

Structure formation in cosmological context 2°

Katarina Kraljic

Observatoire astronomique de Strasbourg



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The Cosmic Dawn: First Galaxies and Cosmic Reionization, IESC Cargèse, 5-11 Oct 2025

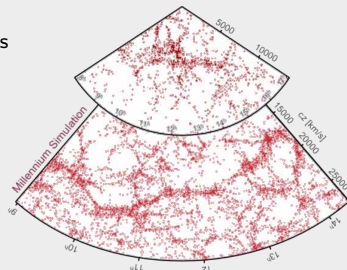
From halos to galaxies

Galaxy populations from halo merger trees

Follow hierarchical growth of DM halos

Populate DM halos with disks

Form an elliptical from merging disks
Re-grow disk after new accretion



time

Côté et al. 2018

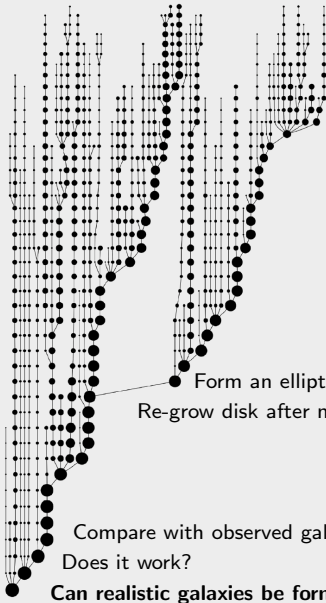
Springel et al. 2006

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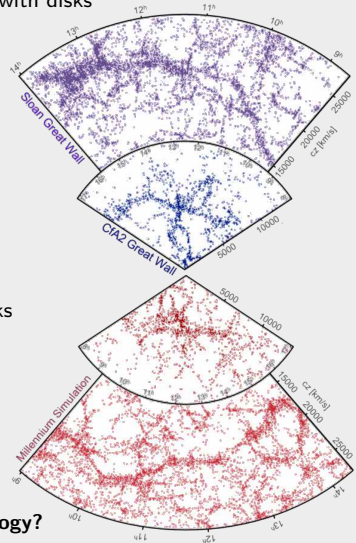
Populate DM halos with disks

Form an elliptical from merging disks
Re-grow disk after new accretion

Compare with observed galaxies

Does it work?

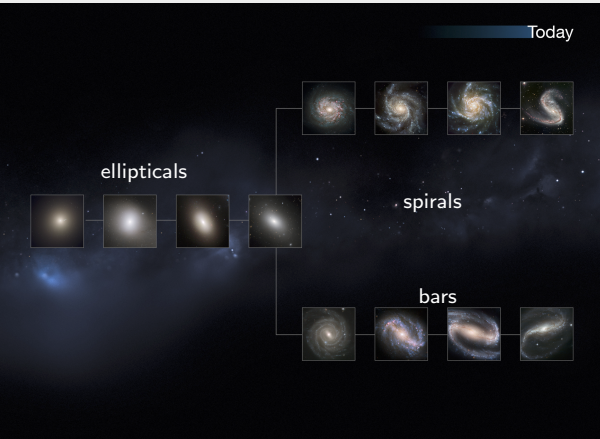
Can realistic galaxies be formed just from cosmology?



Springel et al. 2006

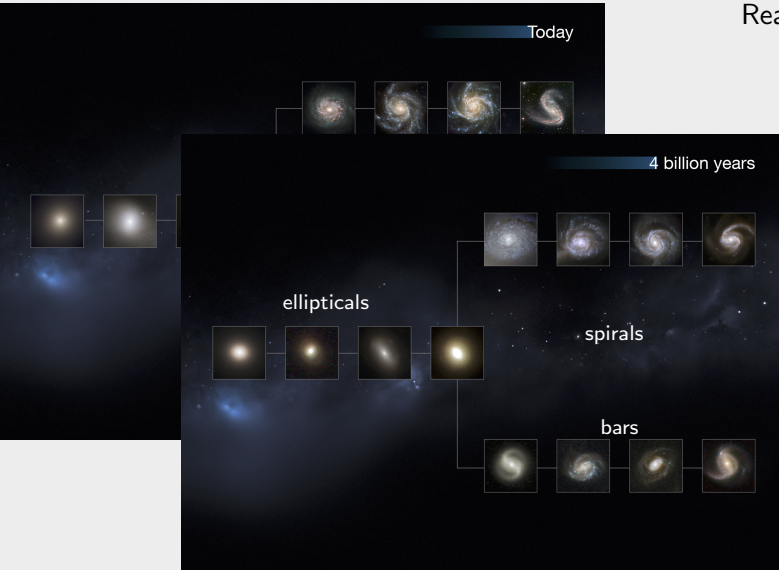
From halos to galaxies

Realistic galaxies



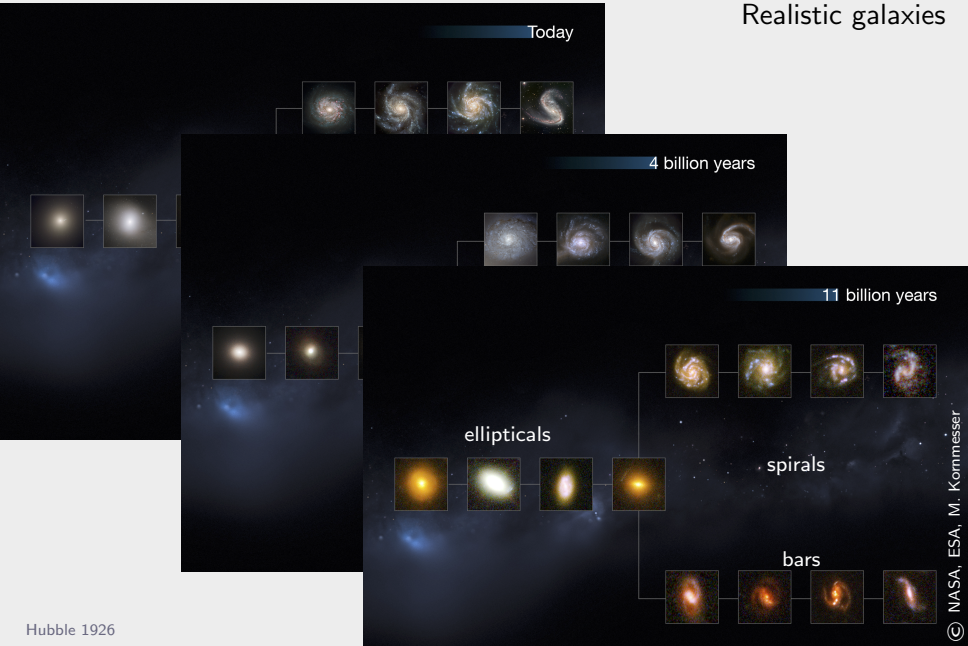
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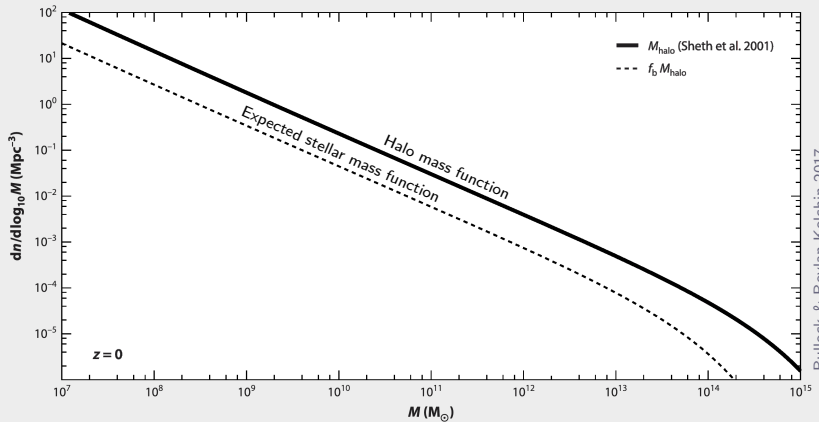
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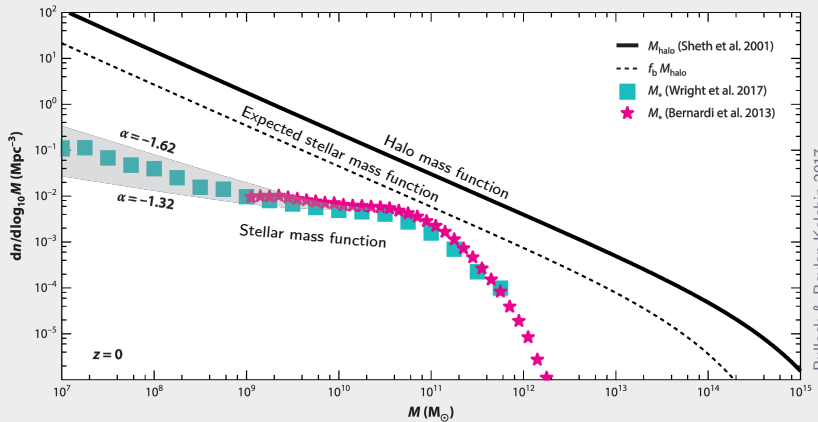
Bullock & Boylan-Kolchin 2017

From halos to galaxies

Can realistic galaxies be formed just from cosmology?

