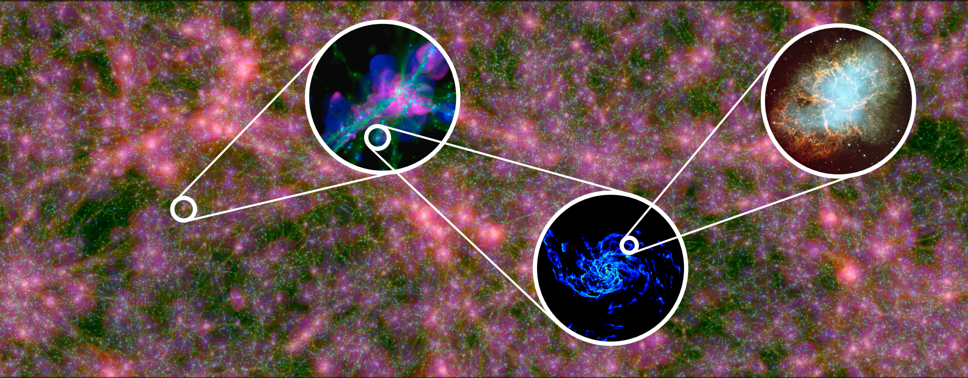
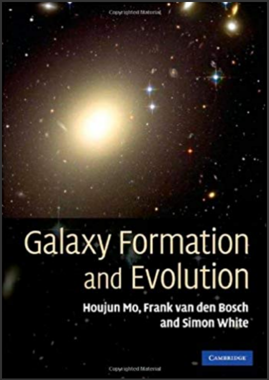
Galaxy formation and evolution: Physical models & Theoretical challenges 1°



Katarina Kraljic

Institute for Astronomy, Edinburgh

July 2019, Petnica



Mo et al. 2010

arXiv:1412.2712v1 [astro-ph.GA] 8 Dec 2014

Physical Models of Galaxy Formation in a Cosmological Framework

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Key Words
galaxy formation, galaxy evolution, numerical simulations, cosmology

Abstract
Modeling galaxy formation in a cosmological context presents one of the greatest challenges in astrophysics today, due to the vast range of scales and numerous physical processes involved. Here we review the current status of models that employ two leading techniques to simulate the physics of galaxy formation: semi-analytic models and numerical hydrodynamic simulations. We focus on a set of observational targets that describe the evolution of the global and structural properties of galaxies from roughly Cosmic High Noon ($z \sim 2$–3) to the present. Although minor discrepancies remain, overall, models show remarkable convergence between different methods and make predictions that are in qualitative agreement with observations. Modelers seem to have converged on a core set of physical processes that are critical for shaping galaxy properties. This core set includes cosmological accretion, strong stellar-driven winds that are more efficient at low masses, black hole feedback that preferentially suppresses star formation at high masses, and structural and morphological evolution through merging and environmental processes. However, all cosmological models currently adopt phenomenological implementations of many of these core processes, which must be tuned to observations. Many details of how these diverse processes interact within a hierarchical structure formation setting remain poorly understood. Emerging multi-scale simulations are helping to bridge the gap between stellar and cosmological scales, placing models on a firmer, more physically grounded footing. Concurrently, upcoming telescope facilities will provide new challenges and constraints for models, particularly by directly constraining inflows and outflows through observations of gas in and around galaxies.

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Somerville & Davé 2014

.. 2000

arXiv:1612.06891v1 [astro-ph.GA] 20 Dec 2016

Theoretical Challenges in Galaxy Formation

Thorsten Naab[1] & Jeremiah P. Ostriker[2,3]
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Key Words
theoretical models, cosmology, galaxy formation, galaxy evolution

Abstract
Numerical simulations have become a major tool for understanding galaxy formation and evolution. Over the decades the field has made significant progress. It is now possible to simulate the formation of individual galaxies and galaxy populations from well defined initial conditions with realistic abundances and global properties. An essential component of the calculation is to correctly estimate the inflow to and outflow from forming galaxies since observations indicating low formation efficiency and strong circum-glactic presence of gas are persuasive. Energetic 'feedback' from massive stars and accreting super-massive black holes - generally unresolved in cosmological simulations - plays a major role for driving galactic outflows, which have been shown to regulate many aspects of galaxy evolution. A surprisingly large variety of plausible sub-resolution models succeeds in this exercise. They capture the essential characteristics of the problem, i.e. outflows regulating galactic gas flows, but their predictive power is limited. In this review we focus on one major challenge for galaxy formation theory: to understand the underlying physical processes that regulate the structure of the interstellar medium, star formation and the driving of galactic outflows. This requires accurate physical models and numerical simulations, which can precisely describe the multi-phase structure of the interstellar medium on the currently unresolved few hundred parsecs scales of large scale cosmological simulations. Such models ultimately require the full accounting for the dominant cooling and heating processes, the radiation and winds from massive stars and accreting black holes, an accurate treatment of supernova explosions as well as the non-thermal components of the interstellar medium like magnetic fields and cosmic rays.

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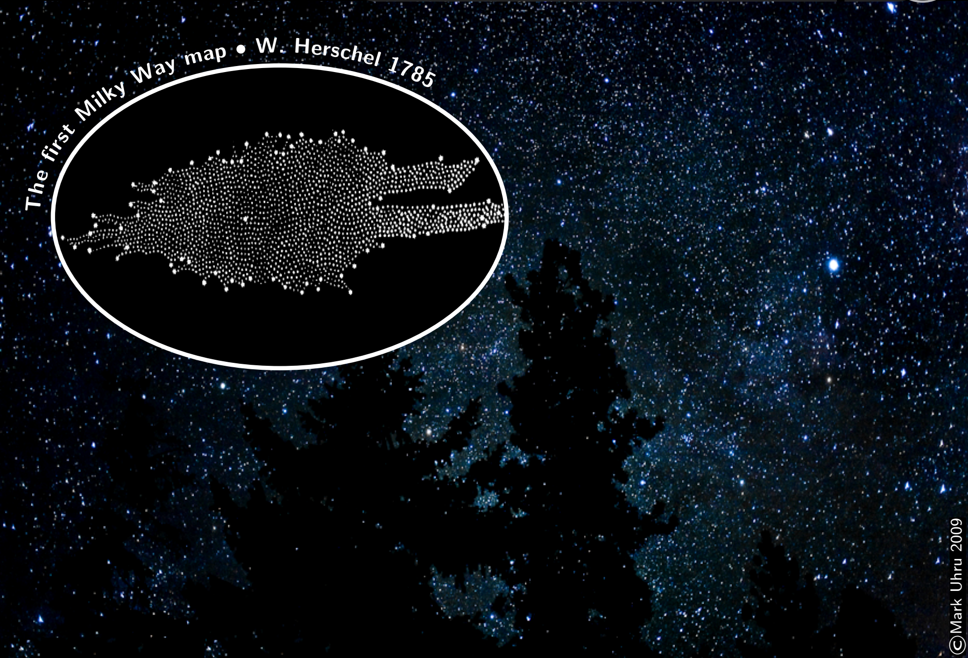
Naab & Ostriker 2016


The first Milky Way map • W. Herschel 1785
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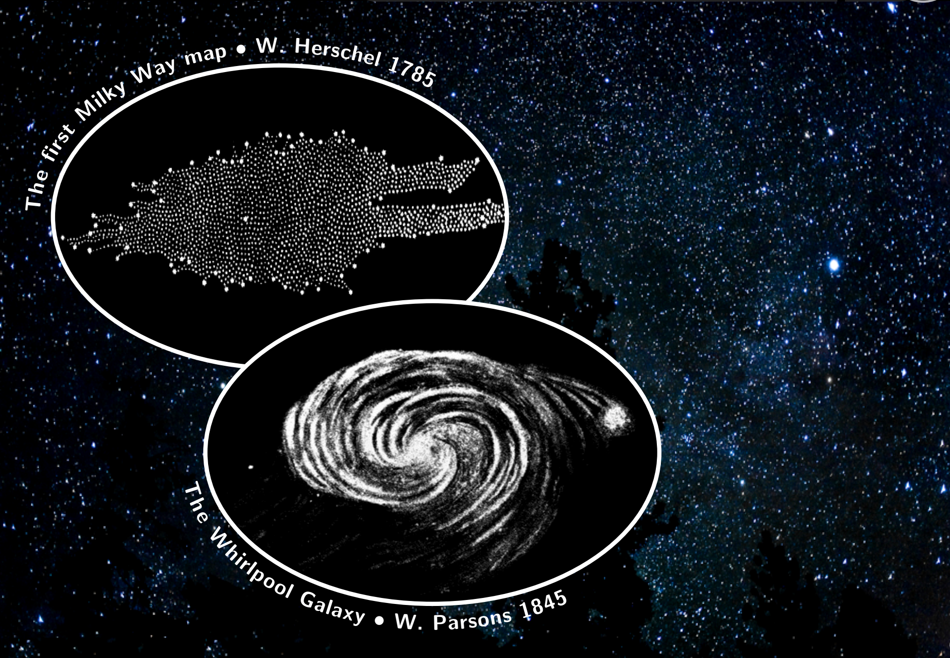
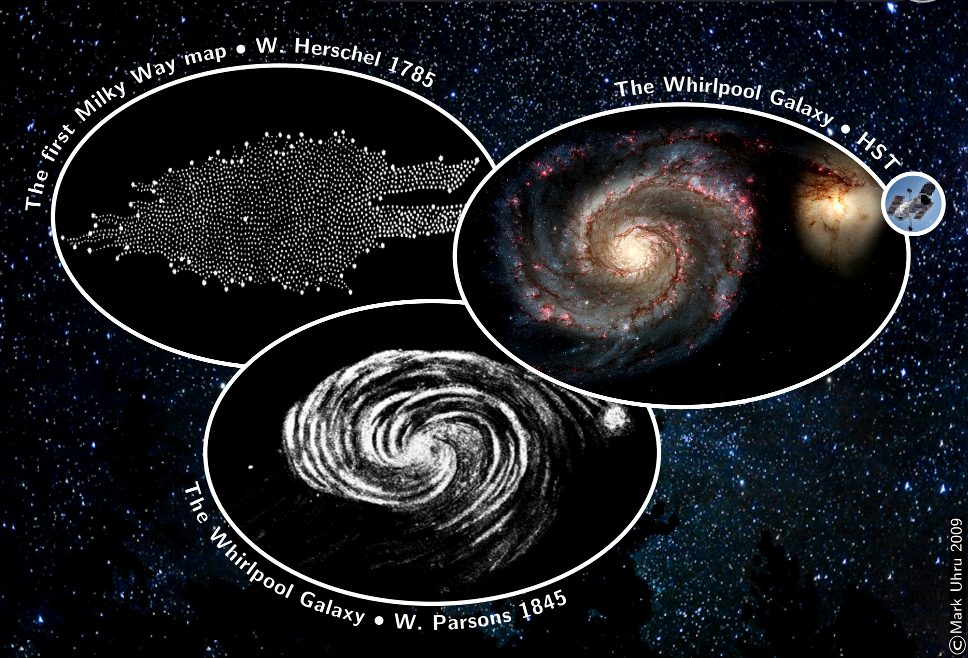

The first Milky Way map • W. Herschel 1785
The Whirlpool Galaxy • W. Parsons 1845


The first Milky Way map • W. Herschel 1785
The Whirlpool Galaxy • HST
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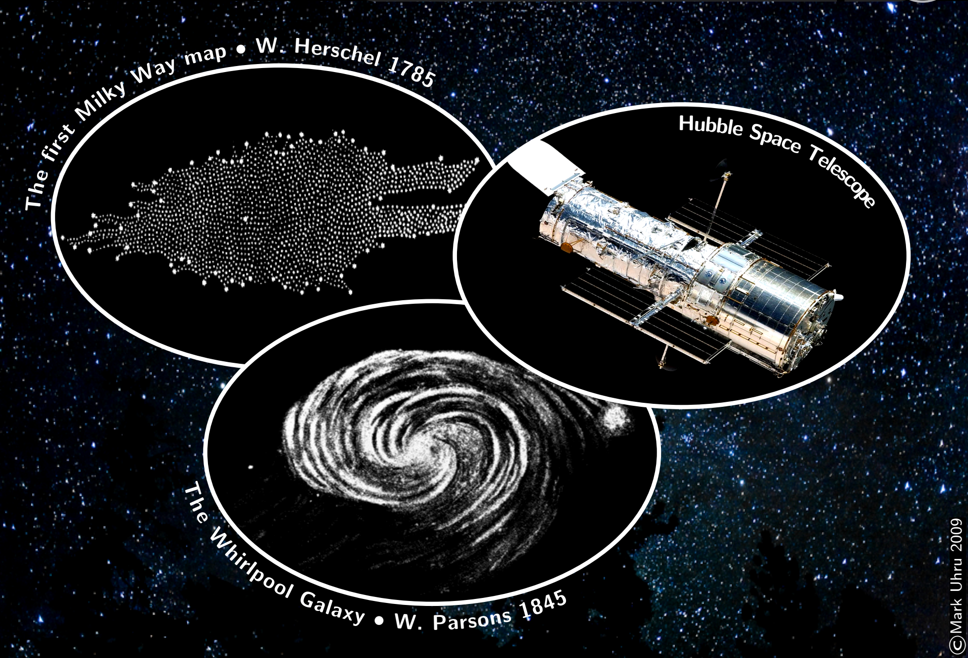
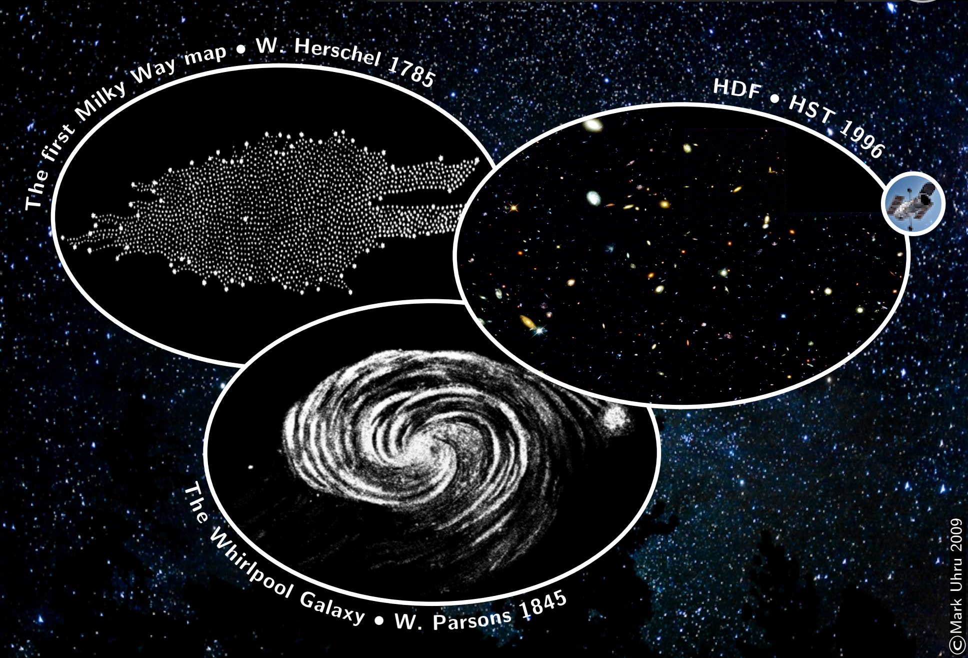

