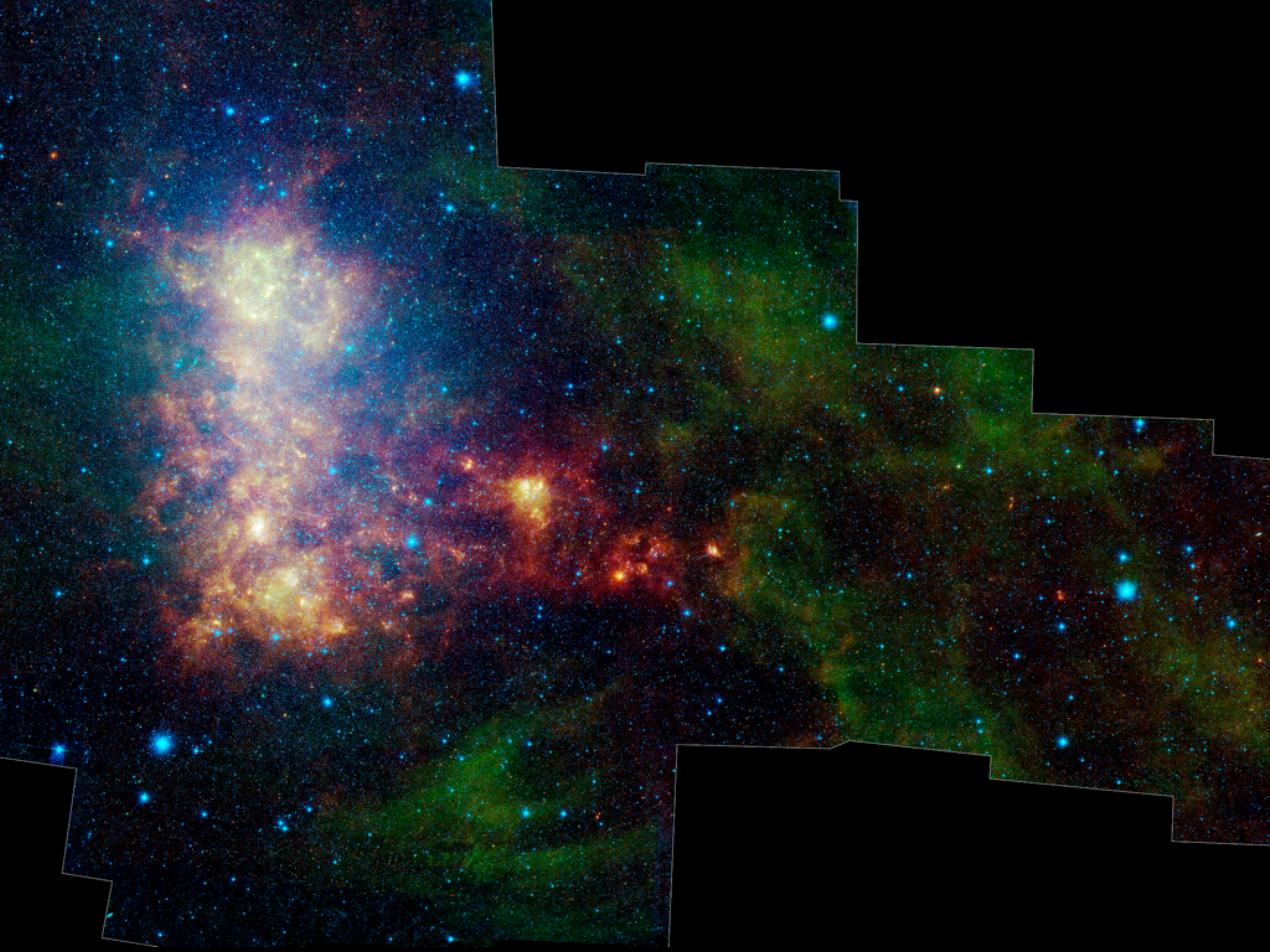
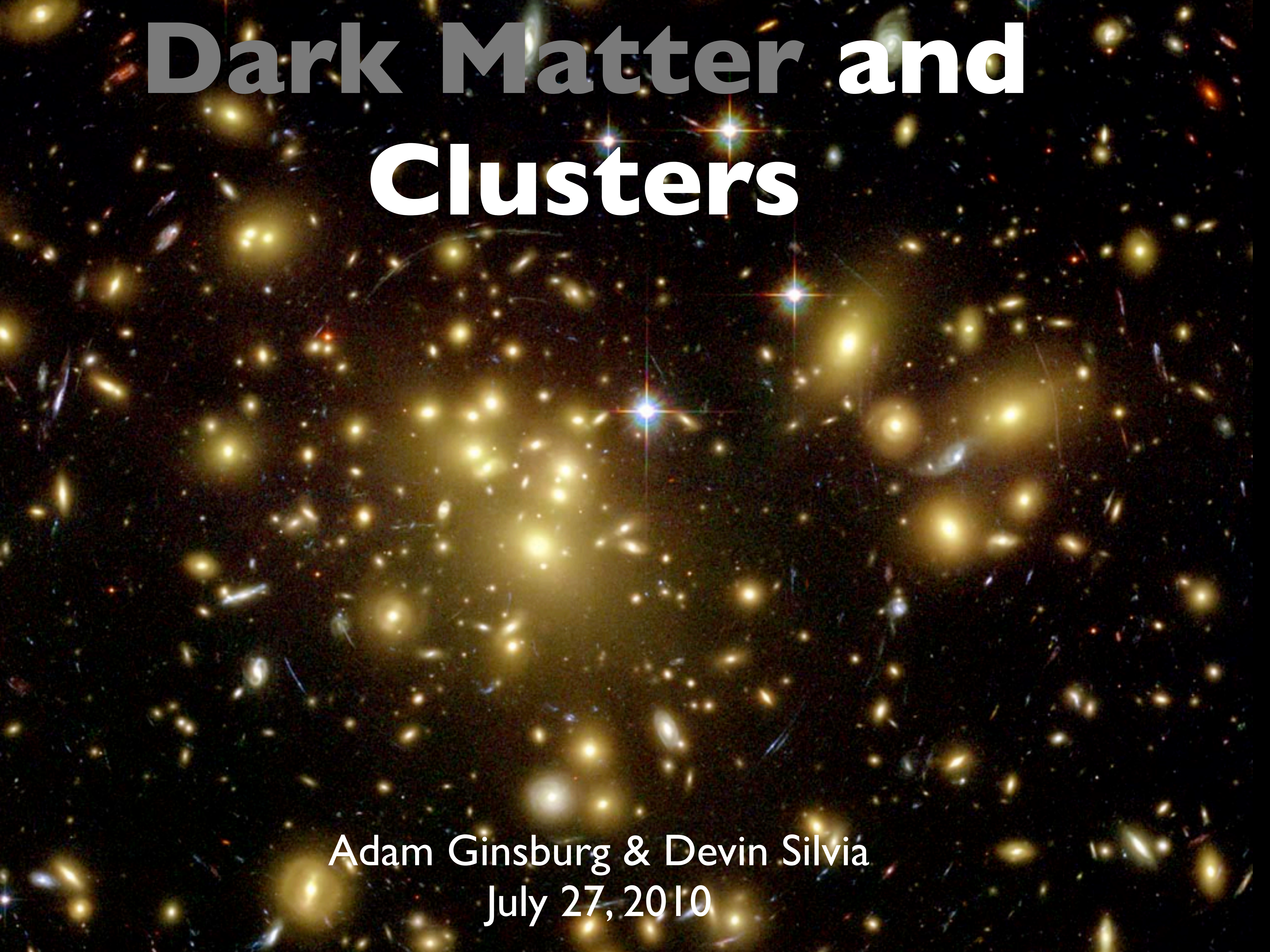


# APODs

Day 17 (July 28th, 2010): Galaxies: Groups, Clusters, & Dark Matter
http://apod.nasa.gov/apod/ap100529.html - Black Holes in mergers -- **Mike B.**
http://apod.nasa.gov/apod/ap080823.html - The Bullet Cluster -- **Raleigh**
Day 18 (July 29th, 2010): Clusters & Large Scale Structure
http://apod.nasa.gov/apod/ap100502.html - Coma Cluster -- **Miles**
http://apod.nasa.gov/apod/ap090716.html - Hercules Cluster -- **Naveen**
Day 20 (August 2nd, 2010): Large Scale Structure & The Distance Ladder
http://apod.nasa.gov/apod/ap091028.html - Furthest galaxy cluster -- **Josh**
http://apod.nasa.gov/apod/ap071211.html - The Universe nearby -- **Emily**
Day 21 (August 3rd, 2010): Cosmology & CMB
http://apod.nasa.gov/apod/ap031231.html - WMAP CMB, the age of the universe -- **Lisle**
http://apod.nasa.gov/apod/ap061007.html - COBE CMB -- **Forbes**
Day 22 (August 4th, 2010): Expansion/Fate of the Universe & Dark Energy
http://apod.nasa.gov/apod/ap010404.html - Type Ia and expansion -- **Tyler**



# Dark Matter and Clusters

Adam Ginsburg & Devin Silvia

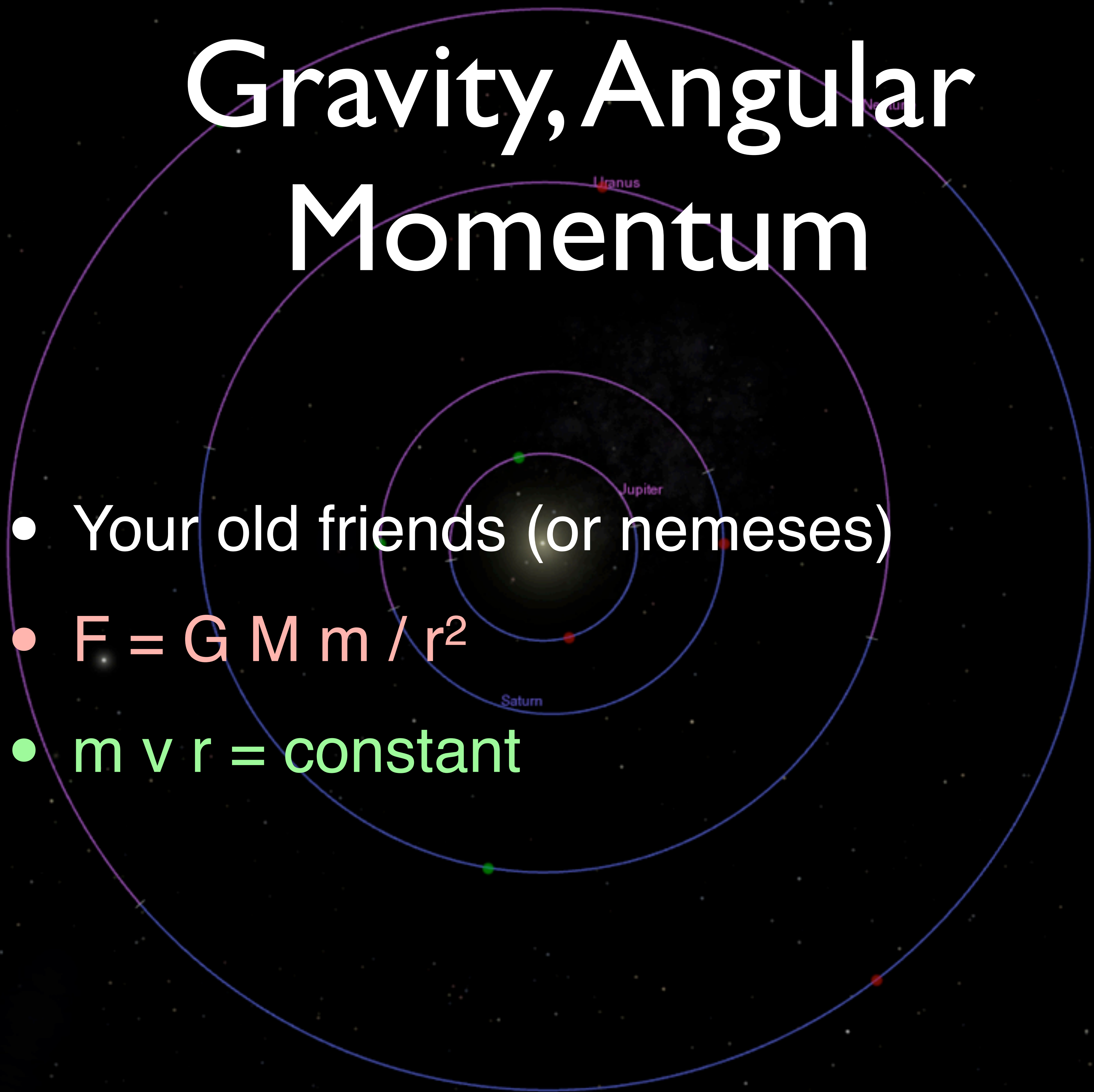
July 27, 2010

# Learning Goals

- If it’s dark, how do we know it’s there?
- What do you mean, dark?
- What are galaxy clusters?
  - What do we use galaxy clusters for?

# Gravity, Angular Momentum

- Your old friends (or nemeses)
- $F = G\, M\, m / r^2$
- $m\, v\, r = \text{constant}$



# How fast do the planets orbit?

- How fast does Saturn move in its orbit compared to Jupiter?

A) Faster

B) The same speed

C) Slower

D) Backwards

What would happen to the planets' orbits if the Sun suddenly turned into a black hole of the same mass?

