Dark Matter:
The Matter We Cannot See That Dominates the Universe

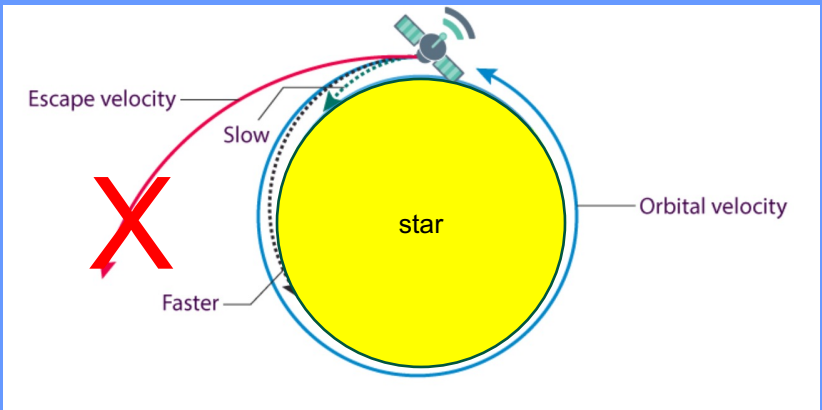
matter that produces so little light (or no light) that we cannot see it

- What is it?
- What is the evidence for it?

1

A new idea*

1784: Englishman and astronomer John Michell imagined a star
- 500 times bigger in radius than the Sun
- same density as the Sun
- **escape velocity: greater than speed of light**



* truly new ideas are exceedingly rare!

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- "all light emitted from such a body would be made to return toward it, by its own proper gravity."
- "if there really should exist in nature [such] bodies ... since their light could not arrive at us, we could have no information from light. Yet if any other luminous bodies should happen to revolve about them, we might still perhaps from the motions of these revolving bodies infer the existence of the central ones."

- such a star would be ***dark***

dark matter = stuff we can't see but that we can infer to exist from its influence on other objects

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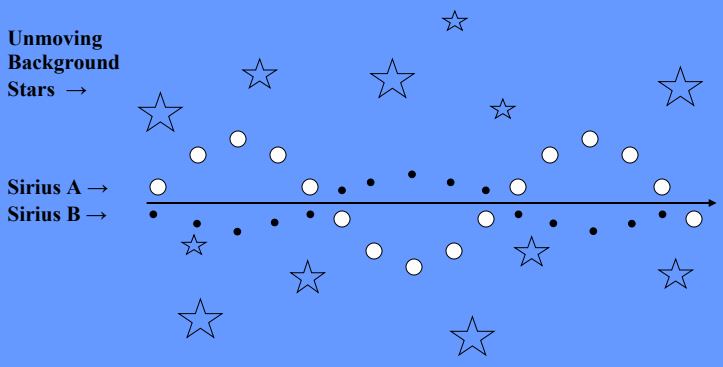
white dwarfs as dark matter

1844: German astronomer Friedrich Wilhelm Bessel: movement of Sirius over a decade indicates it is orbiting around an unseen (dark) companion



1862: American telescope builder Alvan Clark detected Sirius B (a white dwarf) **so it's not dark matter!**

But it is proof of the idea that an 'unseen' object can influence the movement of a visible object

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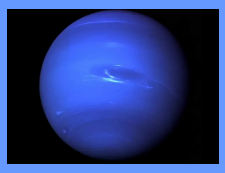
Neptune

1845: John Couch Adams (British) and
Urbain Le Verrier (French)

Problems had been known for decades with orbit of Uranus (discovered in 1781); astronomers could not accurately predict exactly where in the sky it would be next year or beyond



From calculations, both Adams and Le Verrier predicted existence of an unknown planet further from Sun than Uranus whose gravitational pull tugged on Uranus, affecting its orbit

1846: Neptune discovered observationally by Johann Galle using telescope at Berlin Observatory -- **so it's not dark matter!**

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the BIG idea

- *The existence of dark matter can be inferred from the behavior of other objects*
- *but dark matter cannot be discovered directly in any kind of light emitted from or reflected by that matter itself*

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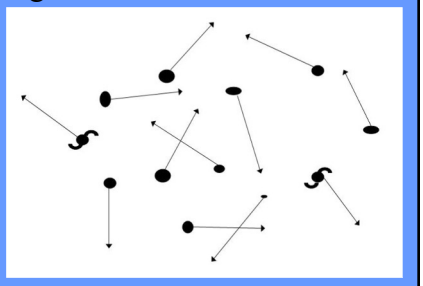
Fritz Zwicky

1933: measured velocities of galaxies in Coma Cluster



discovered: they moved *so fast* they should all escape the cluster
concluded: there must be lots of mass we cannot see inside the cluster that generates the gravitational pull that holds the cluster together

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Cold* Dark Matter

Temperature: measures the average speed of particles in a gas
(*the air in your room is hotter if the molecules are moving faster, the air is cooler if they are moving more slowly*)

Astrophysics:
Cold matter? Velocities much, much smaller than the speed of light (c)
Hot matter? Velocities greater than a few % of the speed of light (c)

c = 300,000 kilometers per second

Coma Cluster : 50X more cold dark matter than cold visible matter

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what would it be?

