An introduction to

Galaxies and Dark Matter

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Dark Matter

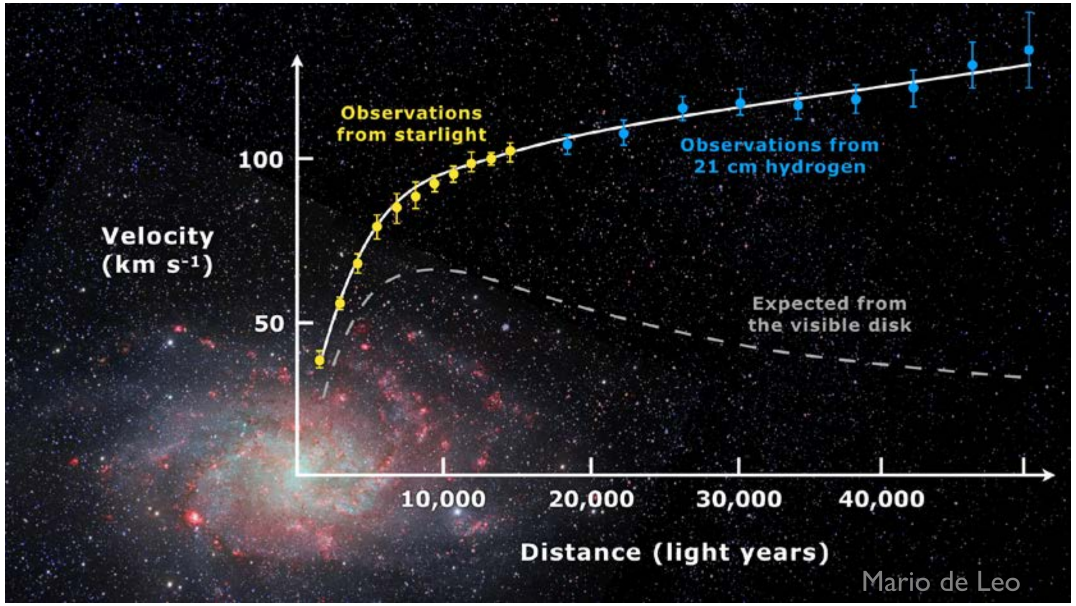
- Matter = stuff with mass
  (i.e. interacts gravitationally)
  - Dark Matter seems to account for ~85% of all matter
    & ~25% of the energy+matter in the universe
- Dark = stuff that does not absorb, reflect, or emit light
  - Thought to be some kind of new particle

Dark Matter Evidence: *Galaxy rotation curves*

- For a small object orbiting a massive object, Kepler's laws of planetary motion apply
- The third law states that the period of the orbit squared is proportional to the semi-major axis (the radius, for a circle) cubed: $T^2 \propto a^3$
- For a circular orbit, $a = R$, and the circumference of the circle is $2\pi R$, which is covered in a period T, which amounts to a velocity $v = \frac{2\pi R}{T}$
- Using the 3rd law, $T \propto R^{3/2}$, so $v \propto \frac{R}{R^{3/2}} = \frac{1}{\sqrt{R}}$
- However, galaxies show v is often not even decreasing for larger radii, implying an extended matter distribution

