24th January 2019 | Durham University Physics Society

Simulating the Universe

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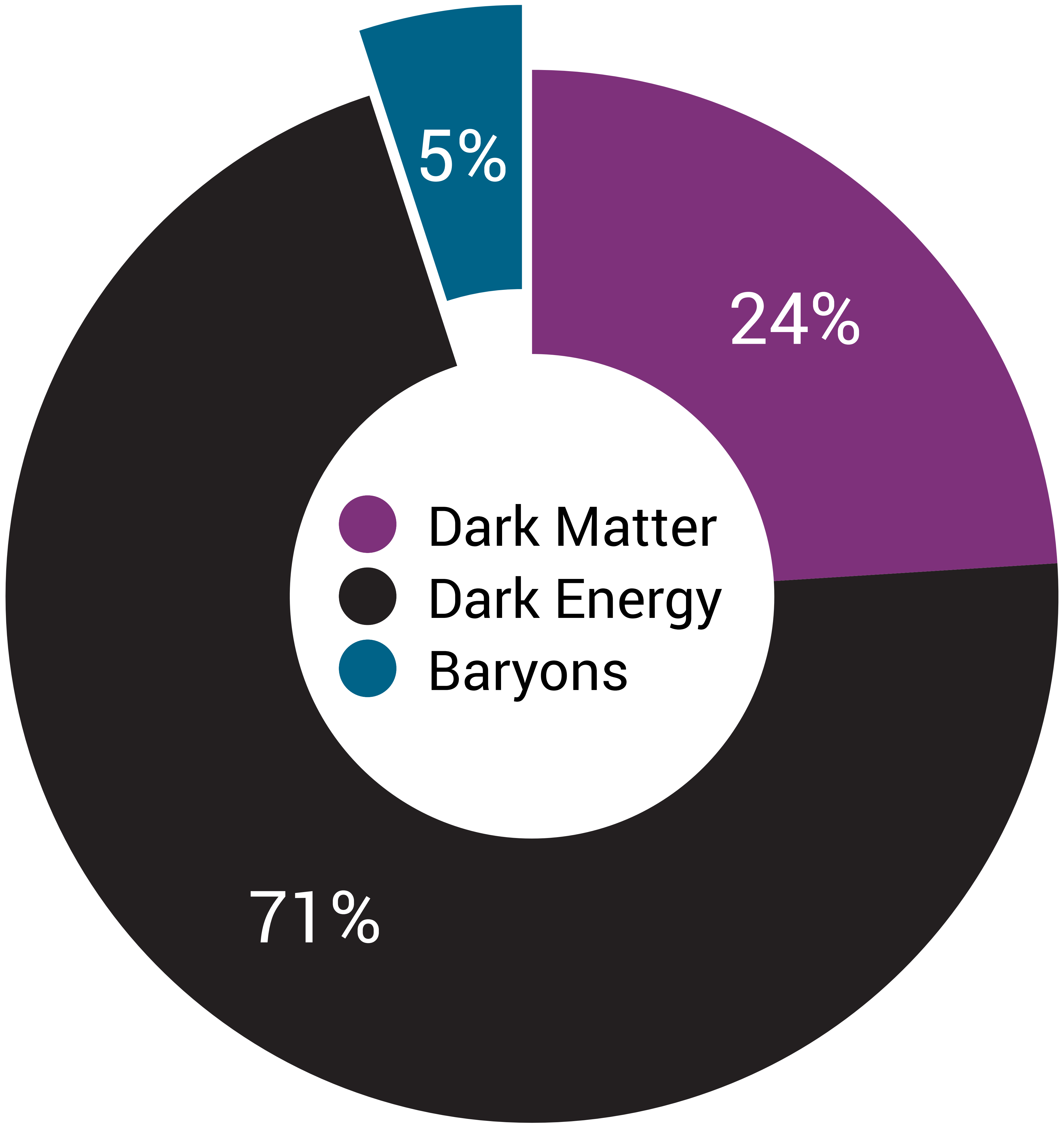
DiRAC intel SWIFT Durham University ICC

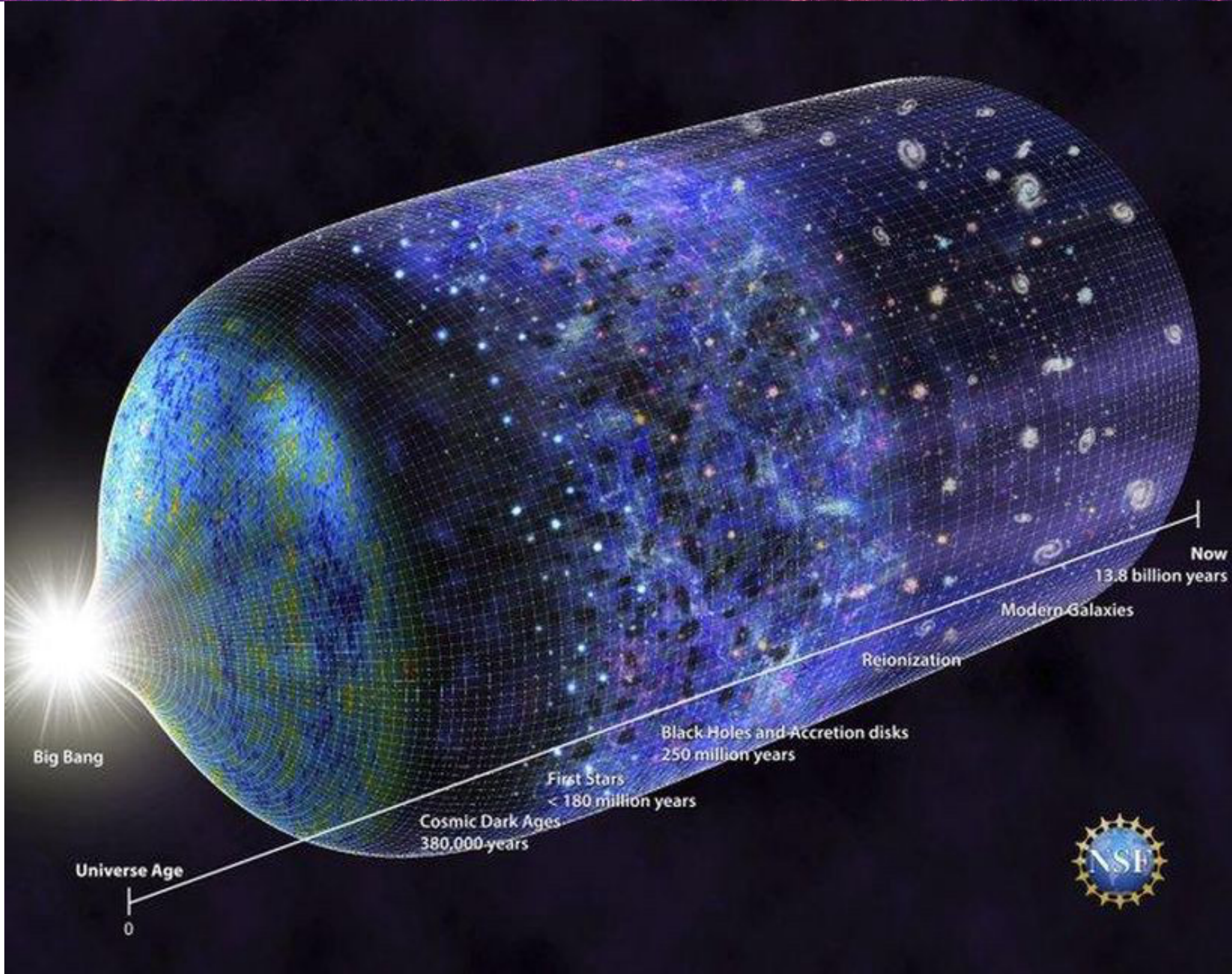
What is the Universe Made of?

- Can’t see the majority of the Universe
- Complete nightmare



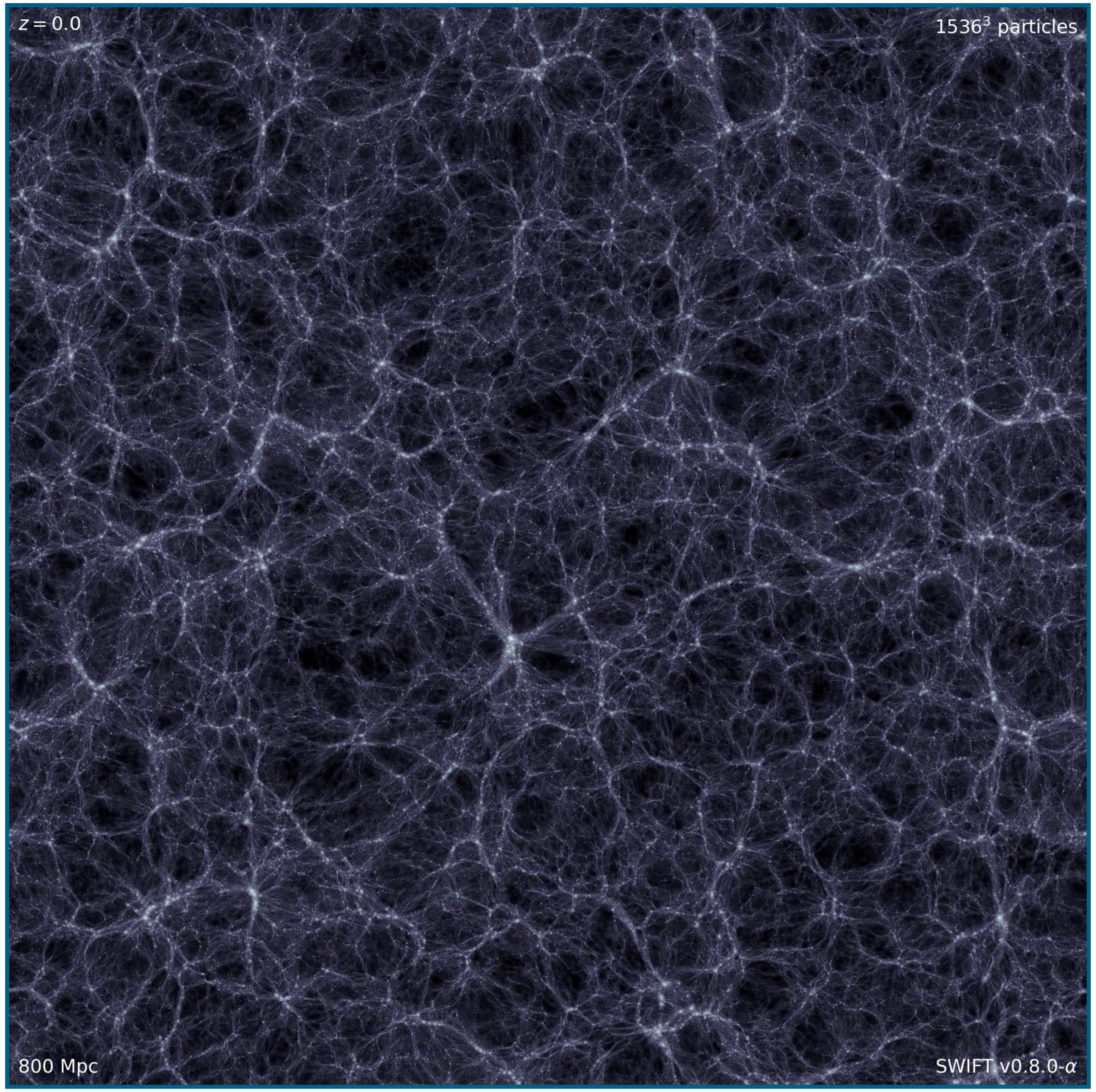
Dark Energy

- Honestly, nobody has a clue about this one
- Affects growth of large-scale structure
- Particle physics estimates differ by a factor of 10^{120}
- Thankfully this doesn't actually change galaxy formation much



Dark Matter

- Dominates gravitational attraction in the Universe
- Probably a WIMP
- Can be modelled as a cold, collision-less fluid
- Important: cannot 'cool'



Baryons!

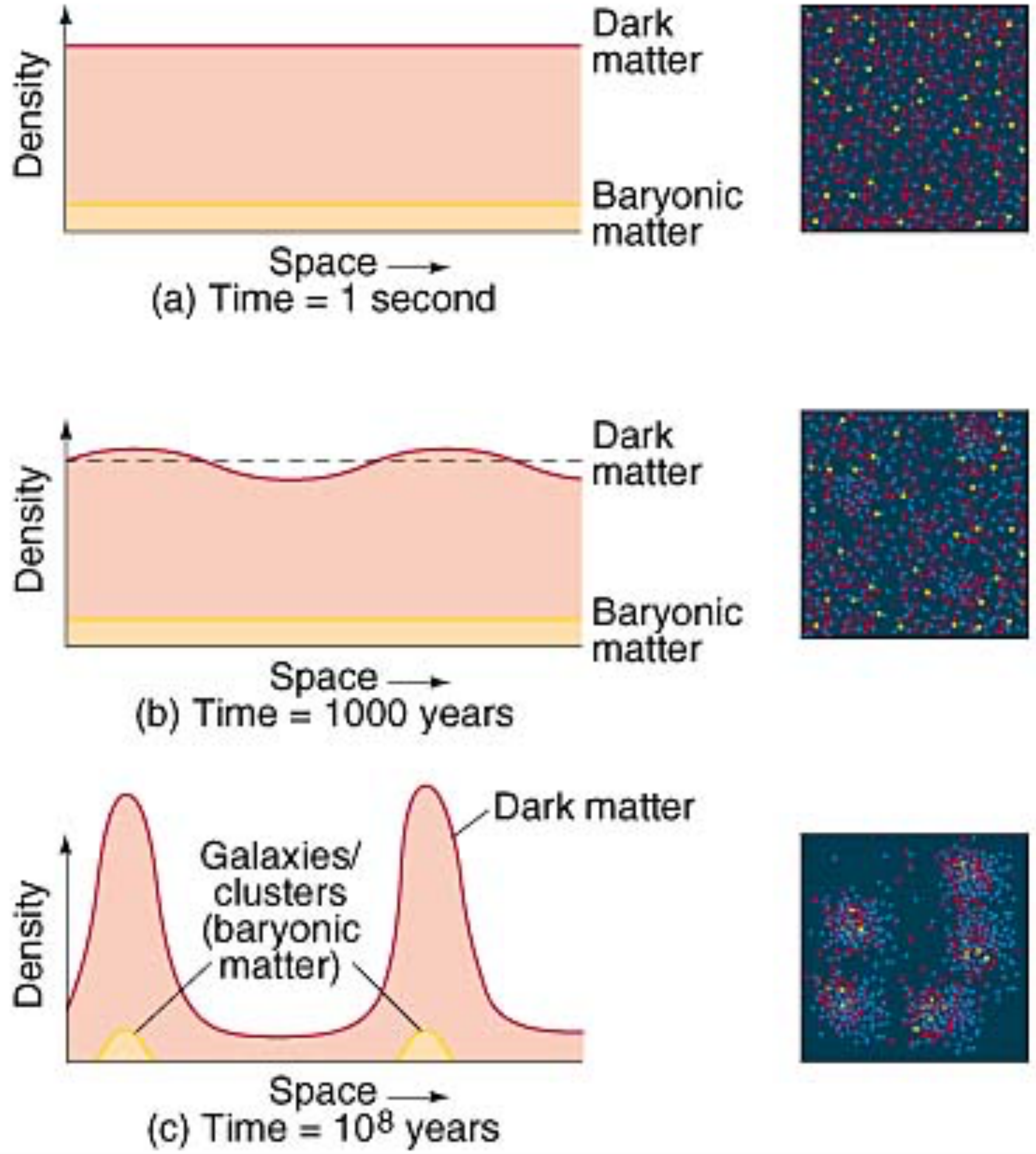
- Everything else
- Gas, stars, black holes, planets, people…
- We can *see* these, so they are quite important.

Galaxy Formation

- Where do galaxies come from?
- Dark matter and dark energy are actually quite easy, the difficult bit is the baryons.
- How can we connect cosmology (amount of stuff) to observables (e.g. distribution of masses of galaxies)?

