Galaxy formation and Evolution

We will discuss the basics of:
- ★ The Big Bang
- ★ Large scale structure formation
- ★ The first stars and galaxies
- ★ The present day Universe

Sterrewacht Leiden

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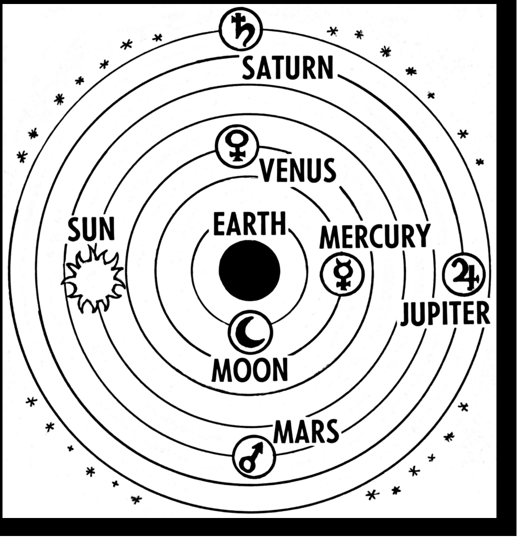
With contributions from Prof. Rychard Bouwens, Leiden Observatory

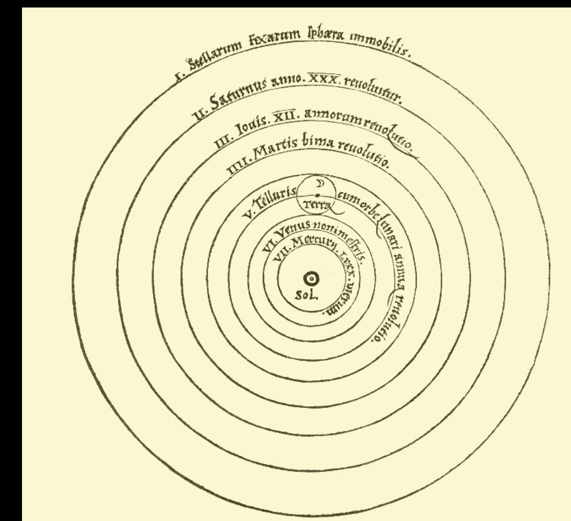
Pre Copernican Universe

Earth is at the centre of the eternal, unchanging Universe: based on Ptolemy's Almagest 150 AD



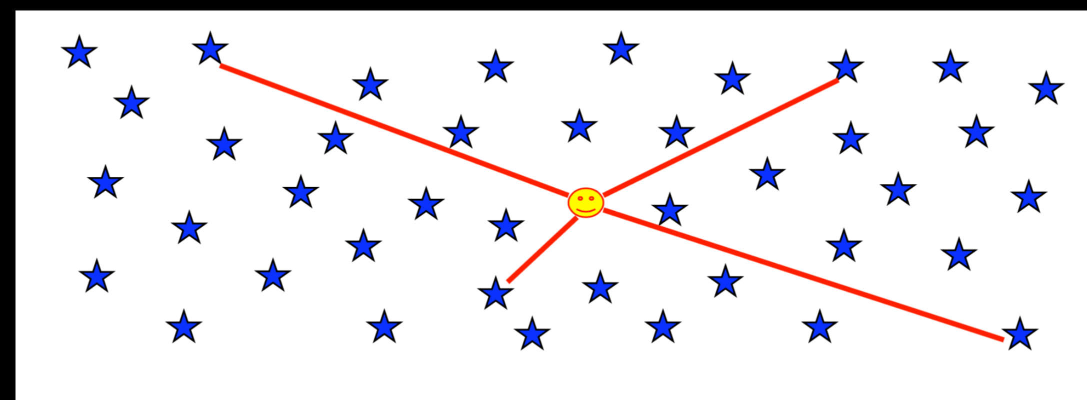
There is nothing special about the location of Earth in the Universe

- Work lead by Copernicus, Bruno, Galileo, Kepler
- The Universe was still viewed as eternal and unchanging
- Newtonian Universe



Olber’s Paradox

In the 19th century, an astronomer named Heinrich Olbers stumbled on a contradiction that could not be easily explained: why doesn't the night sky look uniformly bright? A sky that is uniformly bright would appear to glow, yet our night sky appears black with a scattering of stars, planets, and galaxies dotting the observable sky.



Olber's Paradox

- Dust attenuation
- Edge to the stars
- Universe/stars has a finite age
- Contractions and expansions

The Universe has a finite age

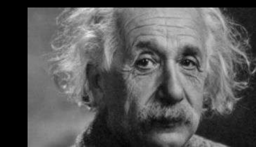
Butdustwillheatandreradiate
Edge to the stars : ViolatesCopernicanPrinciple
Finite age: Violates permanency
contractions/expansions: Nonoticeableeffectunlessextreme

Why is the Universe not permanent

- Problems with:
  1. Olber's paradox
  2. Conservation of Energy
  3. Ages of Earth, meteorites, and stars.

Energy conservation: for stars to shine indefinitely they would require an infinite fuel reserve

Einstein’s Universe

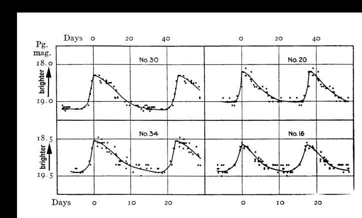


- In order to achieve a static Universe Einstein introduced a counter-balance to his GR models, the famous cosmological constant : agreed with Austrian physicist and philosopher E. Mach (1838-1916) regarding the genesis of the property of inertia.

- According to Mach, the inertial mass of any body is due to the influence of the universe as a whole.

Hubble–Lemaître Law

- Discovery of extra-galactic sources.
- Comparison between redshift and Cepheid variables showed that galaxies were moving away from us: recession velocity is proportional to the distance.



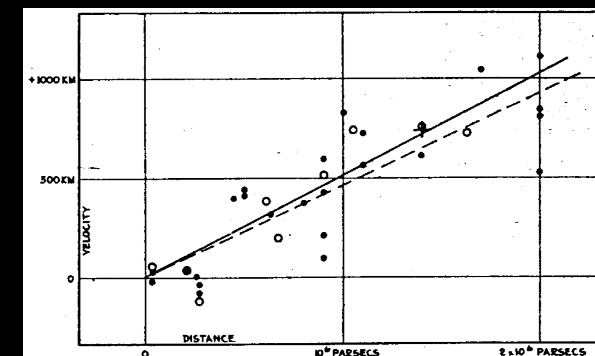
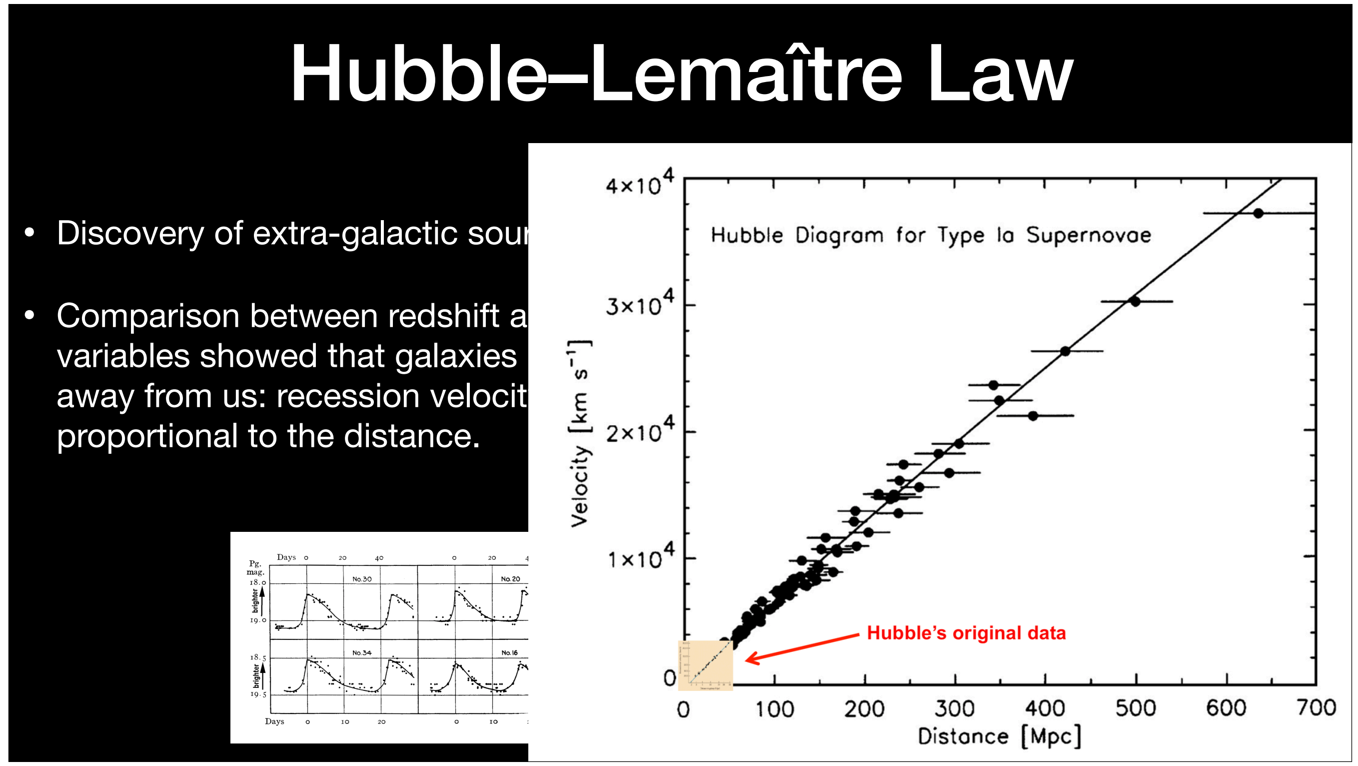


FIGURE 1

- ProvedthatM31wasexternaltoourgalaxy.
- Hubblecollectedmanygalaxyimagesandspectra
- MeasuredbrighteststarsandCepheidvariablestogetdistances
- Alsousedbrightestclustermember
- Measuredoffsetofcommonspectralfeaturestogetvelocity



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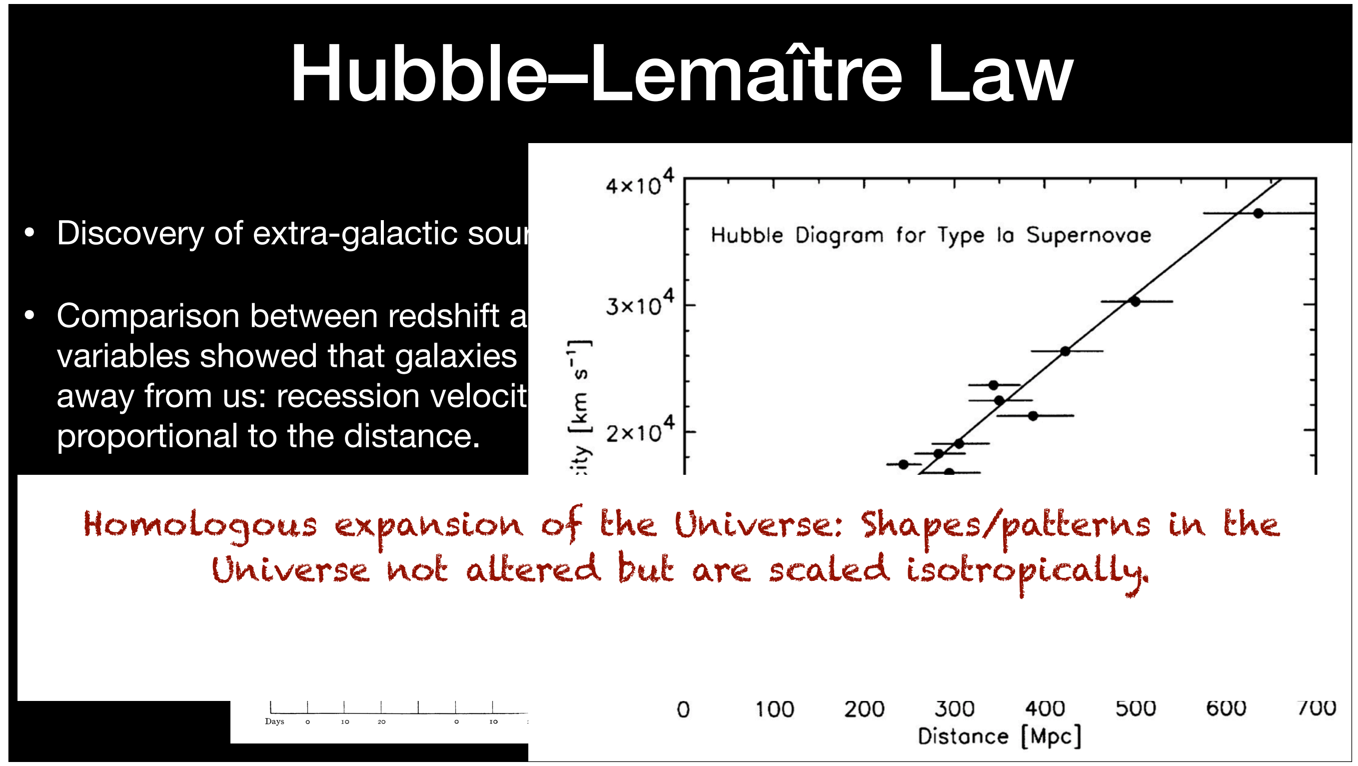

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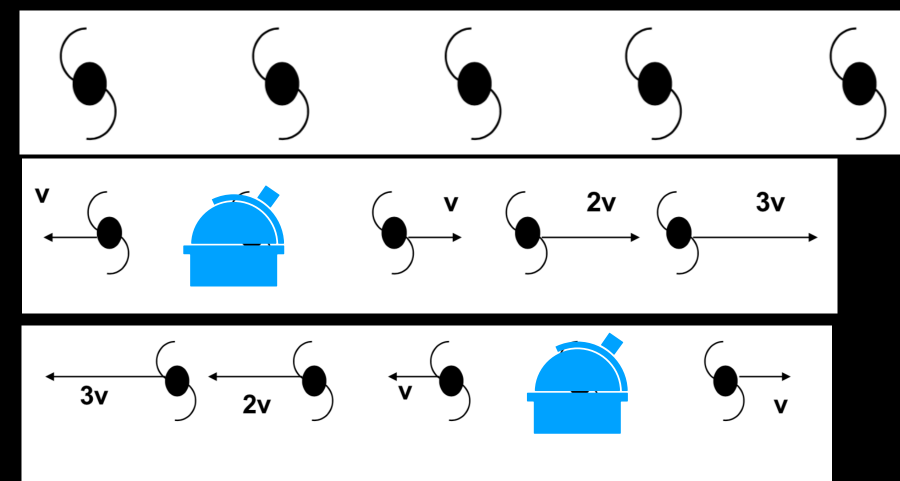
The universal expansion of the Universe

- If we are not in a special place in the Universe why is most galaxies moving away from us?



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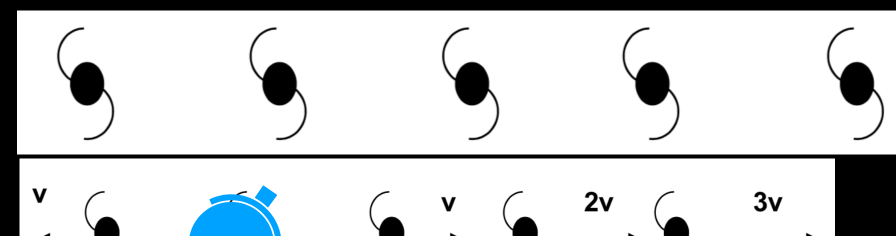
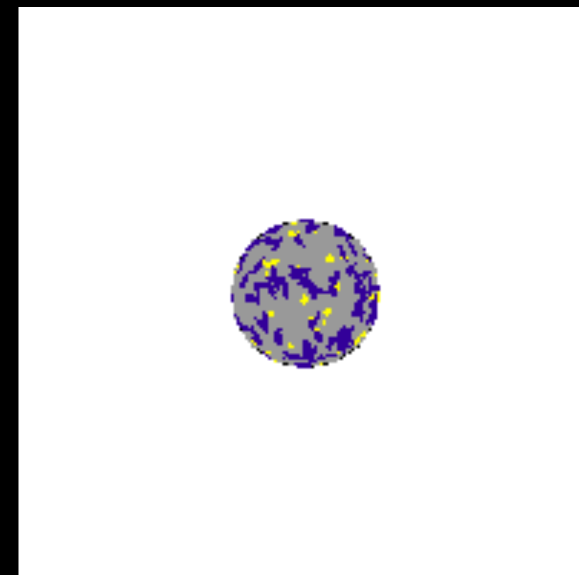


Does not violate the Copernecian principle: if A sees B receding, then B sees that A is receding. The diagrams from the two different points of view are identical except for the names of the galaxies.

The universal expansion of the Universe



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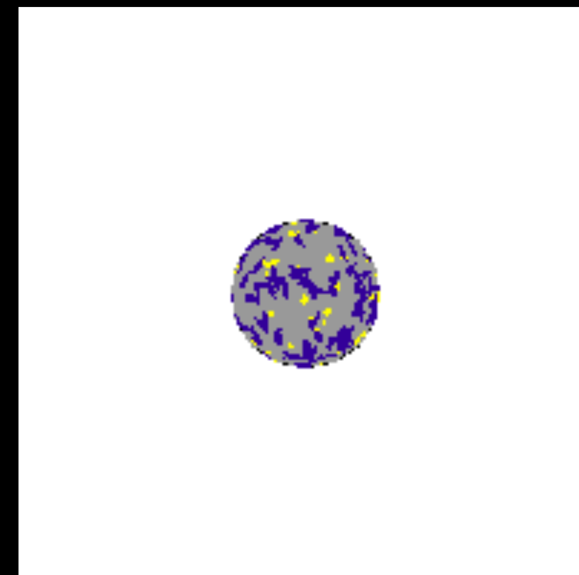


The age of the Universe

$$t_{Age} = \frac{1}{H_o} = \frac{1}{75} s.Mpc / km$$

$$t_{Age} = \frac{1}{75} \times \left(\frac{10^6 \times 3 \times 10^{16}}{10^3} \right) = 4 \times 10^{17} s$$

$$t_{Age} = 4 \times 10^{17} \times \left(\frac{1}{365.25 \times 24 \times 60 \times 60} \right) yrs$$

$$t_{Age} = 1.267 \times 10^{10} yrs$$

$$t_{Age} \approx 13 Gyrs$$

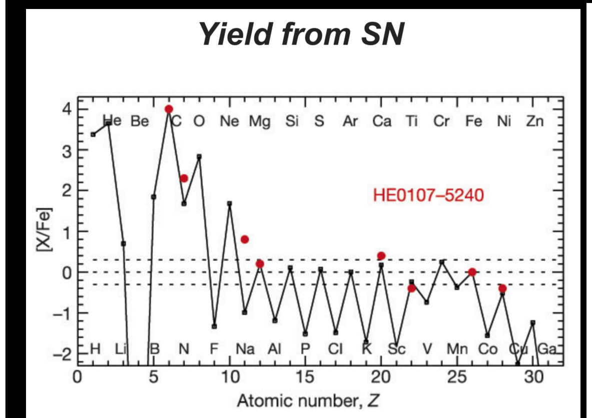
The Big Bang theory

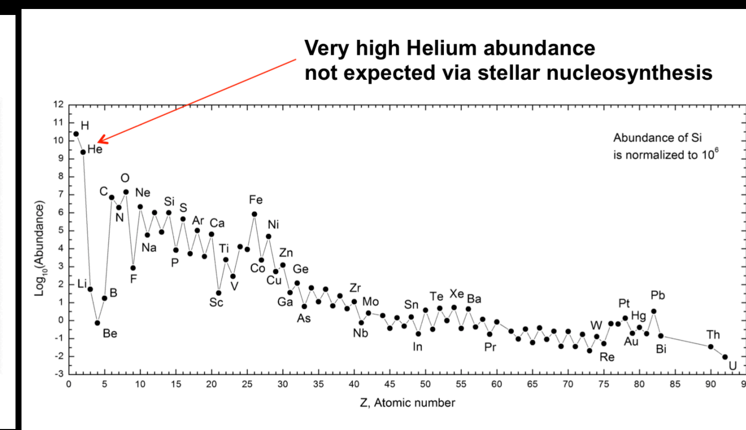
The Big Bang theory

The Big Bang theory

* Developed by Alexander Friedmann and Willem de Sitter on Einstein's general relativity models
* General relativity - cosmological constant provided the basis for expansion
* Solved a few problems know then:
    * Correctly predicts the abundances of light elements
    * Explains the CMB as relic of the hot initial phase
    * Naturally accounts for the expansion of the Universe
    * Provides a framework to understand the formation of cosmic structure

The He problem





http://adsabs.harvard.edu/abs/1967QJRAS...8..313T

Early Universe was radiation dominated

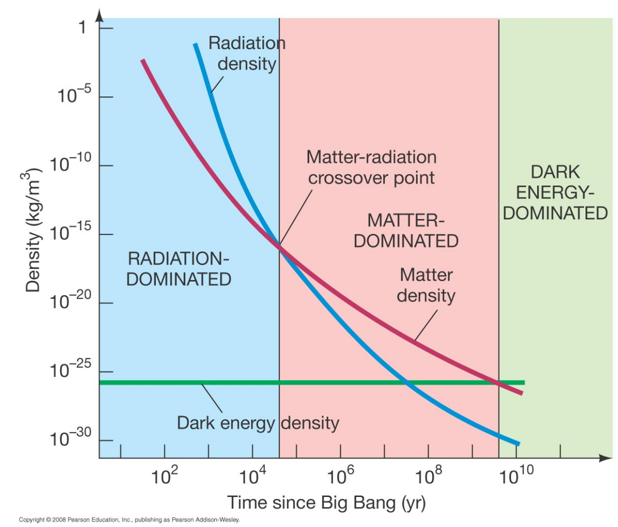


Figure Credit: Pearson Education Inc. Pearson Addison-Wesley

Looking back in time

– Radiation-matter coupling (i.e., ionised to compton scattering)

– Nuclei split apart (D=2Mev, Fe=7 MeV)
– Neutrons/protons —> Quarks (n=939.6MeV, p=938.3MeV)

– Quarks destroyed (~GeV+)
– Pure energy bath (matter being formed and anhilated - abundant energy)

– Singularity, creation event (Big Bang)

t=0

Solution to the He problem

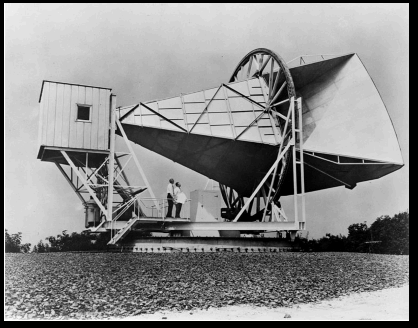
- The high density in the early Universe made it possible for Deuterium to find a partner to produce He

$$p + n \rightarrow {}^{2}D,\ D + p \rightarrow {}^{3}He,\ D + D \rightarrow {}^{4}He$$

- From big bang cosmology 25% of the baryonic mass is He
- D abundance from QSO sight-lines is a measure of the baryon density of the universe —> 1H atom per $8m^3$

The Comic Microwave Background (CMB)

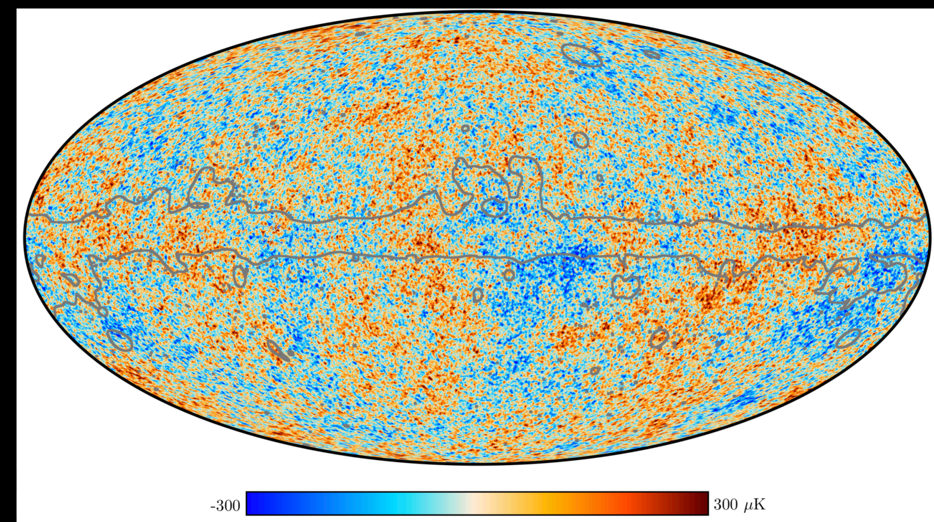
- Predicted by George Gamov, 1948: a perfect black body spectrum should exist with T≈5K