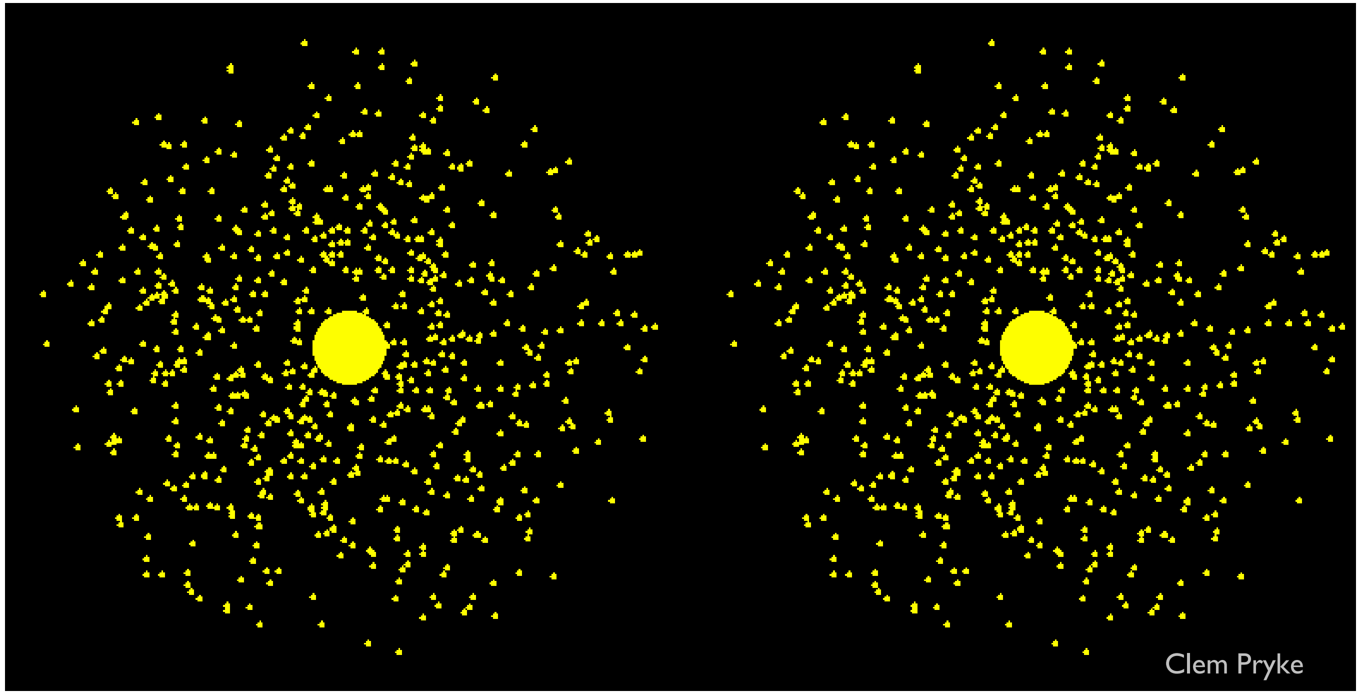
Modern data (Wolfram Alpha Knowledgebase 2018)