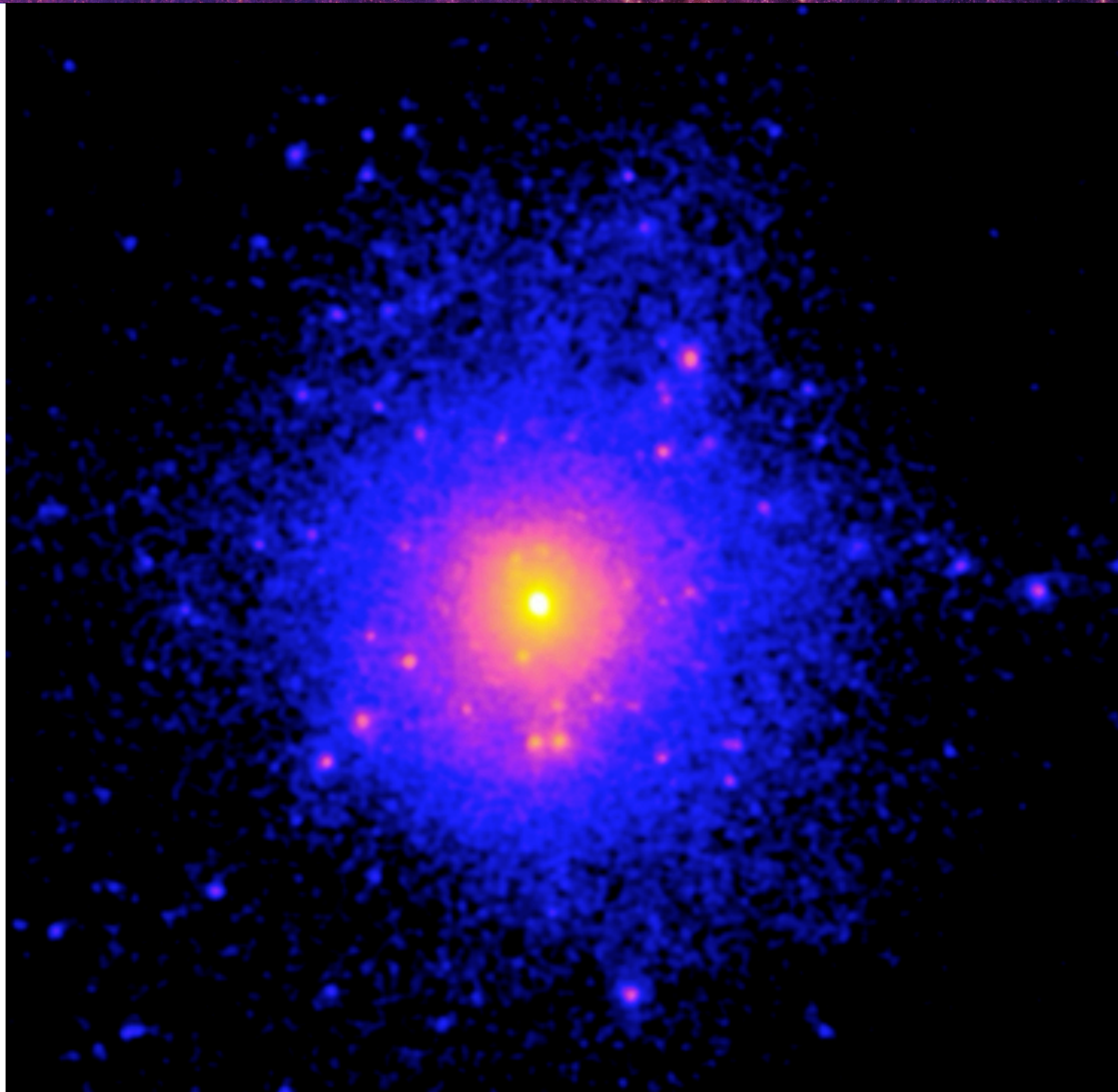
Dark Matter

- Dark matter drives galaxy formation
- Dense dark matter halos form
- These merge to form larger halos
- Gas falls into these halos and makes galaxies



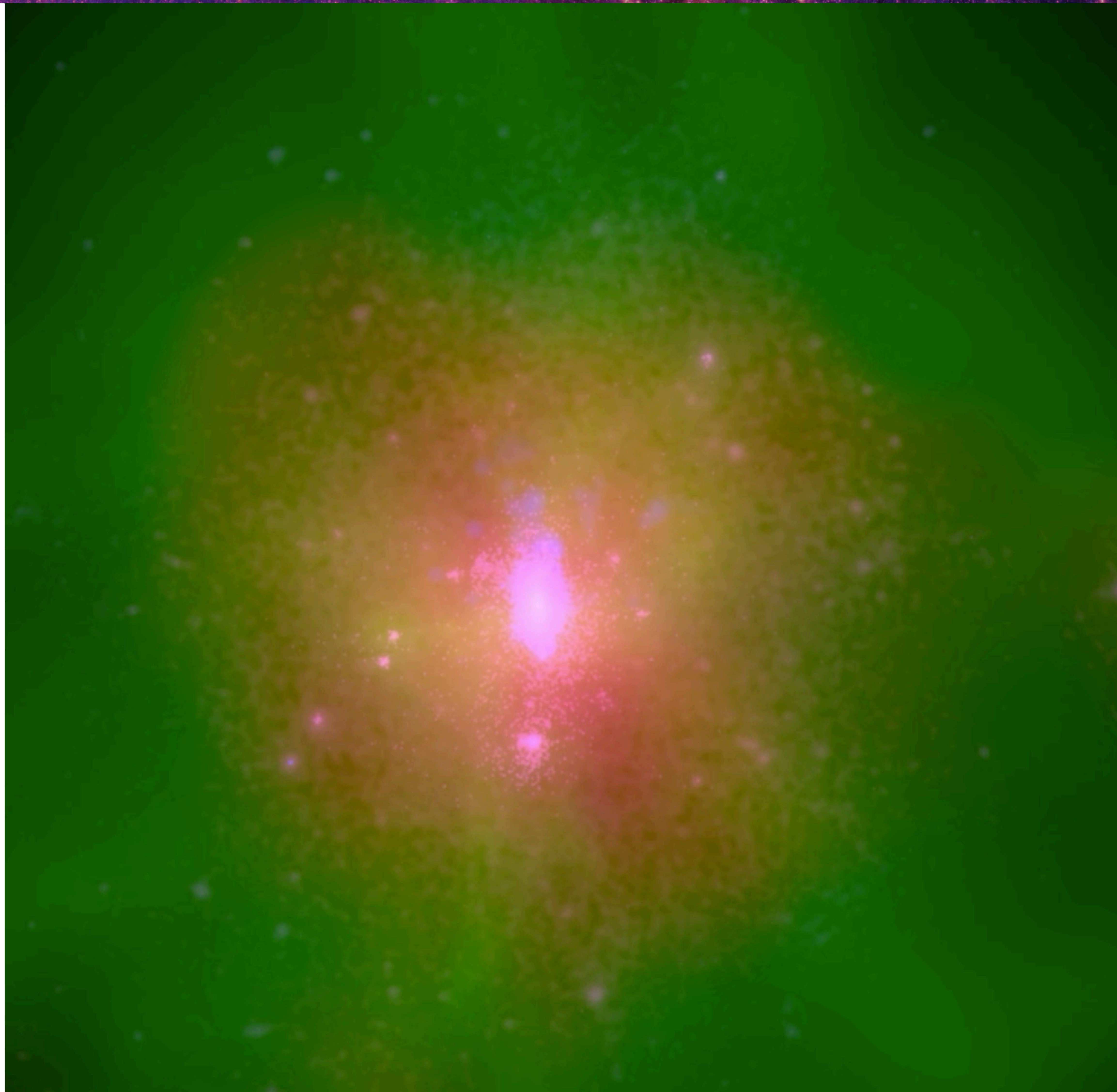
Dark Matter Halos

- Dark matter is collisionless
- Cannot ‘cool’
- Hence halos are spherical (conservation of angular momentum)
- They have a very well characterised density profile (NFW)!



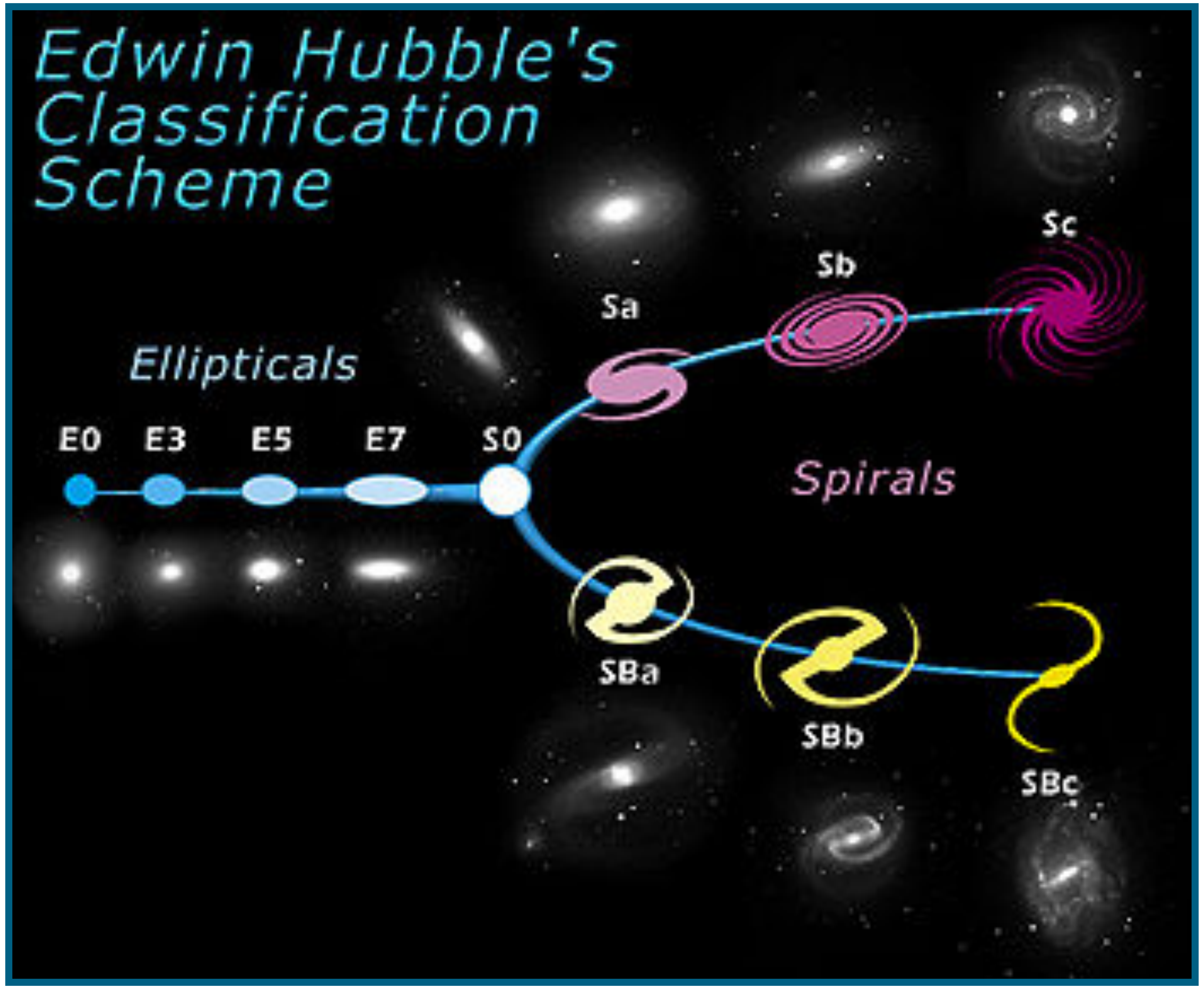
Gas Cooling

- Gas, unlike dark matter, *can* loose angular momentum
- This allows it to fall into the deepest part of the halo's potential well
- This makes the gas even more dense
- The energy loss from cooling is nonlinear!



Galaxies?

- So we've got a dense ball of dark matter
- A dense disk of gas
- That's a galaxy, right?



I think you'll find it's a bit more complicated than that

Ben Goldacre

Bestselling author of *Bad Science* and *Bad Pharma*


Galaxies in the Real Universe

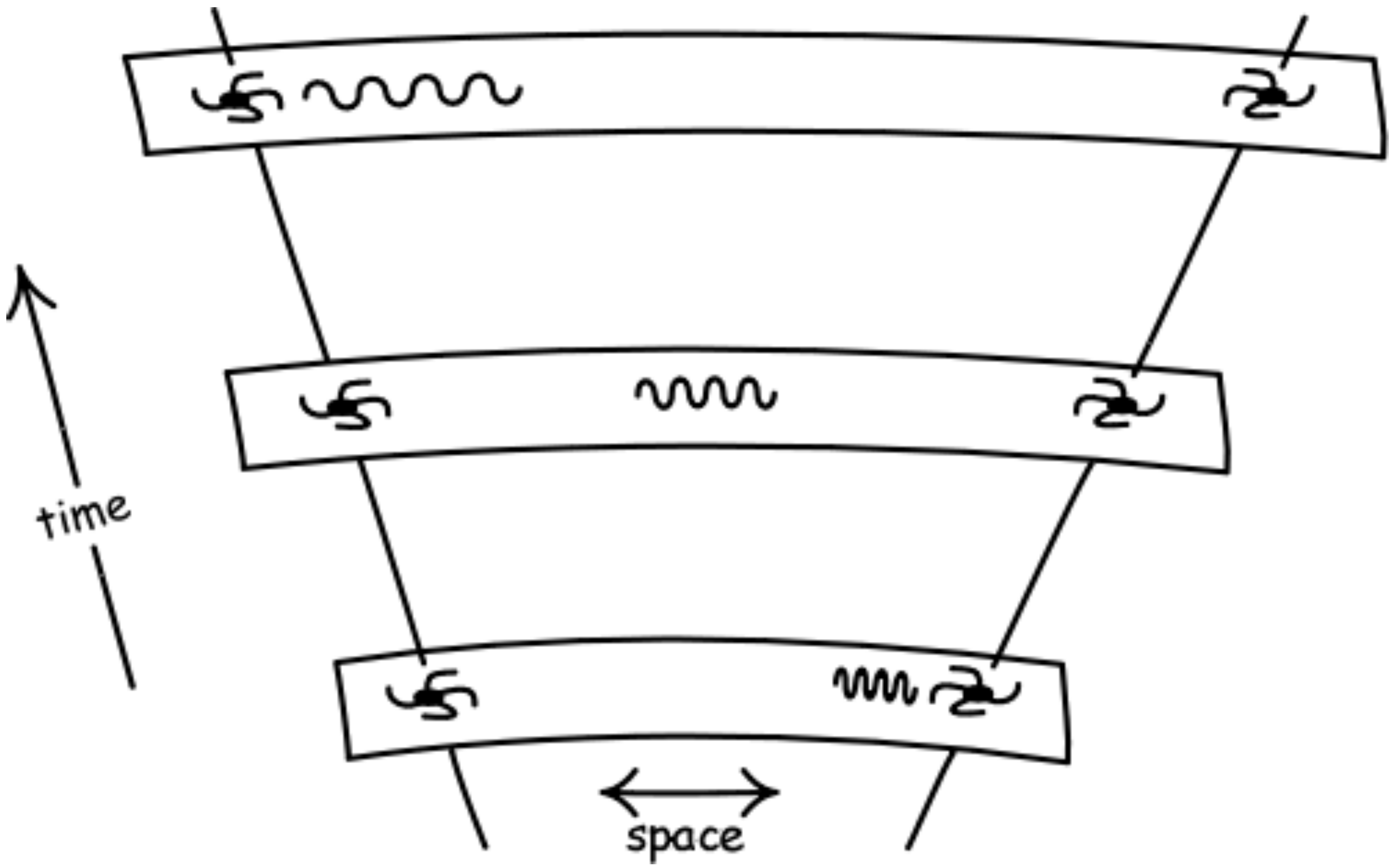
Timescales: The Biggest Killer

- Typical timescales in galaxy formation are ~100s of millions of years

- Your grand^{400000}children will be able to see significant changes in the galaxy population

