Galaxies

NCTS Summer School Workshop

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NTHU

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Outline

- What are galaxies?
- The astrophysical ingredients of galaxy formation;
- Cosmology and dark matter;
- A simple sketch of current galaxy formation theory;
- A few quick comments on simulations and future observations.

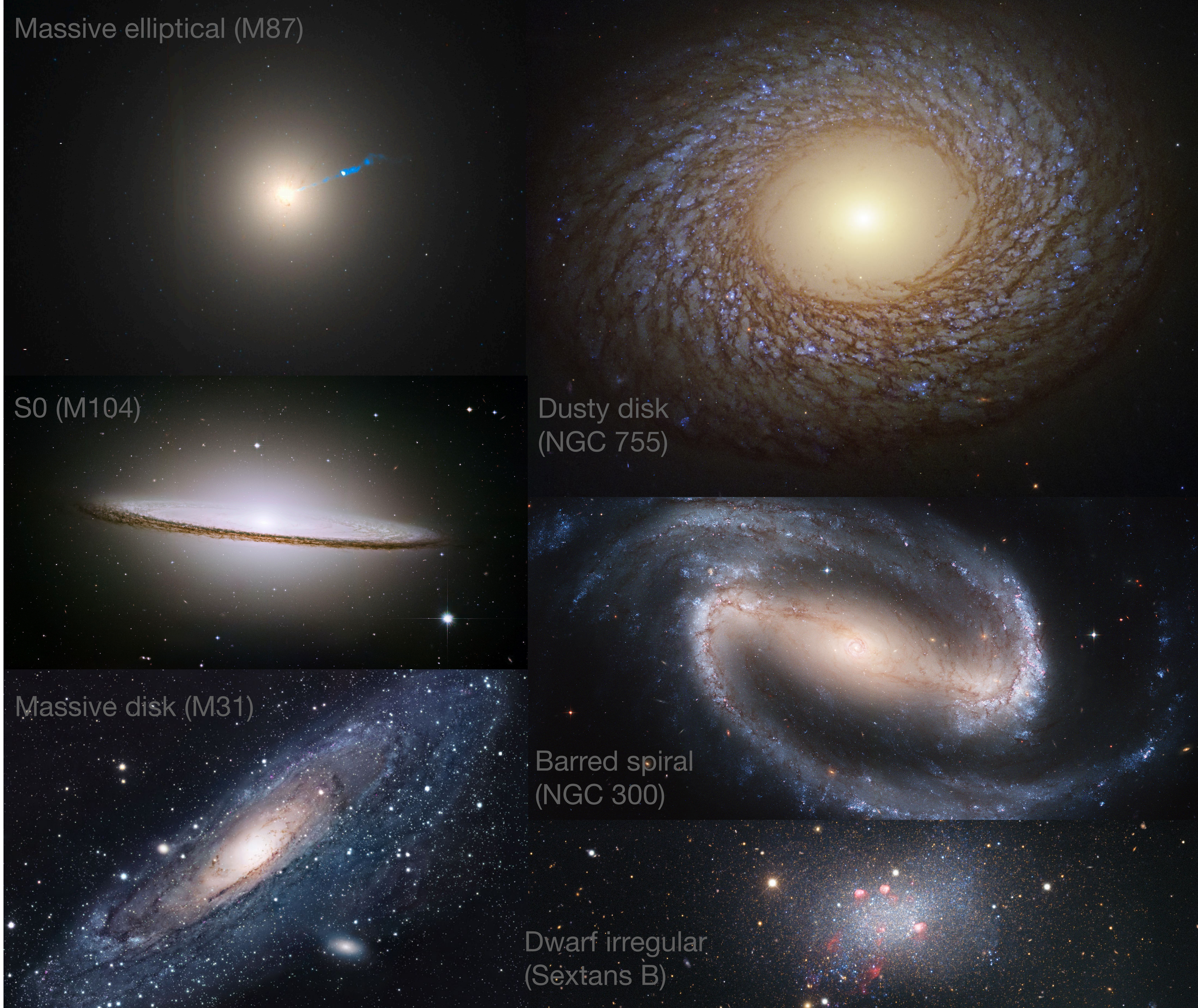
Please “raise hand” to ask questions. Write your question in the chat window. You are welcome to ask questions by email, WebEx chat or Slack (program students) after the talk and any time during the workshop.

This is a theory-oriented talk aimed at undergraduate students on our NCTS summer program.

The ⚠️ symbol appears where I’ve deliberately ignored something important for simplicity.

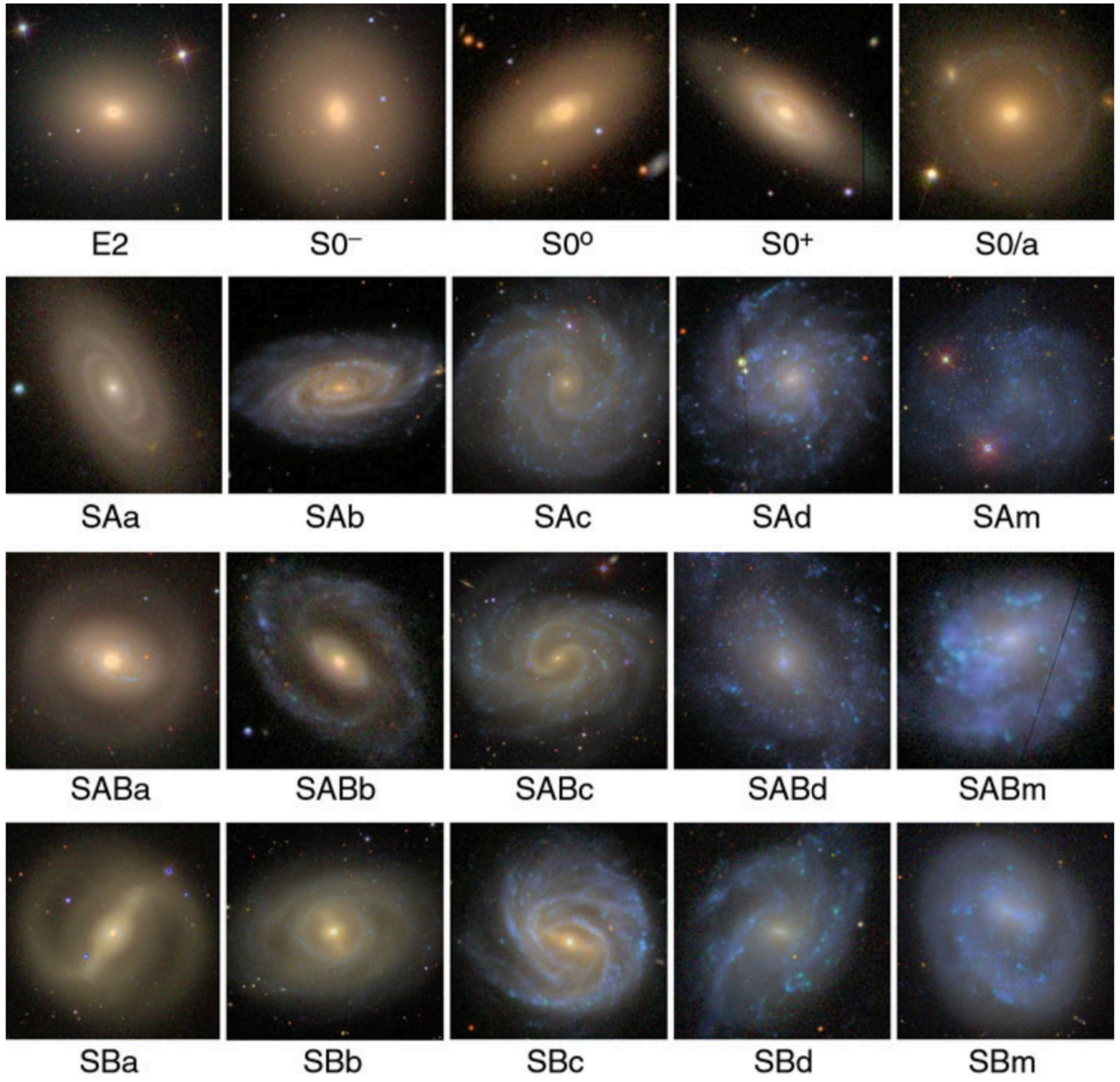
What are galaxies?

- Collections of stars, gas, dust and black holes (**baryons**).
- Bound together by the gravity of a much larger mass of **dark matter**.
- The Milky Way has a stellar mass of $\sim 6 \times 10^{10}\,\mathrm{M}_\odot$ and a stellar radius of $\sim 15\,\mathrm{kpc}$.



What is the galaxy population?

- There are lots of different types of galaxy: bright/faint, red/blue, elliptical/disk/irregular…
- We live an era of 'massive' surveys (1-100M objects, e.g. SDSS), soon to get bigger (e.g. Rubin/LSST), covering wavelengths from X-ray to radio over large fractions of the sky.
- These data have given us a big-picture overview of almost the whole **galaxy population**, at least at low redshift.



R.J. Buta, *Planets Stars and Stellar Systems V6, Ch. 1, Fig. 1-48, Springer, 2013*

Large scale trends in the galaxy population

Big picture: the statistics of galaxies and the correlations between their properties.

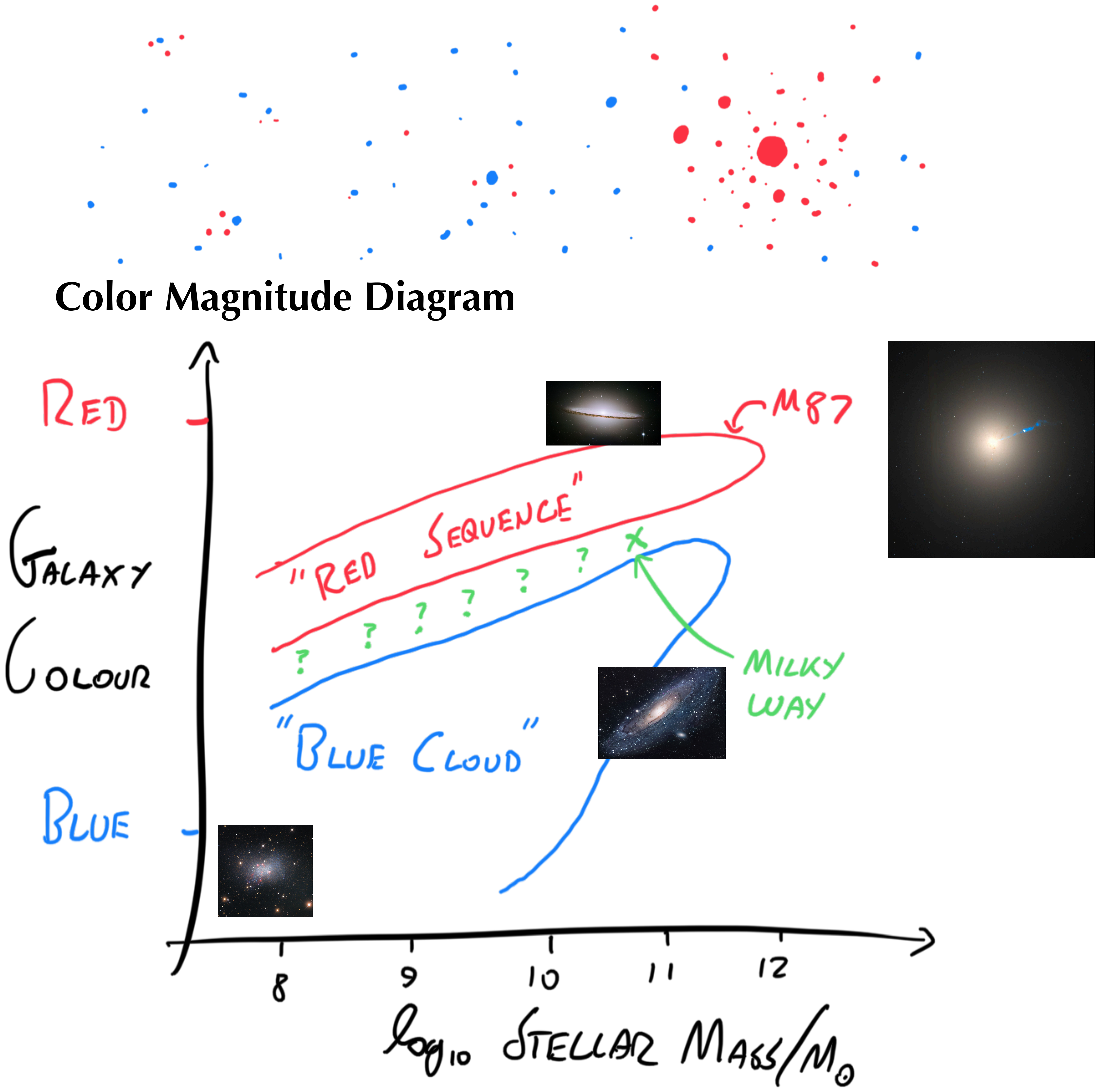
- There are more faint galaxies than bright ones:

Galaxy Stellar Mass Function
(present day)

Large scale trends in the galaxy population

Big picture: the statistics of galaxies and the correlations between their properties.

- There are more faint galaxies than bright ones;
- Brighter galaxies tend to be redder and older;
- Brighter galaxies tend to be ellipticals;
- Brighter galaxies cluster together more;
- Brighter galaxies have bigger central black holes;
- Etc. Etc.

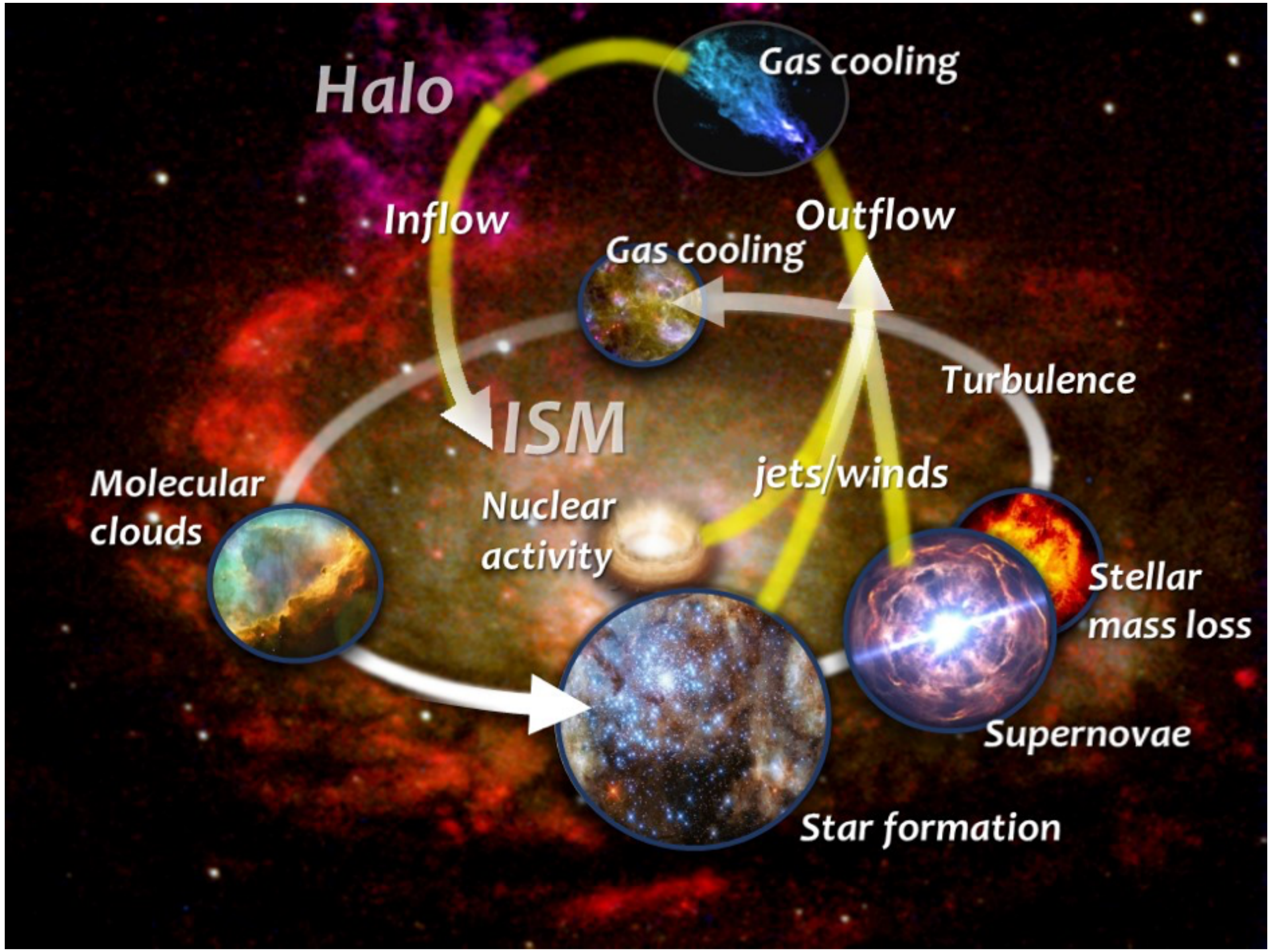


Why?

Baryonic astrophysics

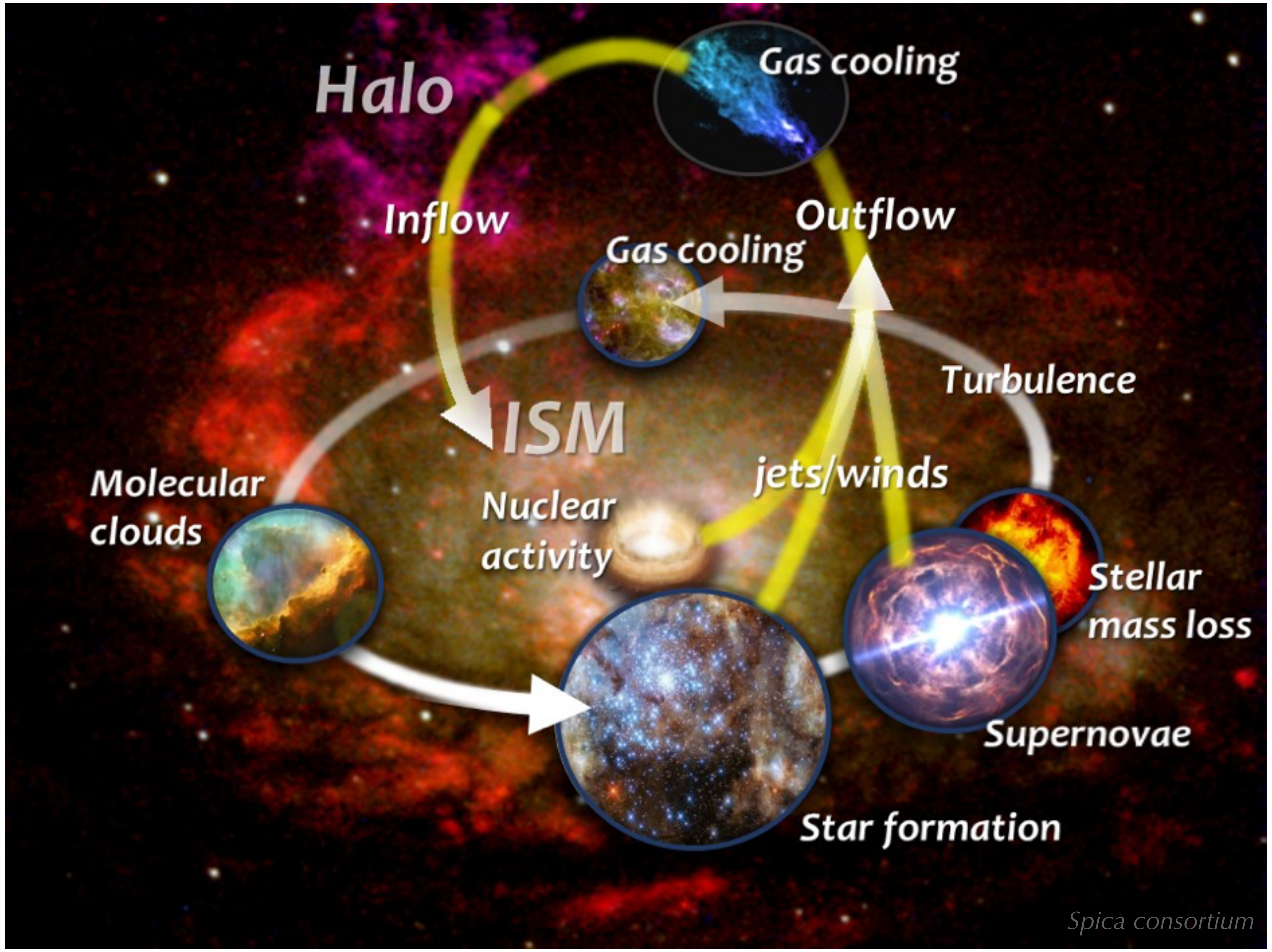
- To make a galaxy-sized mass of stars, we need a galaxy-sized lump of gas (baryons, i.e. ordinary matter, mostly hydrogen) that is very dense and very cold (10K).
- I'll talk about where those lumps of cold gas come from later.
- Once dense gas starts turning into stars, a cycle begins that involves many different astrophysical processes acting simultaneously.
- The interactions between these processes determine the rate of ongoing star formation and change the appearance (shape, color, gas content) of the galaxy over time.
- **This is often call the *baryon cycle*.** Most parts of the cycle will be covered by other talks in the workshop.

