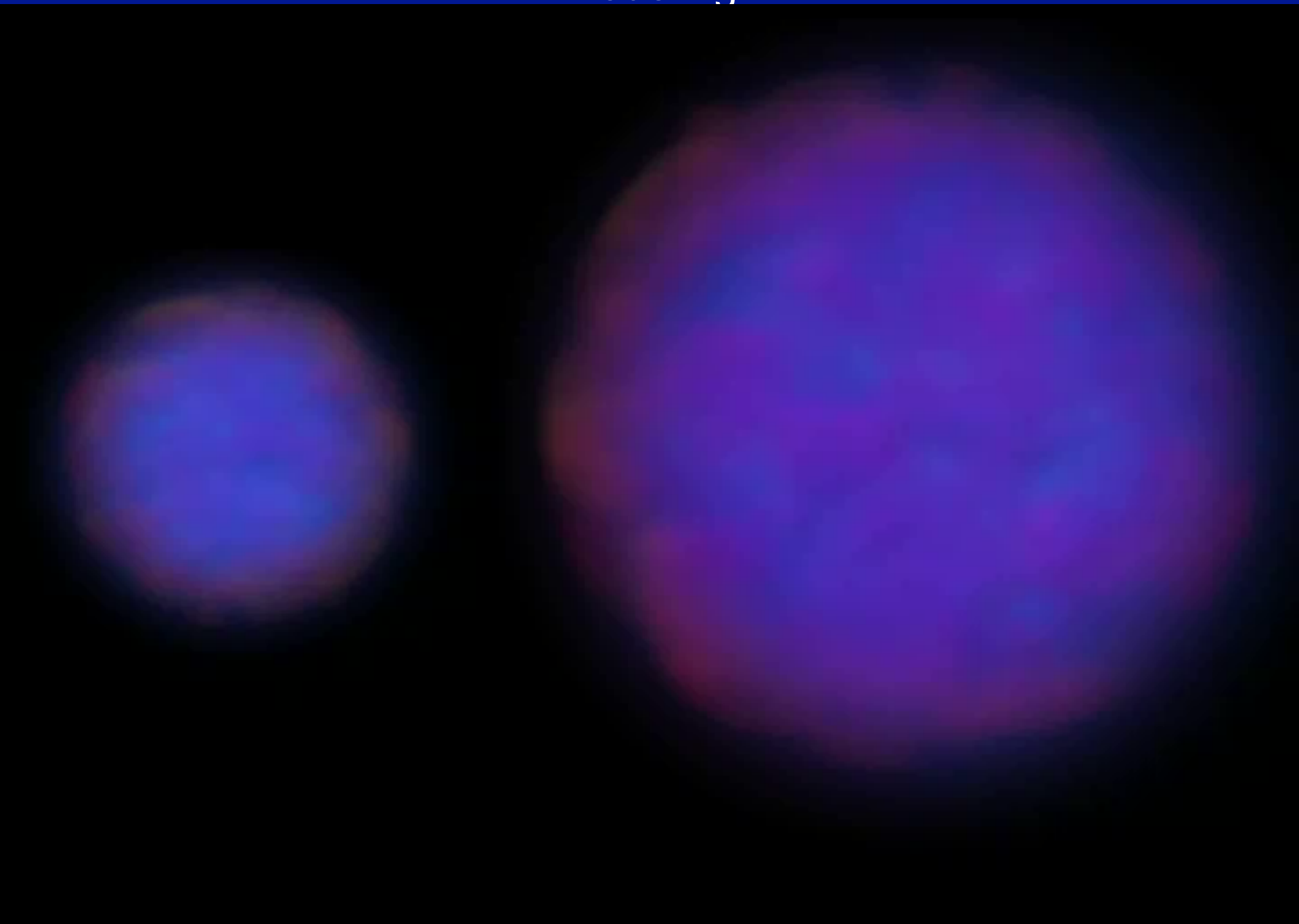
