Lighting Up The Dark:
The Mystery of Dark Matter

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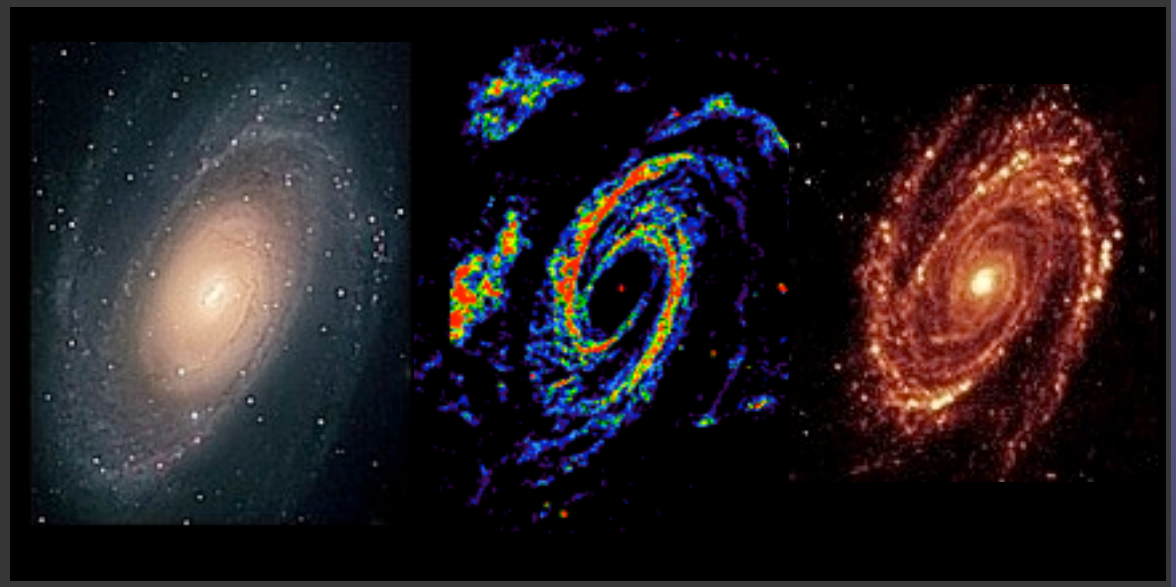
Galaxies

Our galaxy: the Milky Way

~100,000 light years across

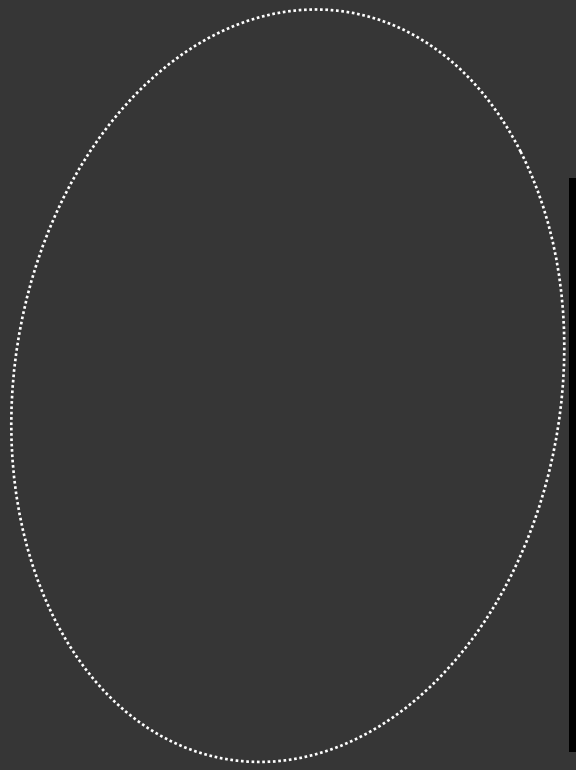
Galaxies

What are galaxies made of?

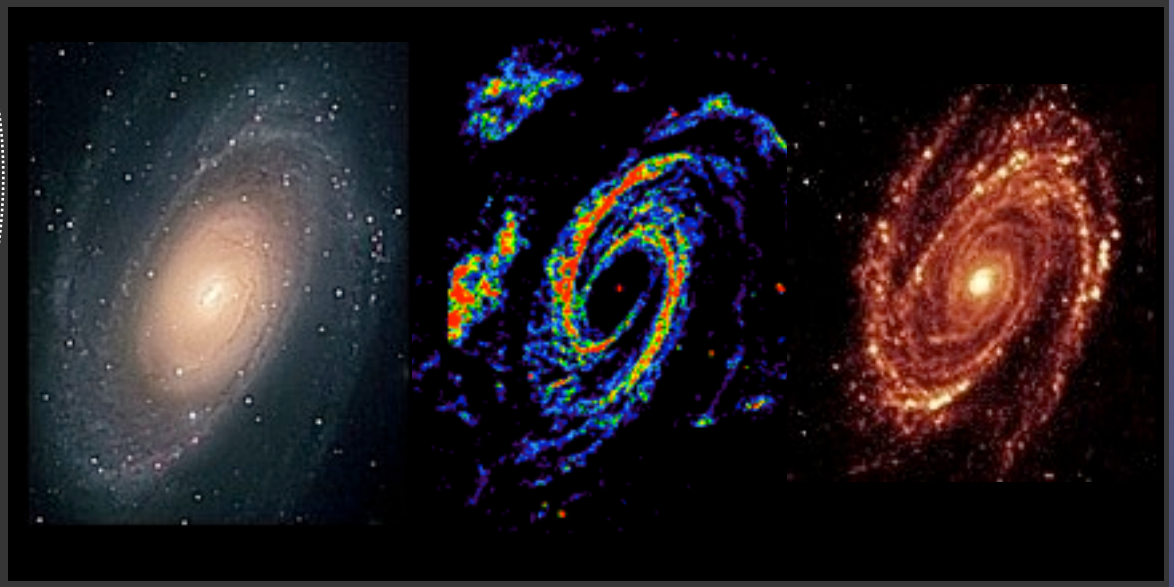


What are galaxies made of?

Dark Matter (90%) + Normal Matter (10%)

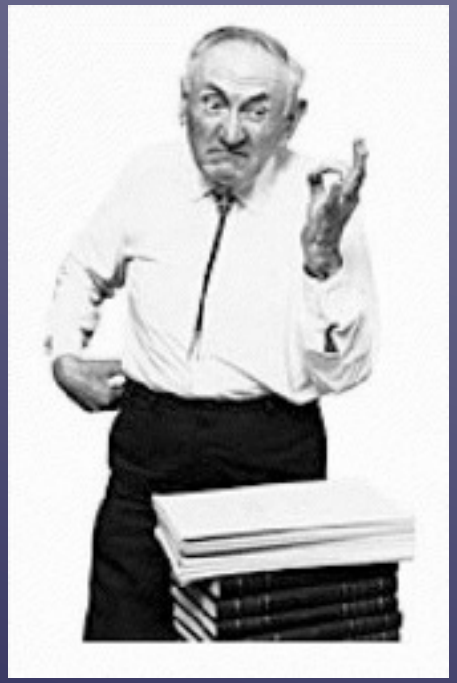


Stars | Gas | Dust



Optical | Radio | Infrared

Dark Matter



Existence was first postulated in the 1930s from observations of galaxy motions - there was apparently a lot more mass than could be seen!

Fritz Zwicky, Caltech professor

Dark matter has since been confirmed through observations of:

- fast-moving galaxies in clusters
- fast rotation of stars and gas in spiral galaxies
- gravitational lensing (strong and weak)

Dark Matter - What is it?

Unlike normal (baryonic) matter, dark matter doesn't emit or absorb light.
Detectable through its gravitational effects!
It can 'bend' light by bending space.

Likely a slow-moving ('cold'), as yet undiscovered, weakly-interacting massive particle (WIMP).

Not sure exactly what it is, but there are a lot of possible particles it could be. There are on-going experiments in mines underground around the world to detect it directly!