Cold dark matter

matter that moves at speeds that are fast enough to escape the gravitational pull of individual galaxies but not fast enough to escape the gravitational pull of the entire cluster of 1000s of galaxies

so what could be 'hiding' in between the galaxies but inside of the cluster of galaxies?

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Chandra Telescope (1999)

X-ray astronomy

Einstein Observatory (1978-1981)

- X-rays are emitted by **hot** plasma

  plasma = ionized, charged particles
  hot = millions to hundreds of millions of degrees

- X-rays do NOT penetrate Earth's atmosphere (fortunately ☺ for us)
- X-ray astronomy must be done using telescopes in orbit

XMM-Newton Telescope (1999)

Uhuru Telescope (1970-1973)

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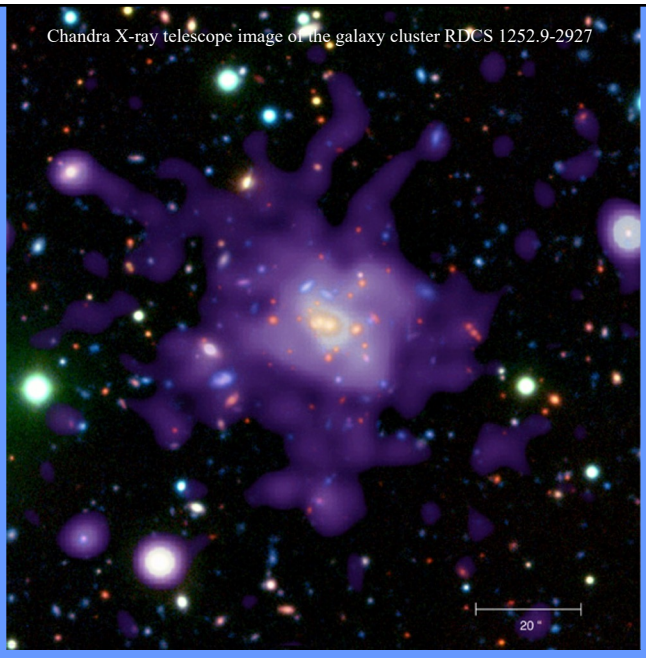
Emission from 70-million-degree gas is seen as the purple and white fuzz and blobs.



The X-ray image is presented on top of a visible light image of the cluster (all of the small dots and smudges are the galaxies seen in visible light).

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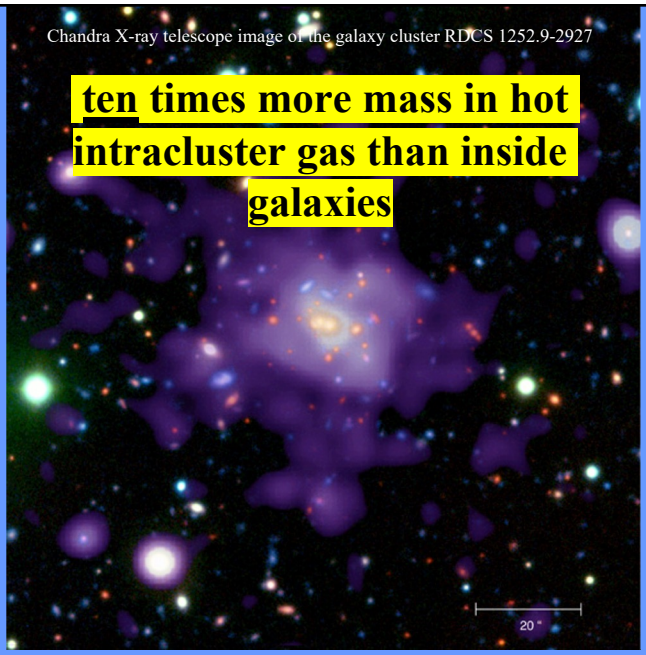