Penzias and Wilson: Nobel Prize 1978

UnliketheexpansiontheCMBwaspredictedbeforeitsdiscovery
BigBangmodeladoptedoverSteadyStatefollowingCMB
astheUniverseexpandsitcools

All Sky CMB Map



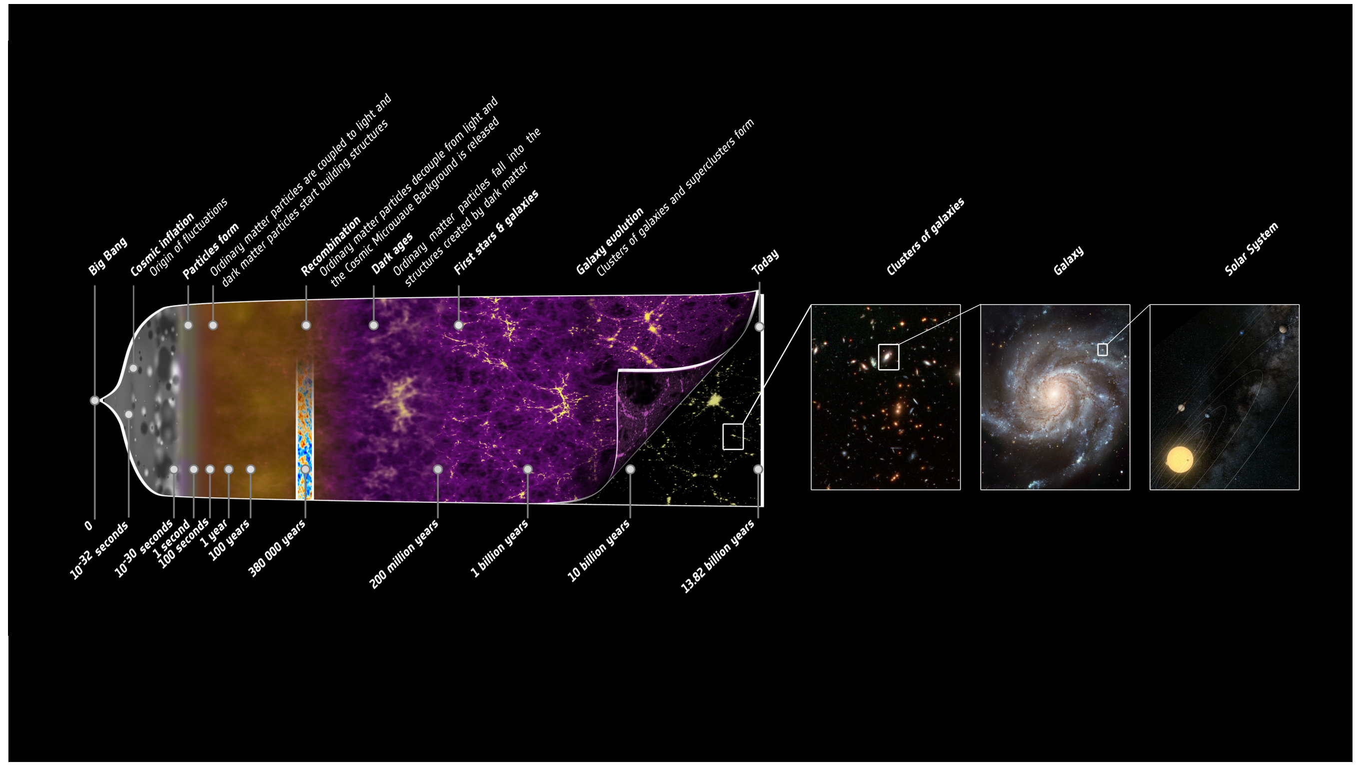
Problems with the Big Bang model

- Origin of the Universe
- The horizon problem
- The flatness problem
- Origin of the baryon asymmetry
- Monopole problem
- Origin of primordial density fluctuations
- Nature of dark matter
- Nature of dark energy

Horizon problem—> 1 degree isotropies expected, observed all sky with CMB

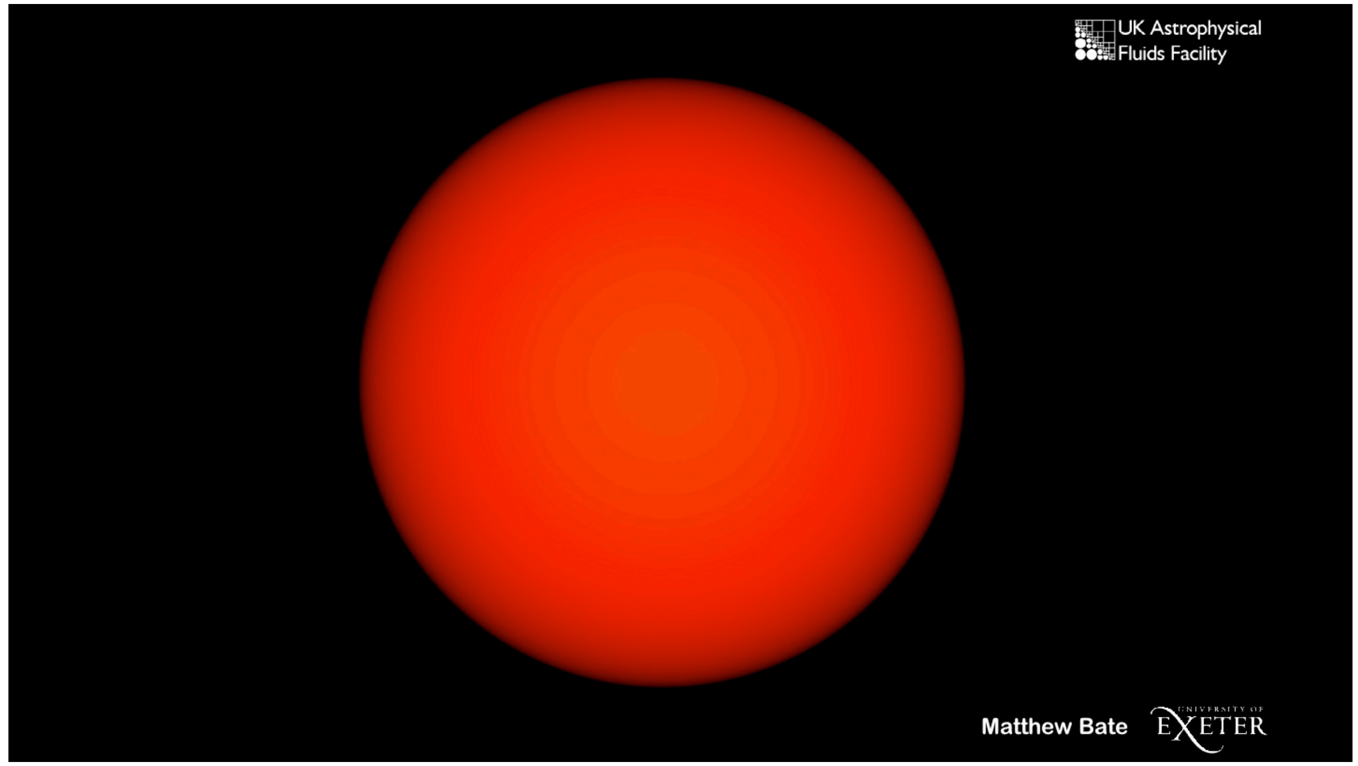
The early Universe according to the Big Bang theory

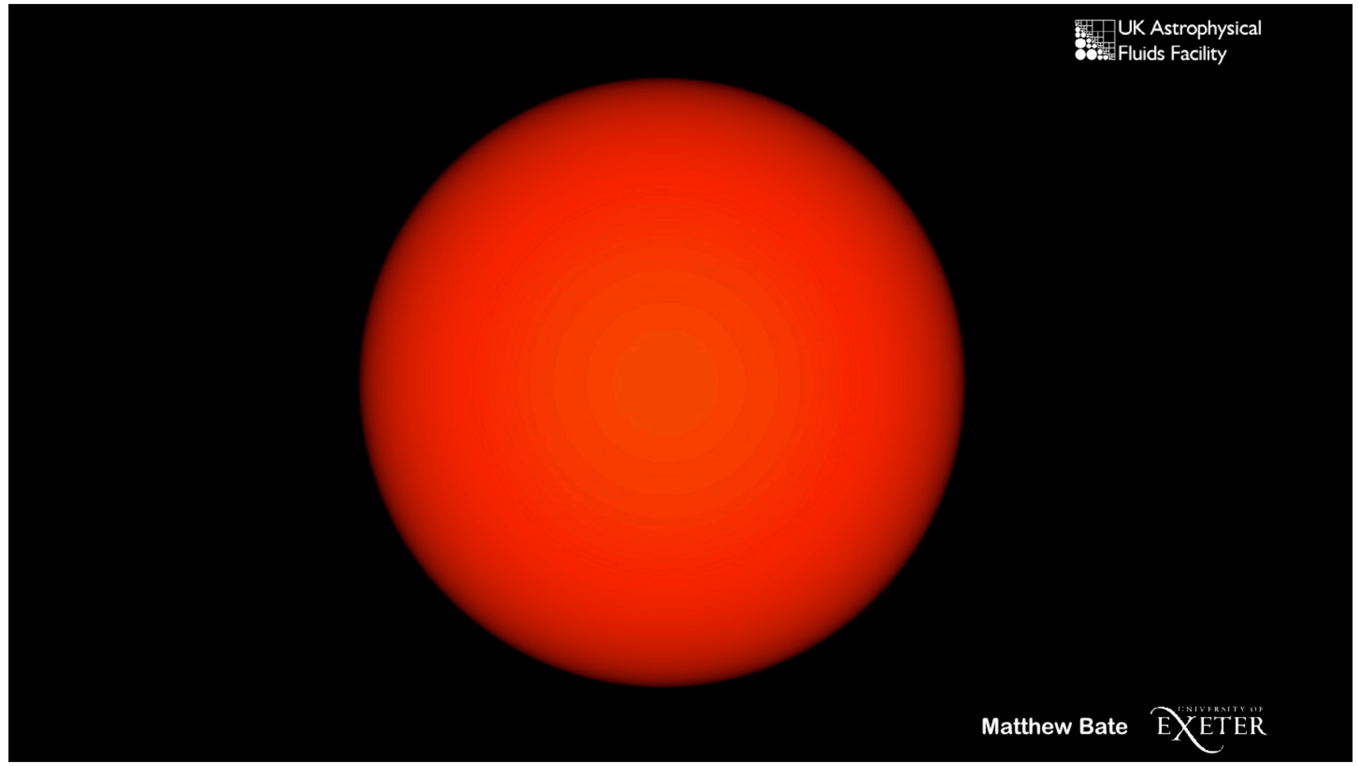
- Big Bang: singularity, energy appearing from nowhere
- Inflation: the rapid exponential expansion phase of the Universe
- Matter-antimatter annihilation: symmetry broken, high photon-to-baryon ratio
- The quark soup: All possible particles co-exist bubbling in and out of existence.
- Baryogeneis: neutrons and protons made
- Nucleosynthesis: plasma of charged nuclei (75%H, 25%He) + electrons
- Recombination: Neutral atoms, matter and radiation decouple, the surface of last scattering
- Re-ionisation and Galaxy formation


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
Clusters of galaxies
Galaxy
Solar System
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

The first stars

- Recombination: Misleading term meaning the combining of electrons + protons to form neutral hydrogen (z=1100, t= 378, 000 yr)
- The first stars are expected to form around dark matter filaments
- Almost no metals existed: so these stars are metal free and very hot!
- Short life time and quick supernovae explosions resulting in the enrichment of metals in the Universe.


UK Astrophysical
Fluids Facility
Matthew Bate
UNIVERSITY OF
EXETER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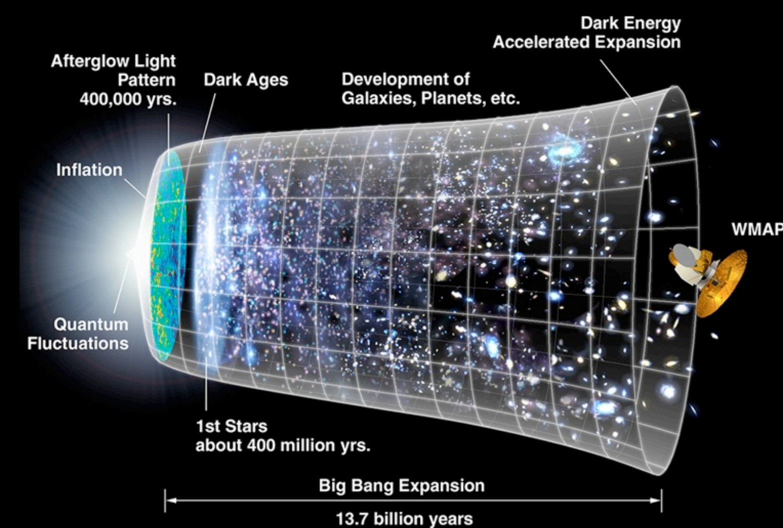
Where Do The Earliest Galaxies Fit into the Timeline of the Universe?



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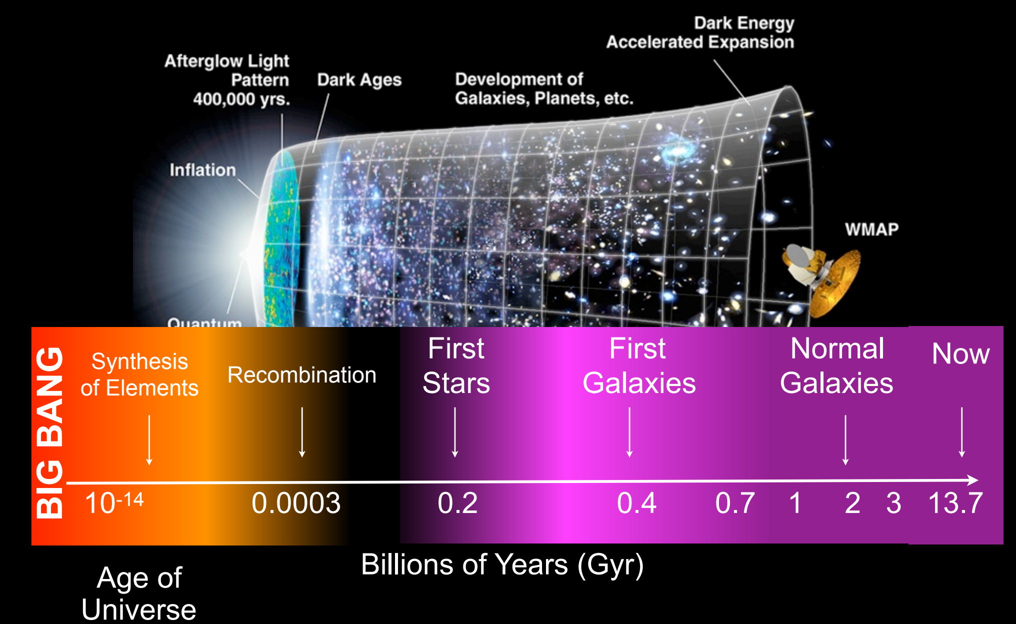

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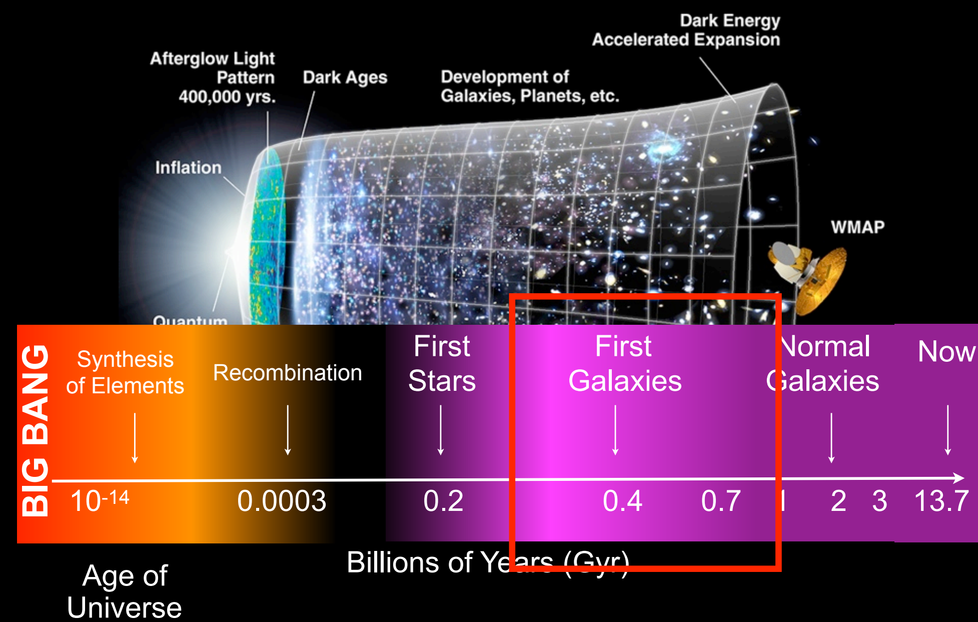
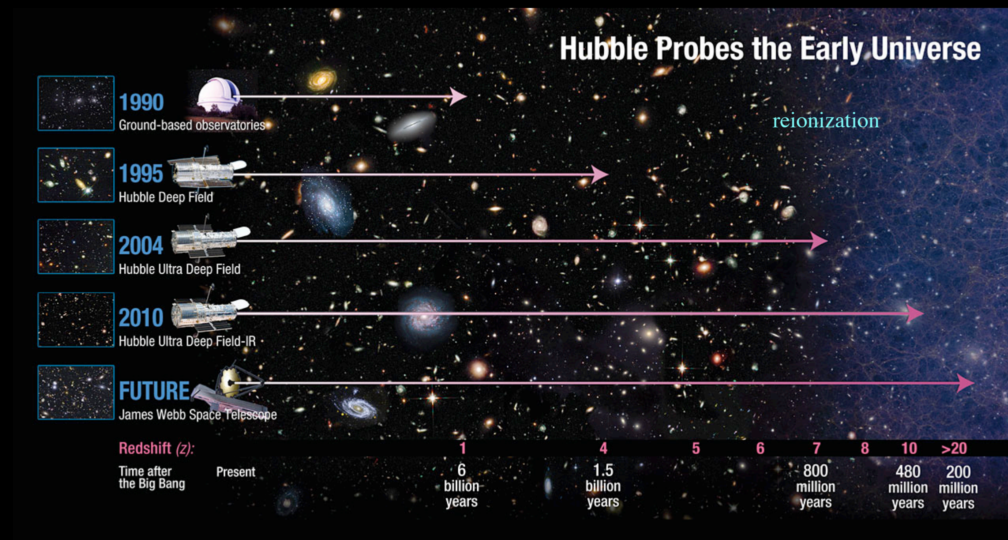


Hubble is now observing galaxies
97% of the way back to the Big Bang,
during the first 500 million years (redshift z > 9.5)

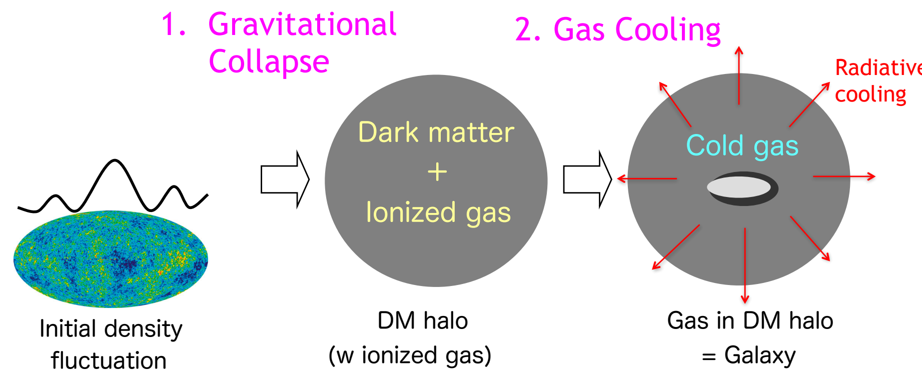


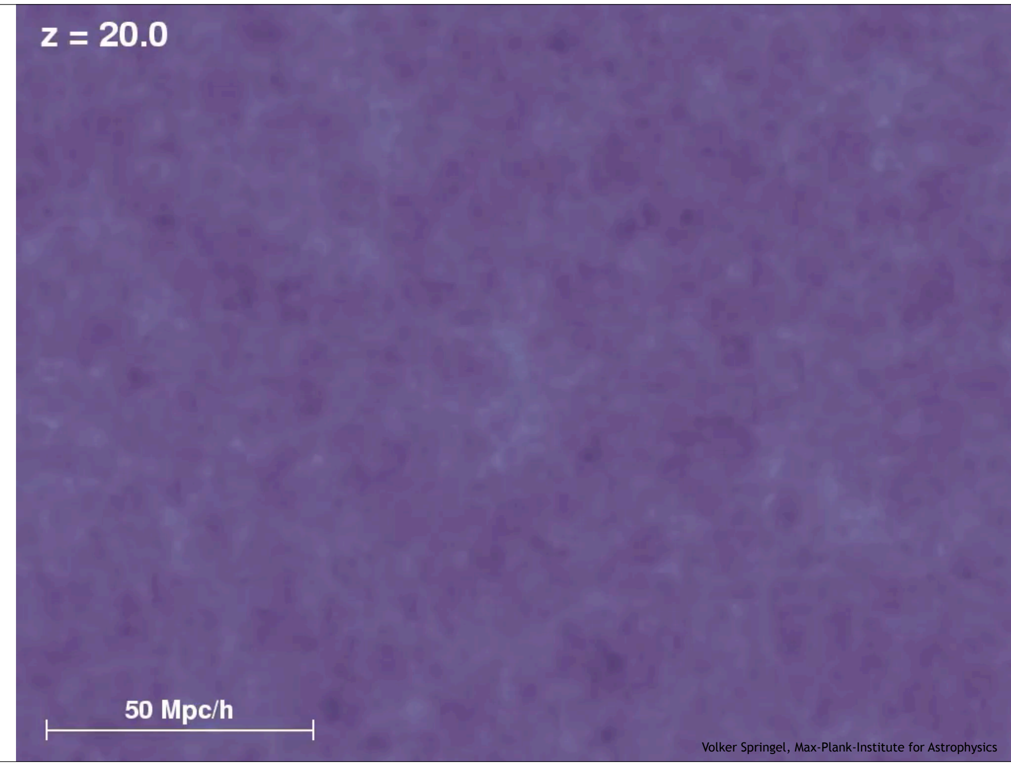
Read TITLE
into the epoch of reionization
Much of this progress is due to the Hubble Deep Field initiatives over the years, pushing to higher and higher redshifts.