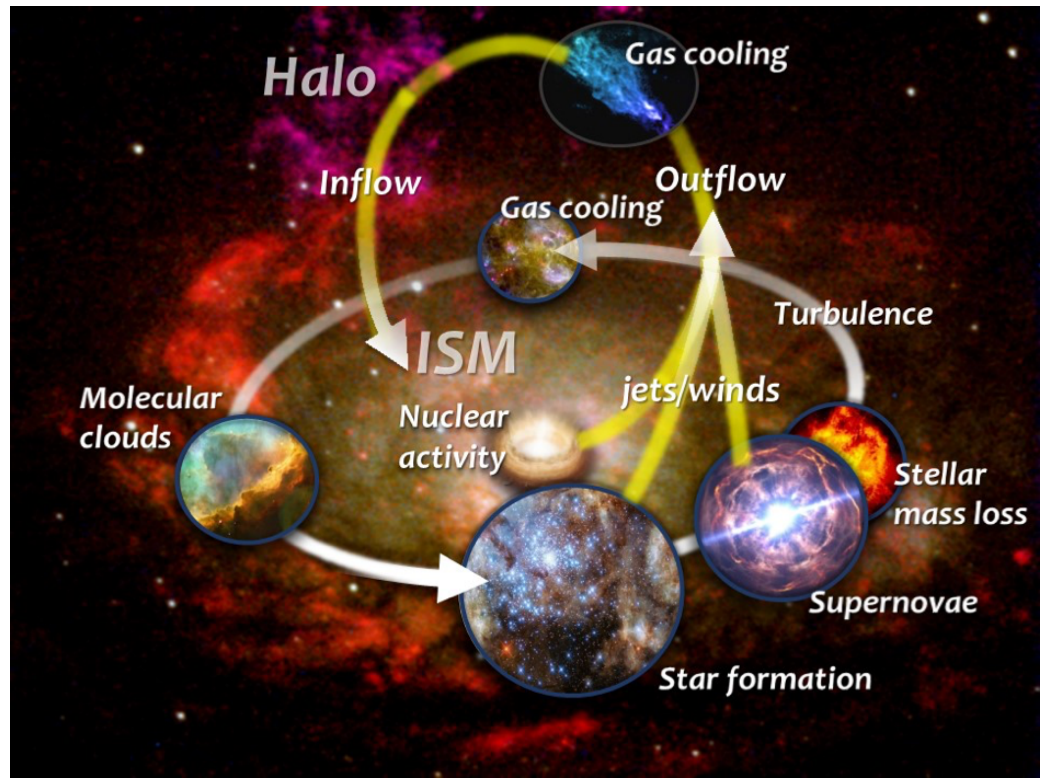
Spica consortium



Baryonic astrophysics

- On small scales, the astrophysics that drives the baryon cycle is extremely complicated.
- Small scales: timescales ranging from seconds to megayears, spatial scales from microns to parsecs, mass scales from 0.1 to 10,000 (or 1M) $M_\odot$.
- Galaxy formation is the average outcome of all these processes interacting over much longer/larger scales.
- **We can try to explain observations of galaxies and statistics of the galaxy population even if we don't have a complete understanding of all these processes.**





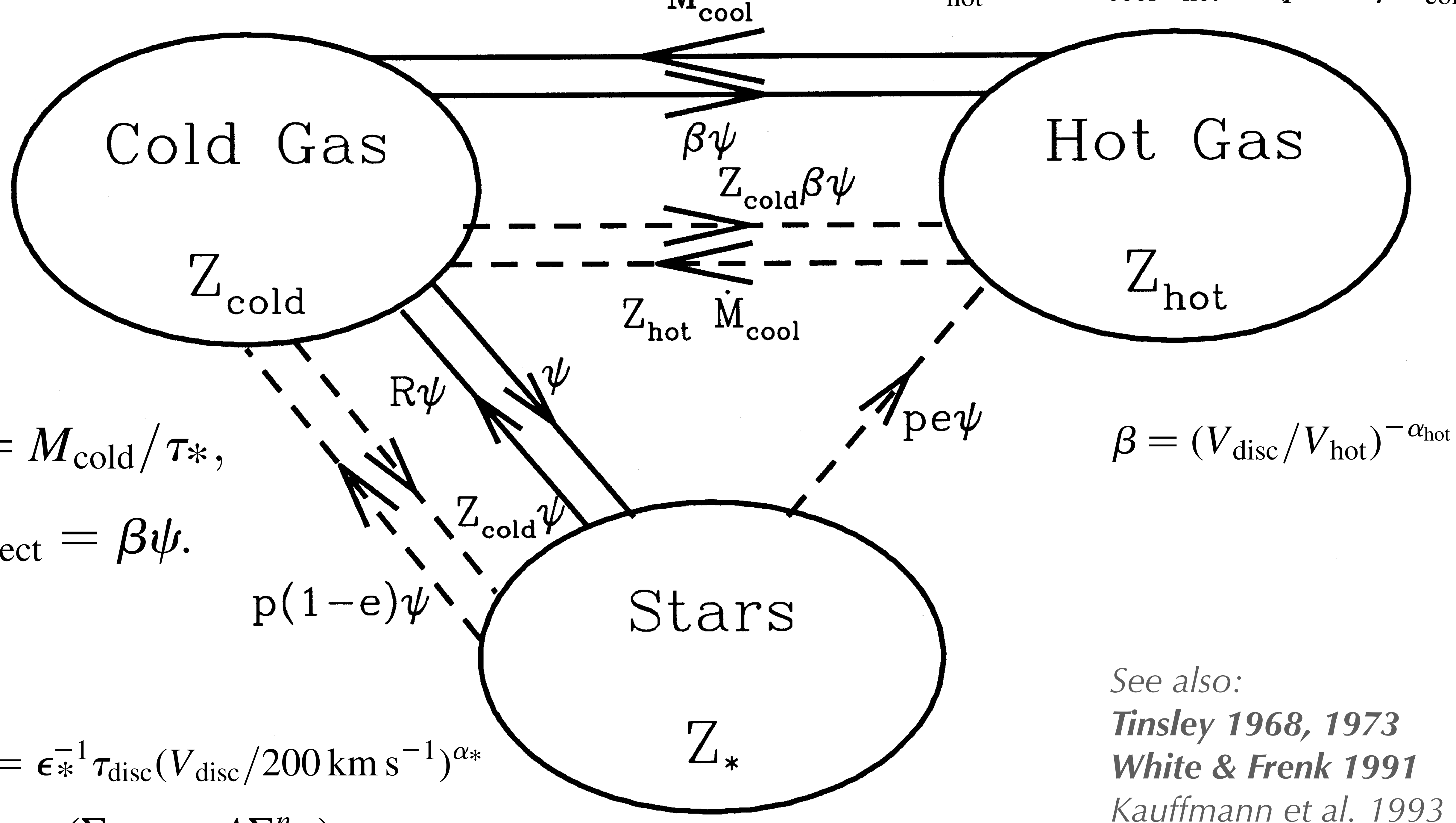
Galaxy formation models

- We can think of the arrows on the baryon cycle cartoon as a **network of coupled partial differential equation equations**.
- These describe the ‘flow’ of baryons between different ‘phases’ (hot gas, cold gas, stars, black holes…).
- They are **physical** equations, but they’re ‘macroscopic’; they apply to whole galaxies rather than individual star-forming clouds.
- **A model of galaxy formation involves specifying these equations and solving them.** ⚠️

Cole et al. 2000 (the GALFORM model)

$$\dot{M}_{\rm cold} = \dot{M}_{\rm cool} - (1 - R + \beta)\psi$$
$$\dot{M}^Z_{\rm cold} = \dot{M}_{\rm cool}Z_{\rm hot} + [p(1-e) - (1+\beta-R)Z_{\rm cold}]\psi,$$

$$\dot{M}_{\rm hot} = -\dot{M}_{\rm cool} + \beta\psi$$
$$\dot{M}^Z_{\rm hot} = -\dot{M}_{\rm cool}Z_{\rm hot} + (pe + \beta Z_{\rm cold})\psi$$



$$\psi = M_{\rm cold}/\tau_*,$$
$$\dot{M}_{\rm eject} = \beta\psi.$$

$$\beta = (V_{\rm disc}/V_{\rm hot})^{-\alpha_{\rm hot}},$$

$$\tau_* = \epsilon_*^{-1}\tau_{\rm disc}(V_{\rm disc}/200\,{\rm km\,s^{-1}})^{\alpha_*}$$
$$(\Sigma_{\rm SFR} = A\Sigma^n_{\rm gas})$$

$$\dot{M}_* = (1-R)\psi$$
$$\dot{M}^Z_* = (1-R)Z_{\rm cold}\psi$$

See also:
Tinsley 1968, 1973
White & Frenk 1991
Kauffmann et al. 1993
Croton et al. 2005
Bower et al. 2006
Lacey et al. 2016

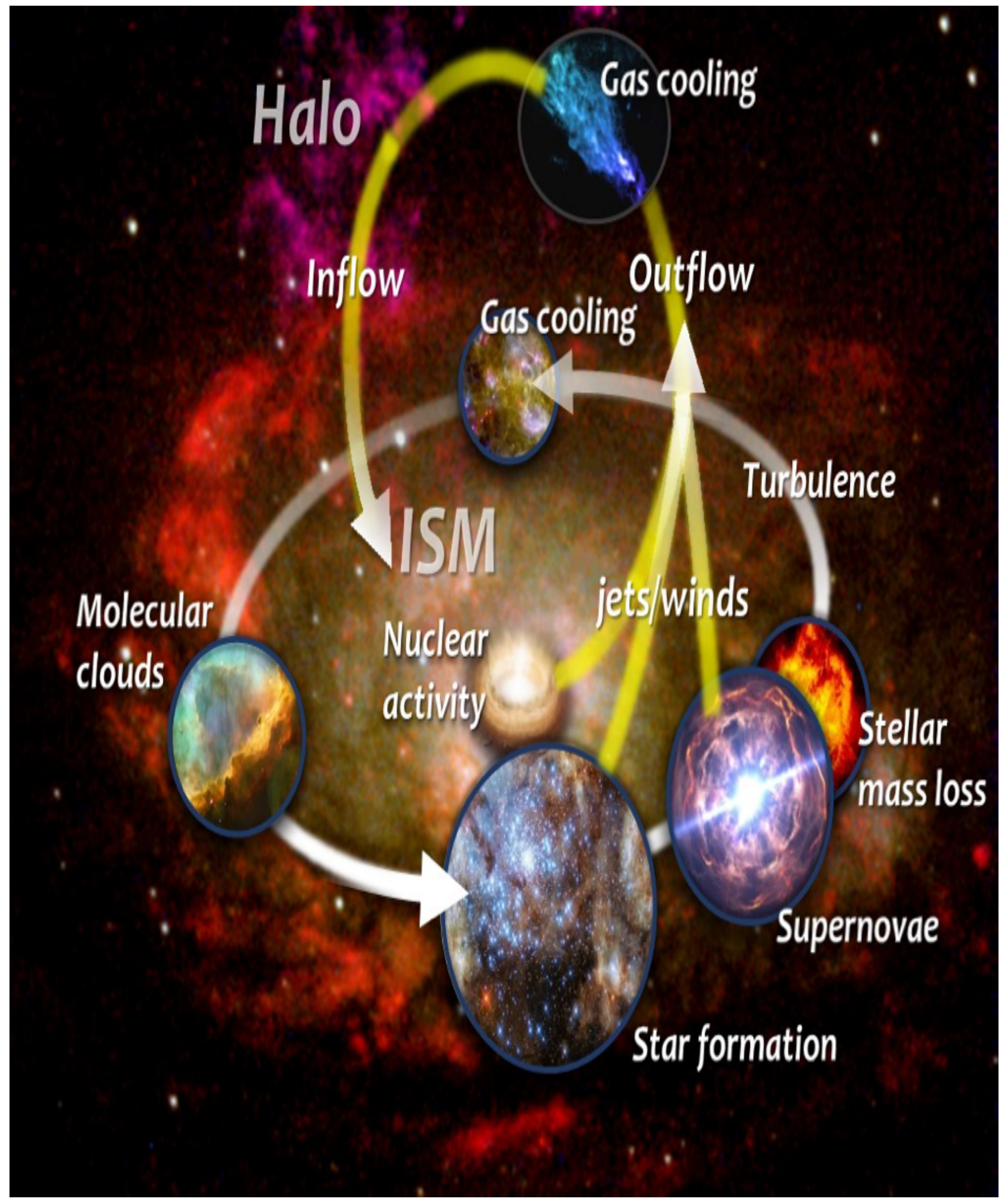
Predicting galaxy formation

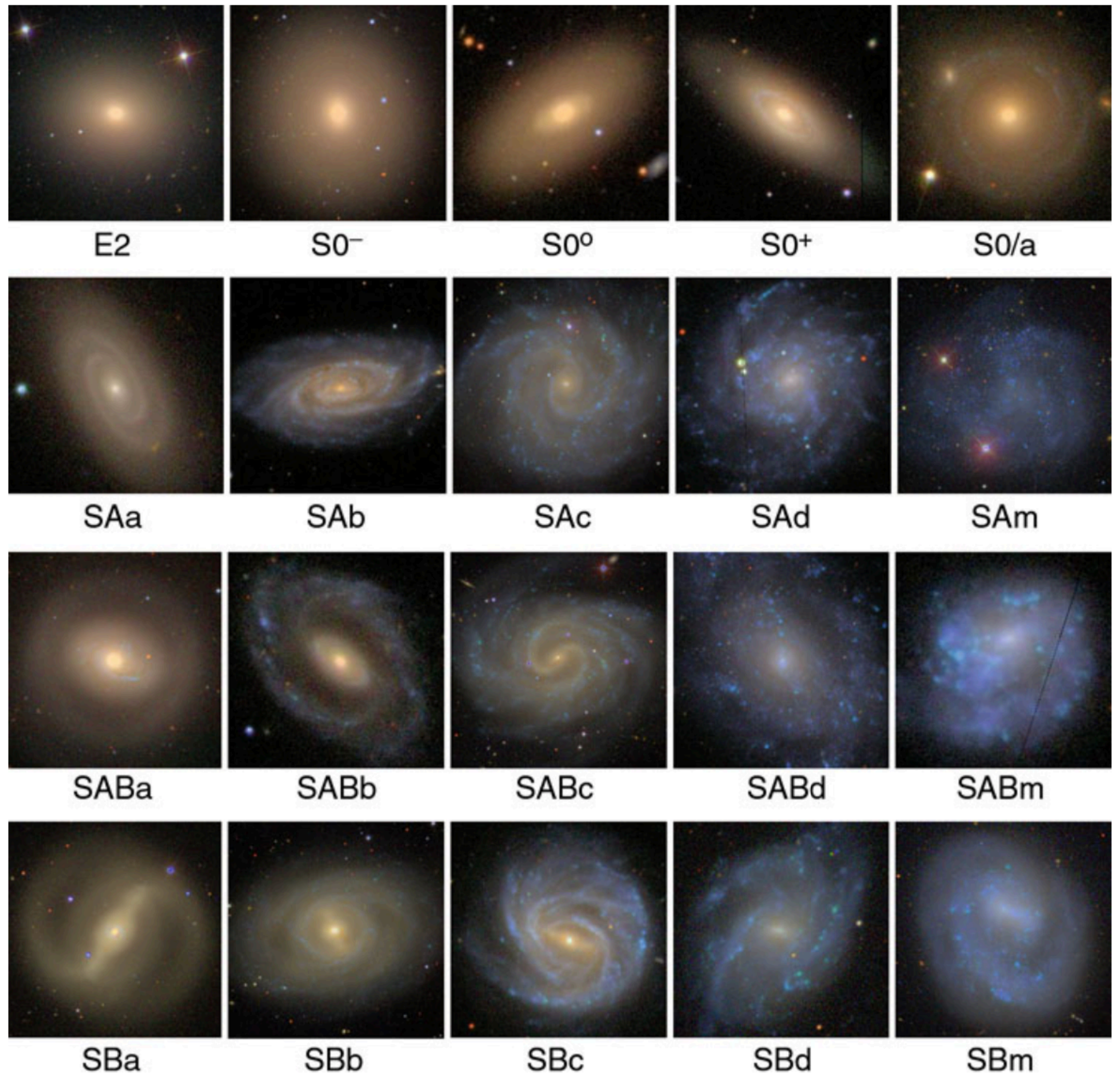
- Predicting the outcome of galaxy formation requires solving those equations **over 0.1-10 billion year** timescales.
- To do that, we need **initial** and **boundary conditions**.
- For example, is the amount of gas available to each galaxy the same? Where does the gas come from? Does it all arrive in the galaxy at once, or slowly? Can gas flow out of the galaxy?
- We want to predict statistics of the galaxy population. Why are there more faint galaxies than bright ones? What ratio of red to blue galaxies do we expect? Why are redder galaxies larger? Etc.

Initial and Boundary Conditions

- With different initial conditions, boundary conditions and timescales, the same processes can produce **very different results**, for individual galaxies and hence population statistics.

