The "Unified Model" for AGN: how to describe these various types of AGN with one basic model?

Central black hole: $\mathcal{M} \approx 10^7 - 10^9\ \mathcal{M}_\odot$, accreting mass at $\approx 1 - 10\ \mathcal{M}_\odot$/yr.

Accretion disk: hot, luminous gas accreting onto the black hole, ≈ solar system sized.

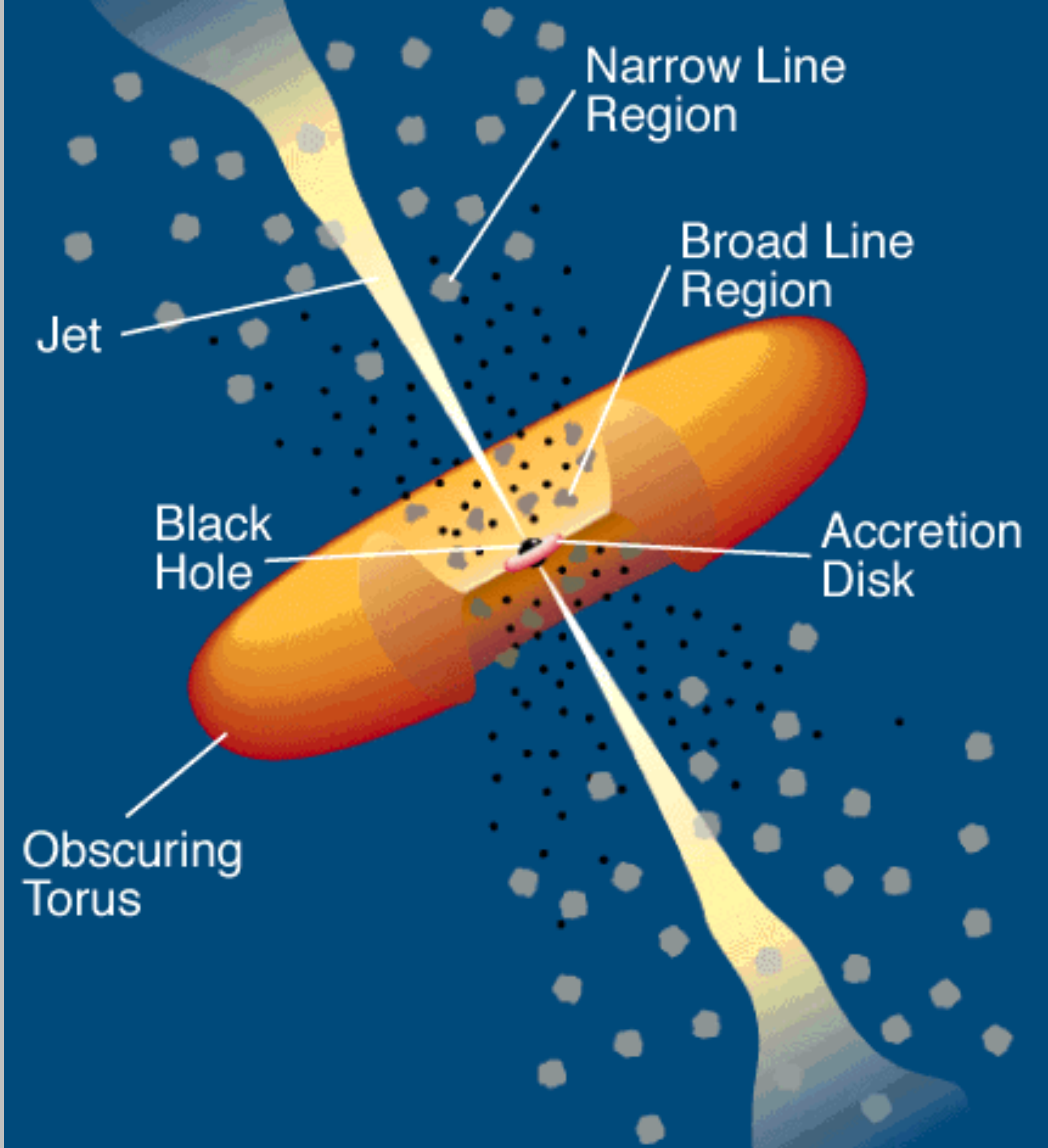
Jets: charged particles moving at relativistic speeds out of the nucleus

Broad-line region: Gas clouds near the accretion disk, turbulent motions at high speed.

Dusty torus: a ring of denser gas and dust surrounding the nucleus. ≈ 0.1 pc in size.

Narrow-line clouds: Gas clouds further out, moving more slowly.

Important: This is all happening on size scales too small to be resolved at the distances of most AGN.

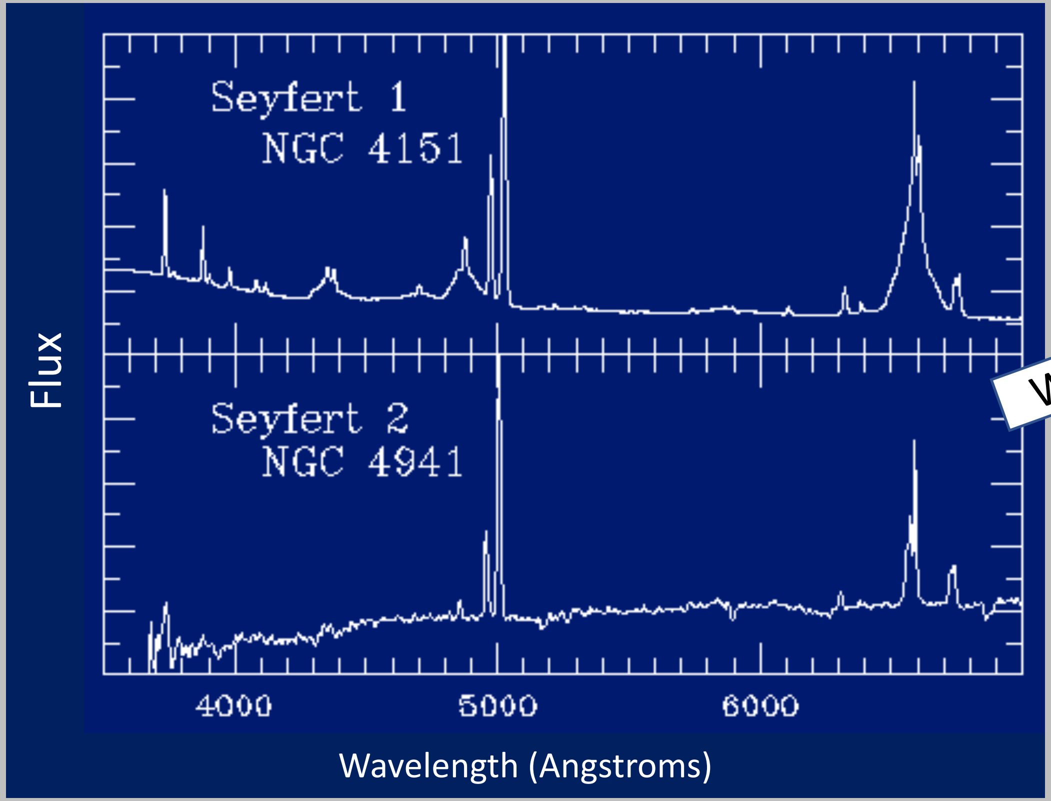


How does this "unify" the different kinds of AGN?

