Alexander Knebe (*Universidad Autonoma de Madrid*)

"It's somewhere between a nova and a supernova -- probably a pretty good nova."

- biased galaxy formation
- internal baryonic processes:
  - supernova feedback
  - active galactic nuclei feedback
- dwarf galaxies

- **biased galaxy formation**
- internal baryonic processes:
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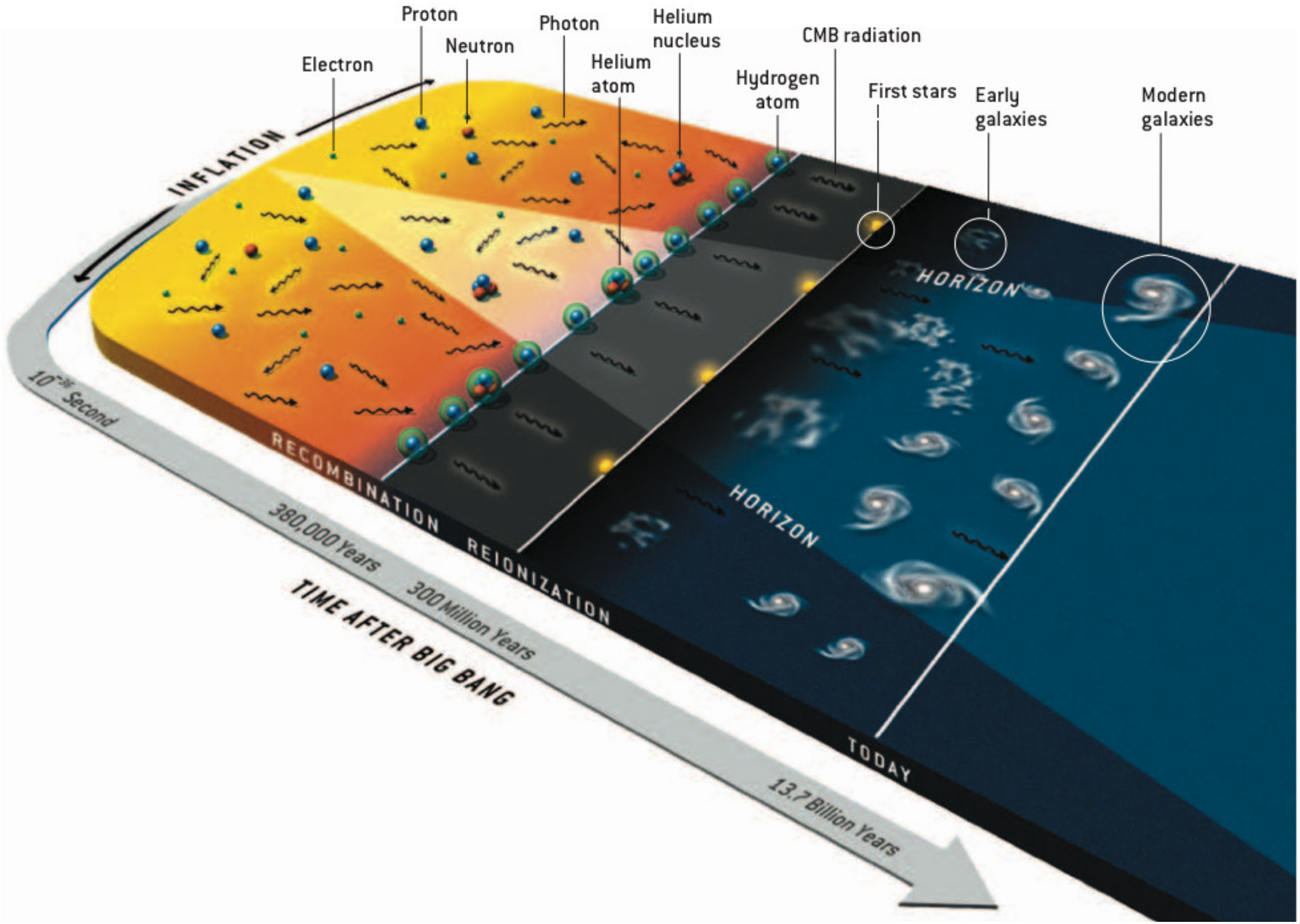
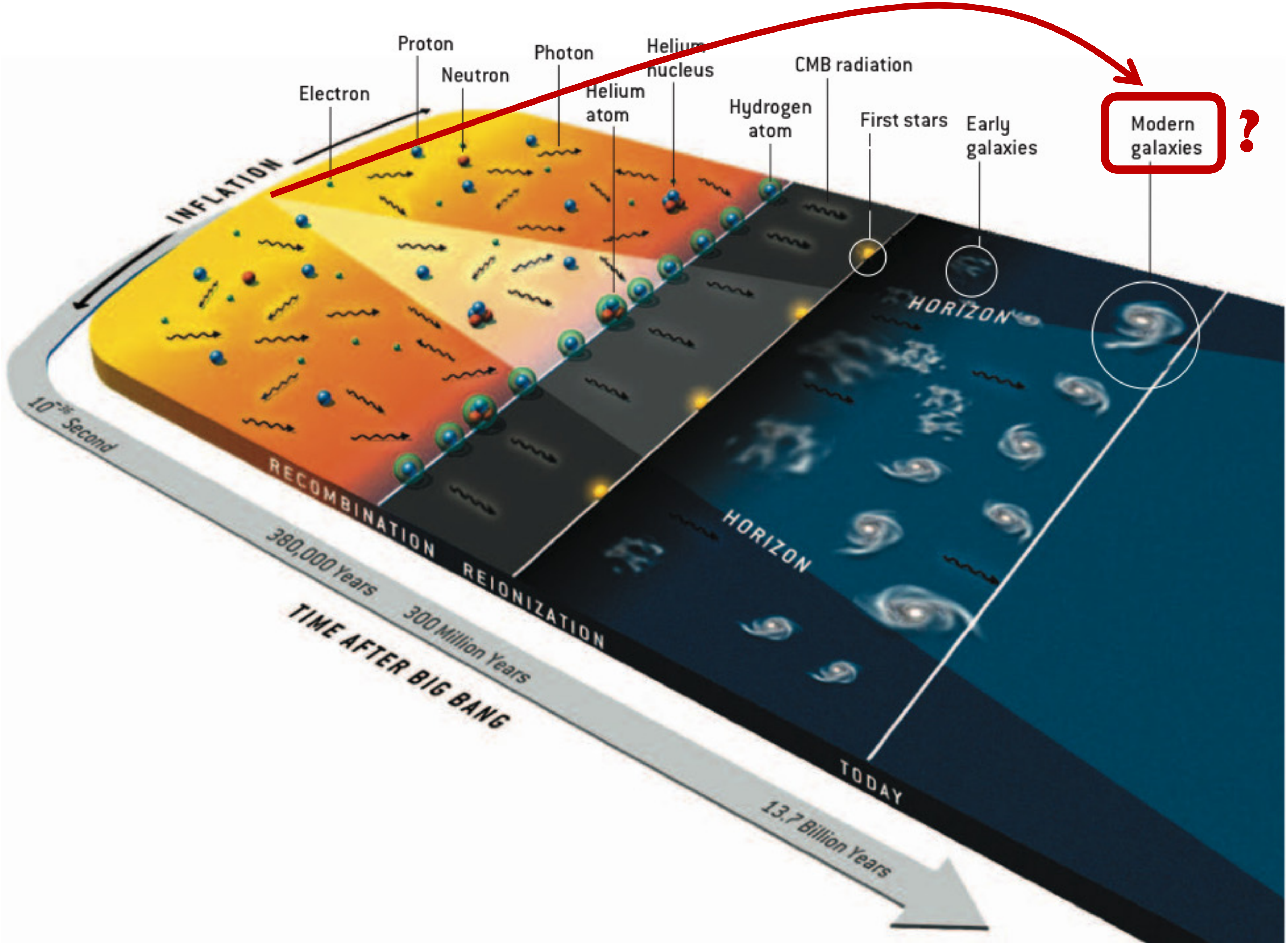
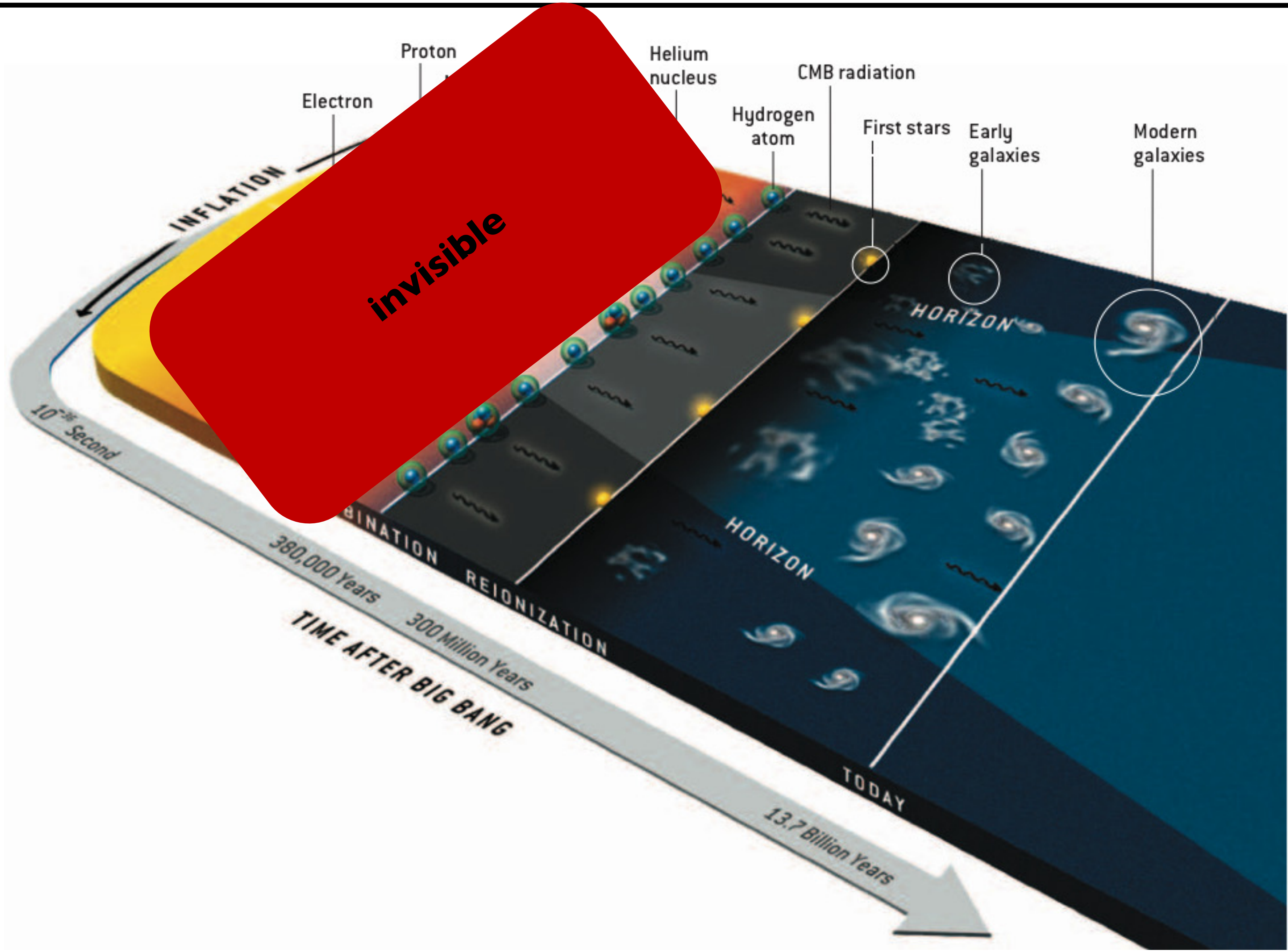

Proton
Photon
Helium nucleus
Neutron
Electron
Helium atom
CMB radiation
Hydrogen atom
First stars
Early galaxies
Modern galaxies
INFLATION
HORIZON
HORIZON
RECOMBINATION
REIONIZATION
TODAY
10^{-35} Second
380,000 Years
300 Million Years
13.7 Billion Years
TIME AFTER BIG BANG

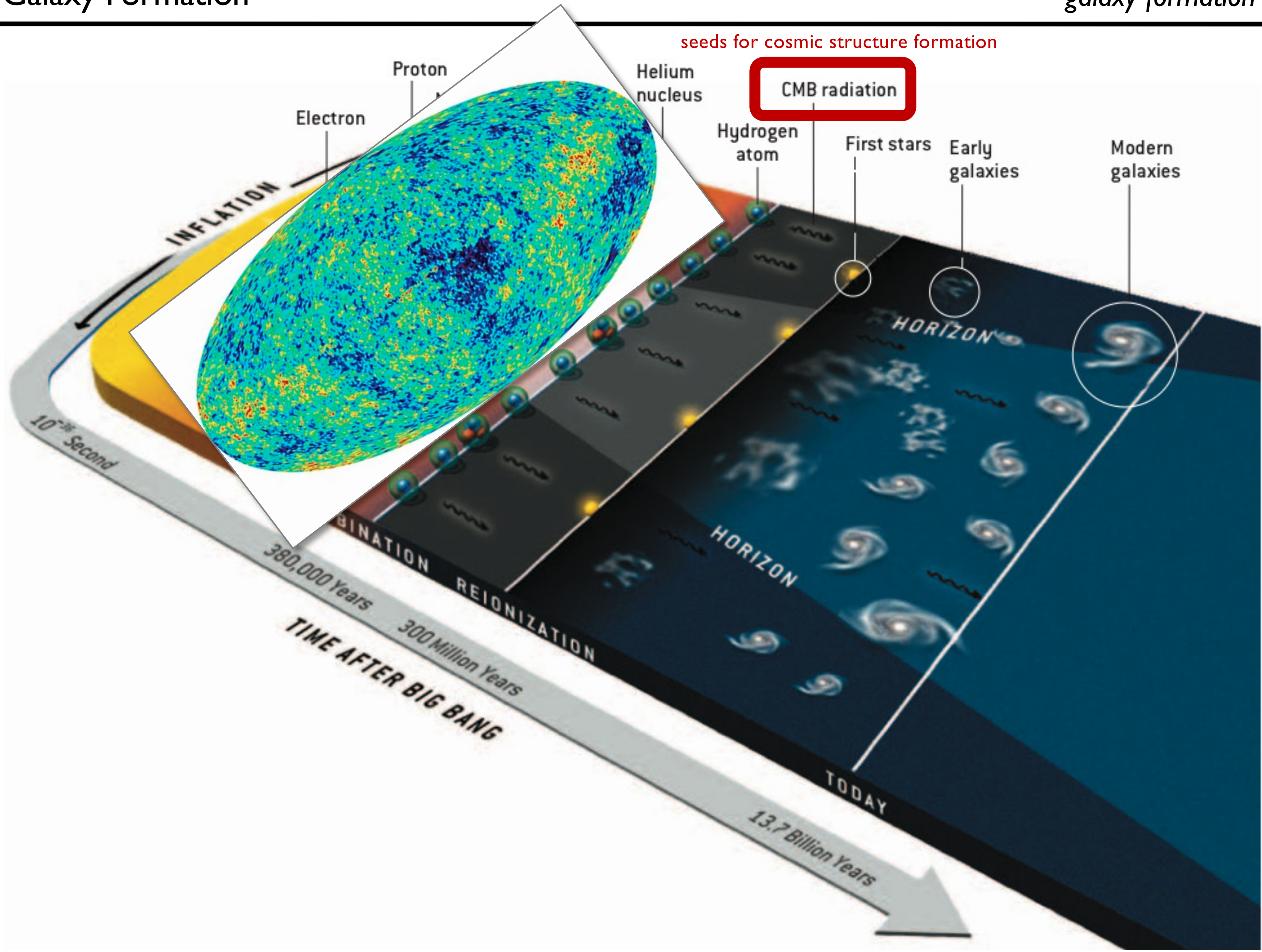
Galaxy Formation



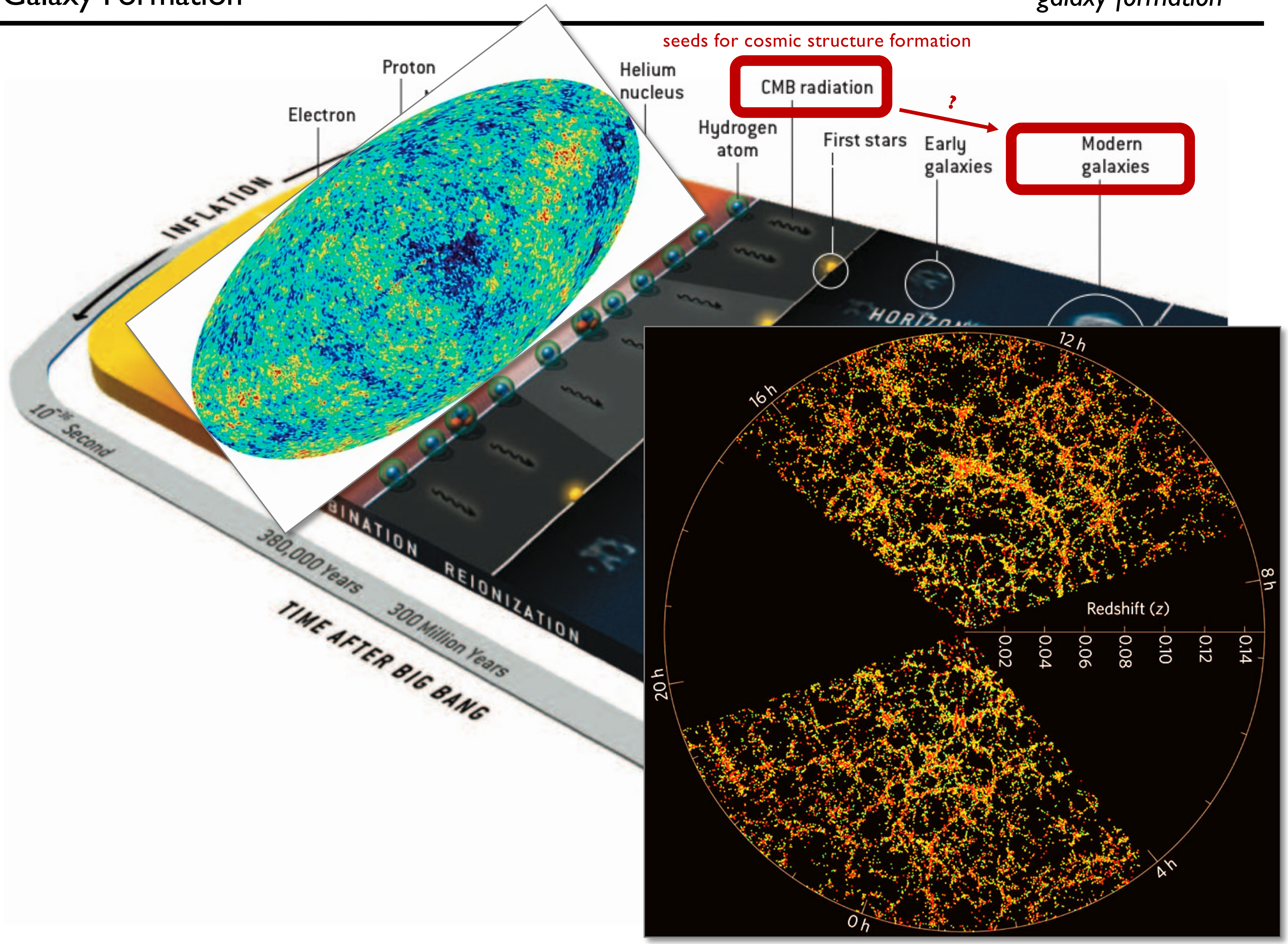
Galaxy Formation



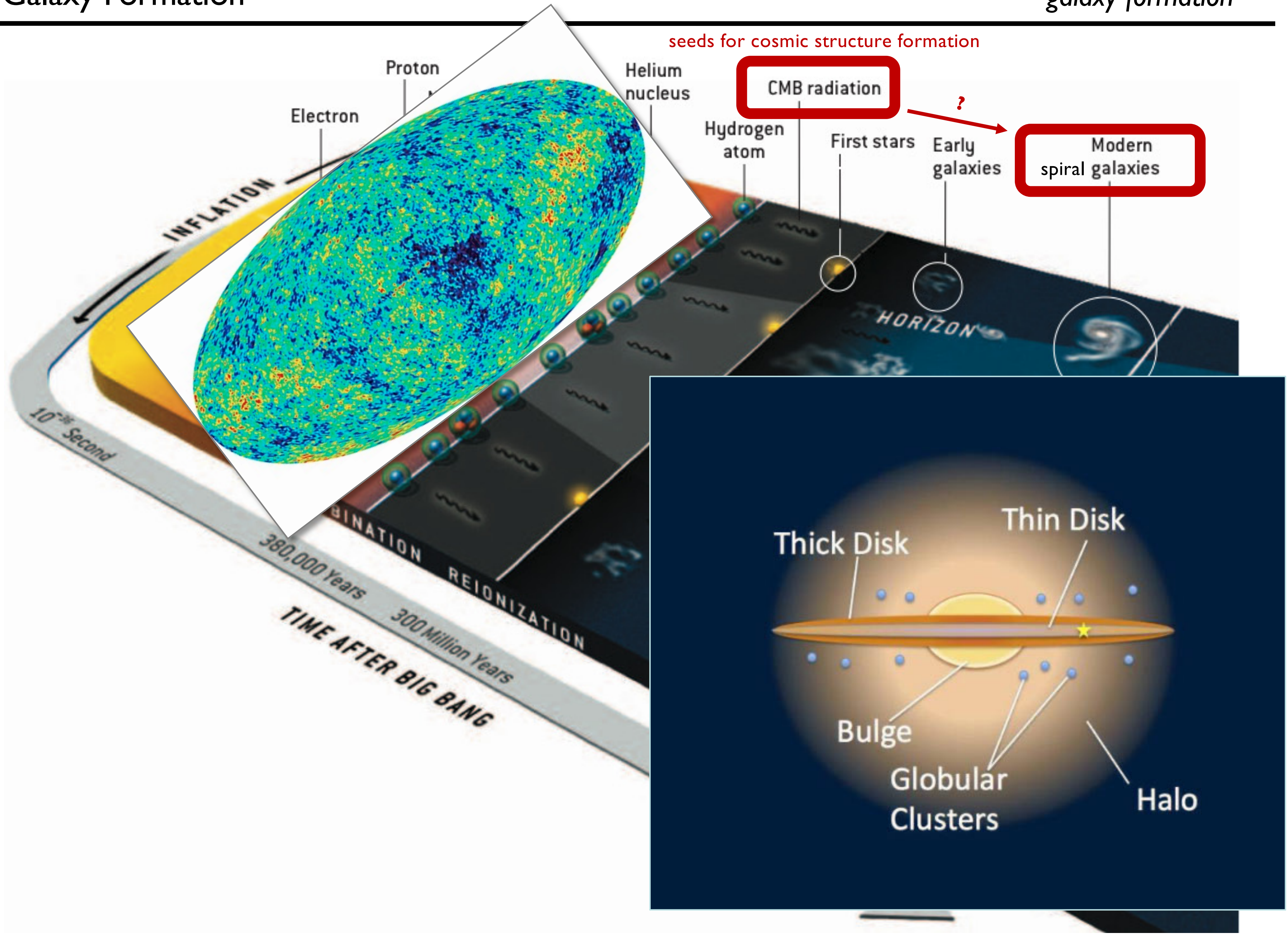
Galaxy Formation



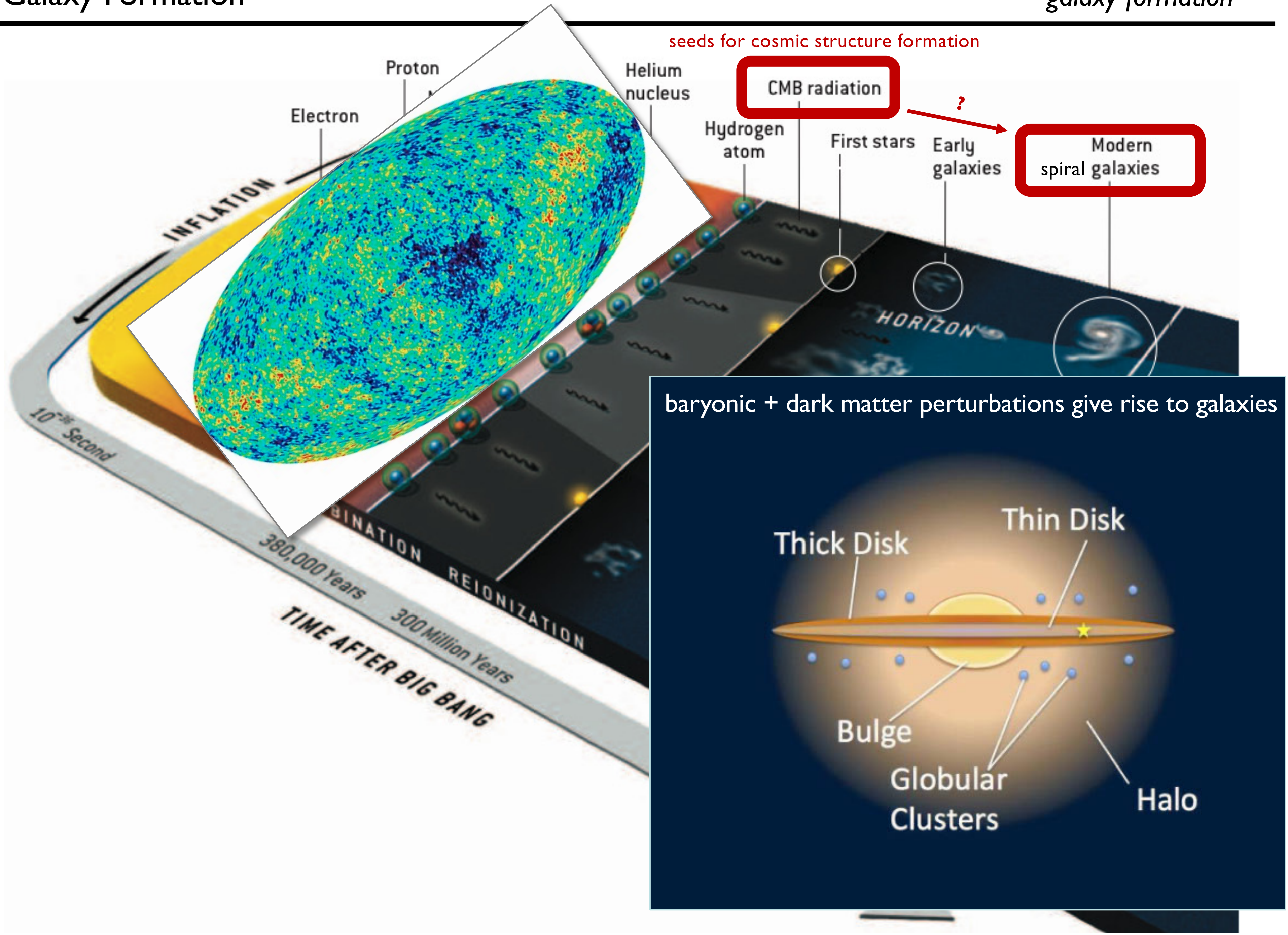
Galaxy Formation



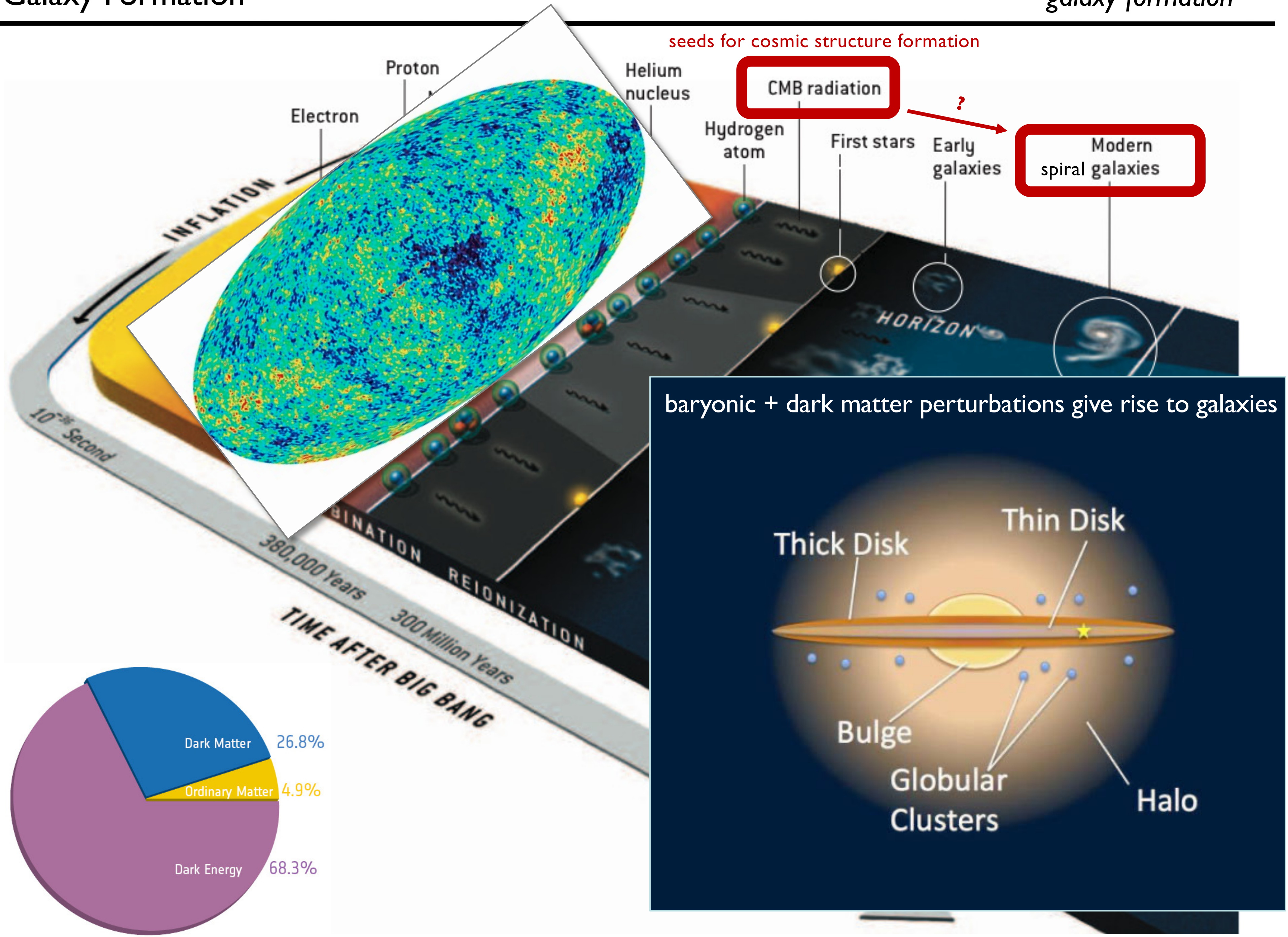
Galaxy Formation



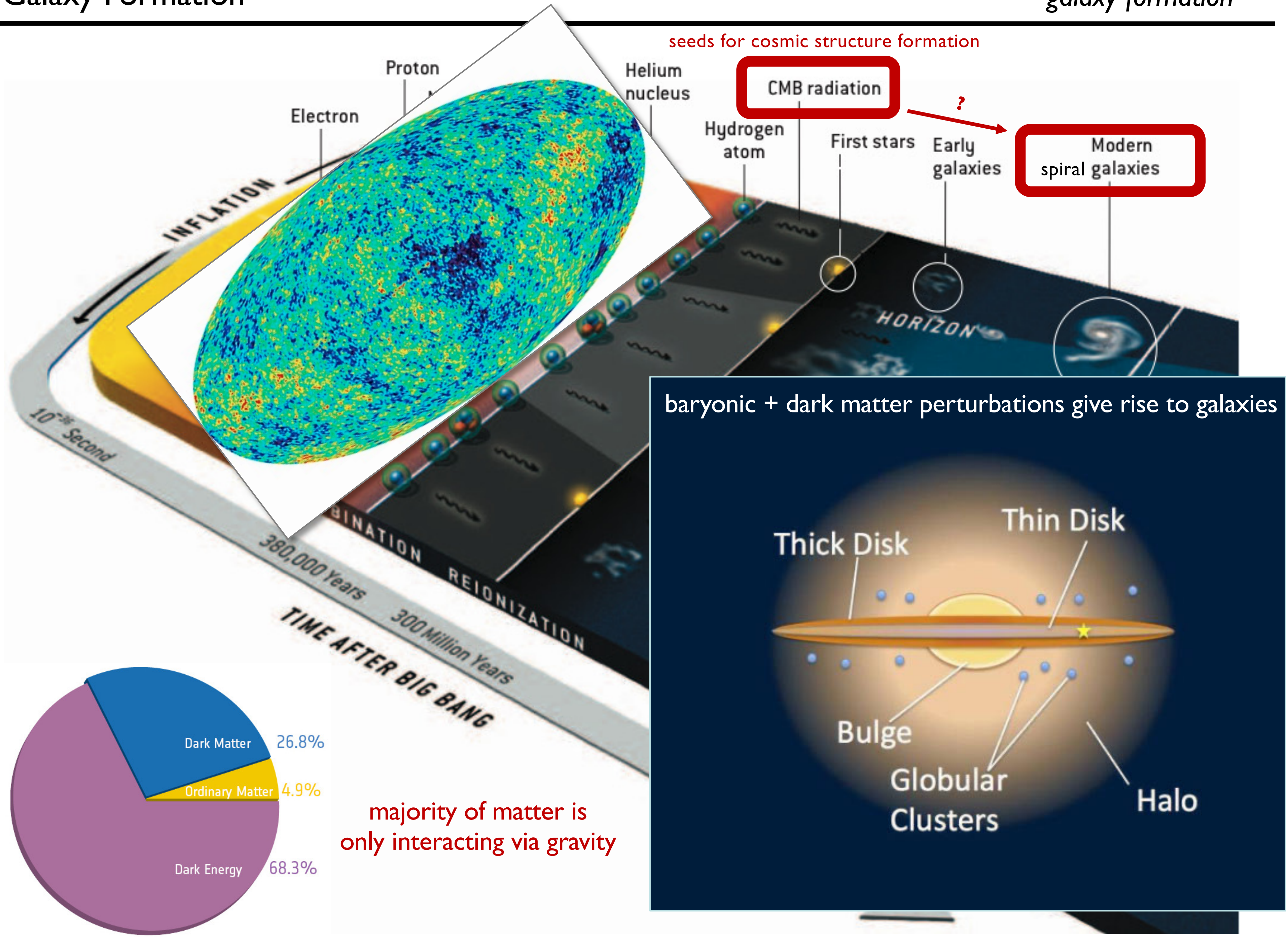
Galaxy Formation



Galaxy Formation

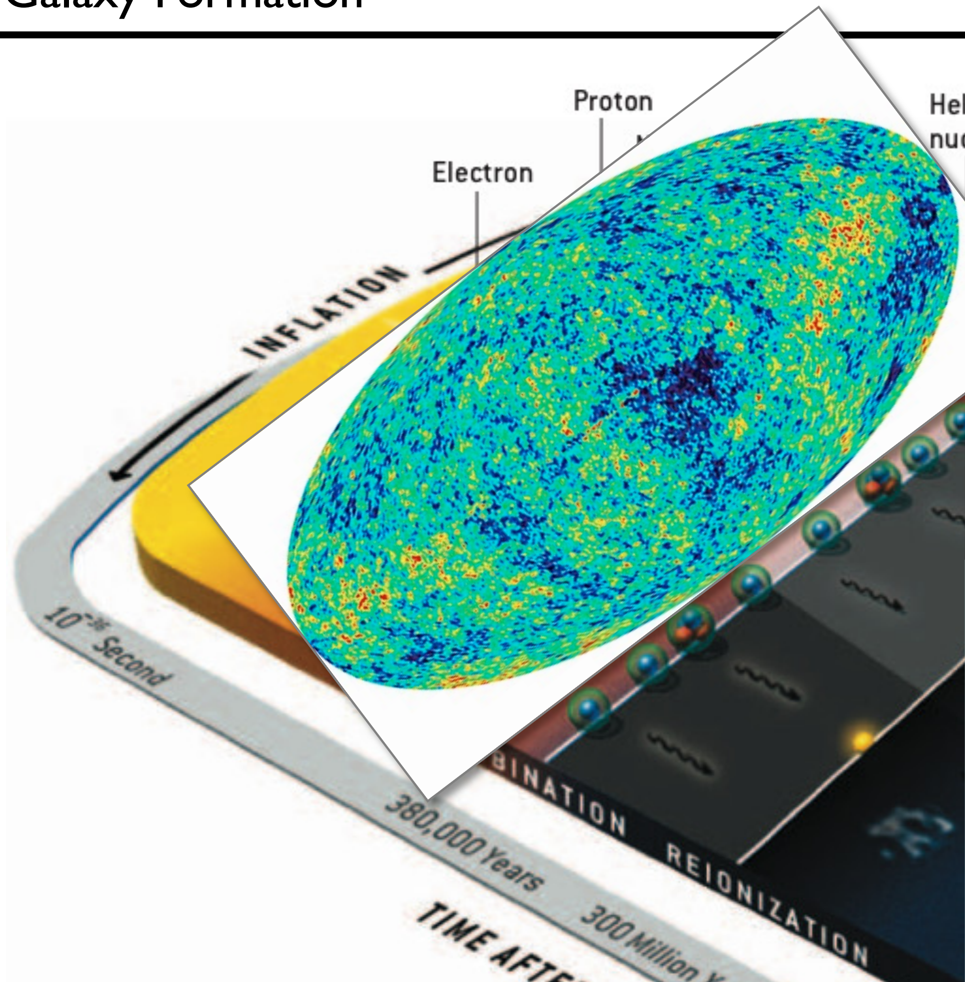


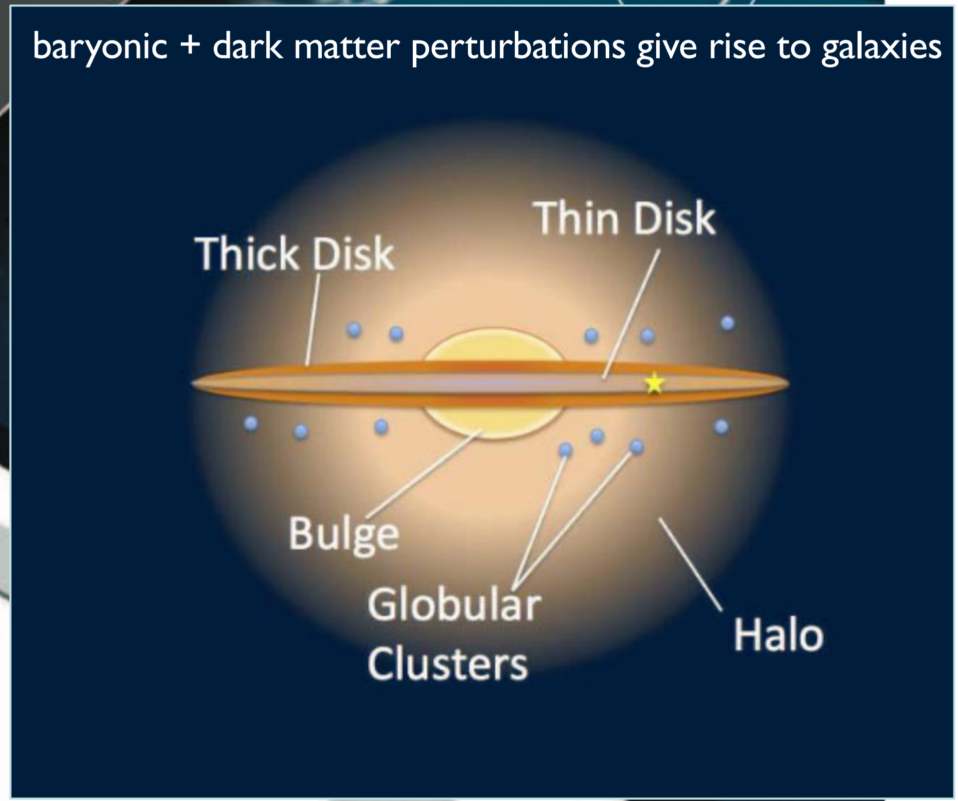
Galaxy Formation

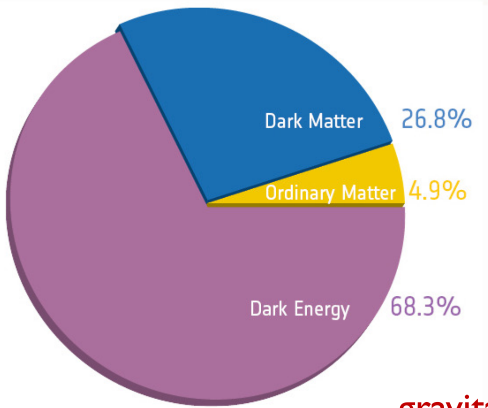


Galaxy Formation

seeds for cosmic structure formation

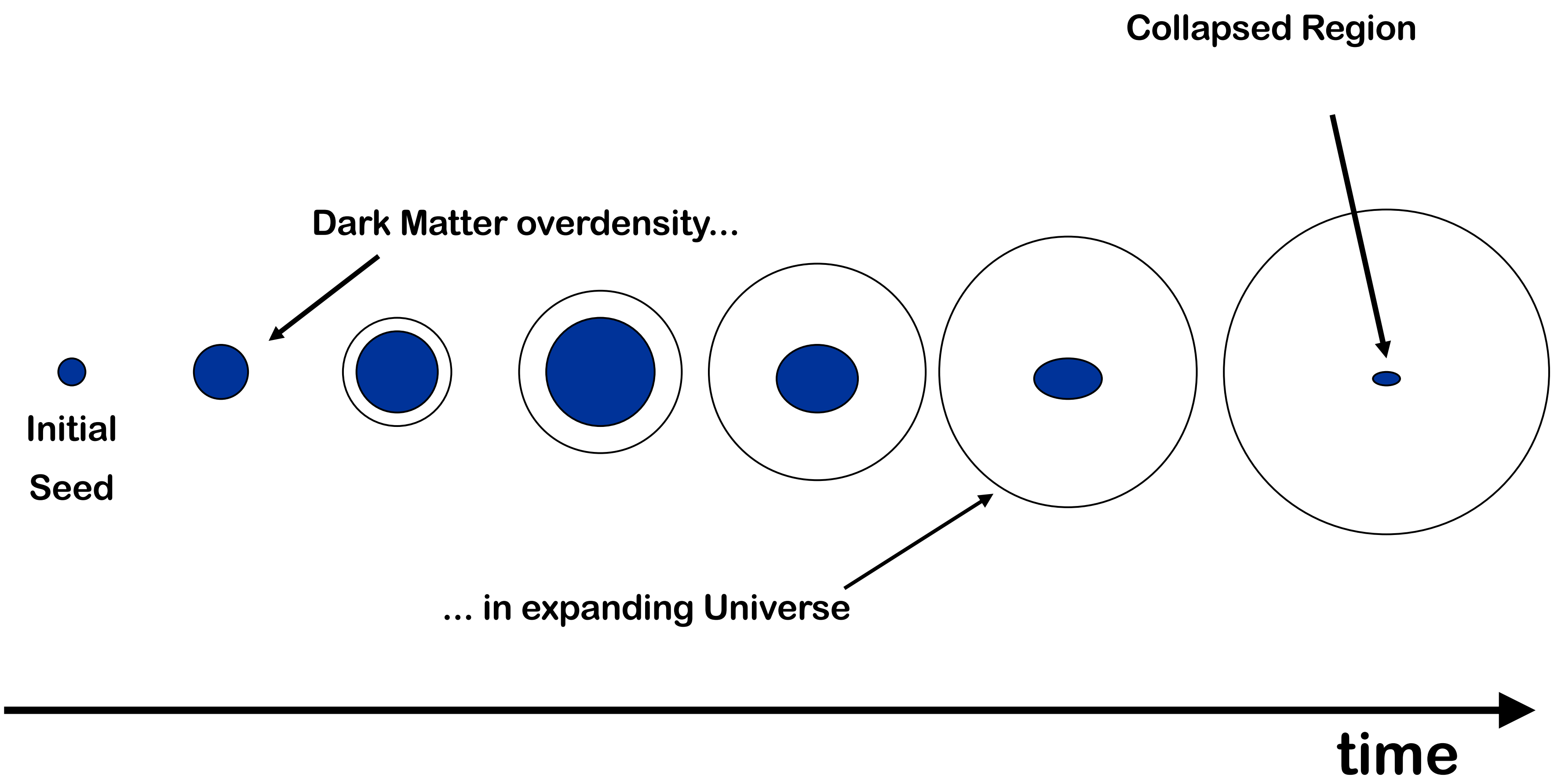


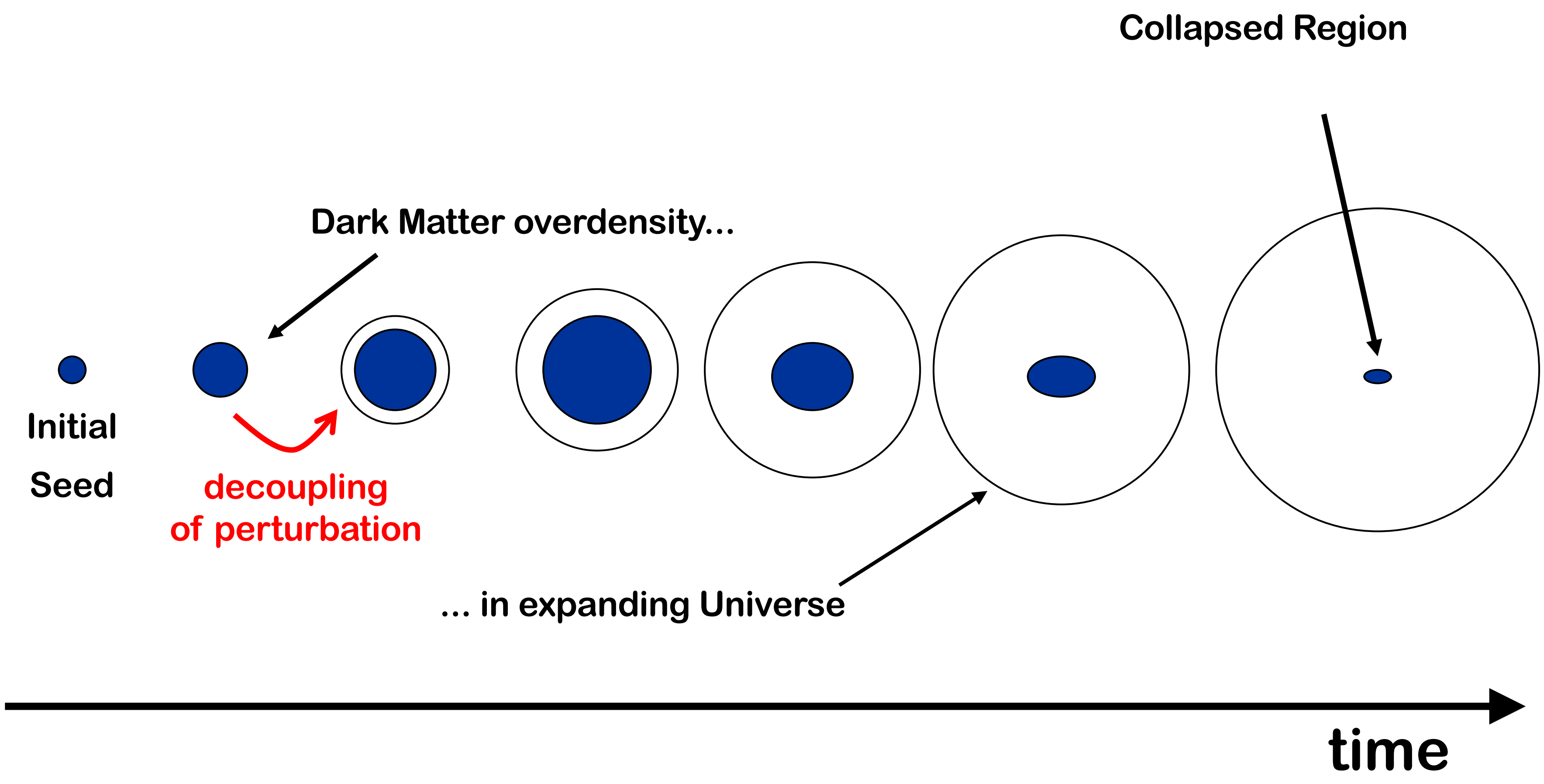




majority of matter is only interacting via gravity

gravitational collapse in expanding Universe →


Collapsed Region
Dark Matter overdensity...
Initial
Seed
... in expanding Universe
time