- **The initial and boundary conditions for galaxy formation come from cosmology.**

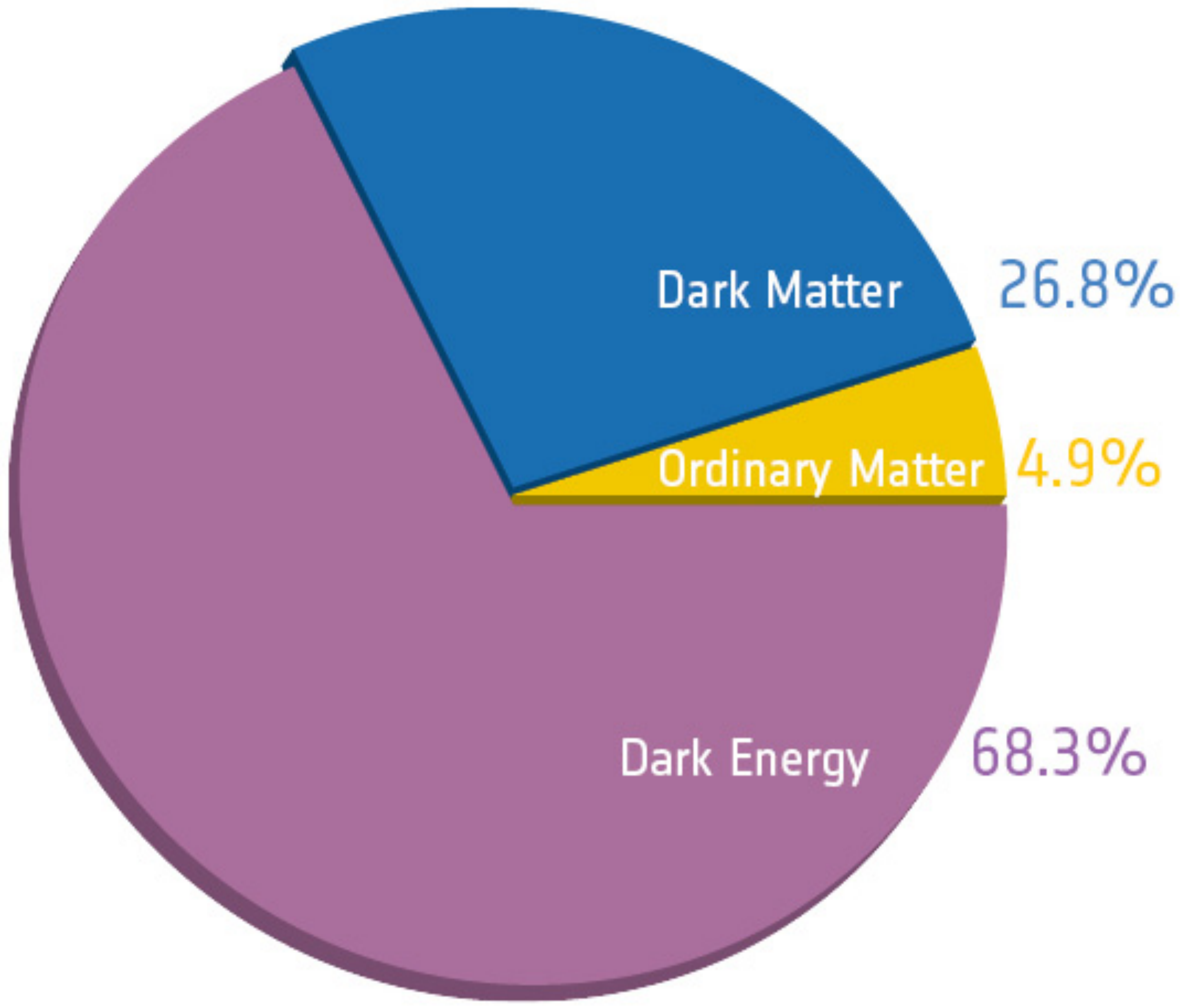




Cosmology

Cosmology is very important

ESA / Planck Collaboration



- A cosmological model describes the content and structure of the Universe as a whole, and how it evolves with time.
- Progress in observational cosmology (mostly over the last 40 years, built on fundamental work by **Peebles**, Zel'dovich and others) has been vital for improving our understanding galaxy formation. The next few slides will explain why.
- A few basic cosmological results:
  - The Universe is expanding from a singularity. It is about 13.7 billion years old.
  - The rate of expansion (~70 km/s/Mpc) depends on the average density of mass and energy in the Universe.
  - The expansion has started to accelerate in the last few billion years.

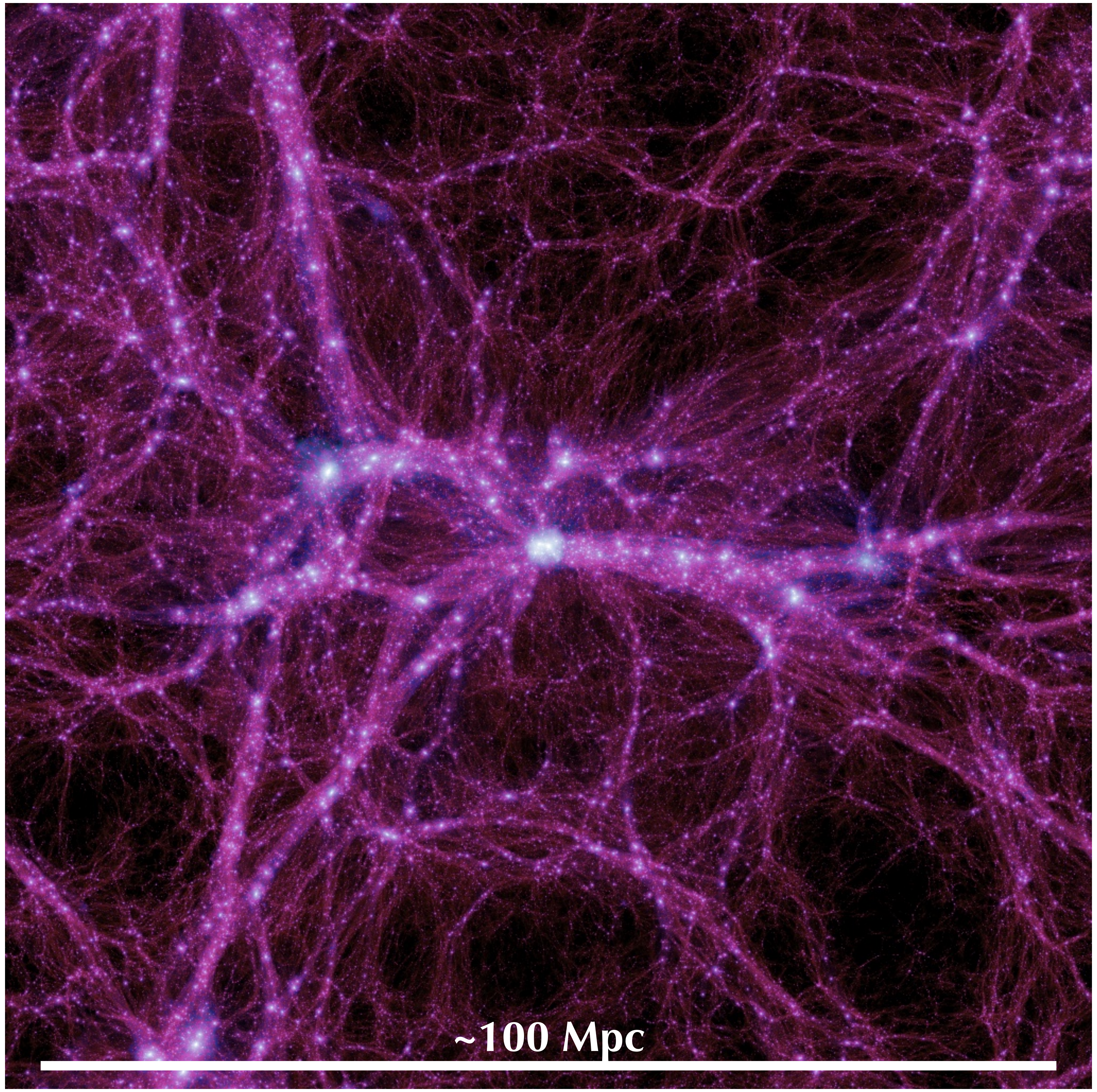
Modern galaxy formation theory is built around the strong evidence that ~80% of the gravitating matter in the Universe is **cold dark matter** (CDM), and 20% ordinary baryons. All that matter is only 25-30% of the total energy density in the Universe! The rest is dark energy. This framework is the ΛCDM model.

The cold dark matter model

The gravity of the dark matter allows patches of the Universe break away from the Hubble expansion and collapse back to very high densities.

These are **dark matter halos**. On megaparsec scales, they are distributed a pattern called the **cosmic web**.

Millennium II simulation
Boylan-Kolchin & Virgo Consortium



ΛCDM boundary conditions for galaxy formation

We can make very precise predictions in the ΛCDM model, because:

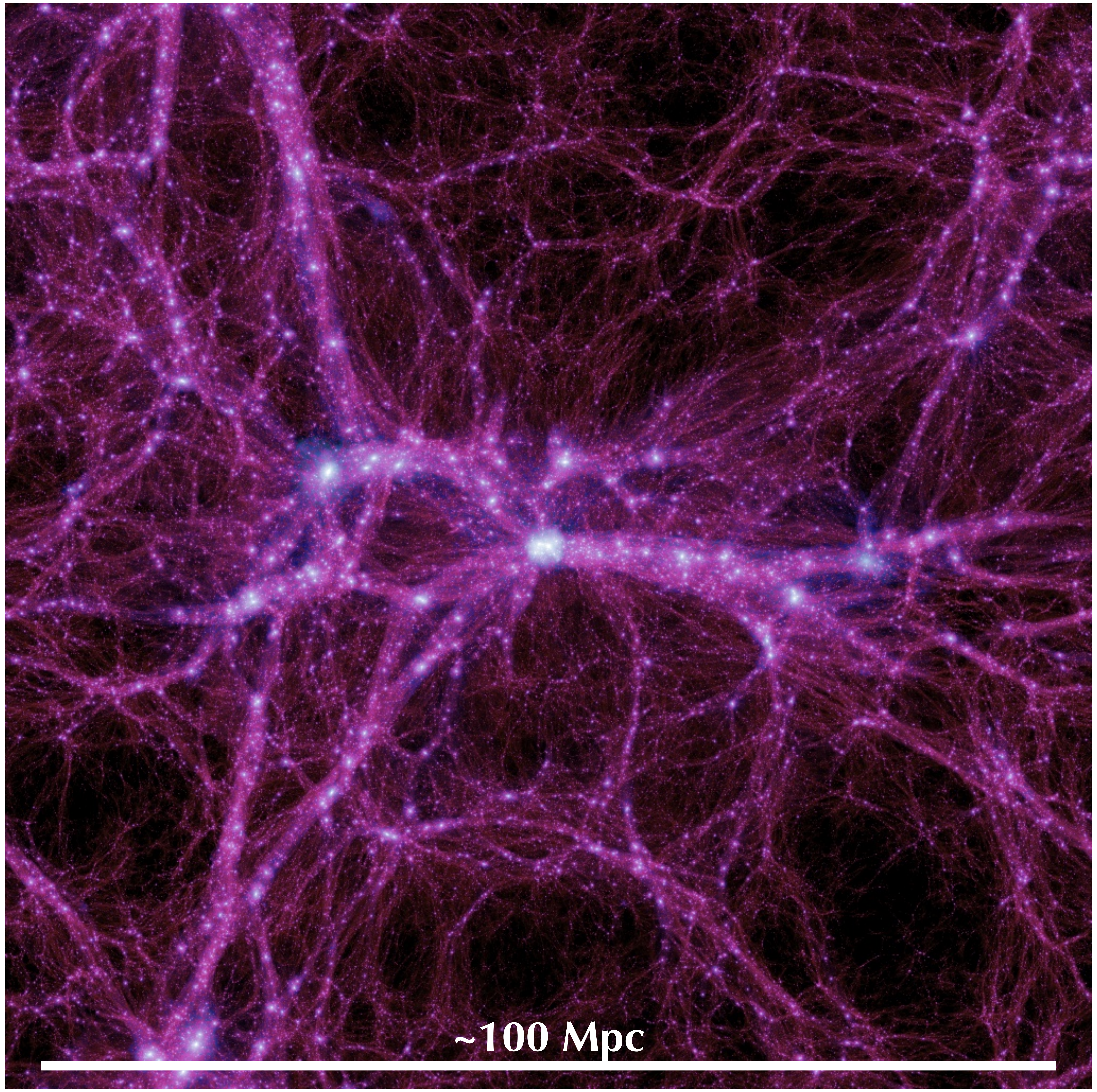
- The underlying physics is simple (gravity);
- The model is specified by a fairly small number of parameters, which have been measured to high accuracy with a variety of independent methods.

Since cosmological predictions are so well specified with current constraints on ΛCDM, it is a very robust starting point for studying galaxy formation, even though the nature of the dark matter and dark energy remain unknown.

In particular, ΛCDM predicts the **number** of dark matter halos of a given mass, **when** they form, how they **grow in mass over time**, and how they are **distributed** in space.

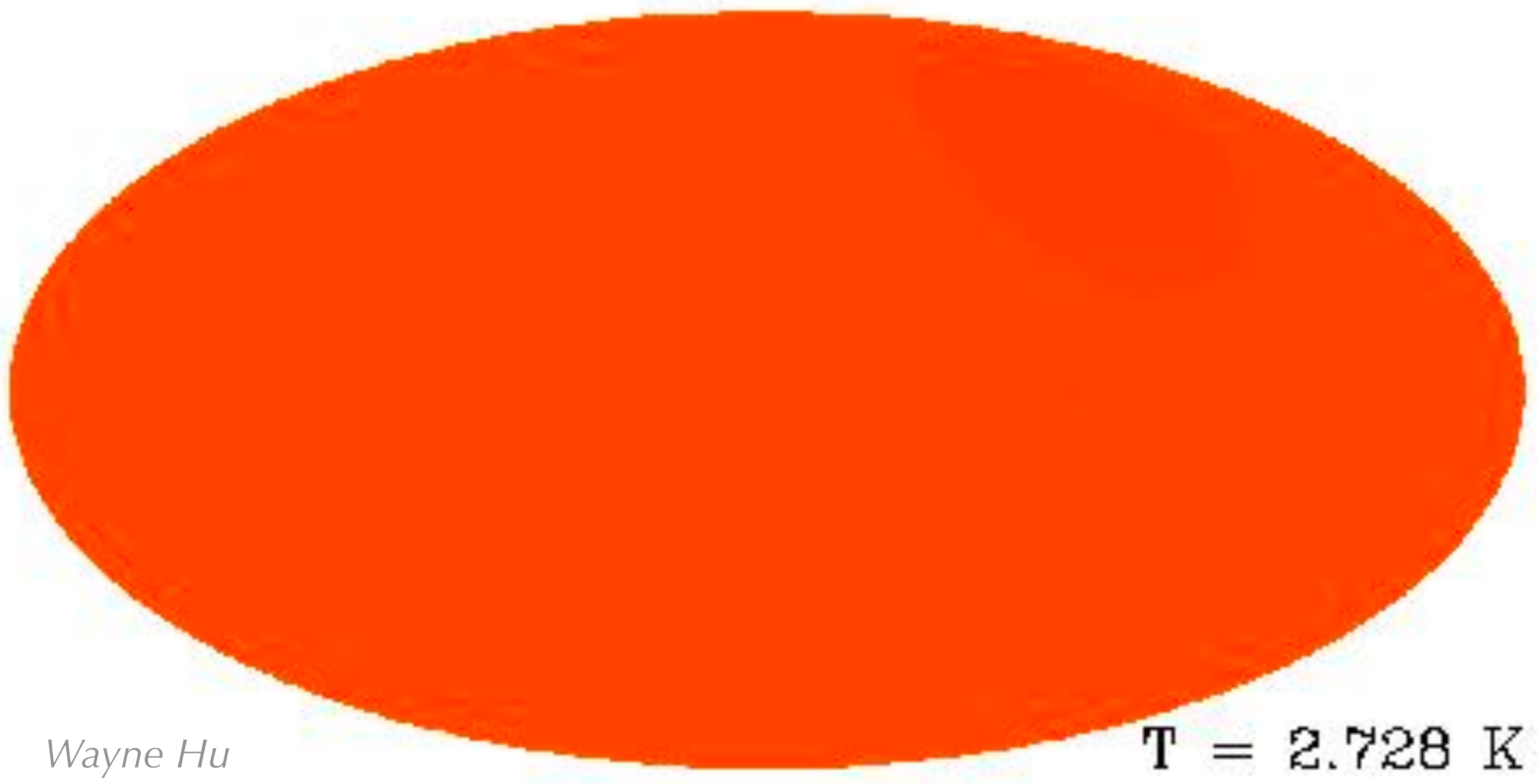
These are the **initial and boundary conditions** we need to solve the equations of galaxy formation.

Millennium II simulation
Boylan-Kolchin & Virgo Consortium



The Cosmic Microwave Background

The **CMB** is near-uniform isotropic radiation with a 2.75K blackbody spectrum.



Wayne Hu

It consists of photons that were last scattered at the **epoch of recombination,** 300,000 years after the Big Bang.

Before then, the Universe was filled with a **hot homogeneous plasma** of photons, free electrons and protons. The Universe was opaque, because photons were very frequently scattered by free electrons.

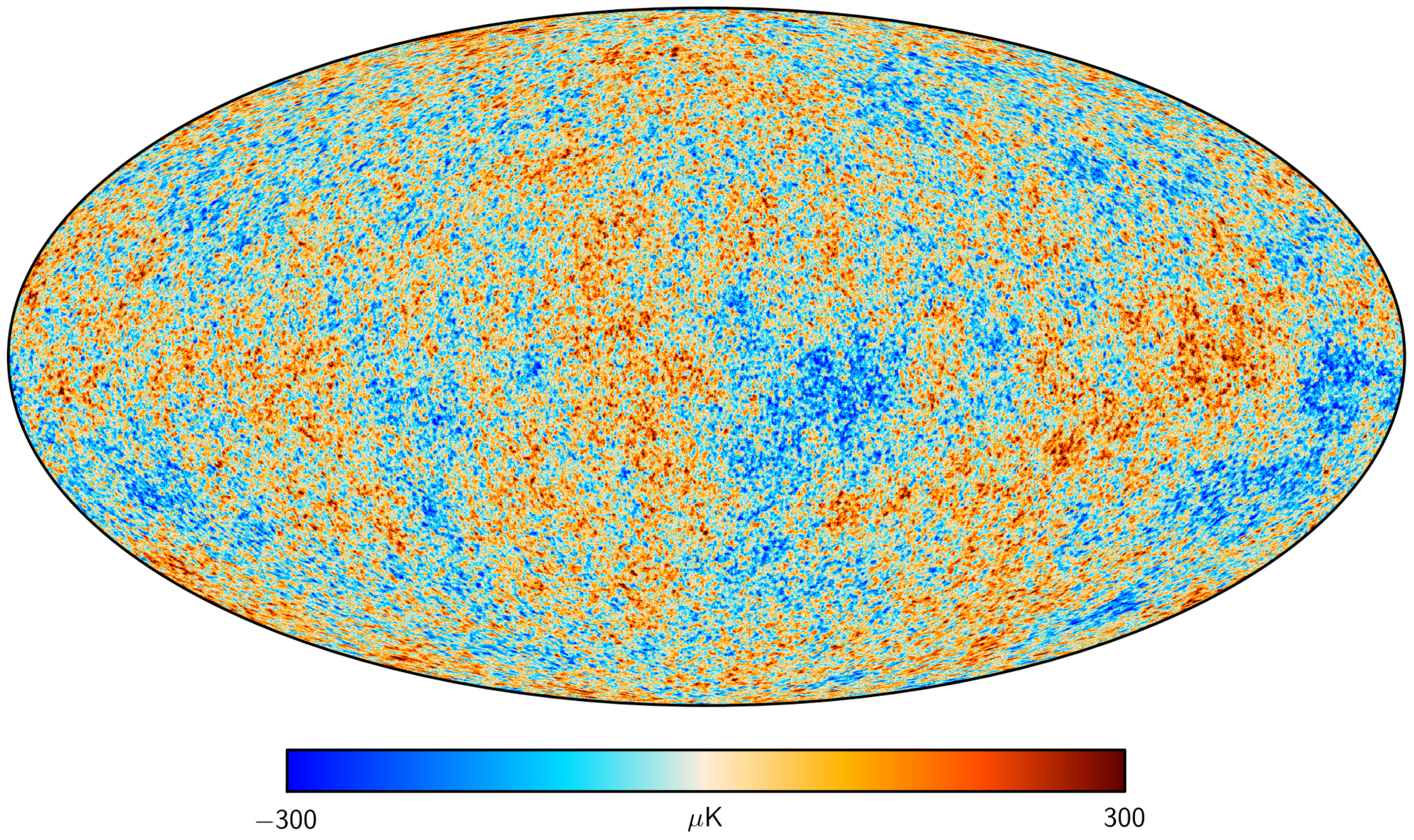
When the plasma cooled below the ionization energy of hydrogen, the electrons and protons combined into neutral atoms. Photons could travel across the Universe without being scattered again.