“Not just no, but *hell* no”

Romeel Davé



Bullock & Boylan-Kolchin 2017

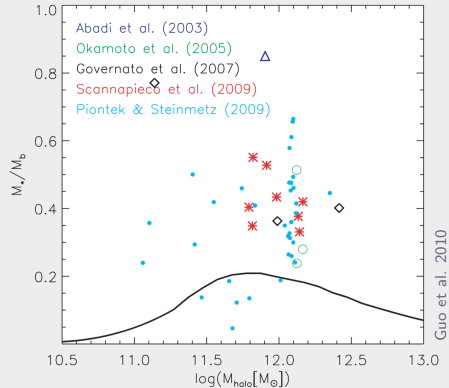
From halos to galaxies

Can realistic galaxies be formed just from cosmology?

Two major issues

1 Overcooling problem:

→ simulated galaxies have **too many stars** / lock **too many baryons** into stars compared to observations



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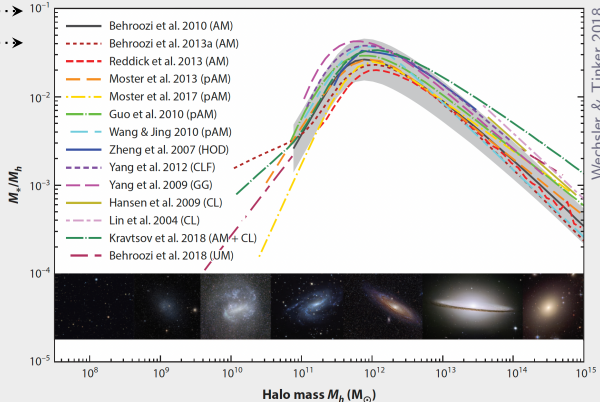
- simulated galaxies have **too many stars** / lock **too many baryons** into stars compared to observations
- cosmic star formation efficiency is lower than expected and mass-dependent

$$\max \varepsilon_{\text{SF}} = \Omega_{\text{b}} / \Omega_{\text{m}} = 0.16 \dots \rightarrow$$

$$\text{infall+SF time } \varepsilon_{\text{SF}} \sim 0.1 \dots \rightarrow$$

$$\text{observed max } \varepsilon_{\text{SF}} \sim 0.03 \dots \rightarrow$$

strong mass and morphology dependence



From halos to galaxies

Can realistic galaxies be formed just from cosmology?

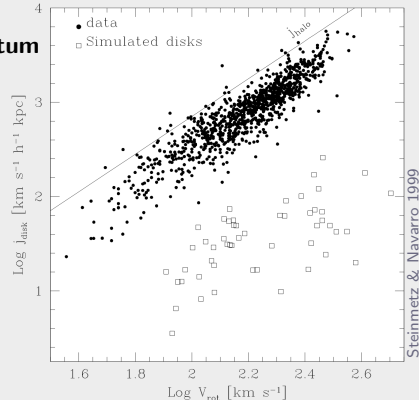
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2 Angular momentum catastrophe:

- galaxies have **much less angular momentum** compared to observations
- galaxies are too bulge-dominated
- merger rate $\propto (1+z)^4$ → early bulge growth is too fast
- too efficient SF and gas consumption at high z → assembly into low- z galaxies via gas-poor mergers



From halos to galaxies

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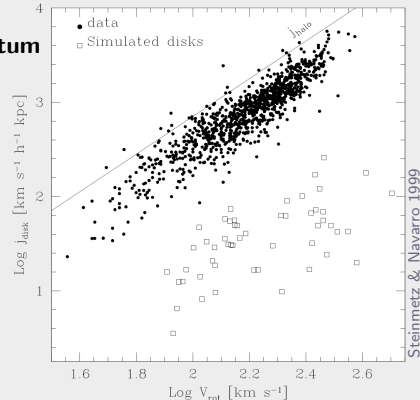
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The solution?

- delay or quench the formation of stars ...
- ...galactic feedback

From halos to galaxies

Can realistic galaxies be formed just from cosmology?

Galactic feedback

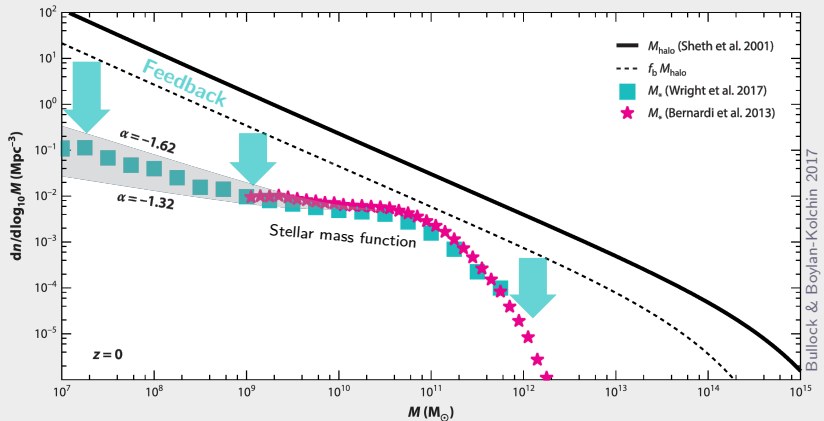
- ▶ **ejective:** gas is removed from the interstellar medium before star formation
→ e.g. some explosion
- ▶ **preventive:** gas is prevented from getting into the interstellar medium
→ e.g. some process keeping the gas hot

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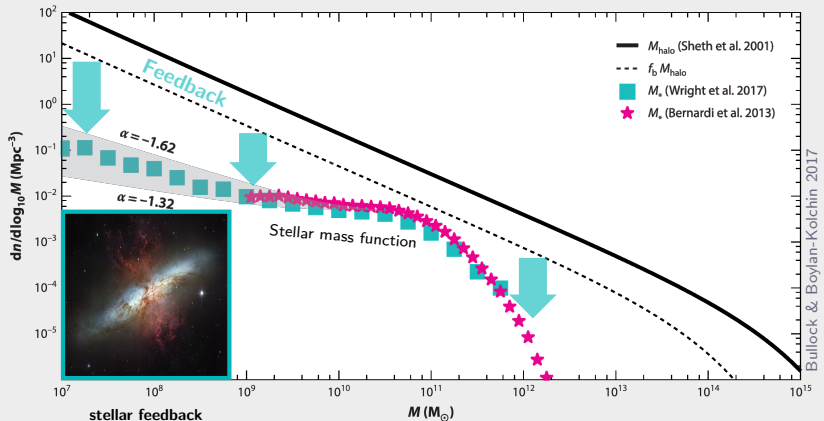


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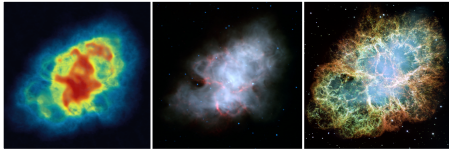
From halos to galaxies

Towards realistic galaxy populations

Stellar feedback: Supernovae

- ▶ core-collapse explosions → singular and final events in a massive star's life
- ▶ release $\sim 10^{51}$ erg per event

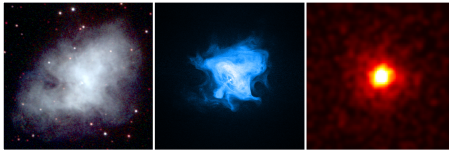
Crab nebula



radio

infrared

visible



ultraviolet

X-rays

Gamma rays

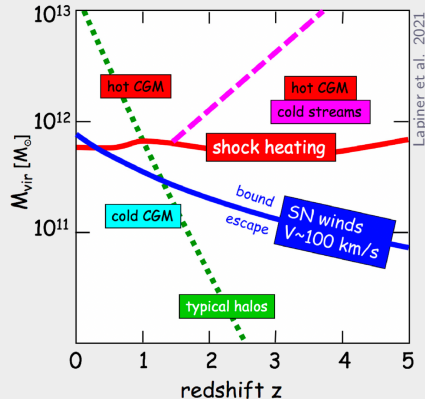
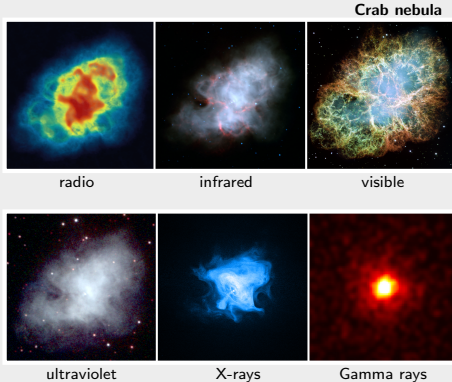
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$M_{\text{halo}} \lesssim 10^{11.7} M_{\odot}$ at $z = 0$ (Dekel & Silk 1986) $\Rightarrow$ star forming galaxies at low $M_{\star}$

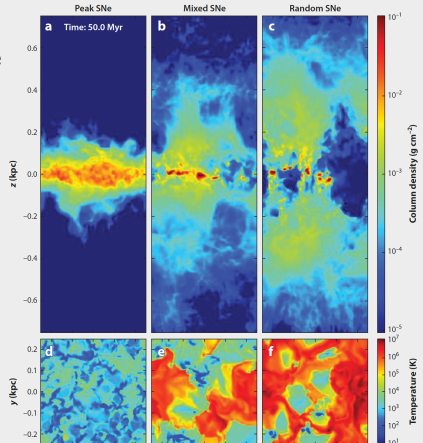


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- ▶ BUT real ISM is inhomogeneous
→ ability to drive outflows impacted by the location of SN explosions



