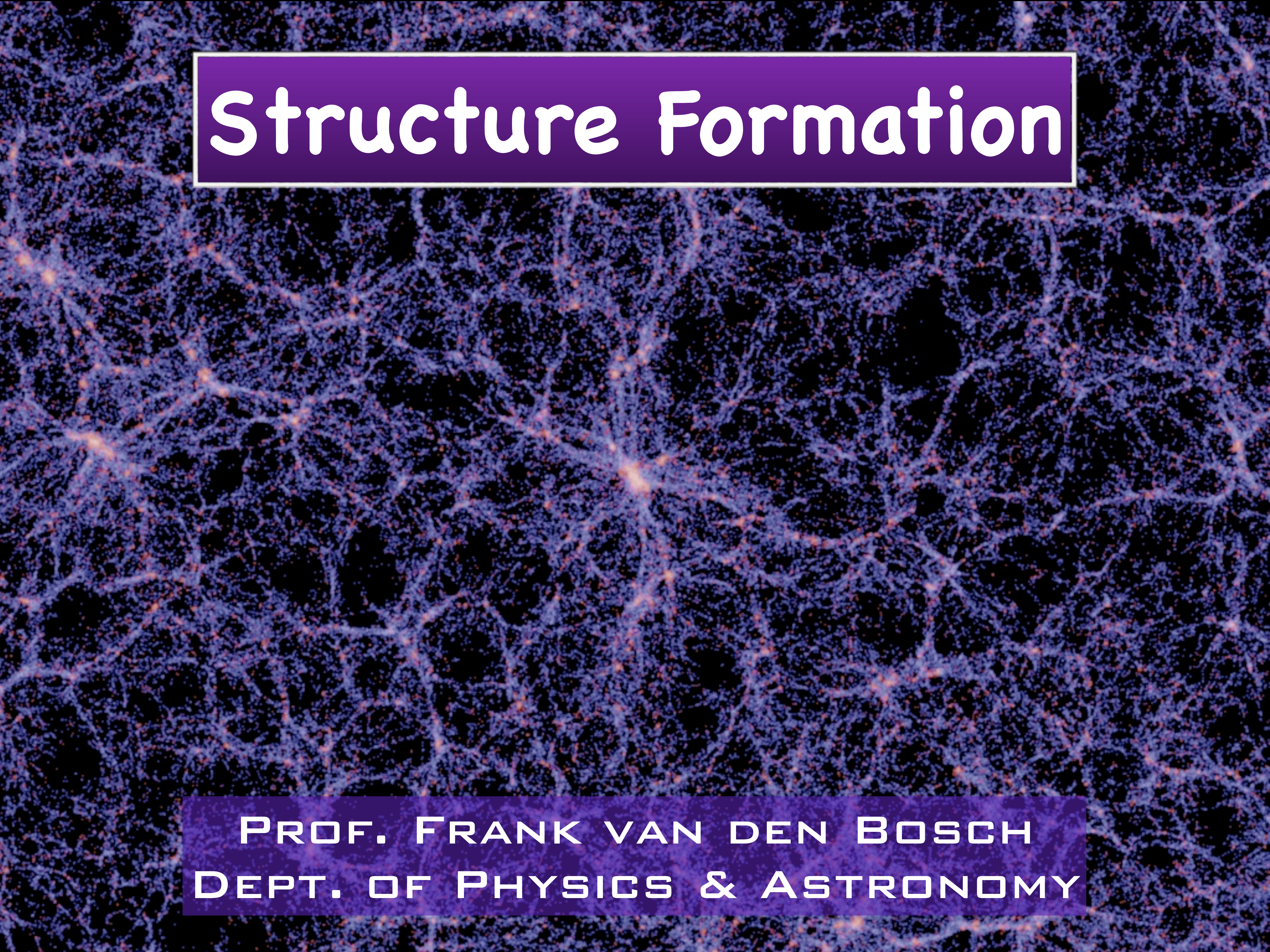
Structure Formation



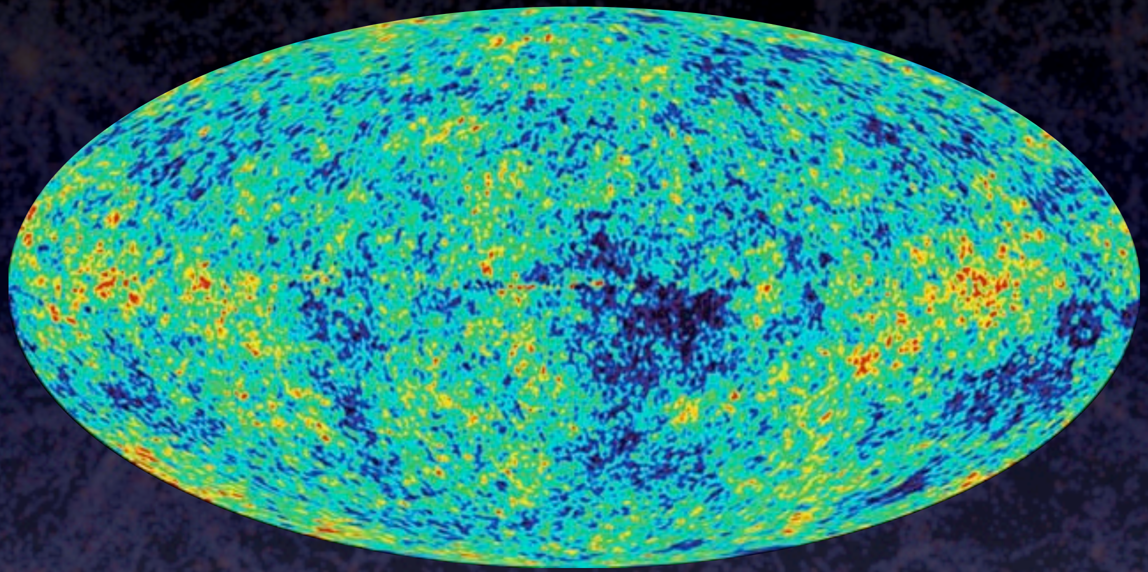
Prof. Frank van den Bosch
Dept. of Physics & Astronomy

Structure Formation

From Inflaton to Milky Way

Prof. Frank van den Bosch
Dept. of Physics & Astronomy

Recap of last week....



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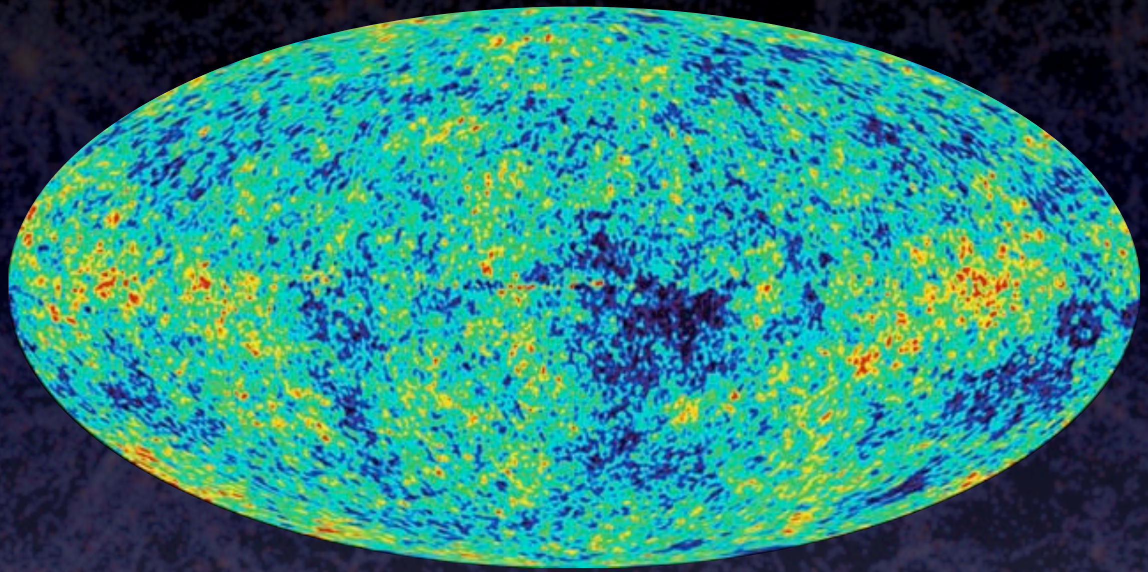

- ★ What is dark matter?
- ★ What is dark energy?
- ★ What is origin of perturbations?
- ★ Why is Universe flat?

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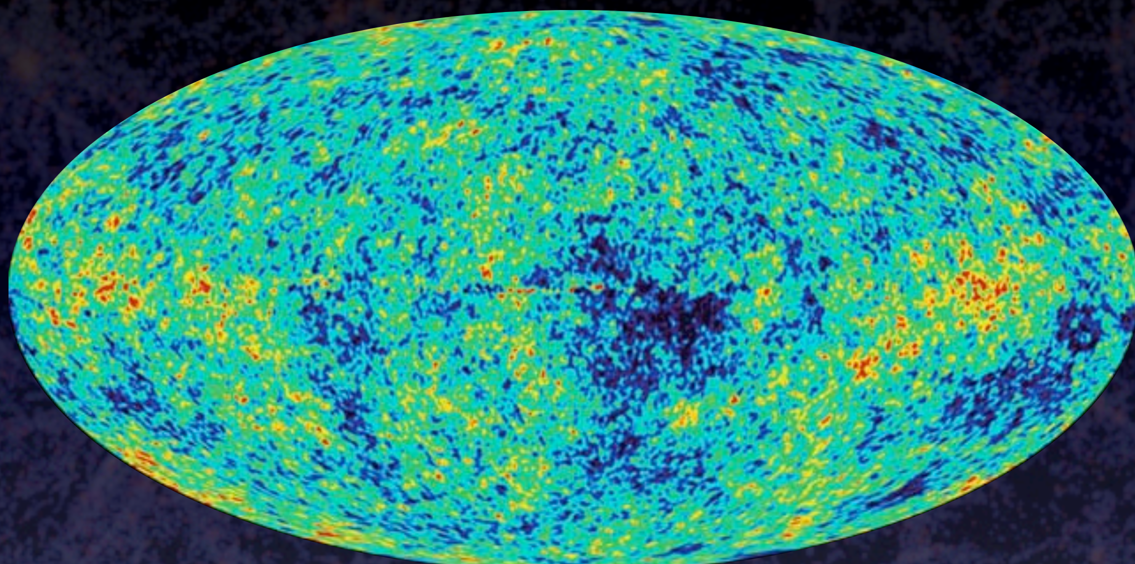

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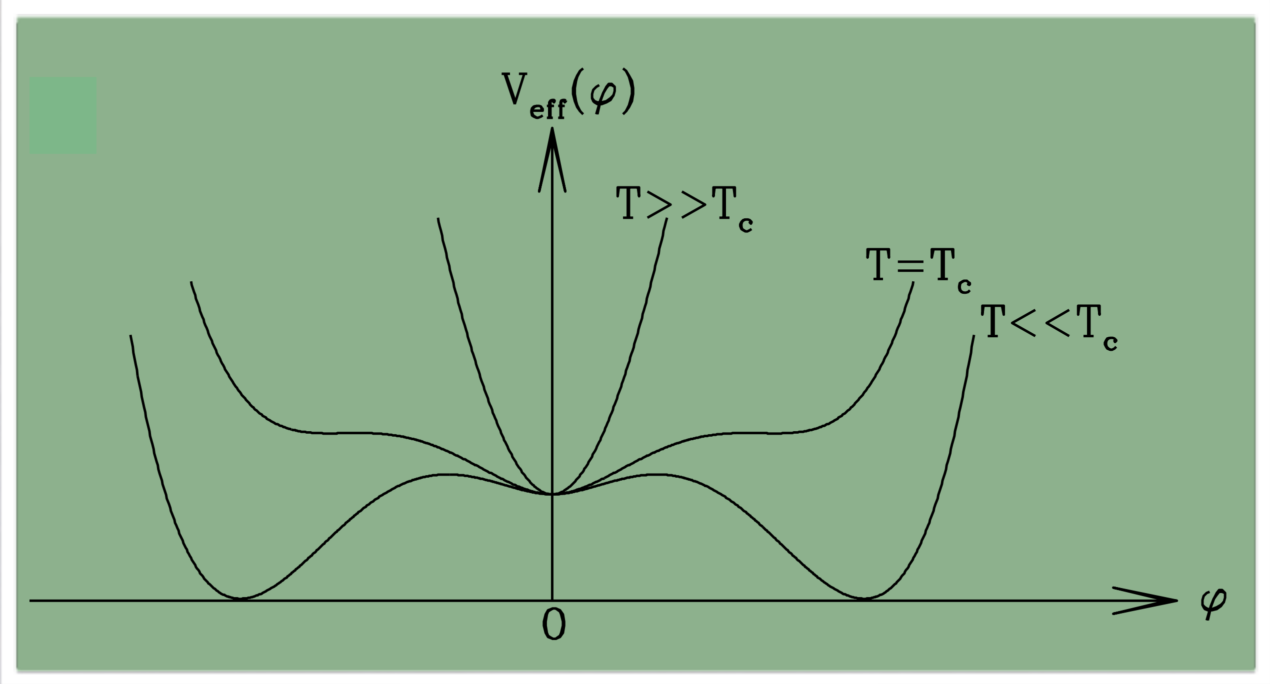
The Inflationary Universe

Inflation

Postulate

Shortly after Big Bang (~10^{-35}s), energy density of Universe is dominated by false vacuum state of a scalar field (the inflaton)



Inflaton acts like dark energy and causes exponential expansion
Inflation stops when inflaton `decays' to true vacuum state.
Energy of inflaton converted to particles & photons.

Inflation is envisioned to lasts for at least ~60 e-foldings, during which size of Universe increased by a factor ~10^{26}

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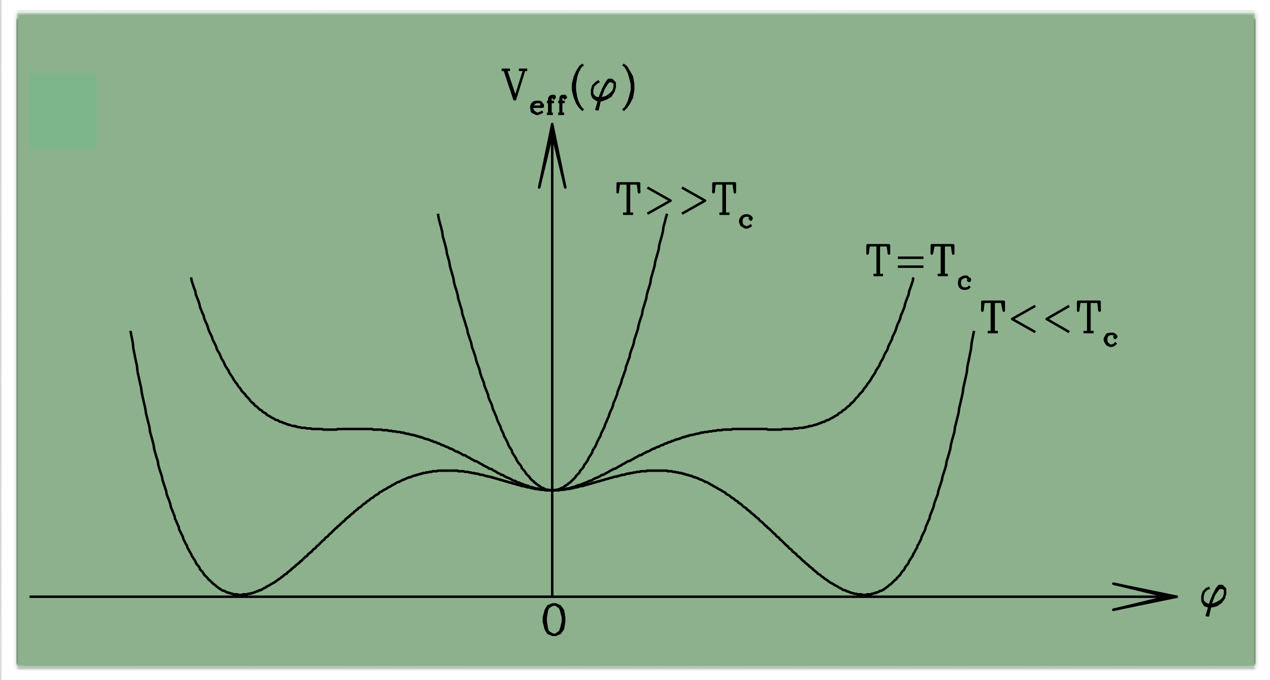

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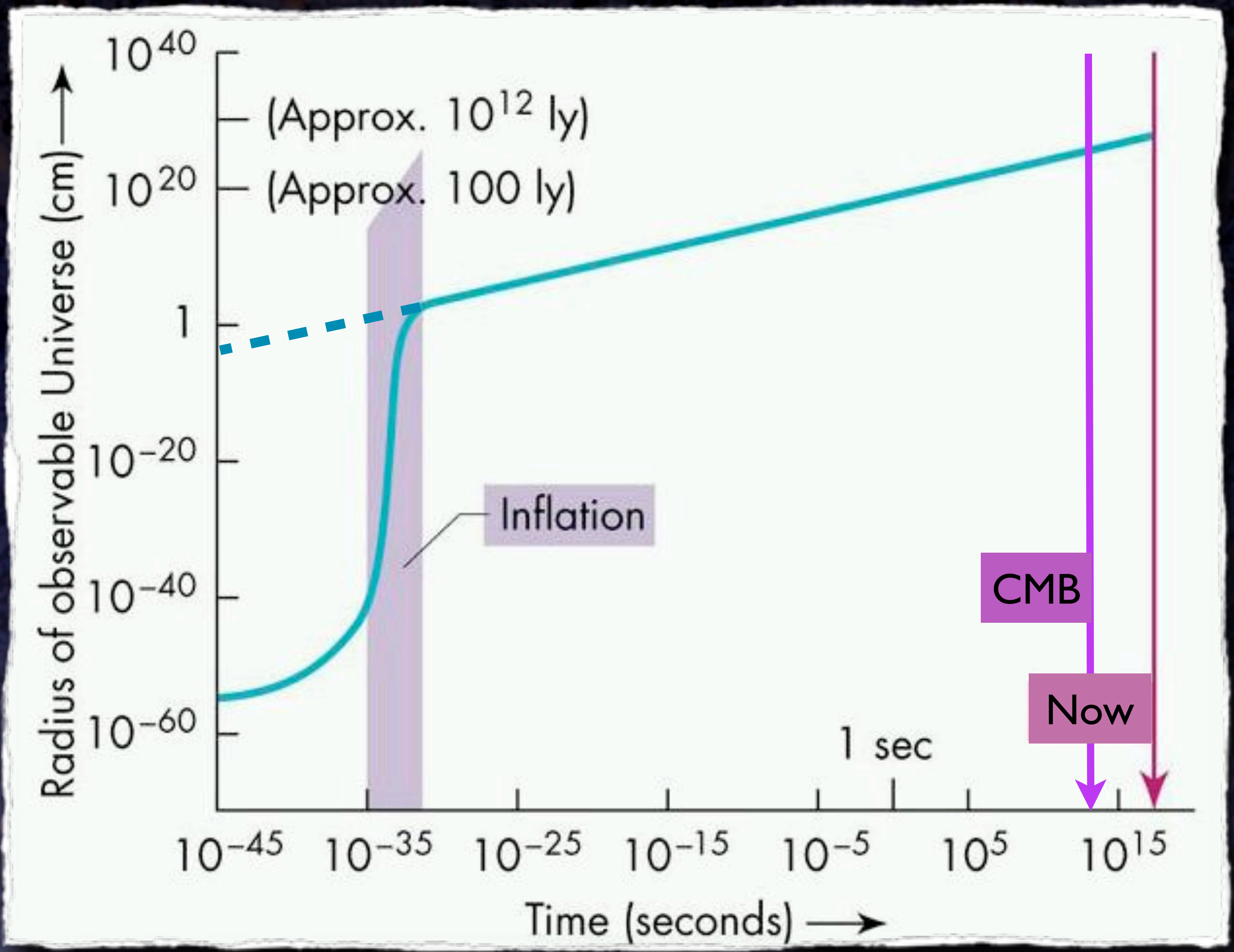
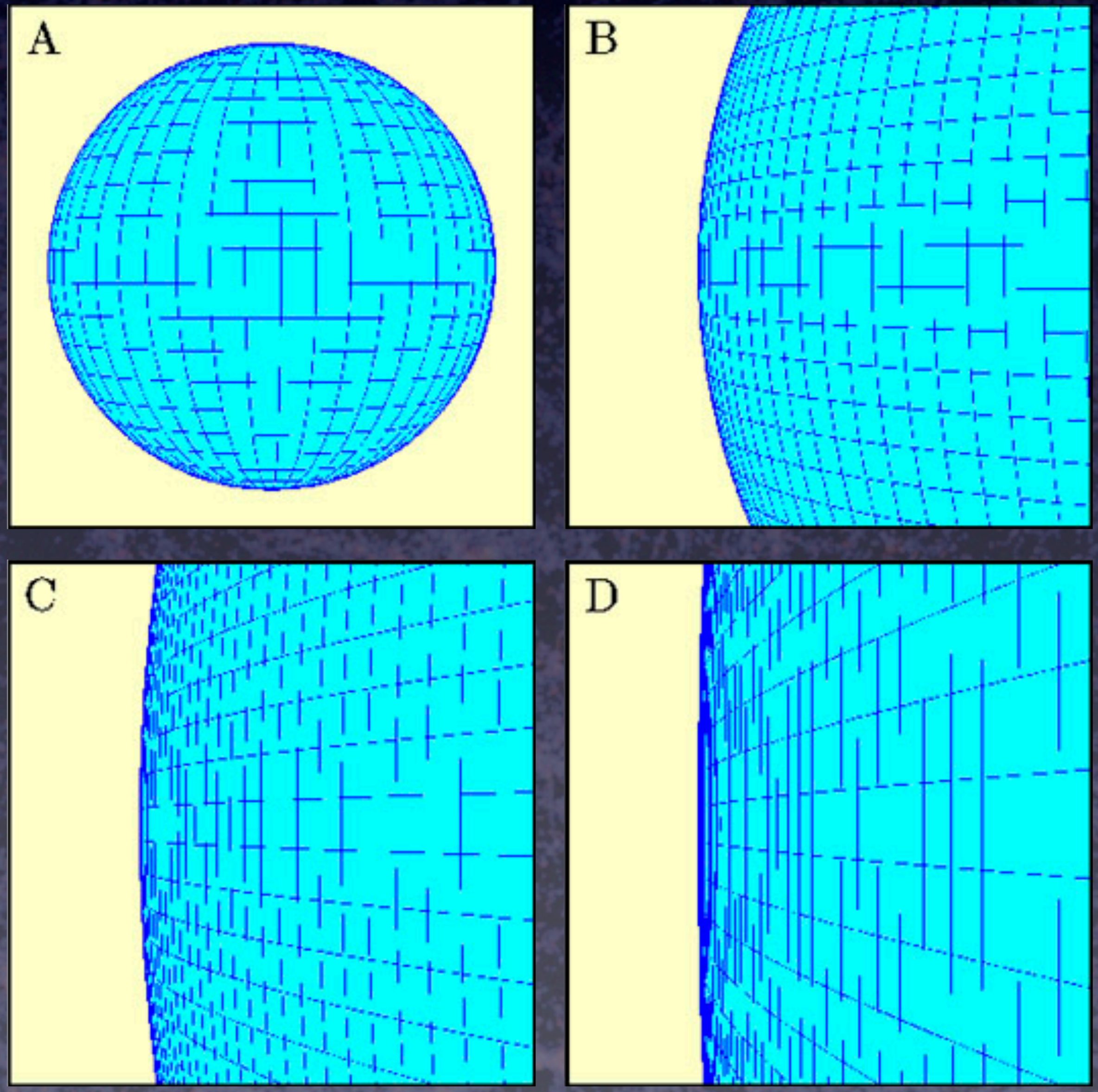
For comparison, since CMB Universe has expanded by factor 10^3

