

Shining a Light on Dark Matter



Andrew Robertson

Carnegie Science, Observatories

Astronomy Lecture Series at The Huntington

March 30th 2026

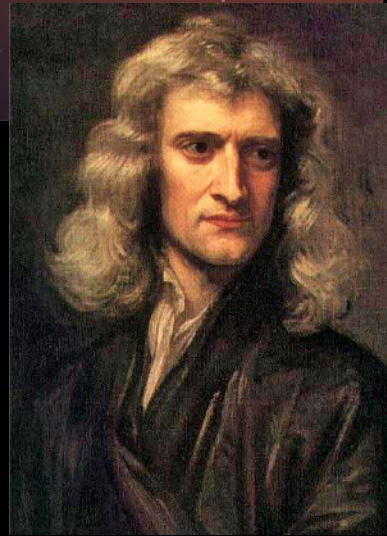
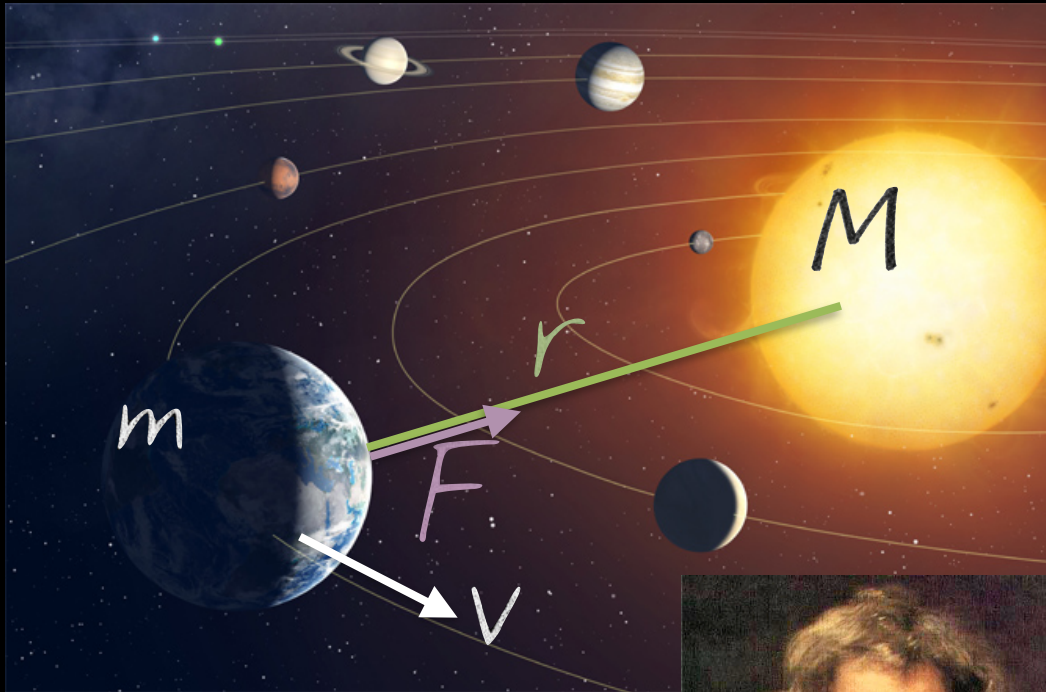
How Much Does a Galaxy Weigh?

Count all the stars!
(and gas, and dust, etc.)



Use gravity

First Consider Weighing the Sun



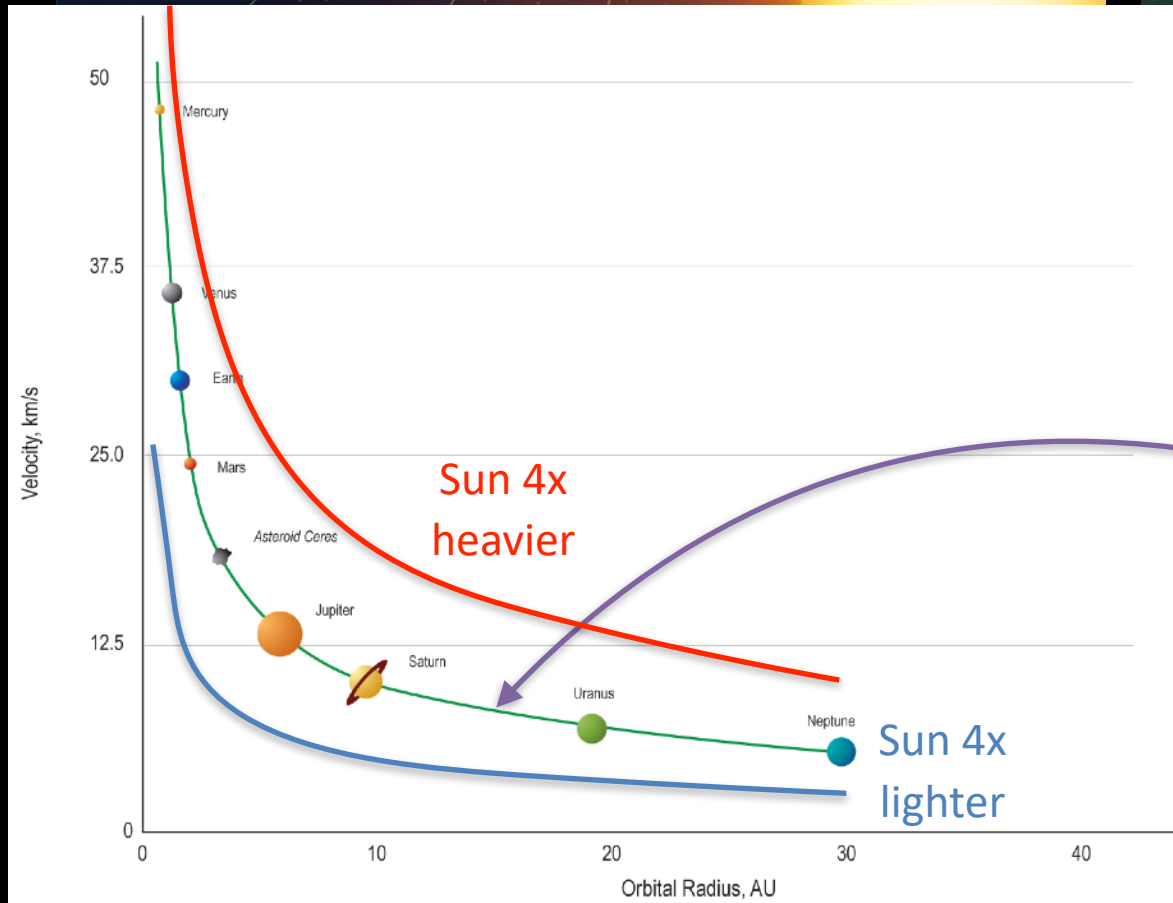
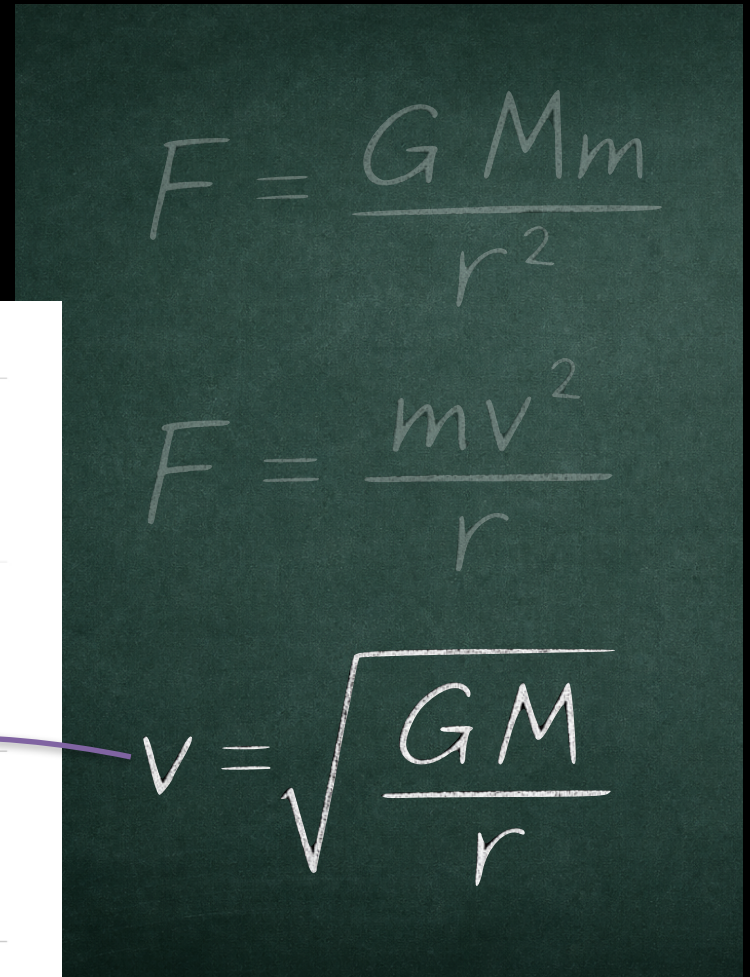
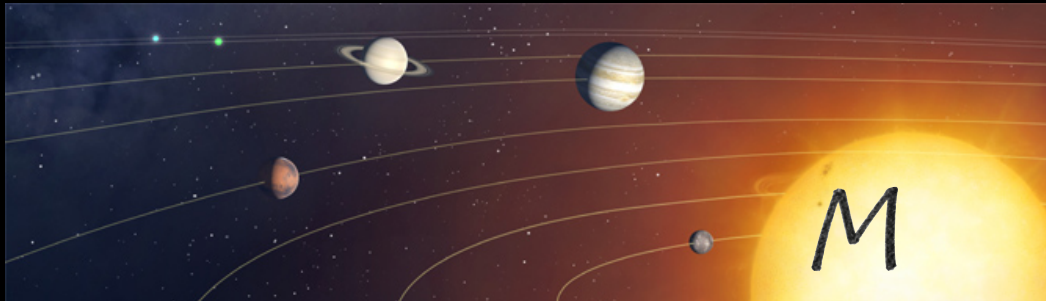
Isaac Newton

$$F = \frac{G M m}{r^2}$$

$$F = \frac{m v^2}{r}$$

$$v = \sqrt{\frac{G M}{r}}$$

First Consider Weighing the Sun



Galactic rotation

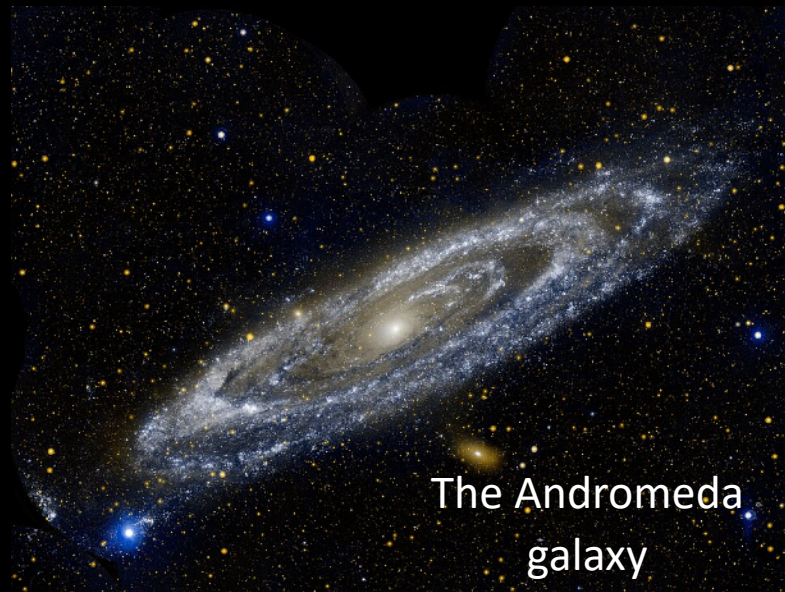


Vera Rubin, 1975

In the 1970s, Vera Rubin began measuring the rotation curves of galaxies



Kitt Peak 2.1-meter telescope



The Andromeda galaxy

How do we measure galaxy rotation?



Stars take 100s of millions of years to orbit the centre of their galaxy, so we don't actually see them moving

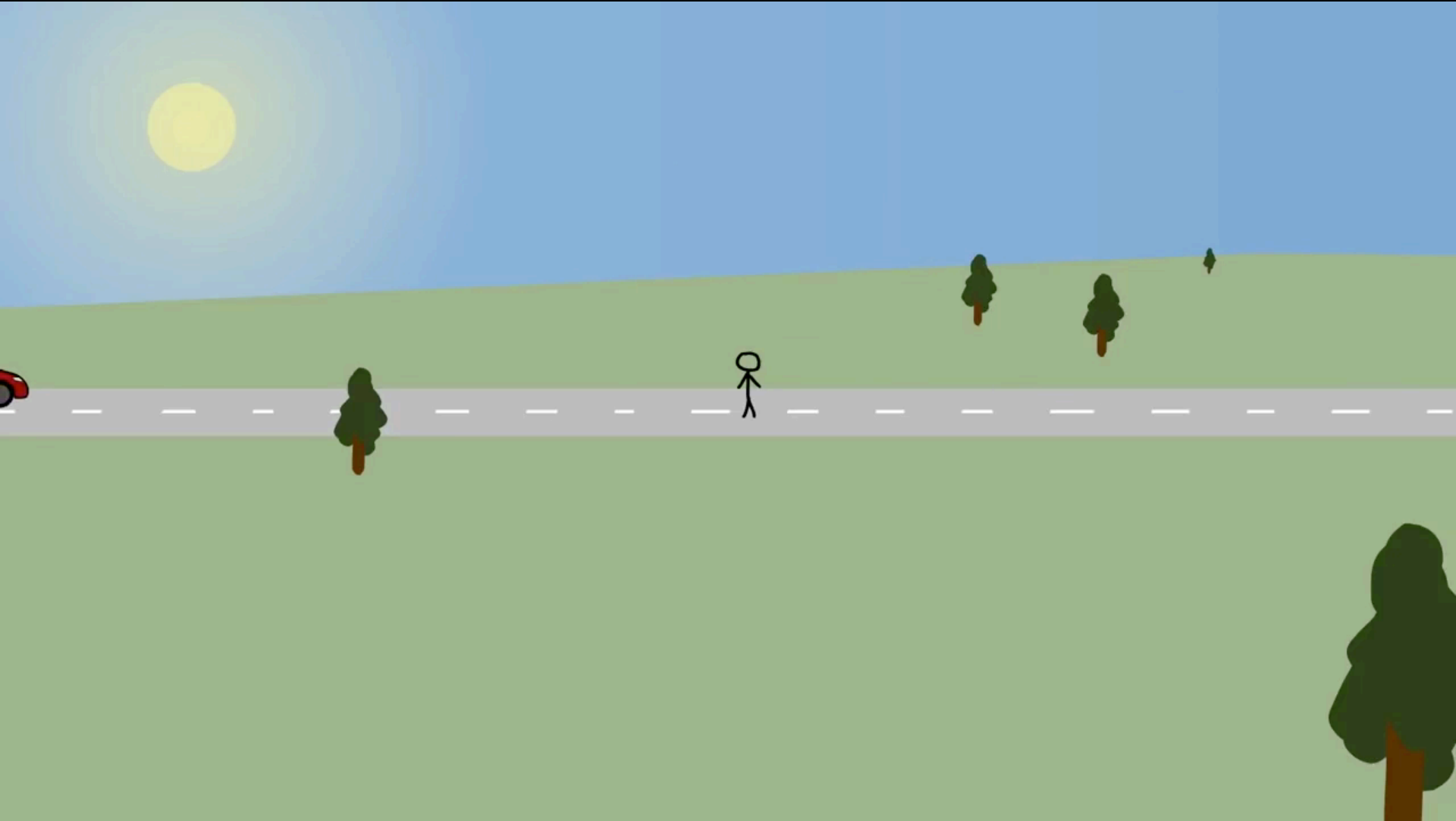
But for galaxies that are not "face on" we can use the Doppler effect



The Doppler Effect

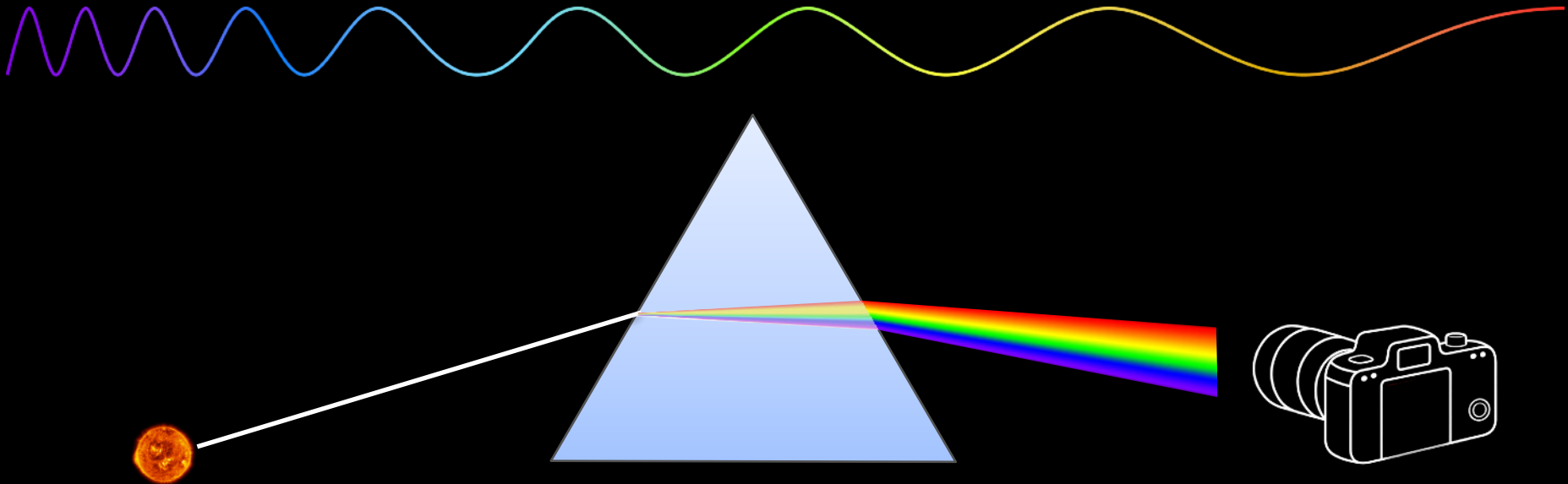


Visualizing The Doppler Effect

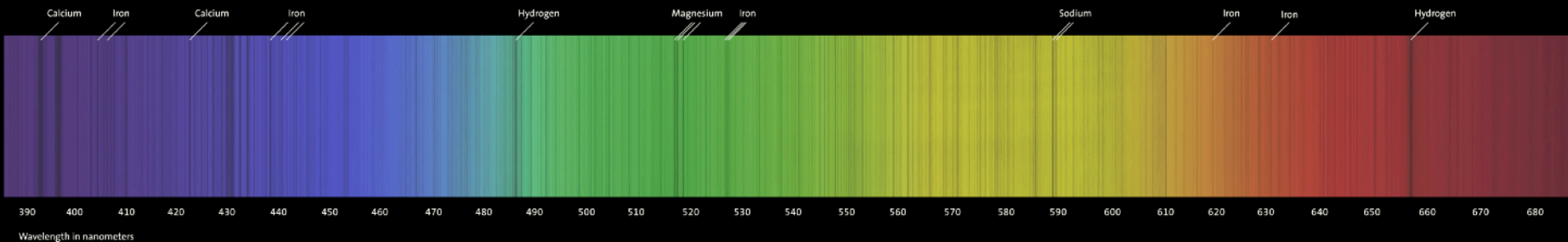


Credit: Alt Shift X

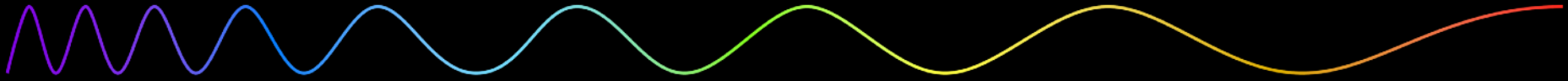
Light is also a wave



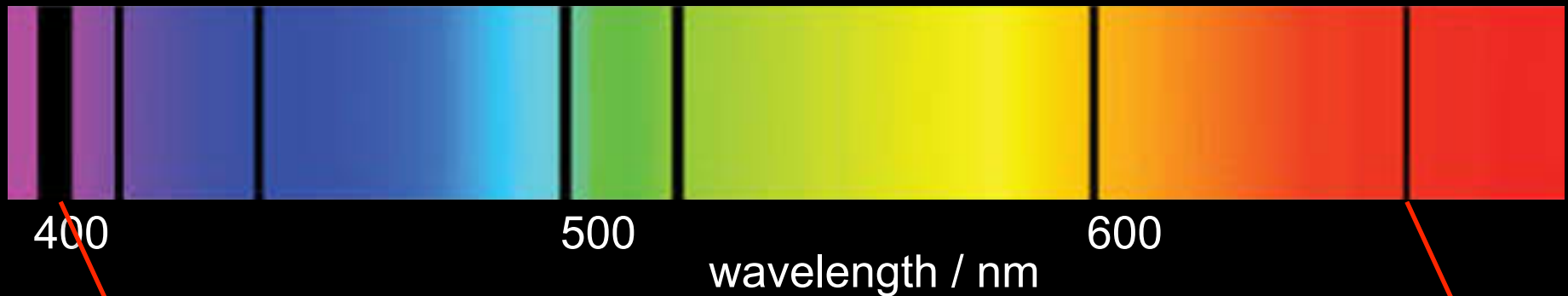
The spectrum of a star is like a fingerprint, with “absorption lines” at specific wavelengths