Collapsed Region
Dark Matter overdensity...
Initial
Seed
decoupling
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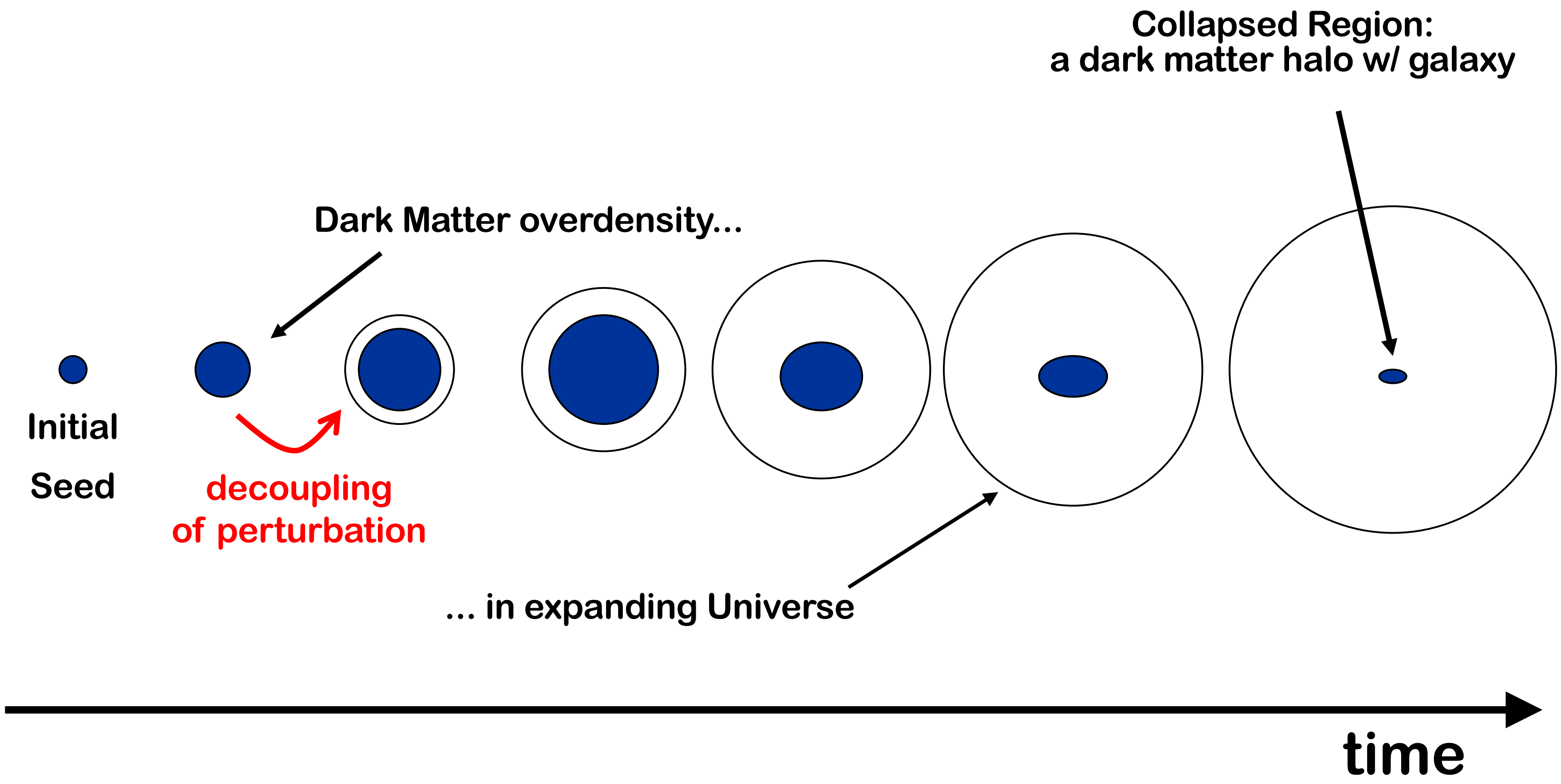
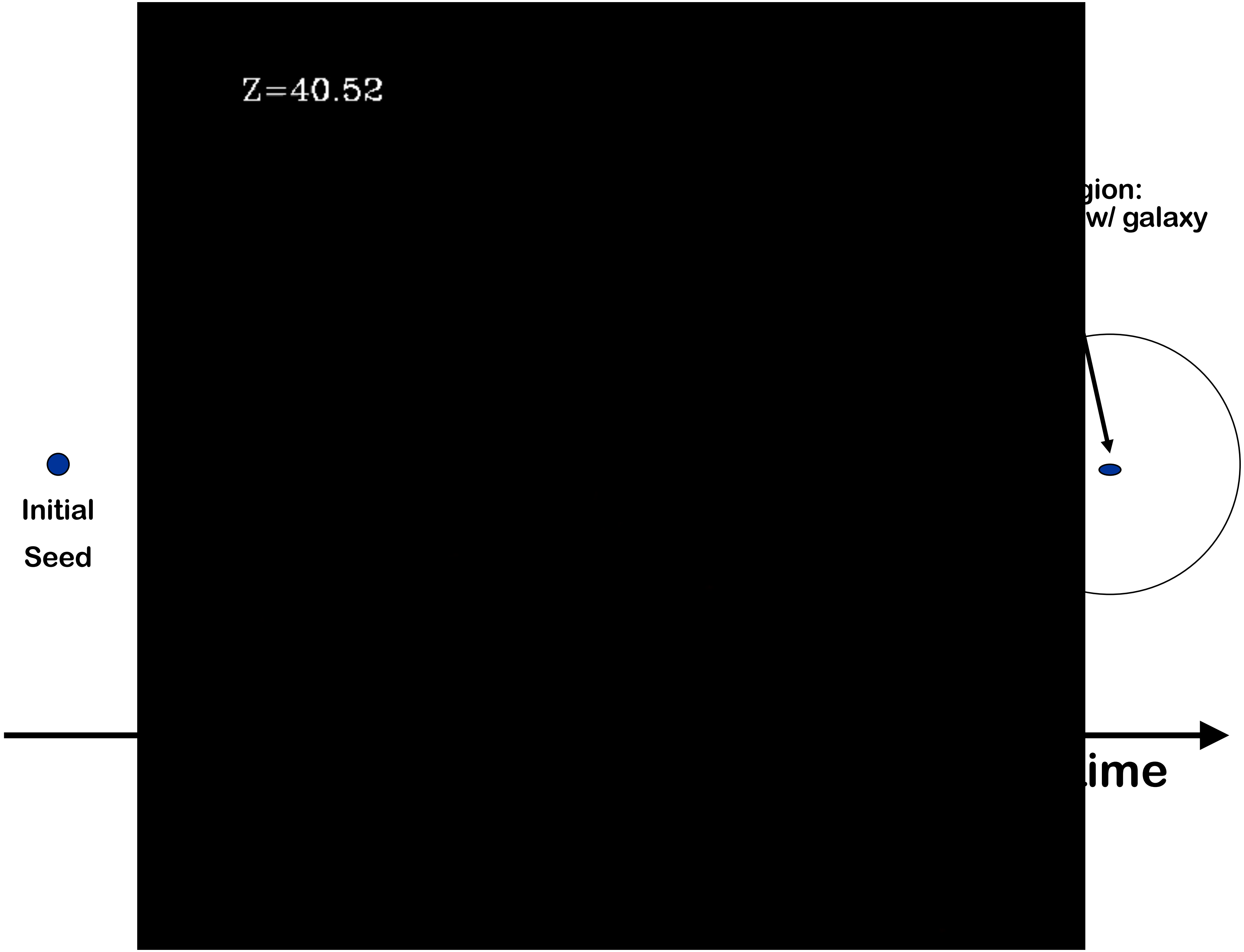
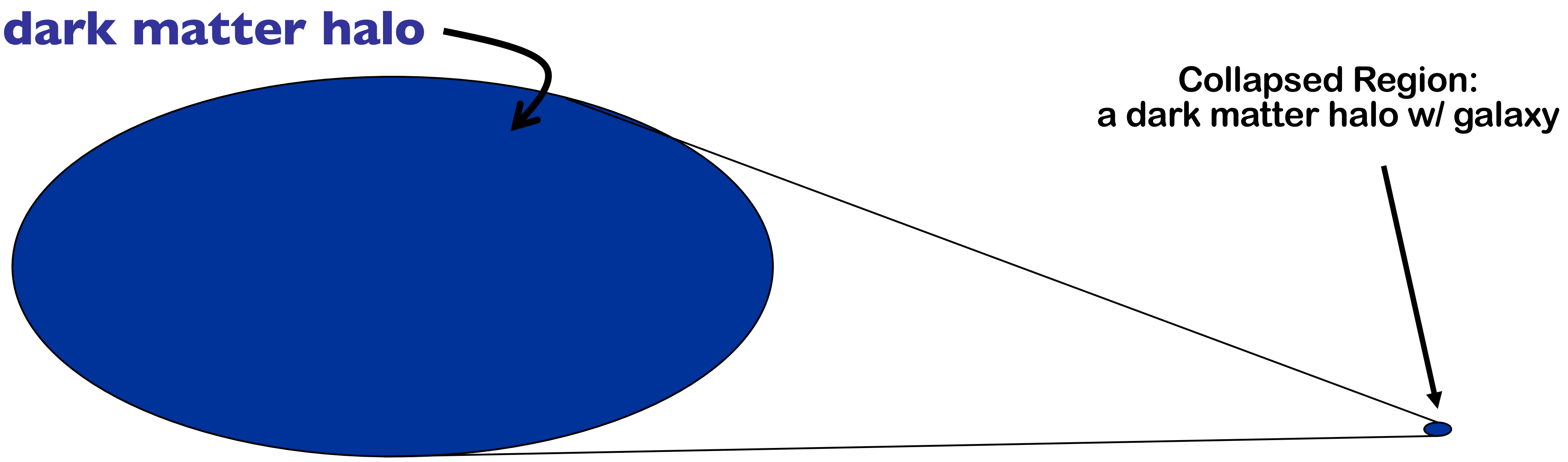
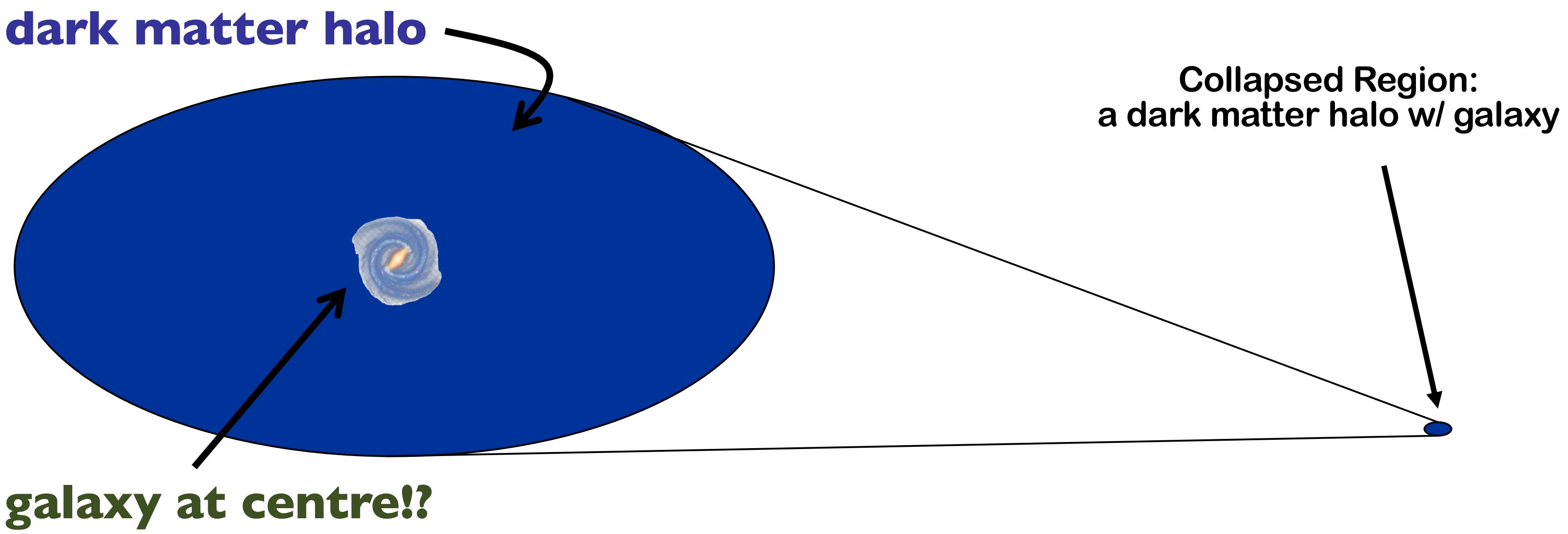
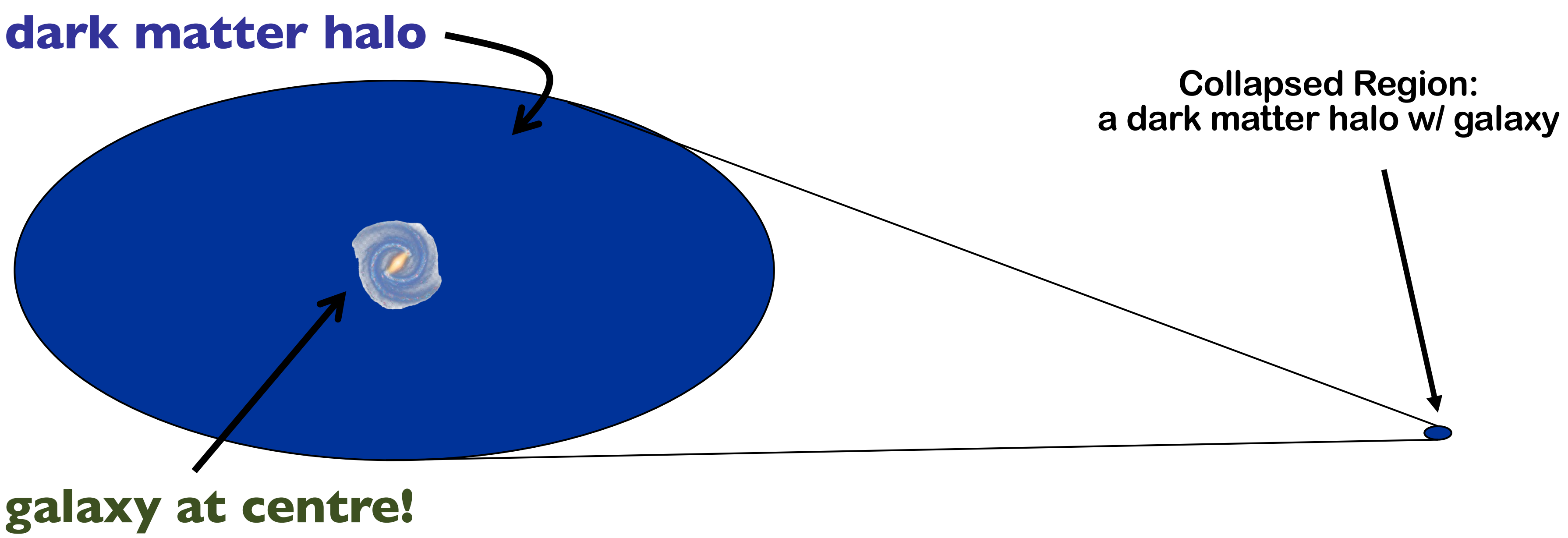

Collapsed Region:
a dark matter halo w/ galaxy
Dark Matter overdensity...
Initial
Seed
decoupling
of perturbation
... in expanding Universe
time


Z=40.52
w/ galaxy
Initial
Seed

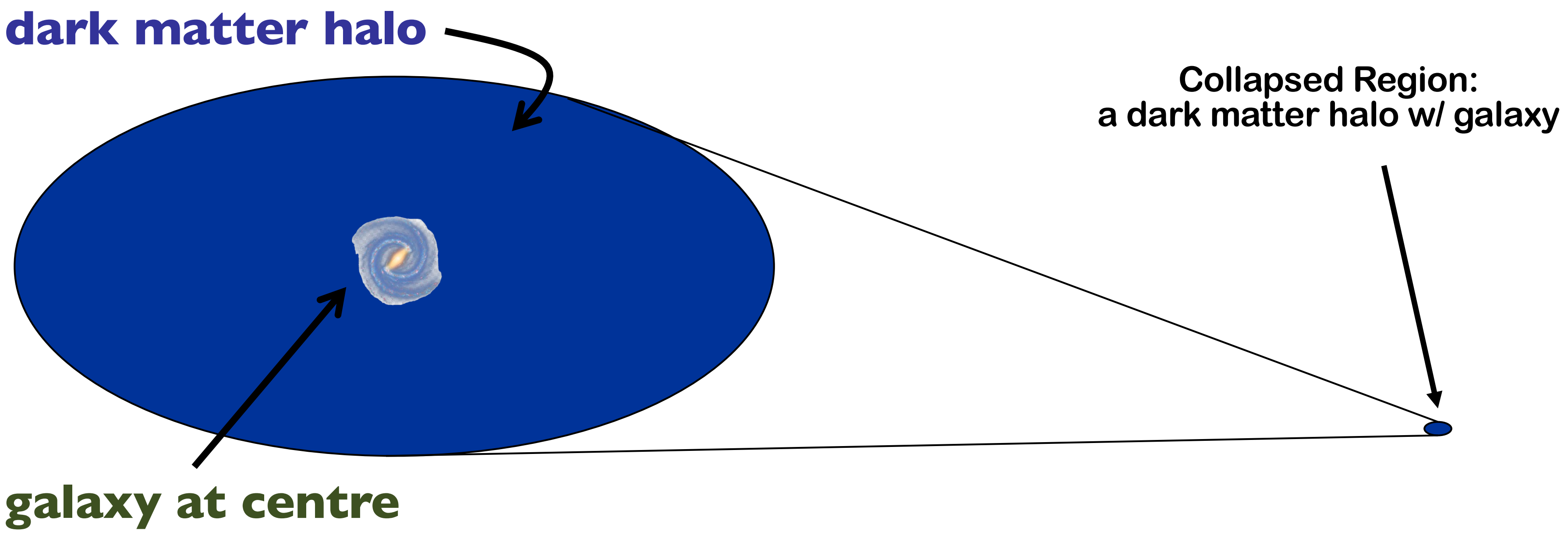

dark matter halo
Collapsed Region:
a dark matter halo w/ galaxy


dark matter halo
Collapsed Region:
a dark matter halo w/ galaxy
galaxy at centre!?



biased galaxy formation:

- a galaxy forms at the centre of a dark matter halo
- the properties of the galaxy are determined by the halo's history



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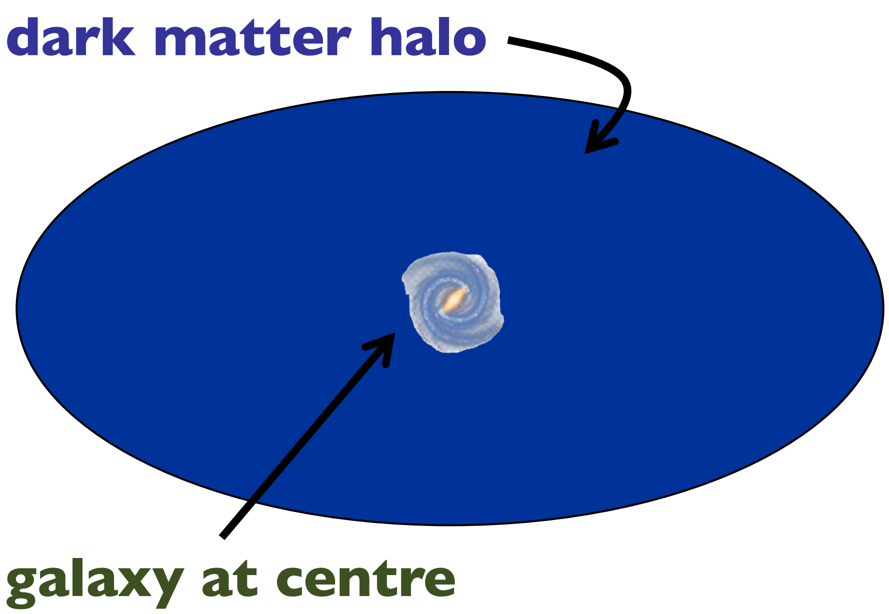
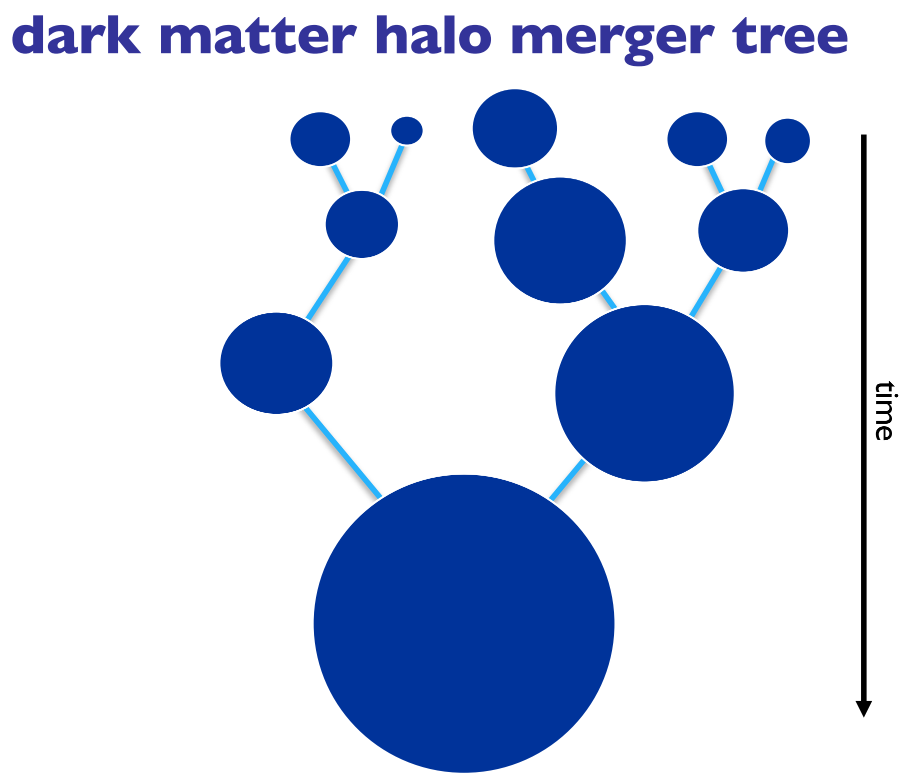
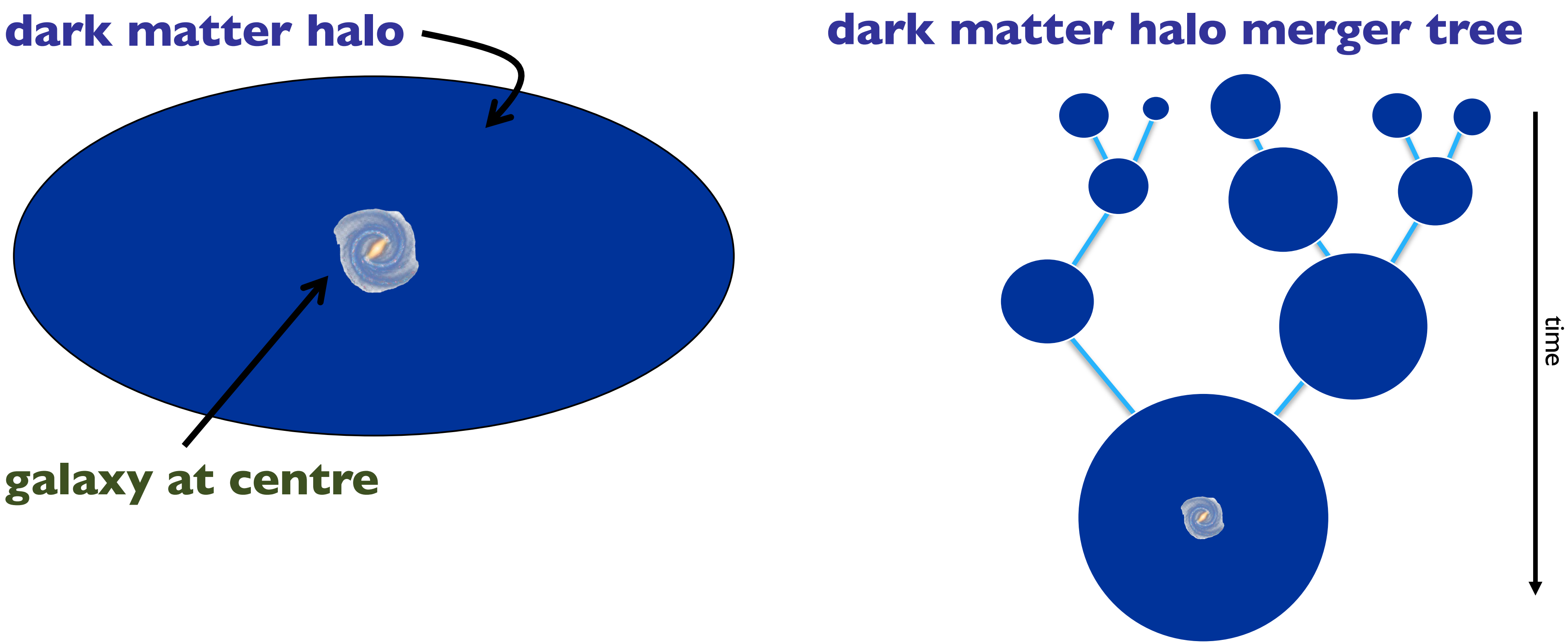
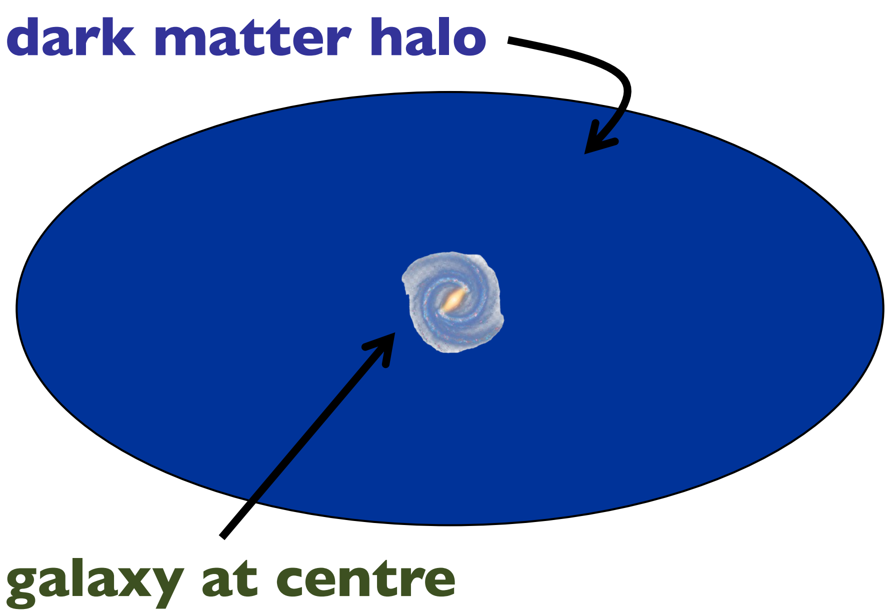
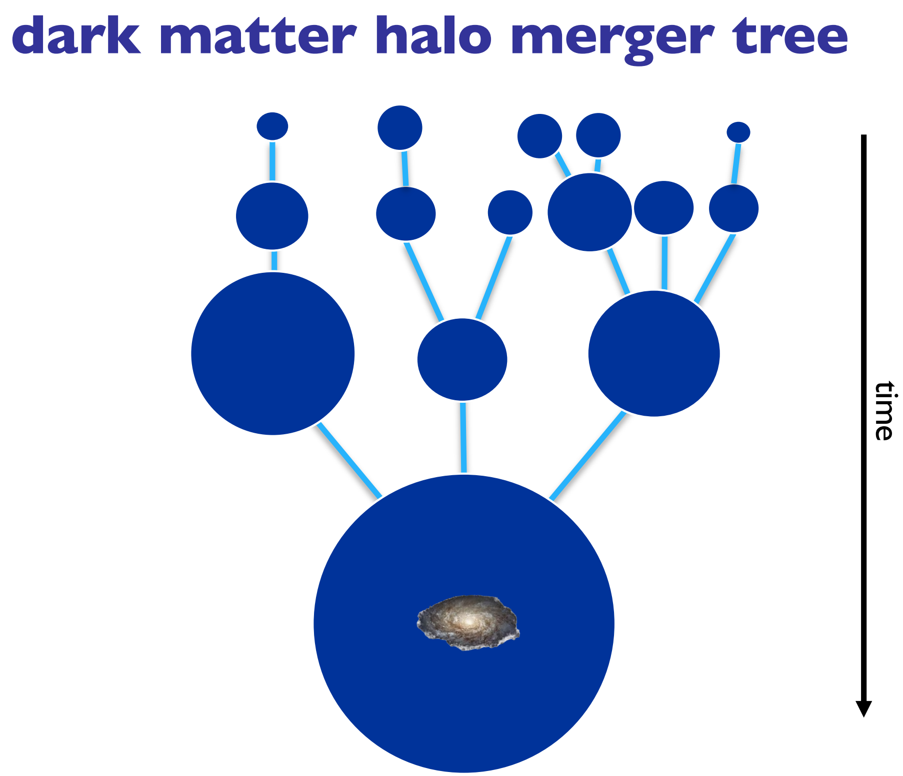

dark matter halo
galaxy at centre


dark matter halo merger tree
time


dark matter halo
galaxy at centre
dark matter halo merger tree
time

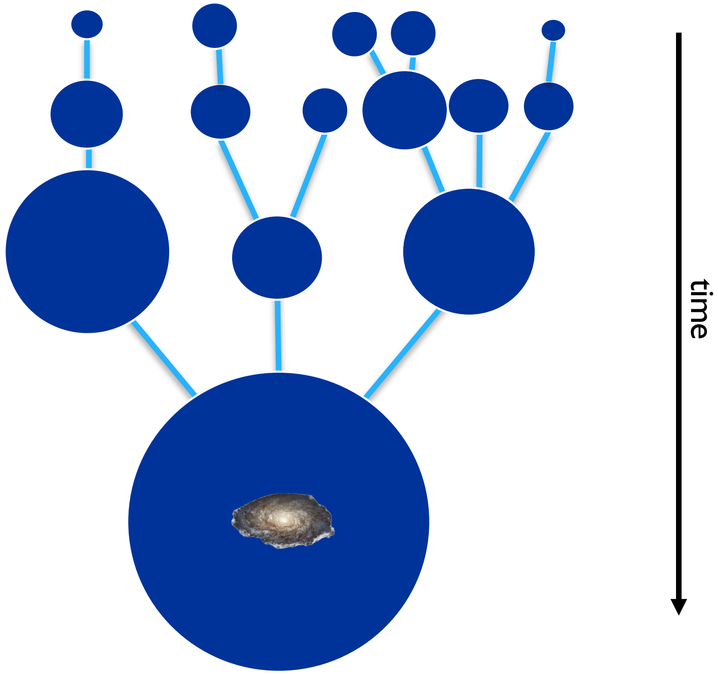

dark matter halo
galaxy at centre


dark matter halo merger tree
time

galaxy formation depends on...

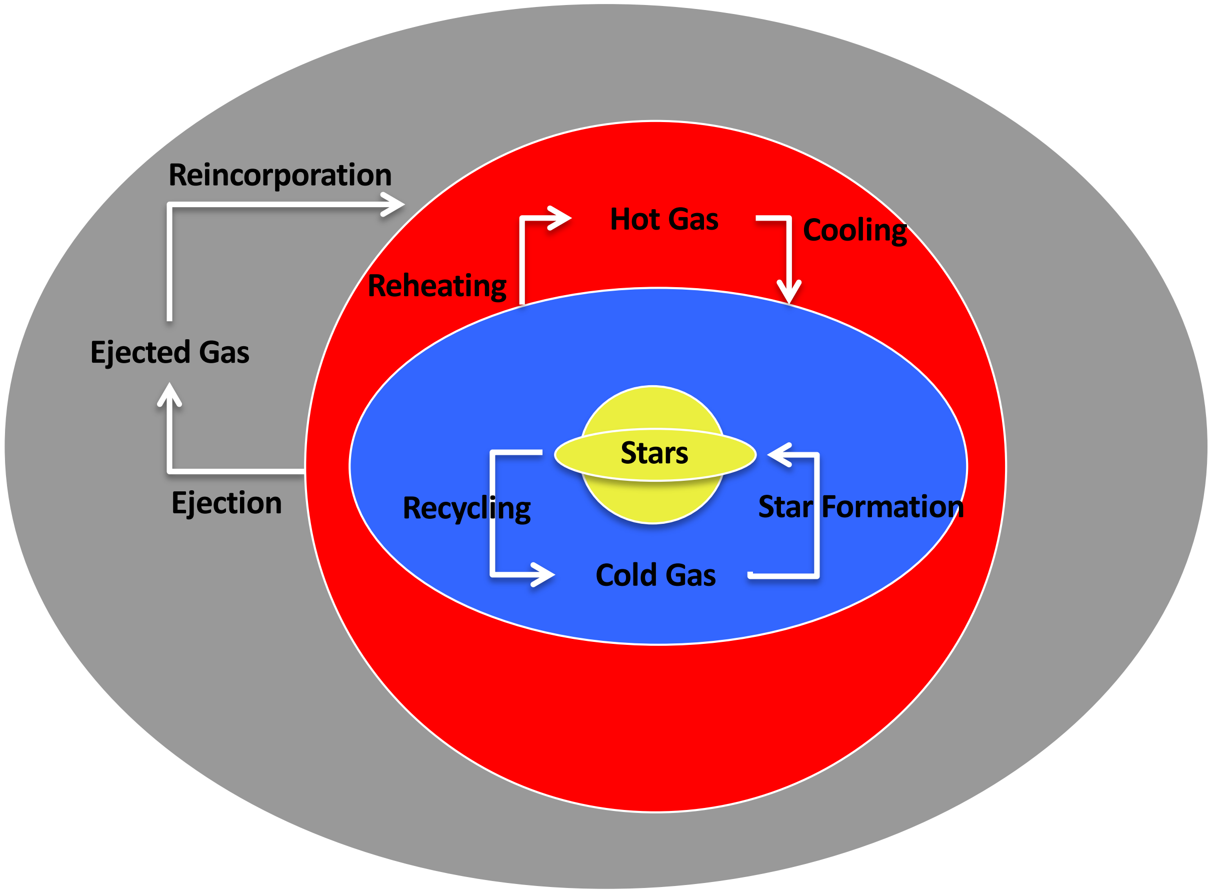
- halo formation history

dark matter halo merger tree

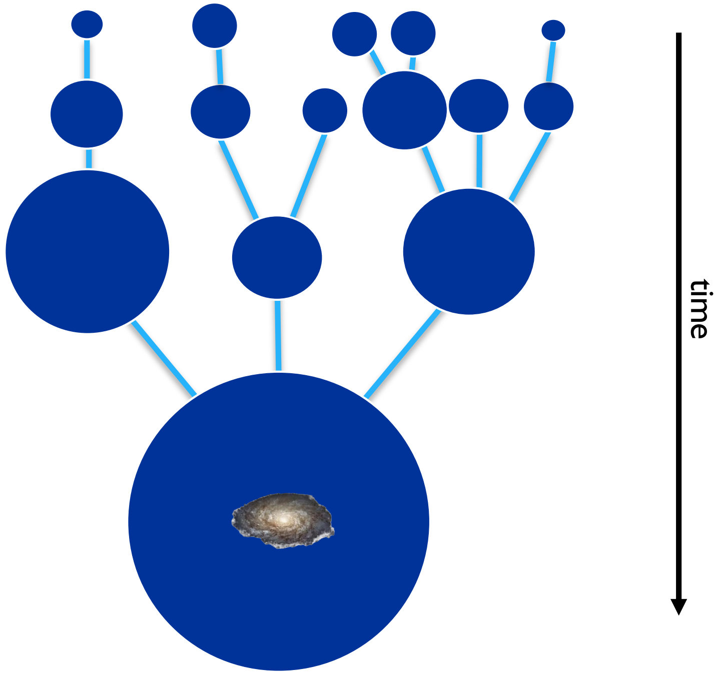


galaxy formation depends on...

- halo formation history
- baryonic physics

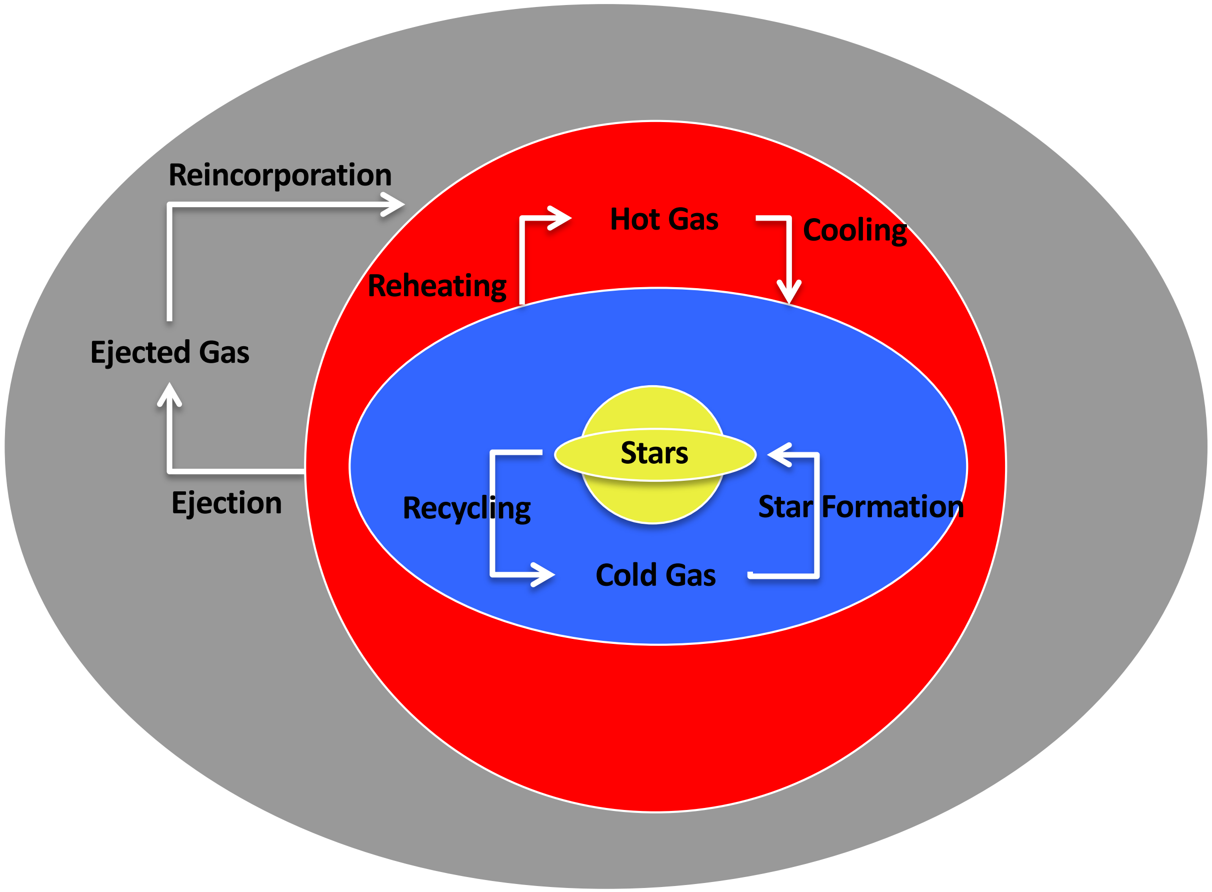


dark matter halo merger tree

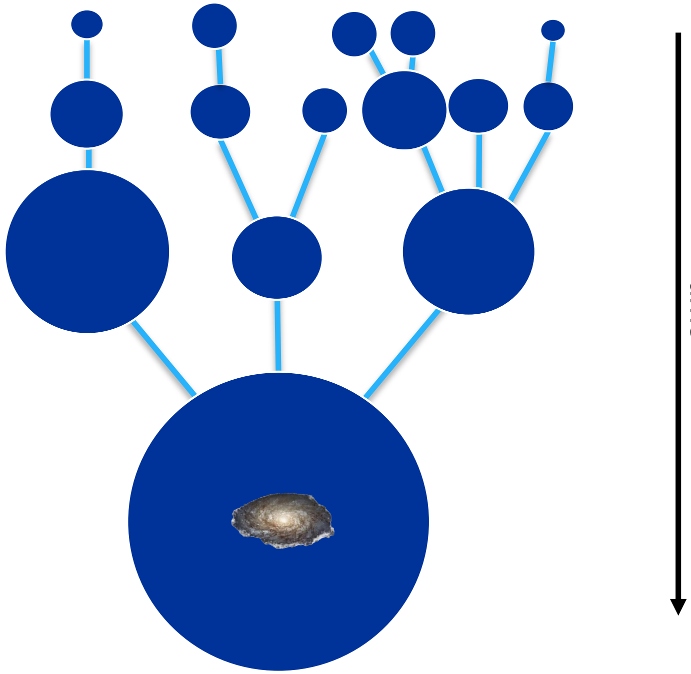


galaxy formation depends on...

- halo formation history
- baryonic physics
- radiative processes



dark matter halo merger tree



galaxy formation depends on...