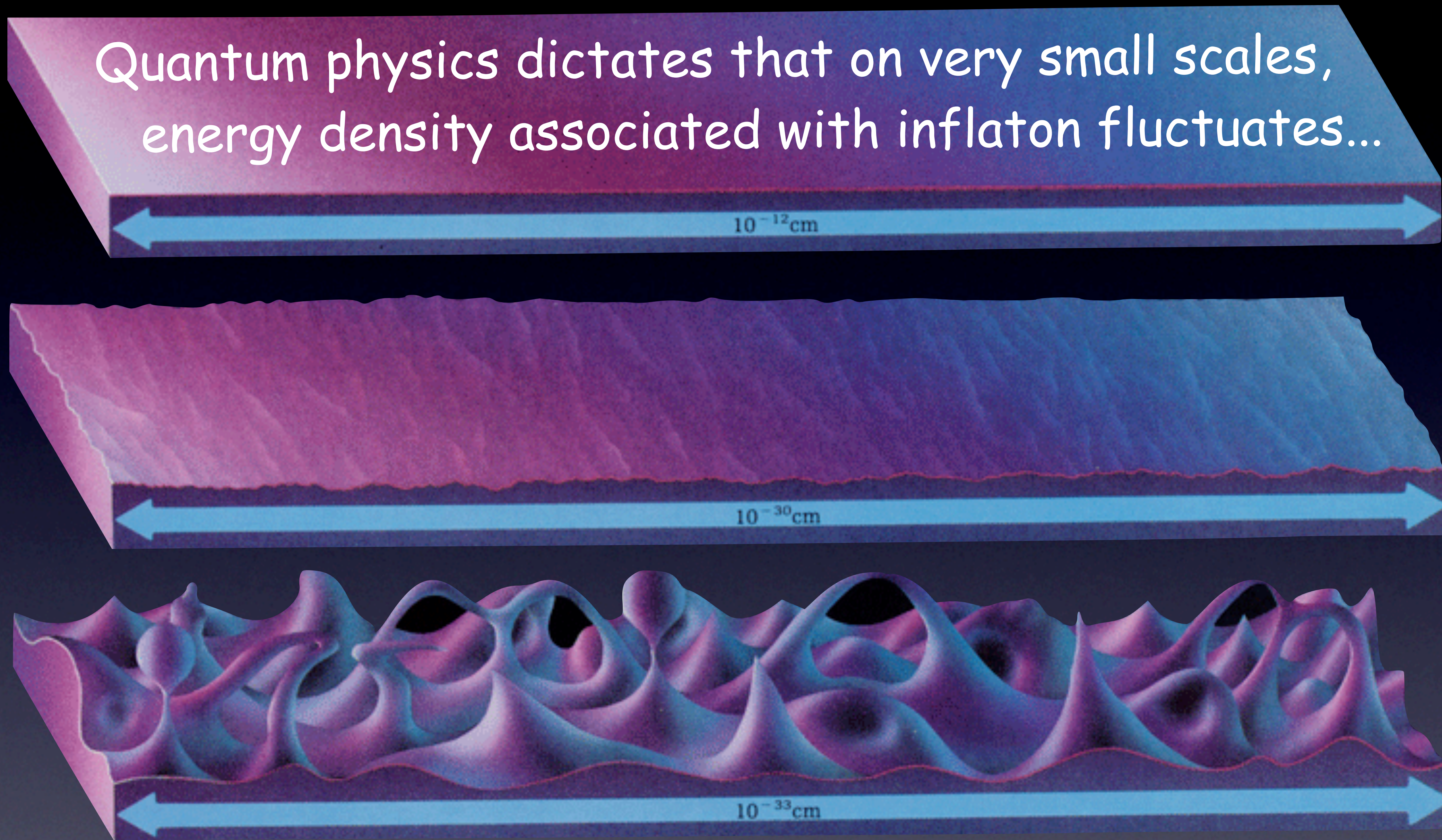
Stretching Space





Because of huge expansion, any pre-existing curvature is inflated away --> post-inflationary Universe is flat

Quantum physics dictates that on very small scales, energy density associated with inflaton fluctuates...

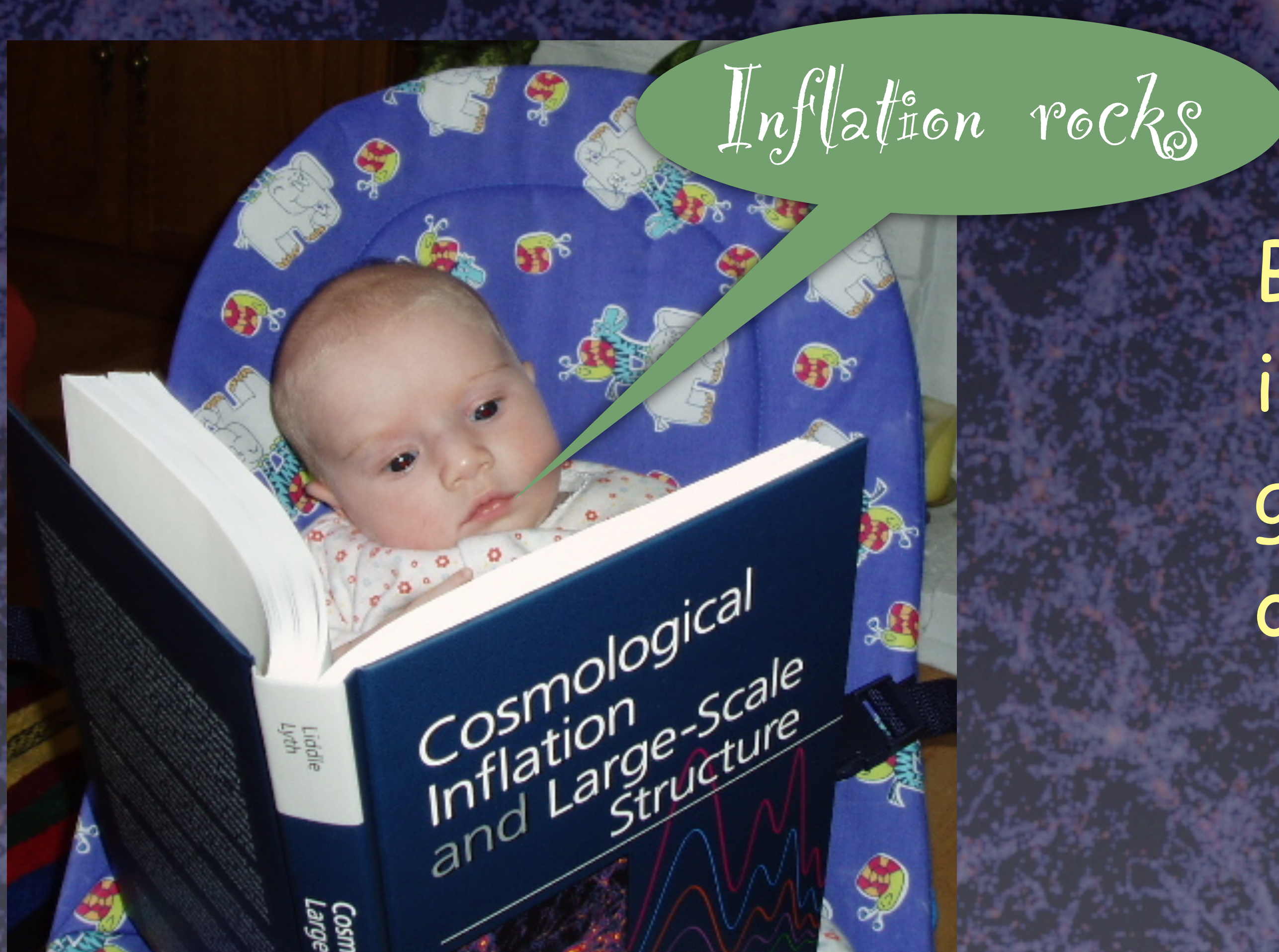


Because of exponential expansion, these quantum fluctuations are inflated to fluctuations in energy density of Universe

The Inflationary Universe

During inflation, a patch the size of a human hair (width) is inflated to patch larger than our Milky Way, in less than 10^{-33} s

Inflation solves the flatness problem in that it inflates away any pre-existing curvature



Because of quantum fluctuations, inflation also automatically predicts generation of density perturbations on wide range of scales

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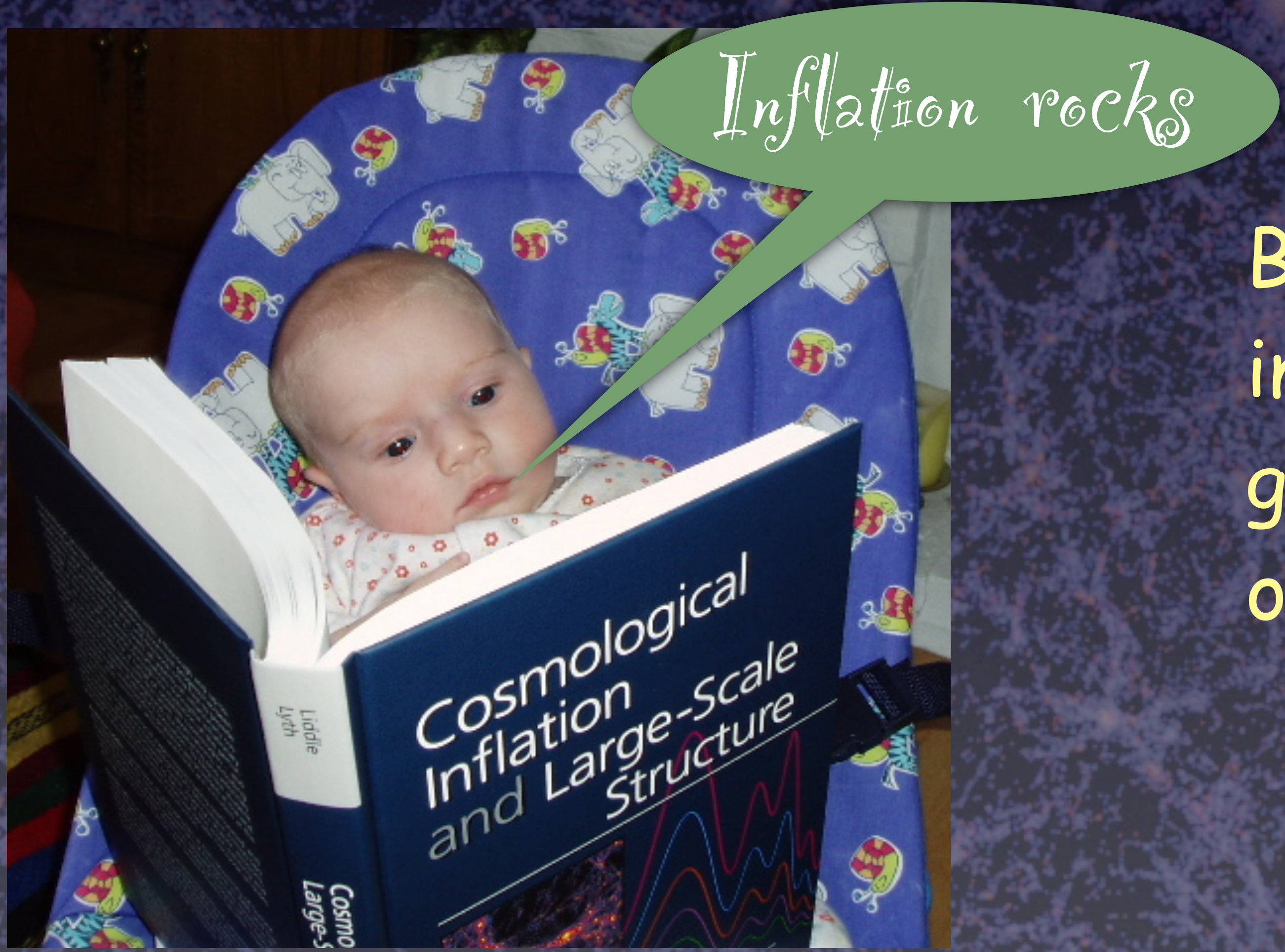

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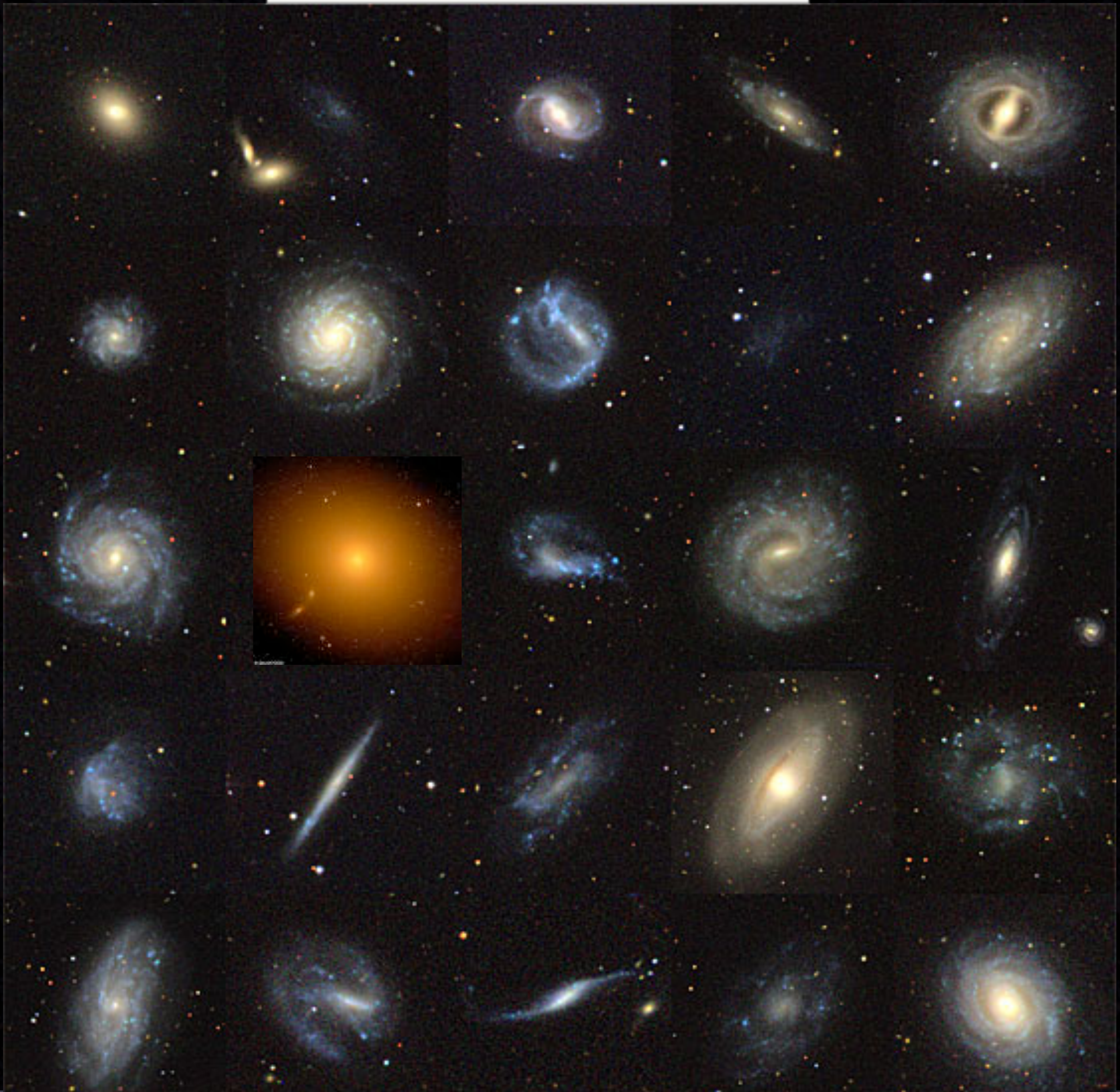
The Structured Universe

The Galaxy Zoo



The Galaxy Zoo

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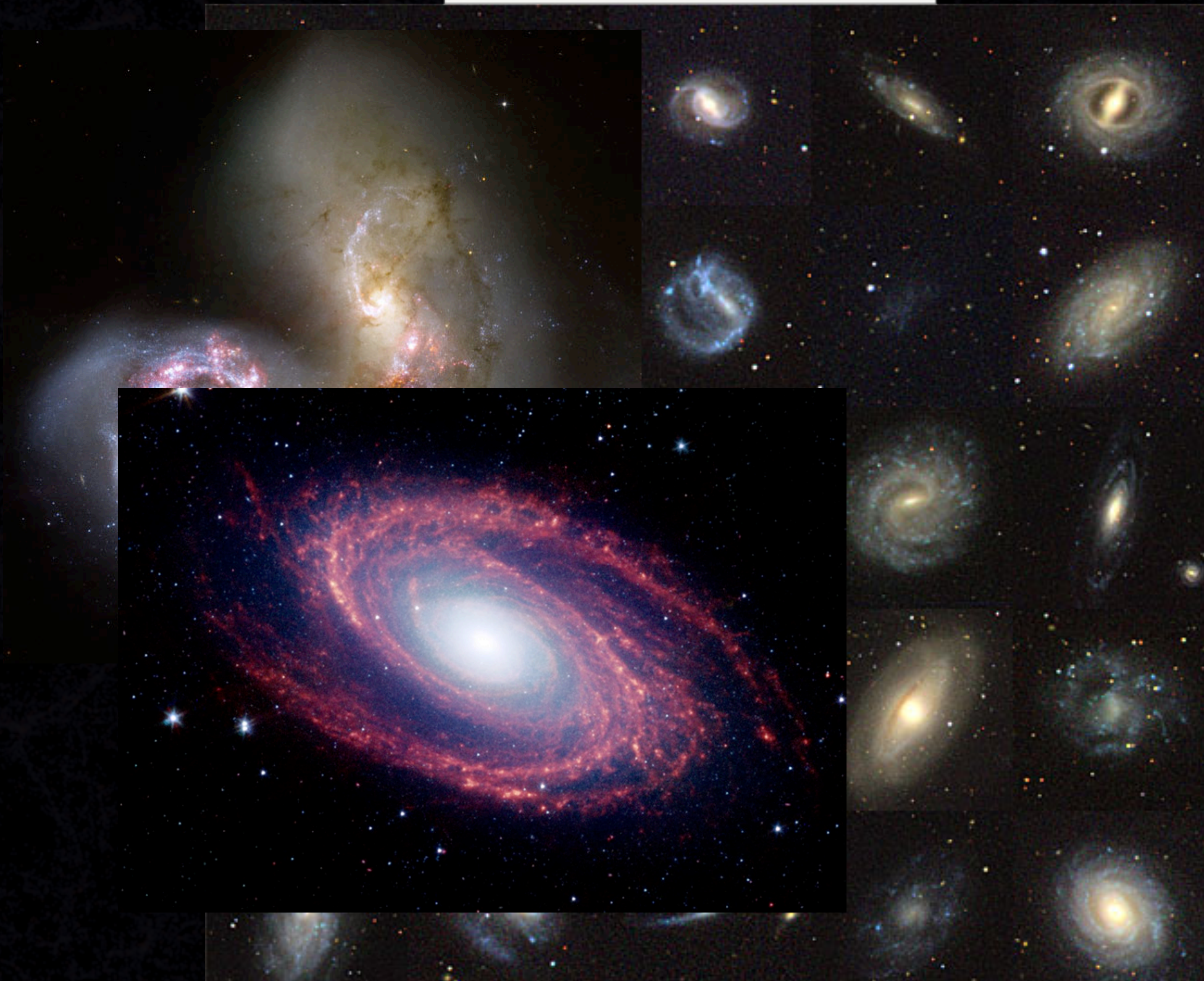

