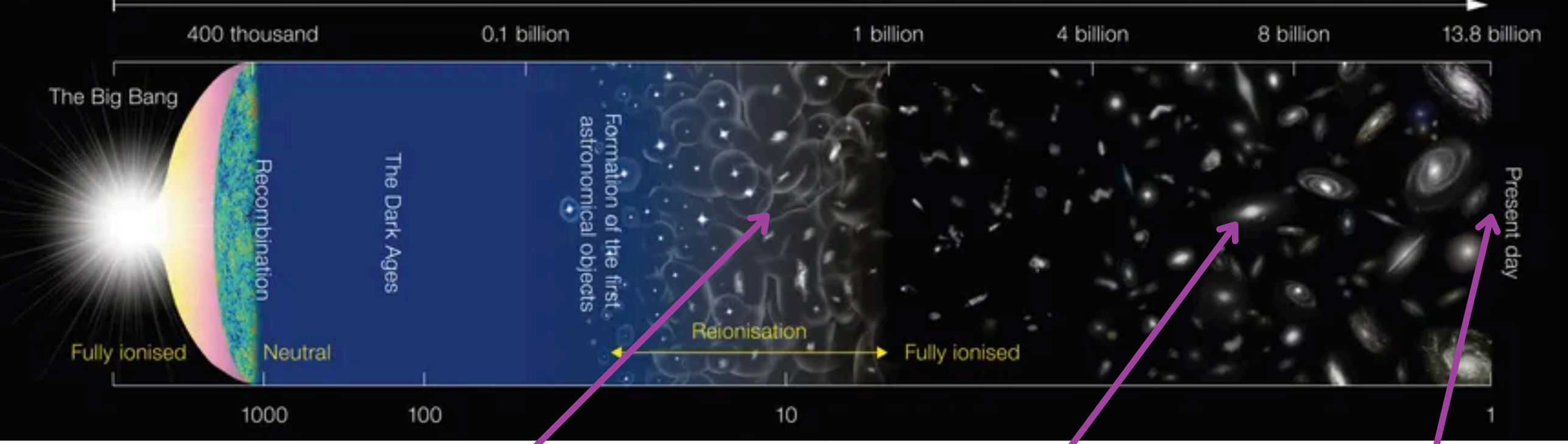
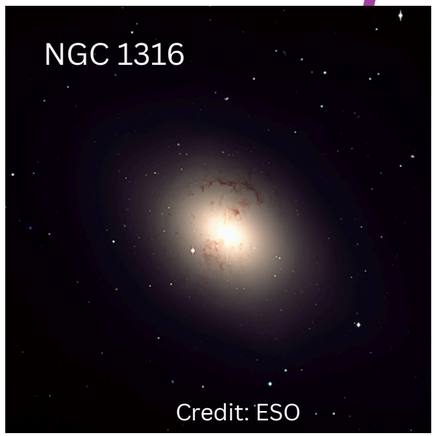
Cosmological Simulations of Galaxies

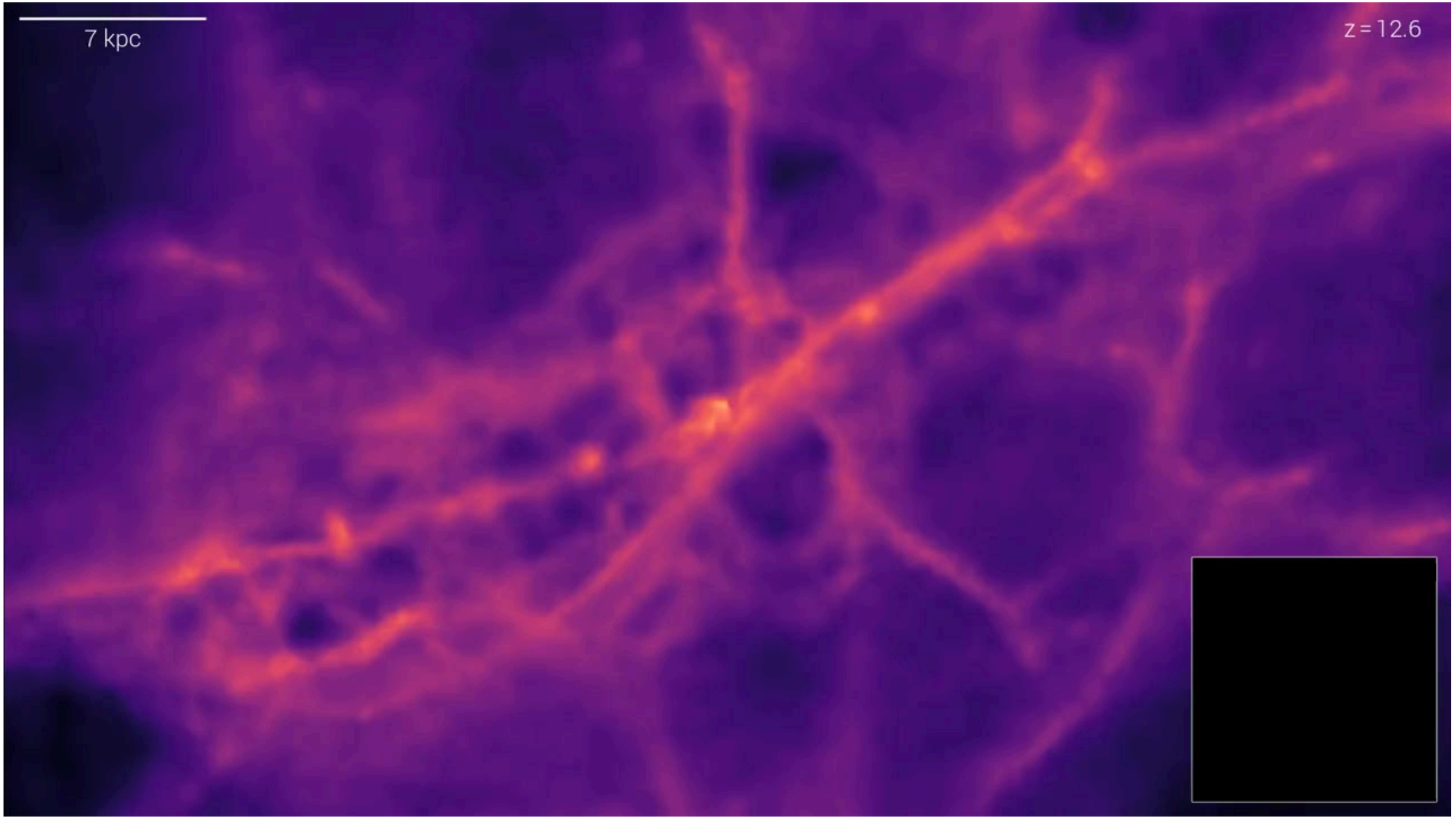
Feldmann & Bieri (2025)