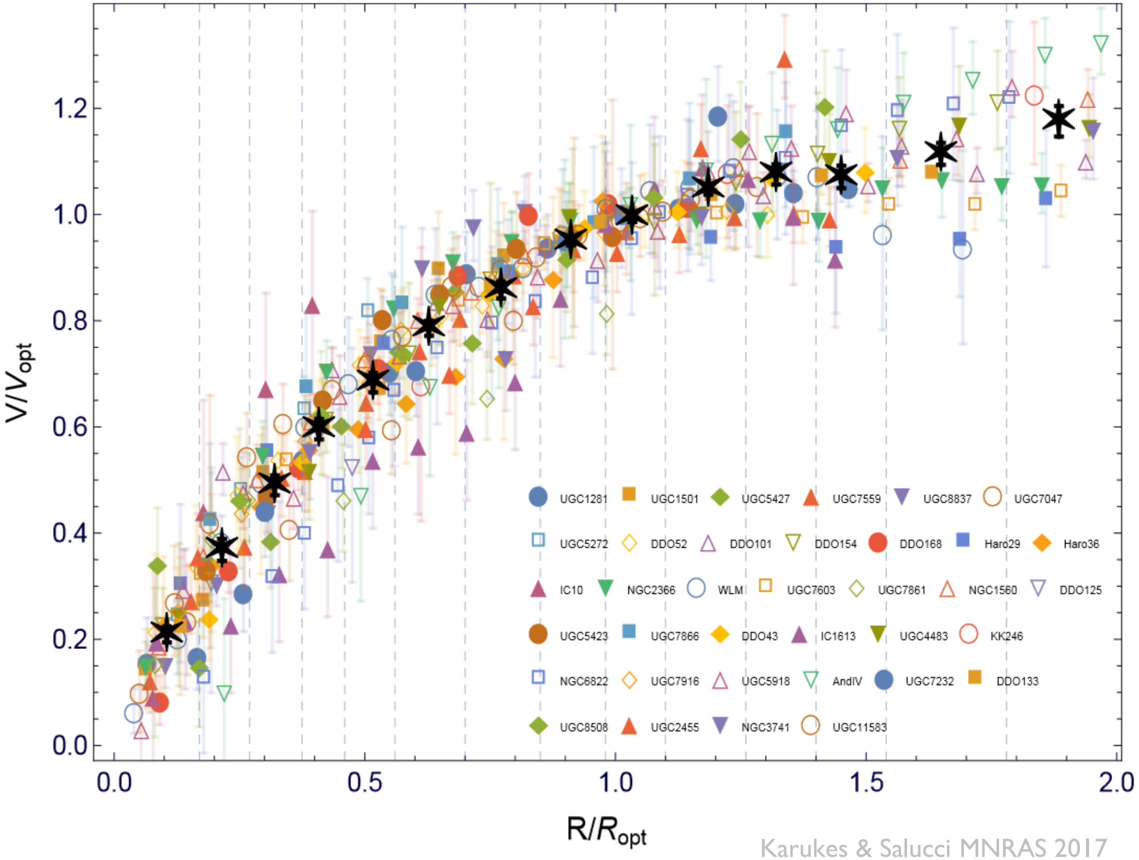
Planet	Semi-major axis (AU)	Period (days)	$\frac{R^3}{T^2}$ (10^{-6} AU^3/day^2)
Mercury	0.38710	87.9693	7.496
Venus	0.72333	224.7008	7.496
Earth	1	365.2564	7.496
Mars	1.52366	686.9796	7.495
Jupiter	5.20336	4332.8201	7.504
Saturn	9.53707	10775.599	7.498
Uranus	19.1913	30687.153	7.506
Neptune	30.0690	60190.03	7.504