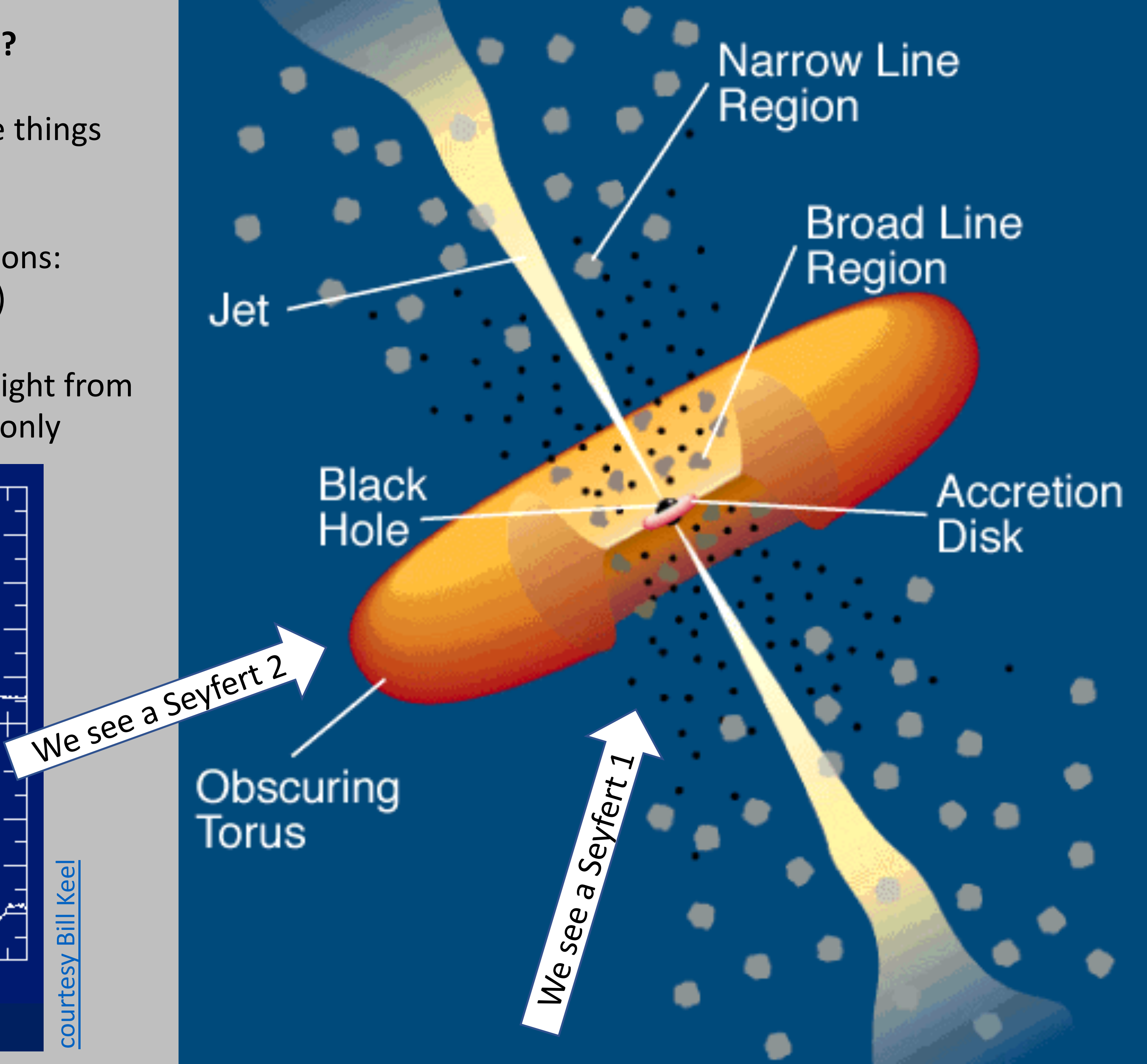
Seyfert (and other) Type 1 and Type 2 AGN: same things seen from different angles.

Type 1: we see light from the inner and outer regions: broad lines, narrow lines, hot accretion disk (blue)

Type 2: we see only the light from outer regions, light from the inner regions is blocked by dust: narrow lines only



courtesy Bill Keel



How does this "unify" the different kinds of AGN?

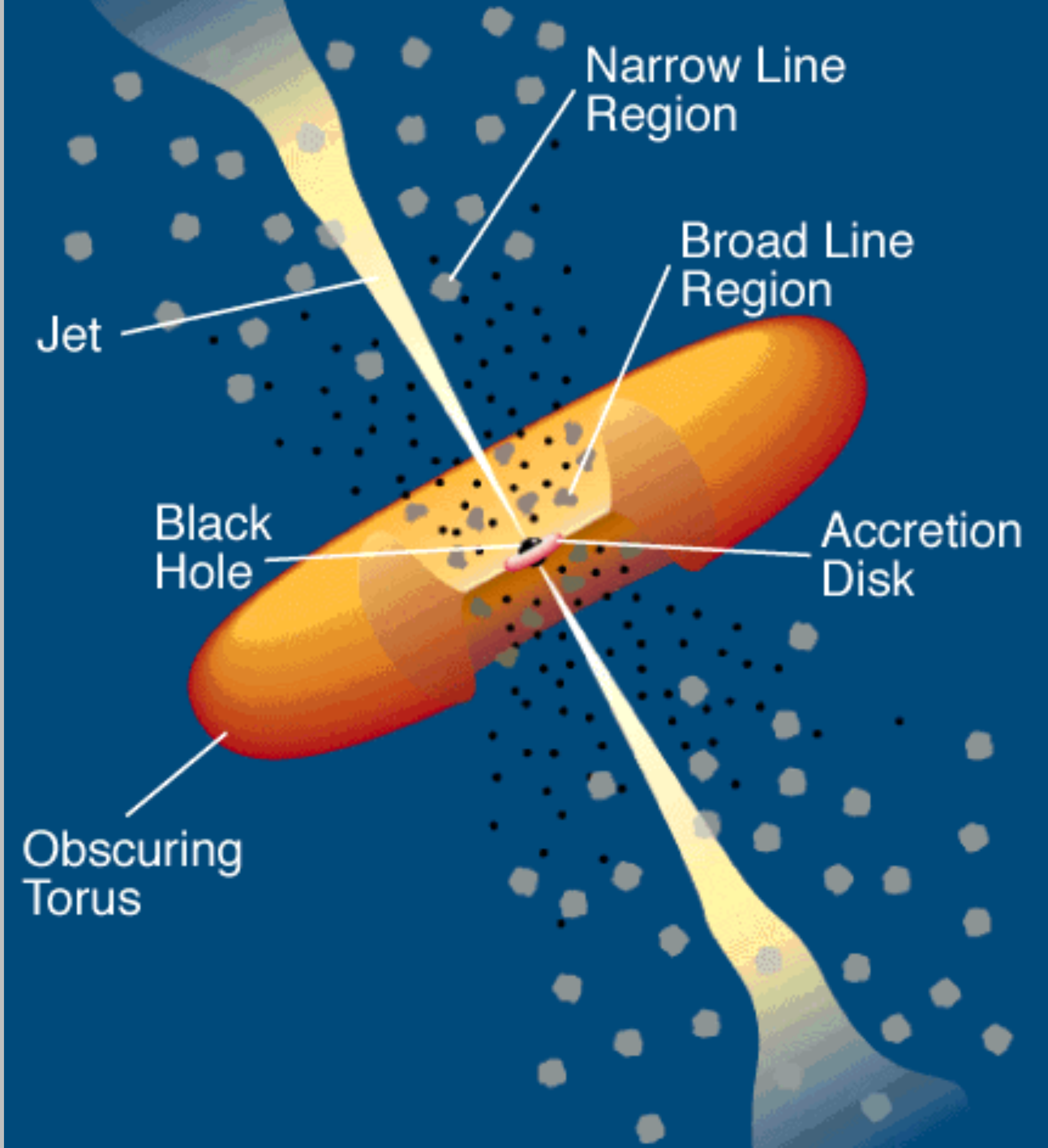
"Radio loud" vs "radio quiet" AGN: Maybe the jet hasn't turned on, or has been choked off somehow?

> *One possibility:* Radio galaxies tend to be ellipticals, spirals are generally not radio loud. Maybe the dense gas in the disks of spiral galaxies blocks the jets from getting out? Ellipticals don't have dense gas, so the jets can expand outwards unimpeded.

Luminous Quasars vs lower luminosity AGN: different amounts of power from "central engine"

> Lower accretion rates: Not as much gas falling in on low luminosity AGN?
>
> Lower mass black hole in low luminosity AGN?

Unified model: Physical differences in detail, but not really physically different mechanisms.