Raffael Jonas & Lena Einramhof



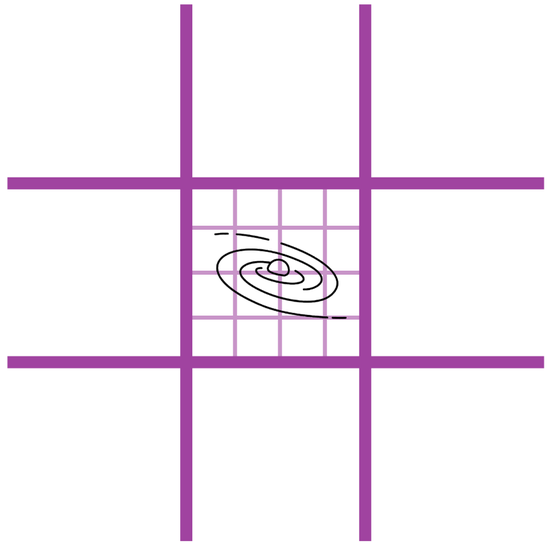


Observations give us snapshots

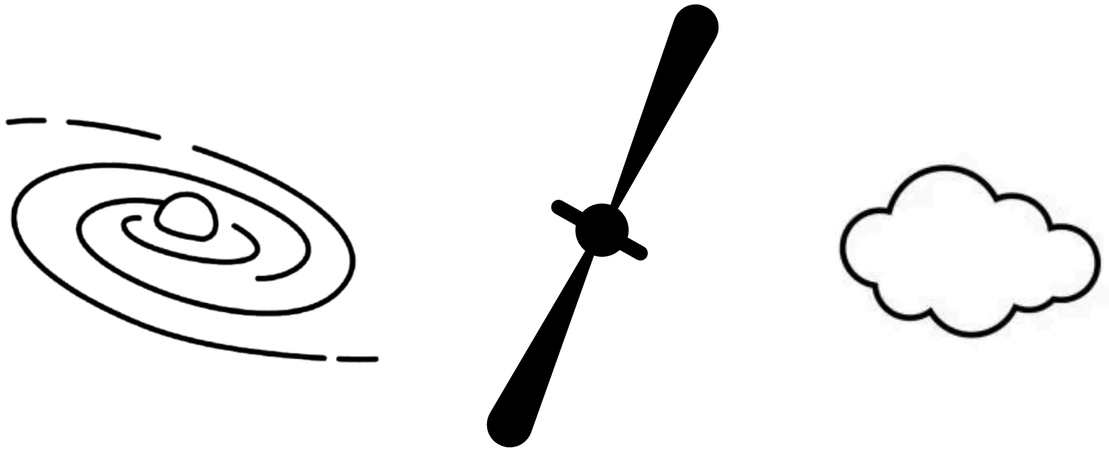


TNG50 Simulation

Zoom-in Simulations



Music (Hahn & Abel, 2011)
GRAFIC-2 (Bertschinger, 2001)