- halo formation history
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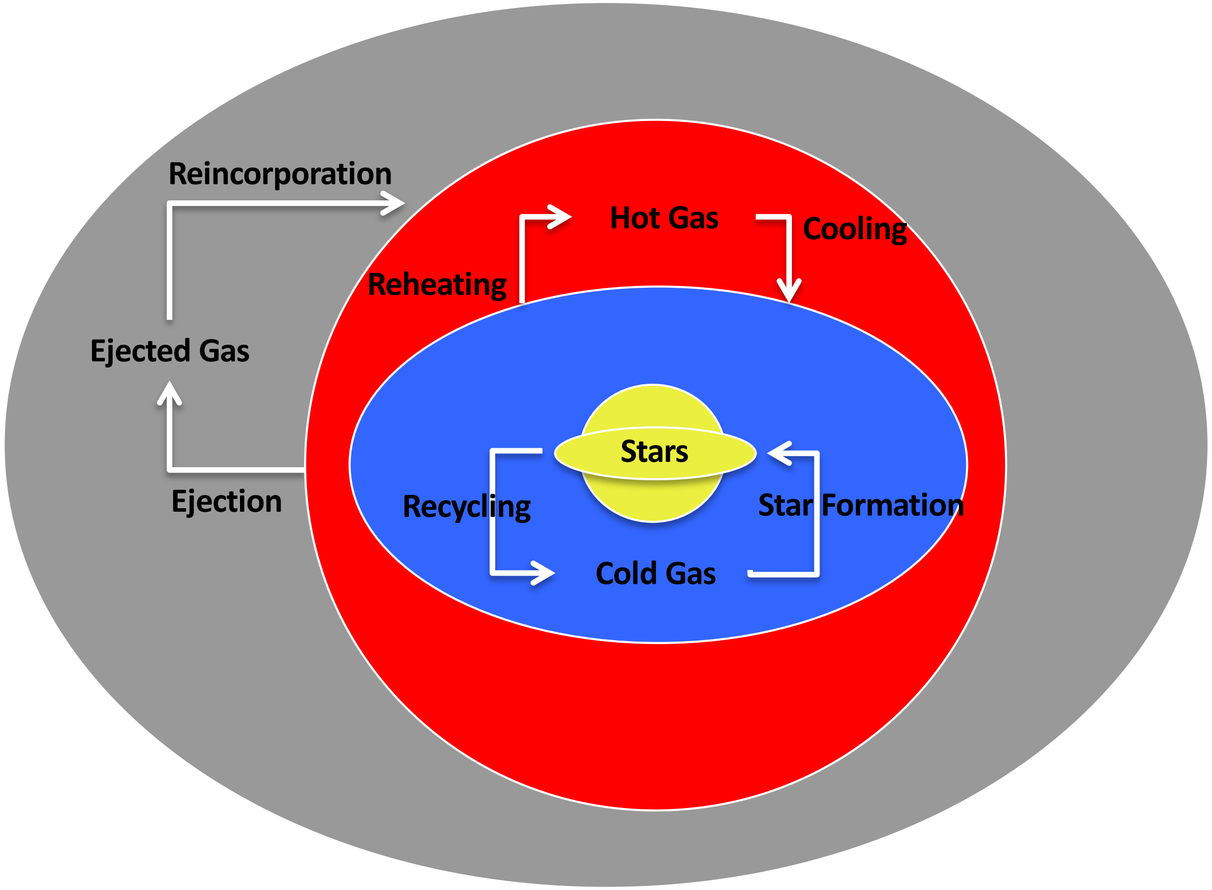
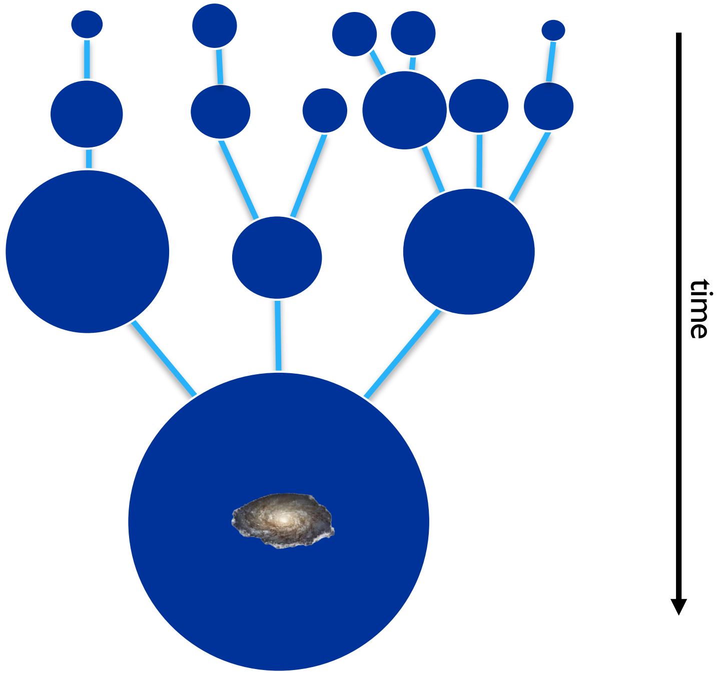
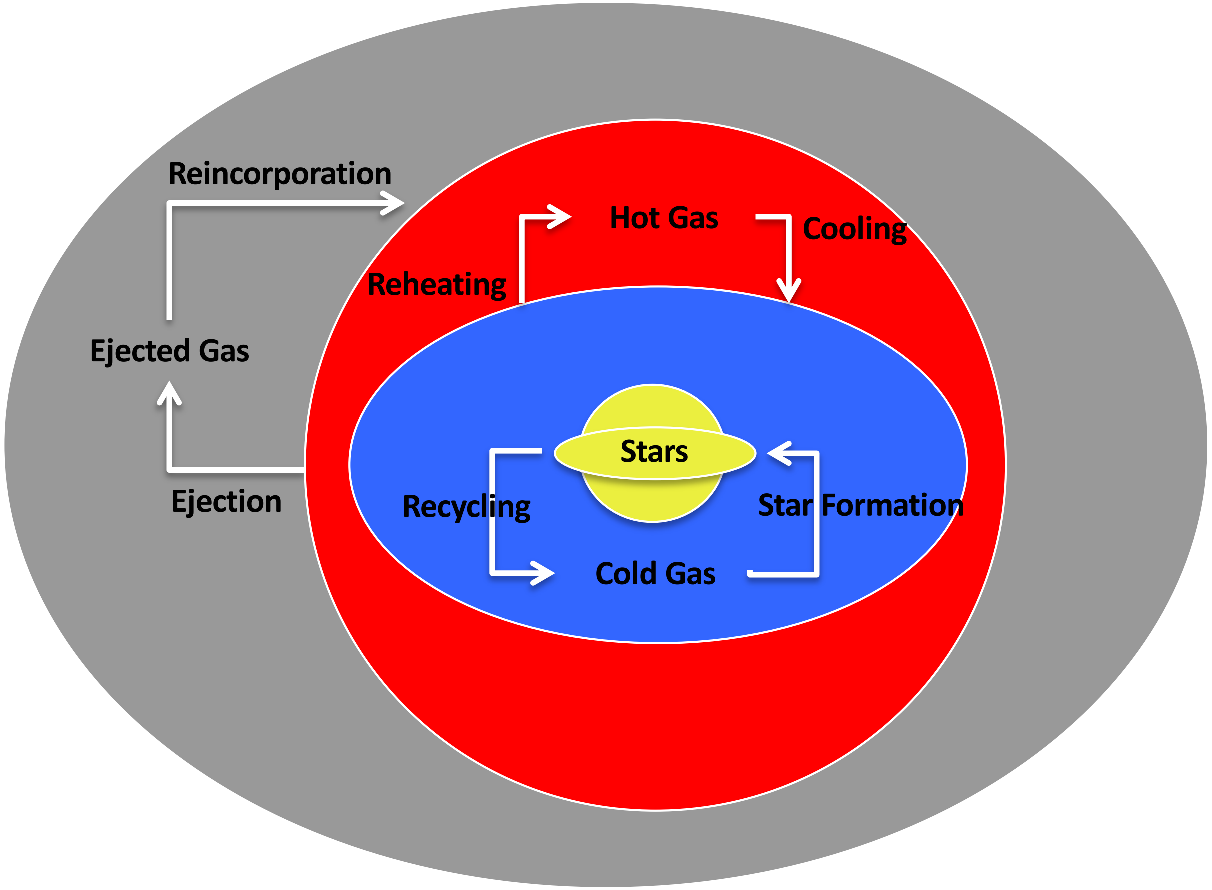


dark matter halo merger tree

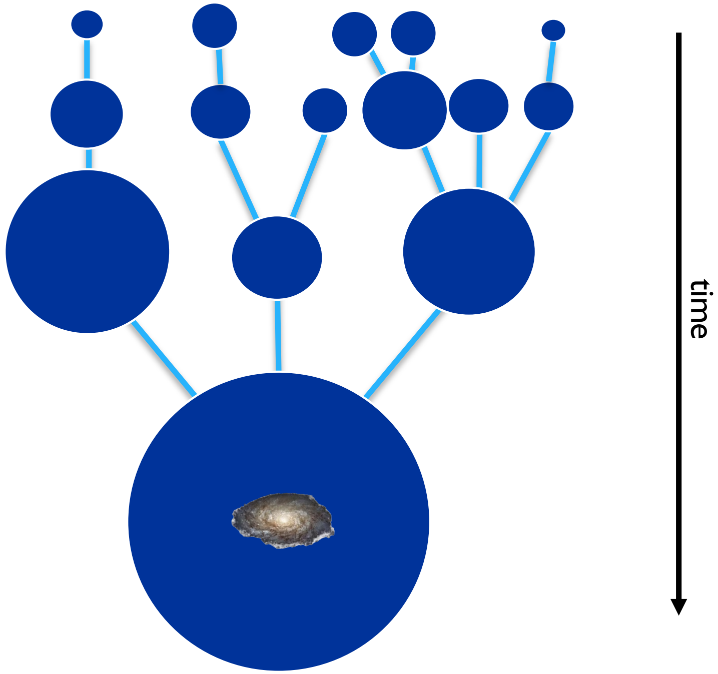


galaxy formation depends on...

- **halo** formation history
- baryonic physics
- radiative processes

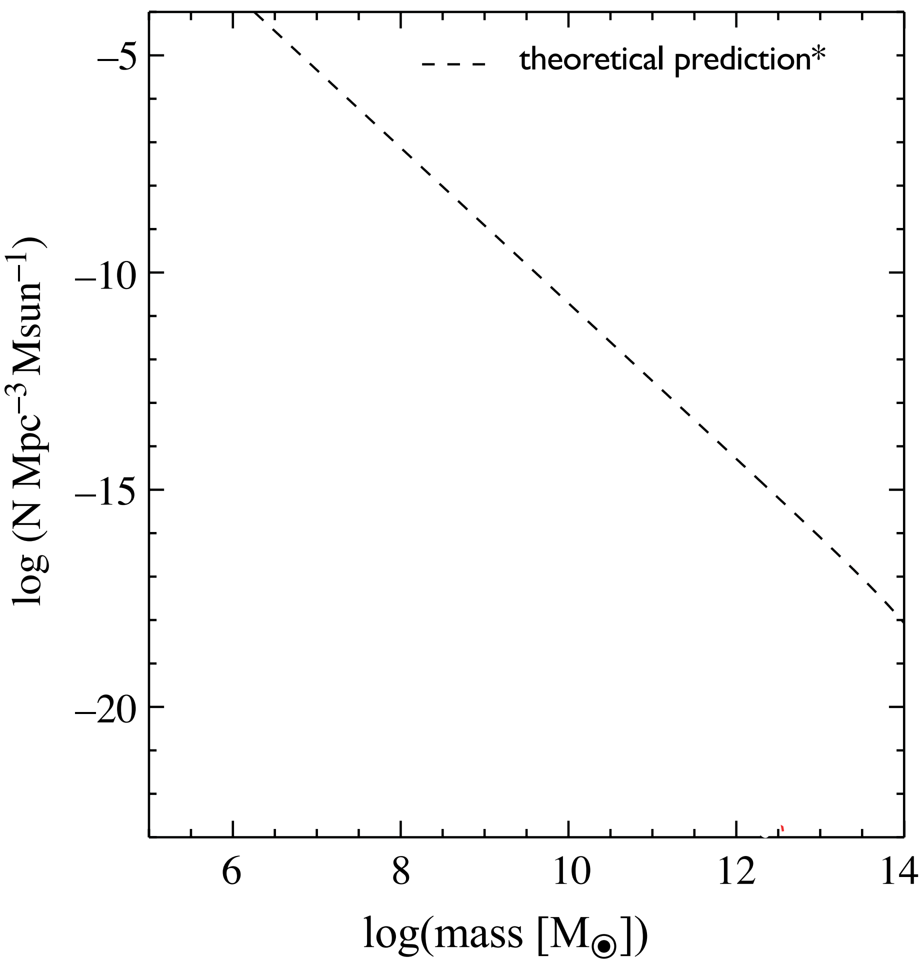


dark matter halo merger tree

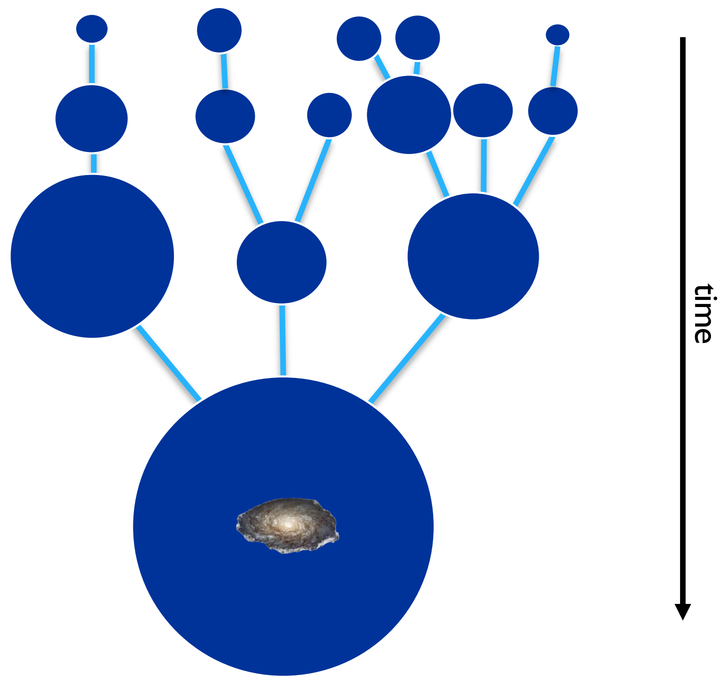


simplest halo property is mass →

biased galaxy formation

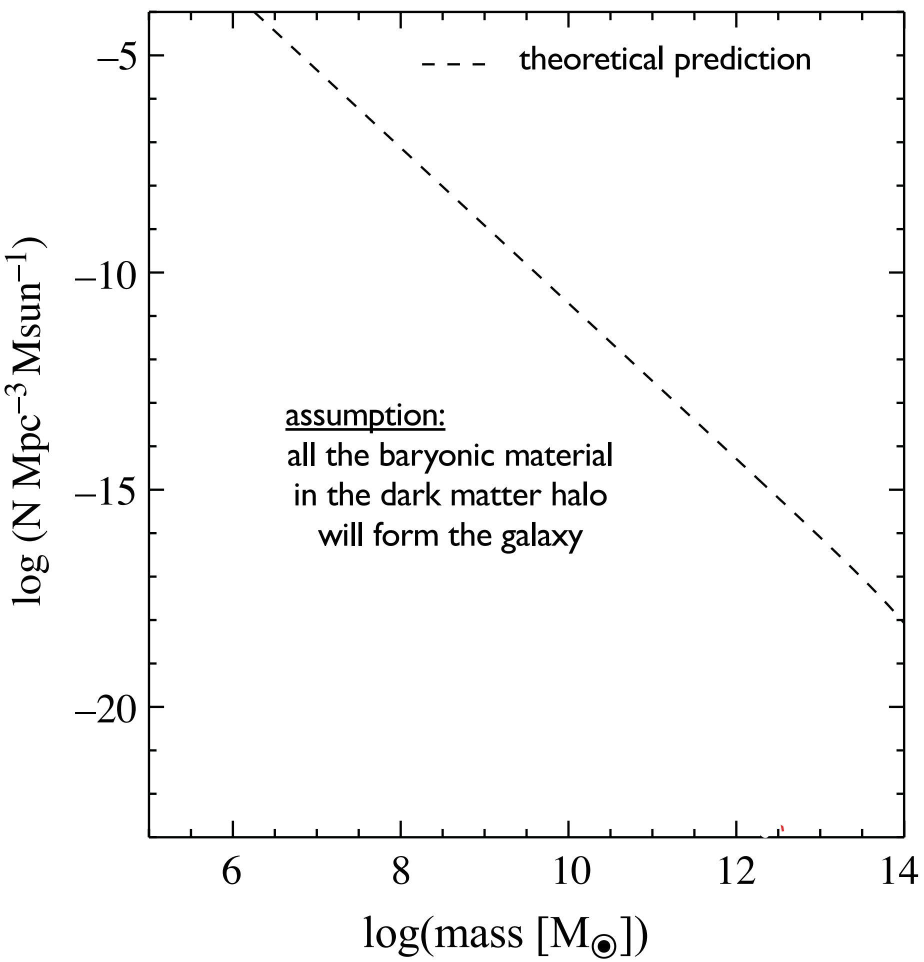


dark matter halo merger tree

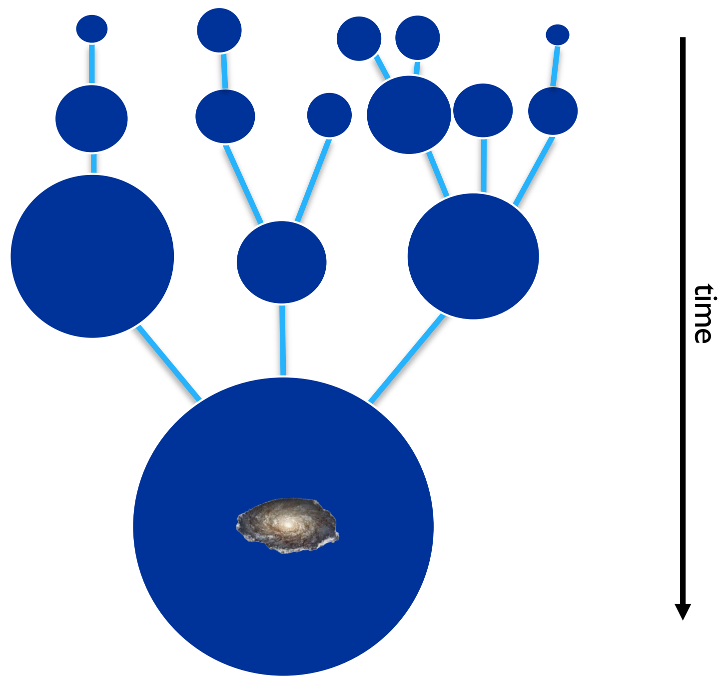


*number of dark matter haloes with a given mass: $\frac{dn}{dM}dM = \sqrt{\frac{2}{\pi}}\frac{\bar{\rho}}{M}\frac{\delta_c}{\sigma_M}\left|\frac{d\ln\sigma_M}{d\ln M}\right|\exp\left(\frac{-\delta_c^2}{2\sigma_M^2}\right)\frac{dM}{M}$ (see Cosmology lecture)

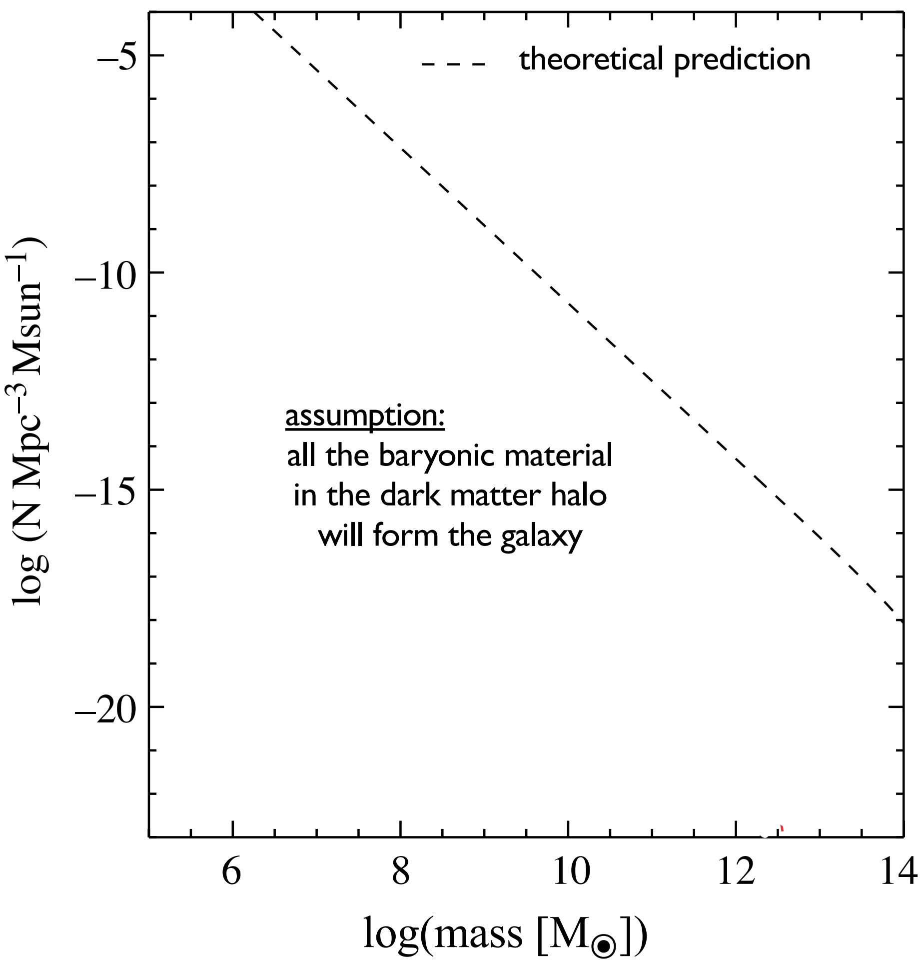
biased galaxy formation

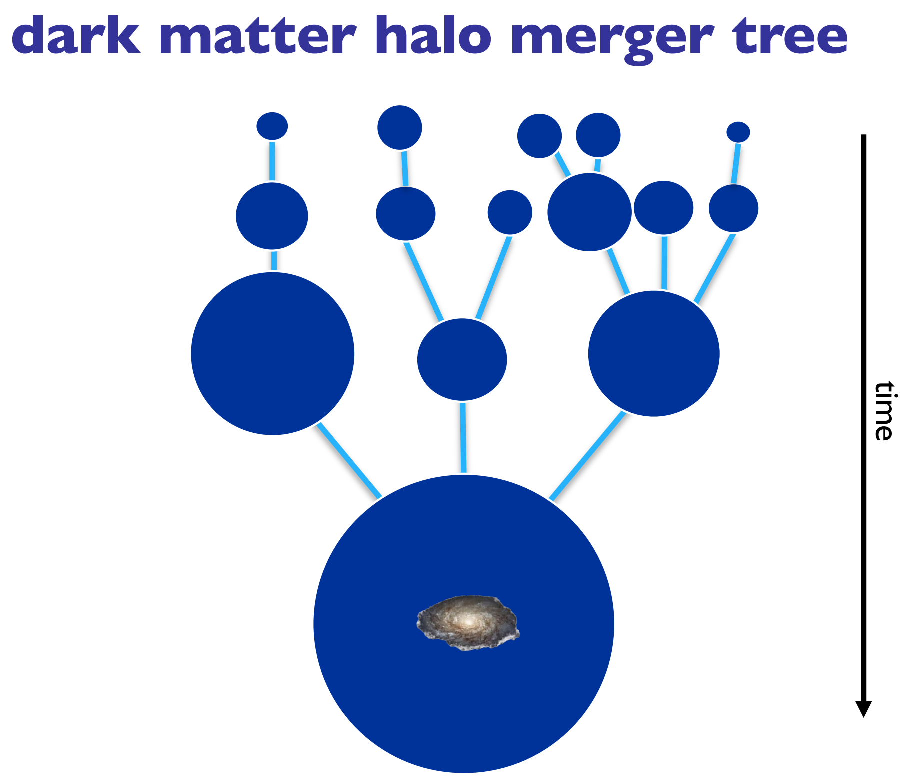


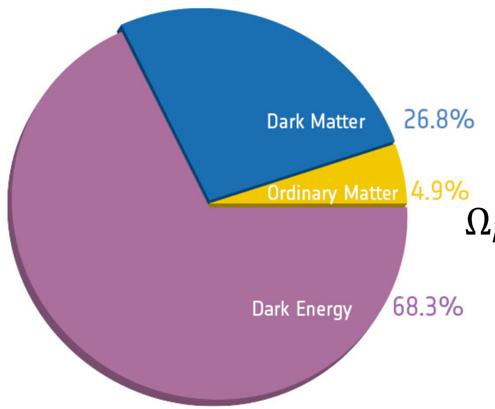
dark matter halo merger tree



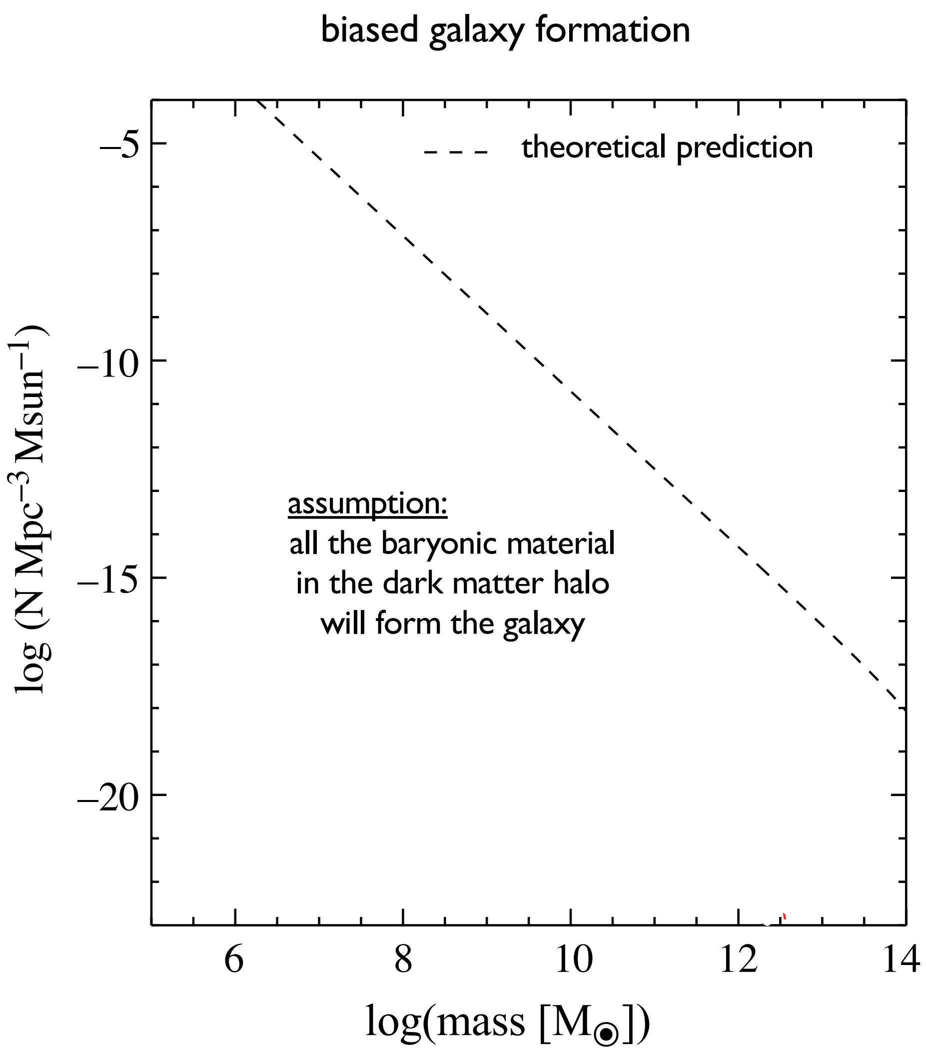
biased galaxy formation



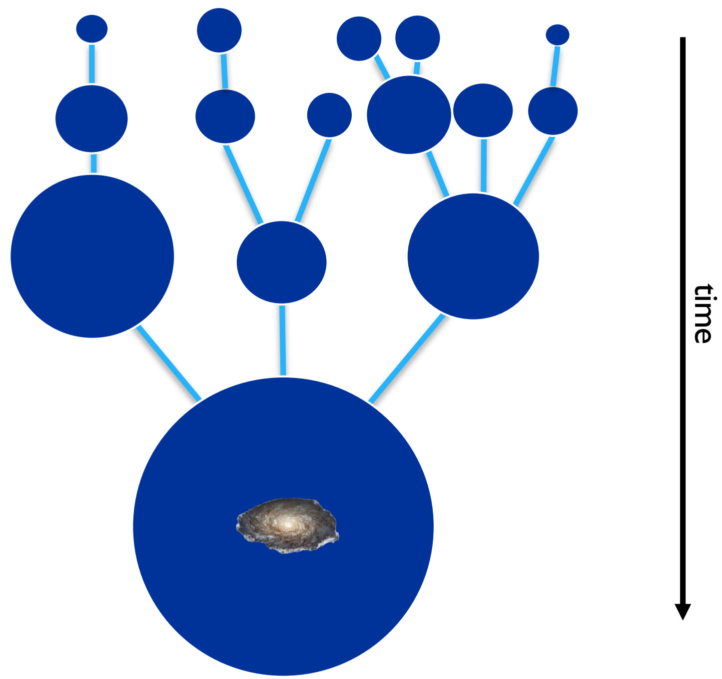




$$\Omega_b = f_b \Omega_m$$

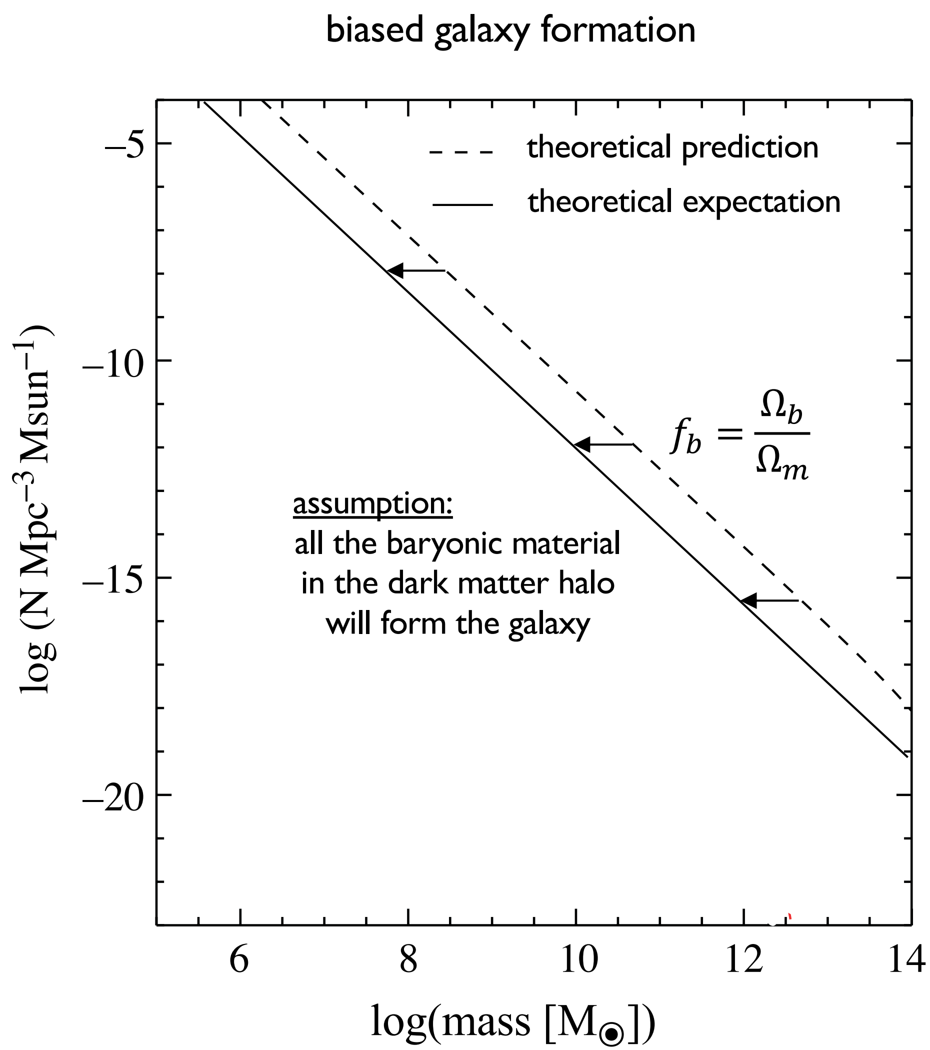


dark matter halo merger tree

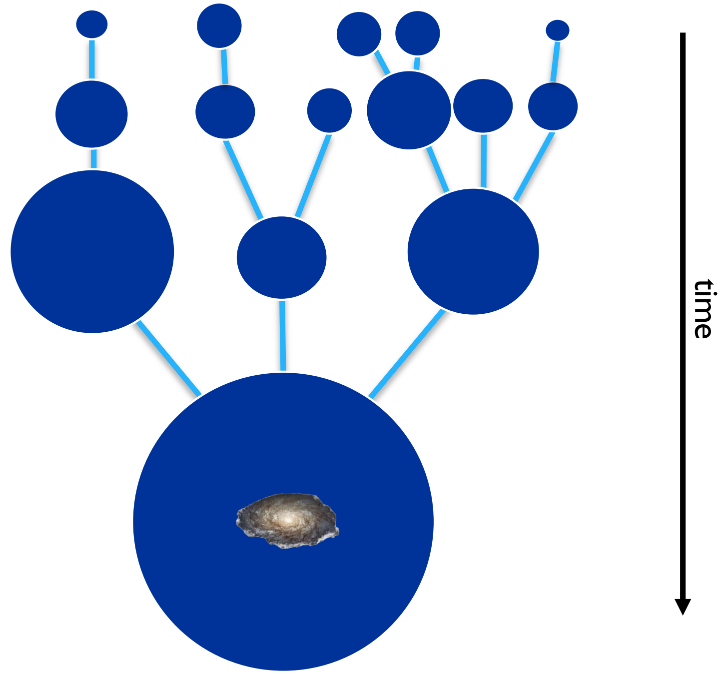


$$\Omega_b = f_b \Omega_m$$

every dark matter halo contains a galaxy with mass $M_{\rm galaxy} = f_b\, M_{\rm halo}$!?



dark matter halo merger tree



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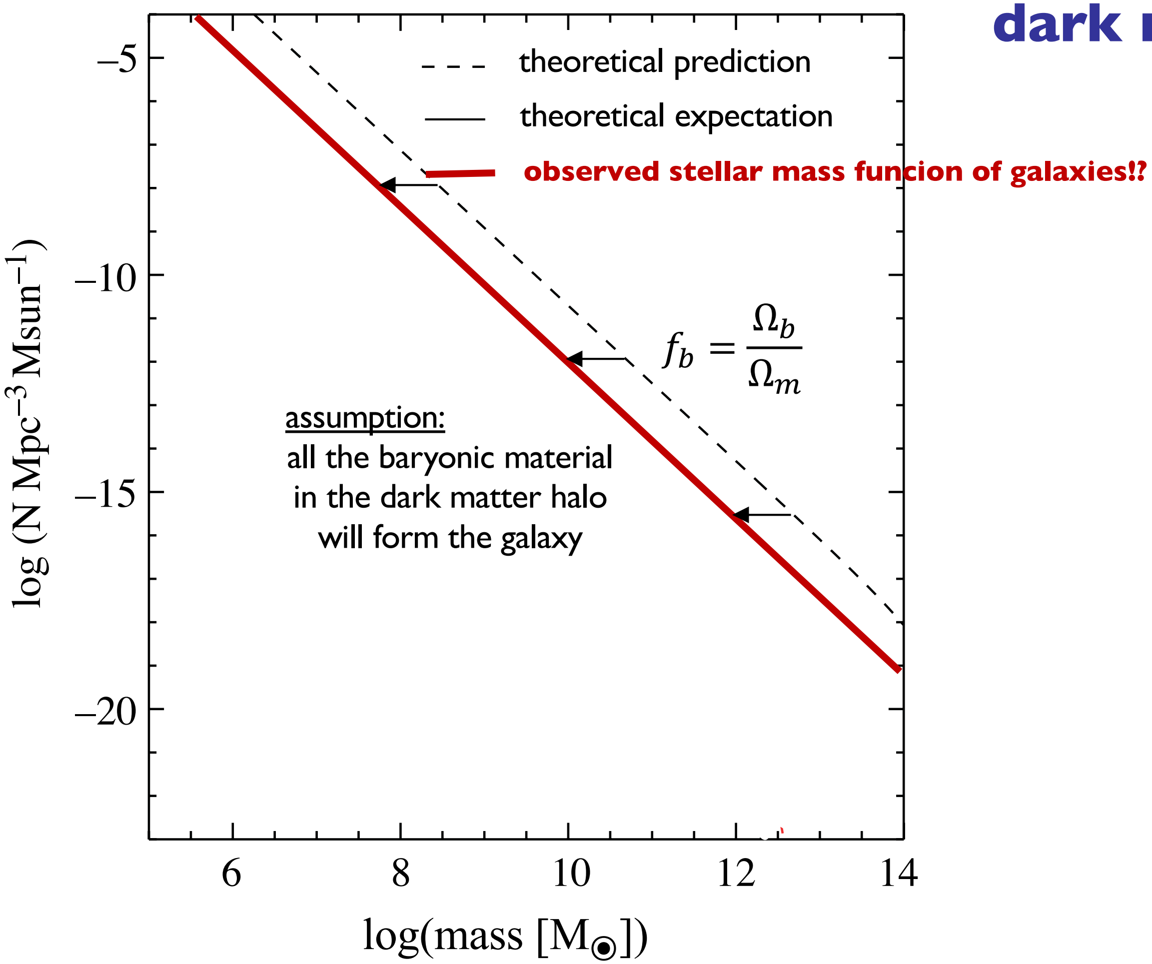
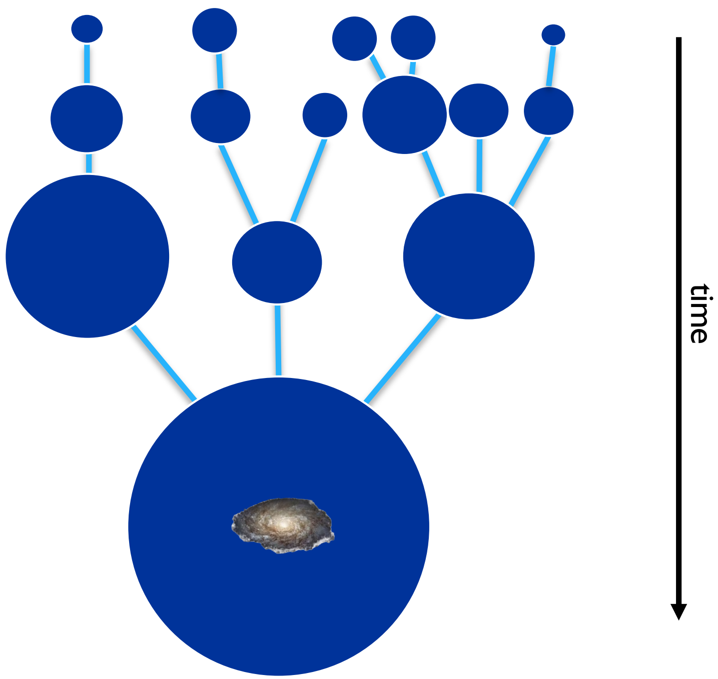
biased galaxy formation



dark matter halo merger tree



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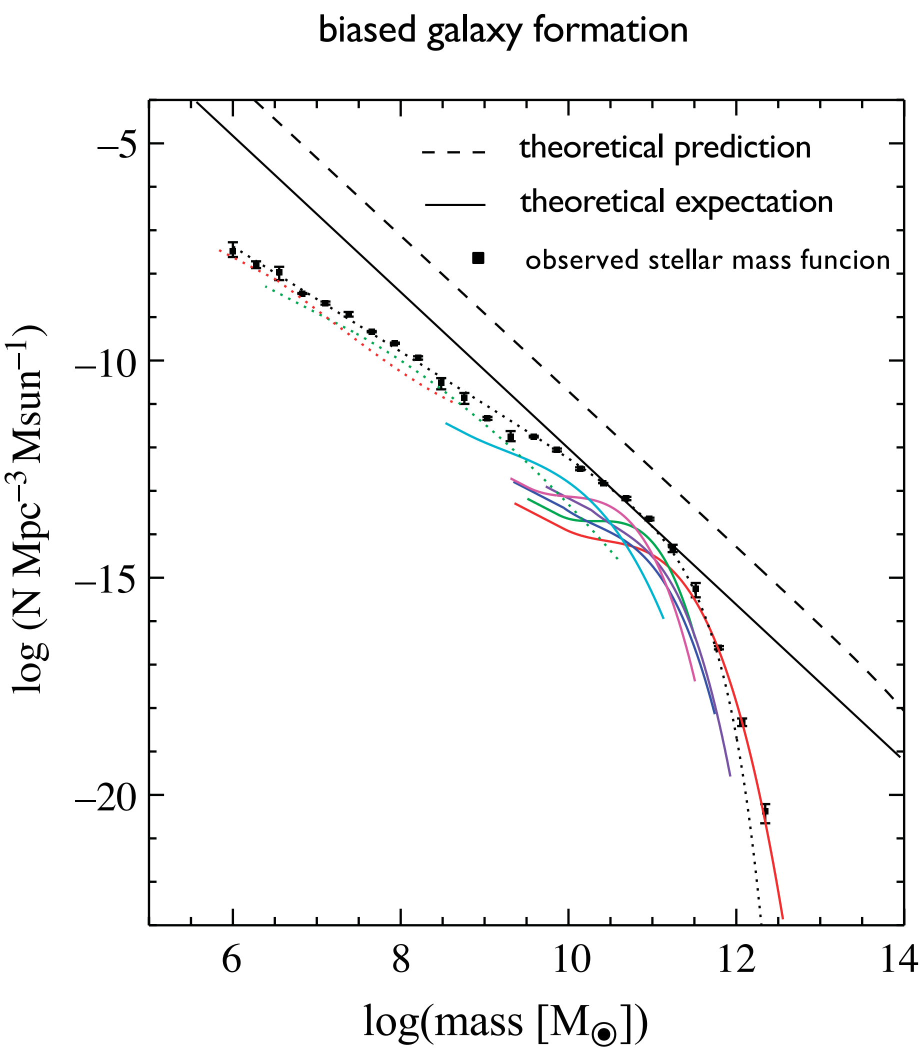
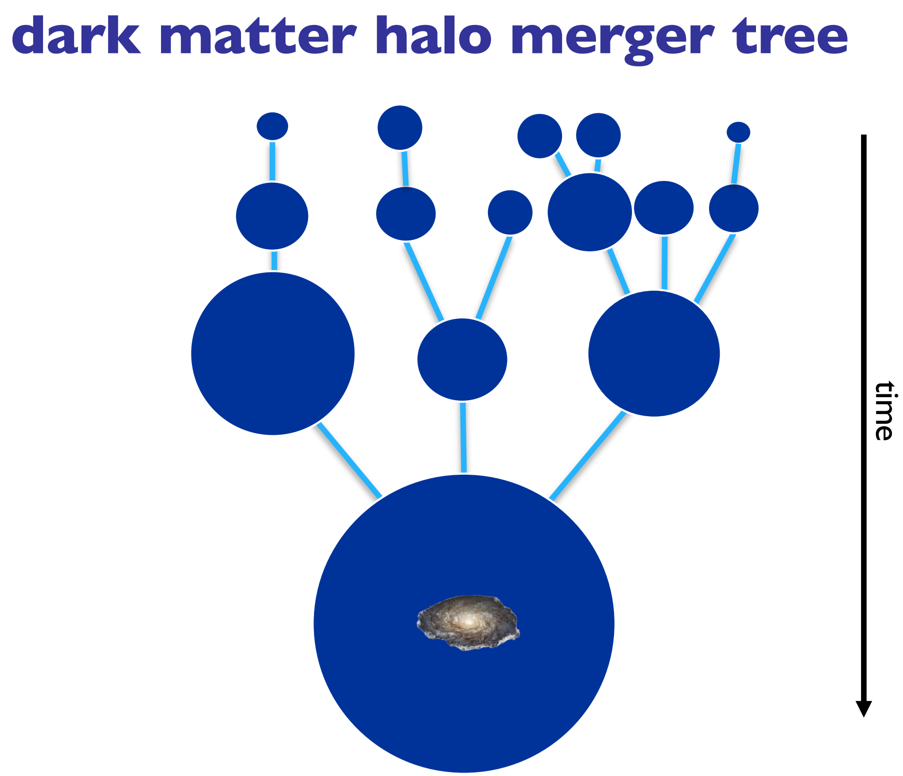
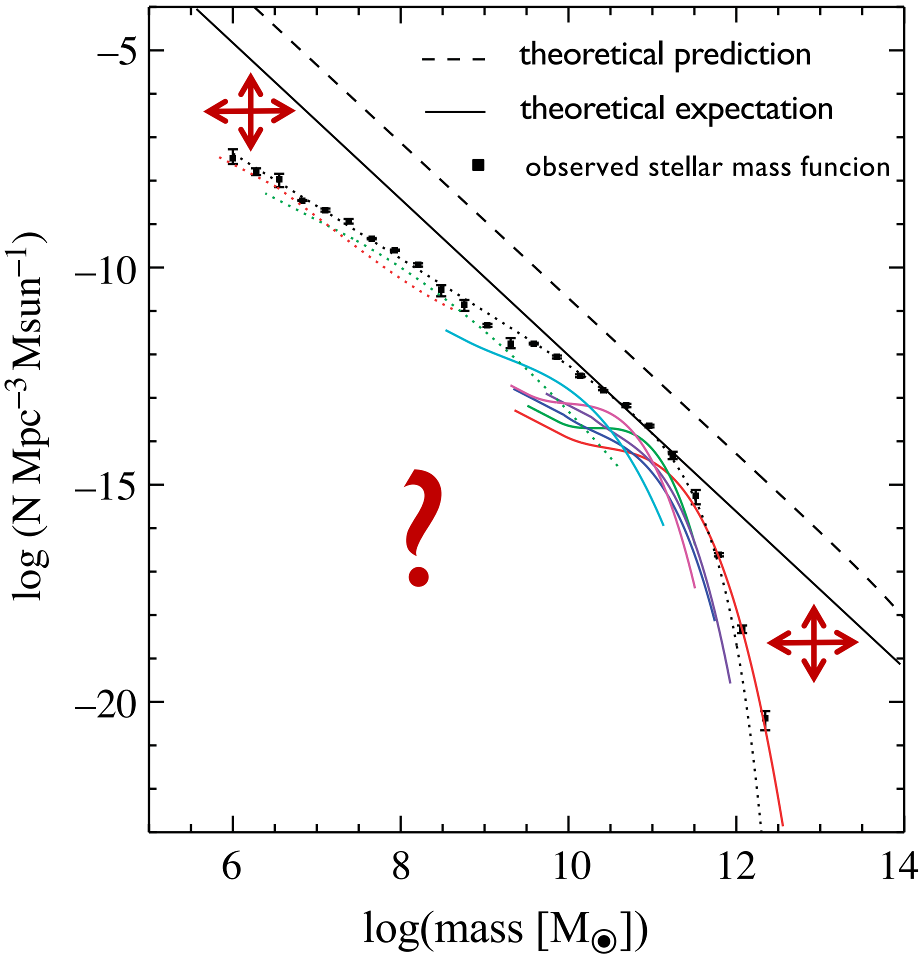
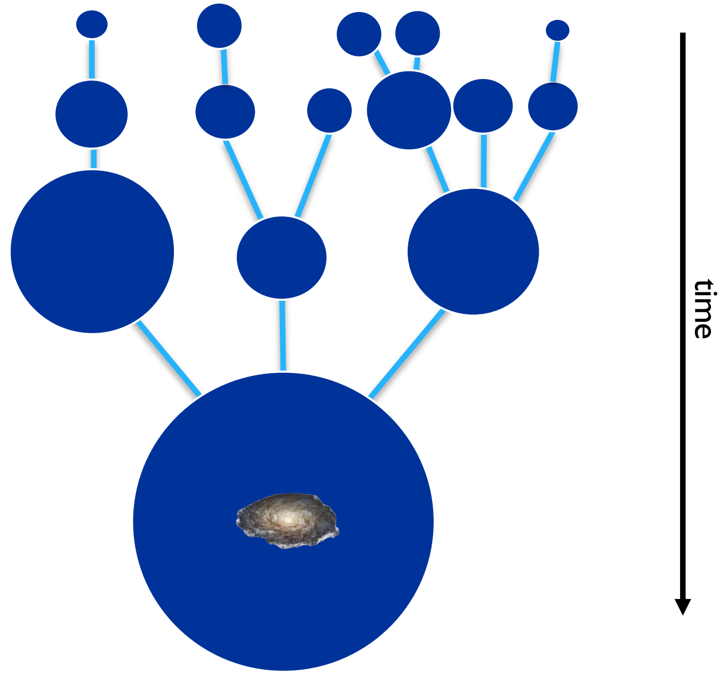

biased galaxy formation
theoretical prediction
theoretical expectation
observed stellar mass funcion
–5
–10
–15
–20
6
8
10
12
14
log (N Mpc⁻³ Msun⁻¹)
log(mass [M☉])


dark matter halo merger tree
time

biased galaxy formation

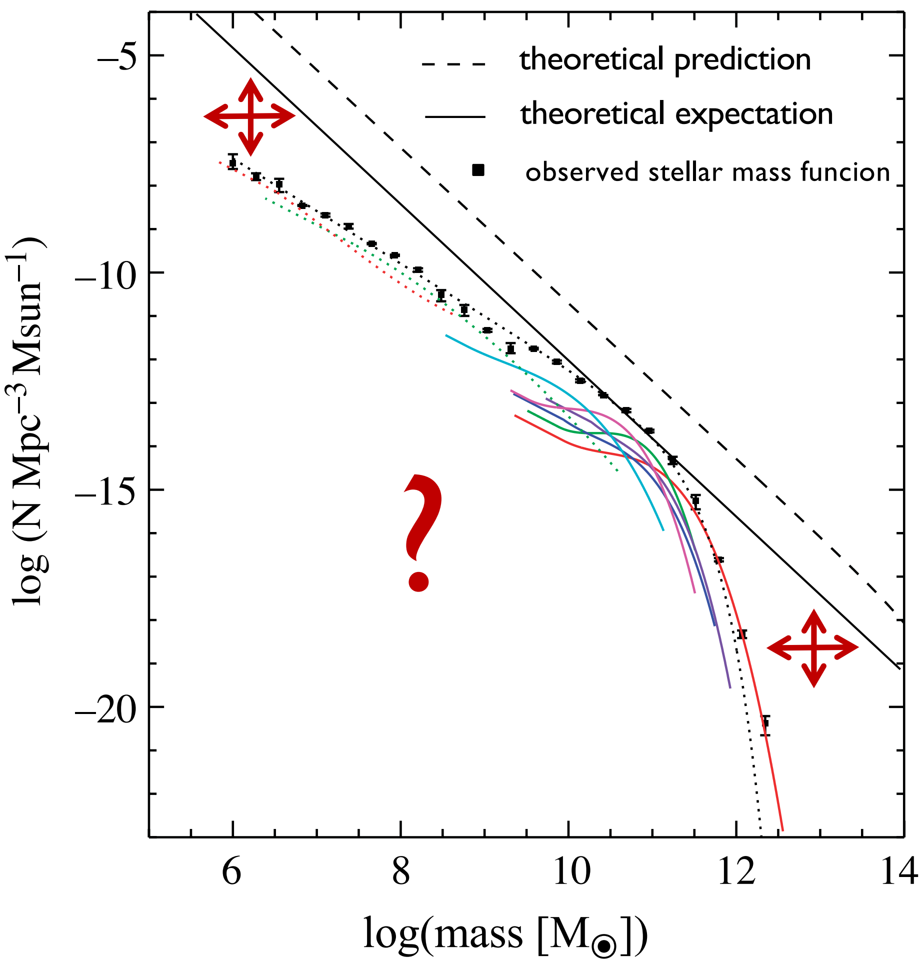


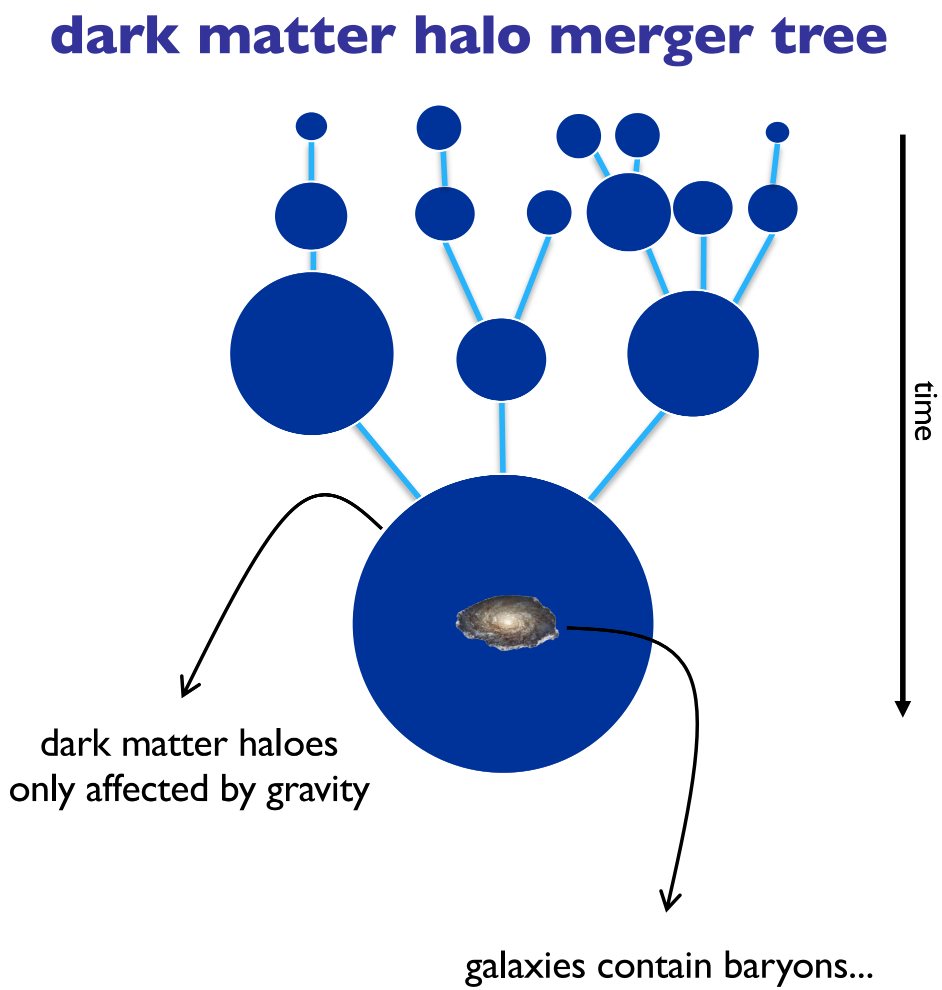
dark matter halo merger tree



something prevented star formation in low- and high-mass galaxies?