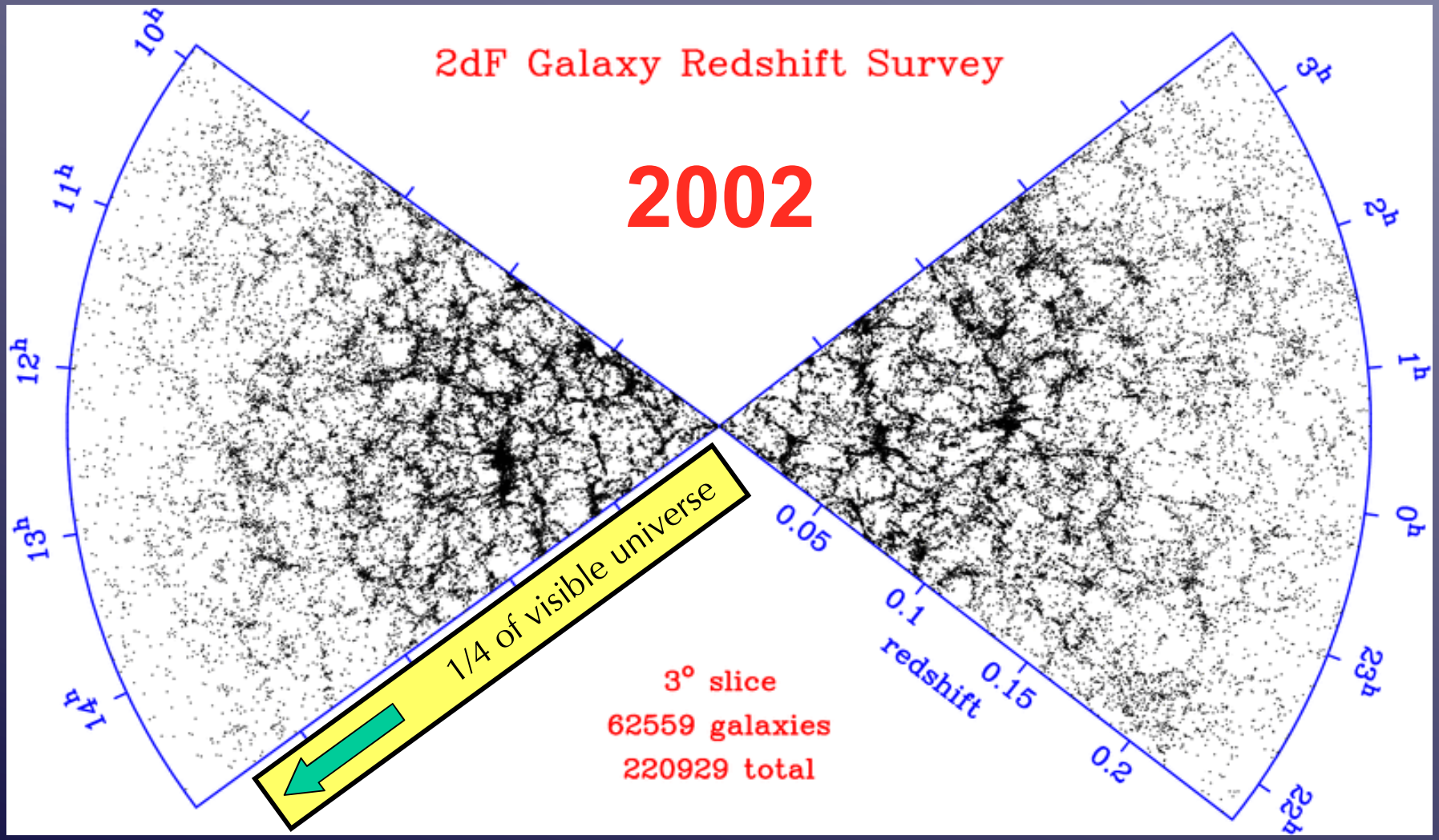
Large-Scale Structure

Galaxies are not evenly distributed in space.

Because of gravity, they tend to form clumps, where many galaxies are found near each other.

This happens on really, really large scales.

Large-Scale Structure



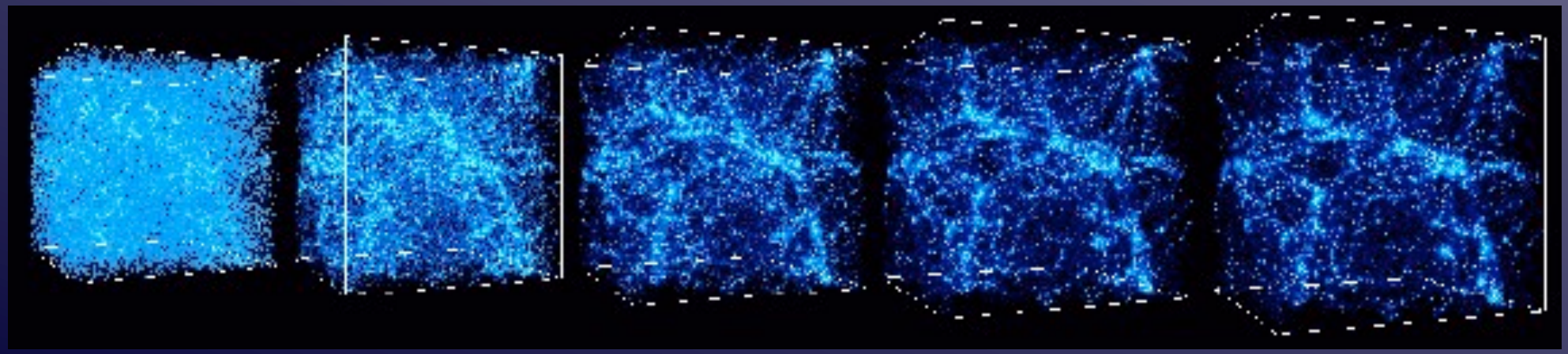
~3 billion light years

Large-Scale Structure

How did this happen?

2 reasons: quantum mechanics and gravity

- Very early universe: hot, dense soup of mass/energy
- Tiny fluctuations: seeds of structure
- Galaxies formed from initially small amplitude lumps
- Process of structure formation continues today!



Time →

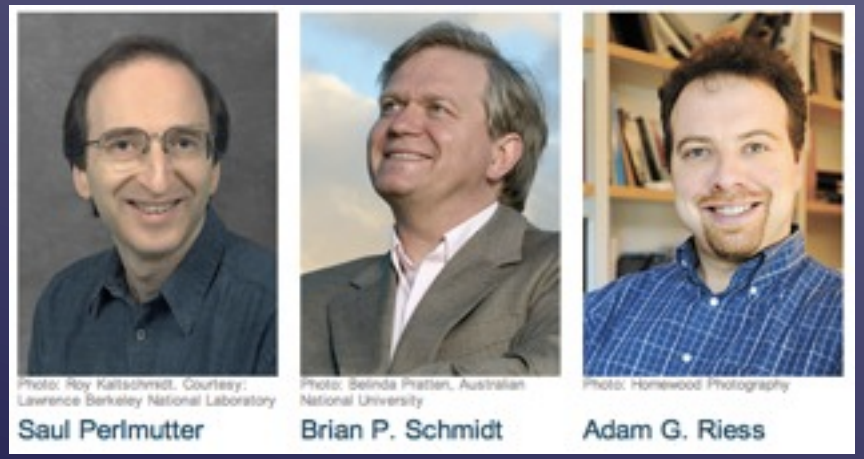
Dark Energy

Observations in 1998 of type 1a supernovae (exploding stars) and their distances (redshifts) revealed that the Universe is not just expanding but is *accelerating*.

The Nobel prize in physics this year was awarded for this discovery.

Called ‘dark energy’ as a reference to dark matter.

Counteracts gravity - a mysterious, repulsive force throughout space.



Dark Energy - What is it?

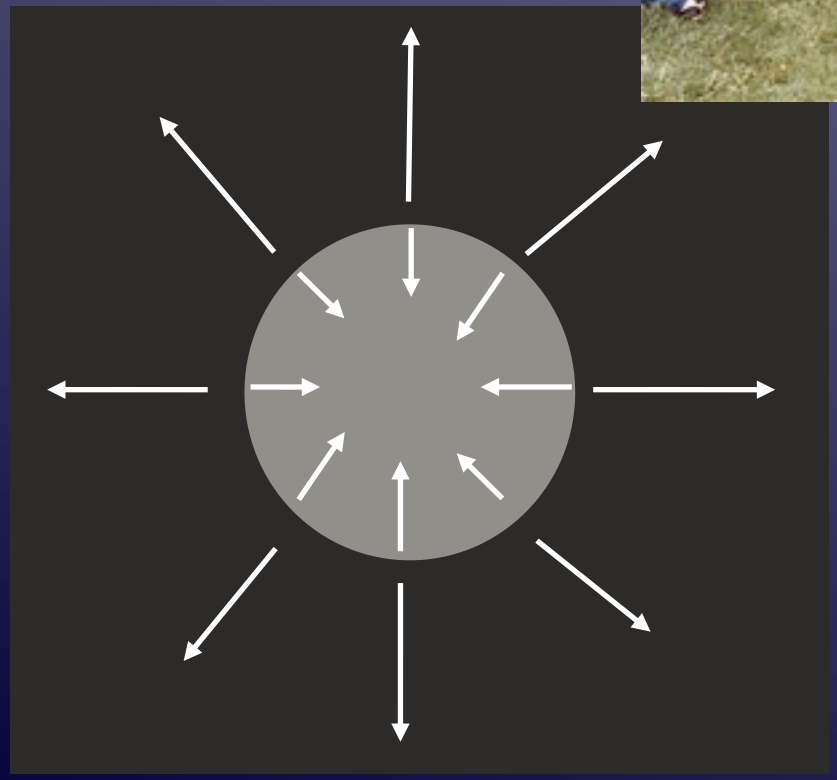
- No one knows!
- Do know that it smoothly fills space, has a constant (or nearly so) density and is repulsive - negative pressure and drives acceleration.
- Could be due to a vacuum energy. Quantum mechanics predicts that empty space isn't empty - lots of short-lived particles coming into and out of existence. These particles provide a net background energy. The more volume of space there is, the more vacuum energy.
- Could be a new force we don't know about yet.
- Our understanding of gravity could be wrong!