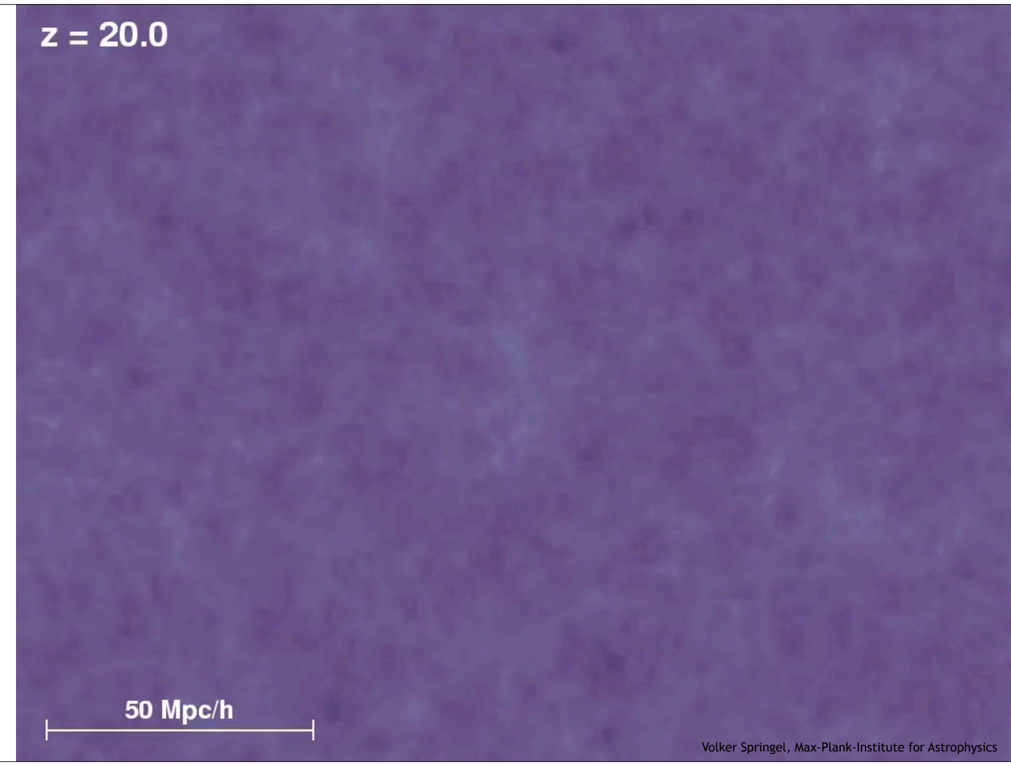
Pauze

Now lets take a small detour to get an overview of the basic picture of galaxy formation

Basic Picture of Galaxy Formation




z = 20.0
50 Mpc/h
Volker Springel, Max-Plank-Institute for Astrophysics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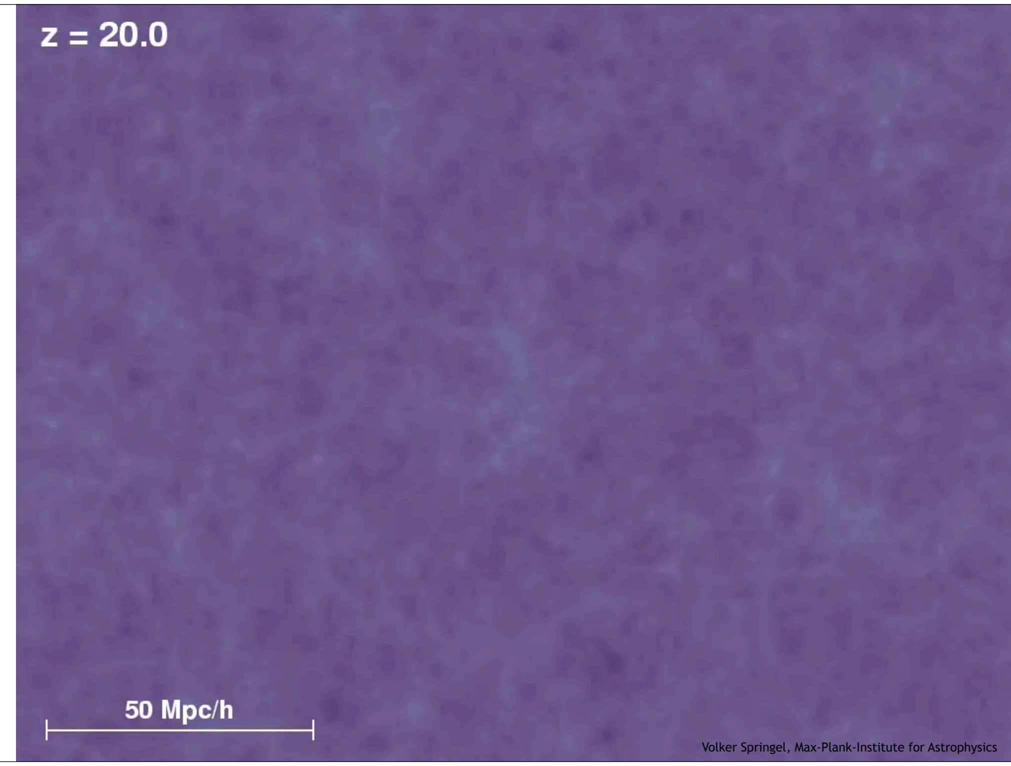
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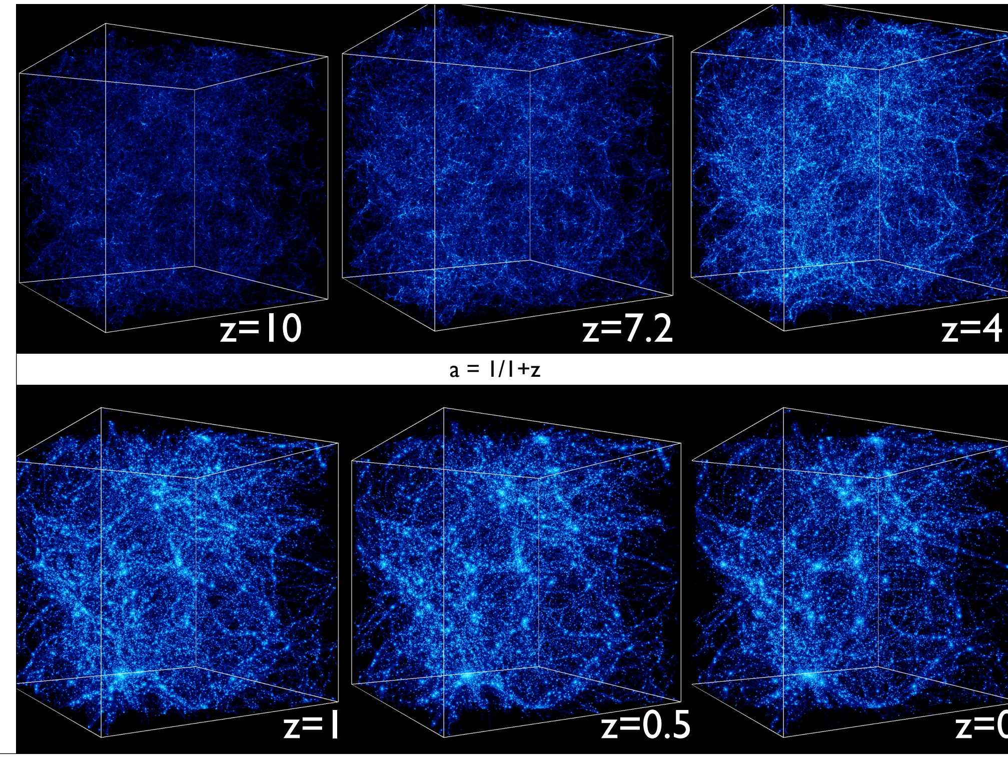
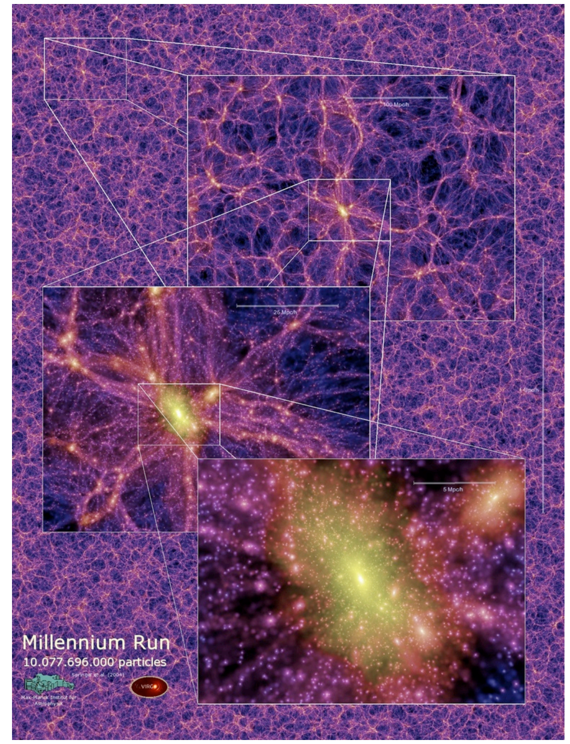

z=10
z=7.2
z=4
a = 1/1+z
z=1
z=0.5
z=0



how to characterize this mess?

structure on a wide range of scales

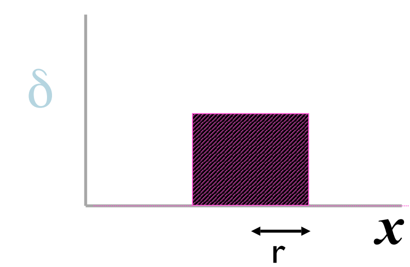
can we understand the collapsed objects (halo formation) analytically?

The 'tophat model' (spherical collapse)

- consider a uniform, spherical perturbation

$\delta_i = \rho(t_i)/\rho_b(t_i)-1$

$M = \rho_b(4\pi r_i^3/3)(1+\delta_i)$



equation of motion for the perturbation
(same as for a closed universe)

$$\ddot{r} = -\frac{GM}{r^2}$$

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at turnaround,

$$E = -\frac{GM}{r_{\max}}$$

for EdS, solving this equation gives the density at turnaround as

$$\frac{\rho_{\max}}{\bar{\rho}} \approx 5.5$$

the perturbation will be in virial equilibrium when

$$2K_{vir} + W_{vir} = 0$$

$$E = K_{vir} + W_{vir} = -W_{vir}/2 \approx \frac{GM}{2r_{vir}} = -\frac{GM}{r_{\max}}$$

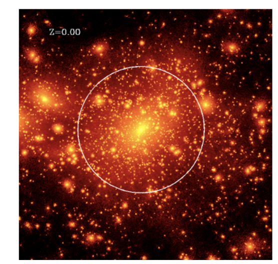
which implies

$$r_{vir} = r_{\max}/2$$

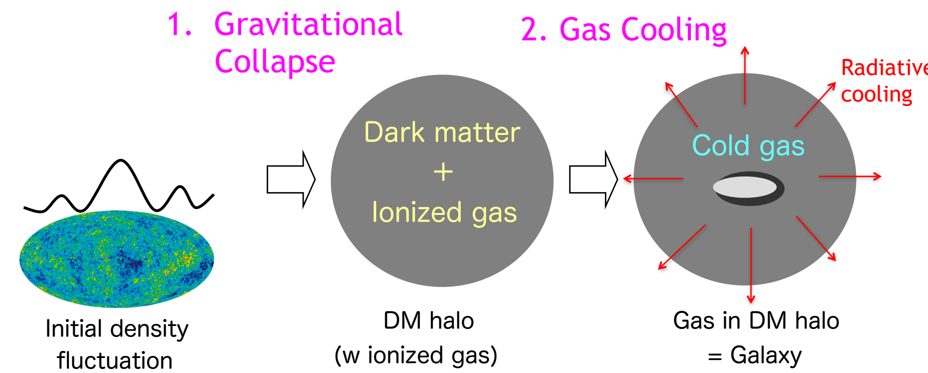
ie, 8 times denser than at turnaround

sadly, halos don't
look like this:

halos
look like this:



Basic Picture of Galaxy Formation



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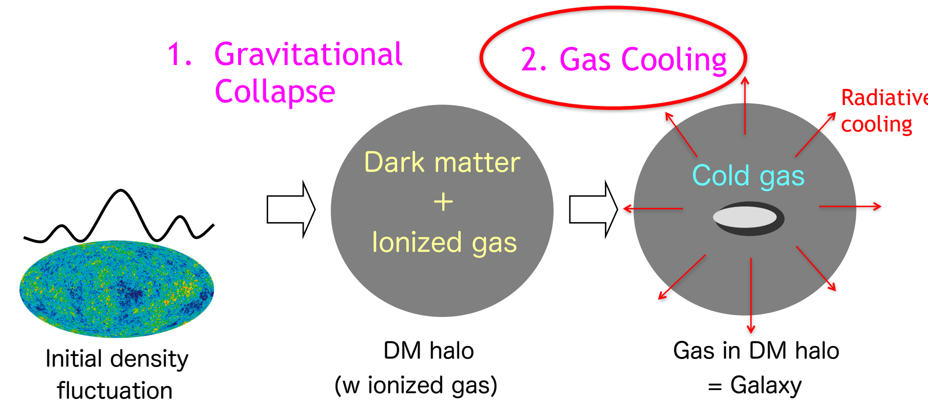

SECOND STEP: Gas cooling

The cooling rate can be expressed as

$$\text{cooling rate} = n^2\Lambda(T)$$

where n is the gas volume density and Λ(T) is the temperature dependent cooling rate.

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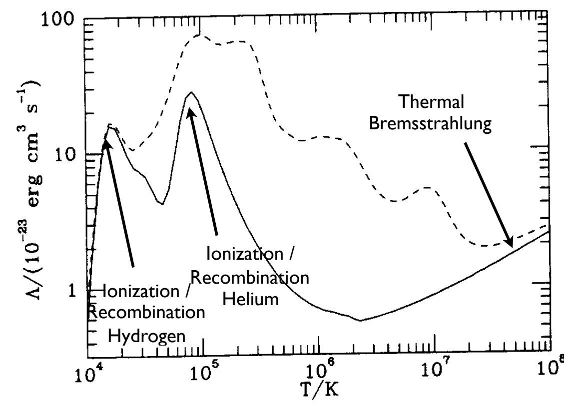

Figure 24.19 The cooling function $\Lambda(T)$. The solid line corresponds to a gas mixture of 90% hydrogen and 10% helium, by number. The dashed line is for solar abundances. (Figure from Binney and Tremaine, *Galactic Dynamics*, Princeton University Press, Princeton, NJ, 1987.)

SECOND STEP: Gas cooling

There are two time scales of interest in thinking about galaxy formation:

(1) dynamical time scale t_{dyn} ($\propto n^{-1/2}$)

(2) cooling time scale t_{cool} ($\propto n^{-2}\,\Lambda^{-1}(T)$)

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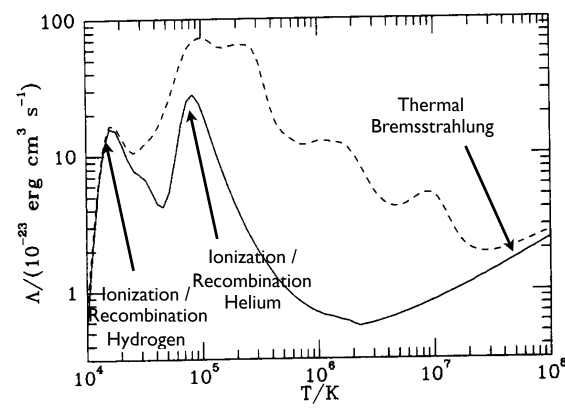

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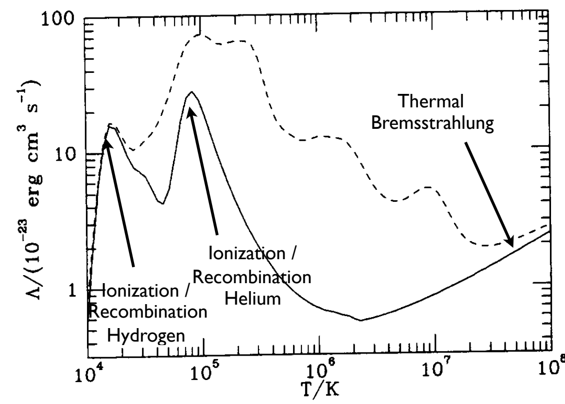
Can write the equivalent

$n^{-3/2} < \Lambda(T)$

on this axis



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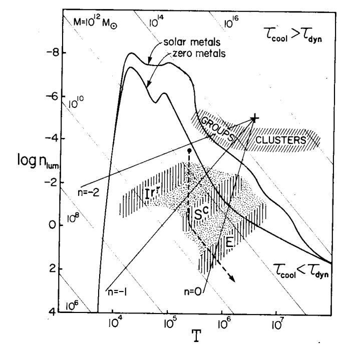

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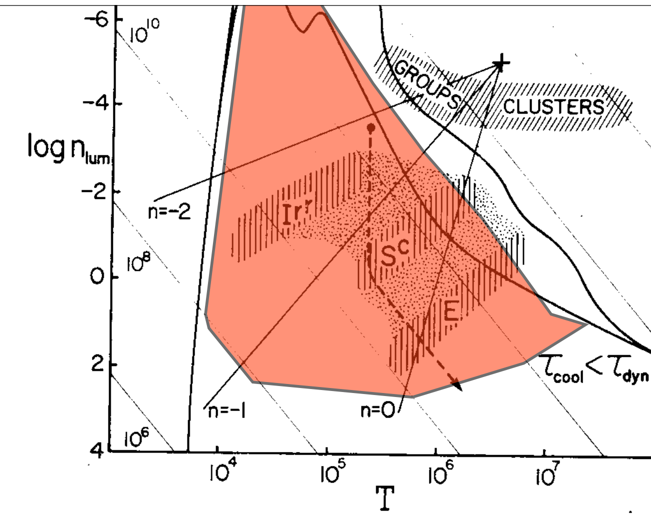

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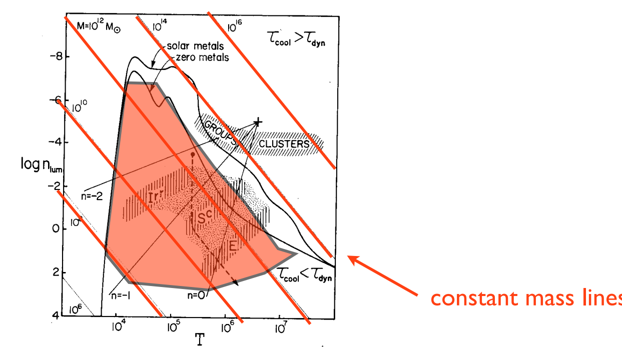

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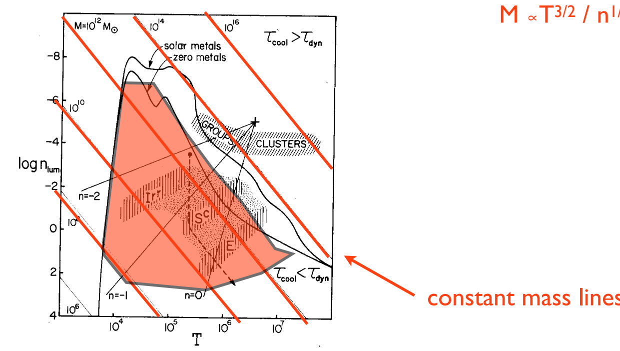

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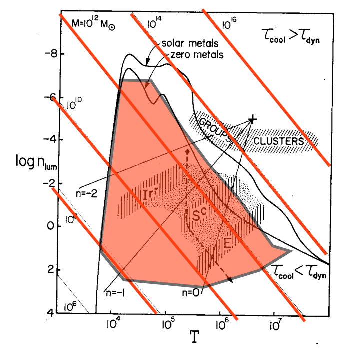

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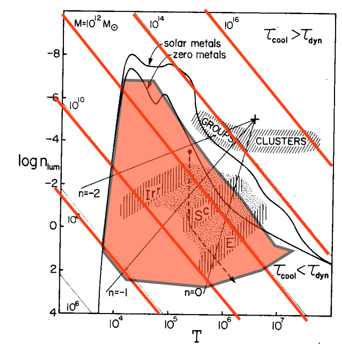

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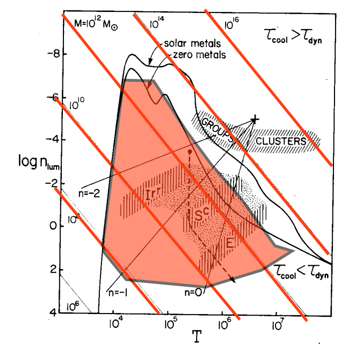

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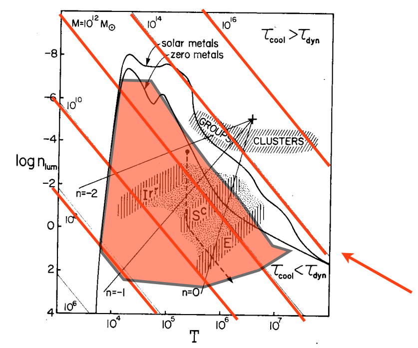

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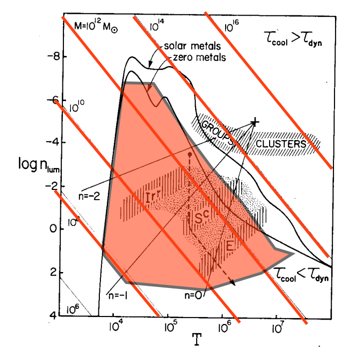

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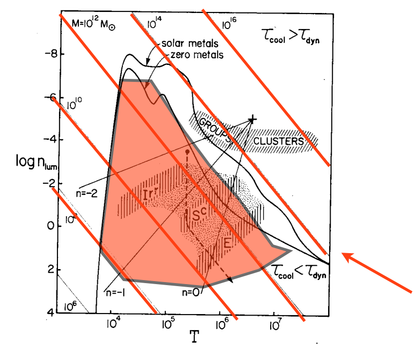

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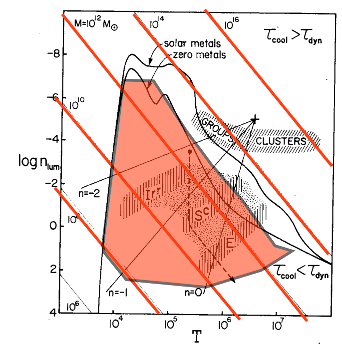

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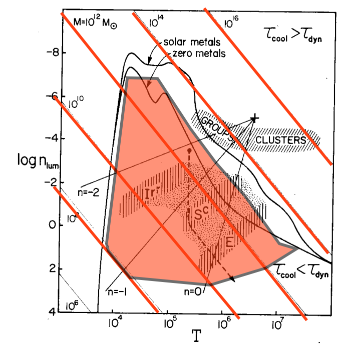

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However for cluster-scale masses (10^{14} M_{sol}), cooling is not efficient... and have lots of hot gas.

constant mass lines

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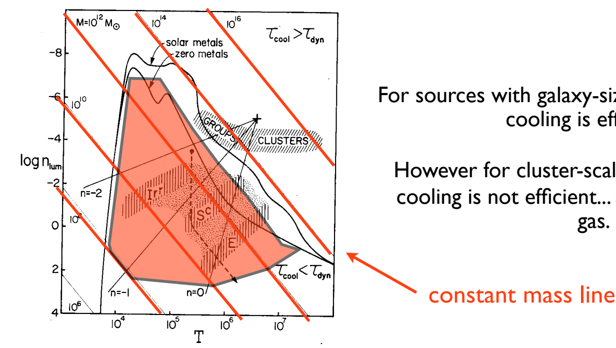
There are two time scales of interest in thinking about galaxy formation:

(1) dynamical time scale t_{dyn} ($\propto n^{-1/2}$)

(2) cooling time scale t_{cool} ($\propto n^{-2}\,\Lambda^{-1}(T)$)

It is likely a function of the mass of gas that cools inside the collapsed halo.