Timescale and Triggering of AGN activity

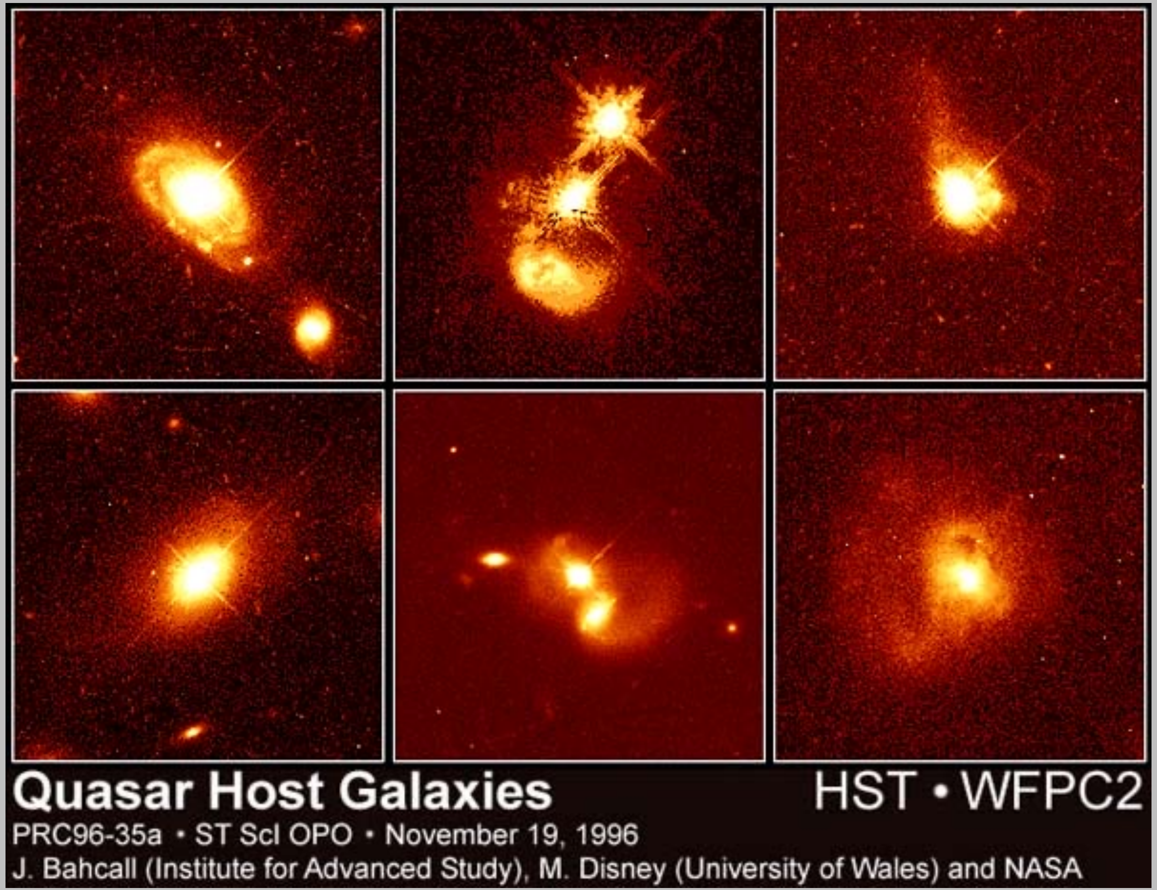
In the local universe, AGN are rare:
- 1 in a million galaxies host luminous quasars
- ≈ 5% of galaxies host bright Seyfert nuclei.

But **most** bright galaxies have black holes.

So whatever triggers AGN activity must be relatively rare event, and the timescale for AGN activity is likely short ($10^7 - 10^8$ years?)

One good possibility: **galaxy interactions and mergers**

- Interactions are good at driving gas into the center of galaxies, where it can fuel an AGN
- Mergers scatter stars violently and grow galaxy spheroids. *If mergers fuel/grow black holes and also build spheroids, this might explain the correlation between black hole mass and spheroid mass.*

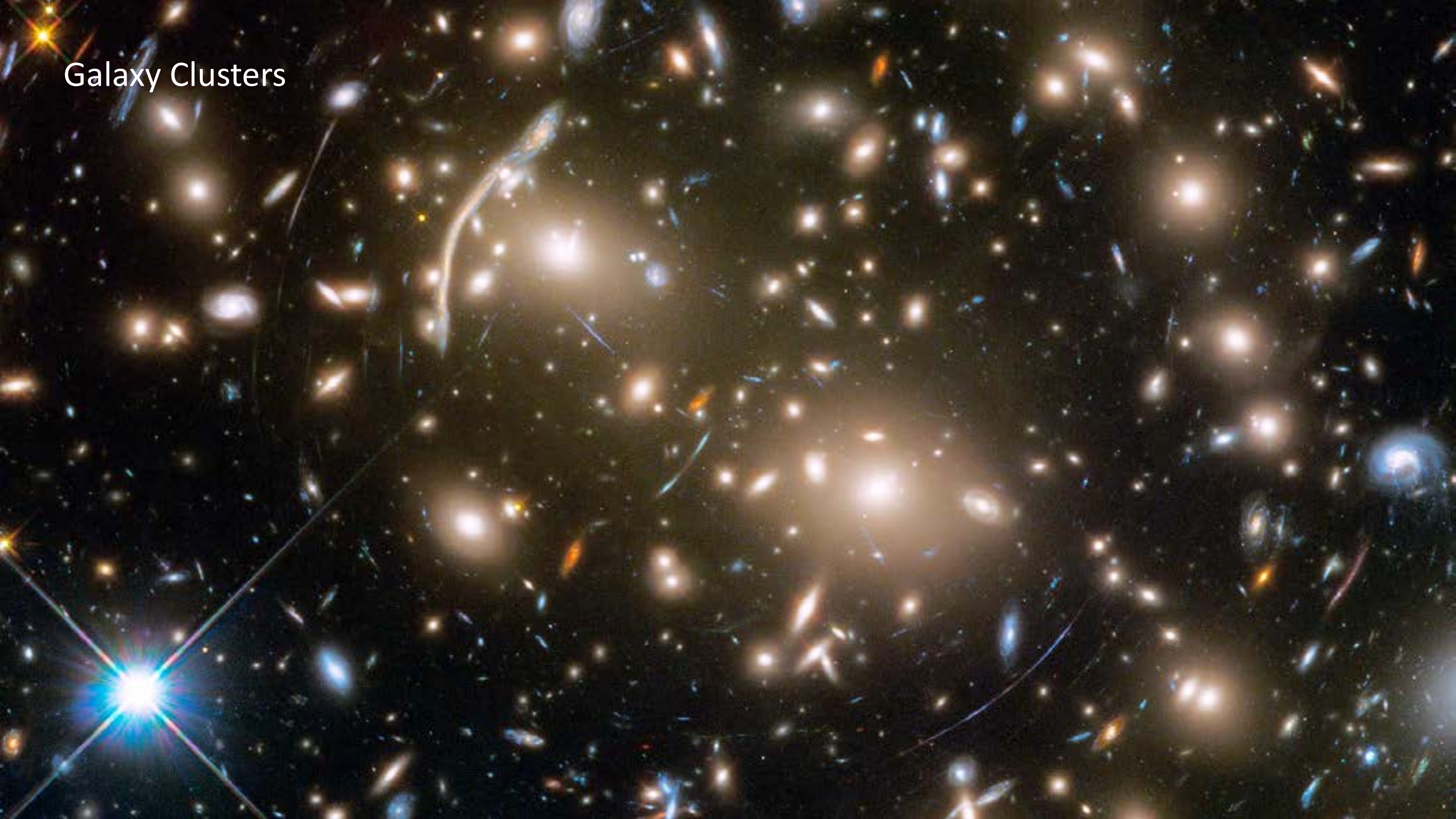


Many AGN are found in interacting or messy systems....
... but so are many non-AGN galaxies.

And also, many AGN are not in interacting systems.