Dark matter and dark energy affect the expansion history of the Universe and therefore affect large-scale structure!

Formation of Structure

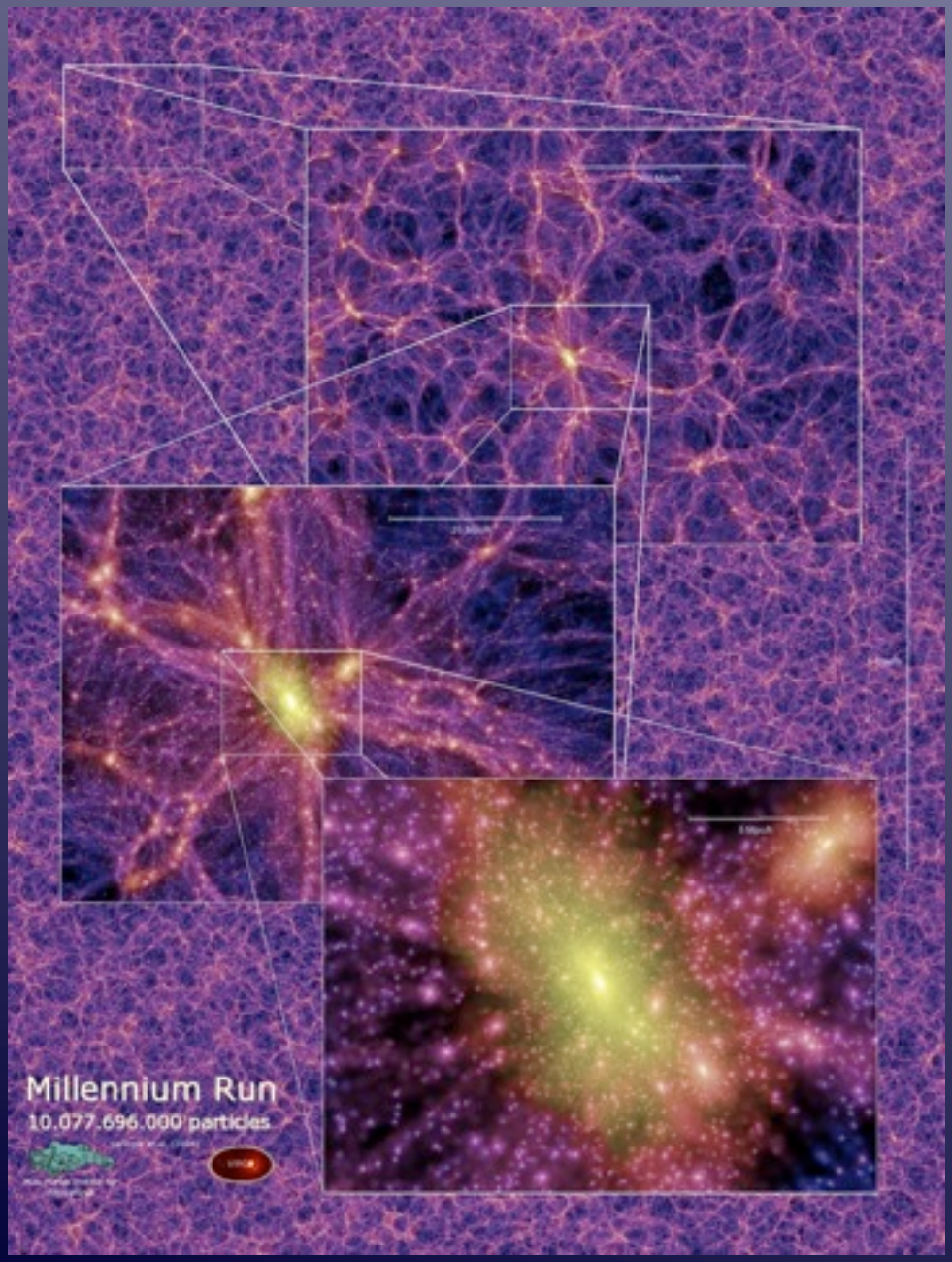
Cosmological expansion / dark energy

Gravity / dark matter



Overdensities grow into gravitationally bound structures. Space between them expands.

Supercomputer Simulation

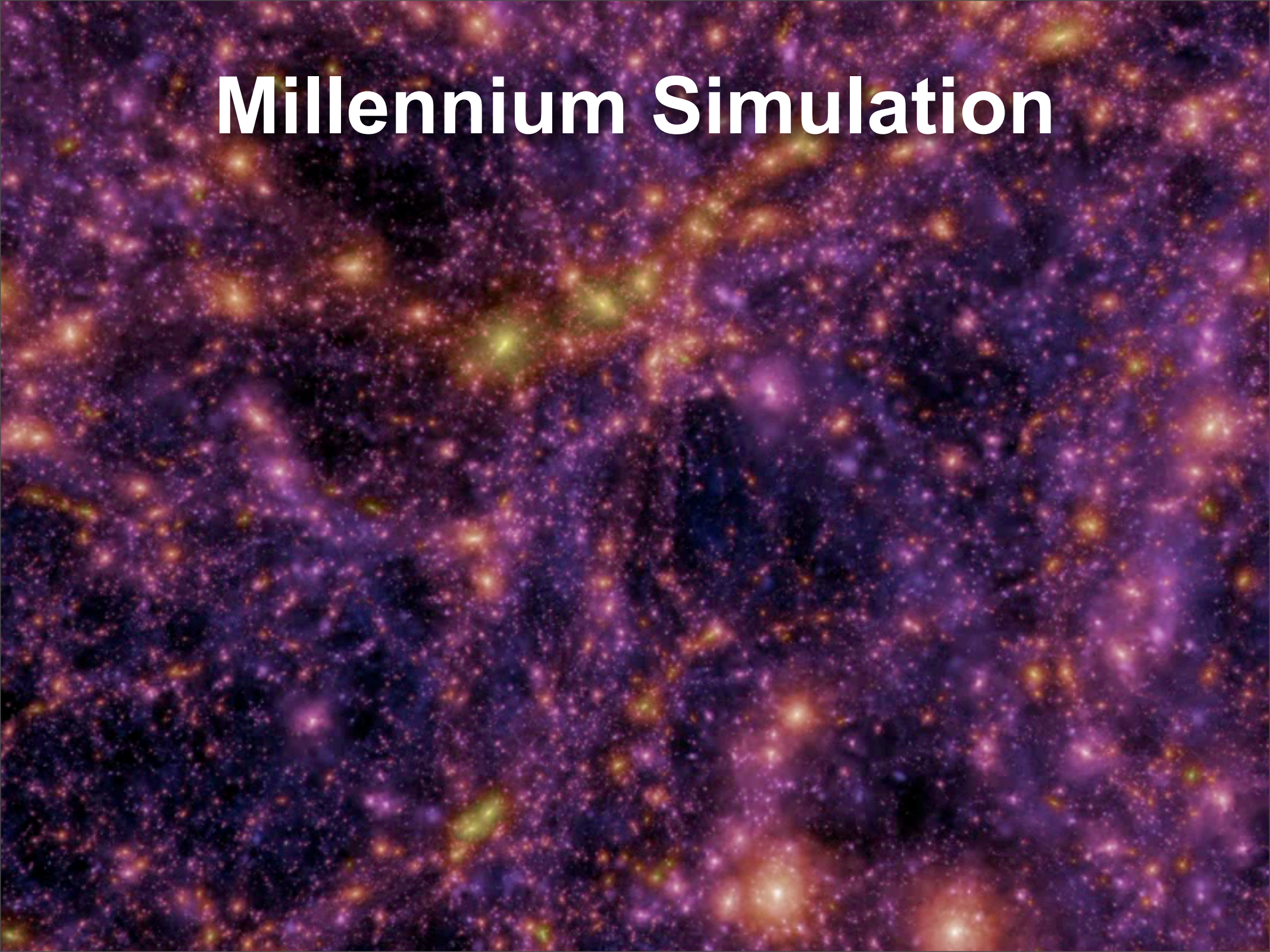


Huge computer simulations of large-scale structure predict the distribution and evolution of dark matter.