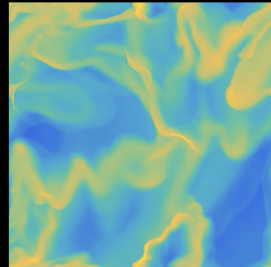
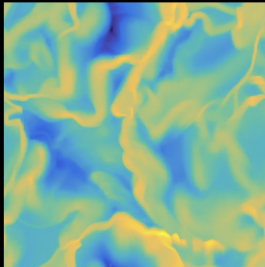
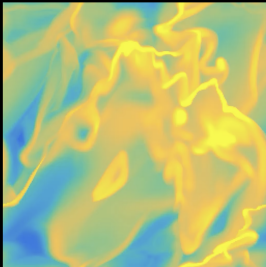
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- ▶ BUT real ISM is inhomogeneous *and* turbulent
 - ability to drive outflows impacted by the location of SN explosions *and* interaction of SNe remnant with dense ISM filaments (e.g. Ohlin et al. 2021)
 - problem: low mass loss

© L. Ohlin



From halos to galaxies

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Stellar feedback: Supernovae ++

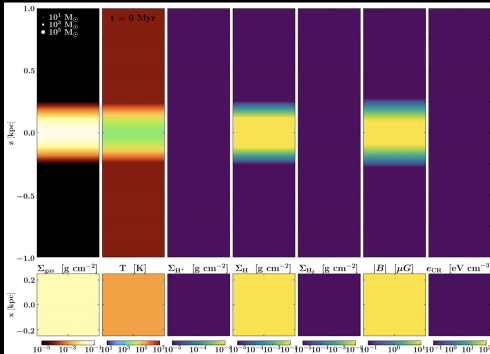
- ▶ Solution: add other processes
 - ▶ **stellar winds/radiation pressure**: pre-SNe feedback, bubbles of low ρ gas around stars $\rightarrow$ easier to push
 - ▶ **SNe delay**: wandering stars exploding in lower ρ gas
 - ▶ **magnetic field/cosmic rays**: large-scale push $\rightarrow$ accelerate gas against gravity

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Magnetohydrodynamic simulation of a stratified gas disk (SILCC project):

- SNe, stellar winds, UV radiation, CRs
- high velocity outflows, but still not enough for a factor of 10 reduced ε_{SF}

Galaxy formation

Towards realistic galaxy populations

Stellar feedback in a cosmological setup

- Zoom-in cosmological simulations: resolution 10 – 30 pc → ‘sub-grid’ recipes

FIRE: radiation pressure, stellar winds, SNe, cosmic rays

Hopkins et al. 2018

NIHAO: ionizing radiation, SNe (delayed cooling)

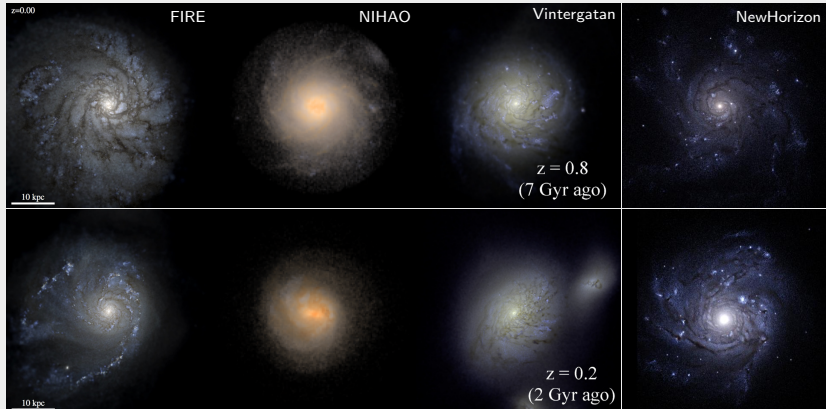
Wang et al. 2015

Vintergatan: radiation pressure, stellar winds, SNe

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NewHorizon: radiation pressure, SNe

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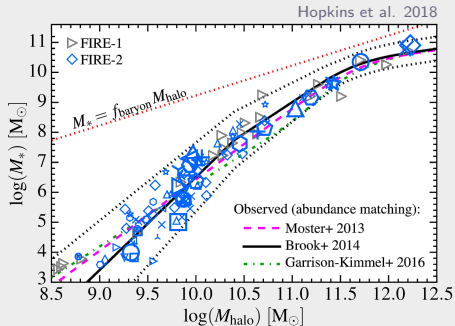
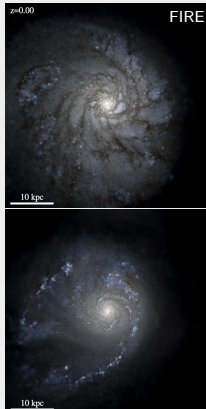
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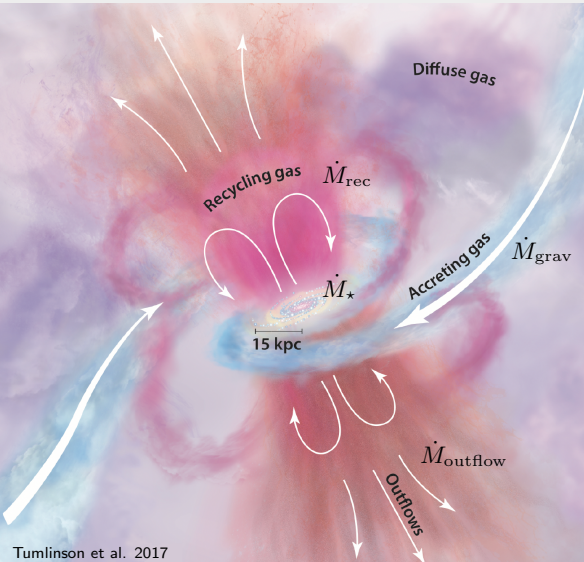
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Galaxy formation

Understanding galaxy populations

Baryon cycle: inflows, outflows, recycling



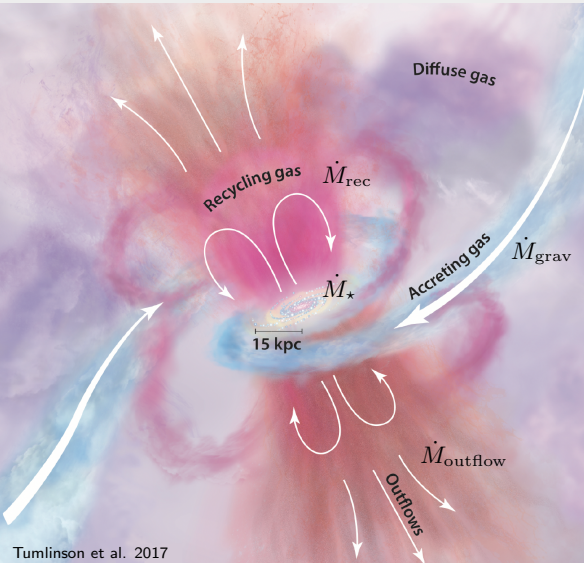
Equilibrium model

e.g. Finlator & Davé 2008, Davé et al. 2012
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$$\dot{M}_{\text{inflow}} = \zeta \dot{M}_{\text{grav}} + \dot{M}_{\text{rec}}$$

ζ - fraction of material that makes into ISM

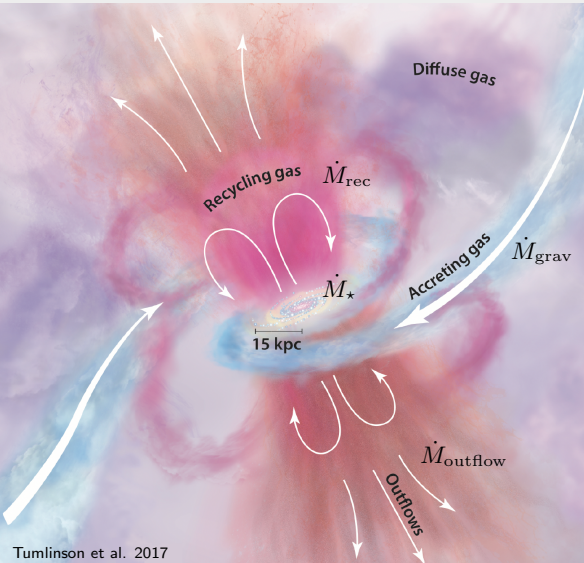
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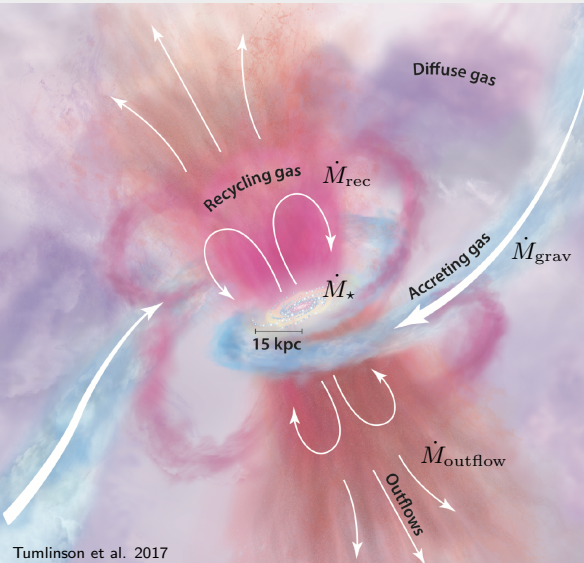
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Equilibrium model