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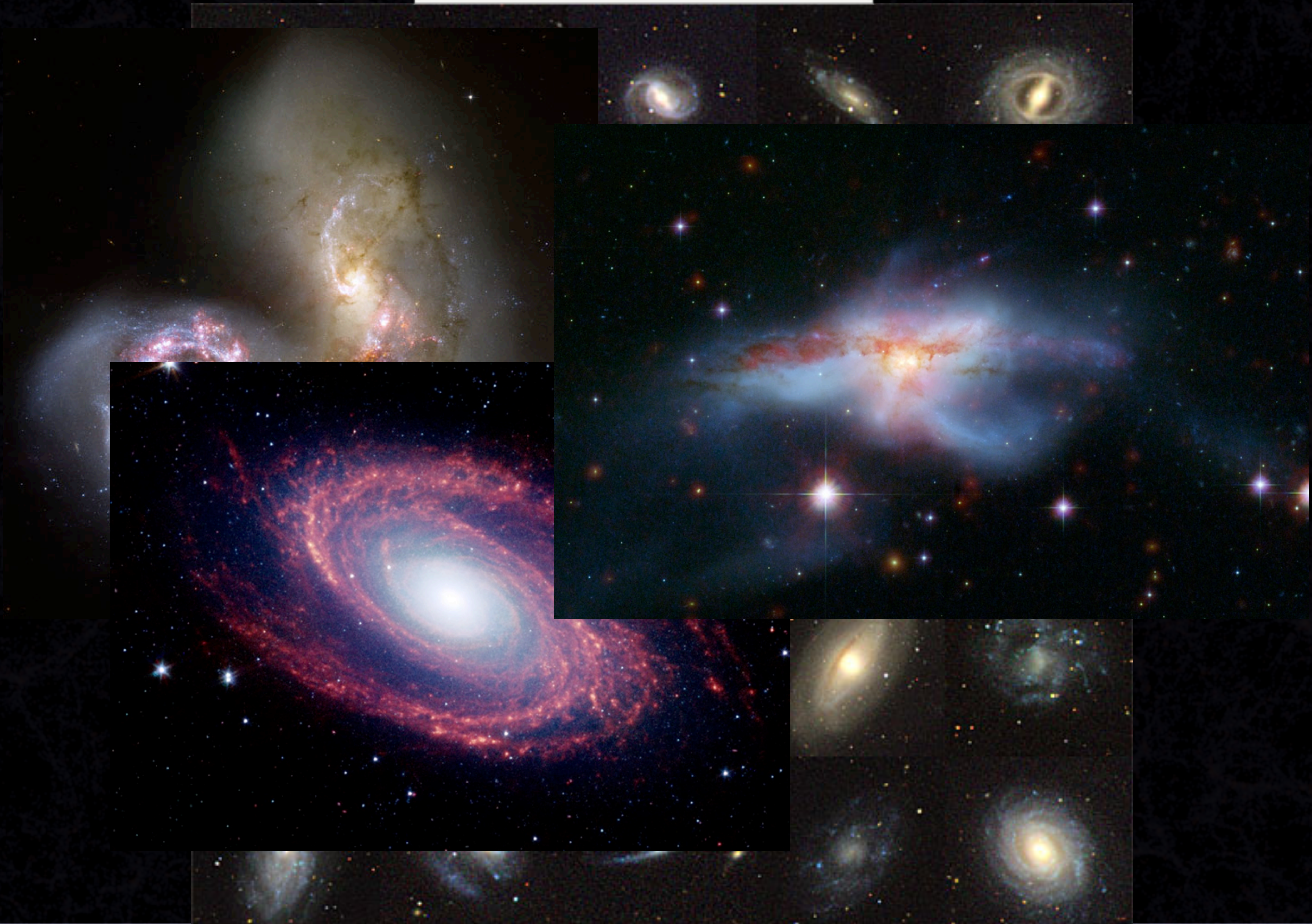

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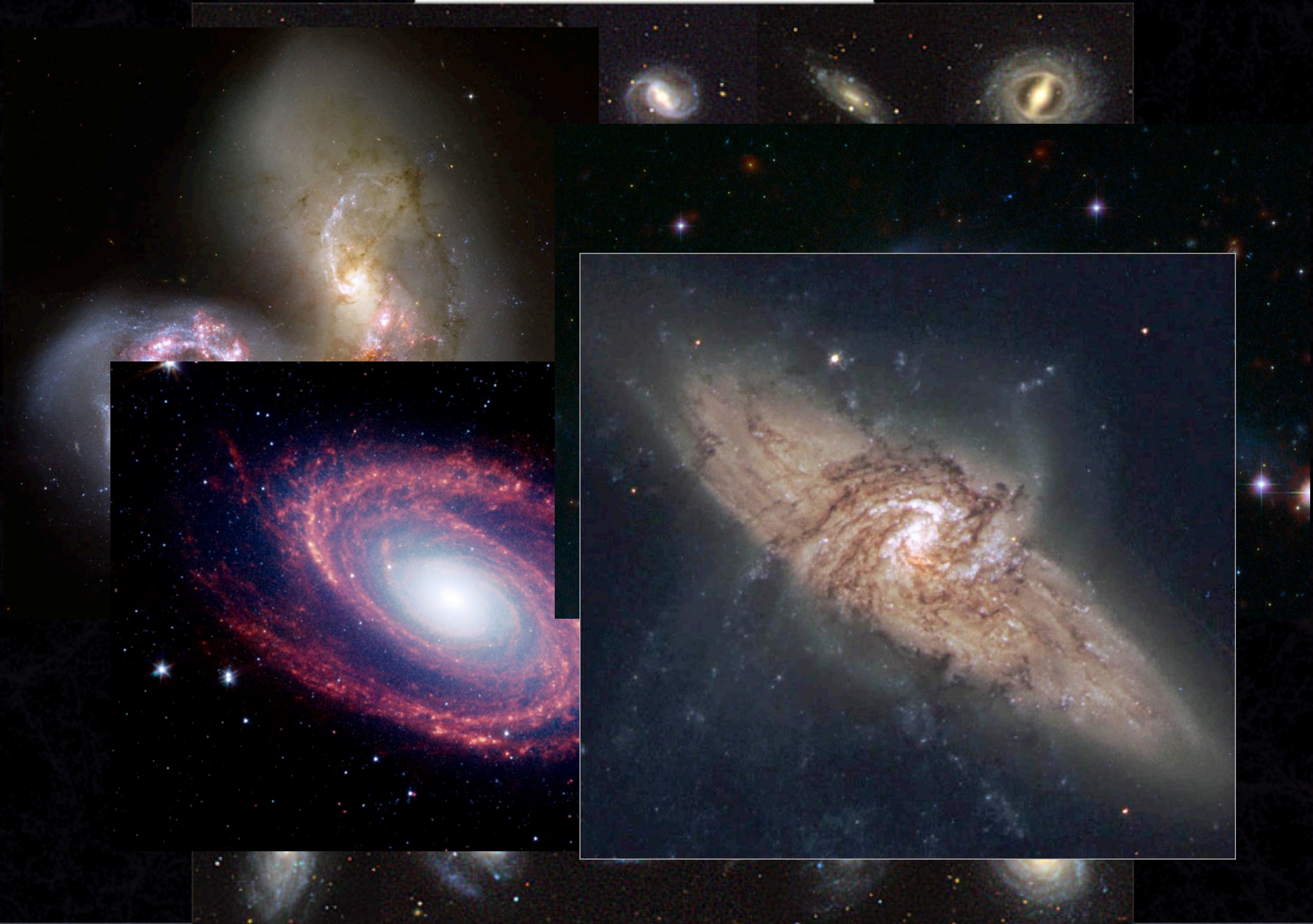

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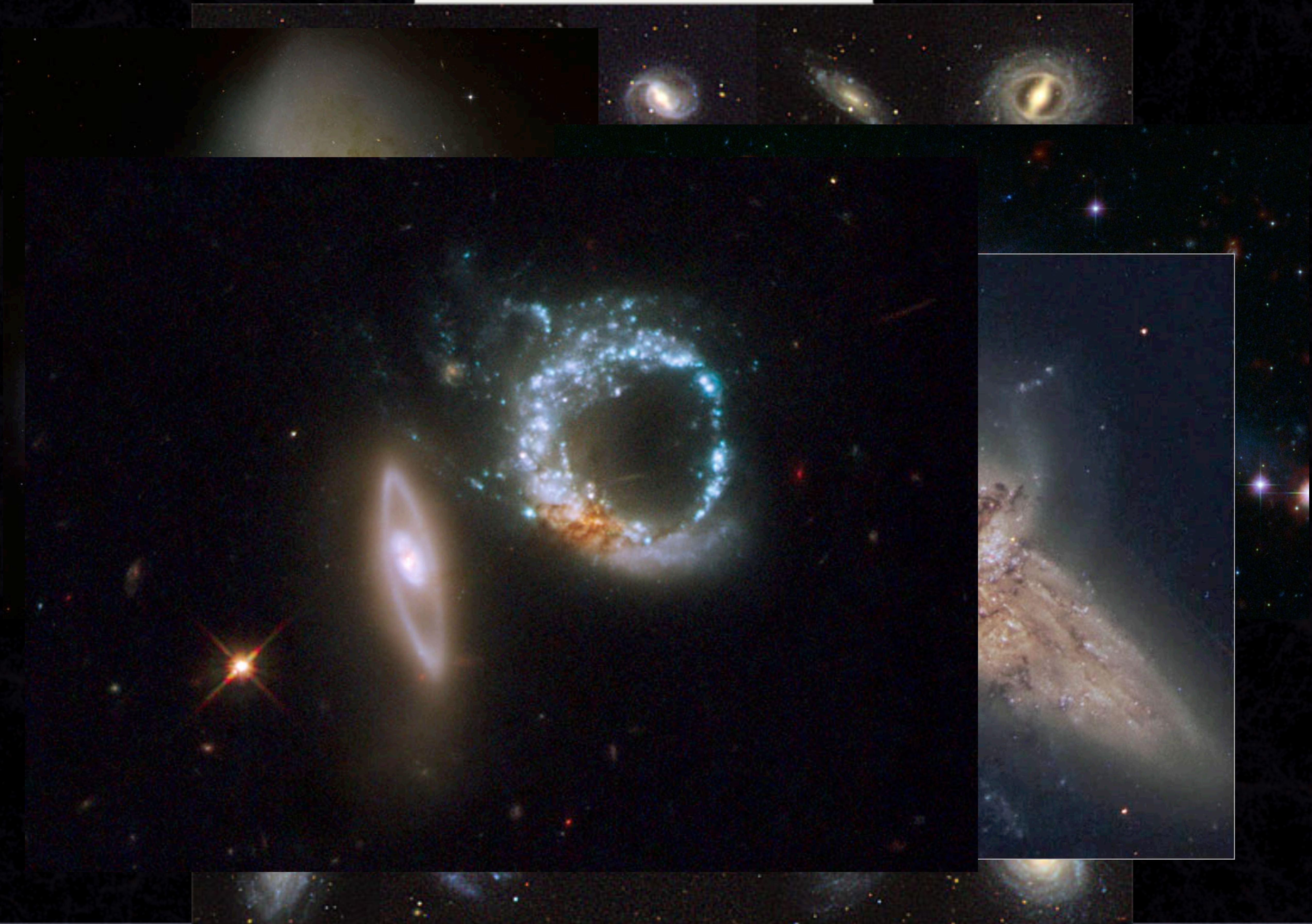

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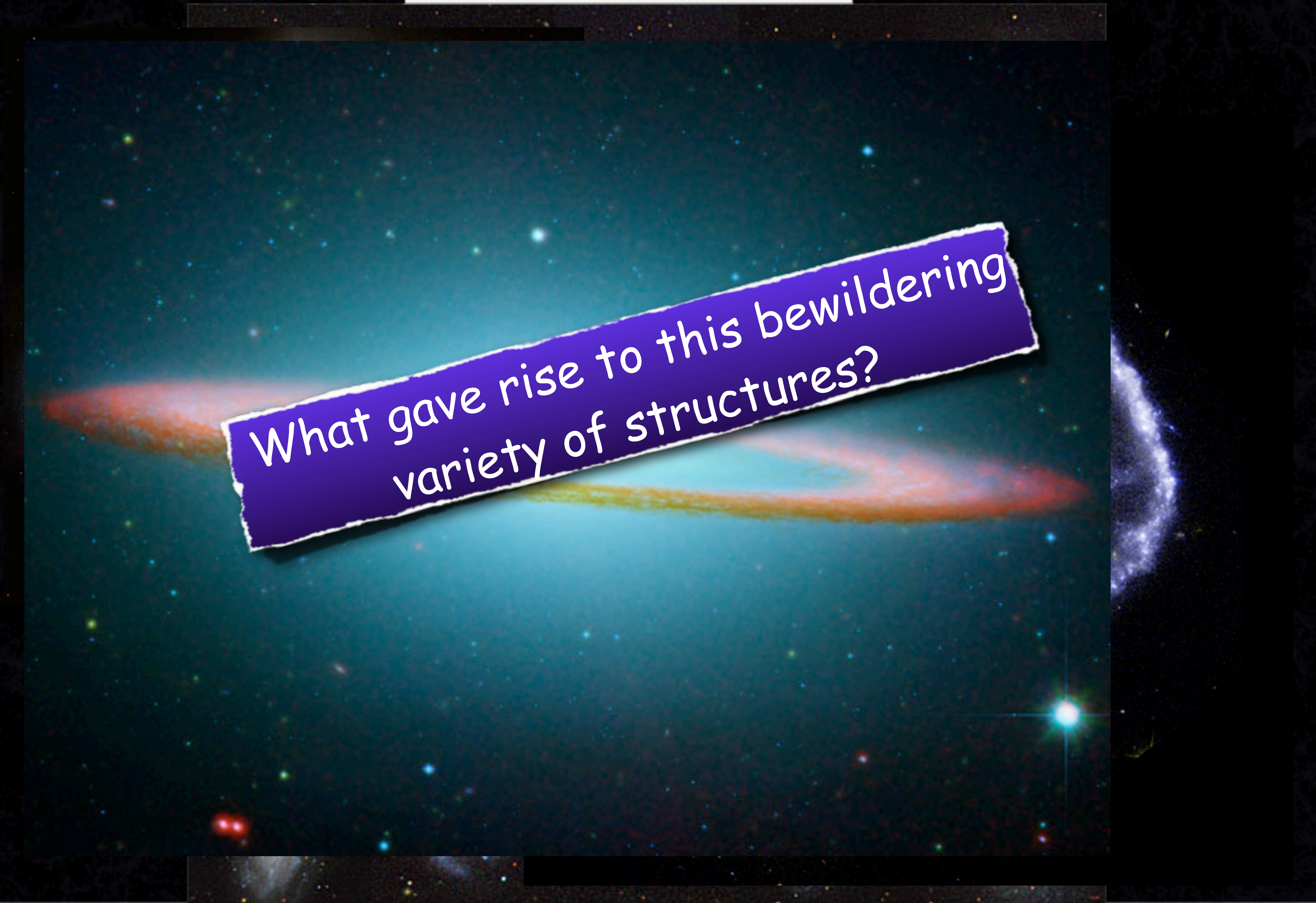
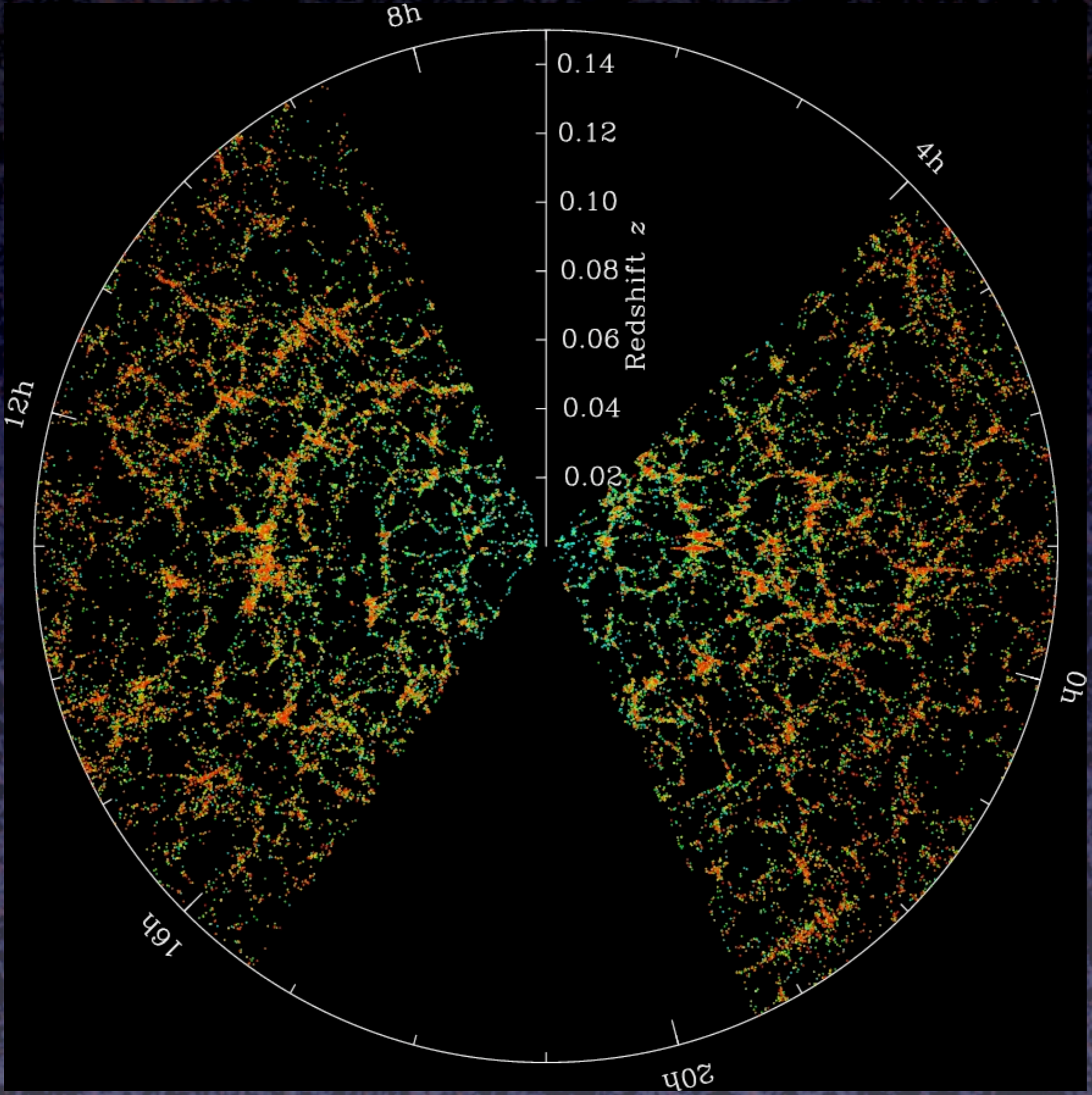


The Distribution of Galaxies

The Milky Way and more than 1.5 million galaxies from 2MASS, color coded according to redshift (blue = near, red = far)