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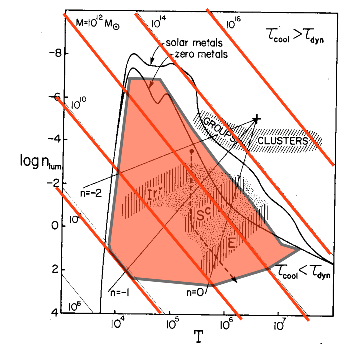

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constant mass lines

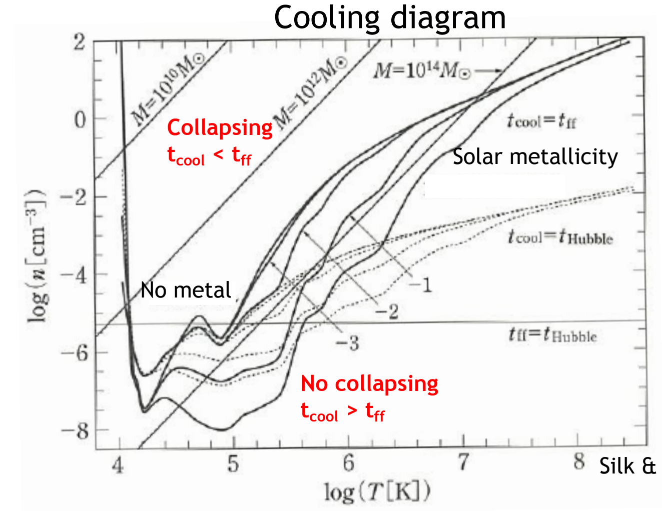
Relevant collapsed halos ~ 10^8 to $10^{12.5}$ solar masses

Baryonic Mass in these Halos < 10^{11} solar masses

Only a small fraction of which cools and forms stars

Conditions for Gas Collapse

Cooling diagram



Silk & Wyse 1993

- $t_{cool} < t_{ff}$: Gas collapse→ dense gas/star-formation(10^{12}Mo)
- $t_{cool} > t_{ff}$: No gas collapse (quasi-static contraction)

Virial temperature as a function of mass and radius: T=GMμm/5kR and M=3/4πR^3rho
For M=const, T^3 propto rho
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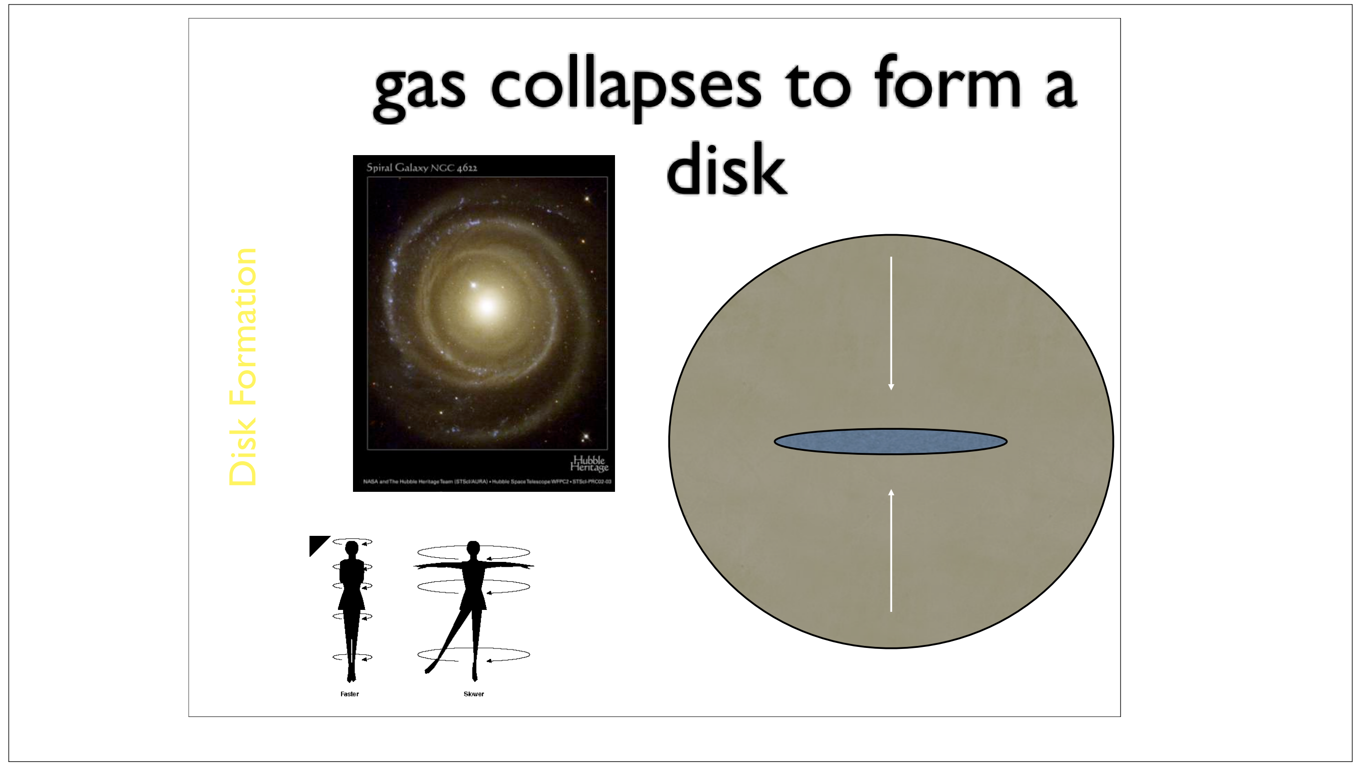

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This results in the formation of a gas disk (for a disk galaxy), since a disk is the minimum energy configuration that still conserves angular momentum.

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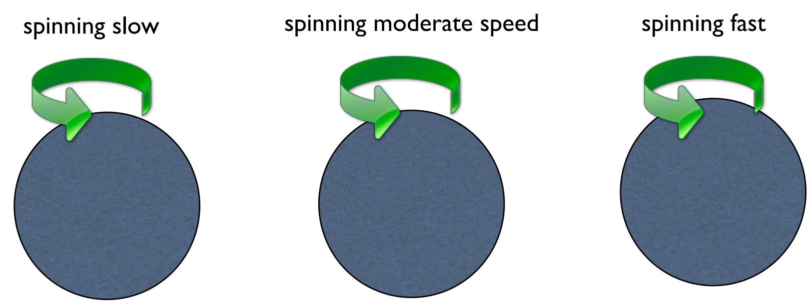

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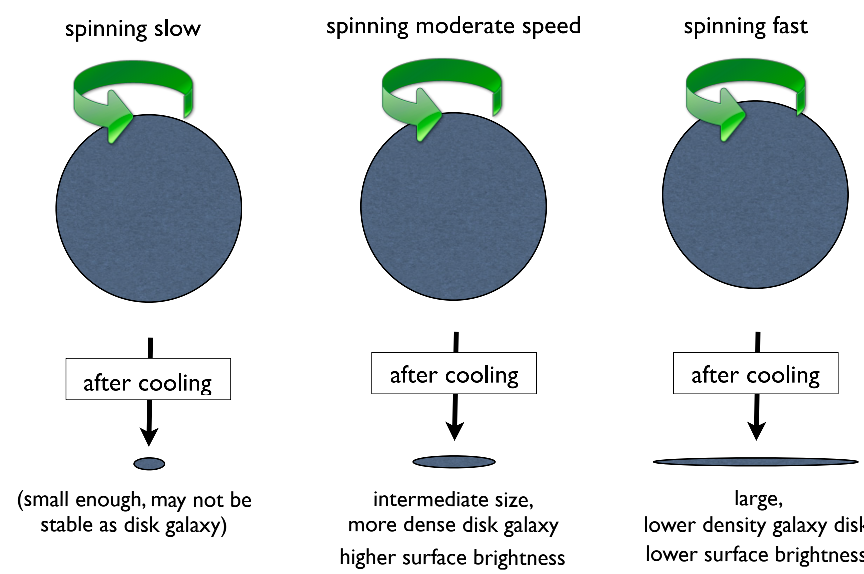

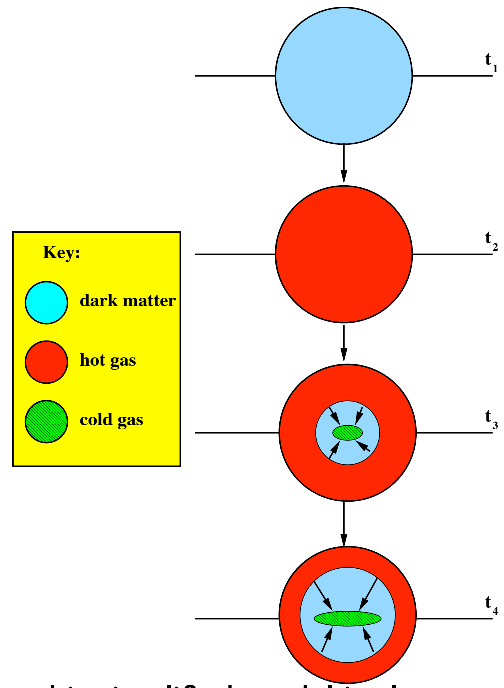

note: this simplified model is almost certainly wrong!

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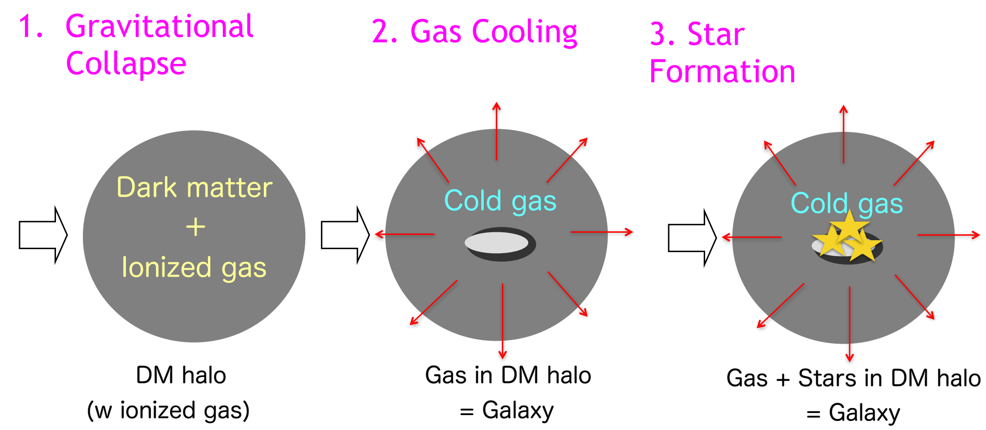
Basic Picture of Galaxy Formation



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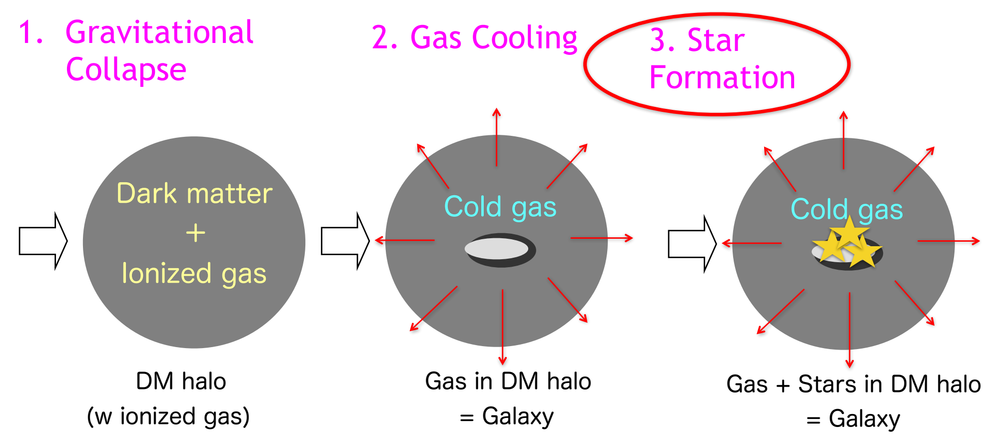

Star-Formation in a Gas Cloud

Star Formation Rate $\propto$ Cool Gas / (time scale$_{SF}$)

Kennicutt 1998

Below 10^4 K: Need H_2/metal cooling, to reach a few 10 K
Enough gas density→Star formation: It is not well understood…

Gas contraction by Jeans instability… What is the mass distribution of newborn stars? (e.g. IMF)

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Kennicutt-Schmidt Law

Kennicutt 1998

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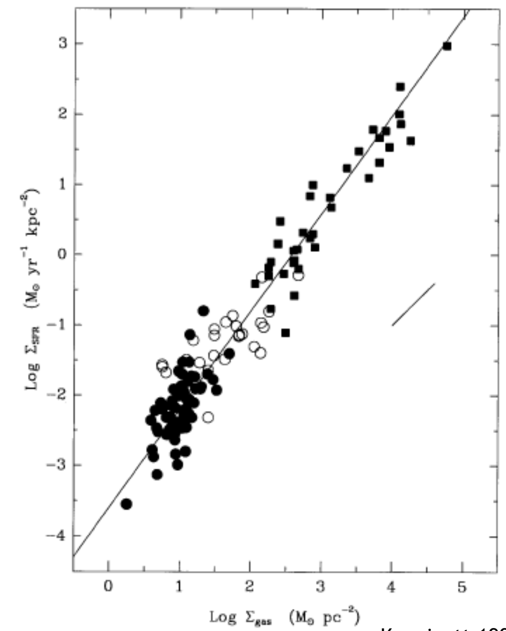
- For modeling, one can use an empirical relation (obs. results) e.g.
  Kennicutt-Schmidt law (Kennicutt98)
  to reduce the model parameters

$$\Sigma_{SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{gas}}{1\, M_{\odot}\, pc^{-2}} \right)^{1.4 \pm 0.15} M_{\odot}\, yr^{-1}\, kpc^{-2}\,.$$



Kennicutt 1998

Below 10^4 K: Need H_2/metal cooling, to reach a few 10 K

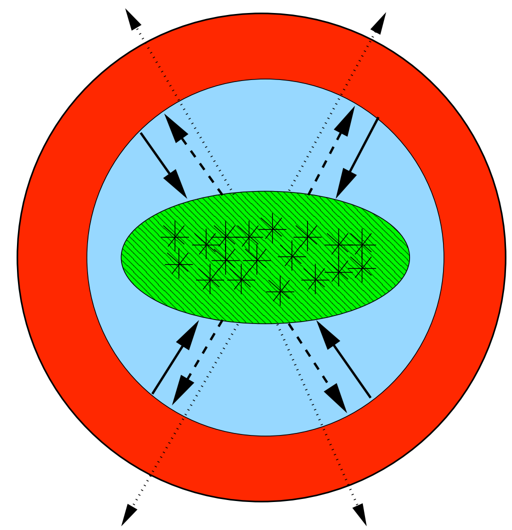
Enough gas density→Star formation: It is not well understood…

Gas contraction by Jeans instability… What is the mass distribution of newborn stars? (e.g. IMF)

As the cool gas forms stars,
there will be SNe explosions…

Virial temperature as a function of mass and radius: T=GMμm/5kR and M=3/4πR^3rho
For M=const, T^3 propto rho
For rho=const, T^3 propto M^2
For T=const, M^2 propto 1/rho

Feedback from Supernova Explosions



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For M=const, T^3 propto rho
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What happens
when two halos
with galaxies at
the
center merge?

Virial temperature as a function of mass and radius: $T=GM\mu m/5kR$ and $M=3/4\pi R^3 \rho$
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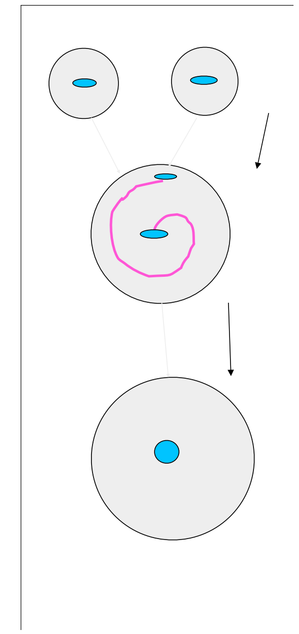

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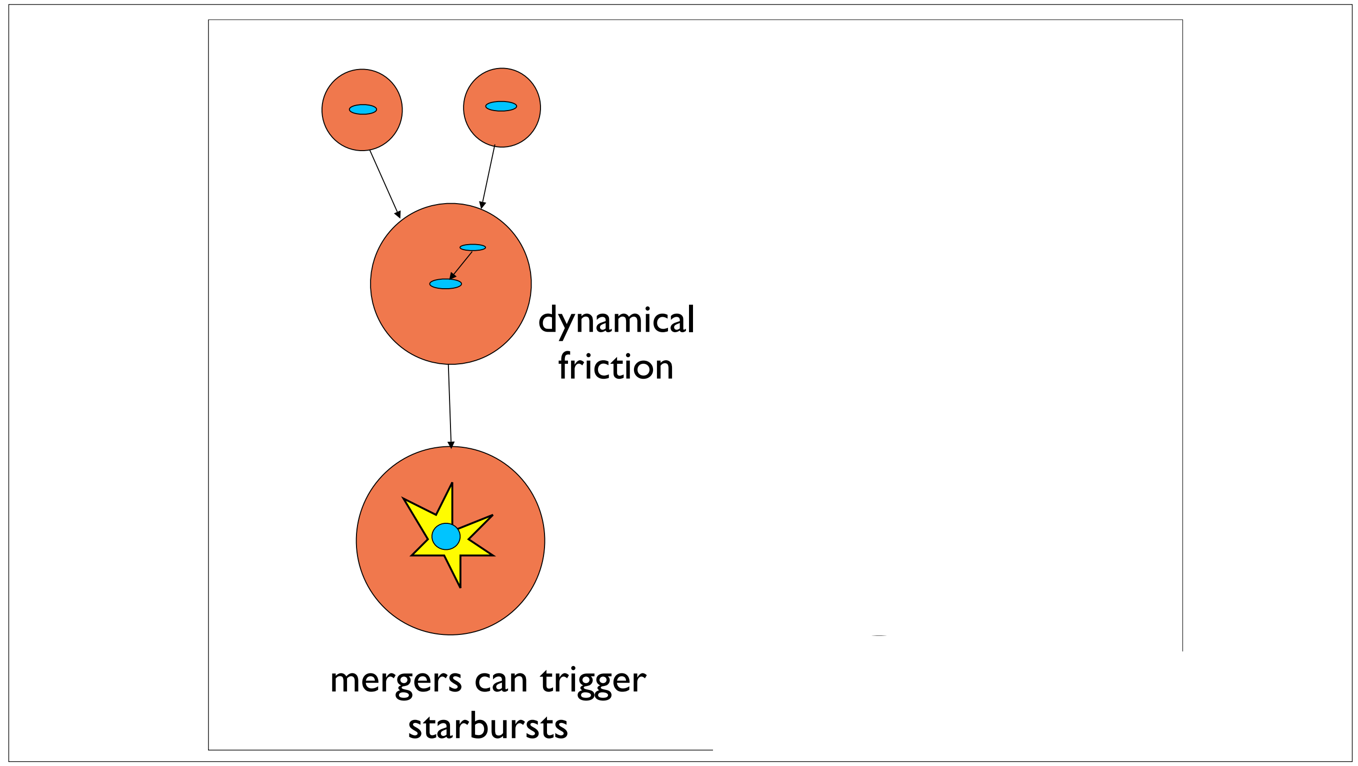

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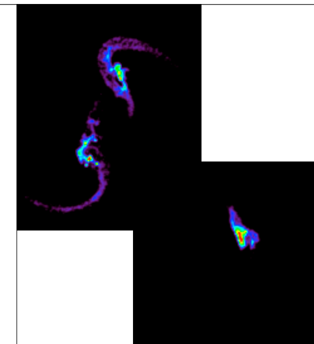
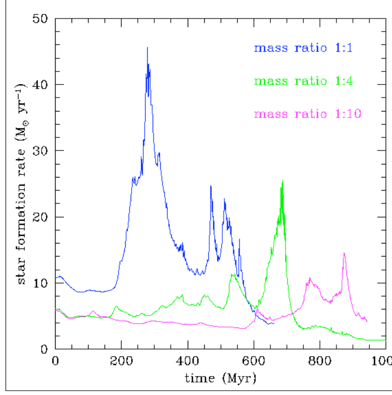
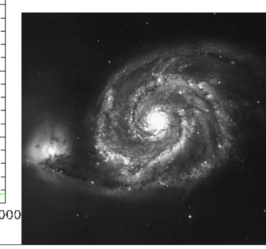
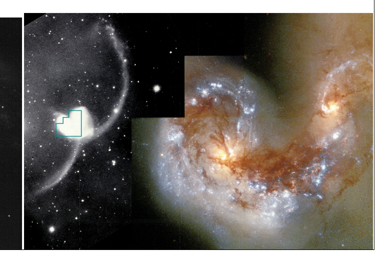


- major merger: trigger big burst, destroy disks, form a spheroid
- minor merger: trigger little burst
    - $e_{burst} = (m_1/m_2)^{\alpha}$







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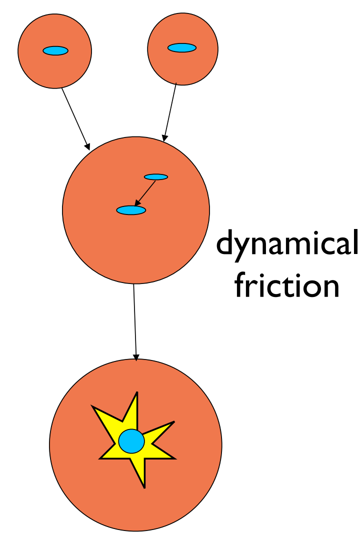

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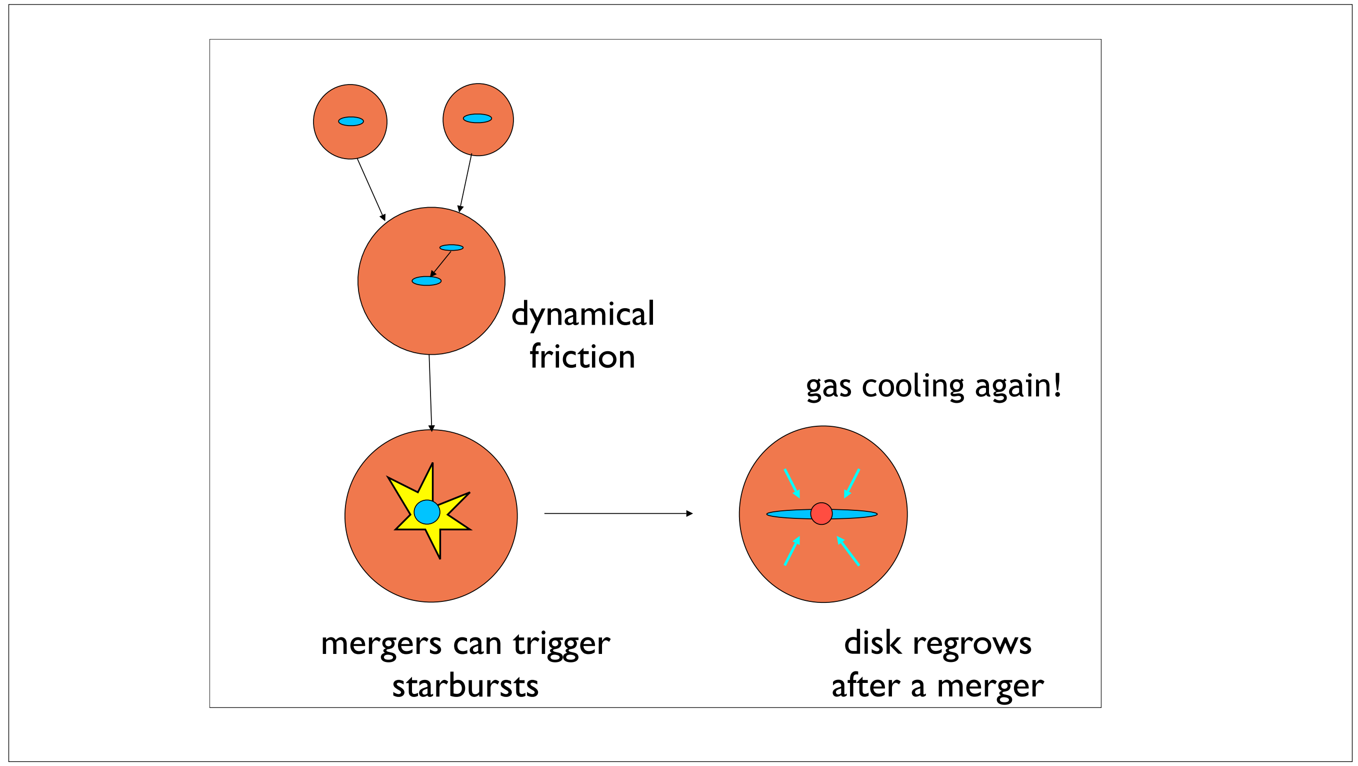

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For M=const, T^3 propto rho
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Gravitationally collapsed sources continue to grow… even after the nominal spherical collapse…

Below 10^4 K: Need H_2/metal cooling, to reach a few 10 K

Enough gas density→Star formation: It is not well understood…

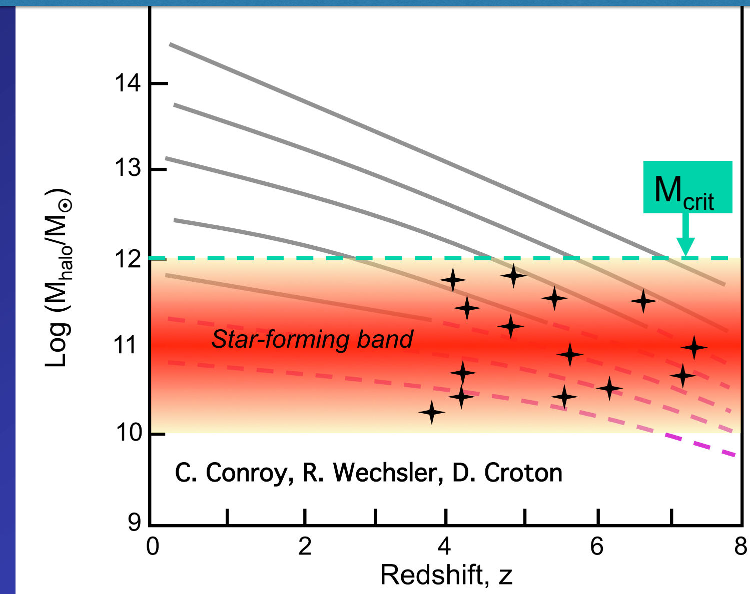
Gas contraction by Jeans instability… What is the mass distribution of newborn stars? (e.g. IMF)

How might we expect a collapsed source to behave as it grows in mass?