This transition happened very quickly.

The CMB is a highly redshifted "snapshot" of the Universe at that instant. ⚠️

Microwave background anisotropies

Our understanding of galaxy formation starts from the tiny **anisotropies** observed in maps of CMB photon temperature.



ESA / Planck Collaboration

These are caused by very small **fluctuations in the density of matter** at recombination. ⚠️

At that time, some parts of the universe were slightly **overdense** (more dense than the average, hotter) and some were **underdense** (cooler)**.**

At recombination, this statistical pattern of high and low density was frozen into the distribution of gravitating matter (dark matter + baryons).

The pattern of density contrasts can be predicted to high precision by the theory of **primordial inflation** and some relativistic plasma physics.

CMB observations, combined with lower-redshift data, put **very tight constraints** on the parameters of those models.

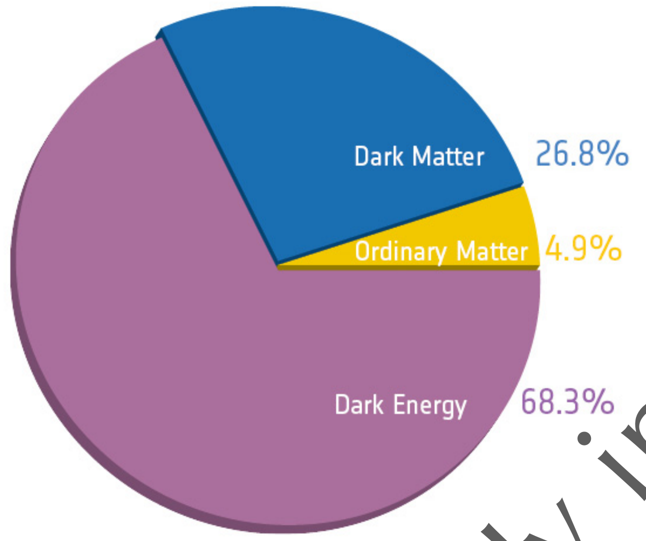
Growth of structure

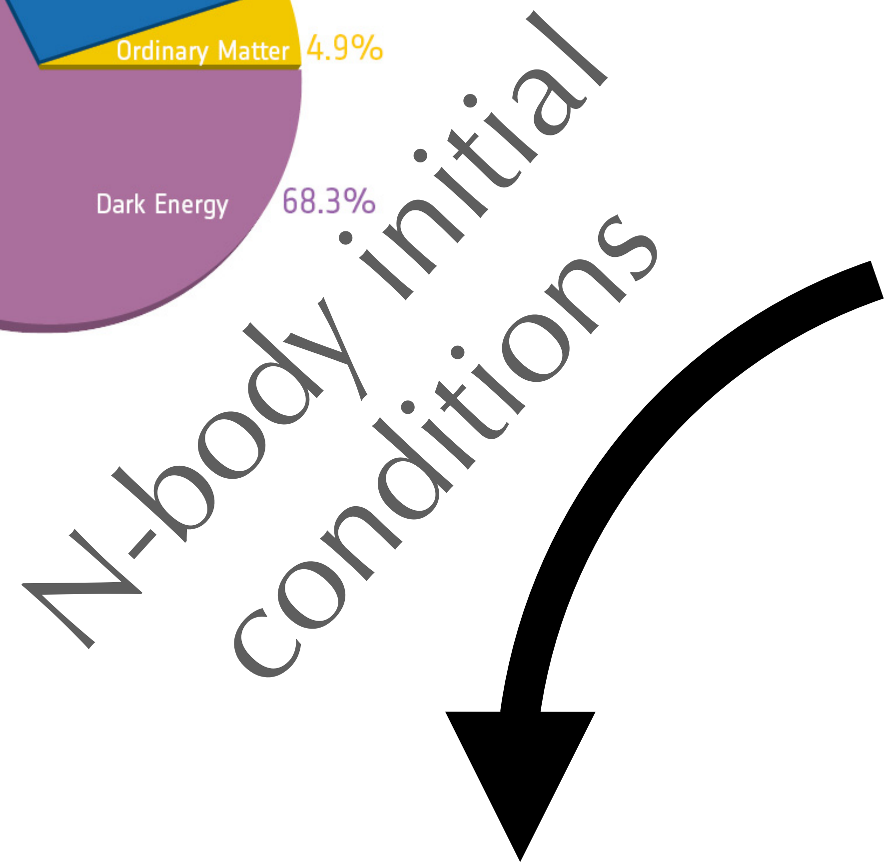
We obtain the **matter power spectrum** at recombination. This our initial condition. We can use it to predict how density perturbations grow over the subsequent 13.5 Gyr.

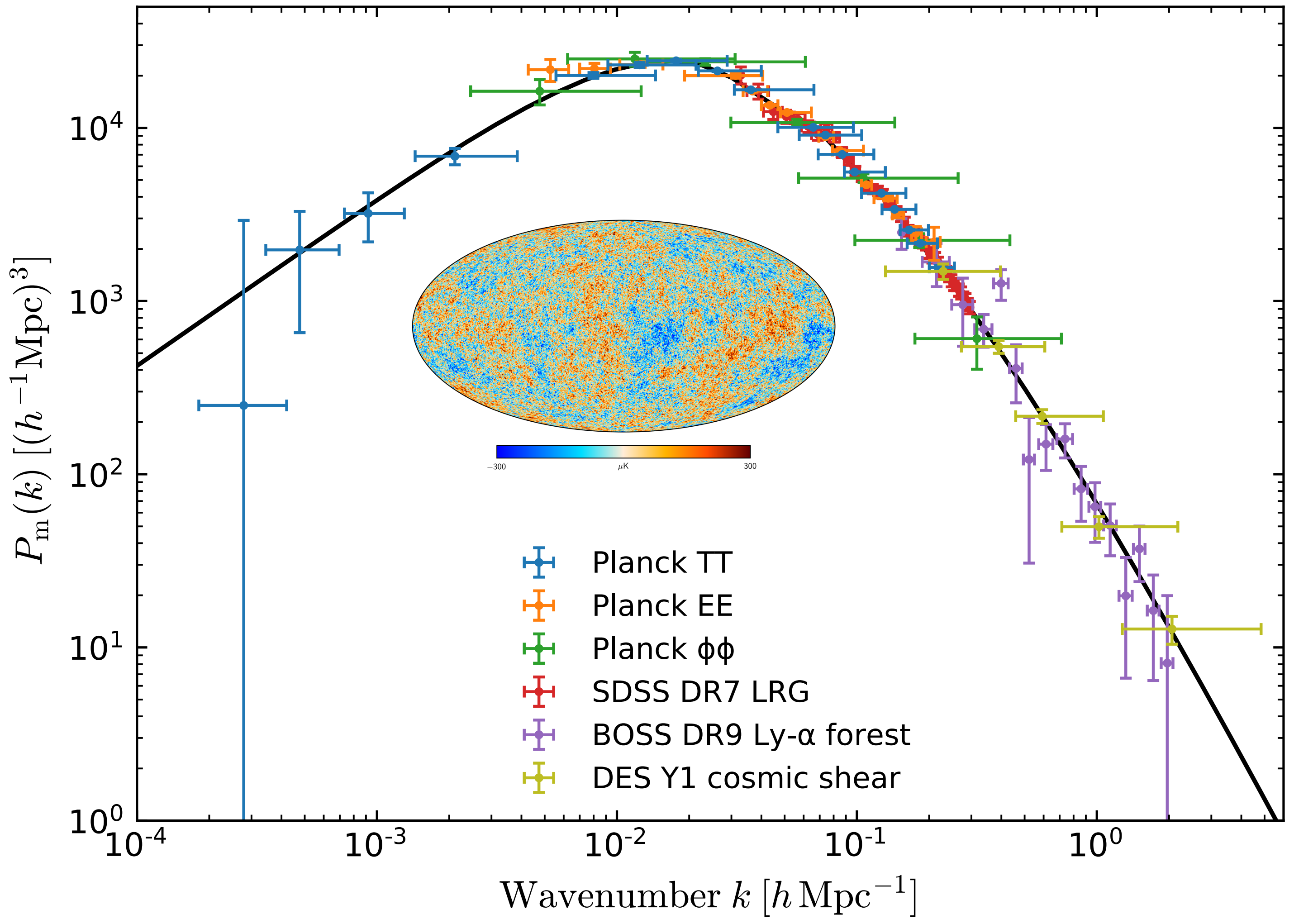
Simple physics: the **background expansion** of the Universe (Friedman equations) and **gravitational clustering** (Newton's law) which **amplifies the density contrasts over time** to create **large-scale structure**.

An analytic **linear theory** can be used when the density contrast is small. When the density is high, we have to rely on direct simulation using **N-body** methods. ⚠️

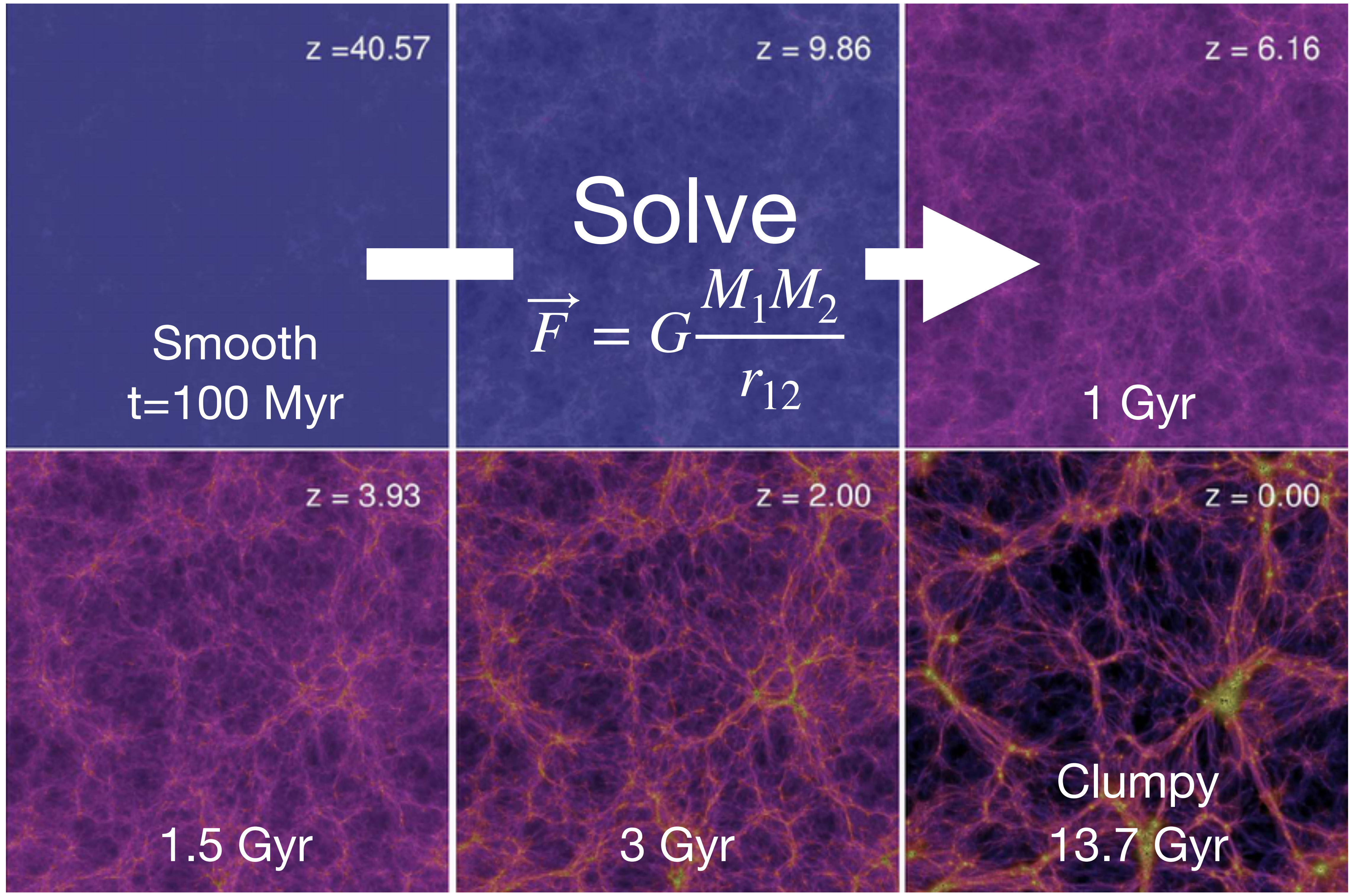
The densest regions undergo runaway collapse into **self-bound** clumps (**halos**) that are about **200 times more dense** than the background. Galaxies form in these lumps.







ESA / Planck Collaboration



Millennium Simulation / Virgo Consortium

Dark matter halos

As the overdense regions collapse, their gravitational potential energy is converted into kinetic energy, as matter streams towards the density peak.

If the collapsing material was baryonic gas, it would heat up; the kinetic energy would be **thermalized**, dominated by random motion (pressure) that could provide support against further collapse. Radiation excited by the collisions would drain energy from the system.

This doesn't happen with dark matter. By definition, dark matter is **collisionless**, it only interacts through gravity.

However, energy is still transferred from streaming to random motion through a statistical process called phase mixing. That random motion is the *equivalent* of pressure in an ordinary gas.

Eventually that 'pressure' (*velocity dispersion*) is enough to support the system against further collapse.

Aquarius Simulation, Volker Springel & Virgo Consortium

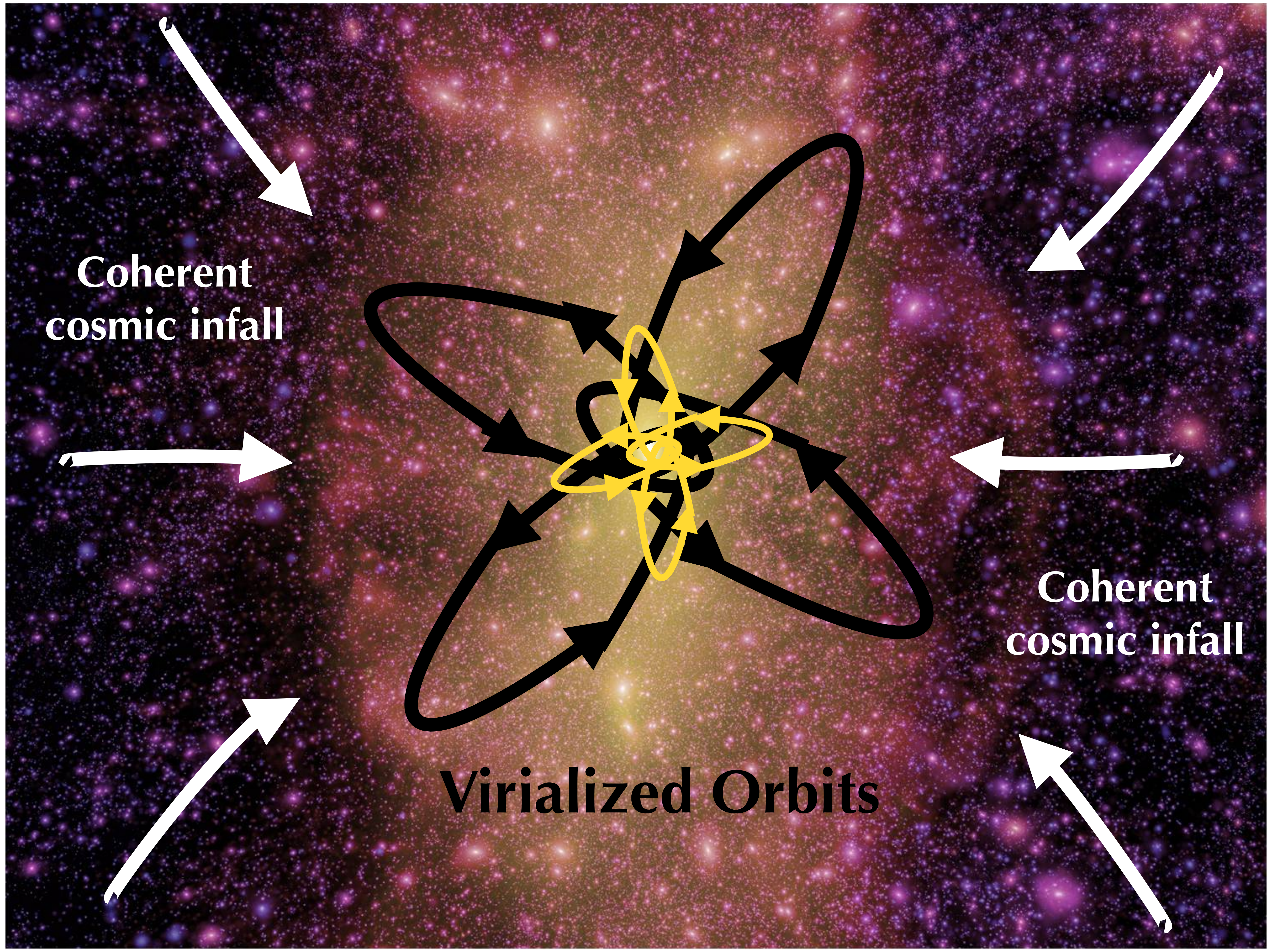
Dark matter halos

This process is called **virialization**, because the resulting equilibrium obeys a result from statistical mechanics known as the **virial theorem** $(2T + W = 0)$.

This defines a characteristic mass and size for a dark matter halo in equilibrium. ⚠️

The Milky Way's halo has a **virial mass** of $\sim 10^{12}\,\mathrm{M}_\odot$ and a **viral radius** of $\sim 200\,\mathrm{kpc}$.

Since the 1990s, we have learned a lot about the internal structure of dark matter halos from N-body simulations.