Light is also a wave



A simplified spectrum of our sun



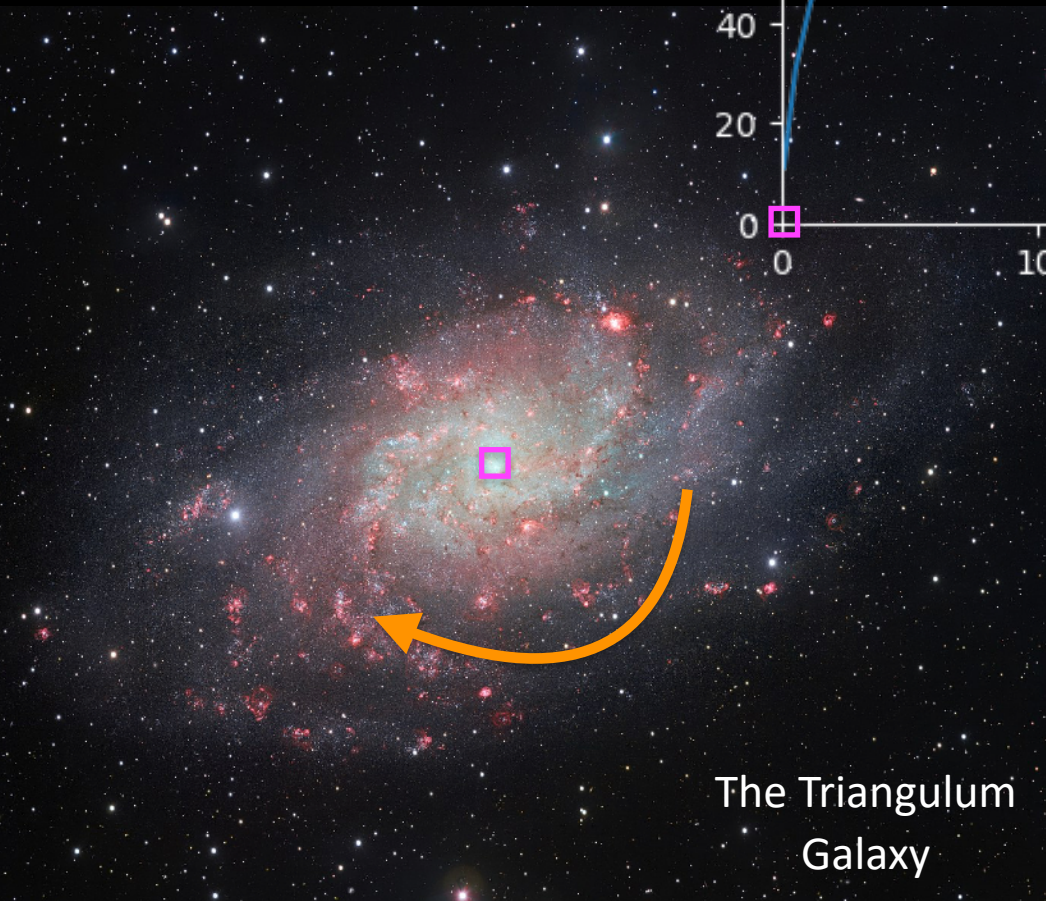
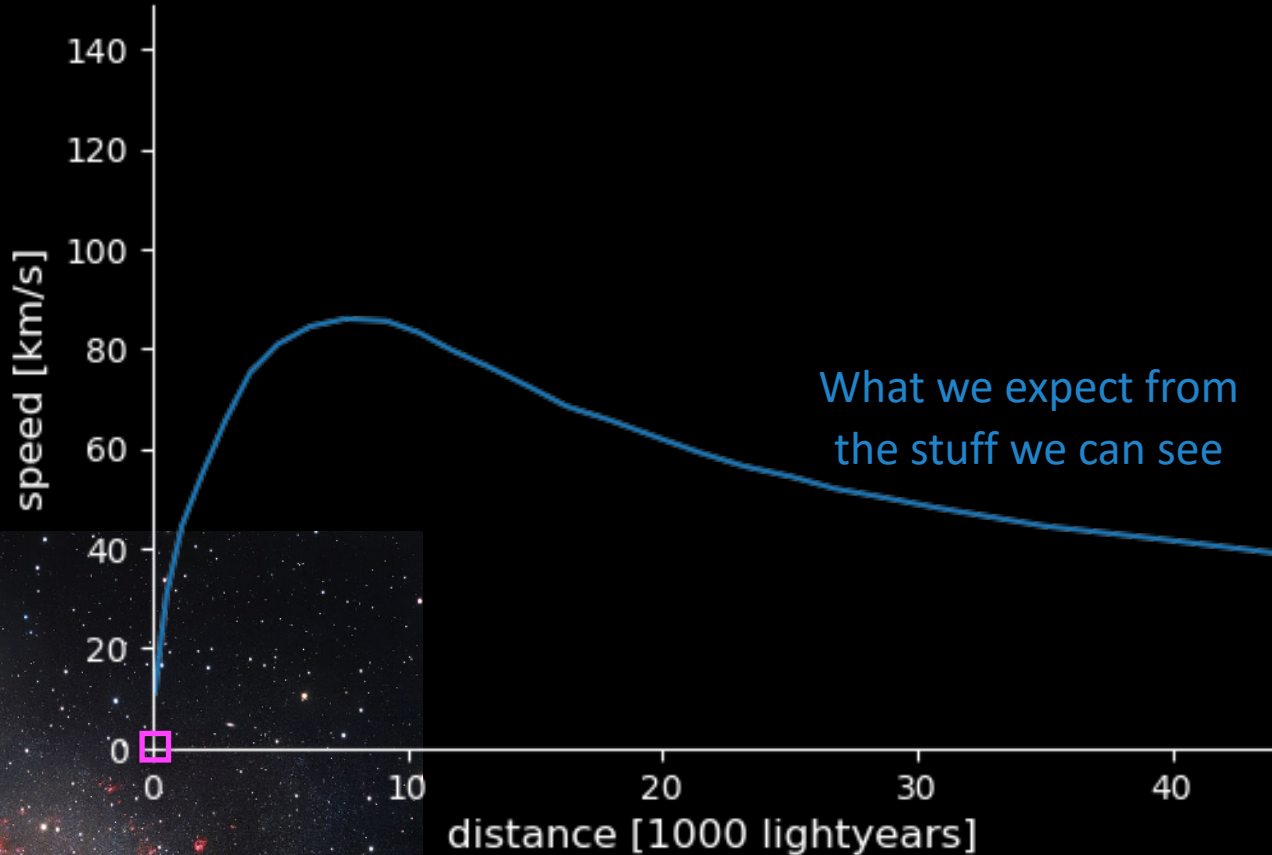
Redshift

Redshift

What we see in a star moving away from us

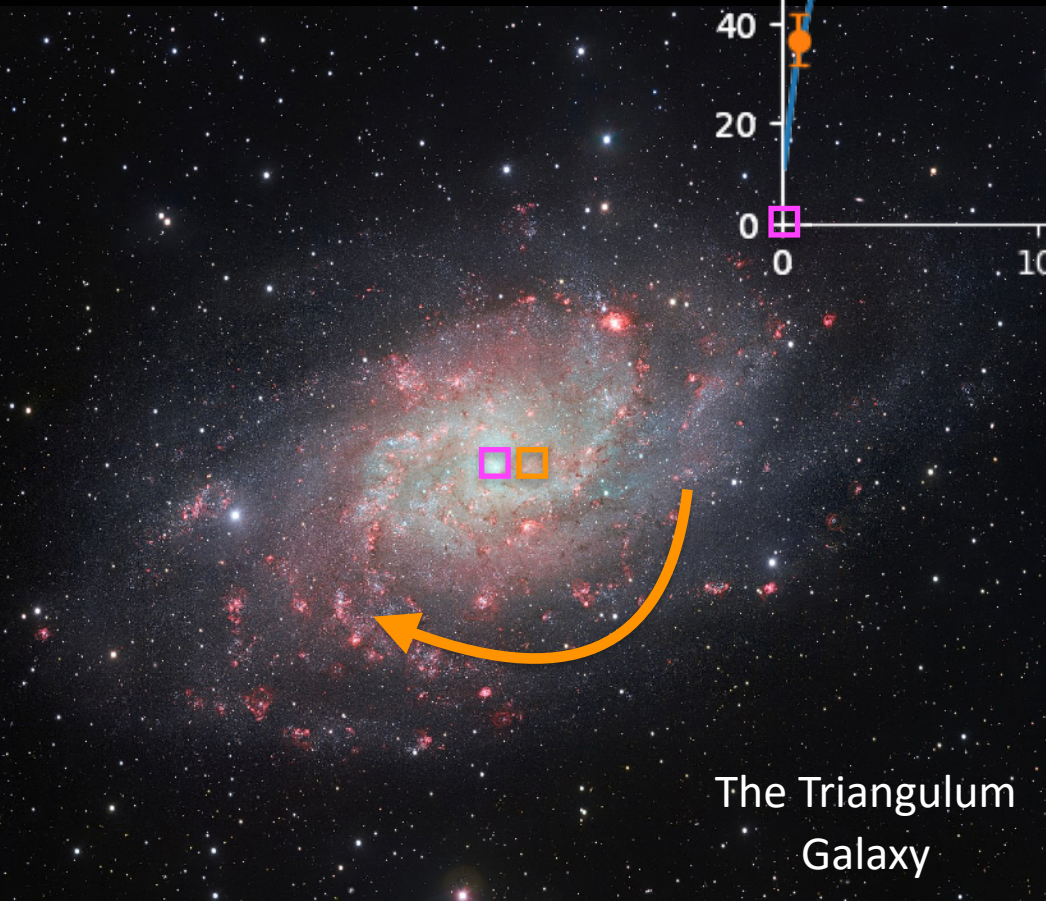
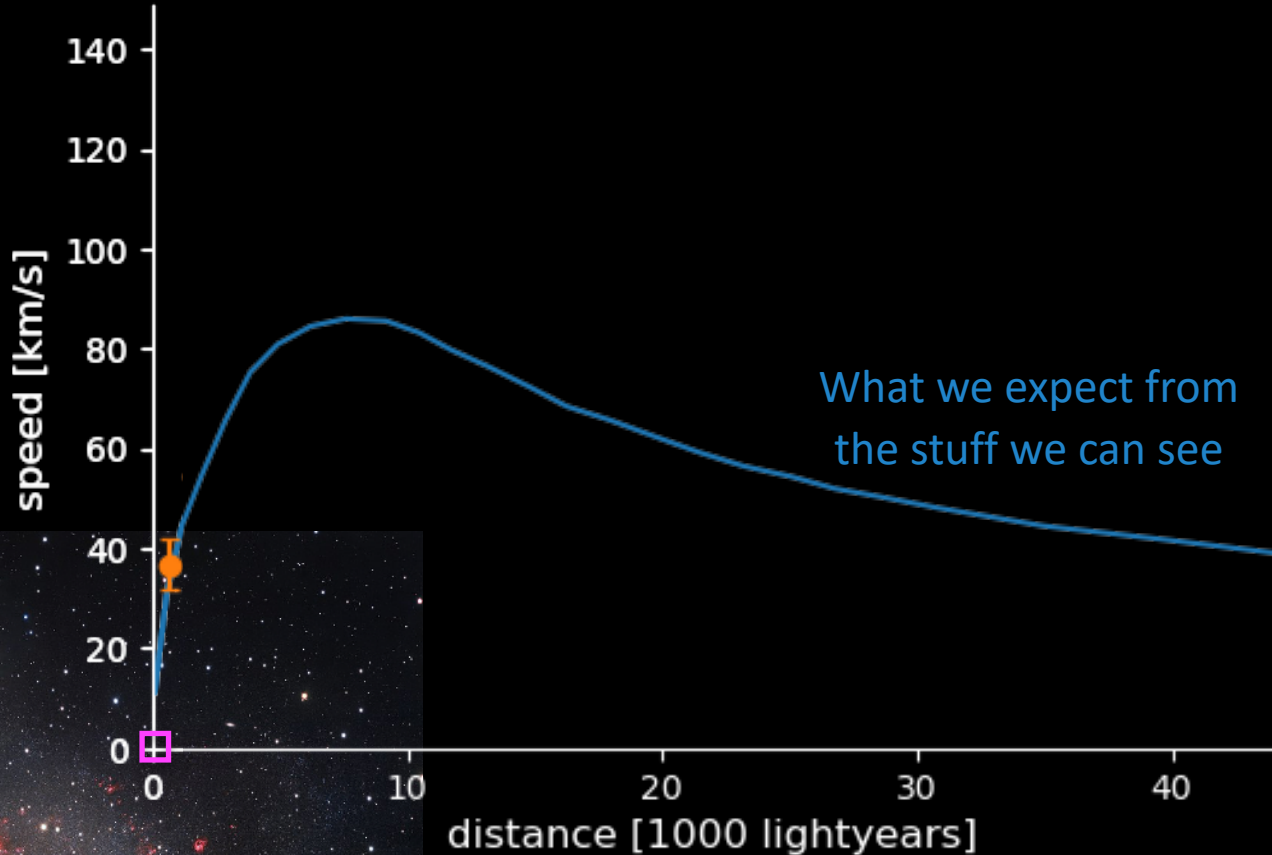


Galaxy rotation

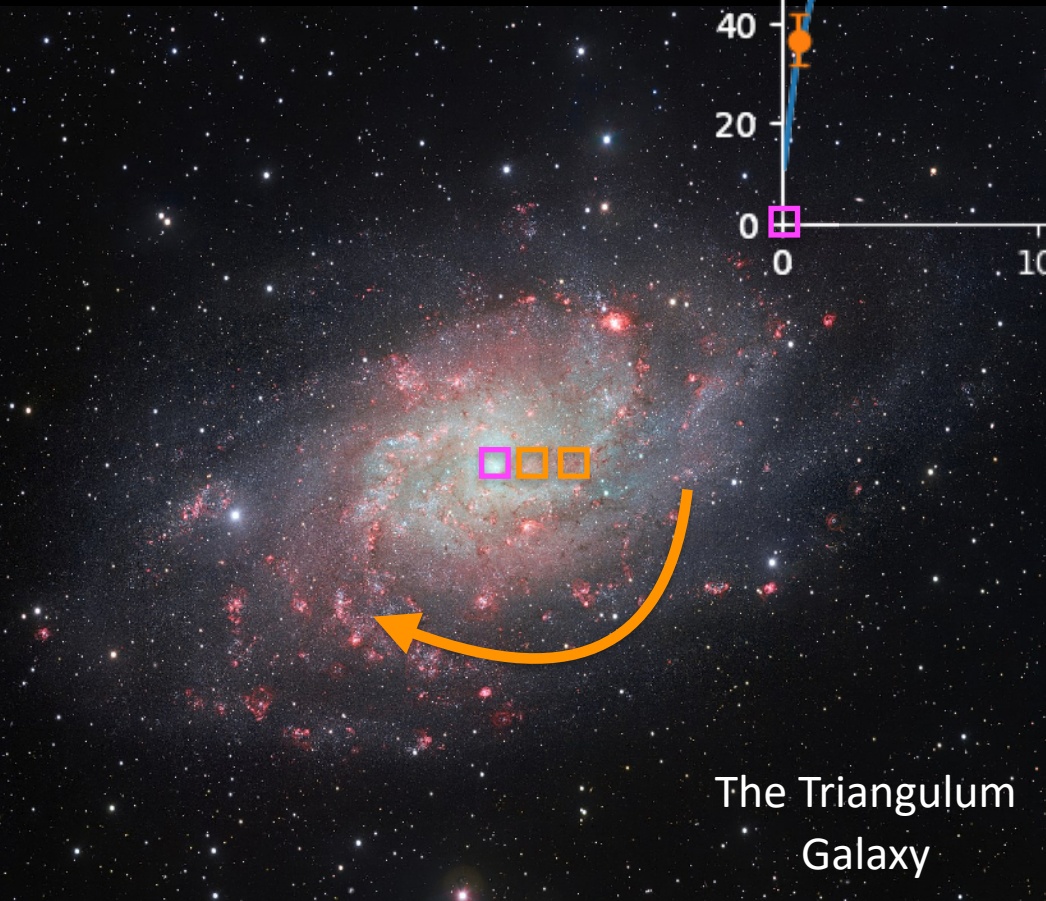
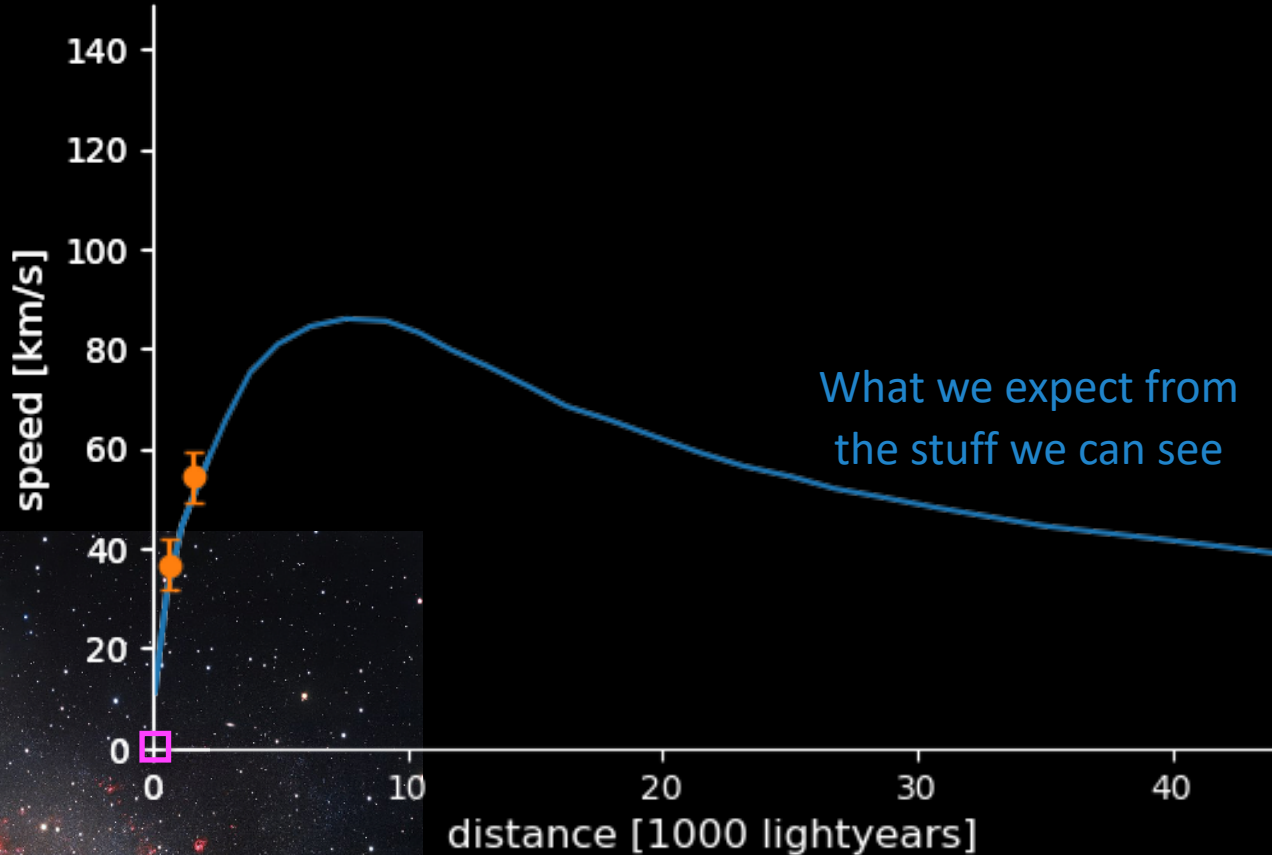


The Triangulum Galaxy

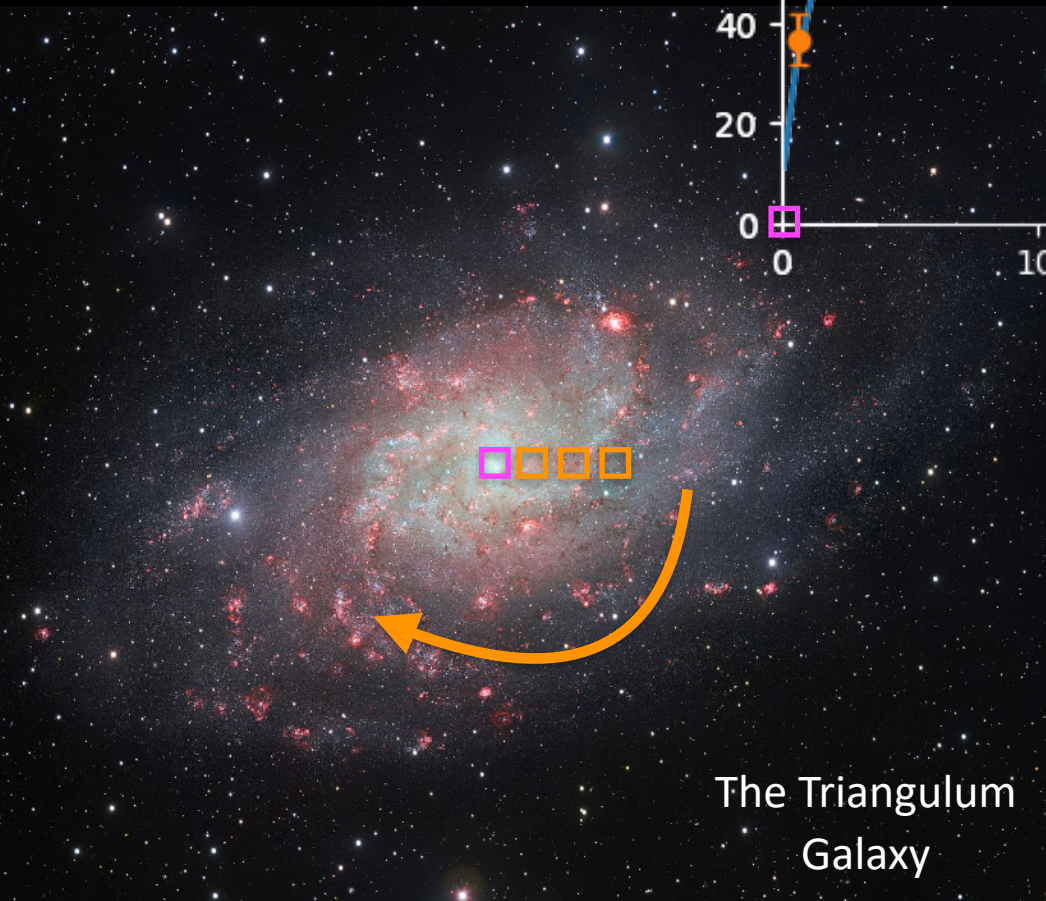
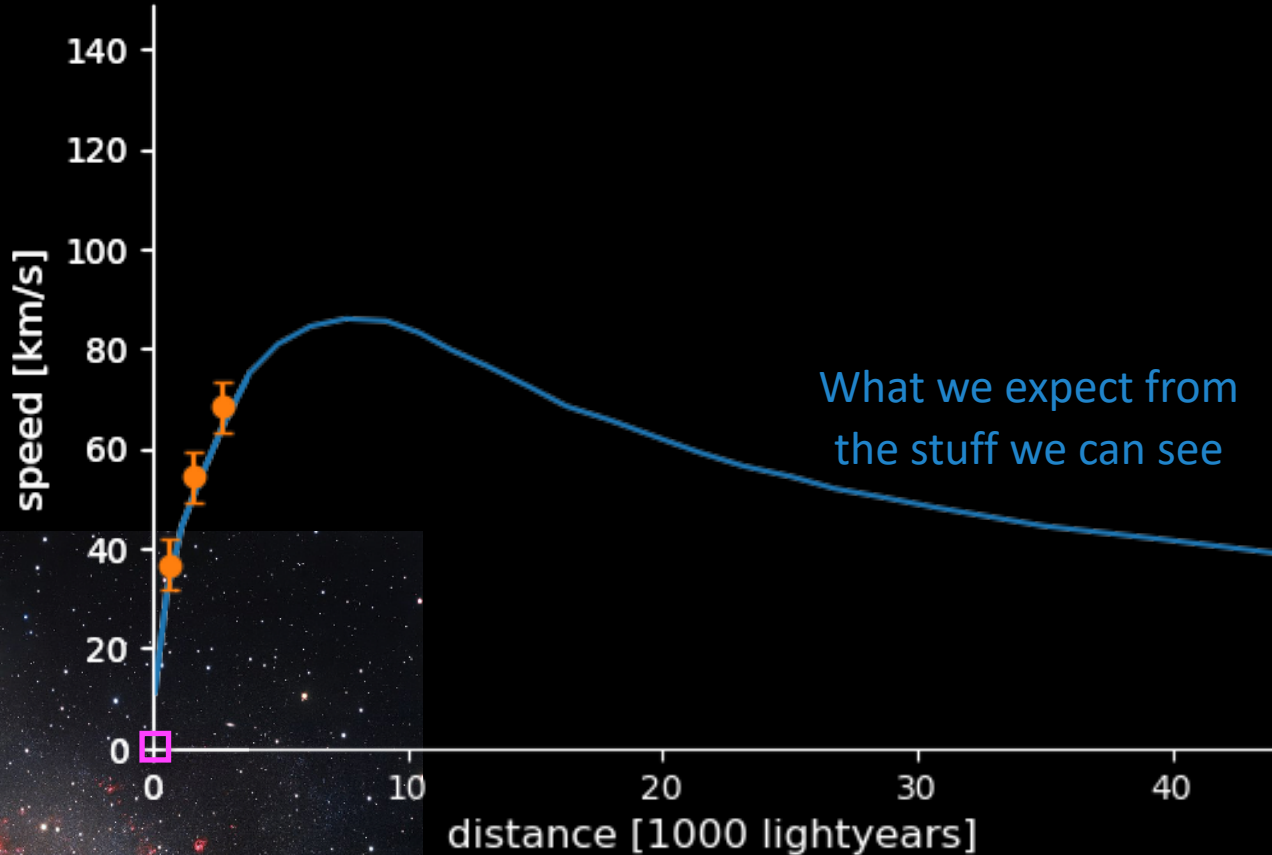
Galaxy rotation