A) They'd fly off along a straight line, as if the string had been cut

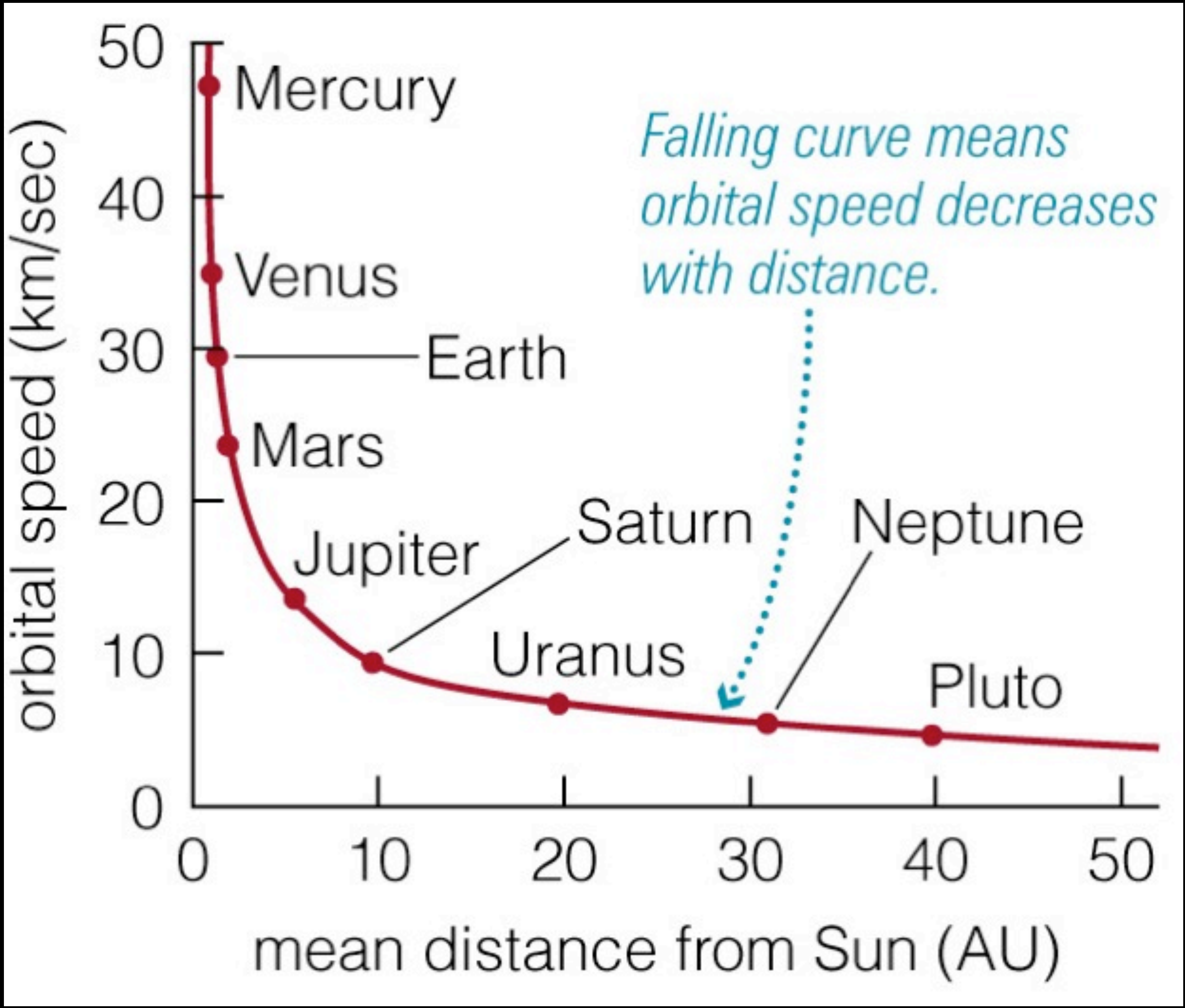
B) They'd continue along their orbits as if nothing had happened

C) They would spiral in to the black hole

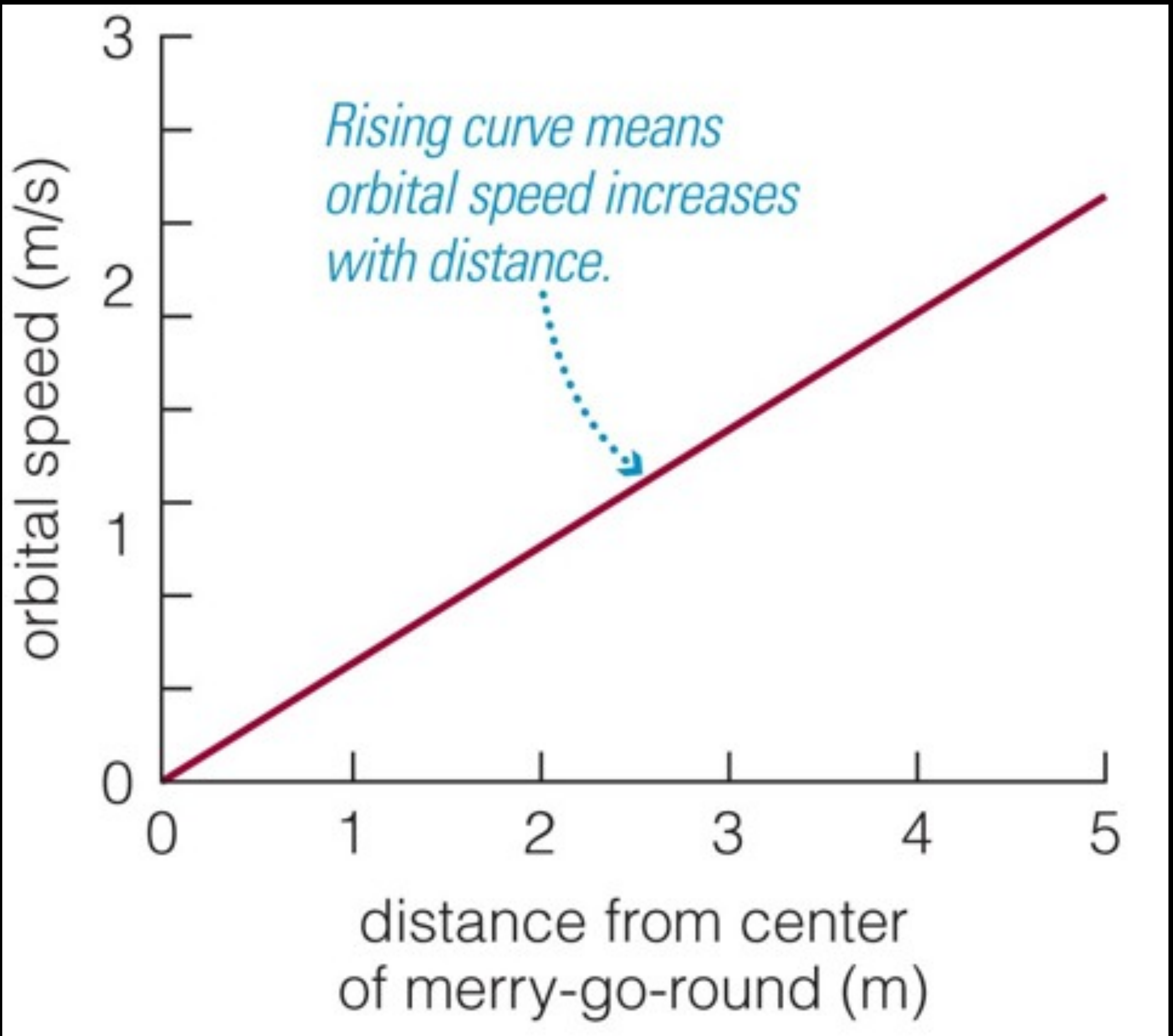
D) They would get cold and tired and then just give up and forget about the whole thing

# Gravity controls orbital speed

- velocity drops as the square root of distance
  - v ∝ 1/√r
- What mass is responsible for nearly all of the gravitational force in the solar system?



# What does a merry-go-round do?




**a** A rotation curve for a merry-go-round.



- Things on the outside go faster
- Gravity won't do this, but "solid body rotation" will

# Rotation Curves

- OK, so if the mass is all in the center, velocity drops off with radius.
- Let's do the same exercise for a galaxy
  - How do we measure the rotation rate of a galaxy?

# Rotation Curves

- OK, so if the mass is all in the center, velocity drops off with radius.
- Let's do the same exercise for a galaxy
  - How do we measure the rotation rate of a galaxy?

Spectroscopy to measure Doppler Shift

- What do you expect the “velocity curve” to do based on where most of the stars are?

A) Decrease with distance, like in the solar system

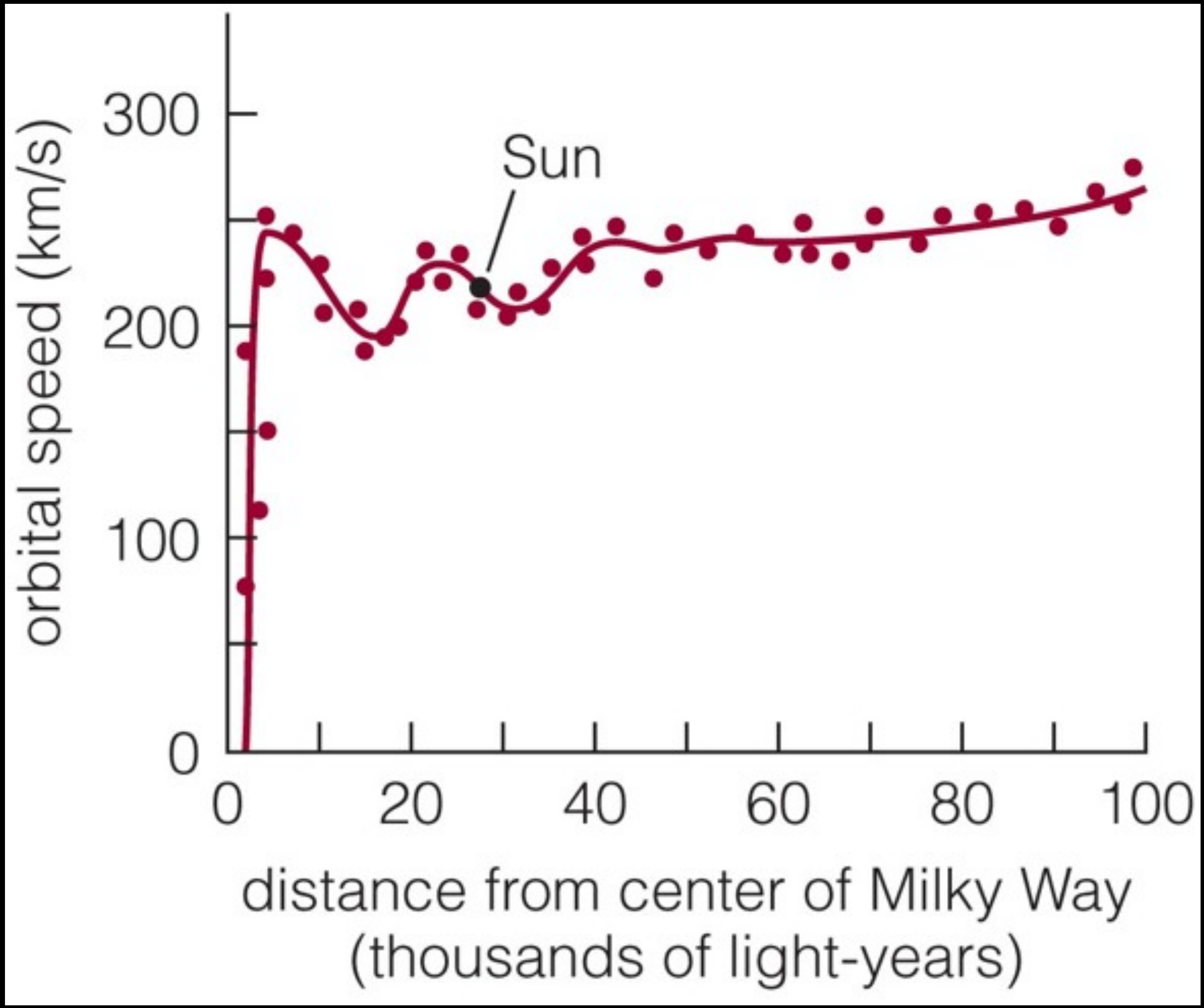
B) Increase with distance, like on a merry-go-round

C) Stay constant

D) Do something wonky; increase and decrease

# What's really there?

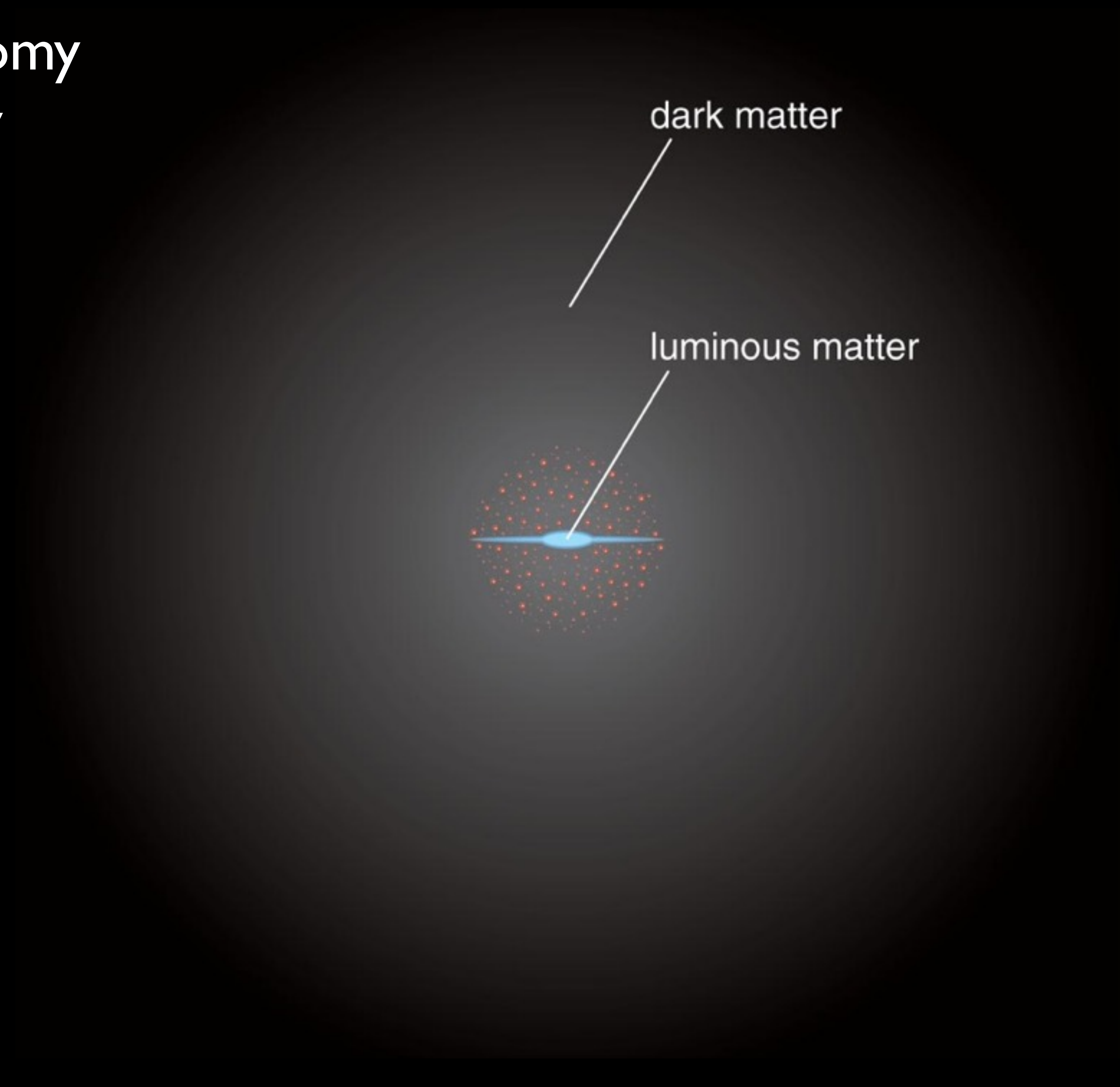
- The orbital speed stays nearly constant!
- That means there's a lot of mass that's not in the center!
- But... it *looks* like most of the mass is in the center