So a direct connection between AGN activity and galaxy mergers *remains unclear*. 😩

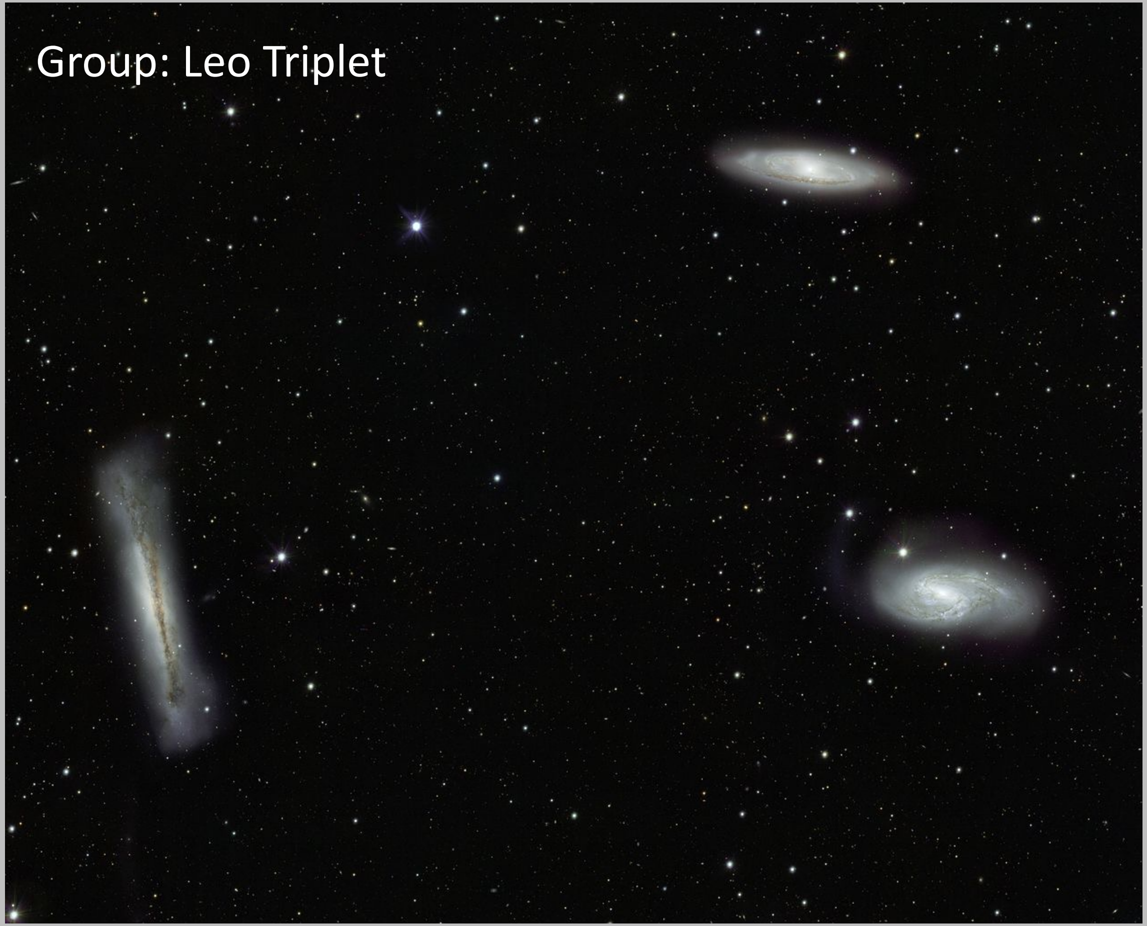
Galaxy Clusters



Galaxy Groups and Clusters

Galaxy groupings come in all sizes: no well-defined difference between groups and clusters.

Many big clusters contain smaller “subgroups”.



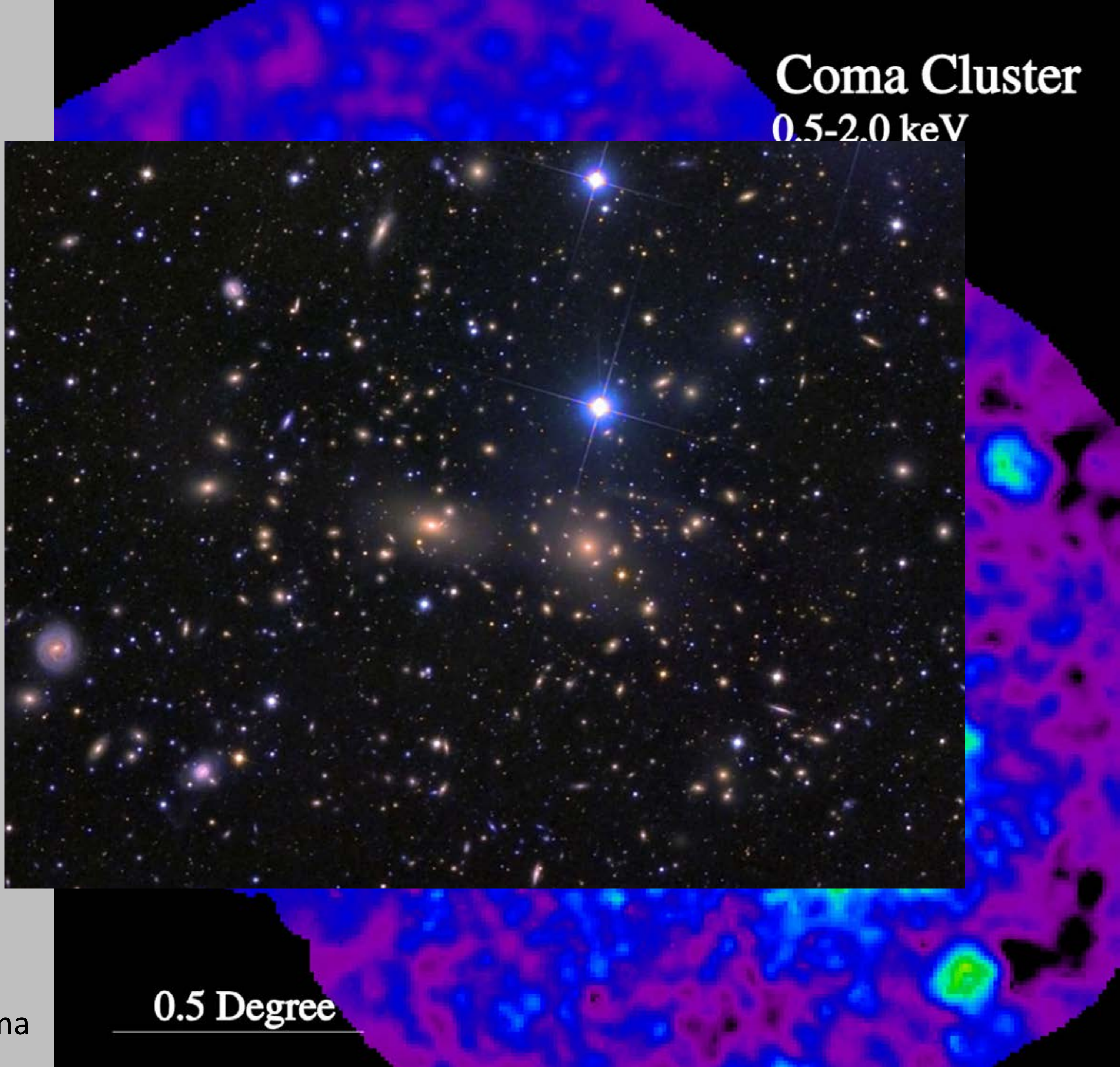
	Groups	Clusters
Galaxies	handful	100’s – 1000’s
Sizes	0.5 – 1 Mpc	few Mpc
Velocity Dispersion	≈ few 100 km/s	≈ 500 – 1000 km/s
Mass	$\approx 10^{13}\ M_\odot$	$\approx 10^{14} - 10^{15}\ M_\odot$

Hot gas in galaxy clusters

Massive galaxy clusters are filled with X-ray emission: free-free emission from hot, ionized $T \approx 10^7$ K gas.

The total amount of hot gas exceeds the total mass of the stars in all the galaxies combined!

Some of this gas may have been blown out from galaxies within the cluster, but most probably was primordial gas that never formed into stars to begin with.



X-ray map of Coma

Galaxy Cluster Masses **(using galaxy velocities)**

kinetic energy

gravitational potential energy

Start with the **virial theorem**: In a system in equilibrium, $2K + \Phi = 0$.

Let's check the virial theorem using circular orbits around a point mass:

Circular speed:

$$v_c^2 = \frac{GM}{R}$$

Kinetic energy:

$$K = \frac{1}{2}mv^2 = \frac{GMm}{2R}$$

Potential energy:

$$\Phi = -\frac{GMm}{R}$$

Virial theorem:

$$2K + \Phi = 2\left(\frac{GMm}{2R}\right) + \left(-\frac{GMm}{R}\right) = \frac{GMm}{R} - \frac{GMm}{R} = 0$$

🥳 👍

Galaxy Cluster Masses (using galaxy velocities)

Start with the **virial theorem**: In a system in equilibrium, $2K + \Phi = 0$.