Galaxy rotation

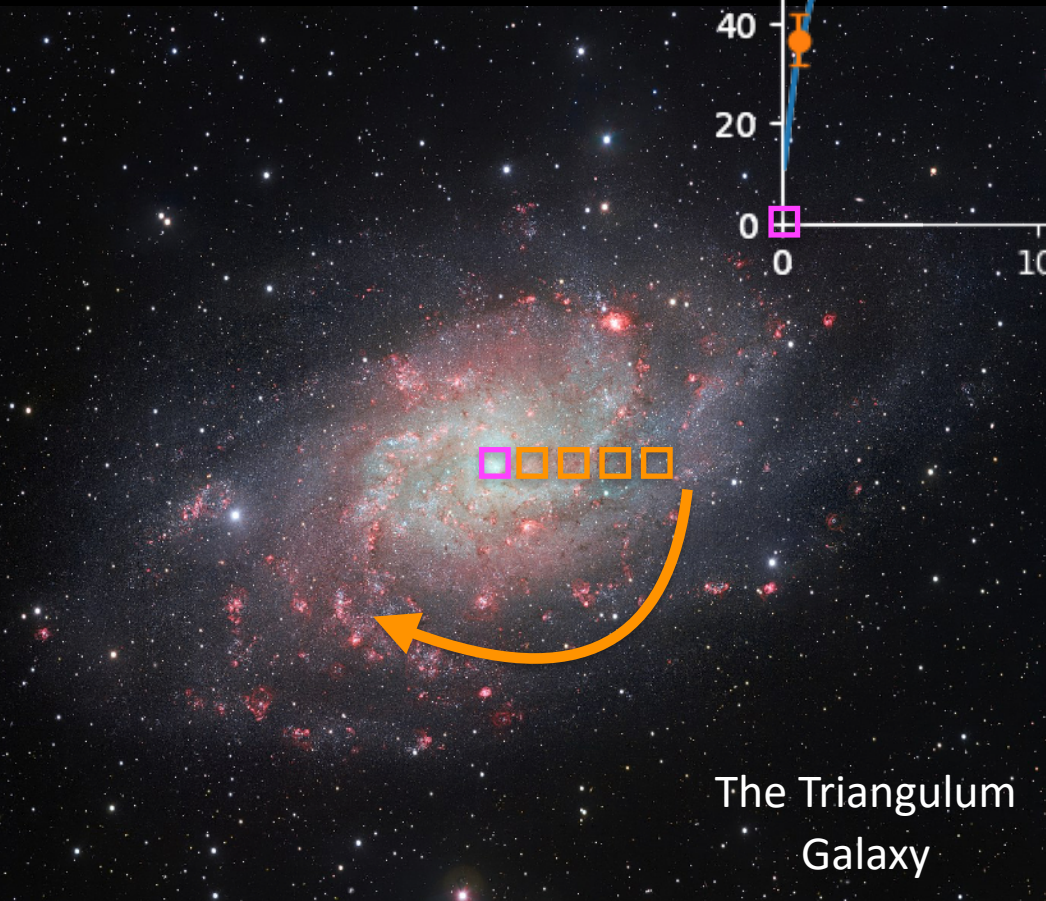
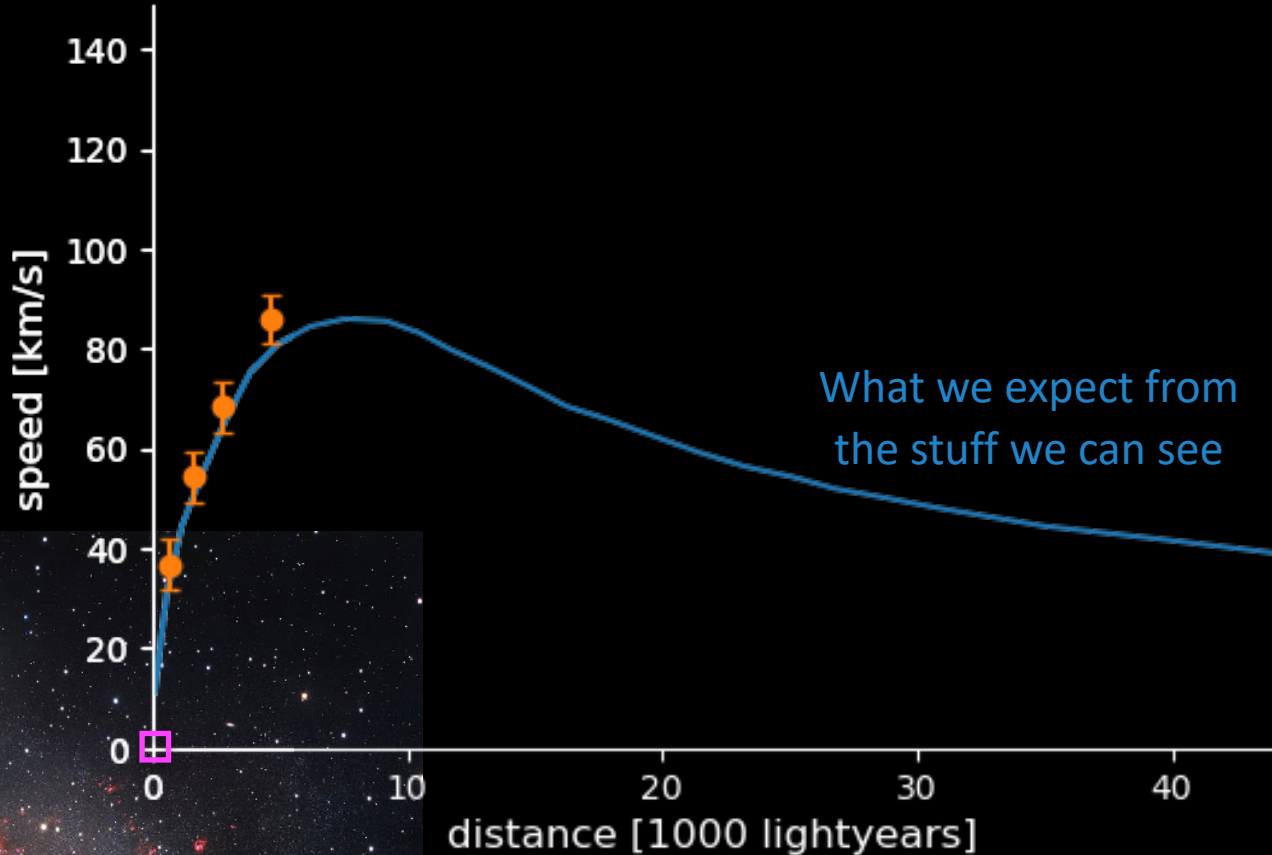


Galaxy rotation



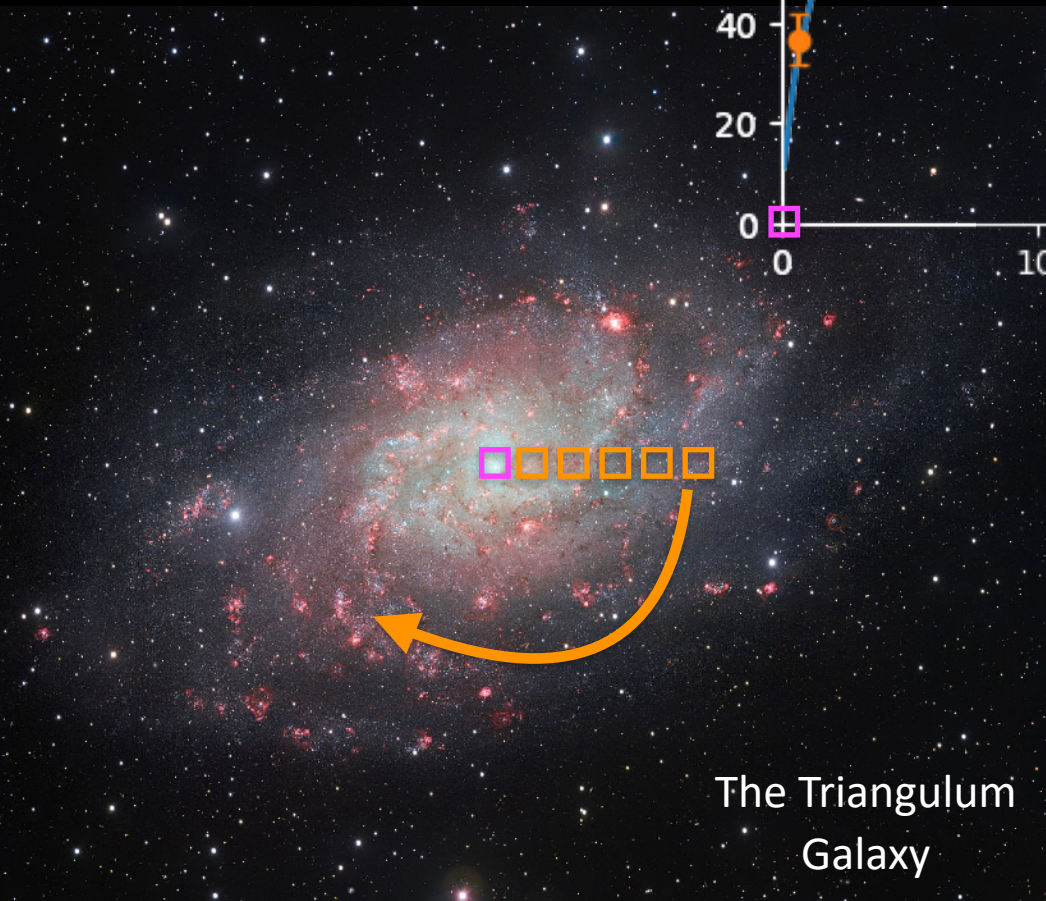
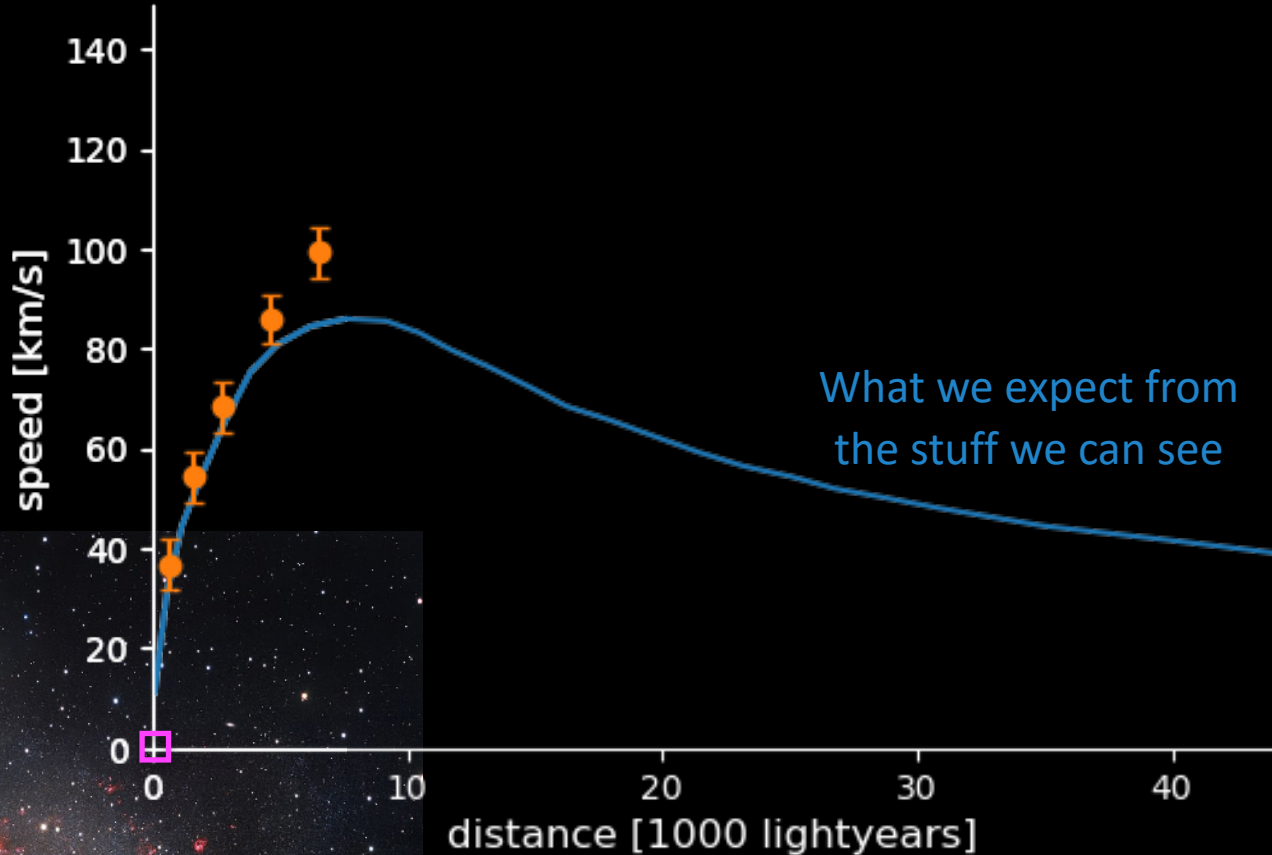
The Triangulum Galaxy

Galaxy rotation



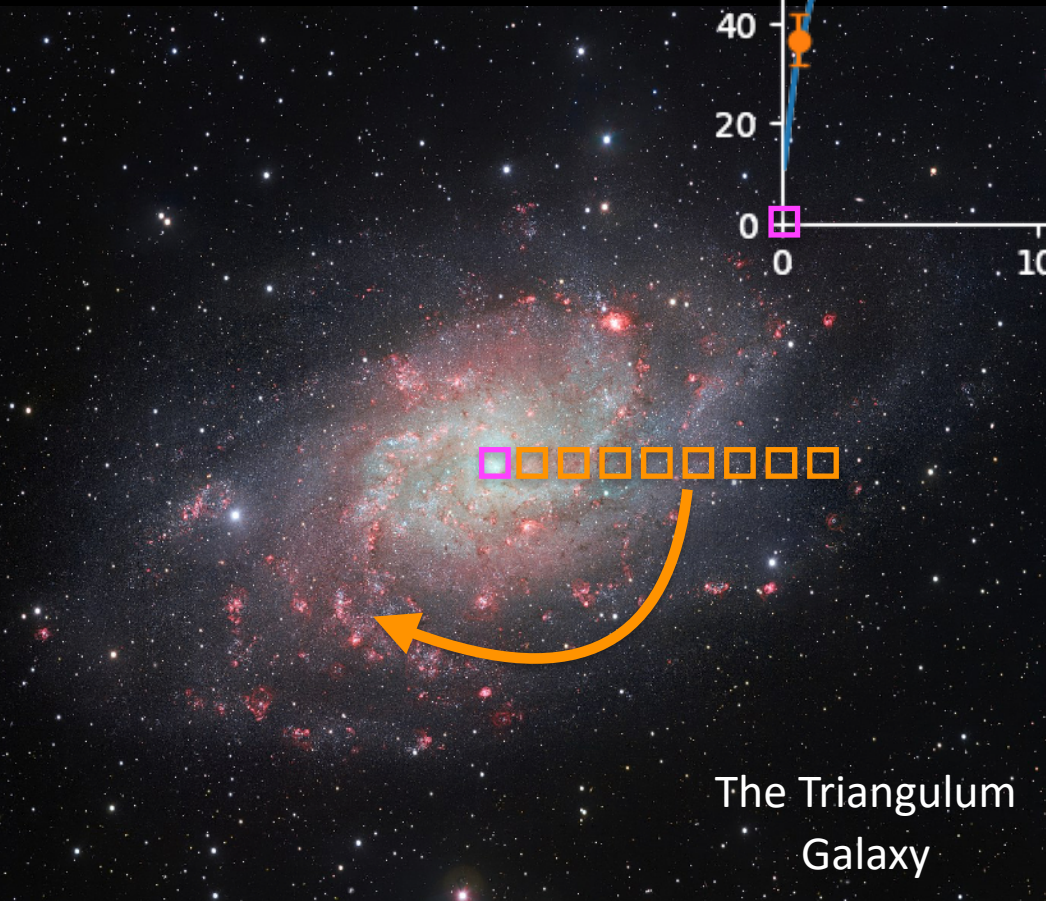
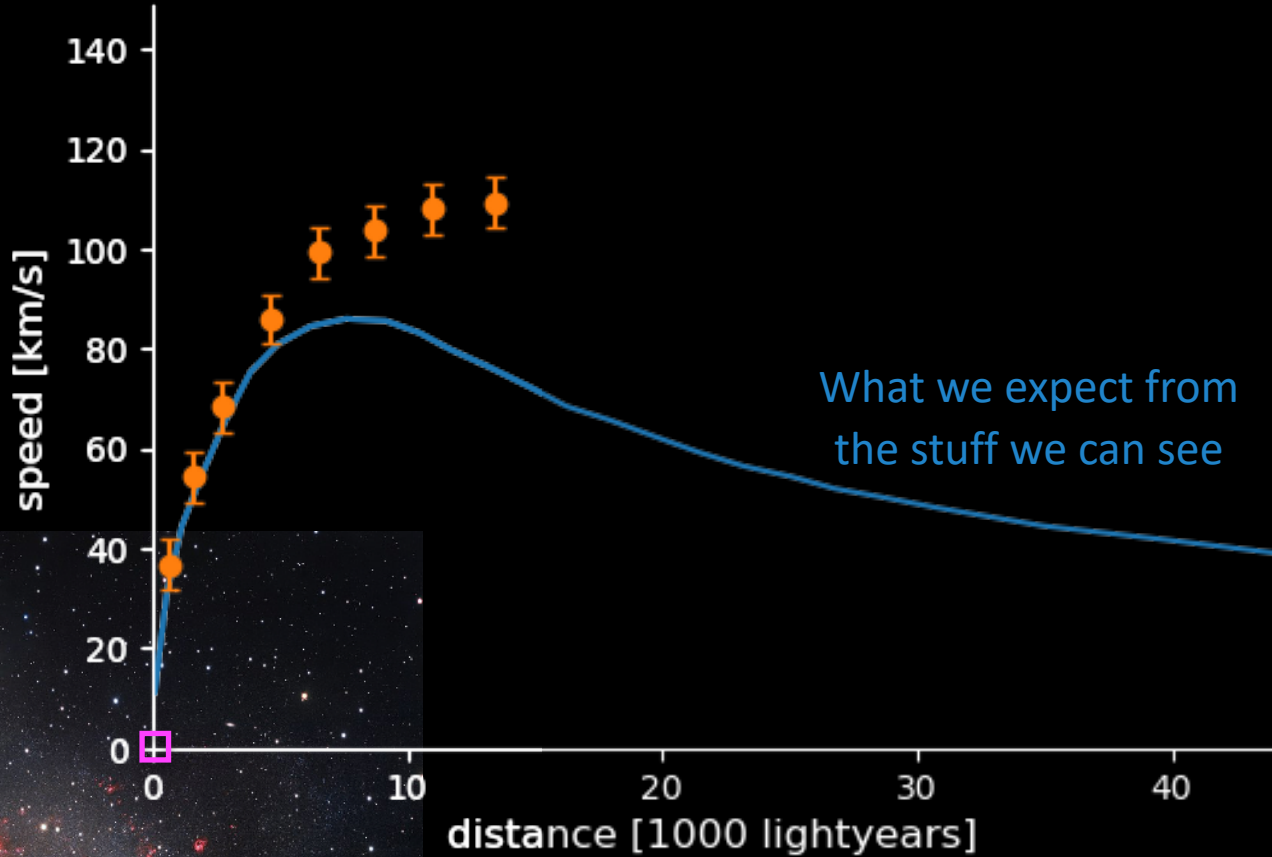
The Triangulum Galaxy

Galaxy rotation



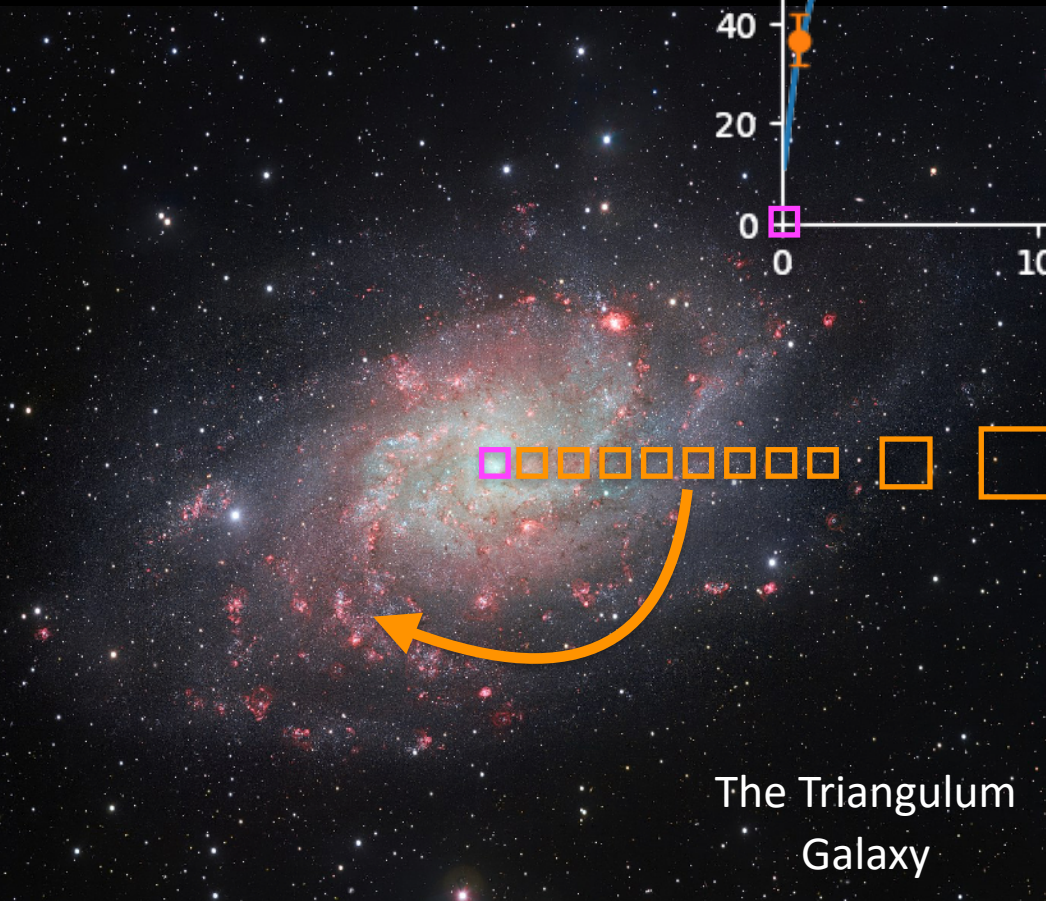
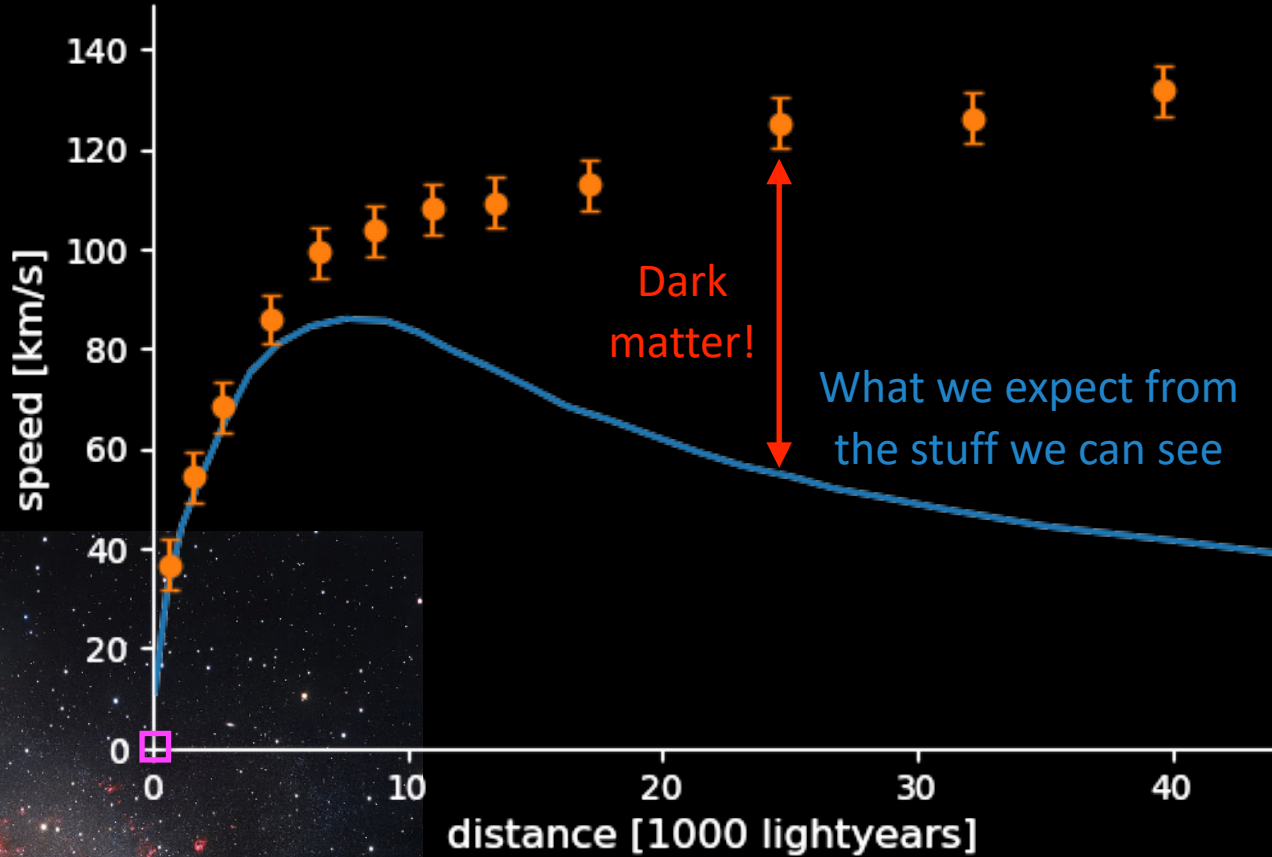
The Triangulum Galaxy