biased galaxy formation





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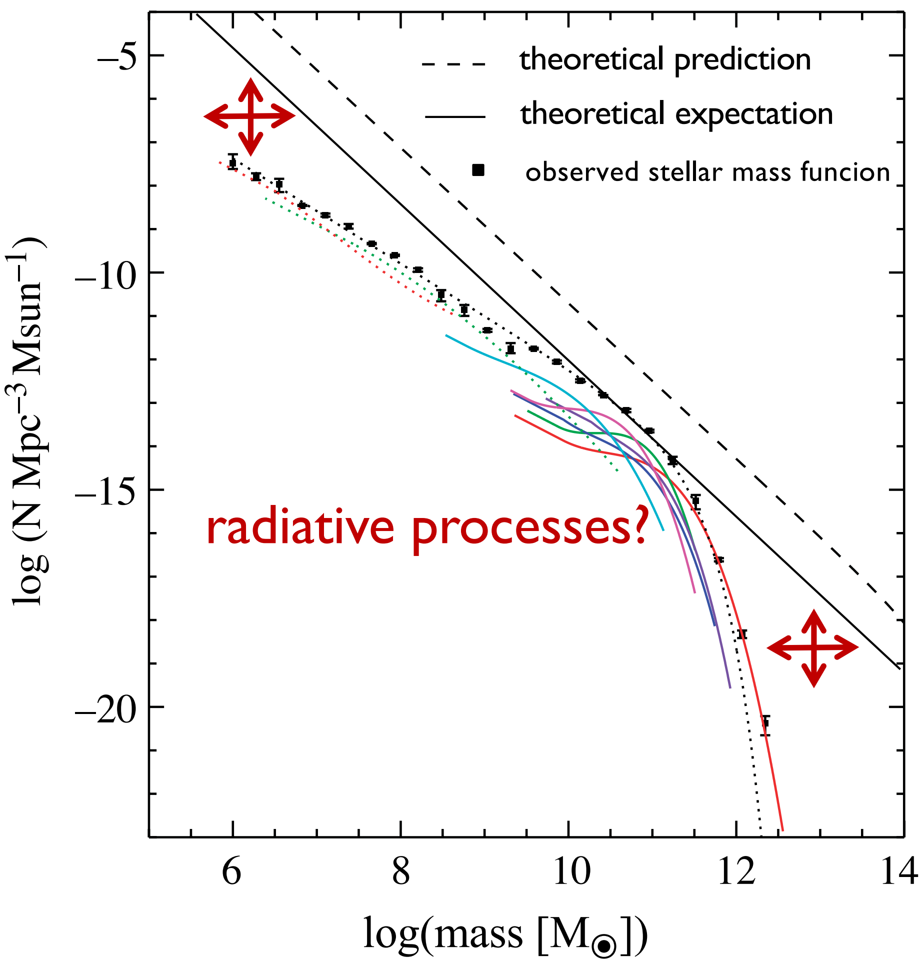

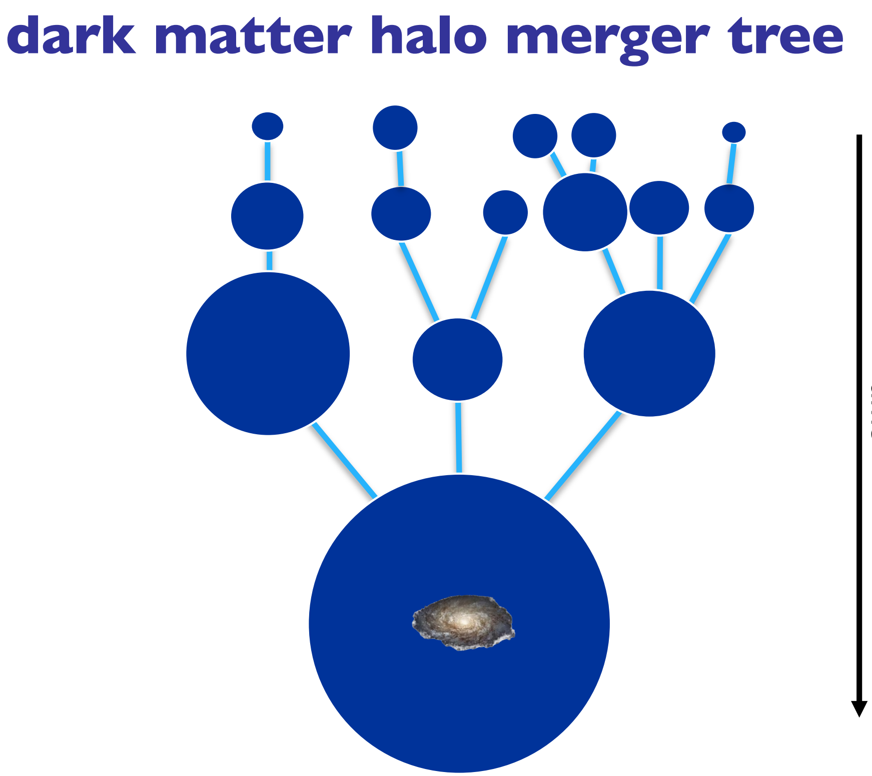

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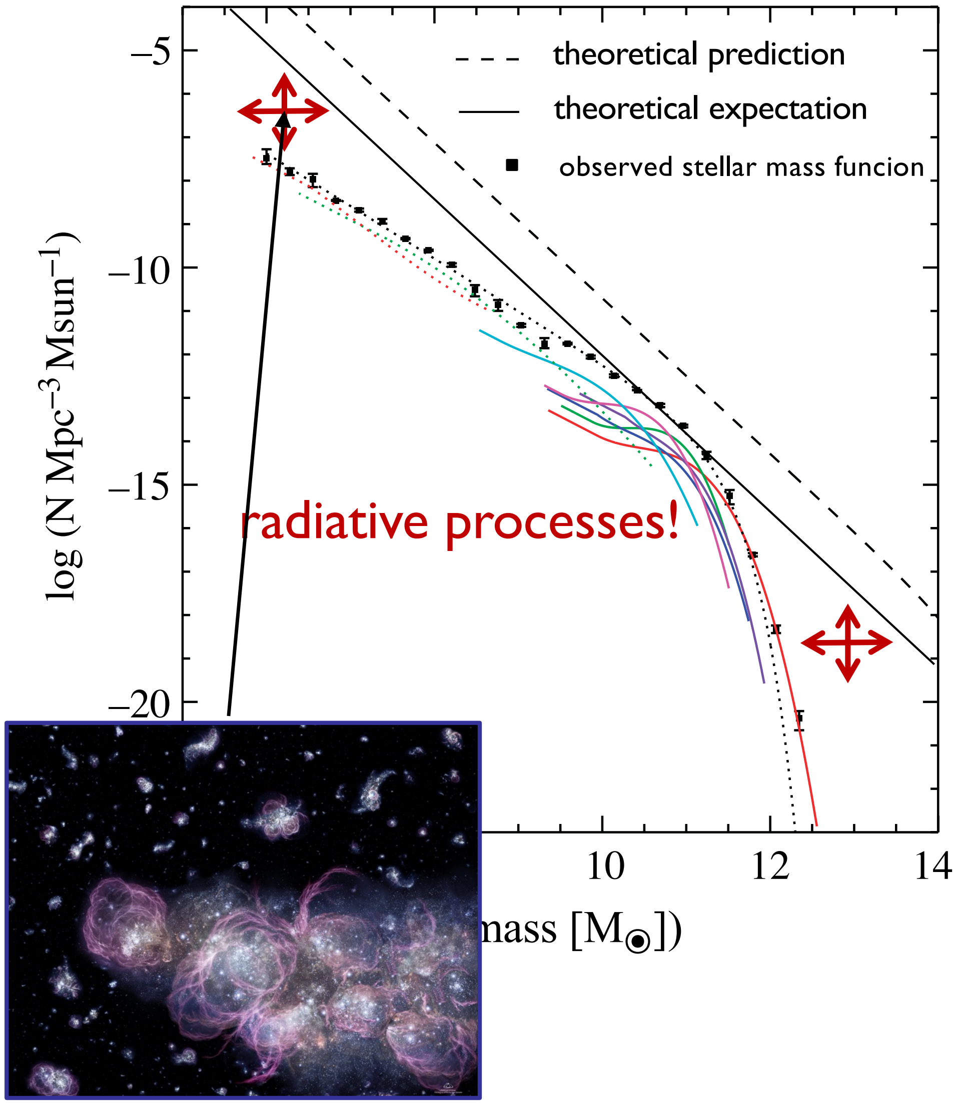
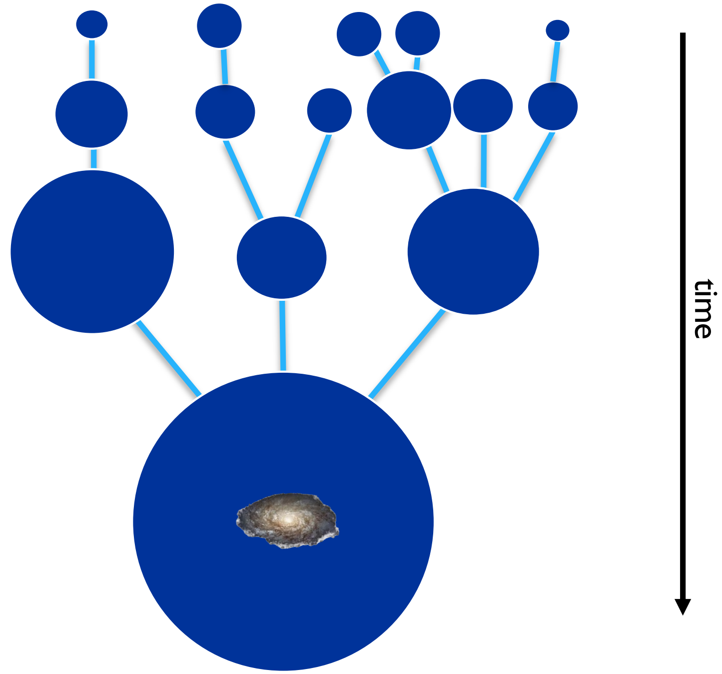
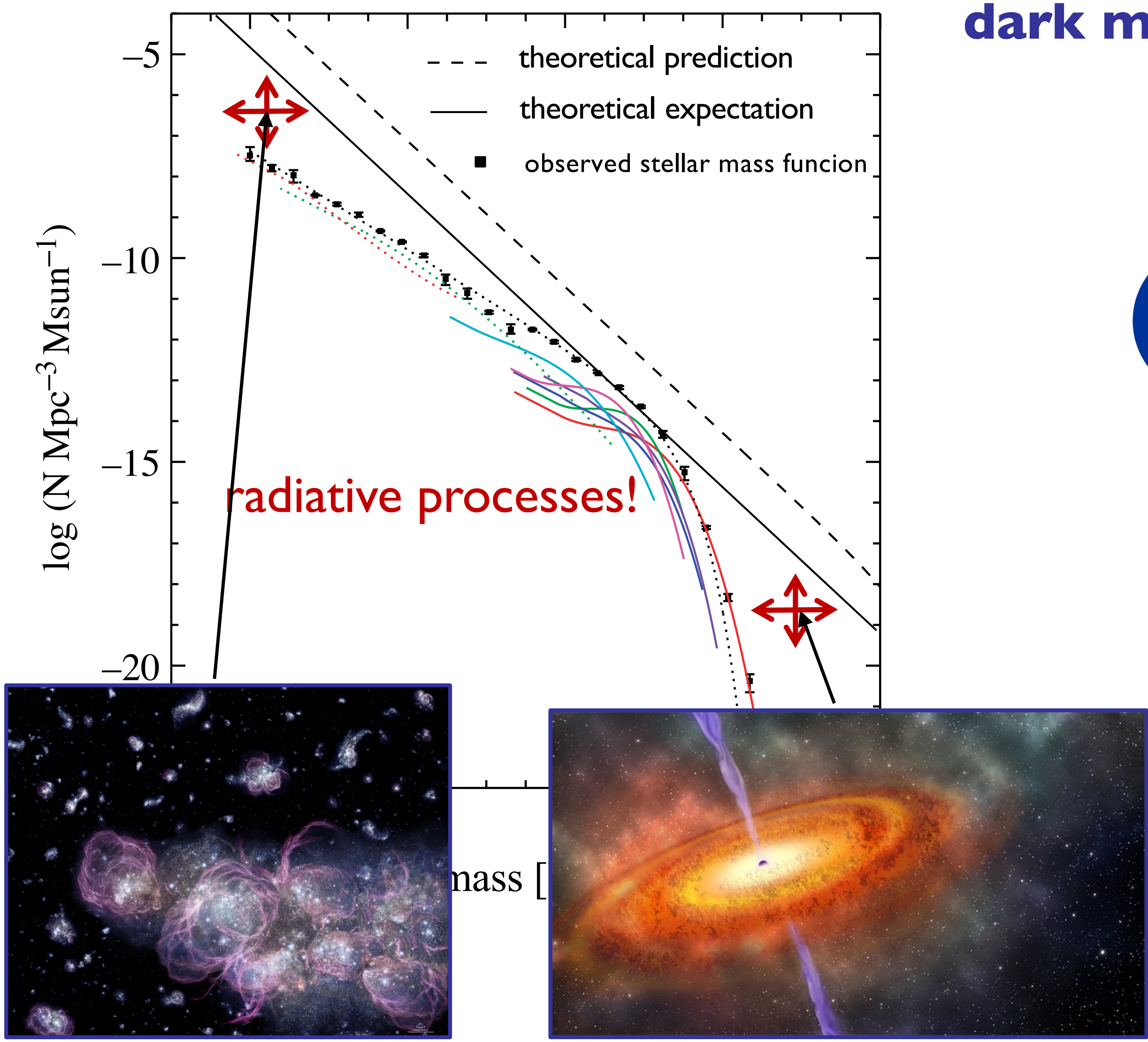


SN explosions

dark matter halo merger tree



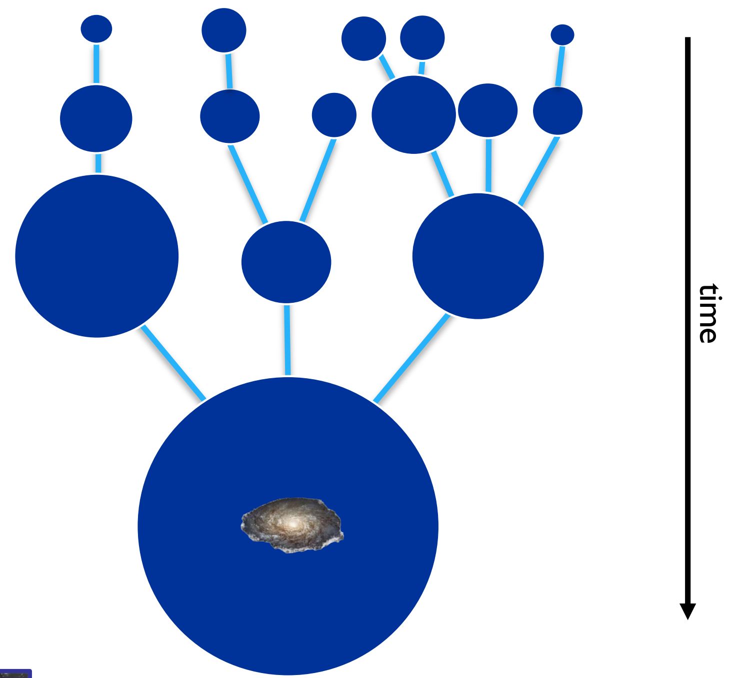
biased galaxy formation



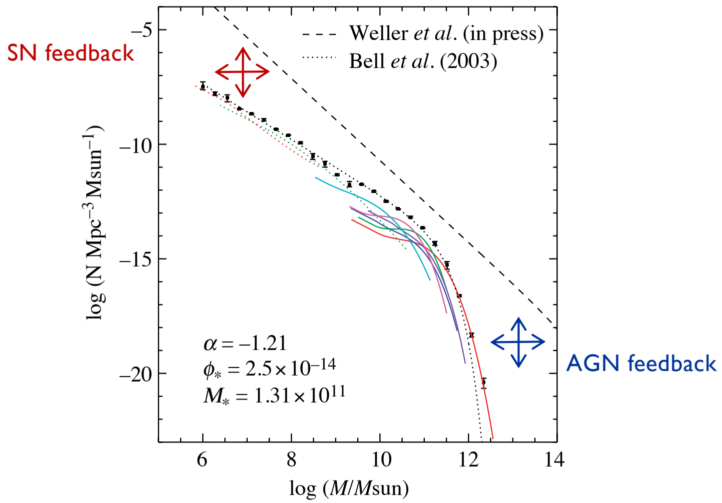
SN explosions

AGN

dark matter halo merger tree



- biased galaxy formation
- **internal baryonic processes:**
  - supernova feedback
  - active galactic nuclei feedback
- dwarf galaxies



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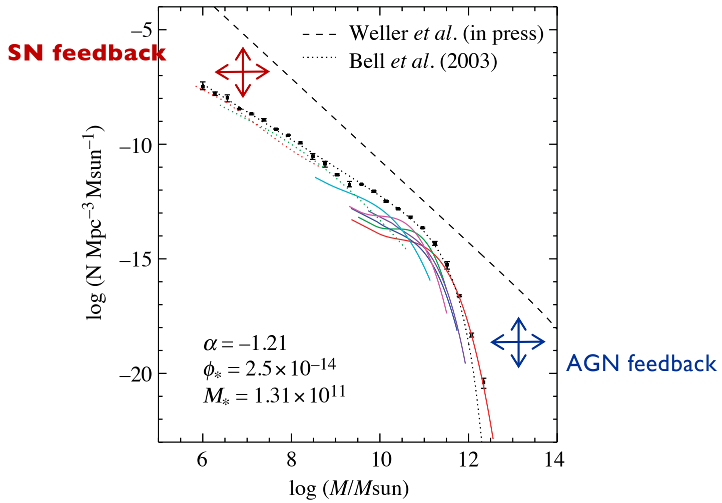
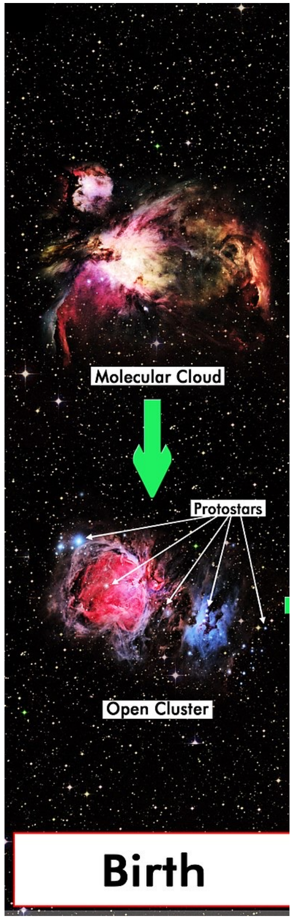


- <u>supernova feedback</u>

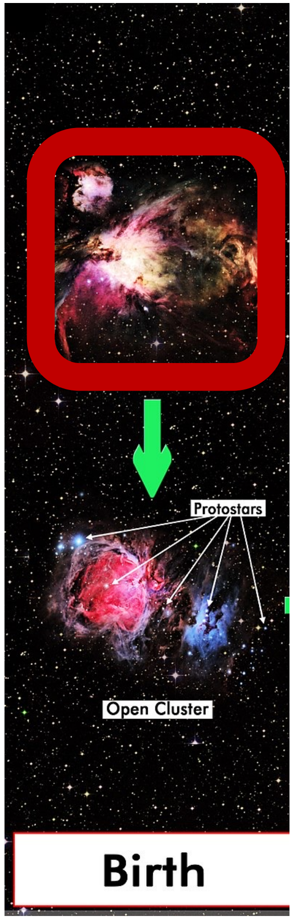
(artist's conception of SN2016aps, the most powerful supernova ever found)

- supernova feedback
    - stellar evolution
    - relevance for galaxy formation and cosmology

- <u>supernova feedback – stellar evolution</u>

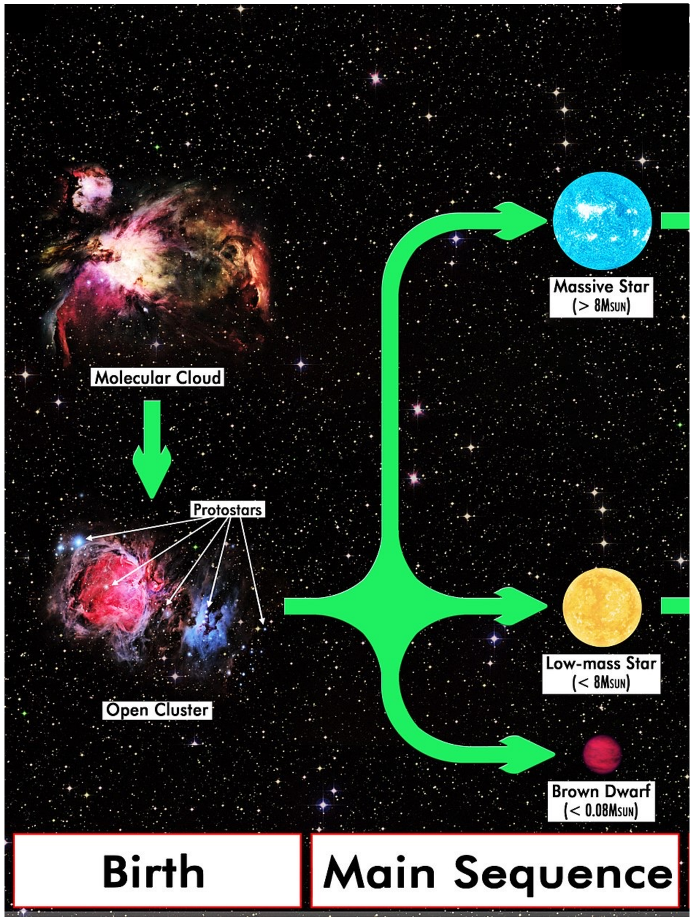


- <u>supernova feedback – stellar evolution</u>

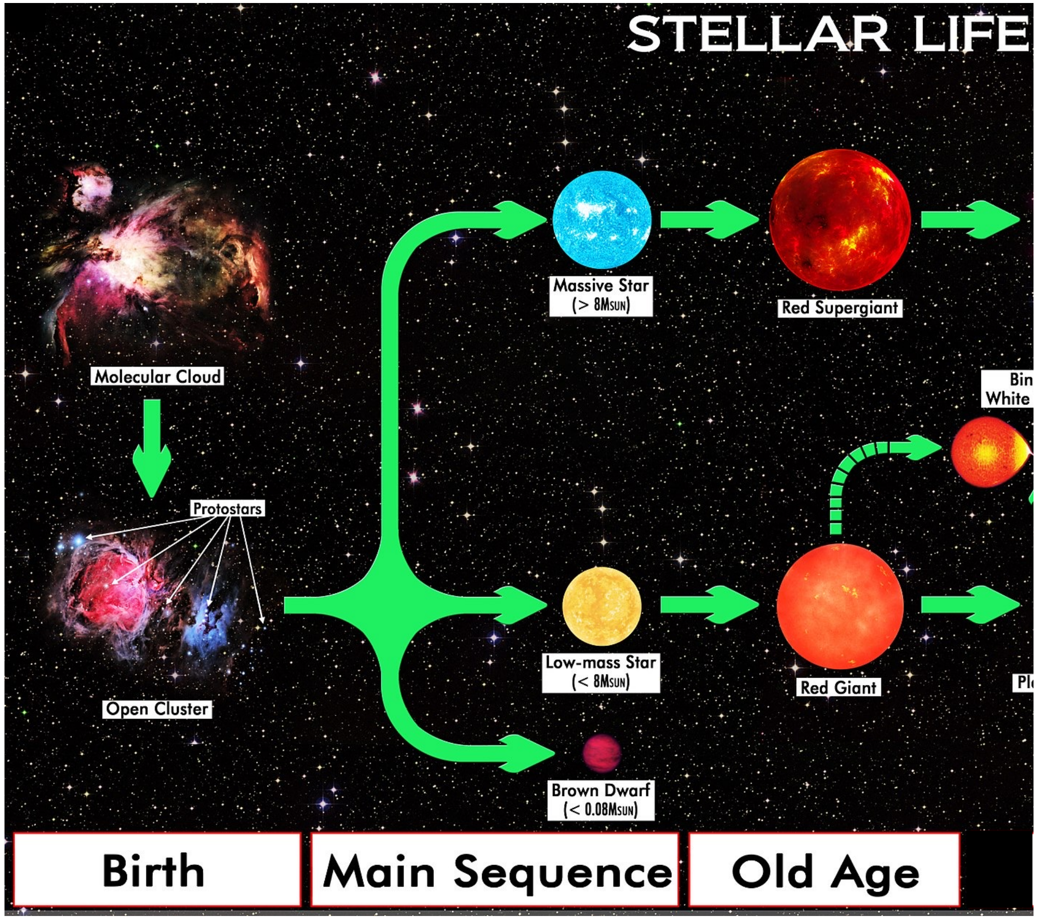


in order to form stars ***cold*** gas is required (remember f_b)!

- supernova feedback – stellar evolution



▪ supernova feedback – stellar evolution



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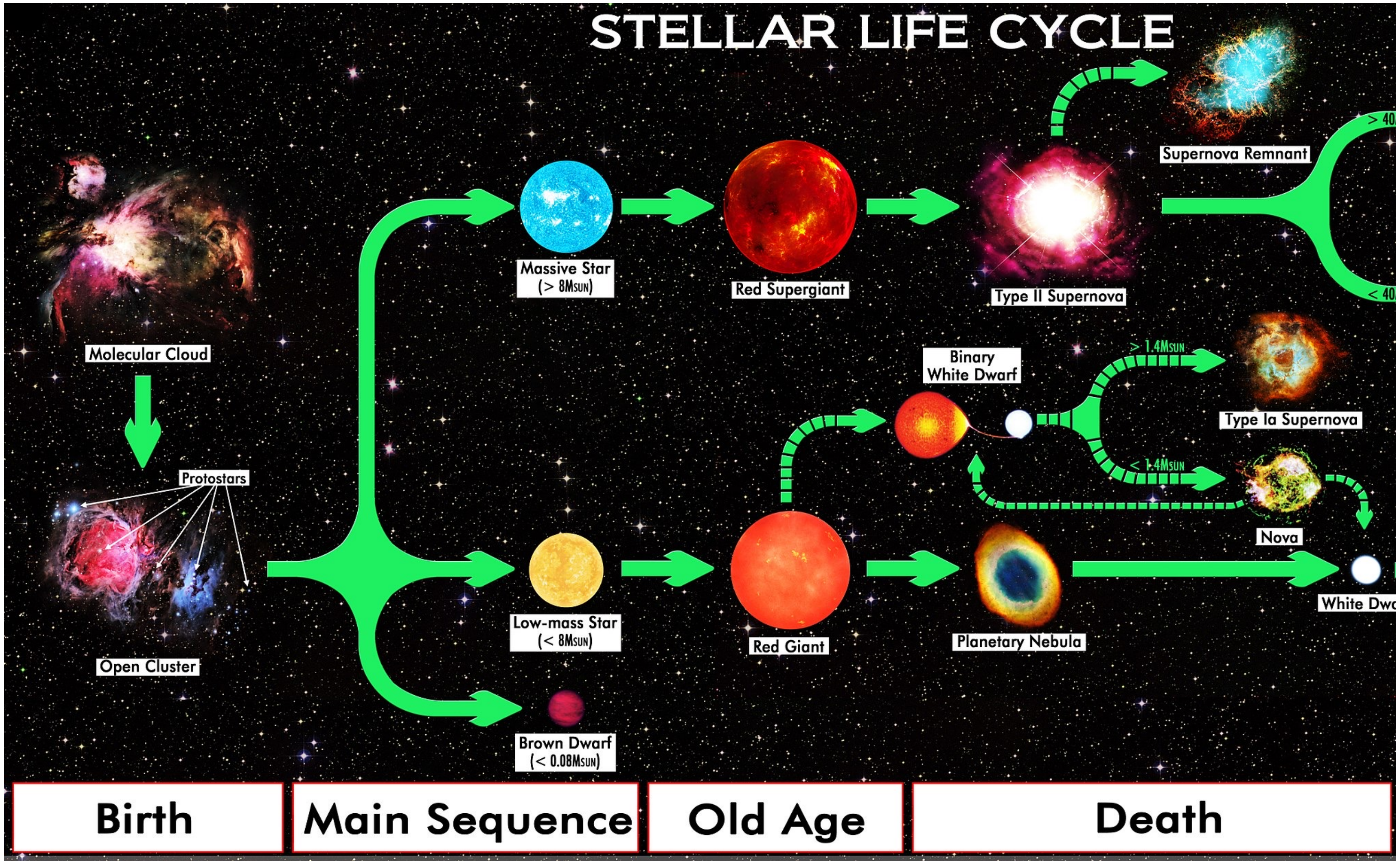

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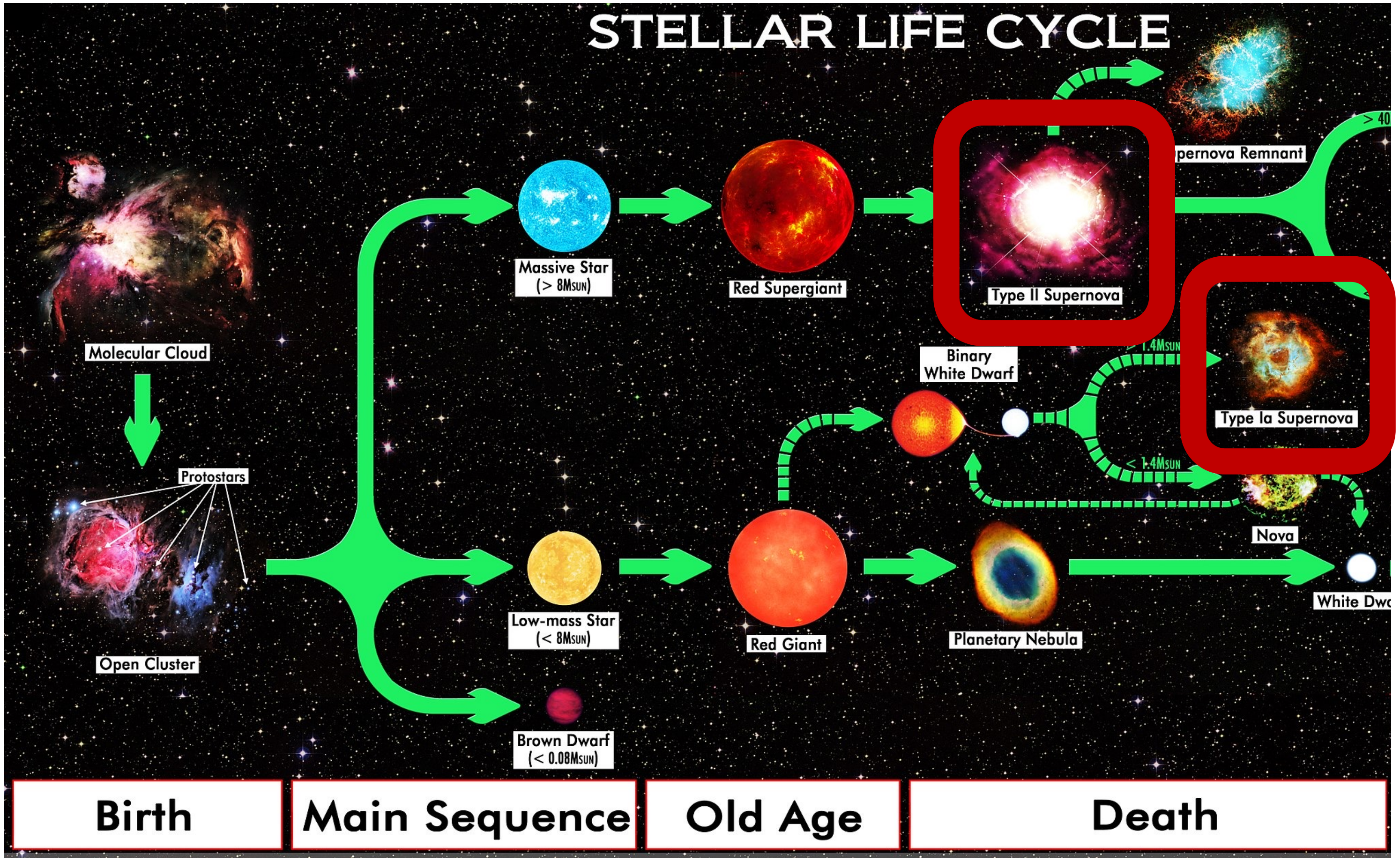

extremely energetic events possibly influencing galaxy evolution!?

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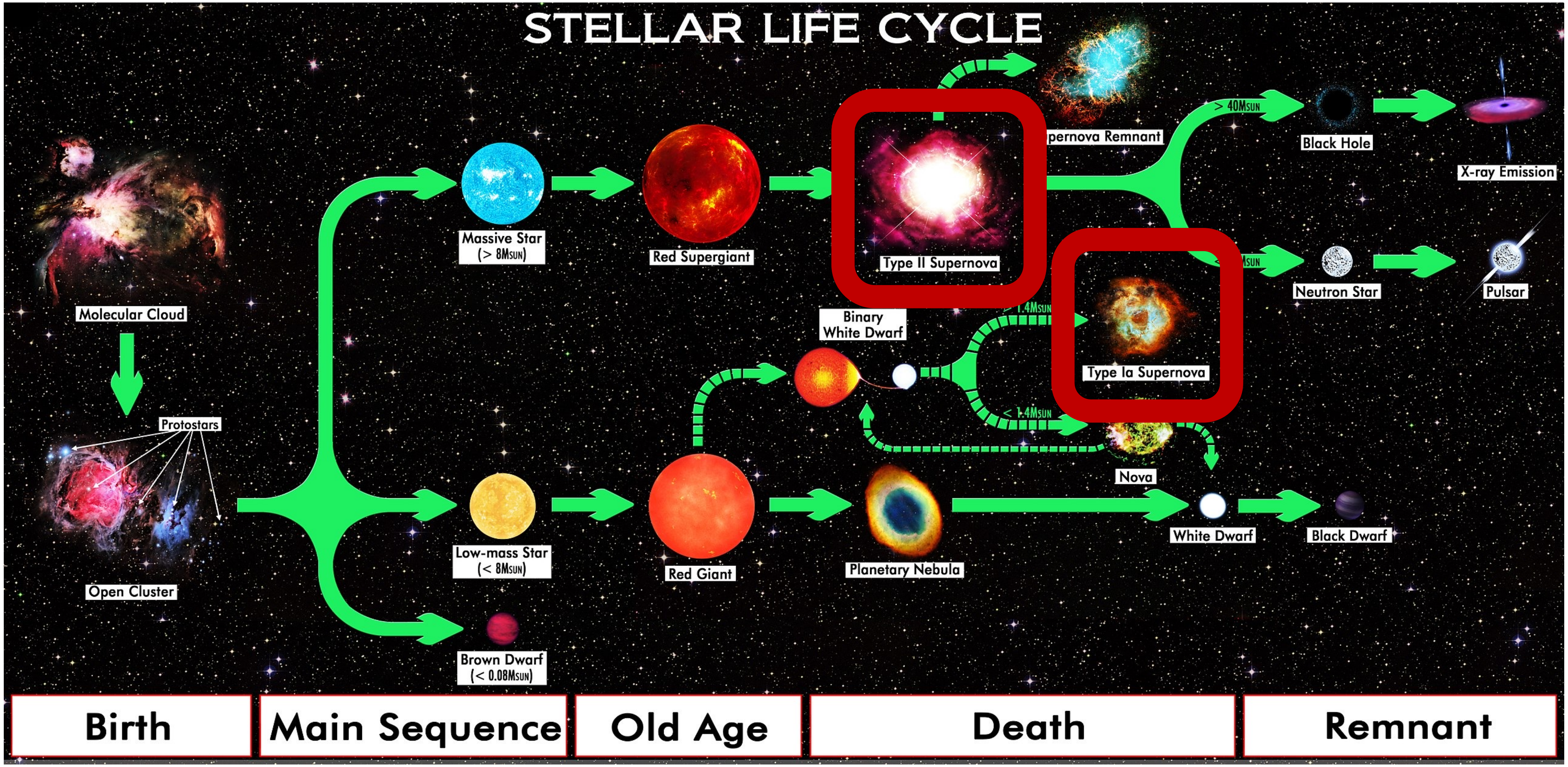

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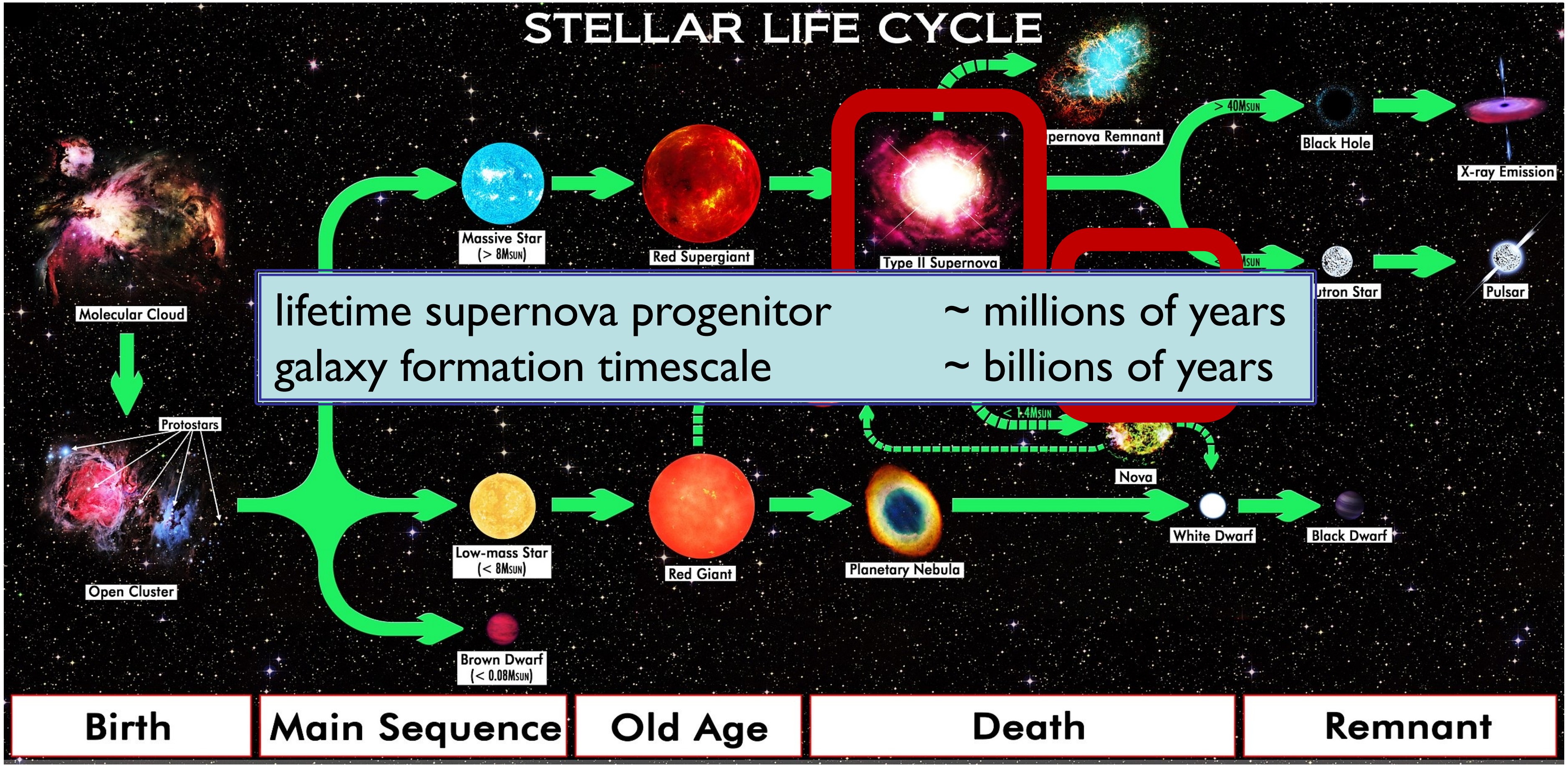

lifetime supernova progenitor	~ millions of years
galaxy formation timescale	~ billions of years

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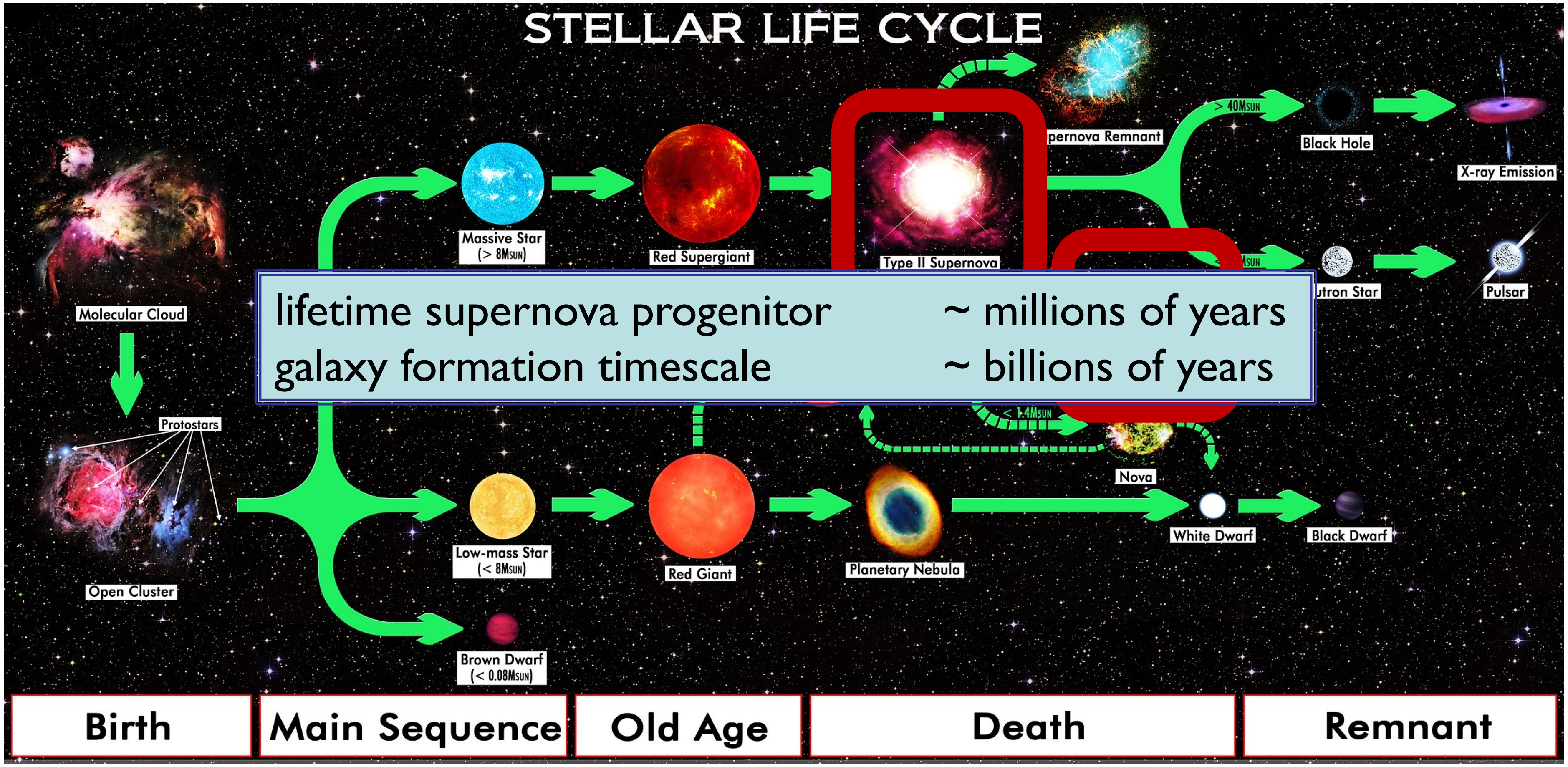

