Reading: OpenStax, Chapter 28, Sections 28.3-28.5

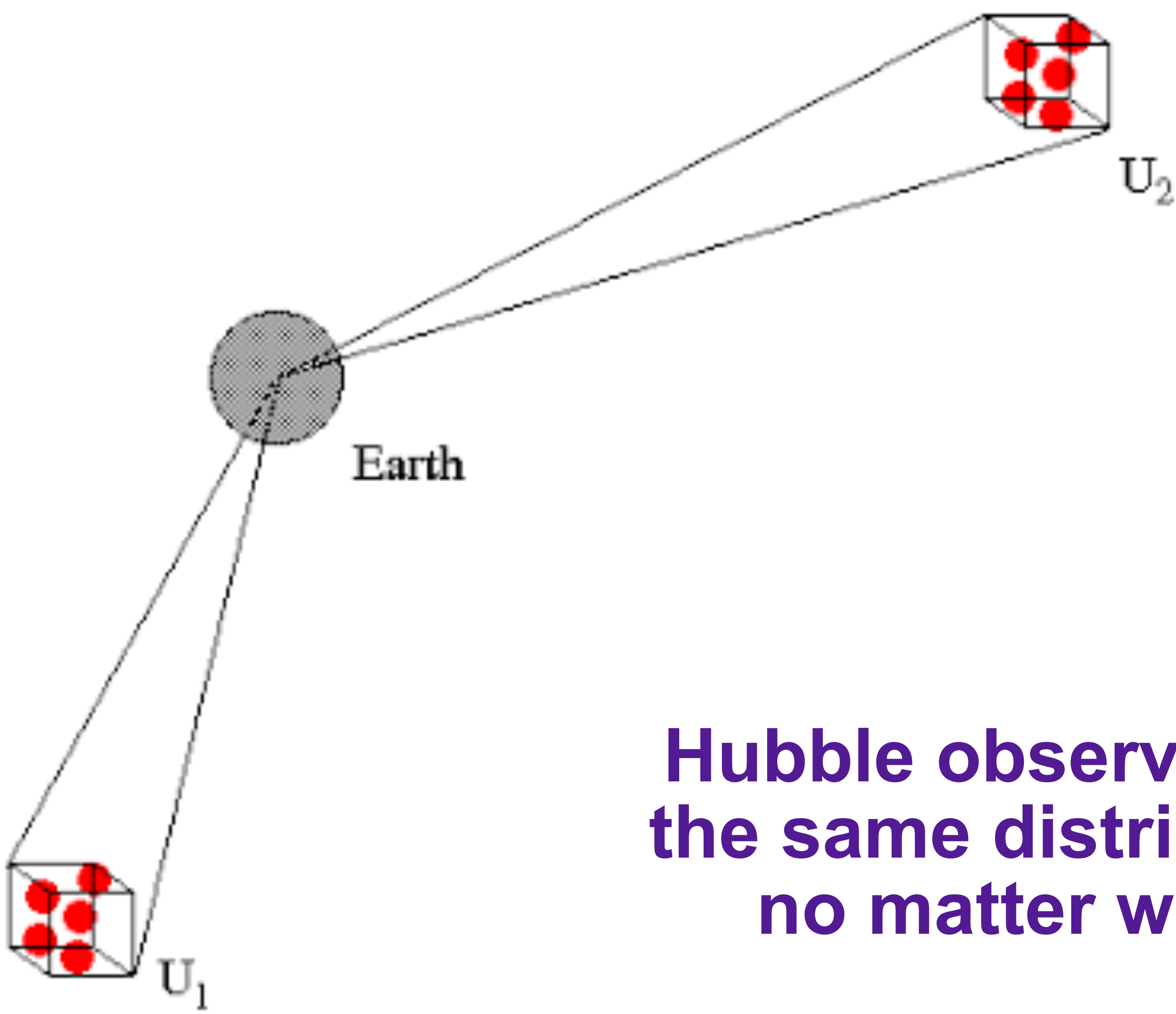
Previously: **Quasars, Active Galaxies, and Monster Black Holes**

- Discovery of quasars — distant objects that are very bright (Hubble Law and redshift — receding very fast and very far away)
- “Active Galaxies” show evidence for high-energy phenomena in and around a small central engine that drives enormous structures
- Supermassive black holes as the engine for AGN phenomena

Today: **Dark Matter and Large Scale Structure**

- Galaxies are mostly found in groups and clusters
- Clusters are further organized into superclusters
- Dark matter is needed to hold clusters together
- The large-scale structure of the visible Universe shows large voids threaded by filamentary superclusters

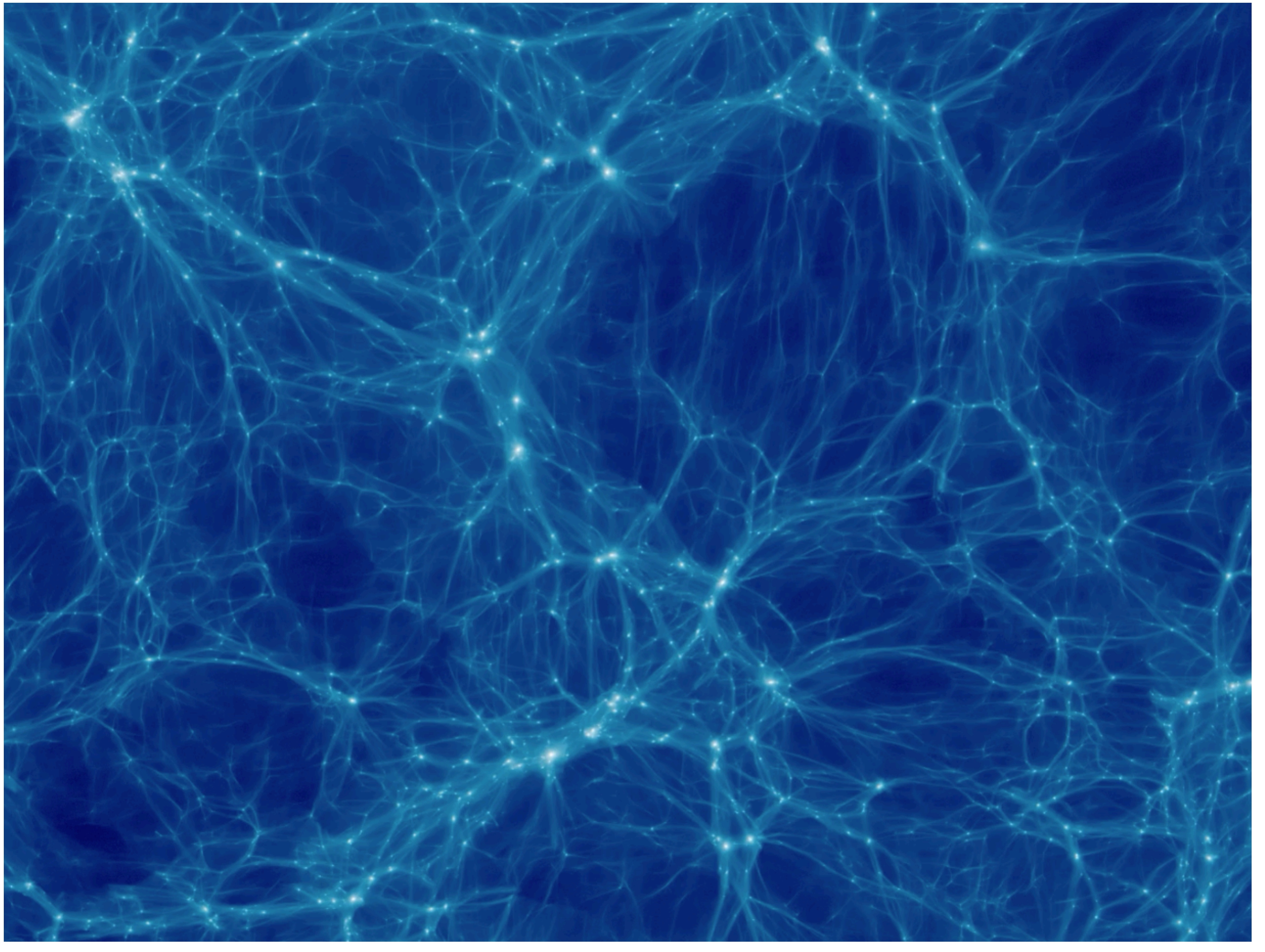
The Cosmological Principle



Hubble observed approximately the same distribution of galaxies no matter where he looked

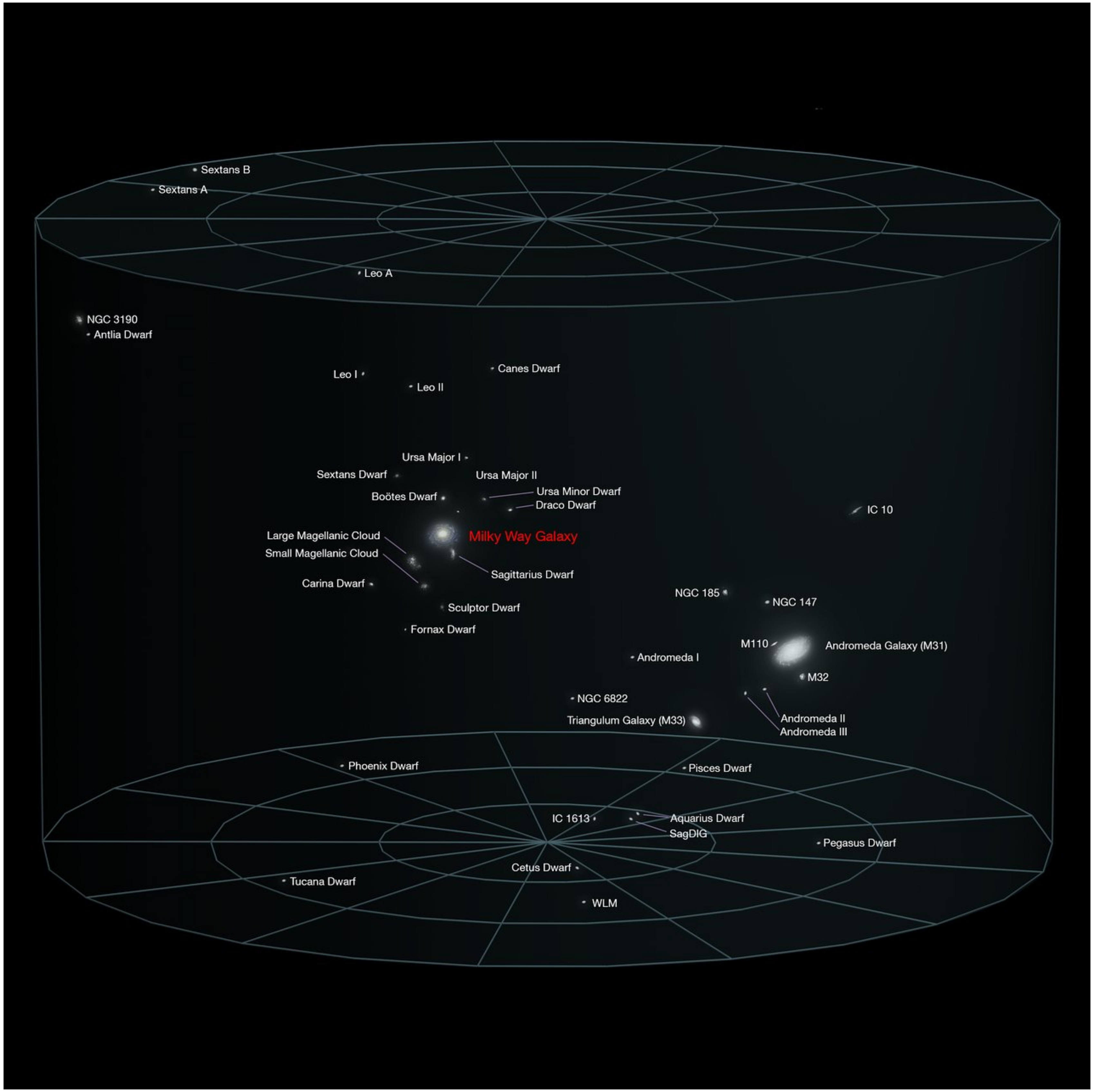
But this is only part of the picture — if we look more closely, we see something different altogether

Large Scale Structure



- At smallest scales, there are groups
- Larger scales: galaxy clusters
- Even larger scales: galaxy superclusters