The first Milky Way map • W. Herschel 1785
Hubble Space Telescope
The Whirlpool Galaxy • W. Parsons 1845


The first Milky Way map • W. Herschel 1785
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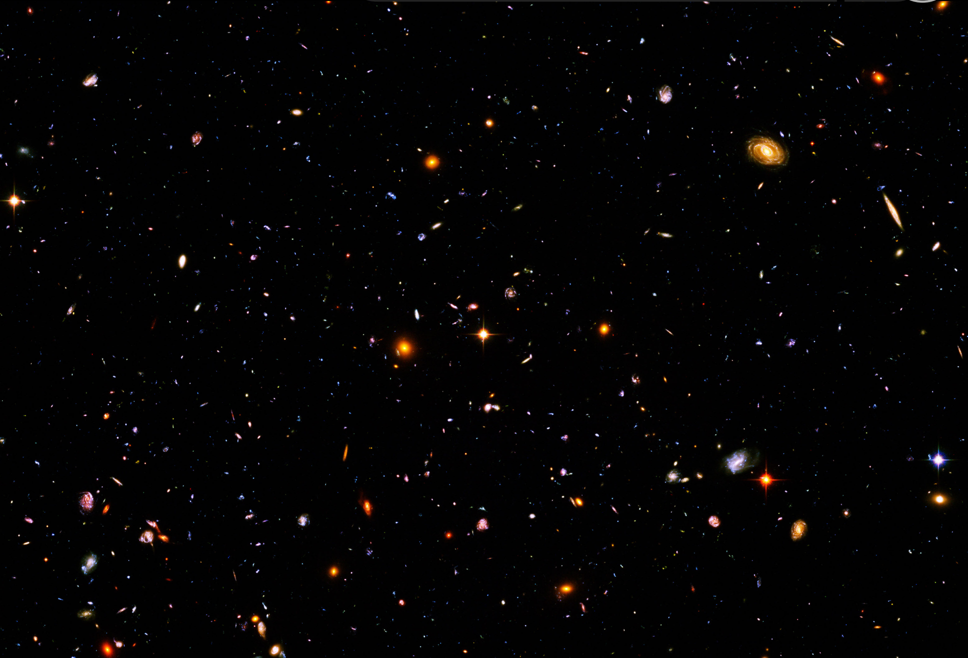

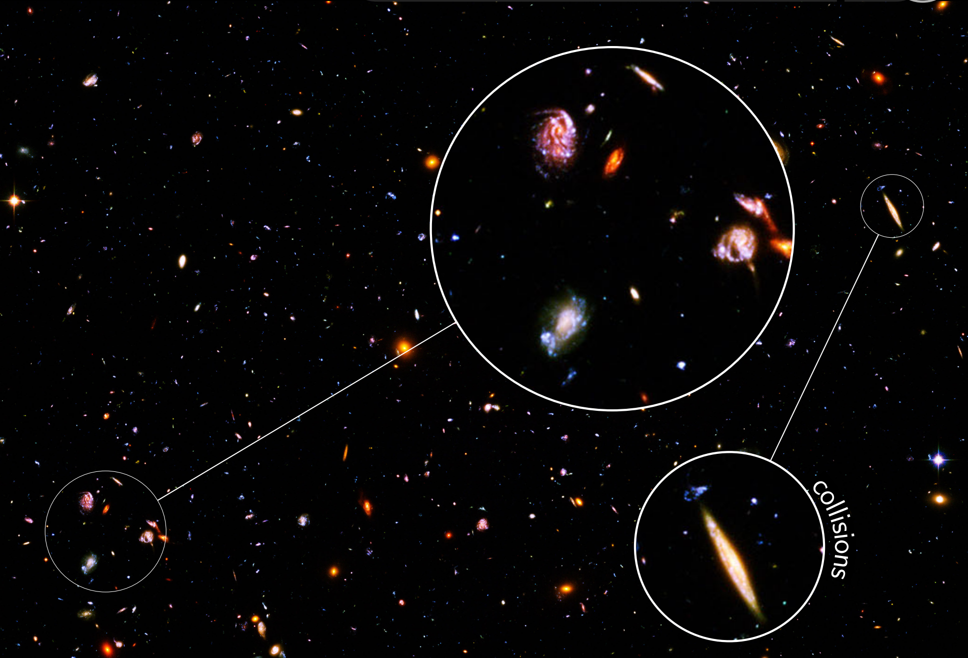
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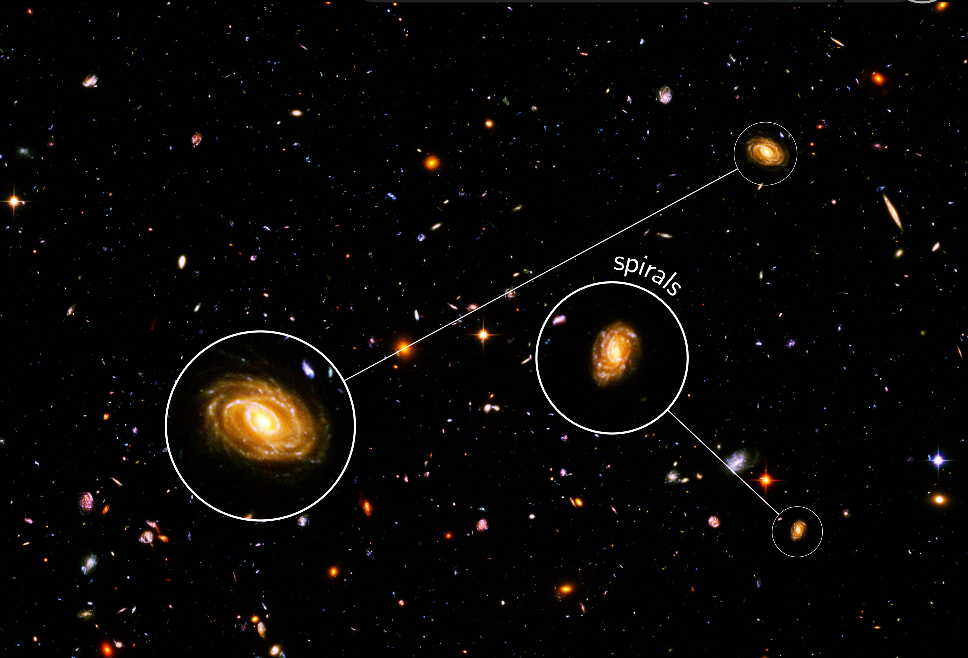
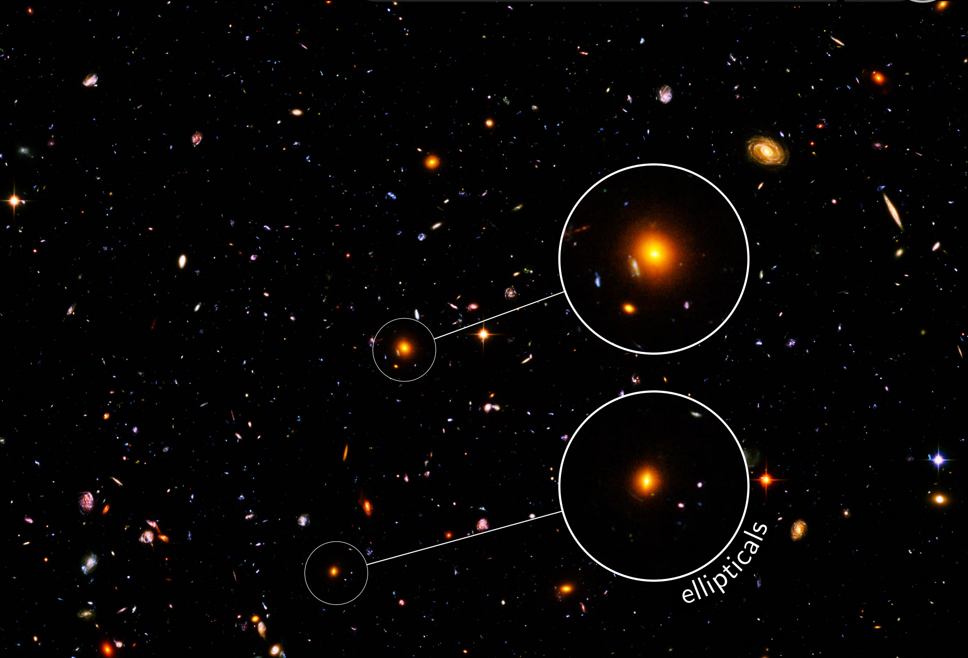
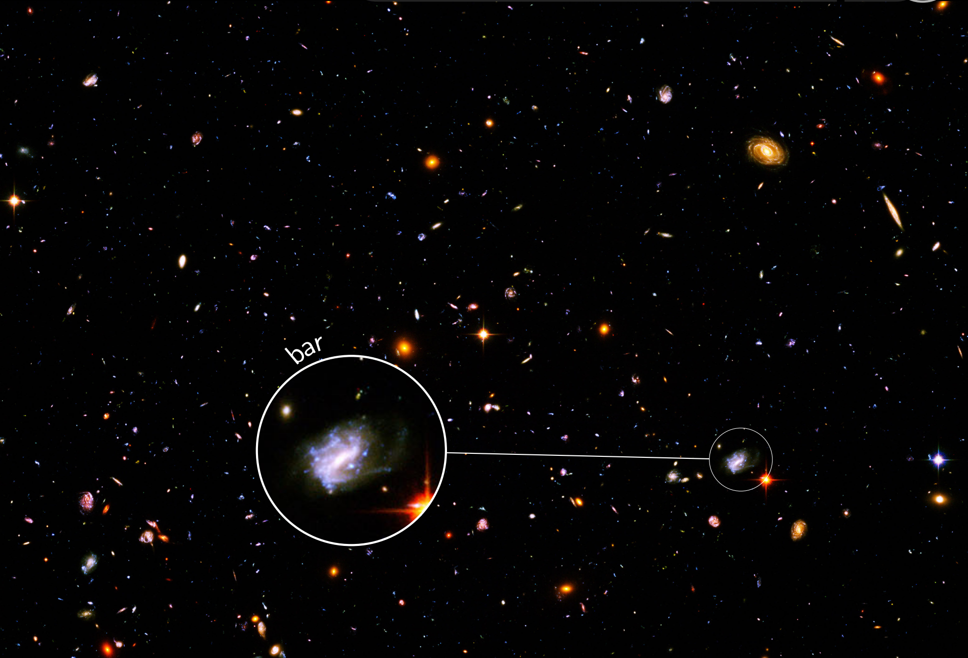
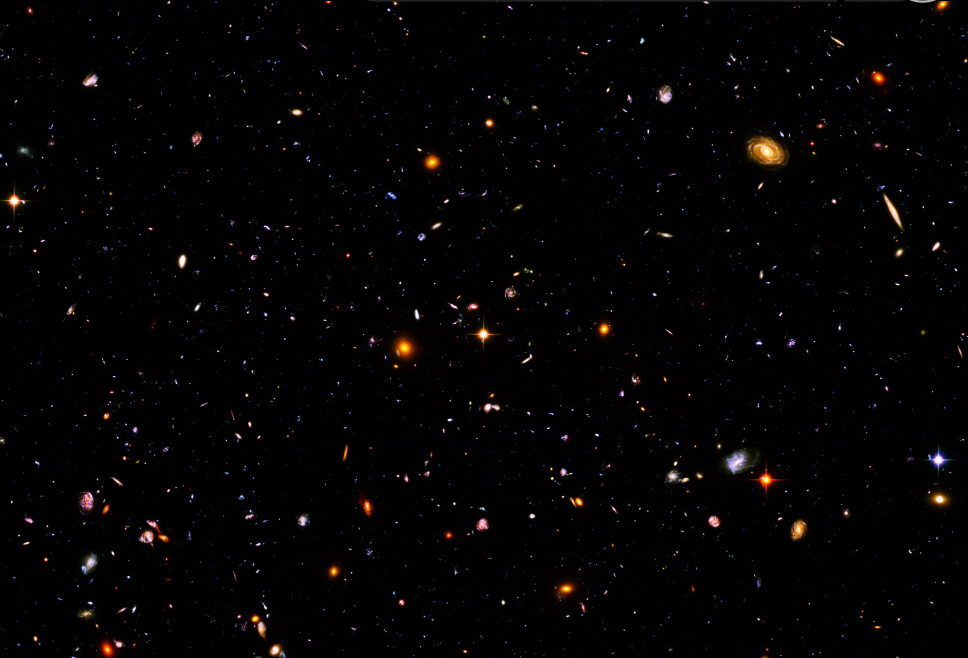