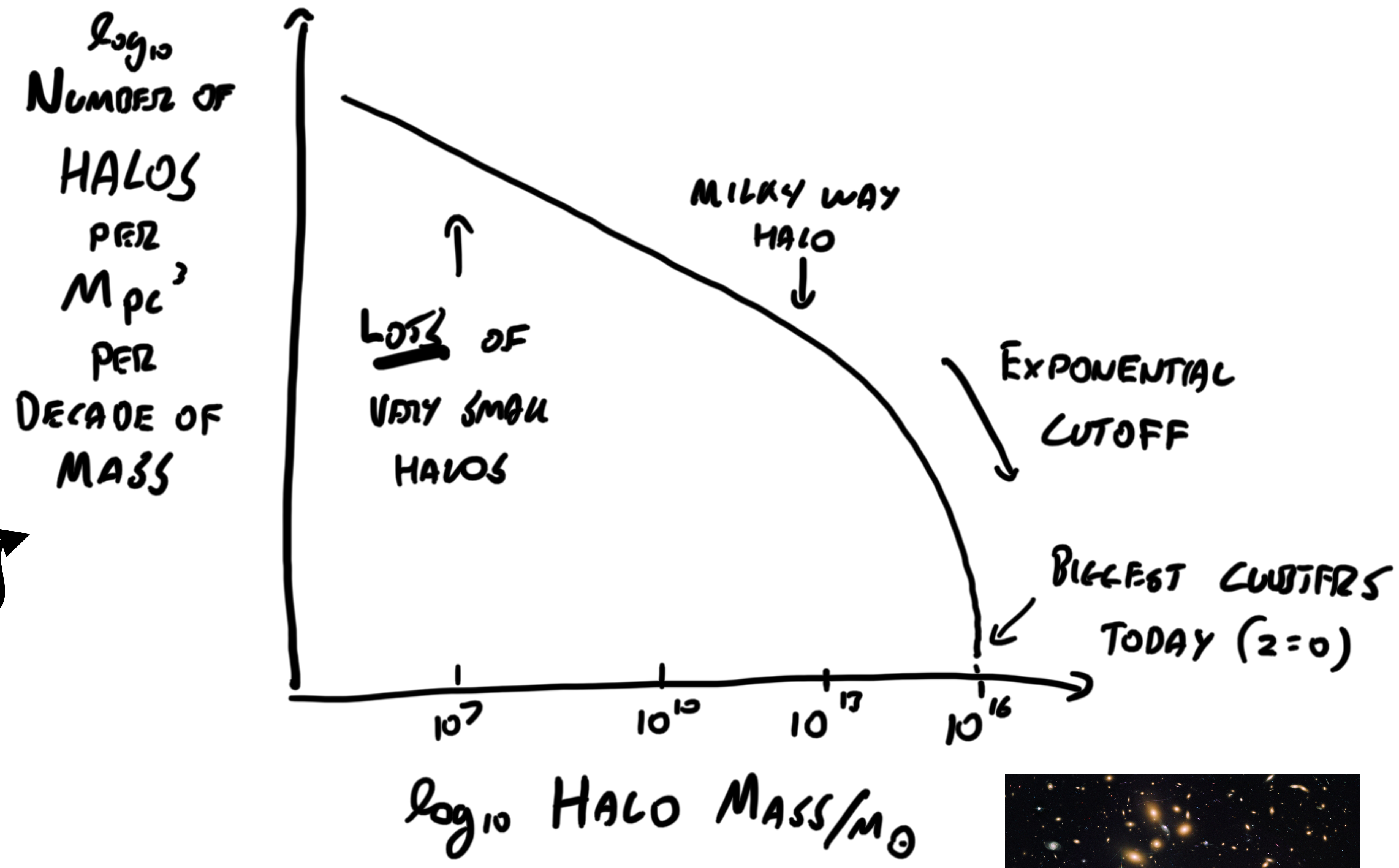
Aquarius Simulation, Volker Springel & Virgo Consortium

Dark matter halo mass function

Combining our understanding of cosmology and dark matter, we can predict **how many dark matter halos of a given mass exist per unit volume of the universe** at any given time.

This is the **halo mass function**. It is very important for understanding galaxies, because galaxies form in dark matter halos.

There are more low-mass halos than high-mass halos. The mass function is a power-law with an exponential cutoff.

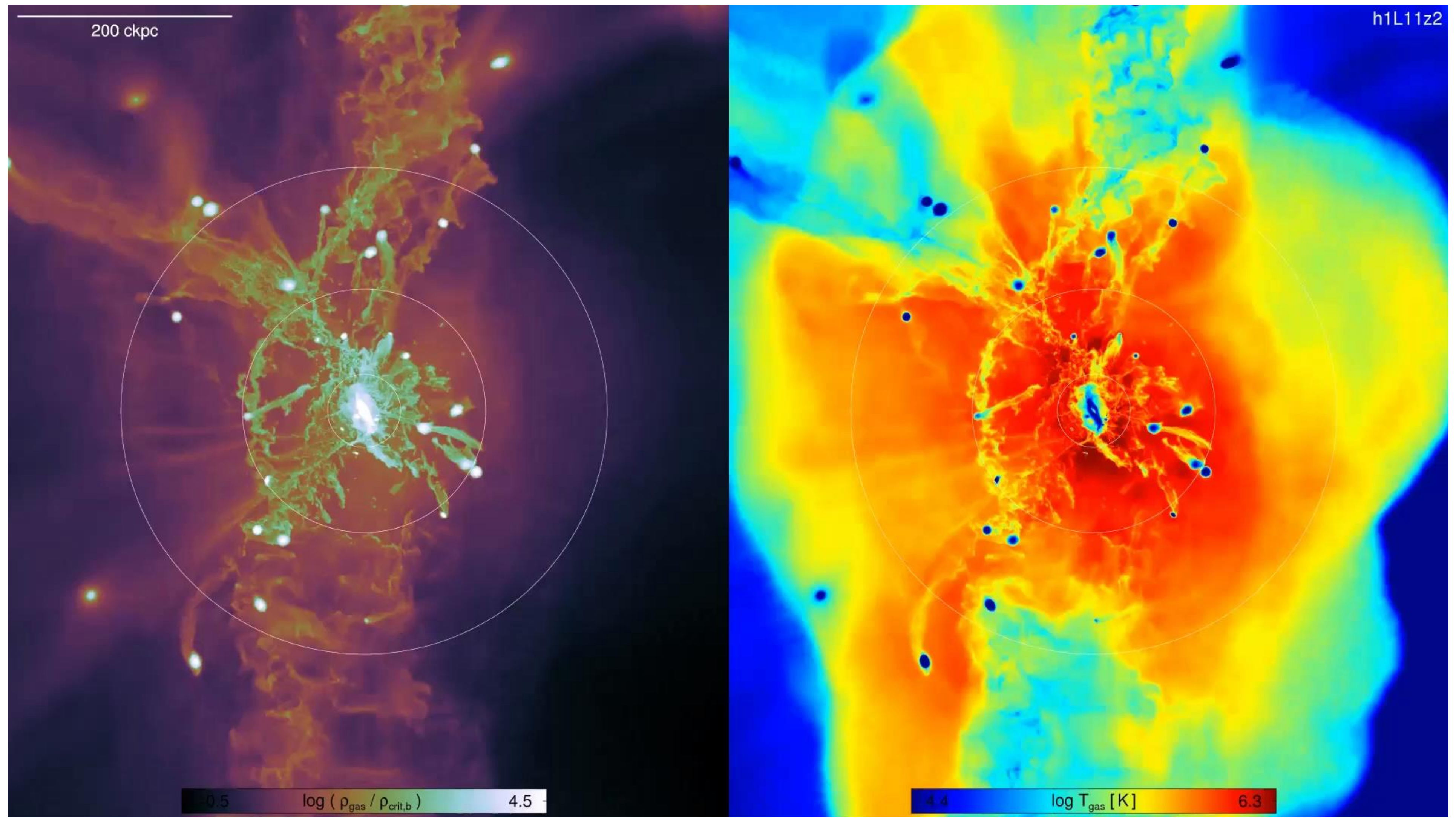


The maximum mass depends on time, because it takes longer for more massive, low-overdensity fluctuations to overcome the Hubble expansion and collapse into a halo. We can identify this scale with the largest **galaxy clusters** around us today, like Coma and Virgo. ⚠️

Back to galaxies…

A quick sketch of galaxy formation

Nelson et al. (2018) / Illustris

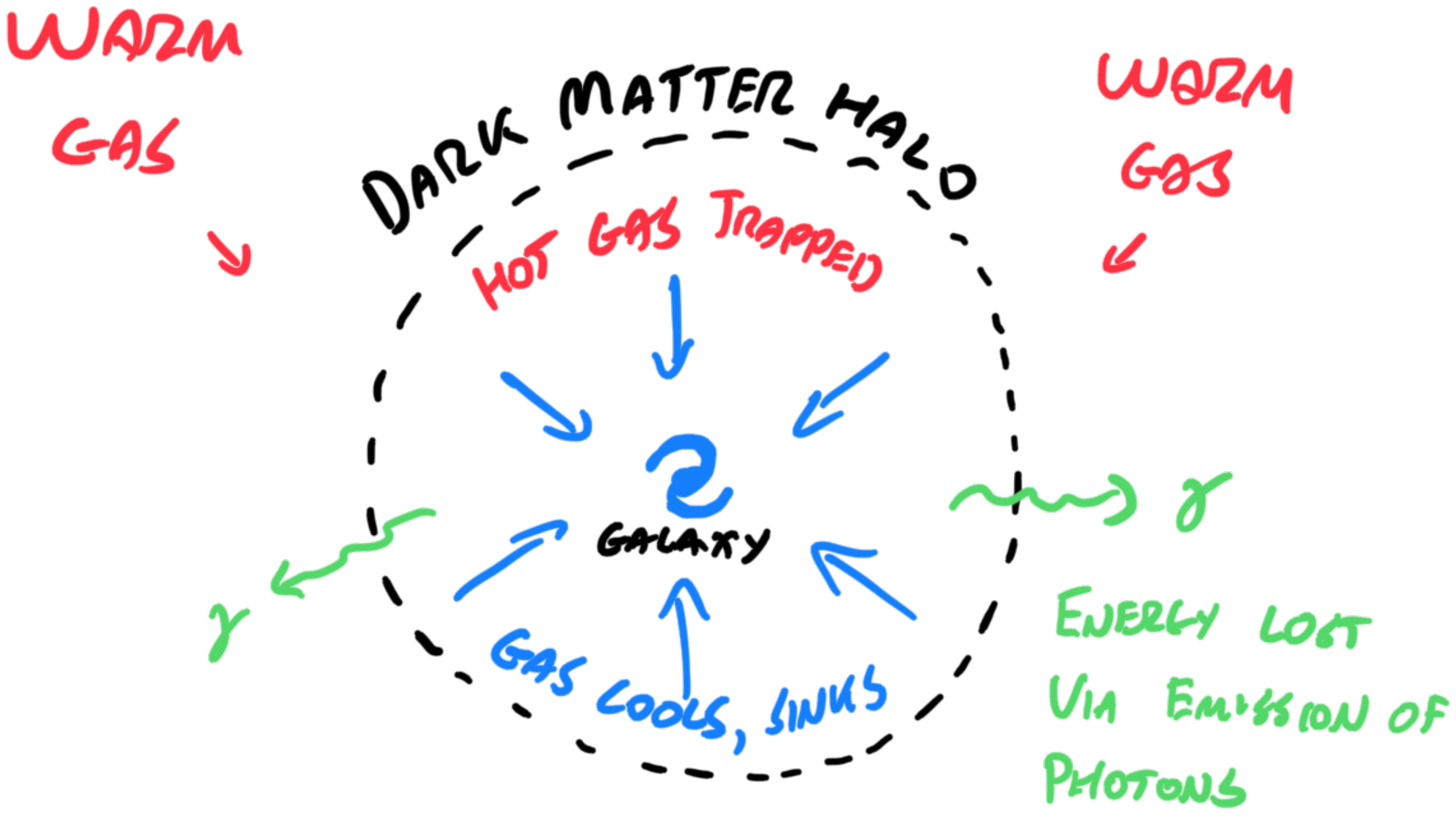


- After the Big Bang, the Universe is very large, smooth and low density. Most of the time, those baryons are warm and ionized (>1000K). ⚠️

- To make a galaxy-sized mass of stars, we need a galaxy-sized lump of gas to be very dense and very cold (10K).

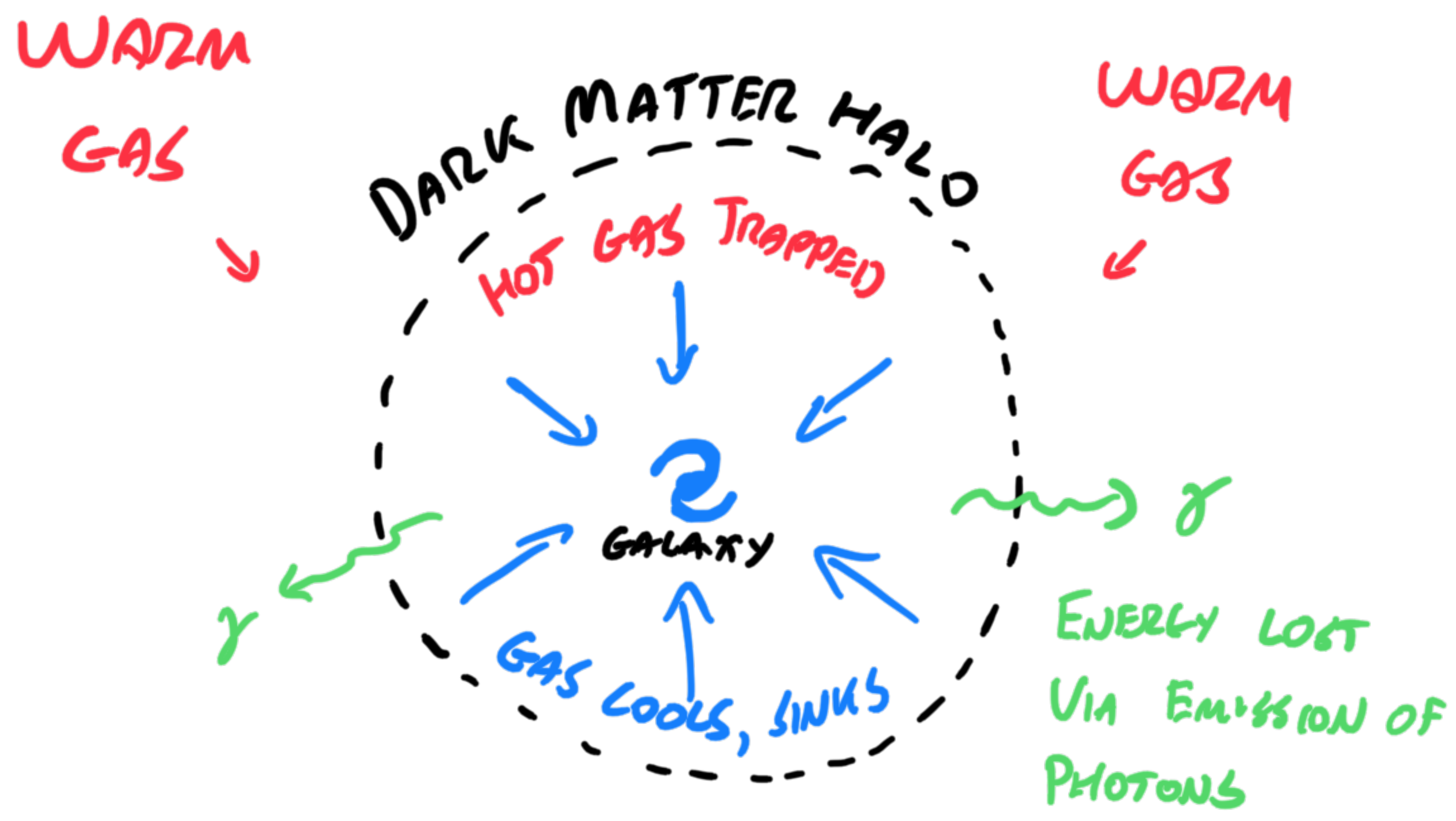
- The only way to build up a lump dense enough to turn into stars on a timescale of ~1-10 Gyr is to **trap the gas** in a dark matter halo.

- That's not enough: the gas also needs to **cool down**. Dense ionized gas undergoes runaway cooling through photon emission and **condenses** at the center of the halo. ⚠️



From halos to galaxies

- Starting from the theory of how dark matter halos grow over time, we can predict the rate at which gas collects in the halo, cools down and **condenses** to form a galaxy.
- The flow of cooling gas **conserves angular momentum**.
- When the gas sinks to the center of the halo, angular momentum (i.e. rotation) supports it against further collapse. The result is a **stable disk with an exponential density profile**.
- **Gravitational instabilities** in the disk form molecular clouds and eventually stars.
- Some of those stars explode as supernovae after a few million years, heating up the surrounding gas and launching it out of the disk again.
- As described earlier, this process cycles baryons through different ‘phases’, at a rate determined by the rate of supply of fresh gas as the halo grows, and by the rate at which stars form and explode.

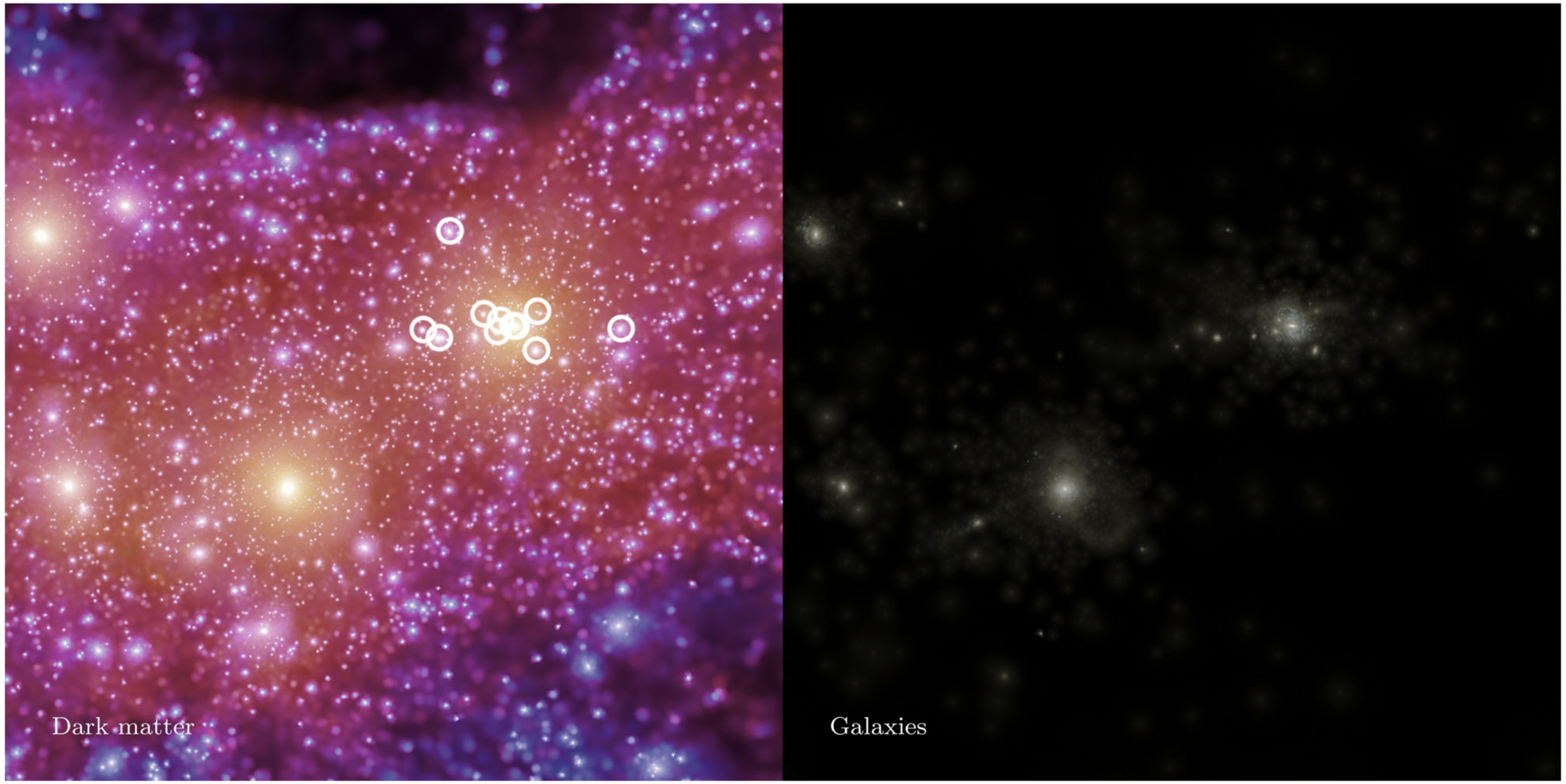


Note: most CDM halos don't have galaxies in them

- For most of the lifetime of the Universe, halos less massive than about $10^8\,M_\odot$ **cannot trap (or cool) any gas, and therefore do not form galaxies.**