The Local Group



- 3 million light years across (~1 Mpc)
- ~60 members
- Three large spirals (MW, Andromeda, M33)
- Two intermediate ellipticals
- Many dwarf galaxies
- At least 50% mass in MW and Andromeda

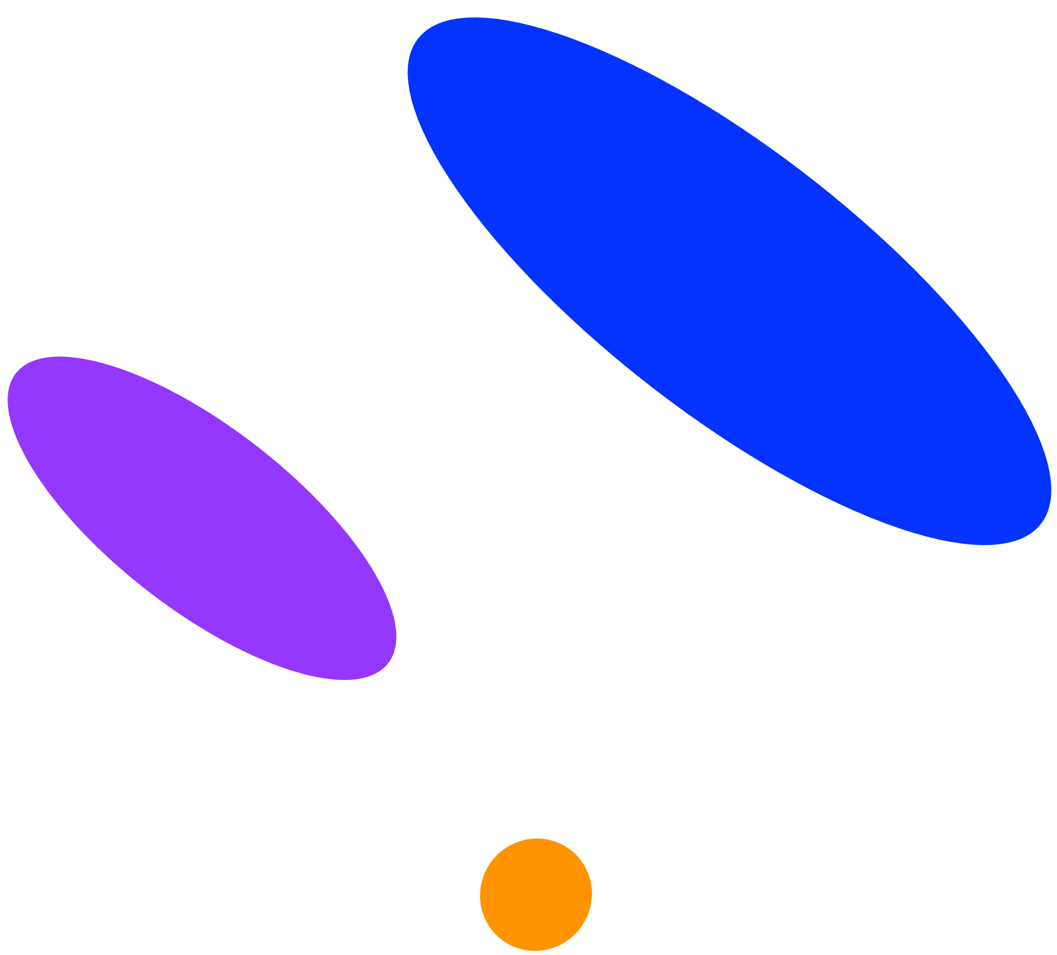
Andromeda Galaxy

M33 (Triangulum Galaxy)

Magellanic Clouds (Dwarf Galaxies)

Local Group galaxies are moving toward/around each other

- But how can this be if the Universe is expanding?
- Locally, gravity is stronger than expansion



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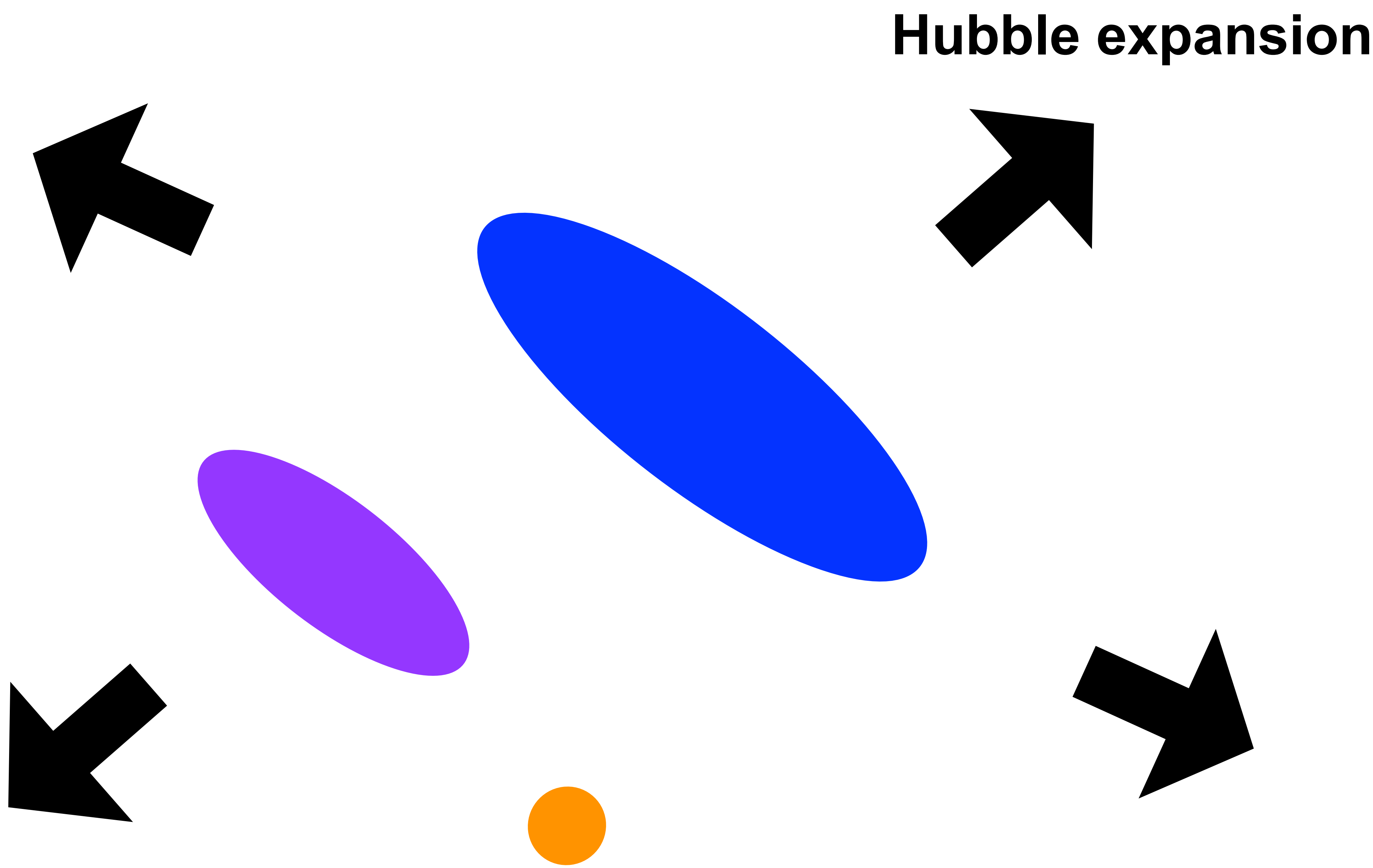

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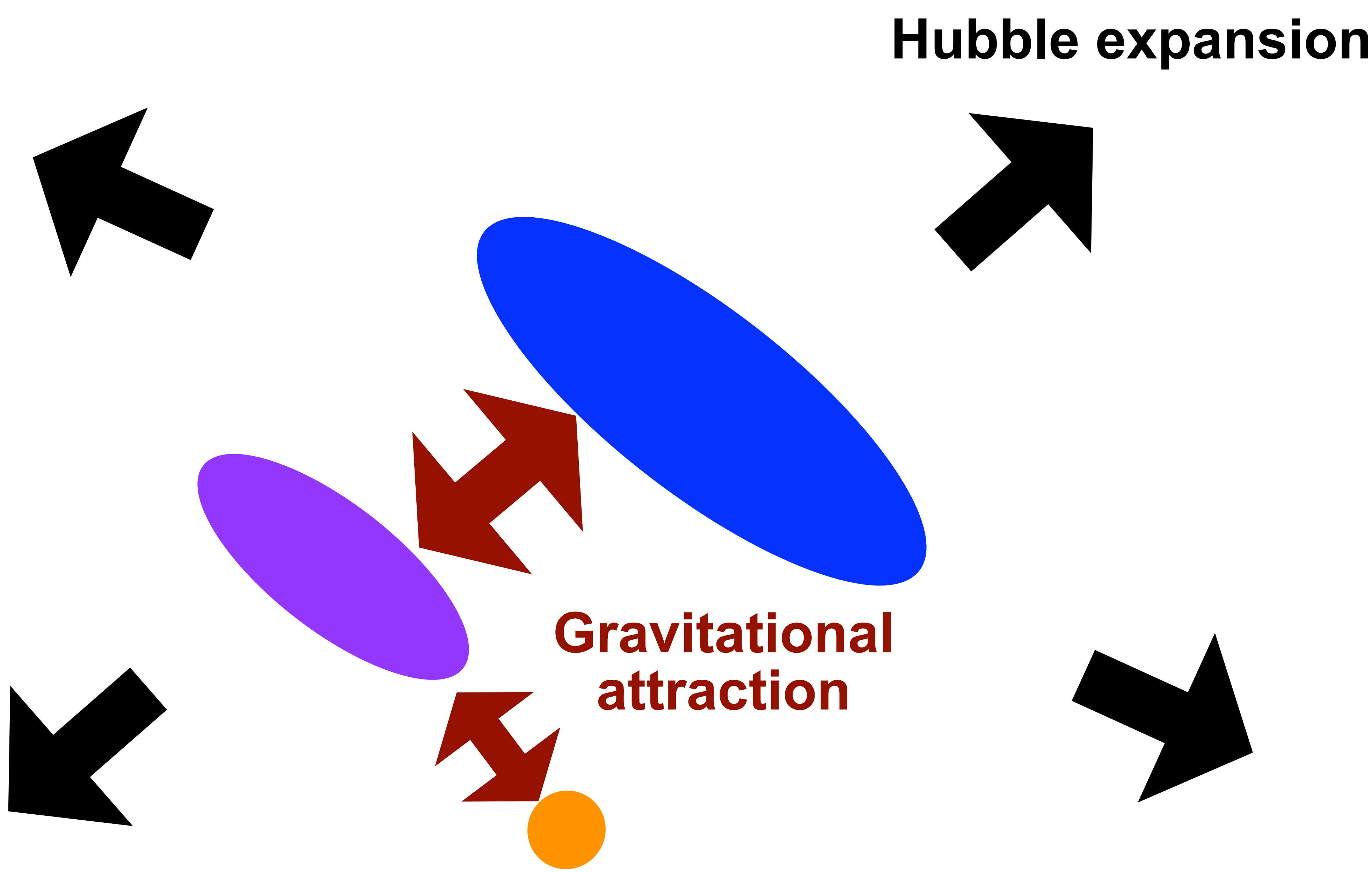