# Enter.... *Dark Matter*

- Eh, not really that dramatic
- We know that there is extra force pulling on gas and stars in the outer galaxy
- It must be from some mass exerting gravitational pull that we can’t see

# Revised anatomy of a galaxy



# How much dark matter?

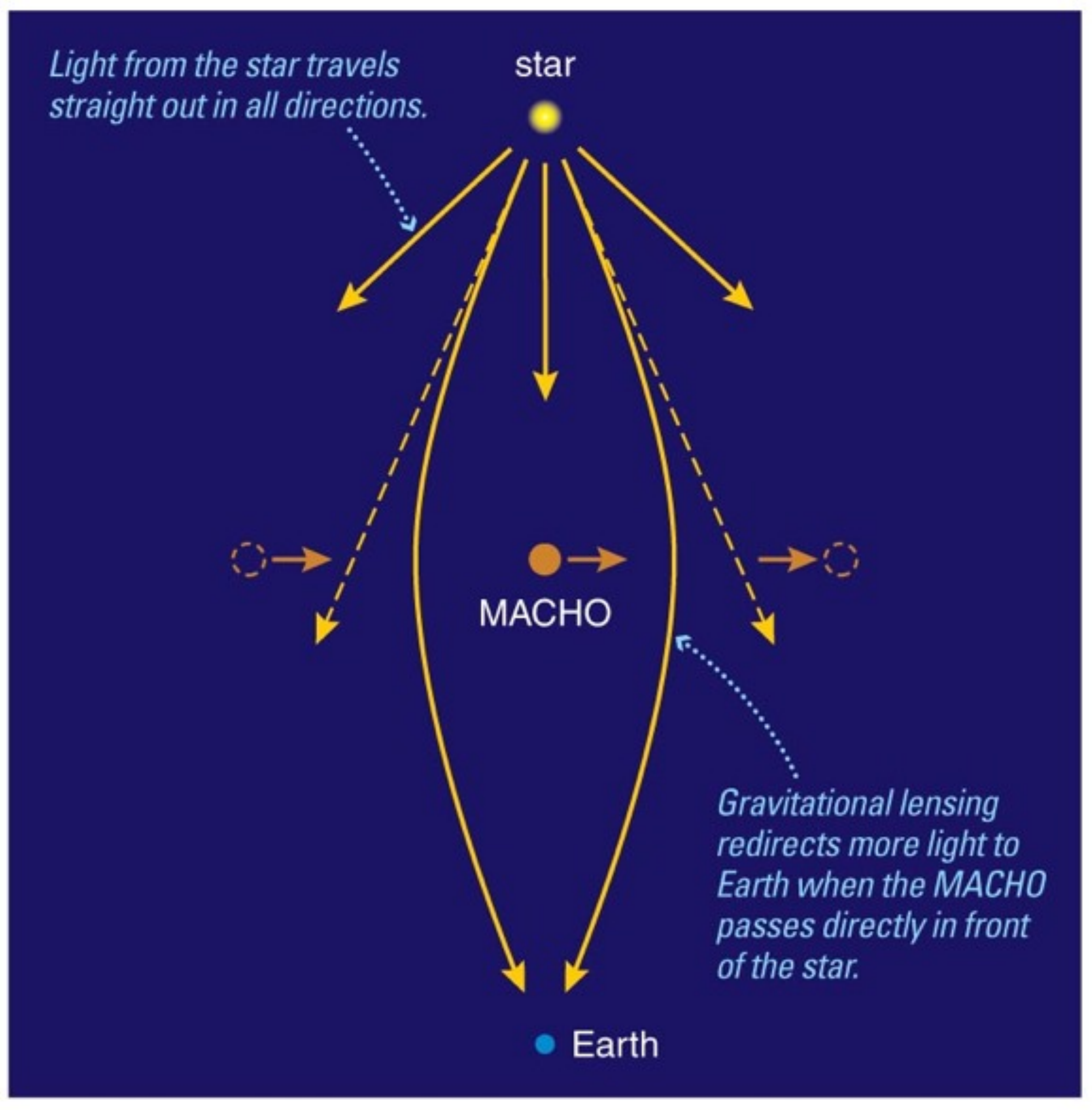
- Only 10% of the matter in a galaxy is from stars, gas, and dust ("normal" matter)
- The other 90% is from dark matter

# What is dark matter?

- Two hypotheses:
  - Dark matter is made of normal matter, but we can't see it because it's too faint
    - Example: black dwarfs, black holes, red dwarfs, brown dwarfs
  - Dark matter is made of extraordinary matter or exotic particles
    - For example, neutrinos
    - Or something else like neutrinos

# MACHOs

- MACHOs are Massive Compact Halo Objects (faint stars/planets)
- We can detect them if they pass in front of stars and lens them, making them briefly appear brighter

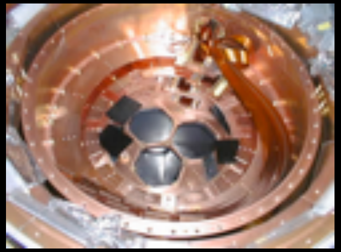


# MACHOs aren't it

- Two big surveys called MACHO and OGLE stared at the LMC and within the Milky Way
- They detected some MACHOs, but not enough (by a lot) to explain dark matter

# Exotic Particles

- WIMPs are Weakly Interacting Massive Particles
  - AKA Cold Dark Matter
  - Like neutrinos, they don't interact with normal matter most of the time
  - But while neutrinos are very very light (at most 1/500 the mass of an electron), WIMPs are heavy (maybe 10x the mass of a proton)
- These are the currently accepted explanation for dark matter. Experiments like the Cryogenic Dark Matter Search (CDMS) are trying to find WIMPs, but haven't yet



# MACHOs

- Since 90% of the mass has to be from dark matter, how many invisible stars would there have to be in the Milky Way for MACHOs to explain dark matter?  (the Milky Way has >100 billion stars)

A) 10 million

B) 10 billion

C) 1 trillion

D) 1 quadrillion

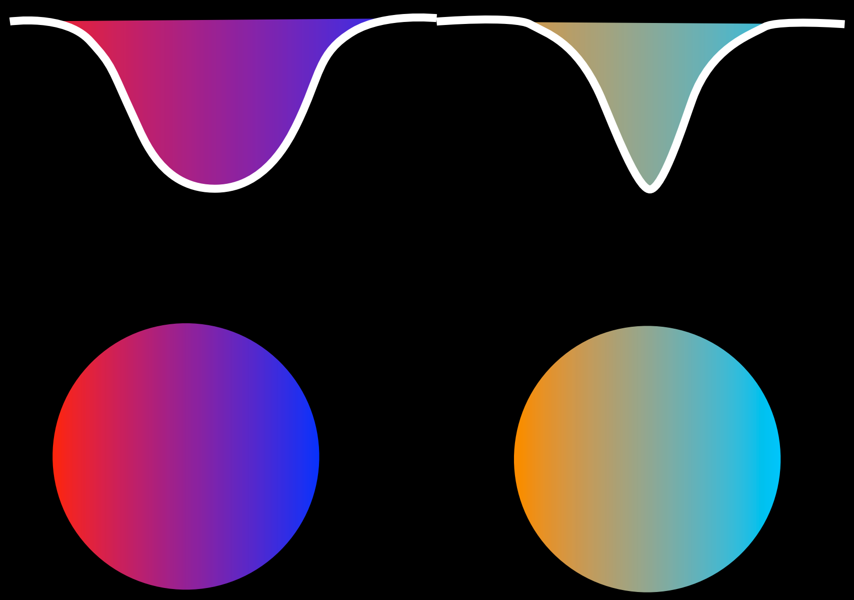
E) 100 bazillion

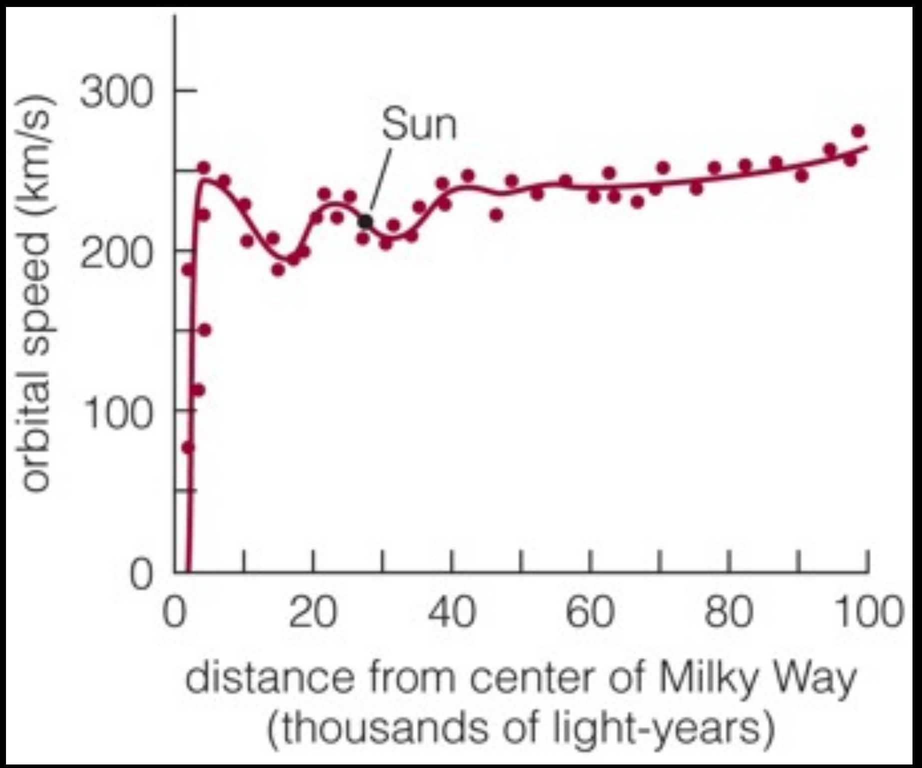
# If we haven't found it, do we *really* know it's there?

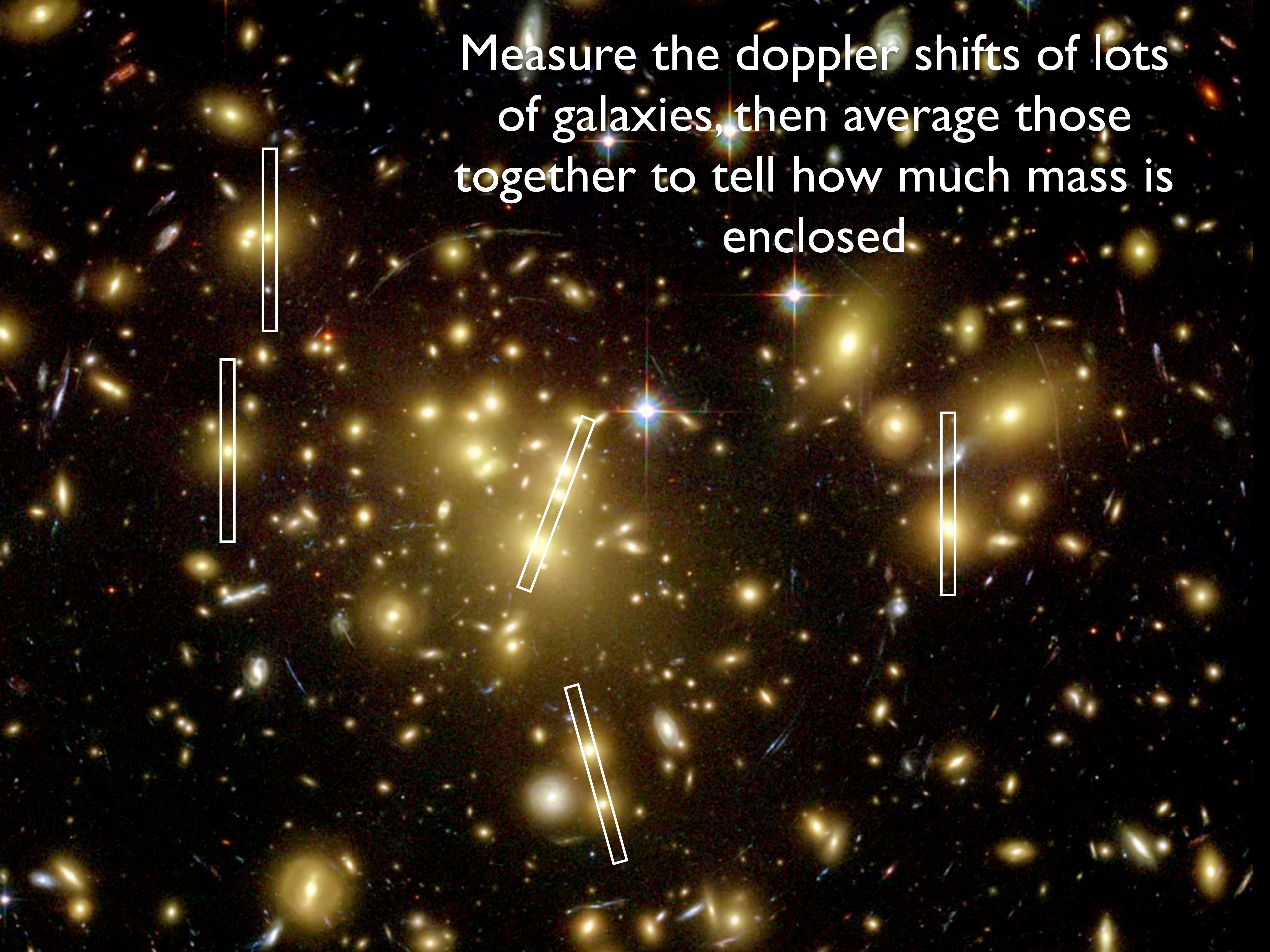
- We see it in galaxies, where else?
- Clusters
  - There are 3 different ways we can tell there is dark matter in clusters
    - Velocities of galaxies
    - Hot Gas x-rays
    - Gravitational Lensing

# Dopplering Galaxy Clusters

- Remember, a faster-spinning planet would have a *wider* emission or absorption line because one side is coming towards, one side is going away from you
- Also, if there is **more mass** in the center of a system, orbits are *faster*
- Put these together: wider lines mean more mass!
    - This is true even for clusters of galaxies and stars, in which they can be orbiting in opposite directions. Then, the width is a measurement of "velocity dispersion"






Measure the doppler shifts of lots of galaxies, then average those together to tell how much mass is enclosed

- We infer the presence of Dark Matter by assuming that galaxy clusters are *gravitationally bound*. If there was no dark matter in these clusters and galaxies were moving at the same speed, what would happen?