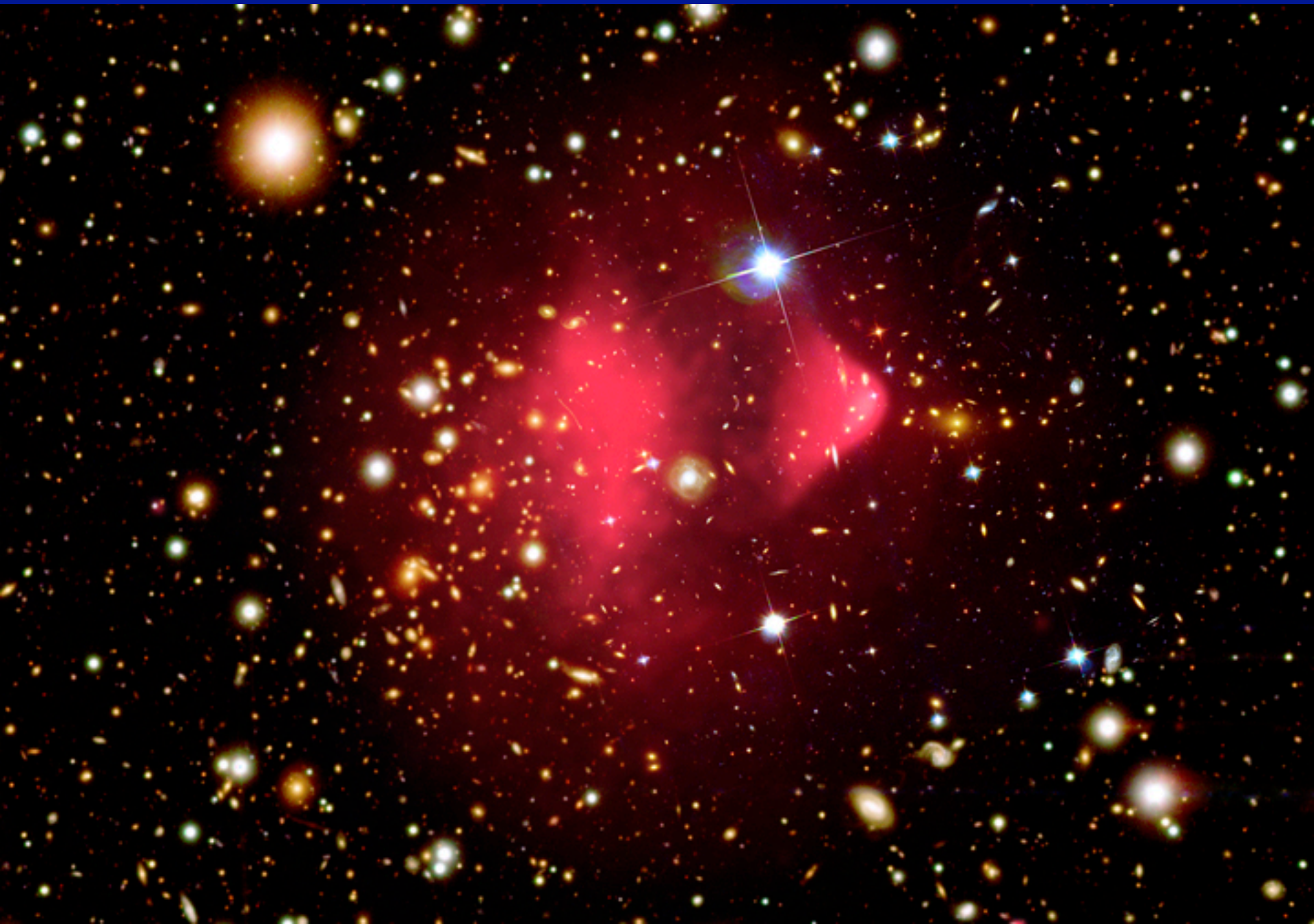


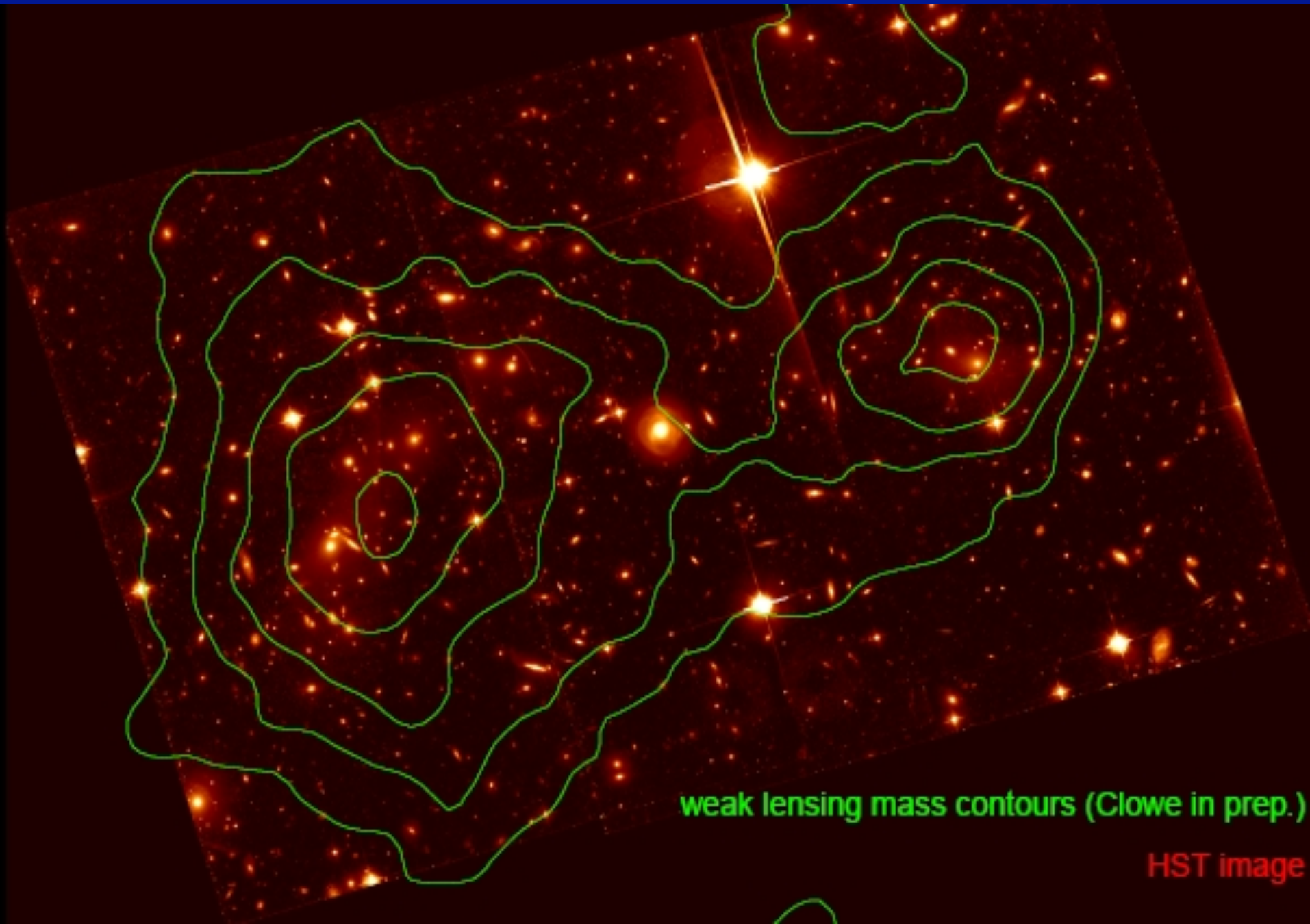