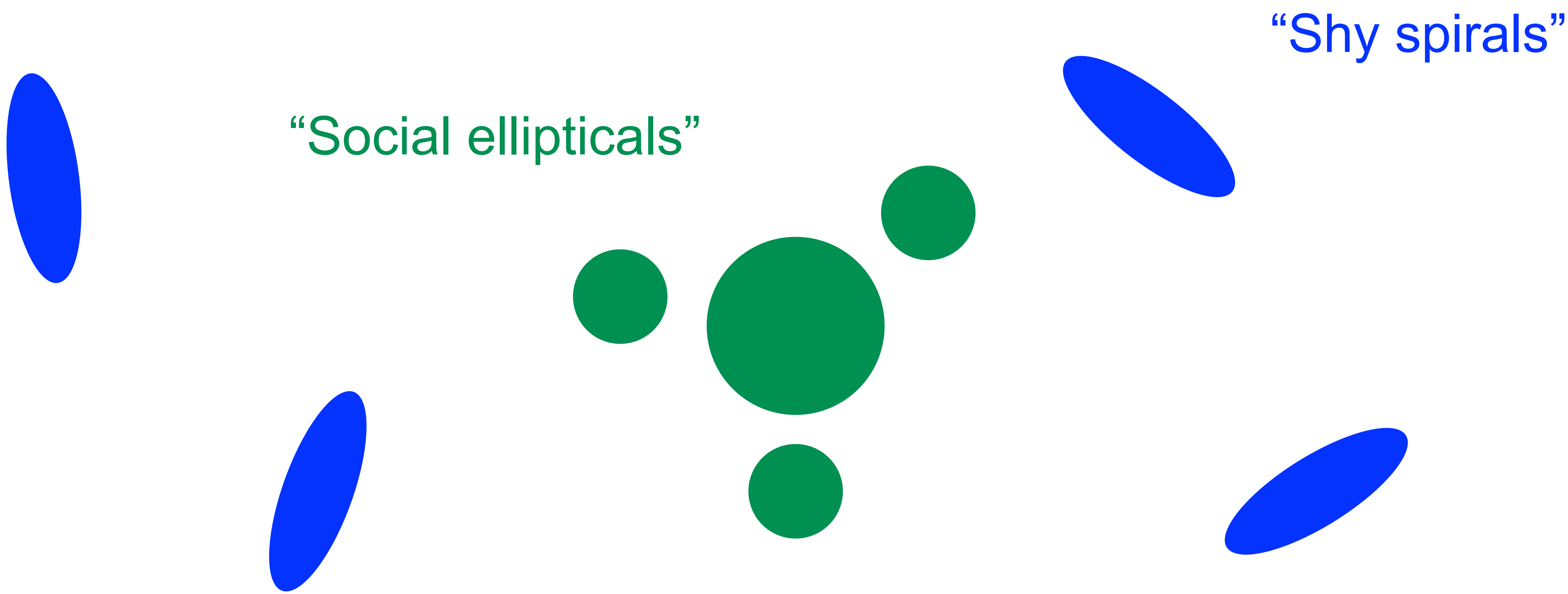
Gravity is the key to explaining large scale structure

Benedikt Diemer

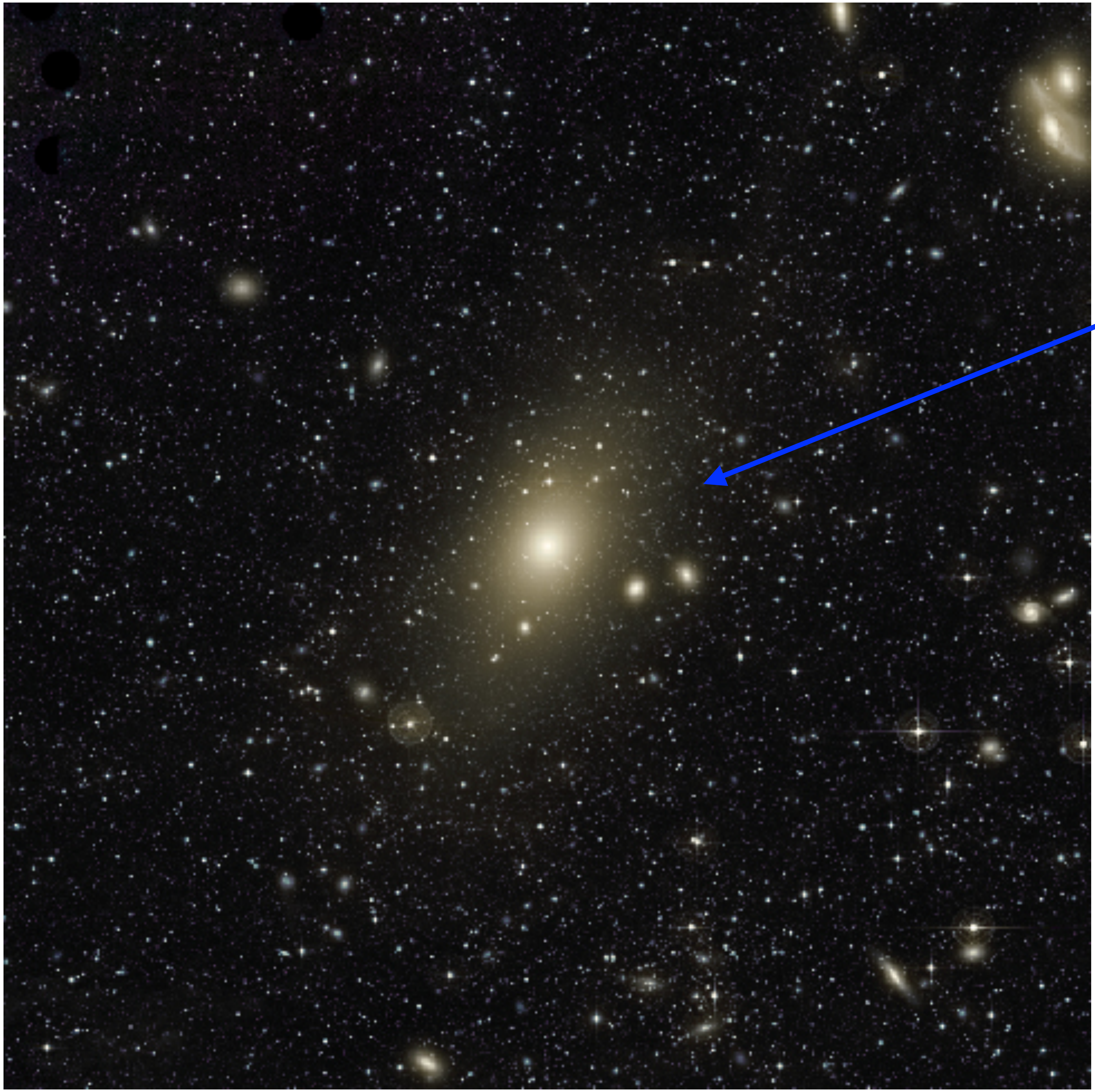
Galaxy clusters

- Much larger than galactic groups
- 1000s - 10,000s of galaxies!!!
- Typically 5-10 Mpc across (~300 MW's lined up!)
- Components:
    - cD (central dominant) "cannibal" galaxy
    - other ellipticals closer together - "social ellipticals"
    - few spirals (these are further way) - "shy spirals"
    - lots of interacting galaxies

Ellipticals near center are the result of mergers

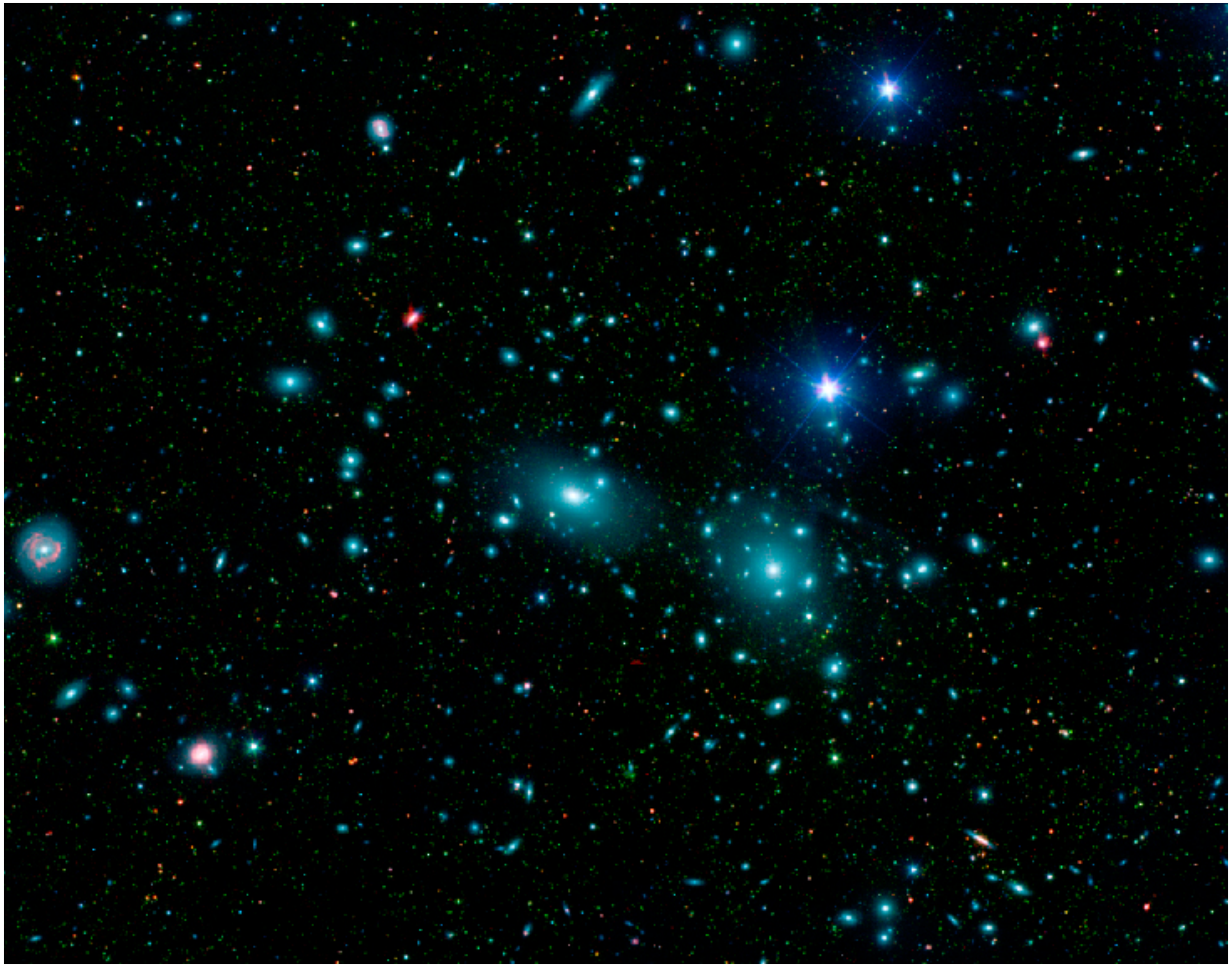


Virgo cluster



- **50 million light years away**
- **1000s of members**
- **M87 (which we've seen previously) is at the center**

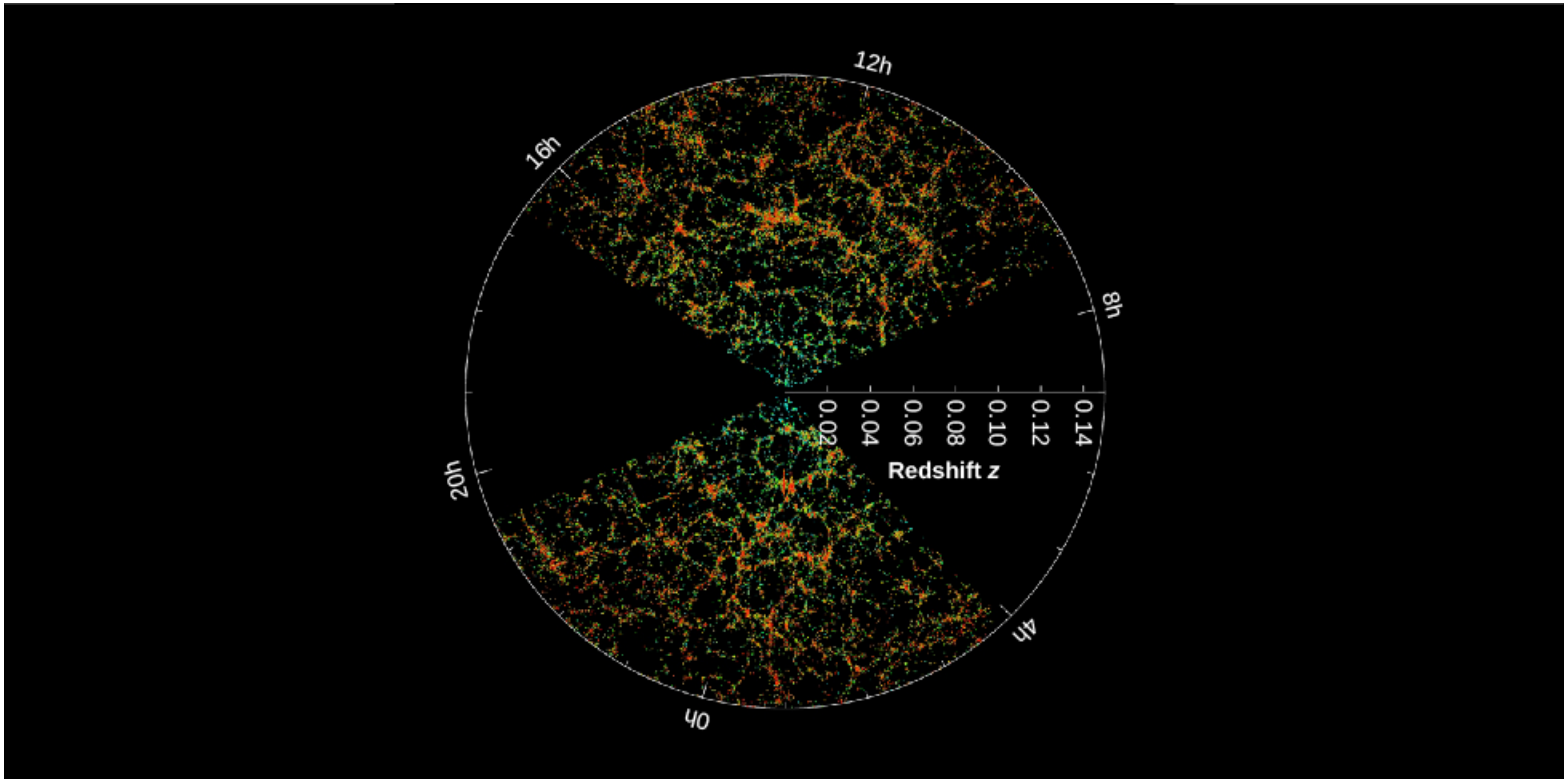
Coma cluster



- **300 million light years away**
- **Maybe as many as 30,000 galaxies!**
- **Total mass: 4×10^{15} M_{Sun}**