A) nothing special, there would just be less mass in the cluster

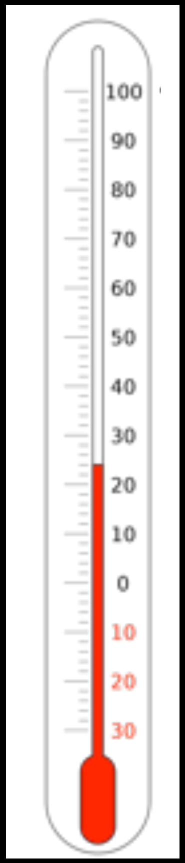
B) the galaxies would all fall in to the center

C) the gas would act like glue and hold the cluster together

D) the cluster would “evaporate” as galaxies escaped from the weaker gravity

# X-ray the clusters

- Clusters are filled with HOT gas
  - about 1 million K
- The gas has very, very low density, but clusters are BIG
- Let's look at a picture...



# BAM! Galaxy Cluster!

- Notice anything weird about this cluster of galaxies?

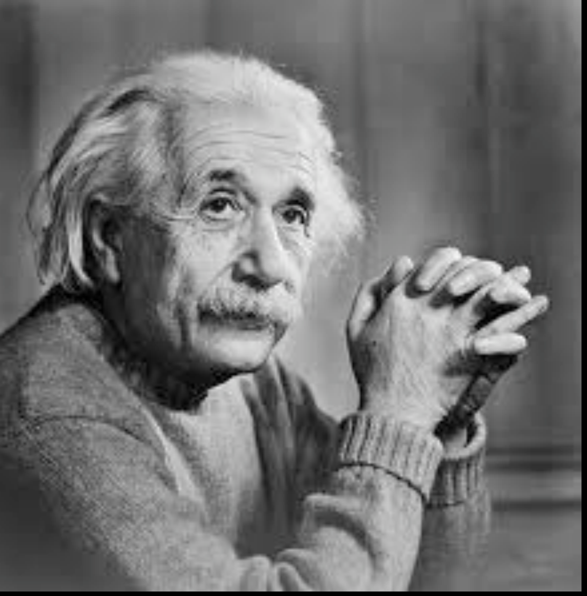
# X-rays and hot gas

- We can only see the really hot gas
  - galaxies don’t even show up in X-rays
- The hot gas outweighs the galaxies by about a factor of 2
- We know there is dark matter because we measure the *temperature* of the gas, and determine that it is so hot, without dark matter, it would evaporate too quickly to be seen

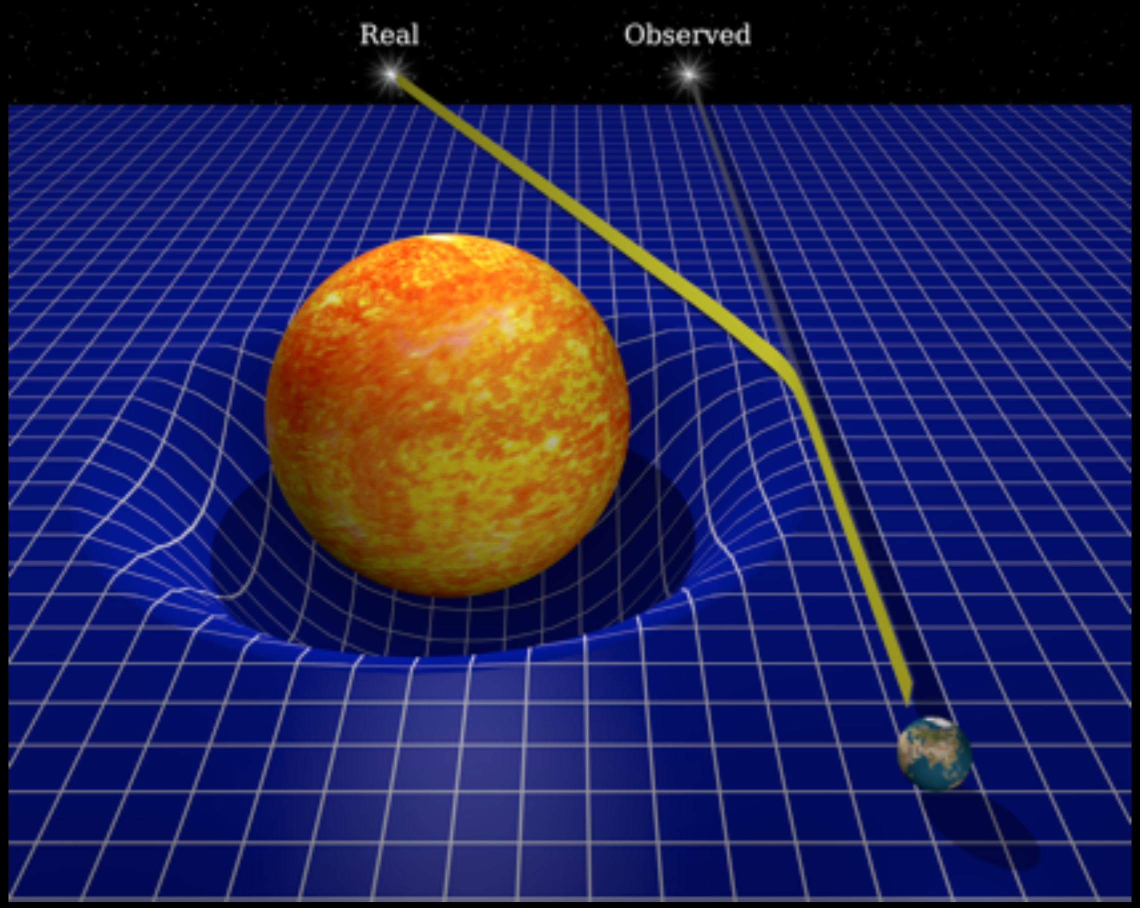
# X-ray the clusters

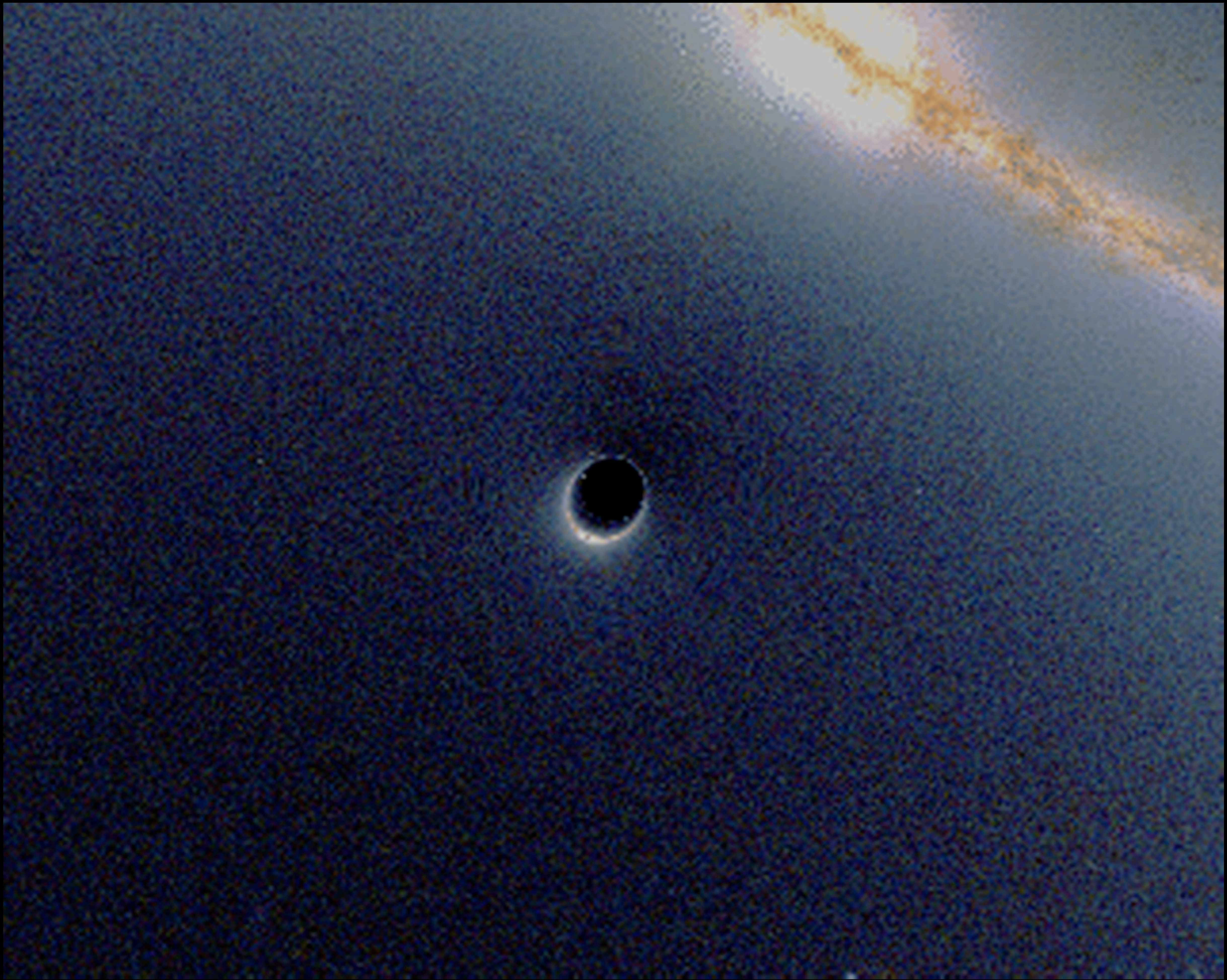
- Lots of galaxies in one big, diffuse, blob of X-ray gas

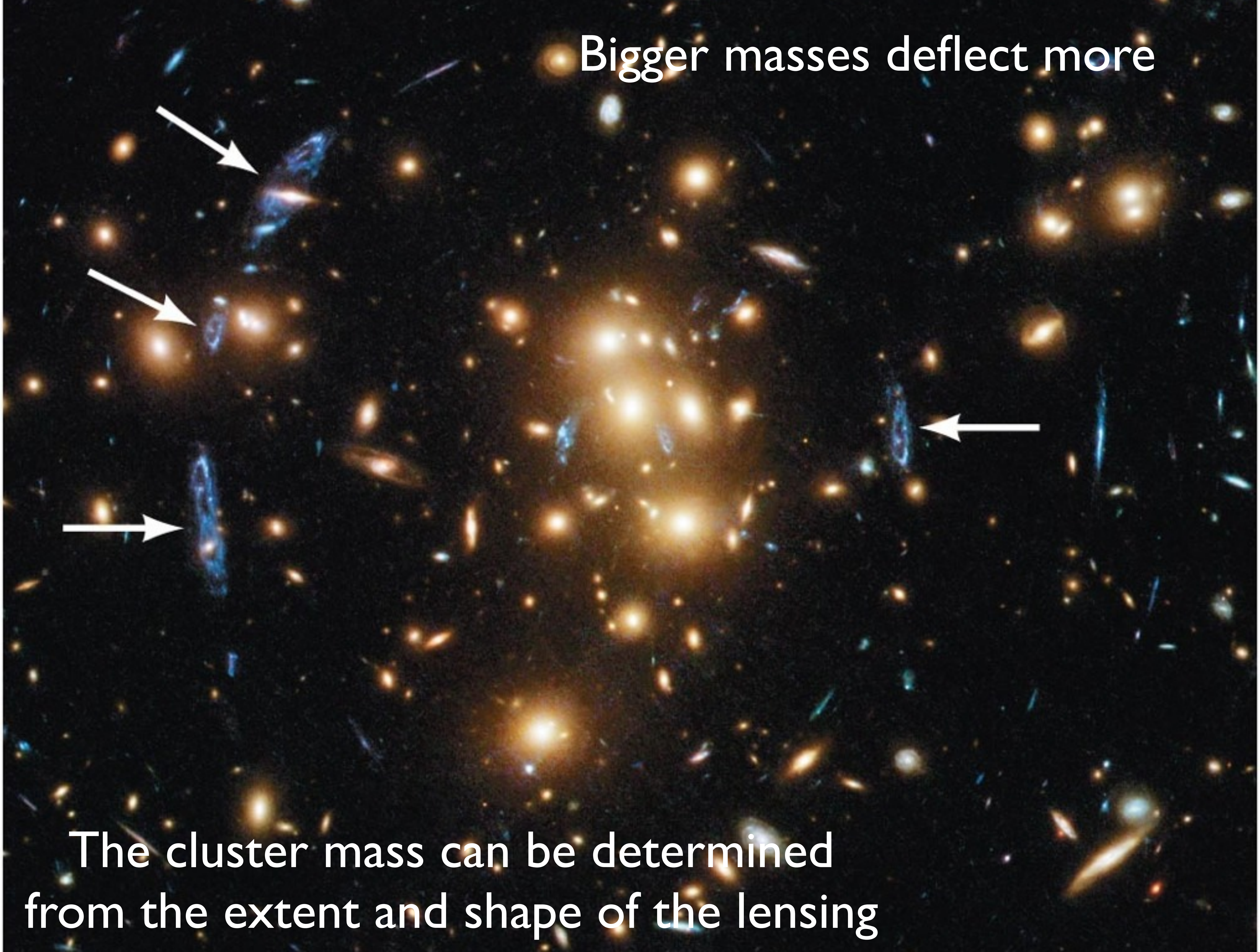
# Gravitational Lensing



- General Relativity says that light curves around massive objects
  - Has been proved in the solar system: stars behind the sun are shifted by a small amount
- Made Einstein famous in 1919: an expedition by Arthur Eddington used a solar eclipse to prove general relativity