Kinetic Energy

For galaxies in a galaxy cluster kinetic energy is approximately:

$$K = \sum_{i=1}^{N_{gal}} \frac{1}{2} m_i V_i^2 \approx \frac{1}{2} M \langle V \rangle^2 \approx \frac{1}{2} M (3\sigma^2) \approx \frac{3}{2} M \sigma^2$$

adding up kinetic energy of each galaxy

M : total mass of galaxies
$\langle V \rangle$: their average 3D speed.

σ^2 : line of sight velocity dispersion, multiply by 3 to get 3D dispersion.

Potential Energy

If we treat the cluster as a ***uniform density sphere*** 😒, of mass M and size R, we can write the gravitational potential energy as:

$$\Phi = -\frac{3}{5} \frac{GM^2}{R} \approx -\frac{3}{5} \frac{GM^2}{\langle R \rangle}$$

Self-gravity of uniform sphere Derived(?) in PHYS 121, 310

$\langle R \rangle$: some characteristic measure of cluster size.

Galaxy Cluster Masses (using galaxy velocities)

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Virial Theorem

$$2K + \Phi \approx 2\left(\frac{3}{2} M\sigma^2\right) + -\frac{3}{5}\frac{GM^2}{\langle R \rangle} = 0$$

so solve for M to get:

$$M \approx \frac{5\langle R \rangle \sigma^2}{G}$$

Galaxy Cluster Masses

Method 1) Using galaxy velocities to get total mass:

$$M \approx \frac{5\langle R\rangle\sigma^2}{G}$$

Method 2) Using starlight to get stellar mass:

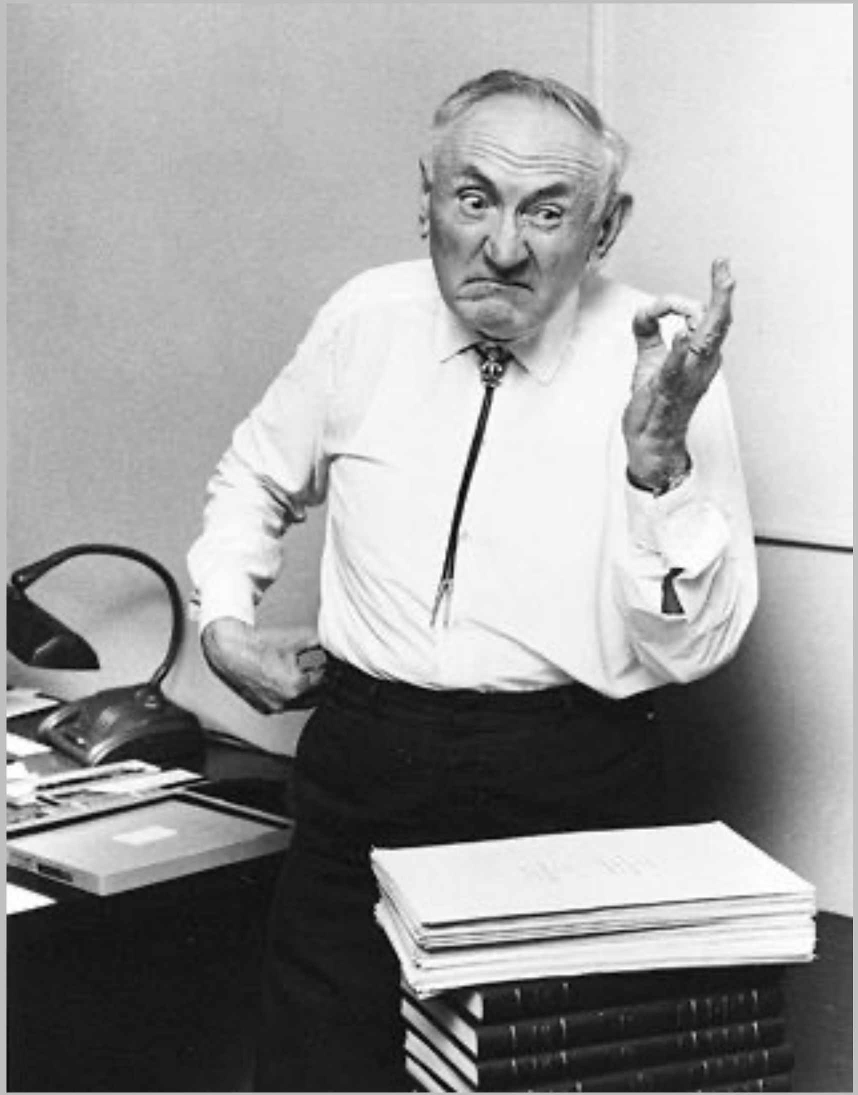
$$M_* = \sum_{i=1}^{N_{gal}} L_i \left(\frac{M}{L}\right)_{*,i} \approx L \left\langle \left(\frac{M}{L}\right)_* \right\rangle$$

These methods do not agree!

There is far more total mass than stellar mass.
Much more than even stellar mass + gas mass.

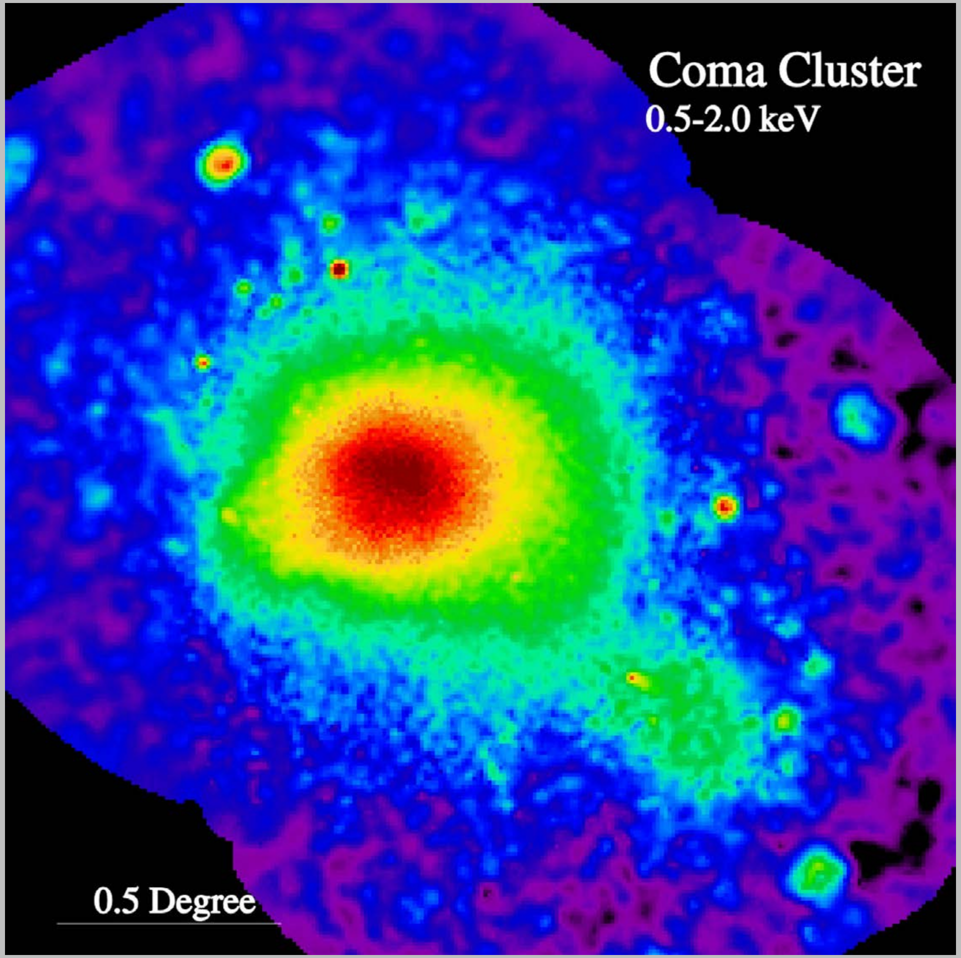
Fritz Zwicky (1933): realized that if the mass in stars was all there was, galaxies are moving way too fast.

He hypothesized "*dunkle Materie*": dark matter.