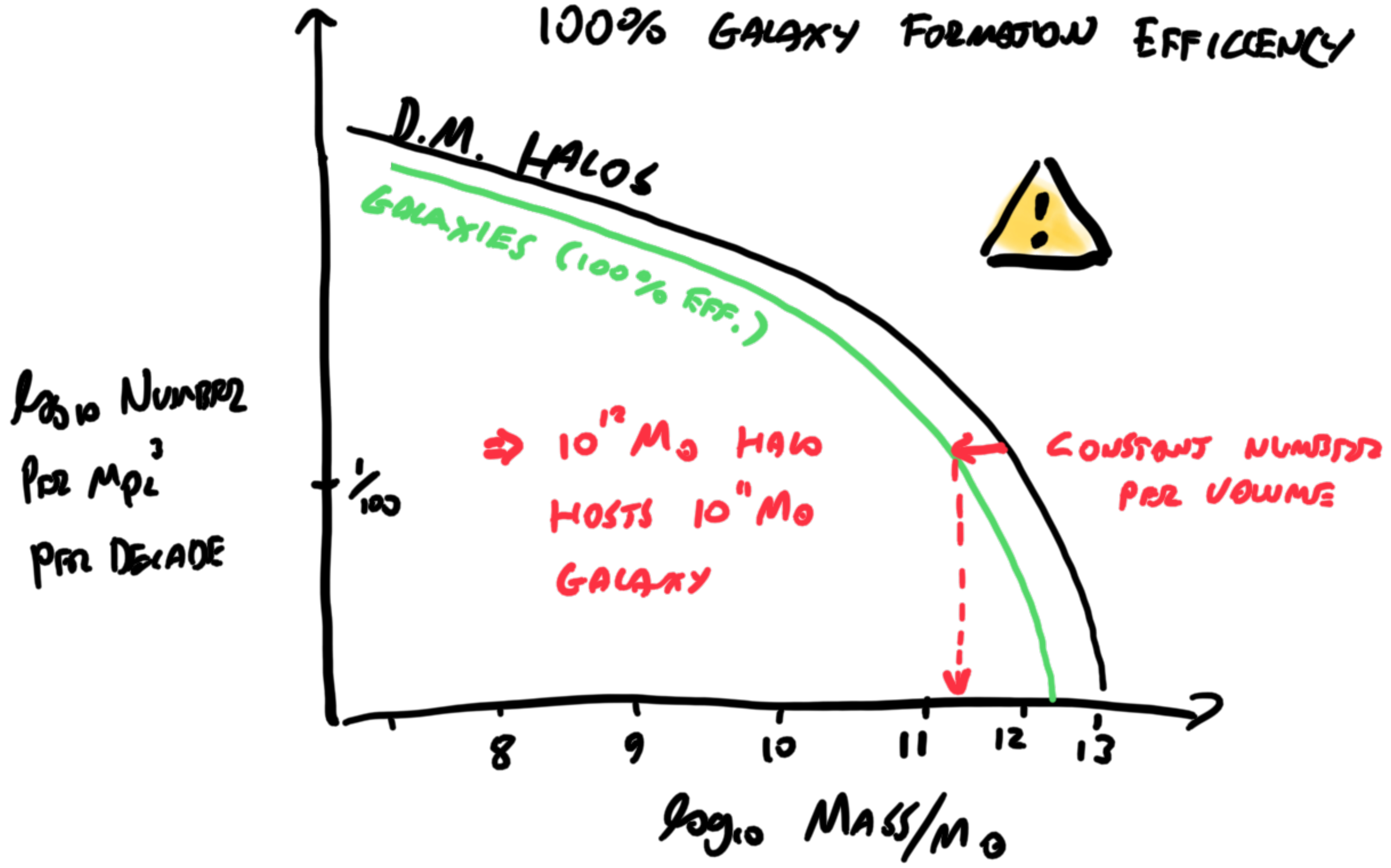
- This is a Very Important Fact, well understood since the 1980s. It follows from the basic atomic physics and thermodynamics. It is not controversial.

Sawala et al. (2011)



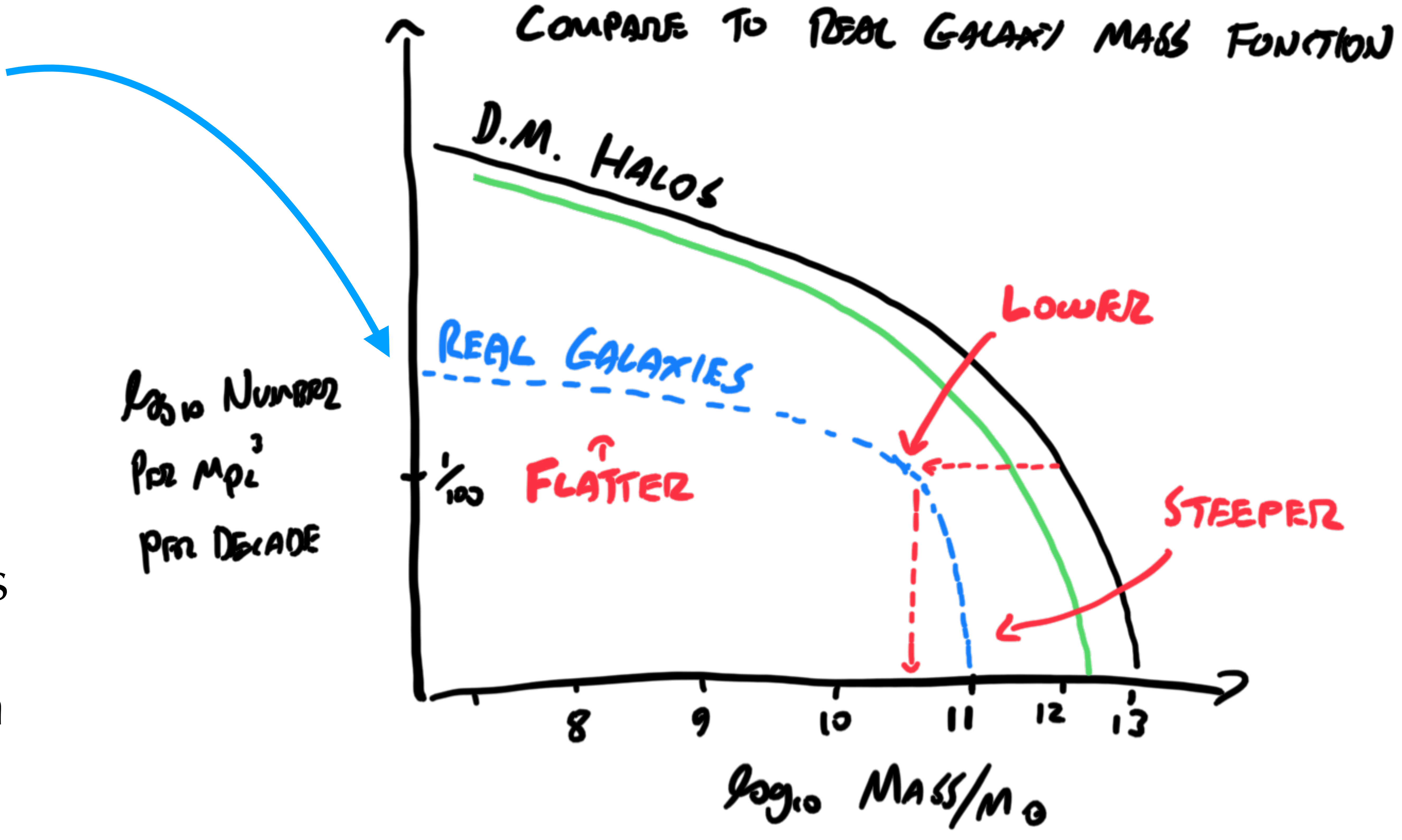
A very simple model of galaxy formation

- What is the maximum amount of gas available to form a galaxy in a given dark matter halo?
- Easy! **Take the mass of the halo and multiply by the average ratio of baryons to dark matter in the Universe (~20%).**
- Simplest possible assumption: 100% of the baryons in halos turn into stars (i.e. the ‘galaxy formation efficiency’ of every dark matter halo is 100%).
- This predicts the galaxy mass function (number of galaxies of a given mass per unit volume) is just the halo mass function, scaled down.



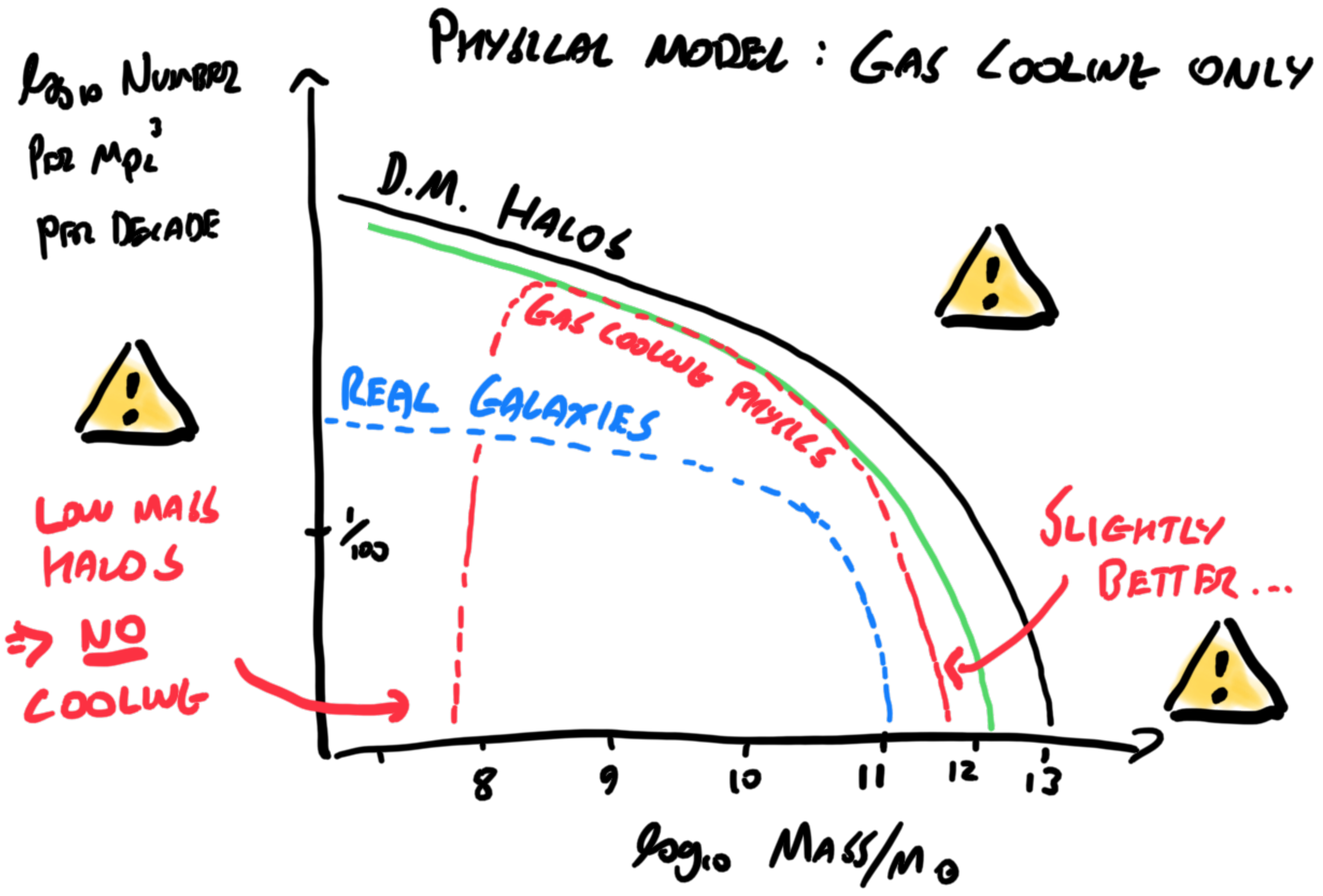
A very simple model of galaxy formation

- Does the real galaxy mass function look like that prediction? **No!**
- At the low mass end, the observed mass function is **flatter**.
- At the high mass end, it is **steeper** than the halo mass function.
- Even in the small range where the slope is similar to that of the halo mass function, the amplitude of the galaxy mass function is **lower**.



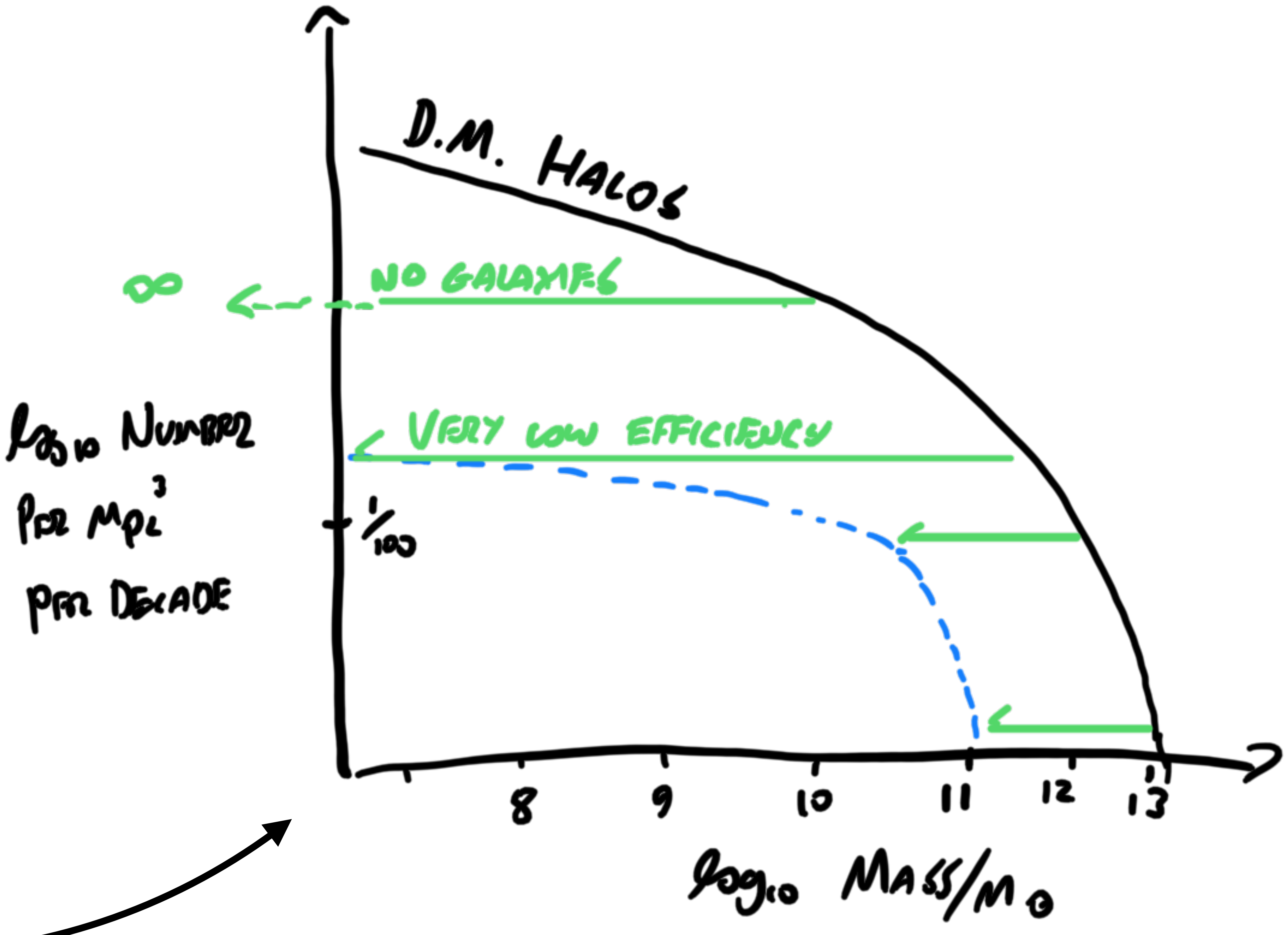
What's missing?

- Not much is wrong with the basic idea.
- The mass of a galaxy **should** scale with the mass of its dark matter halo, but the efficiency is **not 100%**.
- Maybe we need some more physics?
- If we invoked the physics of **gas cooling**, we would predict the galaxy mass function should look something like this.
- A little closer, but still not great! Most halos can cool efficiently.



Formation efficiency from abundance matching

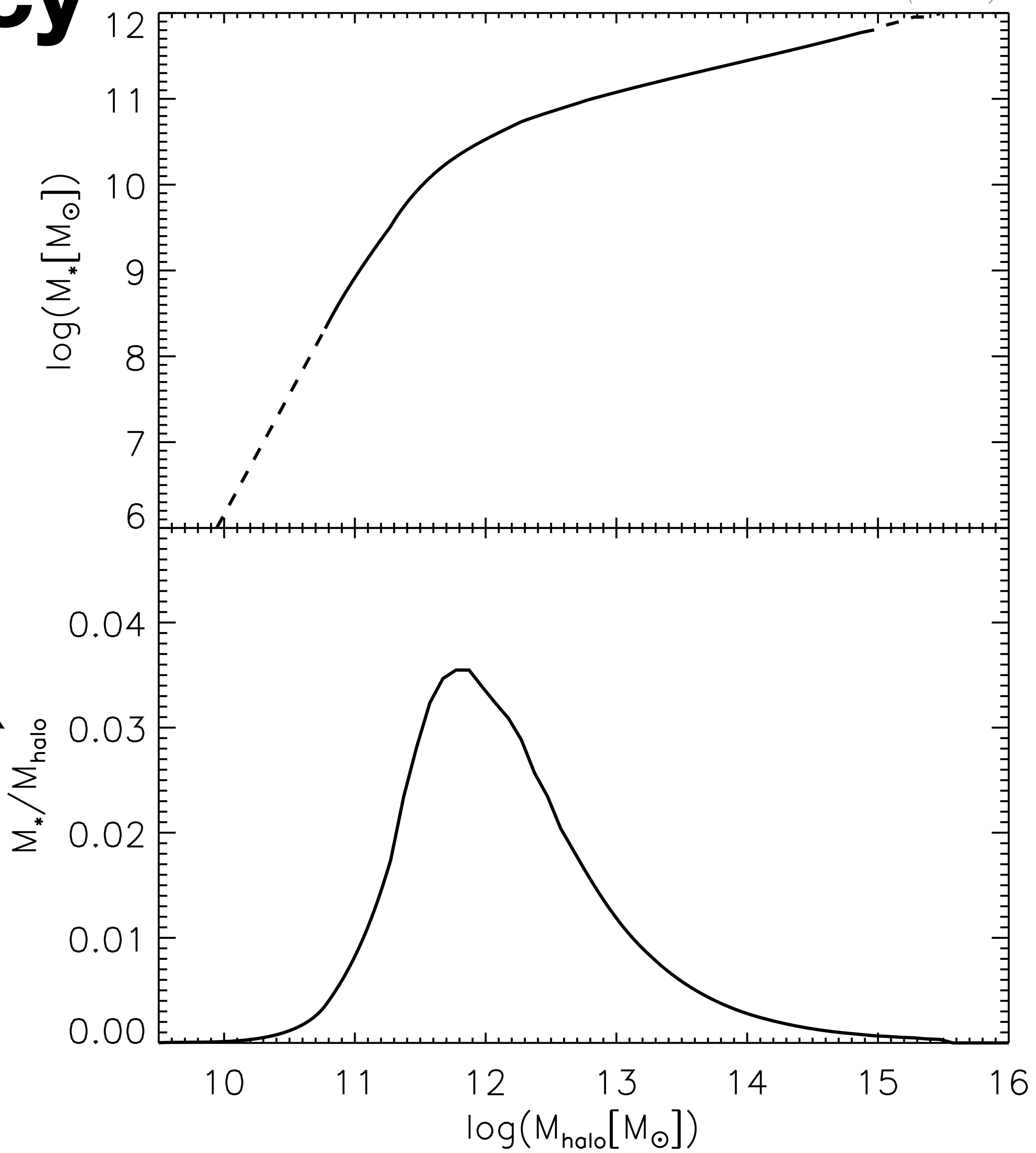
- Clearly, the counts of real galaxies are telling us that **not all the baryons that can cool down end up turning into long-lived stars**.
- The galaxy formation efficiency of a dark matter halo can't be 100%. It must be a lot less. This should be obvious, because we see plenty of gas in galaxies!
- The next step is to consider the efficiency (the average outcome of all the different physics and timescales) to be a **function of halo mass**.
- We can ask **what efficiency we <u>need</u> at each halo mass to produce galaxies with the same abundance (number per unit volume per decade in mass)**.
- That gives us an **empirical relationship** between stellar mass and halo mass, which looks like this.