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Zwicky needs fifty times more mass (somewhere in galaxies or in intracluster matter) than we can see

so even this hot, bright X-ray emitting gas is not enough mass

it is only 1/5 (20%) of what is needed to solve the dynamical problem first identified by Zwicky

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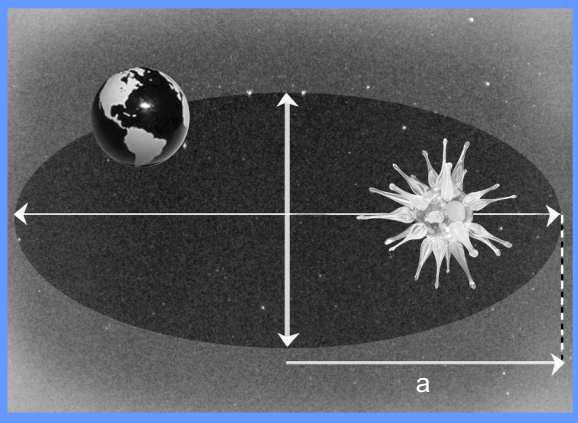
Kepler's Third Law

$P^2 = a^3$



P = orbital period

a = size of orbit
= semi-major axis (ellipse)

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Mass of the Milky Way galaxy

We can use Kepler's Third Law to estimate the mass inside the Sun's orbit around the center of the Milky Way

- Sun's distance from center: 28,000 light years
- Sun's orbital period: 230 million years
- mass **within Sun's orbit** is $10^{11}\ M_{\odot}$

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Isaac Newton's version of Kepler's Third Law

$$P^2 = \left(\frac{4\pi^2}{G(m+M)}\right)a^3$$

M = **all mass 'inside' the orbit**
m = orbiting mass
G = universal constant of gravitation
valid for any object orbiting any other object

Can use this to measure ALL of the mass INSIDE an object's orbit

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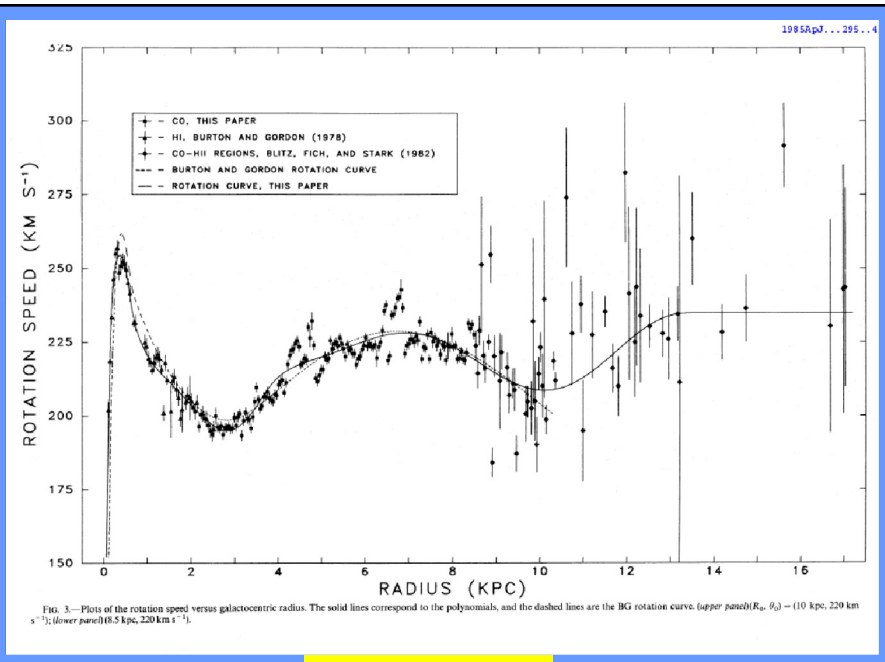

1985: measured rotation curve for the Milky Way

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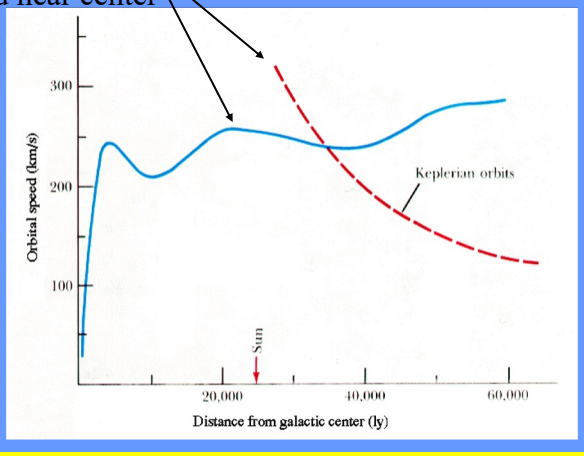
”Keplerian’ rotation curve: like the solar system, with most mass in the Sun)