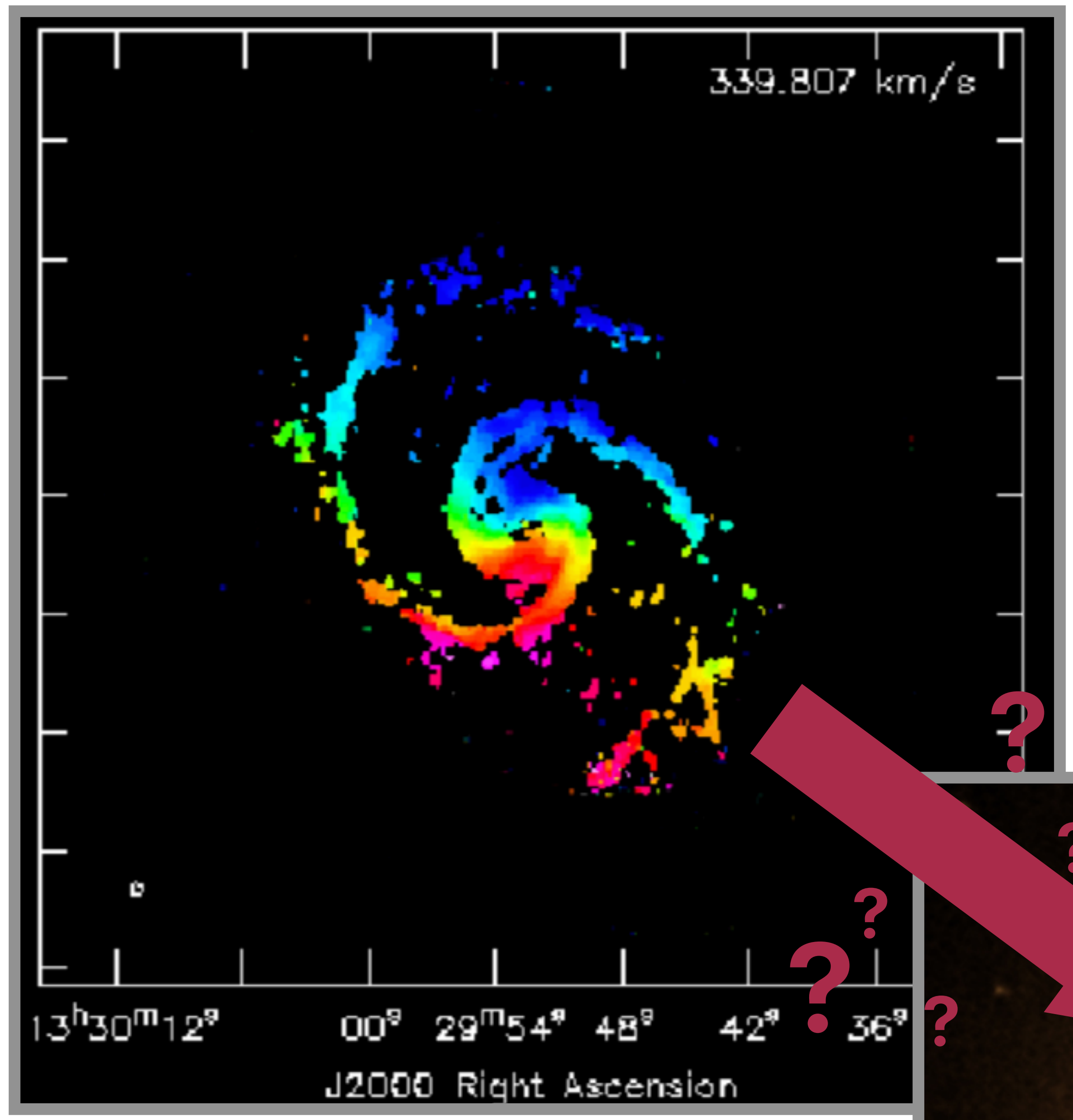
Addendum: Cosmological Redshift

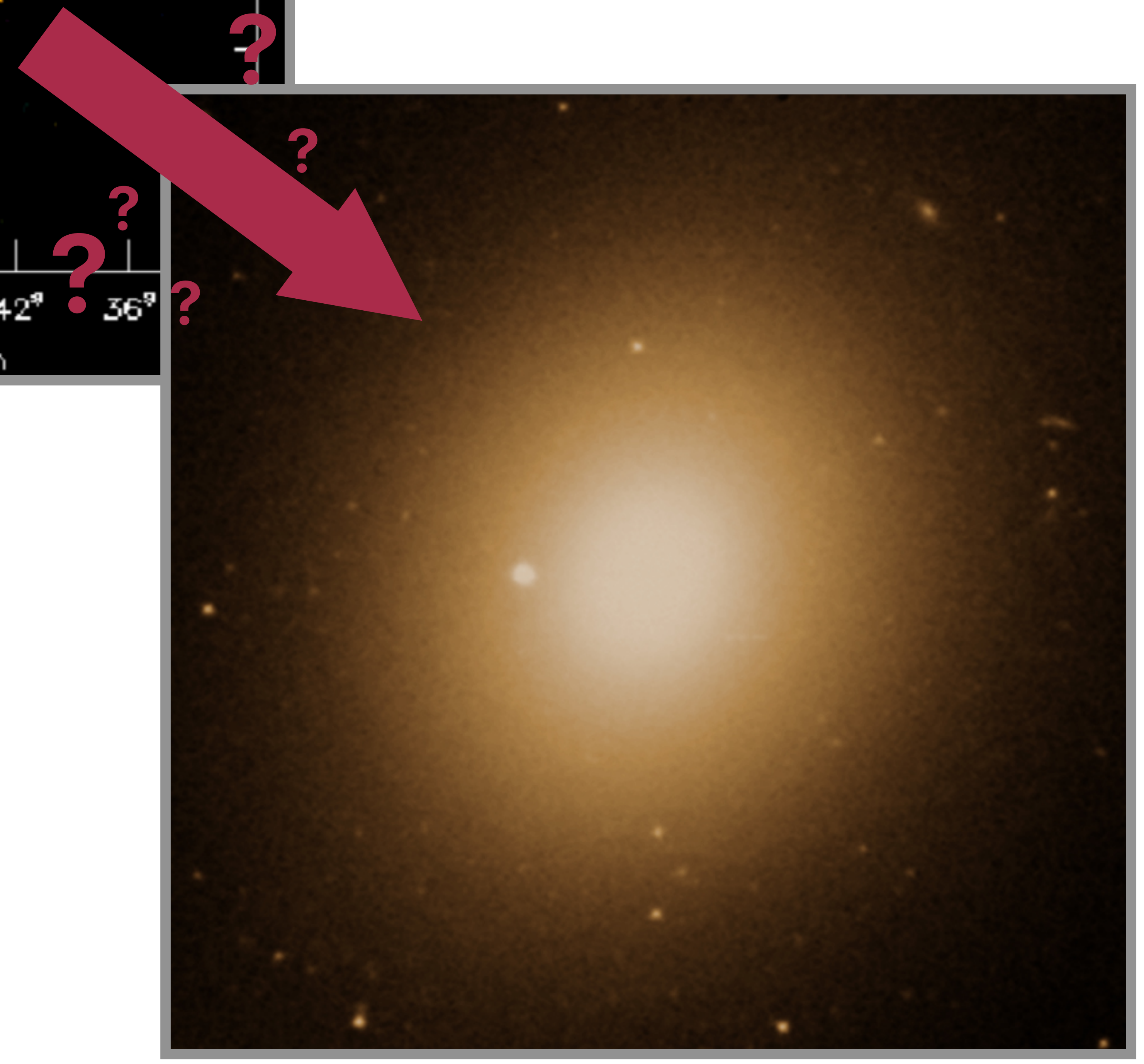
- Astronomers use redshift as a proxy for distance
- Hubble flow, $v = H_0 d$ gives recession velocity, which then gives redshift
- Objects at higher redshifts are also seen further back in time because of light's finite speed of travel.



Progenitor Matching

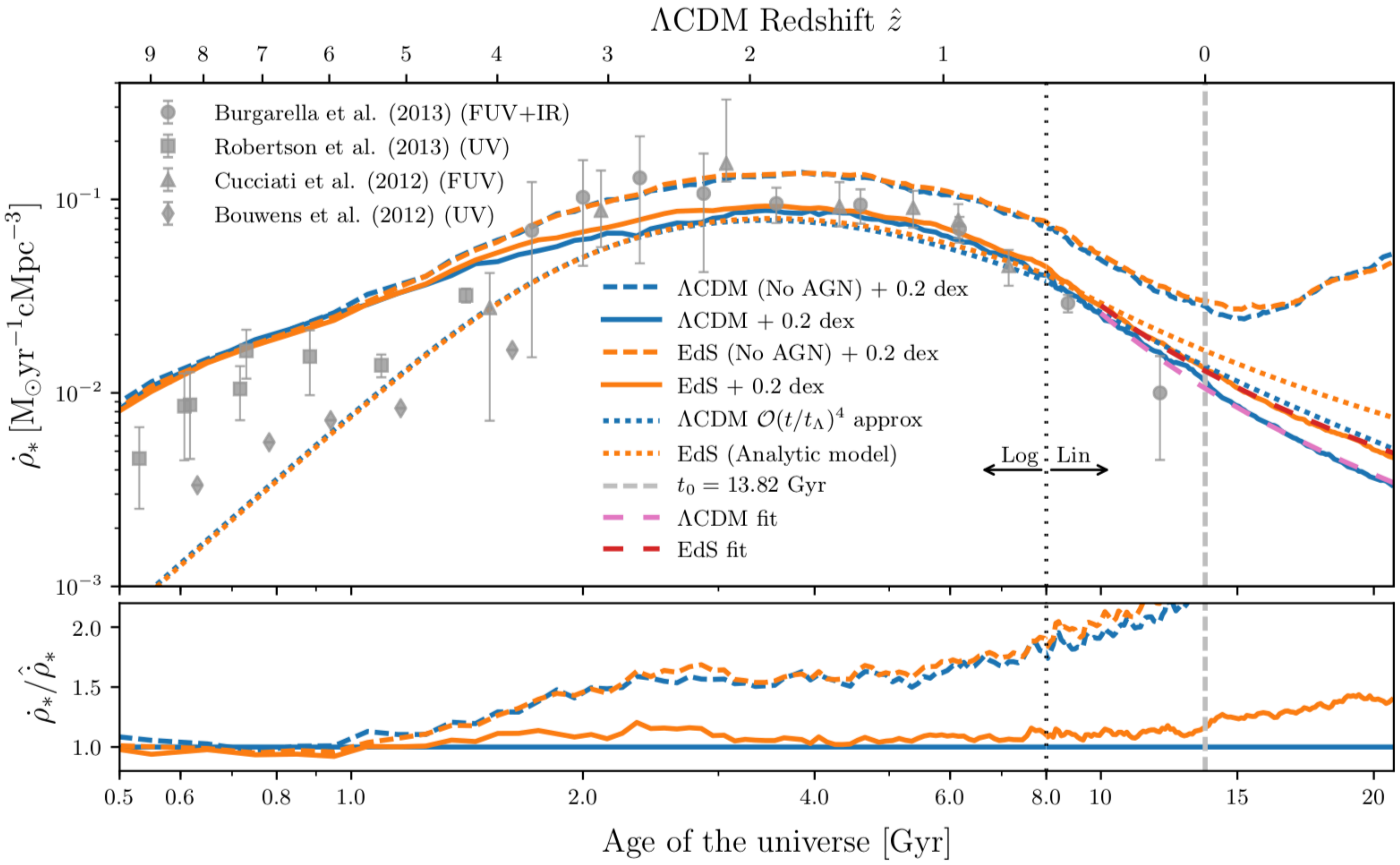
- We must match *different* galaxies to their nearby counterparts (by mass or other properties)
- This is rubbish as we can't see the direct correspondence between objects





Statistics

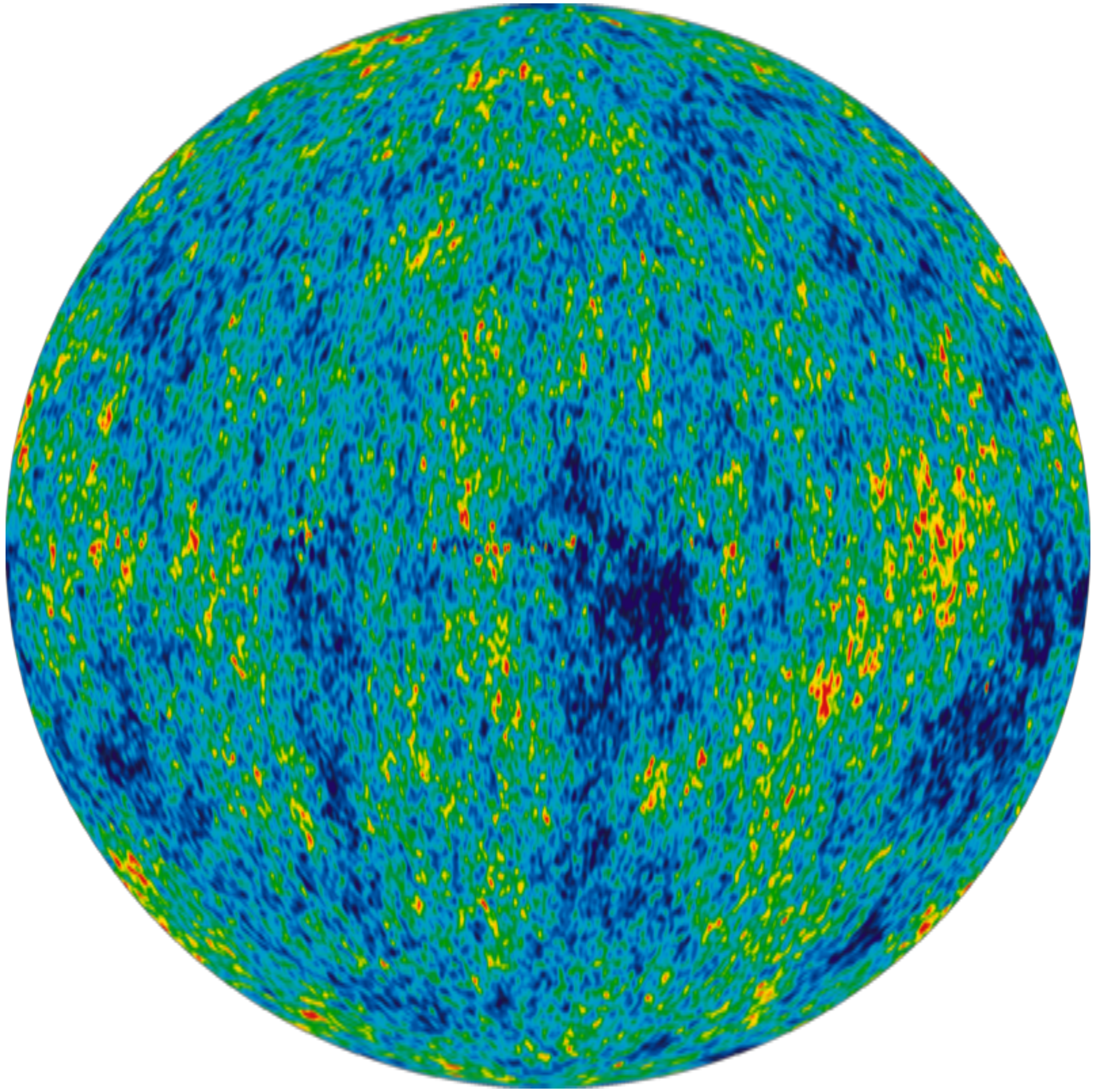
- What we can do is collect statistical information about the galaxy population
- This is a very famous plot that shows the star formation history of the Universe




Understanding Galaxy Formation

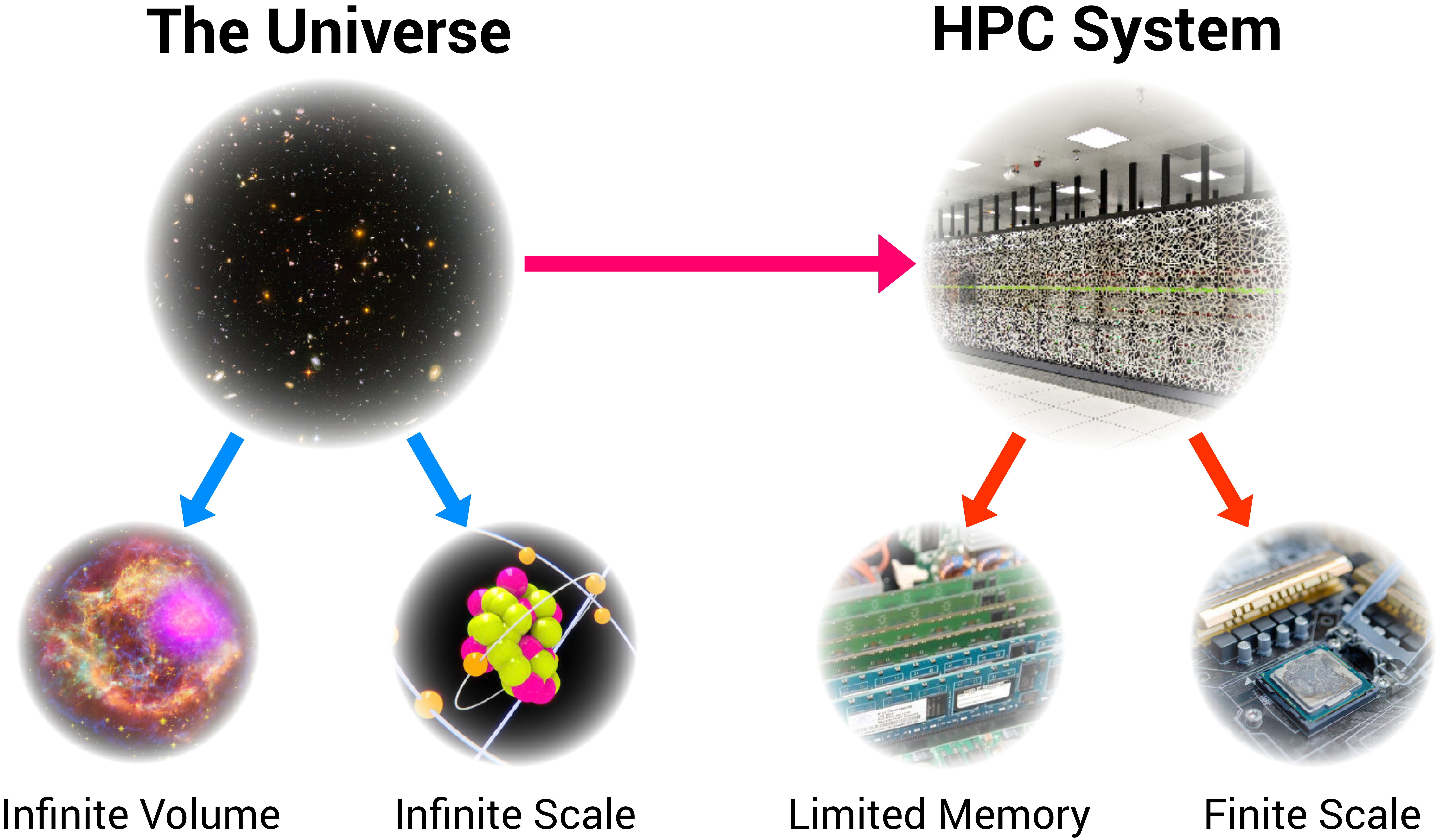
Where can we go from here?

- We have a conceptual idea of galaxy formation
- Also have some statistical properties of the Universe
- No idea how a specific galaxy formed
- Difficult to pin down what processes are important!