spirals

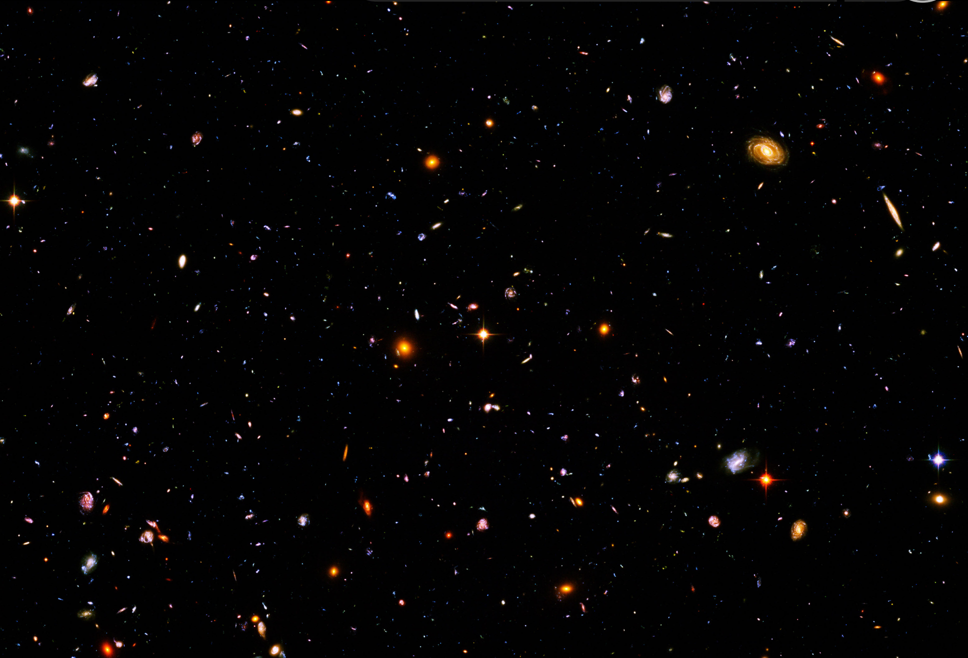

ellipticals

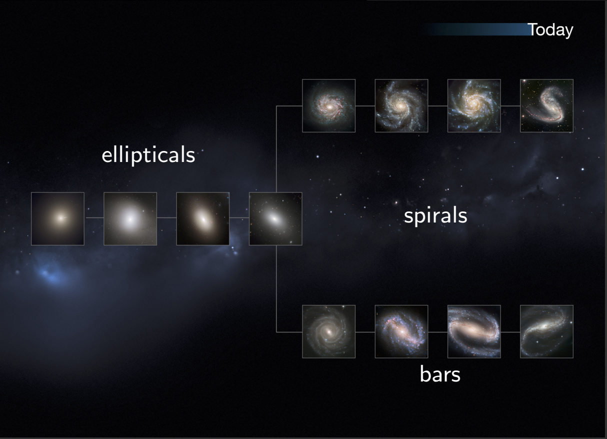

bar

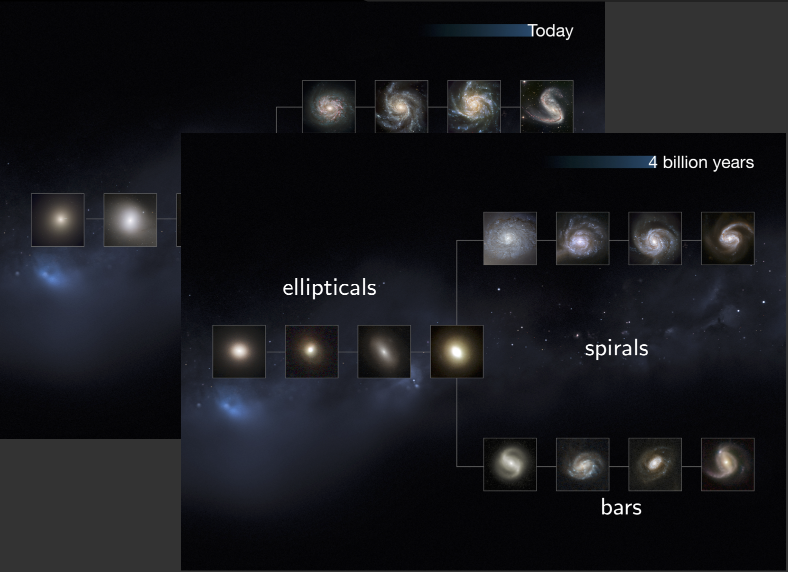


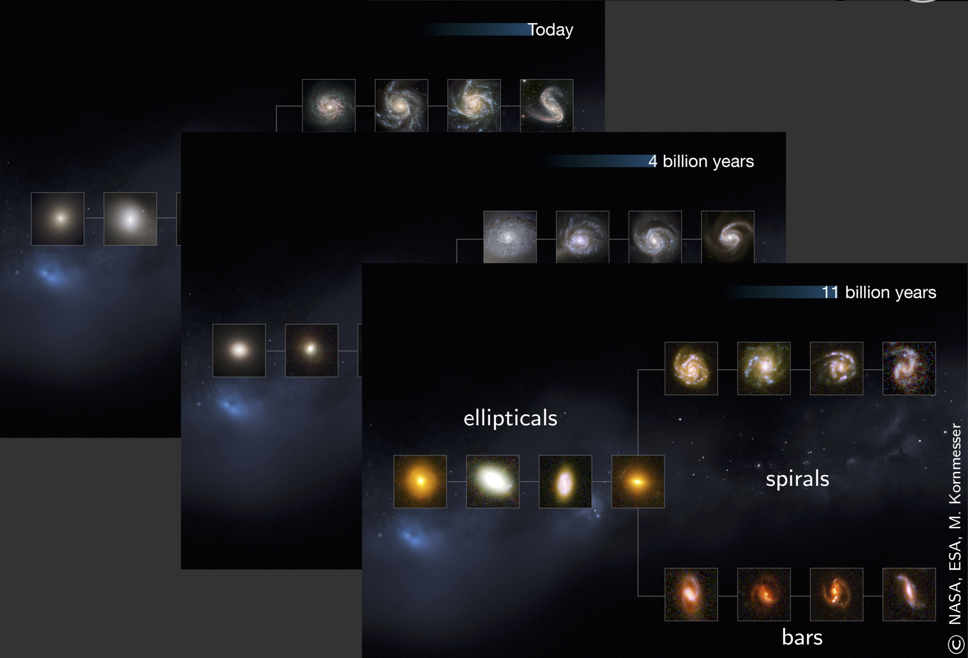
Introduction

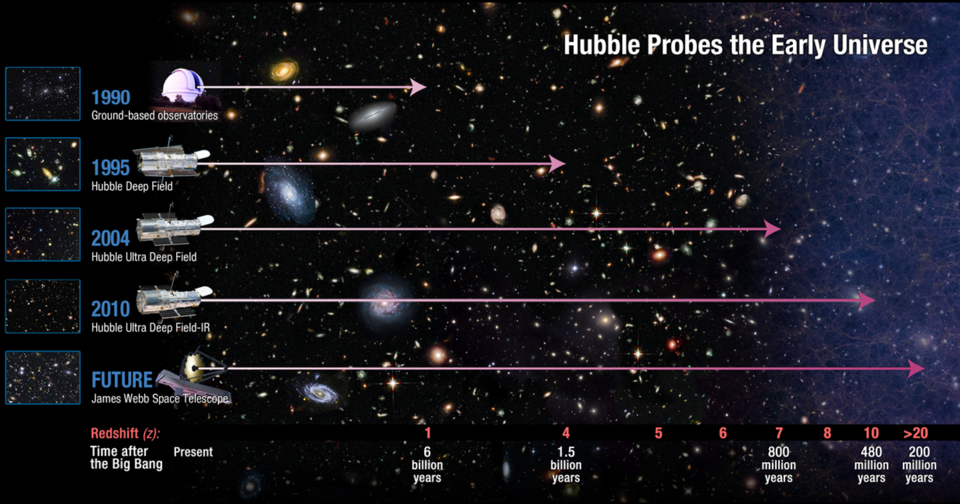
Hubble Ultra Deep Field




Today
ellipticals
spirals
bars

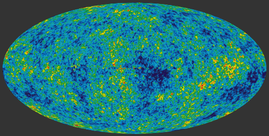

Today
4 billion years
ellipticals
spirals
bars


Today
4 billion years
11 billion years
ellipticals
spirals
bars
© NASA, ESA, M. Kornmesser


Hubble Probes the Early Universe
1990
Ground-based observatories
1995
Hubble Deep Field
2004
Hubble Ultra Deep Field
2010
Hubble Ultra Deep Field-IR
FUTURE
James Webb Space Telescope
Redshift (z):
1
4
5
6
7
8
10
>20
Time after the Big Bang
Present
6 billion years
1.5 billion years
800 million years
480 million years
200 million years

① initial conditions

① initial conditions



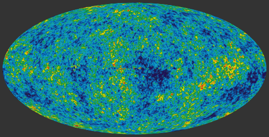
ΛCDM

- CDM paradigm: success on large scales
- simplest (6 parameters only)
- sufficiently accurate

① initial conditions

⊕

② ingredients



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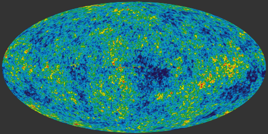

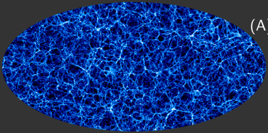

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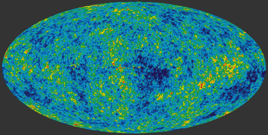

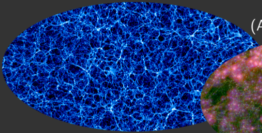

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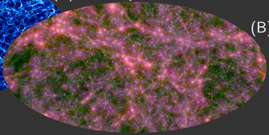

(B) all components

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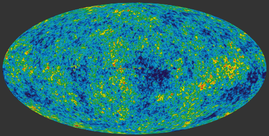
② ingredients

use

③ computational tools



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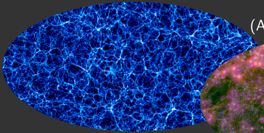

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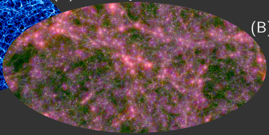

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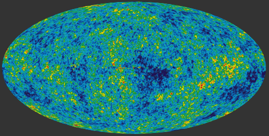

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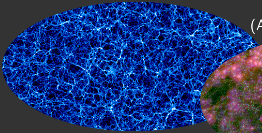

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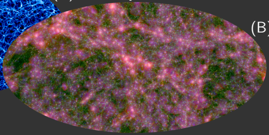


(B) all components

Methods

- numerical simulations
- SAM
- HOD ...

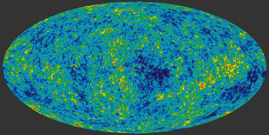
① initial conditions

⊕

② ingredients

use

③ computational tools



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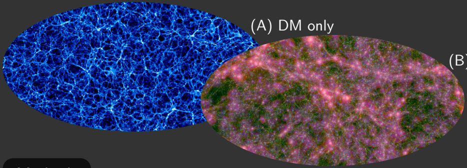

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→ Predictions

① initial conditions

⊕

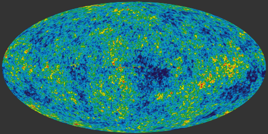
② ingredients

use

③ computational tools

compare

④ observations



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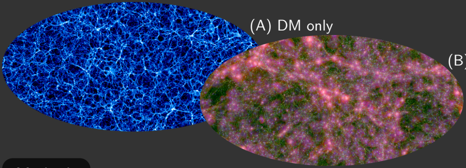

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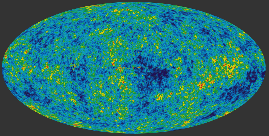

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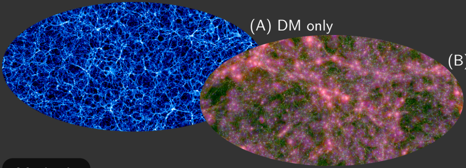

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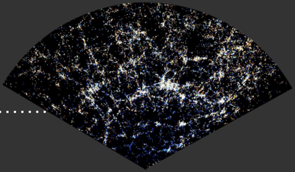

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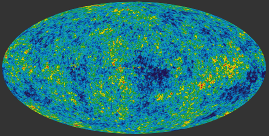

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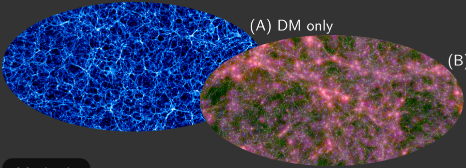

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(B) all components

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③ computational tools

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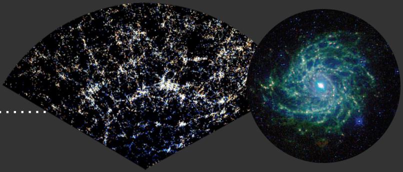
→ Predictions

compare

④ observations



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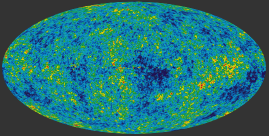

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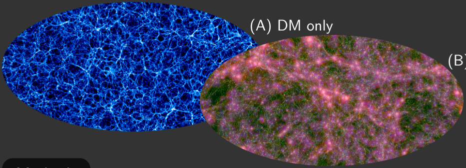