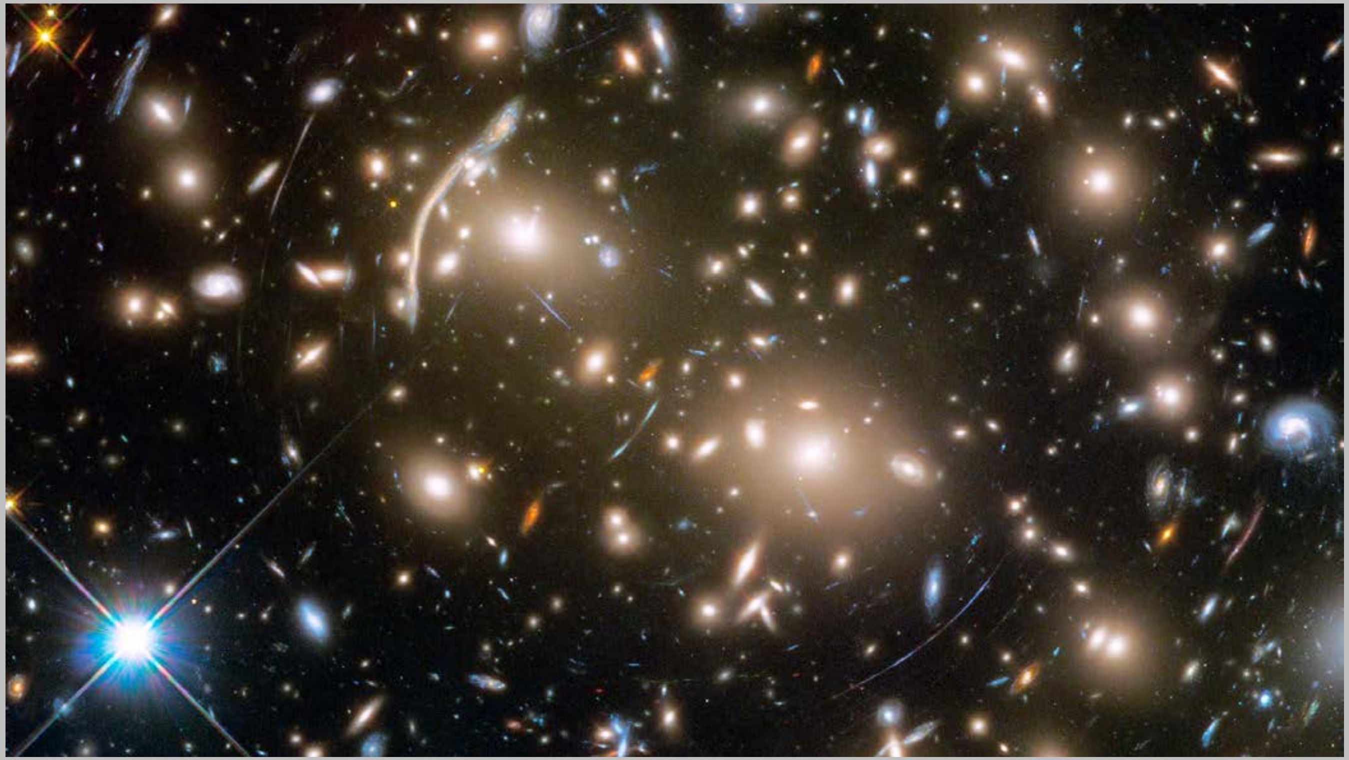


Galaxy Cluster Masses: Other (more recent) methods

Hydrostatic equilibrium: Balance thermal energy of hot X-ray gas with gravitational potential energy of cluster.



Gravitational lensing: the mass of the cluster bends the light from background galaxies, distorting their shapes. This can be modeled to get the cluster mass.



Galaxy cluster mass balance (rough numbers):

- ≈ 10% of total mass is in stars
- ≈ 20% of total mass is in hot gas
- ≈ 70% of total mass is ”missing”: dark matter

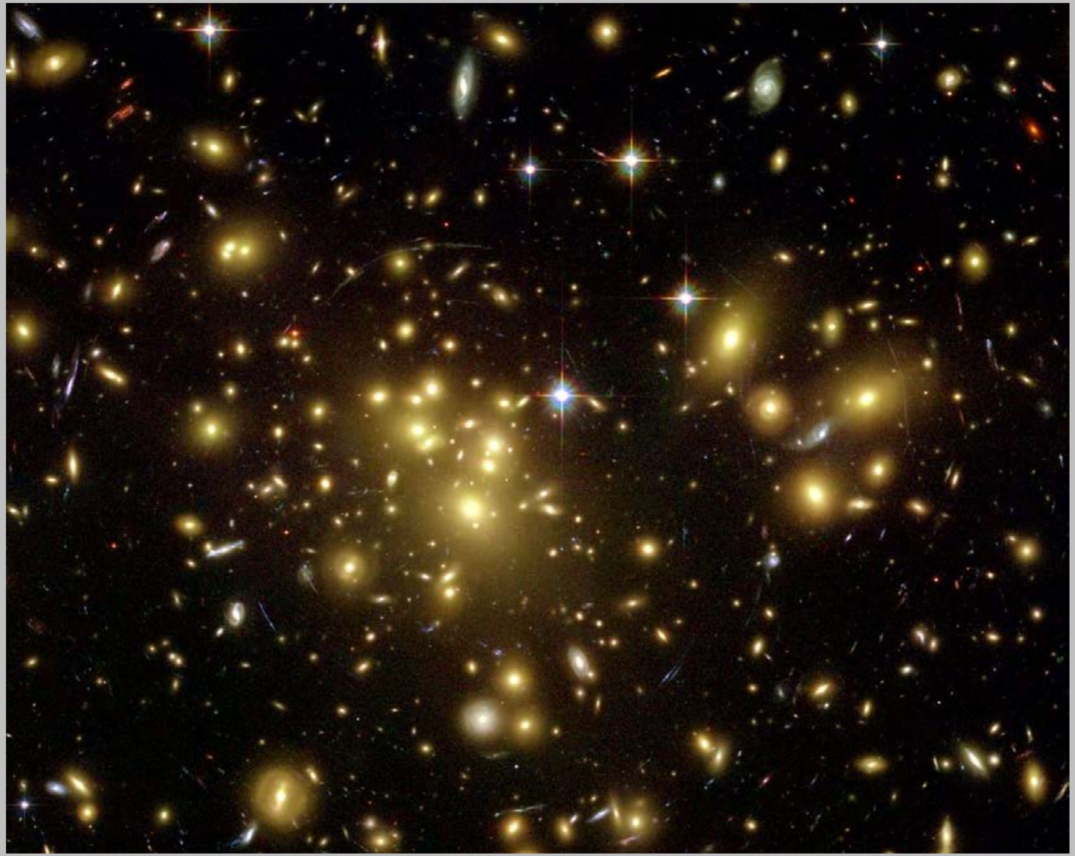
Galaxies: Morphology-Density Relationship

In the local universe, the fraction of galaxy types is a strong function of local environment.