Galaxy rotation



The Triangulum Galaxy

Galaxy rotation



The Triangulum Galaxy

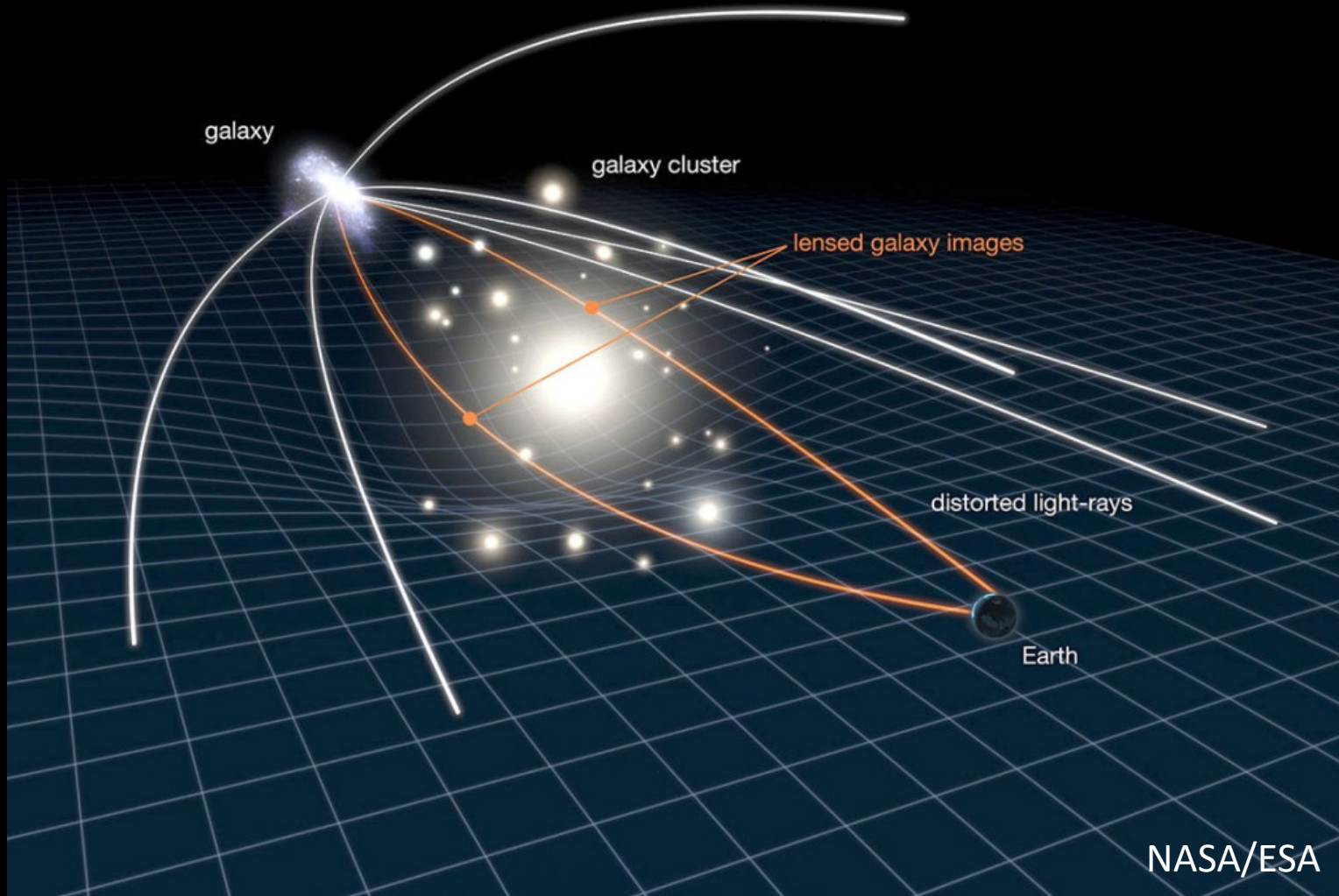
What we
expected to see



We don't just see evidence for dark matter
in the rotation of galaxies



Gravitational Lensing



A near perfect alignment of two galaxies

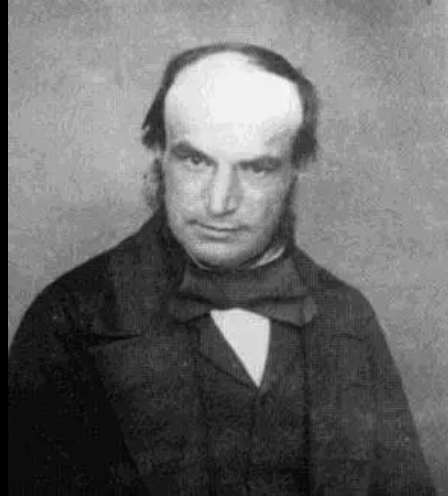


So, are we all convinced that dark matter exists?

The unusual orbit of Uranus

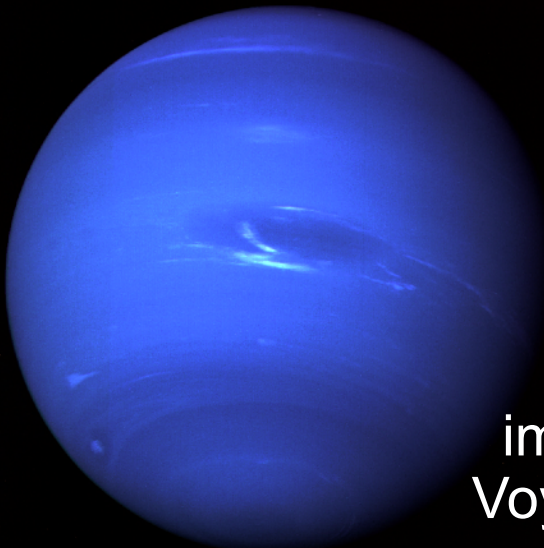


Urbain Le Verrier



John Couch Adams

Independently predicted the position of a new planet, based on anomalies in the orbit of Uranus.



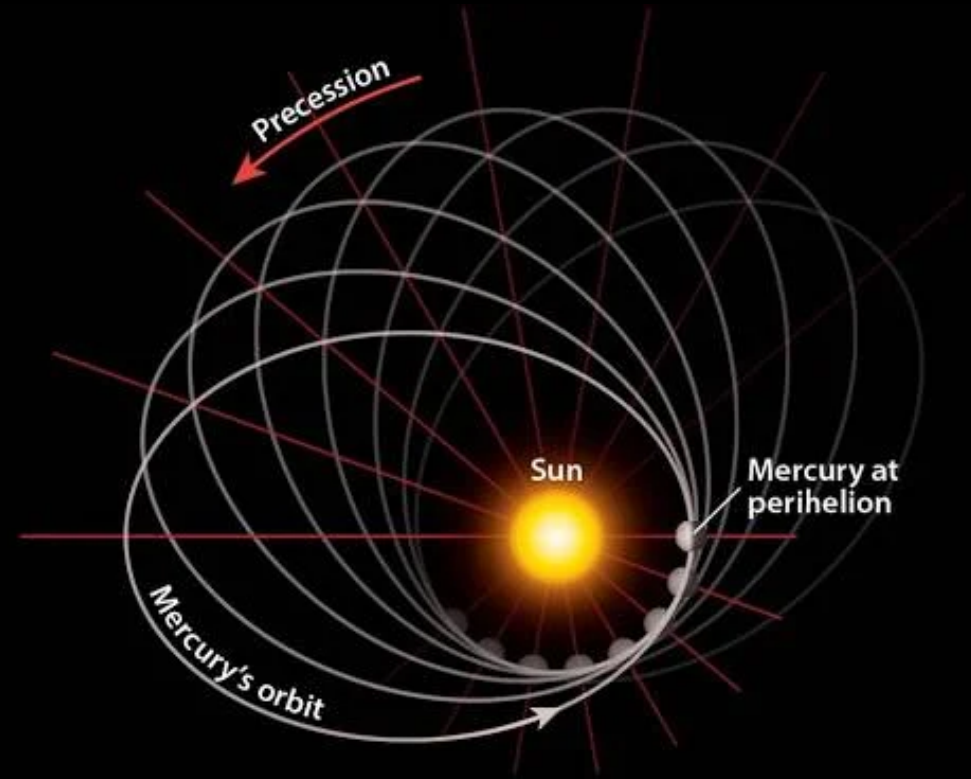
Neptune,
imaged by the
Voyager 2 probe

It was first observed in 1846, just 1 degree away from where Le Verrier had predicted.

The unusual orbit of Mercury



Urbain Le Verrier



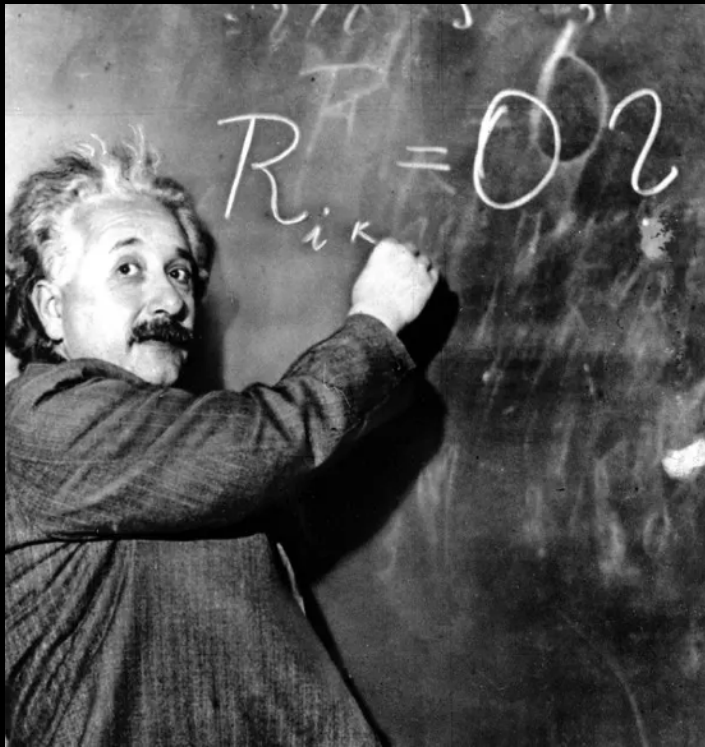
Encouraged by his success with Neptune, Le Verrier posited that the precession of Mercury's orbit was due to an unseen planet inside of the orbit of Mercury.

He even gave the planet a name: **Vulcan**

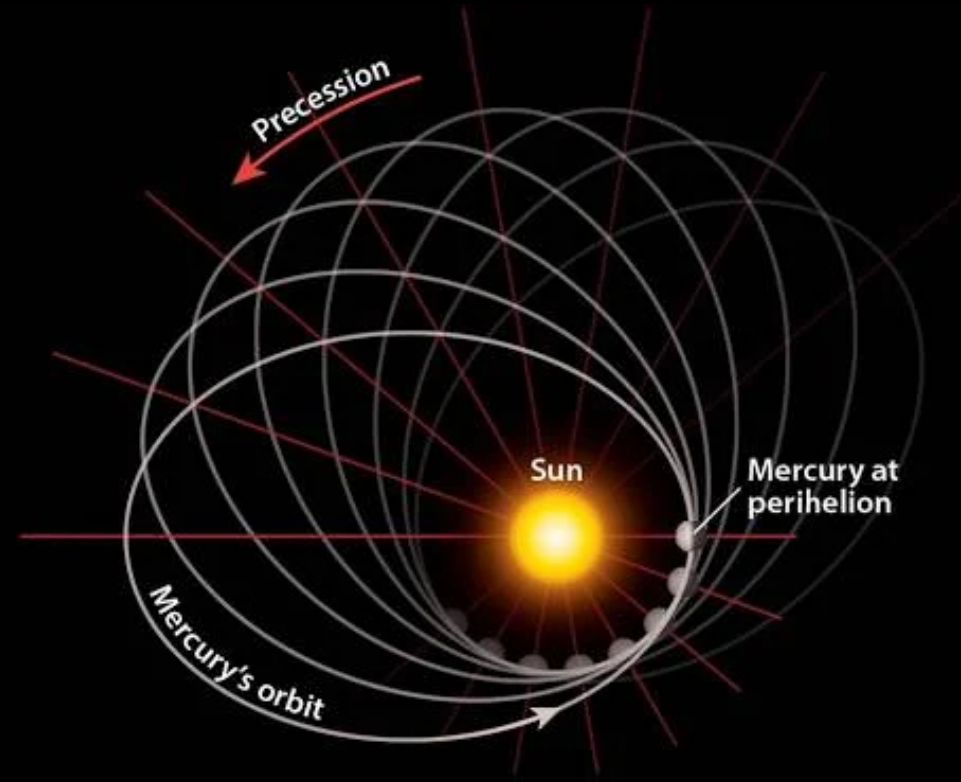
But no such planet was ever found.

The unusual orbit of Mercury

Mercury's orbit
remained a mystery
until 1915

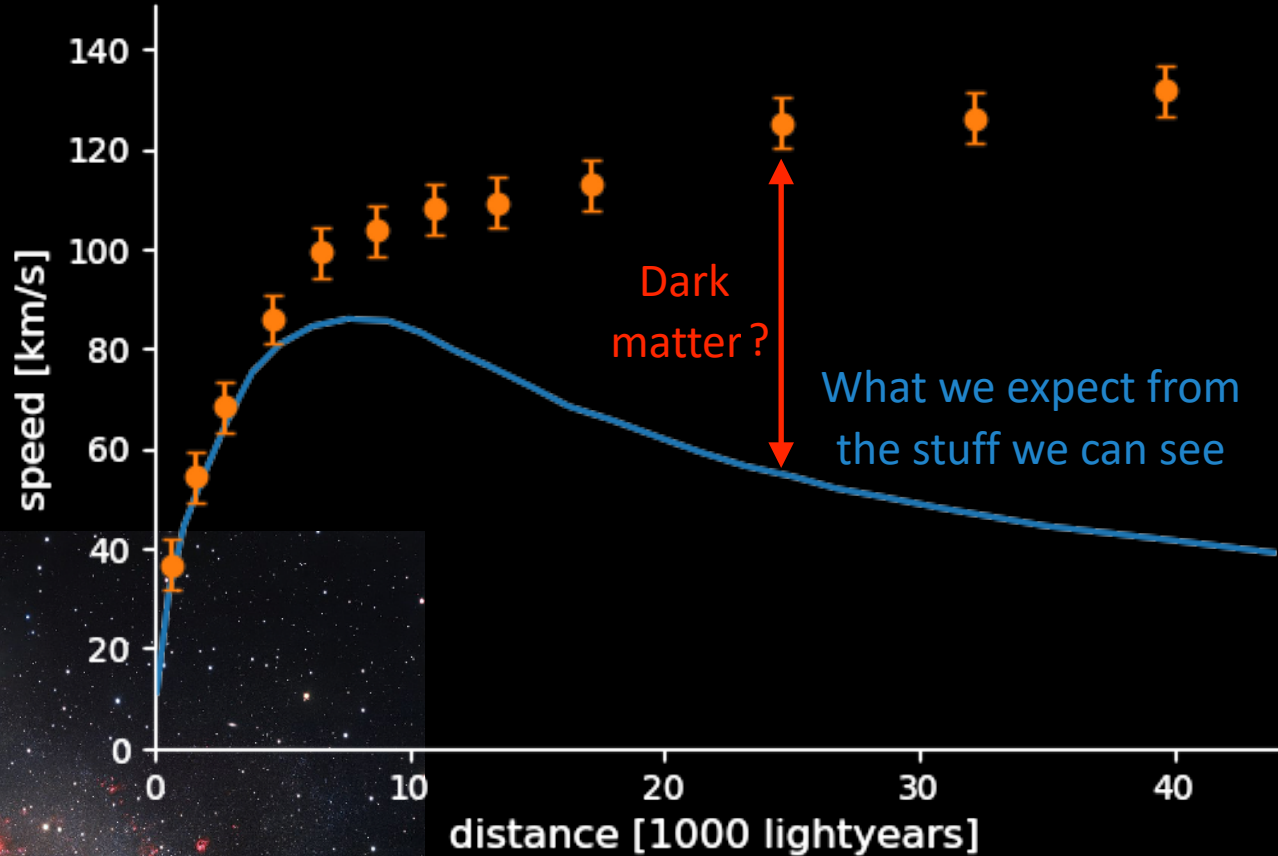


Albert Einstein at the
Carnegie Observatories

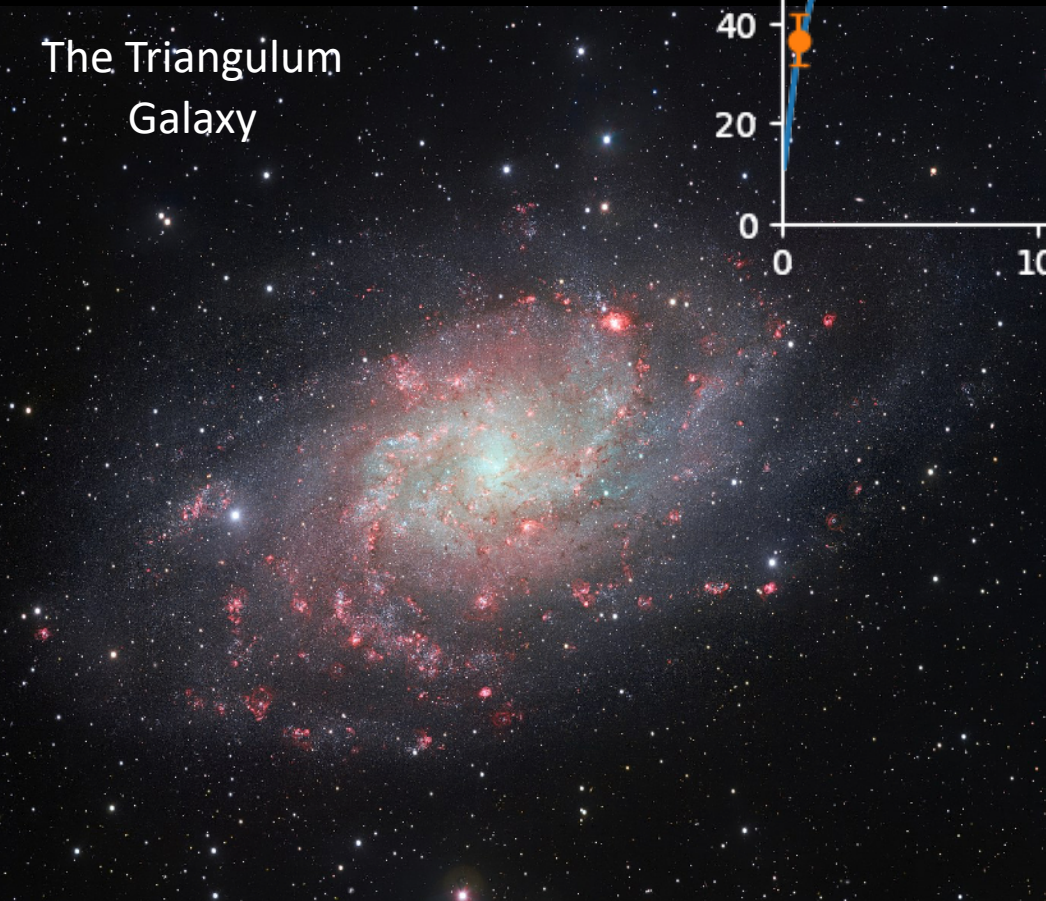


Einstein's new theory of
gravity, General Relativity,
accounted for the precession
of Mercury's orbit.

Instead of
dark
matter...

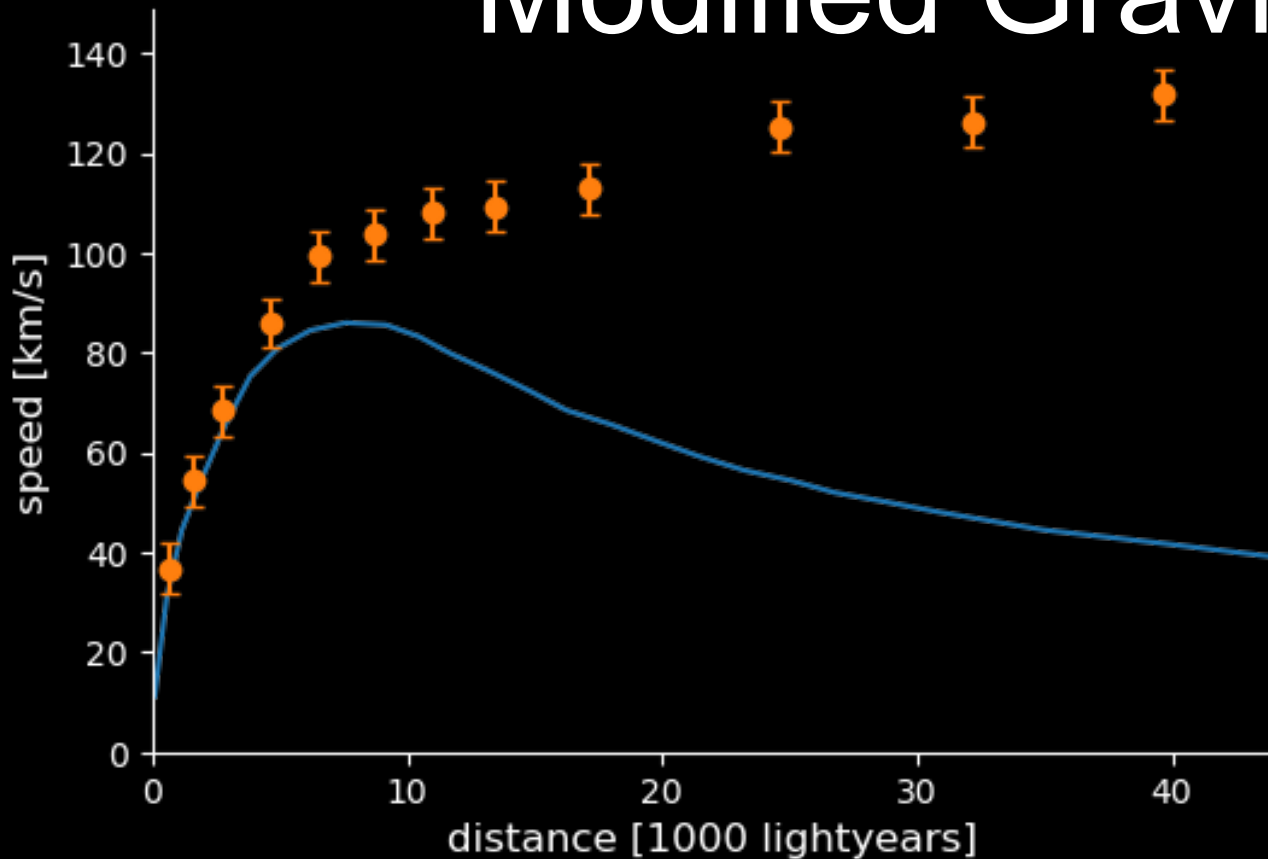


The Triangulum
Galaxy



can we modify
our theory of
gravity?