Galaxy superclusters

- Even larger scales! (~100 Mpc or more)
- Largest structures known in the Universe
- Demonstrated by the "cosmic web"
  - Filaments of galaxies
  - Voids as large as 150 million light years (46 Mpcs)!
  - 90% of galaxies occupy < 10% of volume of space



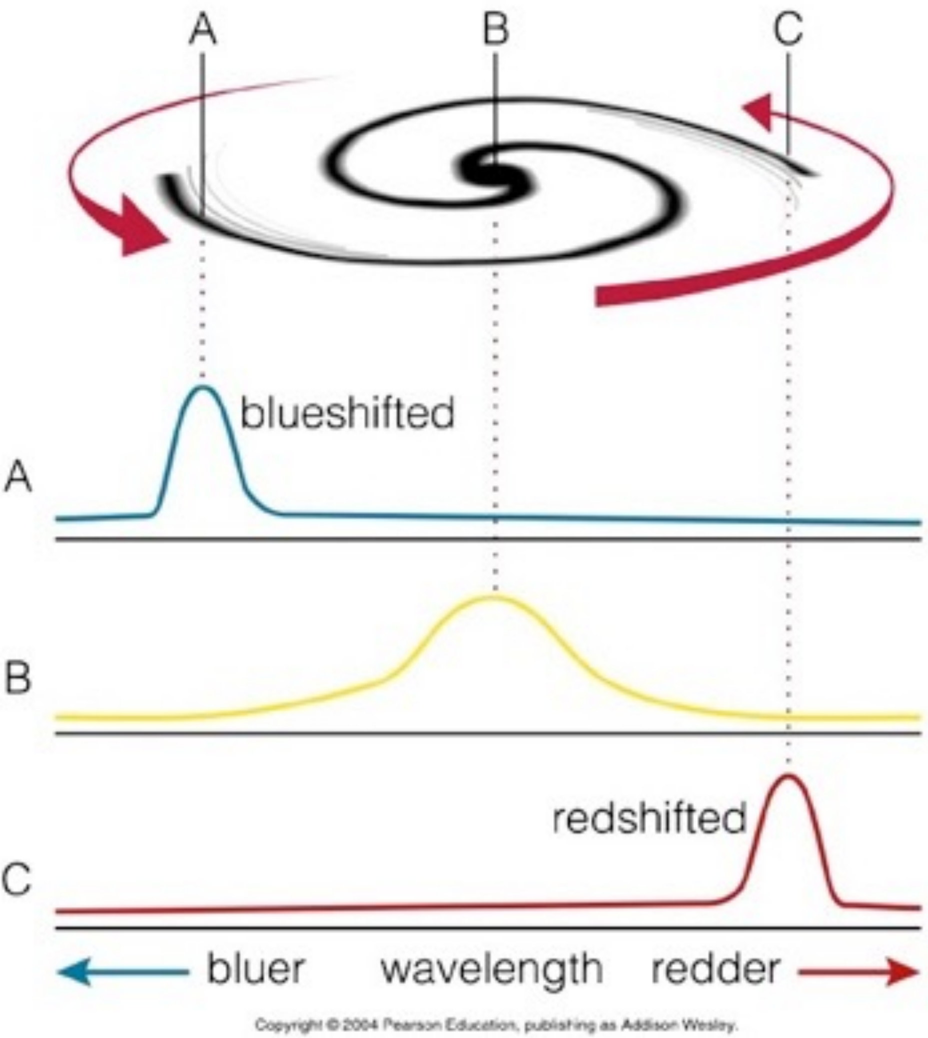
Galaxy superclusters

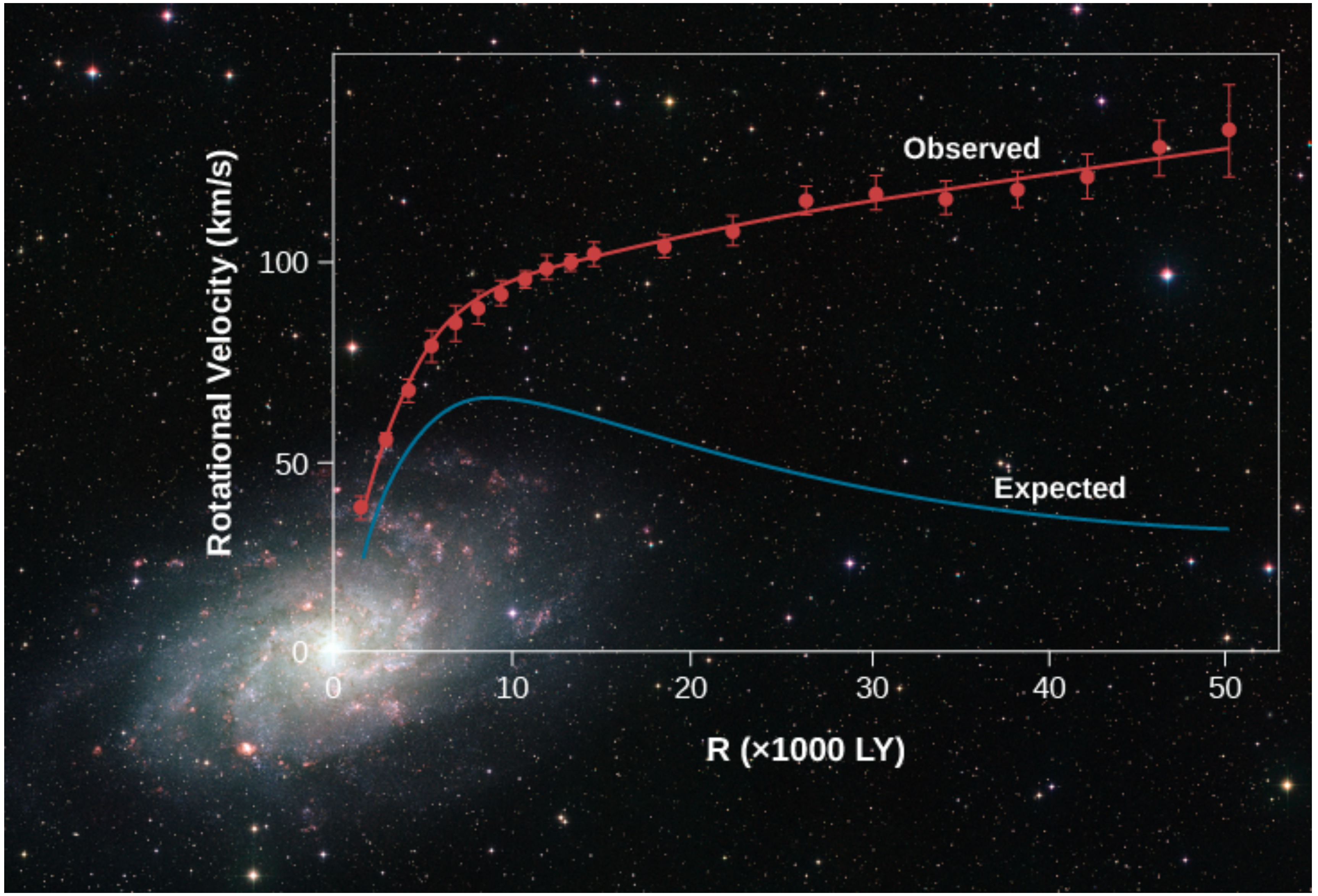
Benedikt Diemer

But the mass that we "see" is not enough to account for this gravitational collapse!!!

Dark Matter!

Dark Matter I (brief review)





In spiral galaxies, matter extends well beyond visible disks

90% of all mass in galaxies is <u>DARK</u>

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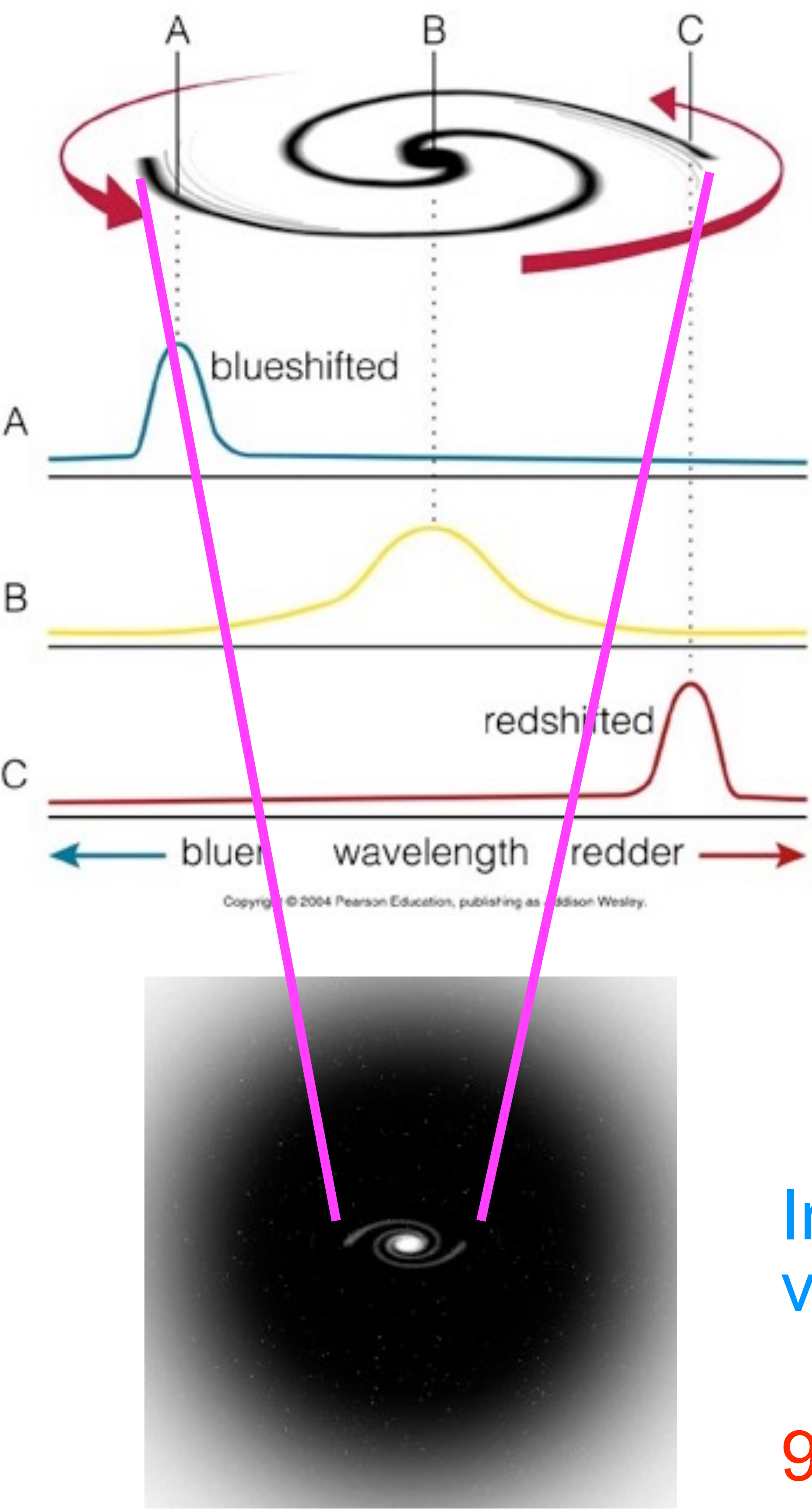