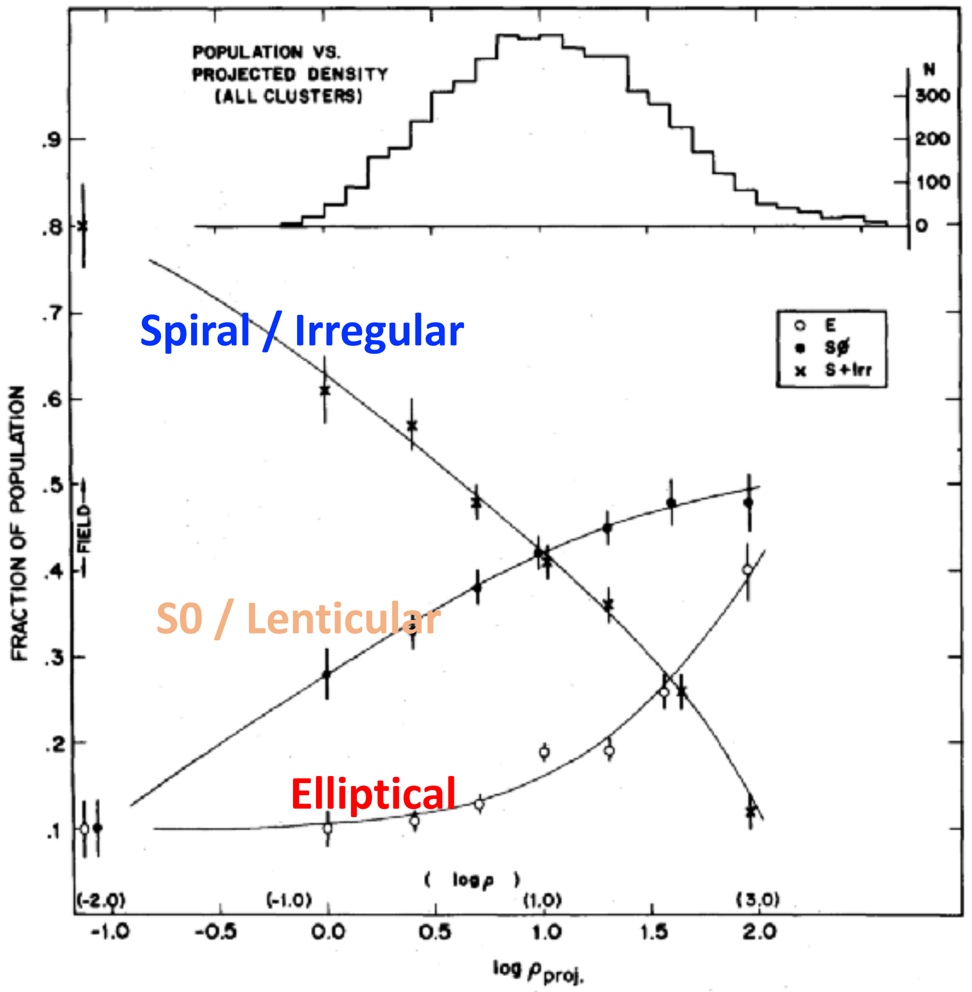
Dressler 1980

Spirals/Irregulars dominate the in the field environment.

S0's and E's dominate in galaxy clusters.



Galaxy Population Fraction



Projected Number Density of Galaxies
log(# per Mpc^2)

Evolution of Cluster Galaxies

Hubble Space Telescope (and now JWST) lets us look at galaxies in distant clusters, to see how things have changed with time.

Higher fraction of star-forming spiral galaxies in the past and a higher fraction of "red and dead" E and S0 galaxies today: galaxy evolution!

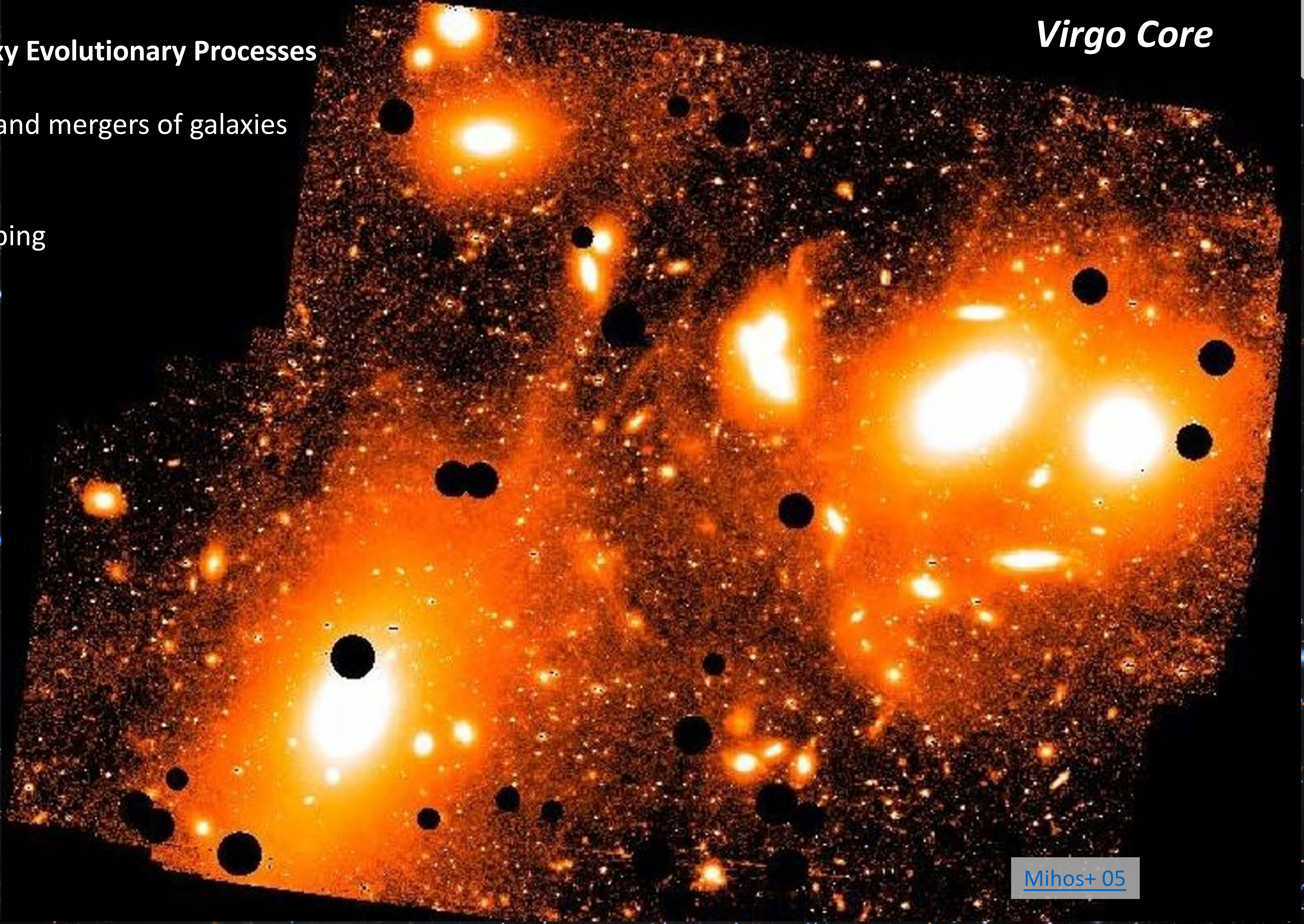
HST image of galaxy cluster MACS J0717+3745. Redshift $z = 0.55$, so we are looking back in time ≈ 5 billion years.

Cluster Galaxy Evolutionary Processes

1) Collisions and mergers of galaxies

2) Tidal stripping

Virgo Core



Mihos+ 05

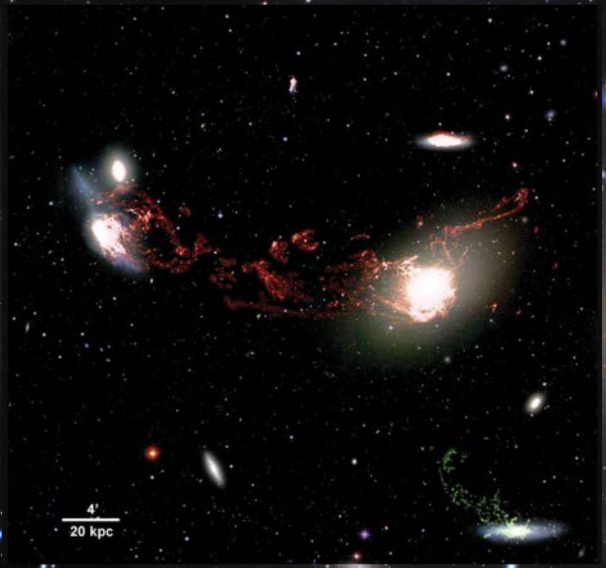
Cluster Galaxy Evolutionary Processes

Virgo Core

1) Collisions and mergers of galaxies

2) Tidal stripping

3) Ram pressure stripping



Cluster Galaxy Evolutionary Processes

1) **Collisions and mergers**: galaxies interact, collide, and sometimes even merge in group and cluster environments.