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extremely energetic events possibly influencing galaxy evolution! **but how?**

- <u>supernova feedback – relevance for galaxy formation</u>

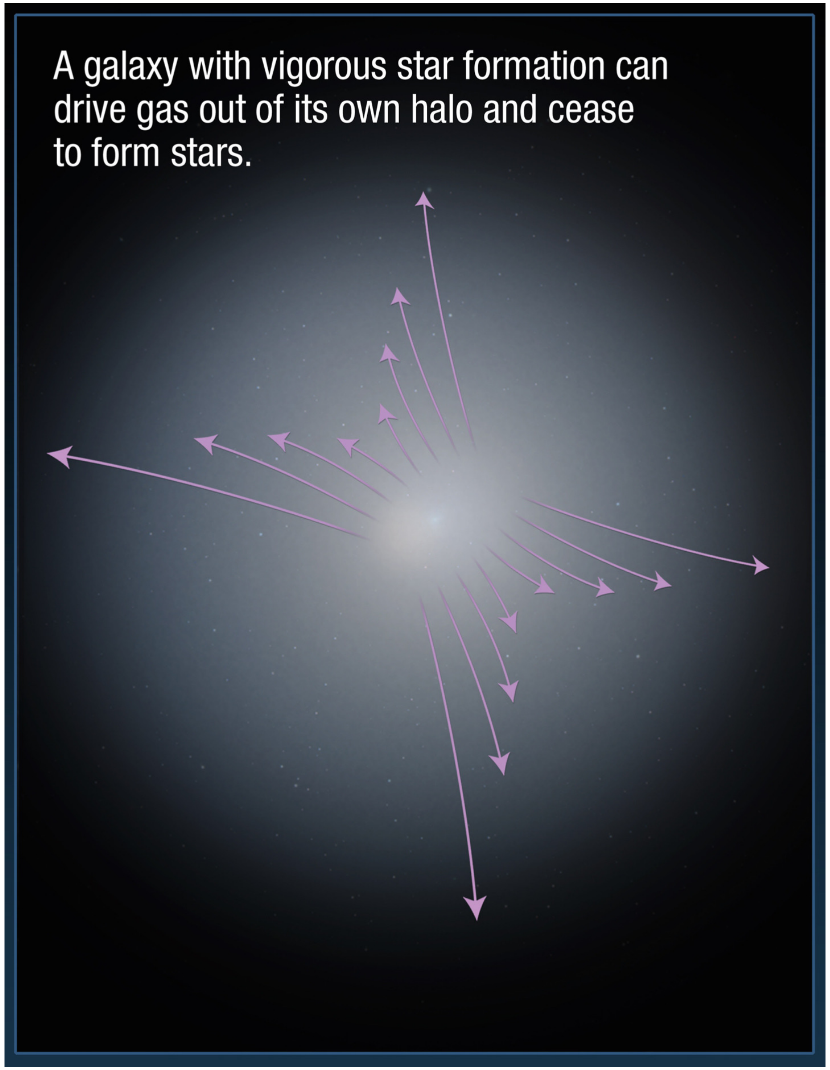

image credit: NASA, ESA, and A. Feild (STScI)

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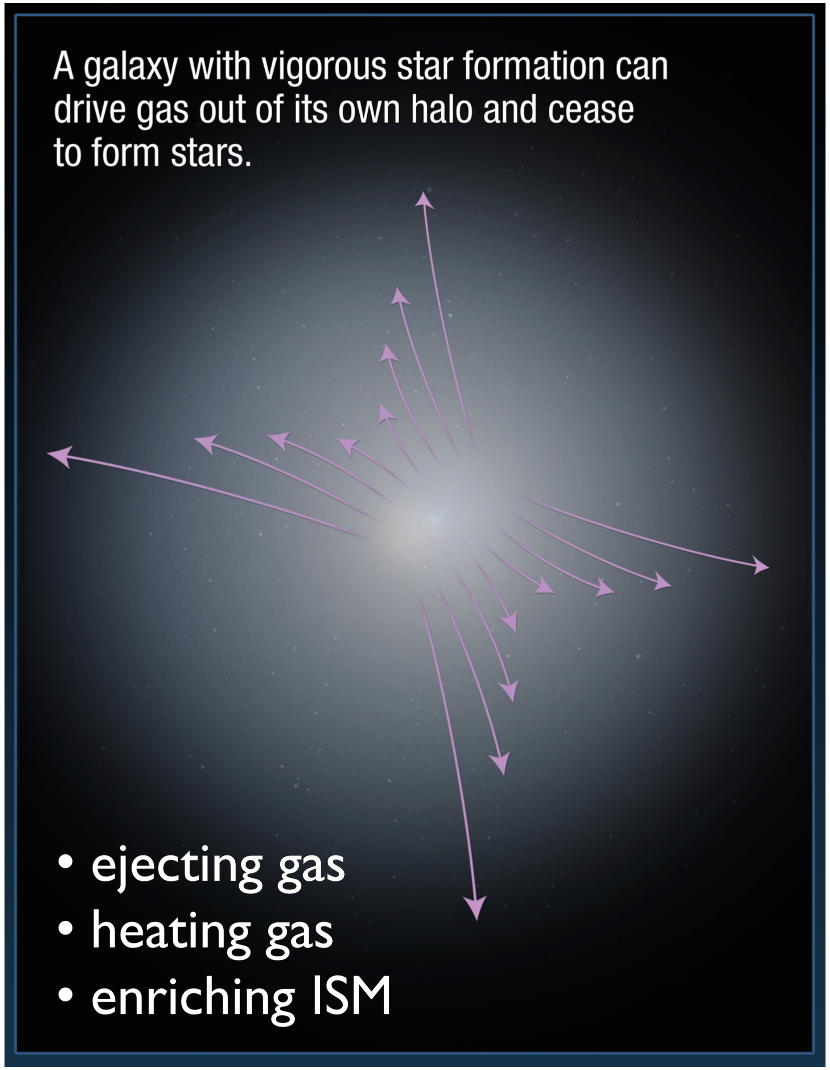

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supernova feedback – relevance for galaxy formation

- ejection, heating, and enrichment

- supernova feedback – relevance for galaxy formation

  - **ejection?**, heating, and enrichment

▪ supernova feedback – relevance for galaxy formation

- **ejection**, heating, and enrichment
  - eject mass from galaxy centre, i.e. giving it kinetic energy beyond escape velocity:

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$$E_{fb} = \varepsilon_{SN} f_{SN} M_* E_{SN}$$

$\varepsilon_{SN} < 1$ = fraction of SN energy available for feedback
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In MW, 100% SN efficiency can eject 40% of the baryonic mass

▪ supernova feedback – relevance for galaxy formation

- ejection, **heating?**, and enrichment

▪ supernova feedback – relevance for galaxy formation

- ejection, **heating**, and enrichment
  - the virial temperature of a dark matter halo!?

▪ supernova feedback – relevance for galaxy formation

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$$E^{*}_{kin,g}$$

*thermal motion of gas <=> kinetic energy of gas

▪ supernova feedback – relevance for galaxy formation

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$$E_{kin,g} = \frac{3}{2} N_g kT = \frac{3}{2} \frac{M_g}{\mu m_p} kT$$

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the gas lives in the potential of **all** material!

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accreting halo is virialized:
$2E_{kin,g} + E_{pot,g} = 0$

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virial temperature of halo

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In MW, every 1 solar mass formed can reheat 17$M_{\odot}$

▪ supernova feedback – relevance for galaxy formation

- ejection, heating, and **enrichment?**

▪ supernova feedback – relevance for galaxy formation

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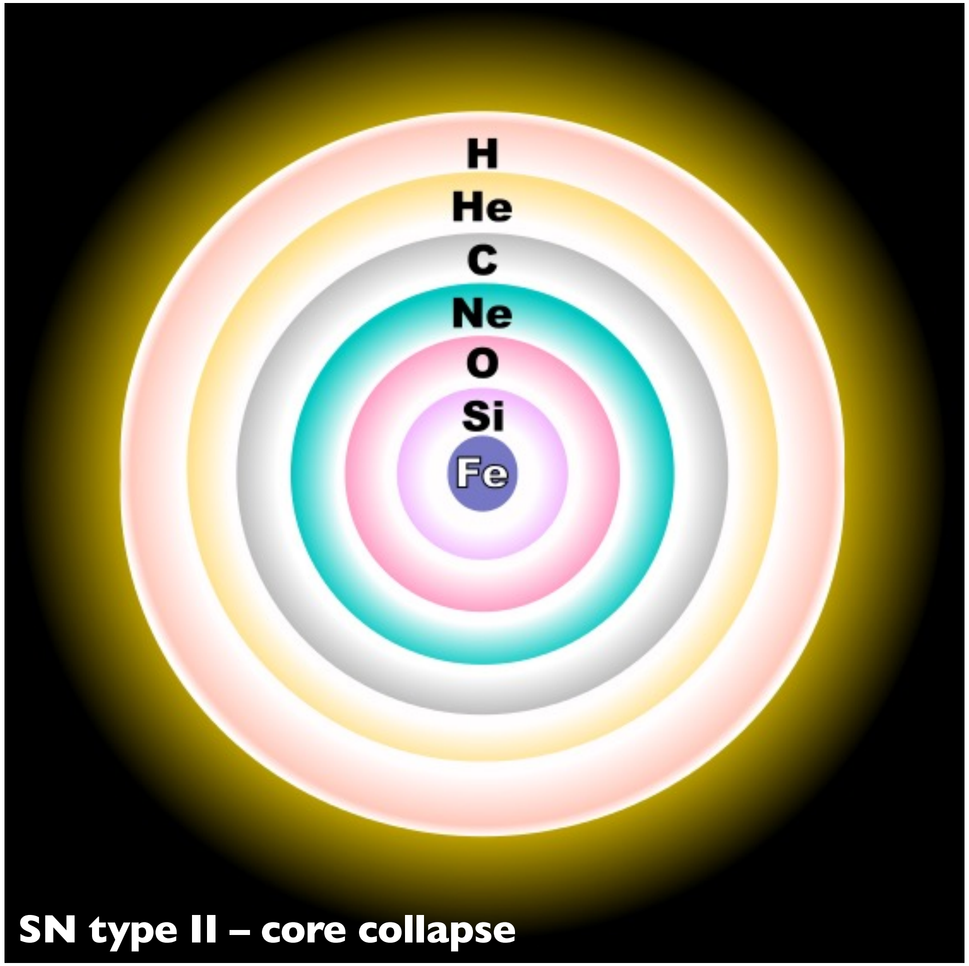

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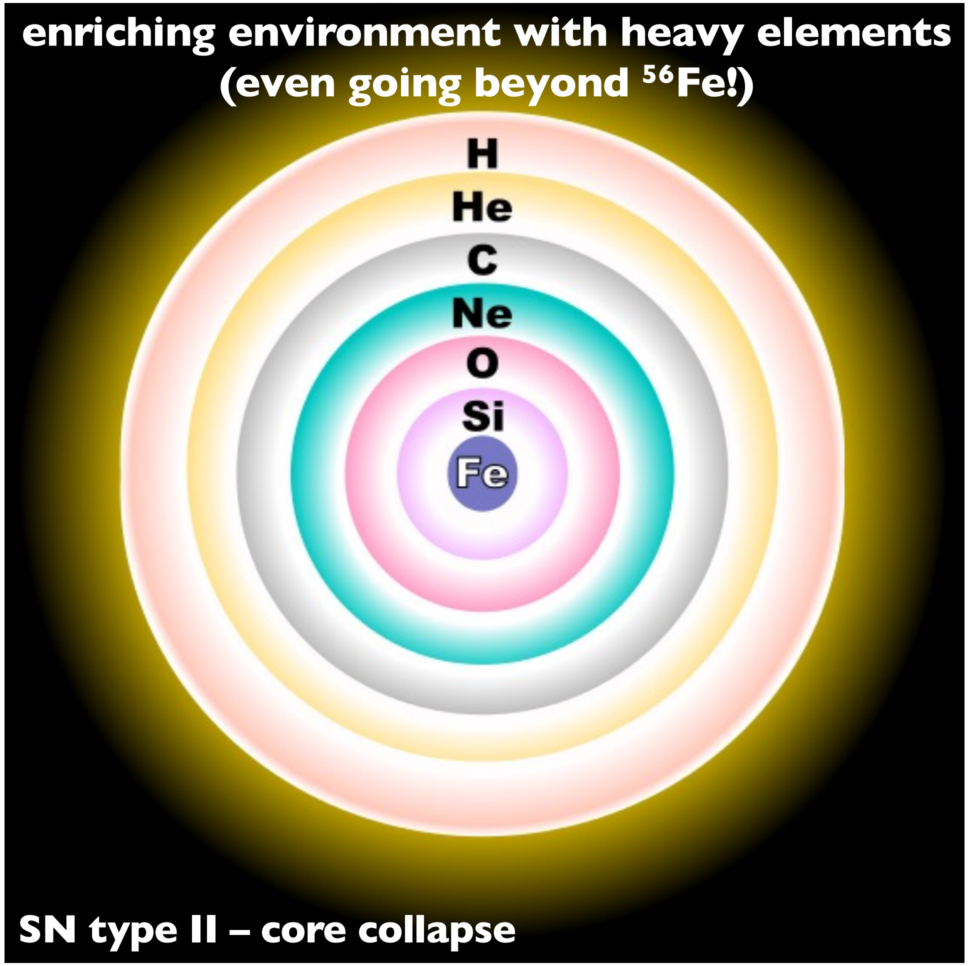

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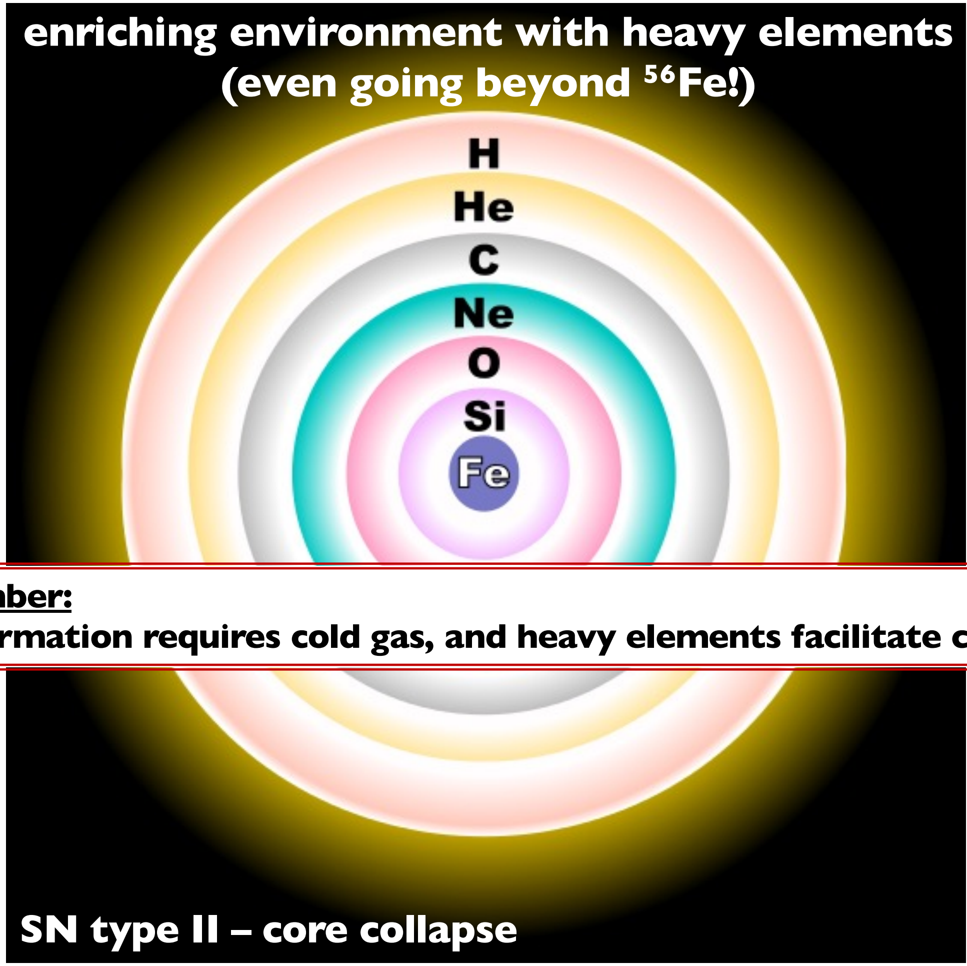


remember:
star formation requires cold gas, and heavy elements facilitate cooling

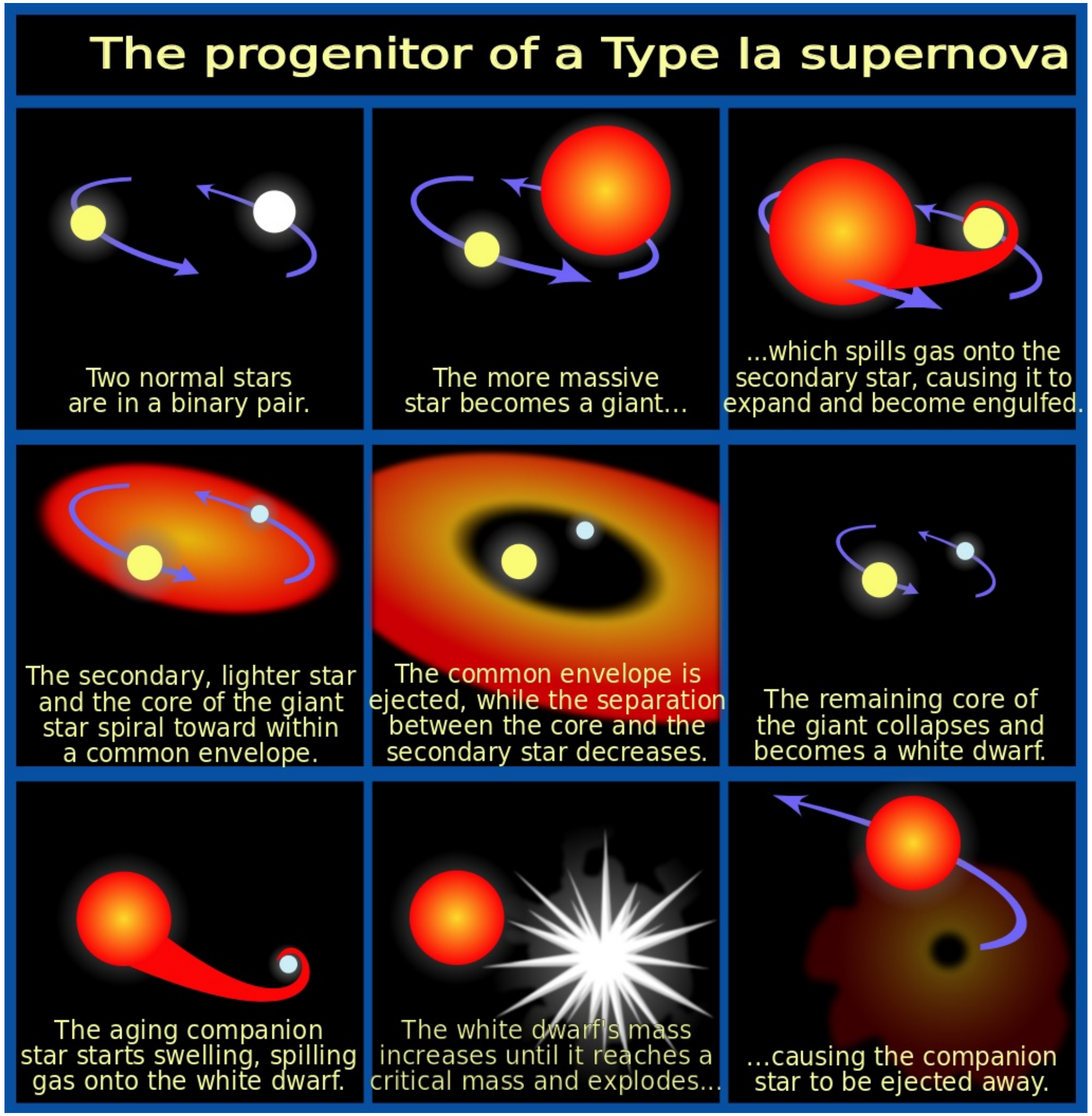
- supernova feedback – relevance for galaxy formation

- supernova feedback

    - stellar evolution
    - relevance for galaxy formation and **cosmology**

- supernova feedback – relevance for cosmology

- supernova feedback – relevance for cosmology



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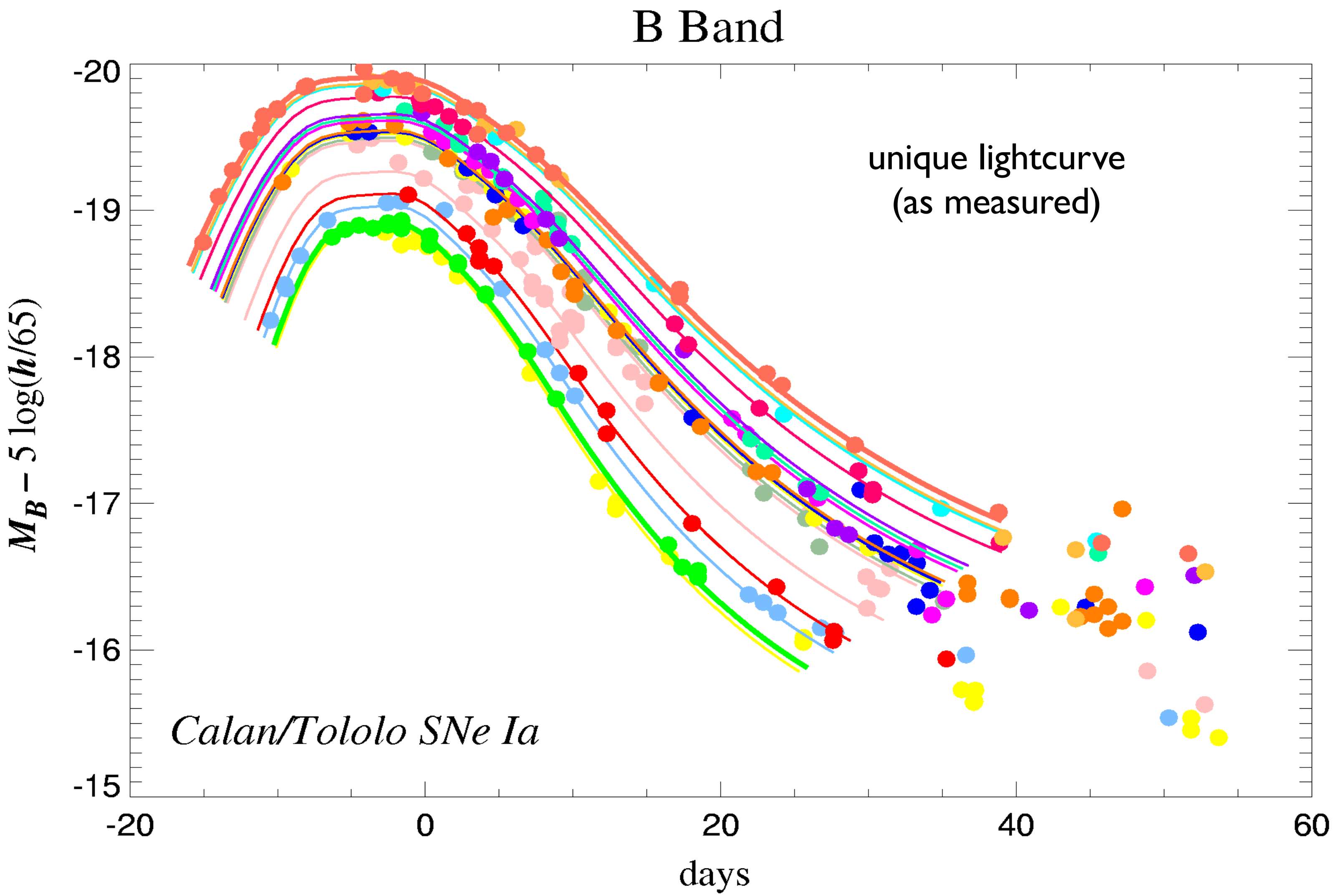

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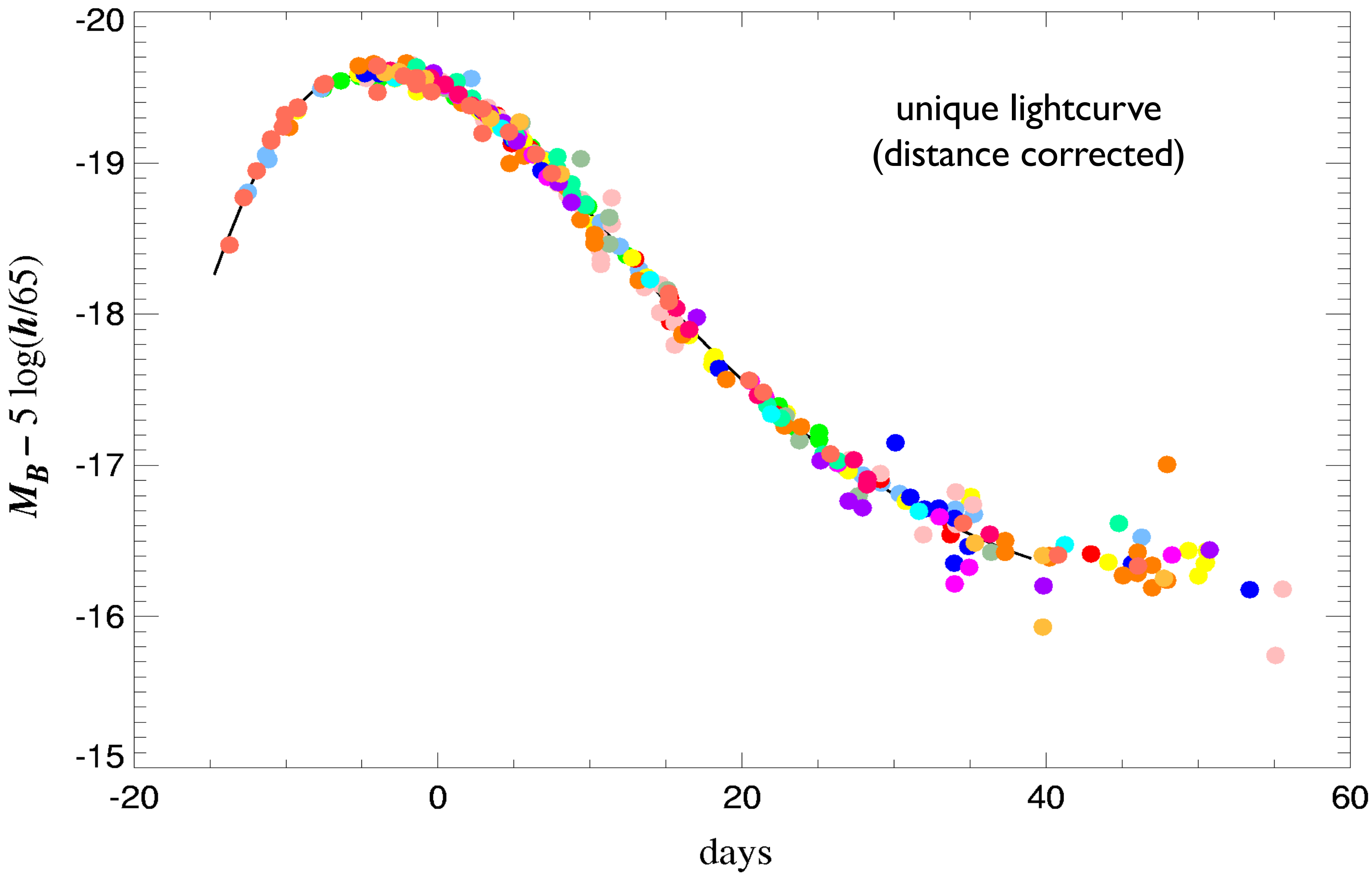

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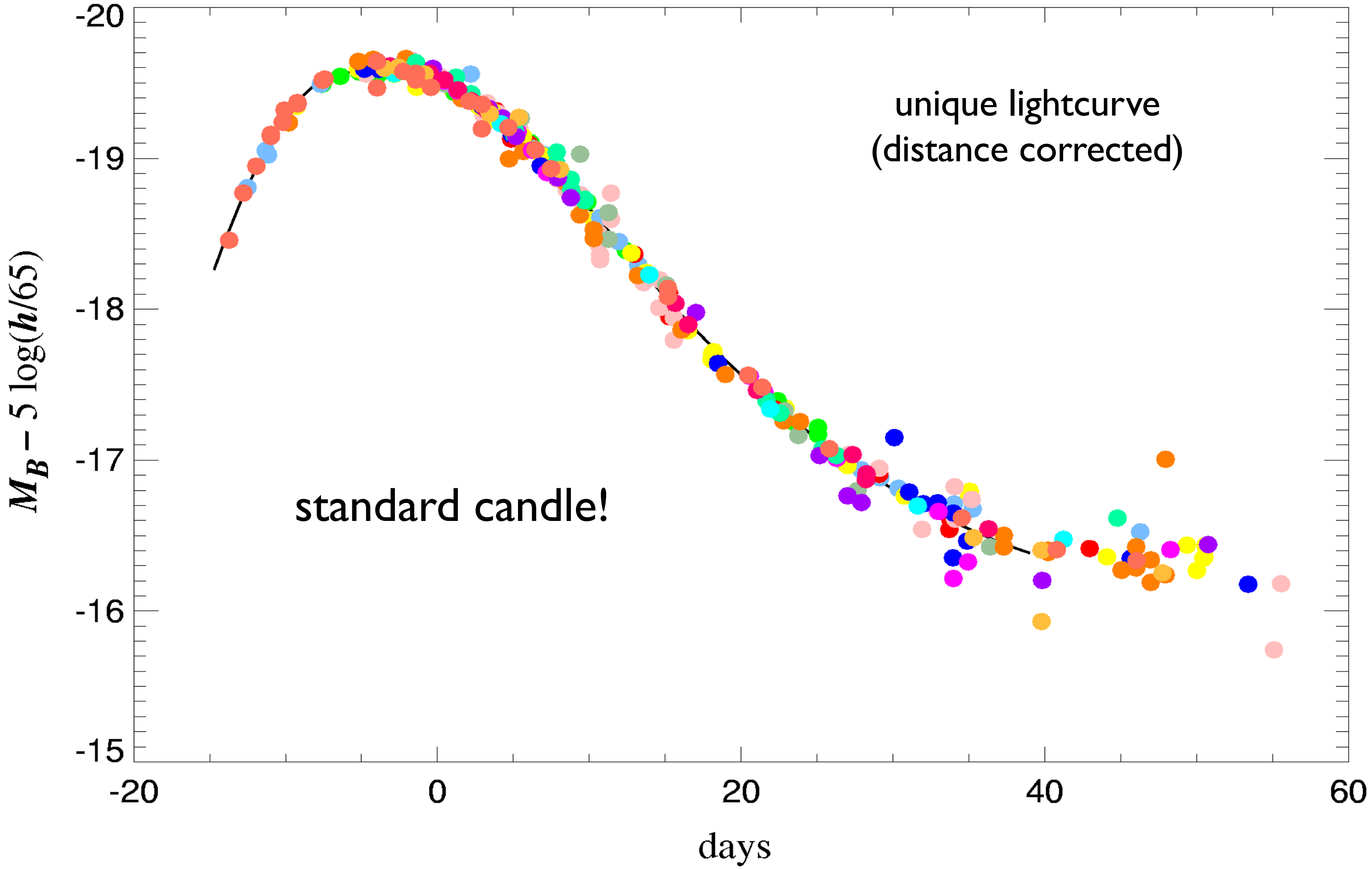

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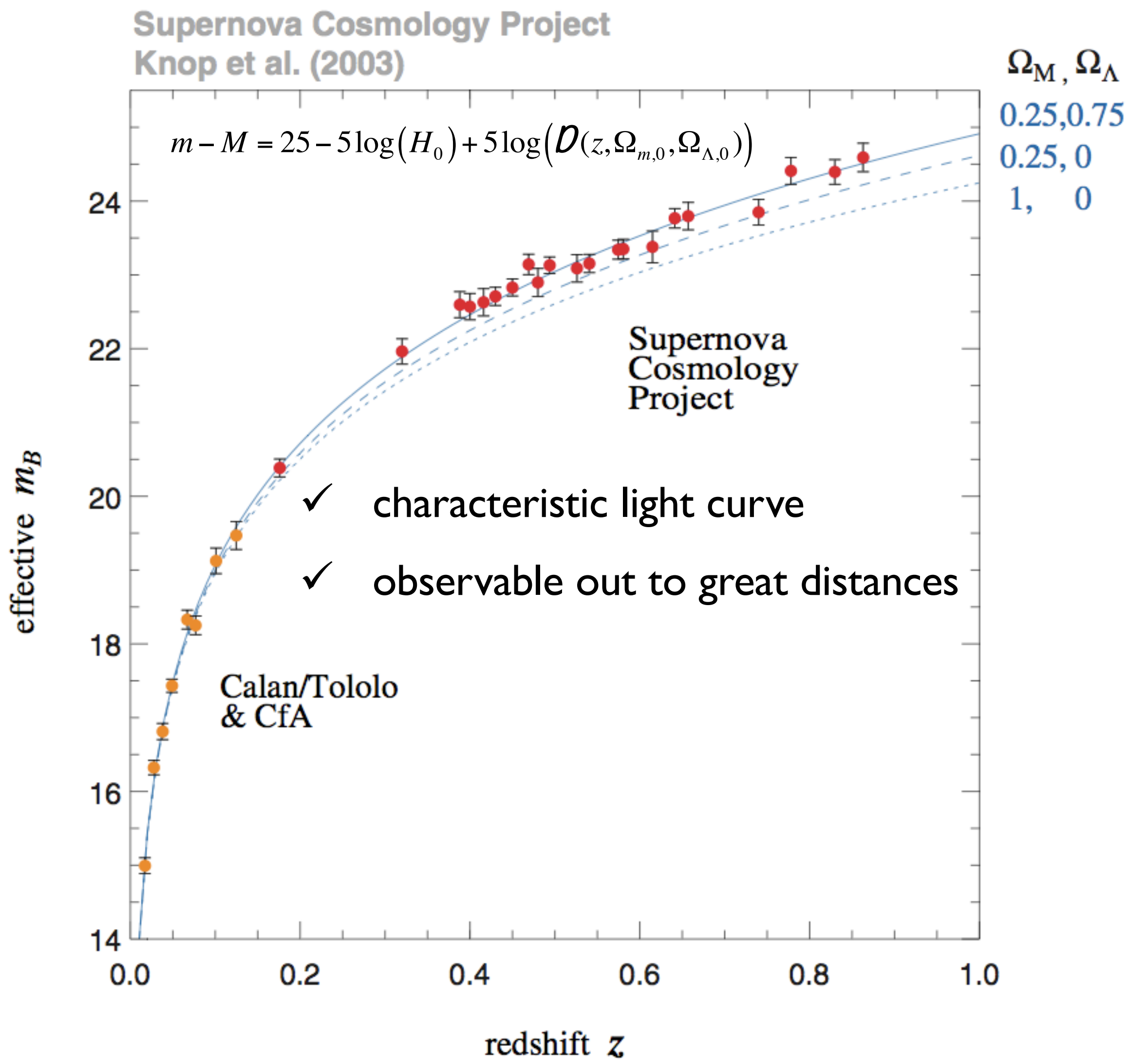
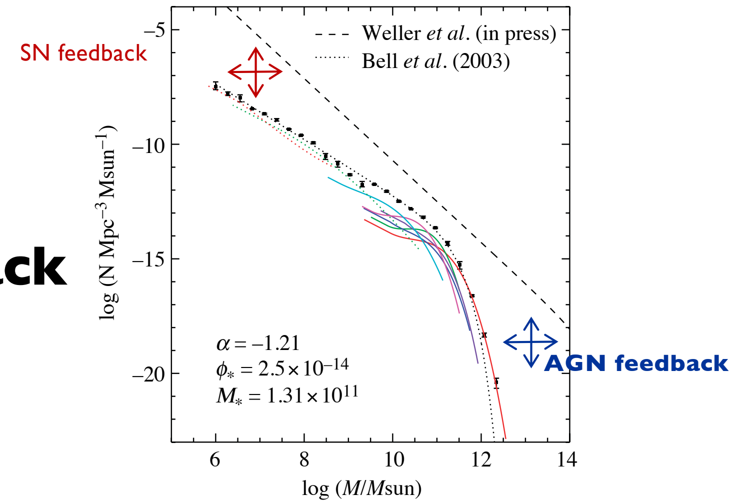


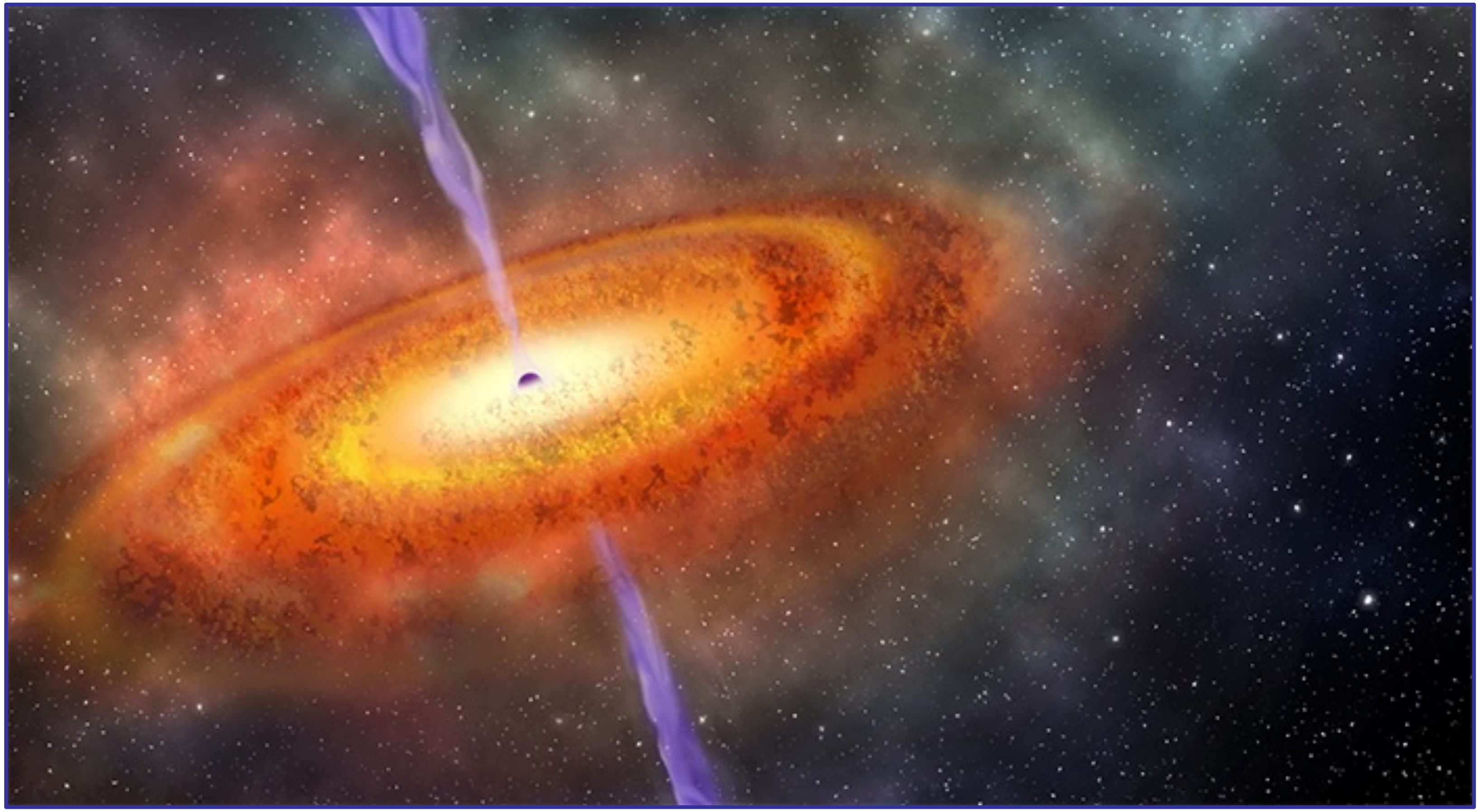
✓ characteristic light curve

✓ observable out to great distances

- biased galaxy formation
- **internal baryonic processes:**
  - supernova feedback
  - **active galactic nuclei feedback**
- dwarf galaxies



- <u>active galactic nuclei</u>



▪ active galactic nuclei – history

- first observed late 1950s as radio sources
- first visible counterpart found by Maarten Schmidt* in 1963

*died on 17/09/2022

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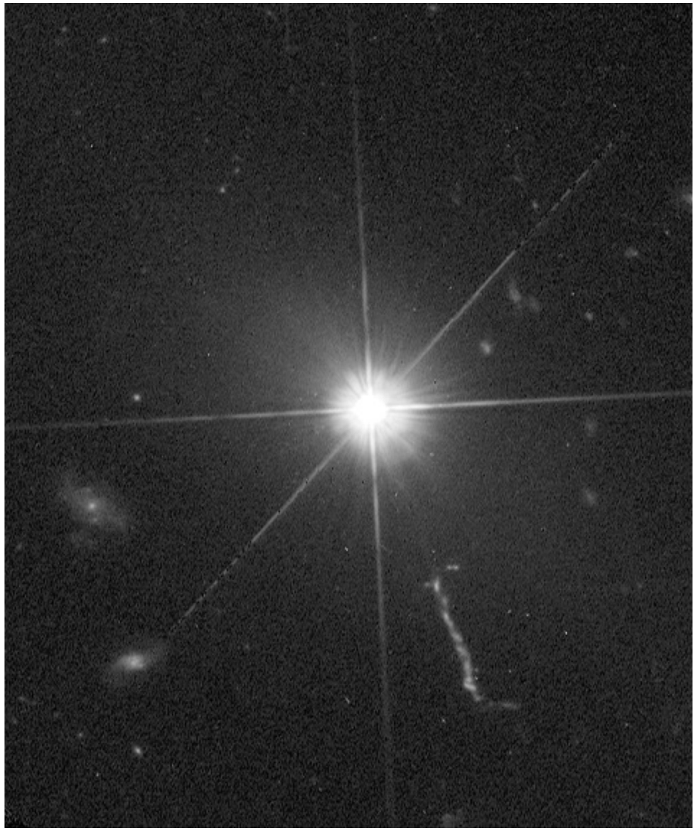

(1963)

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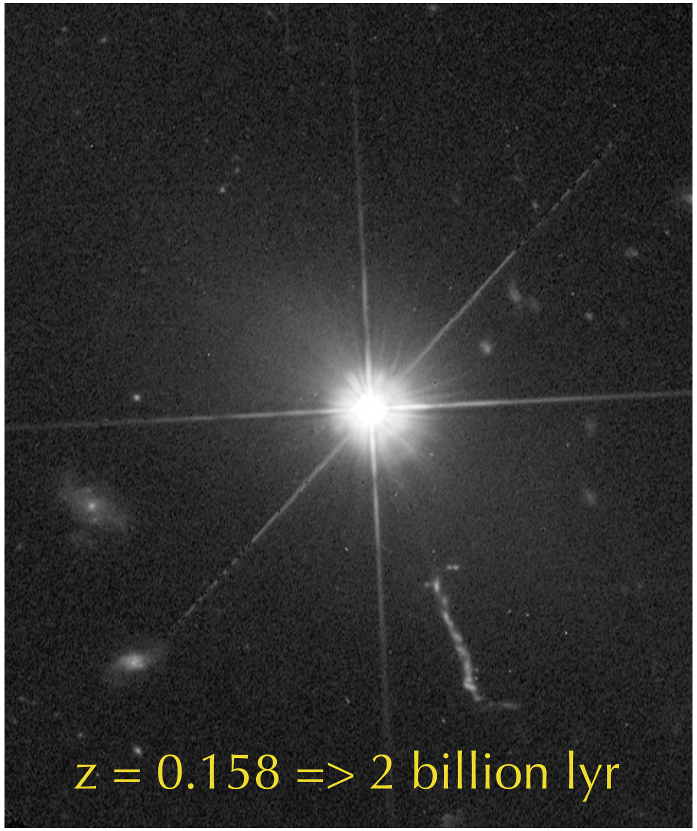

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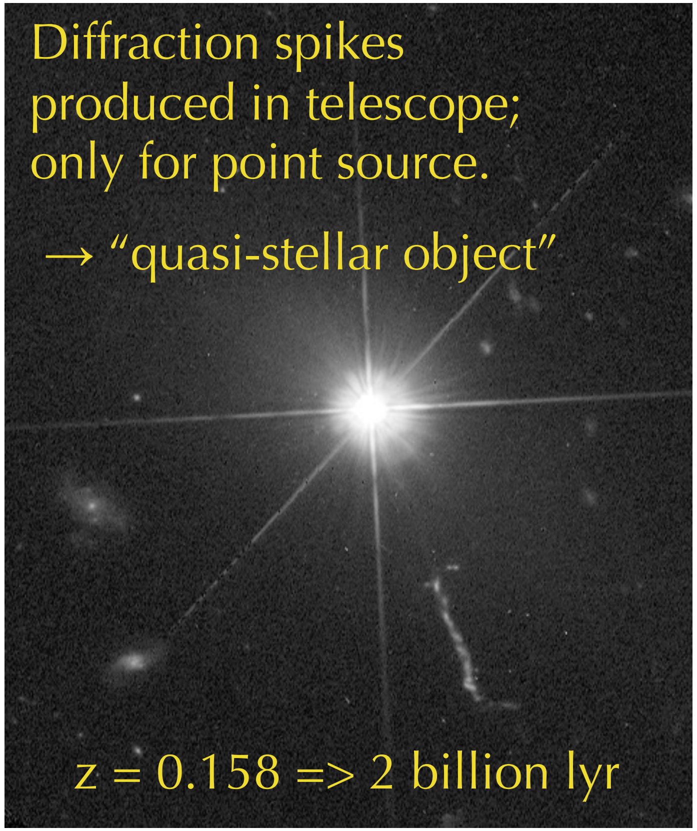