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$$\zeta \dot{M}_{\text{grav}} + \dot{M}_{\text{rec}} = \dot{M}_{\star}(1 + \eta)$$

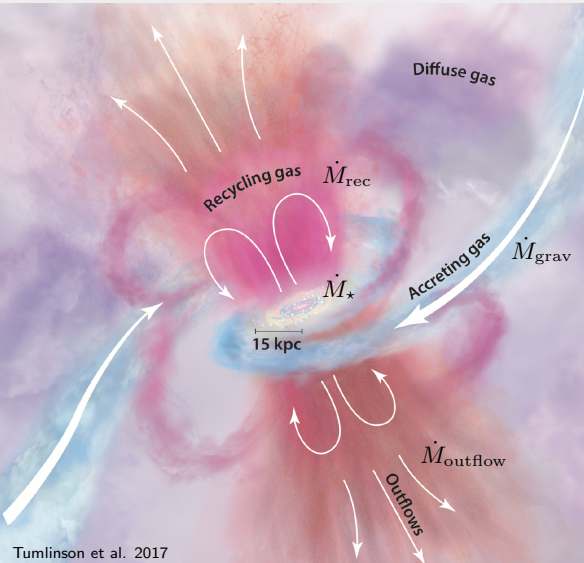
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$$\text{SFR} = \frac{\zeta \dot{M}_{\text{grav}} + \dot{M}_{\text{rec}}}{1 + \eta}$$

Z - metallicity: mass fraction in metals
 y - metal 'yield'

$$Z = \frac{y \text{SFR}}{\zeta \dot{M}_{\text{grav}}} \approx \frac{y}{1 + \eta}$$

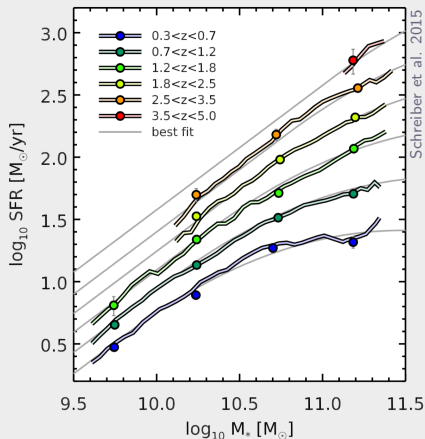
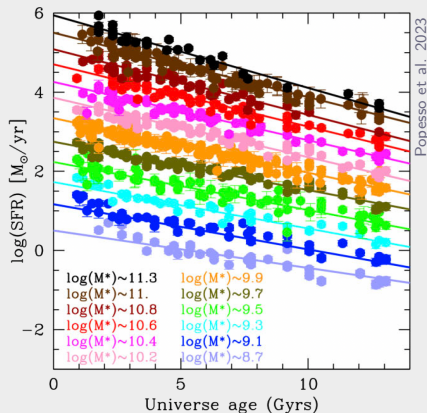
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1 Star forming main sequence

► SFR vs M_* relation:

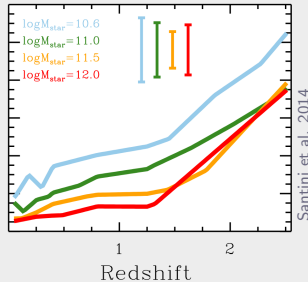
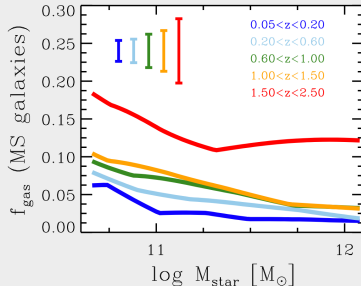
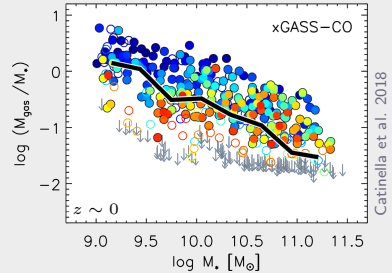
→ close to linear relationship

→ redshift evolution: higher SFR at higher z



2 Cold gas fraction

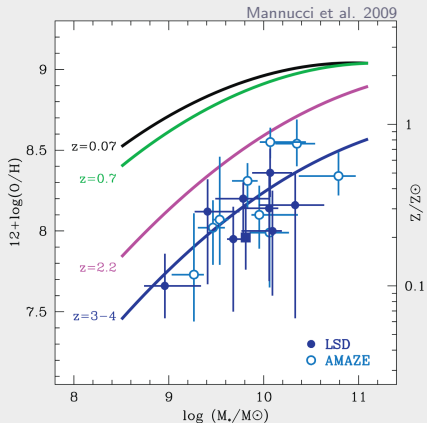
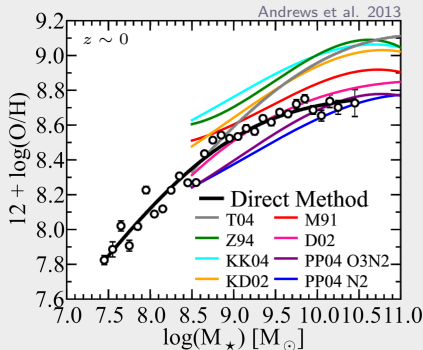
- $f_{\text{gas}} = \frac{M_{\text{gas}}}{M_{\star} + M_{\text{gas}}}$ vs $M_{\star}$ relation:
 - f_{gas} decreases with increasing $M_{\star}$
 - redshift evolution: higher f_{gas} at higher z



3 Mass-metallicity relation

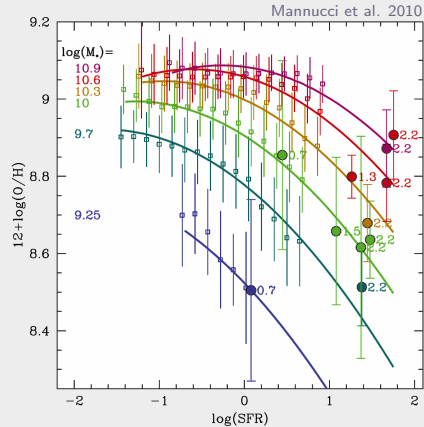
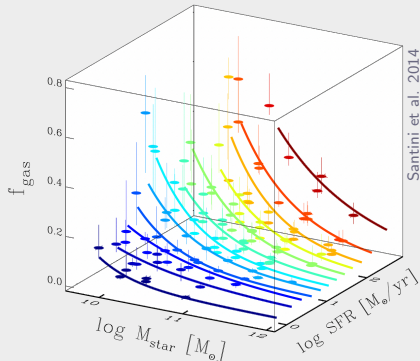
► Z vs M_* relation:

- Z increases with increasing M_*
- redshift evolution: lower Z at higher z



4 Correlated scatter

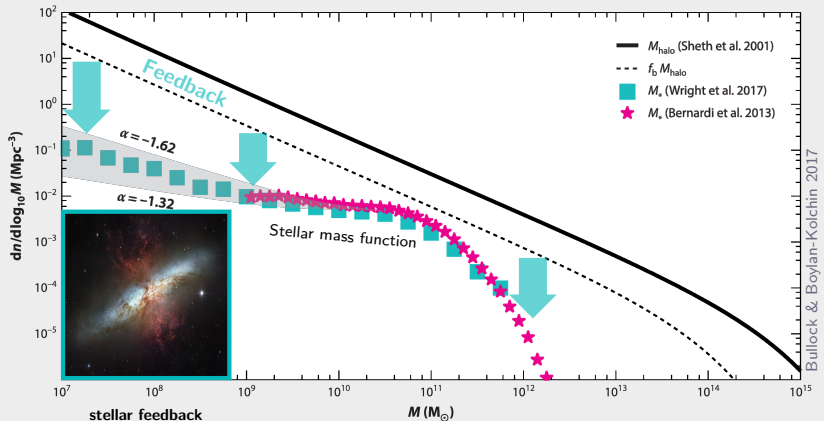
- Fundamental metallicity relation:
→ $M_{\star}$ -metallicity-SFR (also HI) relation
→ no redshift evolution
- Fundamental $f_{\text{gas}}-M_{\star}$ -SFR relation:
→ no redshift evolution



see also Bothwell et al. 2013

Galactic feedback

- **ejective:** gas is removed from the interstellar medium before star formation
→ e.g. some explosion
- **preventive:** gas is prevented from getting into the interstellar medium
→ e.g. some process keeping the gas hot



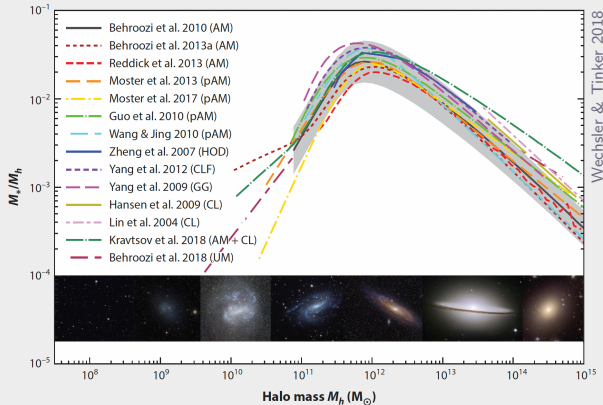
Galactic feedback

- **Stellar feedback:** plausible solution for low galaxy formation efficiency at low mass