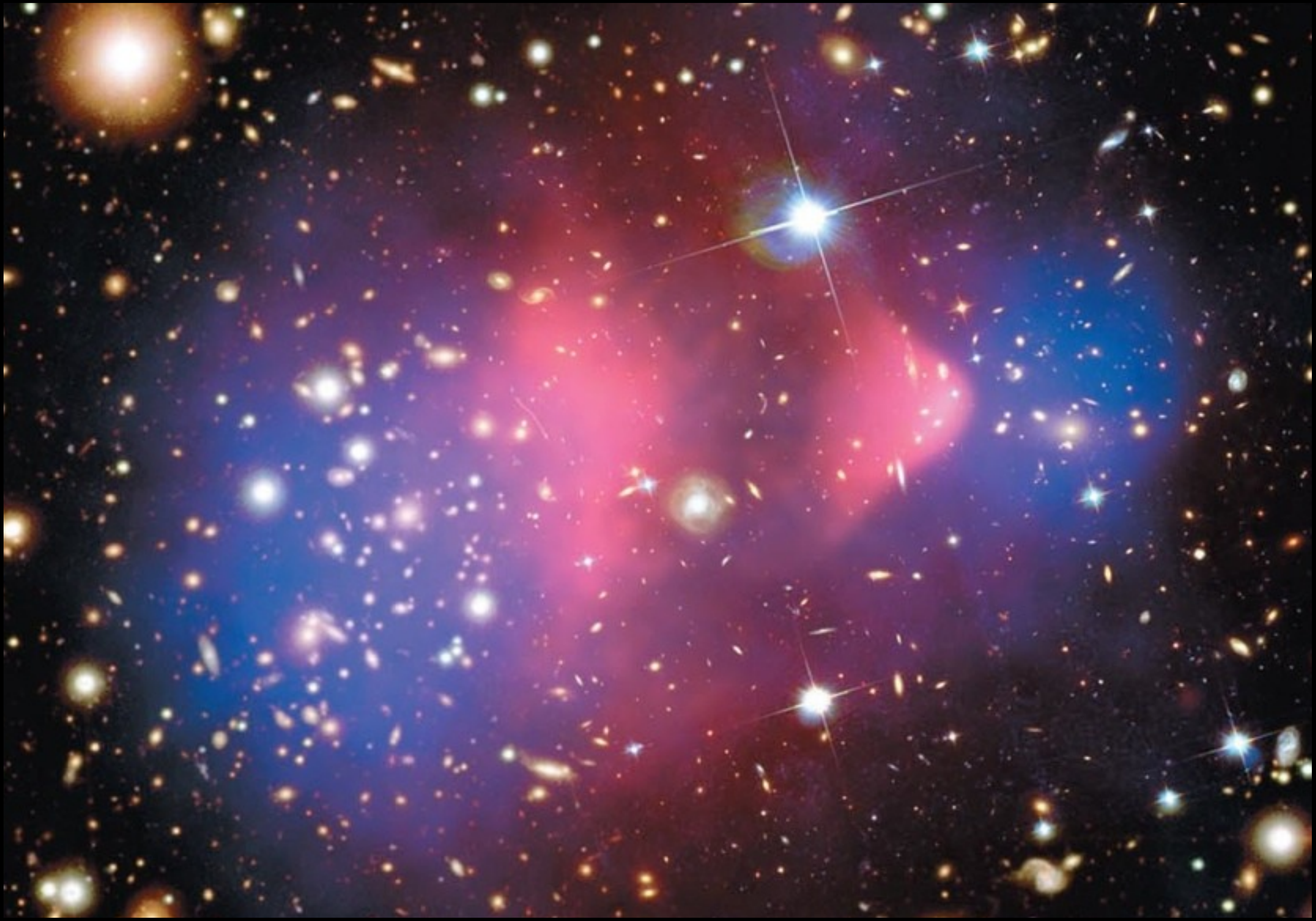




Bigger masses deflect more
The cluster mass can be determined from the extent and shape of the lensing

# Mass, mass, mass

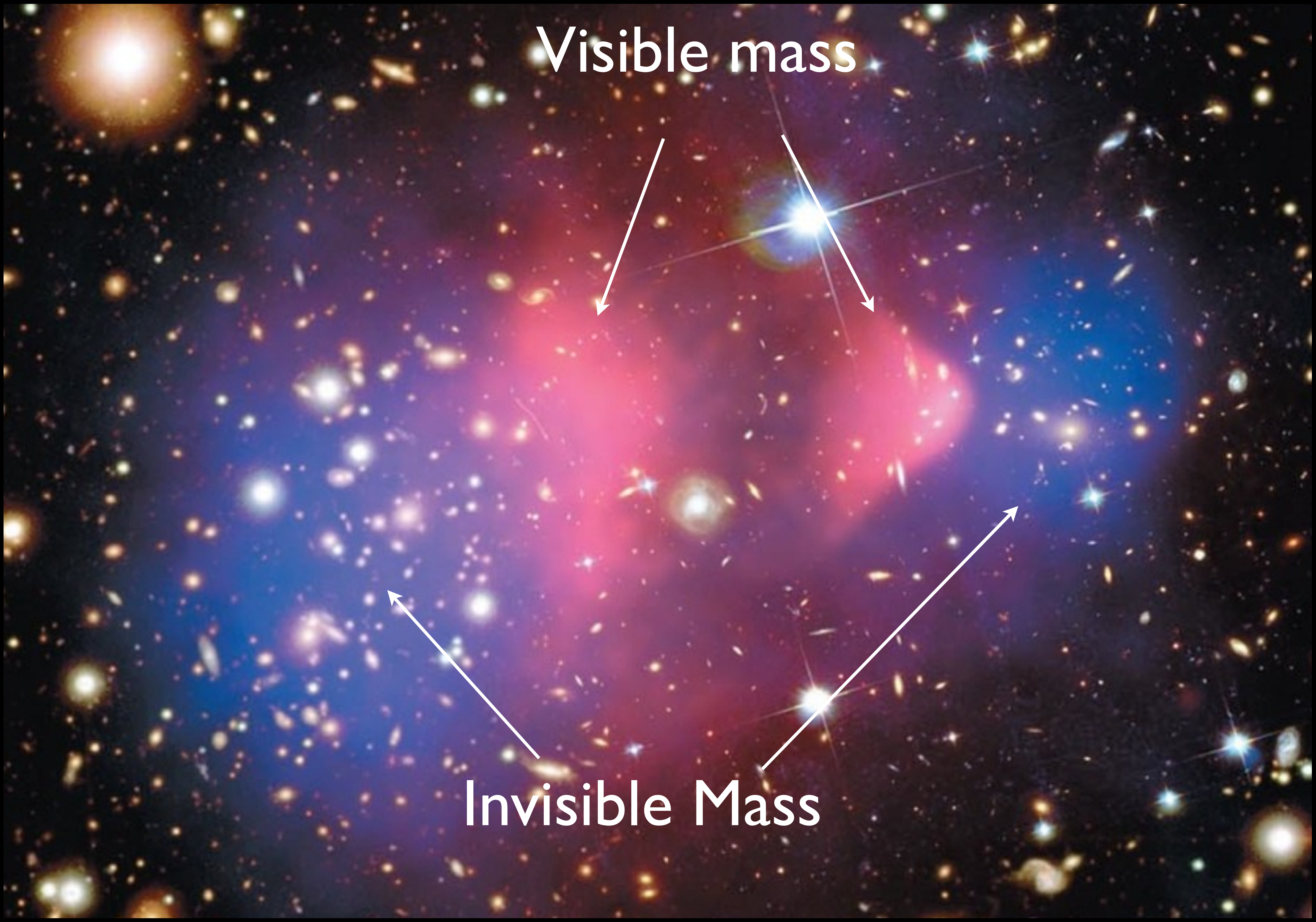
- 3 ways to measure the mass!
- What do they tell us?
    - X-rays say that there's a lot more hot gas than there are stars - but that's still not dark matter
    - Doppler shift and gravitational lensing say there's a lot more mass than we can see

