The formation of disc galaxies in computer simulations

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Halo & galaxy formation is a highly non-linear, multi-scale process that requires the use of numerical simulations.
Galaxy formation physics

- **Gas cooling**: Tabulated cooling tables (metal-dependent)
- **Star formation**: 'Transform' gas under given conditions into stars
- **Supernova feedback**: *main source of heavy elements (affects cooling)*
  * eject enormous amount of energy → regulates star formation + galactic winds

- **Dark Matter Halo**
  - **Infall**
  - **SN winds**
  - **SN feedback**
  - **Cooling**
  - **Cold Gas**
  - **Hot Gas**
  - **Stars**
Galaxy formation physics

- Dark Matter halos form via gravitational instability
- Gas cools down and condenses into the centers of the haloes
- High-density gas fragments and forms stars
- Feedback due to stellar evolution returns energy and chemical elements to the interstellar medium
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Photoionization & chemical composition effects are important

Wiersma et al. 2009
Star formation is unresolved in the simulations.

Still many uncertainties:
- High vs low-mass star formation
- Initial Mass Function (IMF): universal, time-dependent?
- Pop-III (metal-free) stars

In simulations:
Kennicutt-Schmidt law (Kennicutt+2012)
Feedback: in the absence of feedback, too high SFRs and stellar masses → need a physical process that reheats the gas or prevents it from cooling

Supernova (SN) explosions ~ dwarf to MW-mass galaxies

Active Galactic Nuclei (AGN) ~ massive galaxies

Other, under-dominant (?) processes at galaxy scales under debate
1. Start with an Initial Condition, e.g. consistent with cosmological concordance model
2. Run the simulation (including relevant physics), optimize computational cost, e.g. use zoom-in technique
3. Check whether results are consistent with observational results/expectations
Galaxy formation physics

- Galaxies are not isolated

  - Mergers/interactions with other systems
    - Change galaxy morphology – depends on angular momentum
    - Induce instabilities (e.g. bars)
    - Affect star formation and chemical properties

  - Accretion of gas from intergalactic medium (IGM)
    - Contributes gas with different abundance patterns
    - Enhances star formation (provided it penetrates the halo)

  - Galactic winds
    - Mixing of gas enriched within galaxies with gas in the IGM
    - Mixing of gas within halos – galactic fountains
Galaxy formation physics

- Galaxies are not isolated

→ GALAXY DIVERSITY!!
Feedback in galaxy formation simulations
- effects of Supernova (SN) feedback
- variations between models

Galaxy disks
- diversity
- survival/destruction

Galaxy diversity
- environment

Discussion:
- other types of feedback?

Summary
Without feedback mechanisms, the gas efficiently cools down and forms stars. In a cosmological context, this results in:

→ inconsistent with observed SFRs/galaxy stellar masses

CS+ 2008
SN Feedback in galaxy formation

Without feedback mechanisms, the gas efficiently cools down and forms stars. In a cosmological context, this results in:

- inconsistent with observed SFRs/galaxy stellar masses
- very high SFRs at early times → spheroidal, old galaxies
SN Feedback and metallicity

Winds triggered by SN explosions transport mass and metals into the ISM and IGM of galaxies
SN Feedback - problems

- How to implement feedback in simulations?
  - Ad-hoc winds versus cooling shutoff/delayed feedback
  - Input parameters needed, fine-tuning
  - Dependence on numerical choices, resolution
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The Aquila comparison project: the effects of feedback and numerical methods on simulations of galaxy formation

Different codes predict different galaxy properties

e.g. morphologies, gas fractions, SFRs, stellar masses, sizes
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- e.g. morphologies, gas fractions, SFRs, stellar masses, sizes

The circularity parameter $\varepsilon$ measures rotation, $\varepsilon \sim 1$: disk-like rotation

CS+ 2012
Aquila Project results

- Hints on e.g. disk formation from common results

- Galaxies with higher late-time SFRs have more significant disks

CS+ 2012
Aquila Project results

- All simulations predict galaxies with too large $M_{\text{stellar}}$. 