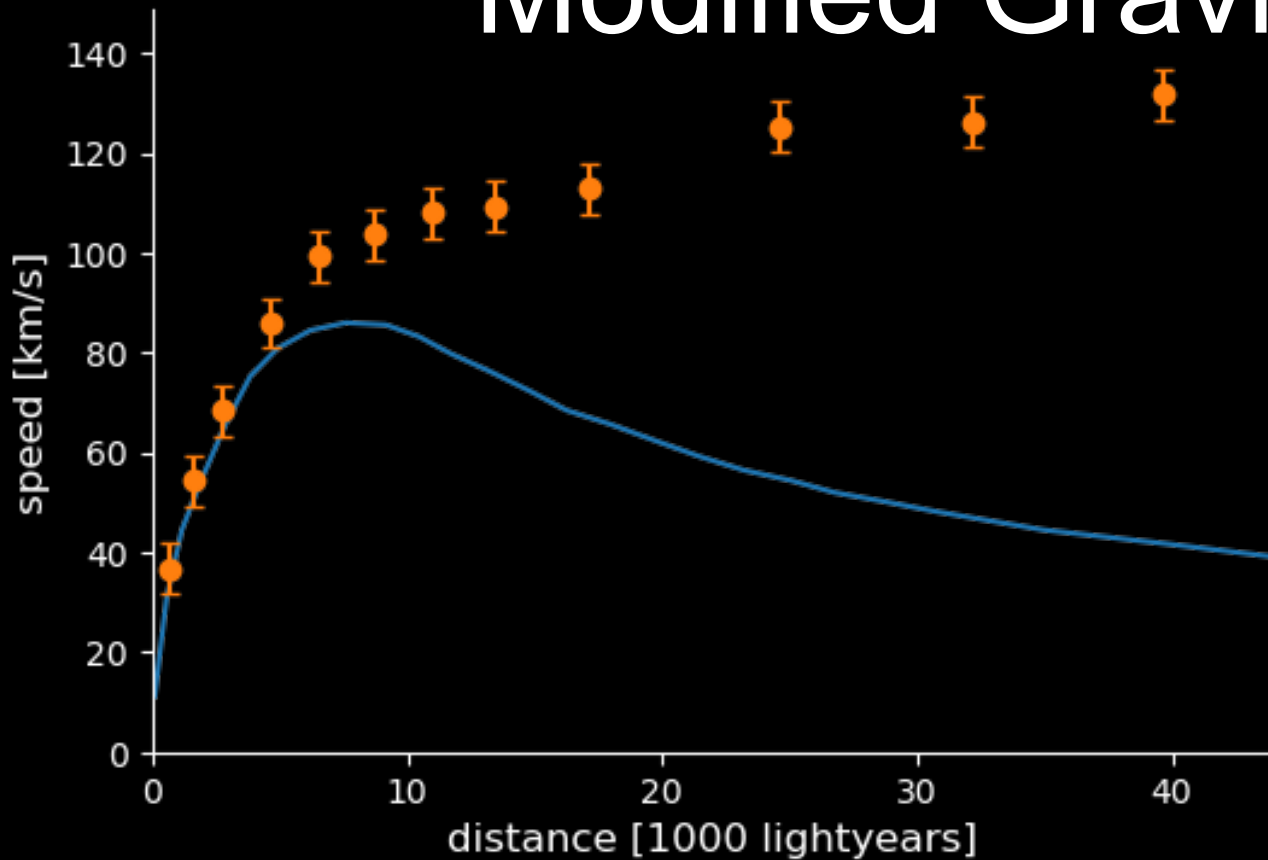
Consider a Simple 'Modified Gravity'



The gravitational
acceleration due to a point
mass, M , a distance, r , away:

$$a_g = \frac{GM}{r^2}$$

Consider a Simple 'Modified Gravity'



This wouldn't show up
in the Solar System if r_0
was large enough

A modified
acceleration law:

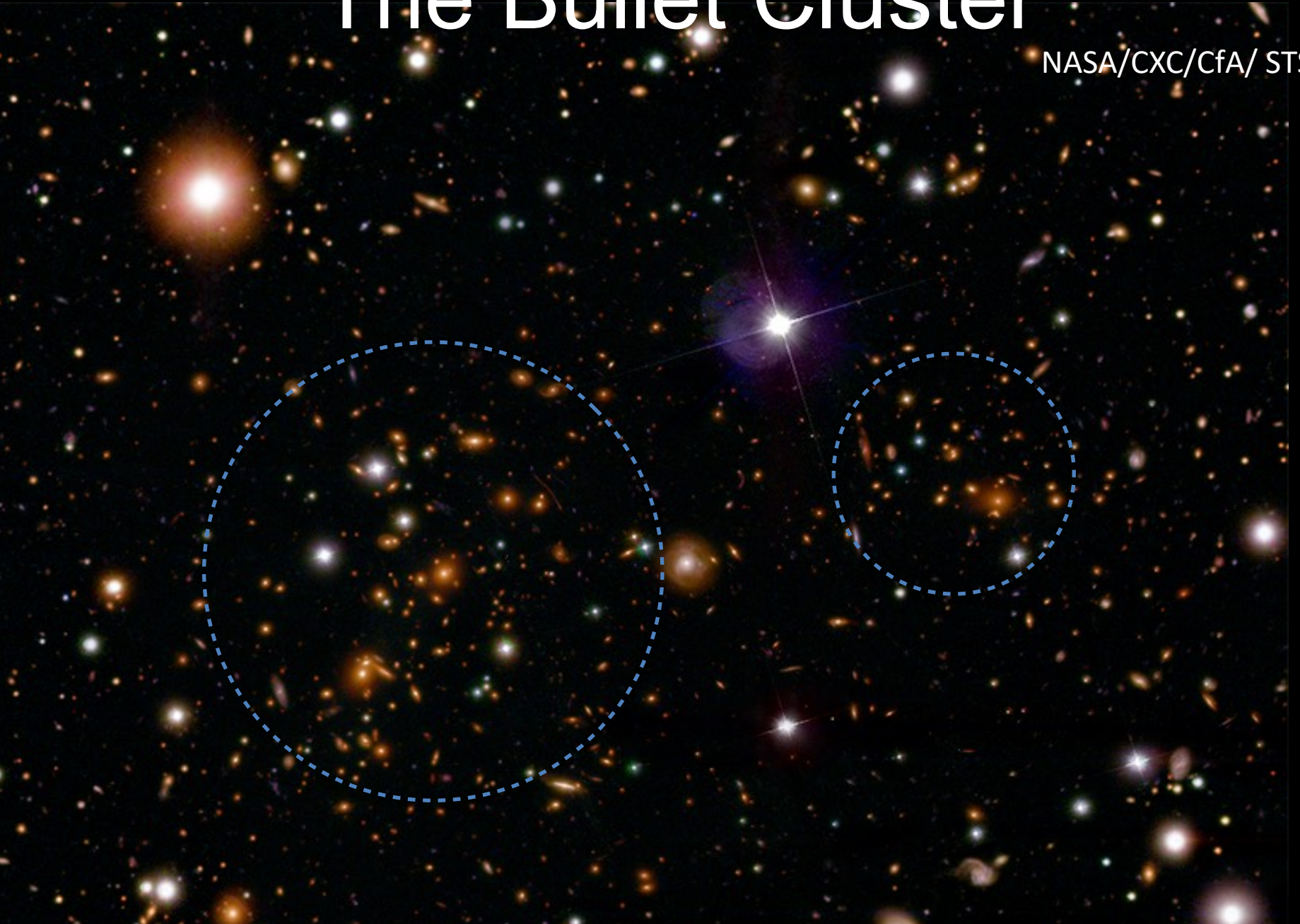
$$a_g = \frac{GM}{r^2} \left(1 + \frac{r}{r_0} \right)$$

How can we distinguish between dark matter, and a modification to gravity?

Find some dark matter that is not in the same location as regular matter!

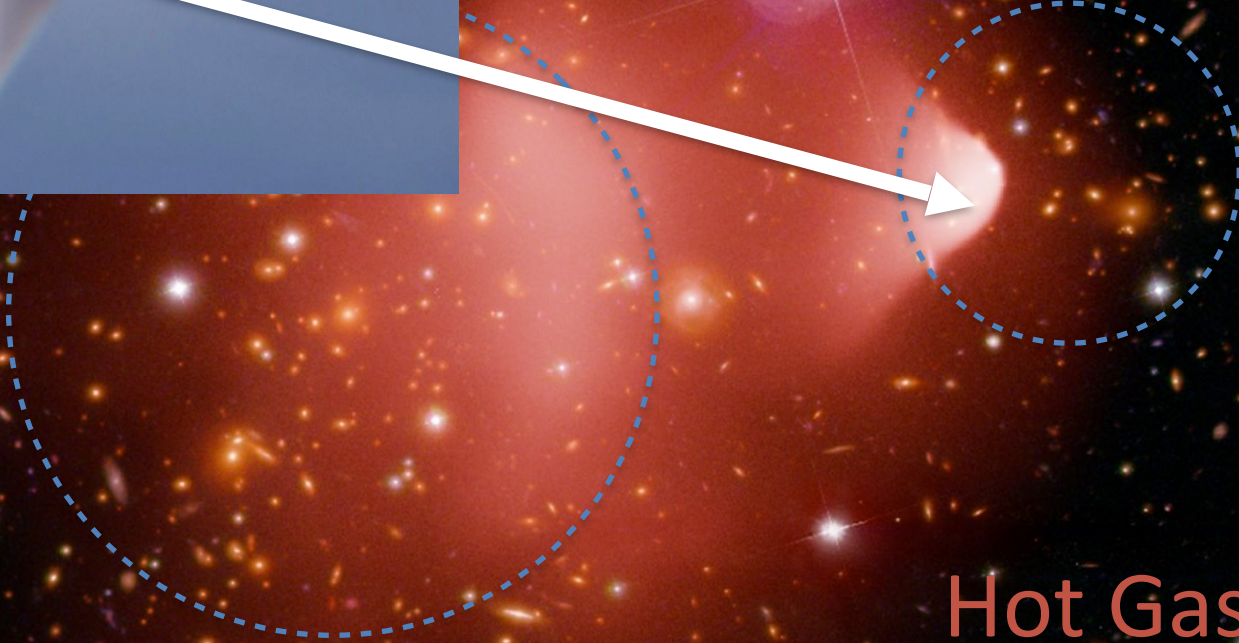
The Bullet Cluster

NASA/CXC/CfA/ STScI



The Bullet Cluster

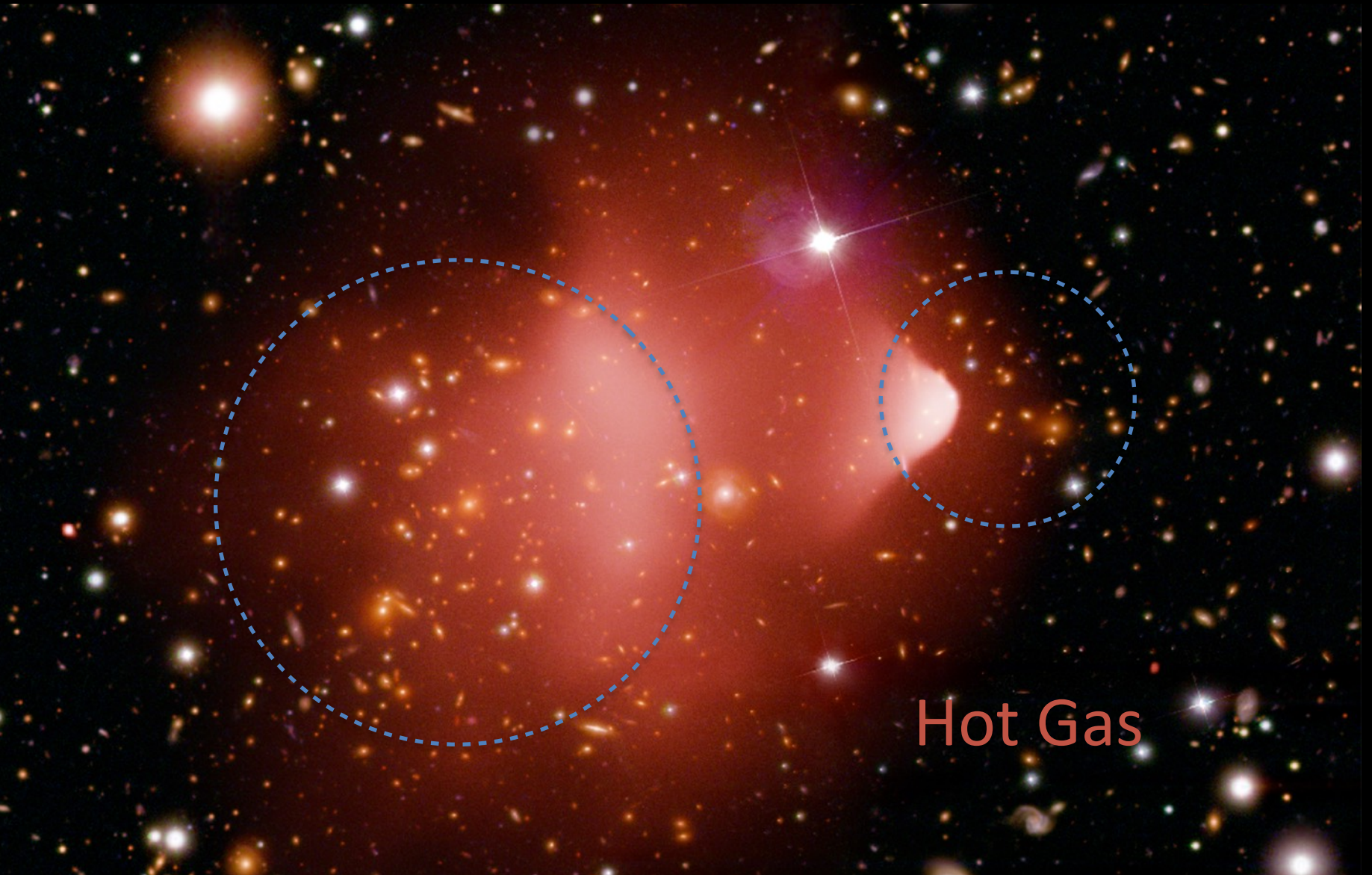
NASA/CXC/CfA/ STScI



Hot Gas

The Bullet Cluster

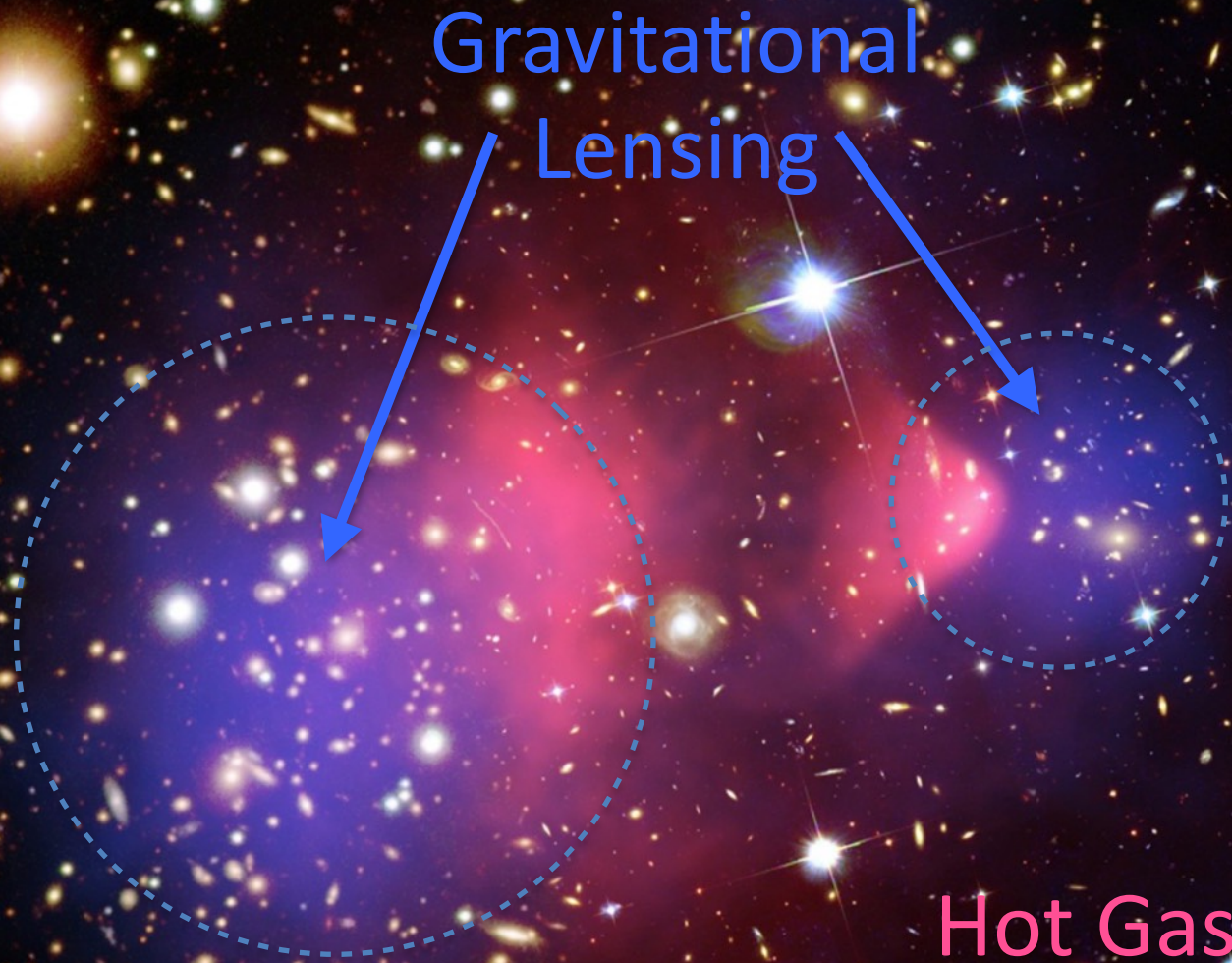
NASA/CXC/CfA/ STScI



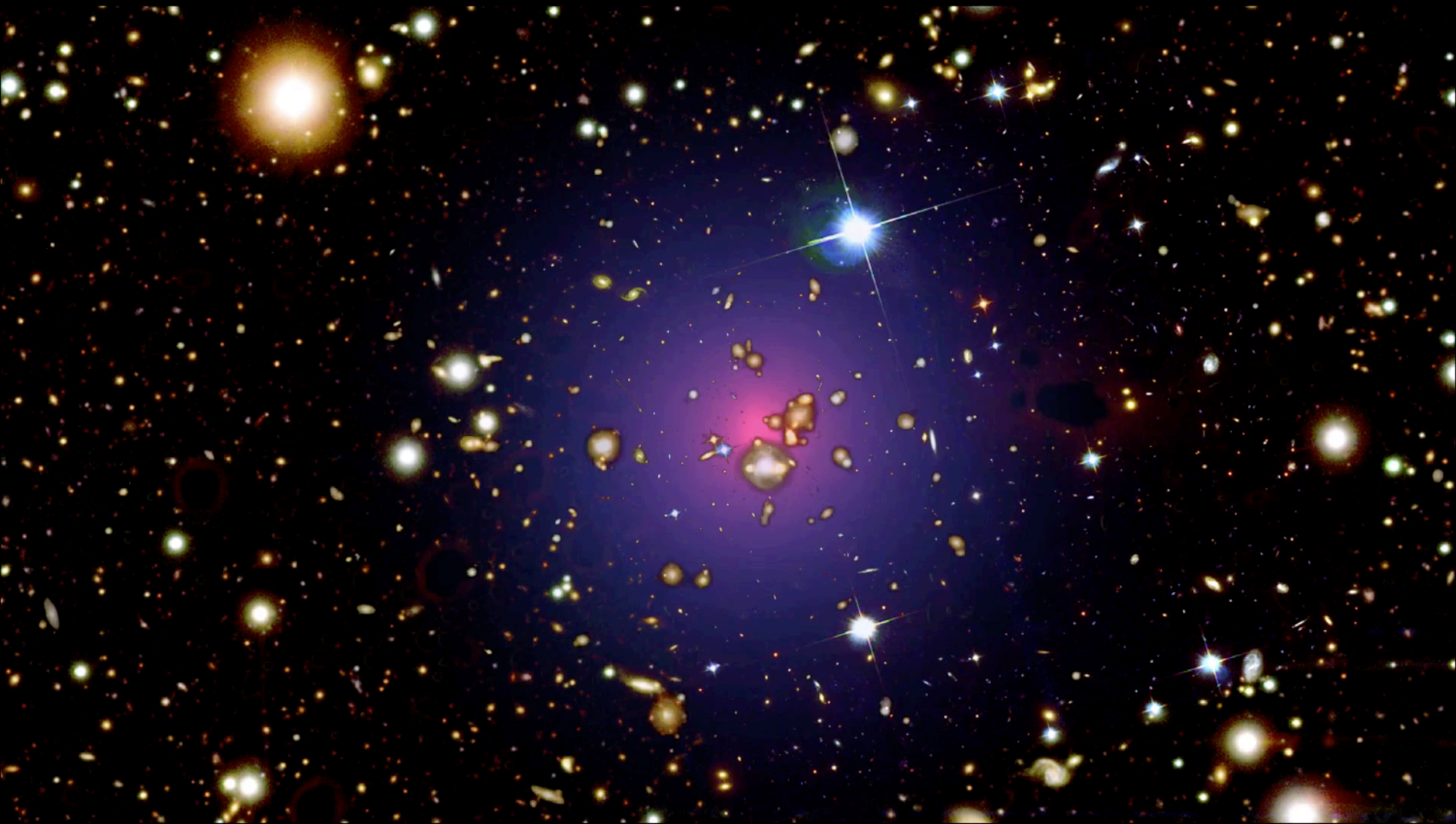
Hot Gas

The Bullet Cluster

NASA/CXC/CfA/ STScI



A Billion Year Video



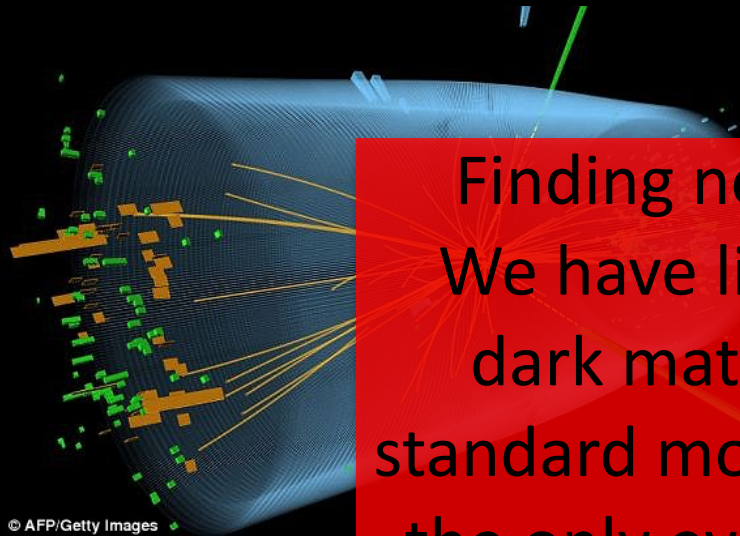
If we are confident dark matter exists, can we work out what it is?