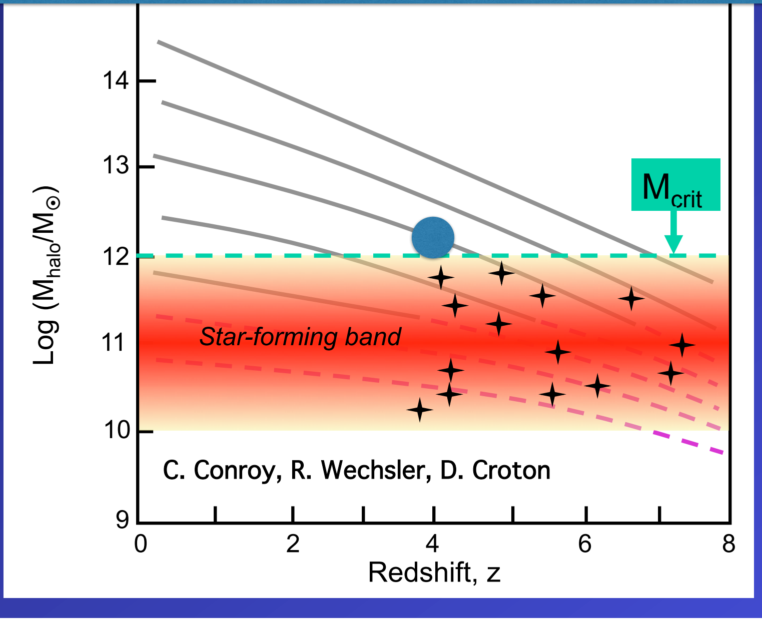
Below 10^4 K: Need H_2/metal cooling, to reach a few 10 K
Enough gas density→Star formation: It is not well understood…

Gas contraction by Jeans instability… What is the mass distribution of newborn stars? (e.g. IMF)

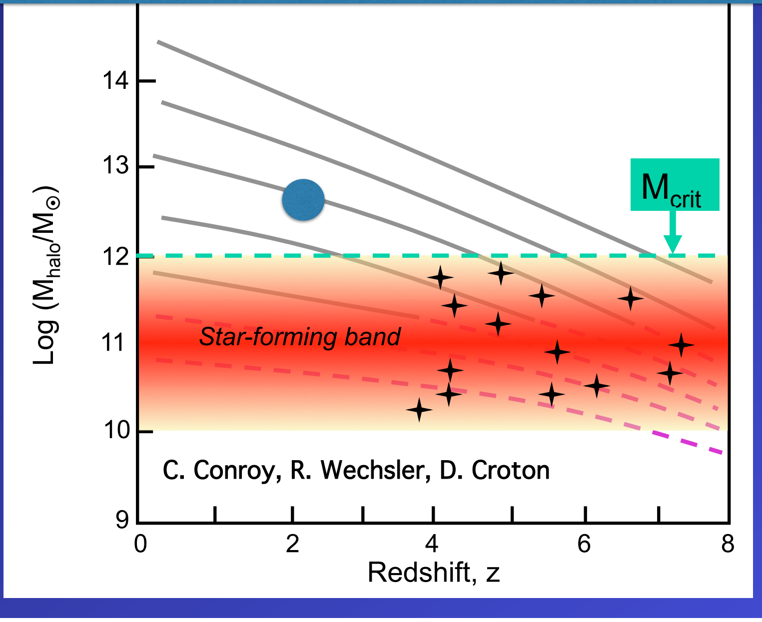
Growing Collapsed Halos Move through Star-Forming Band



Growing Collapsed Halos Move through Star-Forming Band



Growing Collapsed Halos Move through Star-Forming Band



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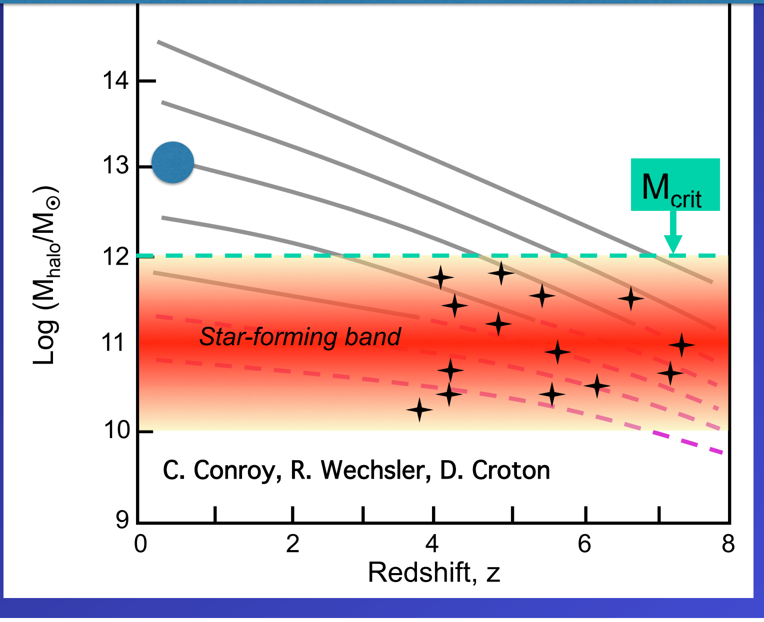
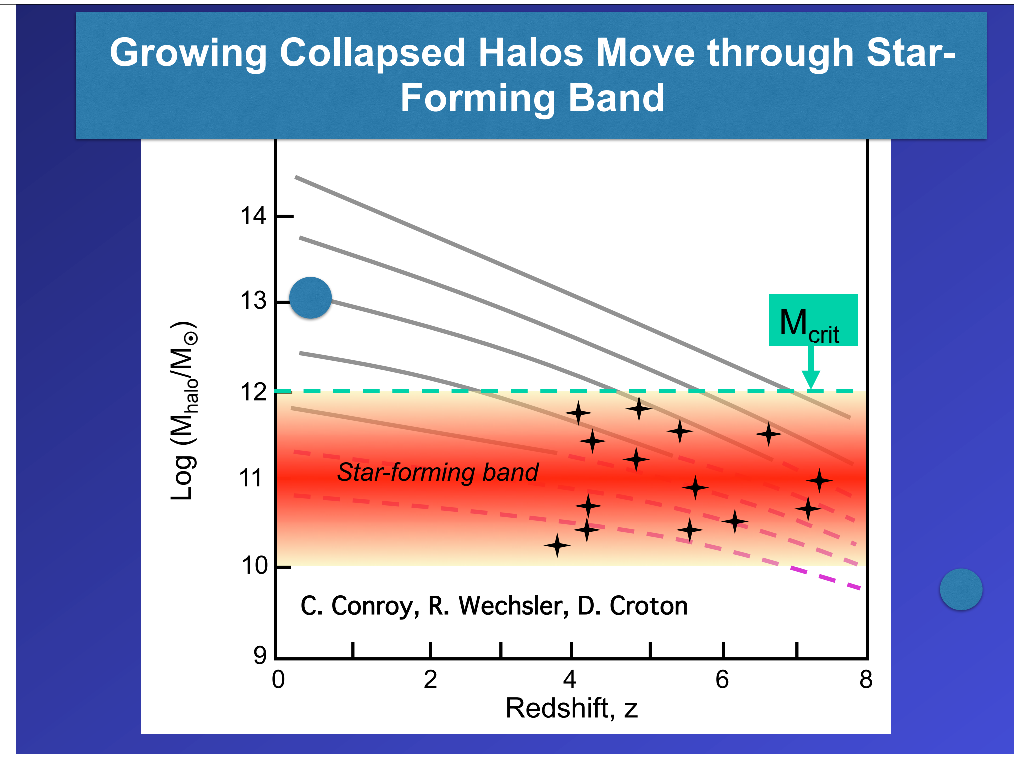
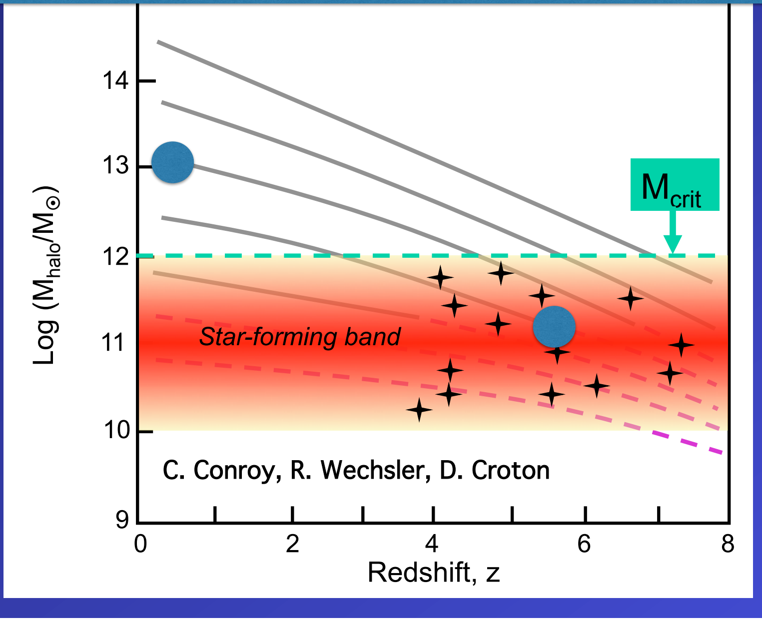
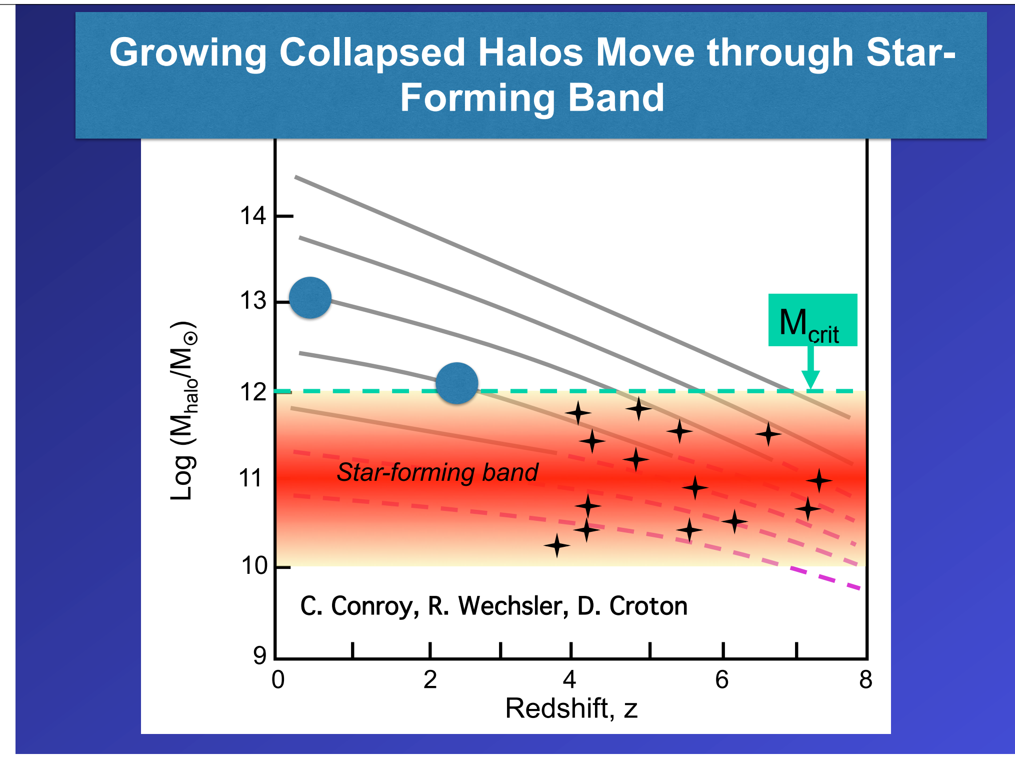



Growing Collapsed Halos Move through Star-Forming Band
Log (M_halo/M_⊙)
14
13
12
11
10
9
M_crit
Star-forming band
C. Conroy, R. Wechsler, D. Croton
0
2
4
6
8
Redshift, z

Growing Collapsed Halos Move through Star-Forming Band

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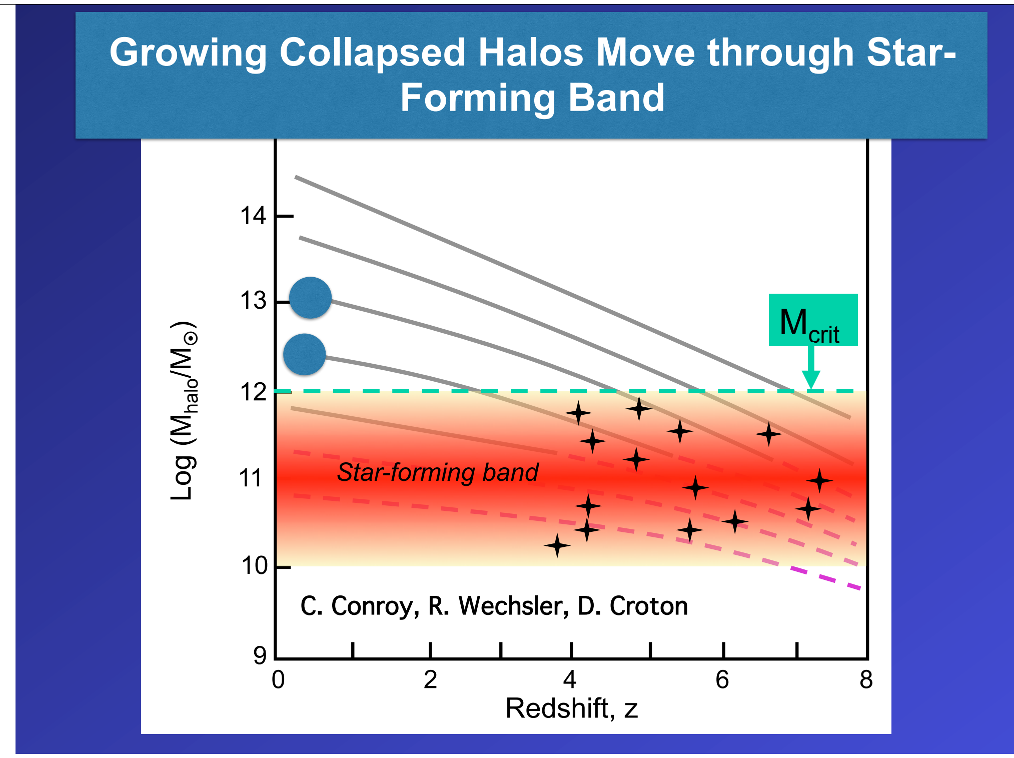
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Redshift, z
M_crit
Star-forming band
C. Conroy, R. Wechsler, D. Croton

What happens as galaxies build up in mass?

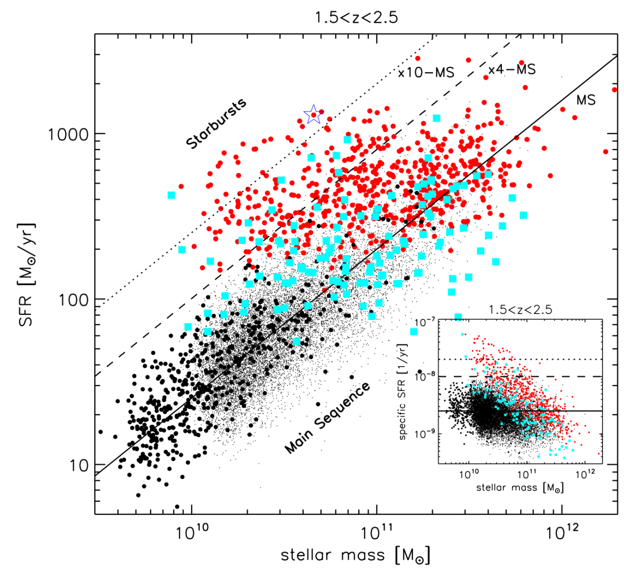
Below 10^4 K: Need H_2/metal cooling, to reach a few 10 K
Enough gas density→Star formation: It is not well understood…

Gas contraction by Jeans instability… What is the mass distribution of newborn stars? (e.g. IMF)

Star Formation Rate

roughly proportional to

Stellar Mass



Brinchmann+*04*; Salim+*07*; Peng+*10*;Elbaz+*07*; Noeske+*07*; Daddi+*07*; Pannella+*09*; Karim+*11*; Rodighiero+*11*

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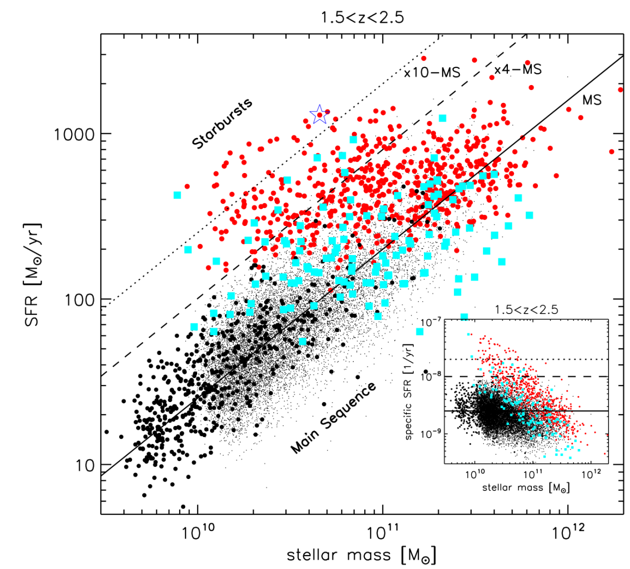
Gas contraction by Jeans instability… What is the mass distribution of newborn stars? (e.g. IMF)

Star Formation Rate

roughly proportional to

Stellar Mass

Earlier Heard Proportional Gas Mass



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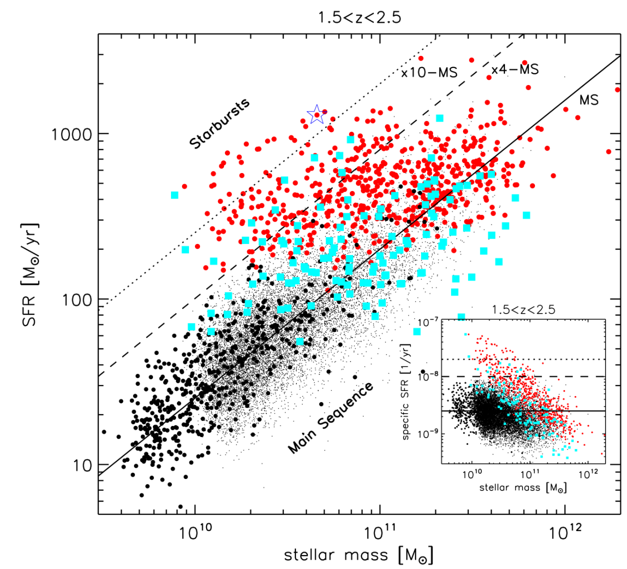
Called
Main
Sequence of
Star Formation
in Galaxies

Starbursts
Above
Sequence



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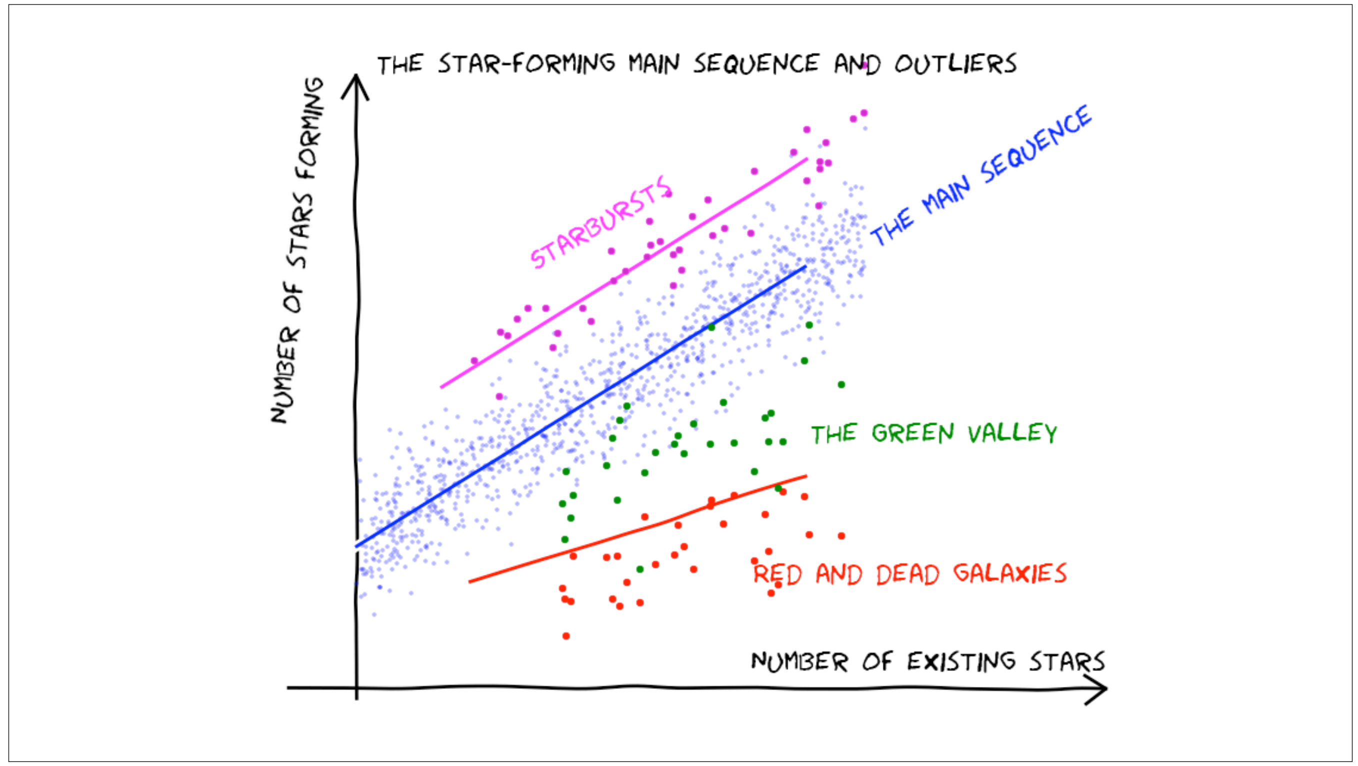

Below 10^4 K: Need H_2/metal cooling, to reach a few 10 K

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Gas contraction by Jeans instability… What is the mass distribution of newborn stars? (e.g. IMF)

Does the main sequence of star formation in galaxies evolve?