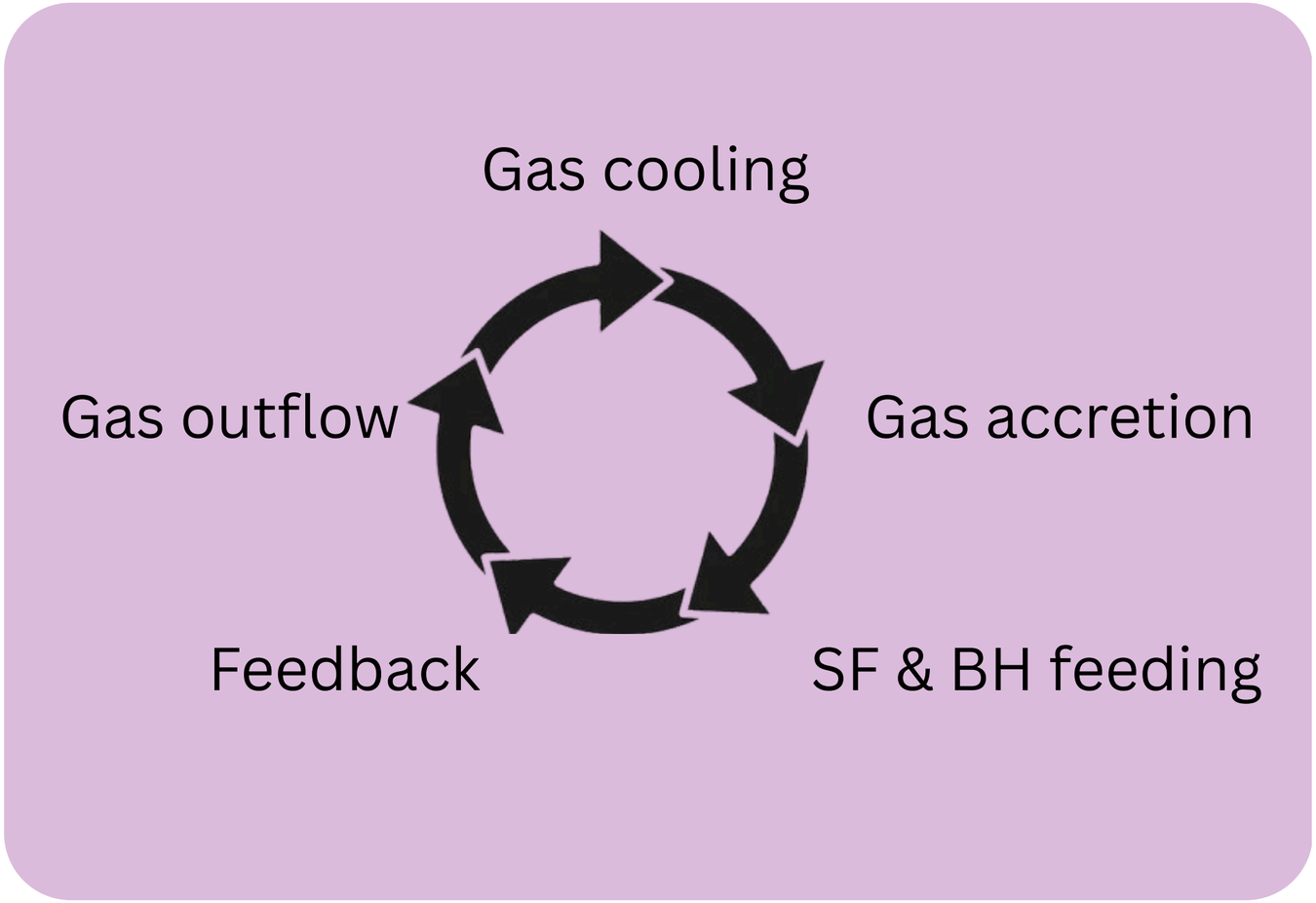


Galaxy AGN ISM

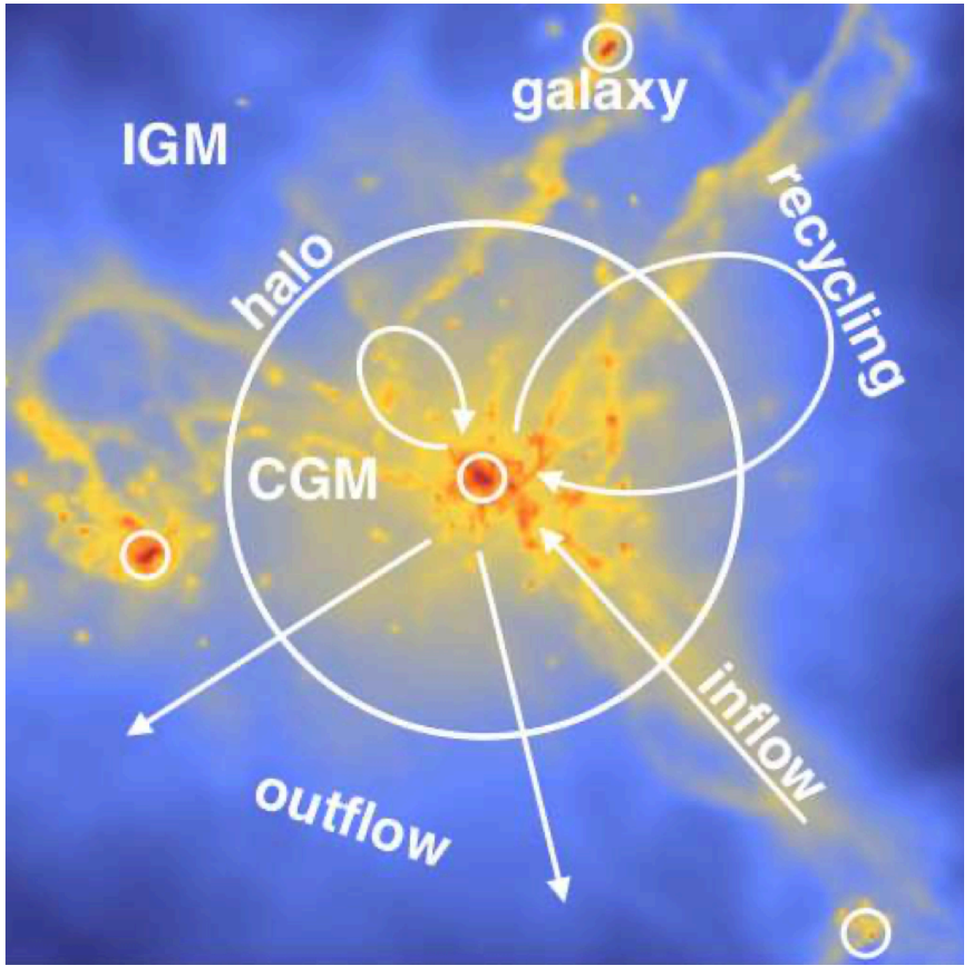
Sub-grid Processes

processes dominating below grid resolution

Baryonic Cycle



van de Voort (2017)