Include dark energy and dark matter, but no baryonic/'normal' matter - no galaxies!

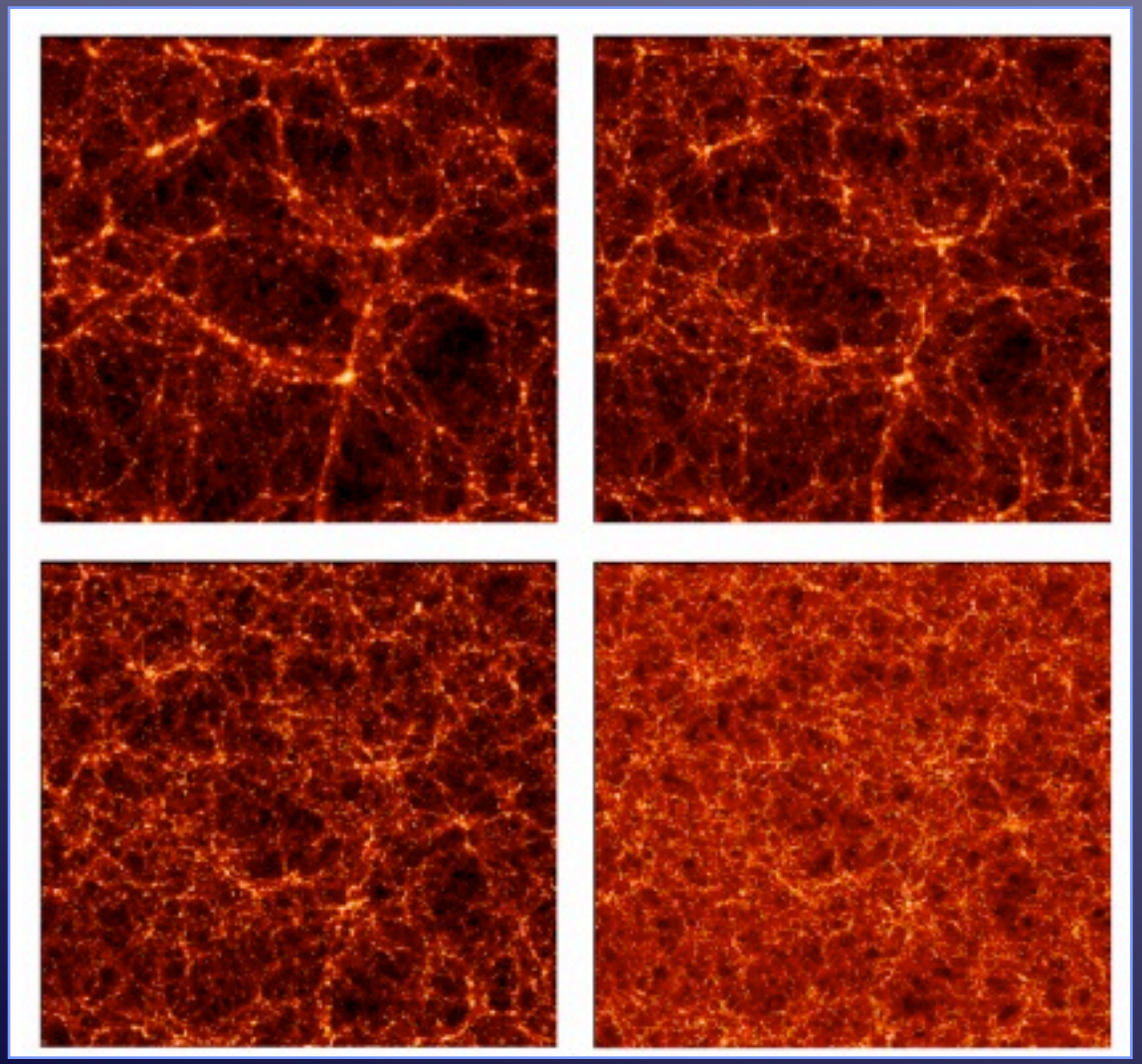
>10 billion particles
2 billion light years wide
25 Tbytes of stored data

Millennium Simulation



Large-scale Structure Evolution

dark matter evolution:



Now 7 Gyr ago

w/ dark energy
(and dark matter)

w/ a lot of dark matter
(and no dark energy)

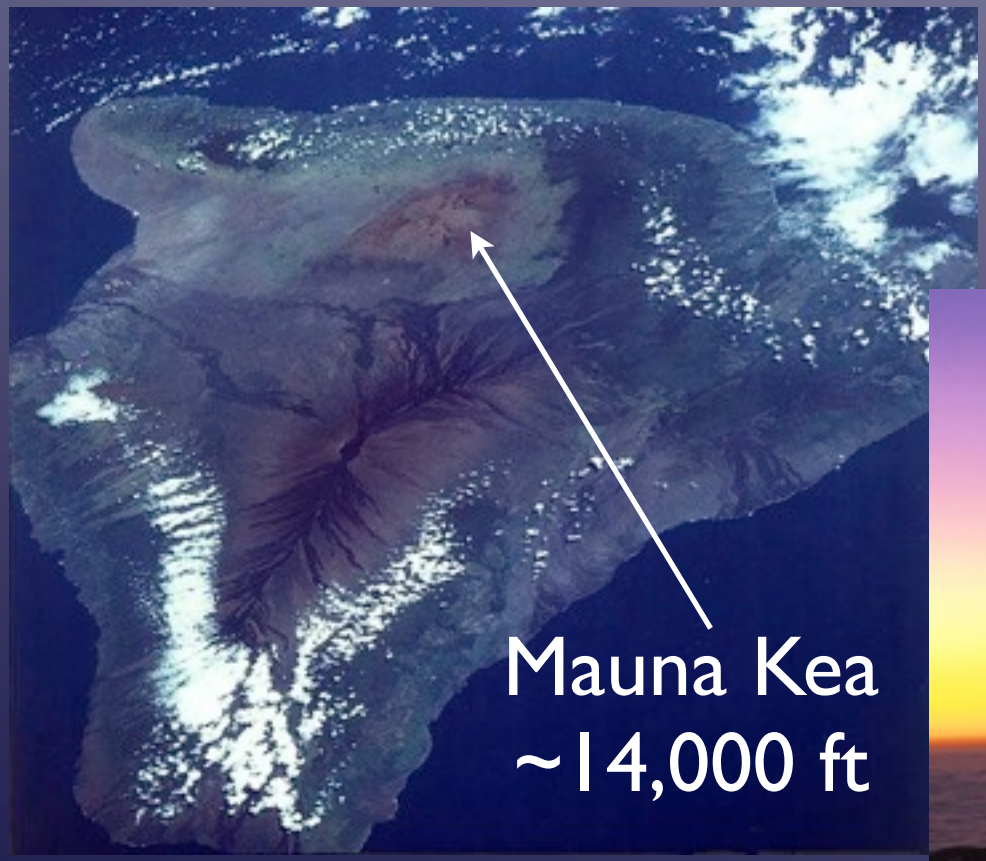
A Survey of Distant Galaxies

Carry out a survey of distant galaxies to test the cosmological model and learn about galaxy evolution.