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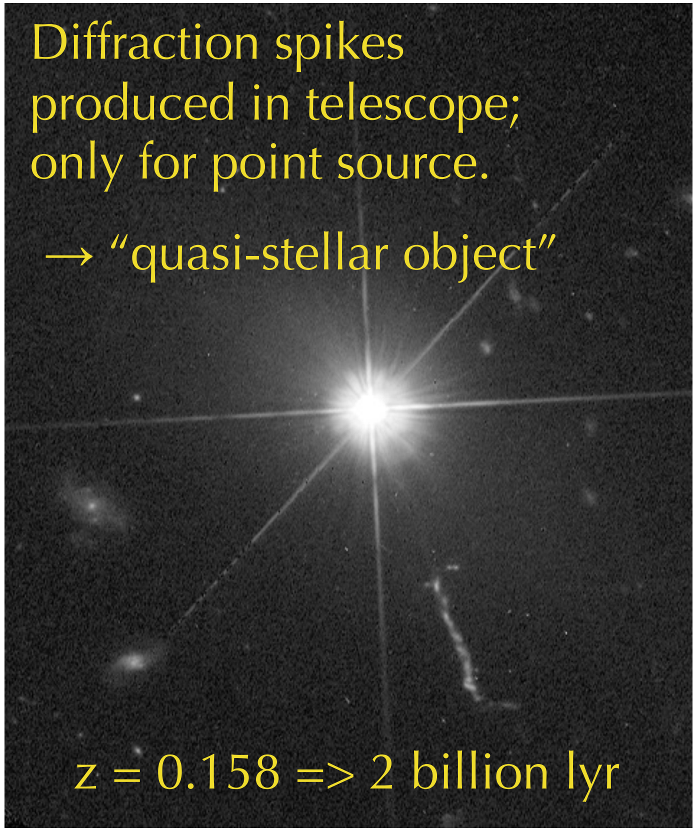

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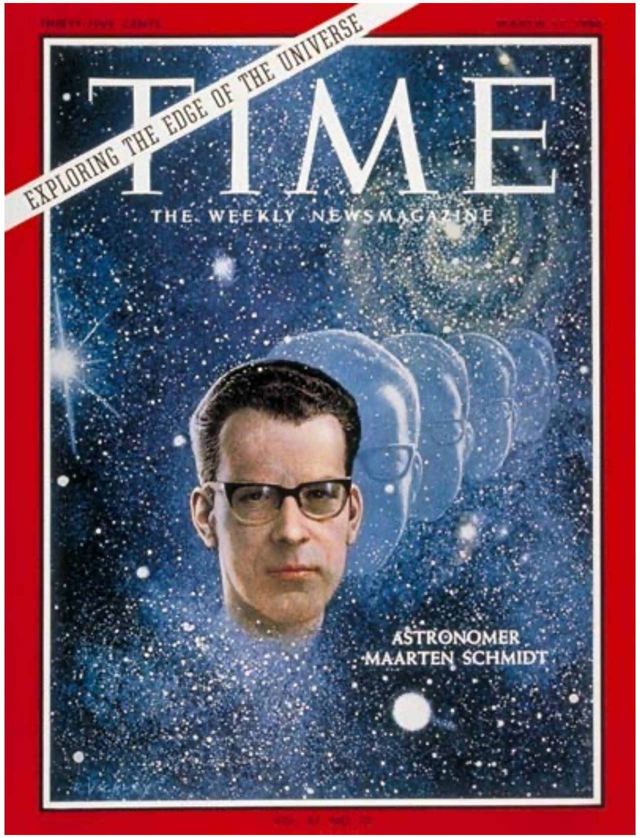

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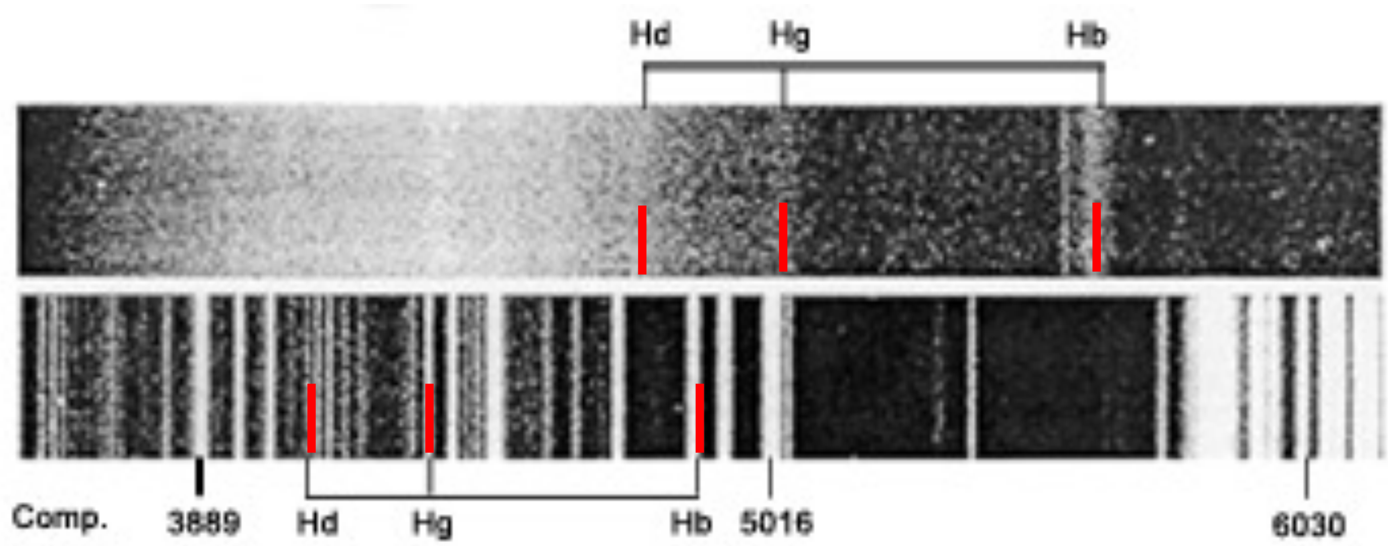

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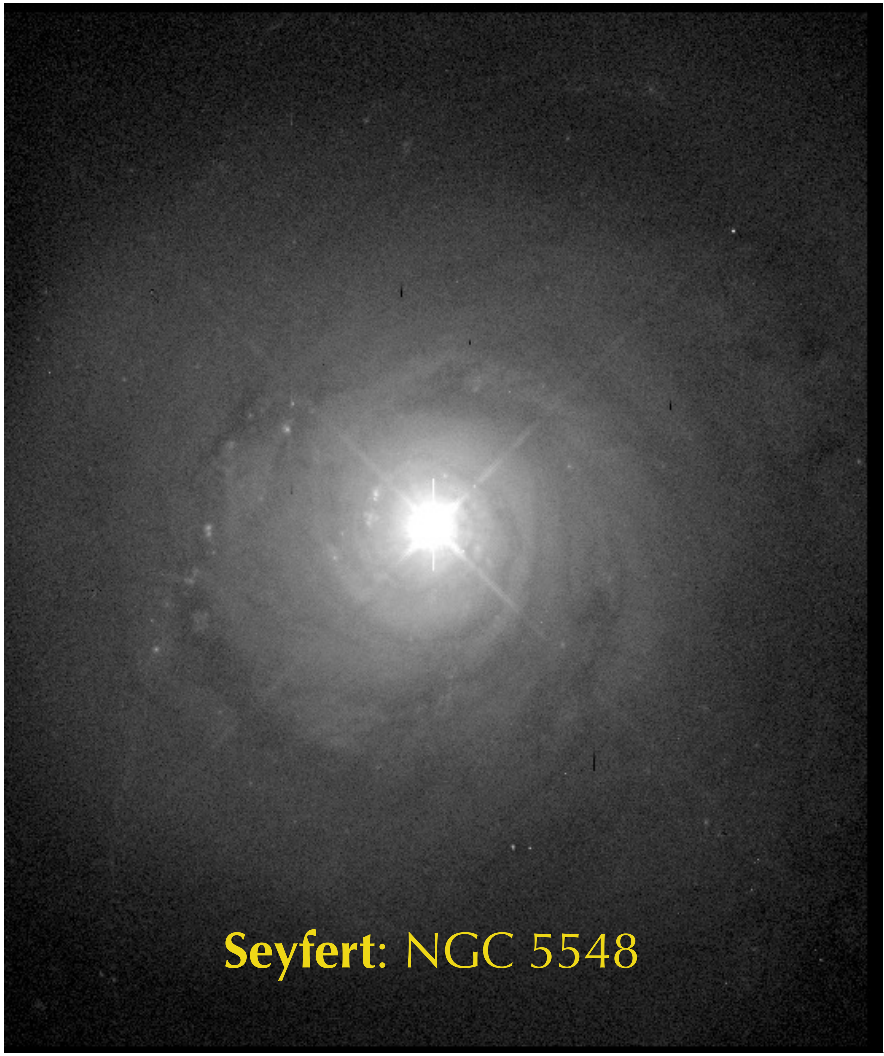

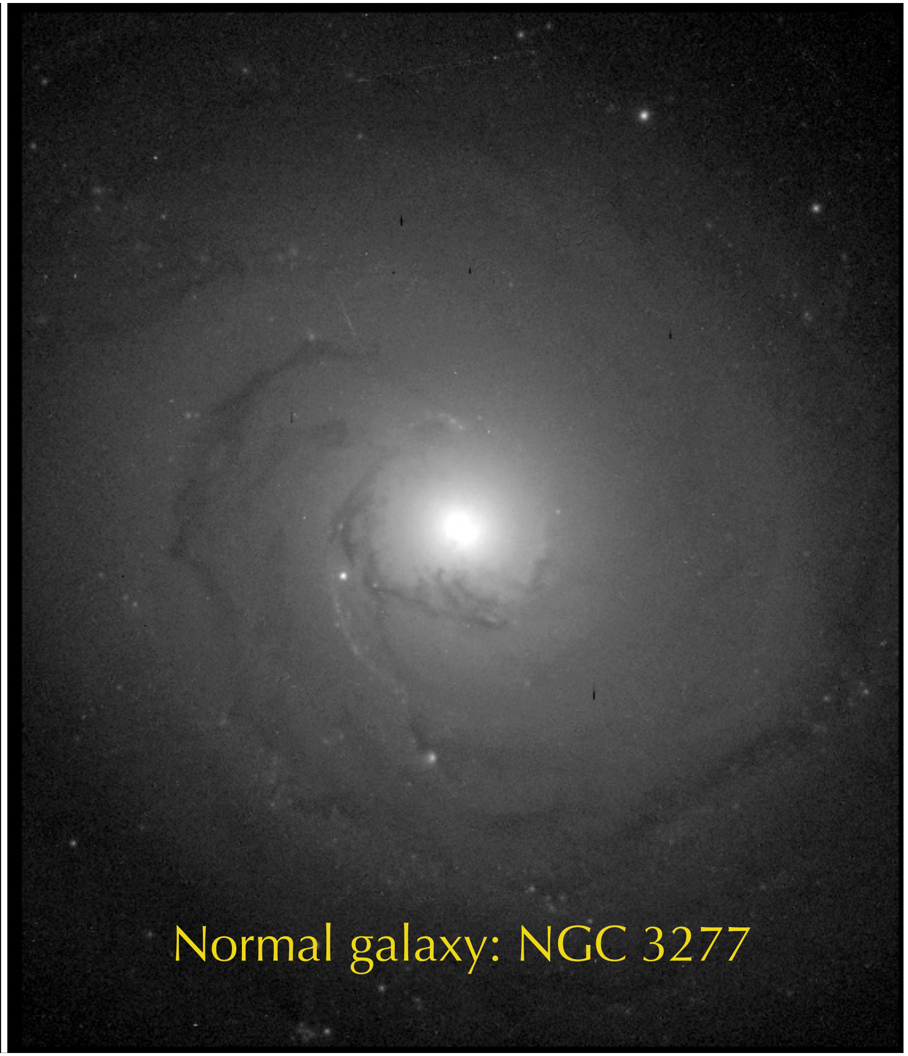

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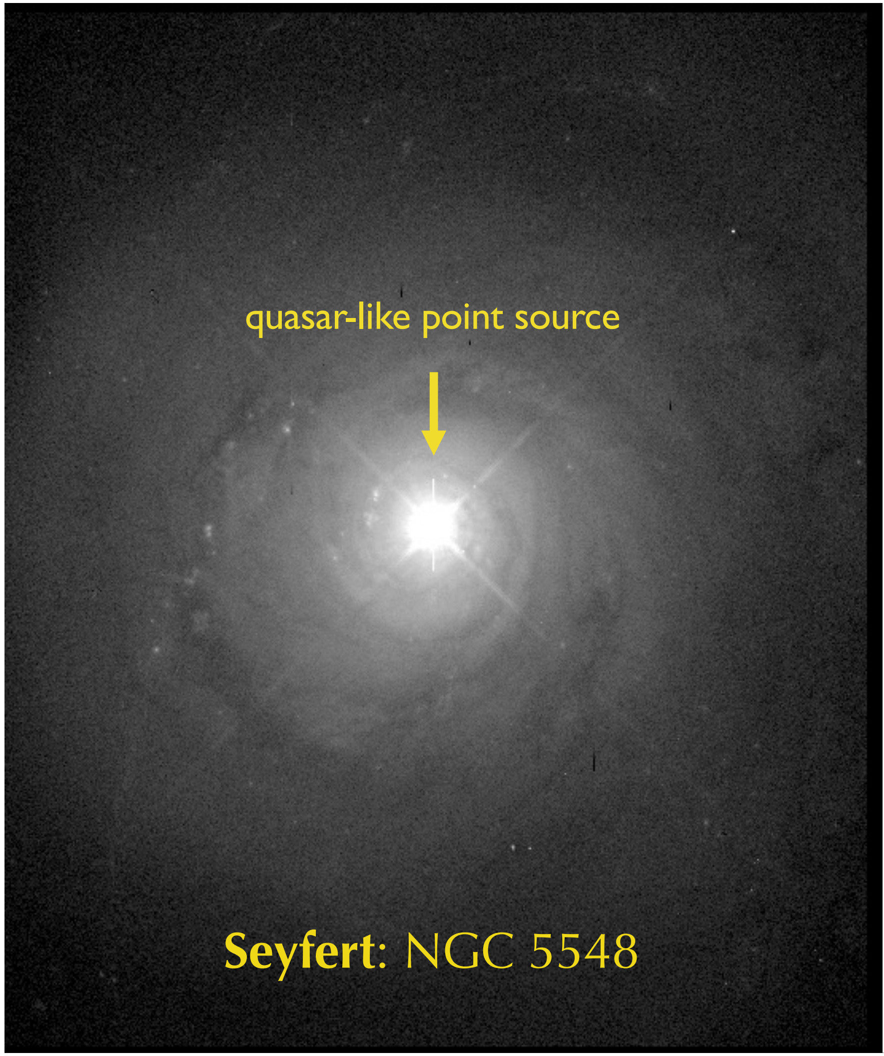

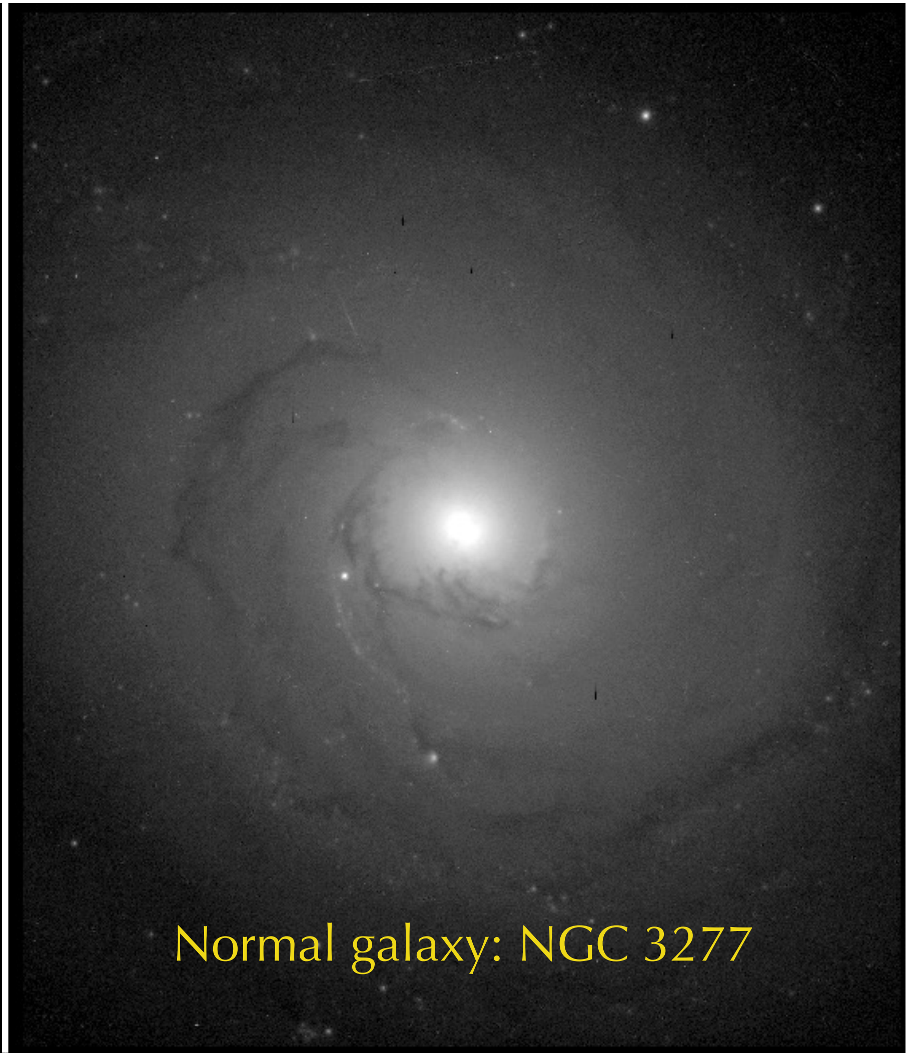

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what else do we observe?

▪ active galactic nuclei – observed properties

- strong, point-like nucleus
- highly luminous (outshining host galaxy)
- SED very different to stars or galaxies
- signatures of highly excitated elements (e.g. O[VI], C[IV], ...)
- broad emission lines suggesting high internal velocities
- high variability (in X-rays)

circular logic: AGN is already the explanation for all this...

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different types of objects with similar properties →

▪ active galactic nuclei – types

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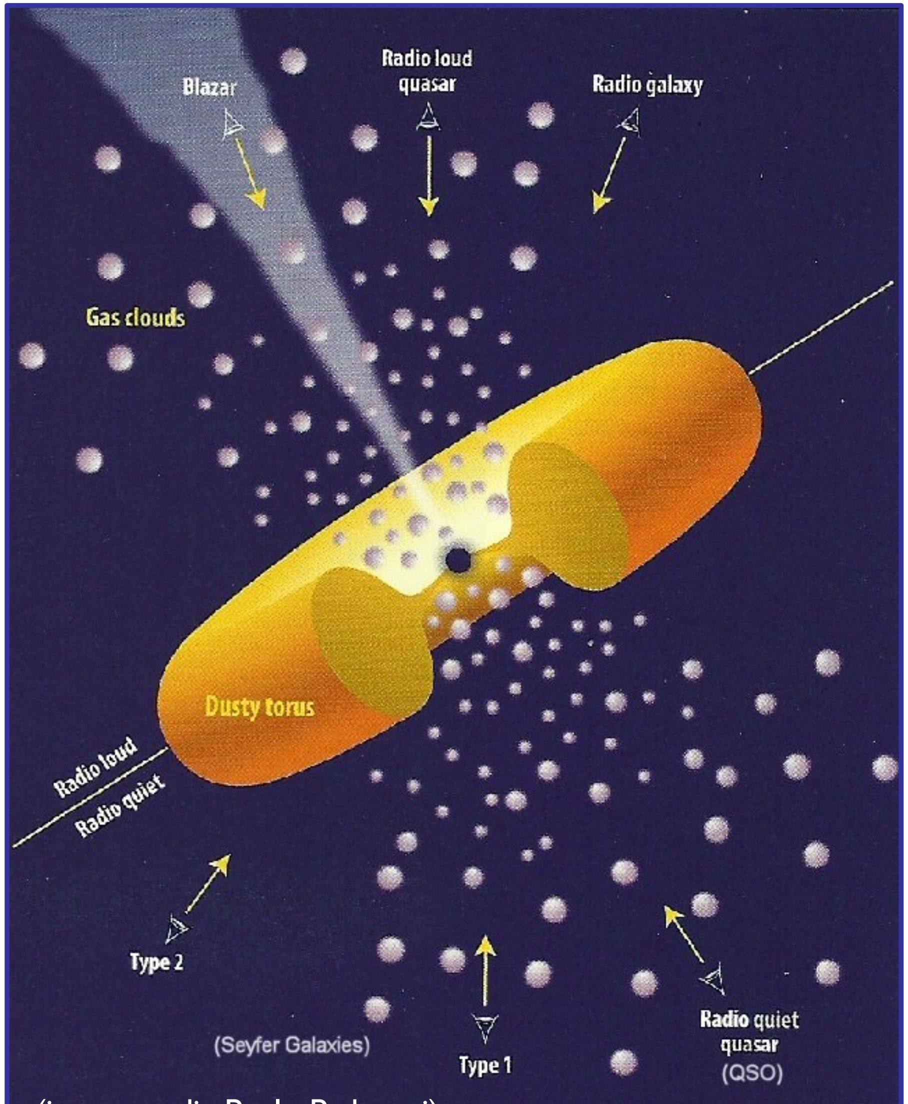
- <u>active galactic nuclei – types</u>

all the same,

just seen from different angles...



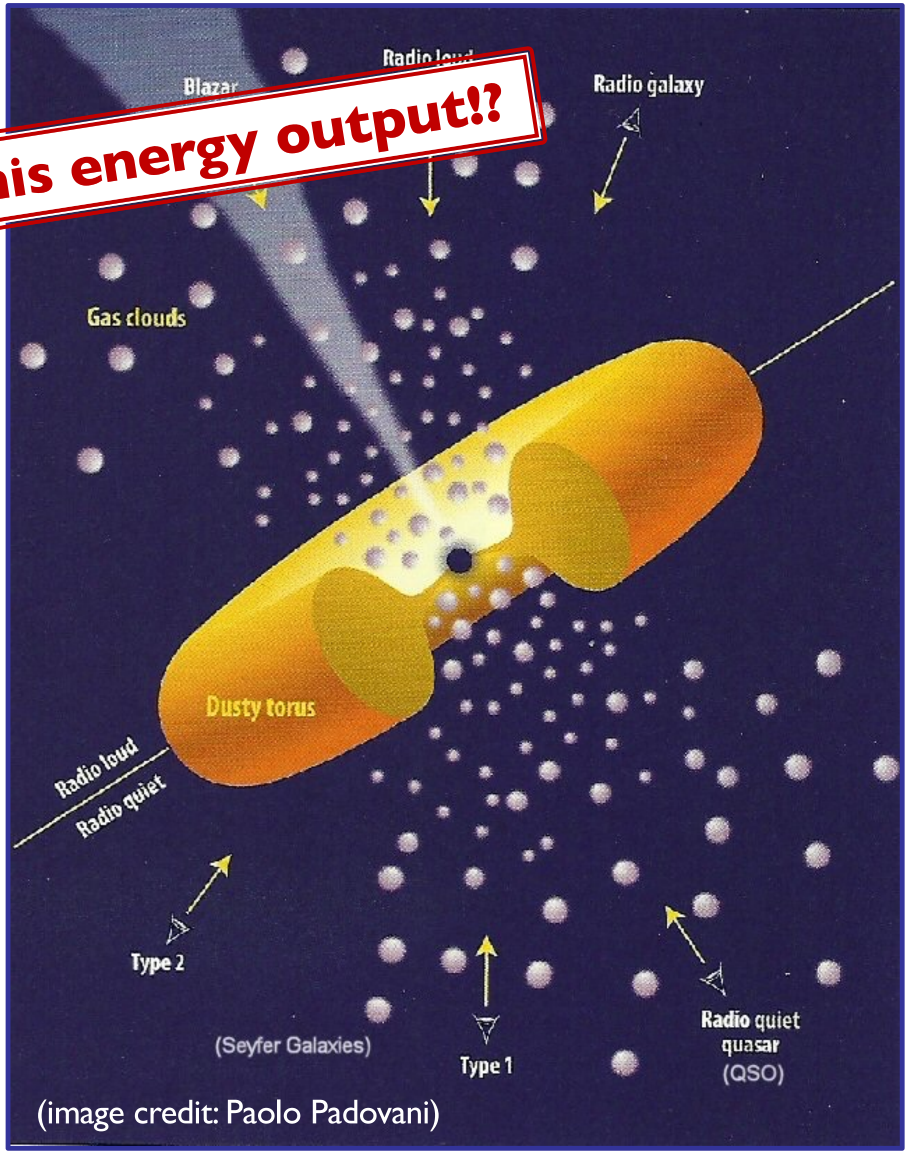
(image credit: Paolo Padovani)

- <u>active galactic nuclei – types</u>

but what powers this energy output!?

all the same,

just seen from different angles...



(image credit: Paolo Padovani)

▪ active galactic nuclei – model(s)

- accretion of mass onto black hole (M_{bh}~10^6-$10^{10}M_{\odot}$)
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black-hole mergers (driving cold gas to centre, 'quasar mode')

$$\Delta m_{bh} = \frac{\kappa_{bh} m_{cold}}{1+\left(\frac{280km/s}{V_{vir}}\right)^2}$$

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(cf. Croton et al. 2016)

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$$\Delta E_{kin} = -\frac{1}{2}\Delta E_{pot}$$

(***exercise***)

▪ active galactic nuclei – model(s)

- accretion of mass onto black hole (M_{bh}~10^6-$10^{10}M_\odot$)
- **gravitational collapse releases energy**

$$\Delta E_{kin} = -\frac{1}{2}\Delta E_{pot}$$ (***exercise***)

only half of the gained potential energy is converted into kinetic energy!

the remaining half is released...

- active galactic nuclei – feedback
  - the energy output from the AGN impacts its environment

▪ active galactic nuclei – feedback

- the energy output from the AGN impacts its environment via
  - radiation
  - particle winds
  - plasma jets

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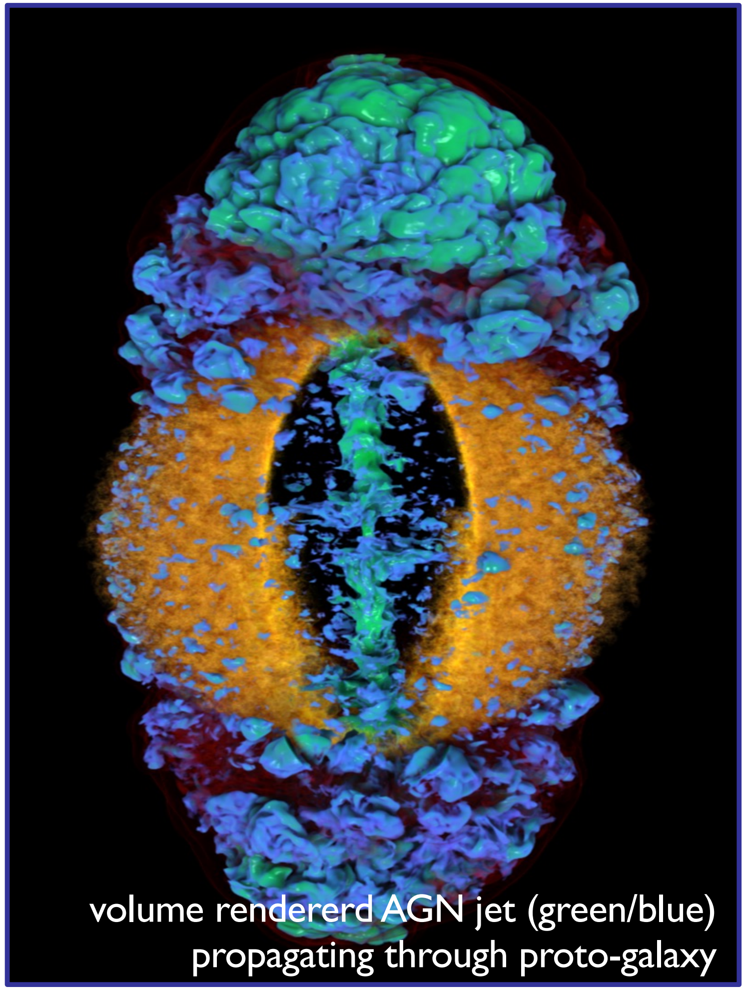

volume rendererd AGN jet (green/blue) propagating through proto-galaxy

(image credit: Ajay Limaye)

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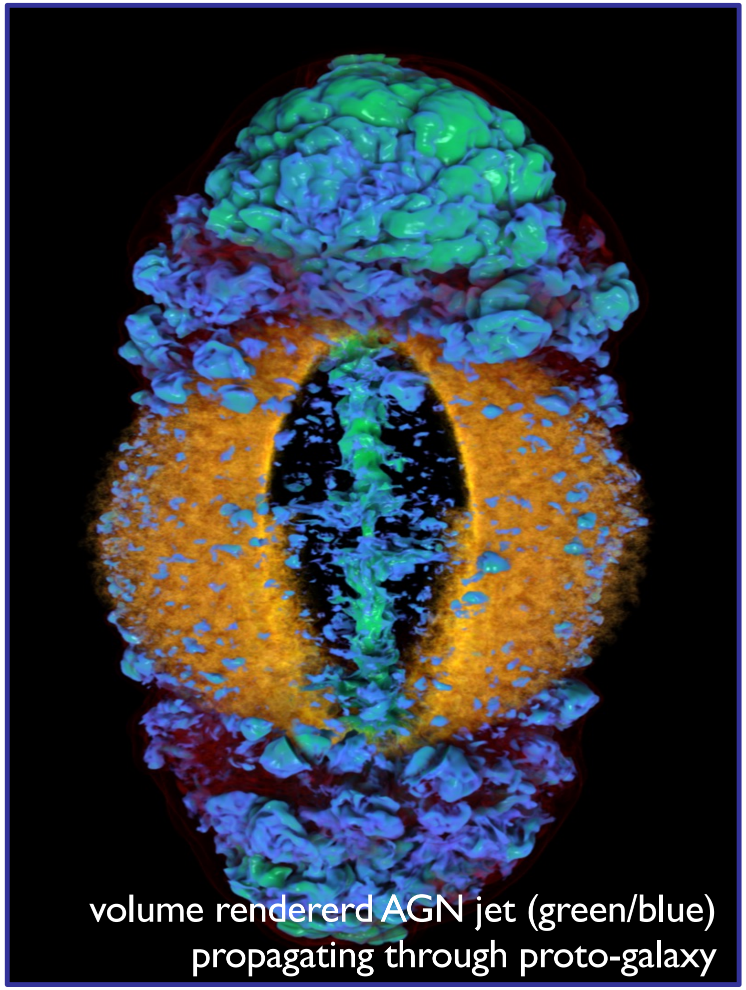
  → prevents gas cooling, and/or

  → expells gas...



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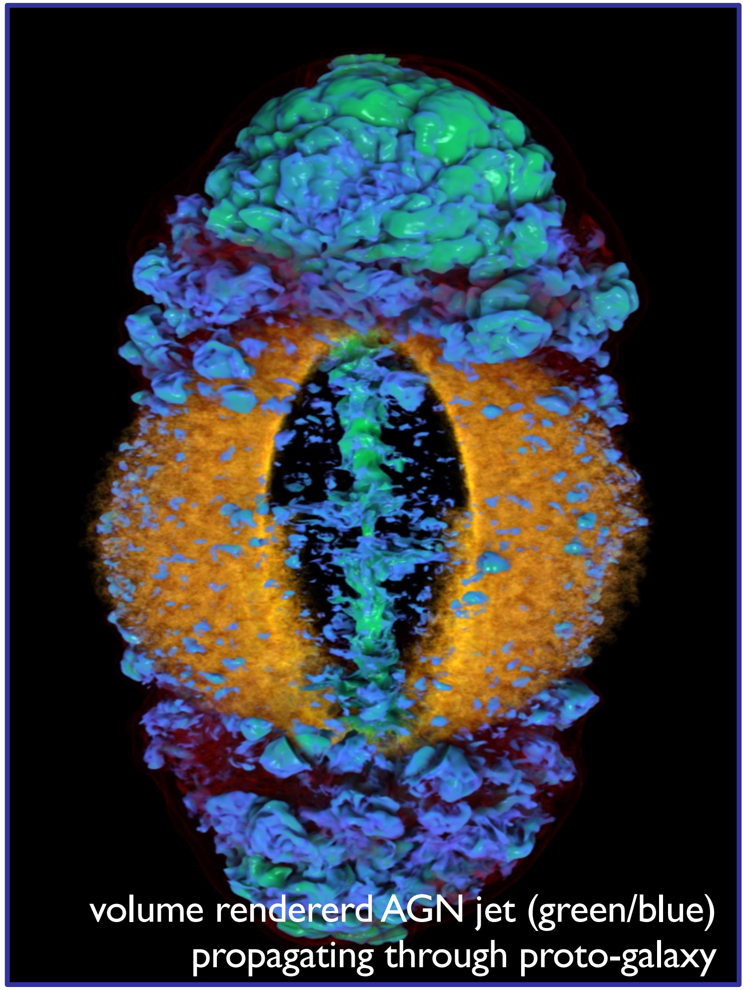
...on galactic scales!*



volume rendererd AGN jet (green/blue) propagating through proto-galaxy

(image credit: Ajay Limaye)

*and even on galaxy clusters scales (cf. Galaxy Cluster lecture)

▪ active galactic nuclei – feedback

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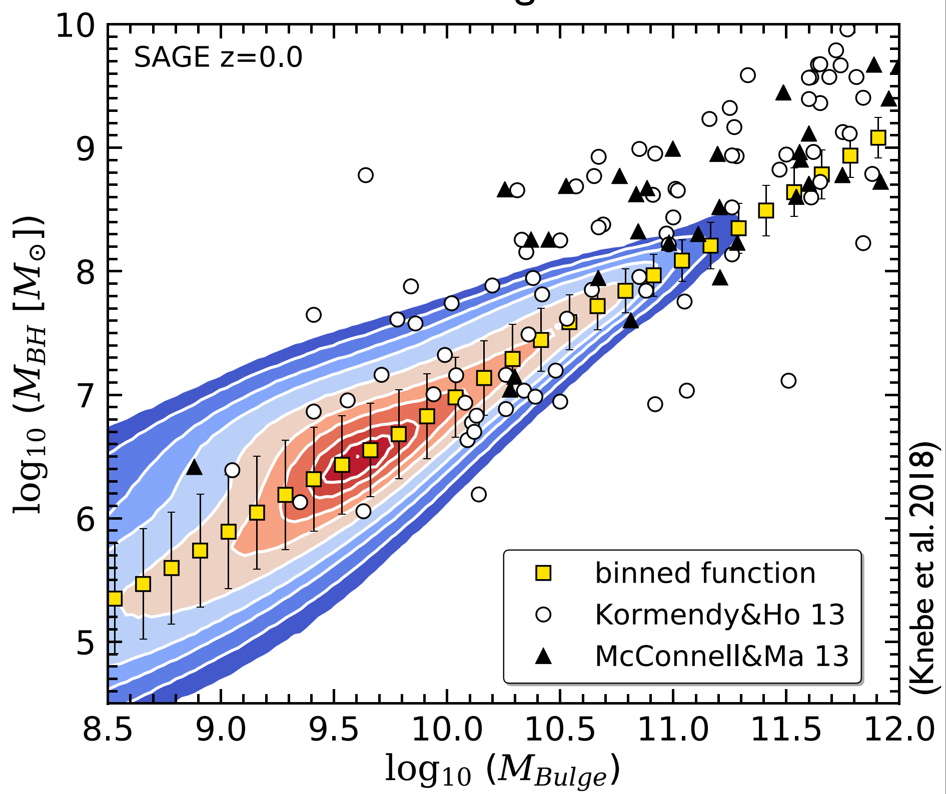
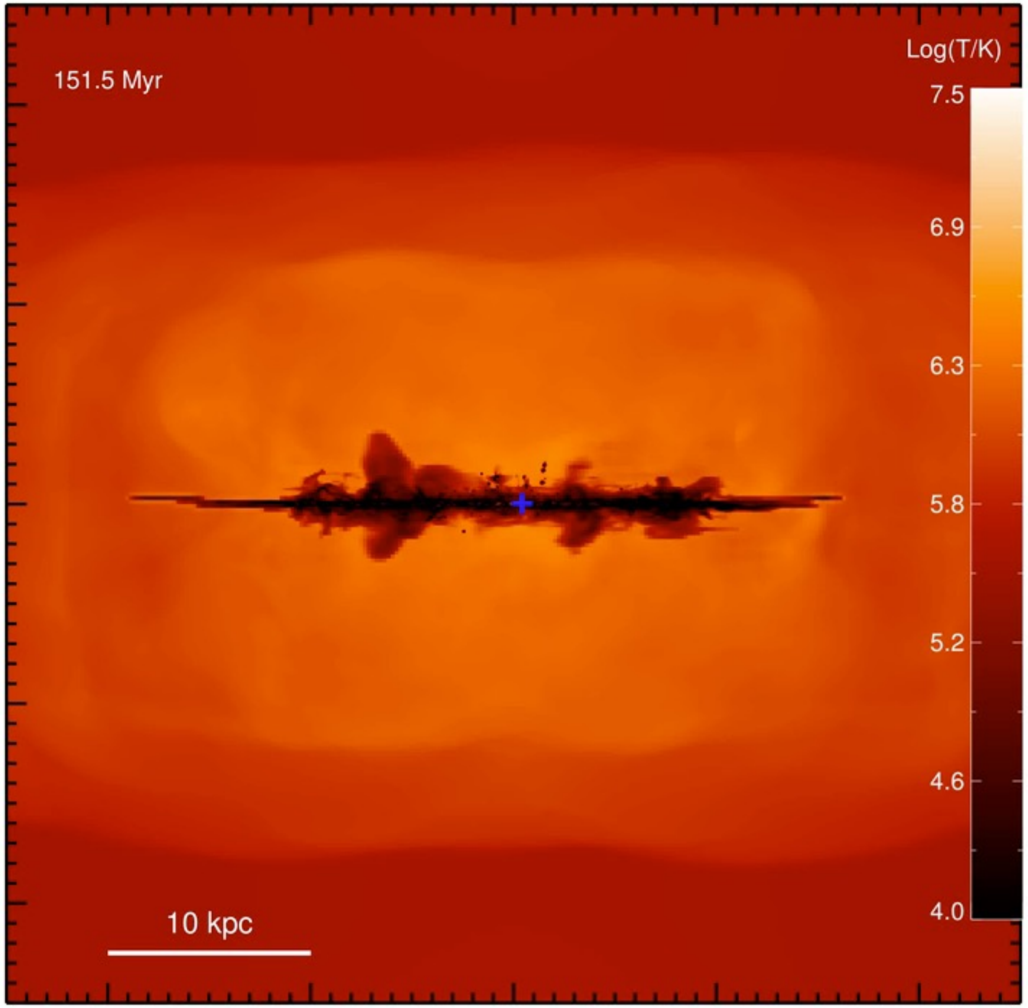
…on galactic scales!

black hole – bulge mass relation



- active galactic nuclei – feedback

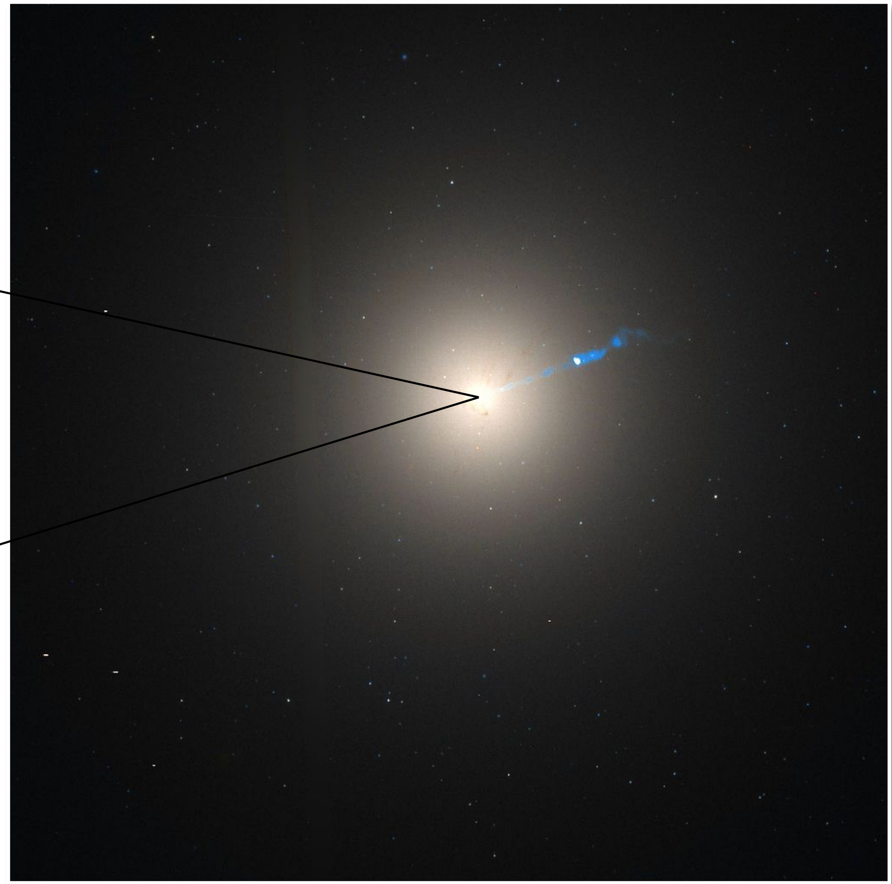


(Gabor & Bournaud 2014)

▪ active galactic nuclei – problem

how to form these super-massive black holes in the first place?

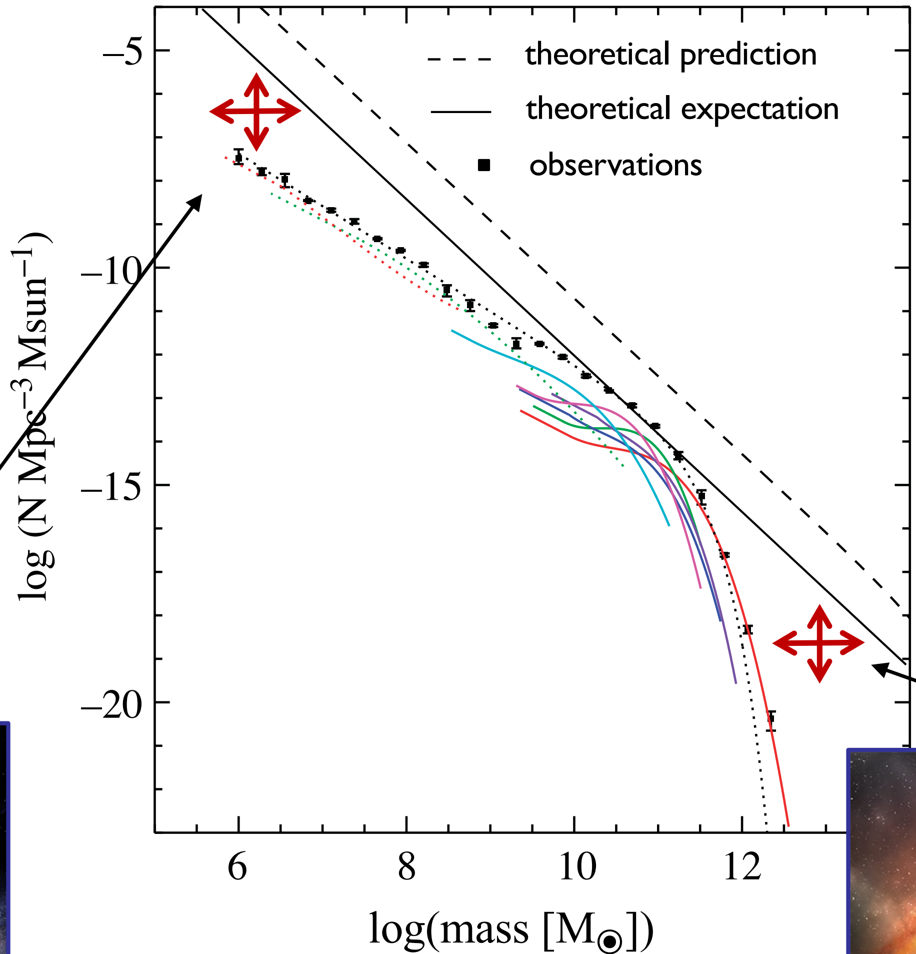
(SMBH with $M_{\rm bh} \sim 10^9\ {\rm M}_\odot$)

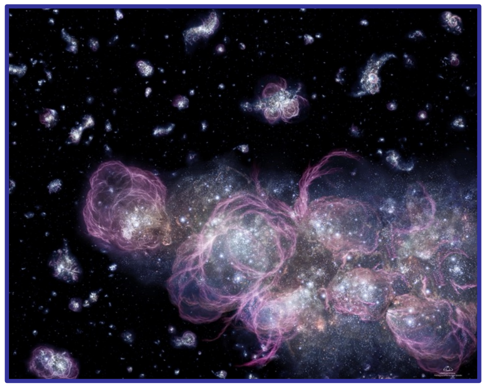


(M87, featuring a plasma jet)

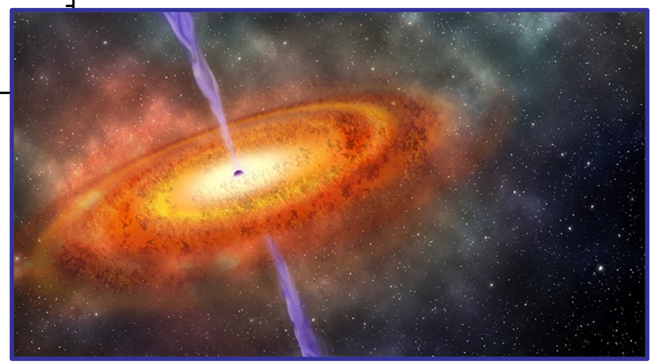
- biased galaxy formation
- **internal baryonic processes:**
  - ✓ *supernova feedback*
  - ✓ *active galactic nuclei feedback*
- dwarf galaxies

radiative processes prevent star formation!