The cosmic microwave background (CMB) as seen by WMAP

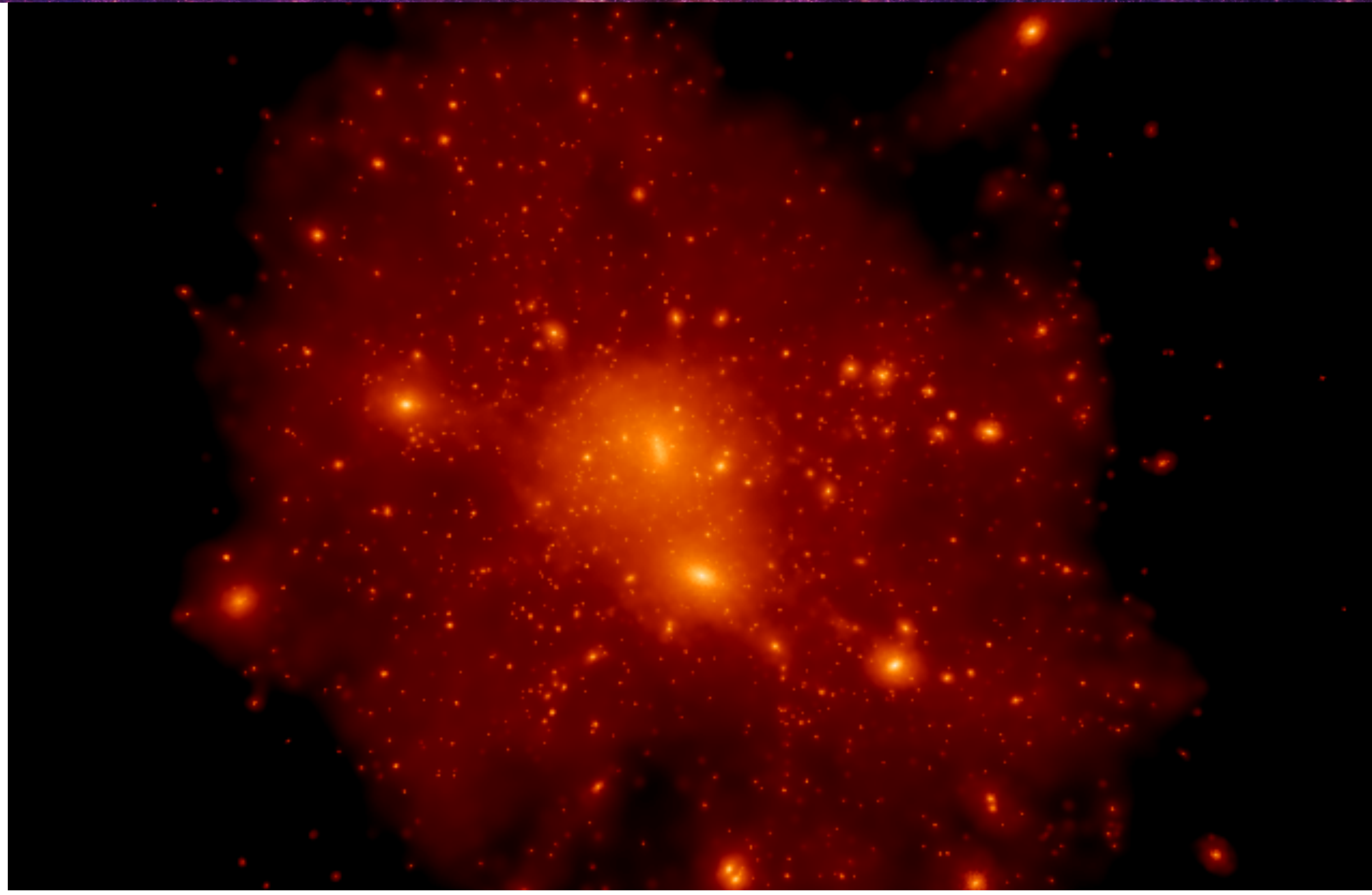
Running a Simulation of the Universe



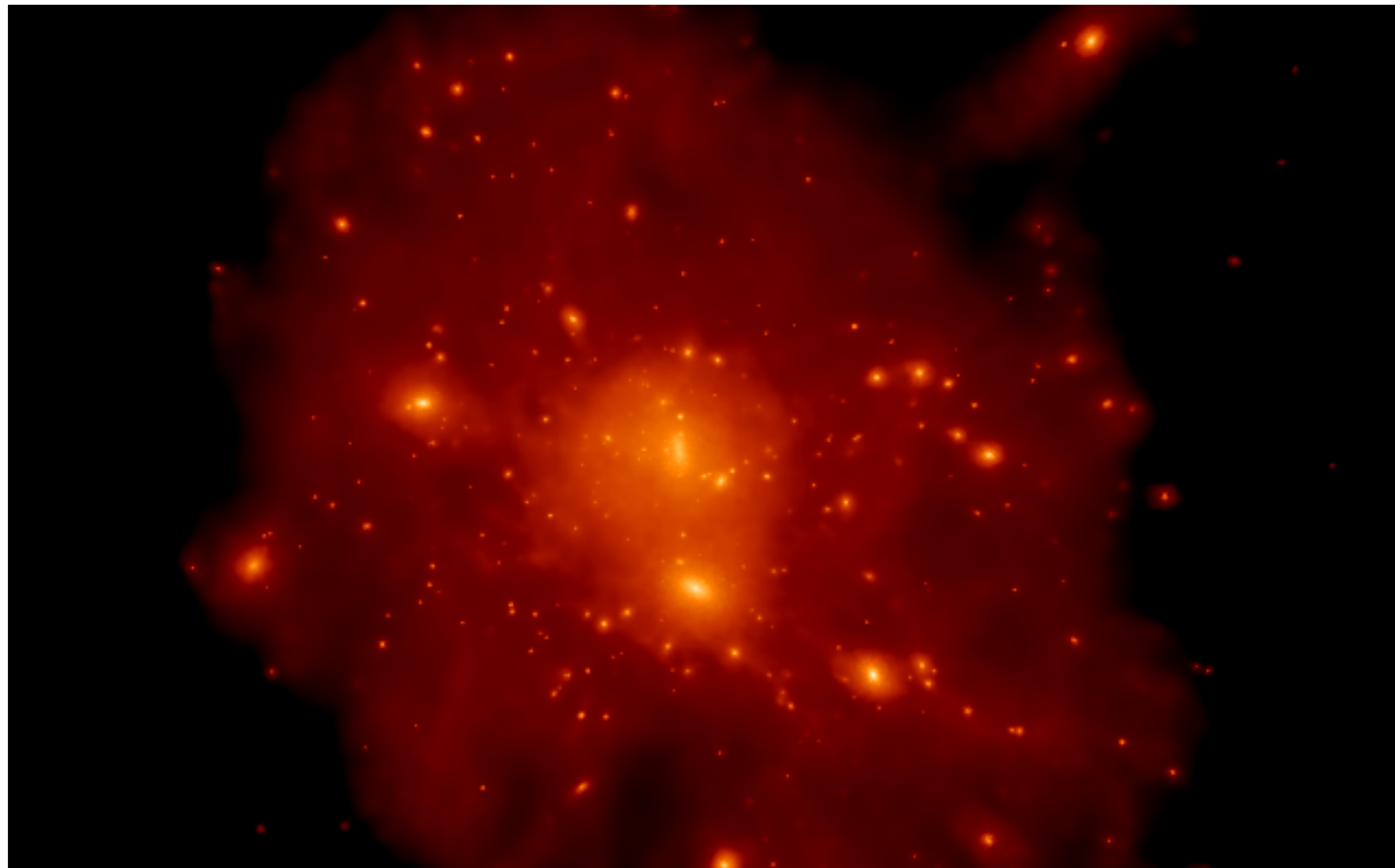
Step 1: Get the Dark Matter Right

- Cosmology tells us *how much* dark matter there is, but not of what *type*.
- We can run gravity-only simulations of dark matter to determine how it affects structure formation in the Universe.
- These allow us to predict e.g. how many satellite galaxies we'd expect around the Milky Way

CDM: WIMP

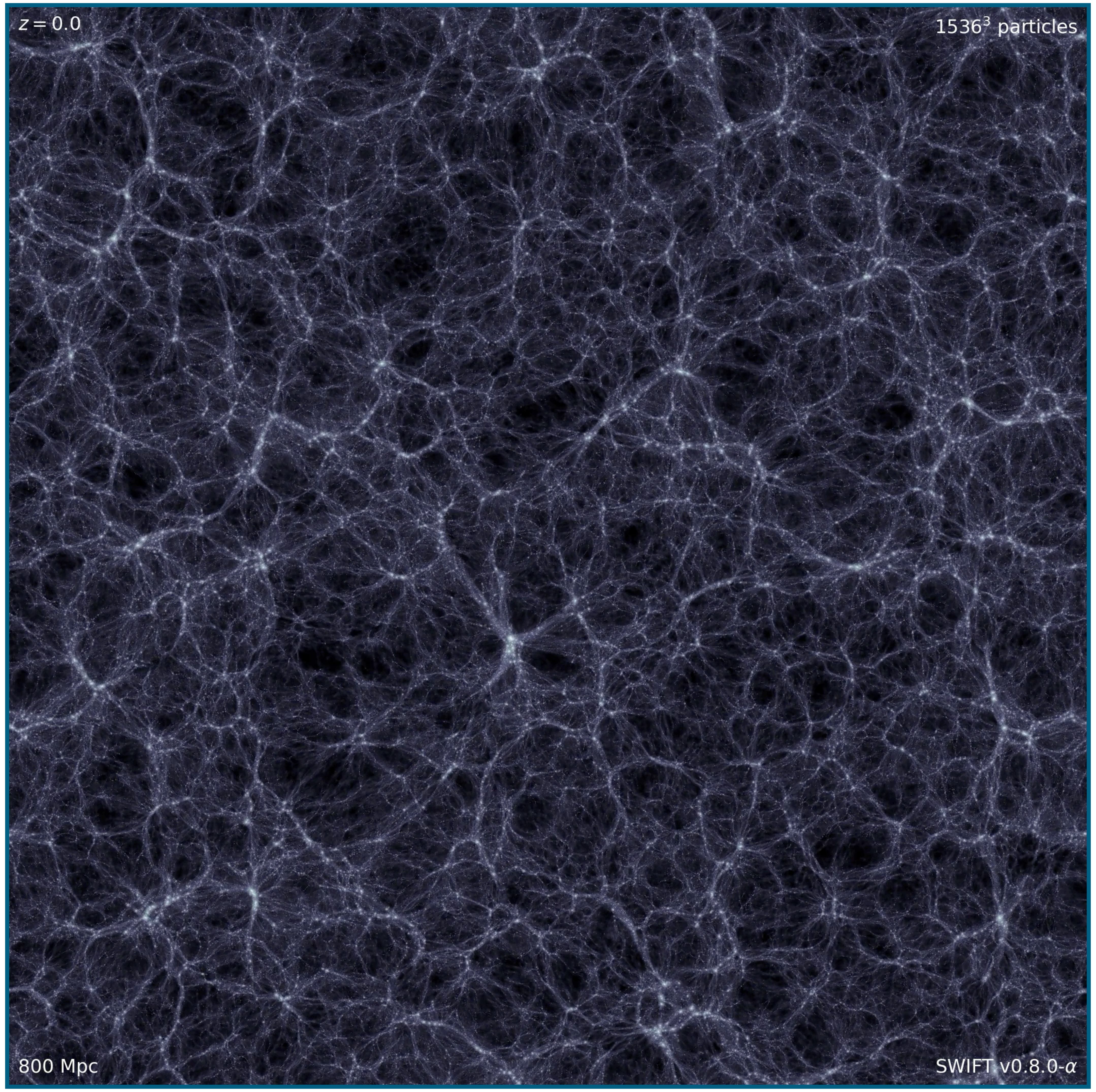


WDM: Neutrinos



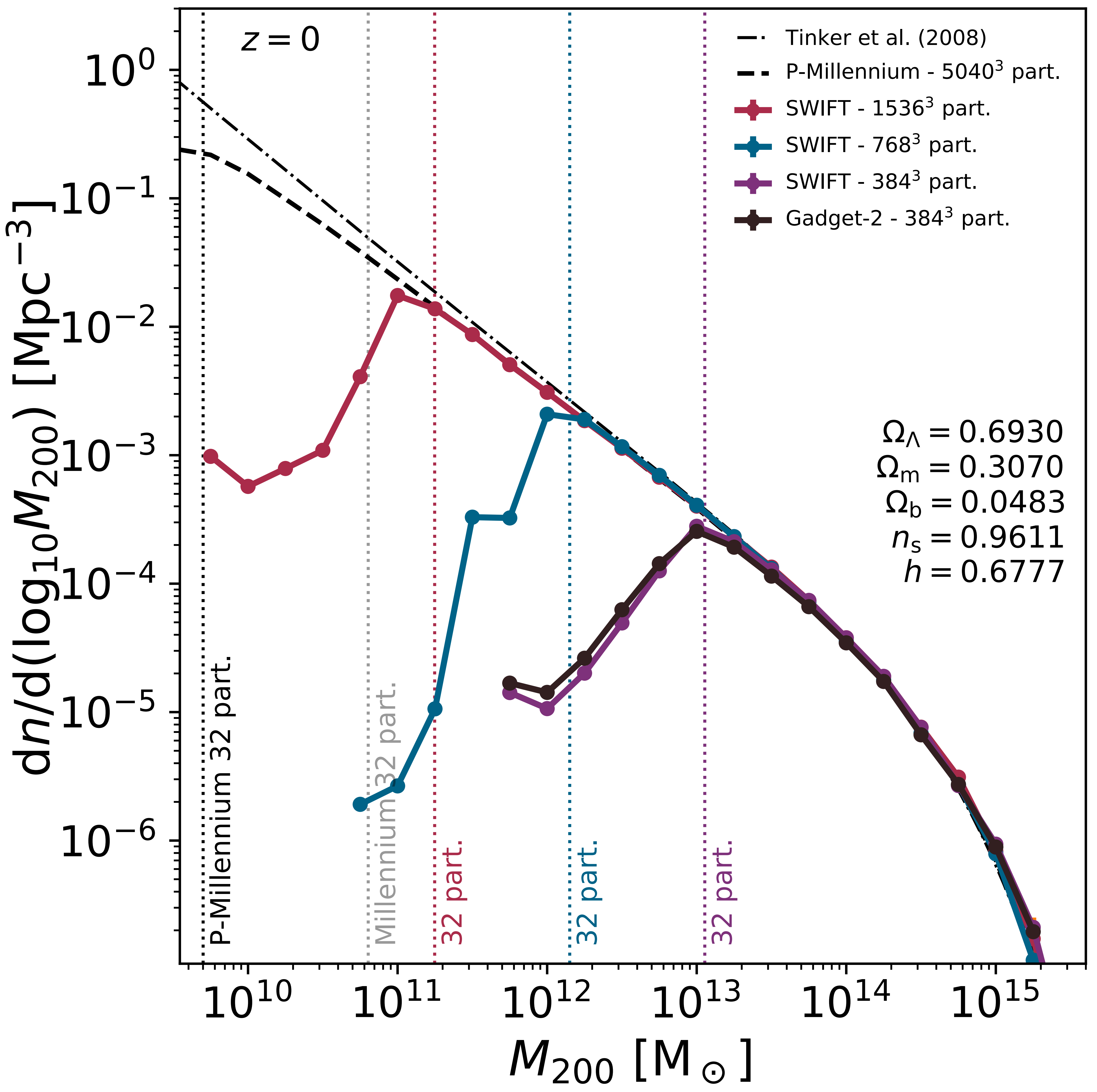
Step 1: Get the Dark Matter Right

- We can run these 'N-body' simulations super fast these days
- 5000^3 or higher (125 billion) particle simulations are not uncommon



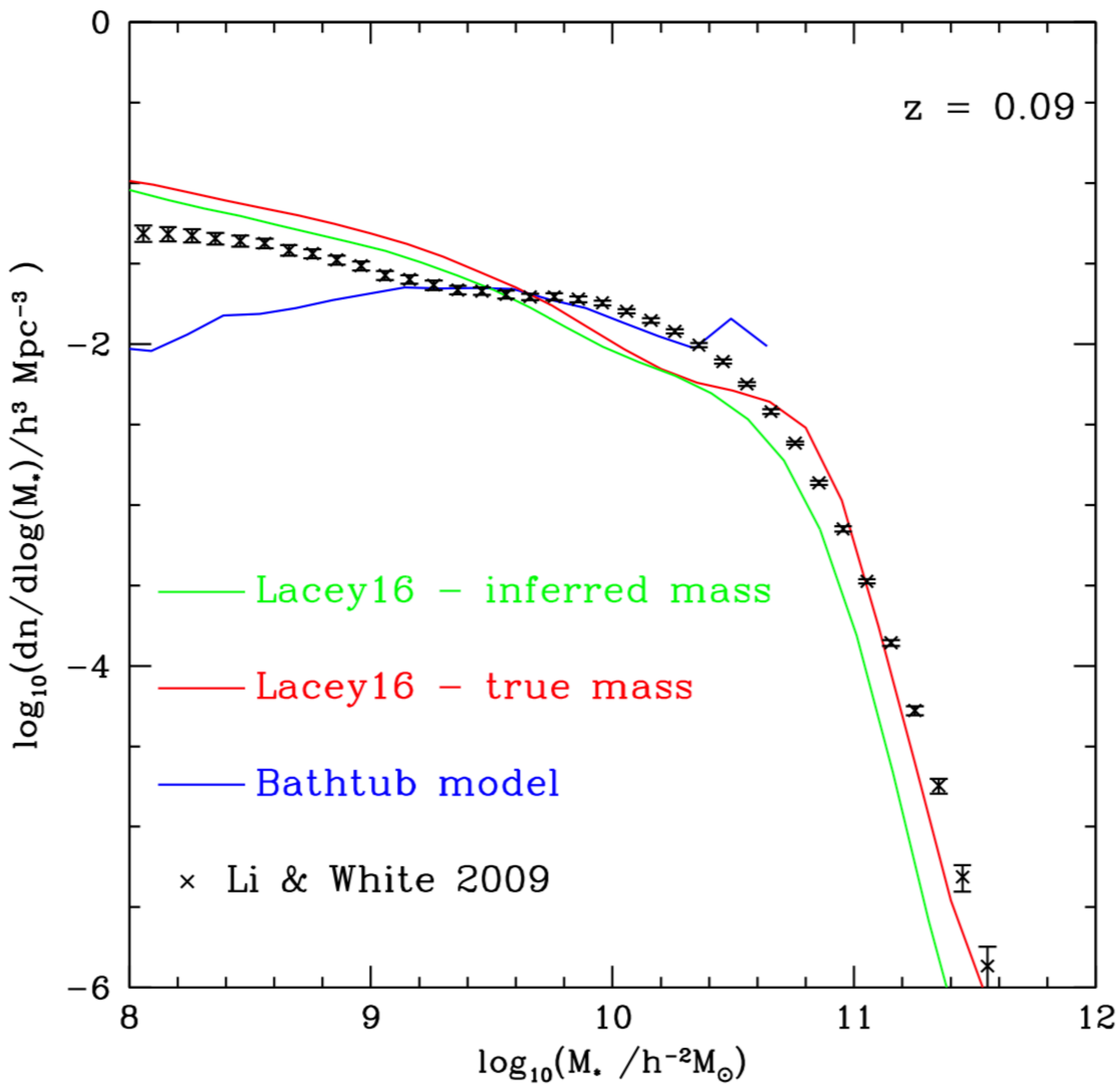
The Halo Mass Function

- Shows the abundance of dark matter halos as a function of mass
- This is self-similar all the way down
- Clearly that's not the same for baryons…



Semi-Analytic Models

- Use the dark matter-only simulations as a base
- Stick on top a 'semi-analytic' model of galaxy formation that has equations to model galaxy properties
- Caveat: these are boring AF and have no pretty pictures



What do SAMs say about Galaxy Formation?