Gas Cooling & Heating

Cooling is vital for molecular clouds ⟶ Stars & Galaxies

dust
collisional excitation

$$\Lambda(T, n, Z, \ldots)$$

Cooling Tables

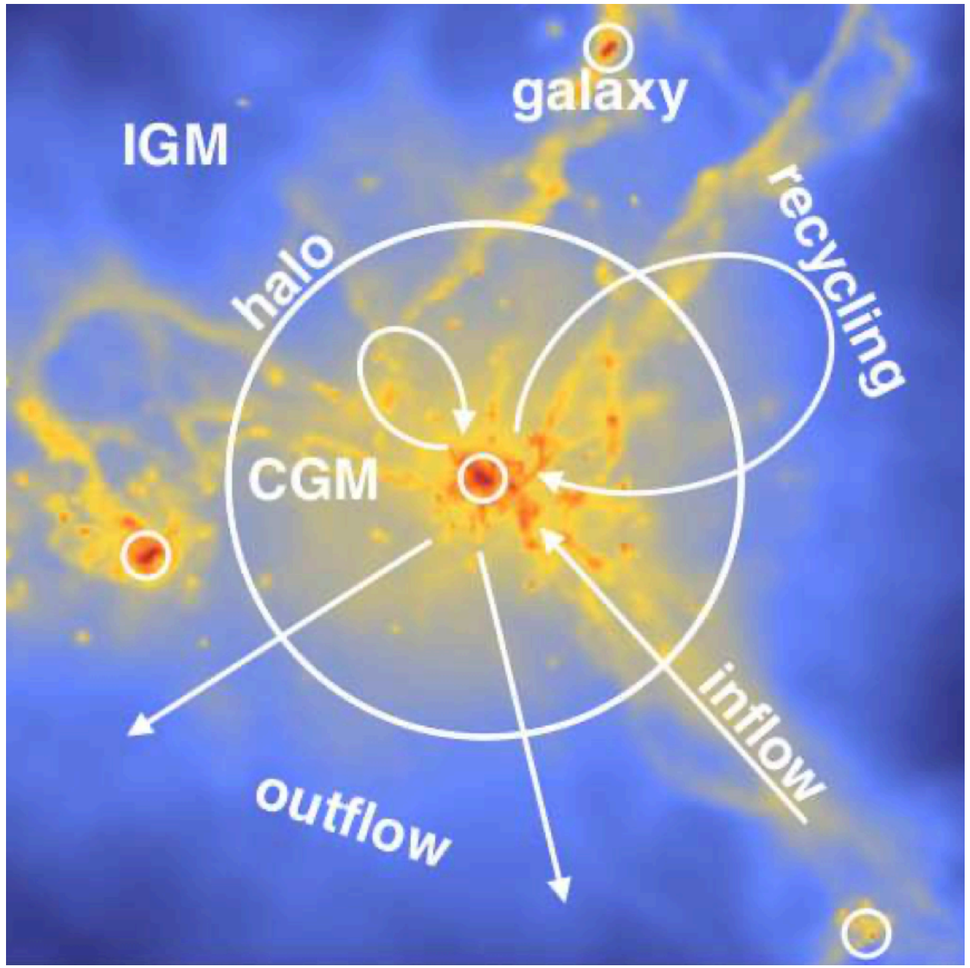
cosmic rays
UV/X-ray backgrounds
supernova feedback