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Enough gas density→Star formation: It is not well understood…

Gas contraction by Jeans instability… What is the mass distribution of newborn stars? (e.g. IMF)

The evolution of the MS galaxies with redshift

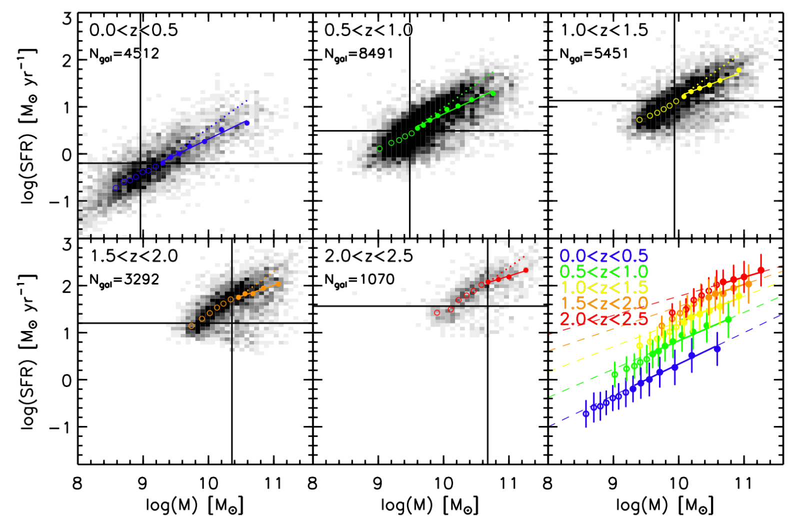


Fig. from Whitaker+*12* (e.g. see also Pannella+*15;* Lee+*15*)

Below 10^4 K: Need H_2/metal cooling, to reach a few 10 K

Enough gas density→Star formation: It is not well understood…

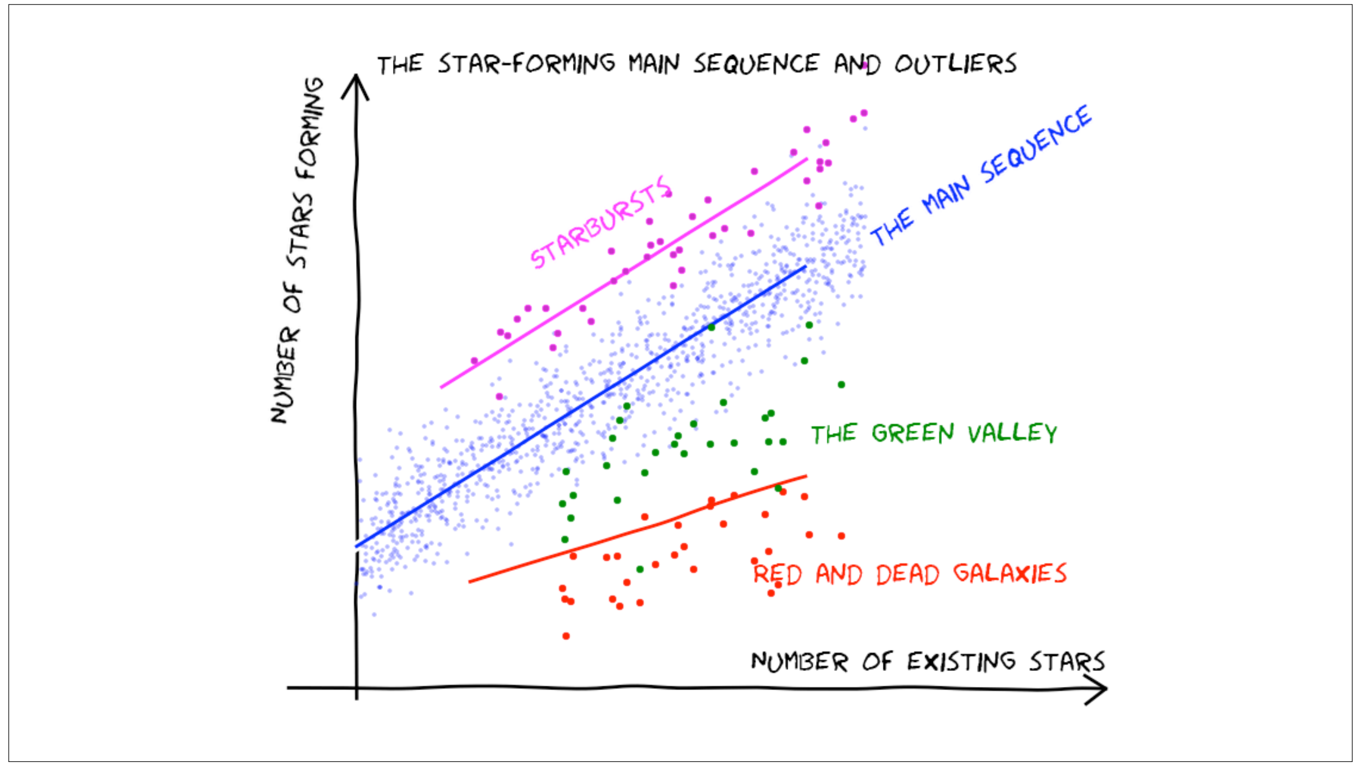
Gas contraction by Jeans instability… What is the mass distribution of newborn stars? (e.g. IMF)

Evolution likely due to evolution in accretion rate of gas across cosmic time…

Below 10^4 K: Need H_2/metal cooling, to reach a few 10 K

Enough gas density→Star formation: It is not well understood…

Gas contraction by Jeans instability… What is the mass distribution of newborn stars? (e.g. IMF)



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Enough gas density→Star formation: It is not well understood…

Gas contraction by Jeans instability… What is the mass distribution of newborn stars? (e.g. IMF)

This relation is mirrored when looking at galaxies as a function of color…

Below 10^4 K: Need H_2/metal cooling, to reach a few 10 K

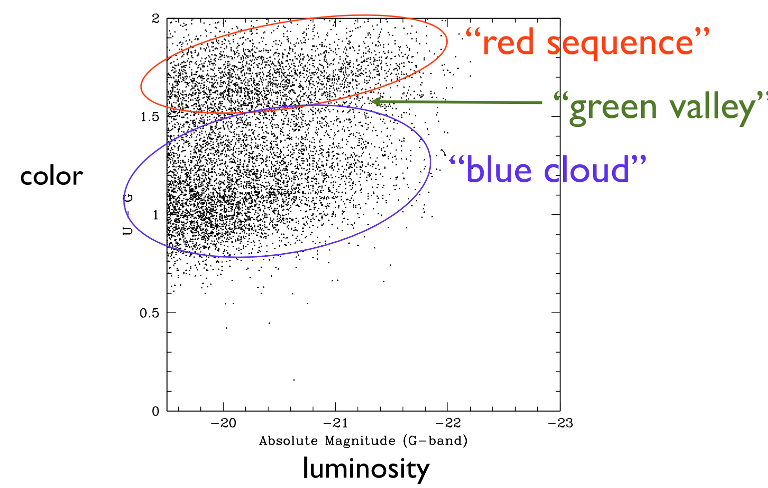
Enough gas density→Star formation: It is not well understood…

Gas contraction by Jeans instability… What is the mass distribution of newborn stars? (e.g. IMF)

When Dividing Galaxies by Color, One Sees a Bimodal Relation

Galaxies whose colors lie on "red sequence"

Galaxies whose colors lie within the "blue cloud"



There is a clear ***bimodality*** to the distribution!

Observational Fact:

Galaxies are found
to be blue and star-forming

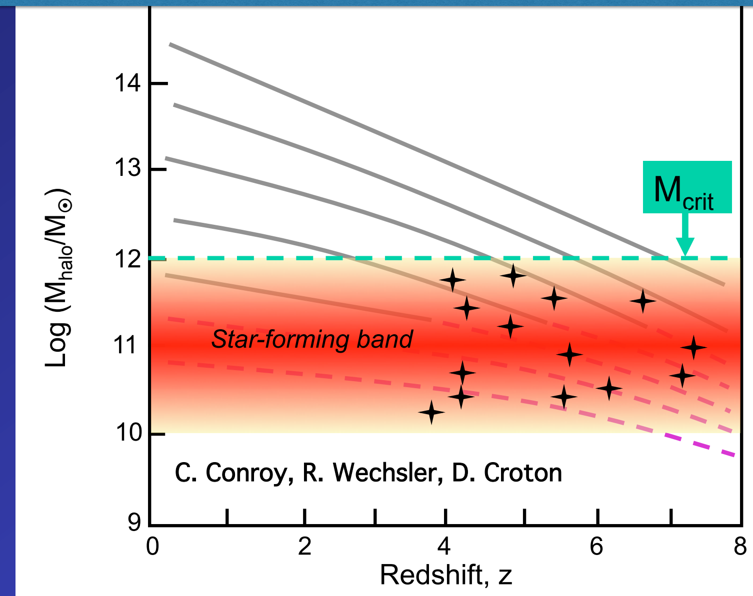
or

red and non-star-forming

Below 10^4 K: Need H_2/metal cooling, to reach a few 10 K
Enough gas density→Star formation: It is not well understood...

Gas contraction by Jeans instability... What is the mass distribution of newborn stars? (e.g. IMF)

Growing Collapsed Halos Move through Star-Forming Band



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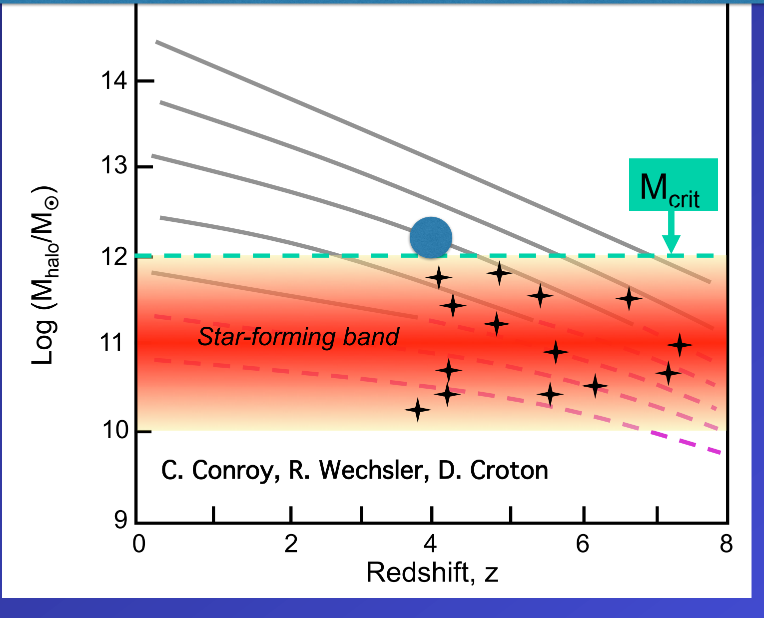

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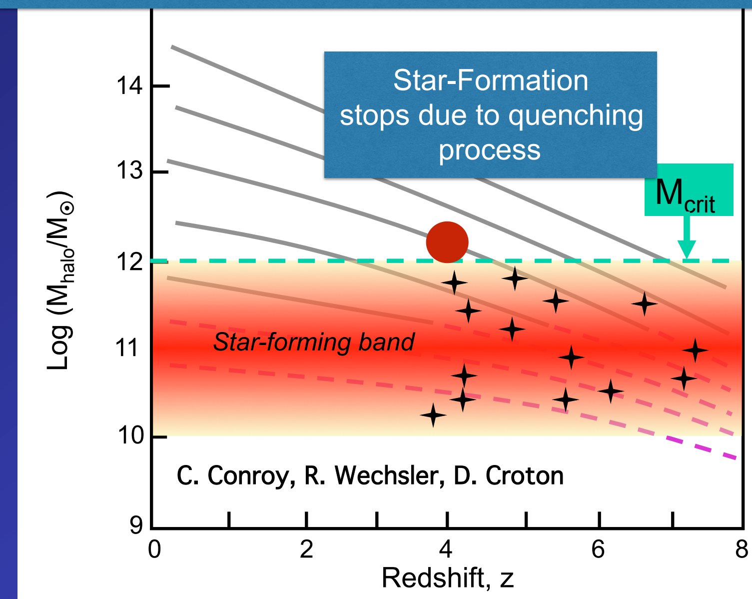
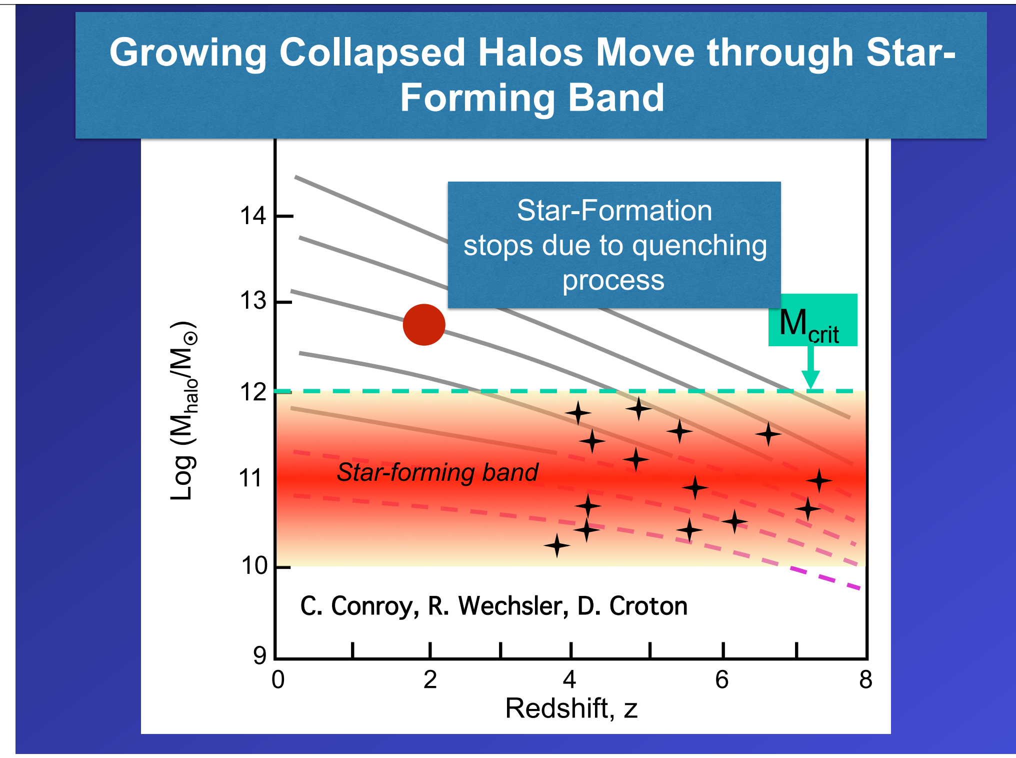
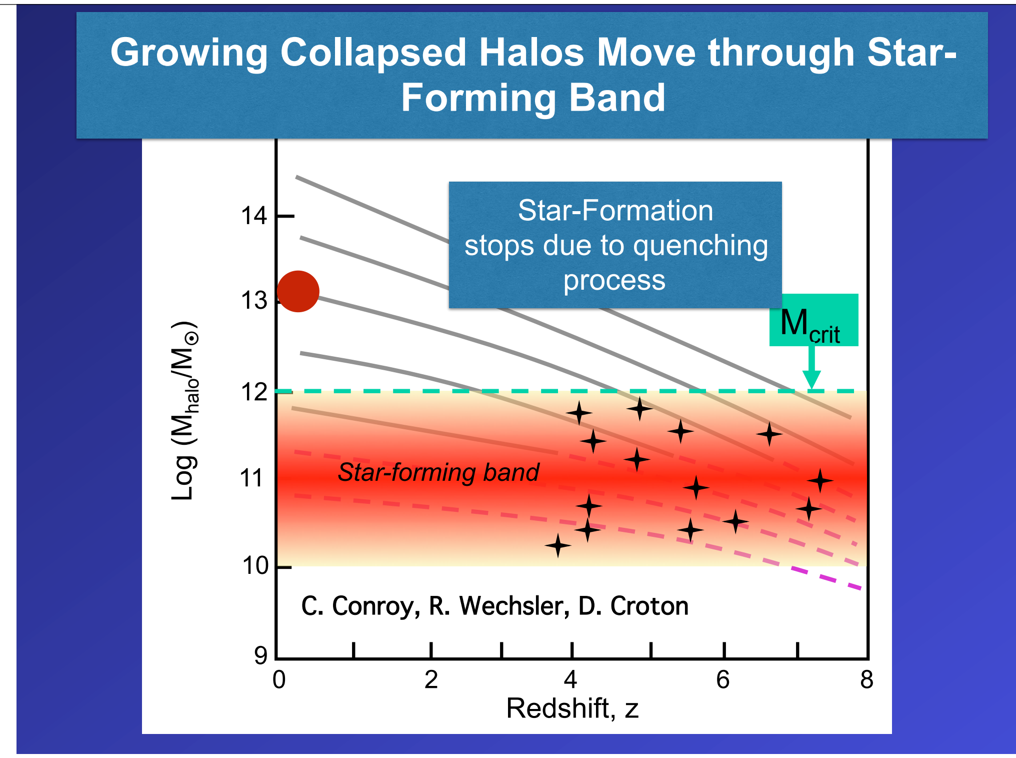




Growing Collapsed Halos Move through Star-Forming Band
Star-Formation stops due to quenching process
M_{crit}
Star-forming band
C. Conroy, R. Wechsler, D. Croton
Log ($M_{halo}/M_{\odot}$)
14
13
12
11
10
9
0
2
4
6
8
Redshift, z



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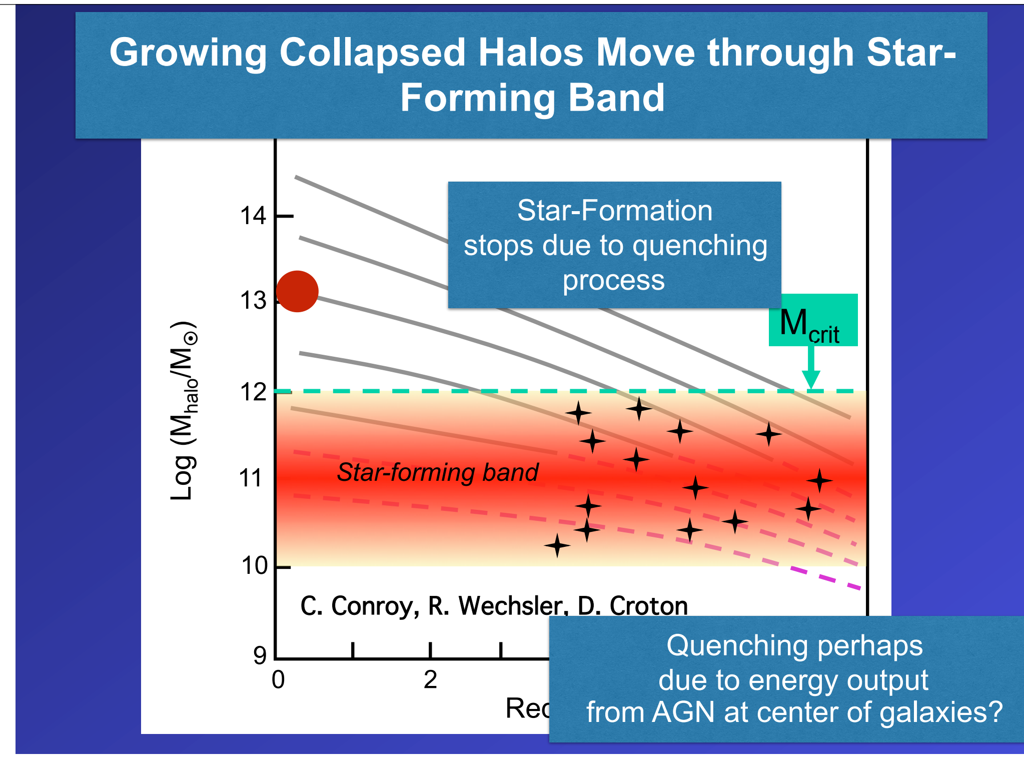
Growing Collapsed Halos Move through Star-Forming Band
Star-Formation stops due to quenching process
M crit
14
13
12
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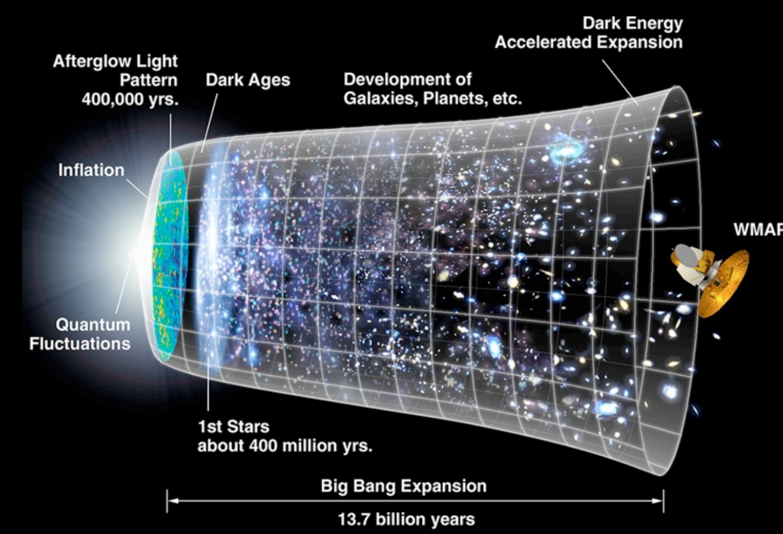
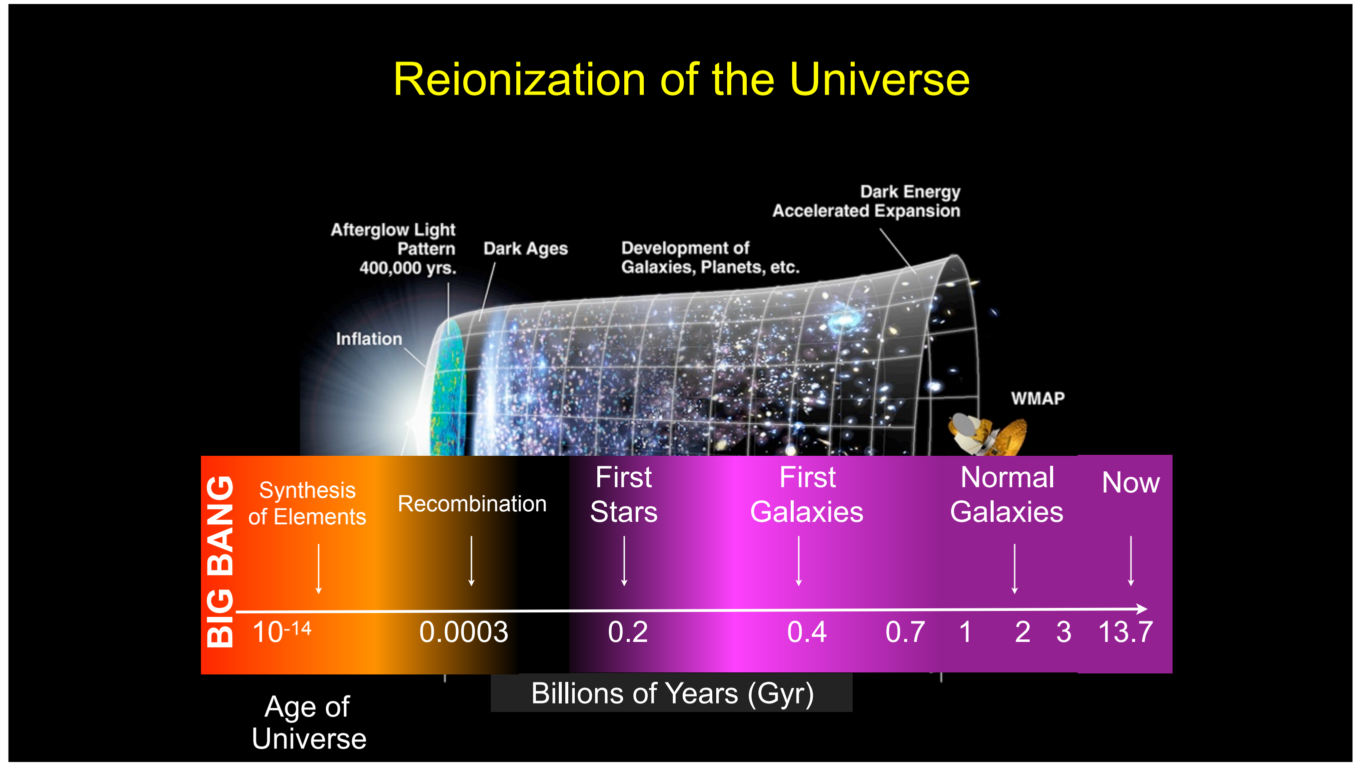
10
9
Log (M halo/M☉)
Star-forming band
C. Conroy, R. Wechsler, D. Croton
0
2
Red
Quenching perhaps due to energy output from AGN at center of galaxies?