Low mass



star-forming, disk
cold gas, dust
small black holes



Galaxy formation

Towards realistic galaxy populations

Galactic feedback

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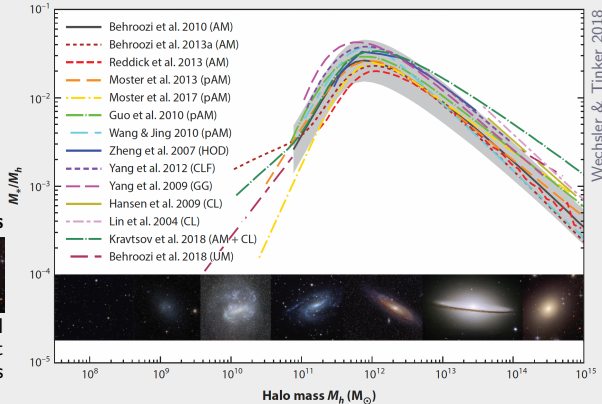


star-forming, disk
cold gas, dust
small black holes

High mass



quenched, elliptical
hot gas, no dust
large black holes



Wechsler & Tinker 2018

Galaxy formation

Towards realistic galaxy populations

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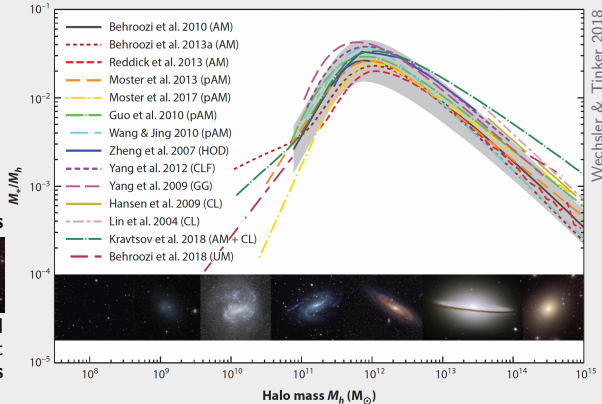


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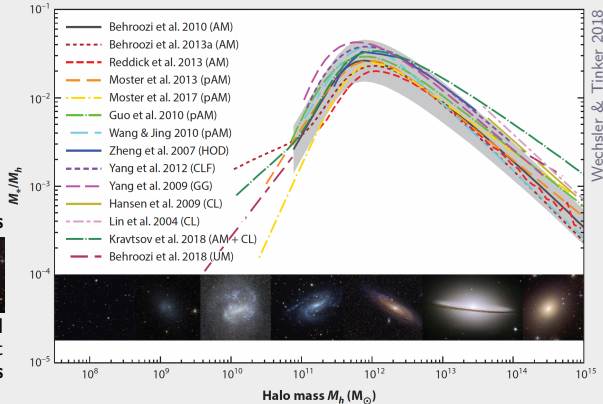


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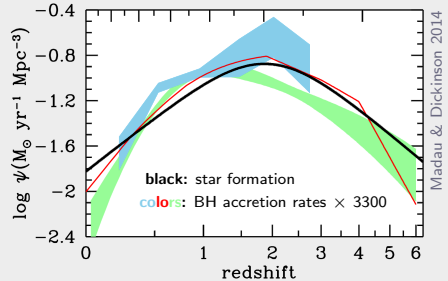
- **Black hole feedback:** can this be a plausible solution at high-mass end?

Galaxy formation

Towards realistic galaxy populations

Galaxy-Black hole connection

- BH growth follows SF growth

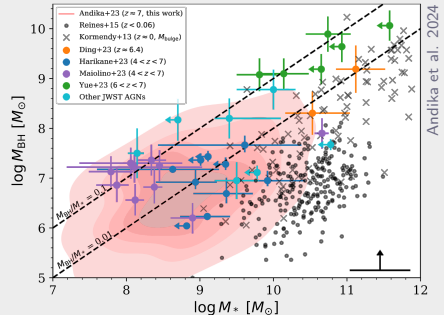
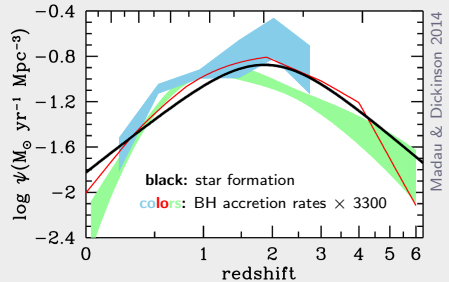


Galaxy formation

Towards realistic galaxy populations

Galaxy-Black hole connection

- ▶ BH growth follows SF growth
- ▶ BH mass correlated with stellar mass

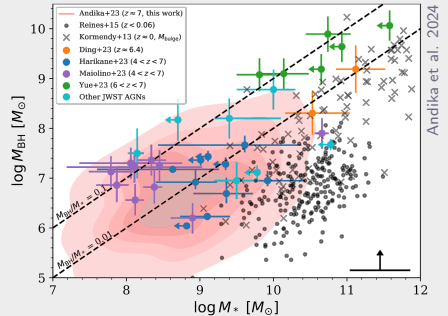
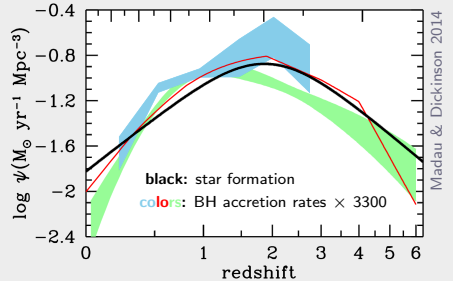
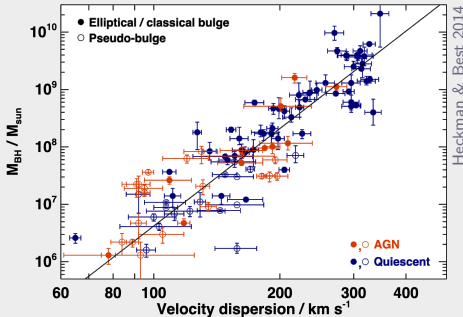


Galaxy formation

Towards realistic galaxy populations

Galaxy-Black hole connection

- ▶ BH growth follows SF growth
- ▶ BH mass correlated with stellar mass
- ▶ BH mass correlated with bulge (σ_*) even better

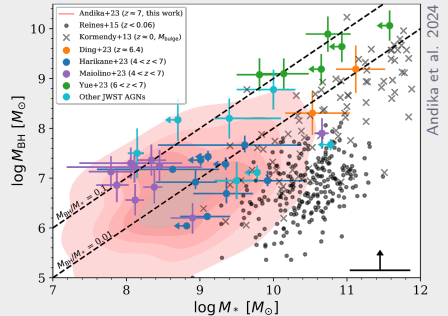
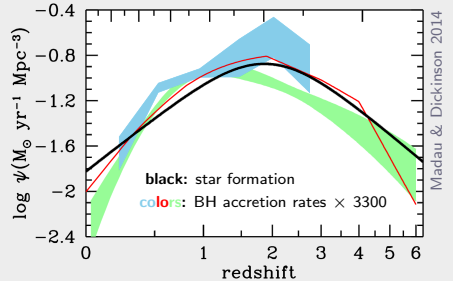
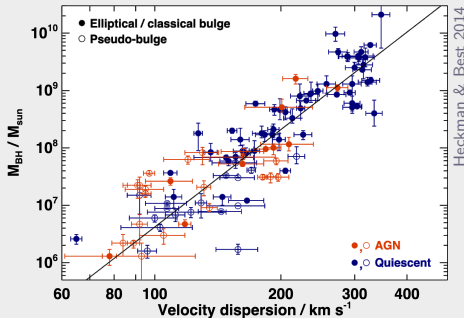


Galaxy formation

Towards realistic galaxy populations

Galaxy-Black hole connection

- ▶ BH growth follows SF growth
 - ▶ BH mass correlated with stellar mass
 - ▶ BH mass correlated with bulge (σ_*) even better
- ⇒ galaxies and black holes:
- ▶ grow together
 - ▶ both fed by (cold) gas



Galaxy formation

Towards realistic galaxy populations

Black hole growth

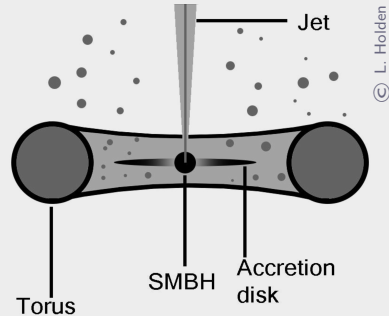
► accretion:

$$\rightarrow \text{Eddington rate: } \dot{M}_{\text{Edd}} = \frac{L_{\text{Edd}}}{\eta c^2}$$

$$L_{\text{Edd}} = \frac{4\pi G M_{\text{BH}} m_{\text{p}} c}{\sigma_{\text{T}}} - \text{Eddington luminosity:}$$

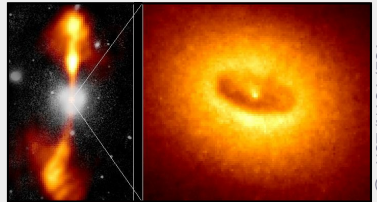
balance between the outward radiation force
and inward gravitational force

η - radiative efficiency: fraction of mass-energy
of the accreted material converted into radiation



© L. Holden

NGC 4261



© HST/NASA/ESA

Galaxy formation

Towards realistic galaxy populations

Black hole growth

► accretion:

→ Eddington rate: $\dot{M}_{\text{Edd}} = \frac{L_{\text{Edd}}}{\eta c^2}$

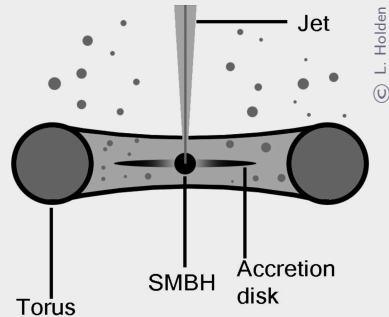
$L_{\text{Edd}} = \frac{4\pi G M_{\text{BH}} m_{\text{p}} c}{\sigma_{\text{T}}}$ - Eddington luminosity:

balance between the outward radiation force and inward gravitational force

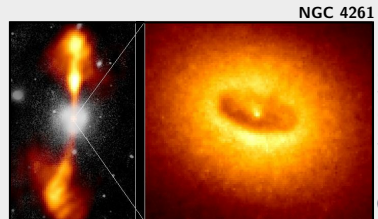
η - radiative efficiency: fraction of mass-energy of the accreted material converted into radiation

→ Eddington ratio: $f_{\text{Edd}} \equiv \frac{\dot{M}_{\text{BH}}}{\dot{M}_{\text{Edd}}}$

- at high f_{Edd} : strong radiation winds (few 1000 km/s)
- at low f_{Edd} : energetic jets (**B** advected with gas)



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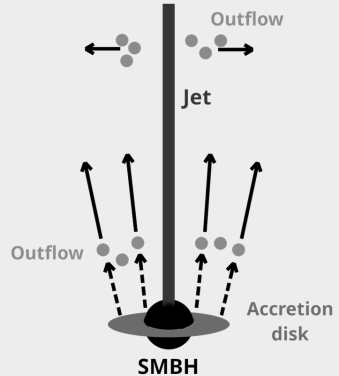
Galaxy formation

Towards realistic galaxy populations

AGN feedback

► AGN winds (“quasar mode”)

- at high f_{Edd} (prevalent)
- radiatively driven out of torus
- outflow velocities $v \sim 500 - 2000$ km/s
- seen in H_α , OIII, CO, X-ray



© L. Holden

Centaurus A



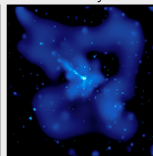
optical



IR



X-ray



radio



Galaxy formation

Towards realistic galaxy populations

AGN feedback

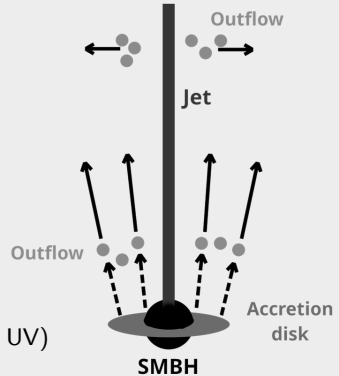
► AGN winds (“quasar mode”)

- at high f_{Edd} (prevalent)
- radiatively driven out of torus
- outflow velocities $v \sim 500 - 2000$ km/s
- seen in H_α , OIII, CO, X-ray

► AGN jets (“jet mode”)

- at low f_{Edd} (can occur at high)
- driven by spun up **B** near BH
- seen in radio, X-ray (hard to see in optical, IR, UV)

Blandford & Znajek 1977



© L. Holden

Centaurus A



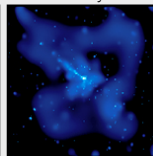
optical



IR



X-ray



radio



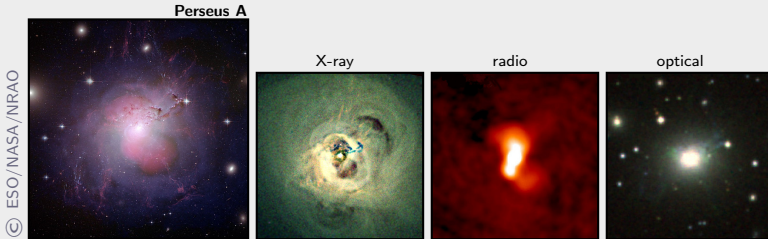
AGN feedback: quenching of galaxies

► jet mode feedback:

- blow bubbles of hot gas
- deposit energy in the surrounding gas ($\sim 10 - 100$ kpc)
- long term heating-cooling balance: cooling restarts $\rightarrow$ feeds BH $\rightarrow$ another jet

► observational evidence:

- bubbles of hot gas in X-ray & X-ray cavities around galaxy



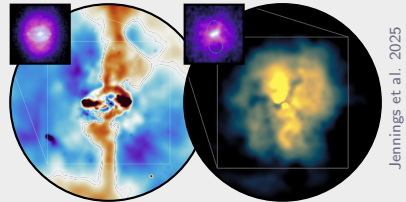
Galaxy formation

Towards realistic galaxy populations

AGN feedback: quenching of galaxies

► zoom-in simulations with jets:

- at $M_{\text{halo}} < 10^{13.5} M_{\odot}$ → expulse gas
- at $M_{\text{halo}} > 10^{13.5} M_{\odot}$ → offset cooling
- net result: evacuated massive halos



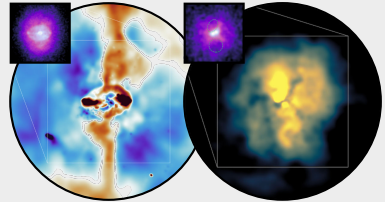
Galaxy formation

Towards realistic galaxy populations

AGN feedback: quenching of galaxies

► zoom-in simulations with jets:

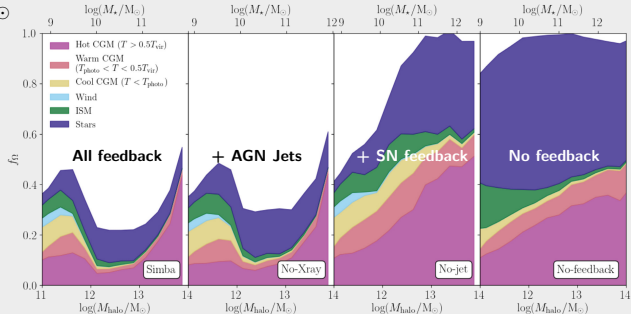
- at $M_{\text{halo}} < 10^{13.5} M_{\odot}$ → expulse gas
- at $M_{\text{halo}} > 10^{13.5} M_{\odot}$ → offset cooling
- net result: evacuated massive halos



Jennings et al. 2025

► large-scale simulations with jets:

- at $M_{\text{halo}} > 10^{12} M_{\odot}$
- jets:
 - overpressurize gas
 - blow out gas



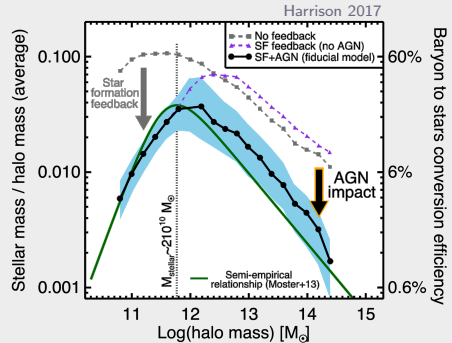
Appleby et al. 2021

Galaxy formation

Towards realistic galaxy populations

AGN feedback in a cosmological setup

- ▶ shapes cosmic galaxy/star formation efficiency

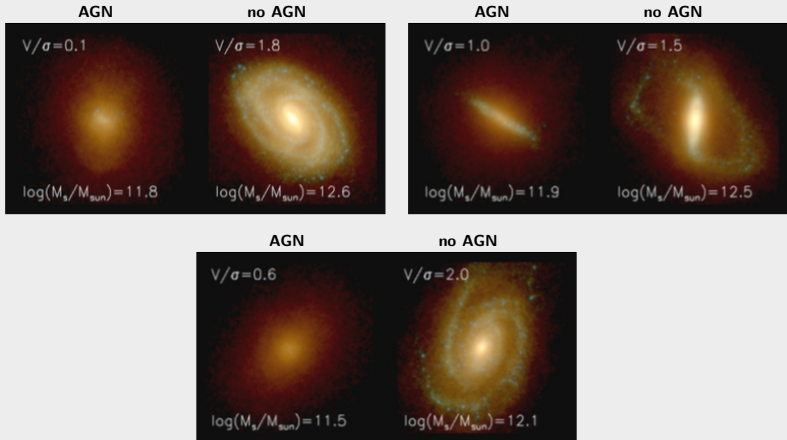


Galaxy formation

Towards realistic galaxy populations

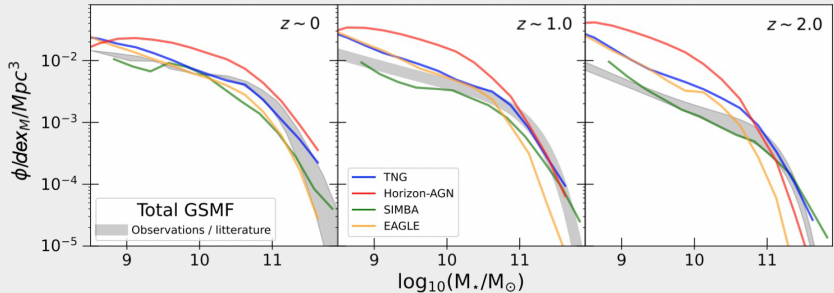
AGN feedback in a cosmological setup

- ▶ shapes cosmic galaxy/star formation efficiency
- ▶ galaxy morphology



Dubois et al. 2014, 2016

1 Stellar mass function



Picouet et al. 2023
HSC-CLAUDS survey

Hydro sims:

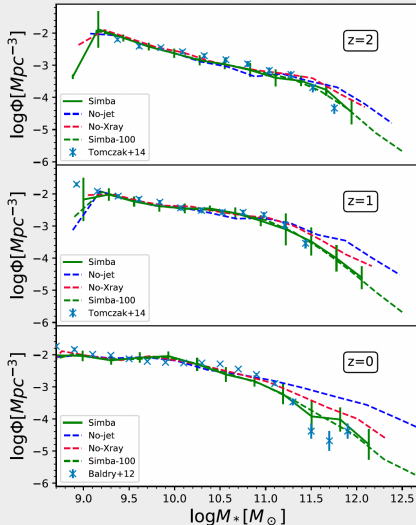
TNG100 (Pillepich et al. 2018)

Horizon-AGN (Dubois et al. 2014)

Simba (Davé et al. 2019)

Eagle (Crain et al. 2015; Schaye et al. 2015)

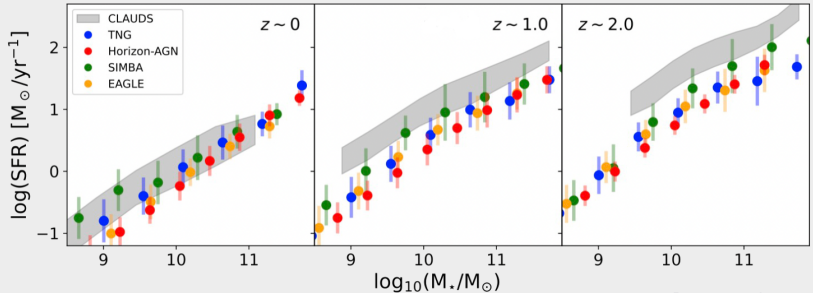
1 Stellar mass function



AGN jet feedback ('No-Xray') results in a substantial truncation of the galaxy stellar mass function

Simba (Davé et al. 2019)

2 Main sequence



Picouet et al. 2023
HSC-CLAUDS survey

Hydro sims:

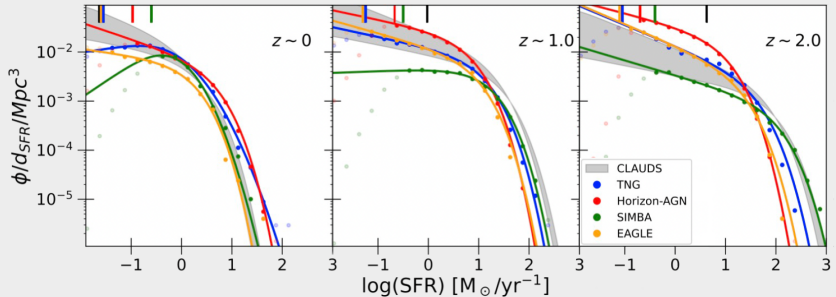
TNG100 (Pillepich et al. 2018)

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Simba (Davé et al. 2019)

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3 SFR function



Picouet et al. 2023
HSC-CLAUDS survey

Hydro sims:

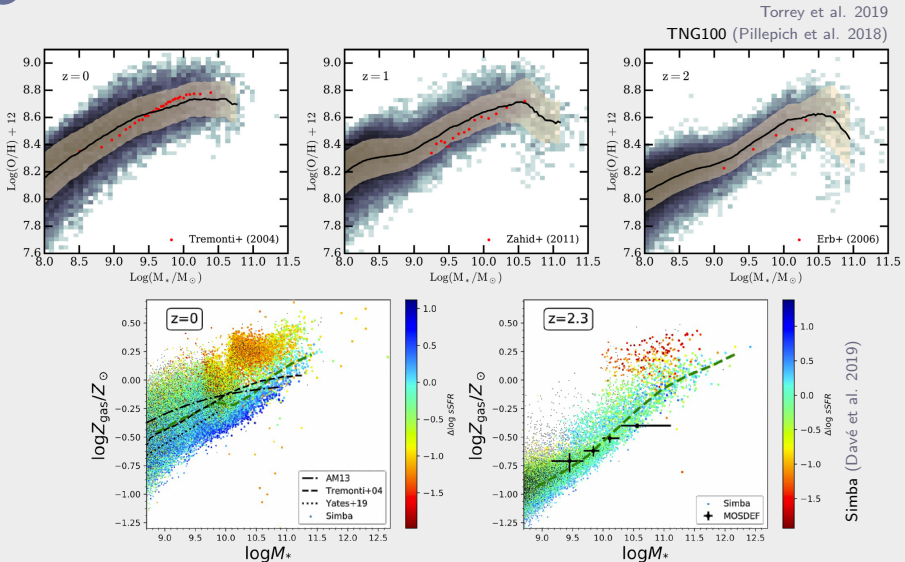
TNG100 (Pillepich et al. 2018)

Horizon-AGN (Dubois et al. 2014)

Simba (Davé et al. 2019)

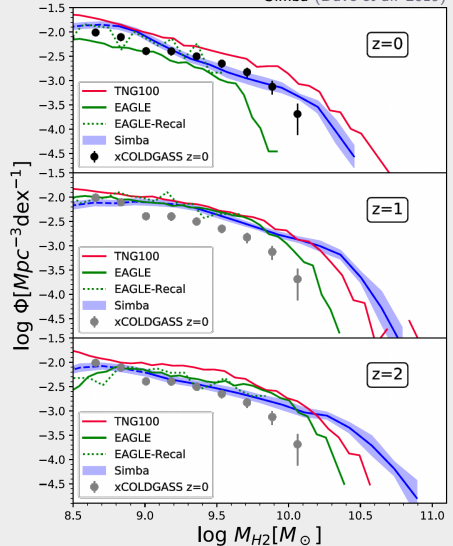
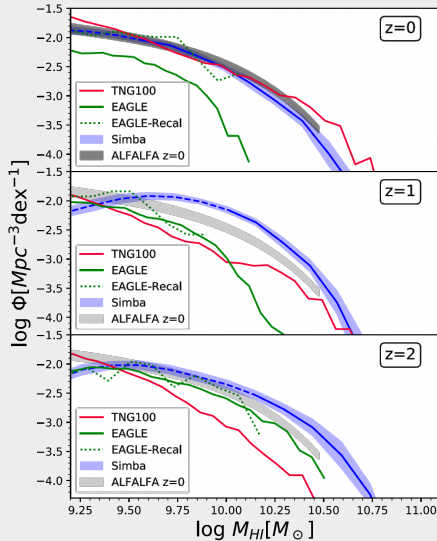
Eagle (Crain et al. 2015; Schaye et al. 2015)

4 Mass-metallicity relation

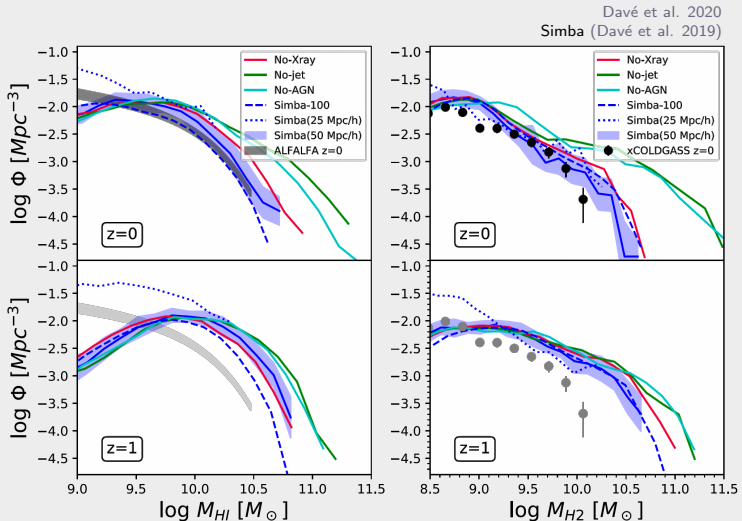


5 Cold gas fraction

Davé et al. 2020
Simba (Davé et al. 2019)