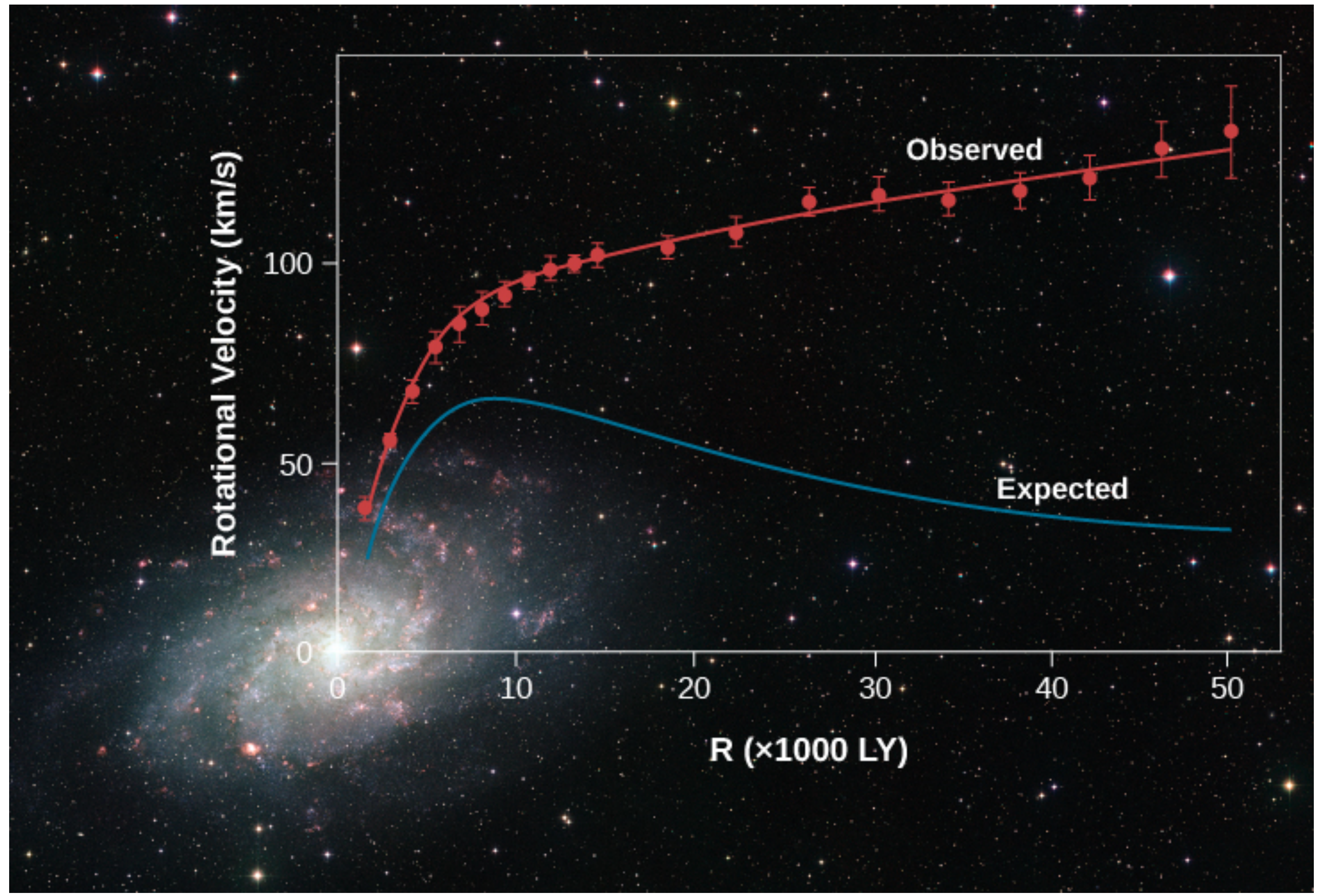

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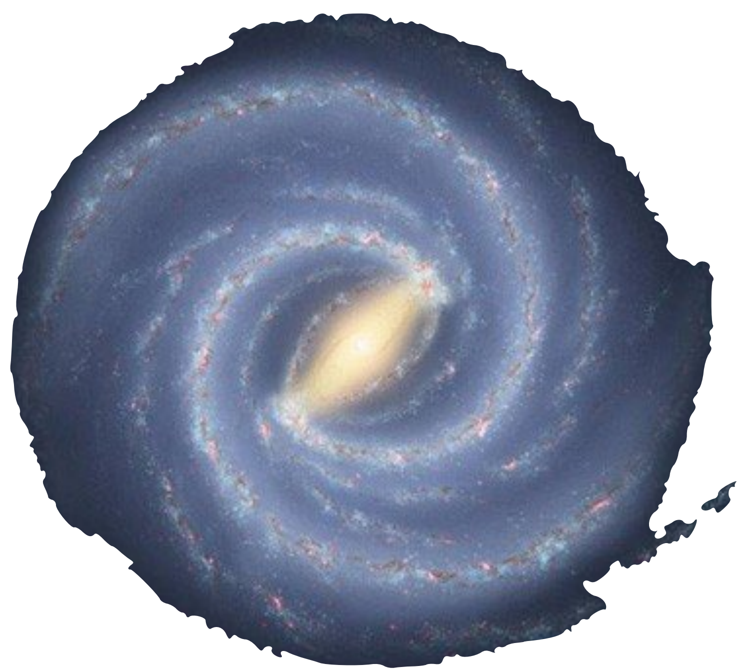
Dark Matter Halos



Dark Matter Halos

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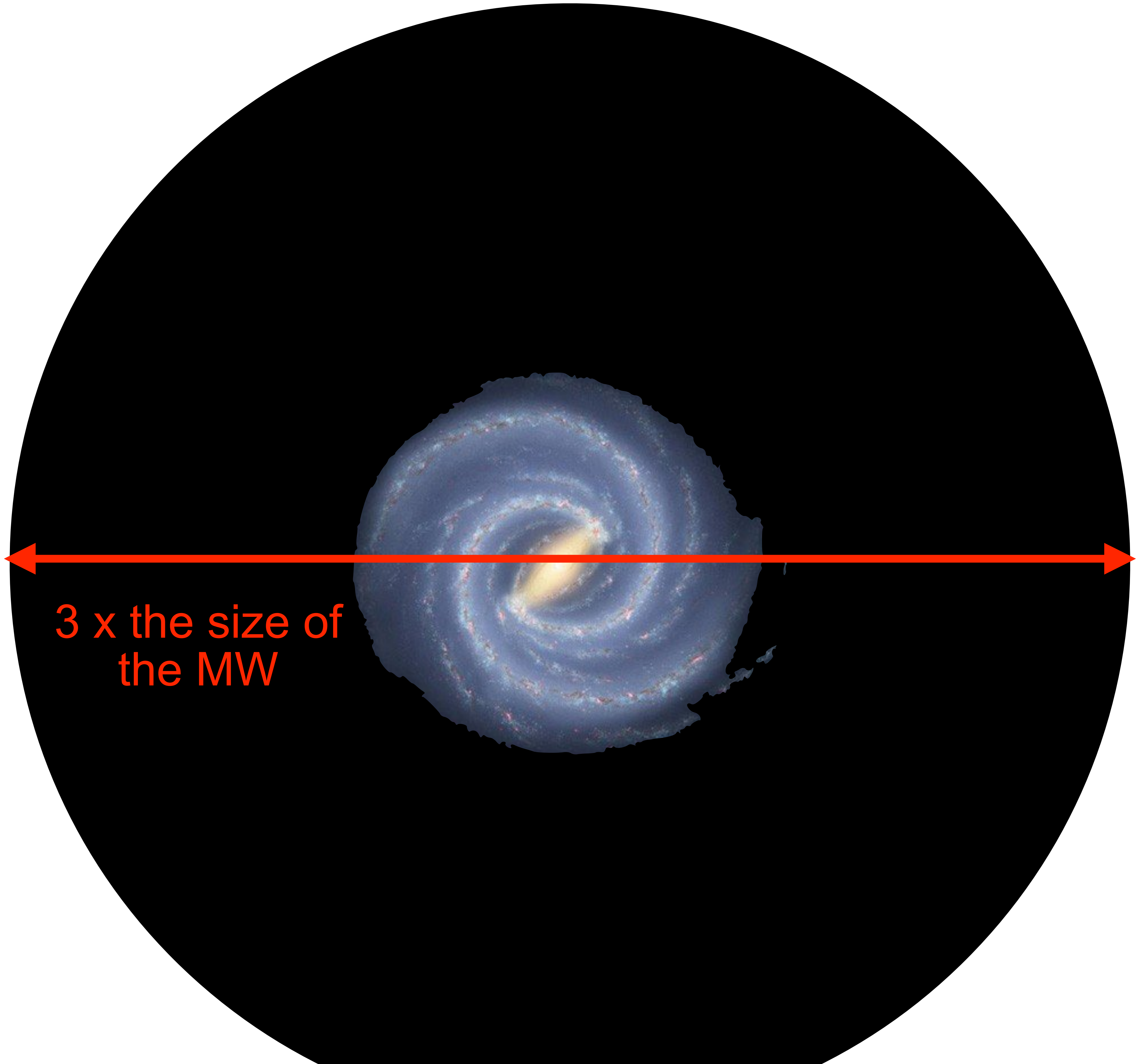

Dark Matter II (in galaxy clusters)

- **Evidence line #1:**
  Galaxy velocities within clusters
  - typical radial velocities ~ 1000 km/s in a big cluster
  - escape velocity (counting galaxies alone) ~ 300 km/s

- **Evidence line #2:**
  Hot gas between cluster members

- **Evidence line #3:**
  Gravitational lensing

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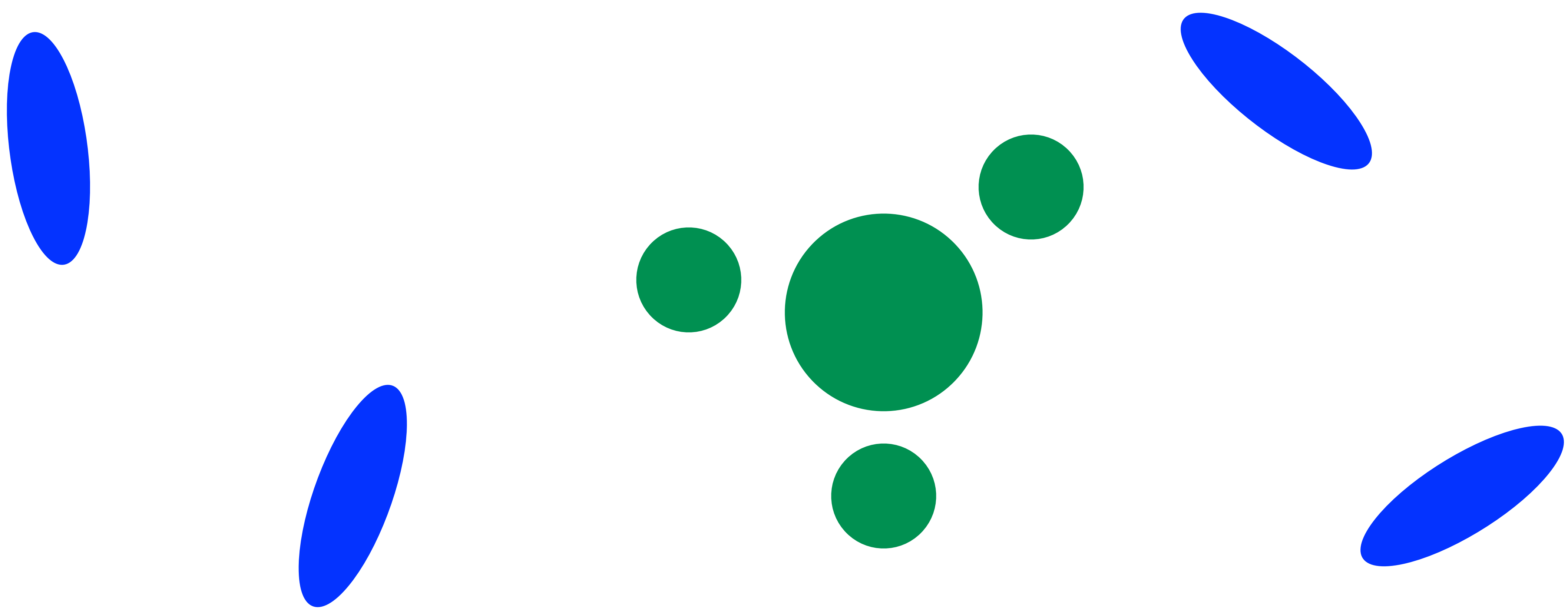