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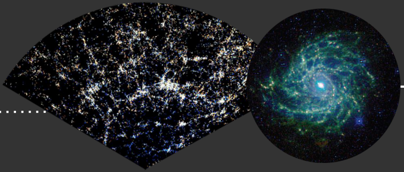
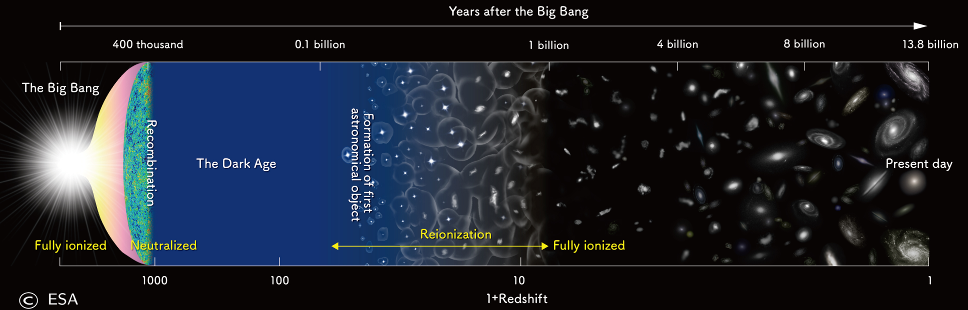
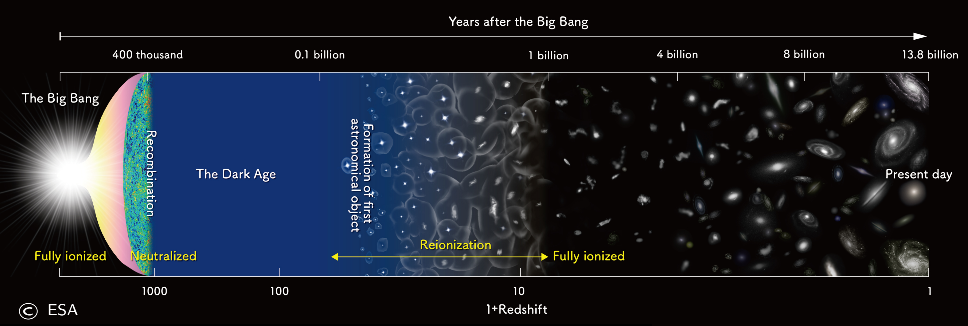
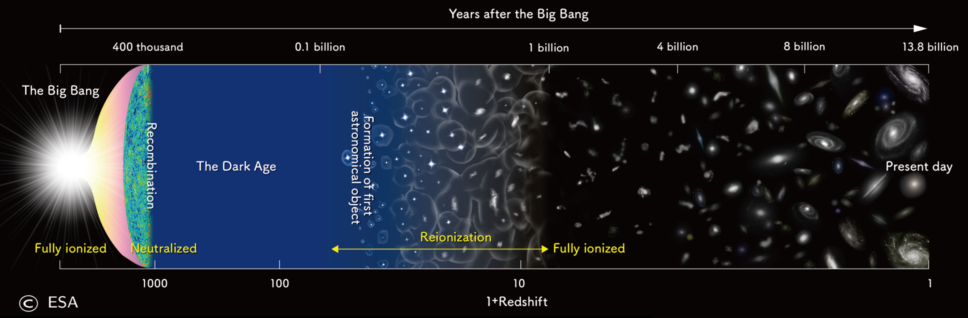


→ Test predictions


Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Age
Formation of first astronomical object
Present day
Fully ionized
Neutralized
Reionization
Fully ionized
1000
100
10
1
1+Redshift



- cosmological principle
- Einstein's theory of GR



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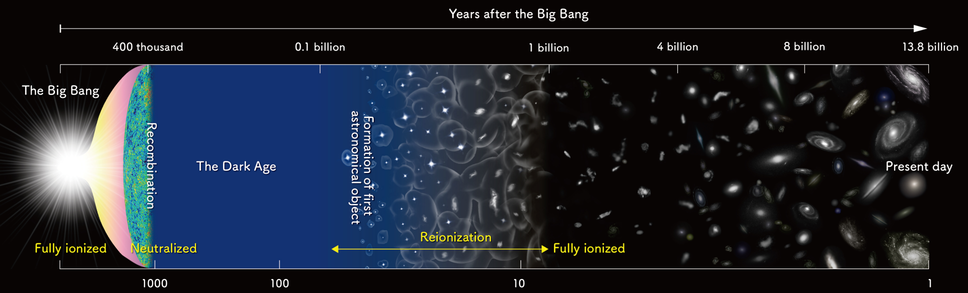
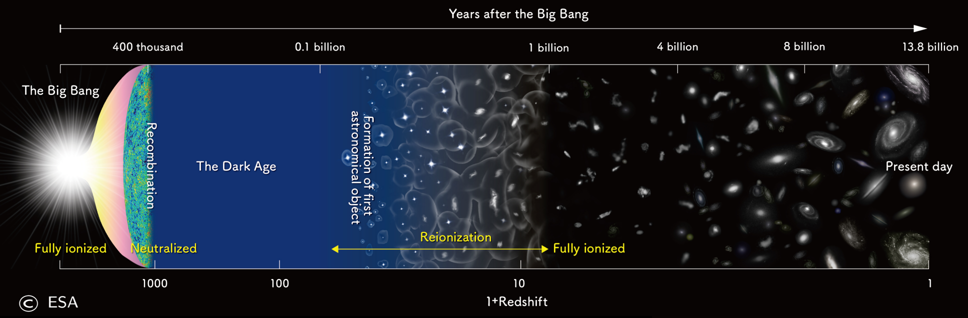
$$\left.\begin{array}{l}\text{cosmological principle}\\ \text{Einstein's theory of GR}\end{array}\right\} \Longrightarrow a(t, \Omega_X)$$

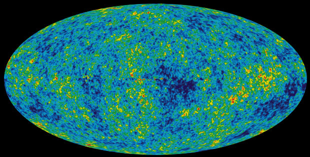


- cosmological principle
- Einstein's theory of GR
- quantum fluctuations



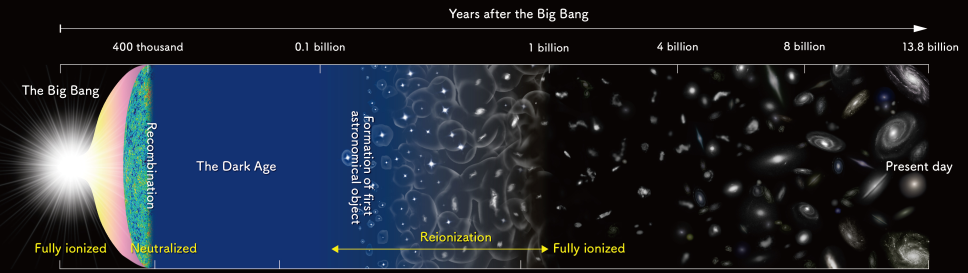
- cosmological principle
- Einstein's theory of GR
- quantum fluctuations

$\Longrightarrow$



CMB

WMAP
Planck . . .



- cosmological principle
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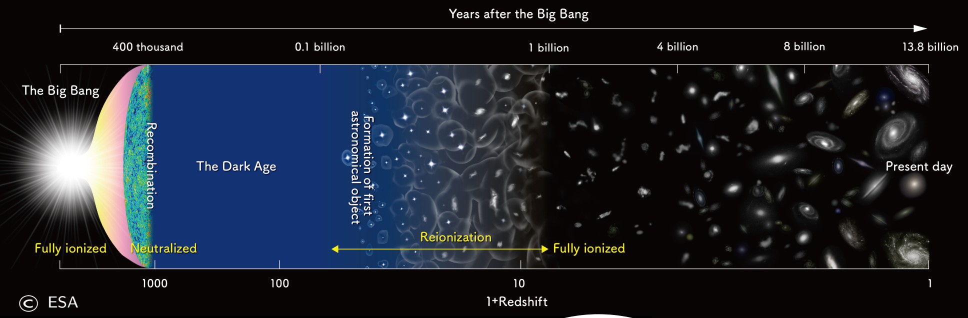
- quantum fluctuations
- standard model (ΛCDM)



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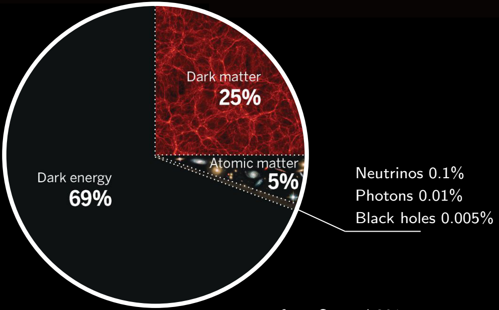
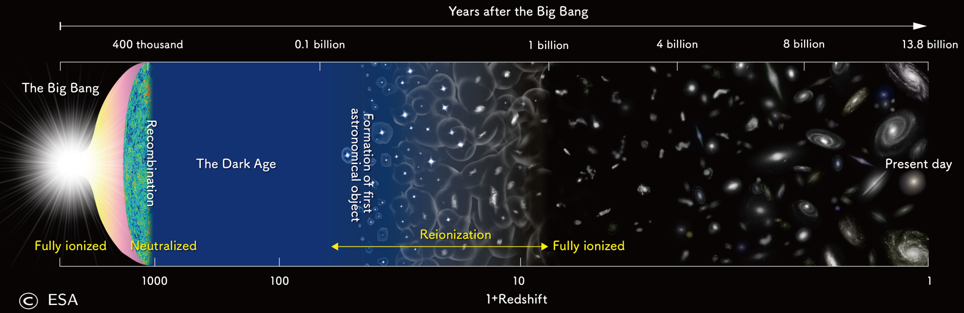


from Spergel 2015



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- Einstein's theory of GR
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- standard model (ΛCDM)
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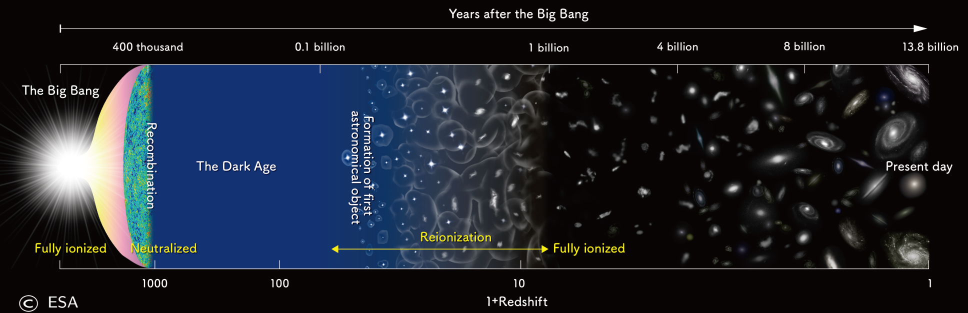

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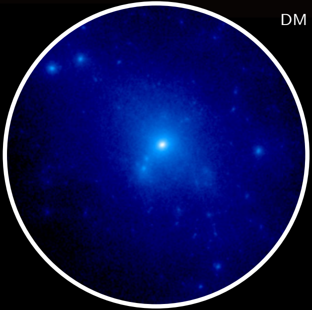

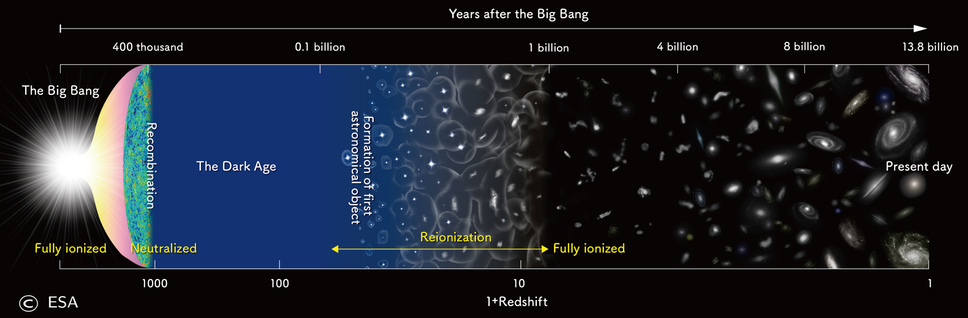

these lectures

Overview

1. Gravity

Overview

1. Gravity
2. Hydrodynamics & Thermal evolution

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2. Hydrodynamics & Thermal evolution
3. Star formation

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Gravity

- "skeleton" for galaxy formation

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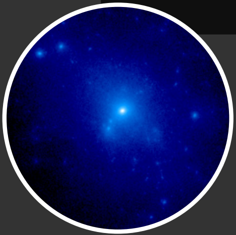

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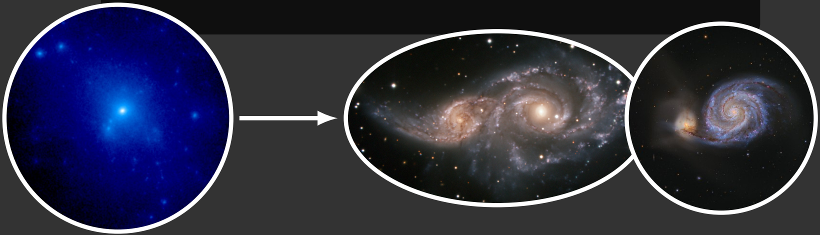

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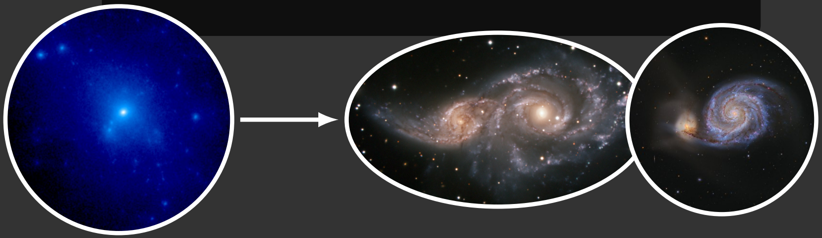

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  - bursts of SF
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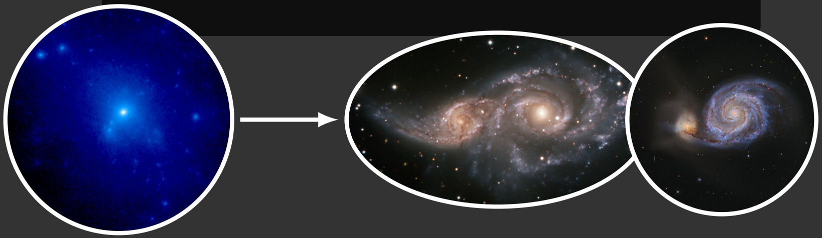
  - transformation of galaxy structure & morphology



Hydrodynamics

- cooling $\longrightarrow$ 2-body radiative processes
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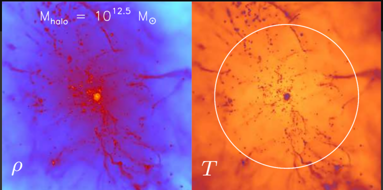

van de Voort et al. 2011

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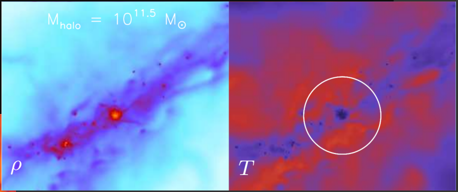