Galactic rotation curve is ***flat***, not ‘Keplerian’; mass not concentrated near center



mass is distributed throughout galaxy and we don’t see it

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Mass (inside) of the Milky Way

- Total mass of MW Galaxy : 10^{12} x mass of Sun
- Total mass in stars + visible gas clouds ≈ 2 x 10^{11} x mass of Sun

at least 80% of mass is not emitting light: cold dark matter

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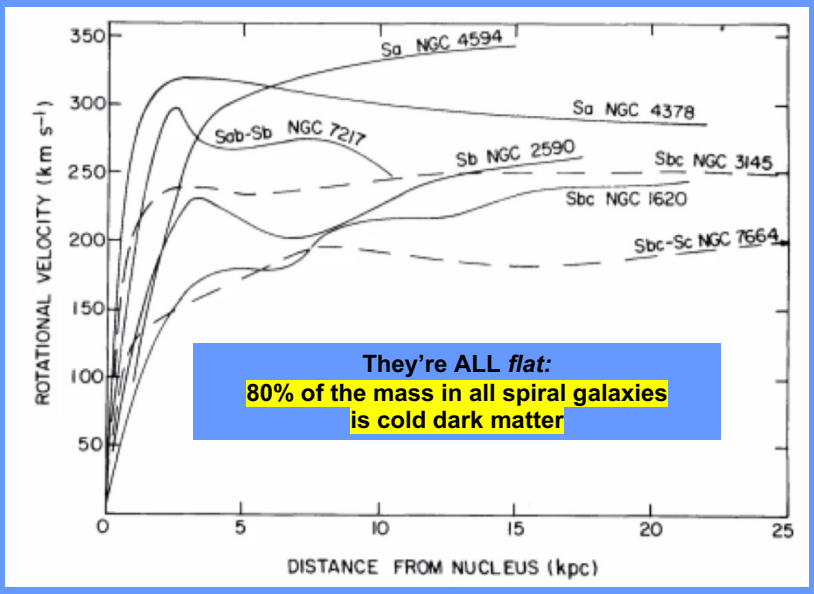

They're ALL *flat:*
80% of the mass in all spiral galaxies is cold dark matter

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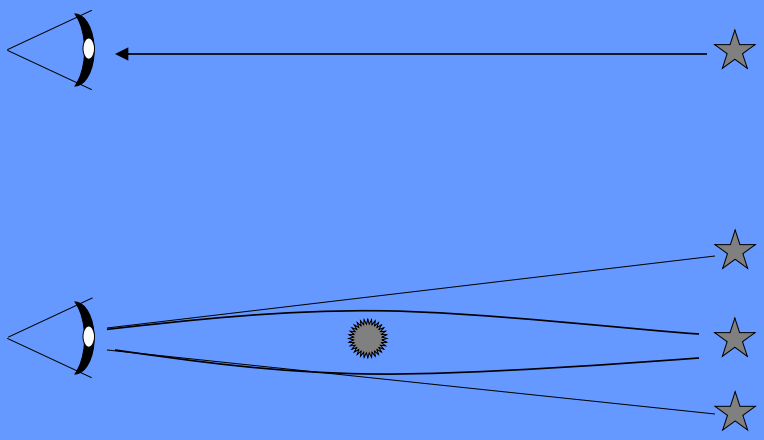
Gravitational lensing



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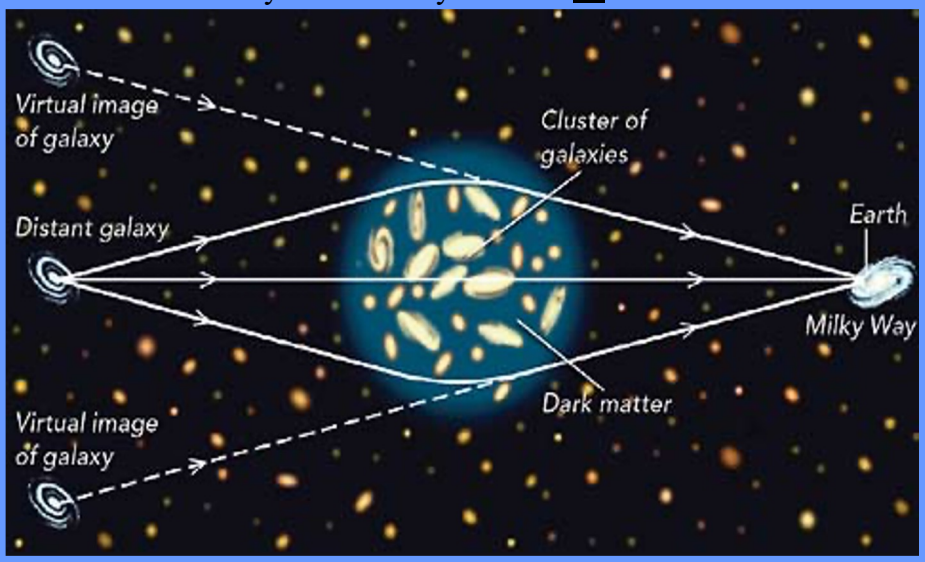
gravitational lensing of galaxies