Modeling



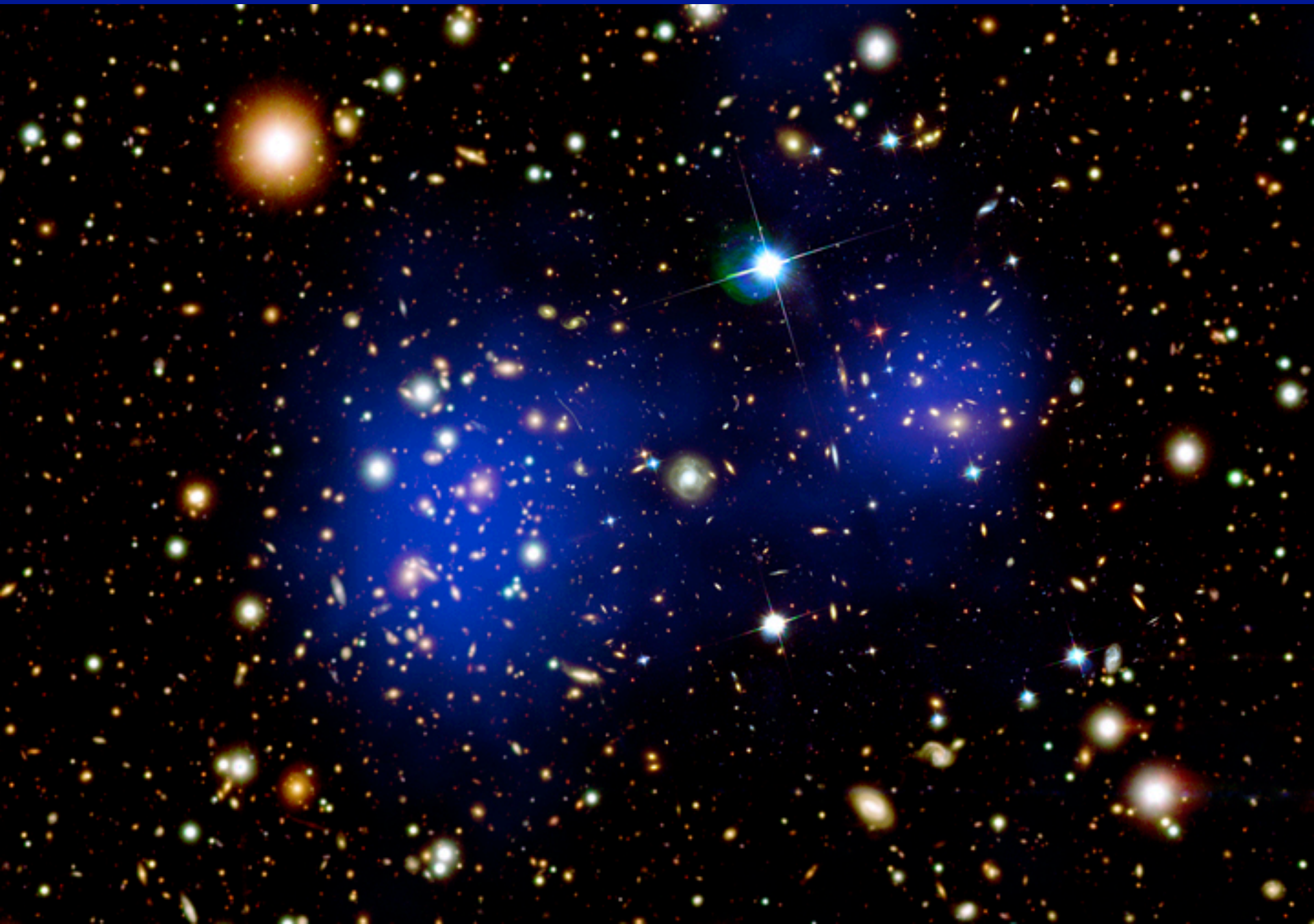
X-ray image



Lensing map



Lensing map



X-ray + Lensing map