Sloan Digital Sky Survey



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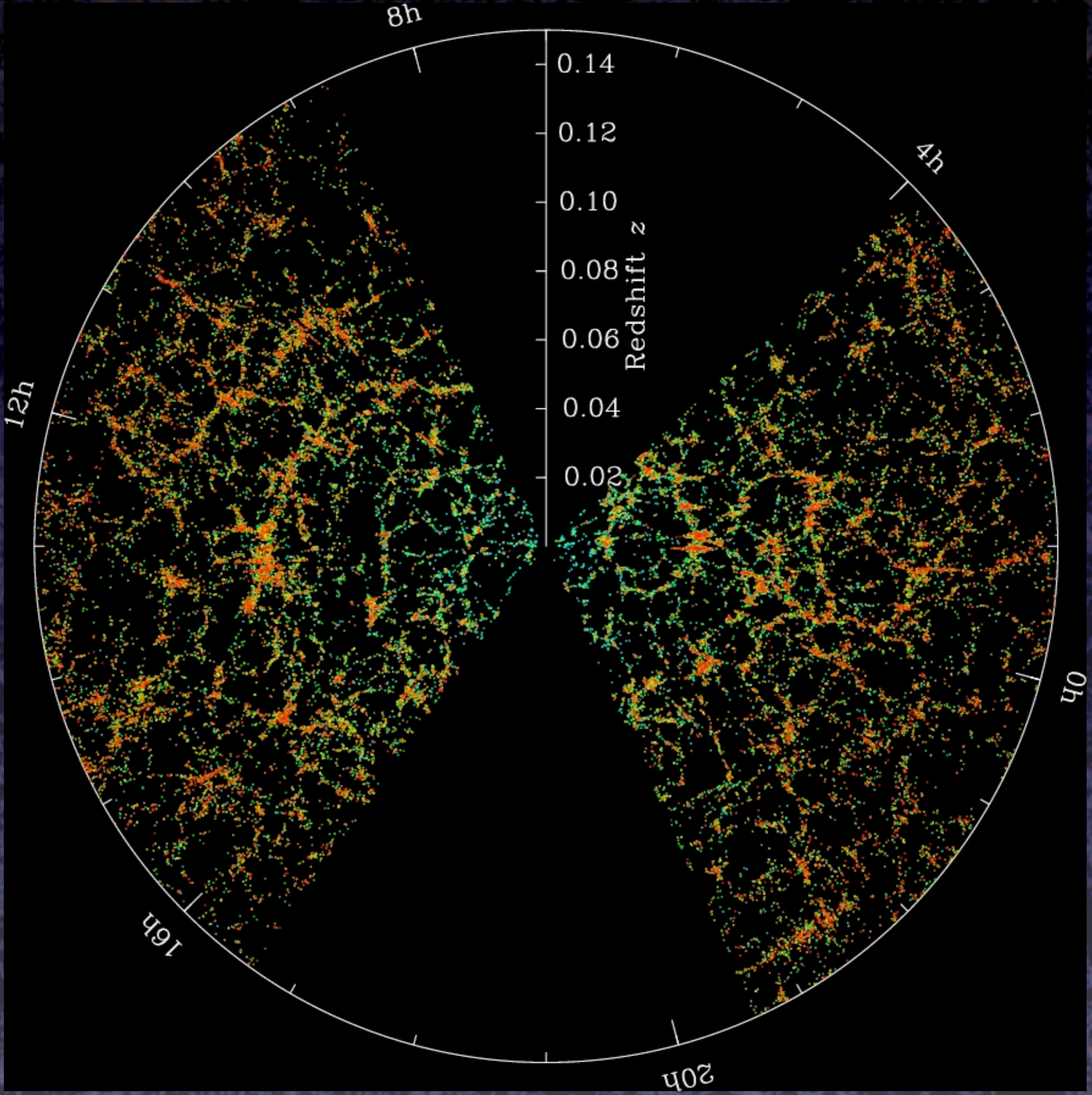
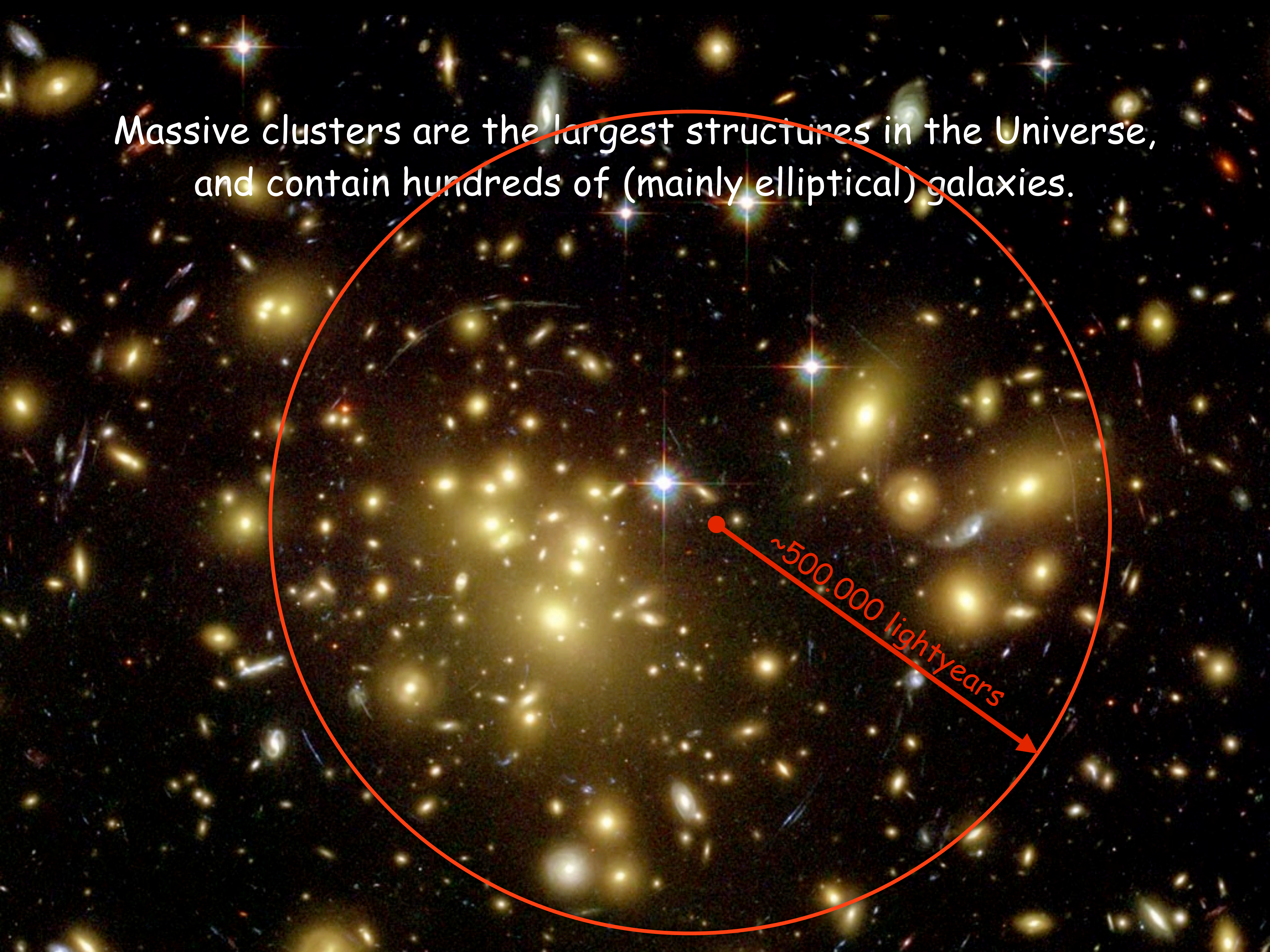


Galaxy distribution is sponge-like; strong clustering

Massive clusters are the largest structures in the Universe, and contain hundreds of (mainly elliptical) galaxies.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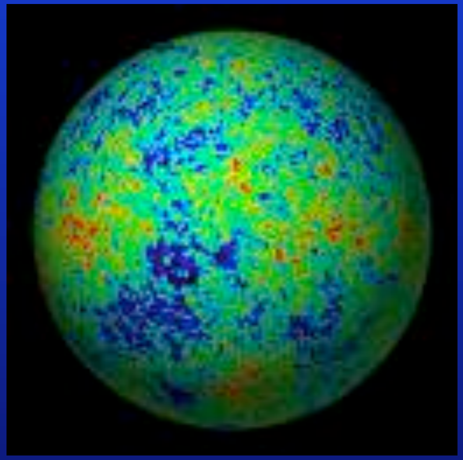
~500.000 lightyears

The Puzzle of Structure Formation

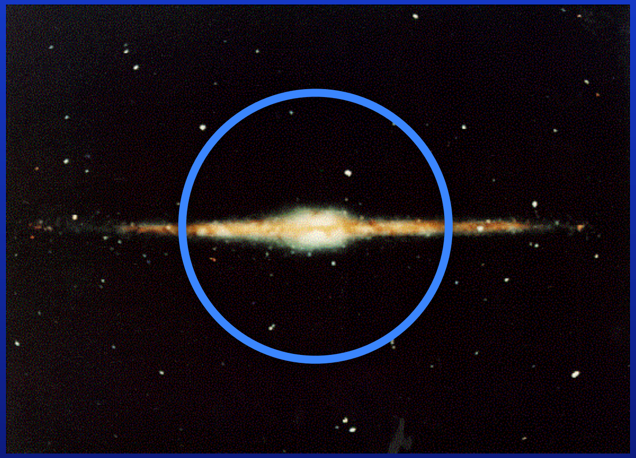
At recombination:



$|\delta| < 10^{-5}$

13 Gyr

Today, within Solar radius of MW



$\delta \simeq 10^5$

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}}$$

Dynamical time at Solar radius ~ 250 Myr

The Puzzle of Structure Formation

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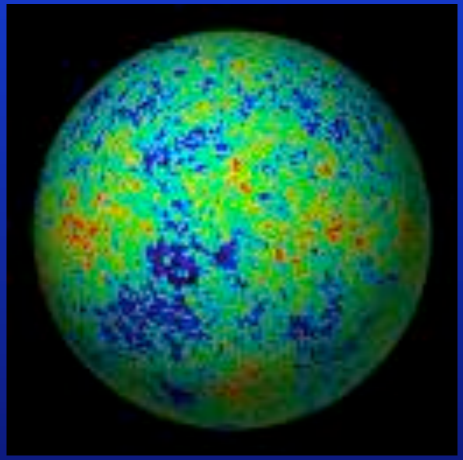

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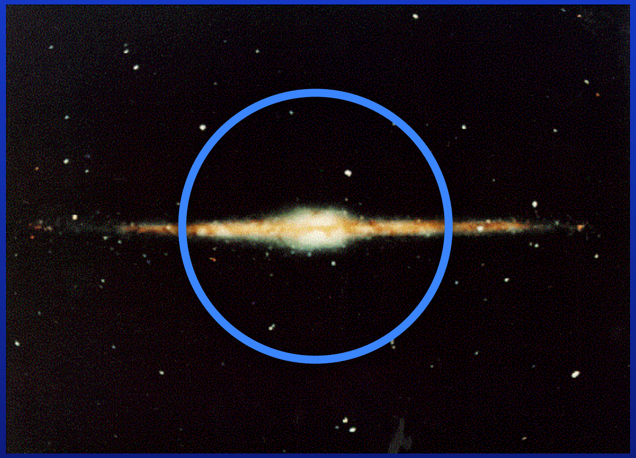

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in less than 50 dynamical times

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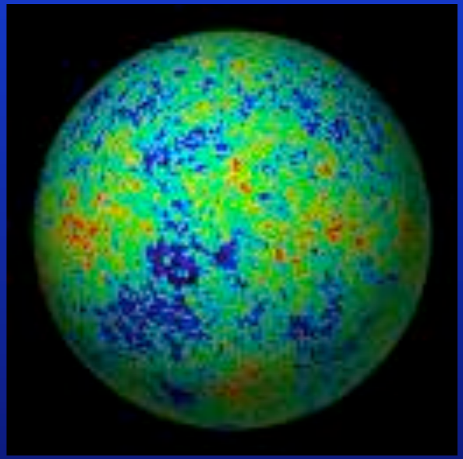

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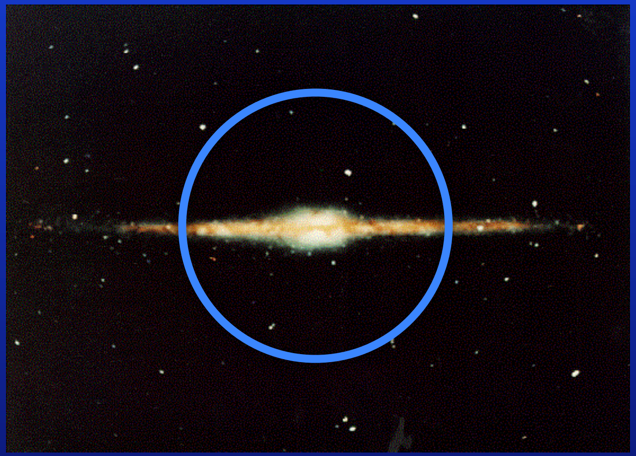

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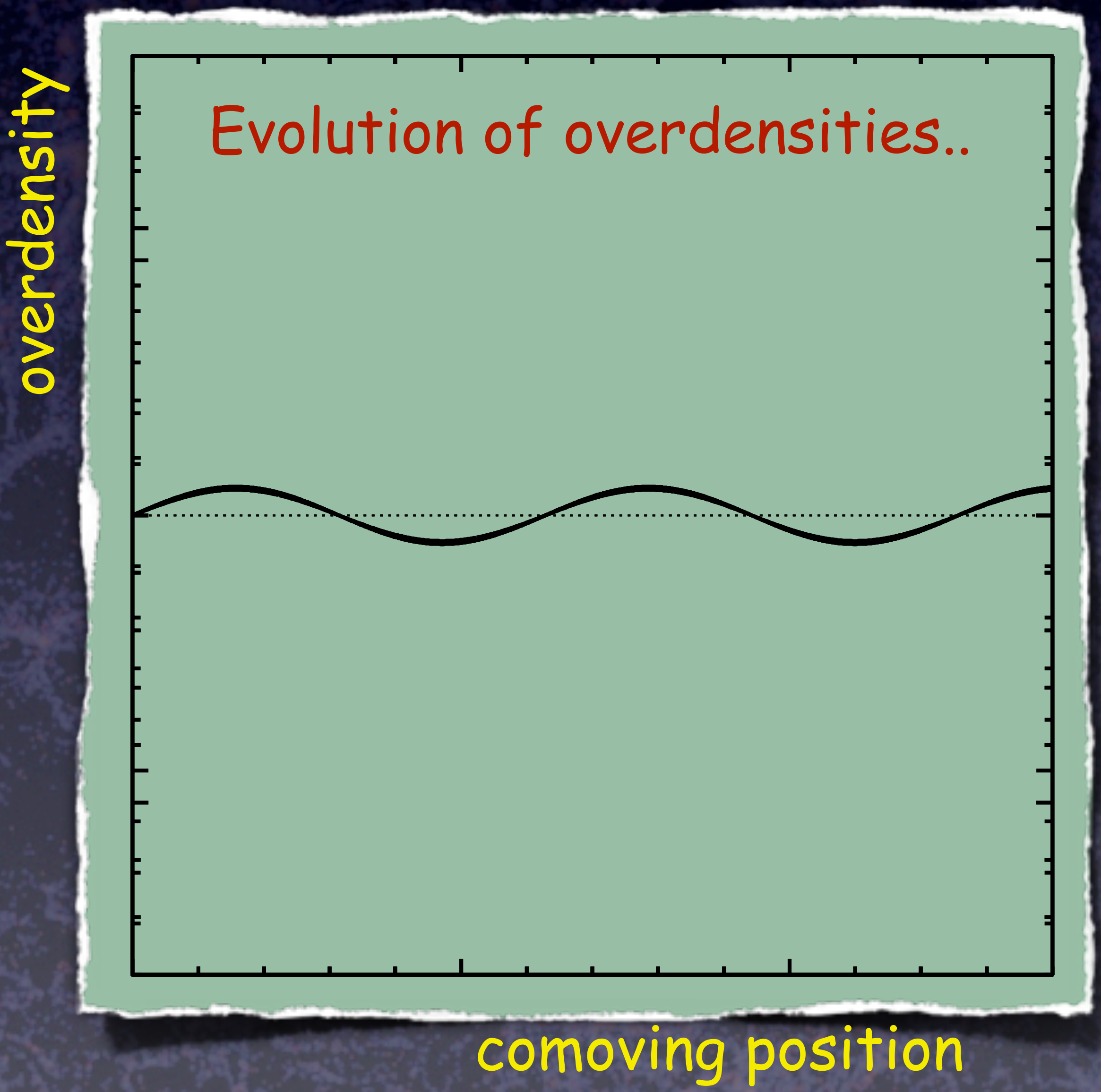
HOW??

The Answer...

Gravitational Instability: slightly denser regions attract matter thus becoming even denser, etc.



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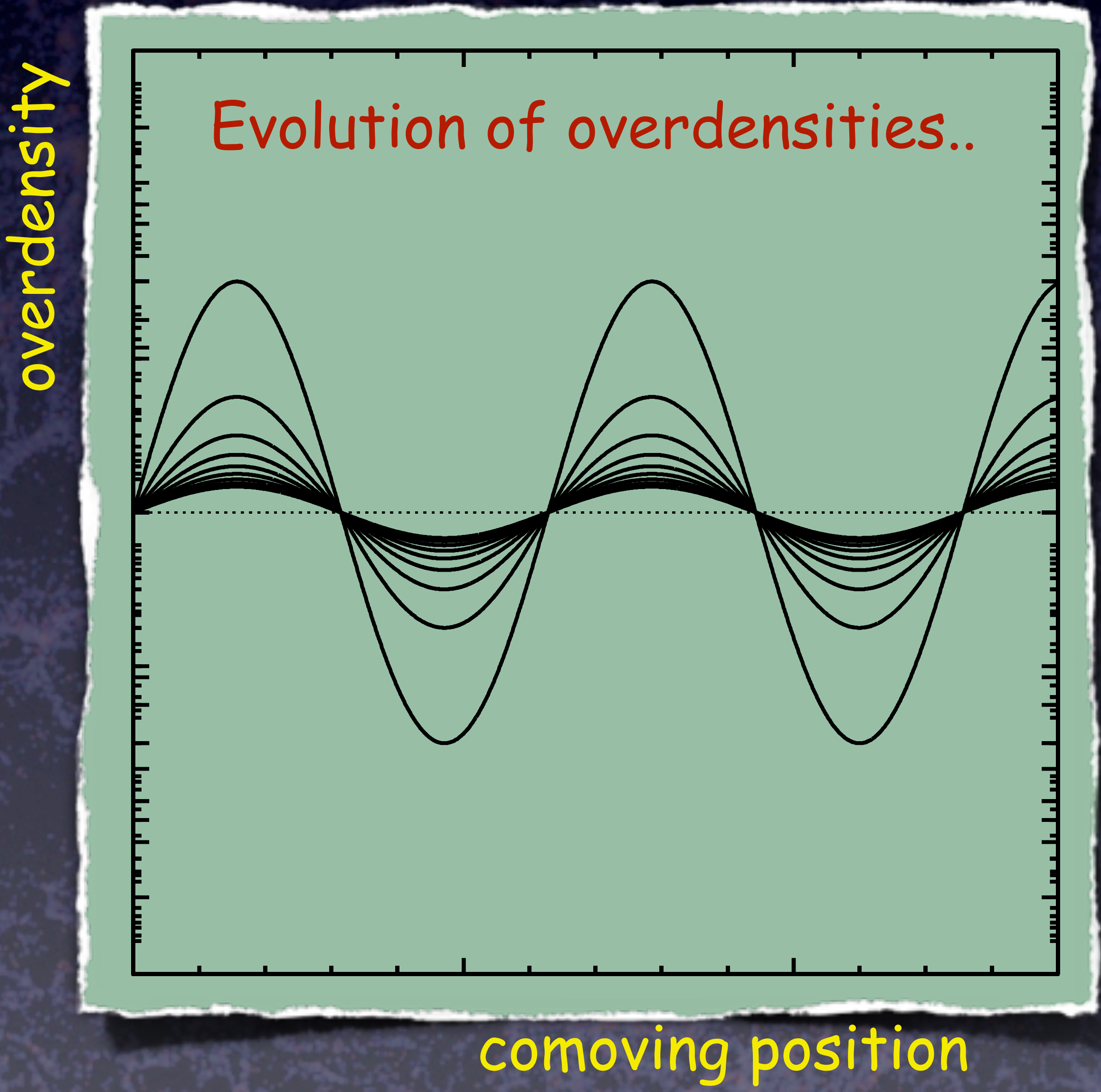
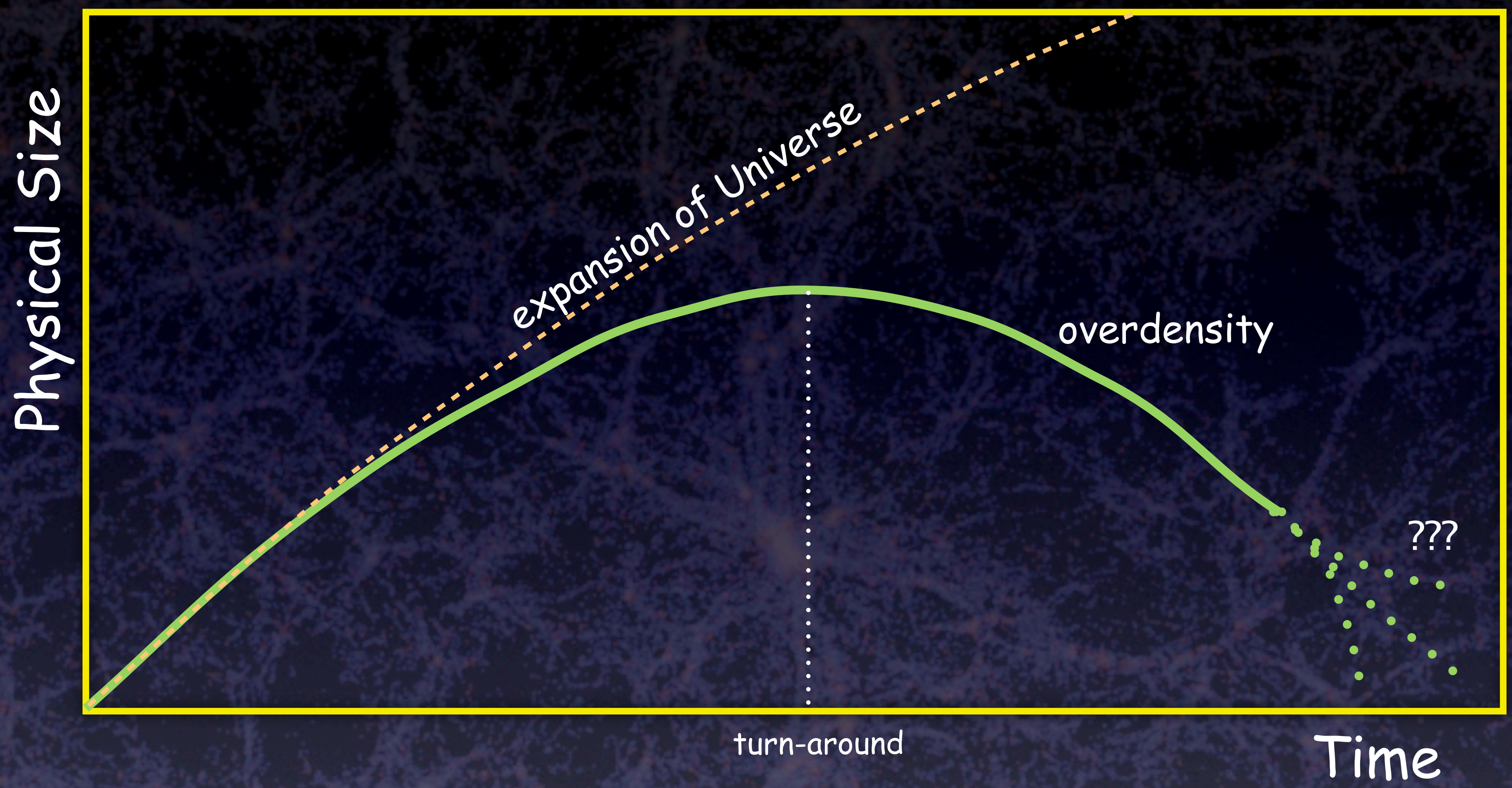


This process continues until overdensities are of order unity.