# Bullet Cluster

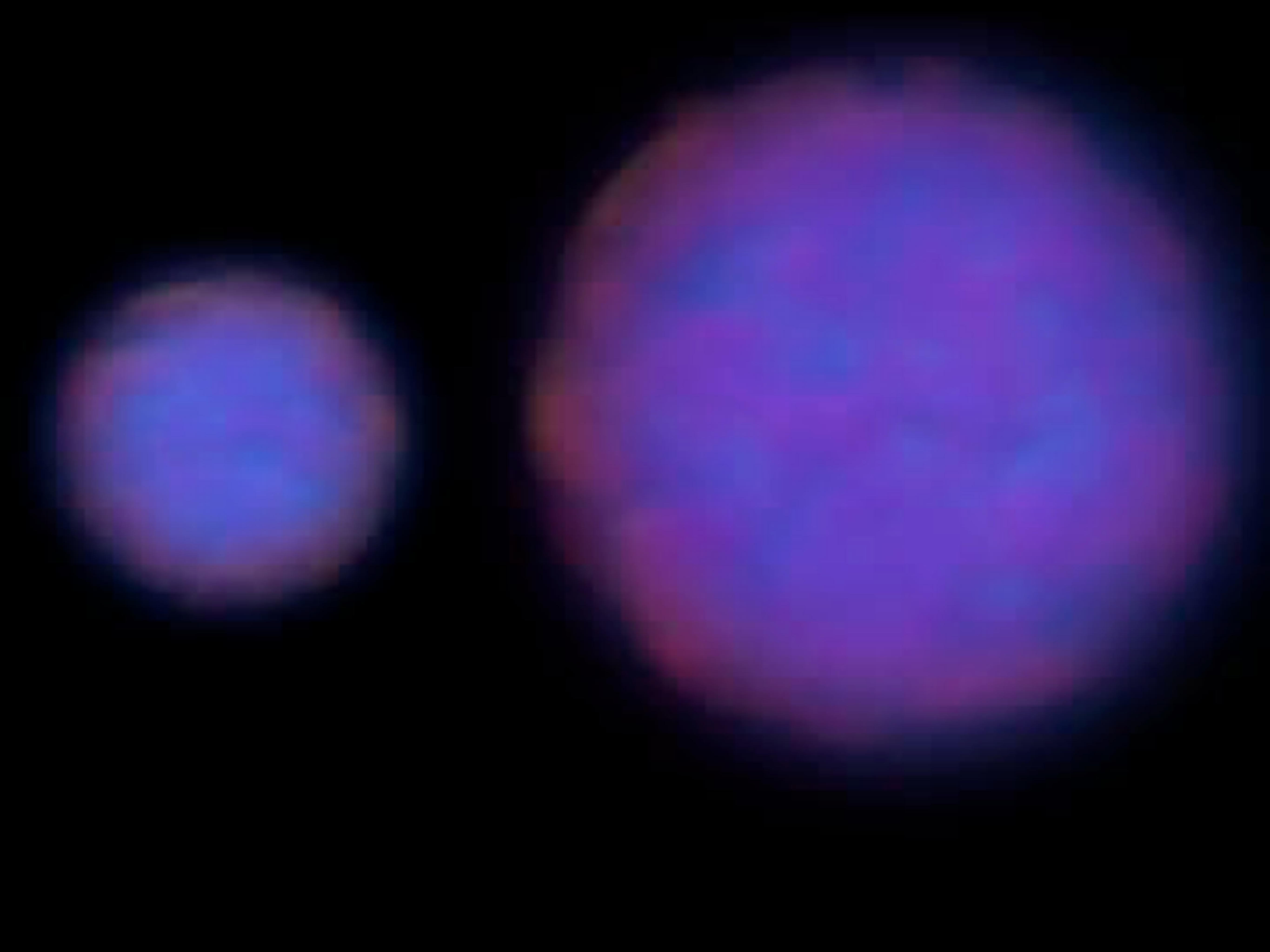


Dark Matter X-rays Optical

# Bullet Cluster

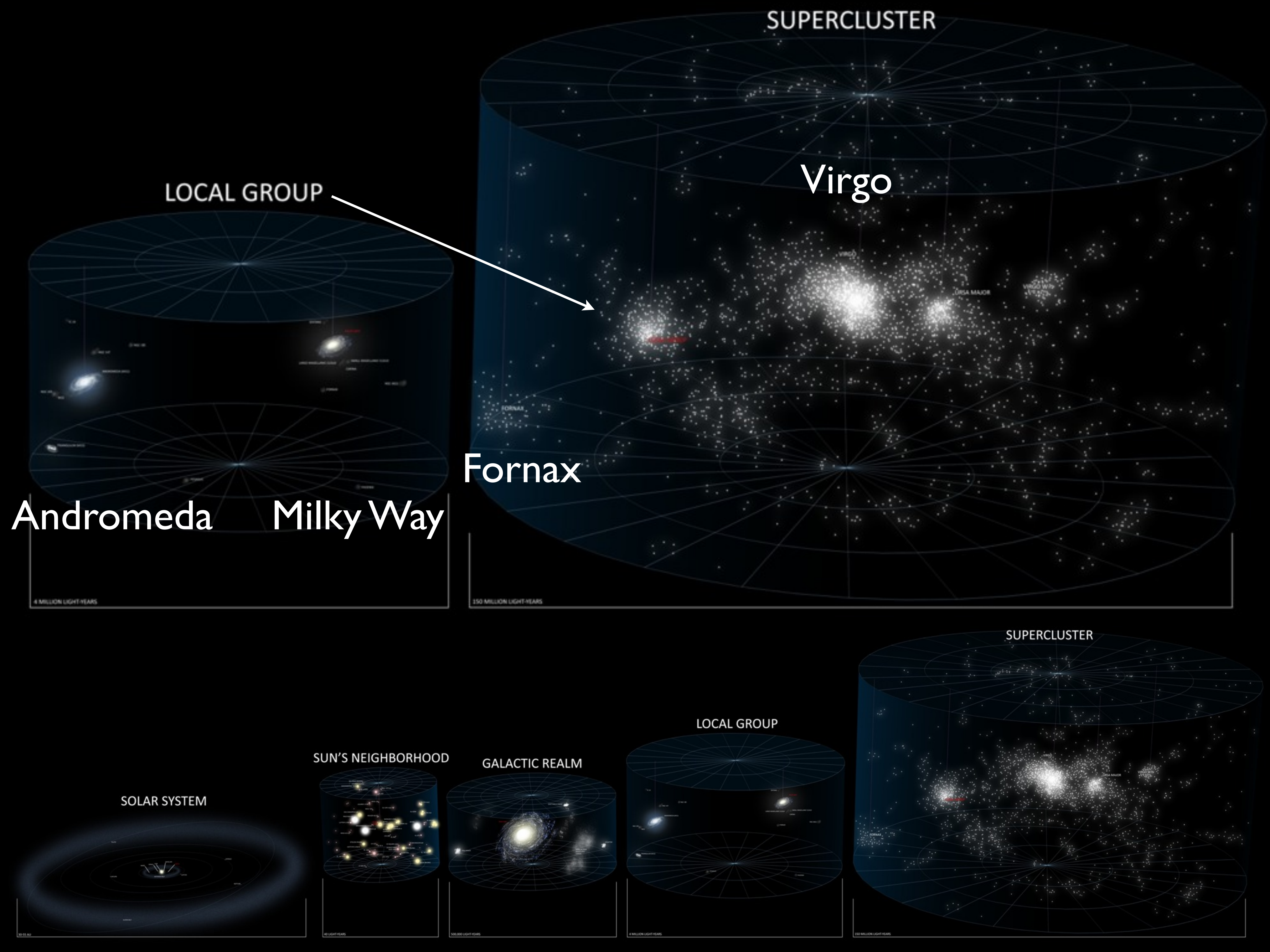



Dark Matter X-rays Optical

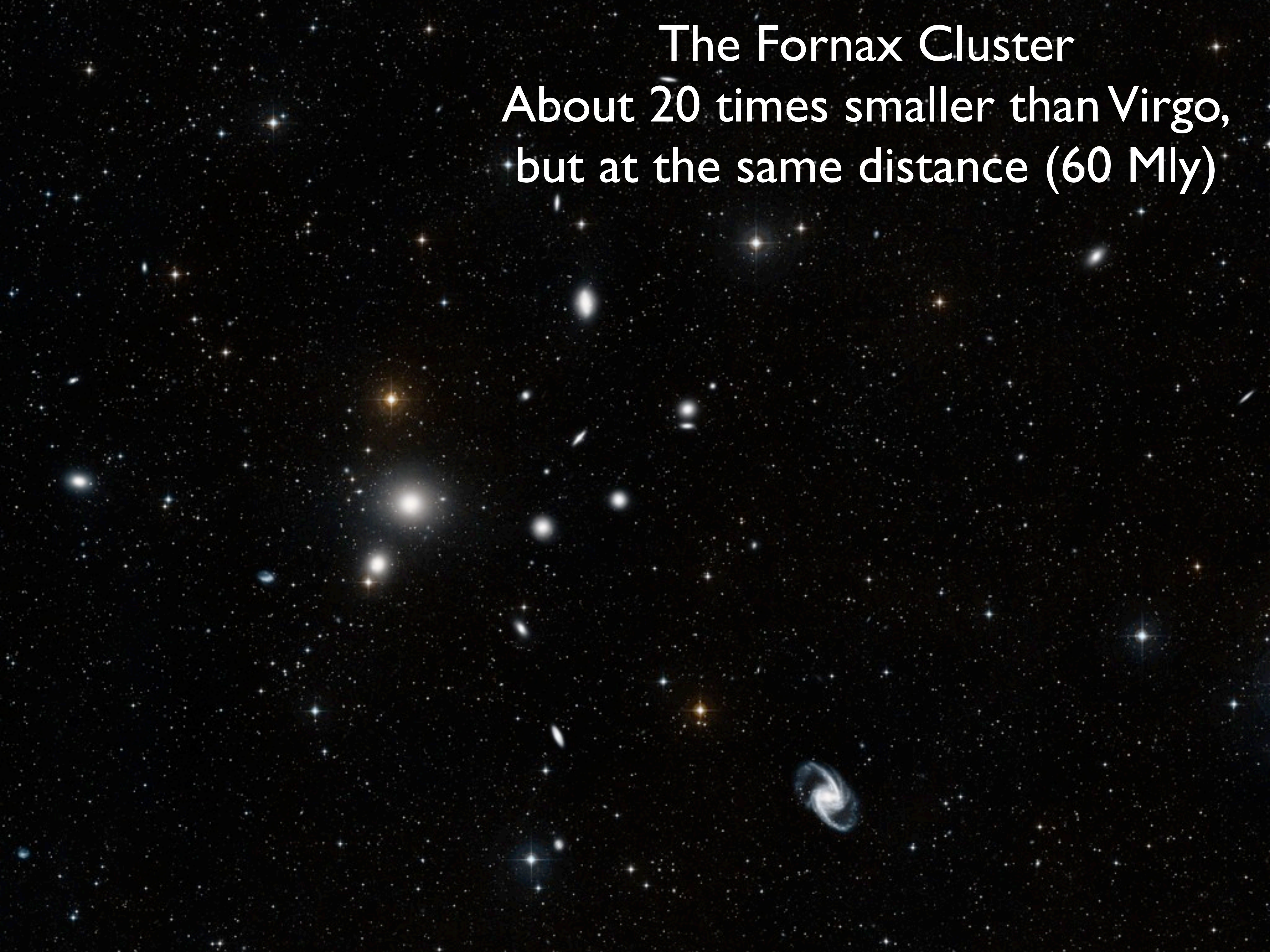


# Break

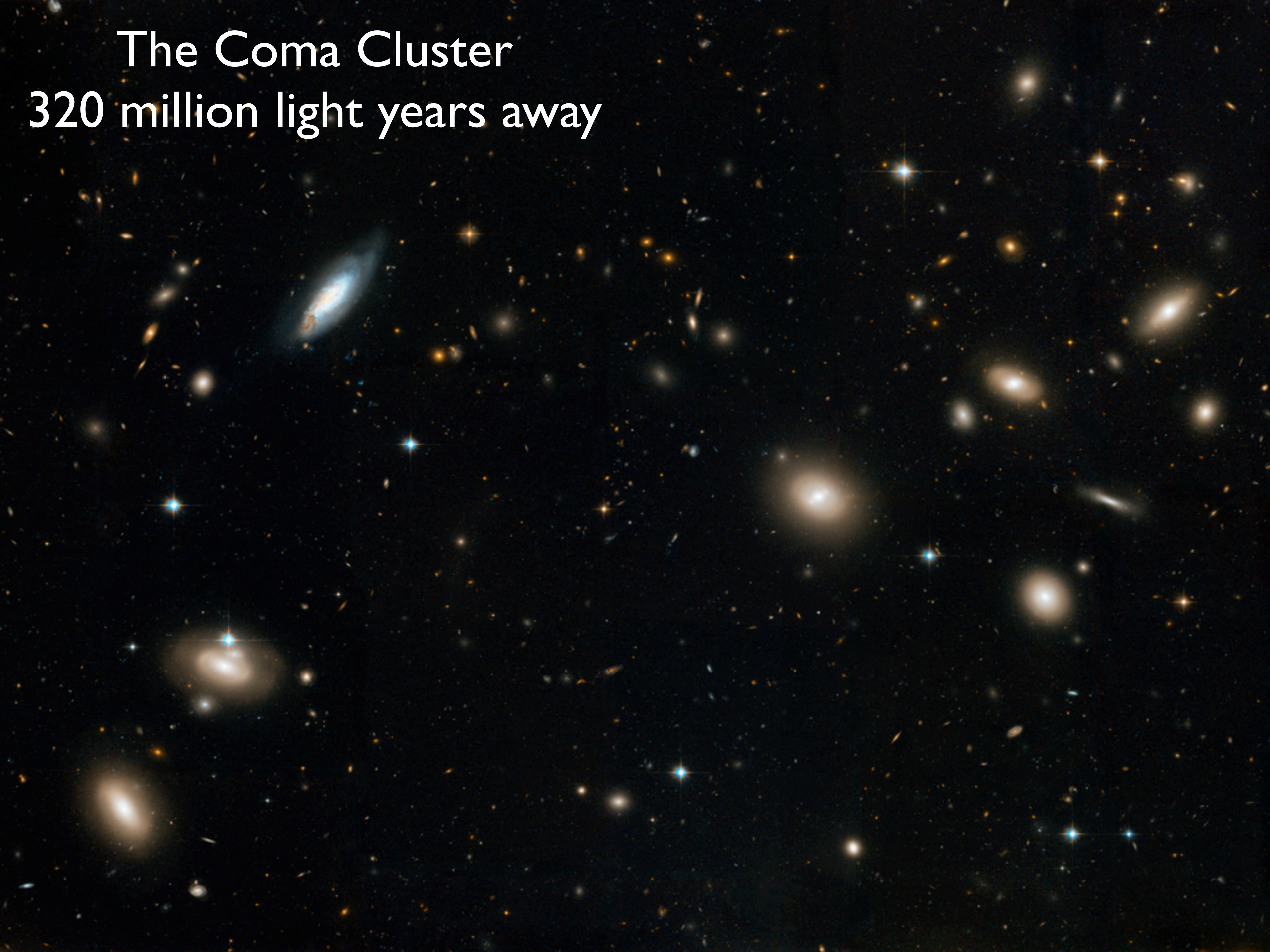
- Come back and do Dark Matter LT

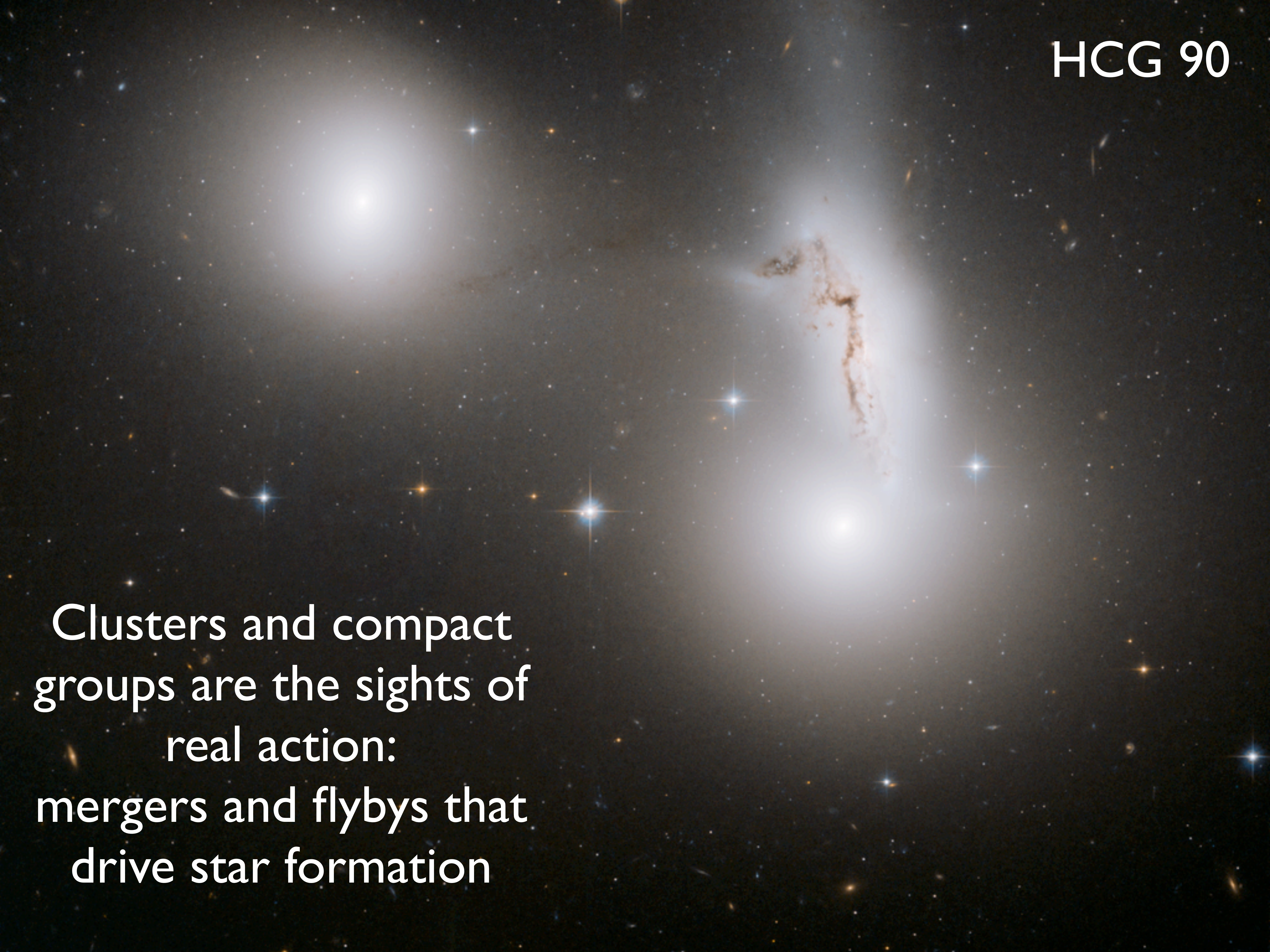

SUPERCLUSTER
Virgo
LOCAL GROUP
Fornax
Andromeda
Milky Way
VIRGO
URSA MAJOR
FORNAX
4 MILLION LIGHT-YEARS
150 MILLION LIGHT-YEARS
SOLAR SYSTEM
SUN'S NEIGHBORHOOD
GALACTIC REALM
LOCAL GROUP
SUPERCLUSTER

# The Fornax Cluster
About 20 times smaller than Virgo,
but at the same distance (60 Mly)



- The nearest supercluster is Virgo, at a distance of 60 million light years
  - At that distance, it is 8 degrees across (16 times the size of the moon!)