Dark Matter Evidence: *Galaxy rotation curves*

Without dark matter | With

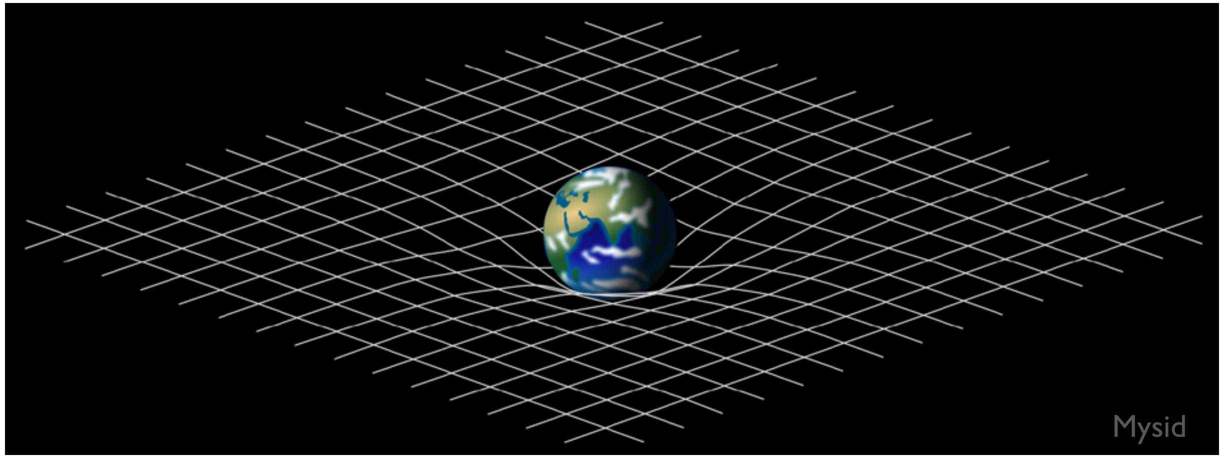


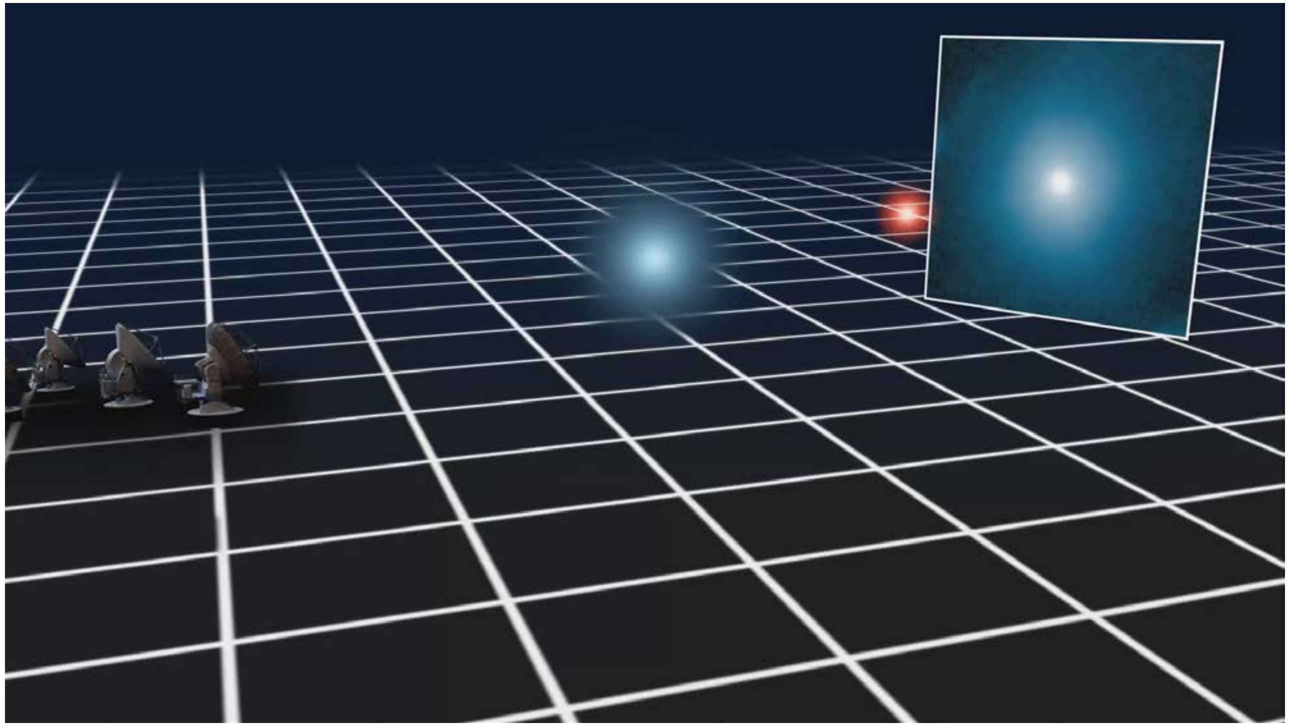


Karukes & Salucci MNRAS 2017

Gravitational lensing

- Light travels to us through spacetime, which can be warped by massive objects
- The amount that light is bent depends on the mass of the object
- The bending of light can cause what looks like multiple copies of a background galaxy, warped into arcs, or a single ring, depending on alignment