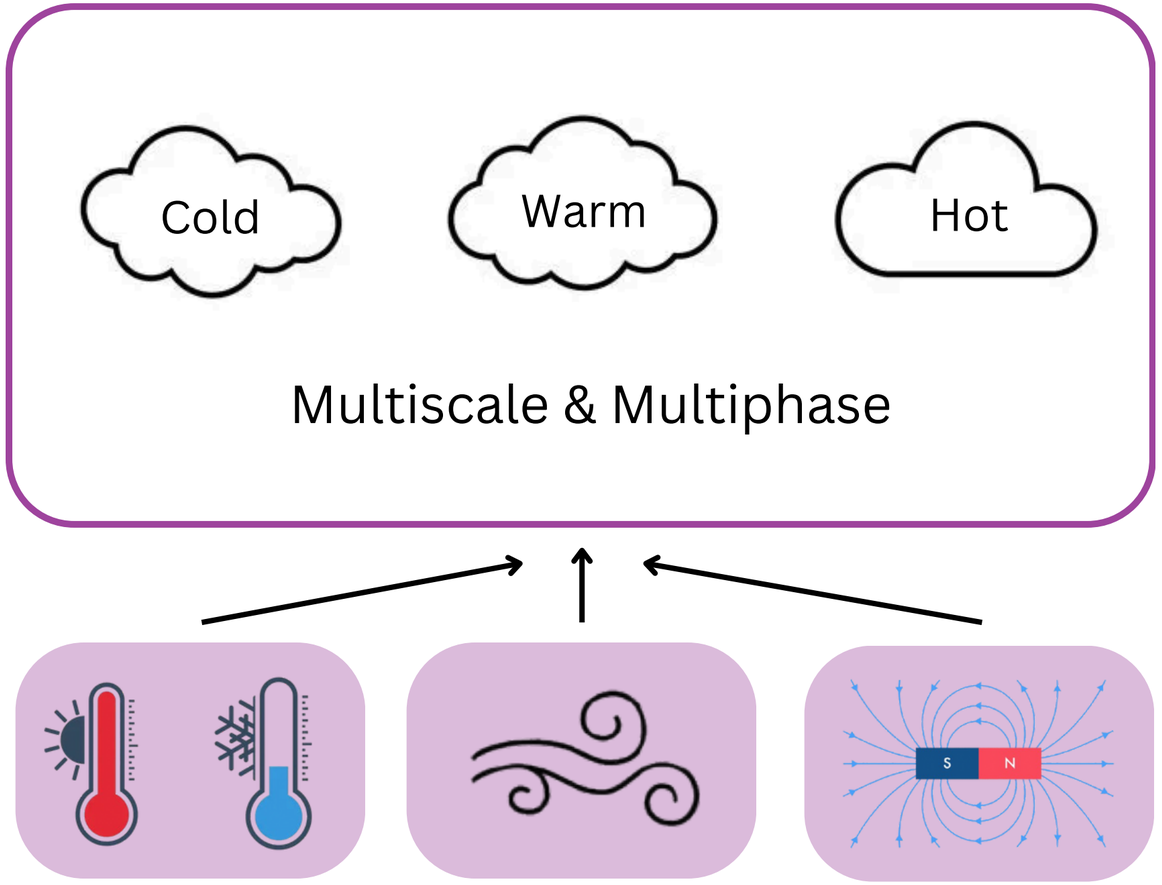
$$\Gamma(T, n, Z, \ldots)$$

Challenges: Resolution,
self-shielding, local radiation fields

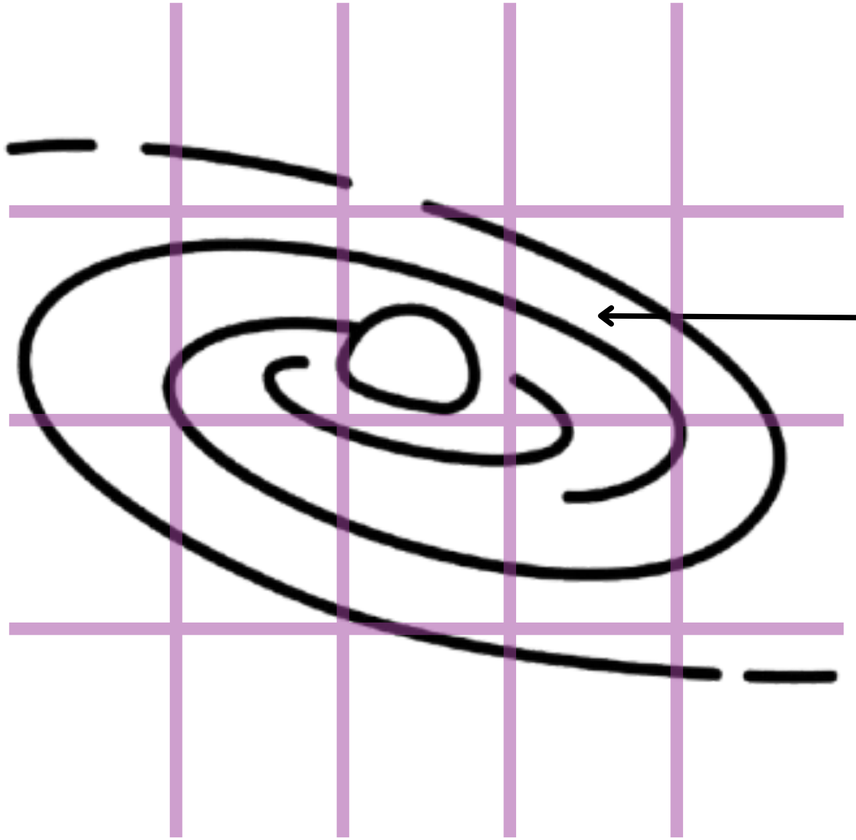
Interstellar Medium

van de Voort (2017)





Star formation & evolution



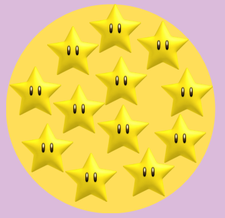
Sub-grid processes → approximation

SF conditions:

- gas density/pressure threshold
- gravitational instability
- converging flows

Schmidt Law: $\Sigma_{\rm SFR} \propto (\Sigma_{\rm Gas})^n \longrightarrow p_{\rm sf}(\rm cell)$

Star particle: single-metallicity & single-age stellar population

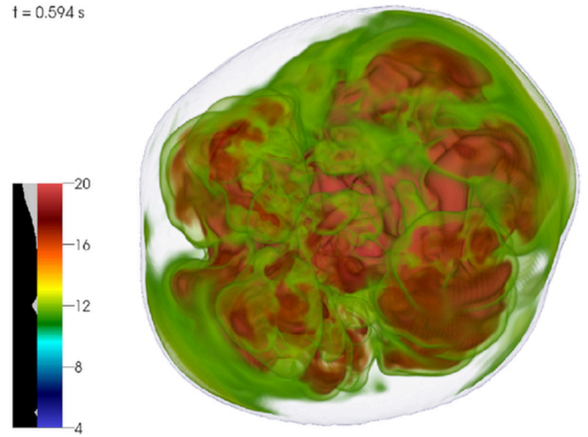


Challenges: chemical enrichment → affects cooling & future star formation, stellar feedback

Stellar feedback

essential for reproducing key galaxy properties

Simulation time-step $\Delta t \lesssim$ Gravitational collapse $t_{\rm ff}$, ISM cooling $t_{\rm cool}$



Burrows (2019)

small spatial & temporal scales
→ sub-grid models

Blast wave travels $\approx 10\ \mathrm{pc}$ in $\approx 10^4 \mathrm{yrs}$

Stellar feedback

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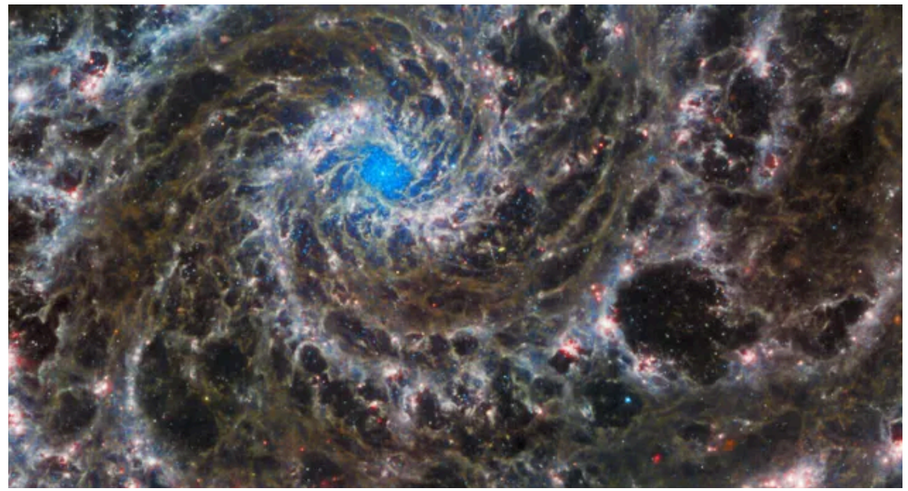
→ sub-grid models