At that point, overdensities `turn around' (stop expanding) and start to collapse...

The Collapse of Perturbations



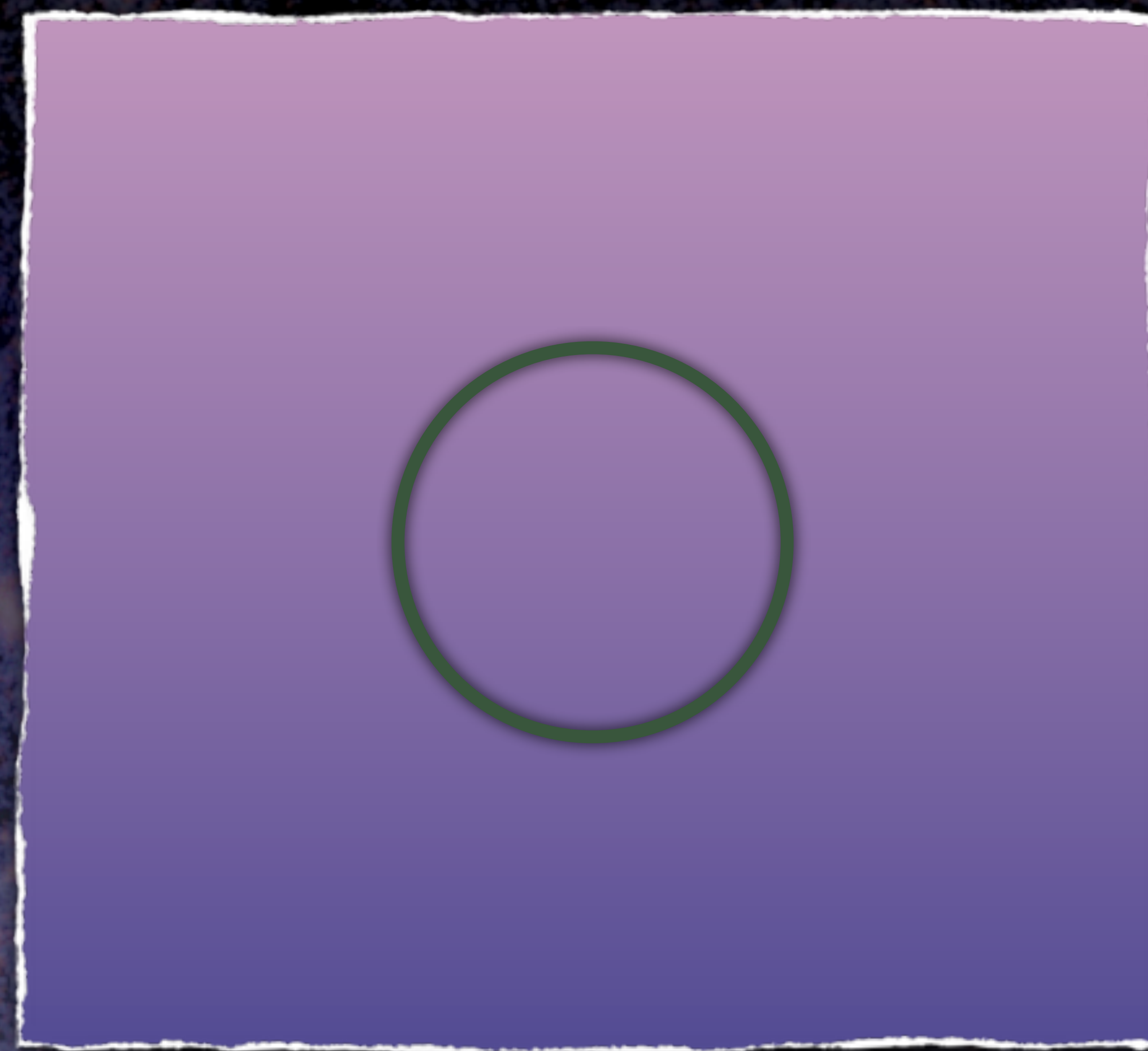
Evolution after turn-around depends on nature of matter

Dark Matter = collisionless → shell crossing

Baryonic Matter = collisional → shock heating

Evolution of shell of Cold Dark Matter

you can think of overdensity as consisting of many individual thin mass shells



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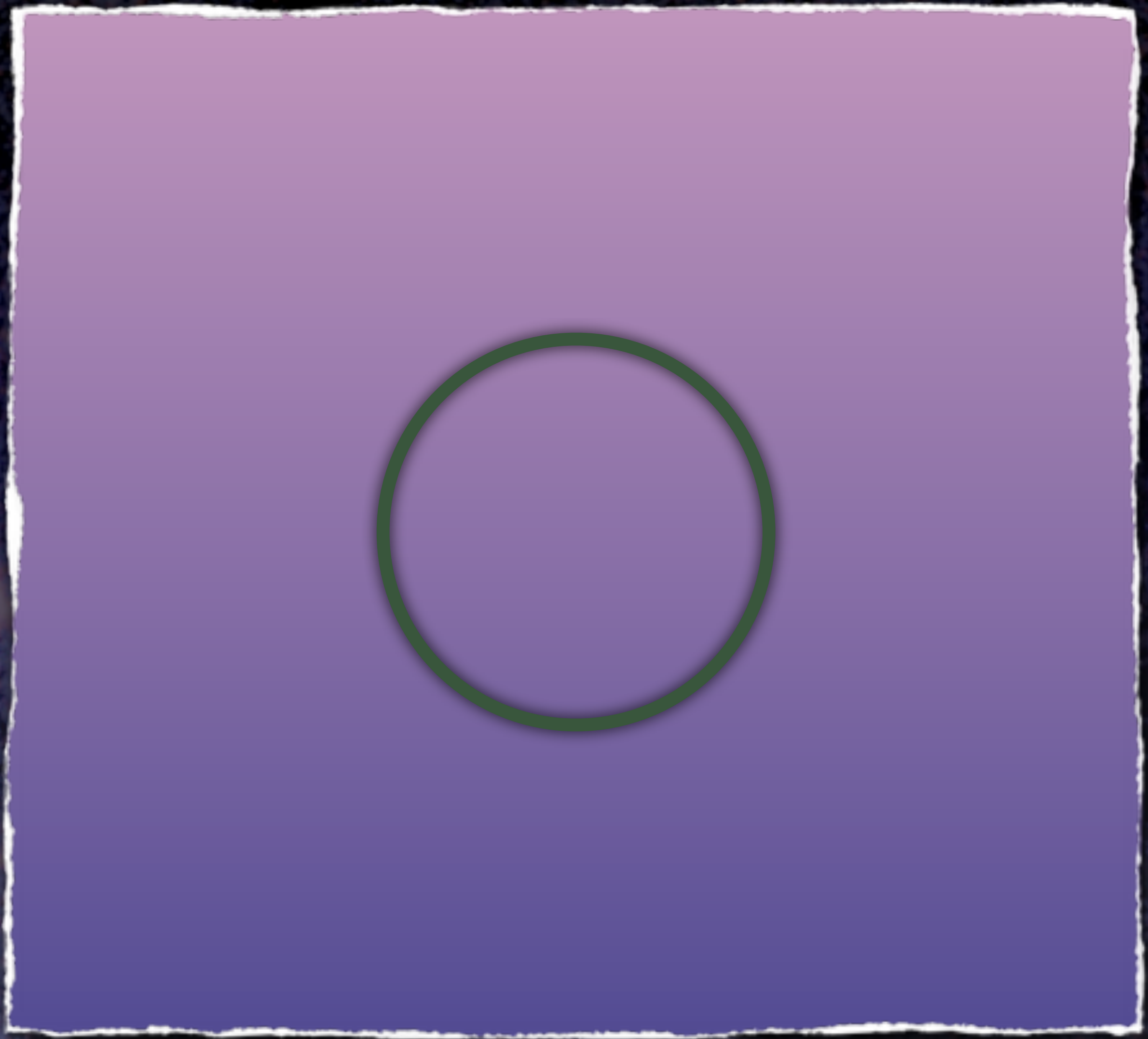
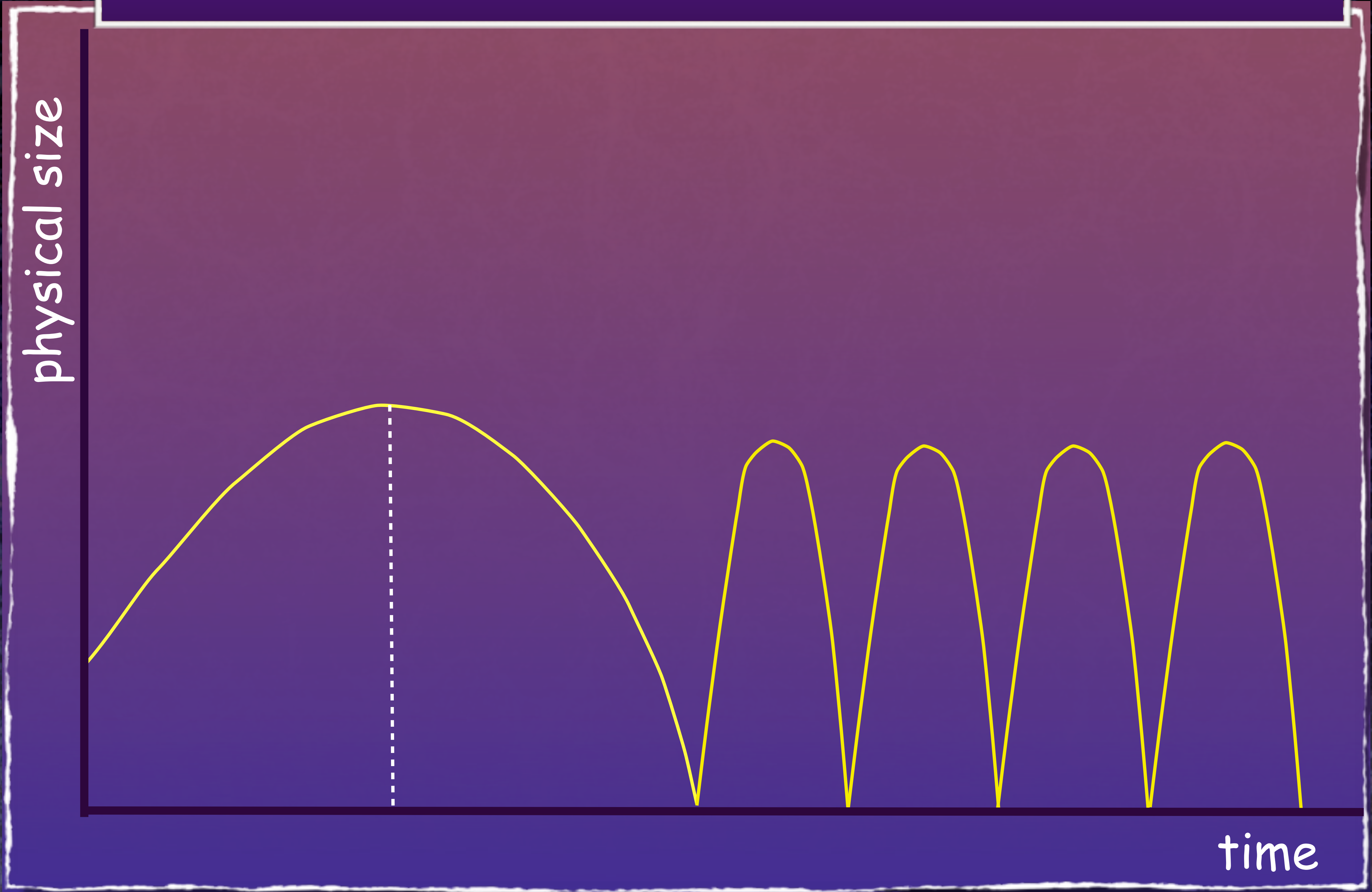


Because dark matter has no pressure, shell crosses itself and starts to oscillate

The Formation of a Dark Matter Halo



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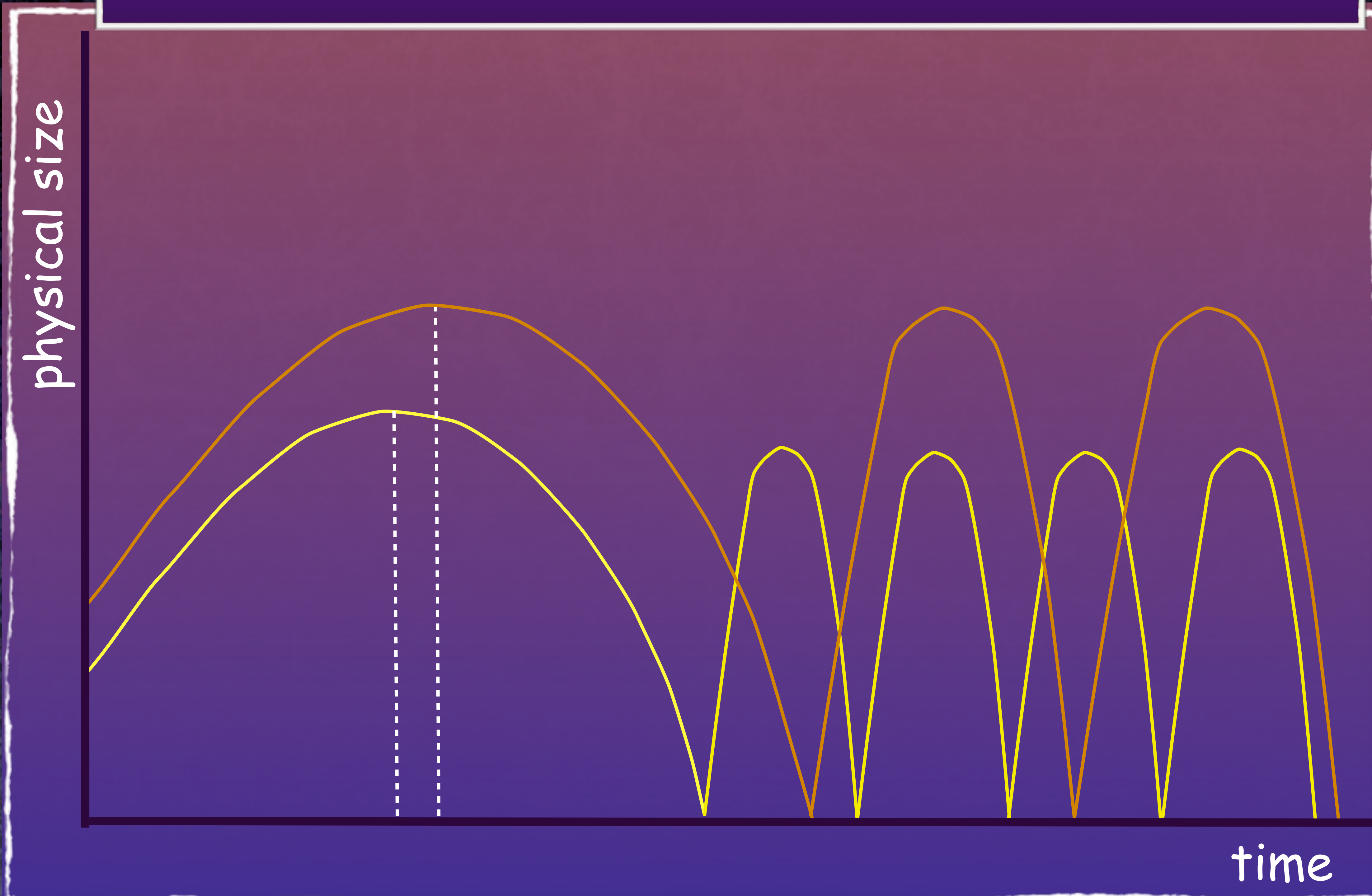

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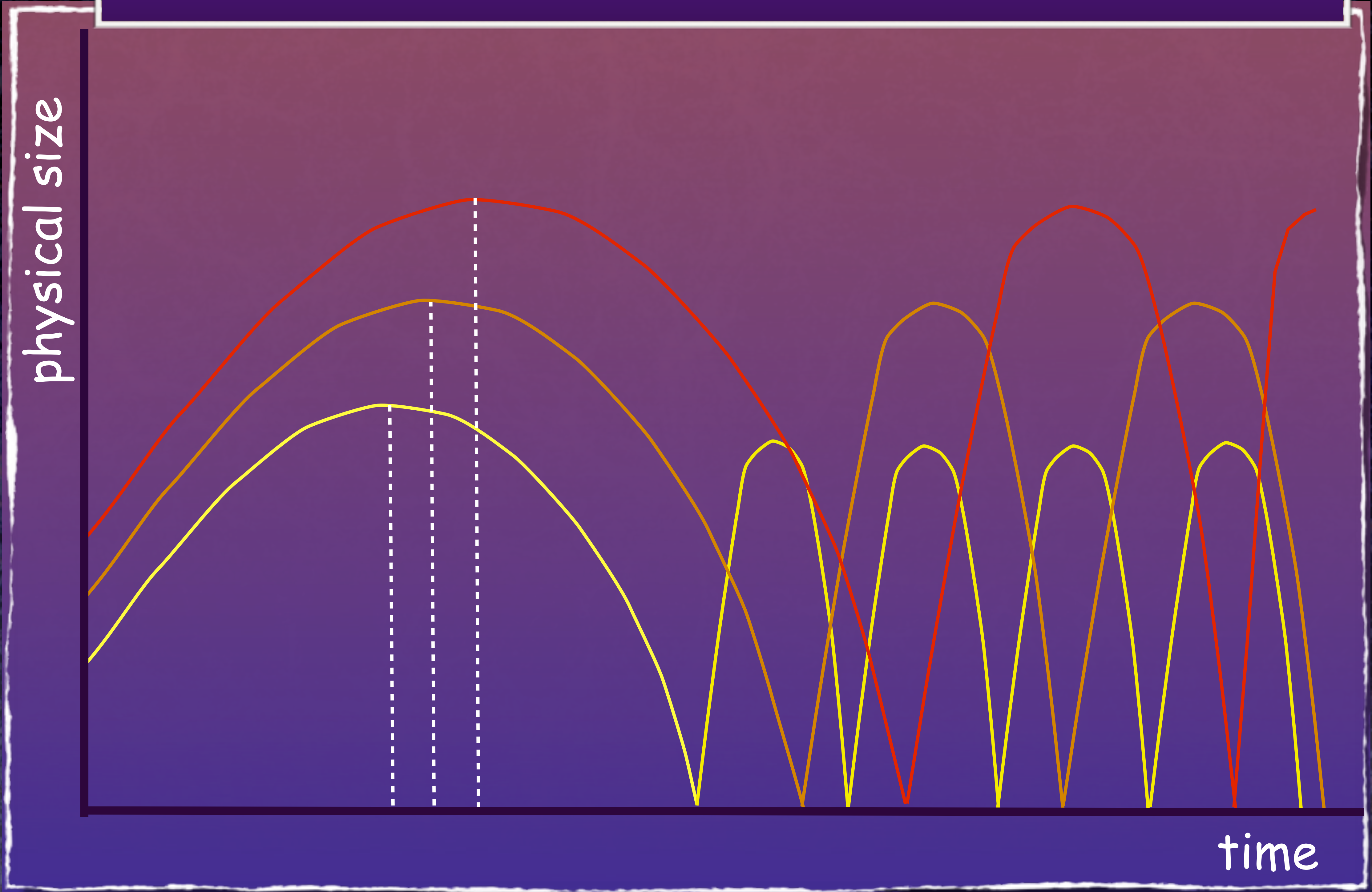