Ways to uncover the nature of dark matter

Make Some (Particle Collider Searches)

Find Some (Direct Detection)

Finding nothing can be useful!
We have limits on how strongly dark matter can interact with standard model particles. But so far the only evidence for dark matter comes from its gravitational effects.



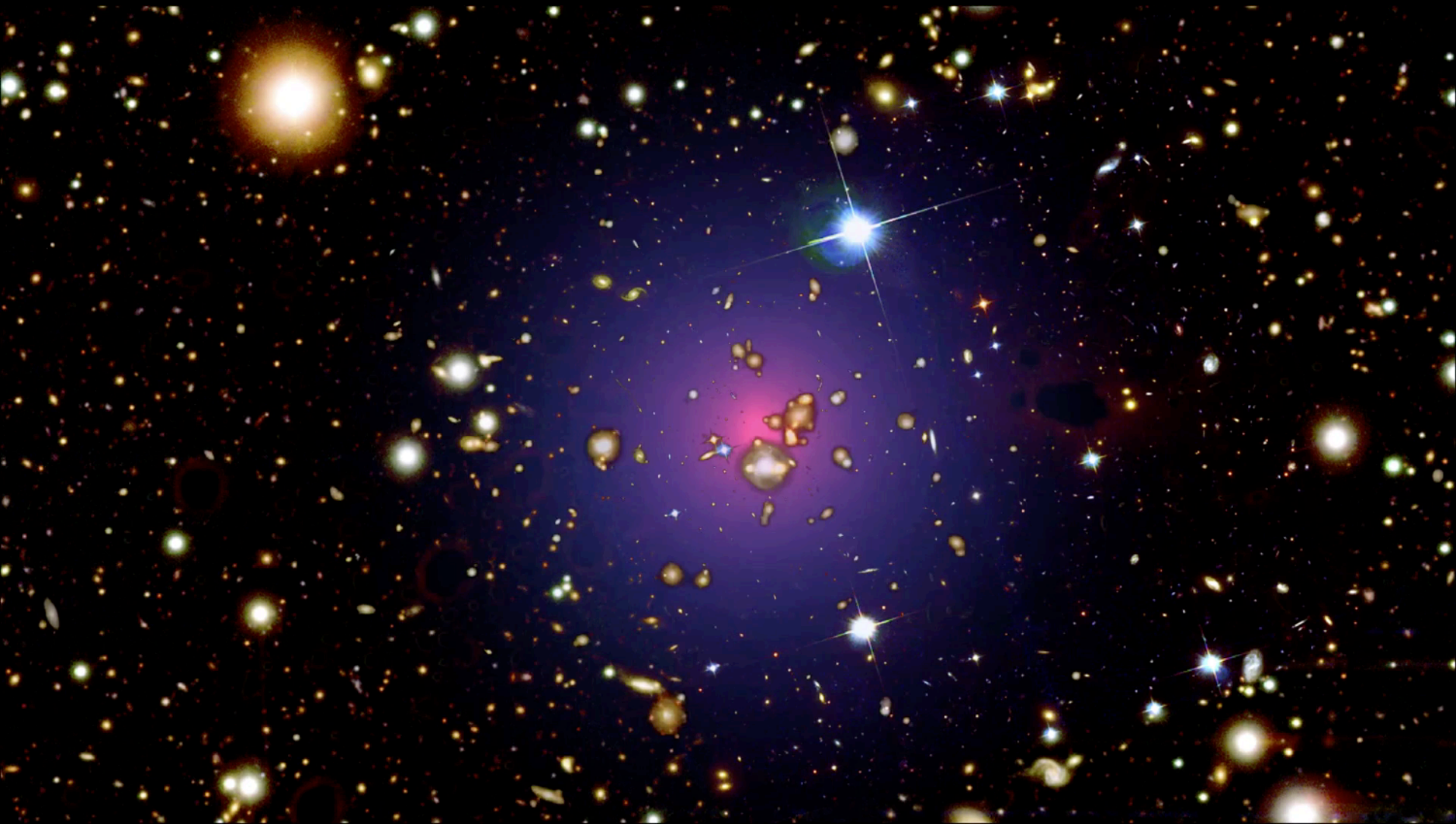
A Dark Matter Particle Collider

NASA/CXC/CfA/ STScI

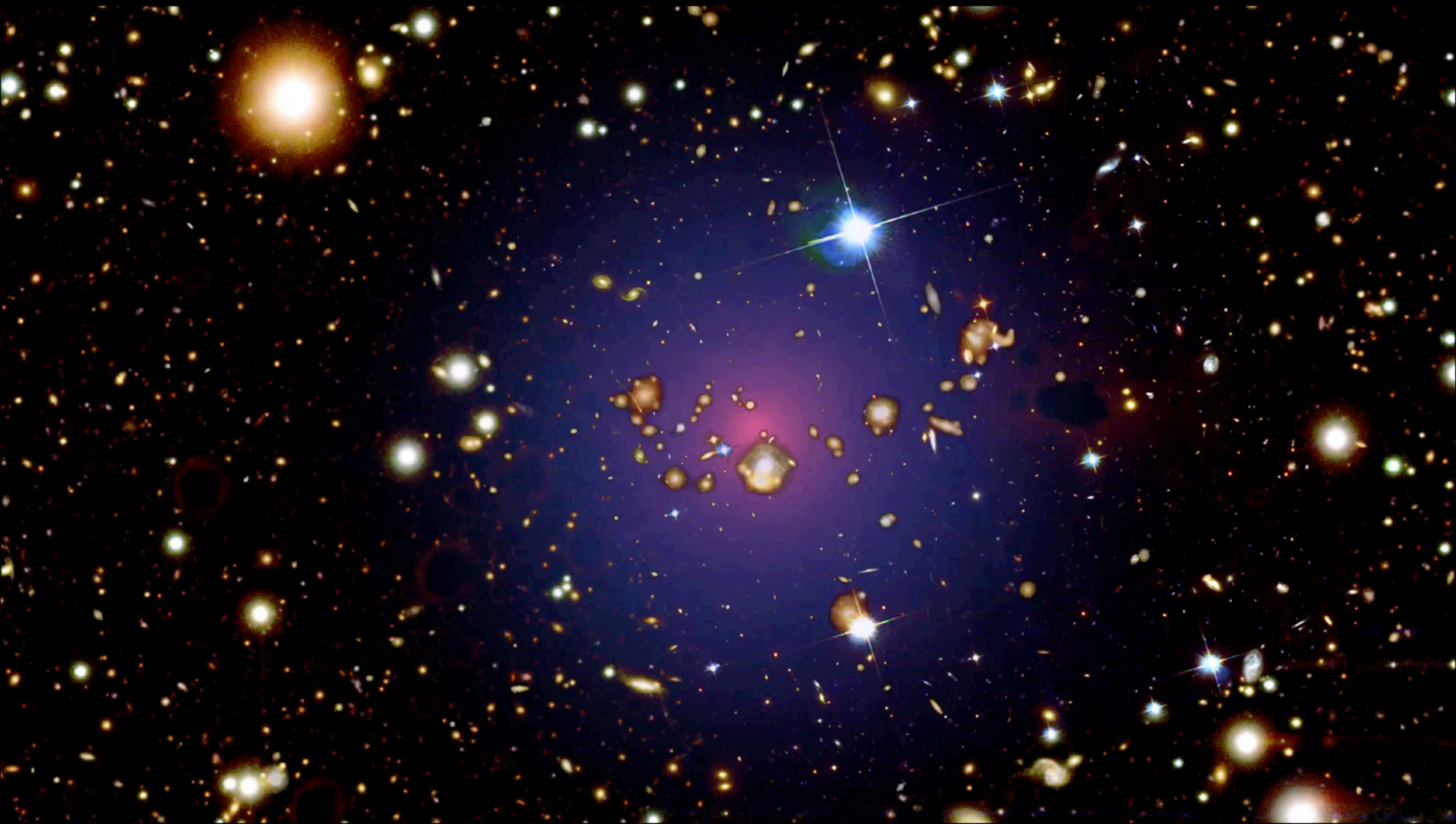


We can use the Bullet Cluster to test for dark matter “self-interactions”

“Collisionless” dark matter



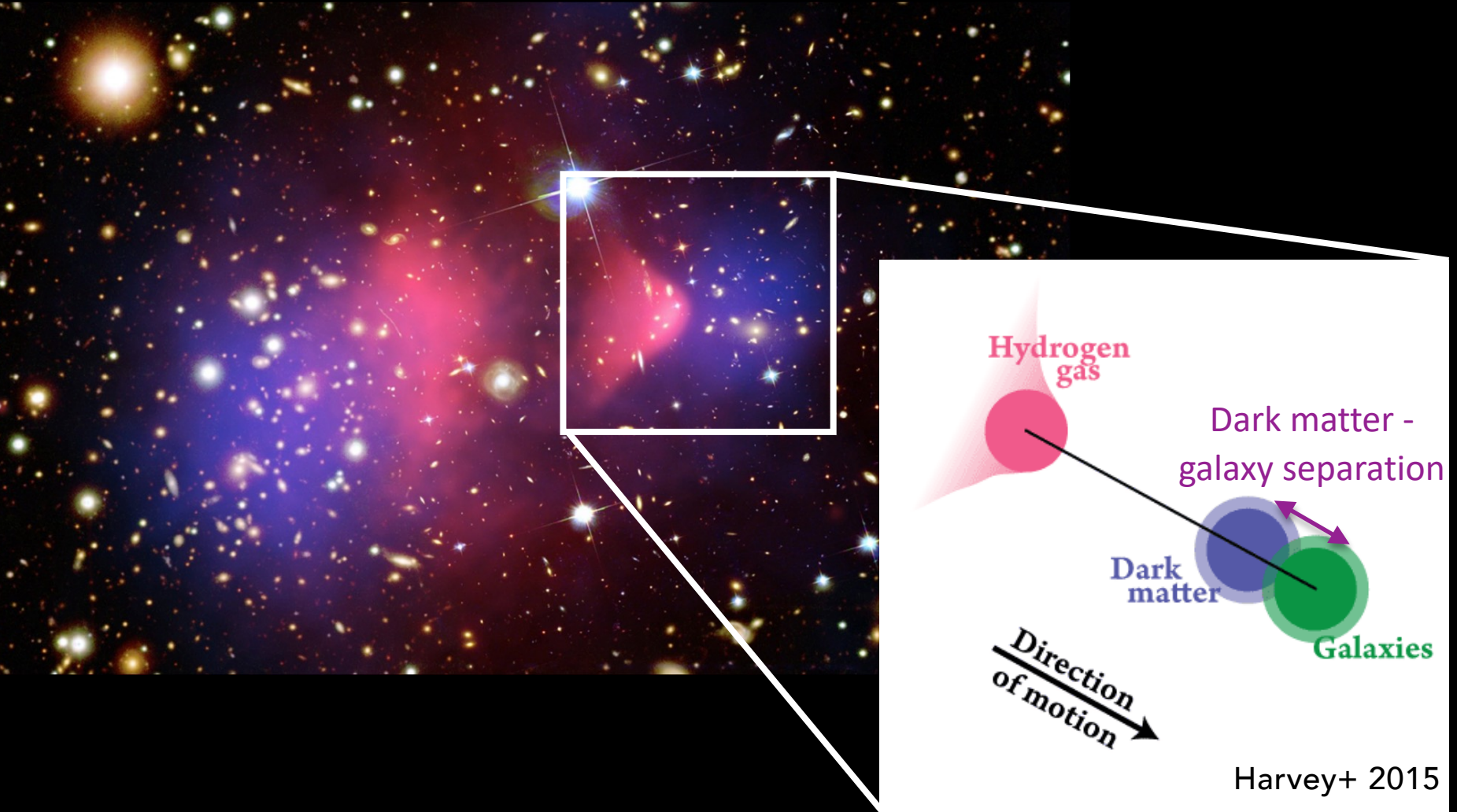
Make dark matter “very sticky”



Make dark matter “very sticky”

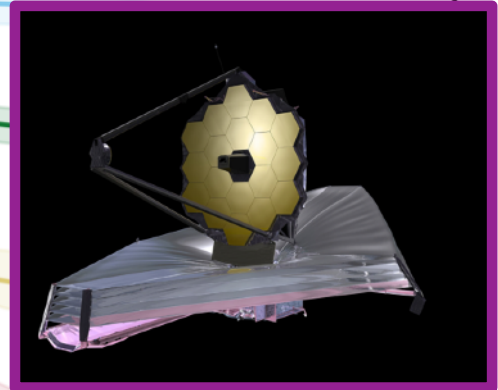
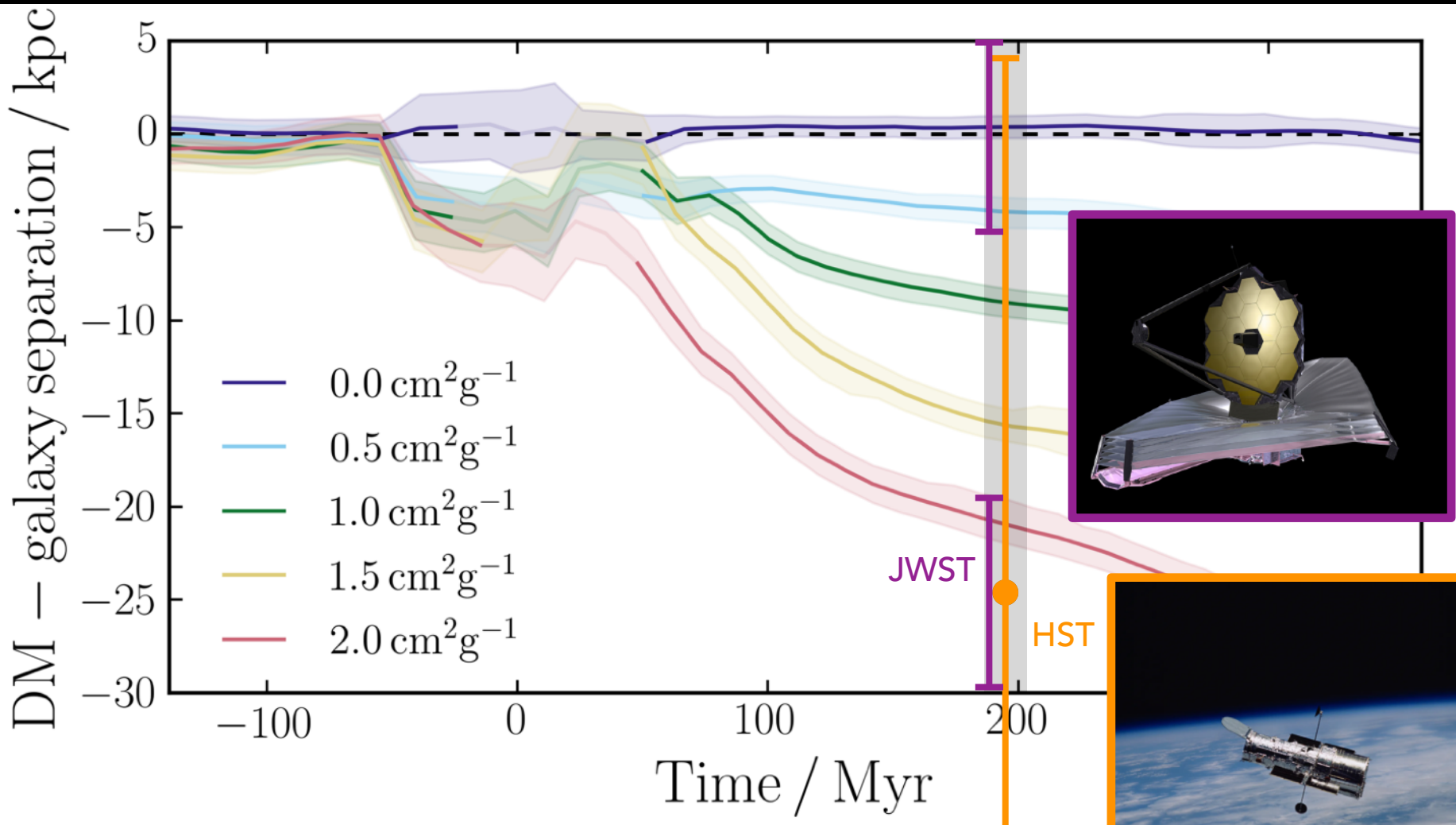


Make dark matter “a bit sticky”