The Coma Cluster
320 million light years away


HCG 90
Clusters and compact groups are the sights of real action:
mergers and flybys that drive star formation


HCG 31

Stephan's
Quintet

Back to Virgo...

M87, a boring elliptical...

# OR IS IT?!!?!

M87's nucleus is active

(it has an Active Galactic Nucleus, or AGN)

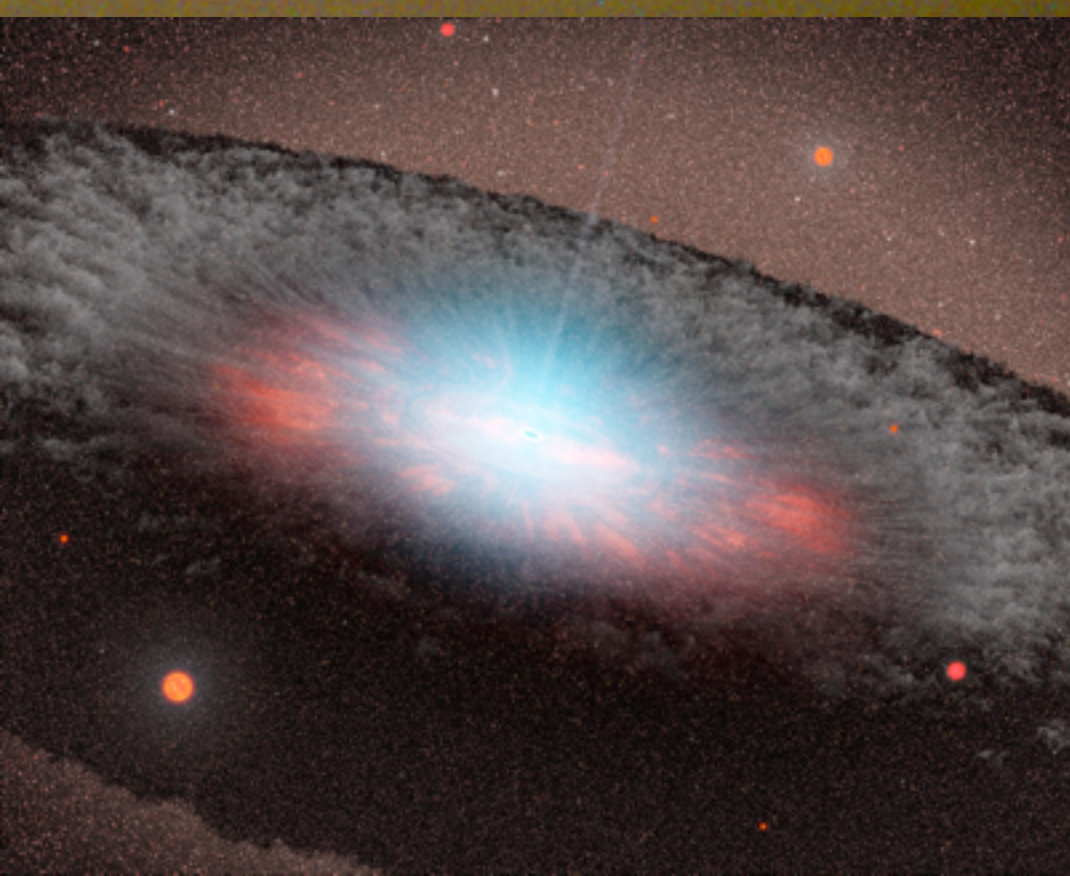
There's a jet coming out at near light speed

What does a jet indicate?

M87's nucleus is active
(it has an Active Galactic Nucleus, or AGN)

There's a jet coming out at near light speed
What does a jet indicate?

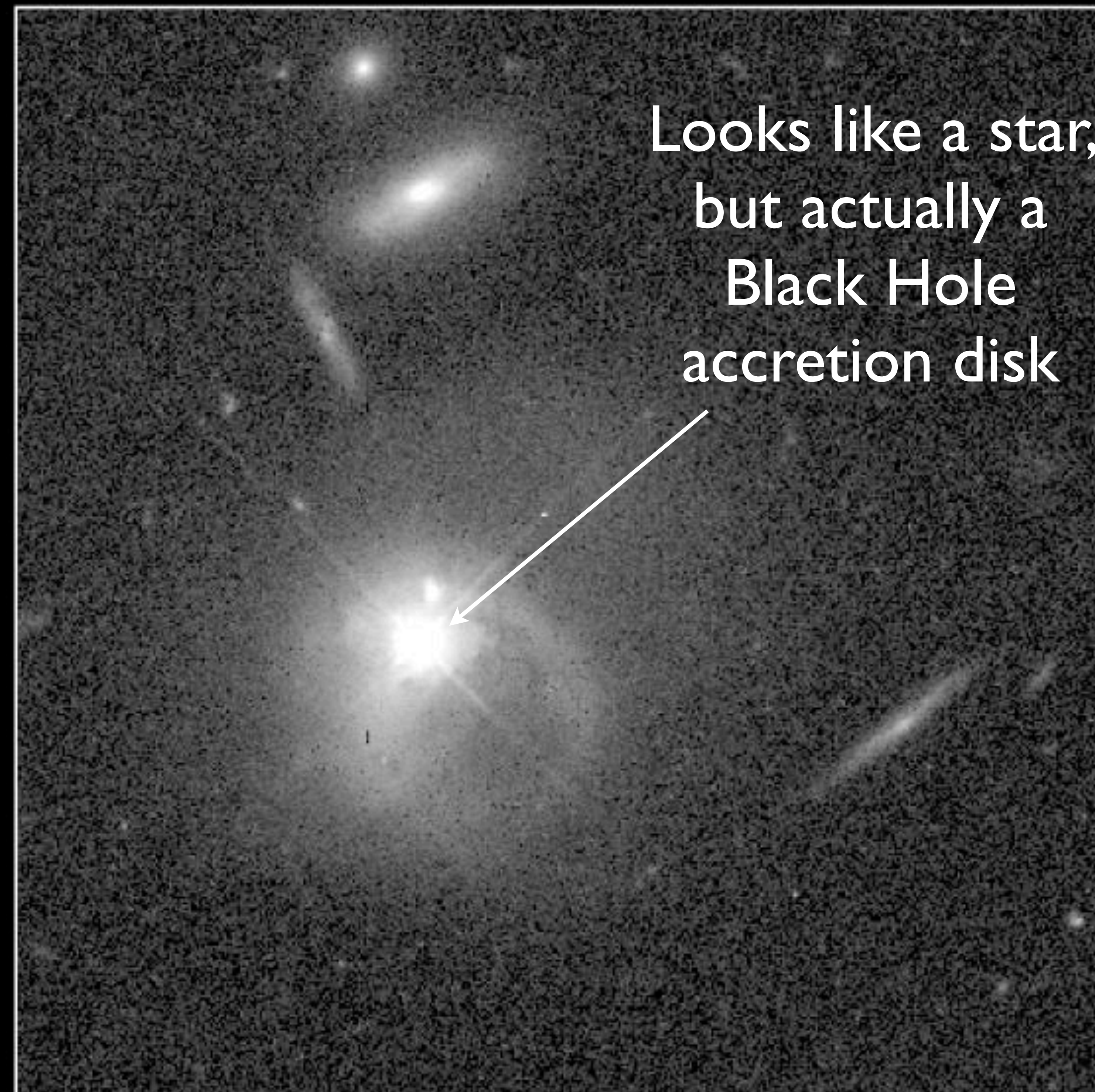
Accretion Disk!



3 billion solar mass black hole
(1,000 times bigger than Sgr A*,
the black hole at the center of the
Milky Way)

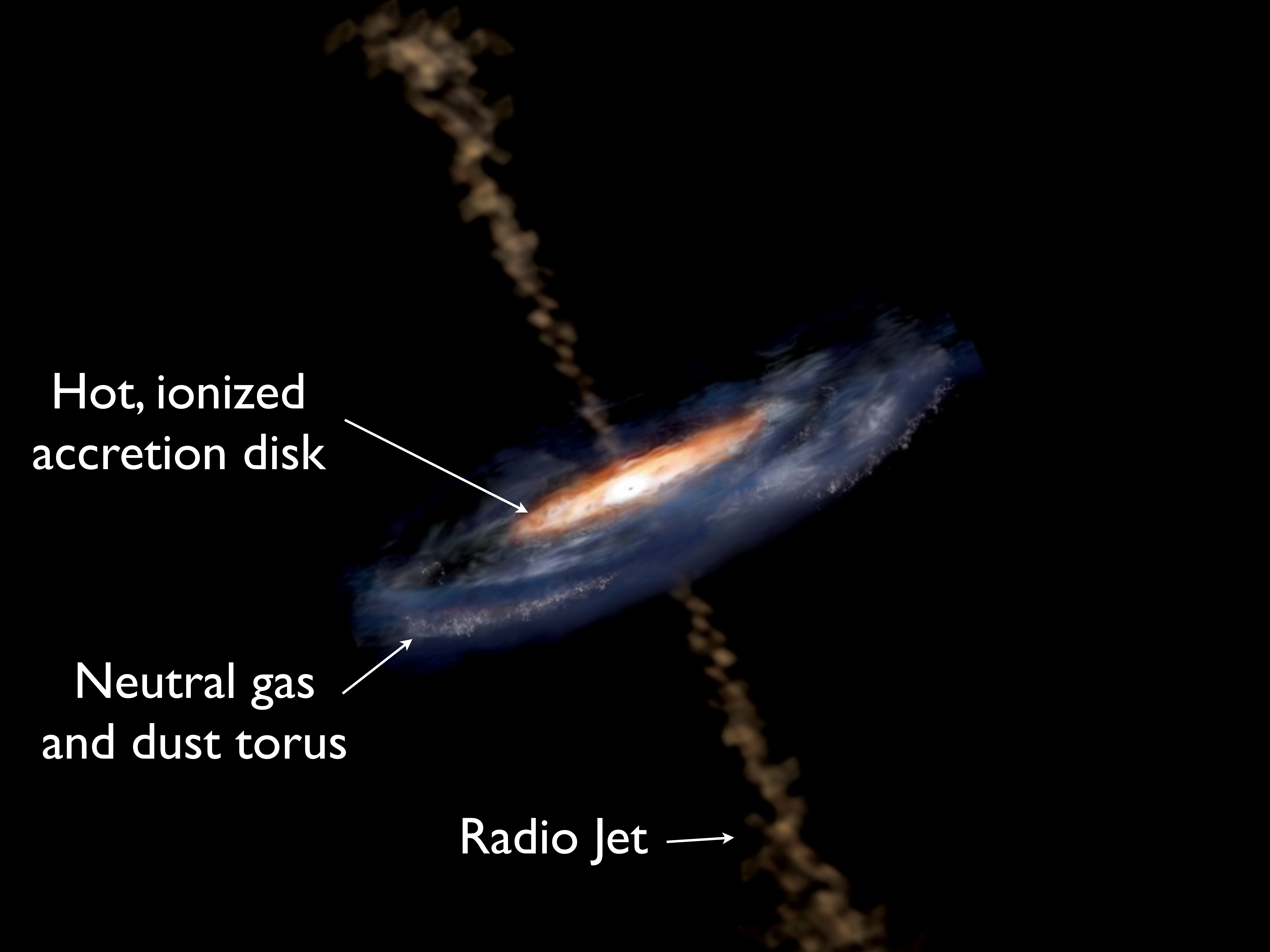
In the early universe, AGN were much brighter.

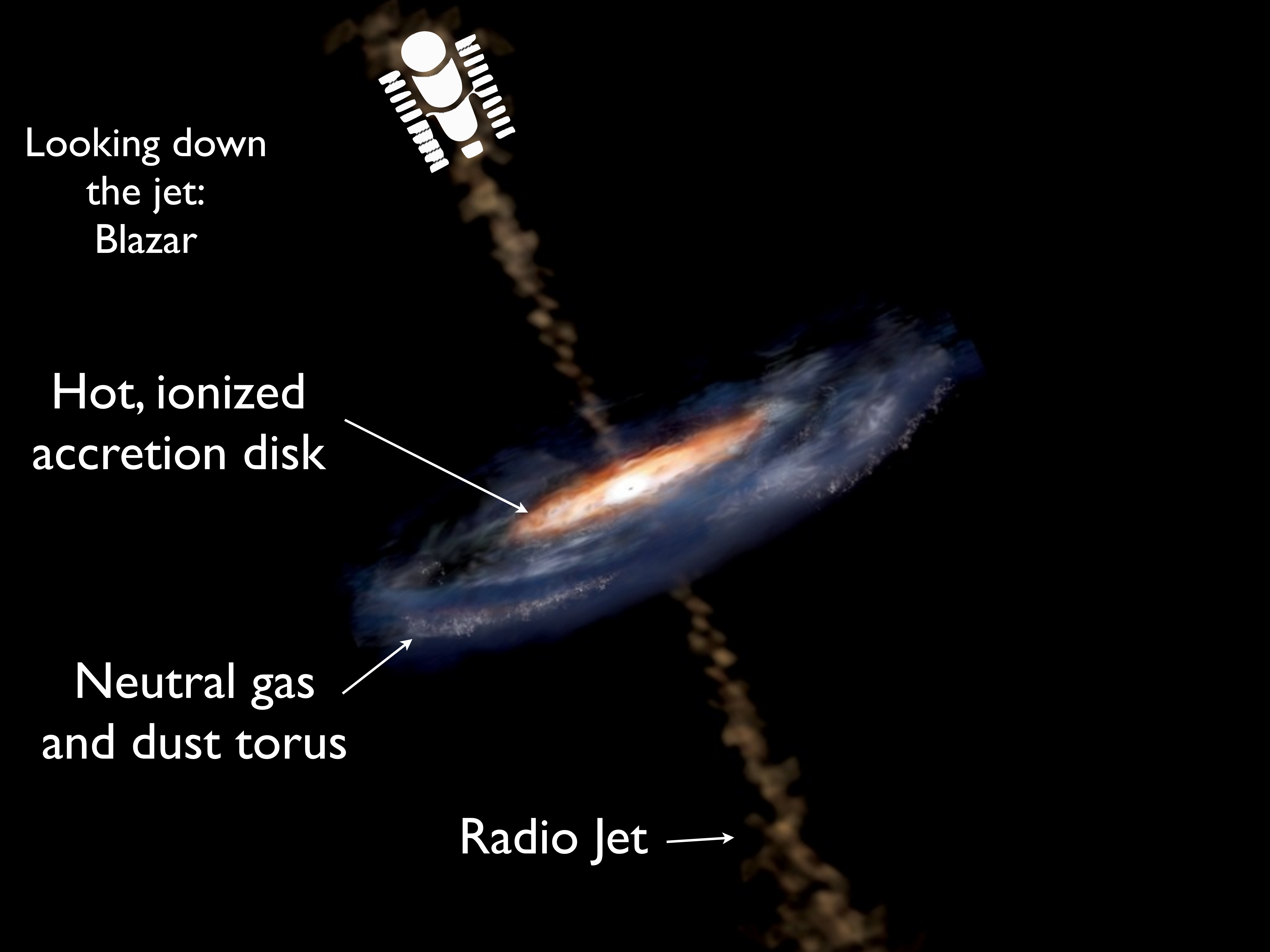
They are called "Quasars" because they are QUAsi-StellAr Radio Sources