Blast wave travels ≈ 10 pc in $\approx 10^4$yrs
SNe+SNR ≈ 100 pc, 10 Myrs

Challenges: impact of SN, stellar winds & radiation on the ISM

Supermassive Black Hole Formation and Evolution

Cannot resolve small scales → seeding

$M_{halo} > 10^{10}\ M_\odot$ → $M_{seed} \approx 100\ M_\odot$

$M_{halo} > 10^{10}\ M_\odot$ → $M_{seed} \approx 10^4 - 10^6\ M_\odot$

Study growth, not formation

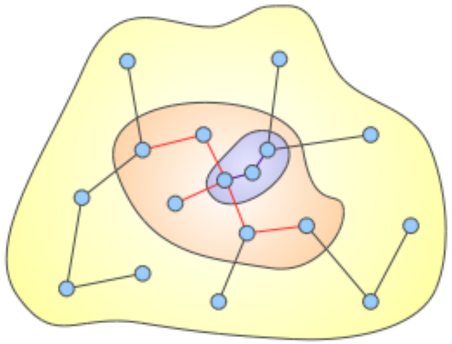
Gas inflow

Merger

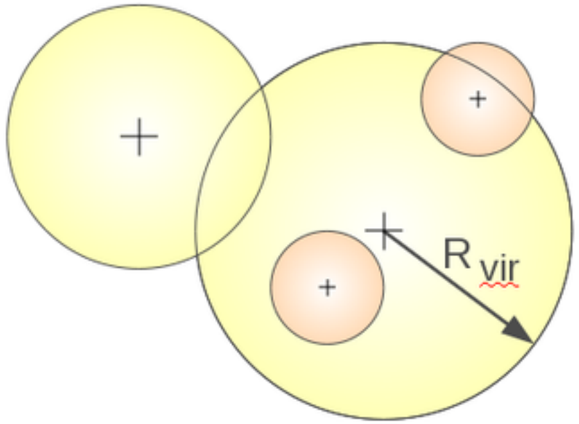
→ M_{seed} increases

Challenge: instantaneous mergers, BH drifts from galaxy center

Halo catalogues



Friends-of-friends

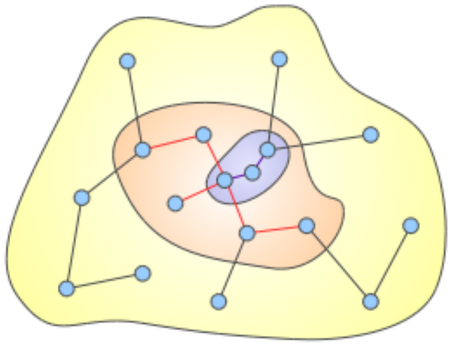


AMIGA halo finder

https://www.cosmosim.org/cms/data/halo-finders/

Analyzing simulations

Halo catalogues



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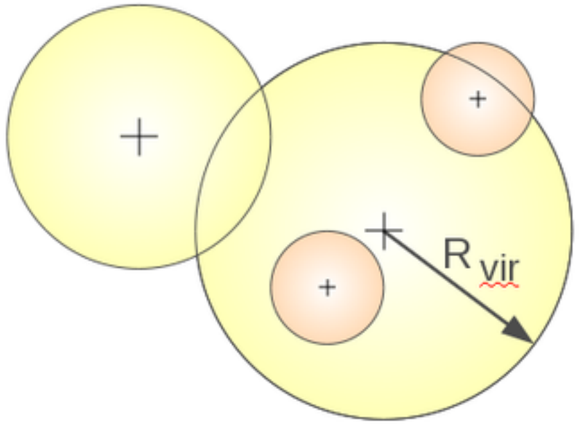

AMIGA halo finder

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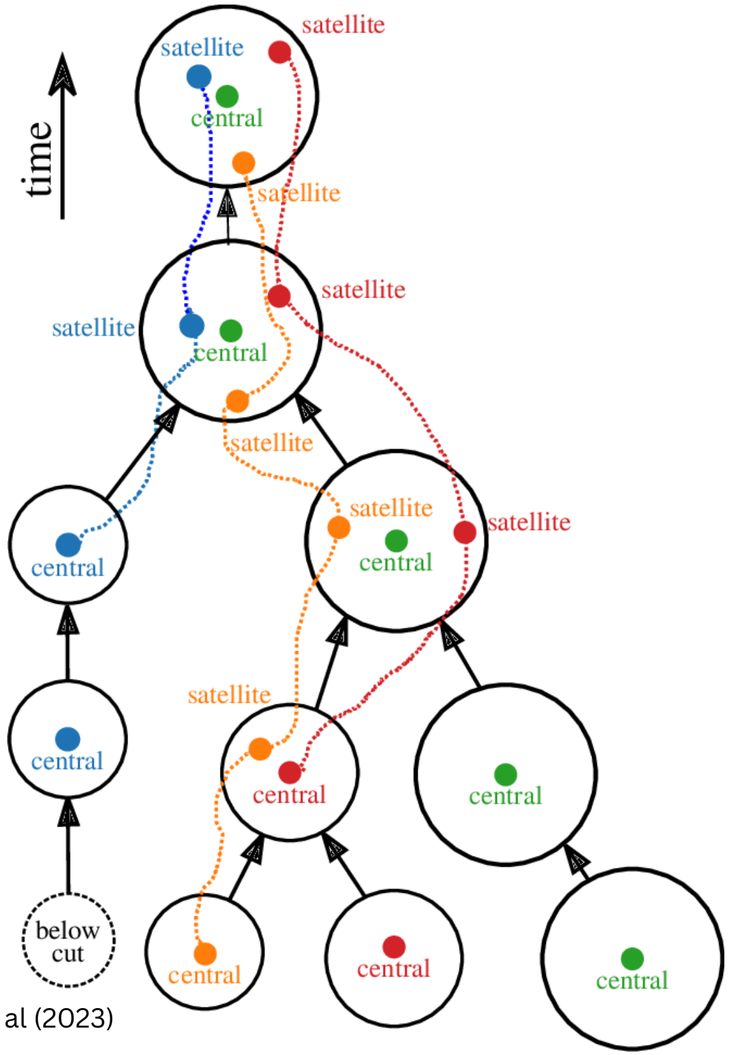
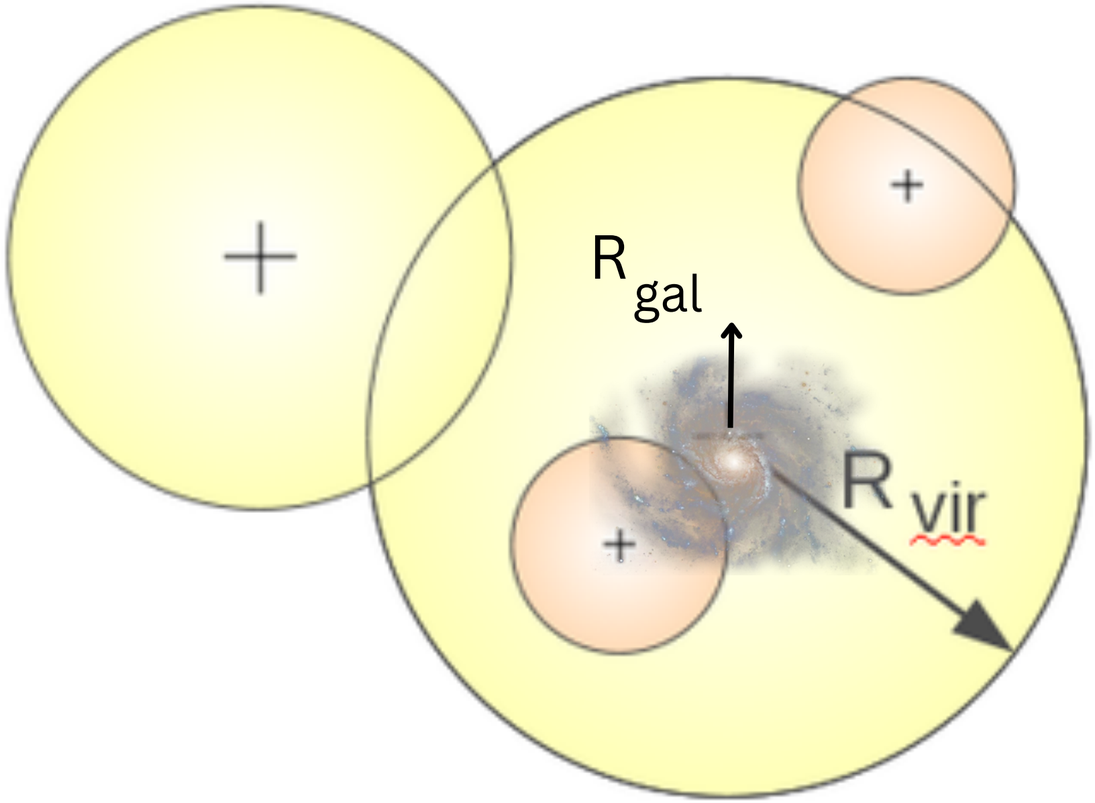
Halo merger trees