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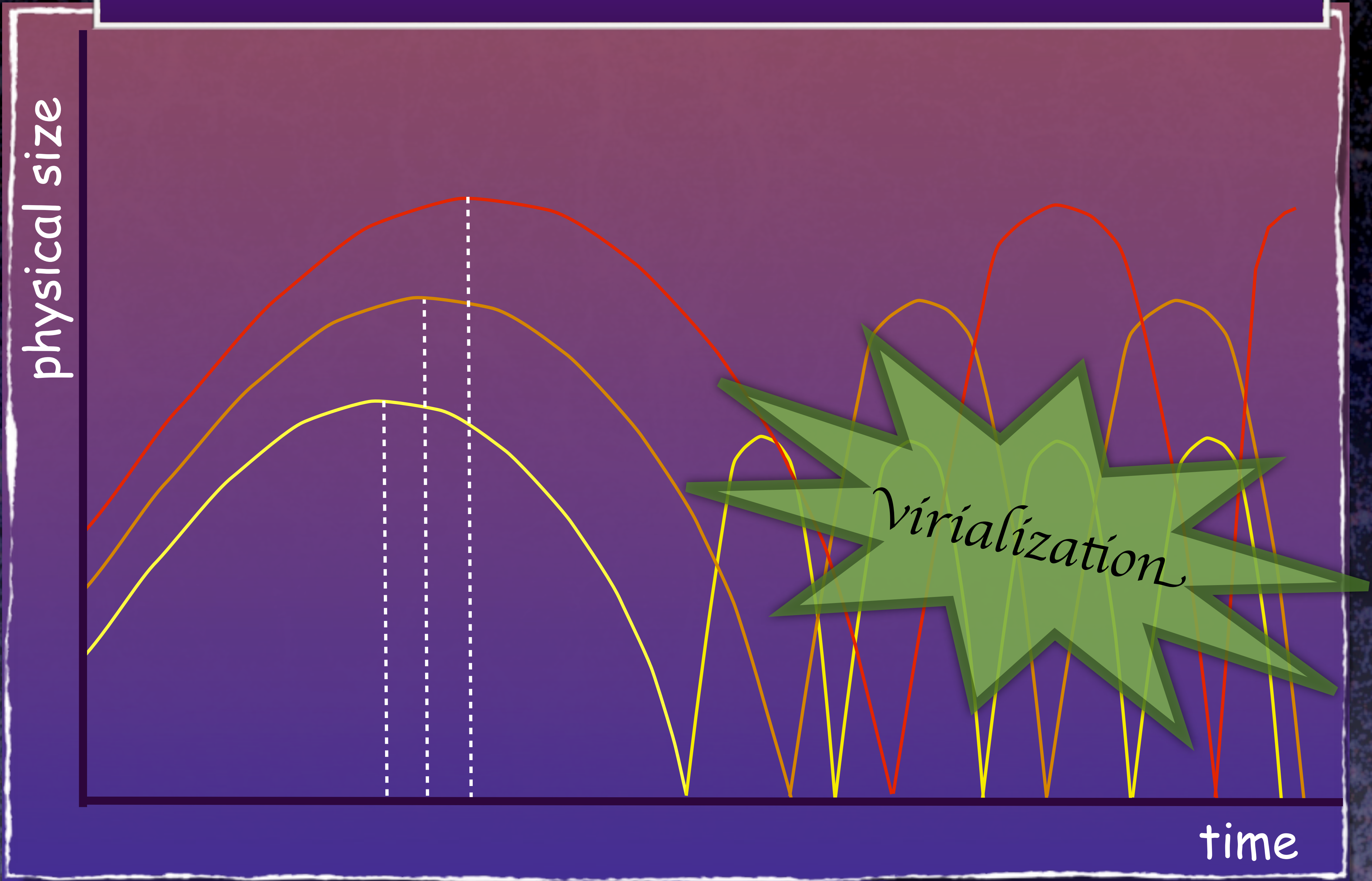
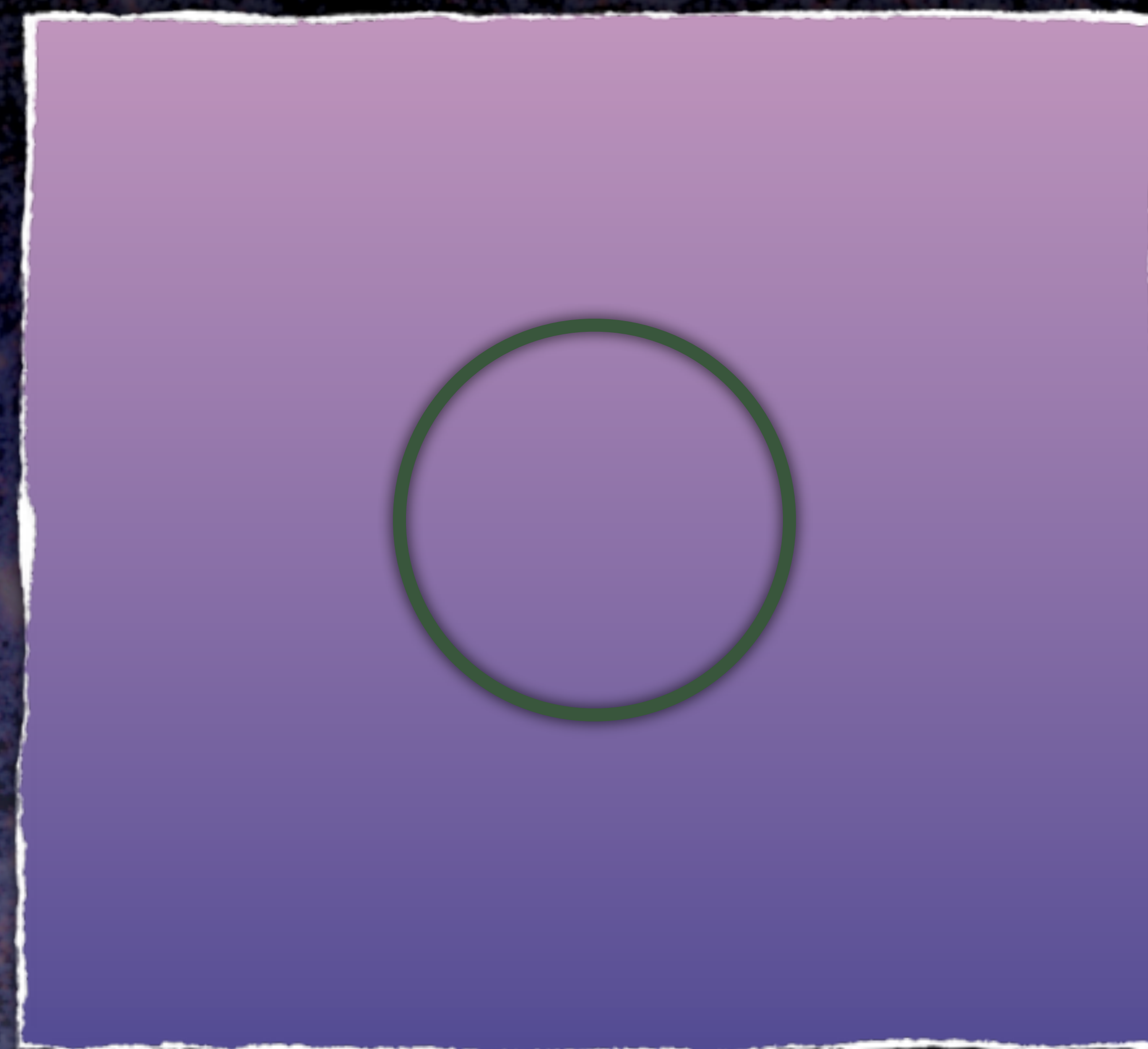


Individual oscillating shells interact gravitationally, exchanging energy (virializing), giving rise to a relaxed dark matter halo

Evolution of shell of Baryonic Matter

you can think of overdensity as consisting of many individual thin mass shells



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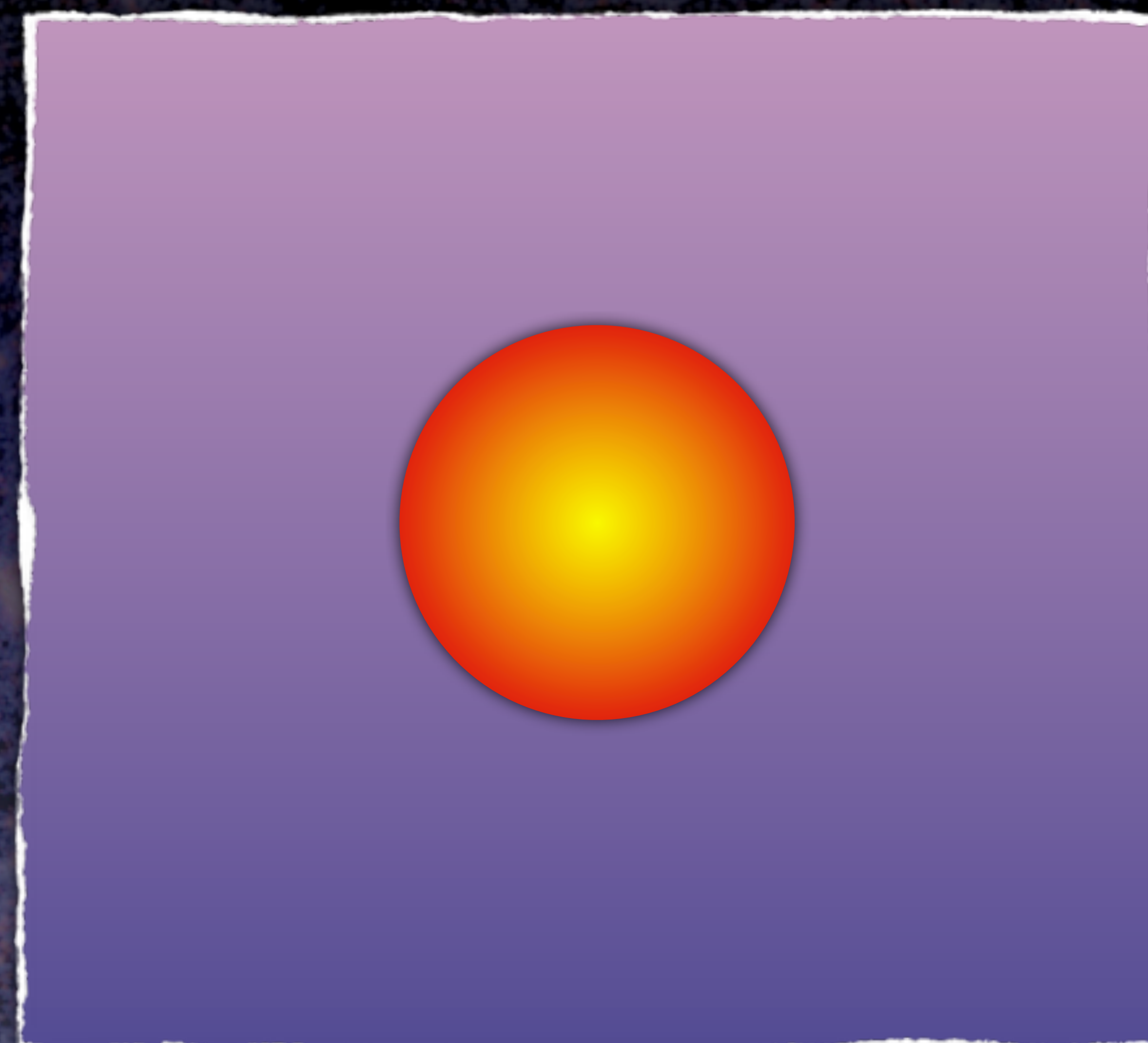


Because of pressure a shock develops, which heats the gas and makes it expand

Evolution of shell of Baryonic Matter

you can think of overdensity as consisting of many individual thin mass shells

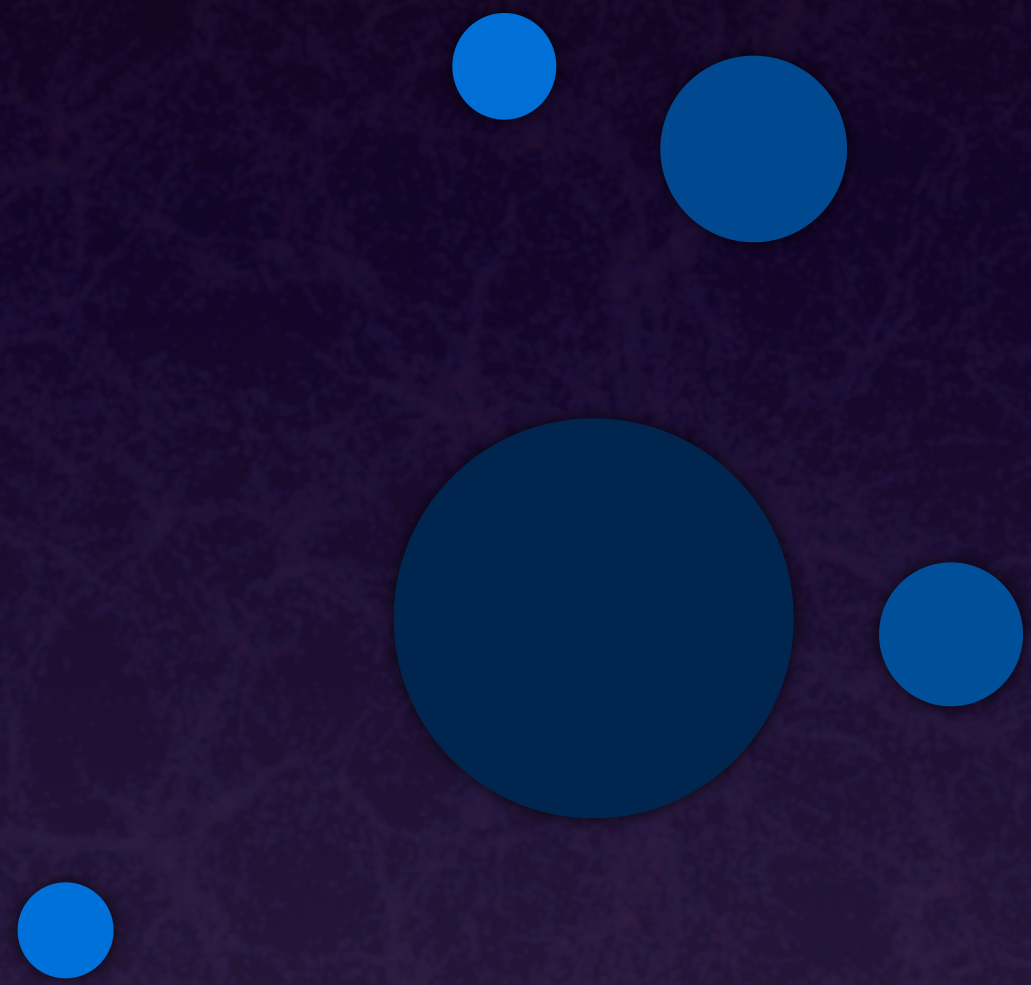
The End Result

A dark matter halo filled with hot gas

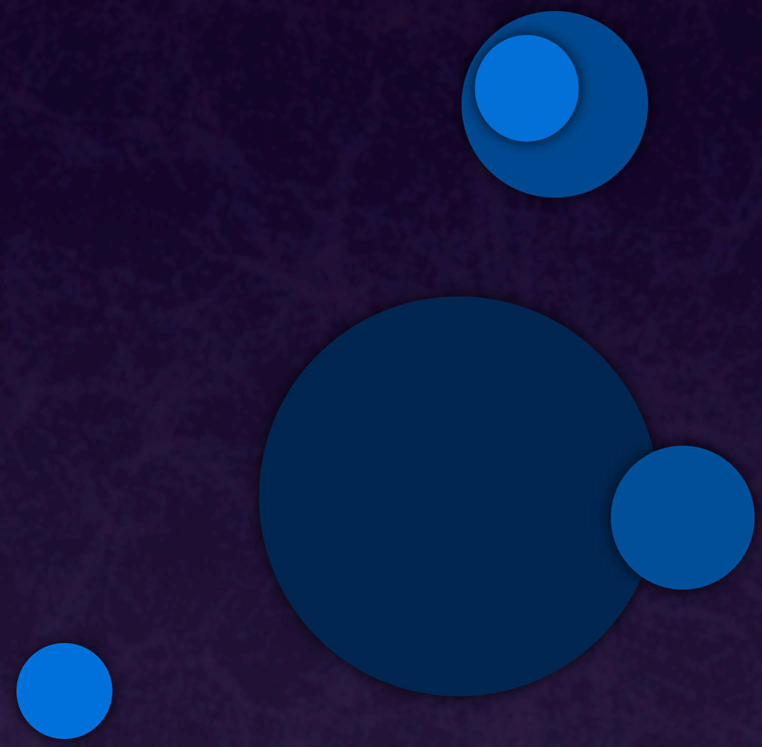
Because of pressure a shock develops, which heats the gas and makes it expand

The Hierarchical Growth of Dark Matter Haloes

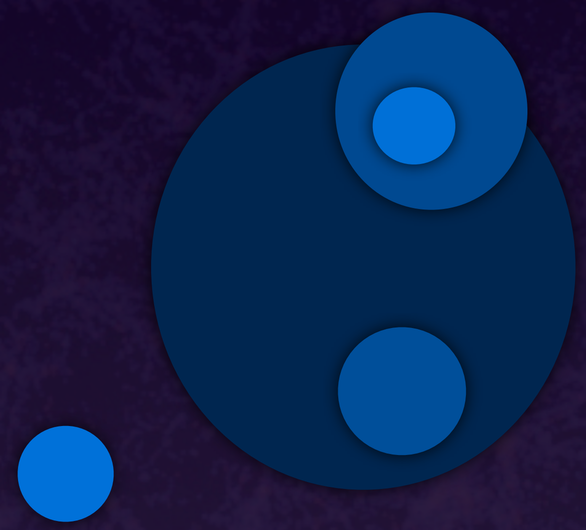
A region in space in which 5 dark matter haloes have formed



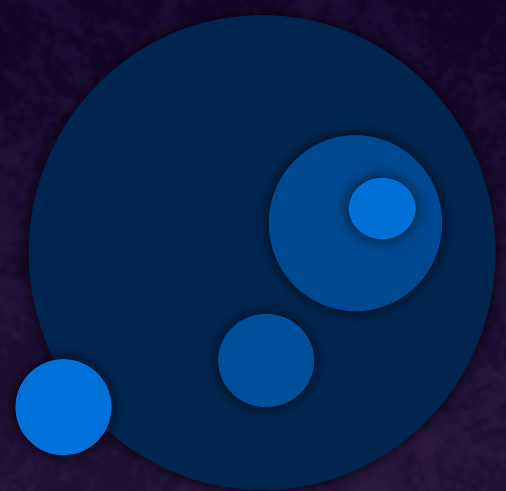
Dark matter haloes attract each other gravitationally...



consequently, they move towards each other....



and merge together, to form bigger haloes....