a way to accurately measure <u>all</u> the mass



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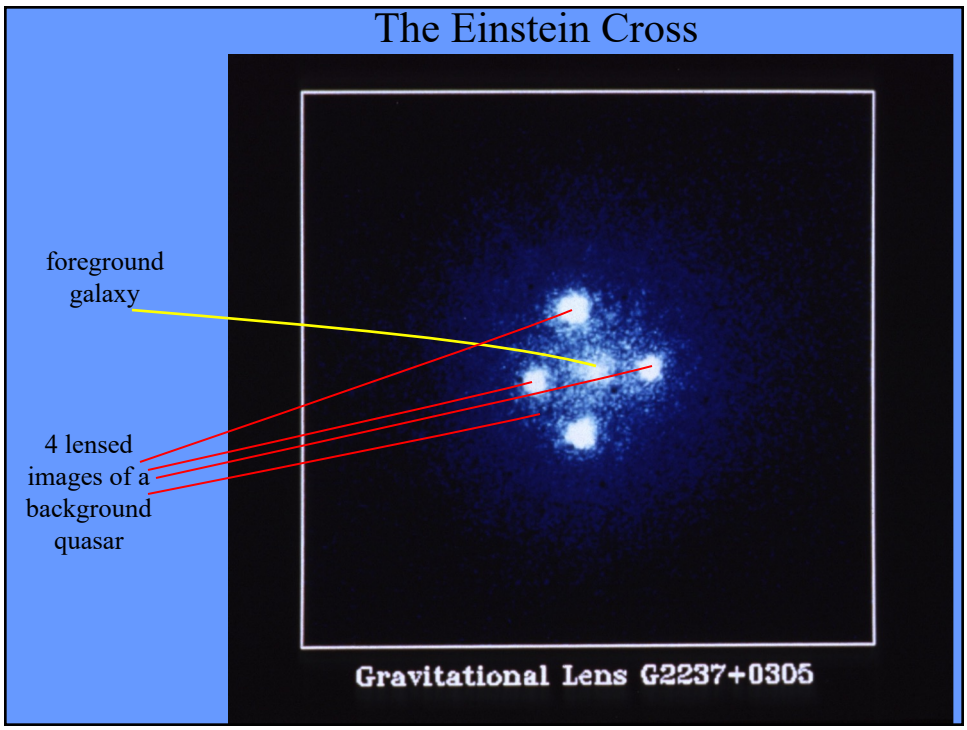
The Einstein Cross
foreground galaxy
4 lensed images of a background quasar
Gravitational Lens G2237+0305

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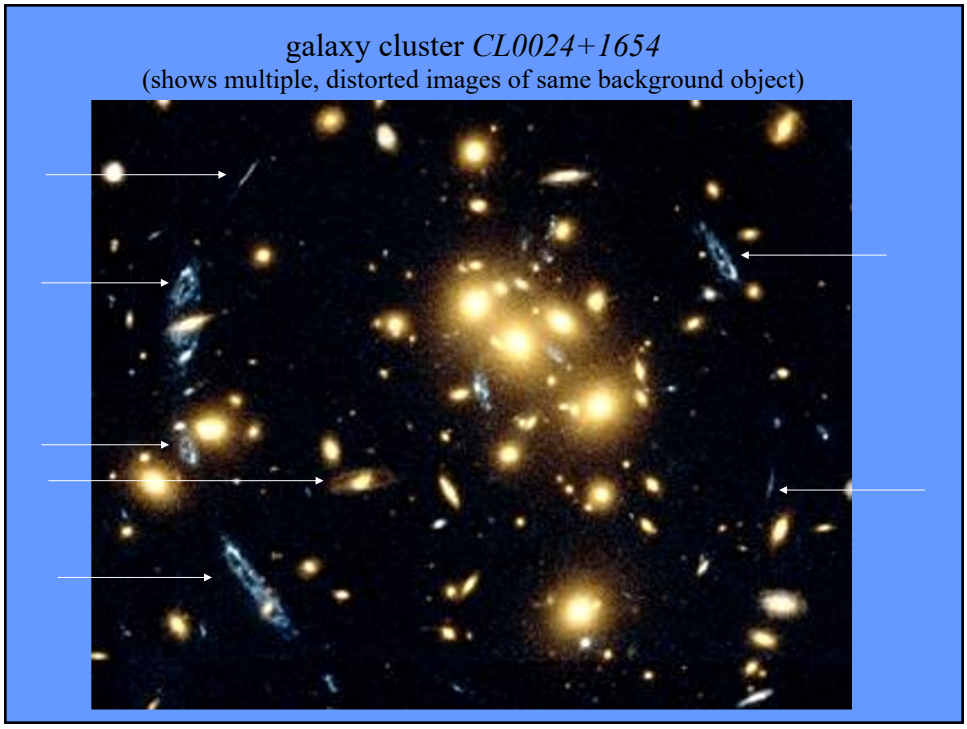
galaxy cluster *CL0024+1654*
(shows multiple, distorted images of same background object)