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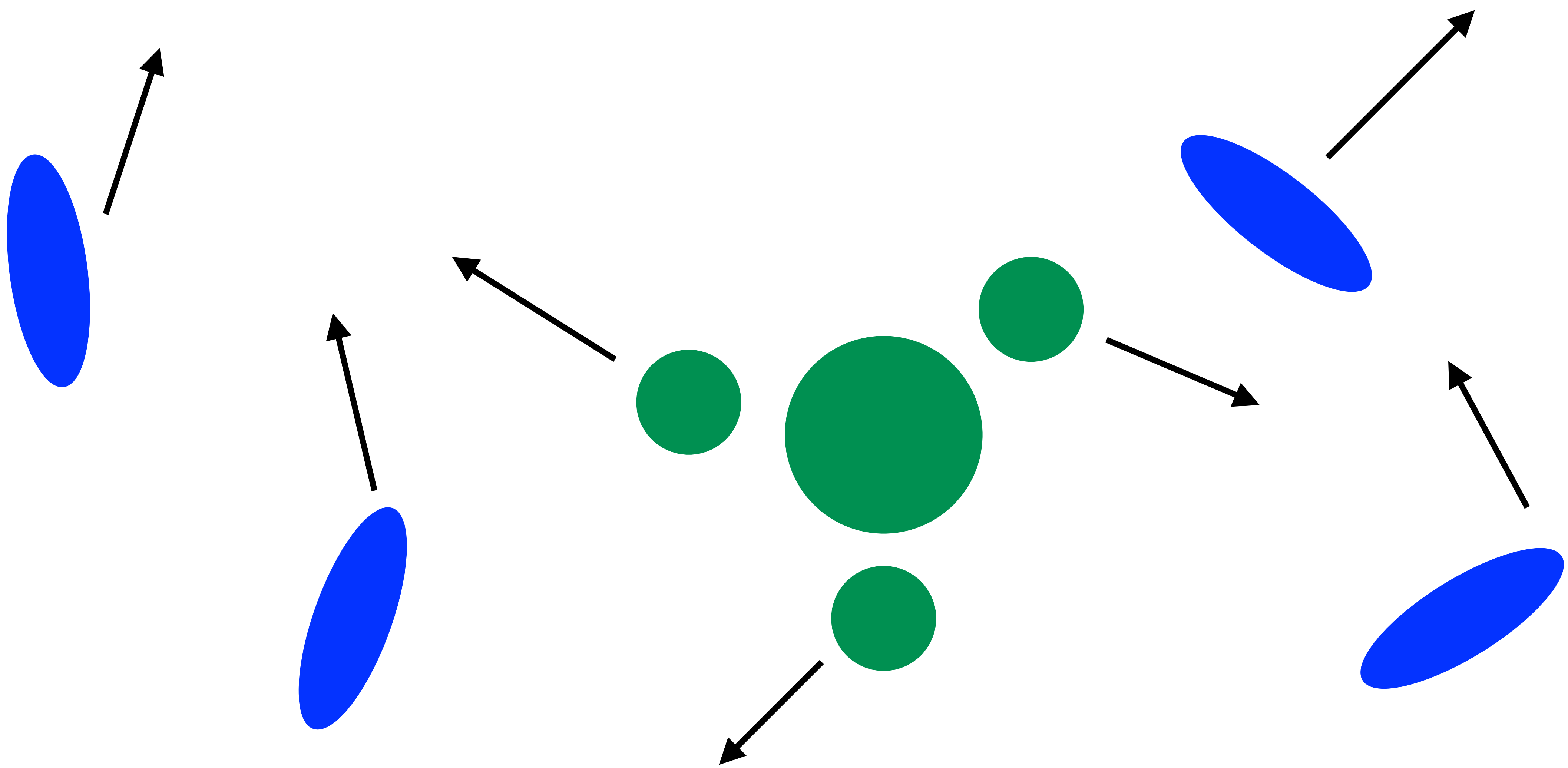

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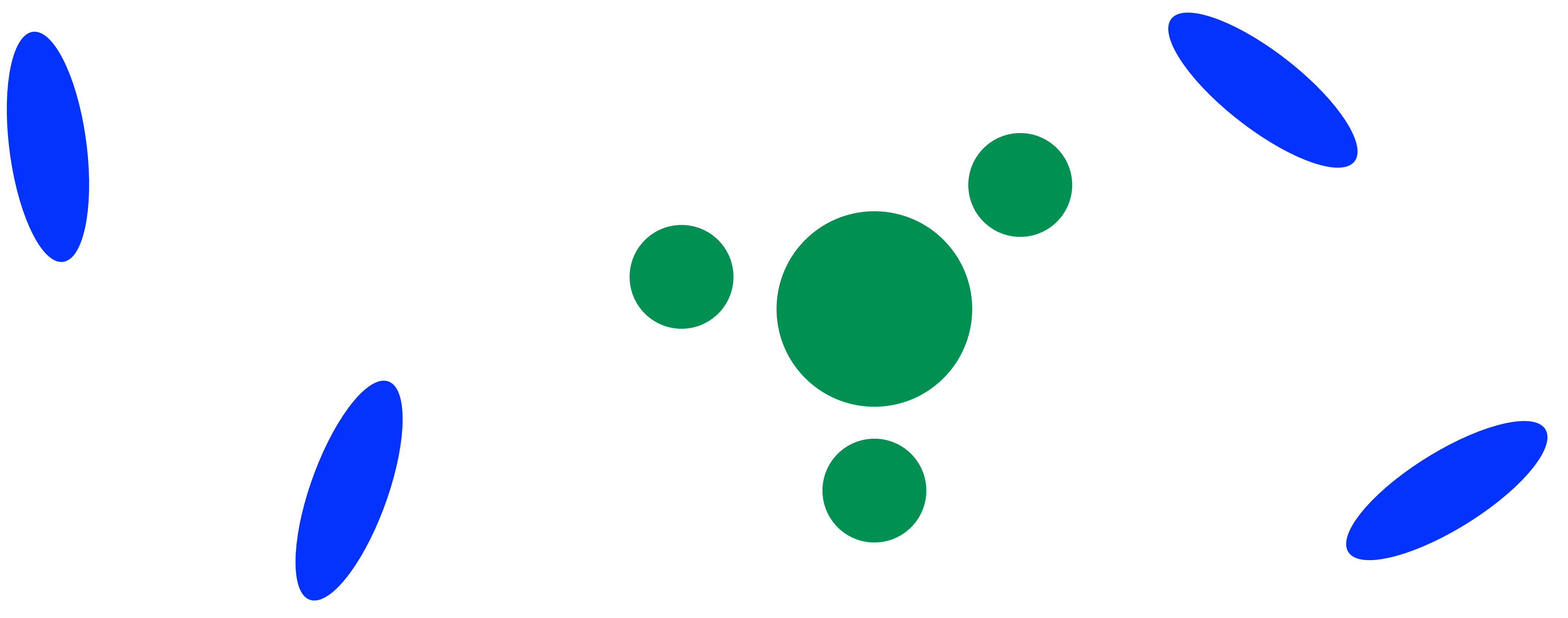

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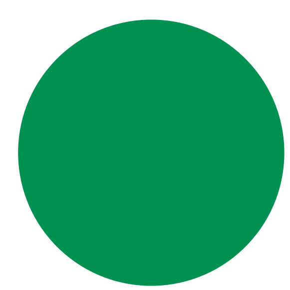

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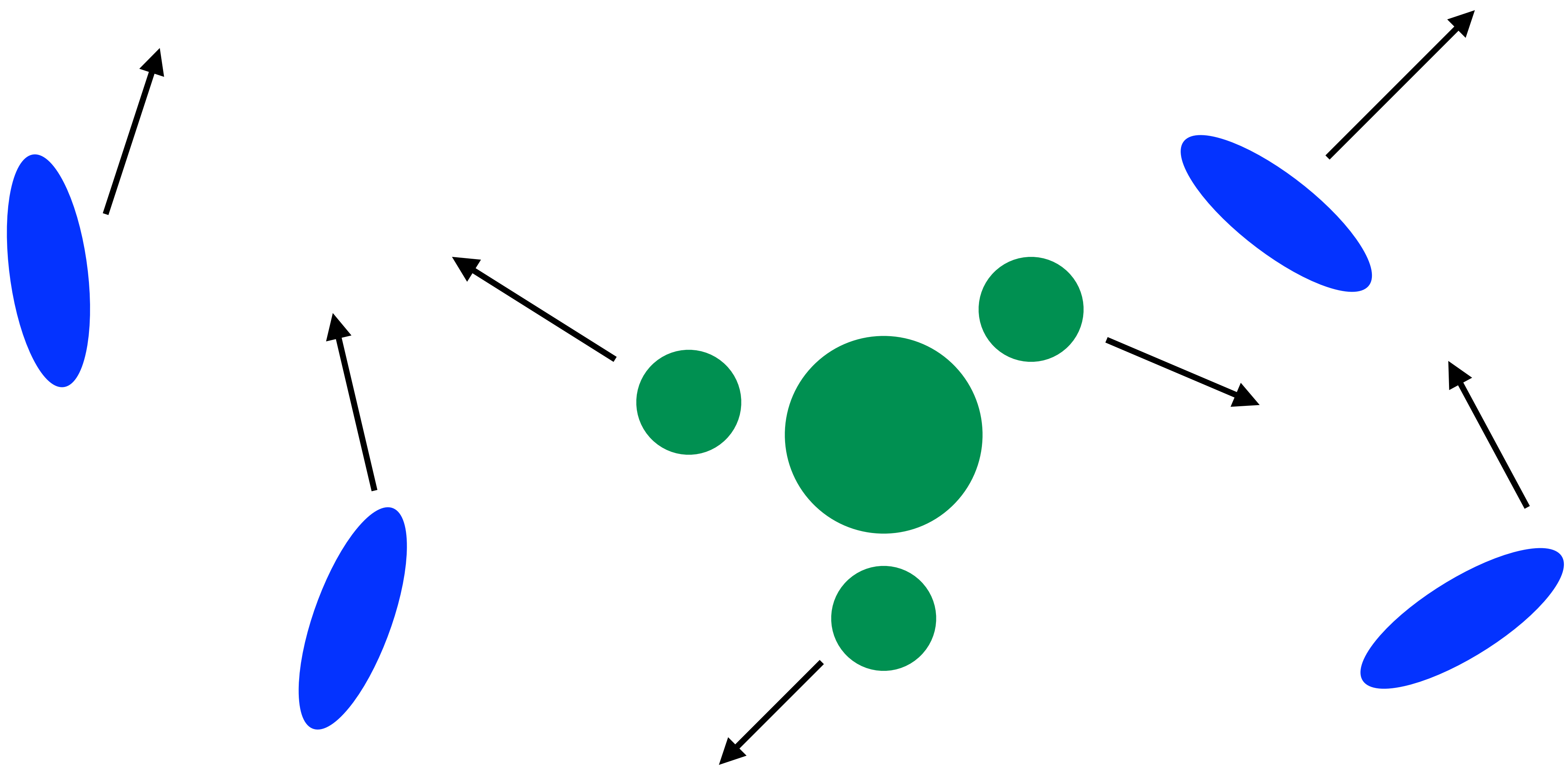