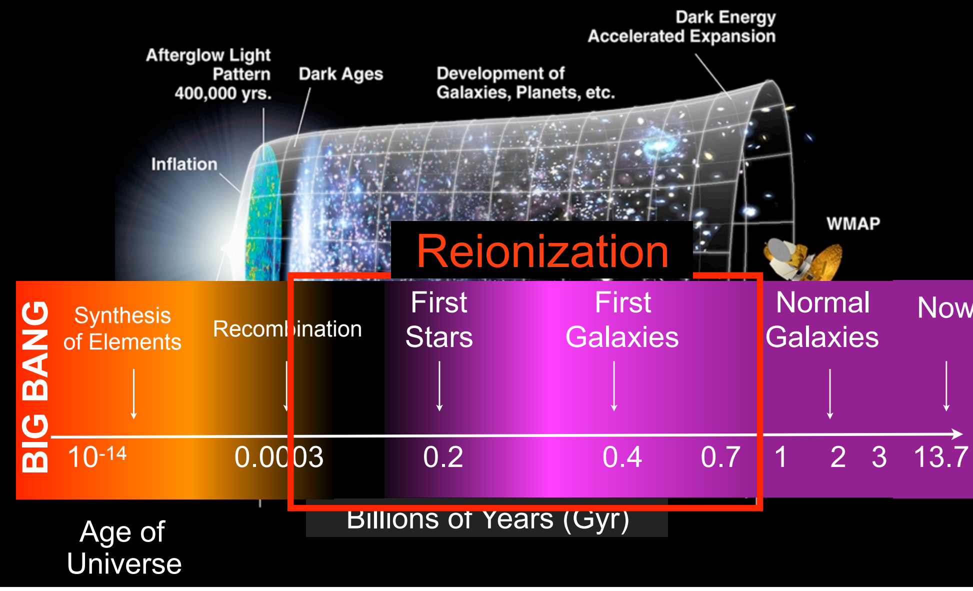
So how does this fit into
shaping our observed Universe?

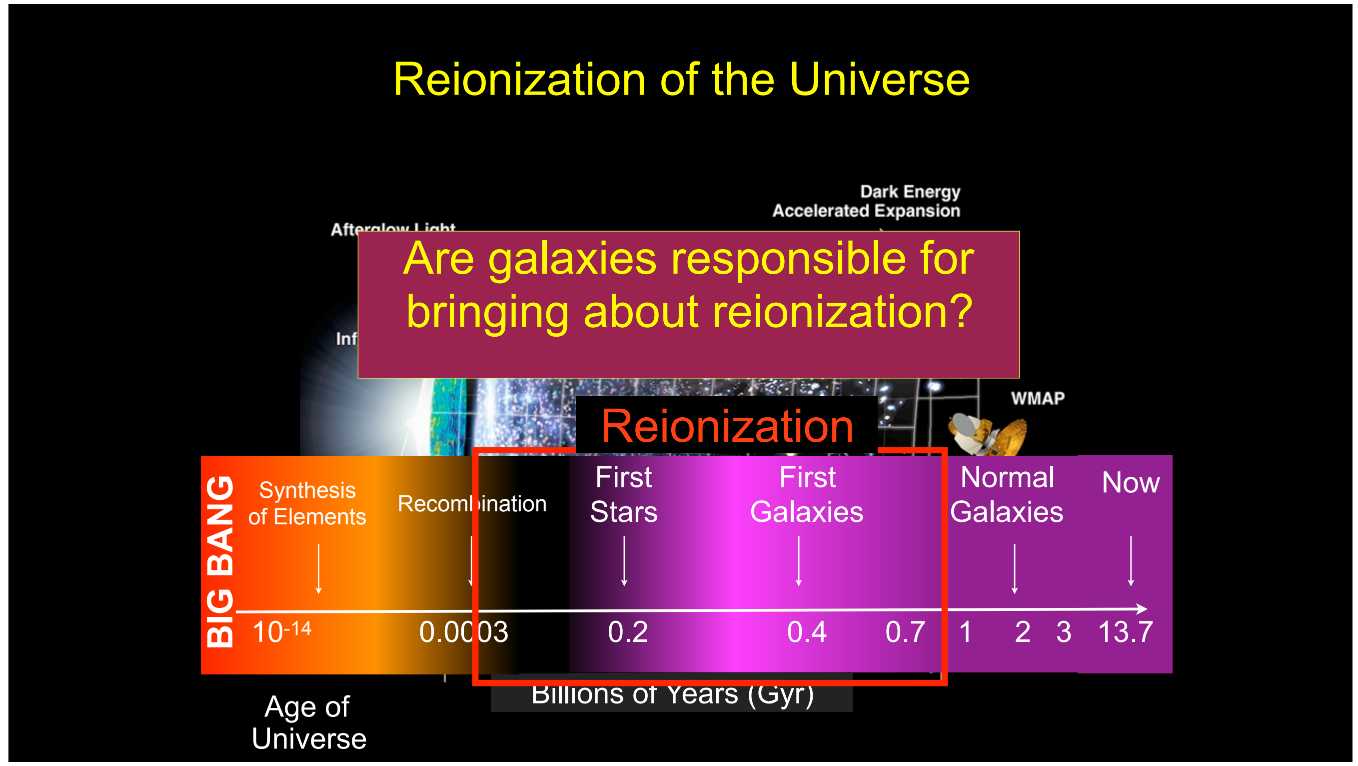
Reionization of the Universe




Reionization of the Universe
Afterglow Light Pattern 400,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Dark Energy Accelerated Expansion
Inflation
WMAP
BIG BANG
Synthesis of Elements
Recombination
First Stars
First Galaxies
Normal Galaxies
Now
10-14
0.0003
0.2
0.4
0.7
1
2
3
13.7
Age of Universe
Billions of Years (Gyr)

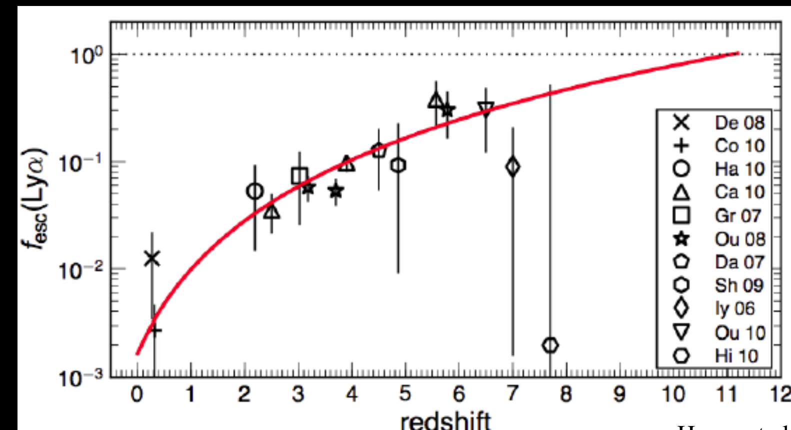
Reionization of the Universe





Reionization of the Universe
Dark Energy
Accelerated Expansion
Are galaxies responsible for bringing about reionization?
WMAP
Reionization
BIG BANG
Synthesis of Elements
Recombination
First Stars
First Galaxies
Normal Galaxies
Now
10^{-14}
0.0003
0.2
0.4
0.7
1
2
3
13.7
Billions of Years (Gyr)
Age of Universe

Lyα Escape Fraction f_{esc}(Lyα) Evolution

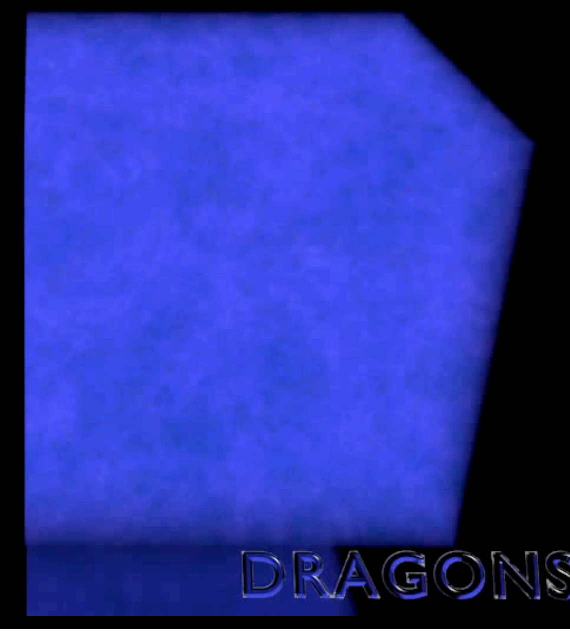


$$f_{\rm esc}^{\rm Ly\alpha}(z < 2.3) = \frac{\rho^{\rm Obs}_{\rm L,Ly\alpha}}{8.7 \times \rho^{\rm Int}_{\rm L,H\alpha}} = \frac{\rho^{\rm Obs}_{\rm L,Ly\alpha}}{8.7 \times 10^{0.4 E_{B-V} k_{6563}} \cdot \rho^{\rm Obs}_{\rm L,H\alpha}},$$

Assuming Case B recombination

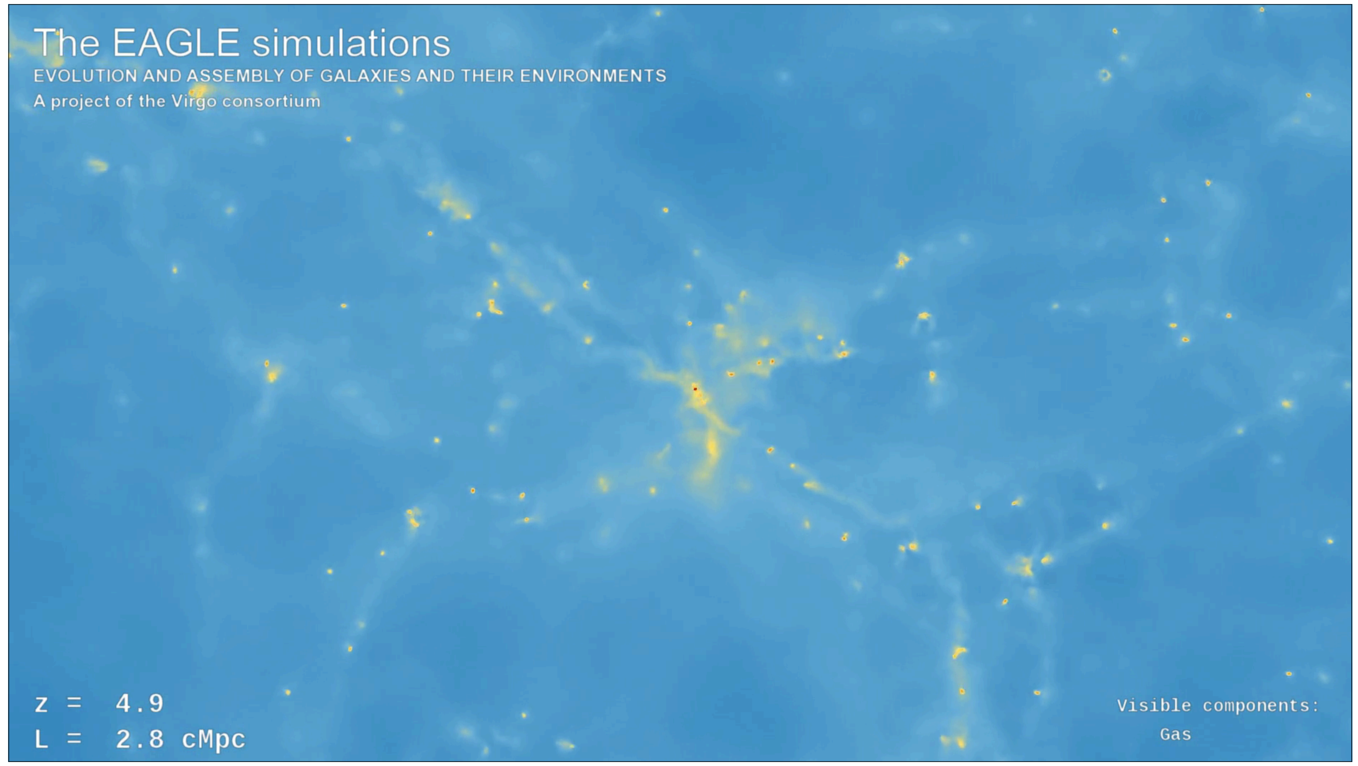
- f_{esc}(Lyα) shows a monotonic increase up to z~6

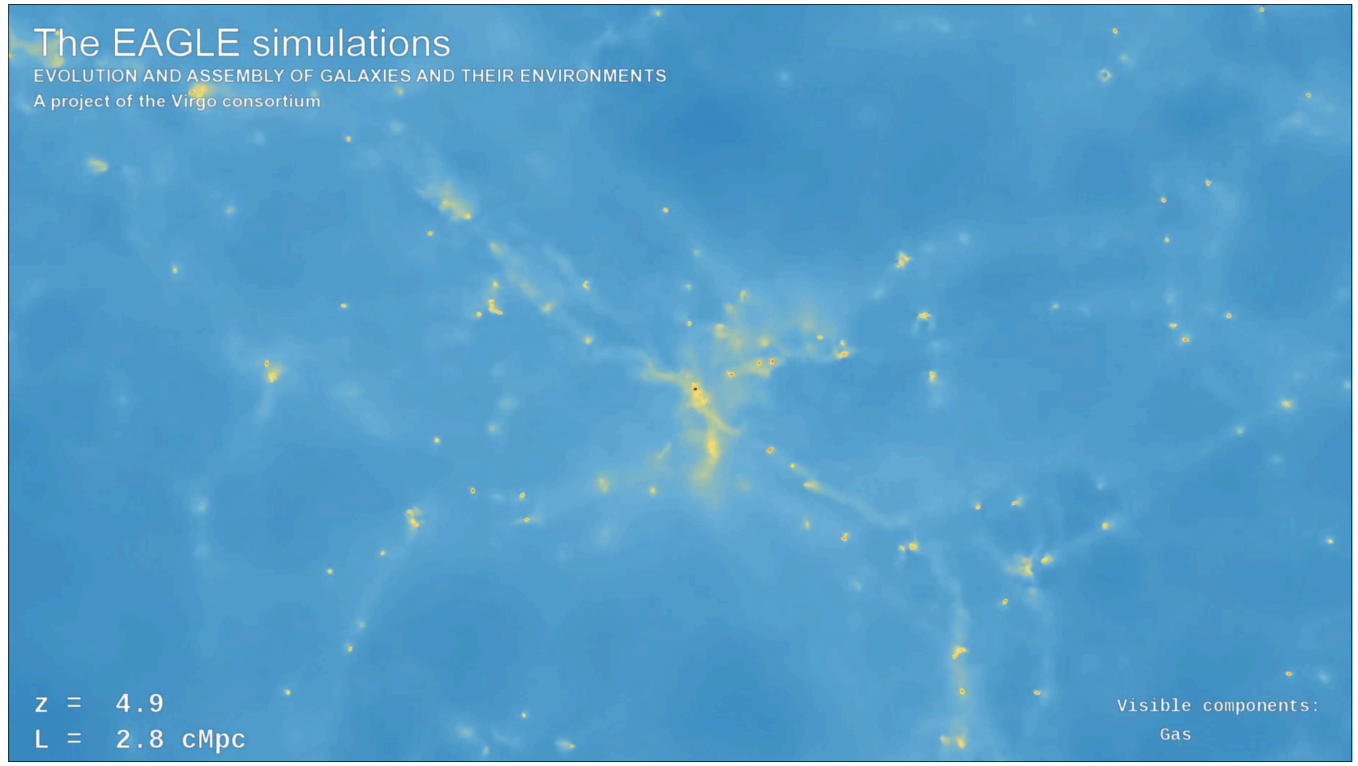
Stellar populations played a fundamental role in the evolutionary processes in the universe



Visualisation: Simon Mutch

Stellar populations played a fundamental role in the evolutionary processes in the universe


The EAGLE simulations
EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS
A project of the Virgo consortium
z = 4.9
L = 2.8 cMpc
Visible components:
Gas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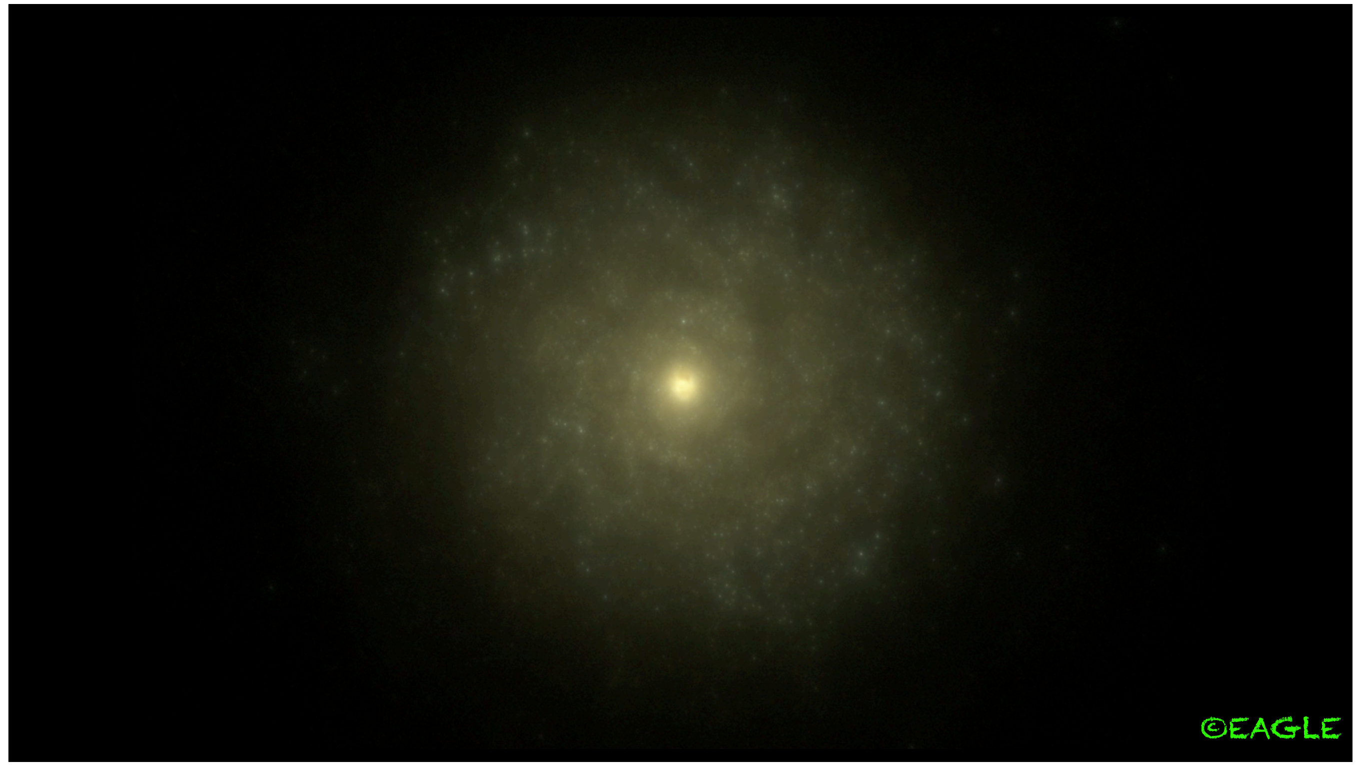
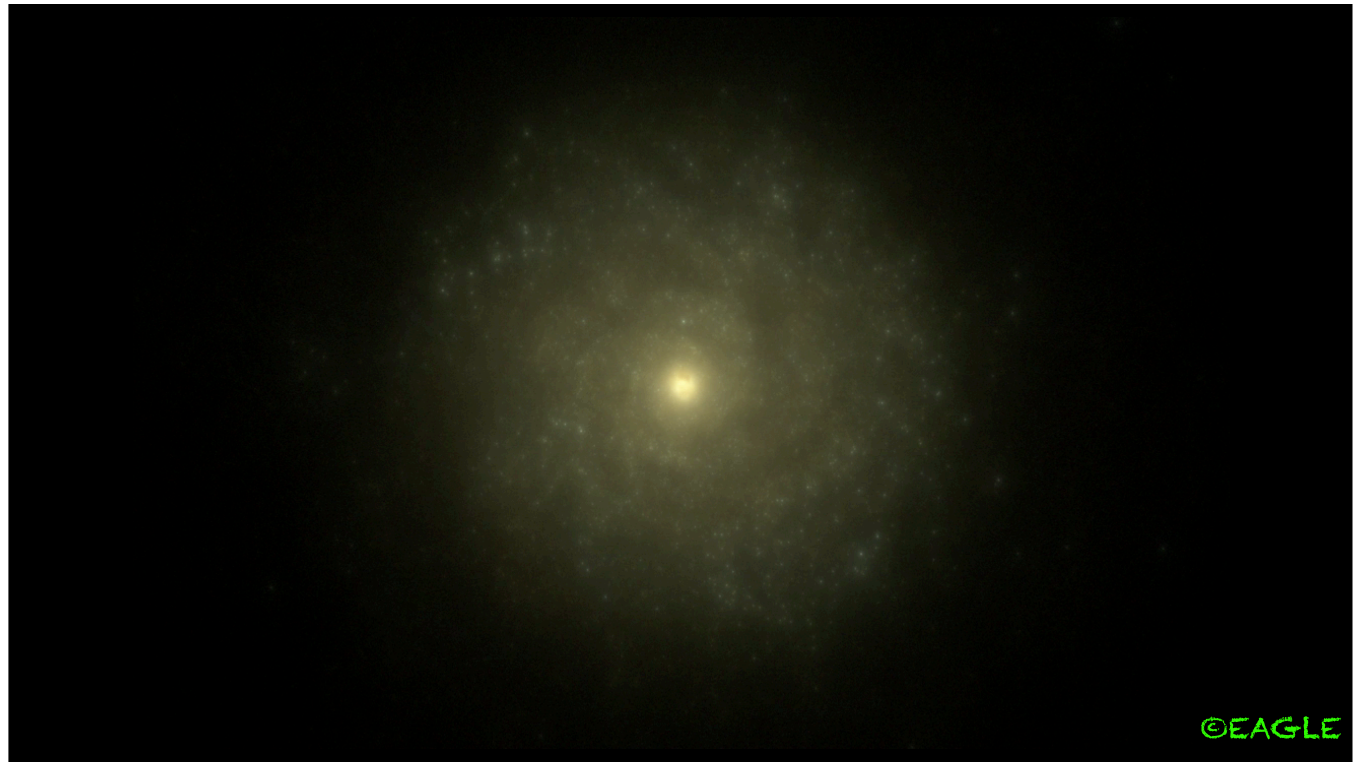