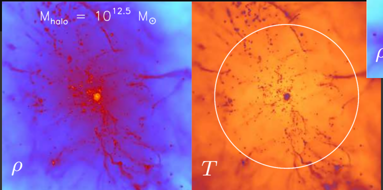

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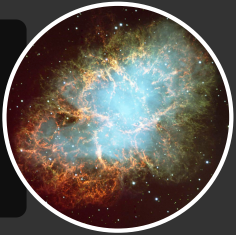

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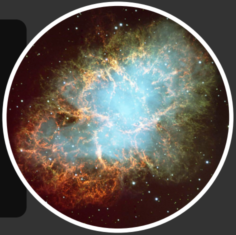

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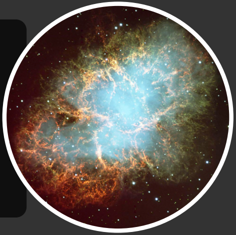

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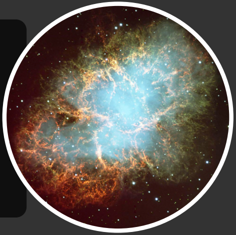

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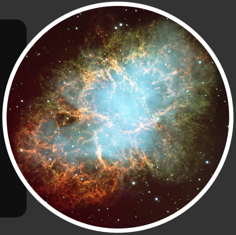

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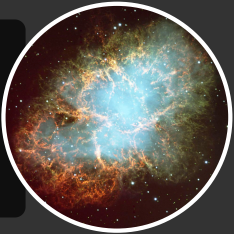

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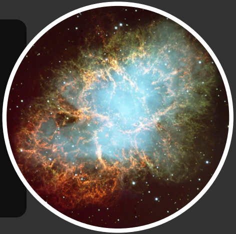

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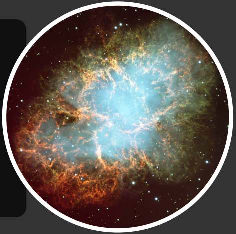

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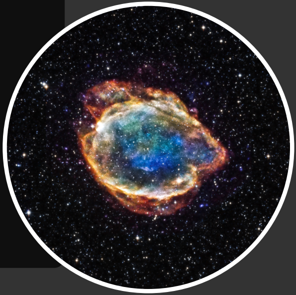

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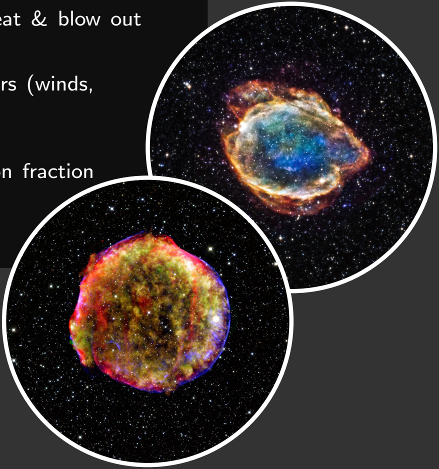

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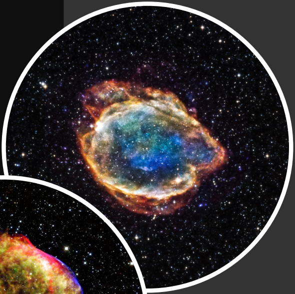

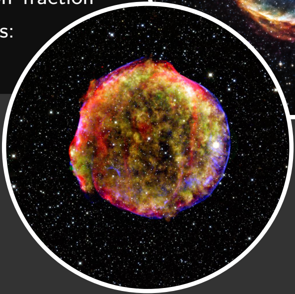

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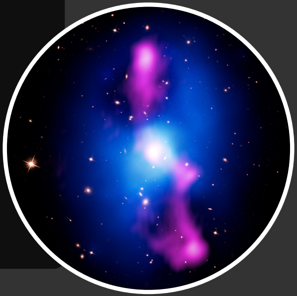

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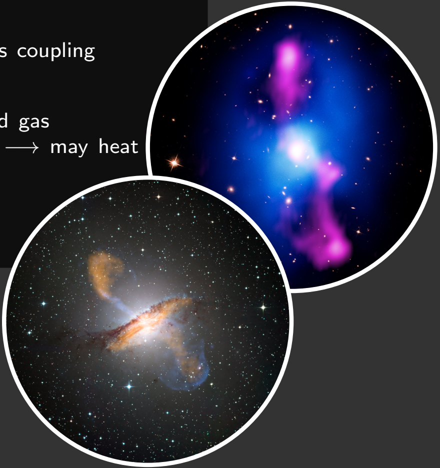

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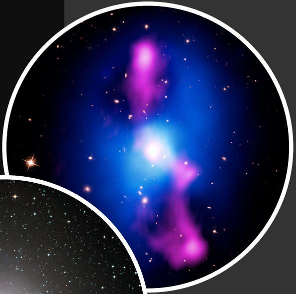

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- post-processing

Methods

(1) "models"

- Halo occupation distribution (HOD) models
  Conditional luminosity function (CLF) models
  Sub-halo abundance matching (SHAM) models
- no modeling of physical processes
- mapping galaxies $\longleftrightarrow$ halos

Methods

1. "models"
2. numerical hydrodynamic techniques
   - most explicit way
   - solve eqs of gravity, hydrodynamics, thermodynamics for DM, gas and stars
   - advantages: predictions for ρ, T, $\vec{v}$, ...
   - drawbacks: high computational cost & arbitrary recipes

Methods

1. "models"
2. numerical hydrodynamic techniques
3. semi-analytic modeling (SAM)

- set of simplified flow eqs for bulk components $\rightarrow$ tracks
    - how much gas accretes onto halo
    - how much hot gas cools & SF
    - removal of cold gas by feedback processes ...
- advantages: reduced computational cost

adapted from Mo et al. 2010

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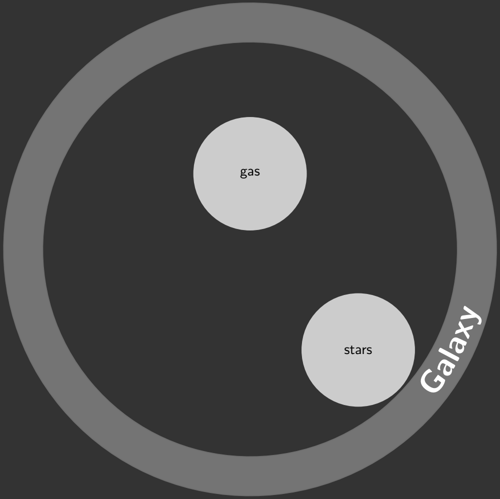

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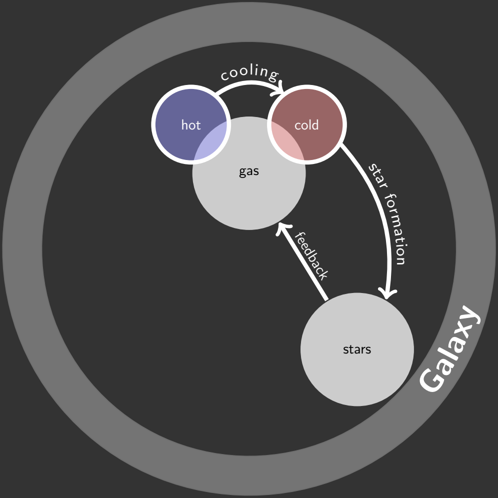

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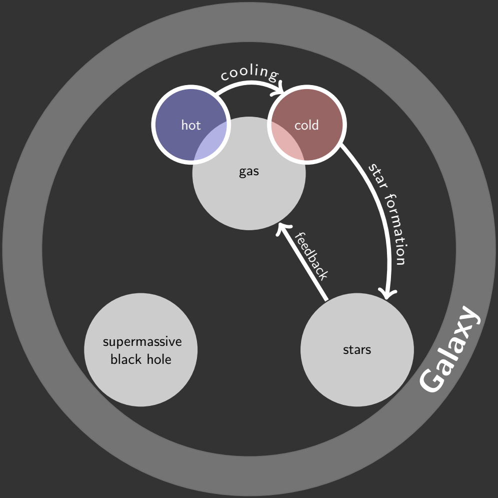

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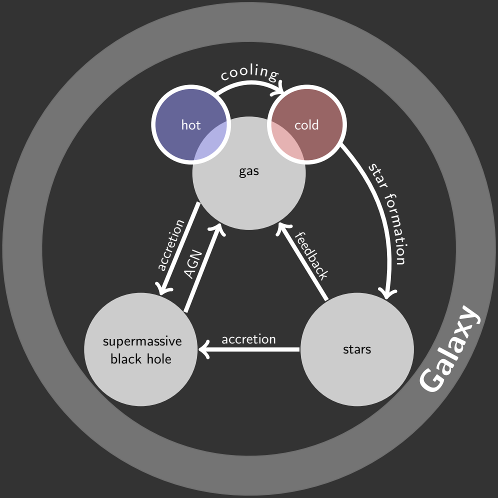

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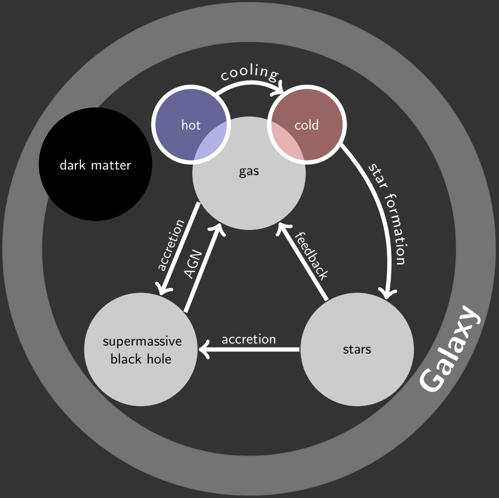

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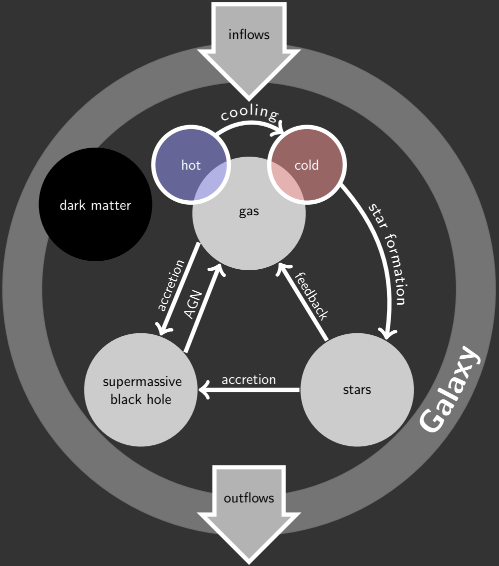

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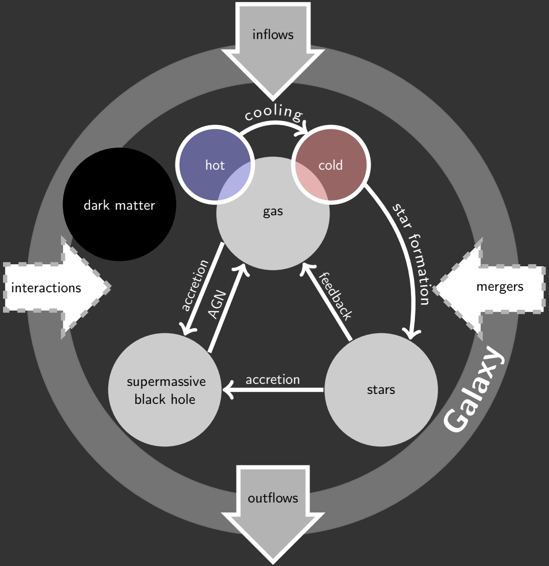

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cosmological initial and
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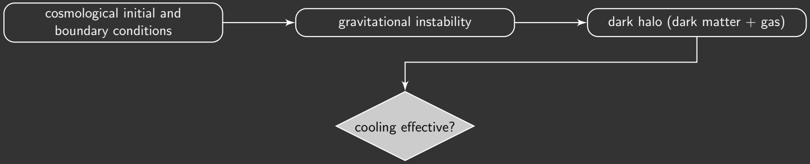

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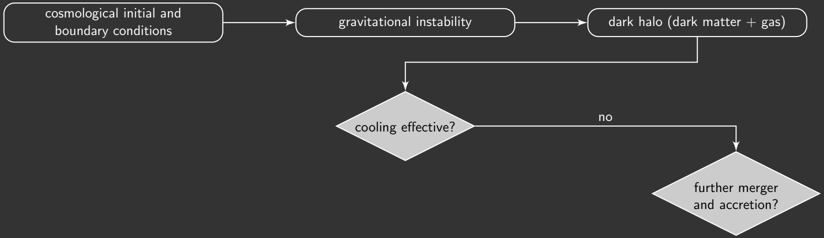

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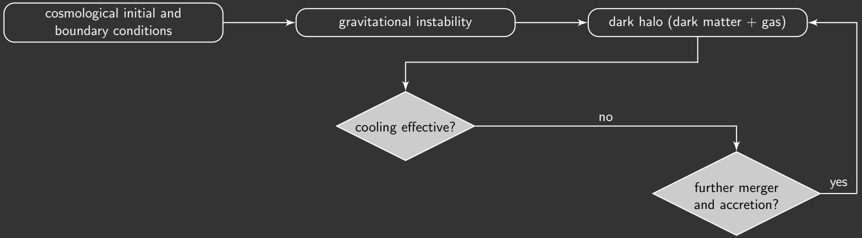

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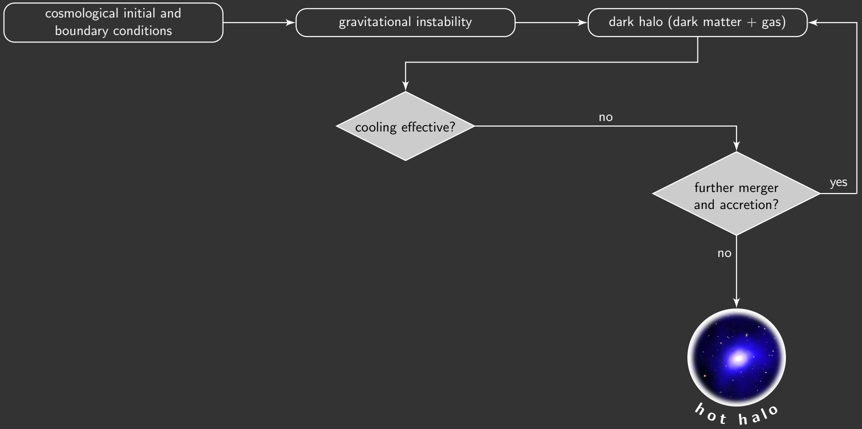