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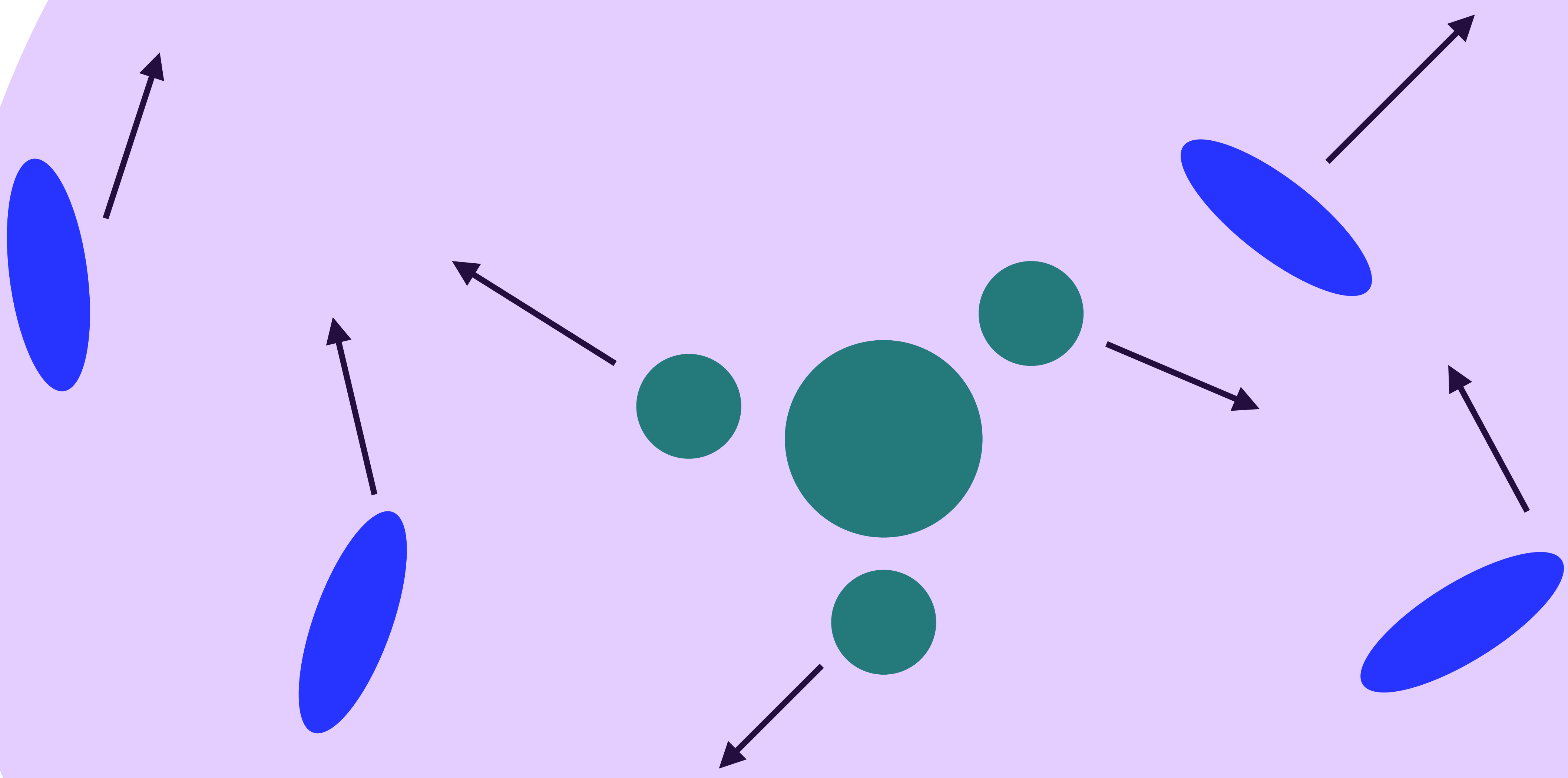
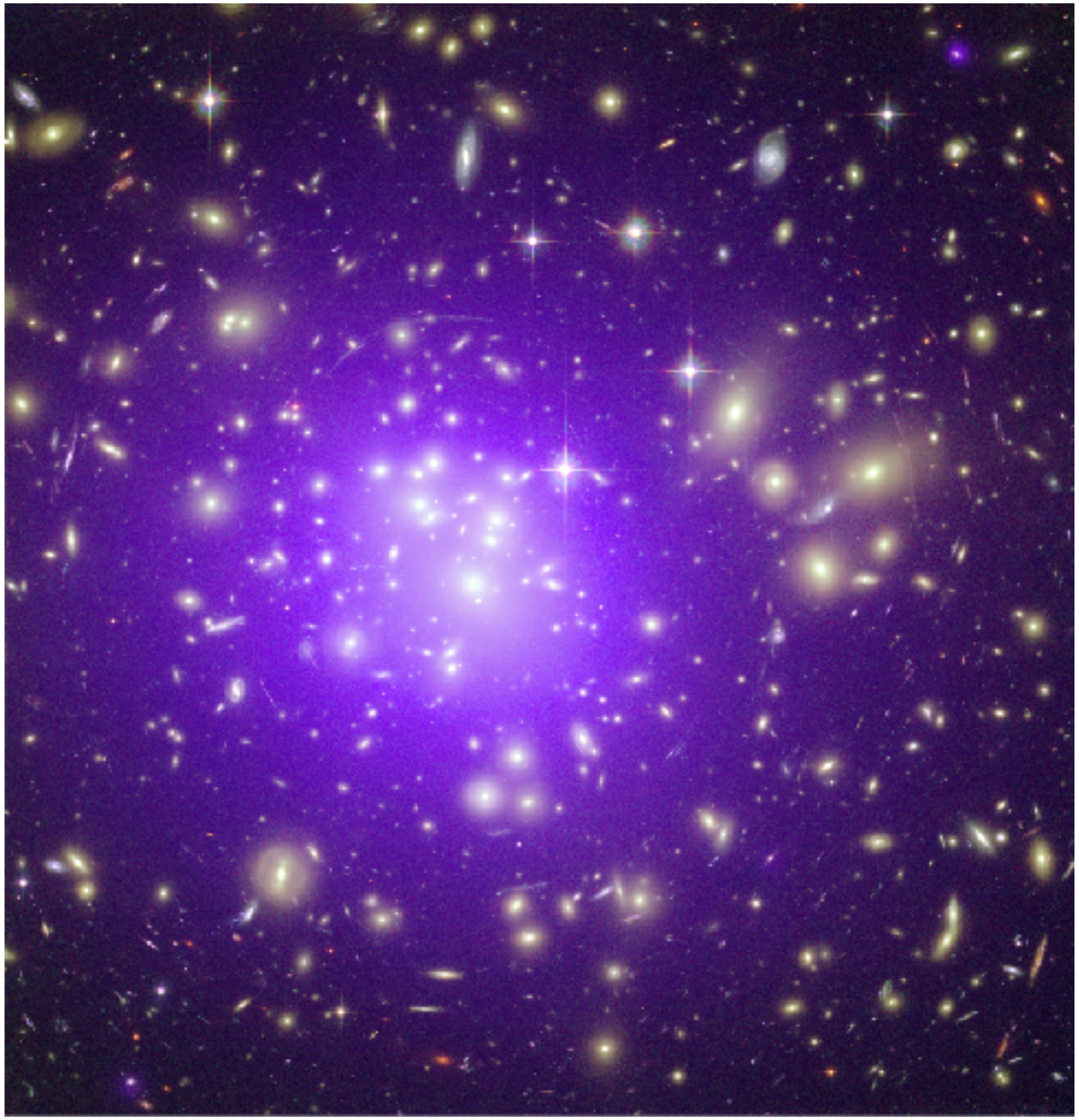


Dark Matter II (in galaxy clusters)

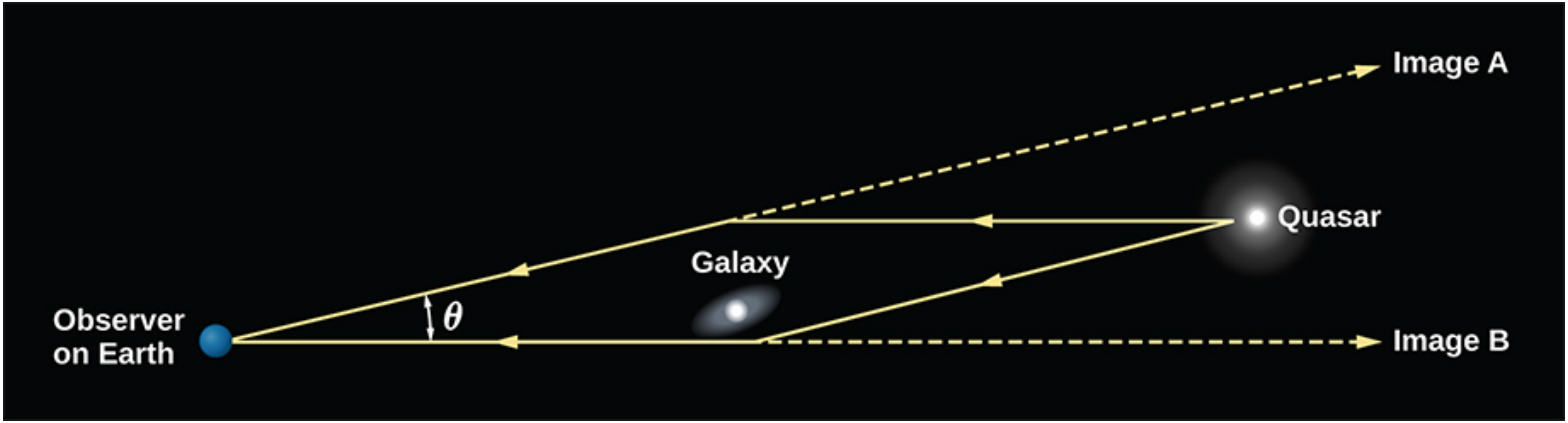
Evidence line #2:
Hot gas in galaxy clusters

- 10^8 K, concentrated at center-of-mass
- Cluster must contain a lot of mass to confine this hot gas - requires more mass than in galaxies alone
- Thermal velocity ~ 1200 km/s must be $< v_{esc}$