©EAGLE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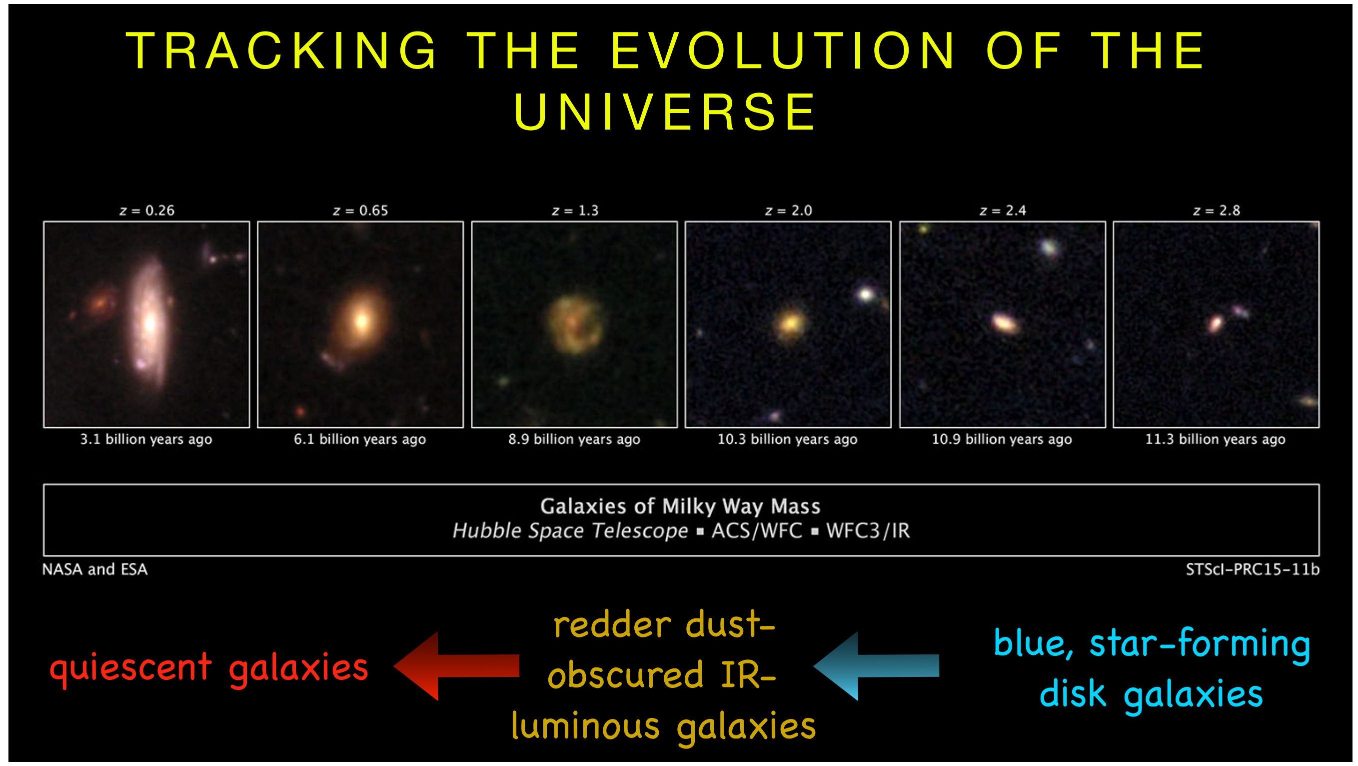
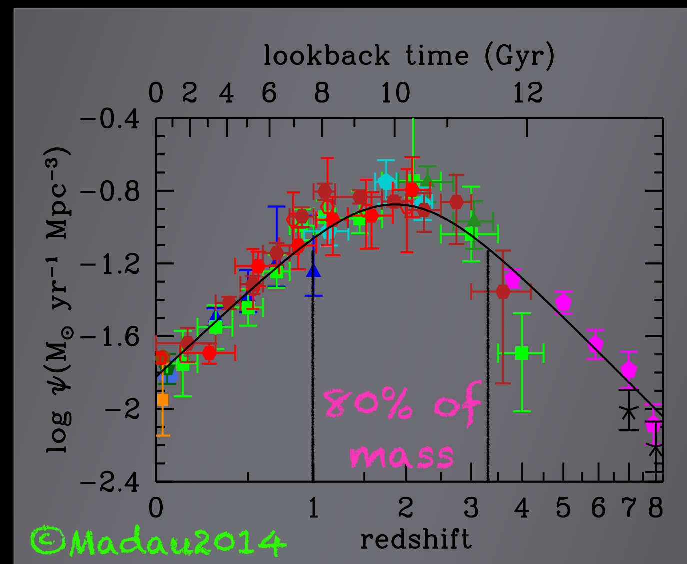
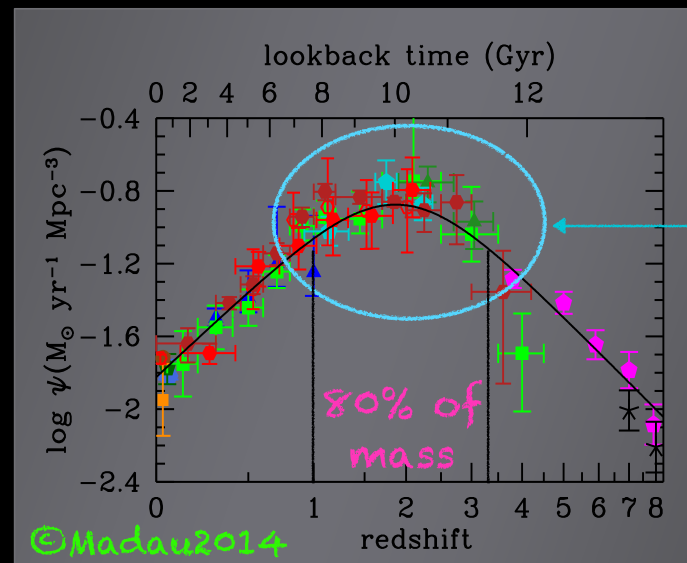


The typical MW-mass and M31-mass progenitors passed through the same evolution stages, evolving from blue, star-forming disk galaxies at the earliest stages to redder dust-obscured IR-luminous galaxies in intermediate stages and to red, more quiescent galaxies at their latest stages. The progenitors of the MW-mass galaxies reached each evolutionary stage at later times (lower redshifts) and with stellar masses that are a factor of two to three lower than the progenitors of the M31-mass galaxies. The process driving this evolution, including the suppression of star formation in present-day M_* galaxies, requires an evolving stellar-mass/halo-mass ratio and/or evolving halo-mass threshold for quiescent galaxies. The effective size and SFRs imply that the baryonic cold-gas fractions drop as galaxies evolve from high redshift to $z \sim 0$ and are strongly anticorrelated with an increase in the Se´rsic index. Therefore, the growth of galaxy bulges in M_* galaxies corresponds to a rapid decline in the galaxy gas fractions and/or a decrease in the star formation efficiency.

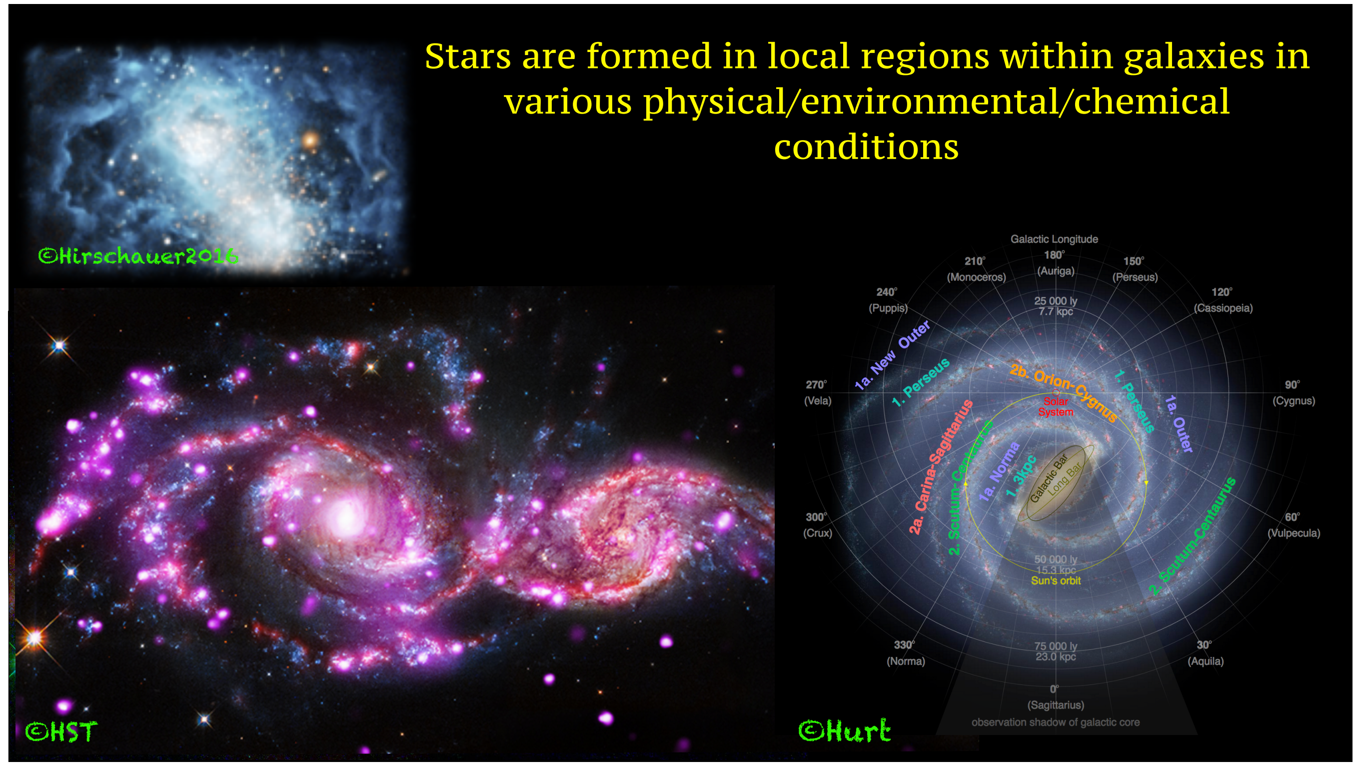
80% OF STARS IN THE UNIVERSE WERE FORMED BETWEEN 1<Z<3



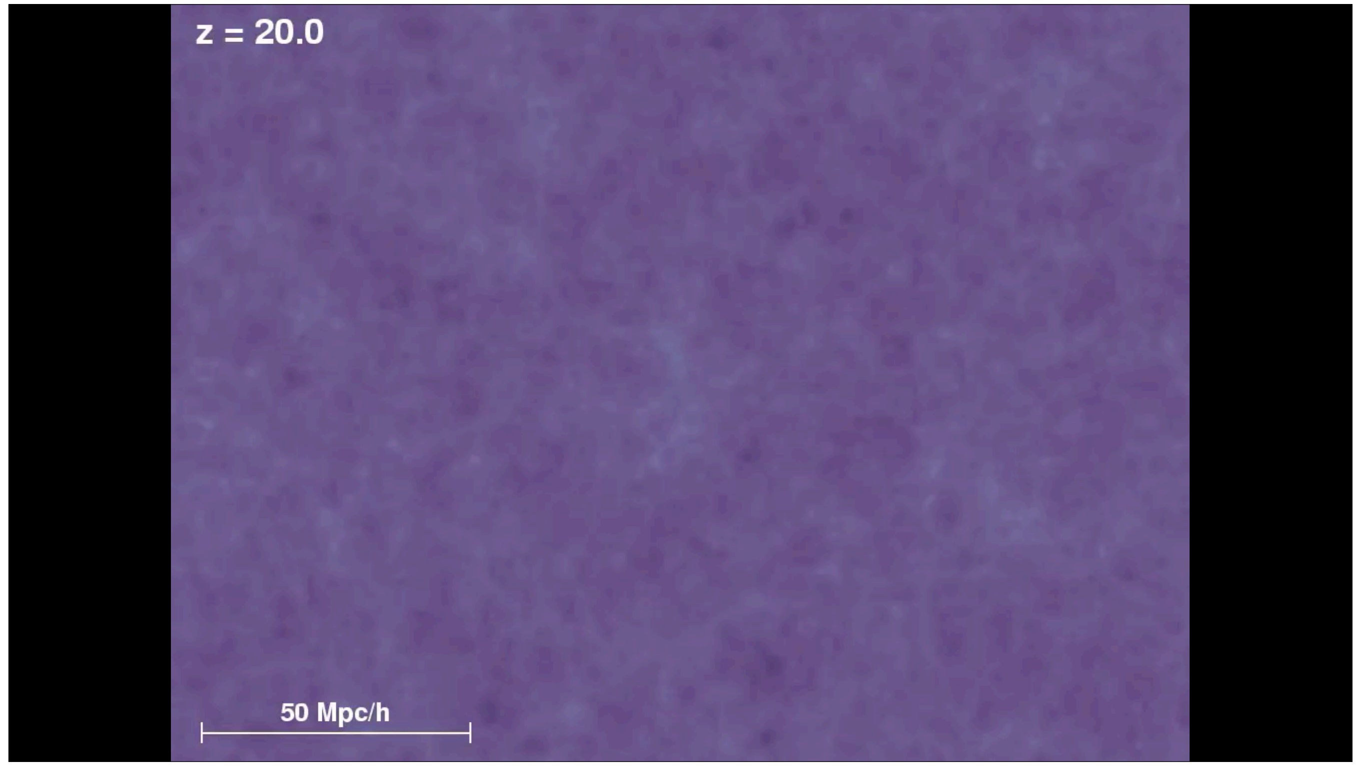
80% OF STARS IN THE UNIVERSE WERE FORMED BETWEEN 1<Z<3



galaxies are young, actively forming stars & rapidly evolving



env—> interaction between gas clouds lead to extra UV flux, strong winds, powerful outflows—> suppress low mass stars increasing cloud surface densities leading to radiation trapping favours the formation of high mass stars.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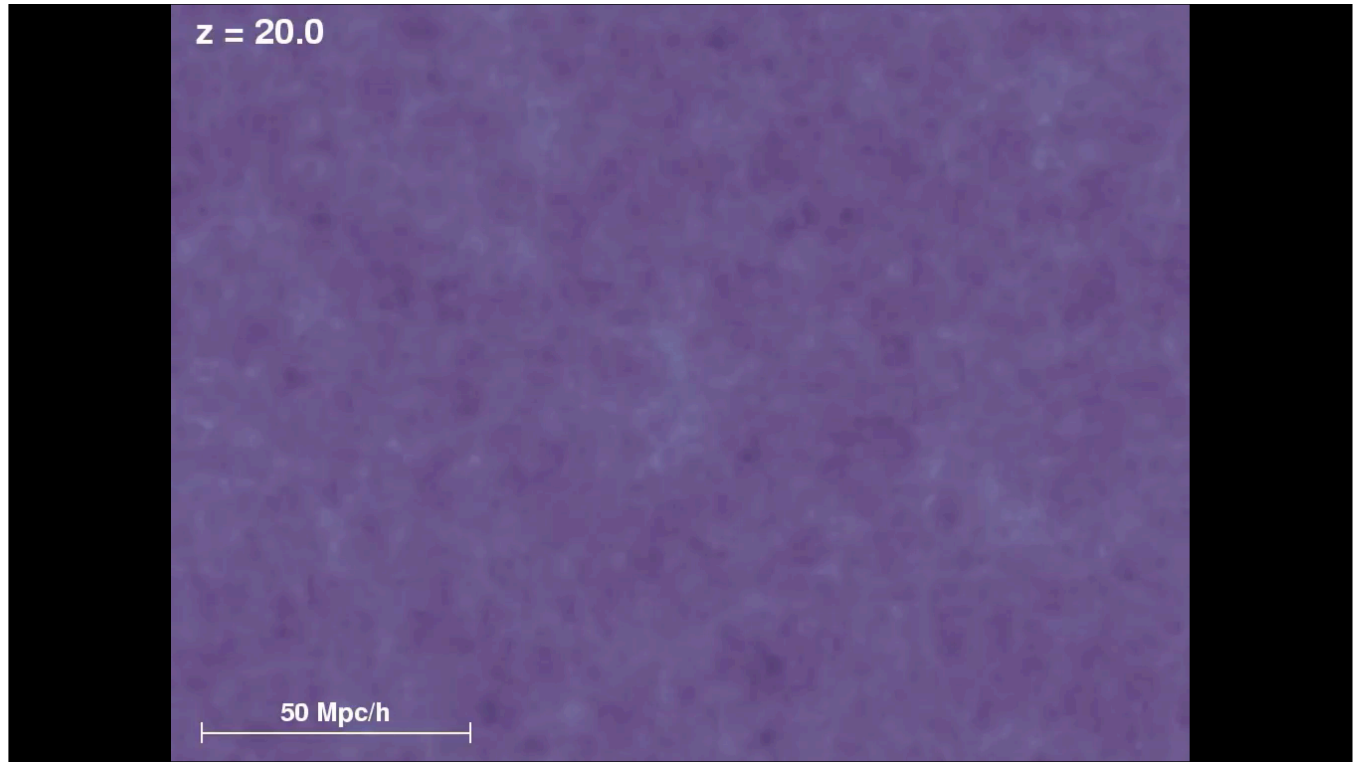
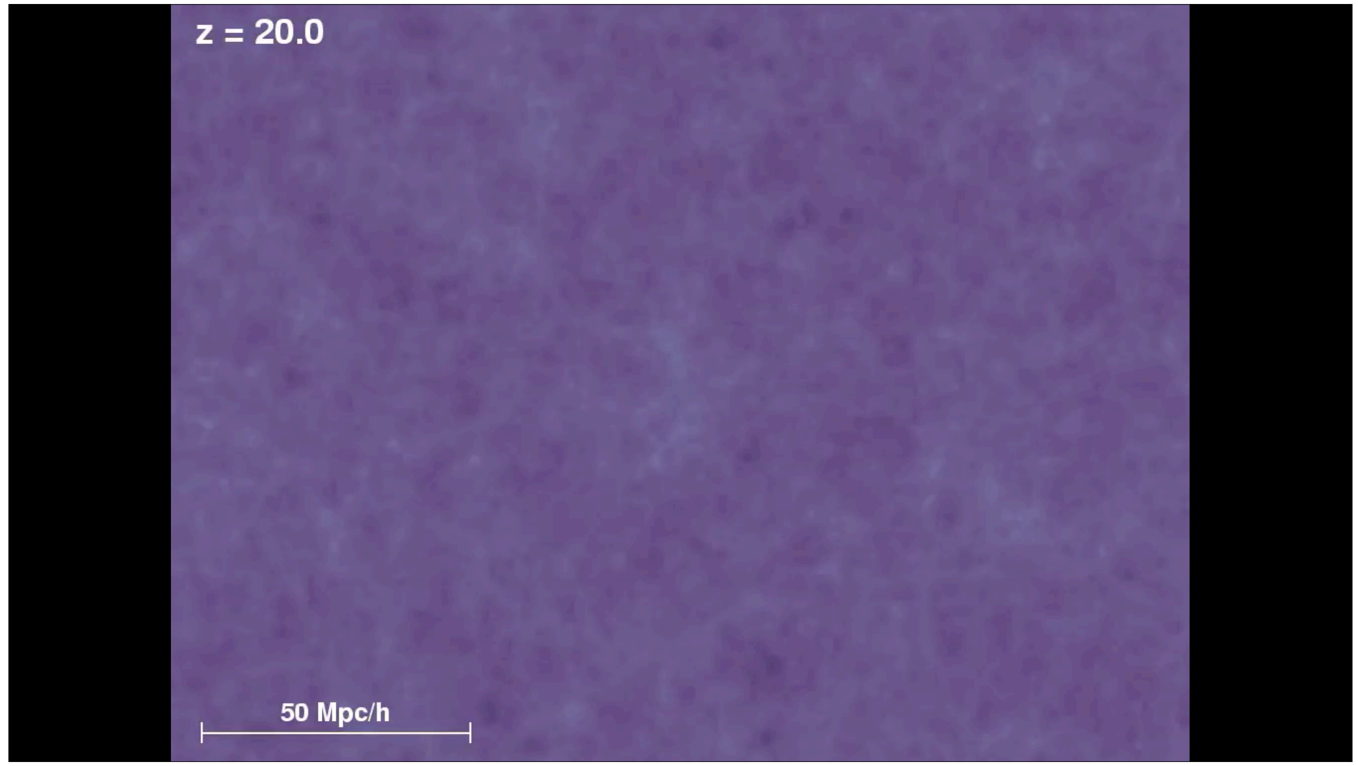
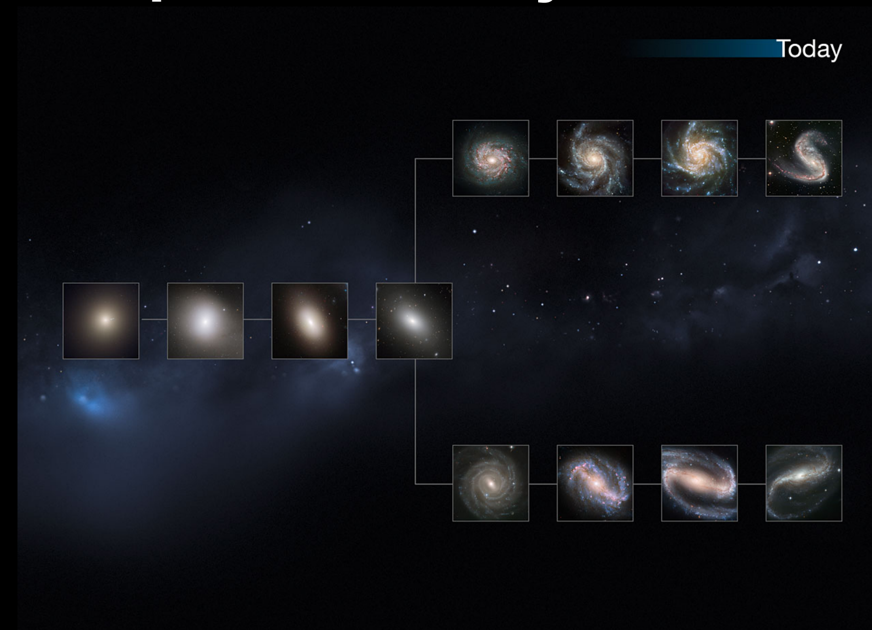
50 Mpc/h


z = 20.0
50 Mpc/h


z = 20.0
50 Mpc/h

The present day Universe



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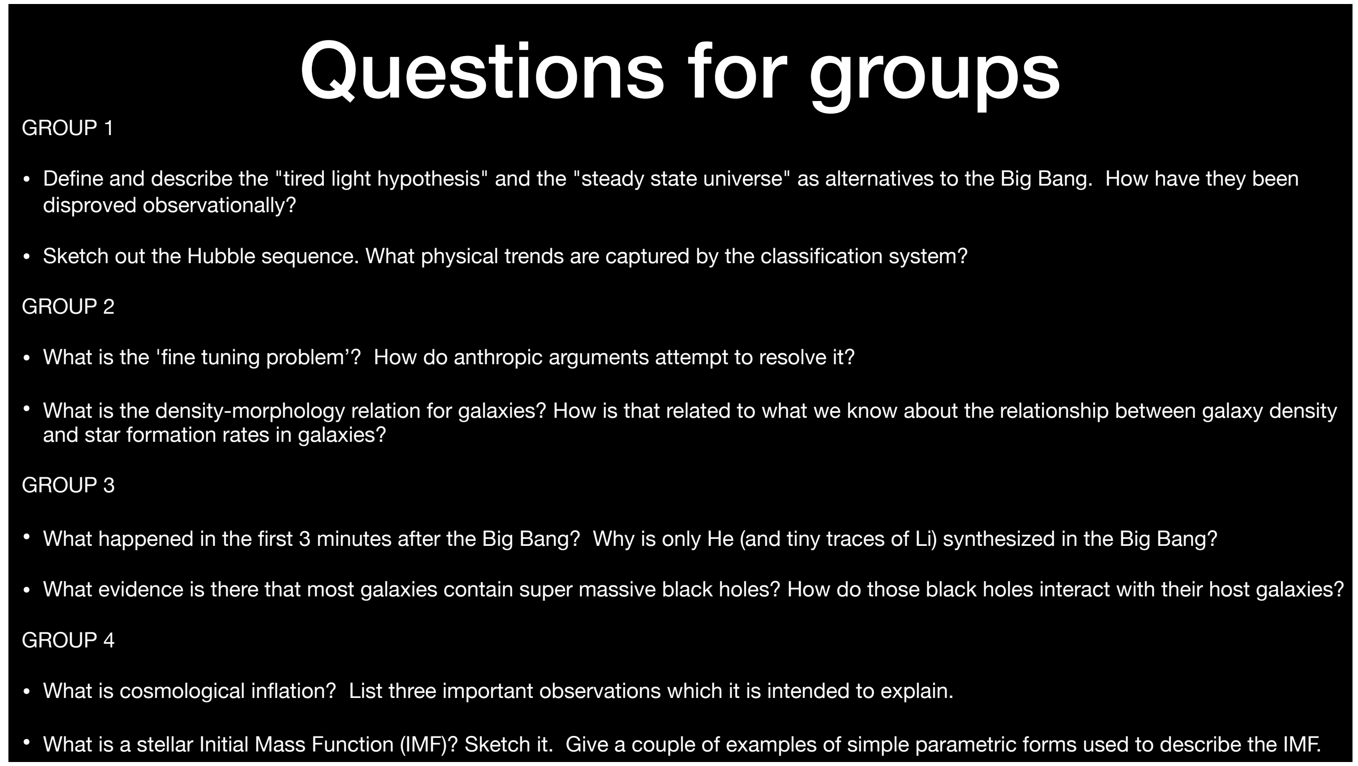

Group 1
Tired light: http://www.astro.ucla.edu/~wright/tiredlit.htm
Steady state: http://www.astro.ucla.edu/~wright/stdystat.htm
Hubble sequence:

Group 2
Fine tuning: Martin Rees and 6 params https://en.wikipedia.org/wiki/Fine-tuned_Universe
Morphology density relation: http://astronomy.swin.edu.au/cosmos/M/Morphology+Density+Relation

Group 3
3 min of Big Bang: https://www.physicsoftheuniverse.com/topics_bigbang_timeline.html
SMBH: http://science.sciencemag.org/content/300/5627/1898

Group 4
Inflation: Needed to explain horizon problem, magnetic monopole, flatness problem
Show Simon Drivers slides

IMF: Baldry plot