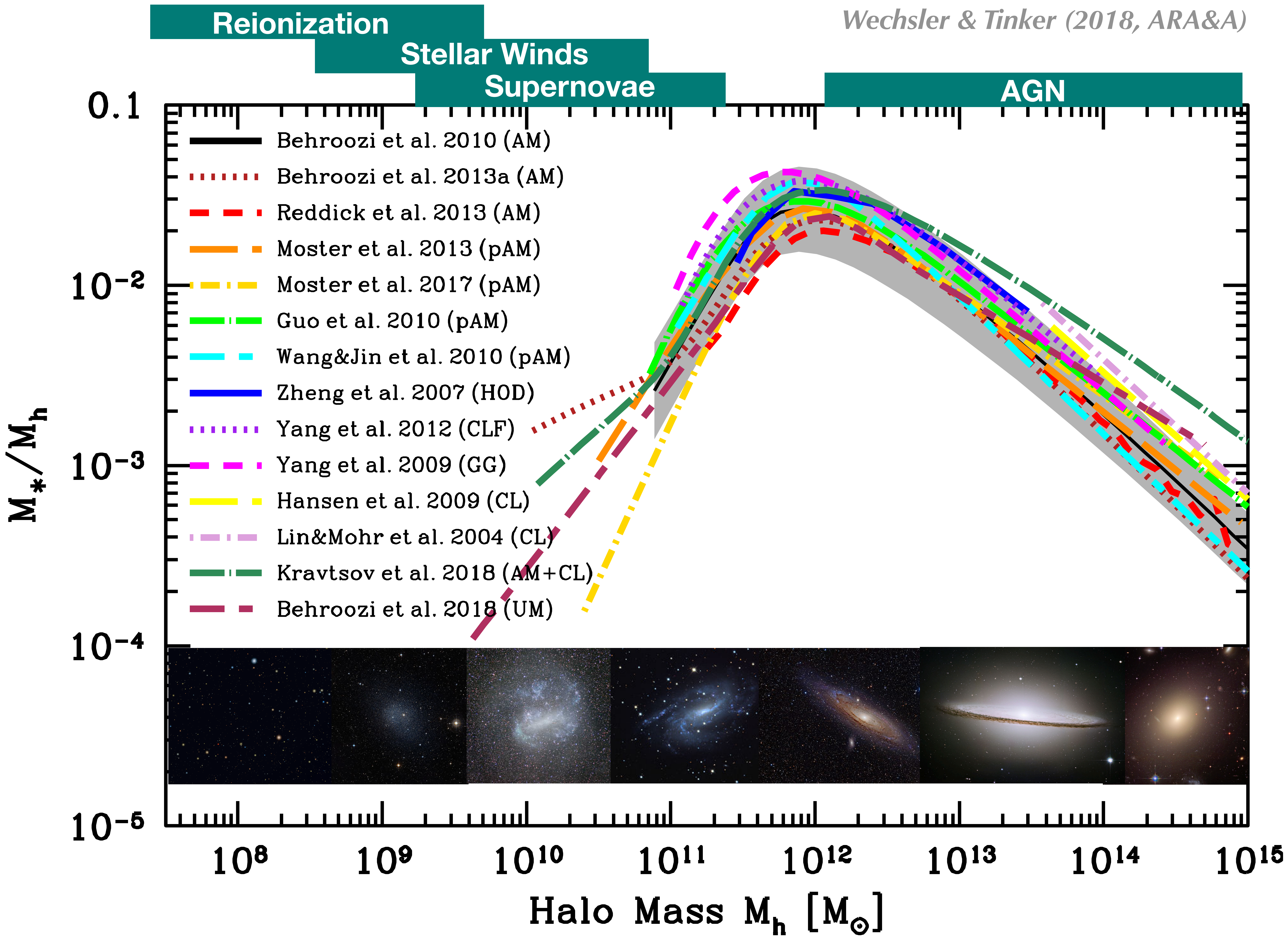


Galaxy formation efficiency

- We can ‘flip’ the diagram on the previous slide to show the stellar mass we’ve associated with each halo mass when we match by cosmic abundance.
- We can divide through by the halo mass to get the fraction of mass in stars.
- We learn that:
  - Galaxies turn at most 4% of the mass of their host halos (i.e. 20% of the available baryons) into stars. The peak is around 10^{12} solar masses (i.e. galaxies of around 10^{10}, i.e. like the Milky Way)
  - The efficiency becomes very, very low at halo masses above and below the peak.

Guo et al. (2010)

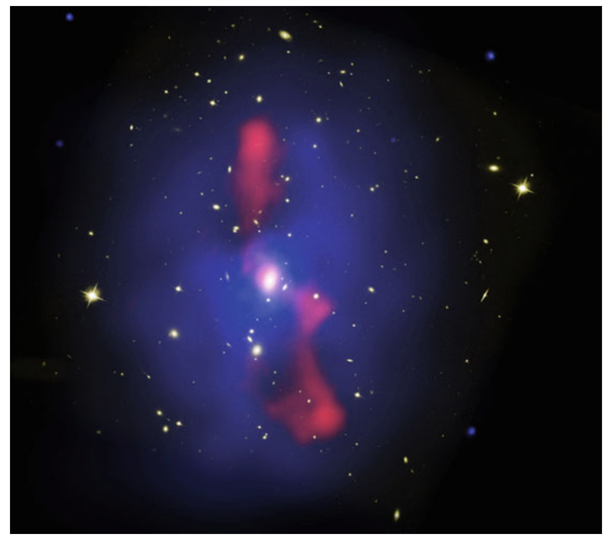



Wechsler & Tinker (2018, ARA&A)
Reionization
Stellar Winds
Supernovae
AGN
Behroozi et al. 2010 (AM)
Behroozi et al. 2013a (AM)
Reddick et al. 2013 (AM)
Moster et al. 2013 (pAM)
Moster et al. 2017 (pAM)
Guo et al. 2010 (pAM)
Wang&Jin et al. 2010 (pAM)
Zheng et al. 2007 (HOD)
Yang et al. 2012 (CLF)
Yang et al. 2009 (GG)
Hansen et al. 2009 (CL)
Lin&Mohr et al. 2004 (CL)
Kravtsov et al. 2018 (AM+CL)
Behroozi et al. 2018 (UM)
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
M_*/M_h
10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15}
Halo Mass M_h [$M_\odot$]

Why does galaxy formation efficiency depend on halo mass?

Feedback

- We need some astrophysics to explain why the efficiency of galaxy formation should depend on the mass of the dark matter halo.
- It can't just be the efficiency of making stars in molecular clouds (molecular clouds don't know which halos they live in).



- Standard explanation:
    - Low halo masses: **supernova feedback** blows away all the gas.
    - High halo masses: jets from a central supermassive black hole keep the hot gas hot (a.k.a. **AGN feedback**).
- **There are strong arguments that the net effect of both processes will scale with the depth of the gravitational potential, i.e. the mass of the DM halo.**

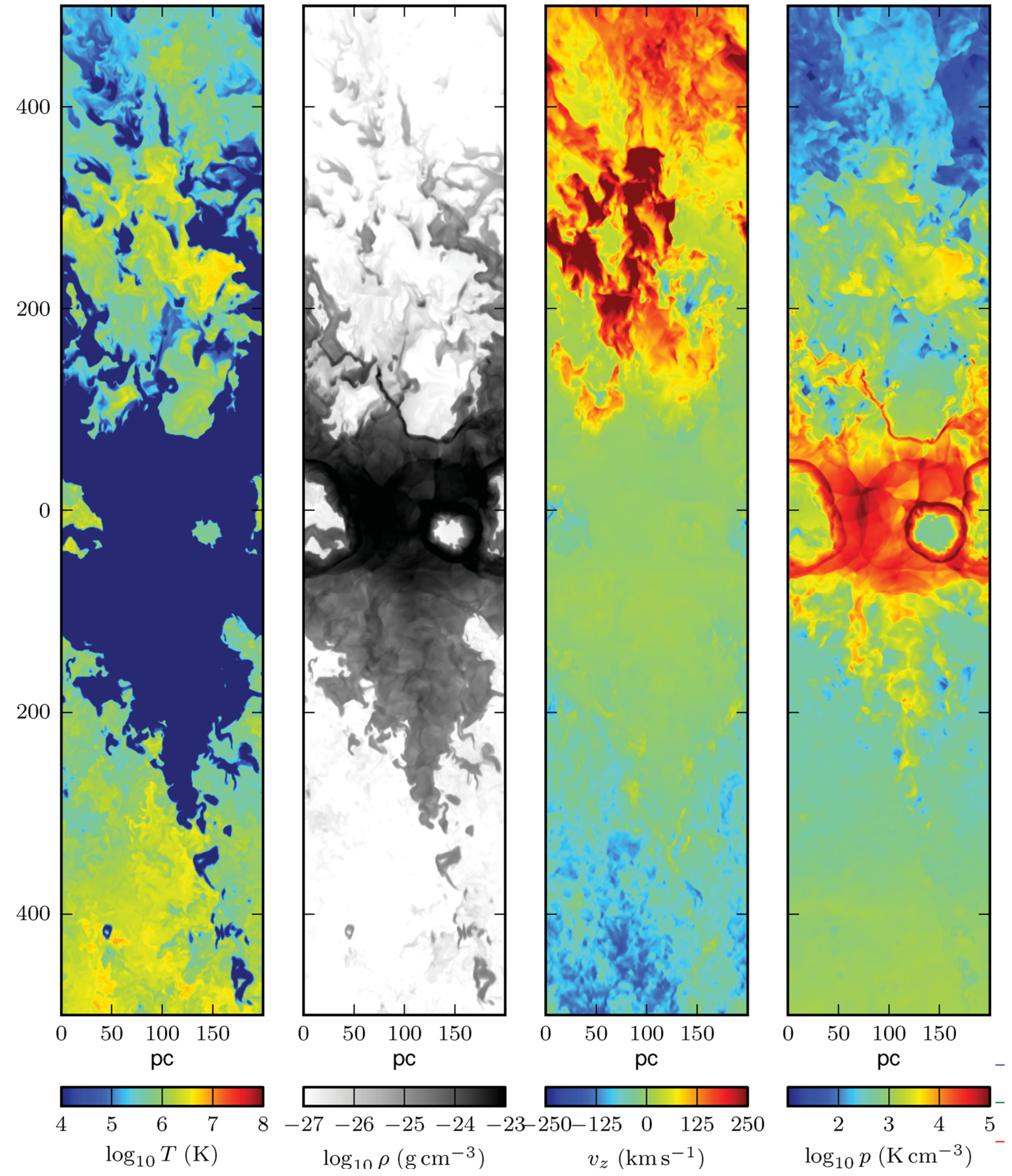
Supernova feedback

- The same amount of energy is released into the ISM by supernova regardless of the mass of the halo.

- However, in a small halo with a shallow potential well, that energy is enough blow all of the gas out of the galaxy, perhaps even out of it its halo.

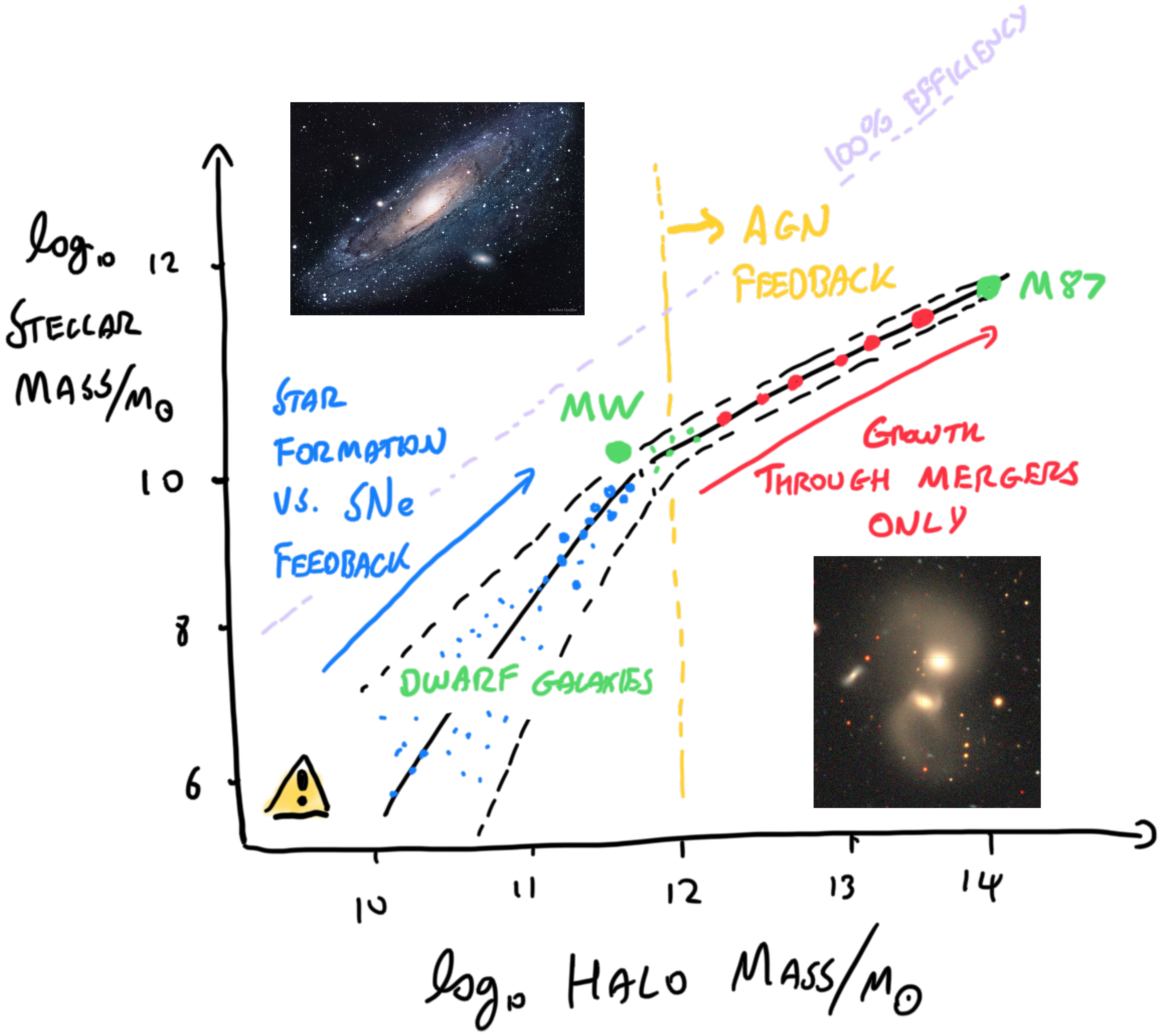
- In a more massive halo, the same amount of energy can't lift the same mass of gas out of the deeper potential. Supernovae are less effective at keeping gas hot and diffuse.

- This is nice and simple, but it's only the start of the story.



Galaxy formation efficiency and galaxy types

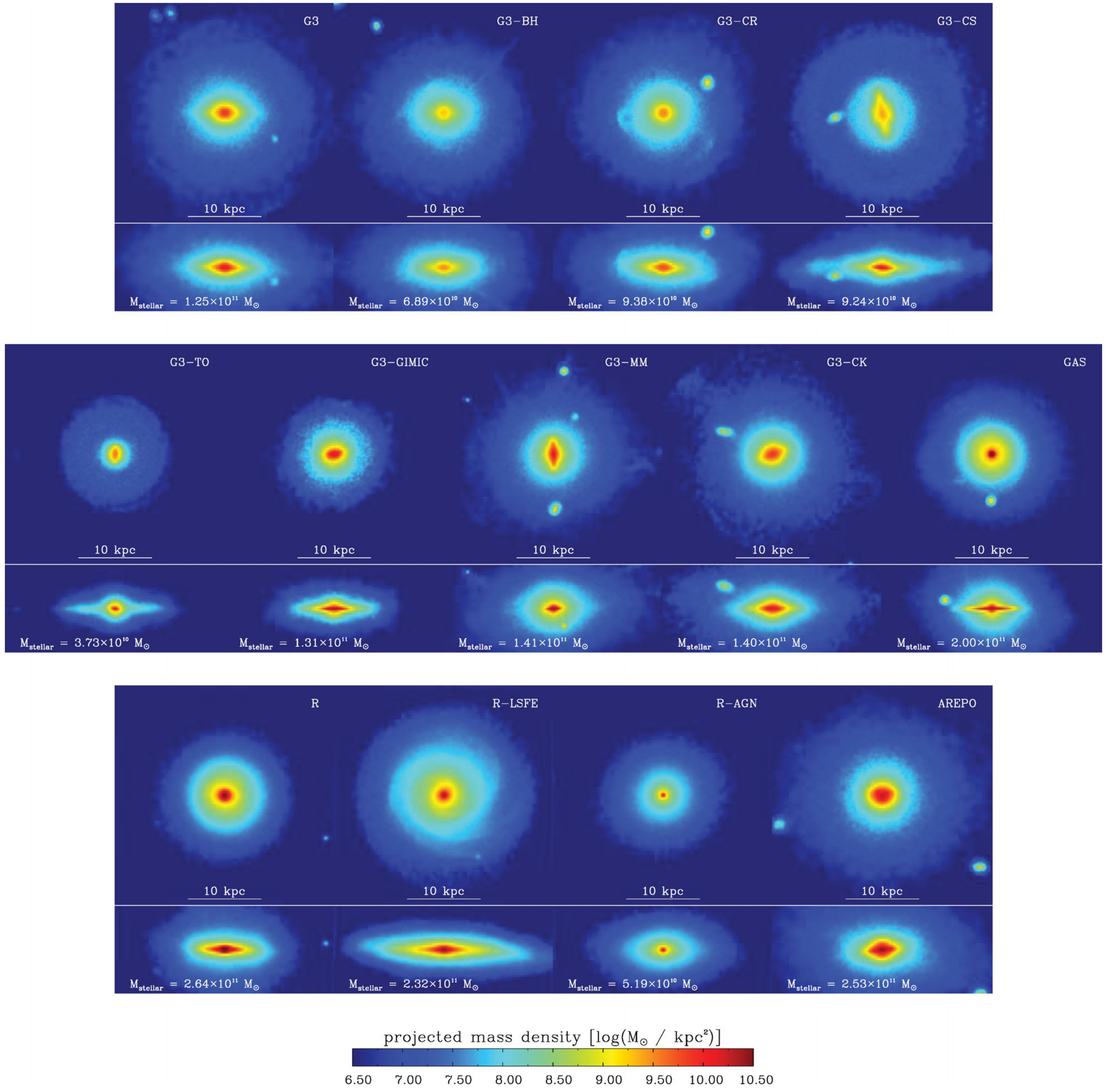
- Galaxies take time to form; their growth rate is tied to the growth rate of their halos.
- When halos reach a critical mass, star formation is shut off by AGN feedback. This is **not** just a stronger version of supernova feedback. It does **not** blow cold gas out of the galaxy. Instead it **stops fresh gas cooling** onto the galaxy.
- As the halo grows further (DM doesn't care about feedback ⚠️), its galaxy can only increases in mass by **merging** with other galaxies.
- Successive mergers between red and dead galaxies builds up the 'red sequence' of elliptical galaxies with low star formation rates in massive halos ⚠️.
- The fact that halo mass correlates with star formation history **and** morphology is responsible for many of the observable correlations seen in big galaxy surveys (e.g. between stellar mass, color, metallicity and size).