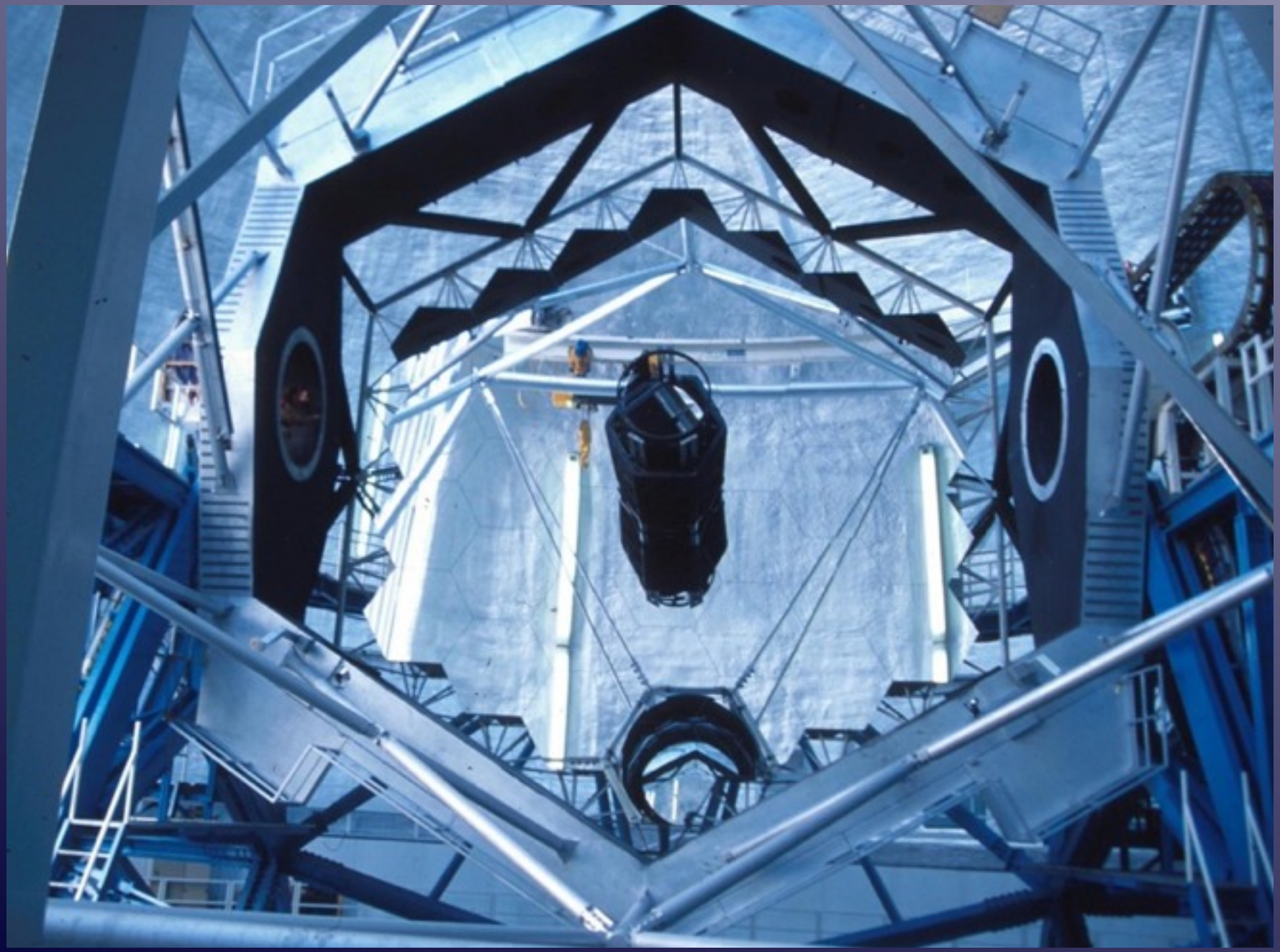
Survey is called DEEP2 - UC collaboration.
~20 people on the team.

Use the largest optical telescope in the world to study faint, distant galaxies.