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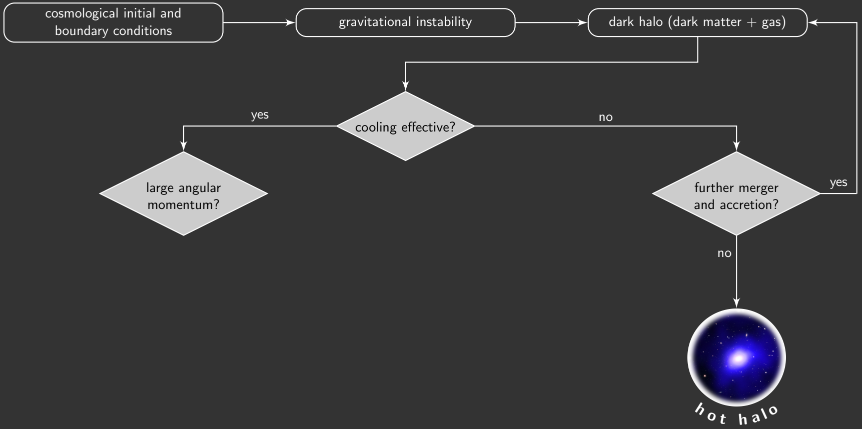

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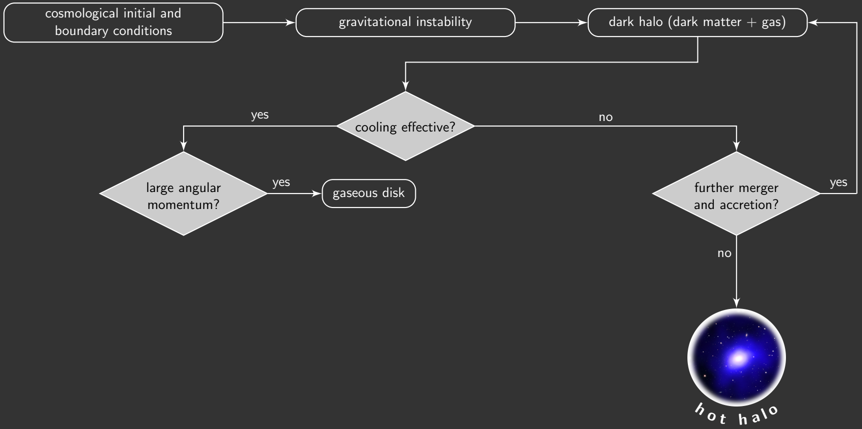

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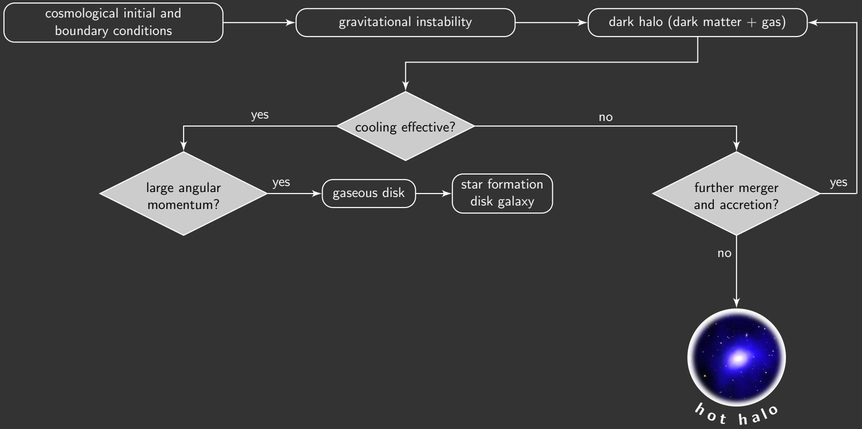

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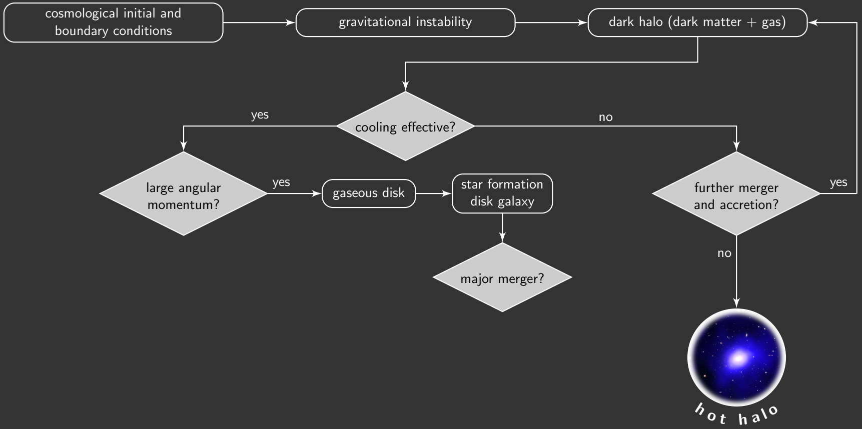

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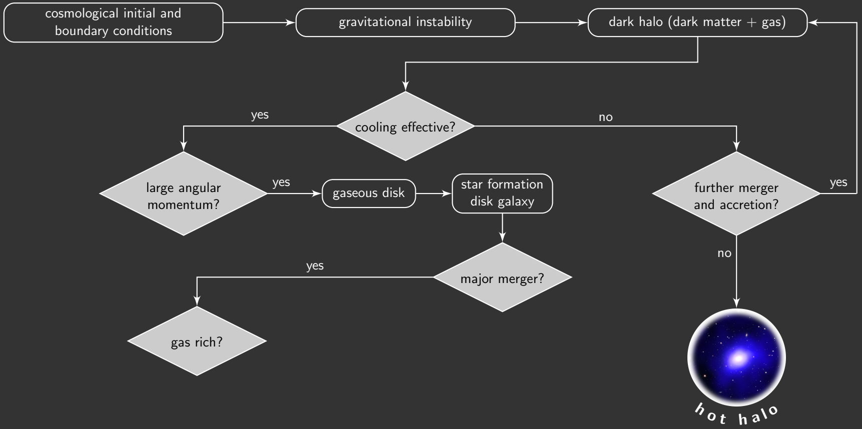

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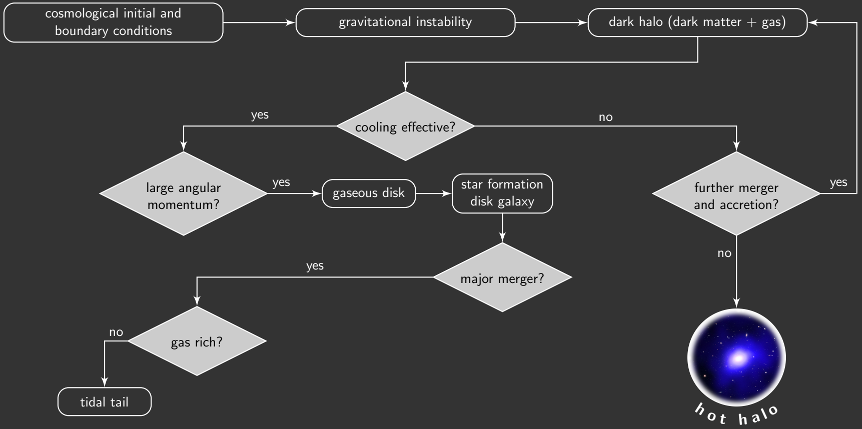

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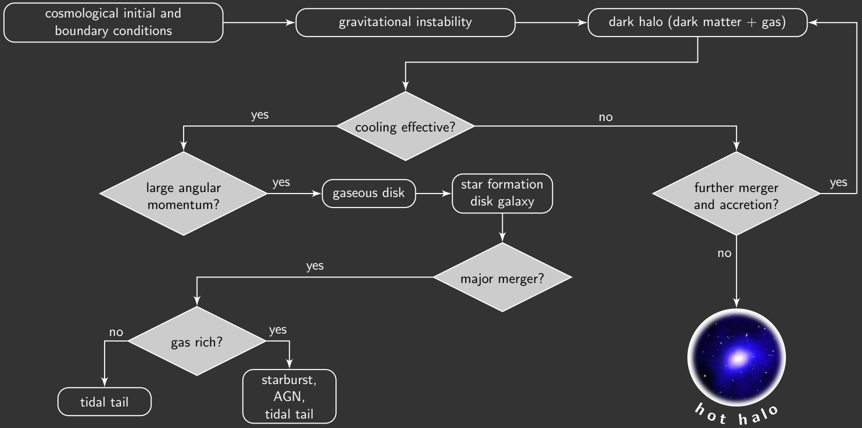

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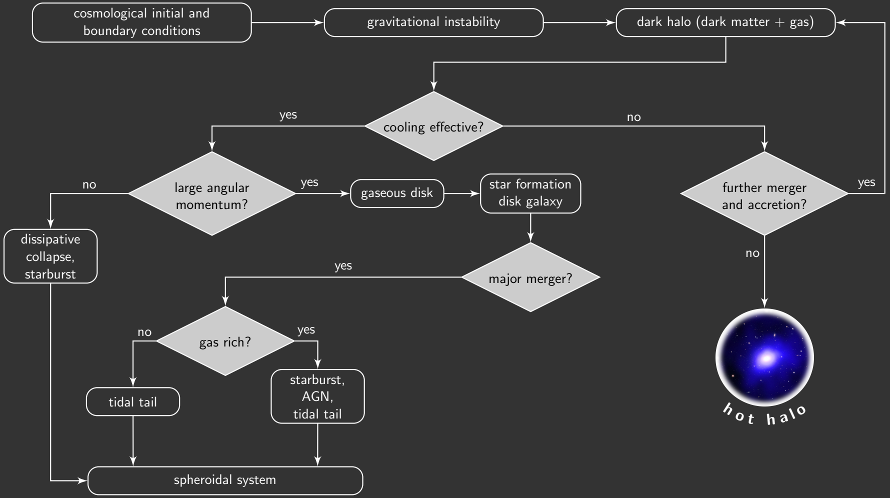

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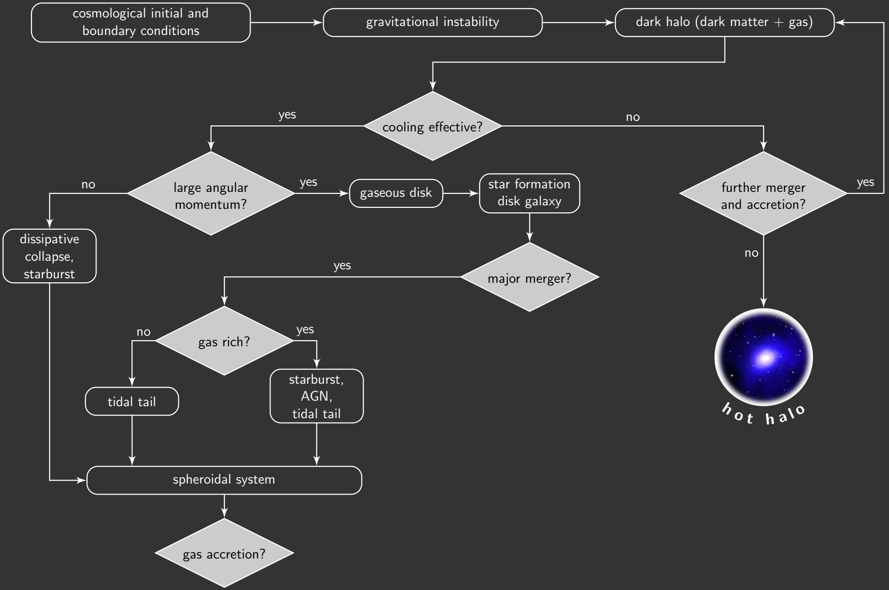

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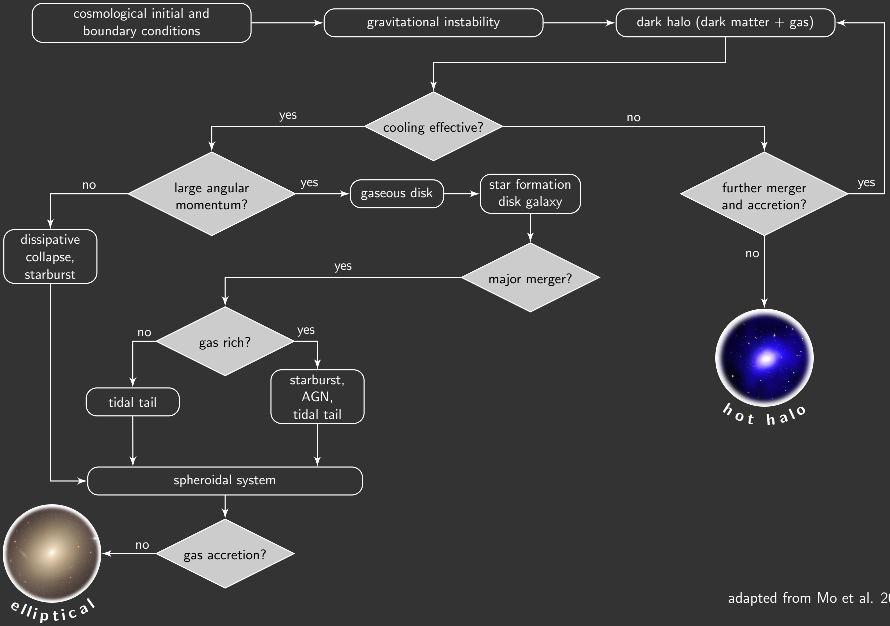