Simulation and Observations

Progress in simulations

Scannapieco et al. (2012)



- In 2012, the Aquila project (Scannapieco et al. 2012) used most of the available state-of-the art simulation codes to predict the formation of a galaxy in the same Milky Way-like dark matter halo.
- The initial conditions and cosmological parameters were identical in all the simulations.
- The resulting galaxies had more than an order of magnitude difference in stellar mass and ranged from ellipticals to disks.
- Conclusion #1: **cooling, star formation and feedback in hydrodynamical models were not particularly well understood in 2012**.

Progress in simulations

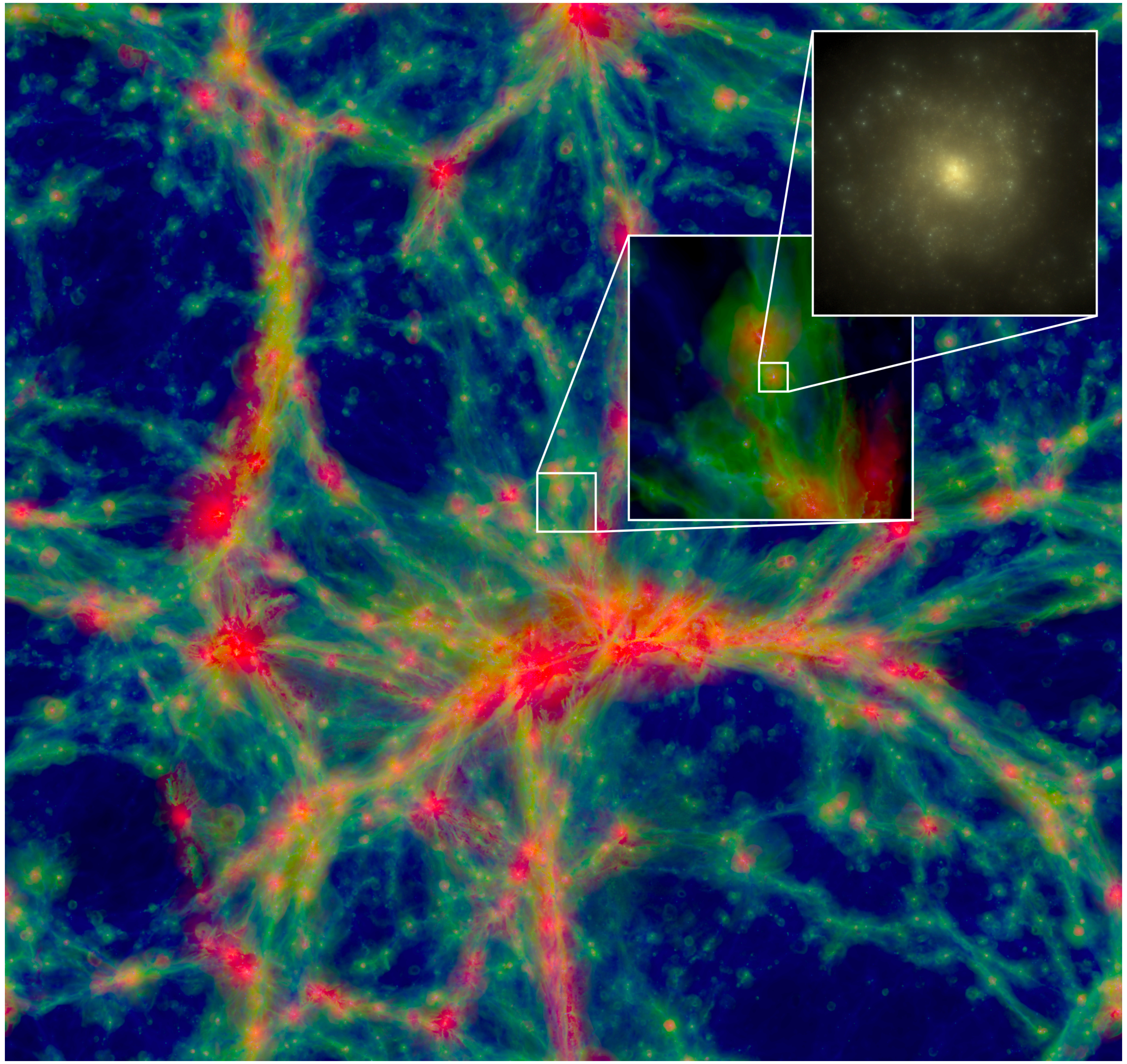
- Conclusion #2: **it's not enough to understand the physics, we also need to understand how we connect small-scale ('sub grid') implementations of that physics to cosmological-scale hydrodynamics.**

- Cosmological hydrodynamical simulations have learned some lessons from traditional semi-analytic approaches, helped by the computational power to simulate large volumes at sufficient resolution for the physics they include (e.g. Vogelsberger et al. 2014, Schaye et al. 2015).

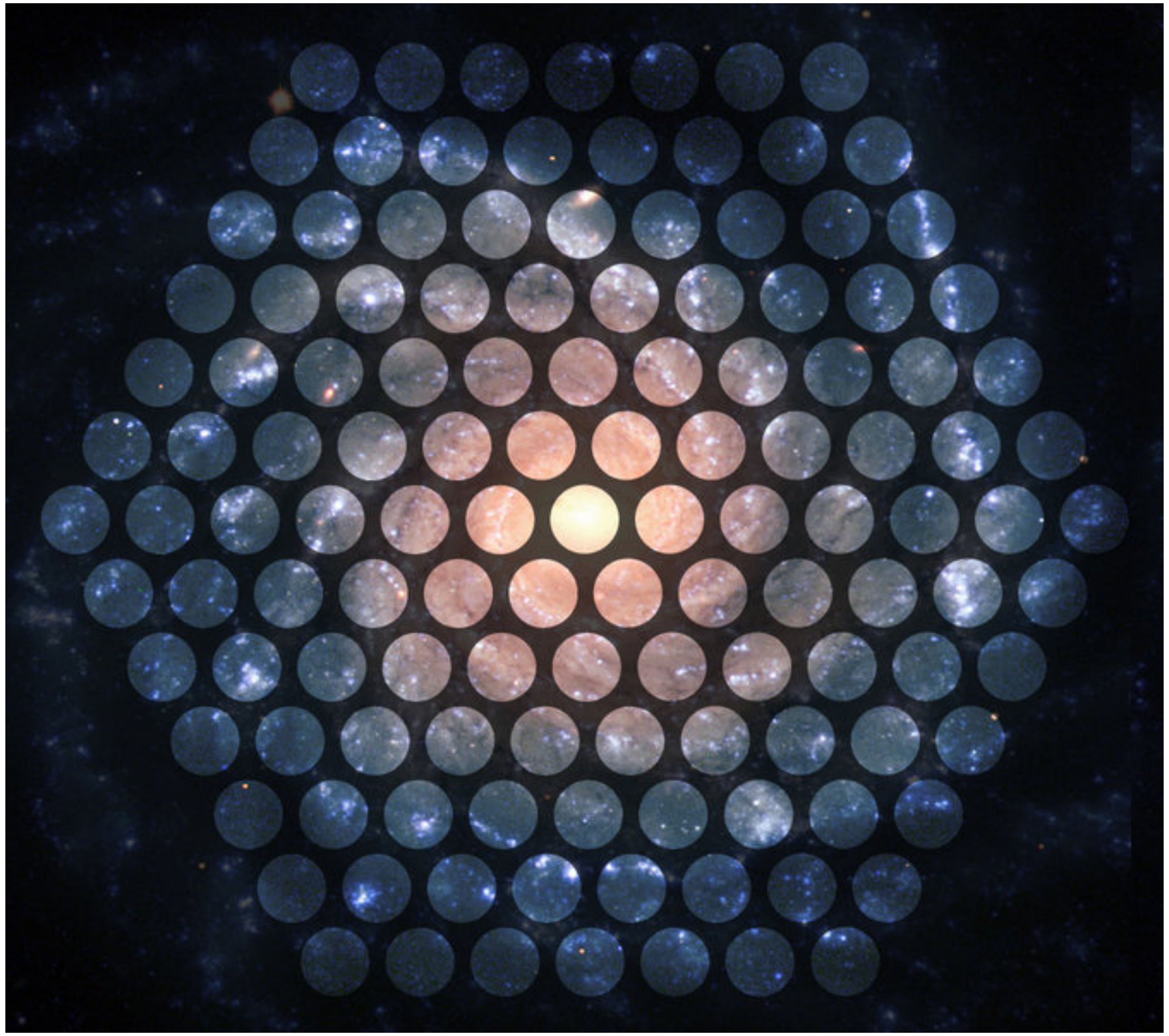
- Hydrodynamical, semi-analytic and empirical approaches have now more-or-less converged on the same story, at least at the level of detail given in this talk.

- We have a new generation of more robust and well-calibrated models, including the Eagle and IllustrisTNG simulations. These will be superseded by simulations that go beyond averages into the microphysics of the ISM.

EAGLE simulation / Virgo Consortium



The baryon cycle



Sloan Digital Sky Survey / MANGA

- Many different models of star formation and feedback can produce similar outcomes at the present day. This is one of the major areas of uncertainty in galaxy formation theory.

- We have a very limited understanding of star formation and feedback. Most models use empirical, macroscopic recipes.

- So far, observations have not put strong constraints on what is actually happening to the hot and warm gas, particularly in galaxies like the Milky Way.

- This is changing. We're now starting to explore the warm ISM and CGM in detail, thanks to deep IFU observations and quasar absorption spectra.

- We're also able to study the diffuse IGM, including the "Lyman alpha forest" (porto-galactic and extra-galactic gas clouds at high redshift).

Dwarf galaxies

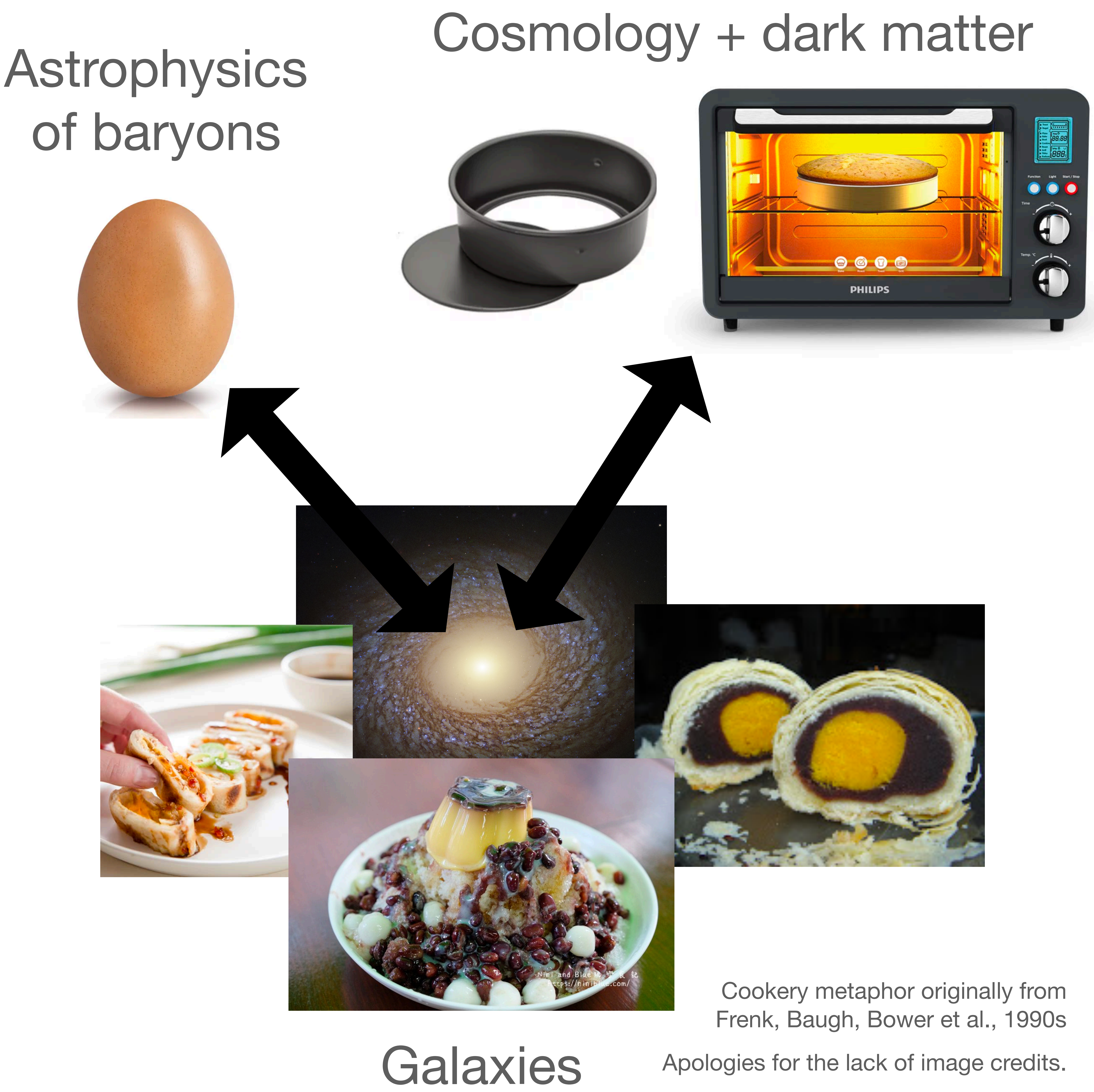
New surveys (like HSC, DESI and LSST) are now able to observe large numbers of very faint galaxies.

These are the most diverse galaxy type of all. They provide another way to constrain the baryon cycle: **galactic archaeology**.

- Lower mass dark matter halos have a wider range of formation times. Some may be relics of the first galaxies.
- They have fewer generations of star formation. Massive galaxies ‘average away’ the imprints of individual star formation and feedback events that could distinguish between models.
- The motions of stars in dwarf galaxies are almost completely determined by the dark matter.

Recap: basic idea

- Galaxies form from the cooling and condensation of gas in dark matter halos (White & Rees 1978).
- To understand galaxies, we need to understand:
  - The cosmological boundary conditions;
  - The important baryonic processes;
  - How those processes interact with each other over 'cosmic' mass, time and distance scales.
- We test this understanding by making predictions that can be compared to the statistics of large galaxy surveys and to detailed observations of individual galaxies.



Cookery metaphor originally from Frenk, Baugh, Bower et al., 1990s

Apologies for the lack of image credits.

Recap: Most Important Points

- Galaxy formation only happens in sufficiently massive DM halos (> $10^8 M_\odot$).
- The evolution of the dark matter halo determines: if/when a galaxy forms; how quickly the galaxy grows; if/when it stops growing.
- Given cosmological parameters, we can make very precise predictions for the evolution of DM.
- Models describe how baryonic processes like cooling, star formation and feedback interact with each other over cosmic time, subject to the boundary conditions imposed by the growth of dark matter halos.
- They explain the variation in the efficiency of galaxy formation with halo mass through a combination of supernova and AGN feedback.
- The biggest uncertainties concern the cycling of baryons through multiple generations of star formation and feedback.
- This simple story explains most of the statistics of the present-day galaxy population, revealed by massive surveys. However, current explanations are not unique, and almost all the details remain to be understood!

Optional Exercise

- A good way to get familiar with the galaxy population is to look at a lot of galaxies and ask "what's that"?
- Go to the DESI Legacy Imaging Survey viewer:

https://www.legacysurvey.org/viewer

- Scroll around the Universe until you find a galaxy *you* think is interesting.
- During the workshop and summer program, share with me and your fellow students on Slack. (Click on the viewer and choose "link here" to get a link to what you're looking at).
- Also see https://www.legacysurvey.org/svtips/ for tips on using the viewer.

Thanks!

A few suggestions for further reading:

- *Basic cosmology:* Andrew Liddle, *An Introduction to Modern Cosmology*, Wiley, 2015 [https://www.books.com.tw/products/F013479486]
- *Cosmology and galaxy formation:* Barbara Ryden, *Introduction to Cosmology*, Cambridge UP, 2016 [https://www.books.com.tw/products/F013876350]
- *Galaxy-halo connection:* Wechsler & Tinker 2018 (ARA&A) [https://doi.org/10.1146/annurev-astro-081817-051756]
- *Galaxy observations:* Blanton & Moustakas 2009 (ARA&A) [http://adsabs.harvard.edu/abs/2009ARA%26A..47..159B]
- *Dwarf galaxies:* Simon 2019 (ARA&A) [https://www.annualreviews.org/doi/abs/10.1146/annurev-astro-091918-104453]
- *Galactic Archaeology:* Helmi 2020 (ARA&A) [https://www.annualreviews.org/doi/abs/10.1146/annurev-astro-032620-021917]
- *Galaxy formation models (semi-analytic):*
  - Guo et al. 2011 (MNRAS 413 101) [http://dx.doi.org/10.1111/j.1365-2966.2010.18114.x]
  - Lacey et al. 2016 (MNRAS 462 3854) [http://dx.doi.org/10.1093/mnras/stw1888]
- Galaxy formation models (hydrodynamical):
  - Vogelsberger et al. (2014) [http://adsabs.harvard.edu/abs/2014MNRAS.444.1518V]
  - Schaye et al. (2015) [http://adsabs.harvard.edu/abs/2015MNRAS.446..521S]
- For advanced study, the standard textbook is **Galaxy Formation** by Mo, van den Bosch & White.

Some key historical papers:

- Eggen, Lynden-Bell & Sandage (1962)
- Tinsley (1968)
- Toomre & Toomre (1972)
- Larson (1974)
- Searle & Zinn (1978)
- White & Rees (1978)
- Frenk et al. (1985)
- White & Frenk (1991)
- Mo, Mao & White (1998)