- A lot.
- Pretty much everything we know comes from these models.
- Important processes:
  - Star formation and stellar "feedback"
  - Black holes and their associated "AGN feedback"
  - Gas cooling

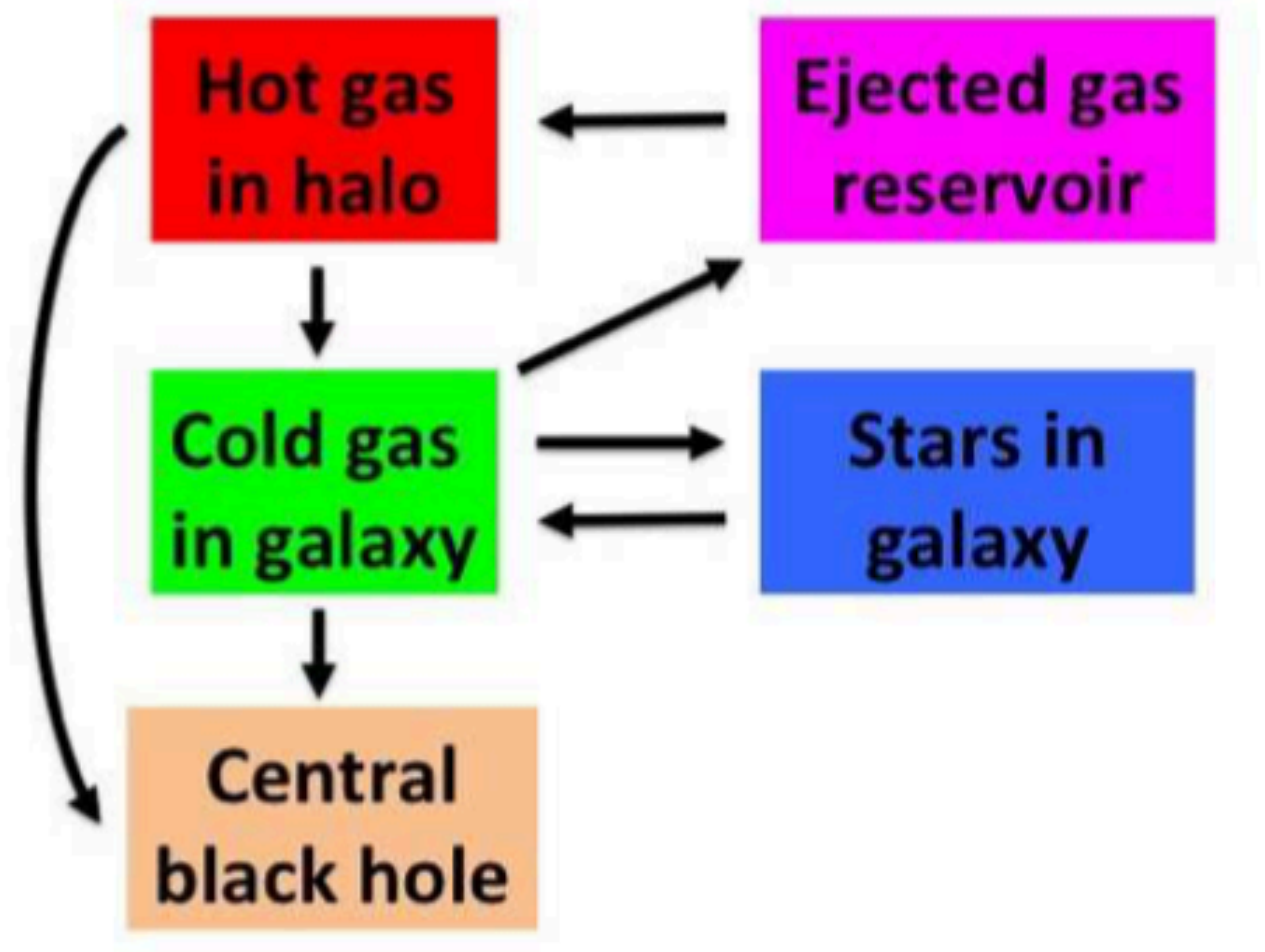
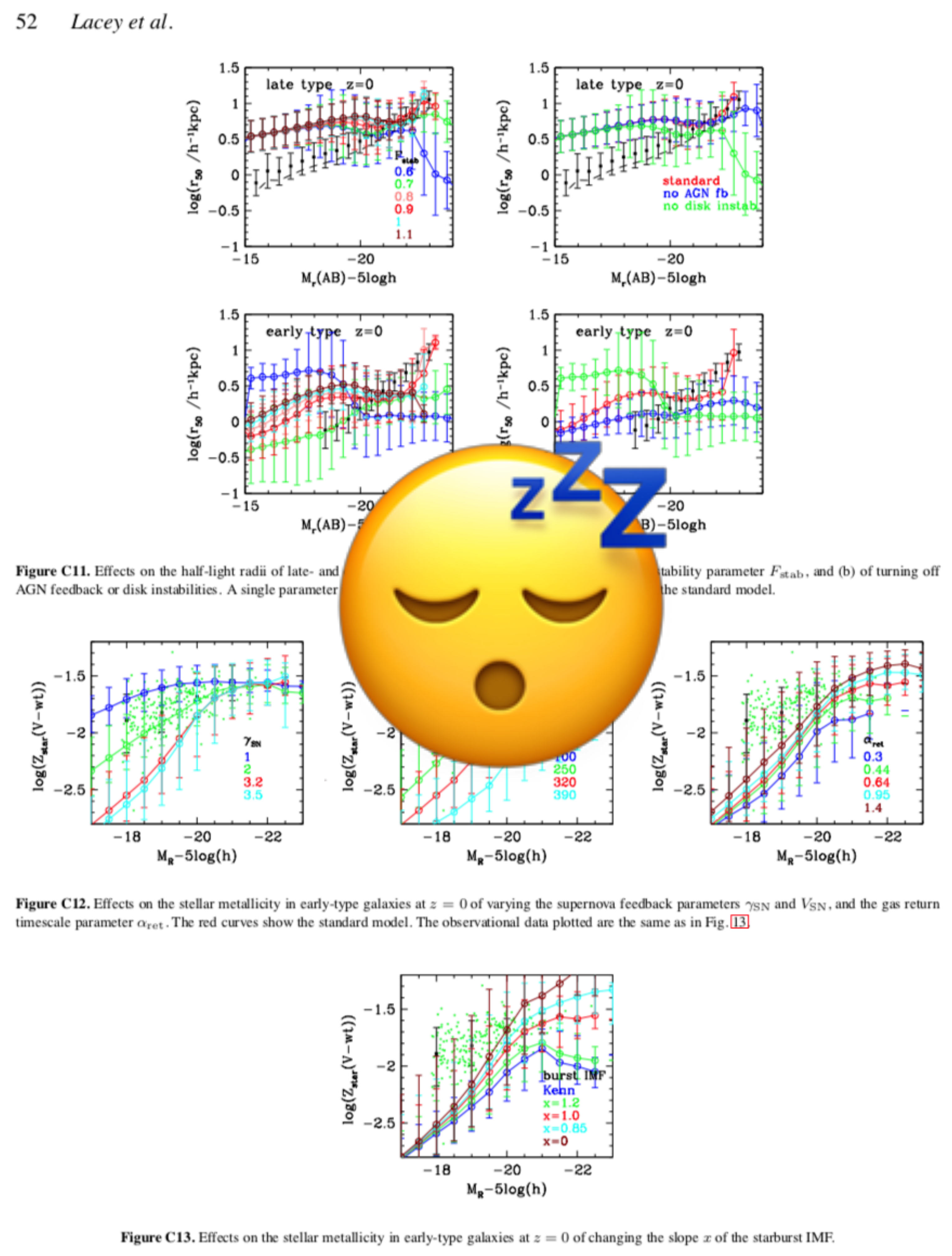


Figure 1. Flow chart showing the different baryonic components in a halo, and transfers between them.

The Problem with SAMs

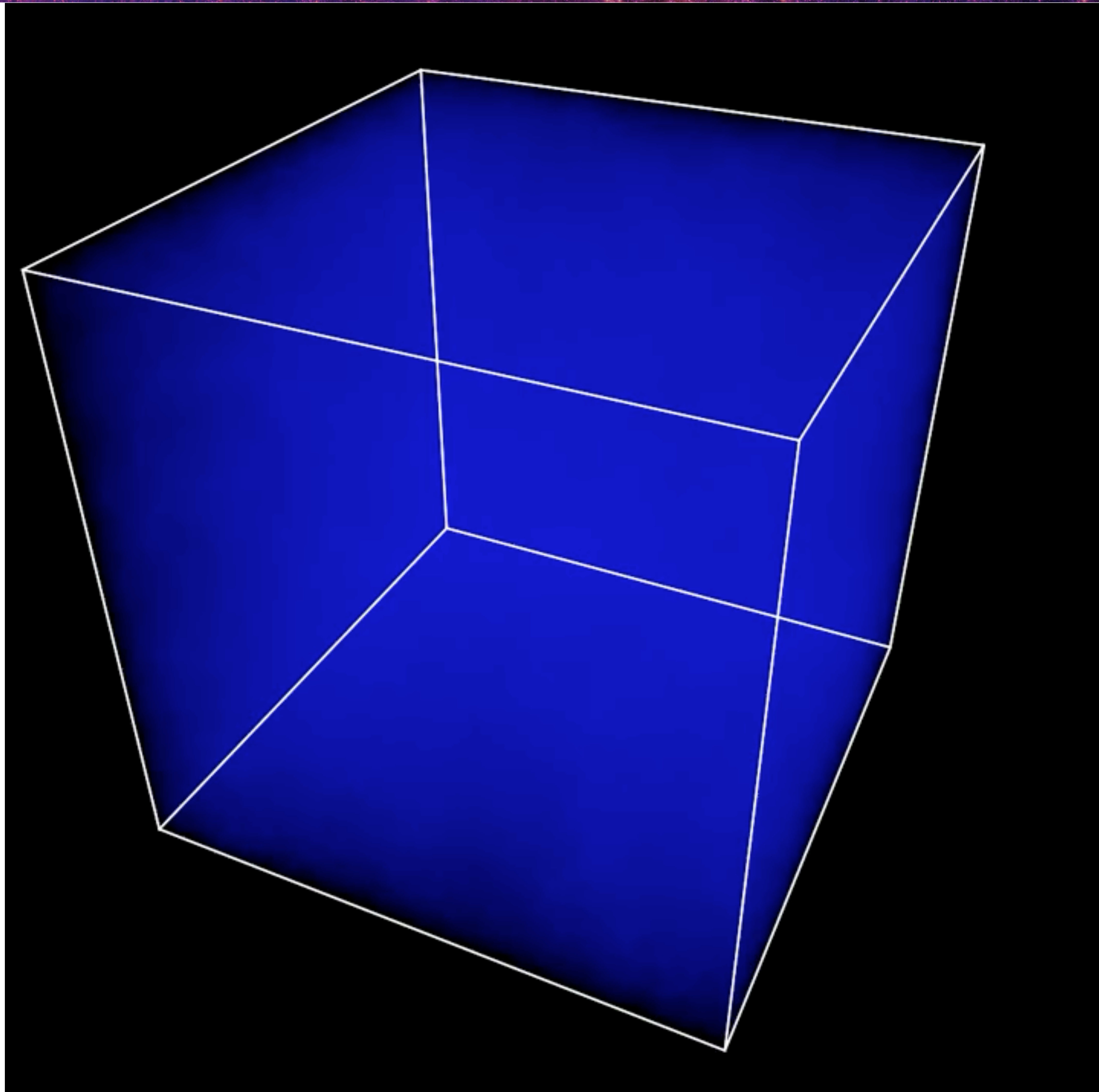
- Boring
- Ugly
- No resolved properties!
- Cannot study the interaction of galaxies with their environment
- Difficult to study galaxy interactions



Cosmological Hydrodynamics Simulations

Step 2: Do it ‘Properly’

- Need to couple (at least) three main key pieces of physics
  - Cosmology
  - Hydrodynamics
  - Gravity
  - (+ Radiative transfer..???)
  - (+ Magnetic fields..???)



Hydrodynamics

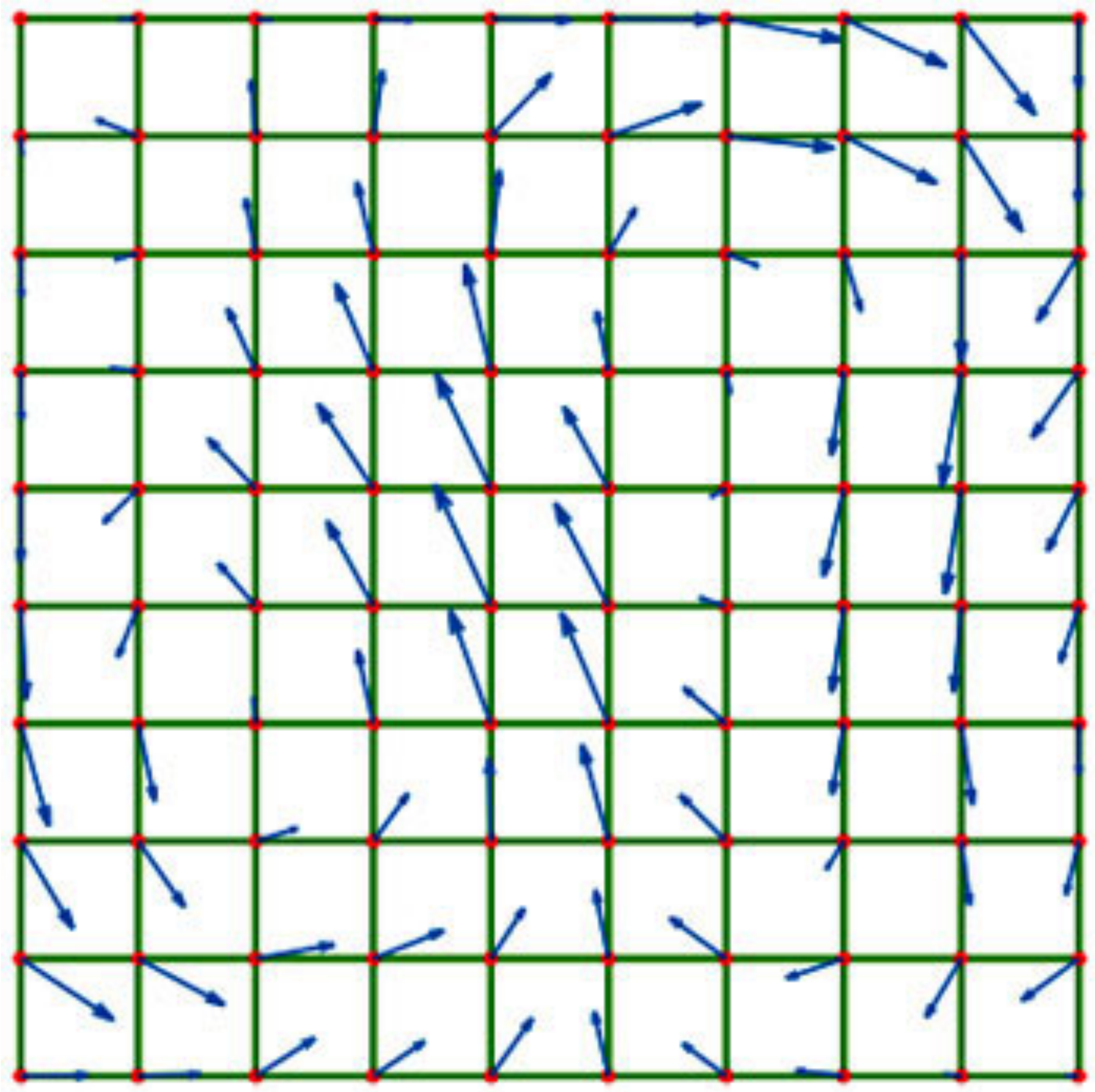
- Typical way to do this: lay down a grid and compute fluid flows between cells

- Several problems:

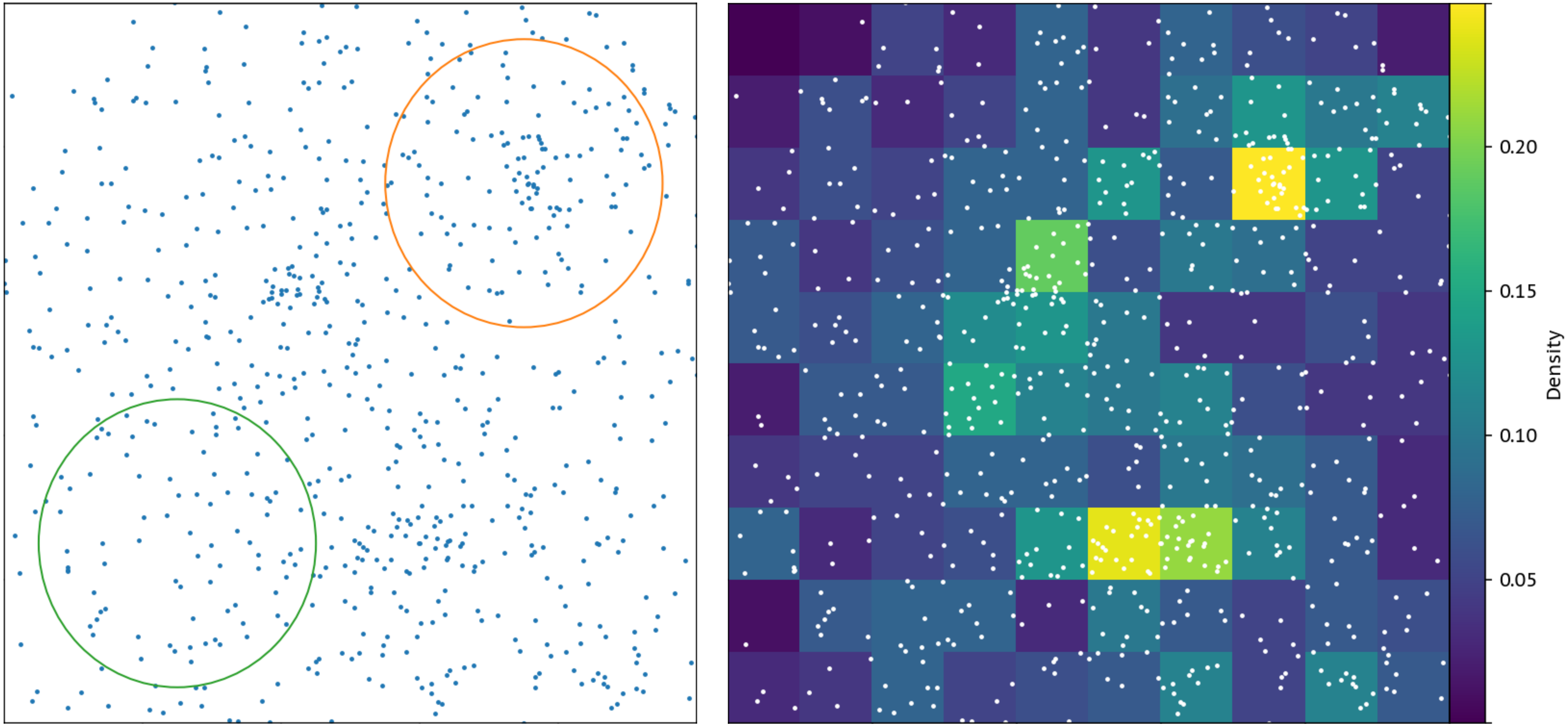
  - Lack of adaptivity

  - **Cannot track fluid flow over time**

  - Makes gravity difficult



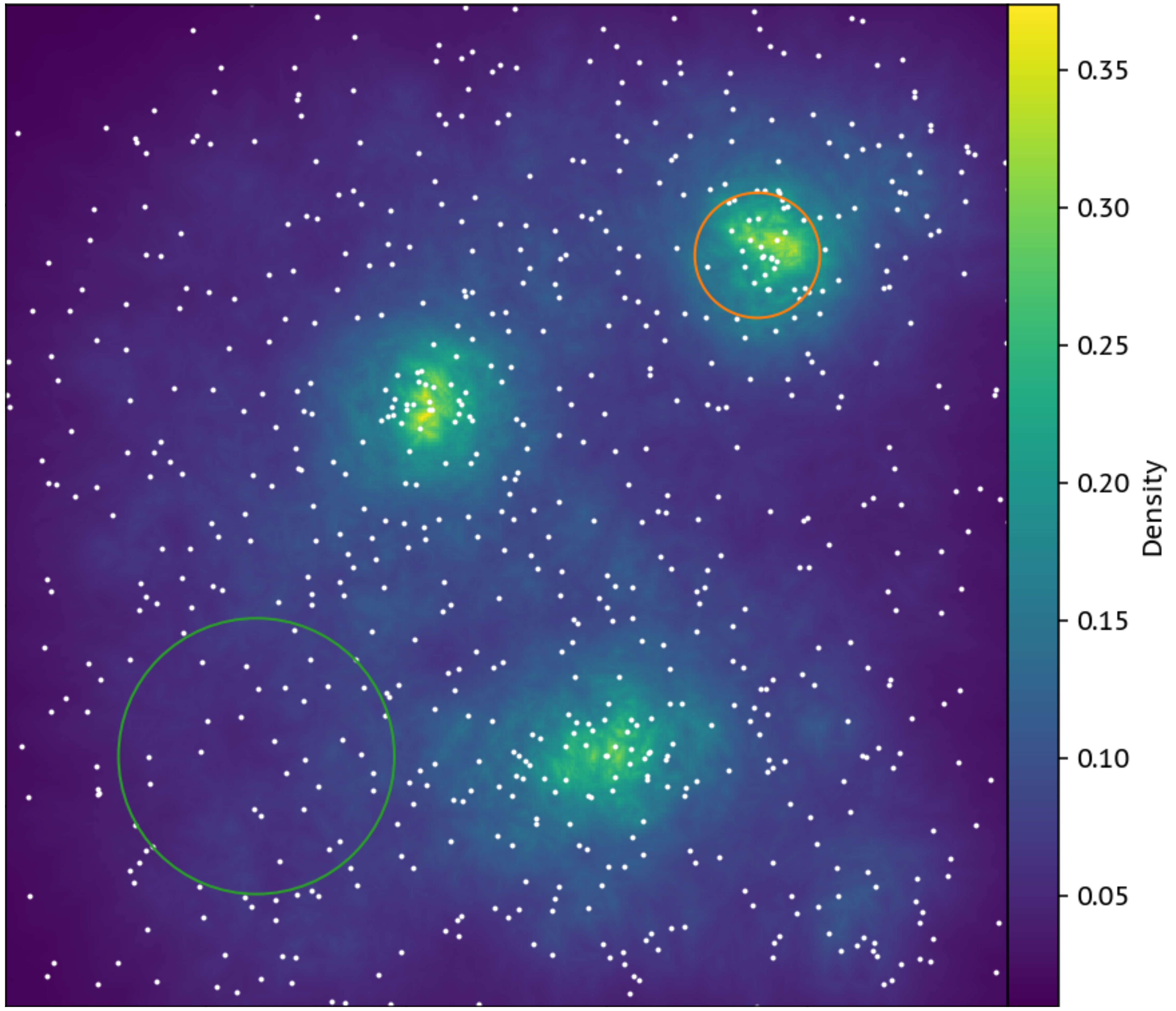
Hydrodynamics with Particles



Improving our Density Estimate

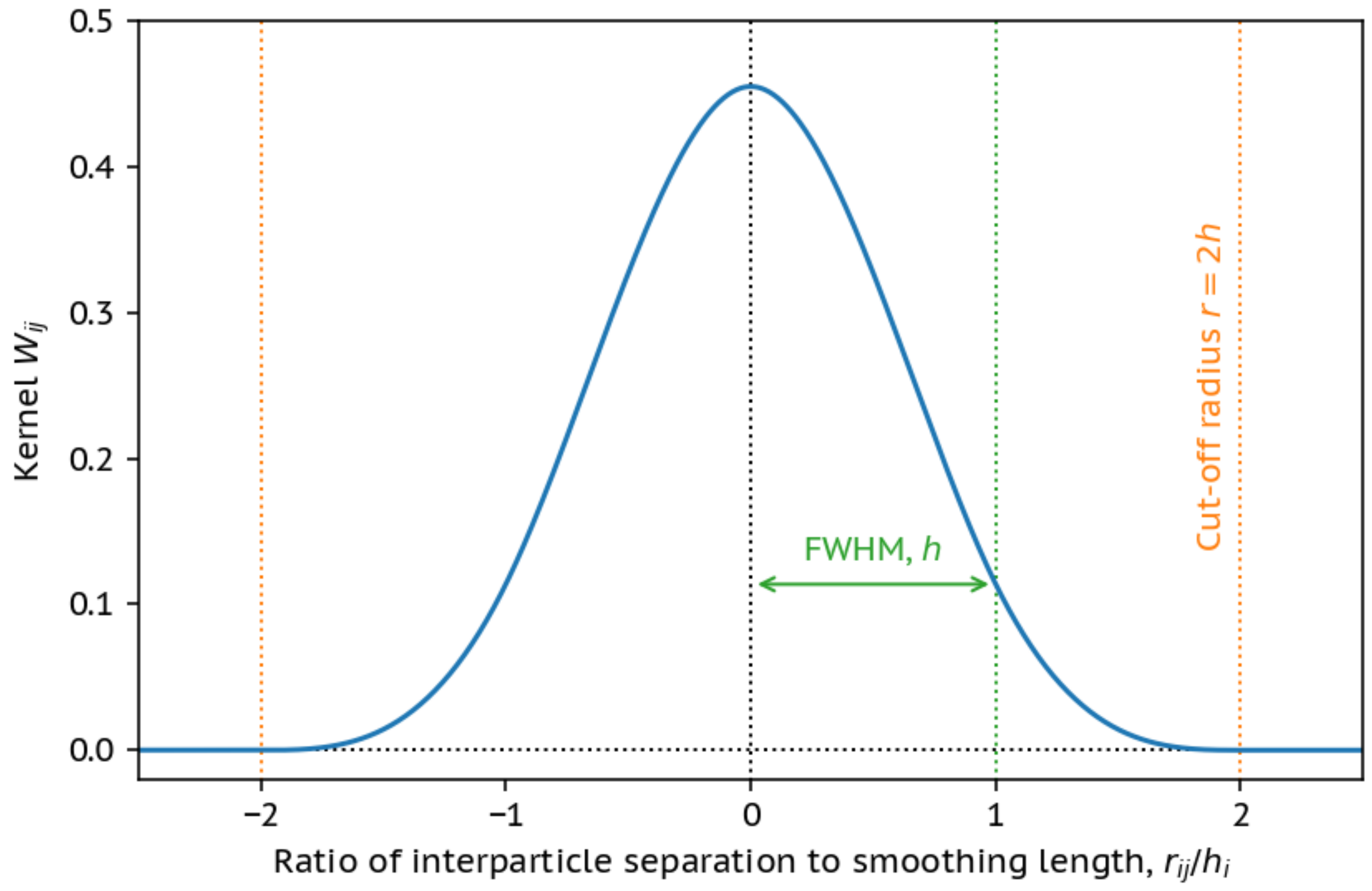
- What if we change the volume we consider for each particle?
- Set R such that our volume encloses 30 particles.
- Density for each particle is then

$$\rho_i = \frac{30 m_{\rm part}}{\frac{4}{3}\pi R_i^3}$$



Turning Down the Noise

- We can do better! We care less about particles that are further away.
- Weight the contribution from each particle with a “kernel”.
- Size kernel to enclose 30 particles within cut-off radius.

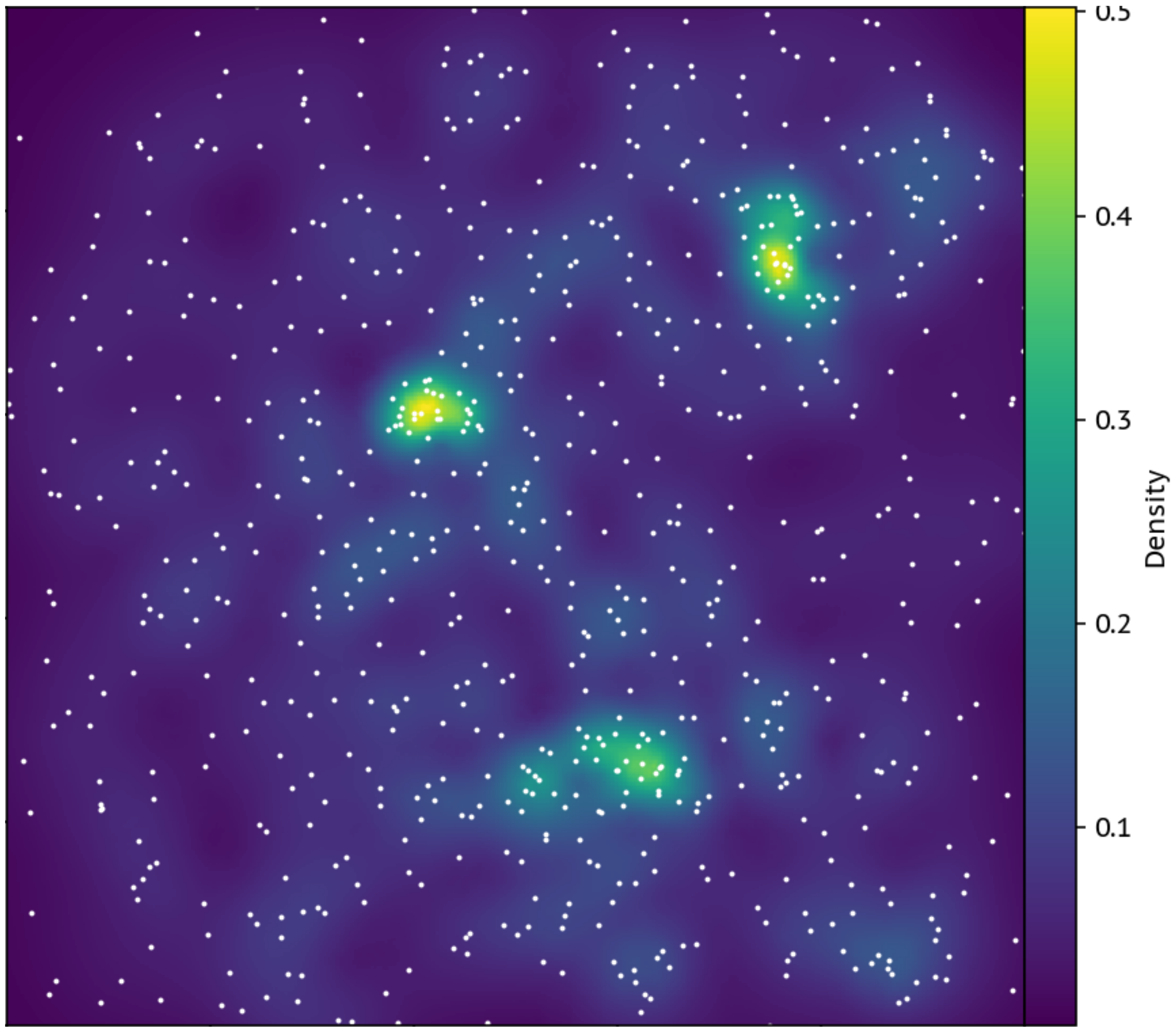


A Smooth Density Estimate

- Density for each particle now given by:

$$\rho_i = \sum_{j=1}^{30} m_{\text{part}} W(r_{ij}, h_i)$$

- Density (+ temperature, tracked by particles) gives pressure, which gives dynamics



Adding in the 'Dynamics'

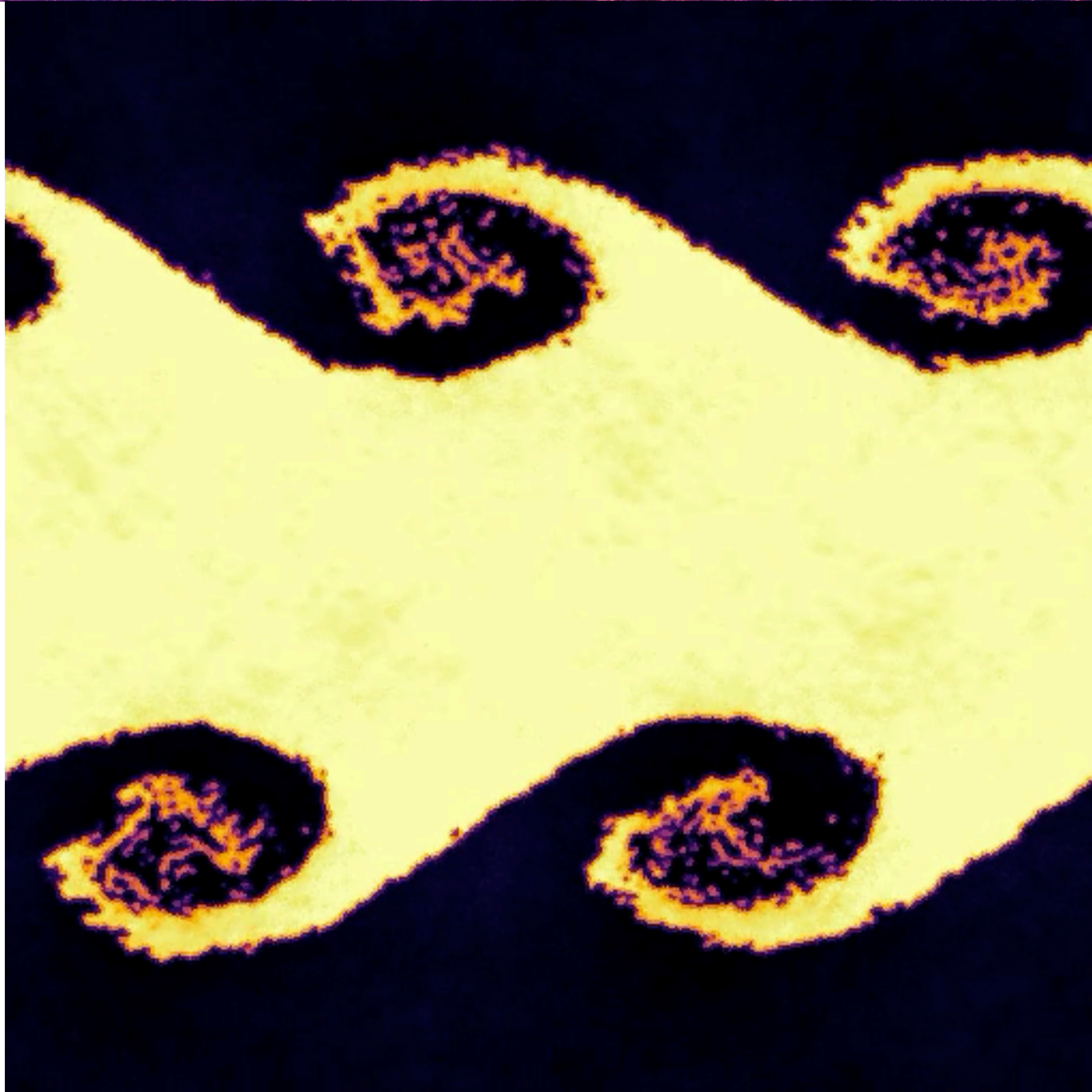
$$L(q,\dot{q}) = \frac{1}{2}\sum_{i=1}^{N} m_i \dot{r}_i^2 - \sum_{i=1}^{N} m_i u_i,$$