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Now we have two ways to identify presence of dark matter in galaxy clusters

1. X-rays to find hot gas between galaxies
   (this will find most of the matter that produces light
2. gravitational lensing, to find total mass (where is it?)

Let's use them both … and compare the answers we get

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The Grand Experiment!

gravitationally lensed background galaxies overlay galaxy cluster
… so most of the mass (which makes the lensing happen) is where the cluster is …
… and most of the mass should be where the hot X-ray emitting gas is …

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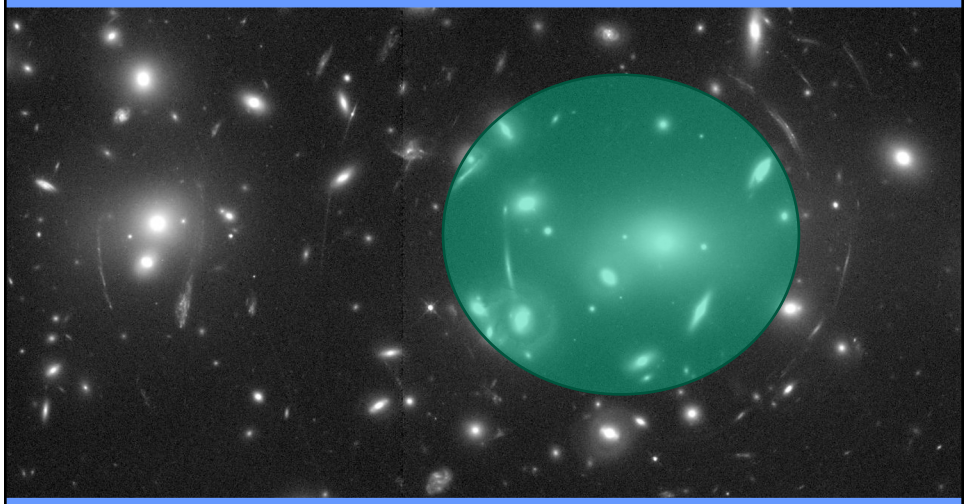
The Grand Experiment!



the hot X-ray emitting gas is where we predicted;
It appears to provide most of the lensing mass (as expected)

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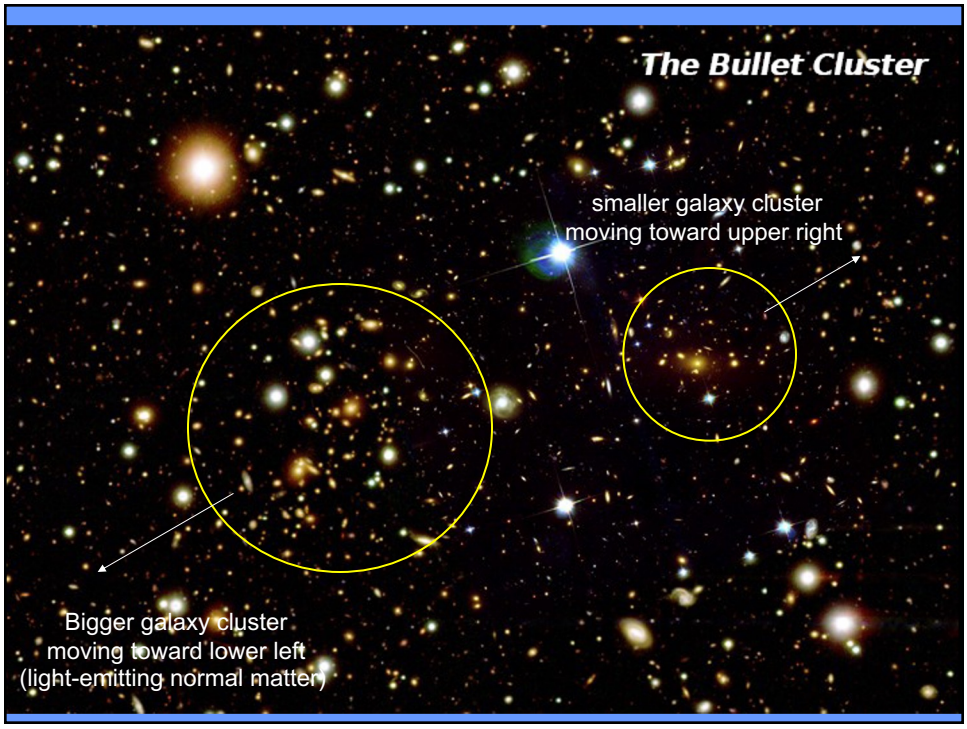