Harvey+ 2015

Slightly sticky dark matter



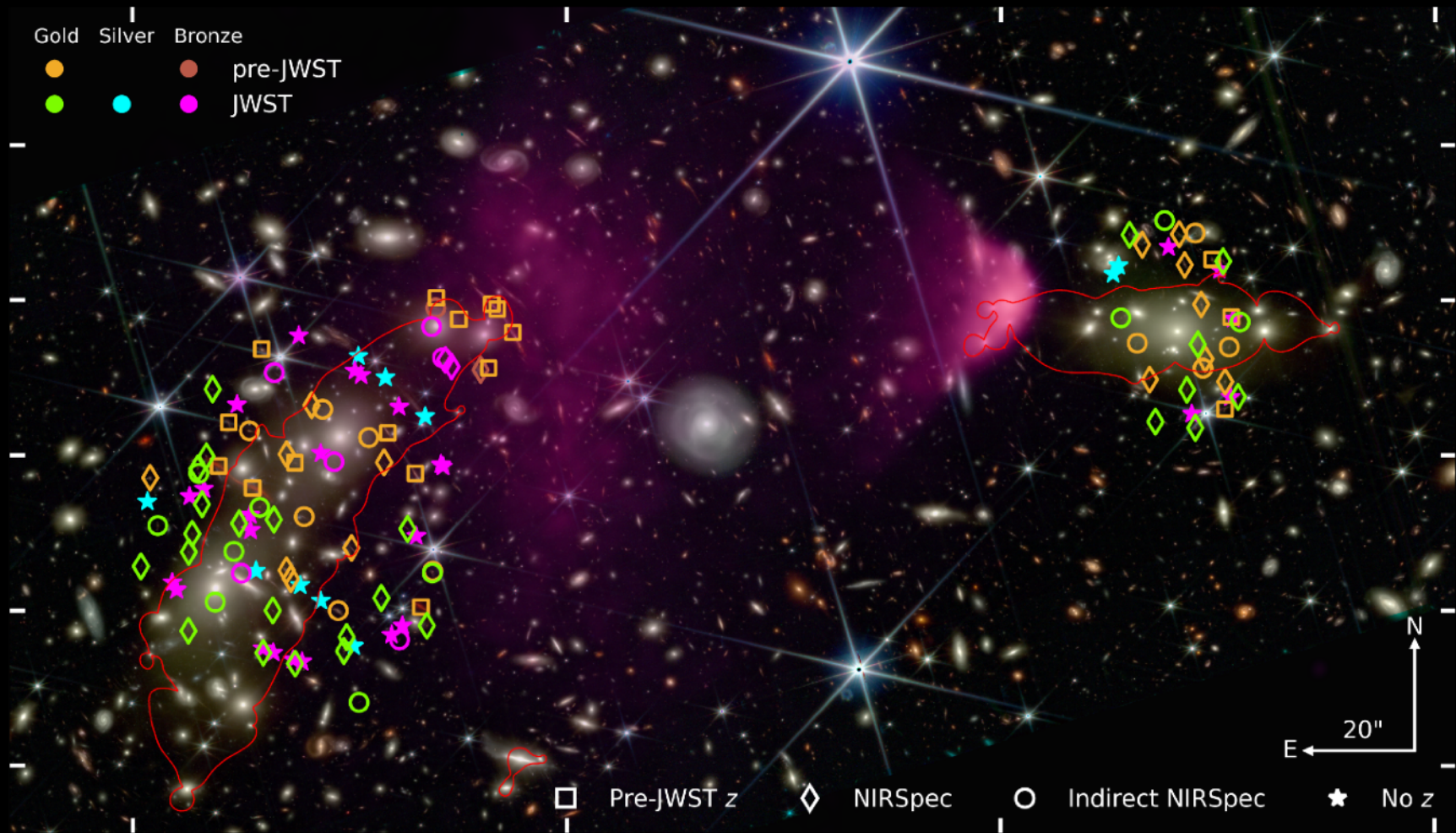
HST - 2006



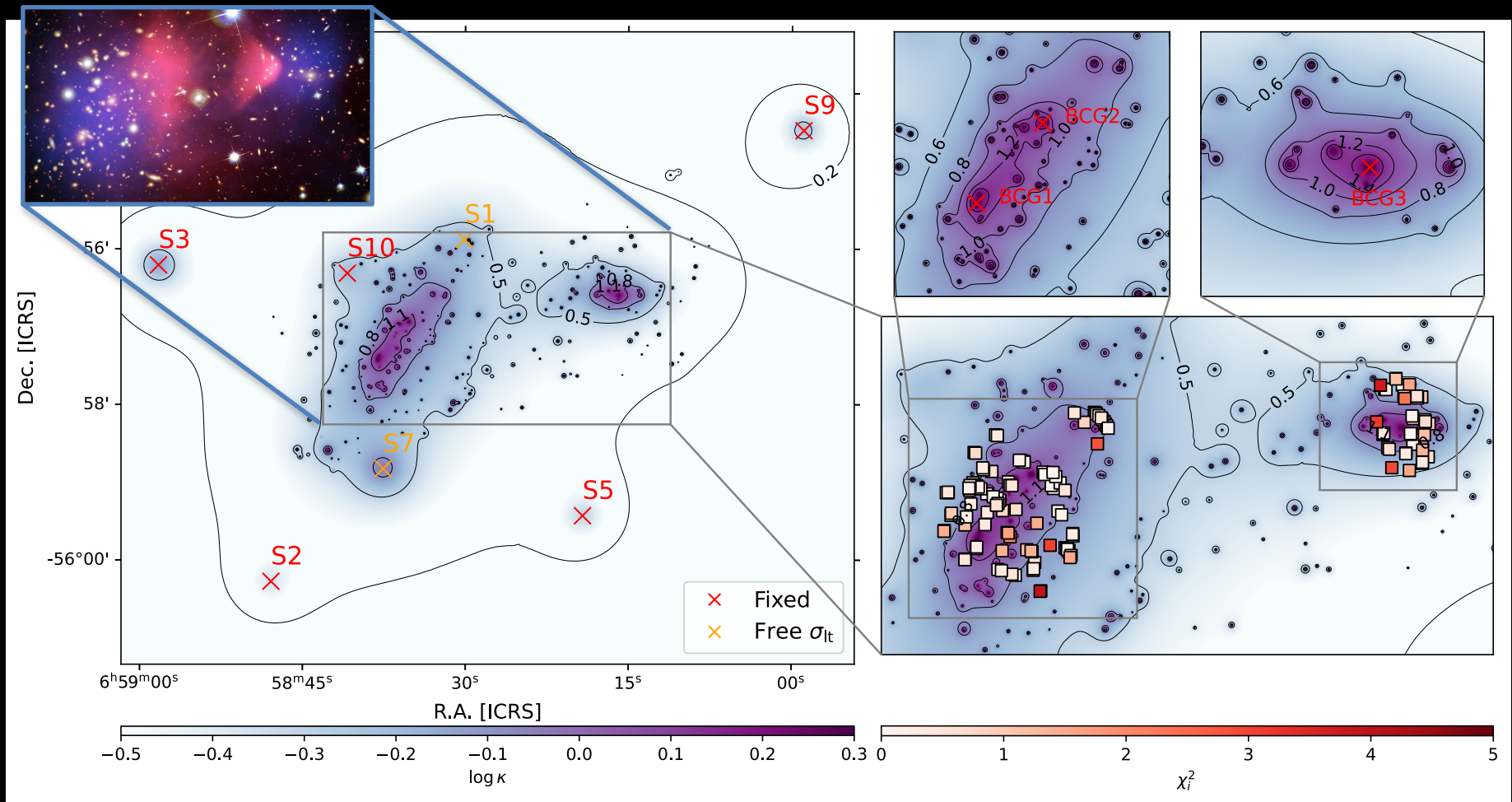
JWST - 2025



IDENTIFICATION OF MULTIPLY-IMAGED BACKGROUND GALAXIES



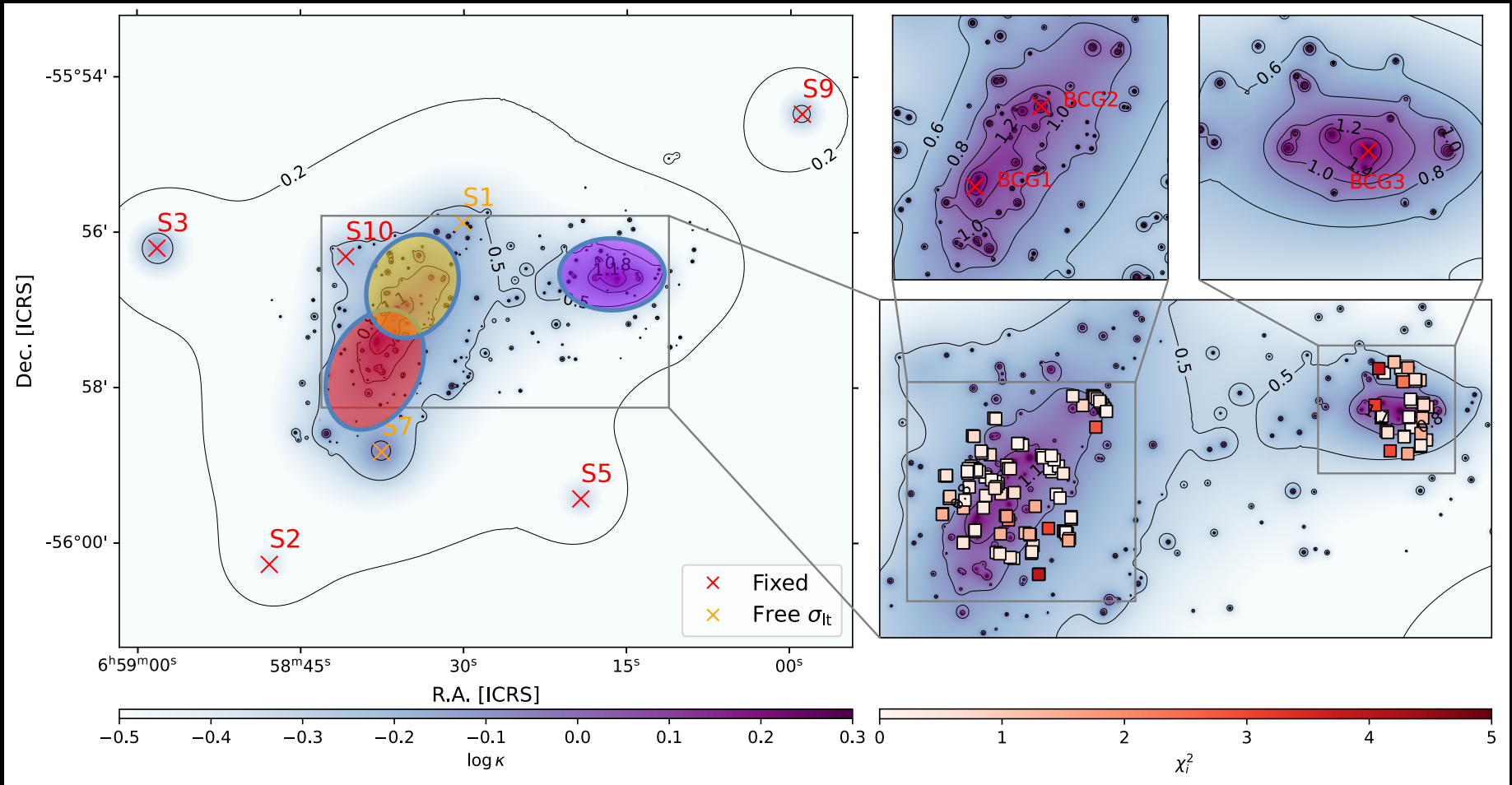
INFERRED MASS DISTRIBUTION



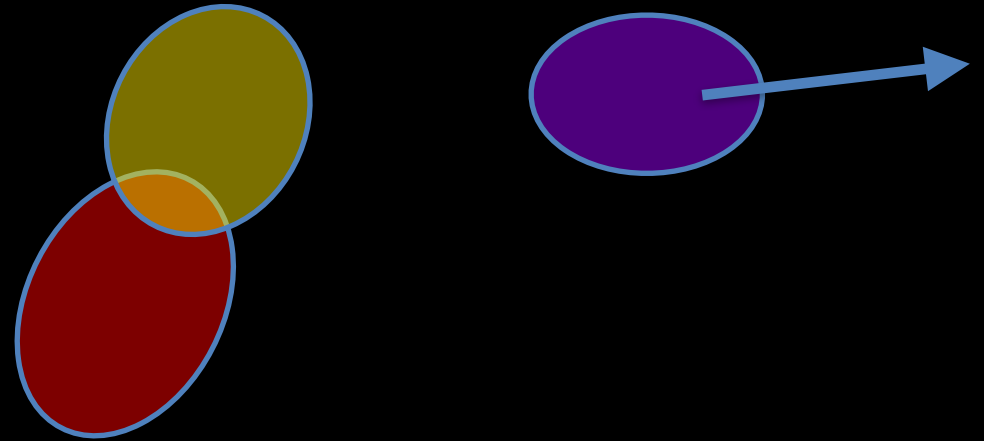
The mass distribution is considerably more complex than previously realised!

Currently thinking about what simulations we need to best interpret our observations.

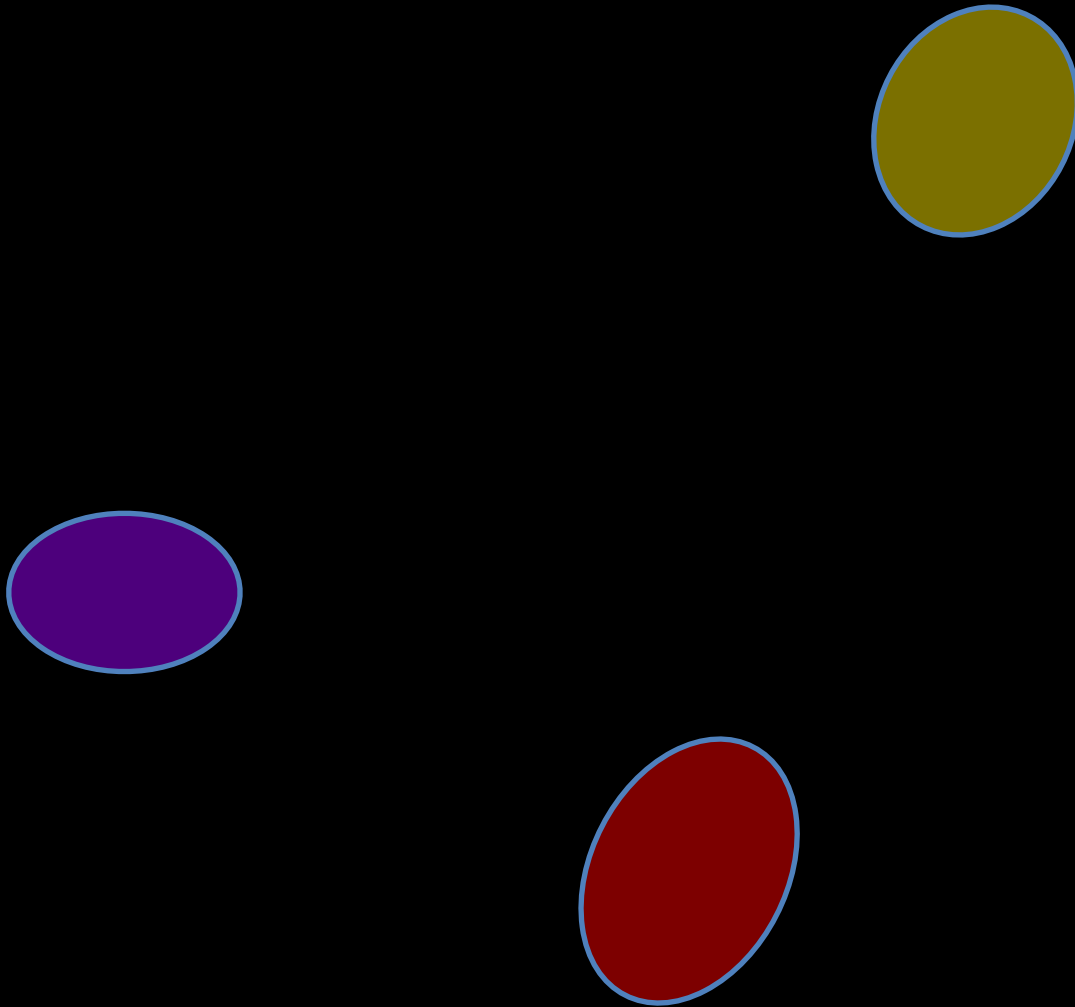
INFERRED MASS DISTRIBUTION



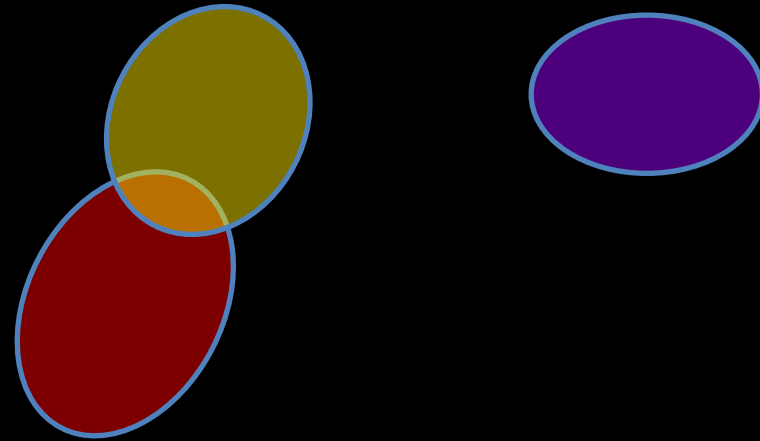
INFERRED MASS DISTRIBUTION



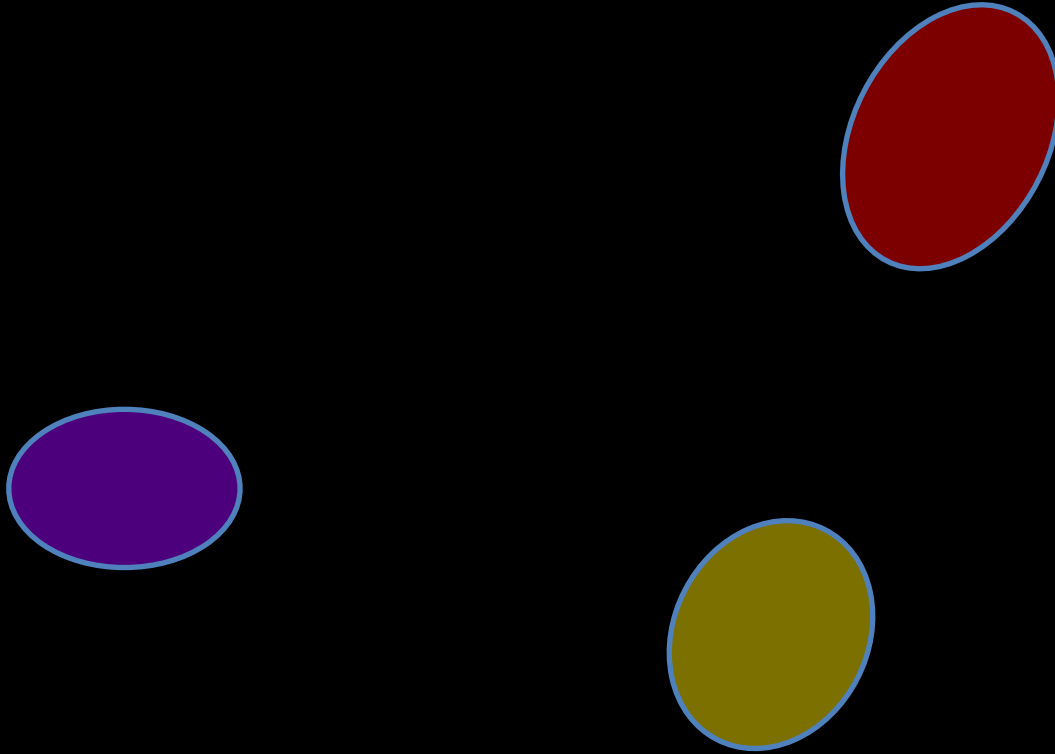
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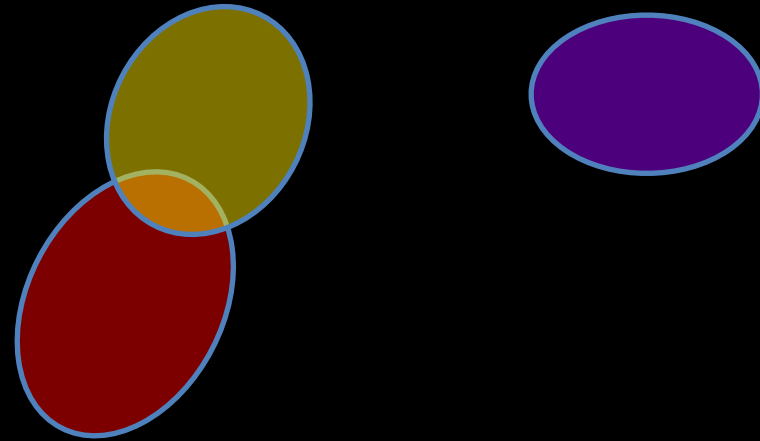
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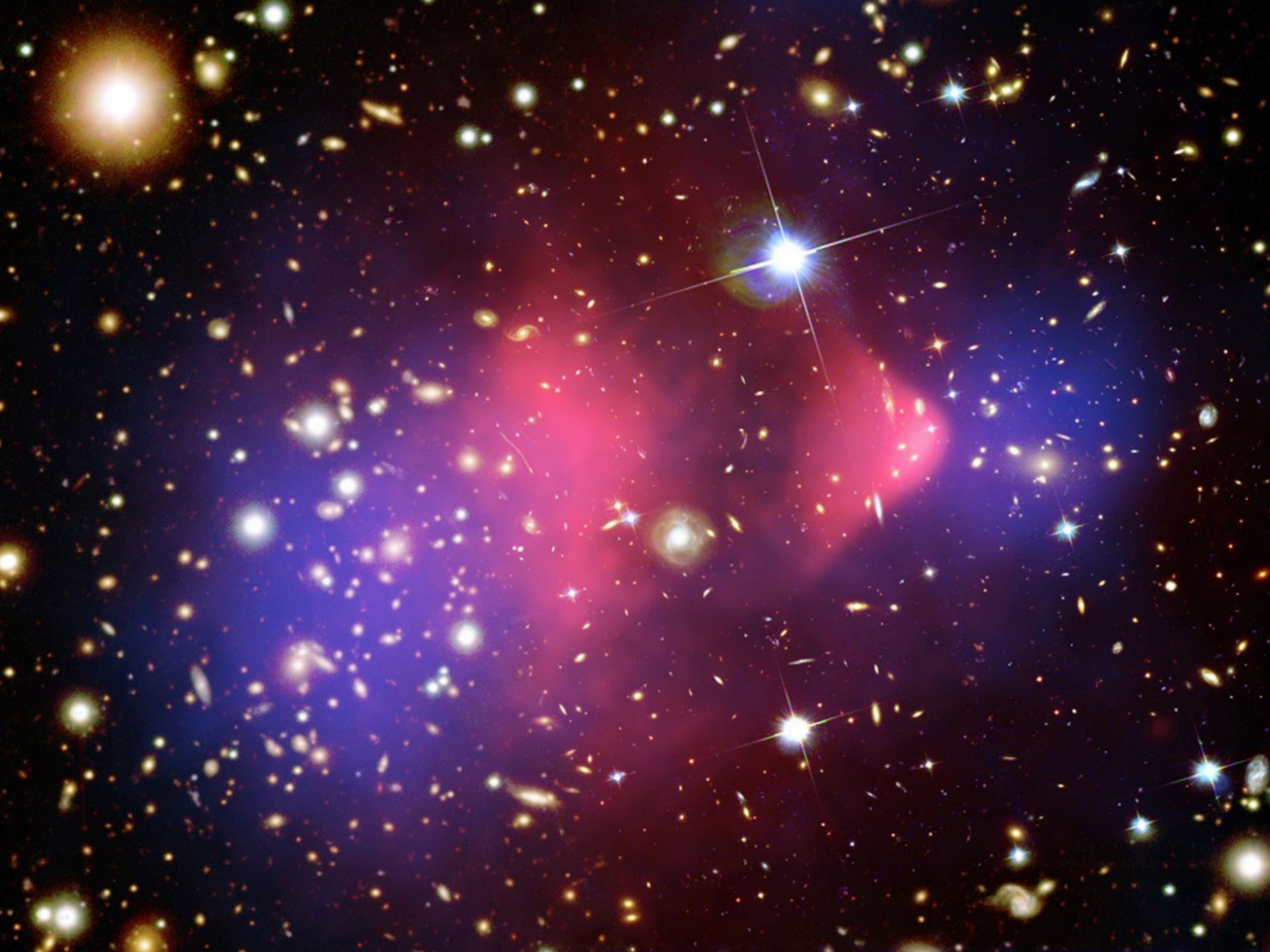