Korytov et al (2023)

Global Galaxy Properties

https://www.cosmosim.org/cms/data/halo-finders/



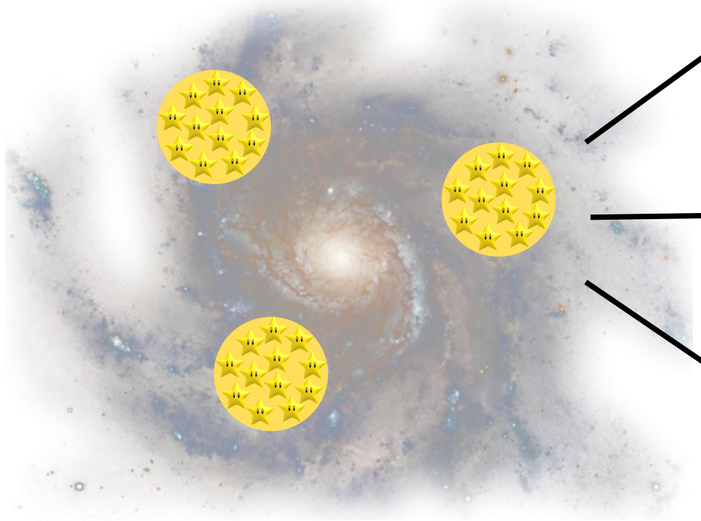
Mass (stars, gas, metals, dark matter)