+

$$\left.\frac{\partial u_i}{\partial q_i}\right|_A = -\frac{P_i}{m_i}\frac{\partial \Delta V_i}{\partial q_i}, \qquad \phi_i(\mathbf{q}) = \kappa h_i^{n_d}\frac{1}{\Delta\tilde{V}} - N_{ngb} = 0,$$

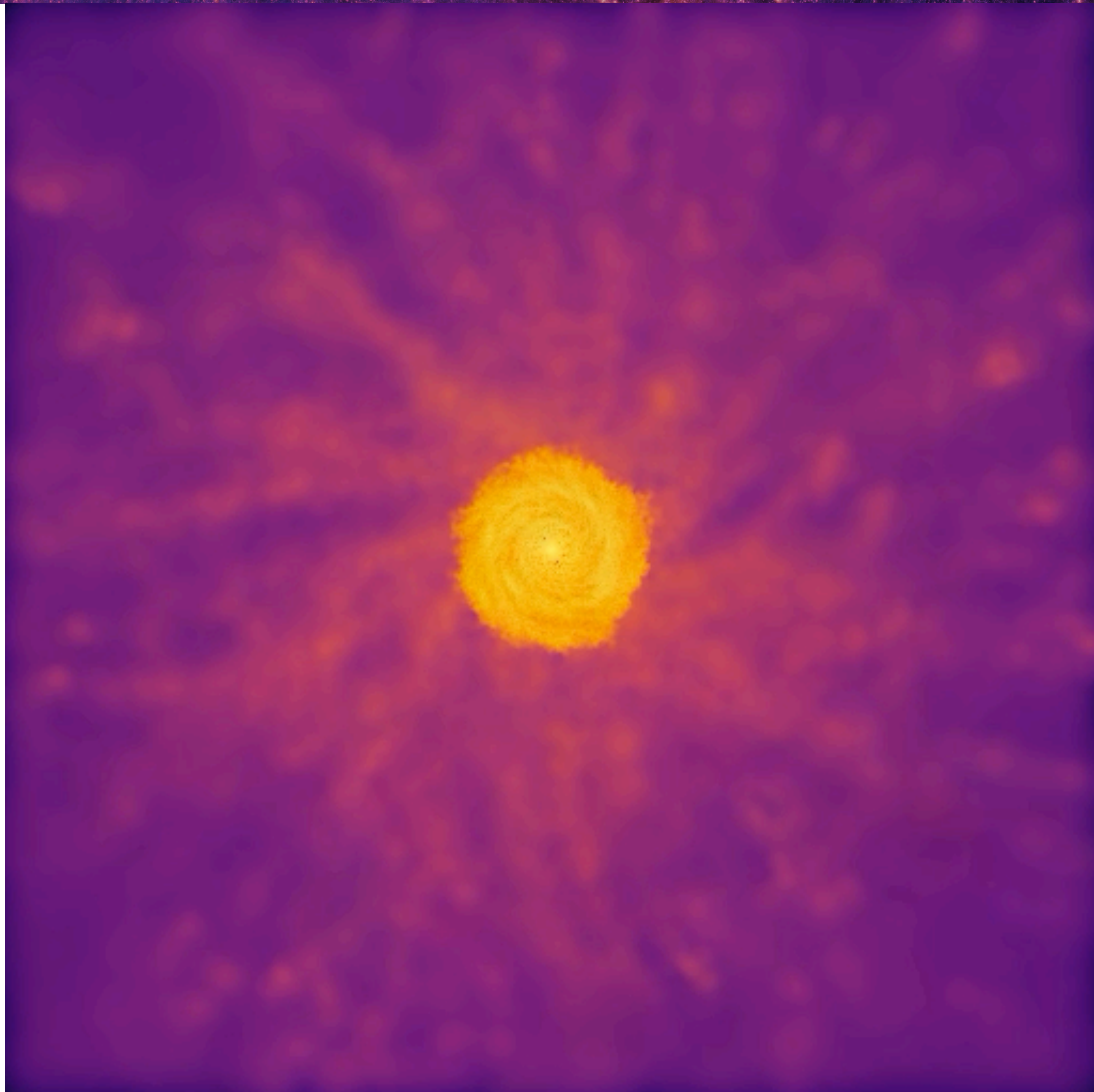
$$m_i \frac{\mathrm{d}\mathbf{v}_i}{\mathrm{d}t} = \sum_{j=1}^{N} P_j \nabla_i \Delta\tilde{V}_j \psi_j + P_j \nabla_i \Delta V_j.$$

$$\frac{\mathrm{d}\mathbf{v}_i}{\mathrm{d}t} = -\sum_{j=1}^{N} x_i x_j \left[\frac{f_{ij}P_i}{y_i^2}\nabla_i W_{ij}(h_i) + \frac{f_{ji}P_j}{y_j^2}\nabla_i W_{ji}(h_j)\right]$$



Sub-Grid Physics

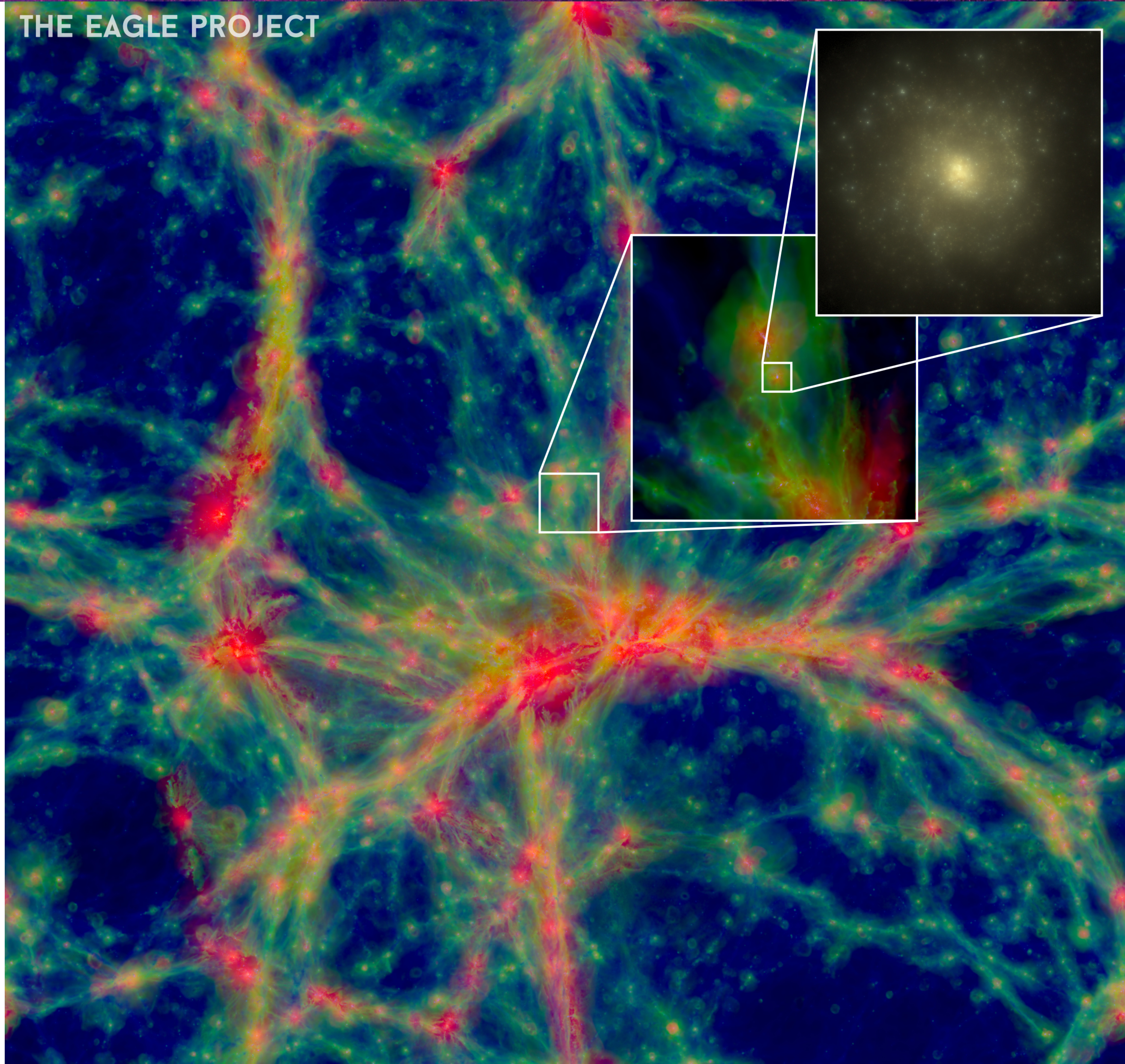
- We cannot resolve everything
- Typical resolution is about 10^6 solar masses
- Lots of processes occur at smaller scales:
  - Gas cooling (atomic transitions...)
  - Star formation
  - Black hole accretion



Galaxy Formation Models

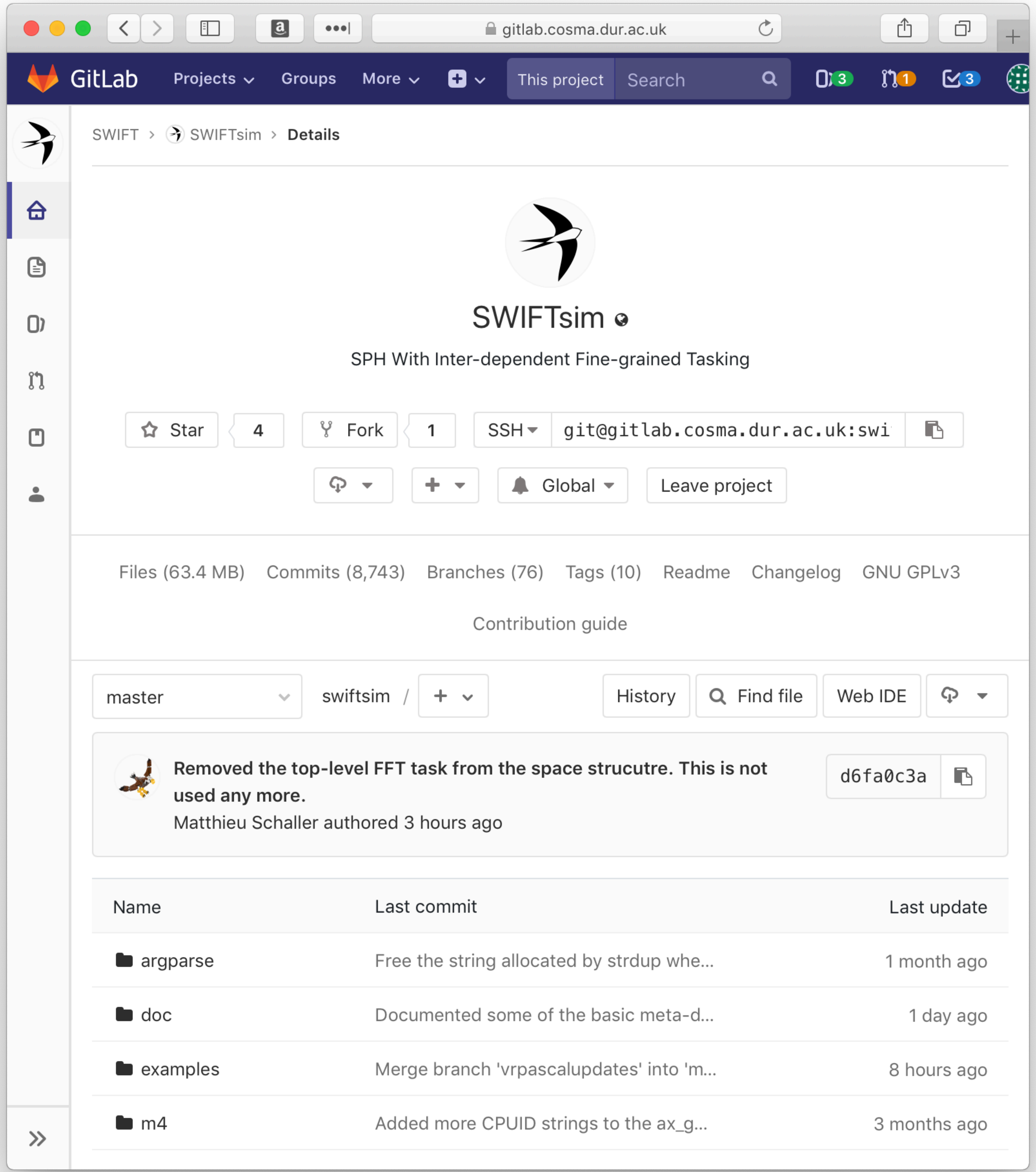
- This 'sub-grid' physics is directly related to the SAMs we discussed before

- They contain similar information, but the full models can be much simpler



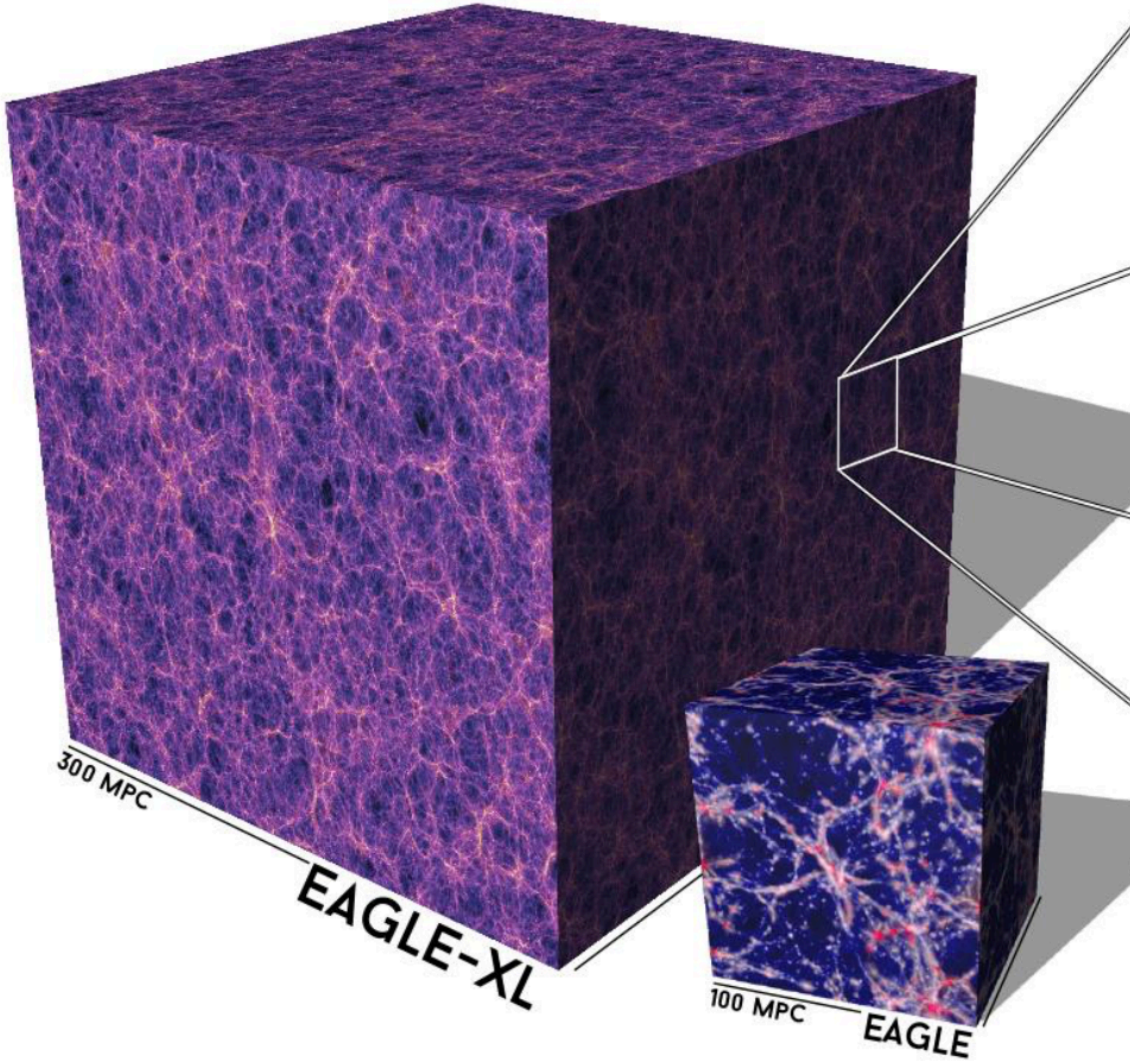
Implementation

- 100’000 lines of open-source C99 code
- Hybrid (MPI + threads)
- Collaboration between astronomy, computer science, and industry
- Supported by DiRAC