INFERRED MASS DISTRIBUTION

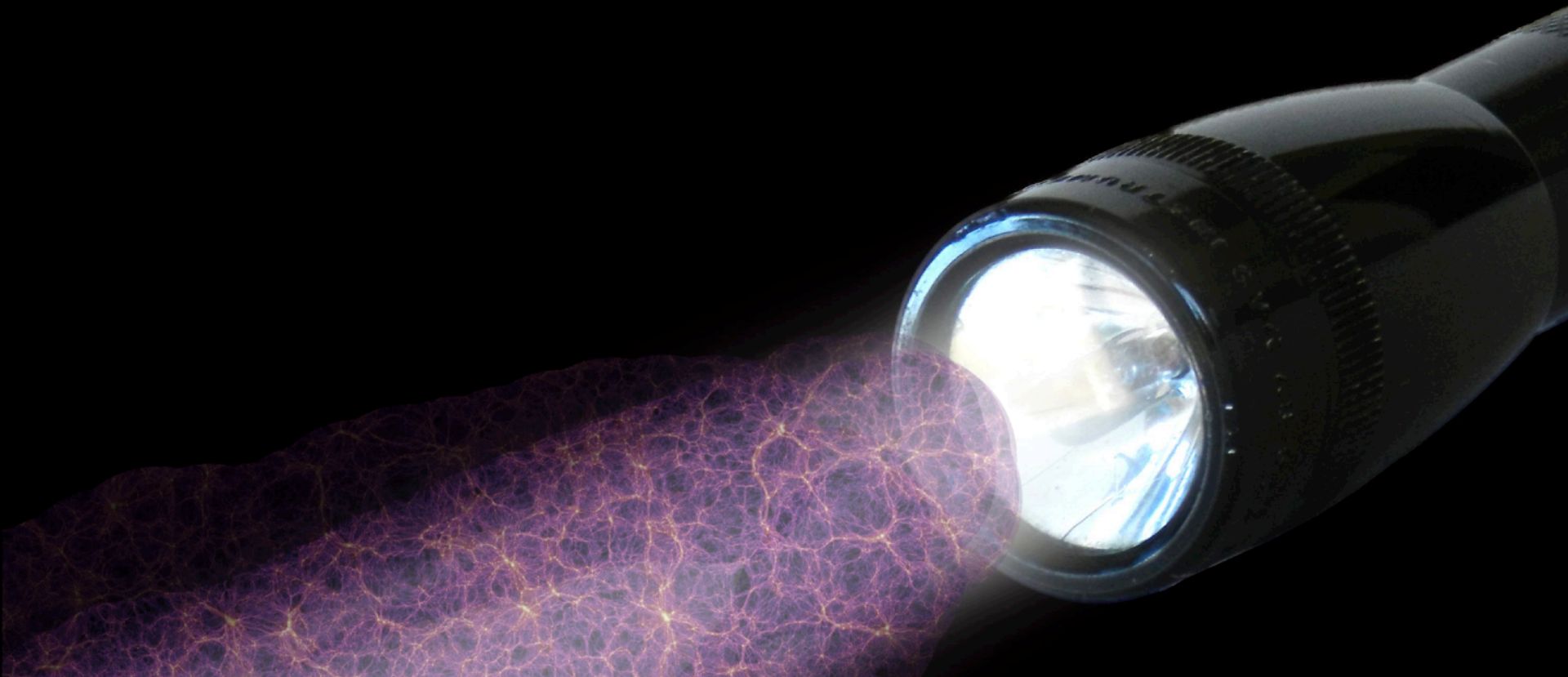


INFERRED MASS DISTRIBUTION



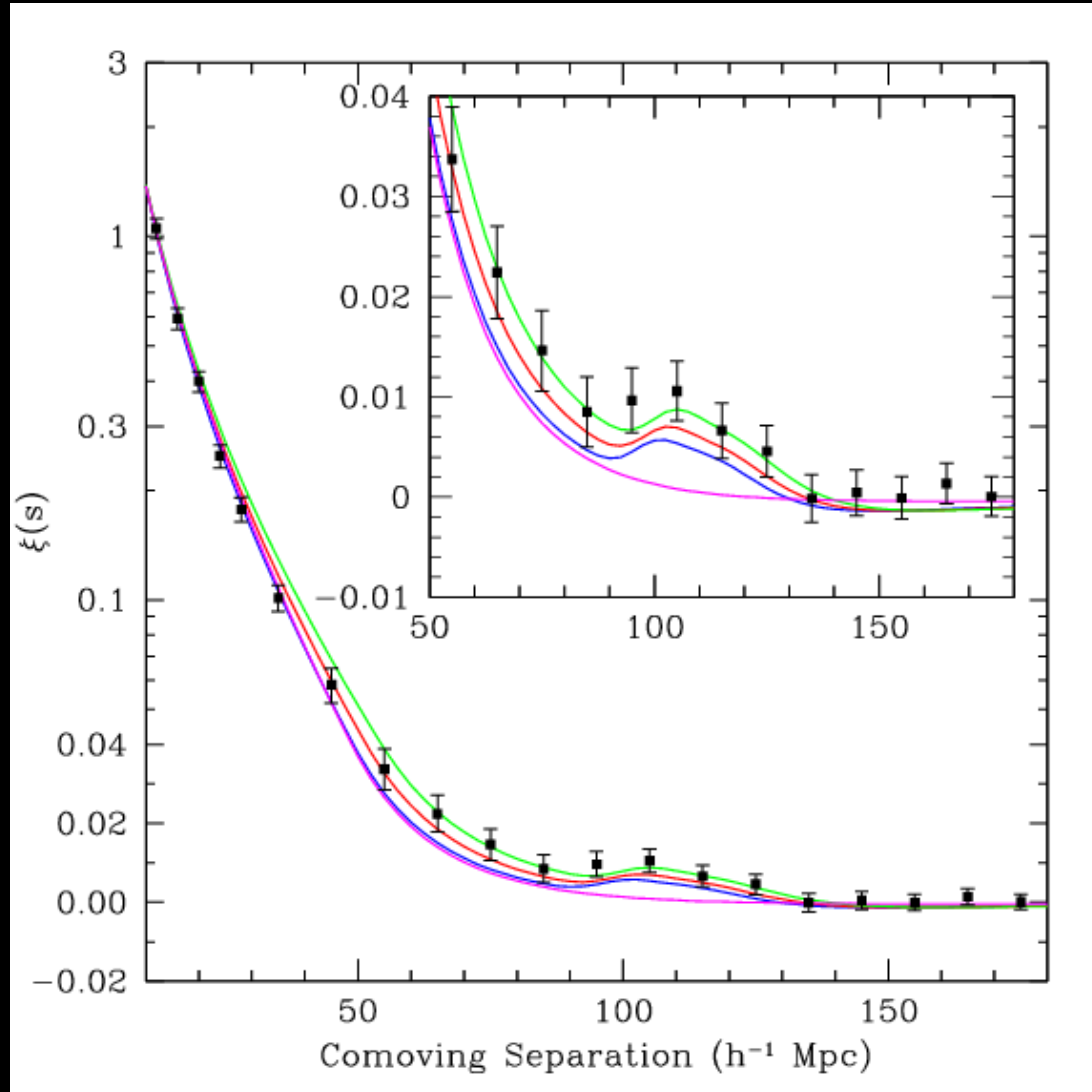


THANKS FOR LISTENING



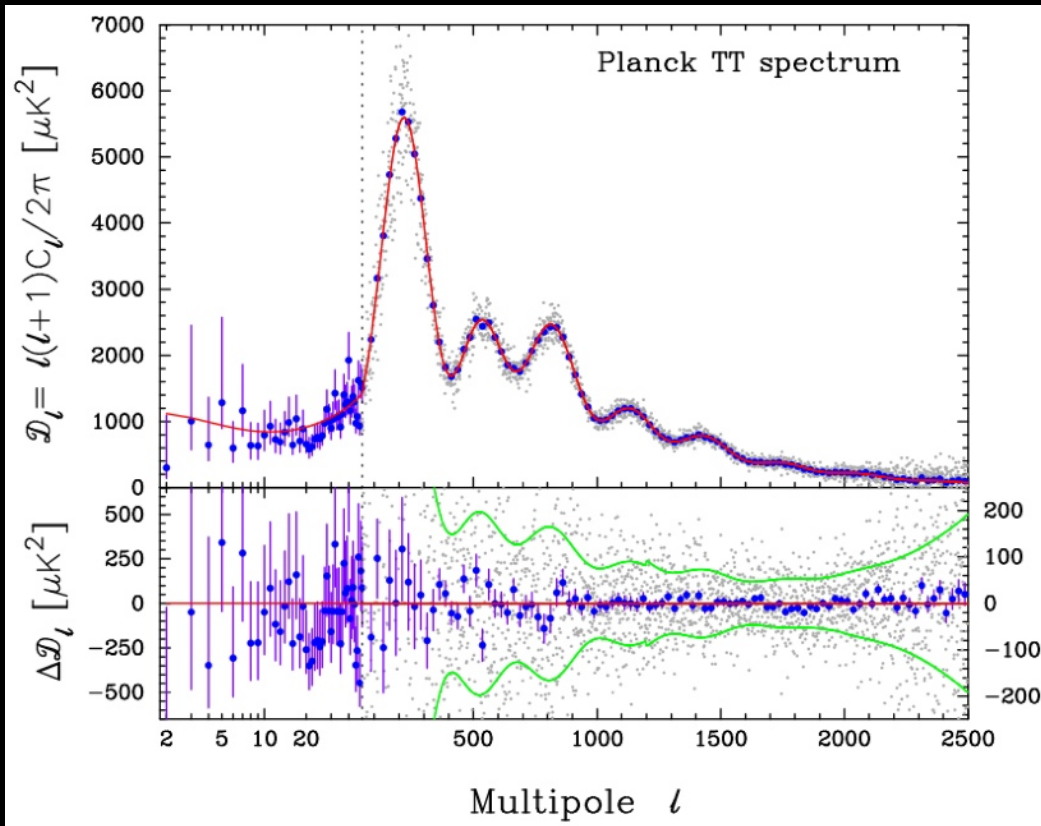
Miscellaneous stuff

Baryon Acoustic Oscillations

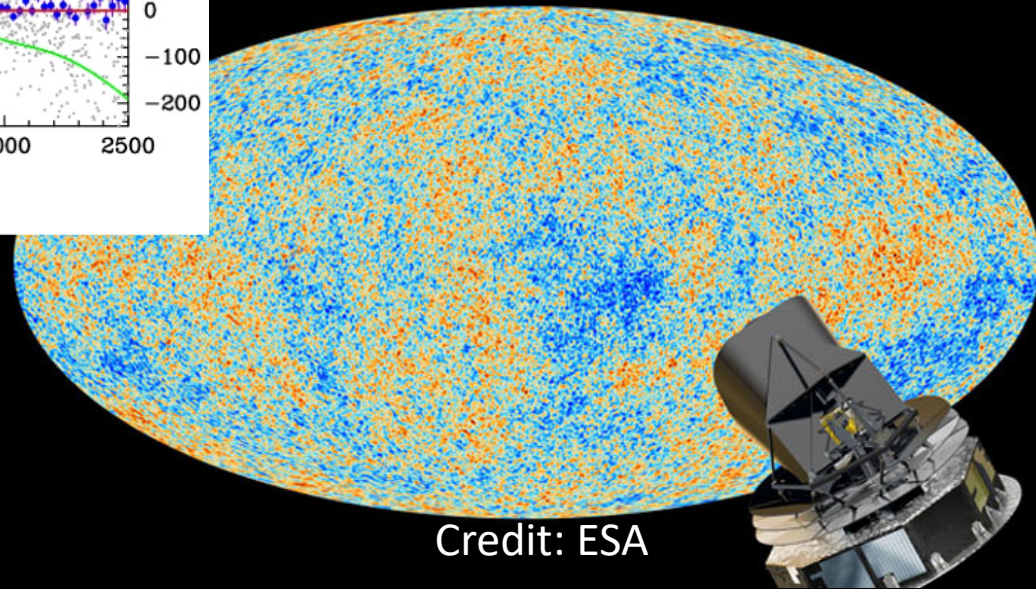


Eisenstein et al. 2005

CMB

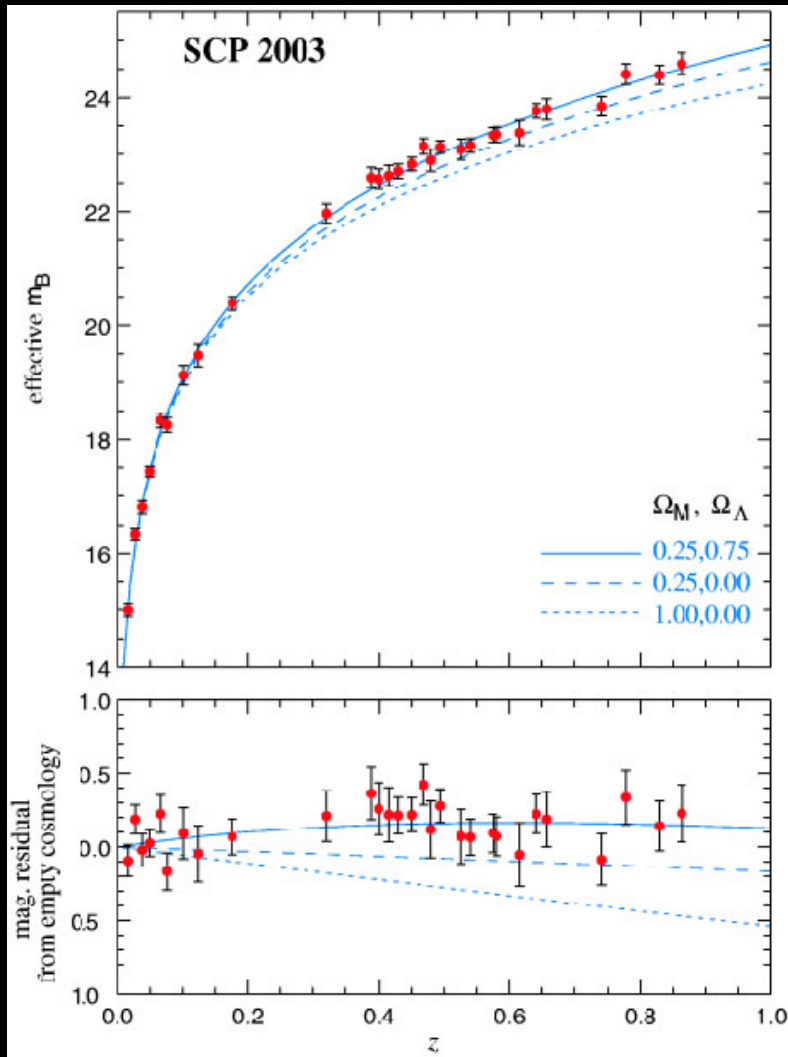


Credit: Planck Collaboration

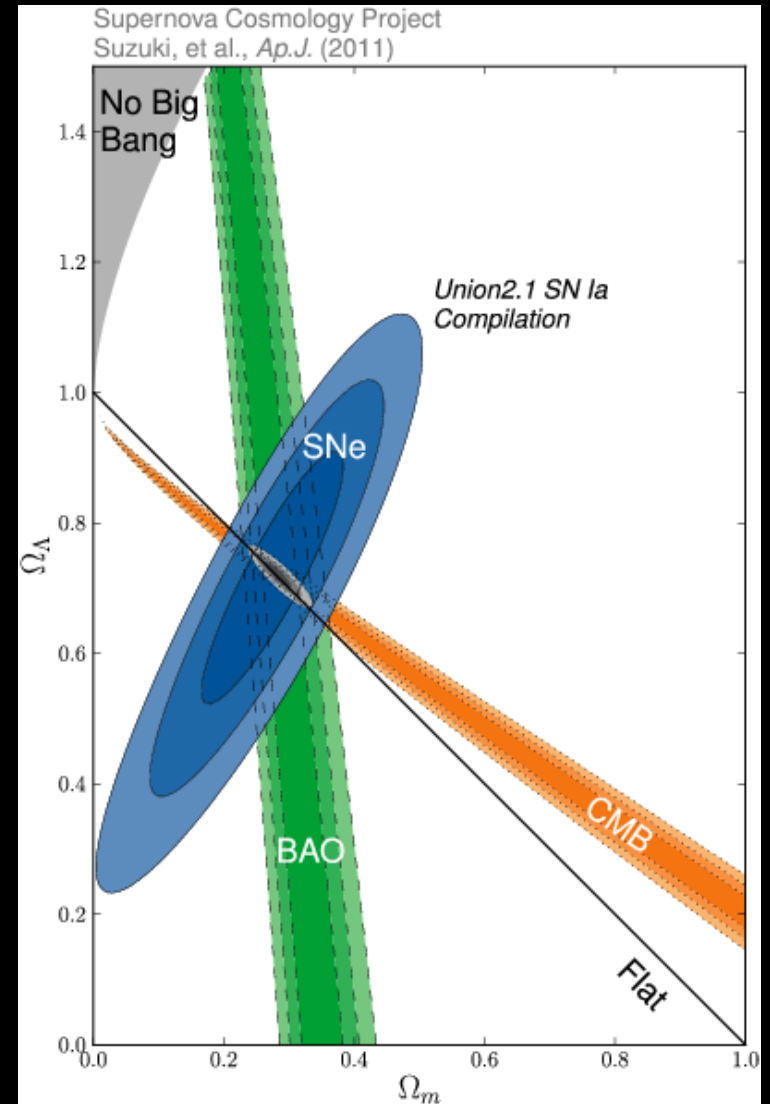


Credit: ESA

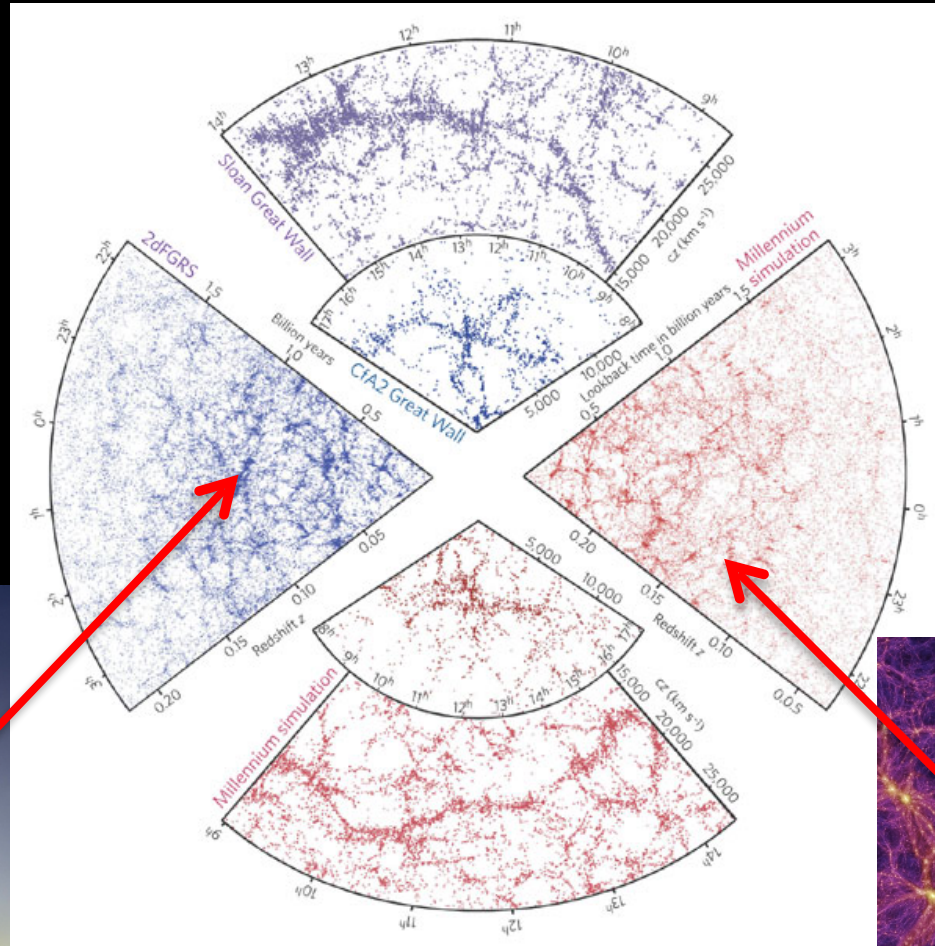
Supernova 1A



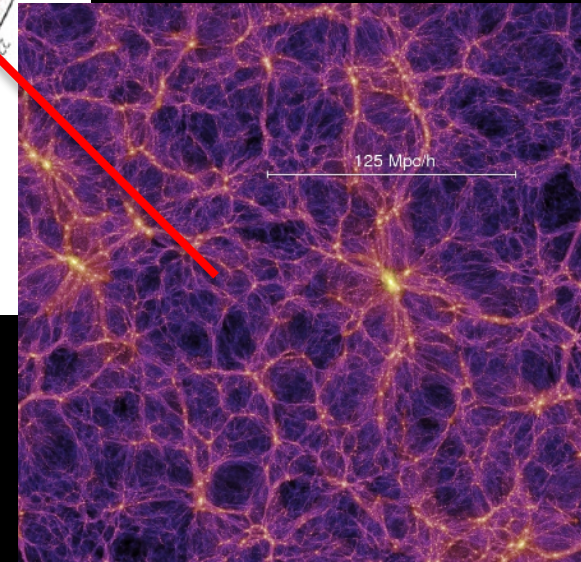
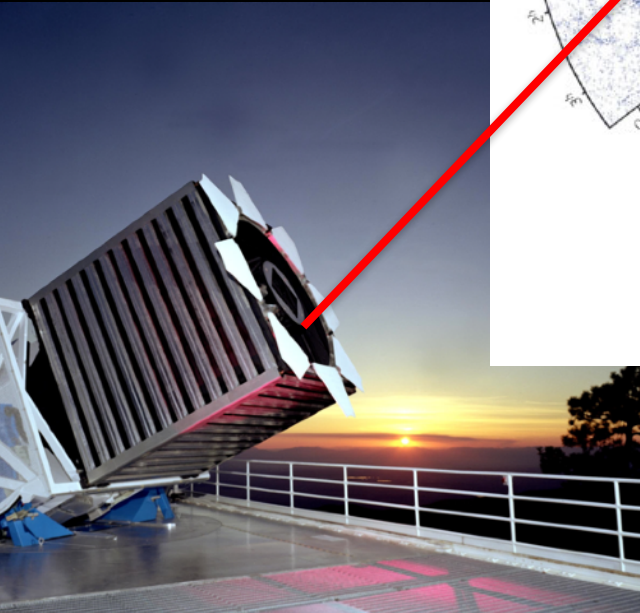
Supernova Cosmology Project 2003



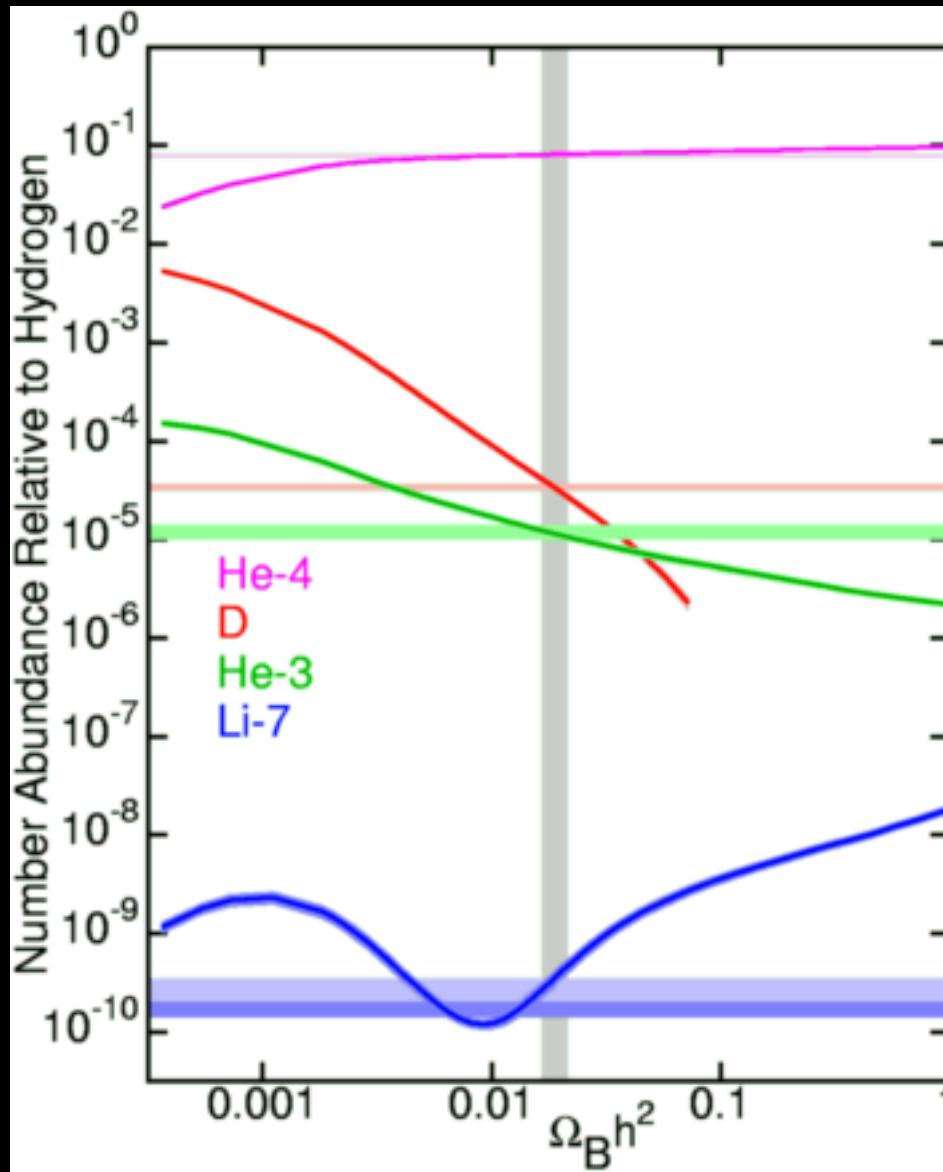
Large Scale Structure



Springel et al. 2006



Big Bang Nucleosynthesis



Other Colliding Clusters

The Baby Bullet



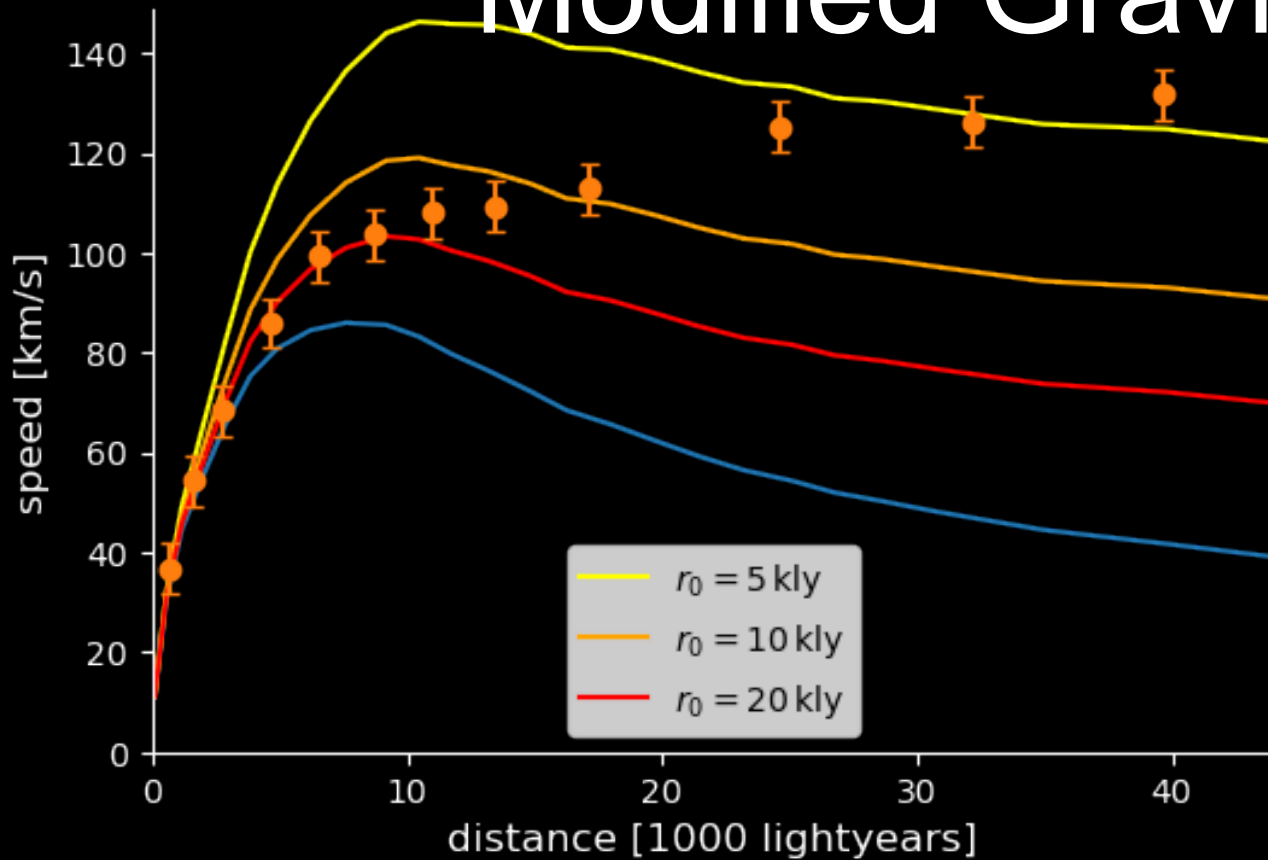
Bradac+ 2008

Pandora's Cluster



Mertens+ 2011

Consider a Simple 'Modified Gravity'



This wouldn't show up
in the Solar System if r_0
was large enough

A modified
acceleration law:

$$a_g = \frac{GM}{r^2} \left(1 + \frac{r}{r_0} \right)$$