Star formation rate

Size

$R_{gal} \approx 0.1 - 0.2\ R_{vir}$

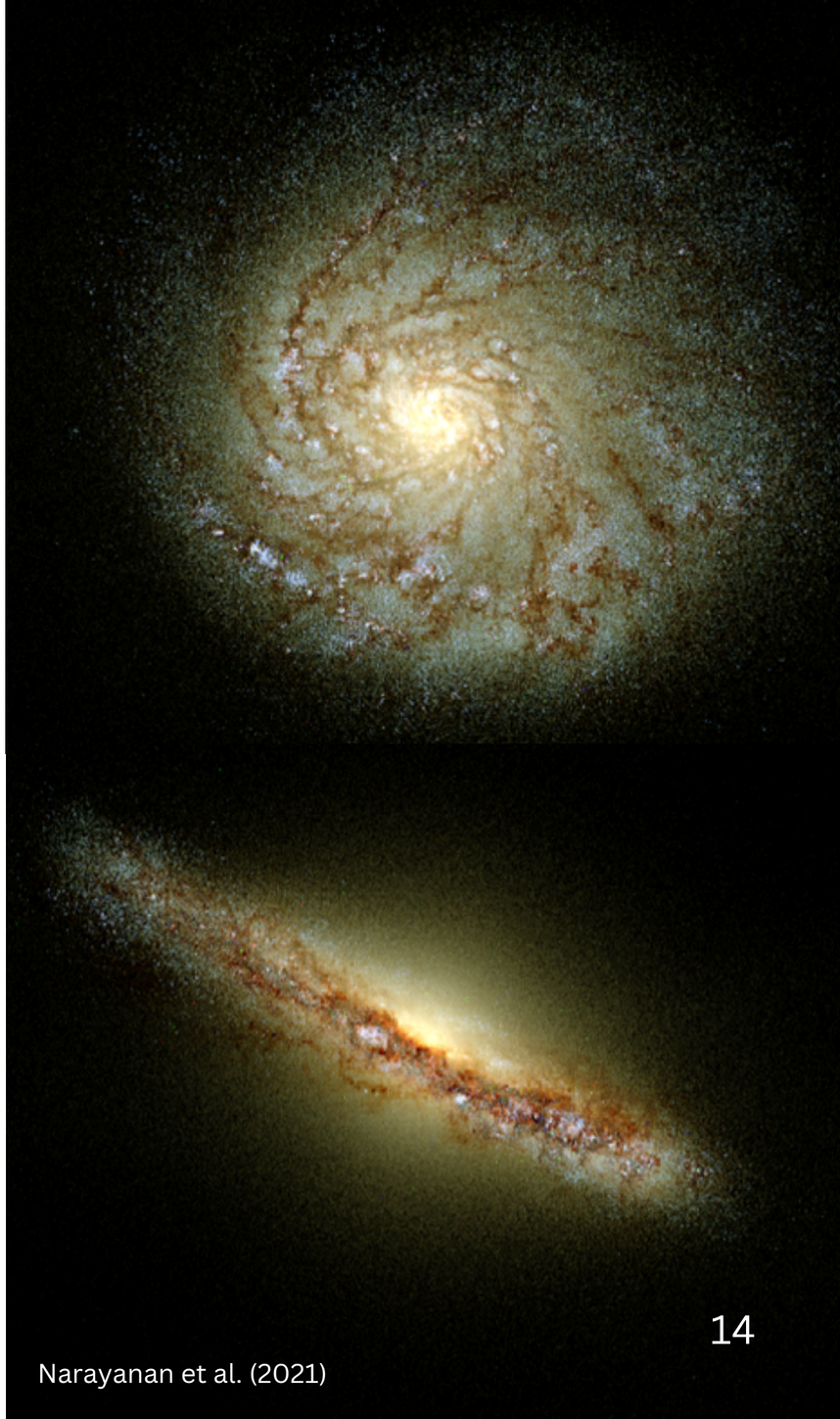
Mock observations



Metallicity

Mass

Age



Narayanan et al. (2021)

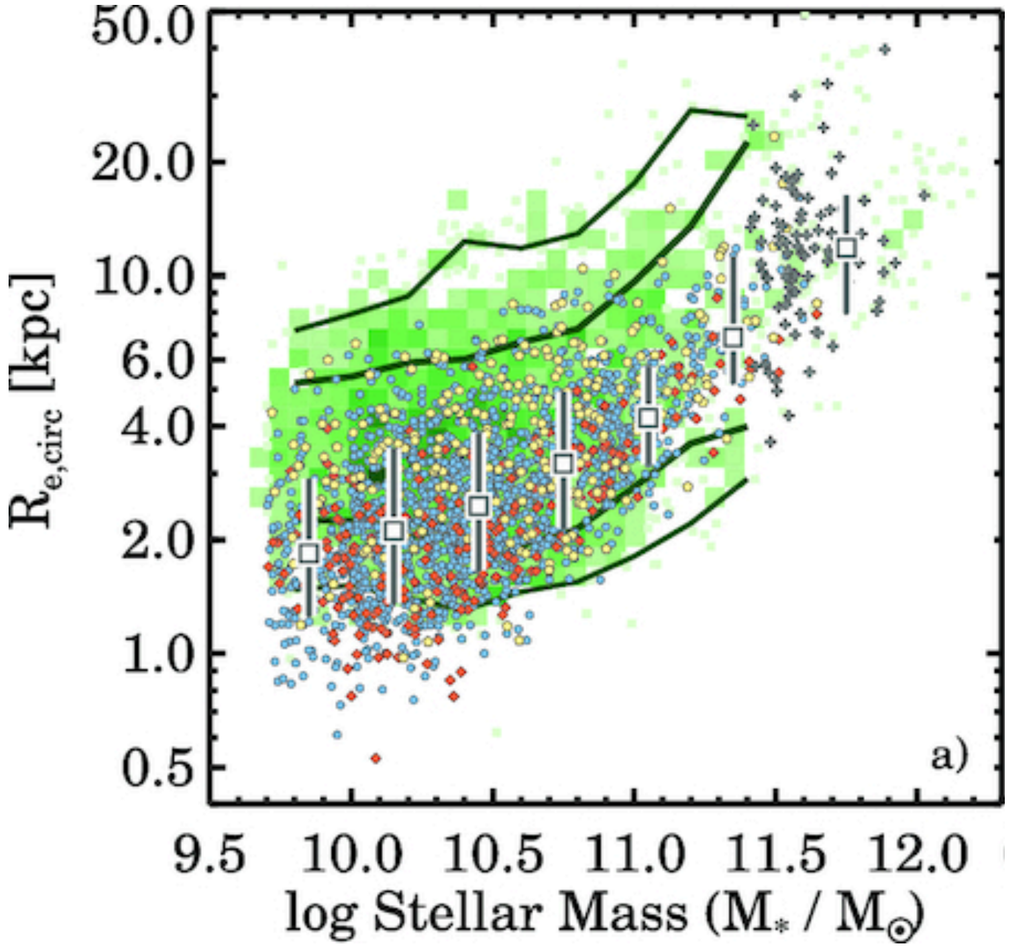
Assessing results

Internal comparison

Comparison with theoretical models

Cross-simulation comparison

Comparison with observations



van de Sande et al. (2018)

Outlook

Limited resolution	Extreme zoom-ins
Uncertain sub-grid models	High-resolution, smaller-scale simulations Integrate additional physics
High computational cost	Advanced hardware Improved parallelization
Need for faster / more predictive modeling	Artifical intelligence Machine learning

Take-away points

1) Simulations allow us to follow galaxy evolution, test physical process and predict observables

2) Modeling the baryonic cycle requires capturing many intertwined processes (cooling, heating, and feedback...) which often must be approximated through sub-grid models

3) Future simulations aim for higher realism, more detailed physics and a deeper understanding of complex galaxy evolution

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