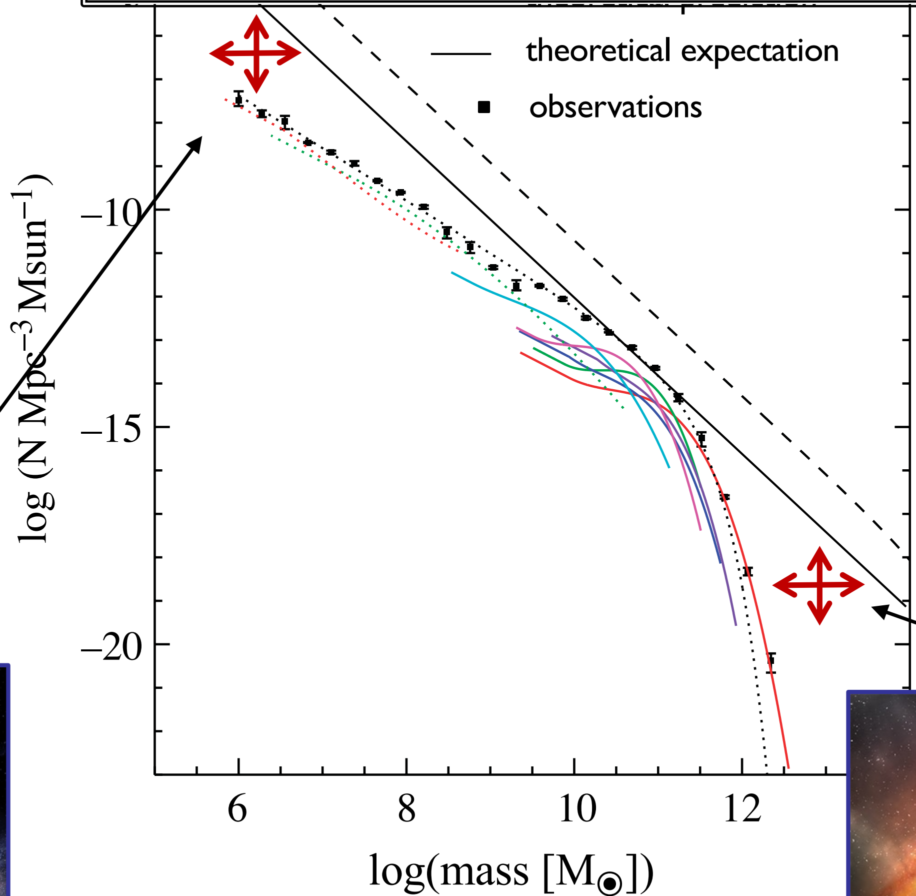
SN explosions

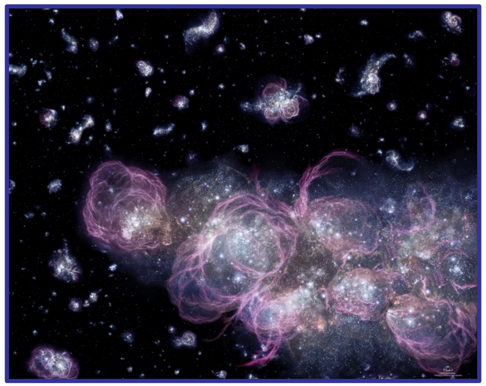


AGN

radiative processes prevent star formation!

is that the only consequence?





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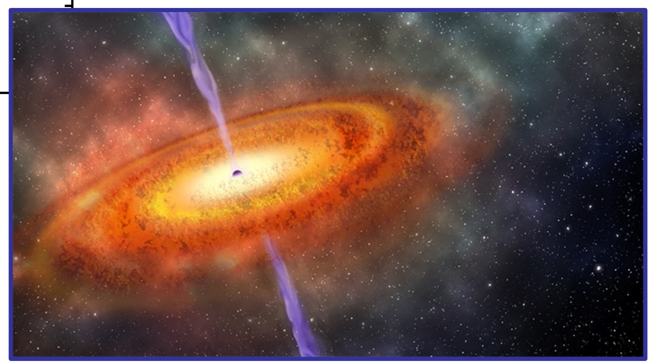

AGN

- influence of (internal) baryonic processes – cusp-core crisis

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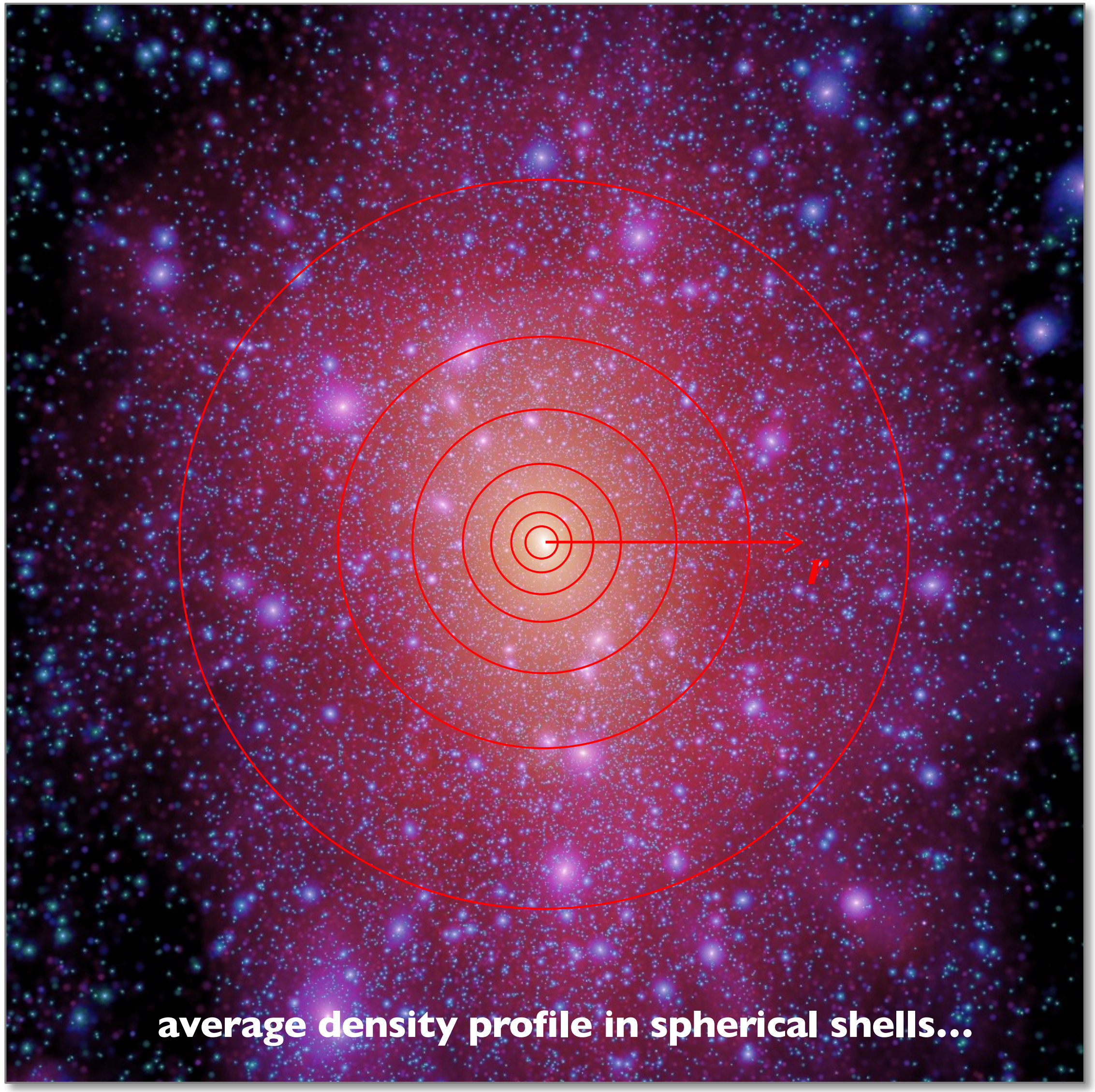
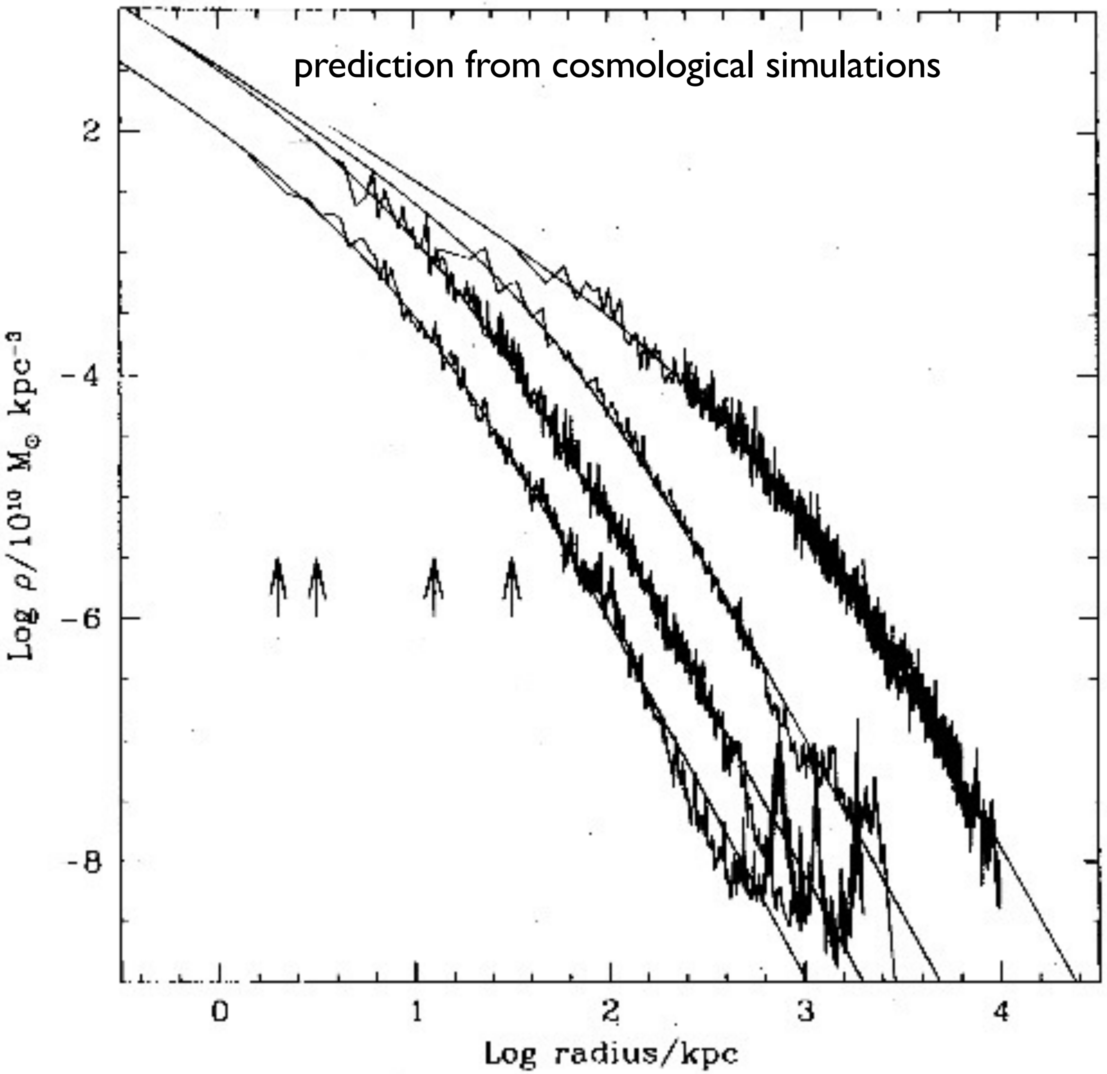


(dark matter halo 'Aquarius-A', Springel et al. 2008)

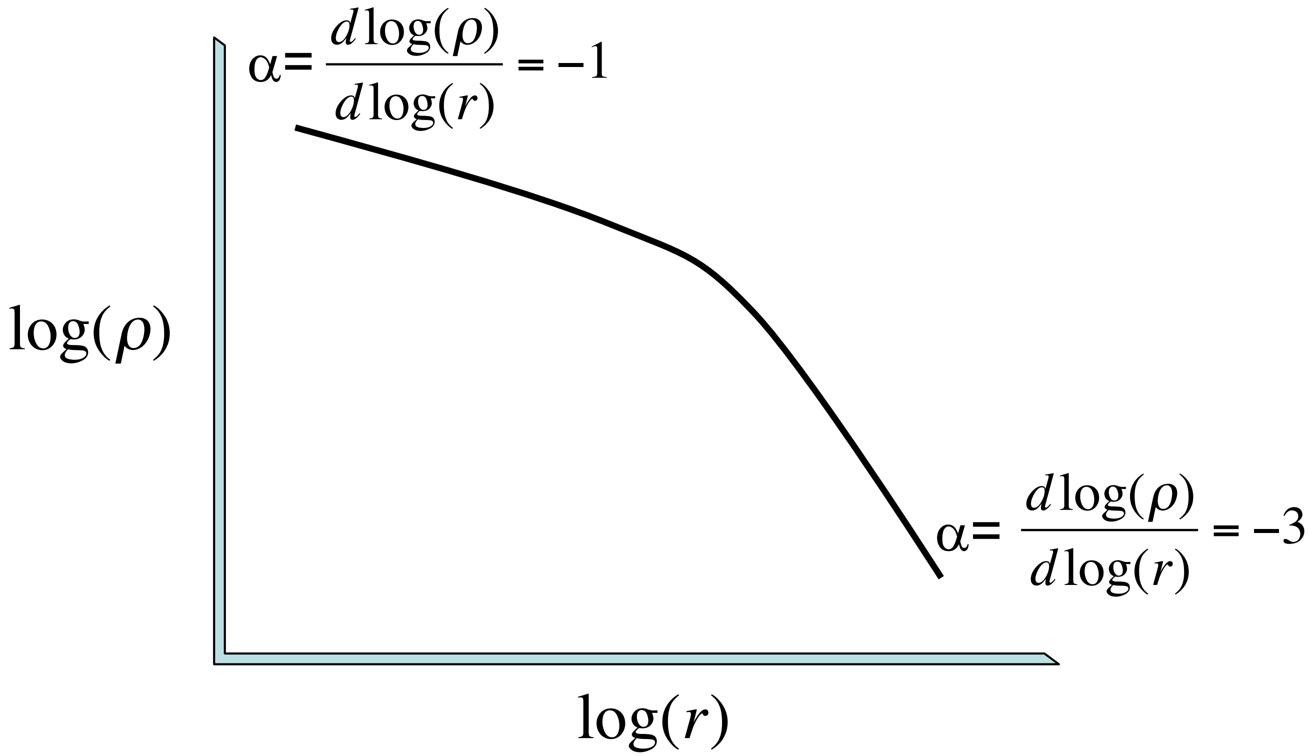
- influence of (internal) baryonic processes – cusp-core crisis



(Navarro, Frenk & White 1996)

- influence of (internal) baryonic processes – cusp-core crisis

prediction from cosmological simulations



- <u>influence of (internal) baryonic processes – cusp-core crisis</u>

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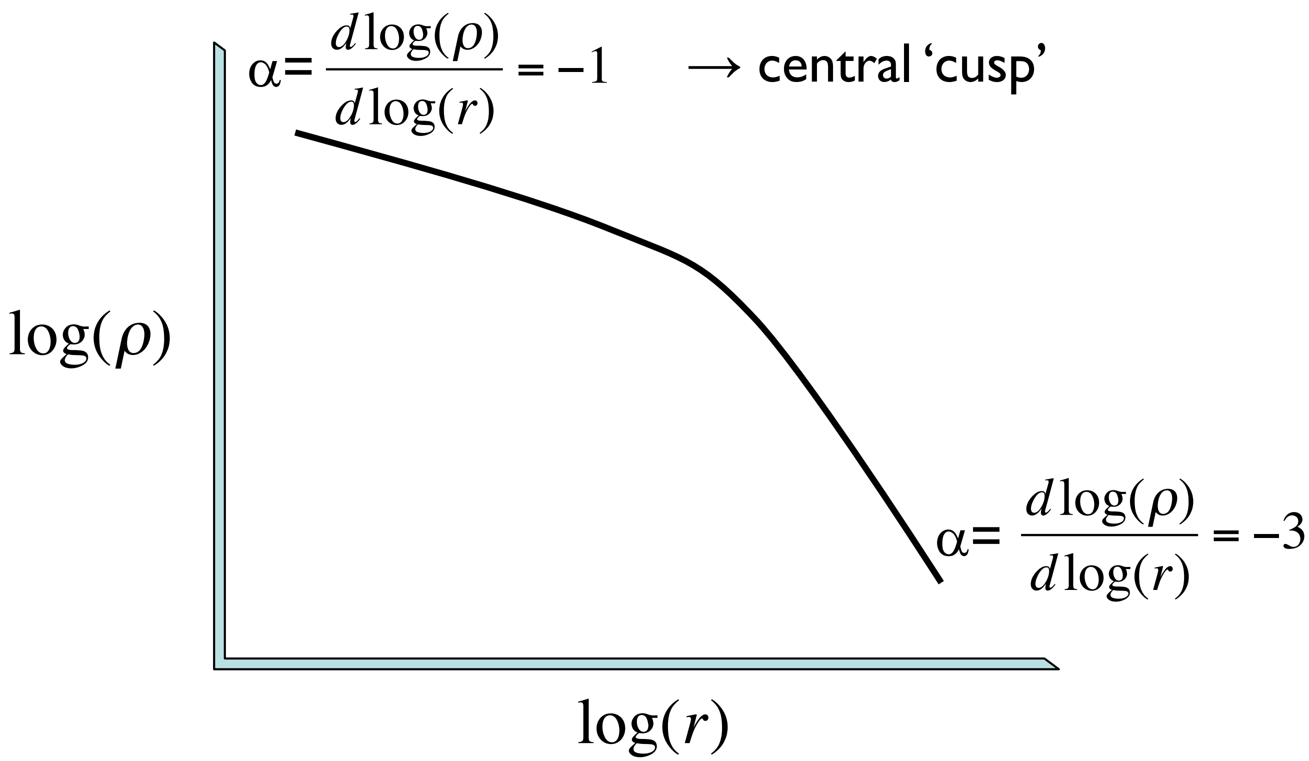
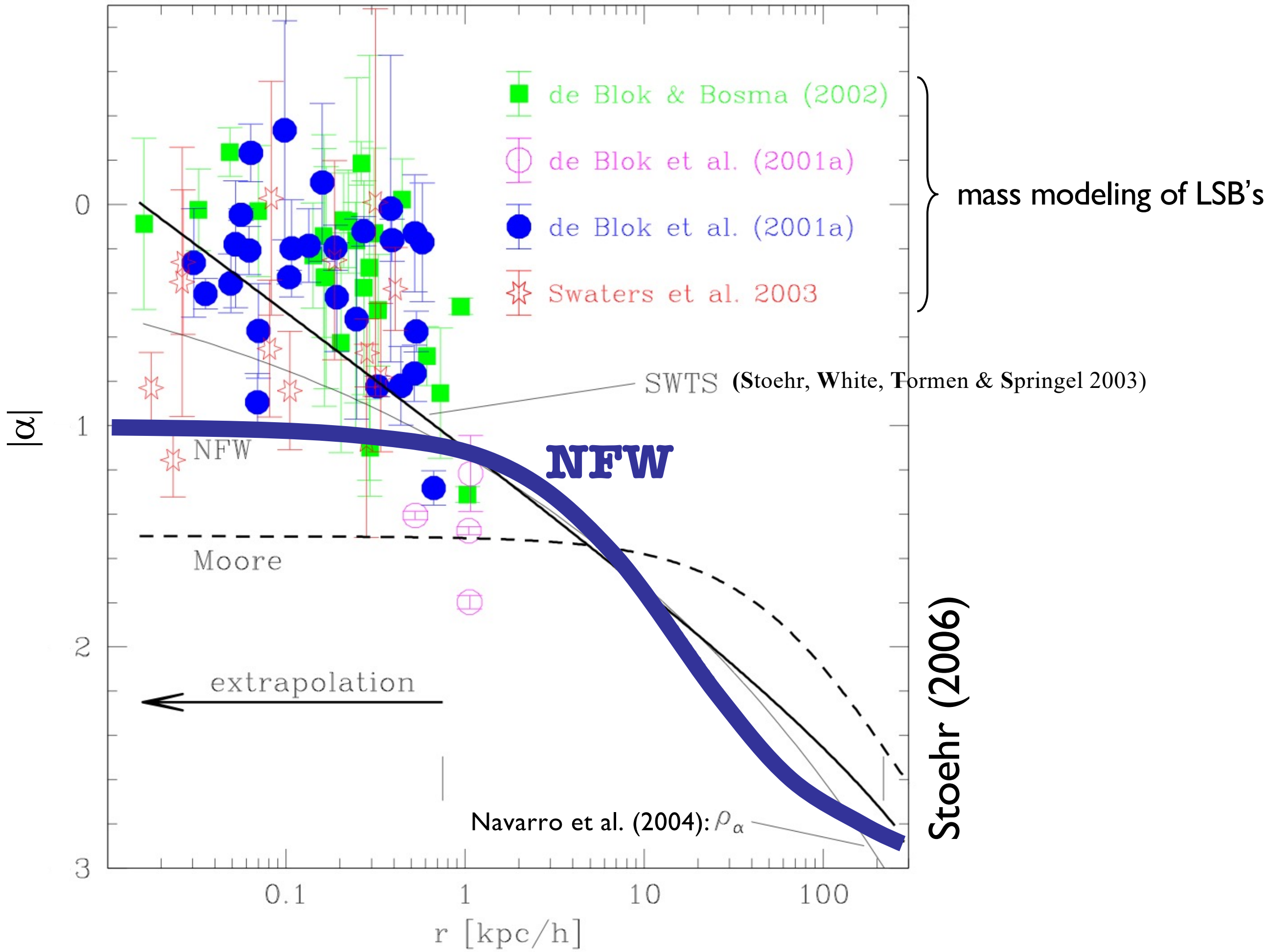


- influence of (internal) baryonic processes – cusp-core crisis

…but cusps do not comply with the dynamics of galaxies



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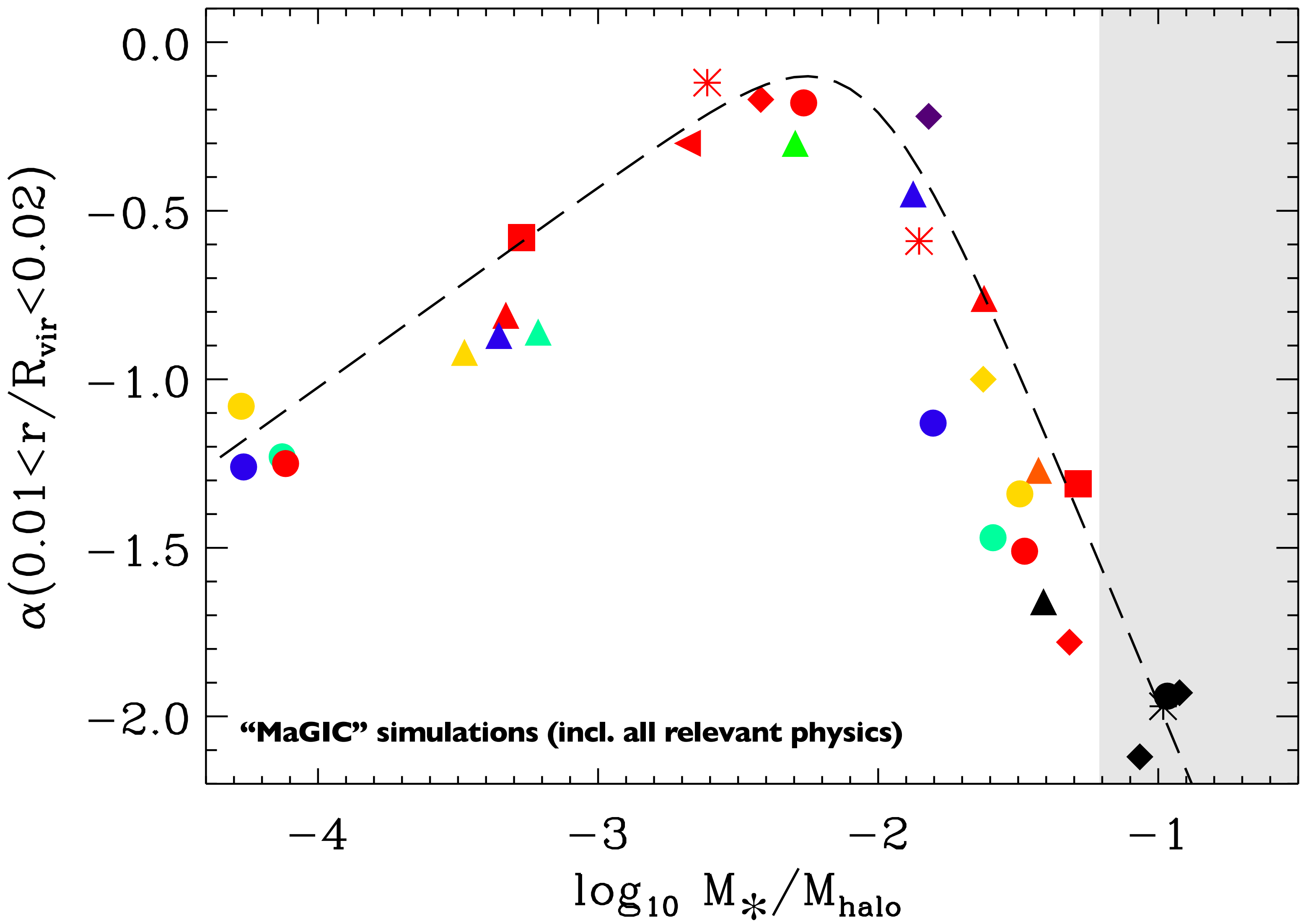
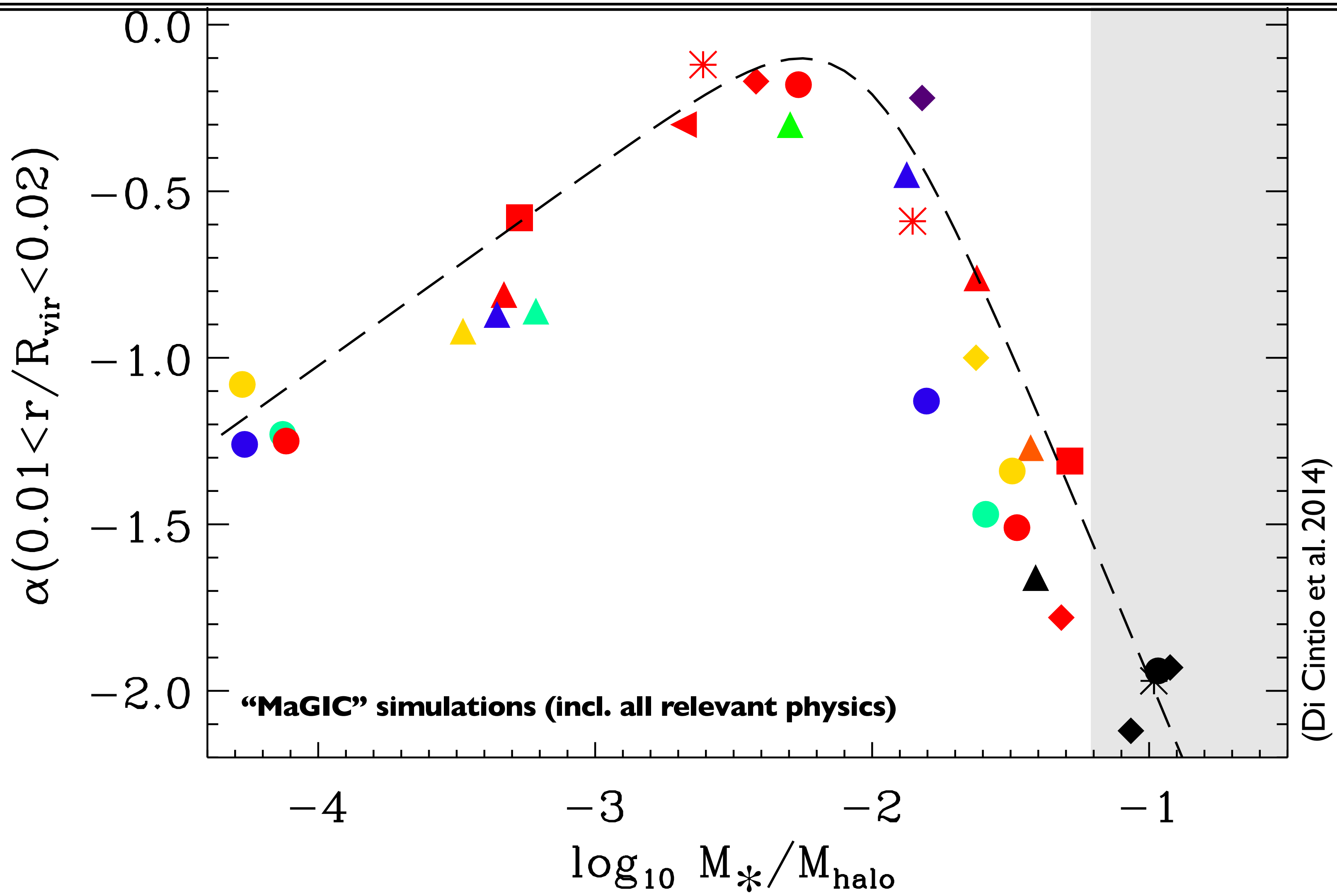


(Di Cintio et al. 2014)

- influence of (internal) baryonic processes

stellar feedback also affects the distribution of dark matter in the centres of galaxies…



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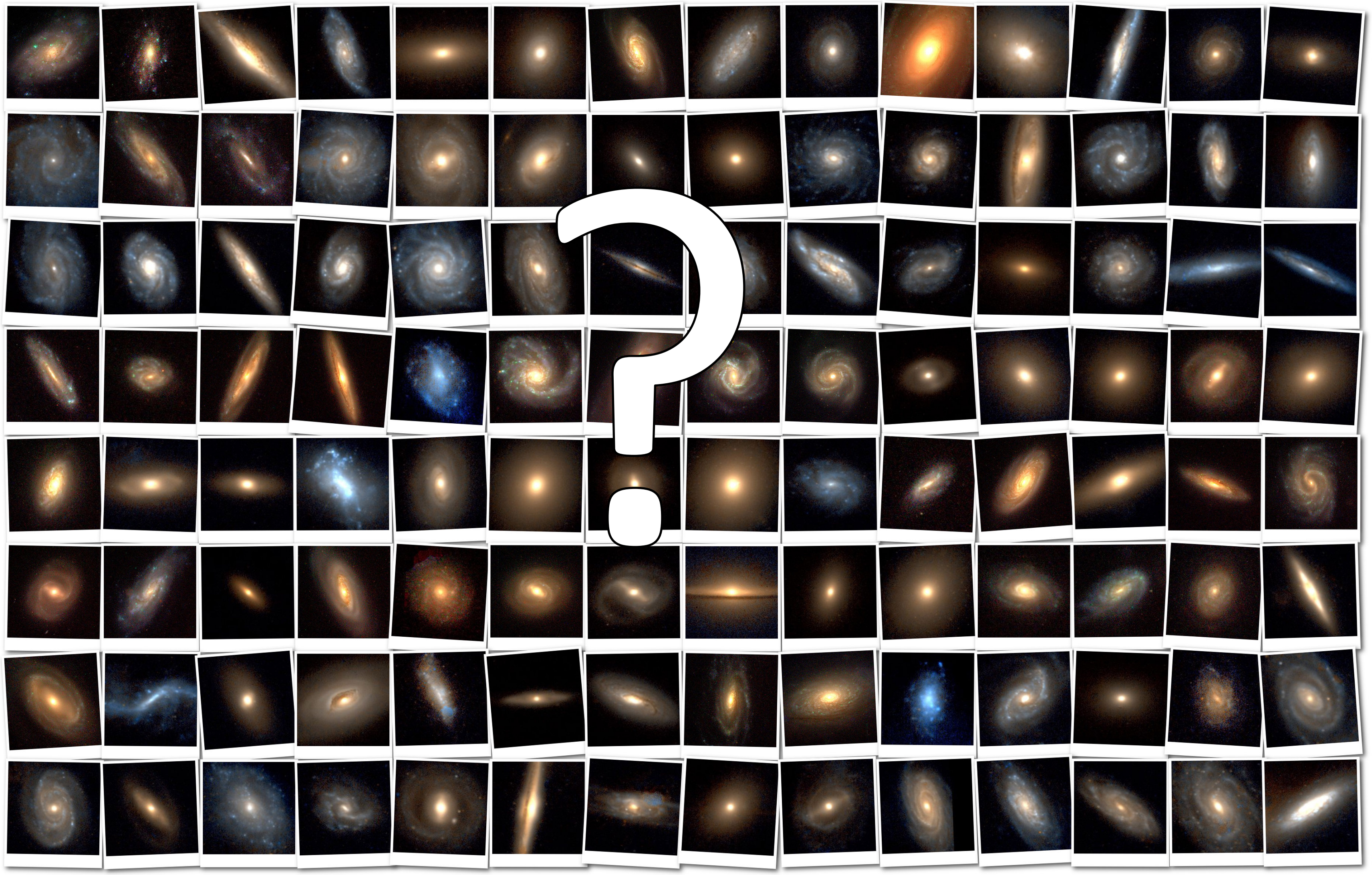
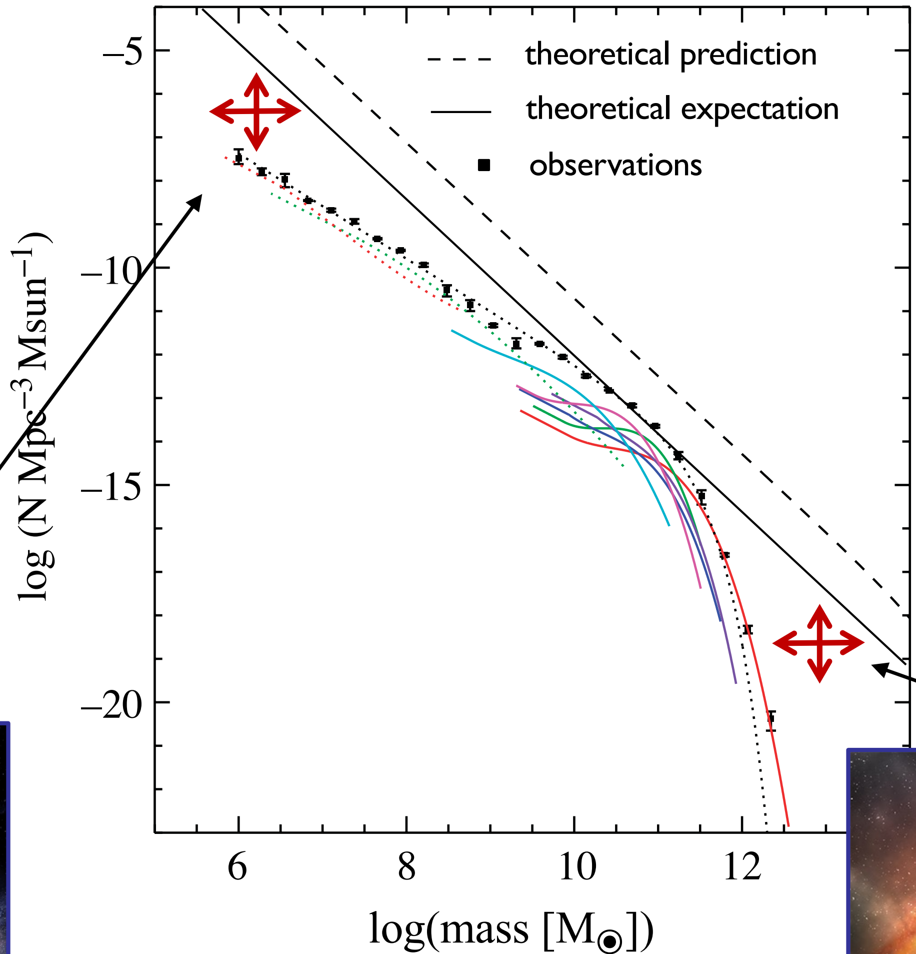
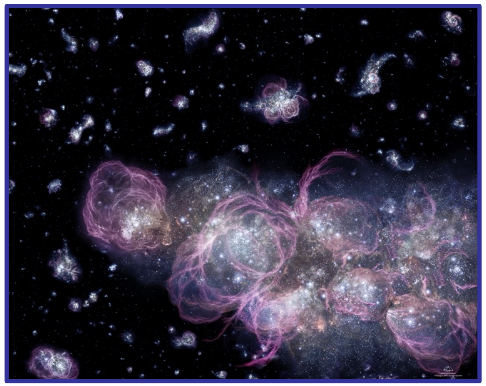
  - ✓ *active galactic nuclei feedback*
- dwarf galaxies

} profound influence on galaxy formation and evolution *and* internal galaxy properties

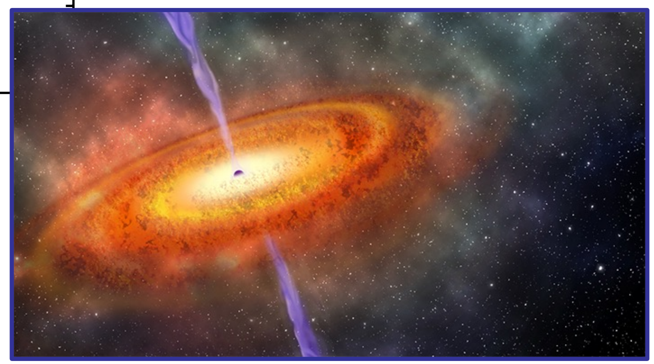

?
Created by Zsolt Frei and James E. Gunn
Copyright © 1999 Princeton University Press

internal baryonic processes influence galaxy formation!





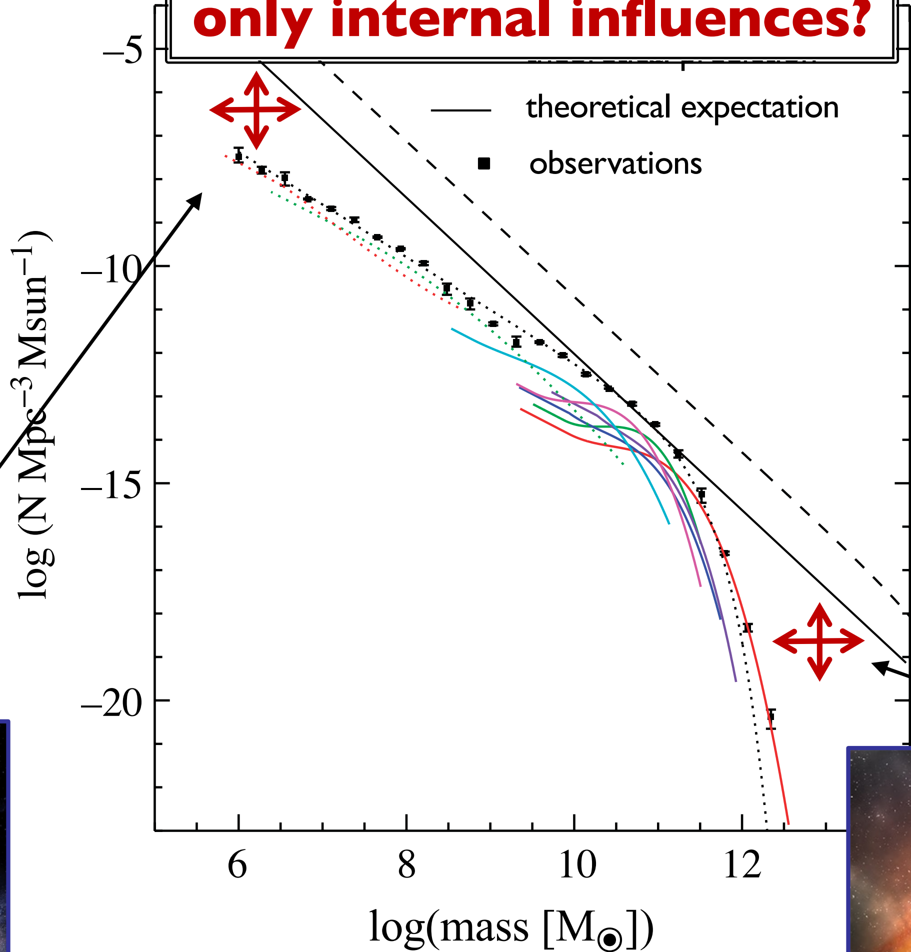
SN explosions

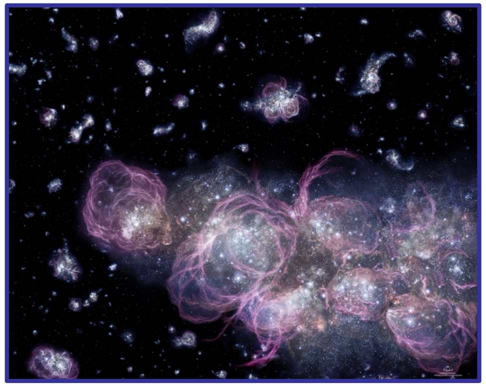


AGN

internal baryonic processes influence galaxy formation!

only internal influences?