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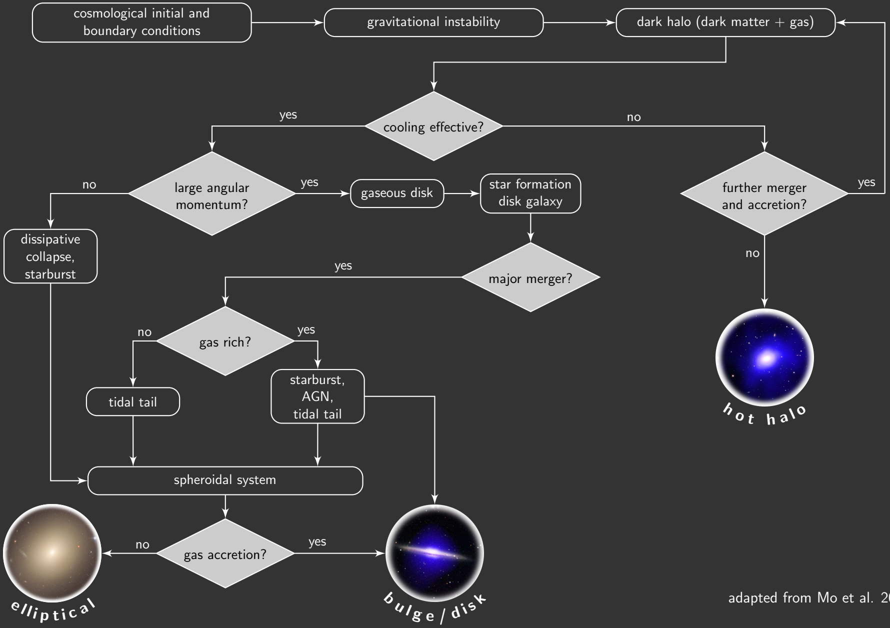

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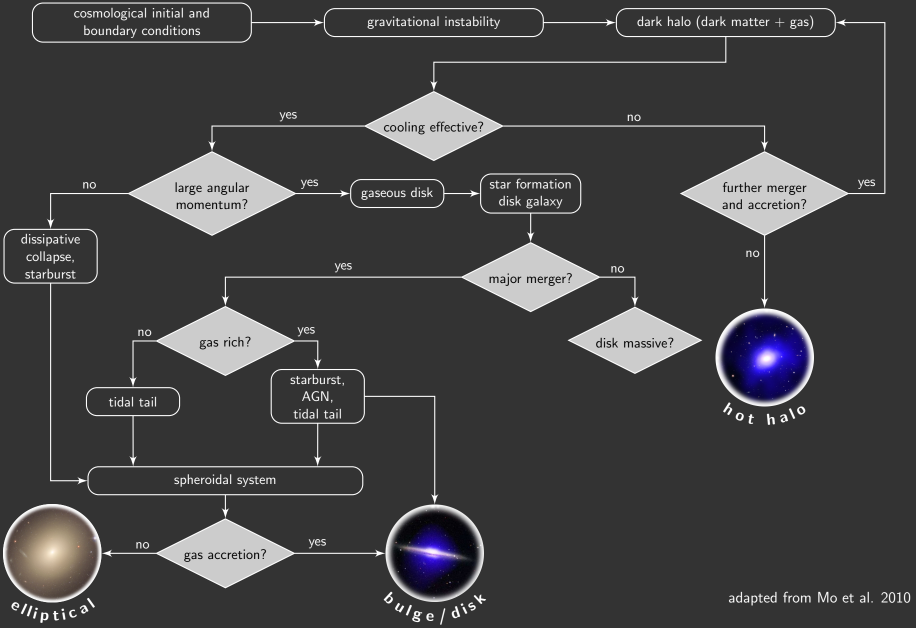

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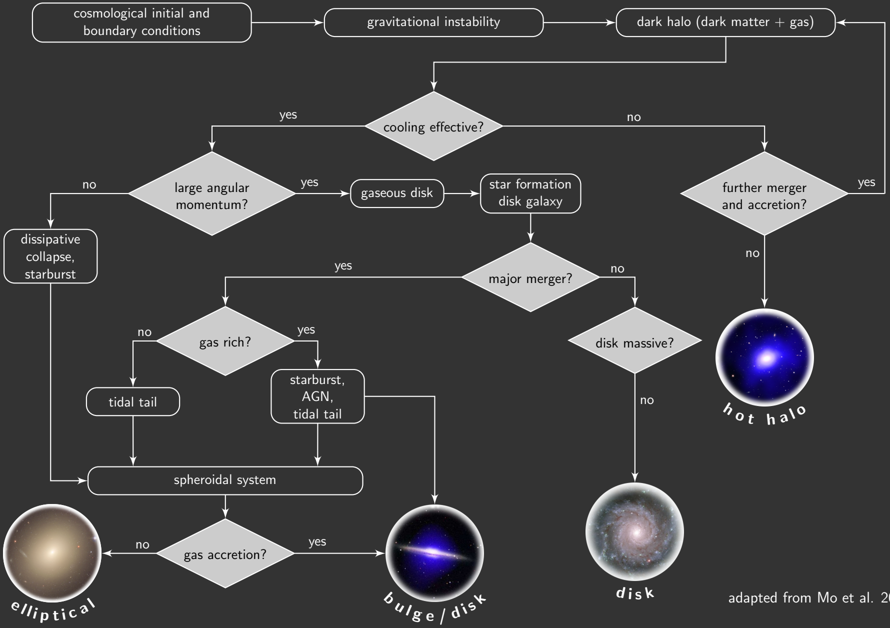

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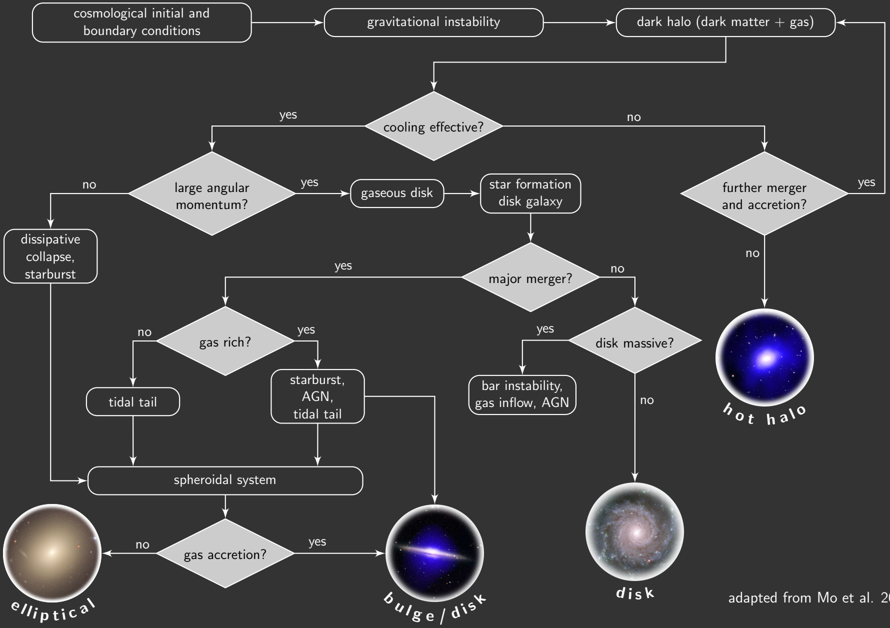

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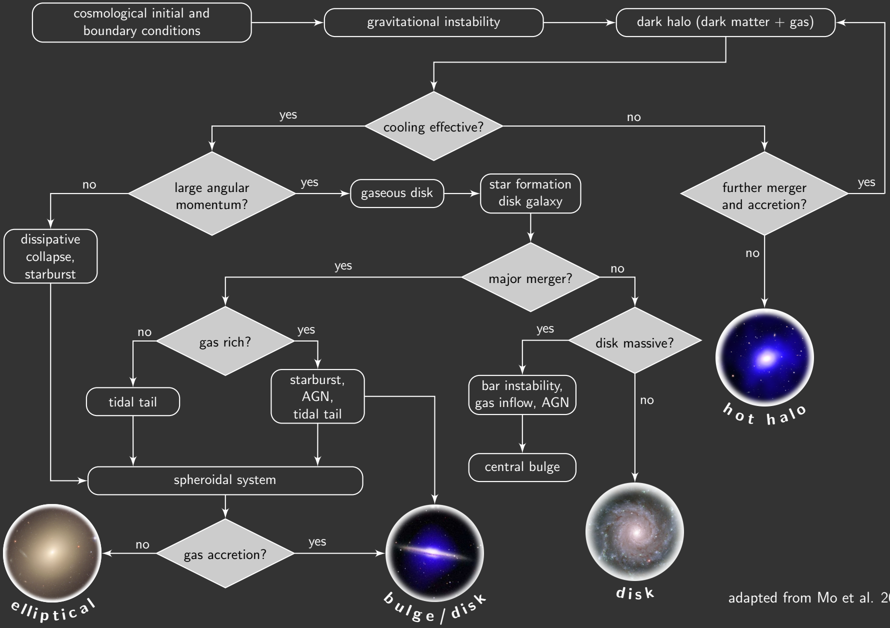

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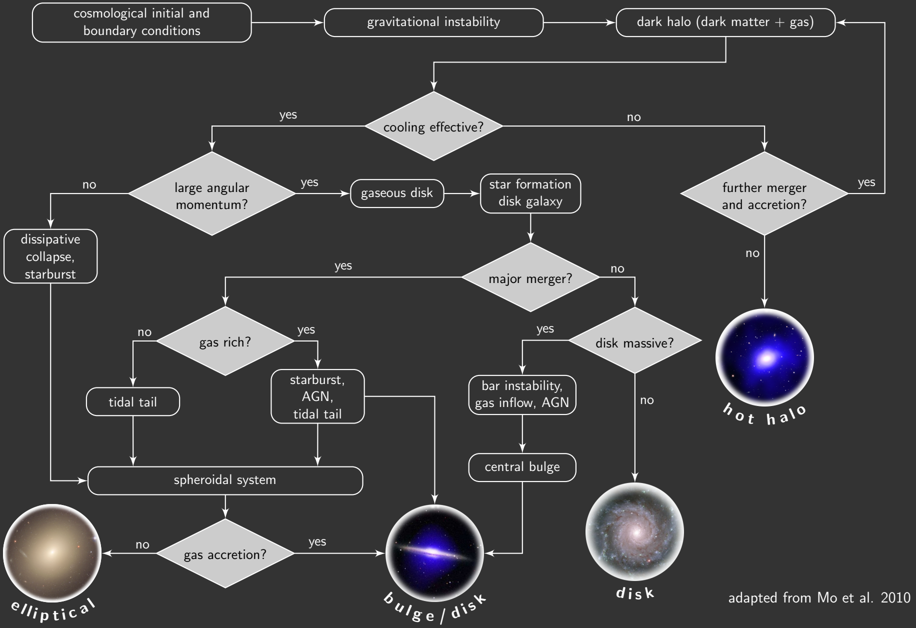

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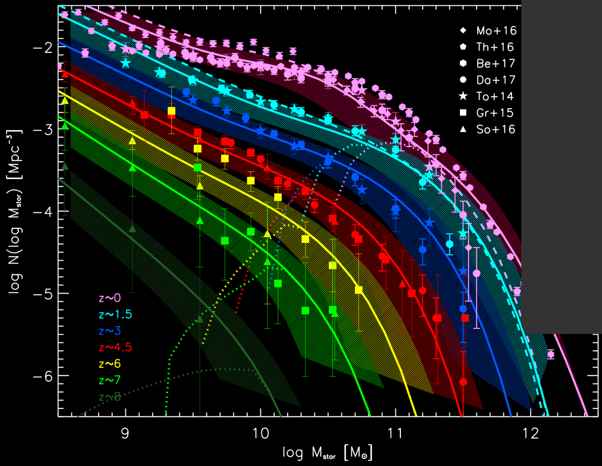
Stellar mass function

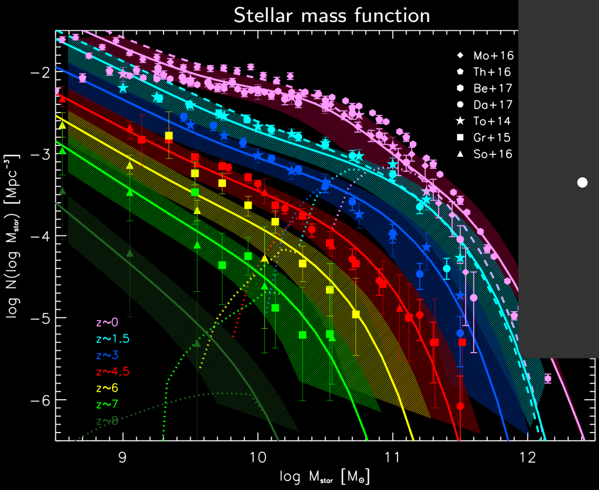


Lapi et al. 2017

Distributions

- distribution functions
  - Schechter function (Schechter 1976)
  - stellar mass
  - luminosity
  - gas mass

(e.g. Blanton & Moustakas 2009)

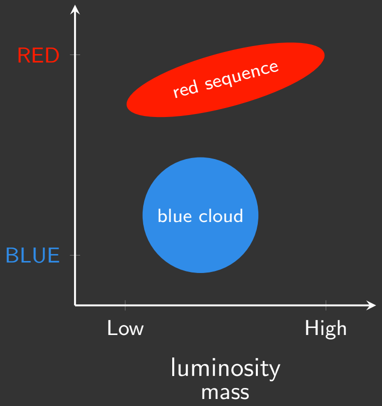


Lapi et al. 2017

Distributions

- distribution functions
  - Schechter function (Schechter 1976)
  - stellar mass
  - luminosity
  - gas mass

  (e.g. Blanton & Moustakas 2009)
- insights
  - hierarchical bottom-up picture (Madau & Dickinson 2014)
  - mass assembly downsizing (e.g. Marchesini et al. 2009, Moustakas et al. 2013)



e.g. Strateva et al. 2001
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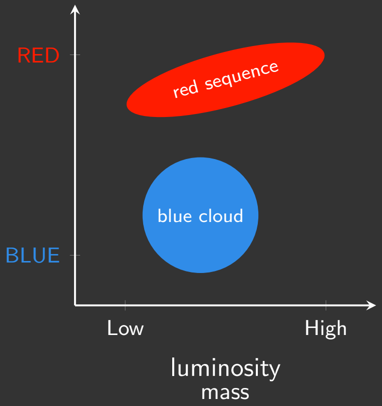
Bimodality