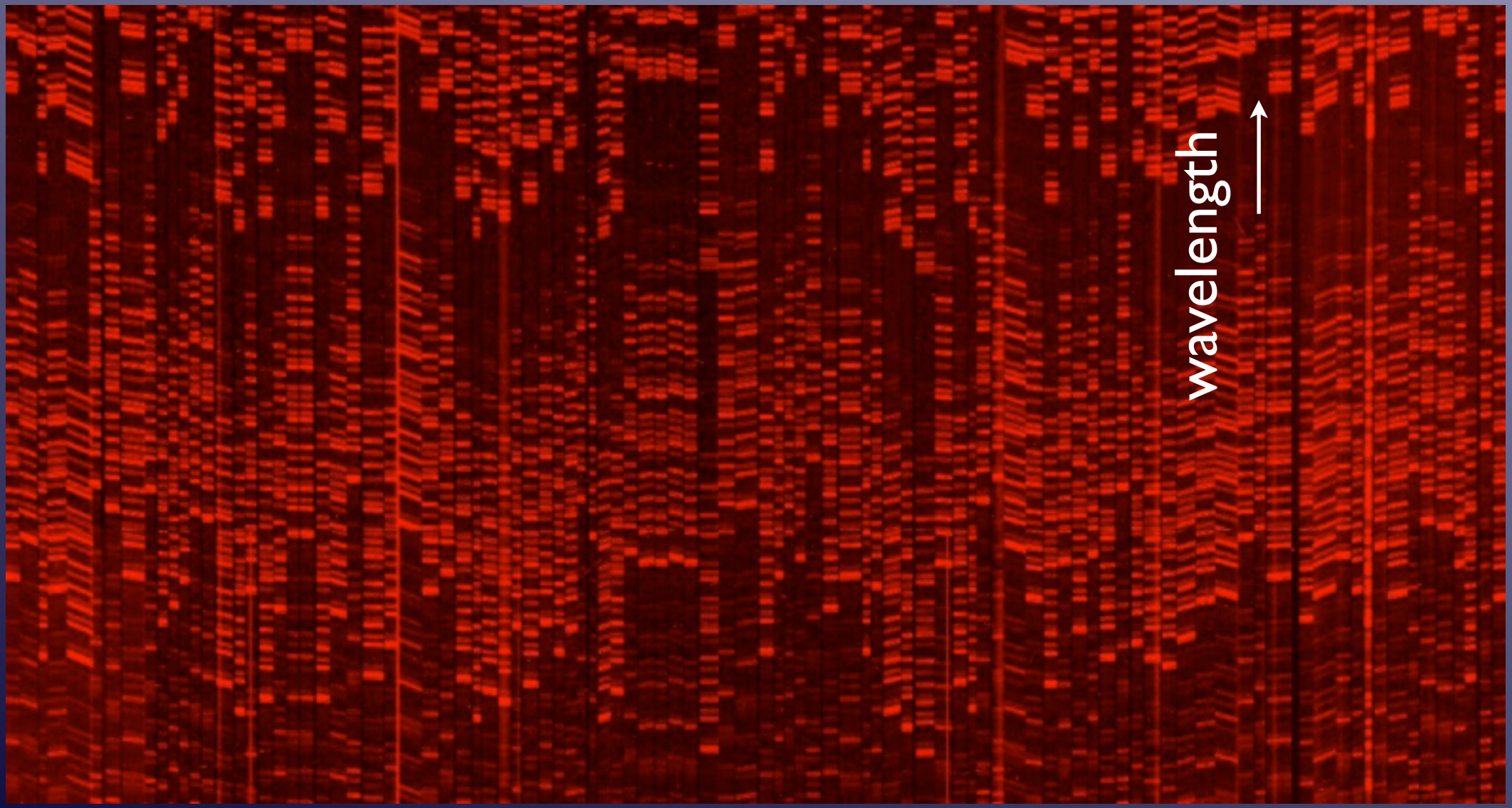
The Power of the Keck Telescope



Keck 10-m telescope

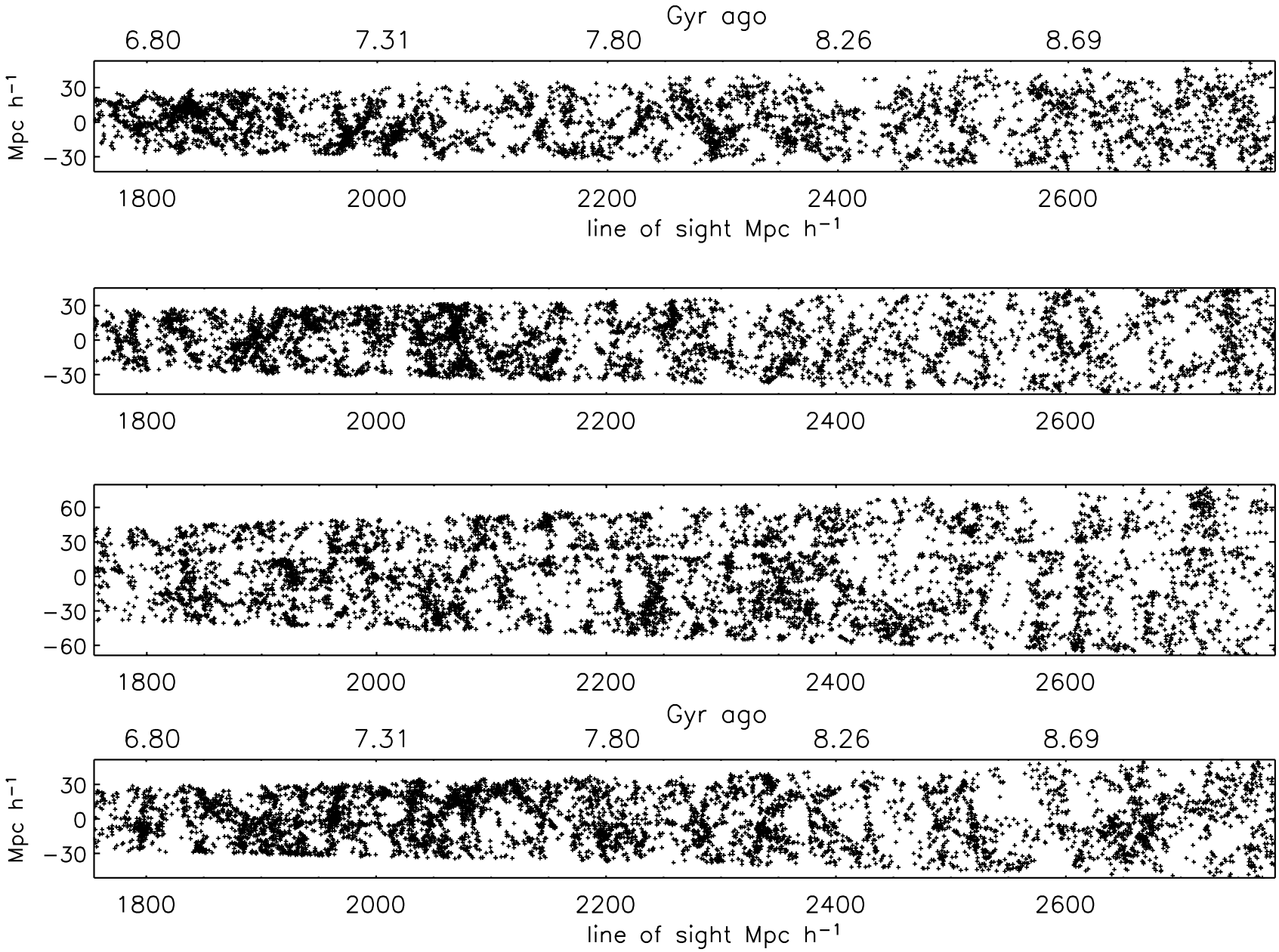


Raw Data - 1/4 of a frame

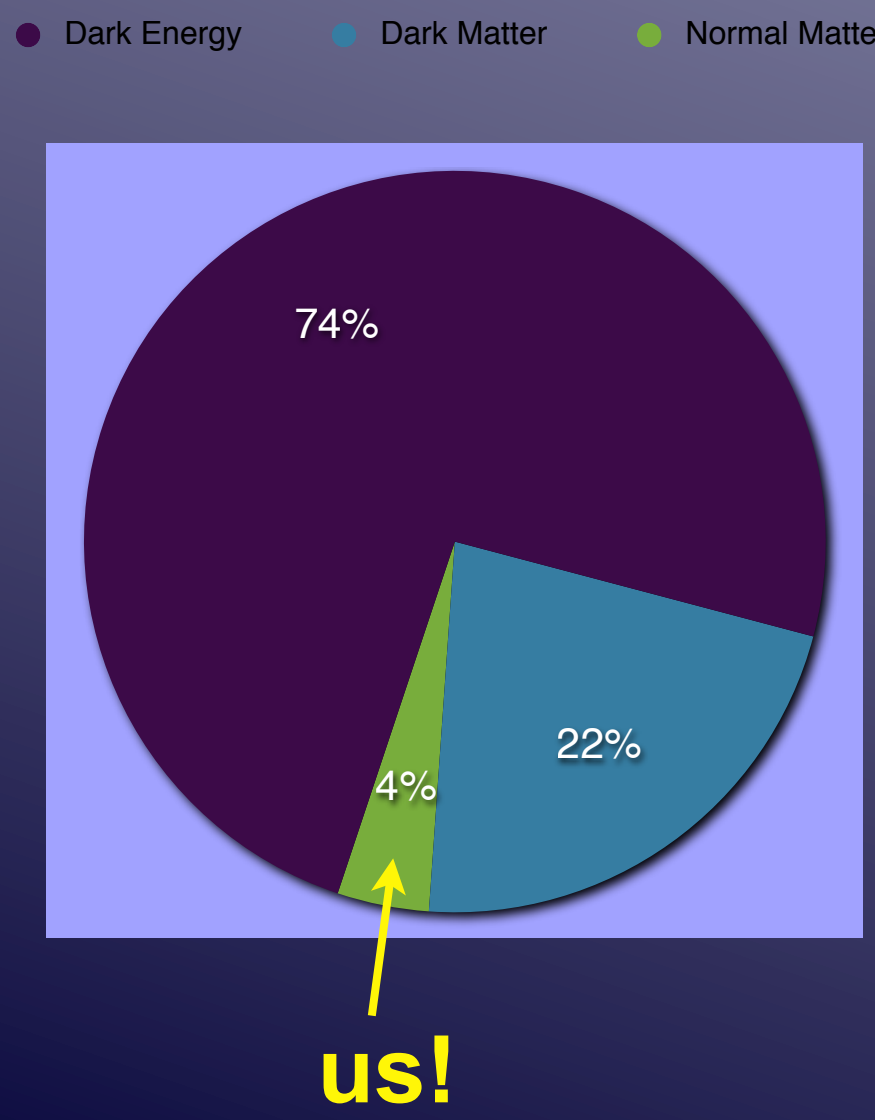


Each column is light from a single galaxy

Distant Galaxy Distribution



How do galaxies cluster?



Depends on what's in the Universe:

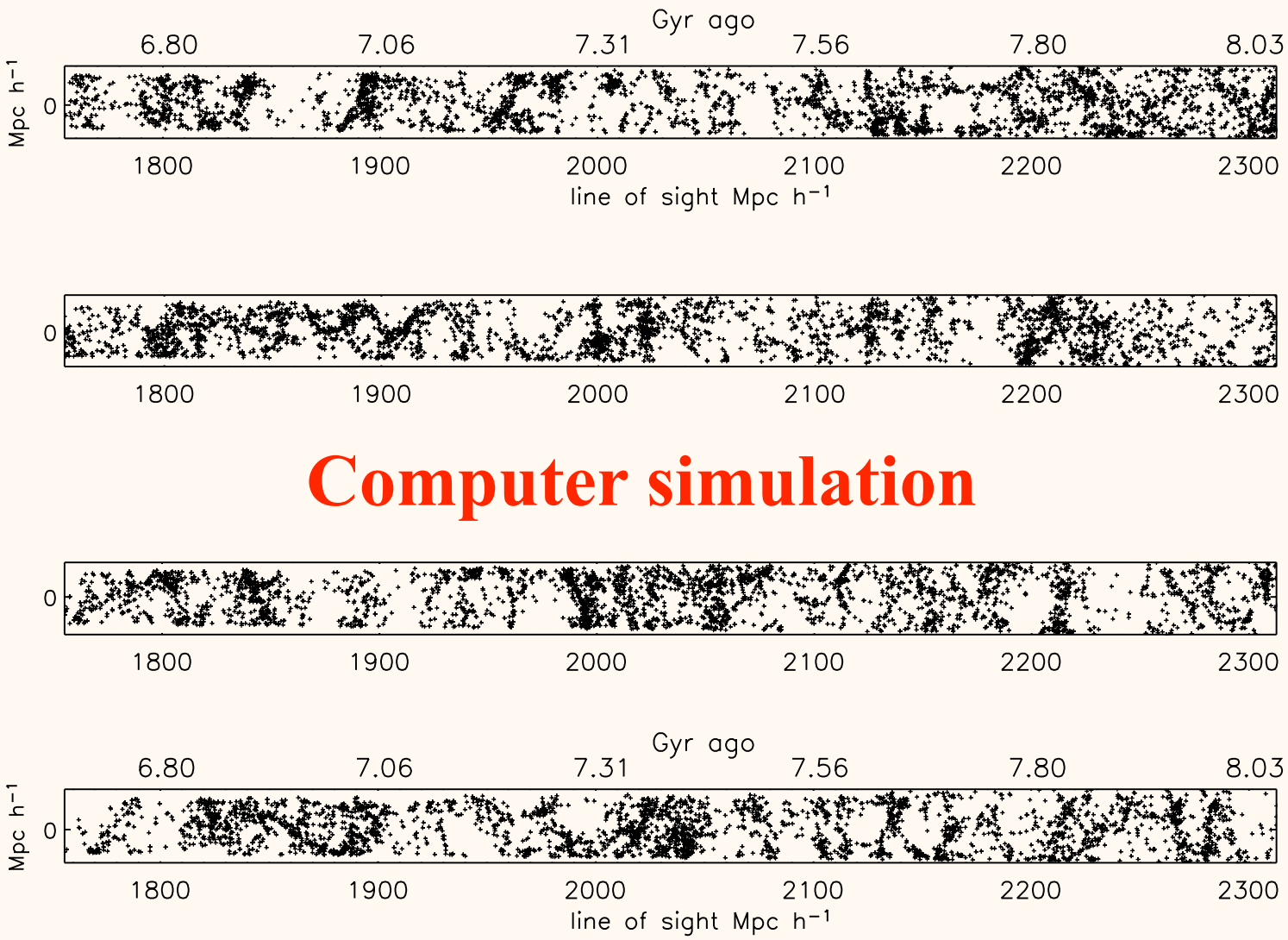
~74% dark energy

~22% dark matter

~4% normal matter

Matches Predictions

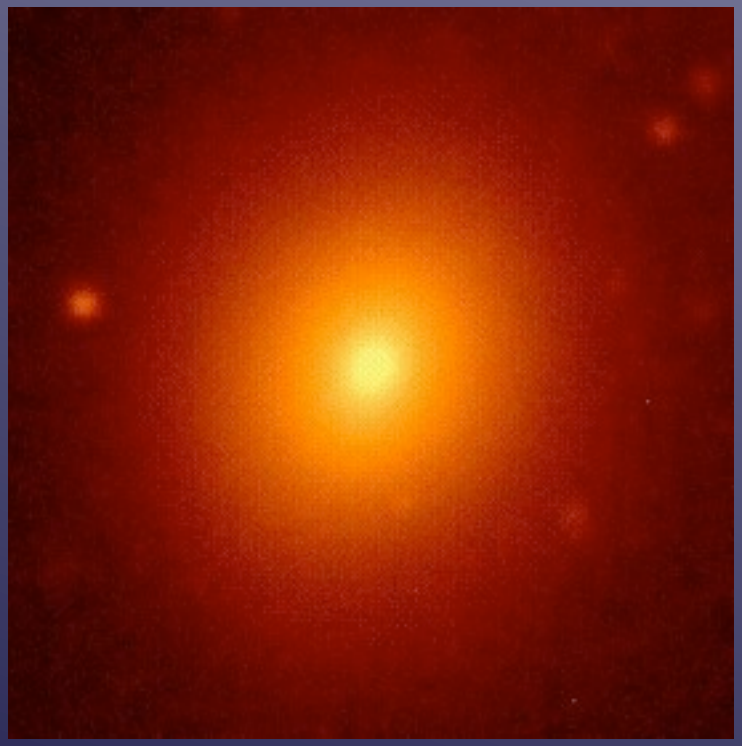
Agrees w/ the cosmological model!



Galaxies Come in 2 Basic Types

spiral, forming stars,
lots of dust and gas,
blue color

elliptical, not forming stars,
little dust and gas,
red color



Add Galaxies

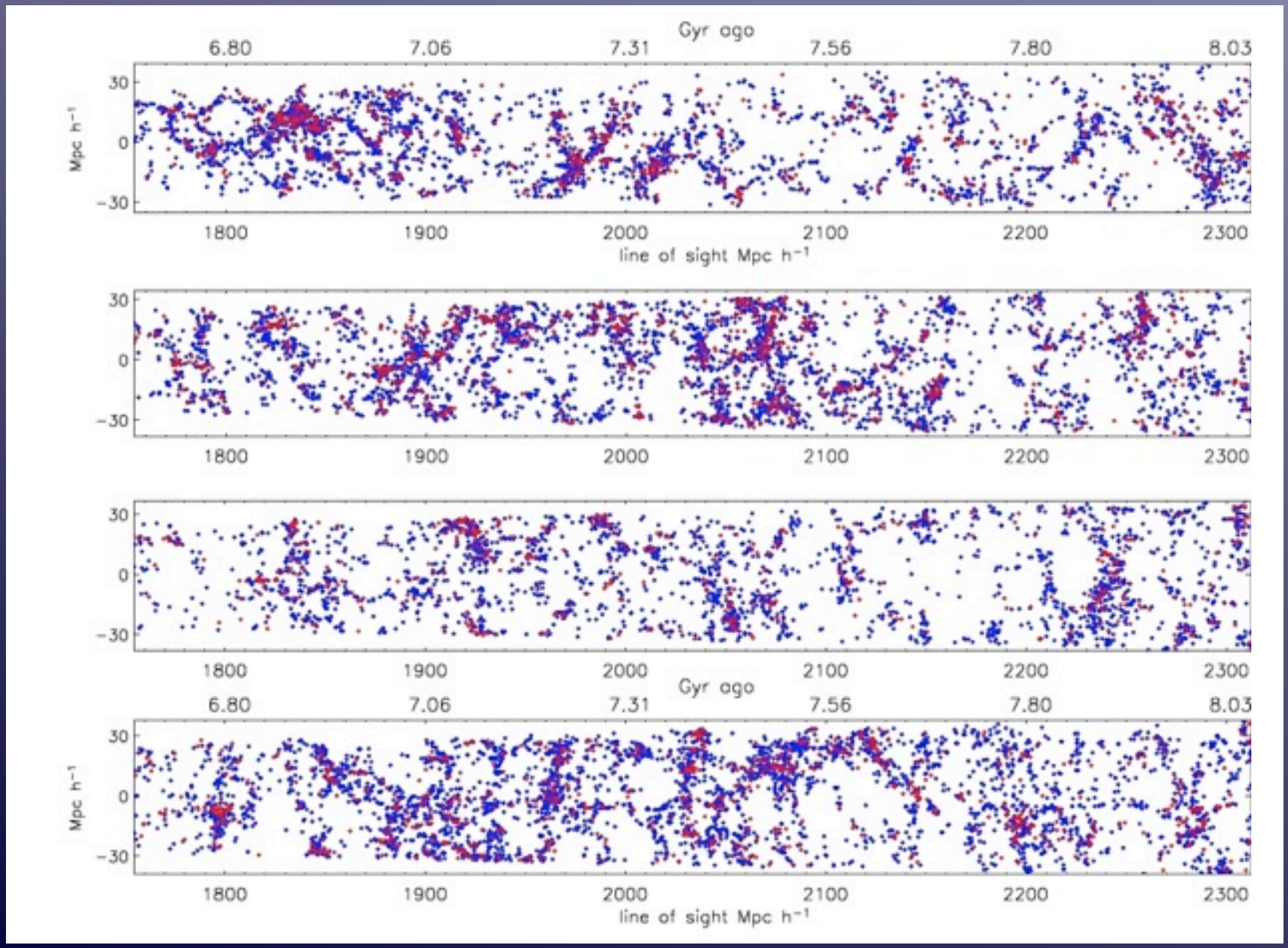
Use 'recipes' for the complicated physics of galaxy formation and evolution

Gas Cooling
Star Formation
Disk creation
Supernovae
Shocks
Outflowing Winds
Black Holes