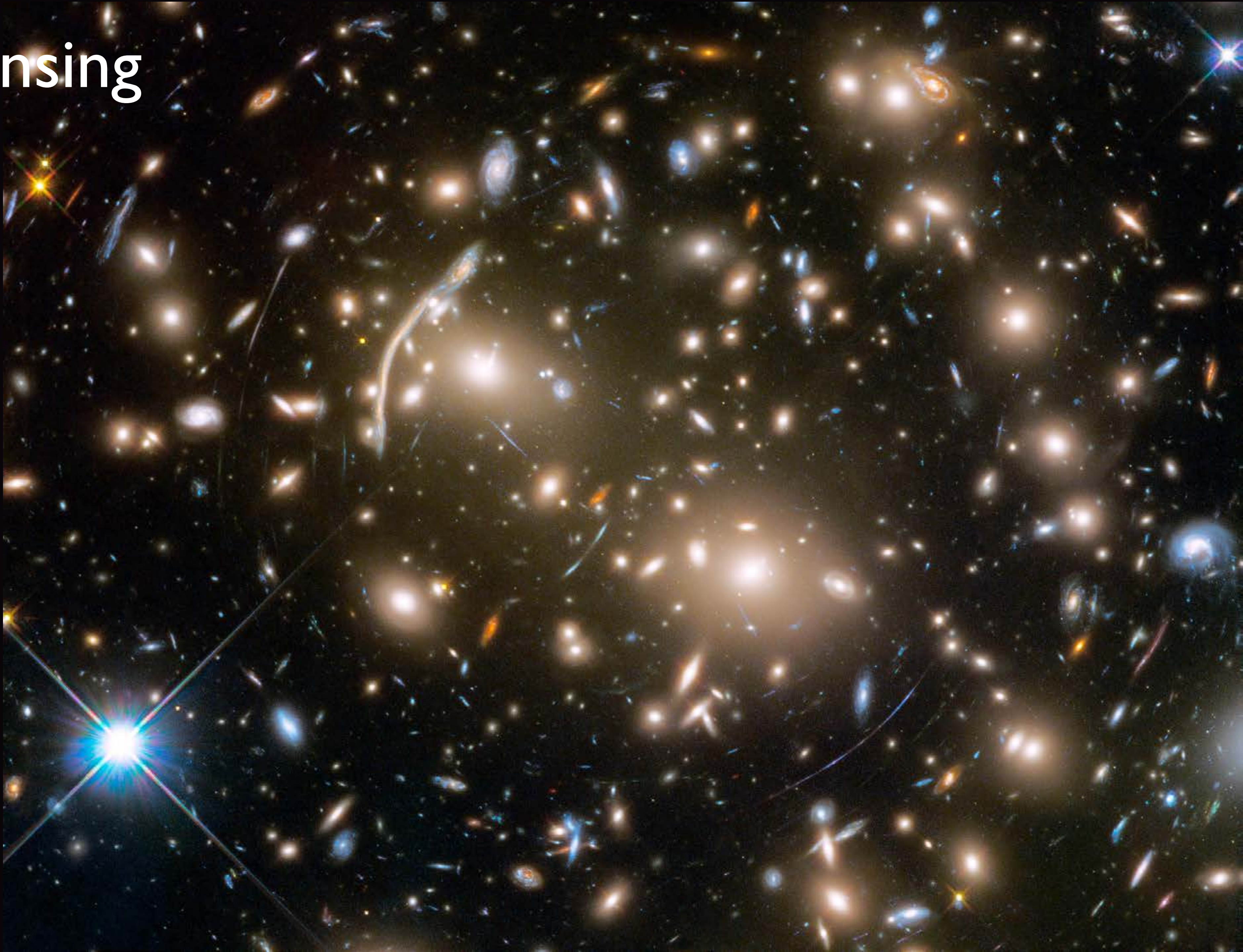




ALMA (NRAO/ESO/NAOJ)/Luis Calçada (ESO)