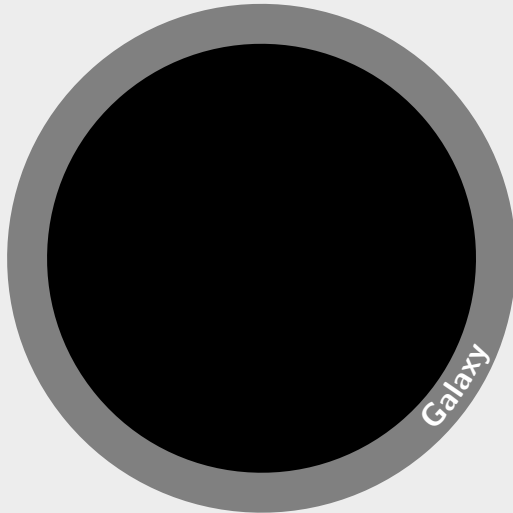


5 Cold gas fraction



Galaxy formation

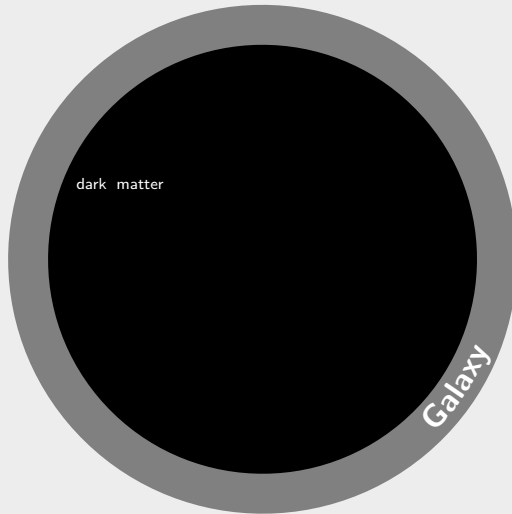
Galaxy components



adapted from Mo et al. 2010

Galaxy formation

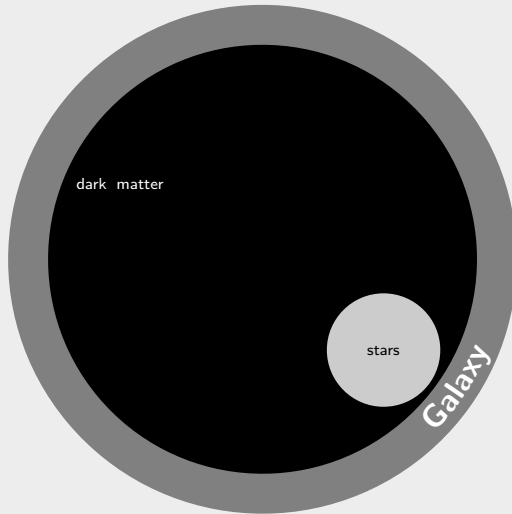
Galaxy components



adapted from Mo et al. 2010

Galaxy formation

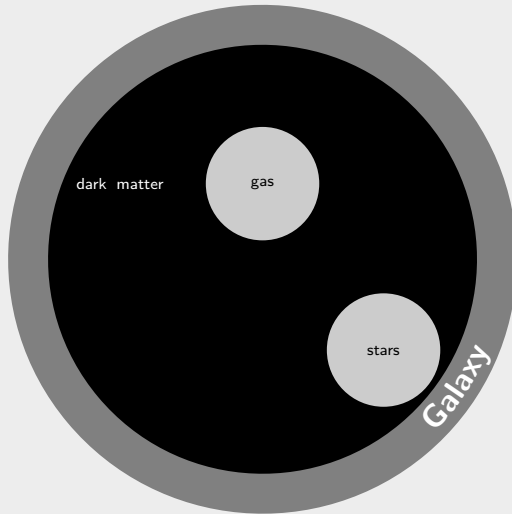
Galaxy components



adapted from Mo et al. 2010

Galaxy formation

Galaxy components



adapted from [Mo et al. 2010](#)

Galaxy formation

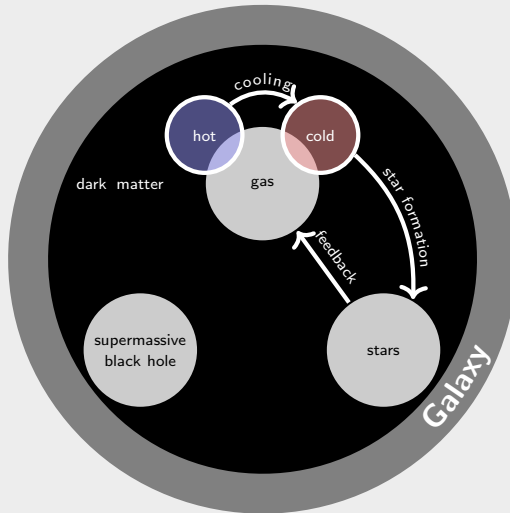
Galaxy components



adapted from Mo et al. 2010

Galaxy formation

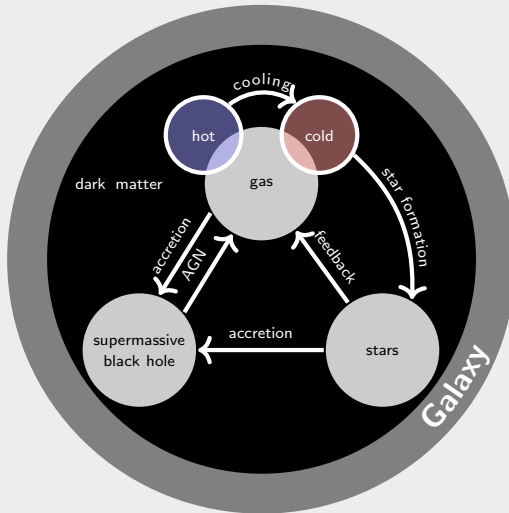
Galaxy components



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Galaxy formation

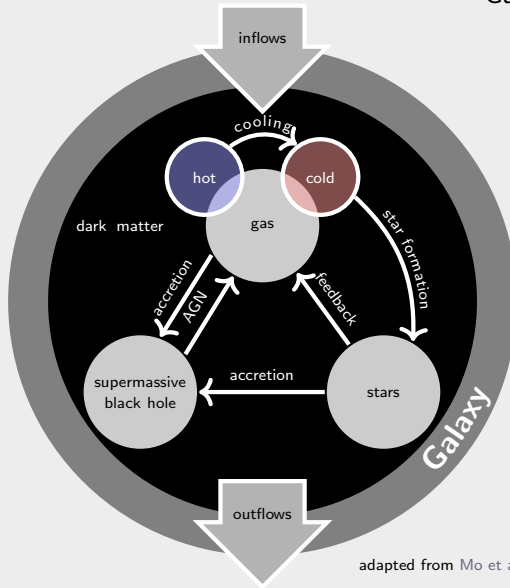
Galaxy components



adapted from Mo et al. 2010

Galaxy formation

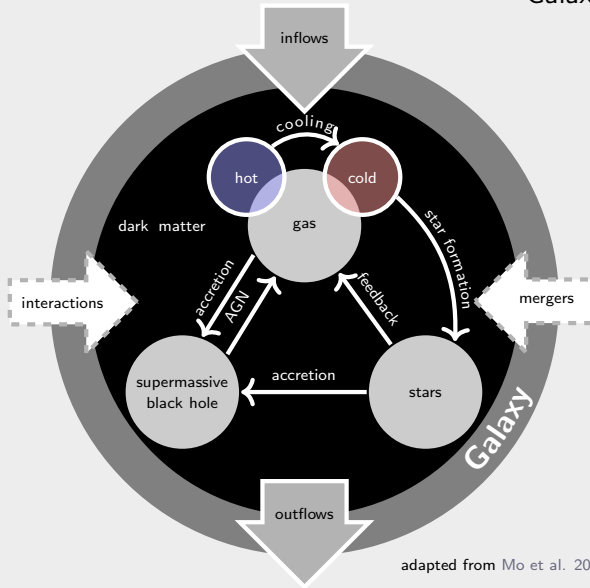
Galaxy components



adapted from Mo et al. 2010

Galaxy formation

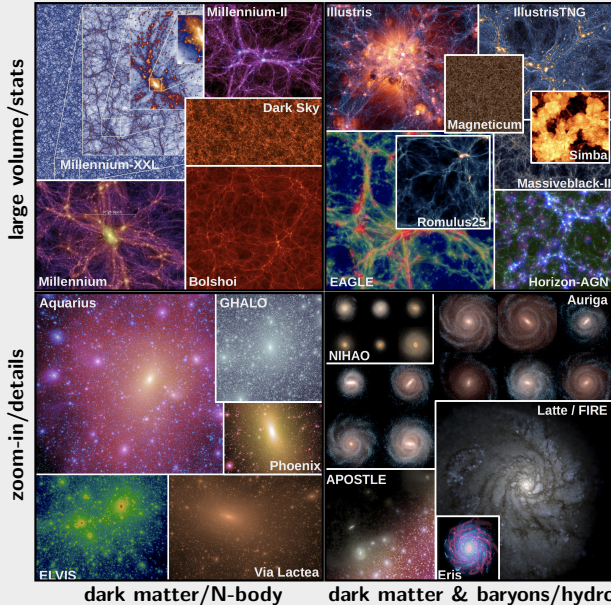
Galaxy components



adapted from Mo et al. 2010

Galaxy formation

Cosmological simulations



adapted from Vogelsberger et al. 2019

Cosmological framework

Initial conditions

- inflation generated initial perturbations on top of homogeneous Friedmann model
- ...

Gravity

- Newtonian gravity in an expanding background
- modified gravity - DM alternative
- modified gravity - DE alternative

Dark matter

- cold DM
- warm DM
- self-interacting DM
- fuzzy DM
- ...

Dark energy

- cosmological constant
- dynamical DE
- inhomogeneous DE
- coupled DE
- ...

Galaxy formation

Ingredients overview

Cosmological framework

Initial conditions

- inflation generated initial perturbations on top of homogeneous Friedmann model
- ...

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- modified gravity - DM alternative
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- ...

Dark energy

- cosmological constant
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- ...

Most important astrophysical processes

Gas cooling

- atomic
- molecular
- metals
- tabulated
- network

ISM

- effective equation of state
- multi-phase

Star formation

- initial stellar mass function
- probabilistic sampling
- enrichment

Stellar feedback

- kinetic
- thermal
- variety of sources: from stars to SNe

SM black holes

- numerical seeding
- growth by accretion prescription
- merging

AGN

- kinetic
- thermal
- radiative
- quasar mode
- radio mode

Magnetic fields

- ideal MHD
- cleaning schemes
- constrained transport

Radiation fields

- ray tracing
- Monte Carlo
- moment-based

Cosmic rays

- production
- heating
- anisotropic diffusion
- streaming