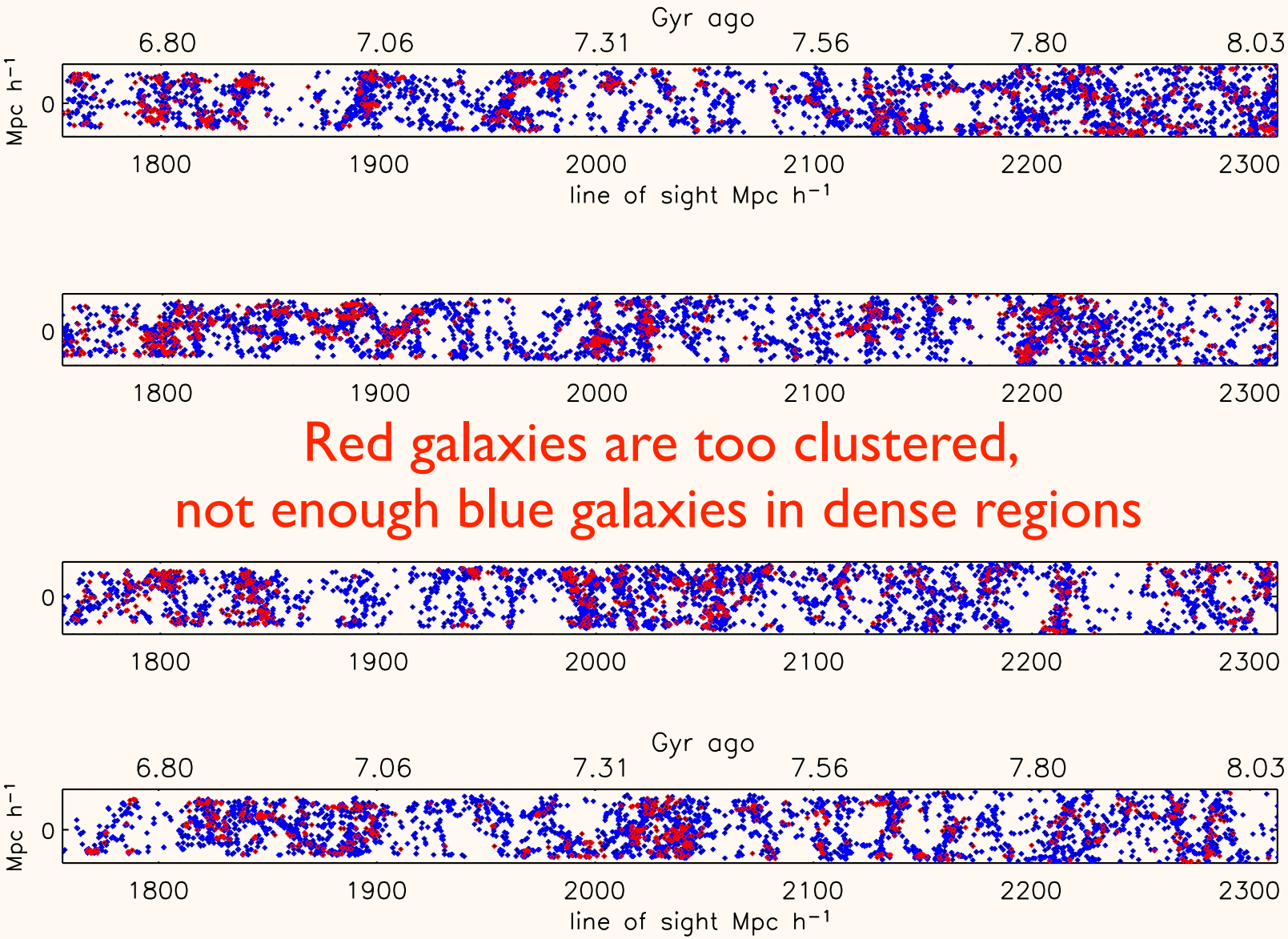
All recipes are tied to observations but have some freedom / wiggle room

Split by Galaxy Type

real data:



Comparison w/ Simulation



Red galaxies are too clustered,
not enough blue galaxies in dense regions

Summary

We know how much dark matter and dark energy there is in the Universe

- but we don't know what it is!

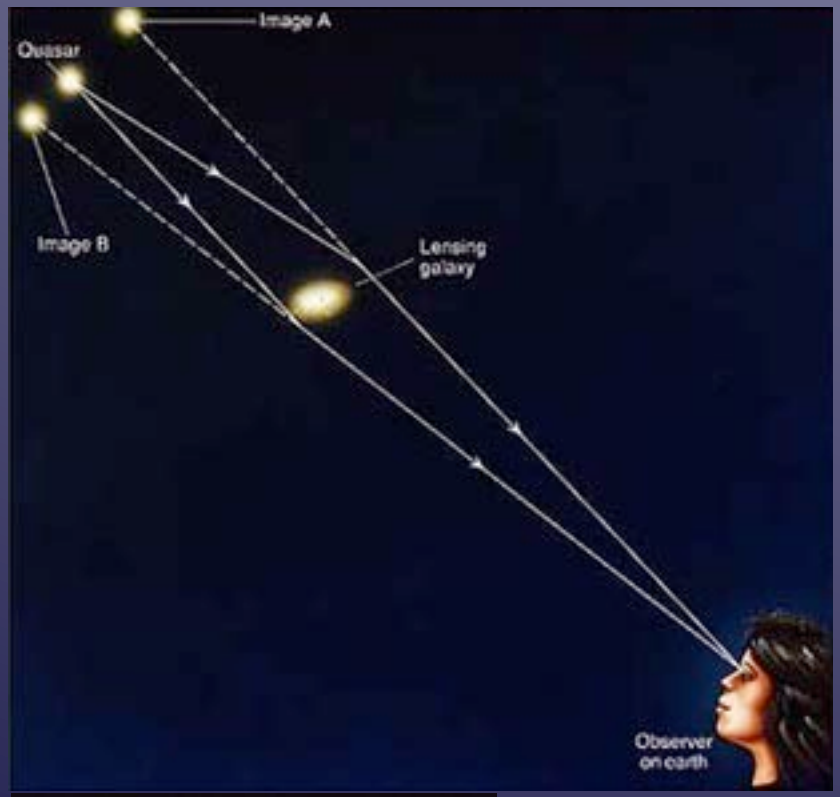
We know what galaxies are made of

- but we don't know how they form or evolve!

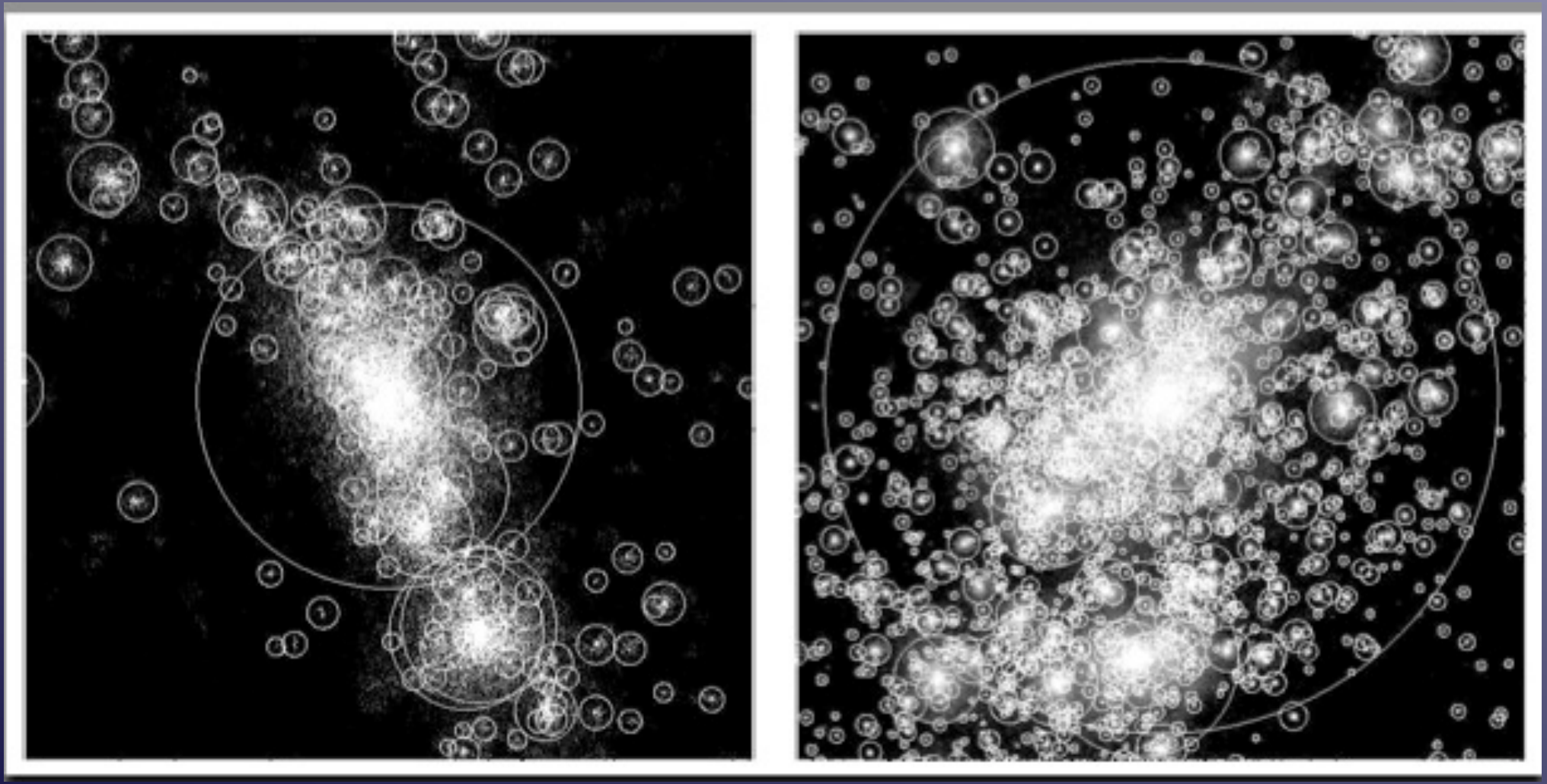
Summary

We still have a lot to learn!

Gravitational Lensing



Dark Matter Halos



Overdensities in dark matter distribution collapse through gravity - dark matter halos. Simulations assume one galaxy at the center of each halo and subhalo, above some mass threshold.