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CS+ 2012
Galaxy disks

Simulations of 8 galaxies, MW-mass, mildly isolated

- Galaxies are diverse
- Some have dominant disks, others don’t
- Some have bars
Galaxy disks

Separate into disk and spheroidal components to study disks

- “Circularity” \( \varepsilon = \frac{J_z}{J_{\text{circ}}} \)
- Dynamical decomposition based on rotational velocity

CS+ 2009
Galaxy disks

- Disk particles populate outer regions
Galaxy disks

- Disks form from late star formation (disks are young)

Total
Disk
Spheroid

CS+ 2009
Galaxy disks

- Disks form from the inside-out

![Graph showing the formation time of disk and spheroid components in galaxy Aq-C-5 at redshifts z = 0.5 and z = 1. The graph plots formation time in Gyr against the radius in kpc. The green circles represent the disk formation, while the other curves depict the formation of the spheroid.](image)

Disk
Spheroid

CS+ 2009
Galaxy disks

- Disks easily destroyed due to merger events

Galaxies with little/no disk at $z=0$

Galaxies with significant disks at $z=0$

- Other process affecting disk destruction?
Galaxy disks

- Disks destroyed/shrinked during periods of misaligned gas accretion

Galaxies with little/no disk at $z=0$

Galaxies with significant disks at $z=0$

$\beta =$ angle between gas and stars

CS+ 2009
Galaxy diversity

- Diversity expected in $\Lambda$CDM coming from diverse merger/accretion histories. E.g. inside-out formation

![Graphs showing stellar age distribution for different regions](image)
Galaxy diversity

- Diversity expected in $\Lambda$CDM coming from diverse merger/accretion histories. E.g. dynamics (morphology)
Galaxy diversity

- Diversity expected in $\Lambda$CDM coming from diverse merger/accretion histories. E.g. disk rotation
Galaxy diversity

- Diversity expected in $\Lambda$CDM coming from diverse merger/accretion histories. E.g. inner structure
Galaxy diversity

- Diversity expected in $\Lambda$CDM coming from diverse merger/accretion histories. E.g. outer structure.
Galaxy diversity

- Diversity expected in $\Lambda$CDM coming from diverse merger/accretion histories. E.g. spheroid dynamics
Galaxy diversity

- Diversity expected in $\Lambda$CDM coming from diverse merger/accretion histories. E.g. gas dynamics.
Galaxy diversity

- Diversity expected in $\Lambda$ CDM coming from diverse merger/accretion histories. E.g. bar formation

CS & Athanassoula 2012
The Milky Way: not an isolated galaxy

- Constrained Local UniversE simulations: CLUES
- Identify MW & M31 candidates
The Milky Way: not an isolated galaxy
The Milky Way: not an isolated galaxy

- Environmental effects: higher SFRs in richer environments (?)
Other feedback mechanisms?

- Most simulations including only SN feedback still have too high SFRs at early times, consuming most of the gas which becomes unavailable for later star formation.

  Radiation pressure from young, massive stars: effects on ISM comparable to SN feedback?
  (e.g. Hopkins+2011, Agertz+2013, Aumer+2013, Stinson+2013)

- Observations of young star clusters in GMCs show that the gas disperses before the first SNe explode
  → The radiation from a young stellar population carries large amounts of energy and momentum
Other feedback mechanisms?

- How to implement radiation pressure in simulations?

  Momentum-driven feedback, parametrized in general as:

  \[ \dot{\rho}_{\text{rad}} = (\eta_1 + \eta_2 \tau_{\text{IR}}) \frac{L(t)}{c} \]

  - \( L(t) \): luminosity of the stellar population
  - \( \eta_1 \): efficiency of radiation absorption/scattering
  - \( \eta_2 \): efficiency of momentum transfer from IR photons
    (re-radiated by dust and scattered by dust grains)
  - \( \tau_{\text{IR}} \): optical IR depth (depends on \( \rho \), \( Z \), \( \sigma \))
Effects of radiation-pressure feedback

- Reduce star formation at early times

Isolated galaxy simulations
Agertz+2013

Aumer+2013
Abundance of disks: invariant to assumptions?

SN + Radiation pressure feedback

Aumer+ 2013
Abundance of disks: invariant to assumptions?

Ad-hoc winds & ISM model
Feedback mechanisms regulate star formation in galaxies, but:

- Significant uncertainties in physical details
- Not clear how to implement at resolved scales
- SN: thermal versus kinetic
- Radiation pressure (?)

Still, simulations help understand relevant physics of disk formation

- Disks are young
- Disks can be destroyed by mergers and by misaligned gas accretion
- Disks can be rebuilt provided gas is available
- Environmental effects on Milky Way might be relevant

Galaxies are diverse in \( \Lambda \) CDM, even at a fixed stellar mass

- Codes should reproduce such diversity