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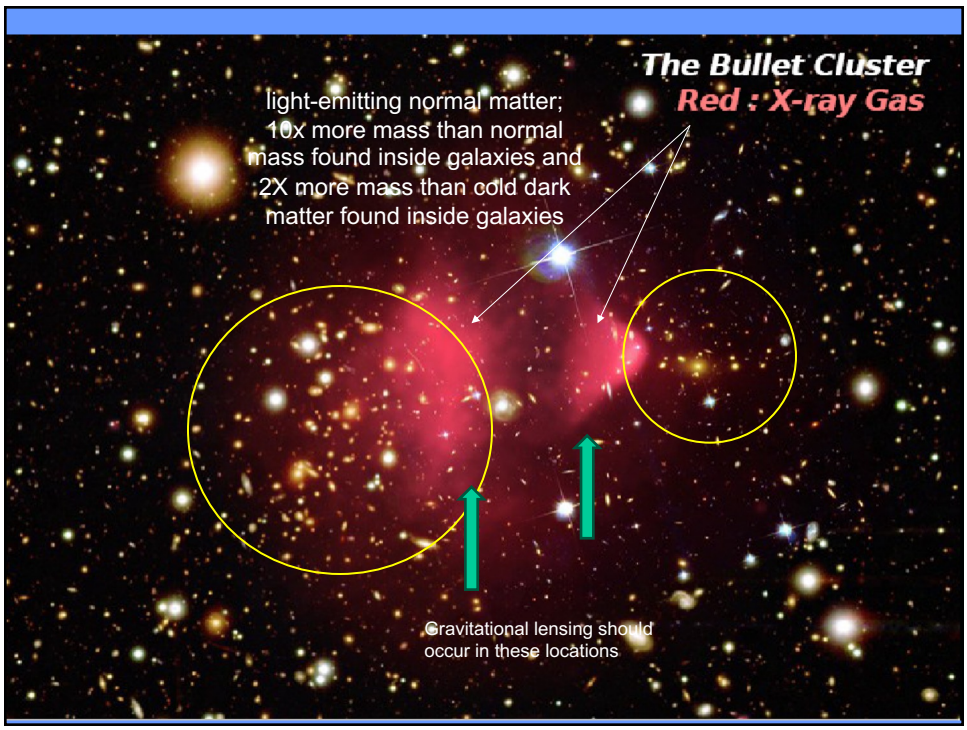
The Bullet Cluster
Red : X-ray Gas
light-emitting normal matter;
10x more mass than normal
mass found inside galaxies and
2X more mass than cold dark
matter found inside galaxies
Gravitational lensing should
occur in these locations