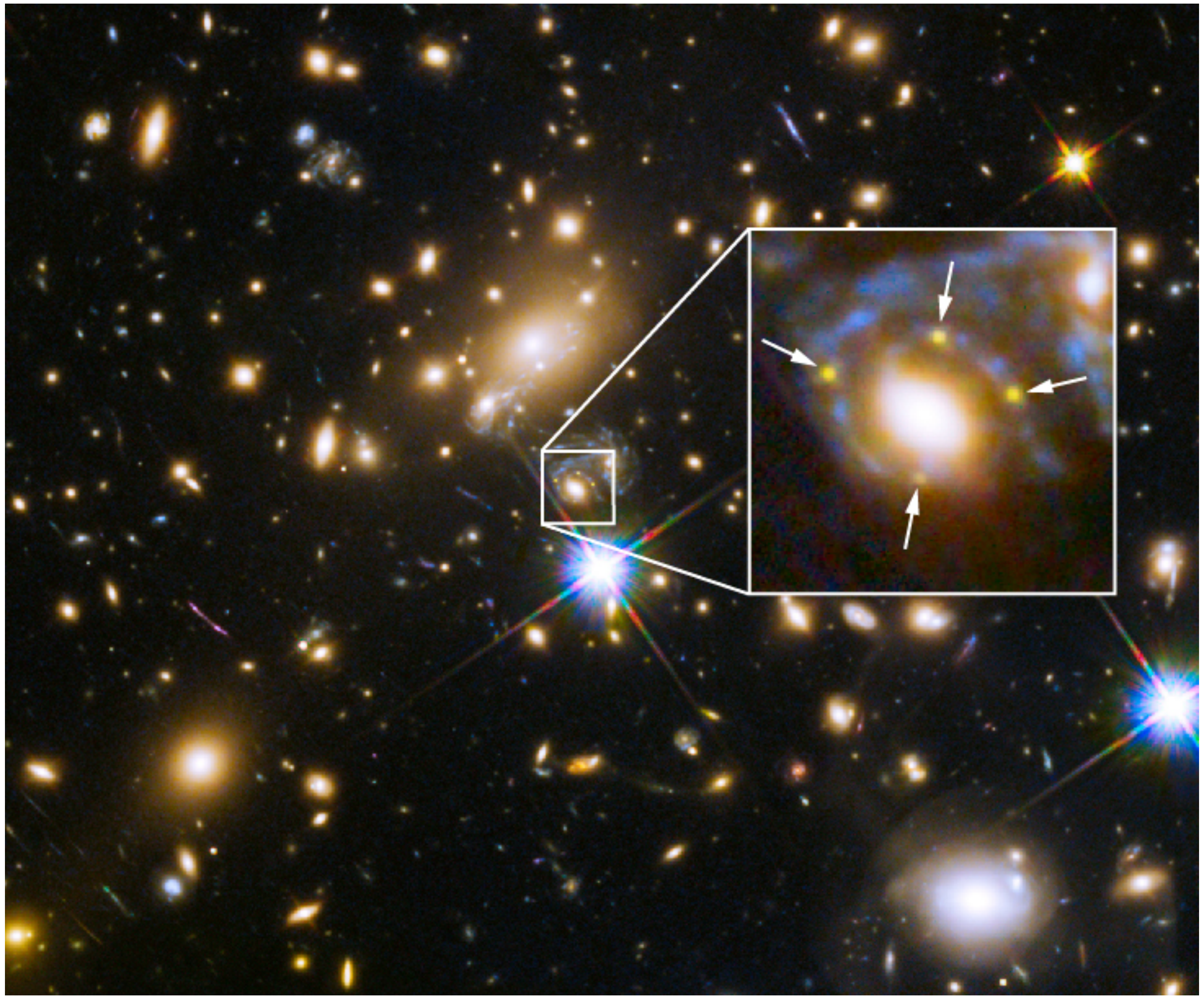


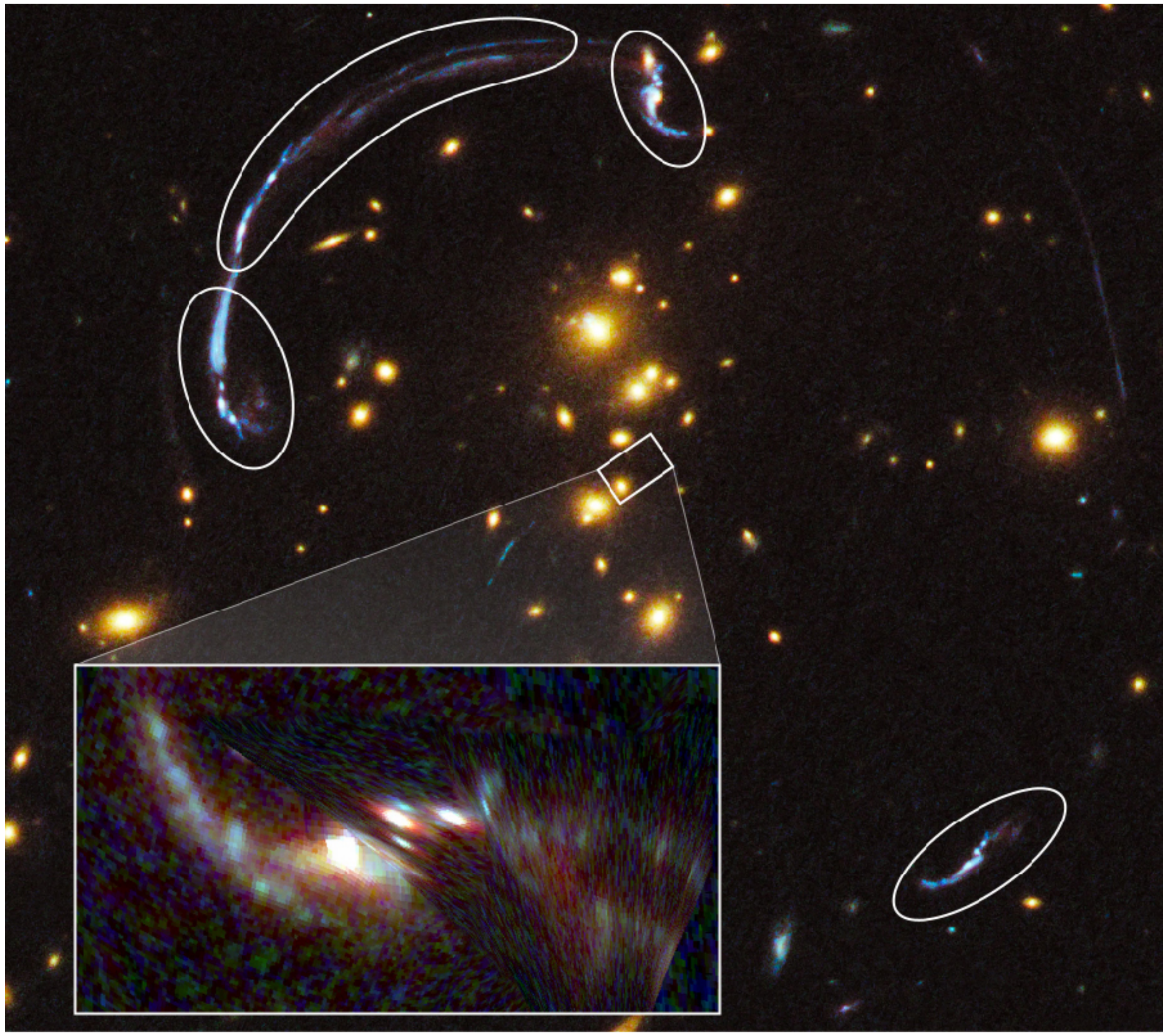
Dark Matter II (in galaxy clusters)

Evidence line #3:
Gravitational lensing

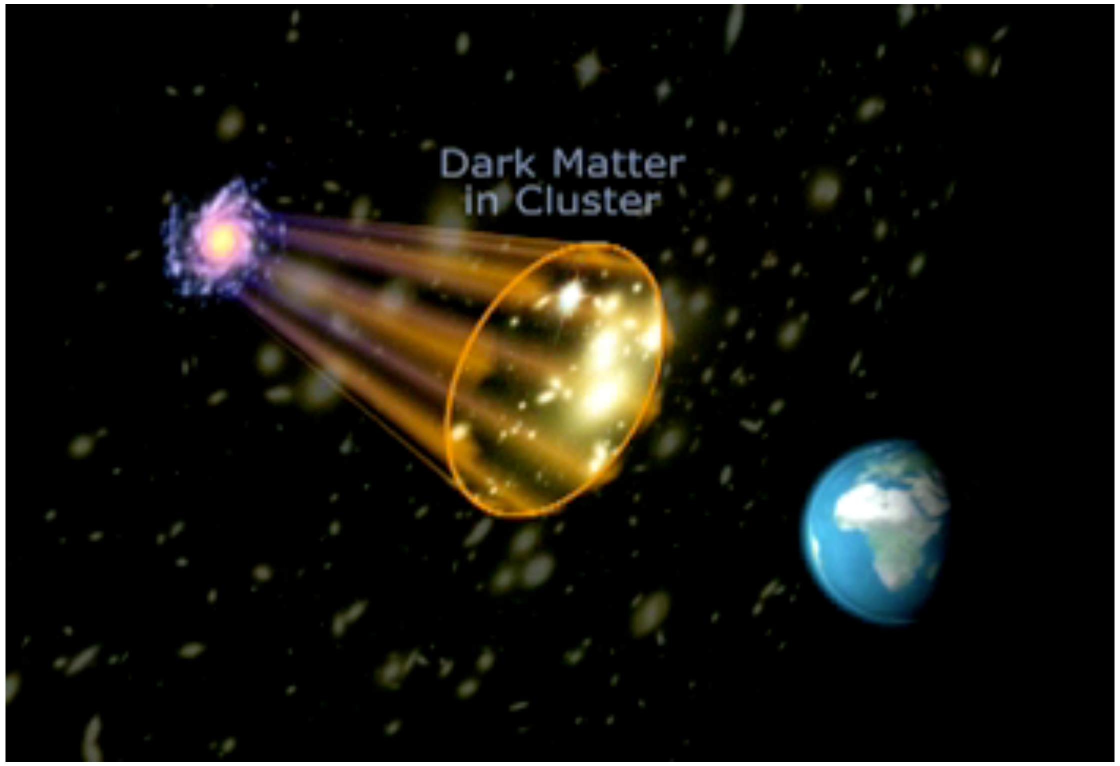


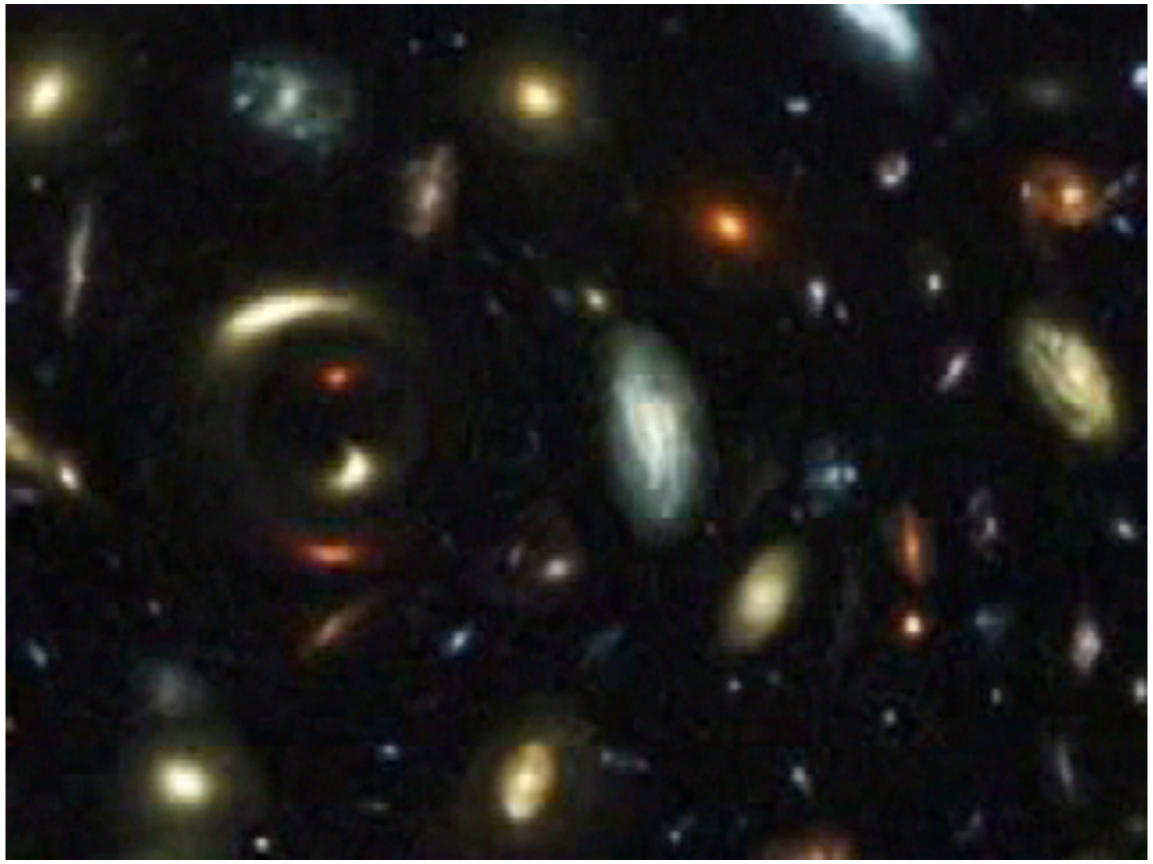
Gravitational Lensing





Gravitational Lensing





The Bullet Cluster

How much mass is there in dark matter?

Mass-To-Light Ratios

Type of Object	Mass-to-Light Ratio
Sun	1
Matter in vicinity of Sun	2
Mass in Milky Way within 80,000 light-years of the center	10
Small groups of galaxies	50–150
Rich clusters of galaxies	250–300

If M/L > 100, then dark matter is present

The Big Picture

1. **Universe started off mostly smooth, with some regions denser than others**
2. **Regions of higher density (both luminous and dark matter) begin to collapse**
3. **Collapse proceeds along filaments**
4. **Smaller objects form first (e.g., dwarf galaxies, globular clusters)**
5. **Smaller objects merge together to form bigger objects**
6. **Groups form**
7. **Clusters form**
8. **Superclusters form**

Before we wrap up, there is one important question to address

What is dark matter?!

Short answer: we don't know

1. **MACHOs (Massive Compact Halo Objects); e.g., black holes without an accretion disk**
2. **WIMPs (Weakly Interacting Massive Particles)**
   - **(a) Hot dark matter (hot means fast moving)**
   - **(b) Cold dark matter (cold as in slow moving)**

Not enough mass in MACHOs

Hot WIMPs would smear out structures -> fewer small galaxies

Cold WIMPs seem to fit best with the observations