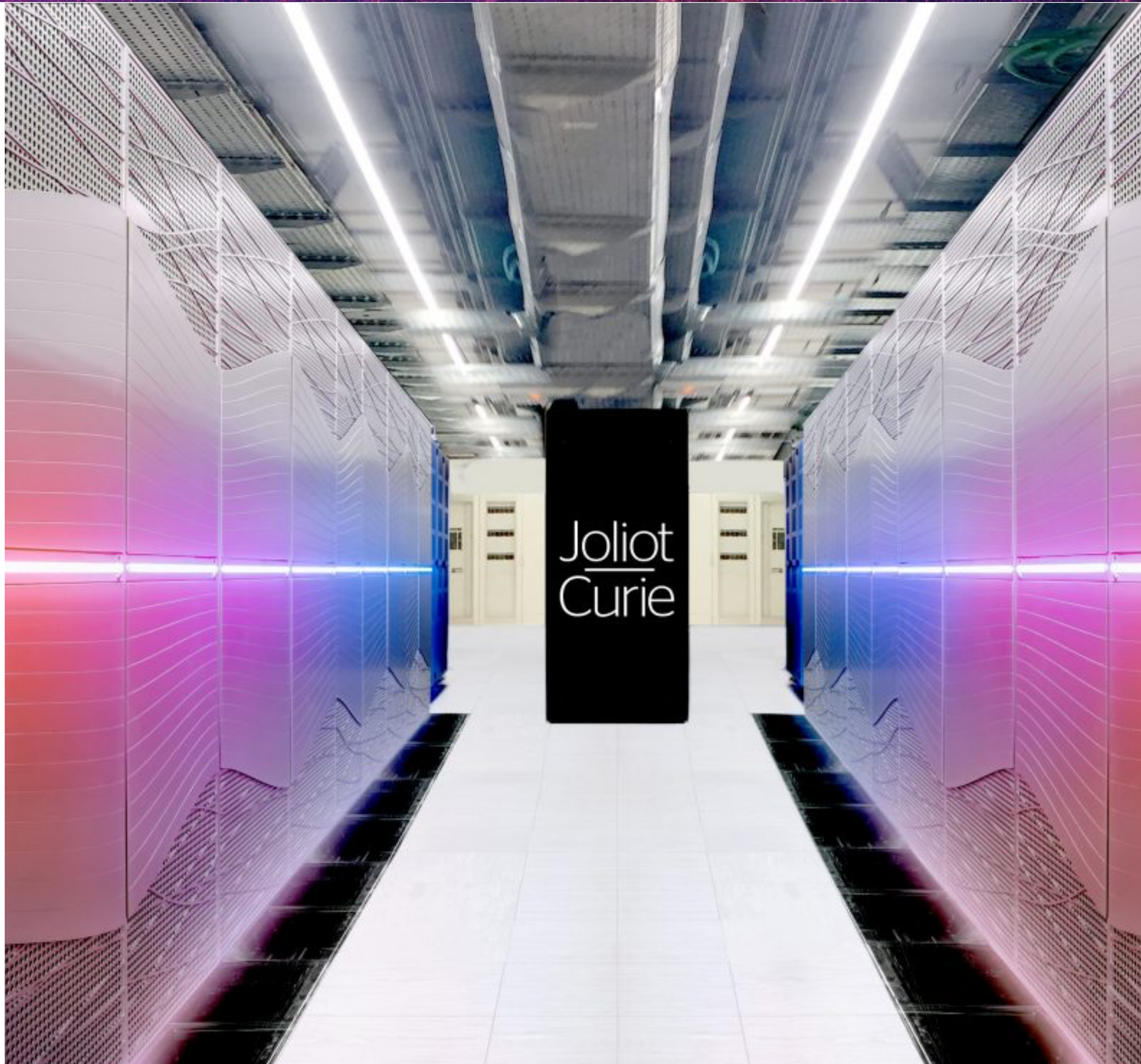
How big?

- Our next big run:
- Nearly **100 billion particles**
- 30’000 galaxies with a mass similar to our own Milky Way
- Each galaxy resolved by 10’000 - 100’000 particles



Computing Resources

- Need Tier-0 resources
- 10s of millions of core hours
- 10’000s of CPUs
- ~200-300 TB of RAM
- Snapshots ~4-5 TB each

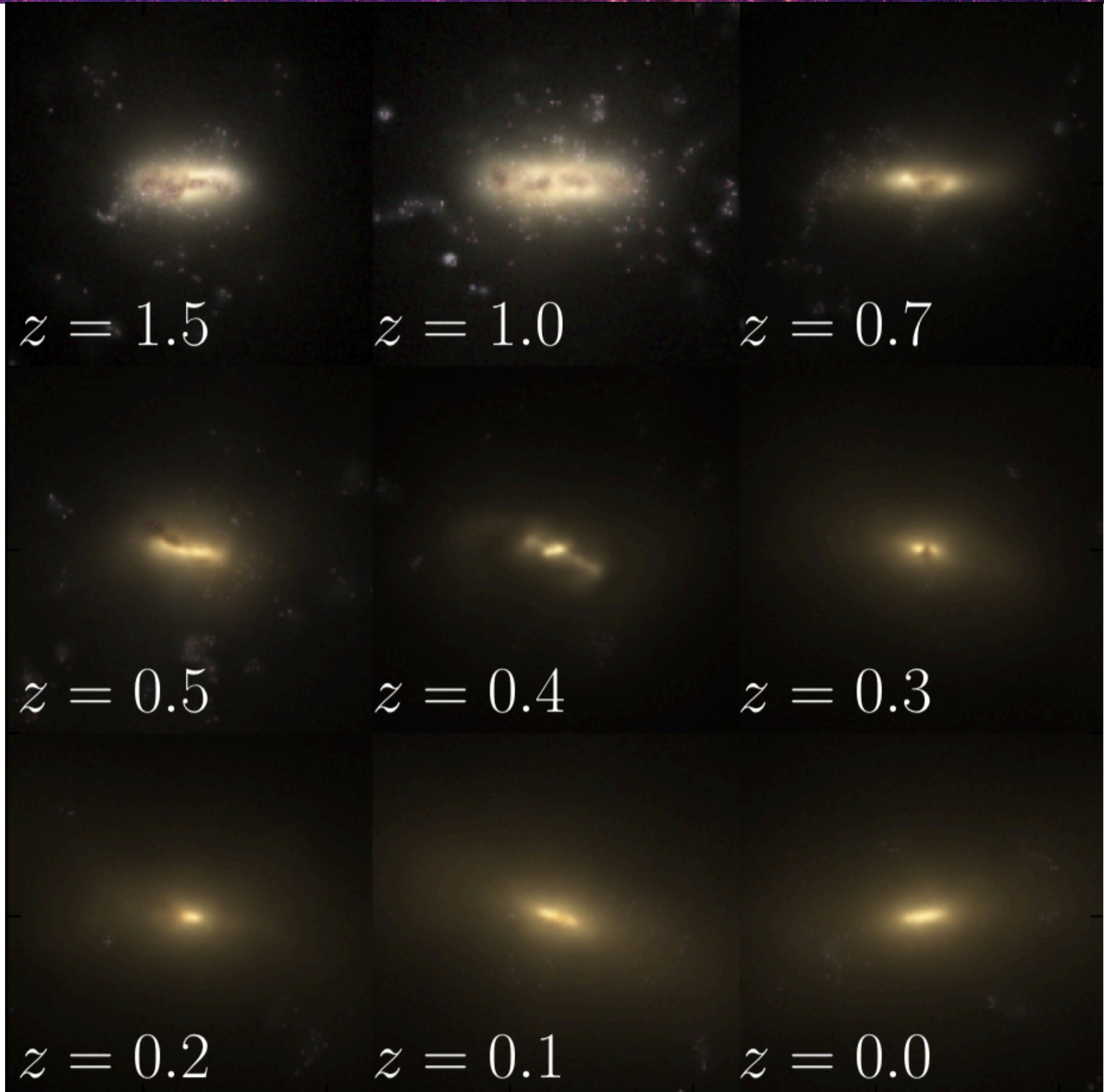


Simulation Output

Seeing Galaxies Grow and Change

- We can see the emergence of the "Tuning Fork" by following *individual* galaxies through their evolution

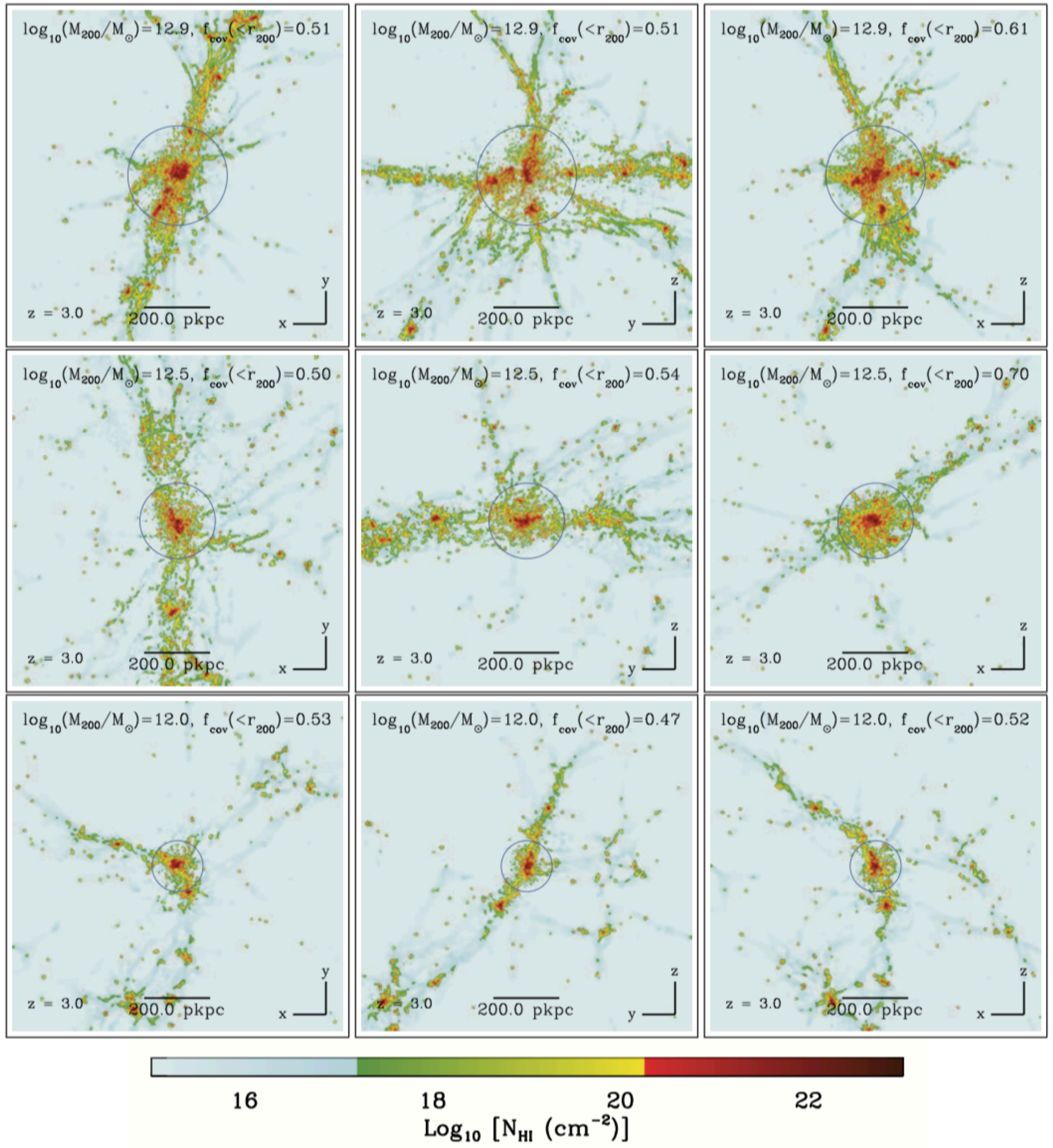
- Turns out that it goes backwards, with Ir -> Spiral -> Elliptical.



Effects on Large-Scale Structure

- Can see how the gas physics changes the morphology of the large-scale structure

- This feeds back into the calibrations (e.g. dust absorption) that we make when observing distant objects.



Huge Predictive Power

- Cosmological simulations have huge predictive power
- They can be used to tell observers where to point their telescopes for the best chance of finding rare objects
- We can also compare abundances of weird objects to see if some are missing, and figure out why.

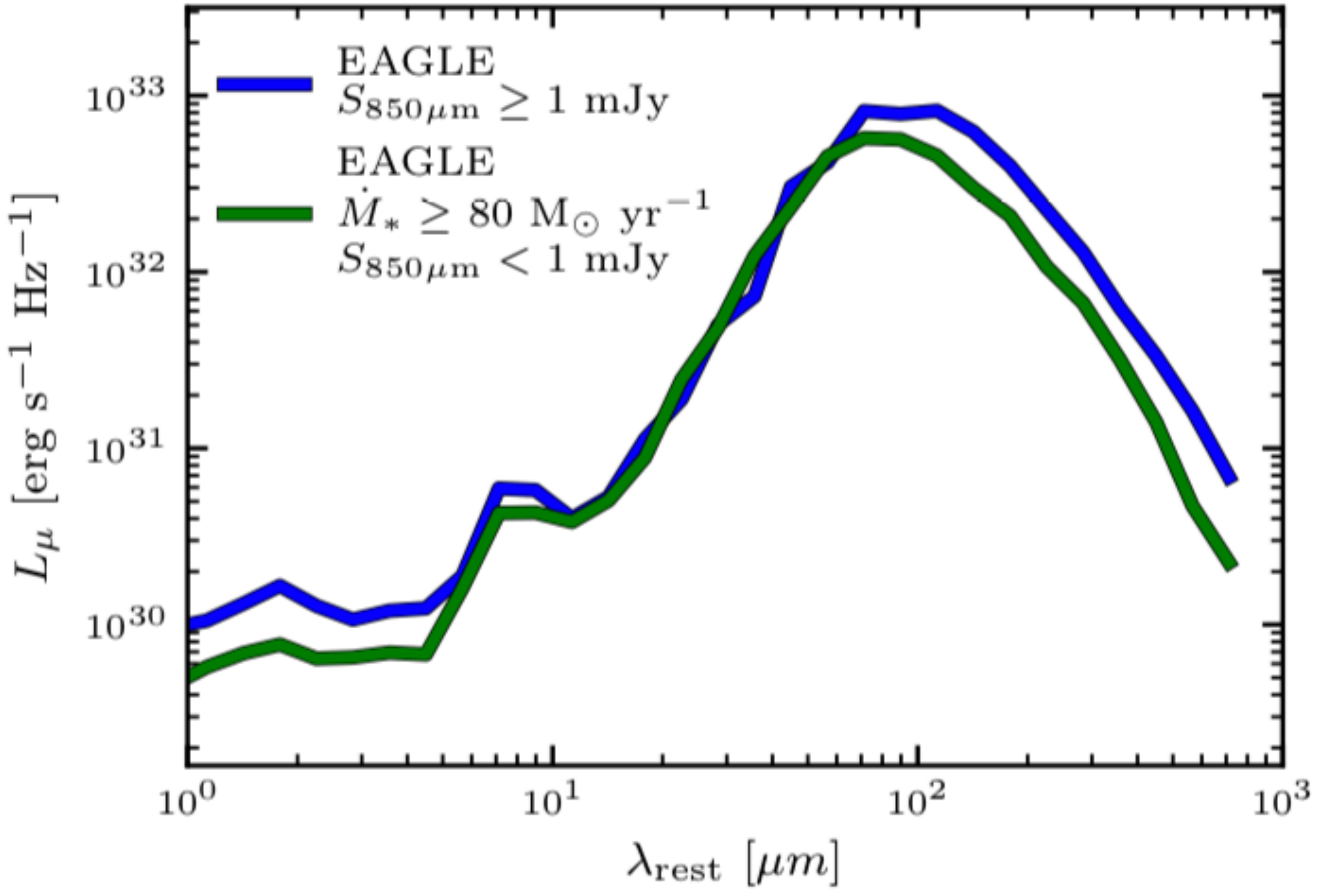


Figure 9. Composite broadband spectral energy distributions (SEDs) for the $S_{850\mu m} \geq 1$ mJy and highly star-forming Submm-Faint galaxies. The leftward shifting of the peak in the dust emission for the highly star-forming Submm-Faint sample signifies hotter dust temperatures than the $S_{850\mu m} \geq 1$ mJy galaxies.

Summary

- Large timescales make cosmology and astrophysics really challenging
- We can address some of this by using cosmological simulations
- To perform a useful calculation, you need some of the largest supercomputers in the world
- We can make pretty movies...