- "red sequence"
  - quiescent galaxies
  - old stellar populations



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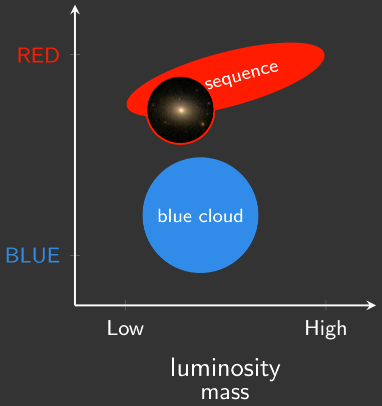

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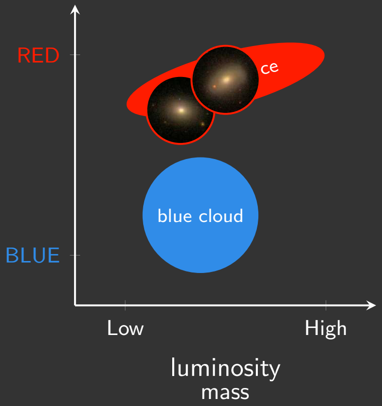

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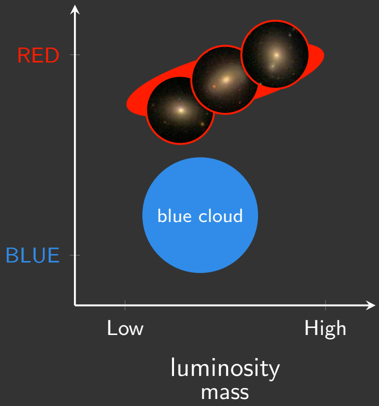

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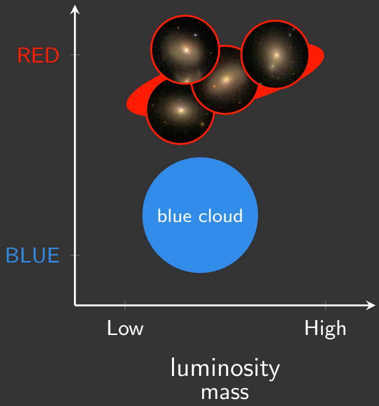

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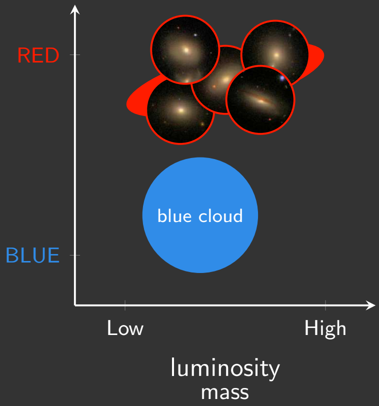

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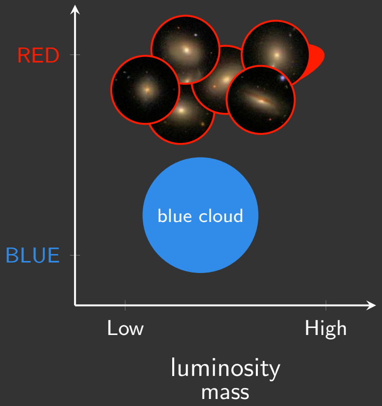

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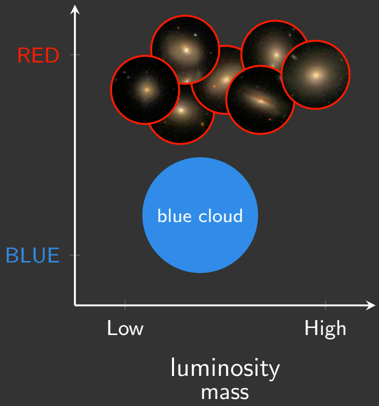

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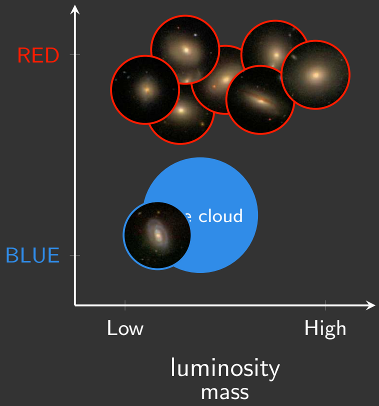

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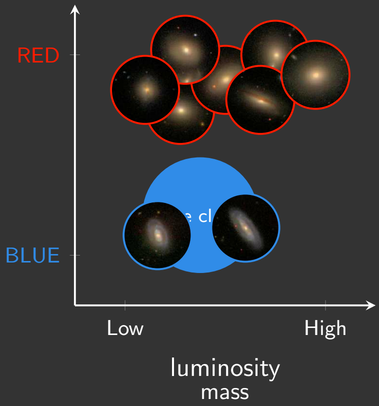

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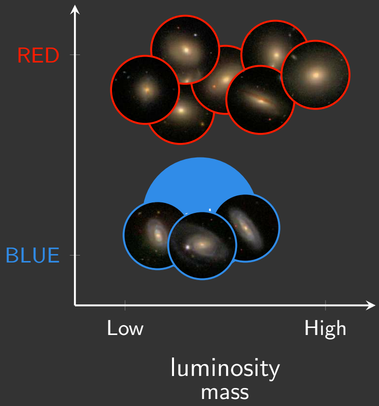

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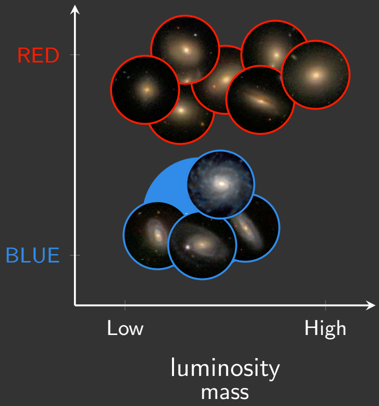

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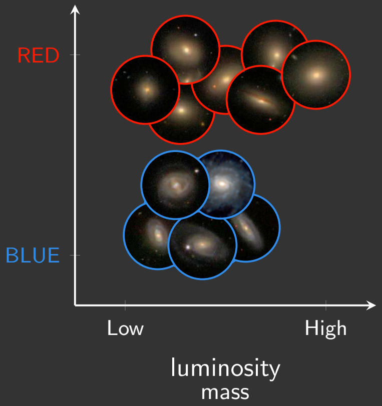

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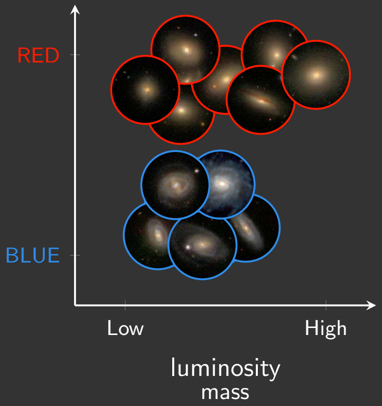

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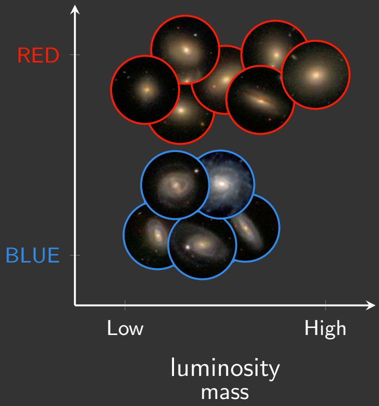
Brammer et al. 2011, Muzzin et al. 2013

Bimodality

- "red sequence"
  - quiescent galaxies
  - old stellar populations
- "blue cloud"
  - SF galaxies
  - young stellar populations
- up to $z \sim 2$ (perhaps $z \sim$ 3-4)



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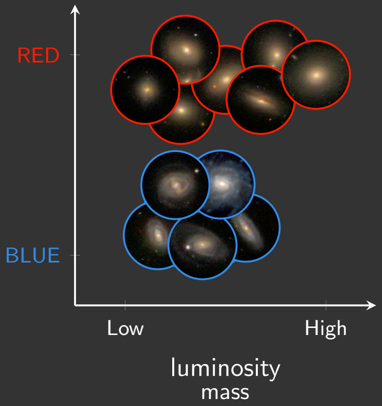
Schiminovich et al. 2007
Brammer et al. 2011, Muzzin et al. 2013
Kauffmann et al. 2003
Blanton & Moustakas 2009

Bimodality

- "red sequence"
  - quiescent galaxies
  - old stellar populations
  - comoving $\rho \nearrow$ with t since $z \sim 2$
- "blue cloud"
  - SF galaxies
  - young stellar populations
  - comoving $\rho \searrow$ or const. with t since $z \sim 2 \Longrightarrow$ "quenching"
- up to $z \sim 2$ (perhaps $z \sim$ 3-4)



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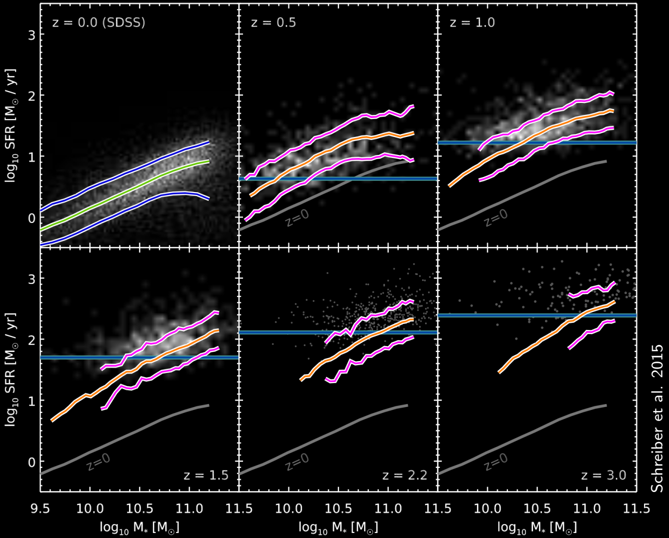
Schiminovich et al. 2007
Brammer et al. 2011, Muzzin et al. 2013
Kauffmann et al. 2003
Blanton & Moustakas 2009

Bimodality

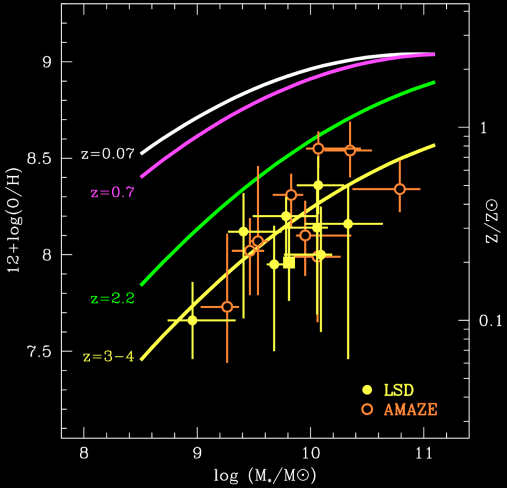
- "red sequence"
  - quiescent galaxies
  - old stellar populations
  - comoving $\rho \nearrow$ with t since $z \sim 2$
  - spheroid-dominated
- "blue cloud"
  - SF galaxies
  - young stellar populations
  - comoving $\rho \searrow$ or const. with t since $z \sim 2 \implies$ "quenching"
  - disk-dominated
- up to $z \sim 2$ (perhaps $z \sim$ 3-4)

① SF main sequence



also e.g. Noeske et al. 2007, Speagle et al. 2014

② Mass-metallicity relation



Mannucci et al. 2009

also e.g. Gallazzi et al. 2005, Tremonti et al. 2004
Erb et al. 2006, Zahid et al. 2013

③ cold gas fractions

- $f_{gas} = \frac{M_{gas}}{M_\star}$
- $f_{gas} \propto M_\star^{-0.57}$
  (Peeples & Shankar 2011)
- significant rise from $z = 0$ to $z \sim 2$
- plateau or possibly a slight decline at $z \geq 2$
  (e.g. Geach et al. 2011, Saintonge et al. 2013, Tacconi et al. 2013, Genzel et al. 2014, Scoville et al. 2014)

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④ scatter dependence

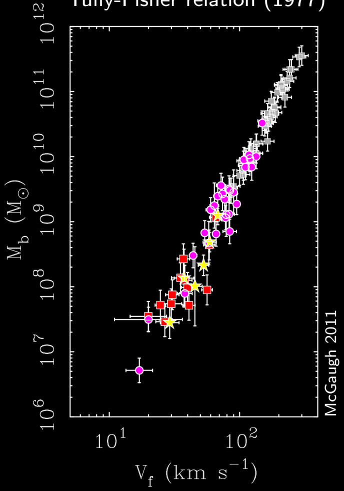
- Mass–metallicity–SFR:
  at fixed $M_\star$ lower Z higher SFR

  (Lara-López et al. 2010, Mannucci et al. 2010)
- Mass–metallicity–$\mathrm{f}_{\mathrm{gas}}$:
  at fixed $M_\star$ lower Z higher $\mathrm{f}_{\mathrm{gas}}$

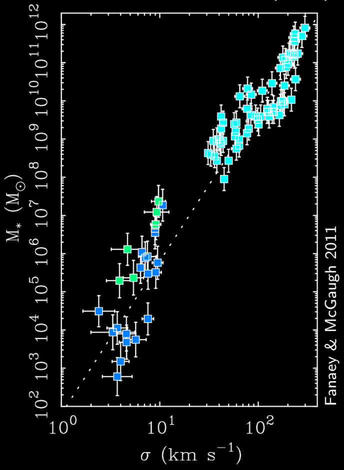
  (Bothwell et al. 2013, Lara-López et al. 2013)

$L\ [M_\star]$ – internal velocity

Disks
Tully-Fisher relation (1977)



Spheroids
Faber-Jackson relation (1976)



$L \ [M_\star]$ – size

Spheroids

Kormendy relation (1977)