SN explosions

AGN

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- internal baryonic processes:
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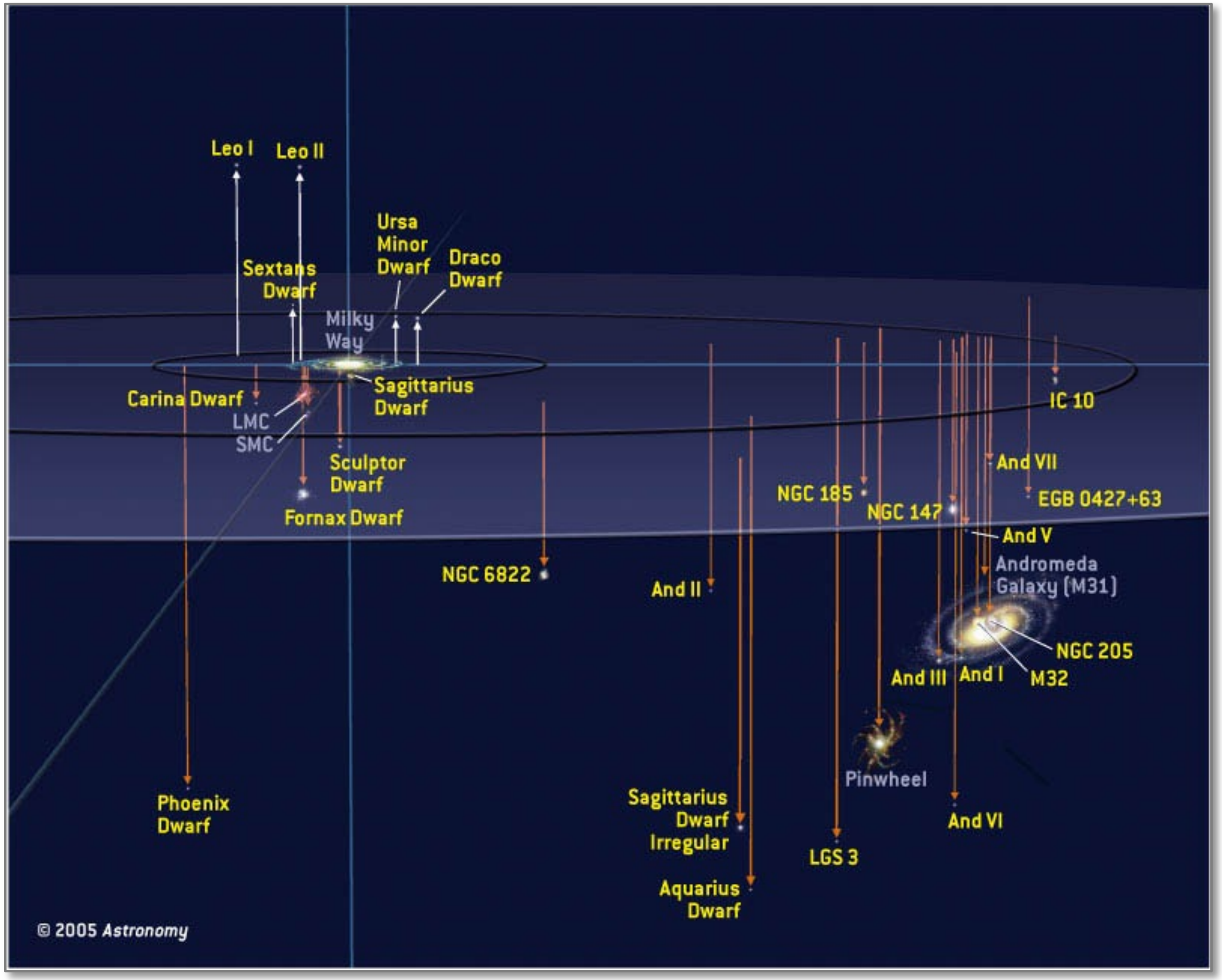
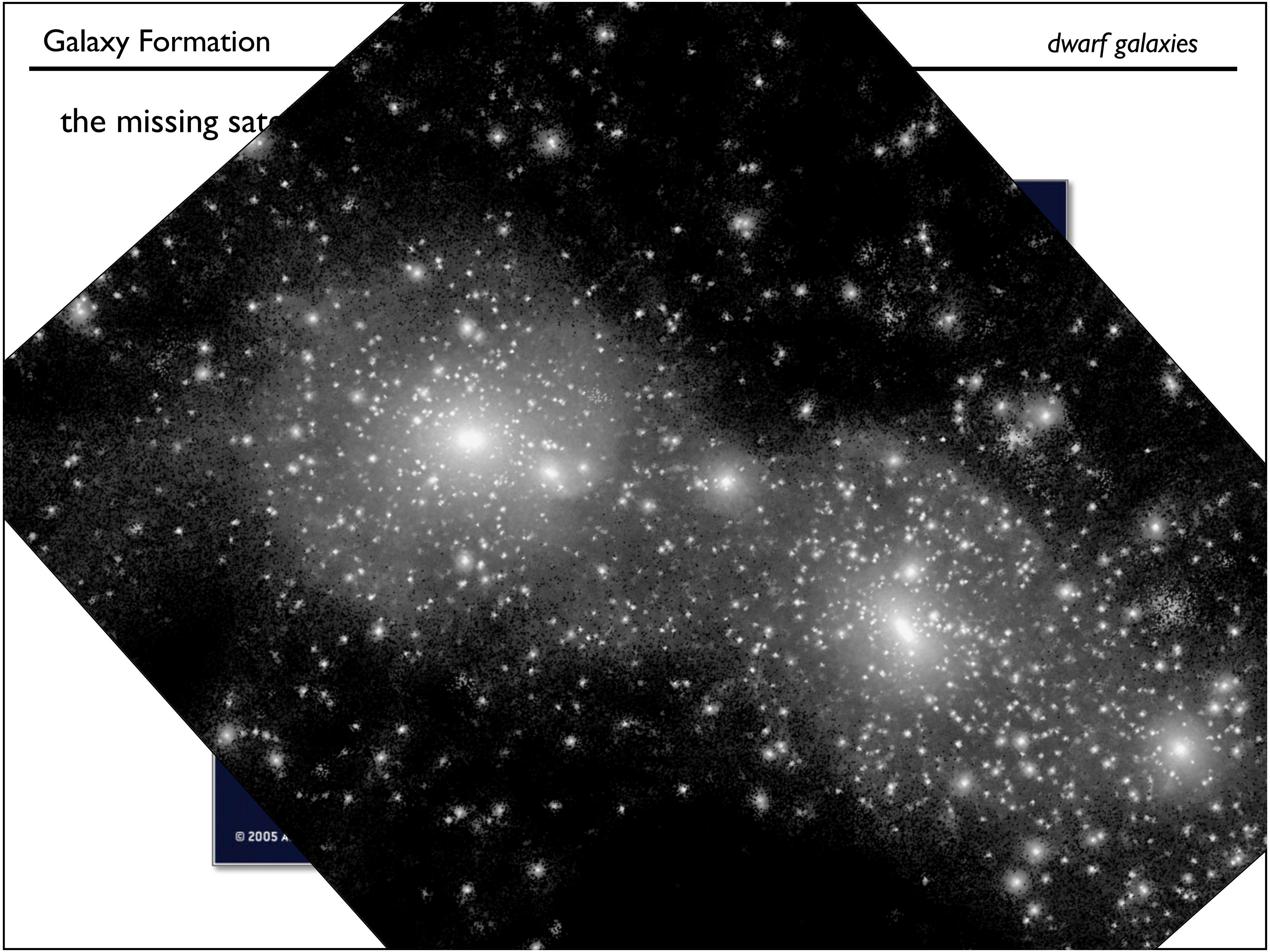
  - active galactic nuclei feedback
- **dwarf galaxies:**
  - internal vs. external effects...

the missing satellite problem

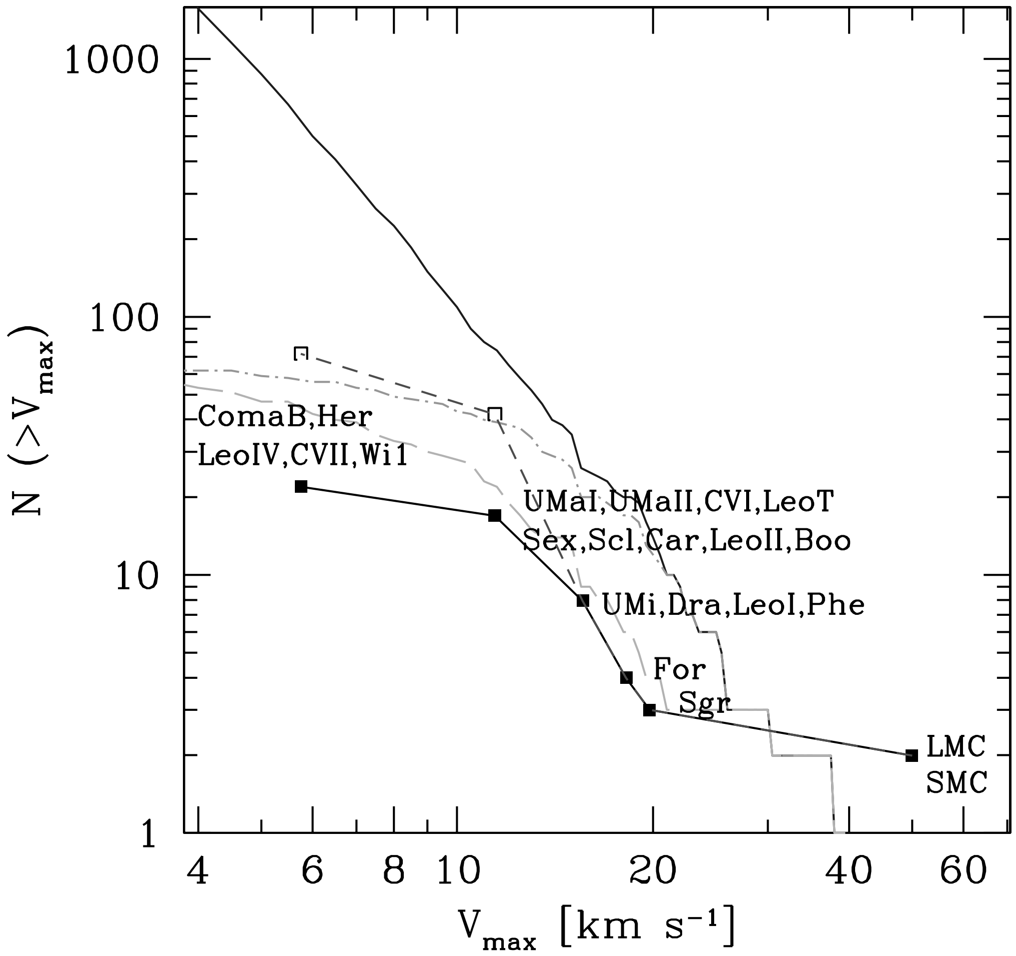


the missing sat



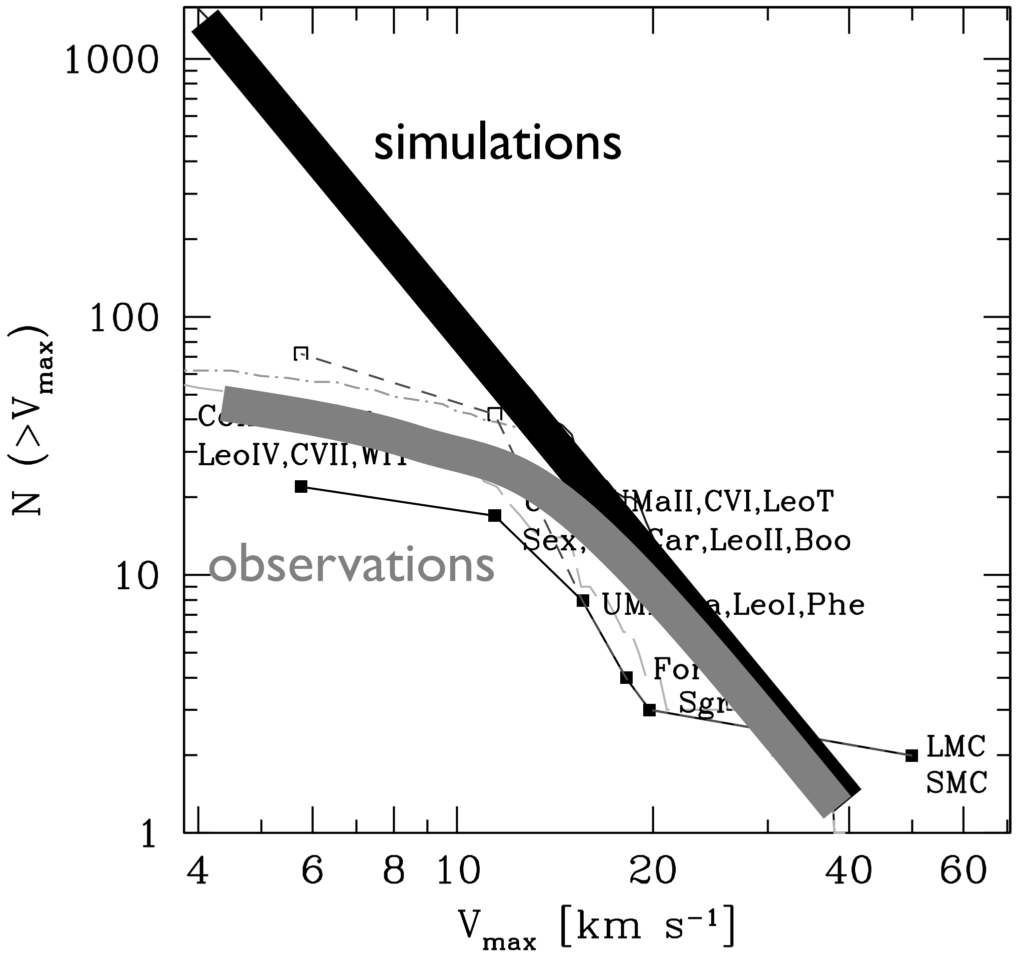
the missing satellite problem

the missing satellite problem – quantified



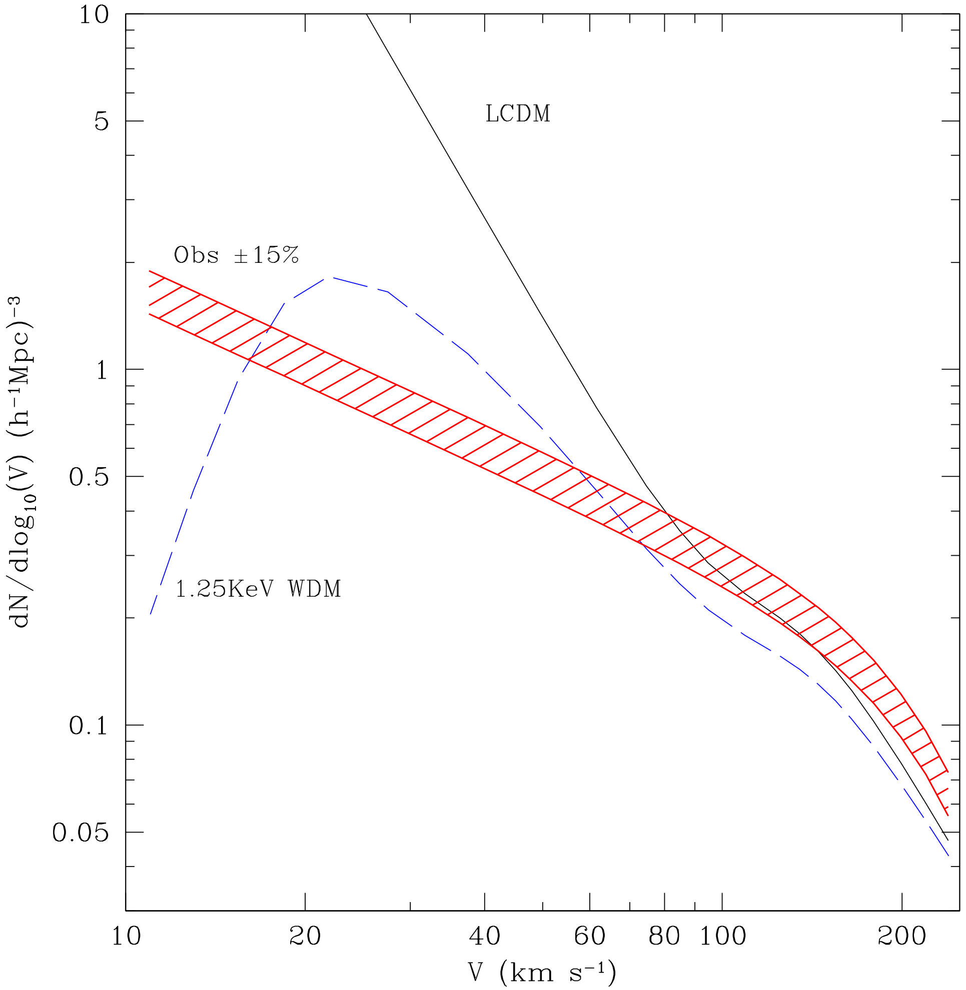
Madau et al. (2008)

the missing satellite problem – quantified



Madau et al. (2008)

the missing satellite problem – quantified for Local Group dwarf galaxies



Klypin et al. (2015)

the missing satellite problem – possible solutions?

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- not (yet) discovered **(e.g. observational problem)**

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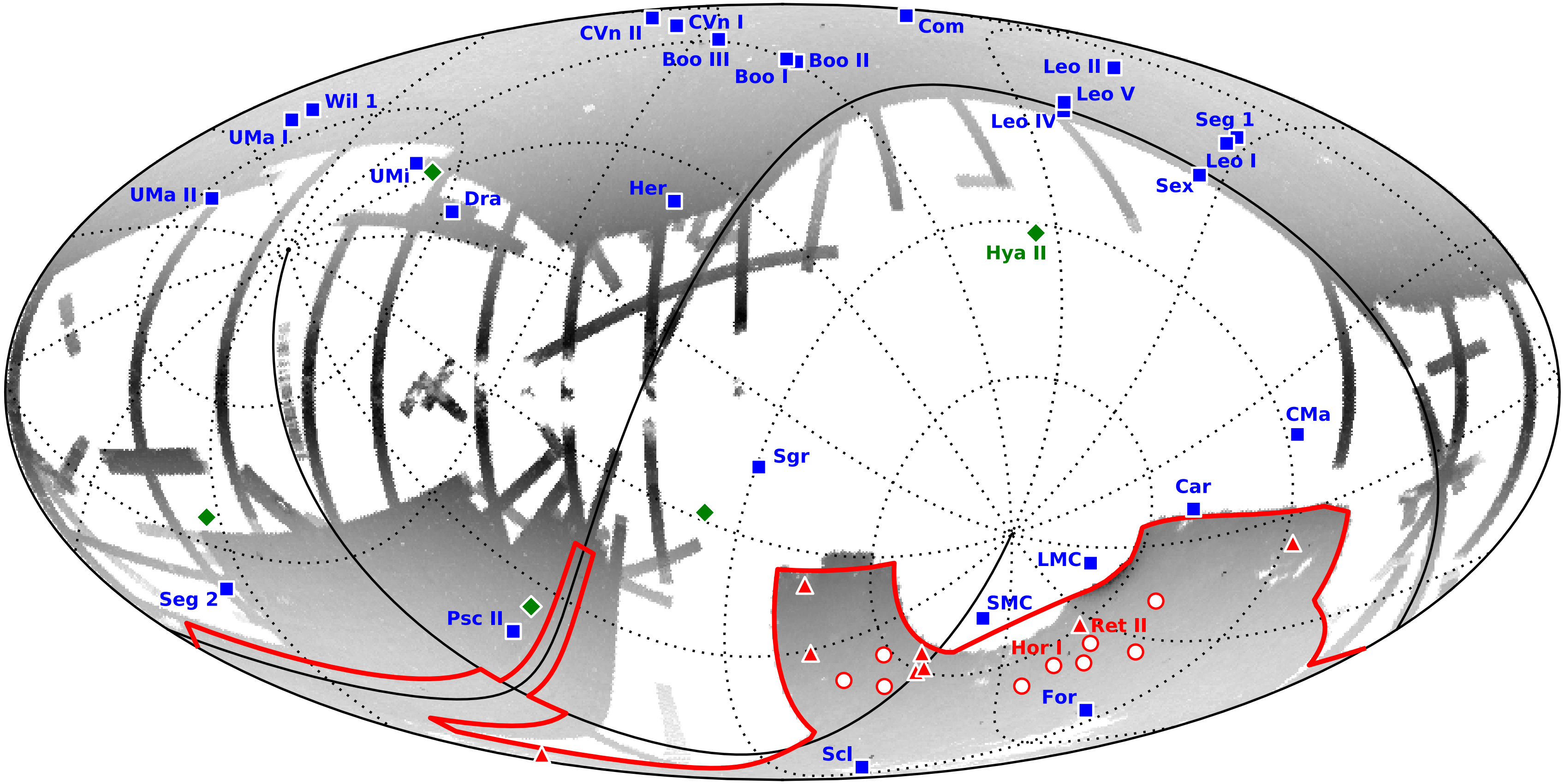

DES Collaboration (arXiv:1508.03622)
(red: new form DES, green: new from others, blue: previously known)

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- internal baryonic feedback

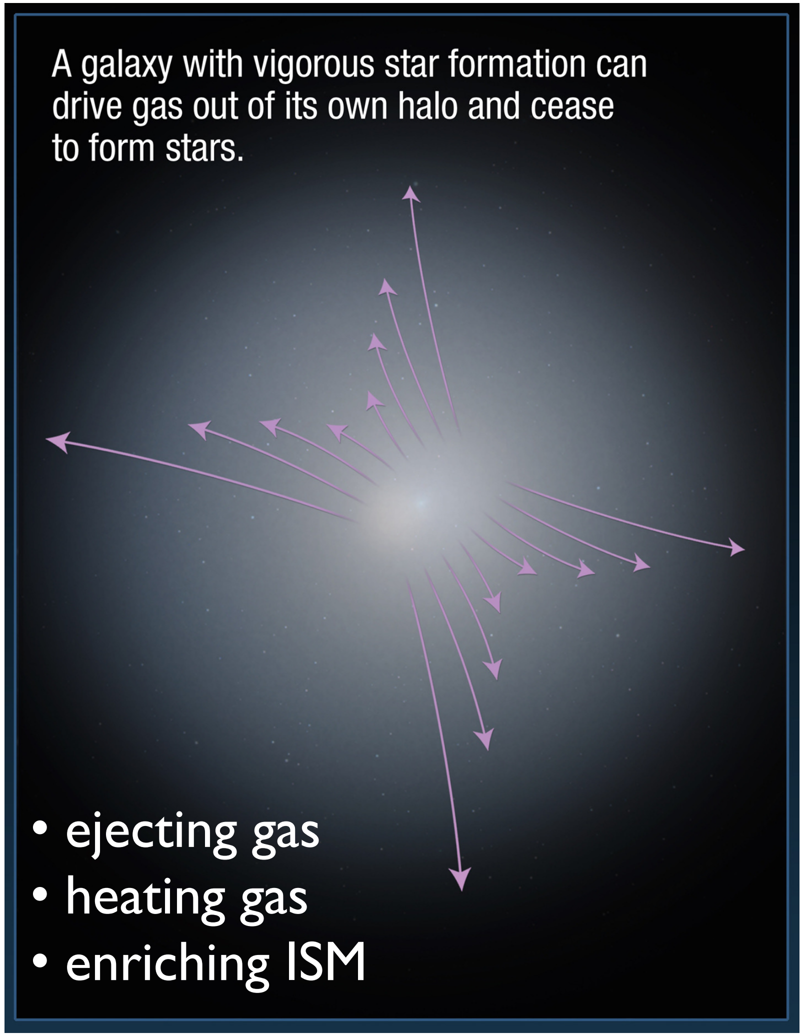
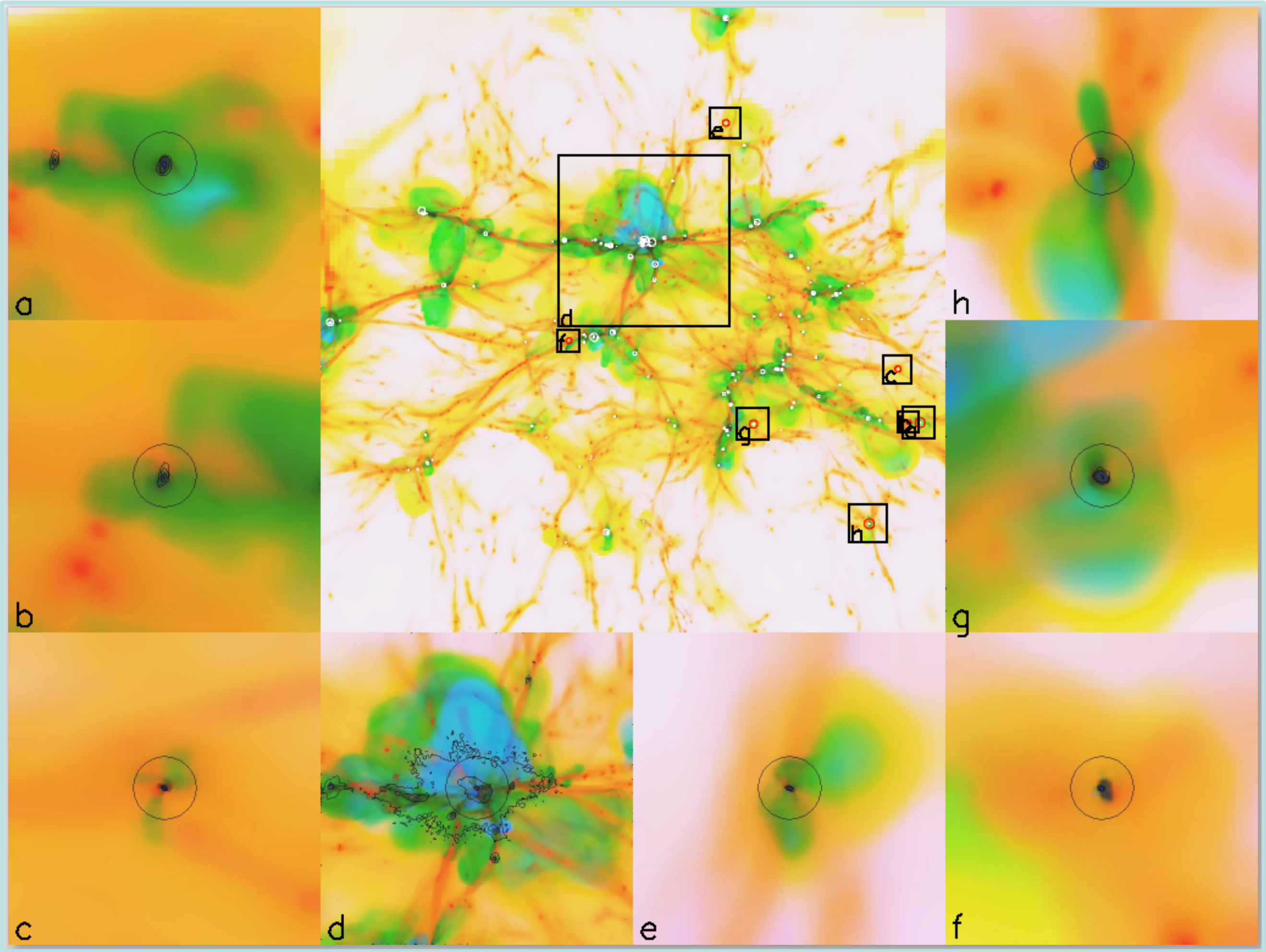


image credit: NASA, ESA, and A. Feild (STScI)

the missing satellite problem – possible solutions

- internal baryonic feedback



(Sam Geen, PhD thesis)

the majority of dwarf galaxies (as modelled in cosmological simulations) show outflows of material...

the missing satellite problem – possible solutions

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the missing satellite problem – possible solutions

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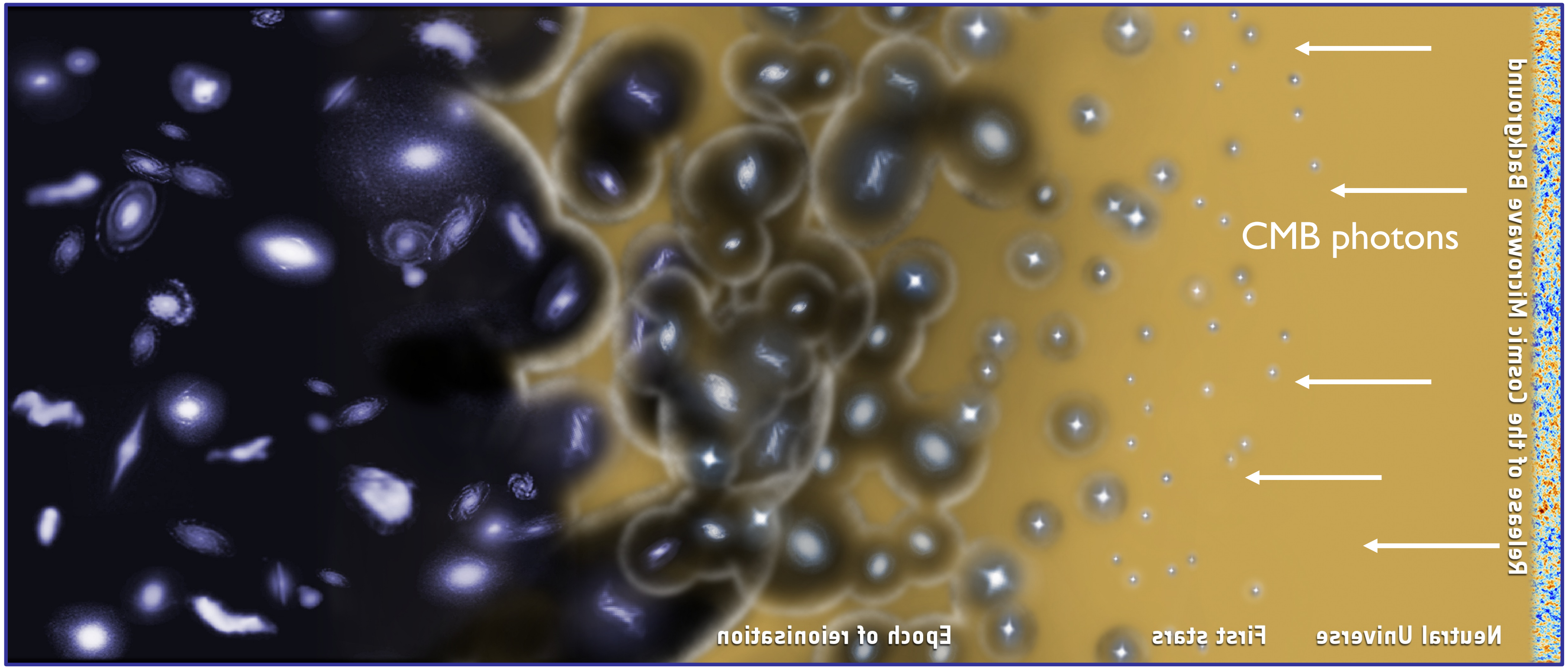

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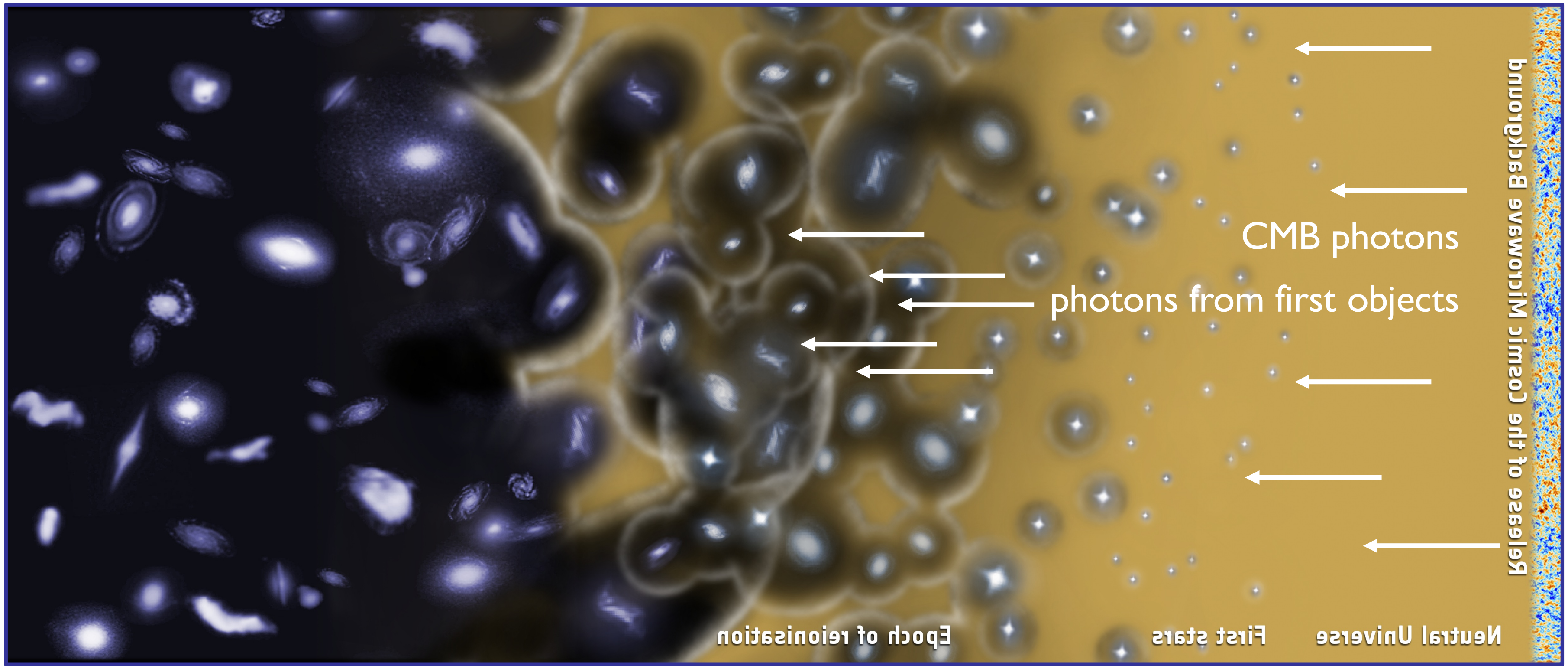

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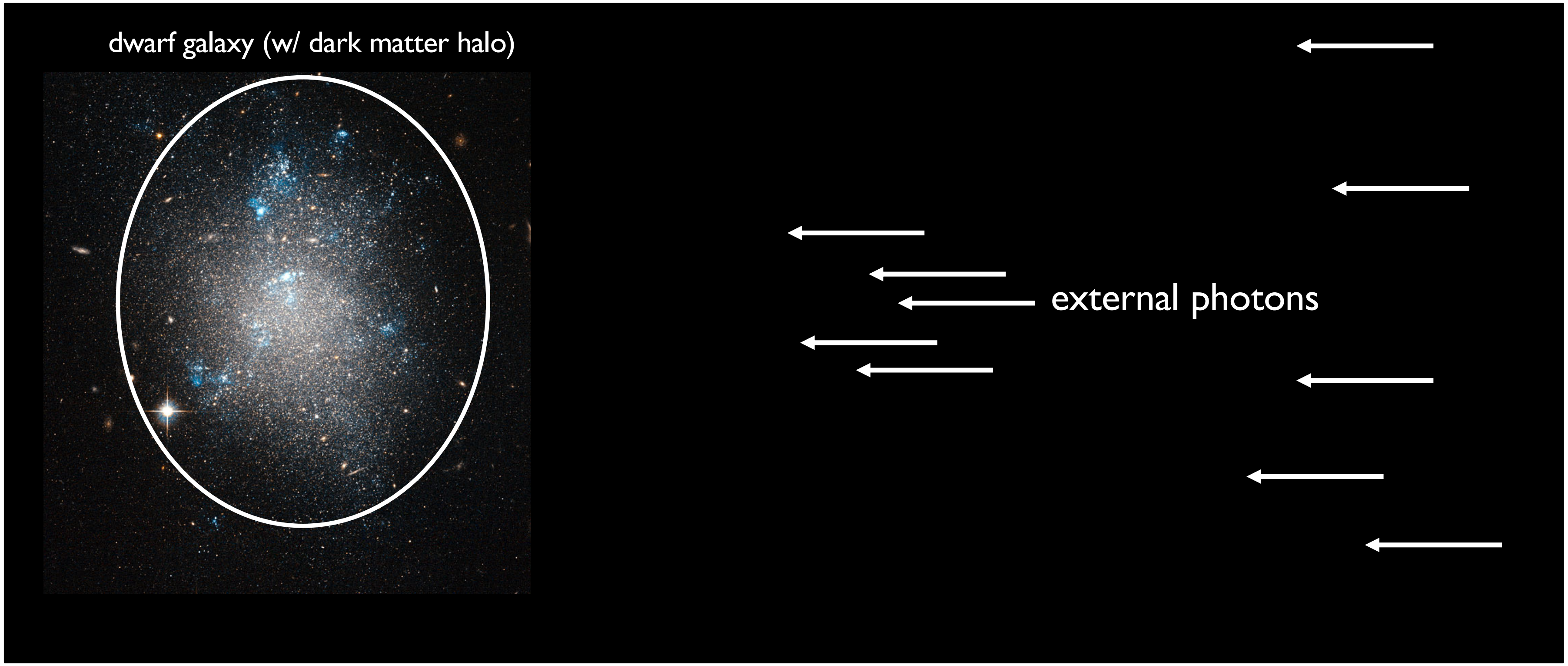

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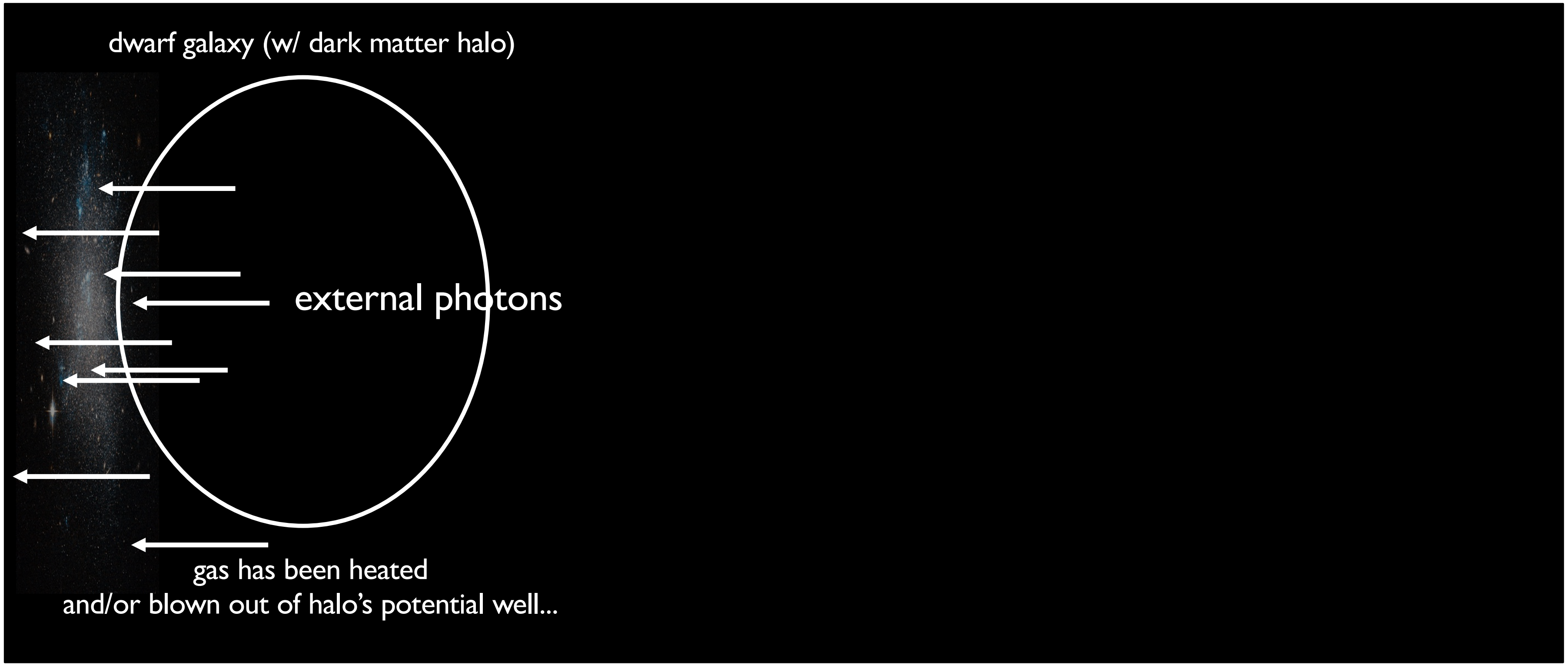

the missing satellite problem – possible solutions

- external UV background - *calculation?*

the missing satellite problem – possible solutions

- external UV background
  - halos with $T_{\mathrm{vir}} \leq T_{background}$ are unable to accrete gas

the missing satellite problem – possible solutions

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  - halos with $T_{\rm vir} \leq T_{background}$ are unable to accrete gas

$$T_{vir} = \frac{1}{5}\frac{\mu m_p}{k} V_{vir}^2$$

the missing satellite problem – possible solutions

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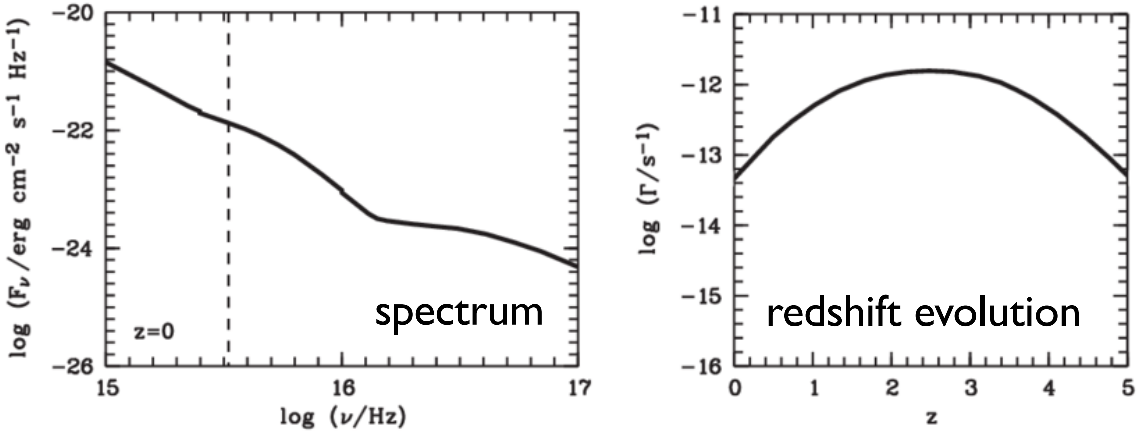
UV background radiation:

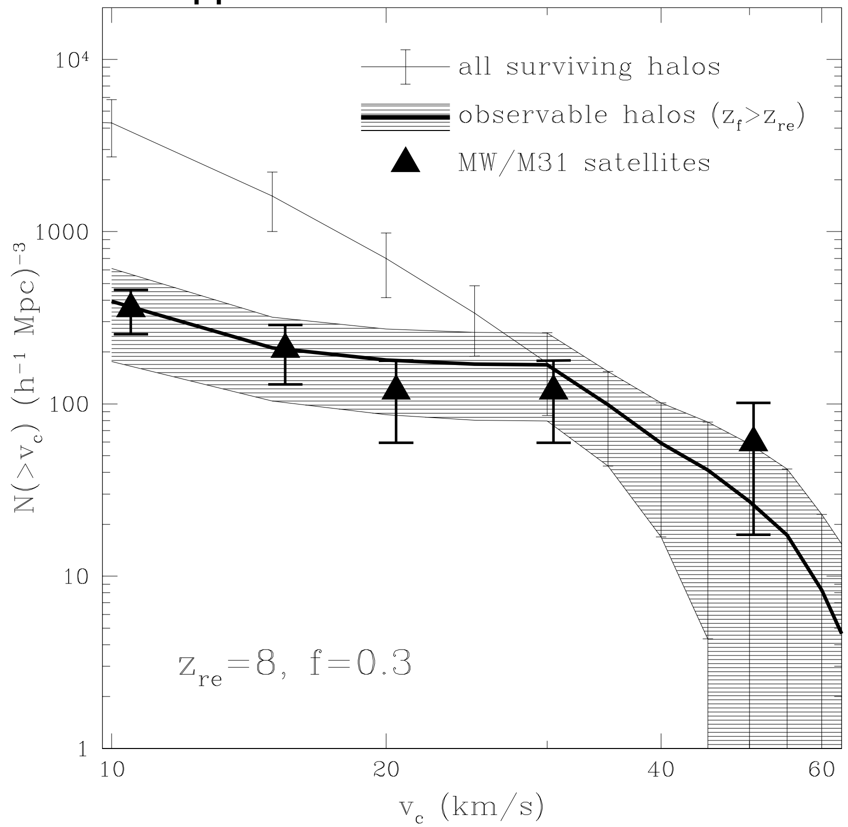


(Haardt & Madau 1996)

the missing satellite problem – possible solutions

- external UV background
  - halos with $T_{\mathrm{vir}} \leq T_{background}$ are unable to accrete gas

application of idea to simulations



Bullock et al. (2000)

V_c = peak of rotational velocity profile

the missing satellite problem – possible solutions

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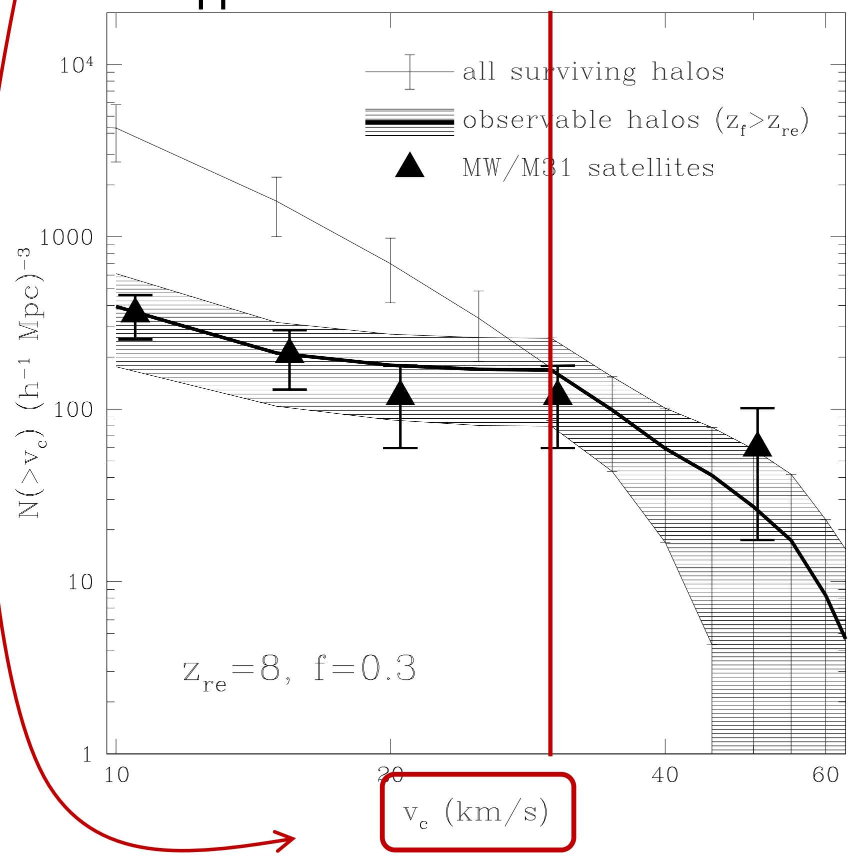


Bullock et al. (2000)

translates into...

"dark matter haloes with V_c<30 km/s are *not* able to form galaxies"

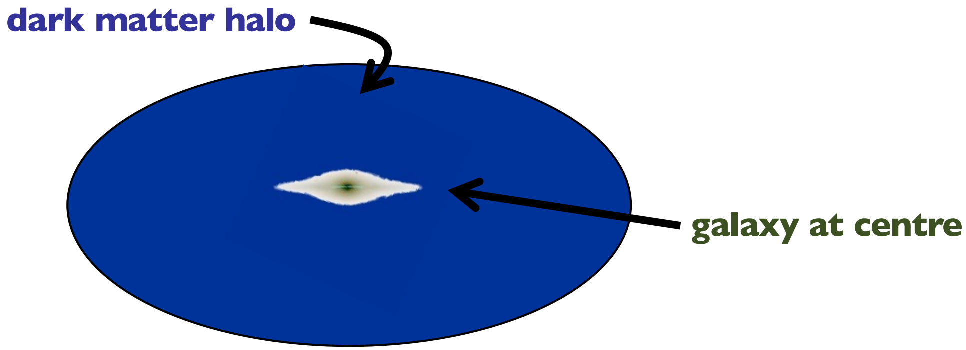
the missing satellite problem – possible solutions

- external UV background – simulation of influence

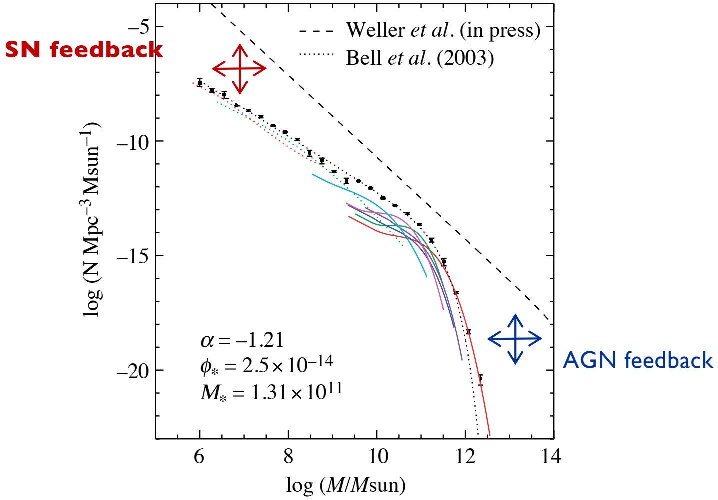
the missing satellite problem – possible solutions

• external UV background – simulation of influence

- biased galaxy formation



- internal baryonic processes:
  - supernova feedback
  - active galactic nuclei feedback



- dwarf galaxies:
  - internal & external effects

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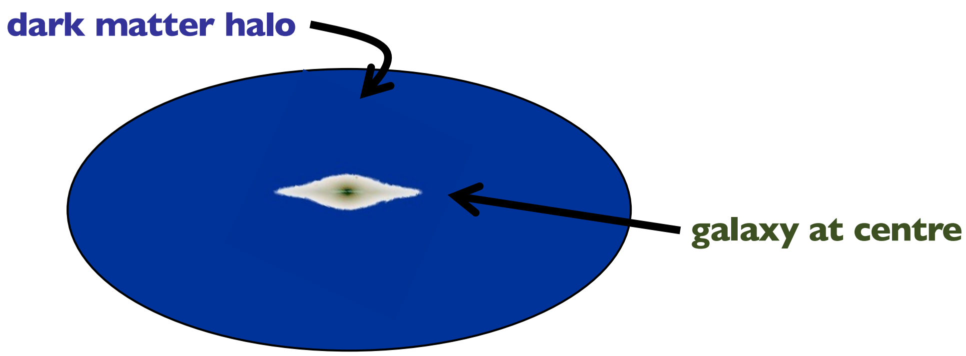

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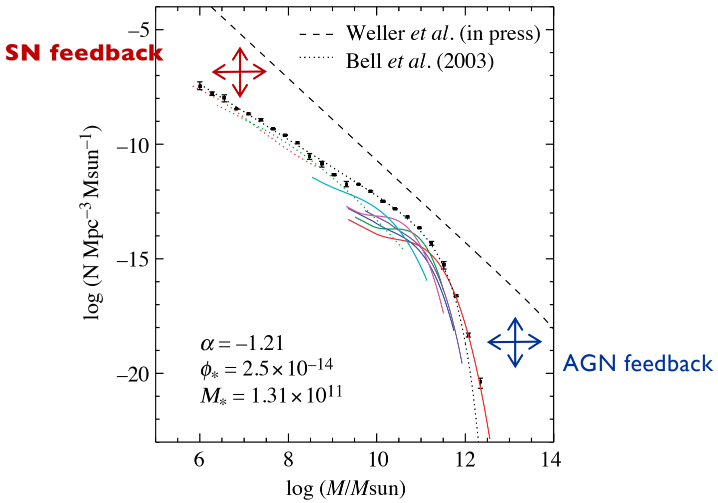

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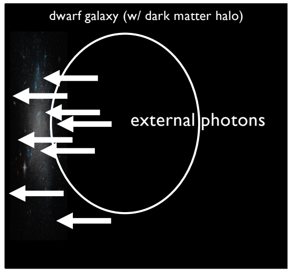

Alexander Knebe (*Universidad Autonoma de Madrid*)

"It's somewhere between a nova and a supernova -- probably a pretty good nova."