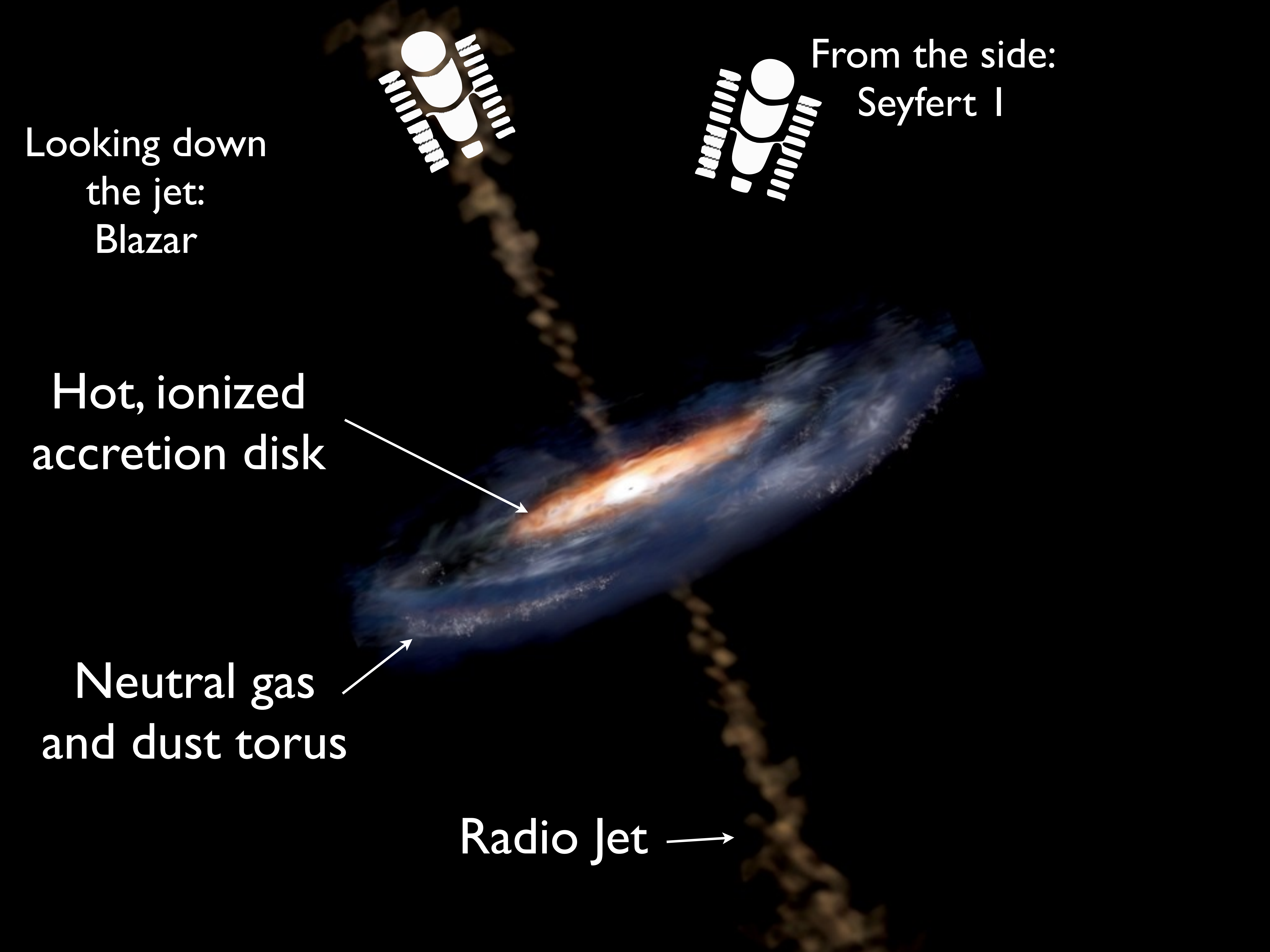



**Quasar PKS 2349** HST • WFPC2

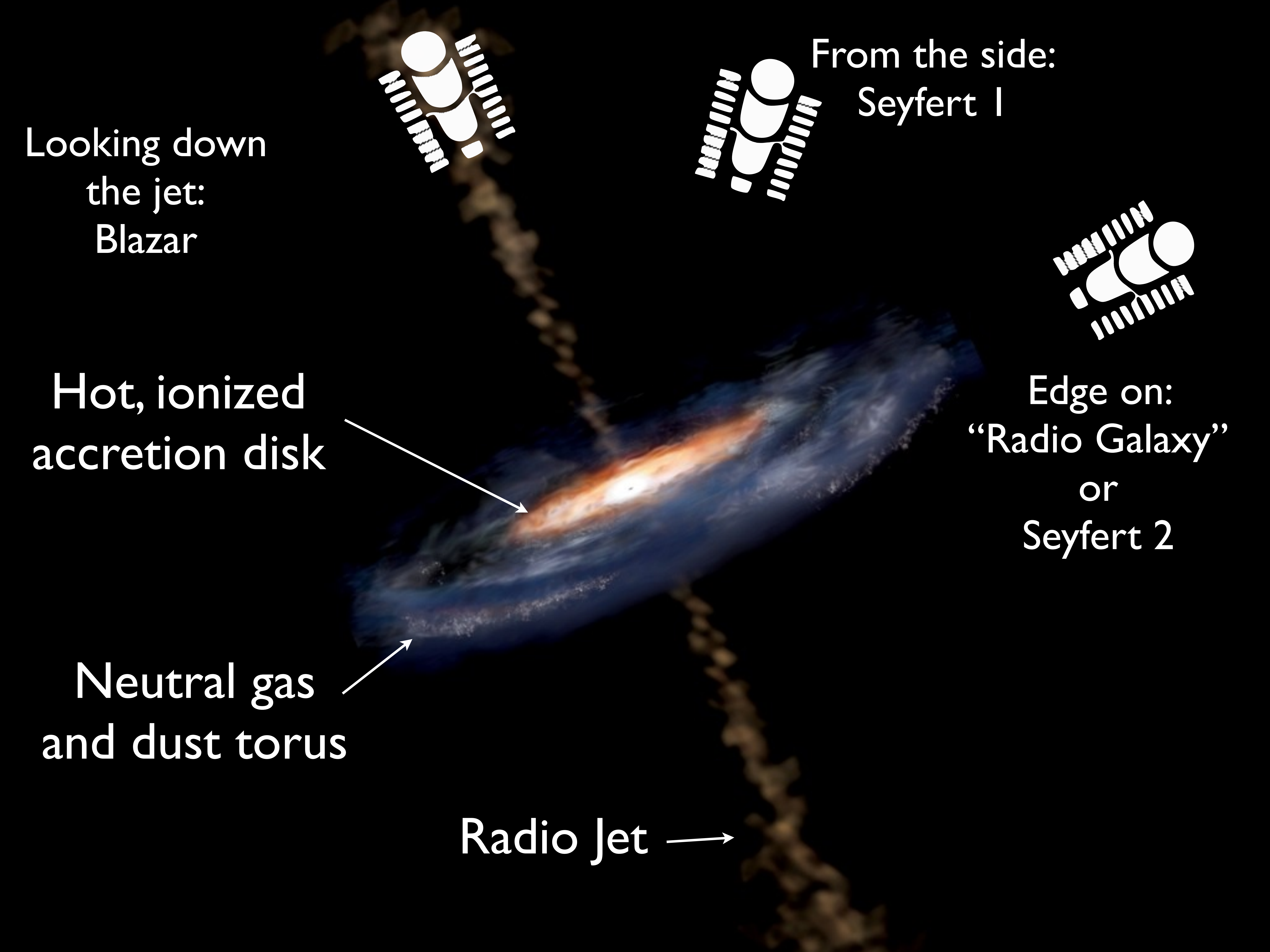
ST ScI OPO · January 1995 · J. Bahcall (Princeton), NASA


Hot, ionized
accretion disk
Neutral gas
and dust torus
Radio Jet

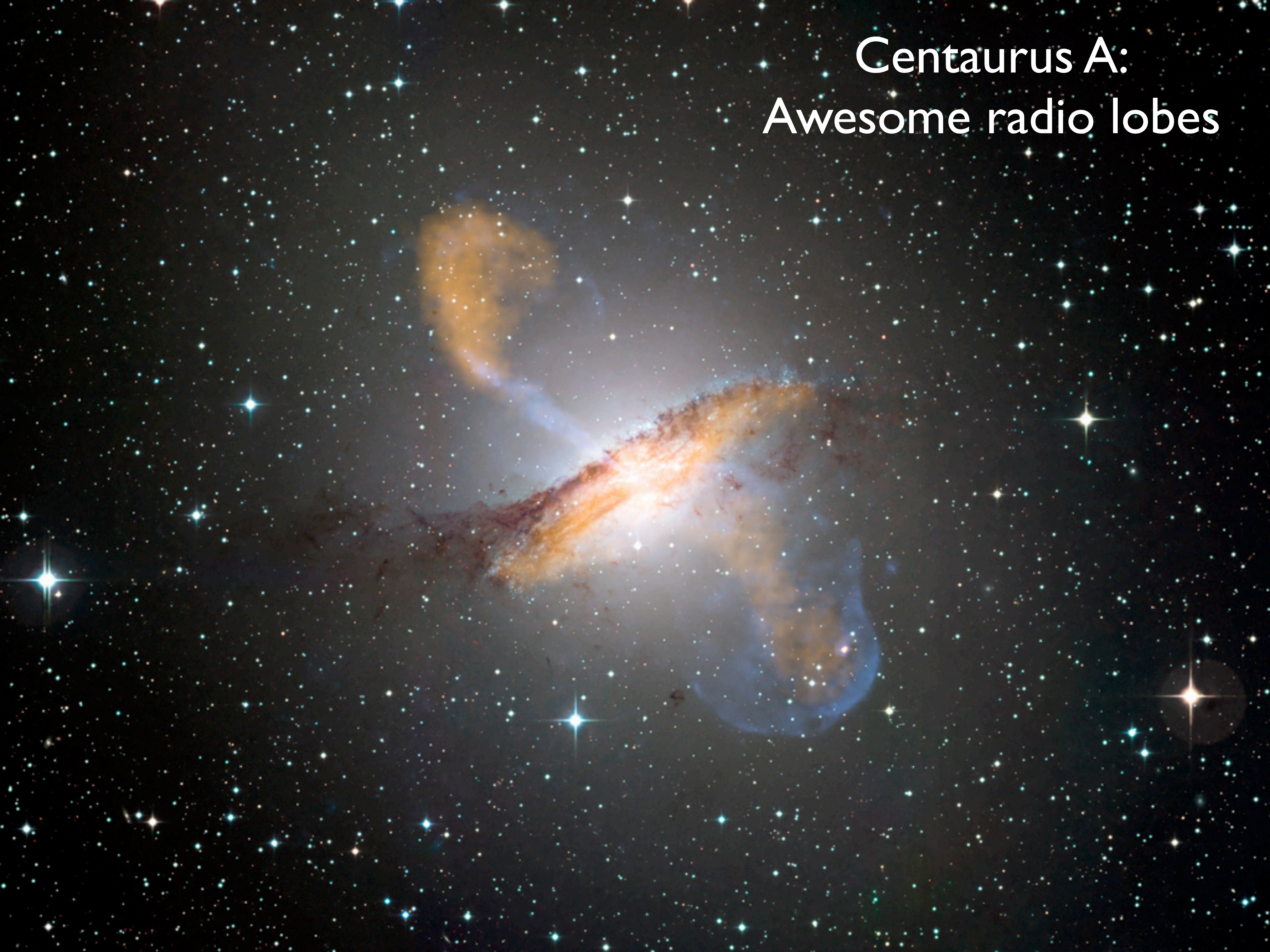

Looking down
the jet:
Blazar
Hot, ionized
accretion disk
Neutral gas
and dust torus
Radio Jet



From the side:
Seyfert 1
Looking down
the jet:
Blazar
Hot, ionized
accretion disk
Neutral gas
and dust torus
Radio Jet


From the side:
Seyfert 1
Looking down
the jet:
Blazar
Hot, ionized
accretion disk
Edge on:
“Radio Galaxy”
or
Seyfert 2
Neutral gas
and dust torus
Radio Jet

Centaurus A:
Awesome radio lobes



# Summary

- If it’s dark, how do we know it’s there?
    - Rotation curves, X-ray clusters, gravitational lensing
- What do you mean, dark?
    - Doesn’t interact with normal matter; doesn’t emit light
- What are galaxy clusters?
    - What do we use galaxy clusters for?
    - Just what they sound like!  But they also have a boatload of hot gas in them, and they’re convenient places to find dark matter
- And maybe we talked about Active Galactic Nuclei, the big black holes at the centers of galaxies