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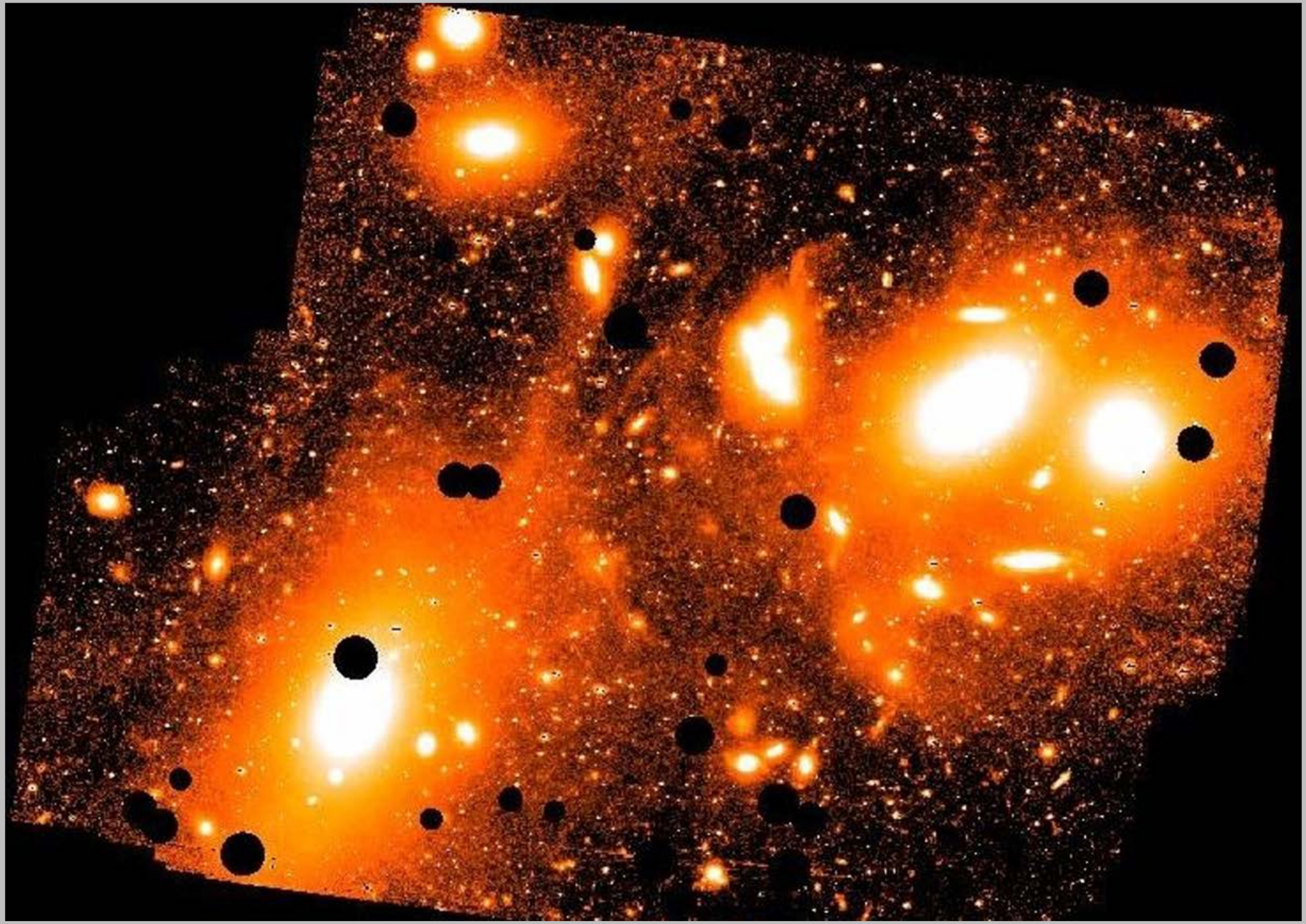


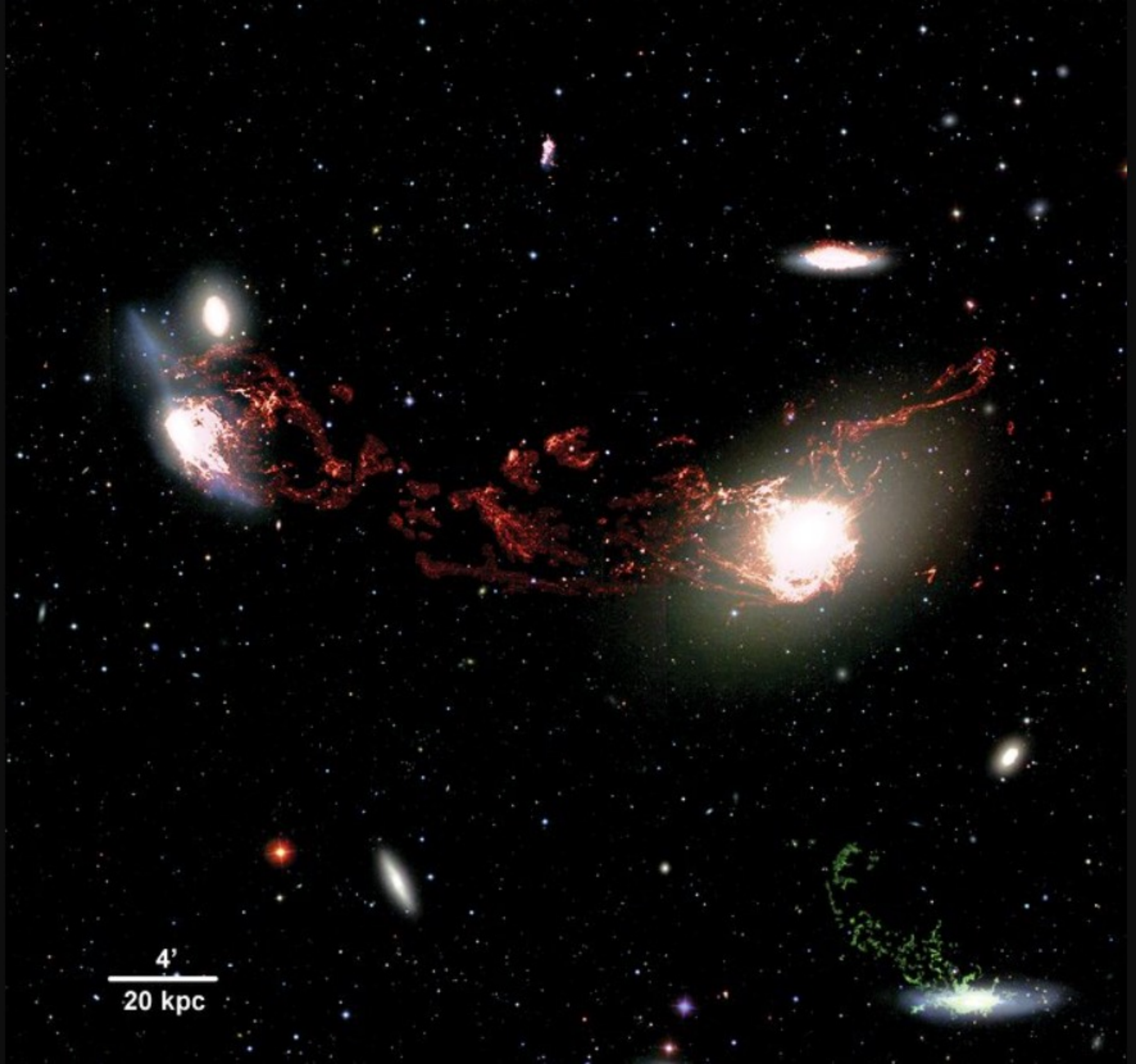
Tidal streams in the Virgo Cluster (Mihos+ 05)

Cluster Galaxy Evolutionary Processes

1) **Collisions and mergers**: galaxies interact, collide, and sometimes even merge in group and cluster environments.

2) **Tidal stripping**: the tidal forces from the cluster's gravitational potential as a whole strips stars from galaxies and even completely disrupt smaller galaxies.

3) **Ram pressure stripping**: In massive clusters, the gas pressure of the hot X-ray gas can completely strip cold star-forming gas out of spiral galaxies as they move through the cluster.



Red and green: filaments of gas stripped out of spiral galaxies in Virgo

Kenney+ 08

Galaxy Cluster Formation

Clusters grow over time as gravity pulls galaxies together.

Hierarchical accretion: small groups form first, then groups of galaxies merge to form small clusters, then small clusters merge together to form big clusters.

Cluster formation is an *on-going process*.

Formation of a galaxy cluster over ≈ 10 billion years of time

Rudick+ 11