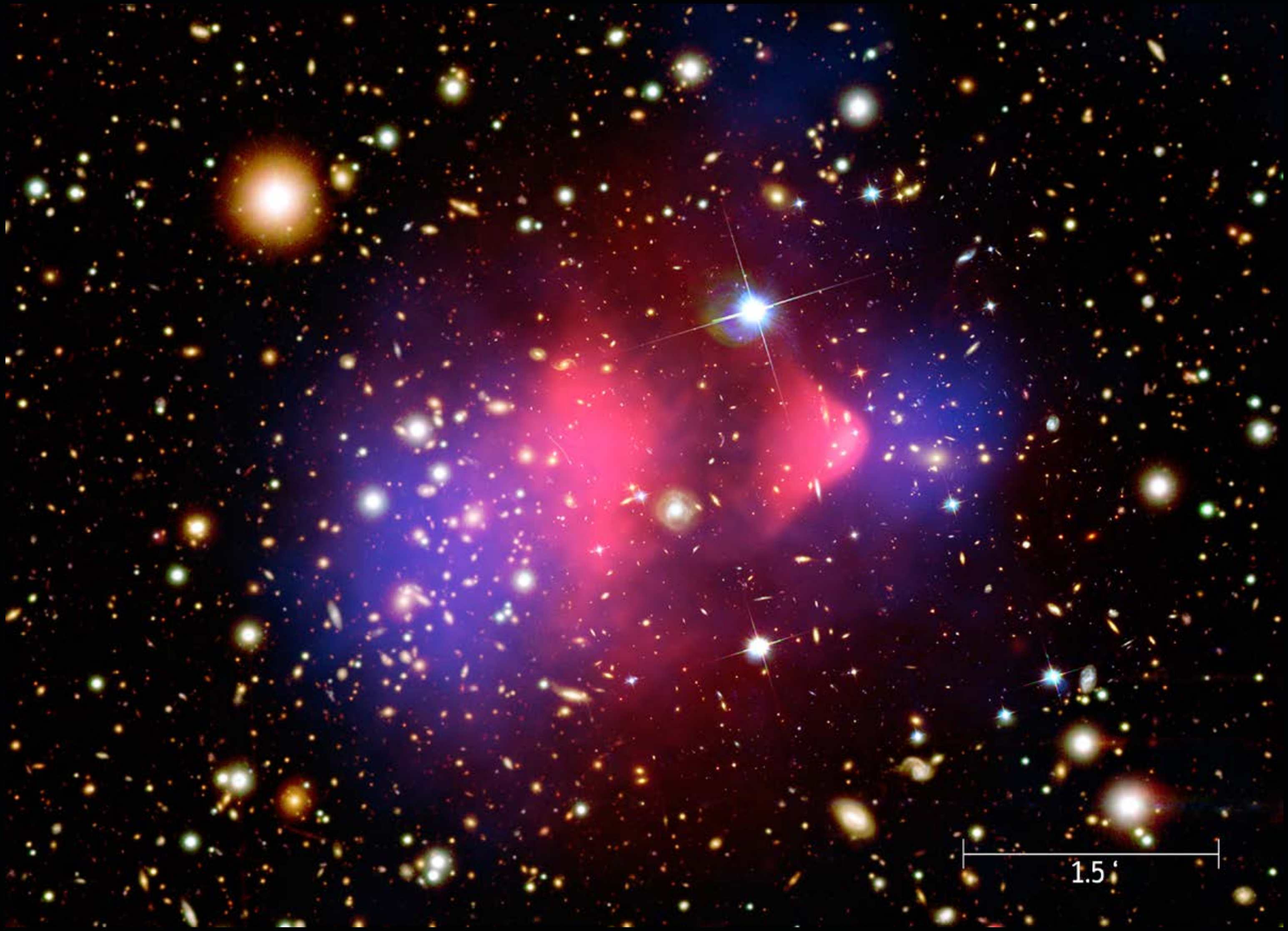
Gravitational lensing

The lens is also a magnifying glass, enabling distant objects to be seen that would otherwise be too dim



Dark Matter Evidence: *Gravitational lensing*

In the Bullet Cluster, colliding galaxy clusters have distinct visible matter and dark matter distributions



NASA/CXC/M.Weiss

What is dark matter?

- The bottom line is that I don't know and neither does anyone else (at the moment)
- But, we can say the following:
  - *It's probably not just black holes:*
    Massive astrophysical compact halo objects (MACHOs) are unlikely because the Big Bang didn't make enough regular matter and we just don't see enough of these
  - *It's probably not neutrinos:*
    Neutrinos are extremely light & weakly interacting particles that are frequently produced in radioactive decay. They are very fast-moving and would thus cause large-scale features (superclusters) to be made first …but we don't see that
  - *It's probably not a problem with the theory of gravity:*
    None of these theories explain all of the observables we need dark matter for
  - *Cold dark matter is a favorite:*
    This would be a new particle. Many researchers are attempting to detect this, based on assumptions about their favorite dark matter candidate.