with substructure

Numerical Simulations

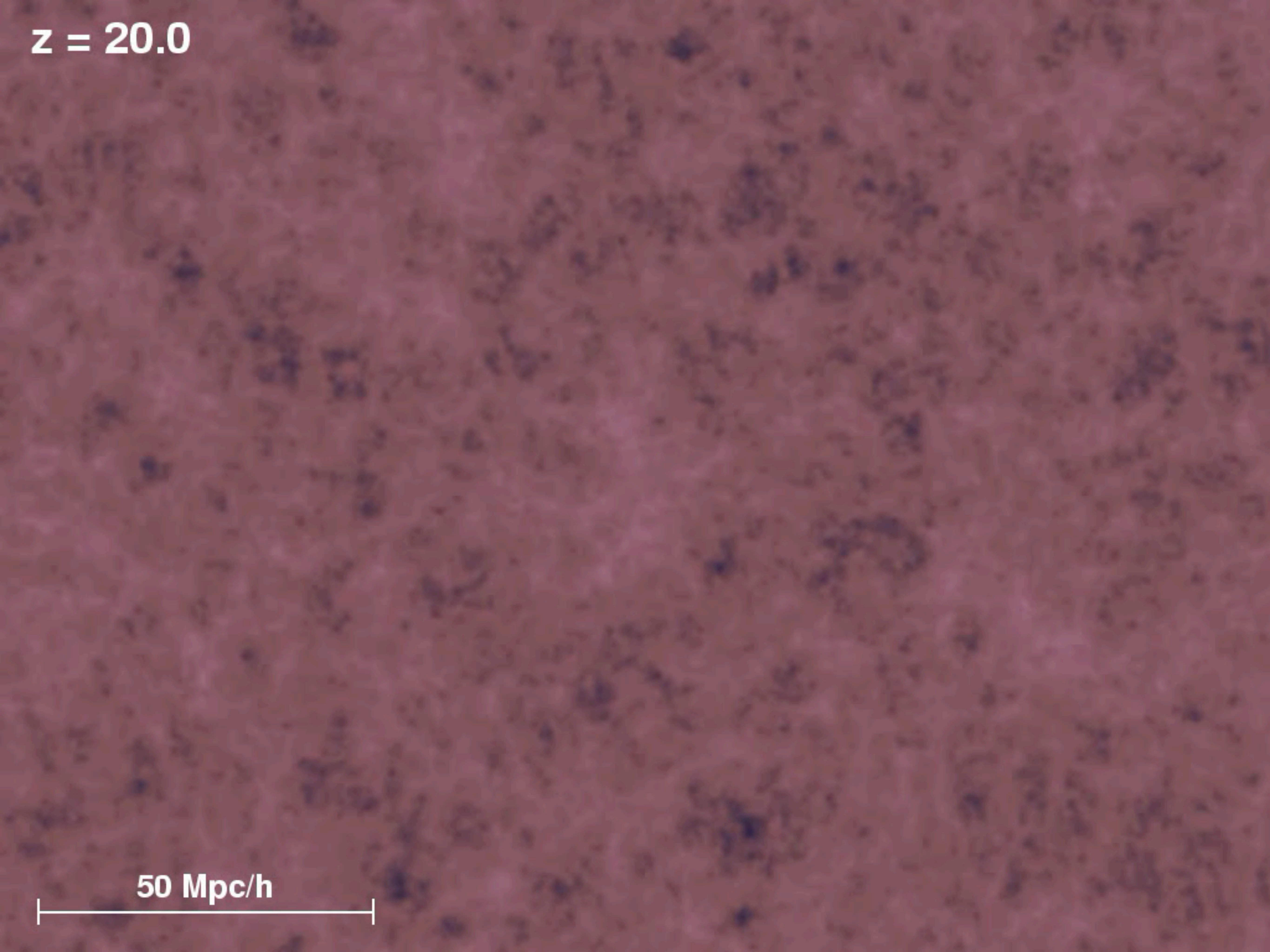
Start with box with many particles, whose spatial distribution reveals tiny fluctuations (as in CMB)

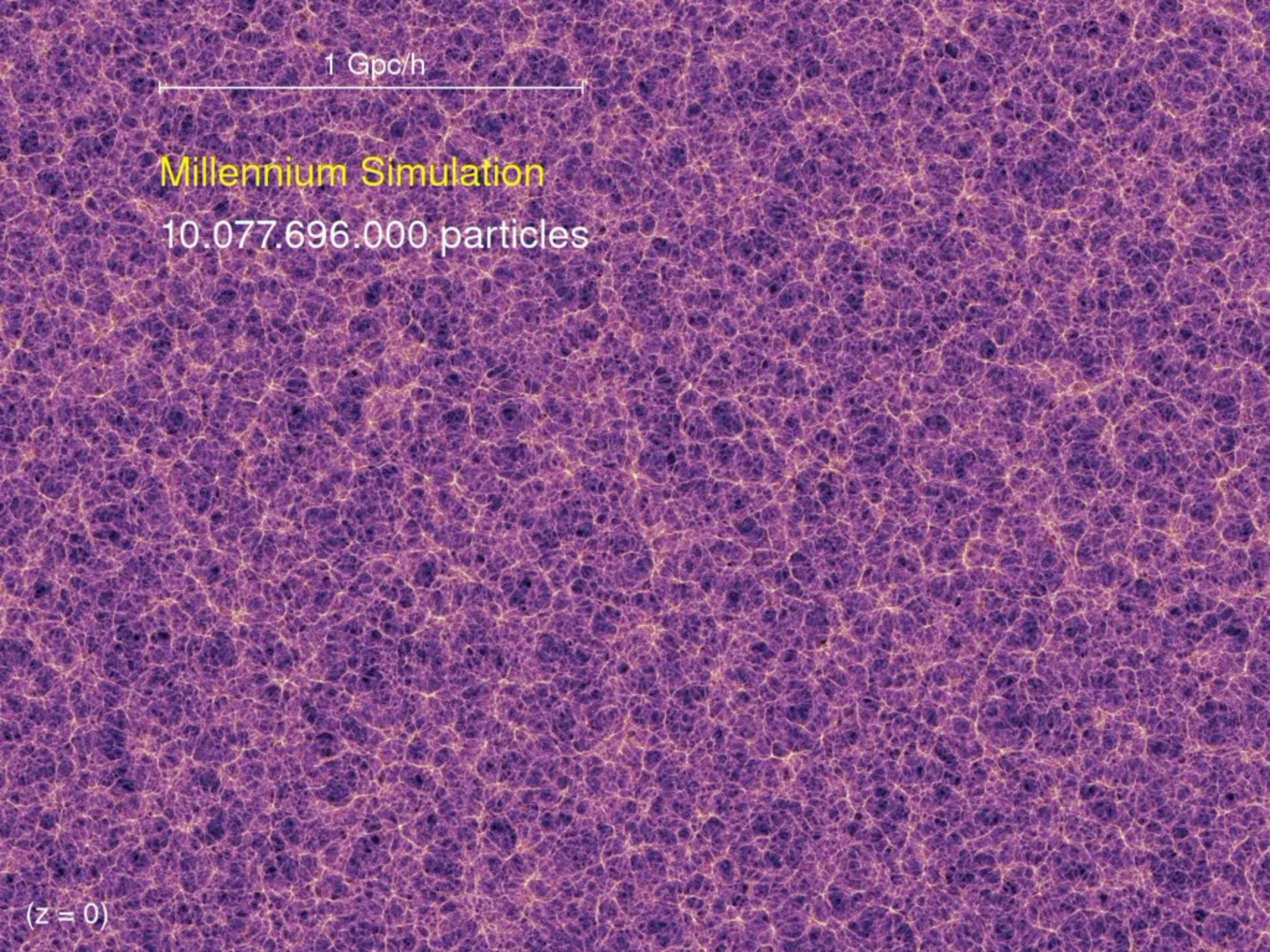
Let box `expand' (as Universe), and compute gravitational force between all particles

Propagate all particles according to the gravitational acceleration

Repeat this procedure for as many time steps as needed

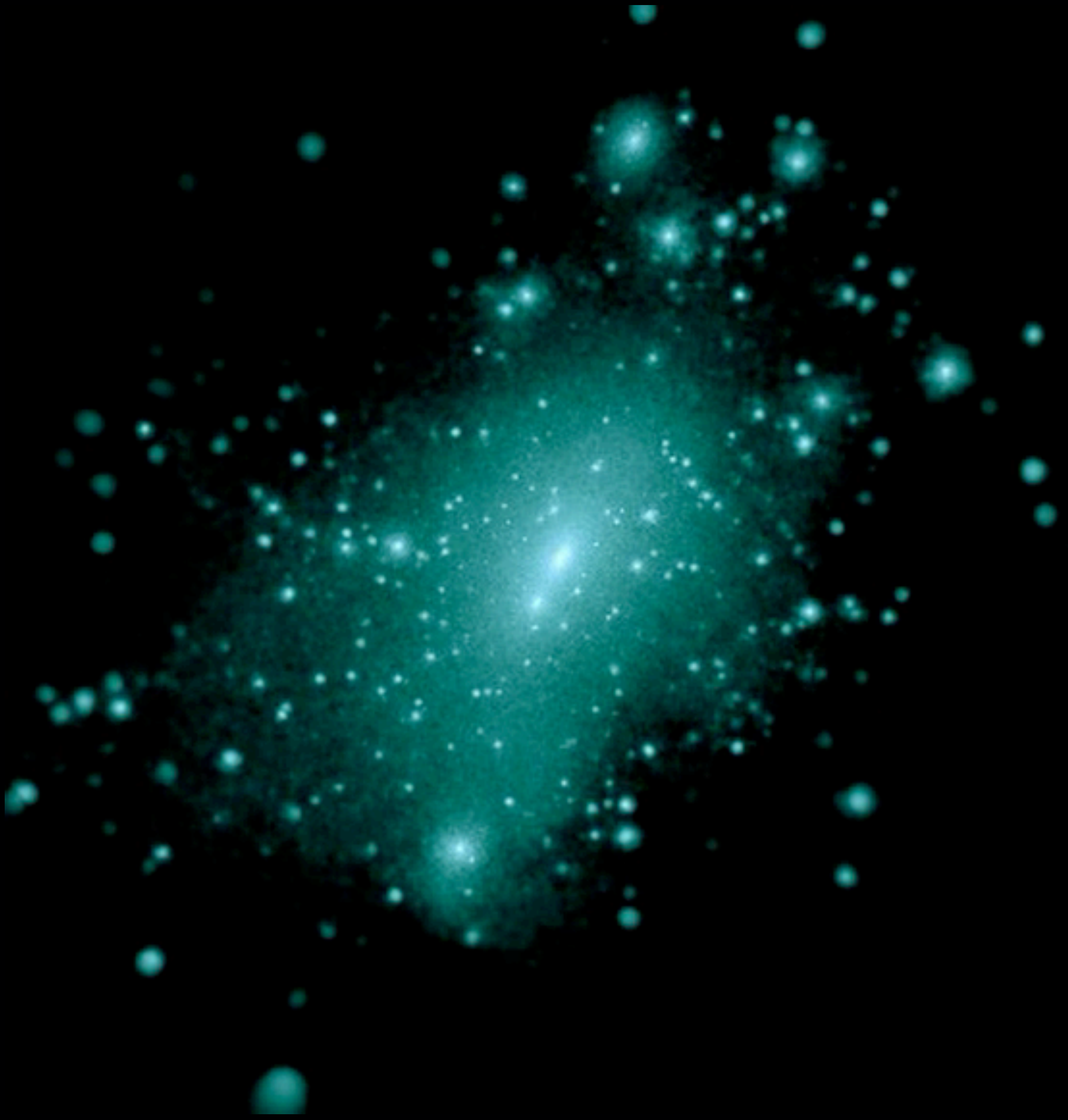
Distribution of dark matter with
tiny fluctuations in initial density


z = 20.0
50 Mpc/h


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

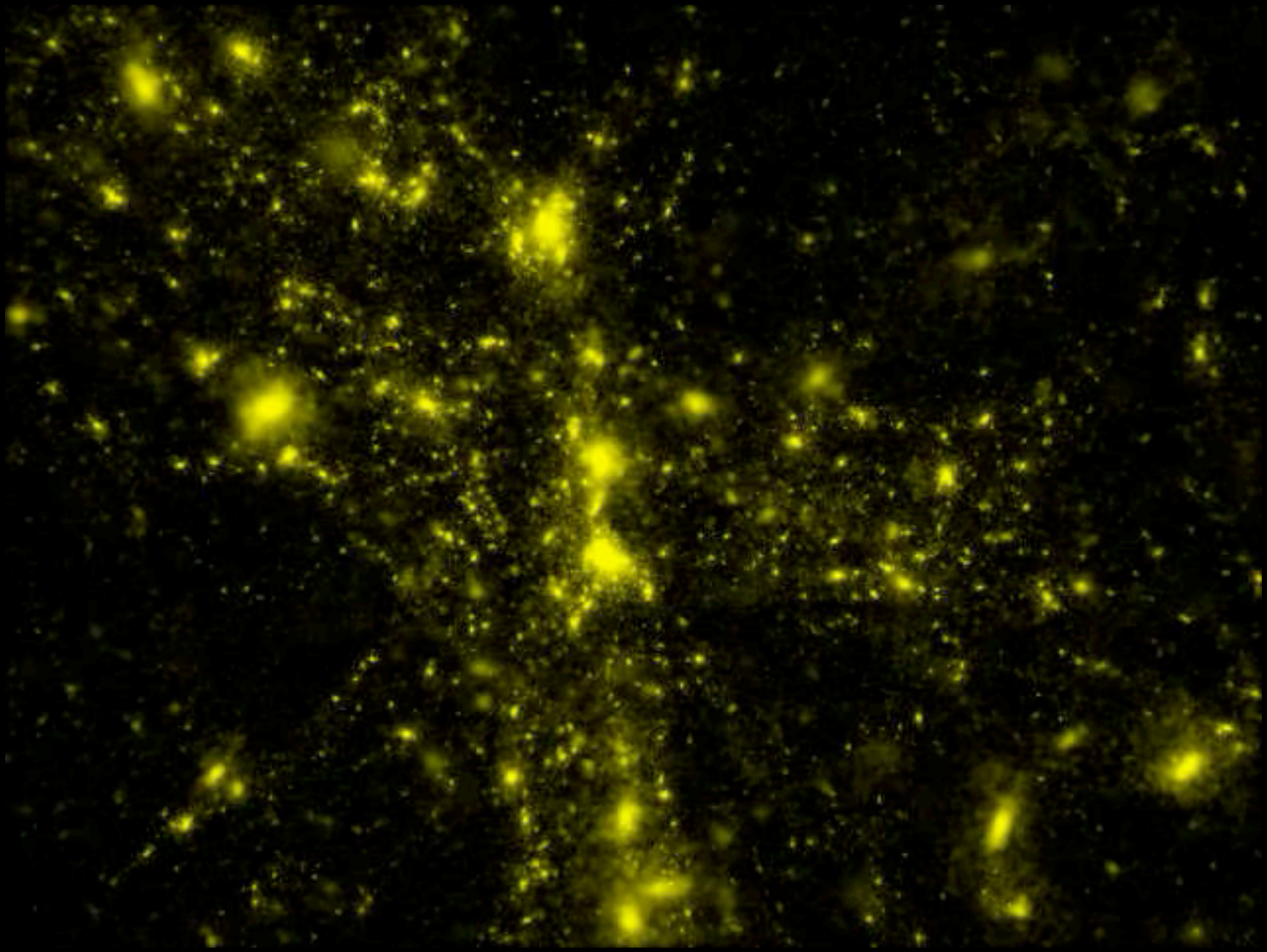
A Close-Up View of a Dark Matter Halo

A Close-Up View of a Dark Matter Halo

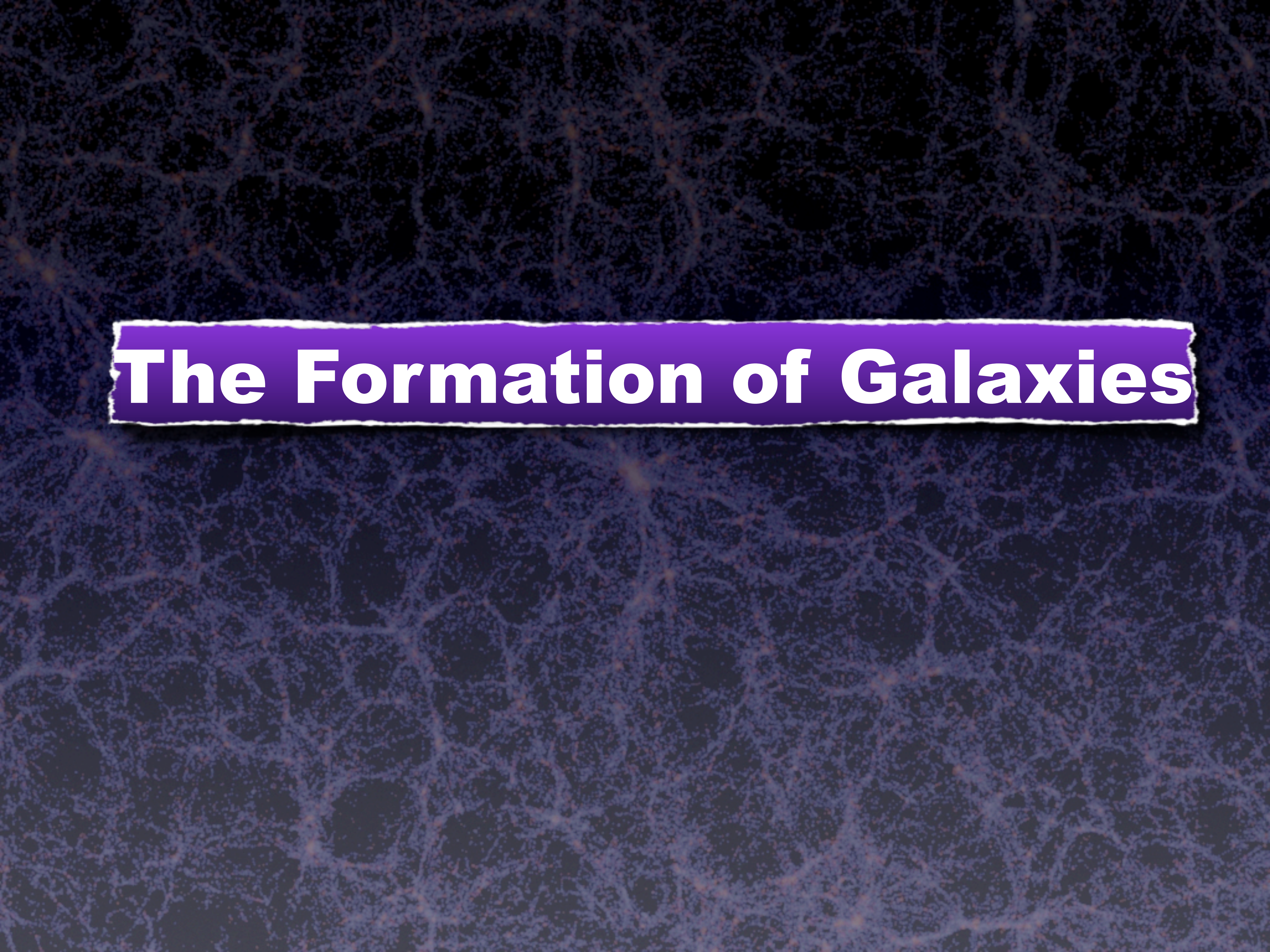


Flying Faster than the Speed of Light…

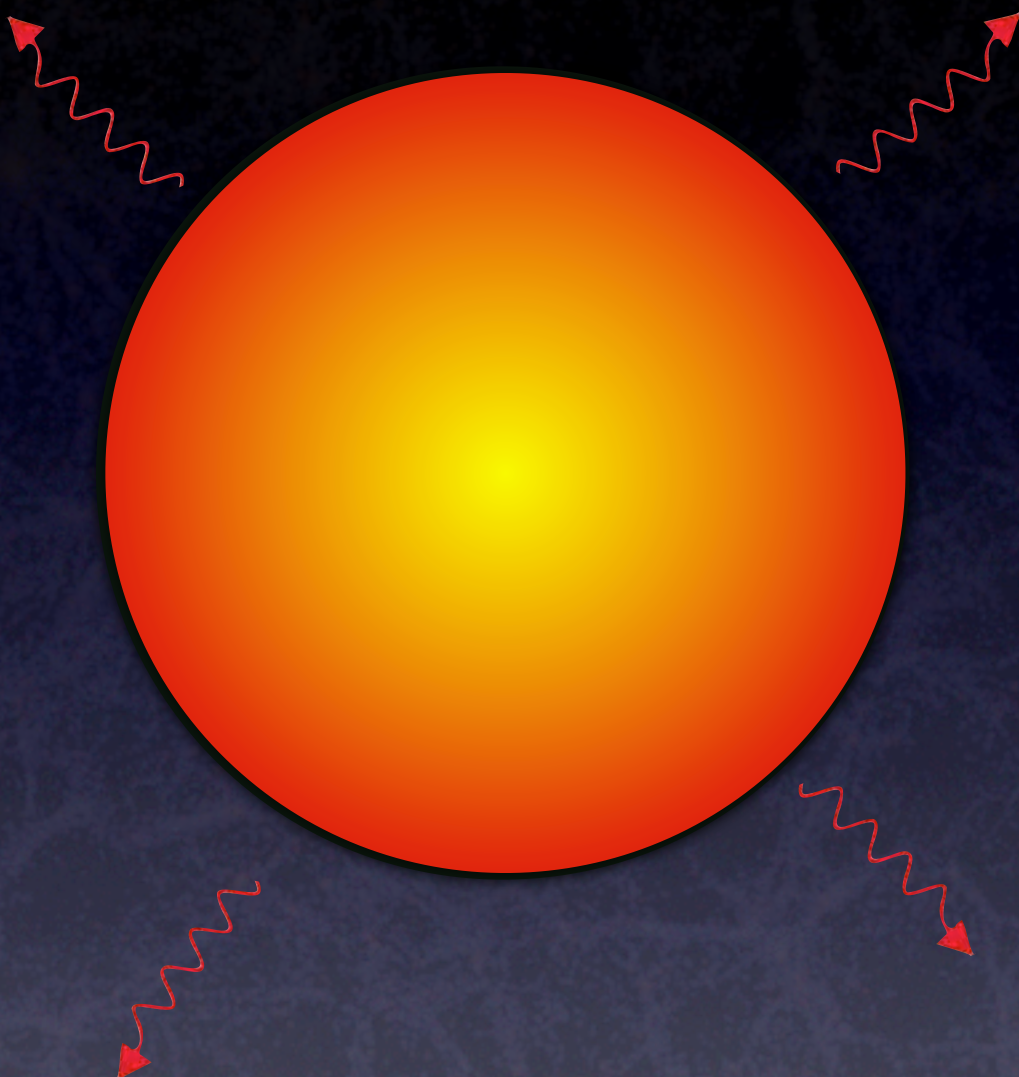
Flying Faster than the Speed of Light...