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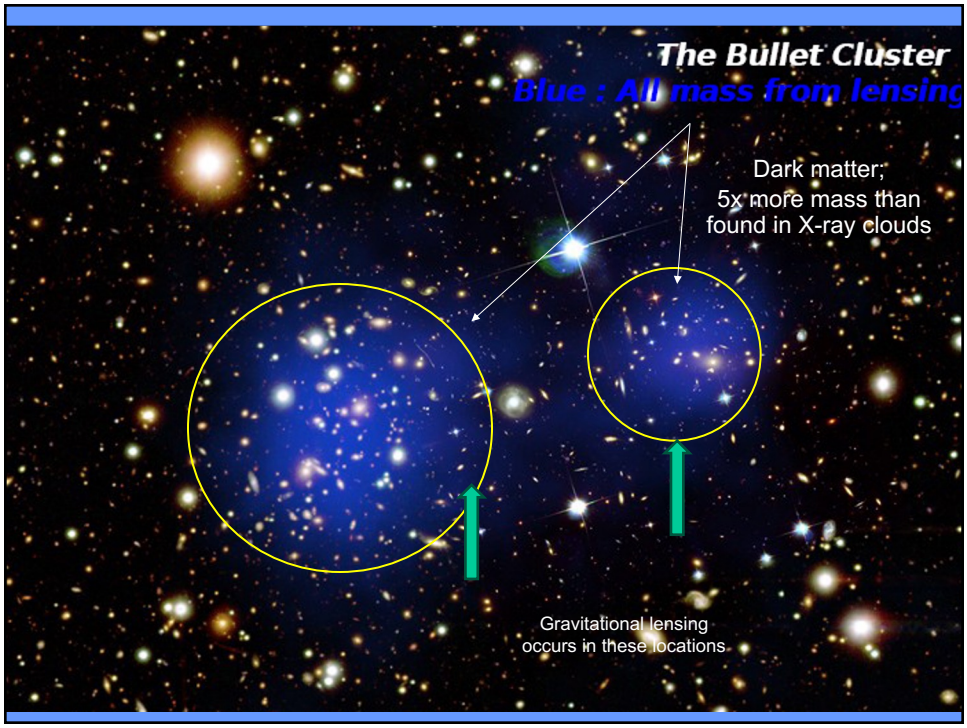
The Bullet Cluster
Blue : All mass from lensing
Dark matter;
5x more mass than
found in X-ray clouds
Gravitational lensing
occurs in these locations

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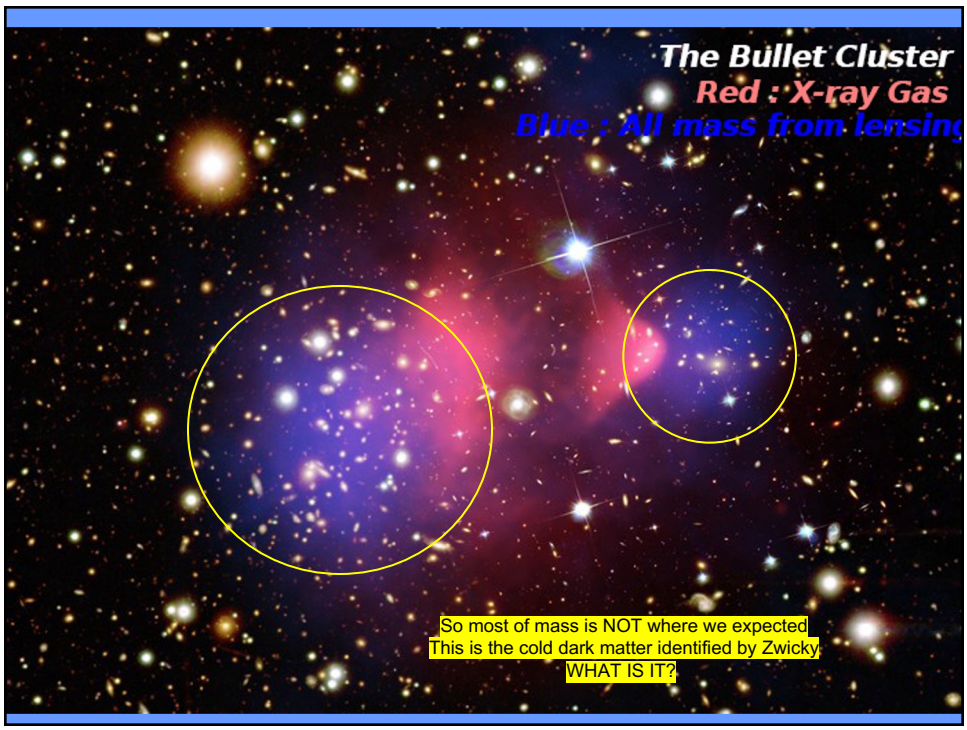

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evidence for cold dark matter

1. High velocities of galaxies in clusters
   reveals that lots of unseen matter must exist to generate enough gravitational pull to hold galaxy together
2. Flat rotation curves of spiral galaxies + hot X-ray gas
   accounts for 1/5 of the mass
   needed to hold the Coma Cluster together
1. gravitational lensing (Bullett Cluster)
   accounts for 4/5 of the mass Zwicky said was needed to hold the Coma Cluster together!
   PROBLEM SOLVED!

BUT WHAT IS COLD DARK MATTER?

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