The Formation of Galaxies



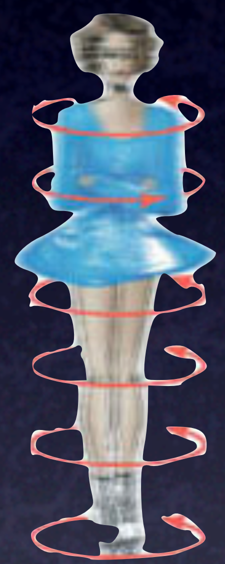
Cooling & Disk Formation



Hot gas radiates, emits photons which carry away energy: the gas cools

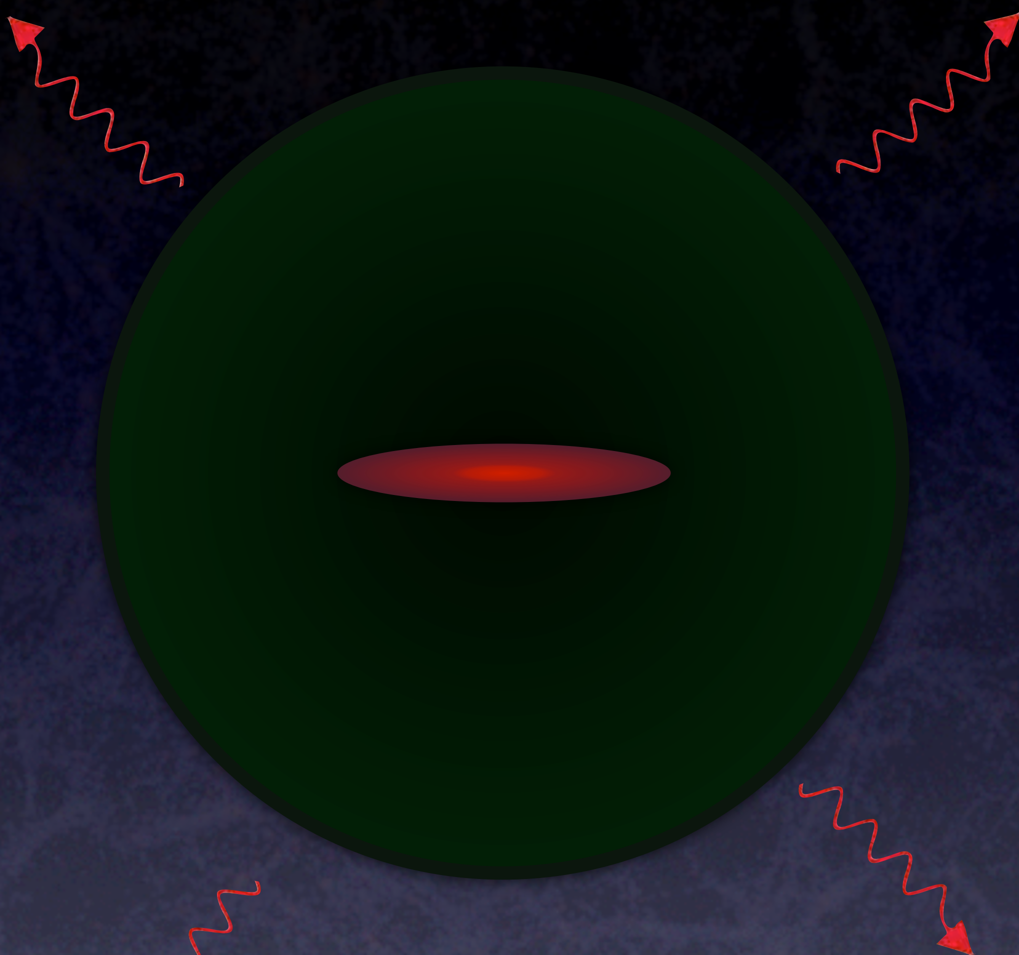
Due to pressure loss, gas starts to contract

Because of angular momentum conservation, the cooling baryons spin up and form a thin disk



Inside the disk the density gets very high, causing fragmentation and star formation: a disk galaxy is born...

Cooling & Disk Formation



Note that dark matter does NOT cool.

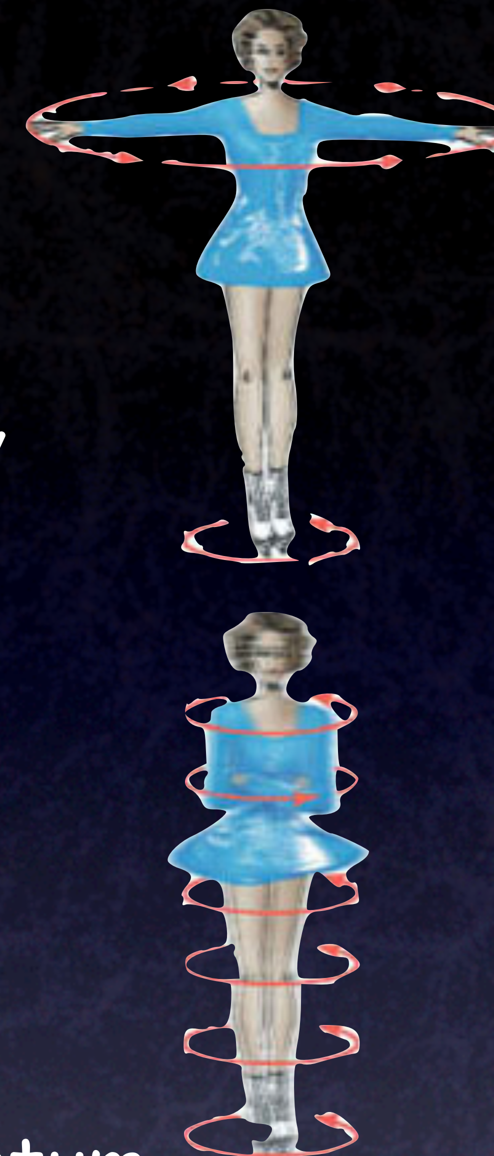
Hot gas radiates, emits photons which carry away energy: the gas cools

↓

Due to pressure loss, gas starts to contract

↓

Because of angular momentum conservation, the cooling baryons spin up and form a thin disk



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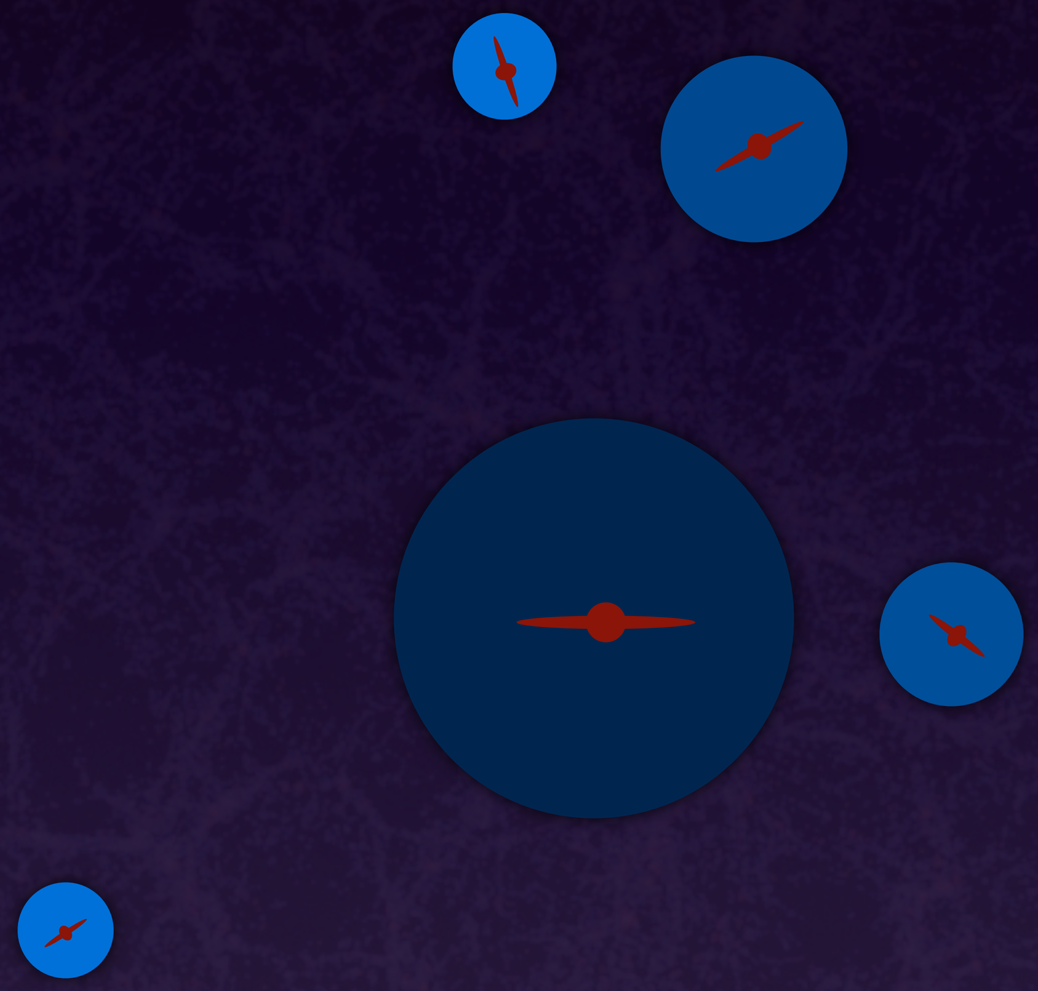
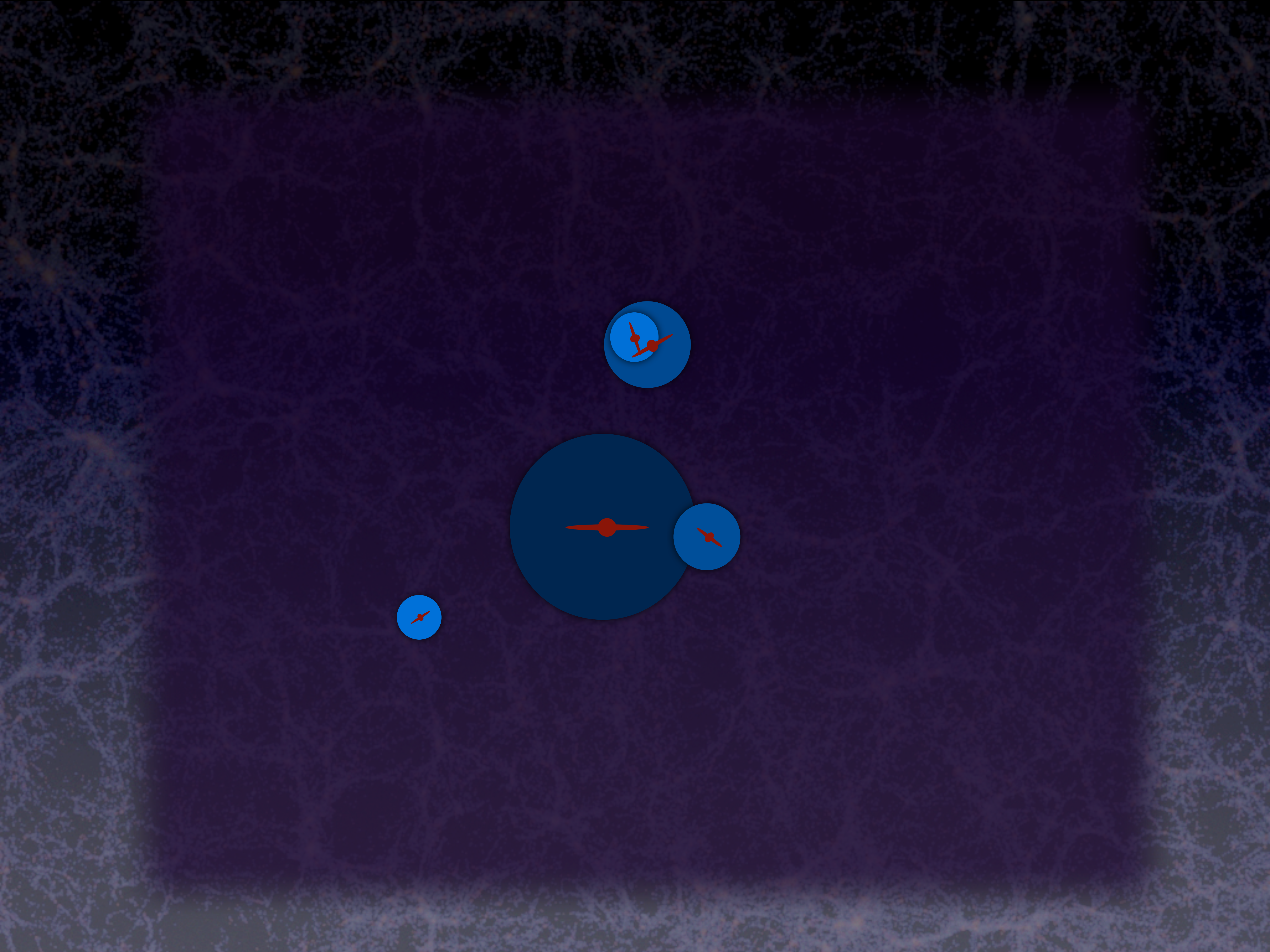
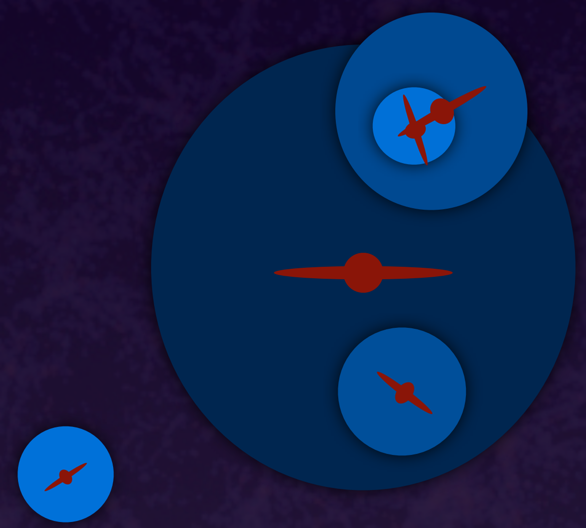
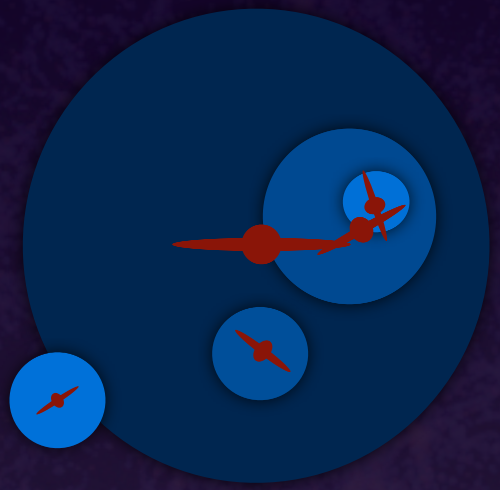
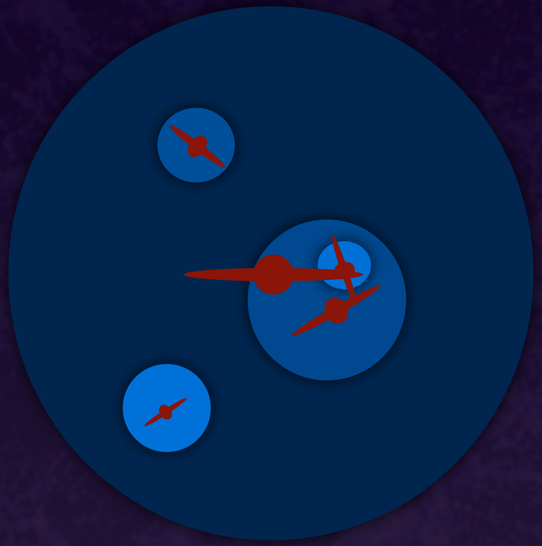


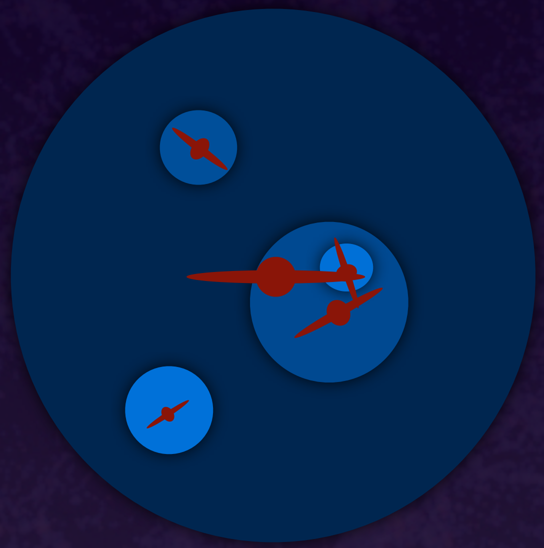








If dark matter haloes host galaxies, clusters are a natural outcome of hierarchical formation in CDM Universe



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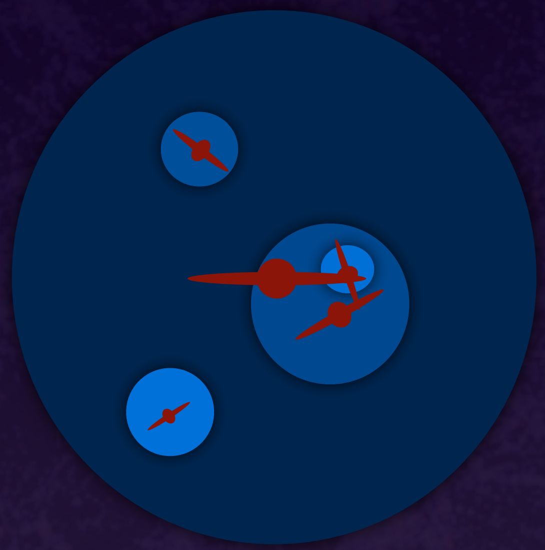

But what happens when two galaxies collide??

When two disks collide…

When two disks collide...

...an elliptical emerges

Galaxy Formation in a nutshell...

- Small perturbations, due to quantum fluctuations, grow and collapse to form dark matter haloes
- Baryonic gas is shock heated to high temperatures
- Baryonic gas cools and settles in center of halo; angular momentum conservation --> disk galaxy
- Disks merge giving rise to population of ellipticals especially in denser environments (clusters)

Outstanding Problems: Some Feedback Please...

Simple calculations of cooling rates and
star formation efficiencies predict that
virtually ALL baryons should have formed stars

Outstanding Problems: Some Feedback Please...

Simple calculations of cooling rates and star formation efficiencies predict that virtually ALL baryons should have formed stars

But observations show that only ~10% of baryons have turned into stars

Outstanding Problems: Some Feedback Please...

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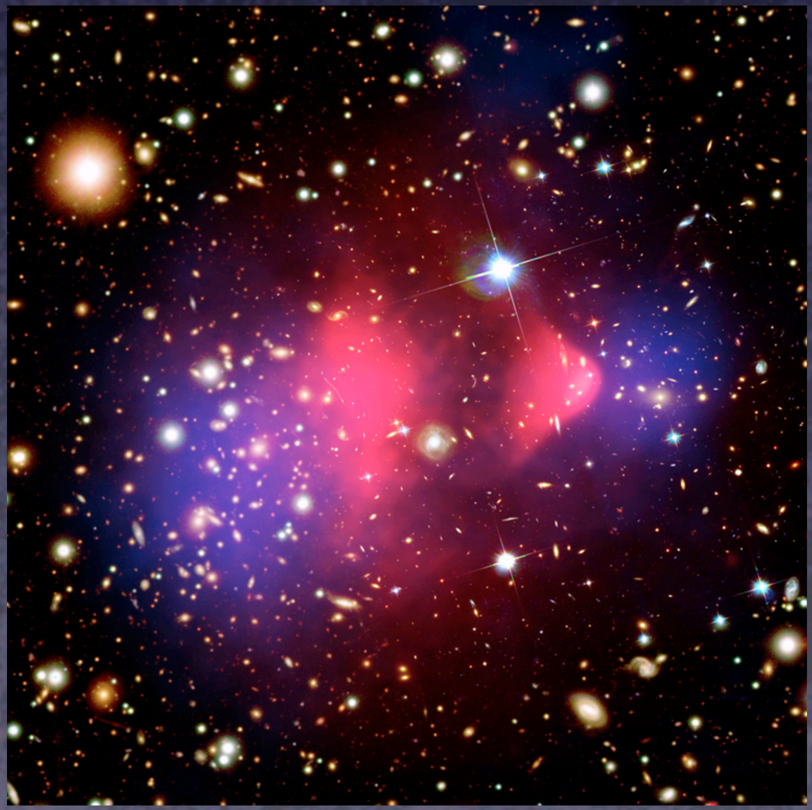
Where are the other 90% ?

Hot gas in clusters (observed)

Warm-hot gas in filaments (elusive)



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Why so few stars ?

Feedback from supernovae & AGN?

We do NOT understand this process...


Thank you
for believing...


Remember me ?