Zoom in Cosmological simulation: From dark matter, gas and stars to spiral galaxies

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Bogotá 4-20-2020

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outline

- Initial conditions
- N-body dynamics (Dark Matters and Stars)
- Hydrodynamics (Gas)
- Galaxies (SF vs FB)
- The Dark Matter connection
- Prospective and new questions

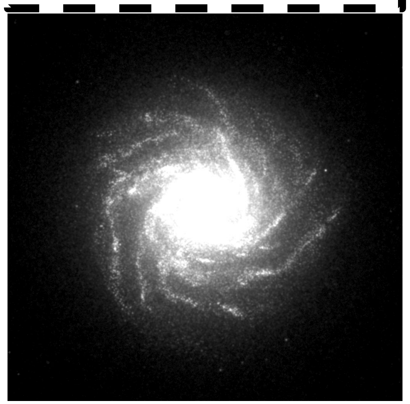
How do we want to simulate it?

To study formation and dynamics of spiral galaxies like ours

why?

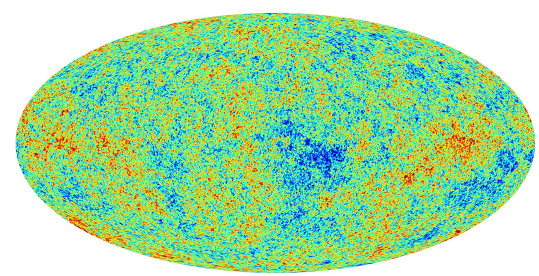
What do we want to simulate?

A spiral galaxy

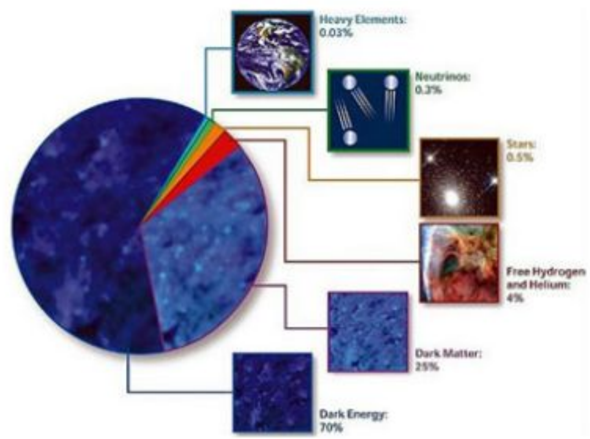


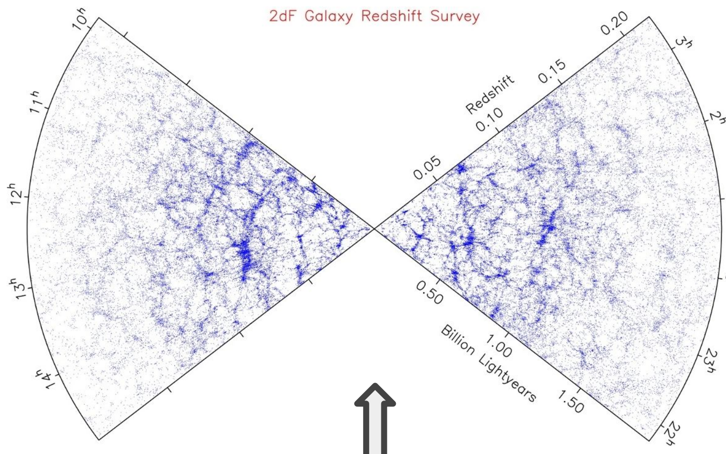
where?

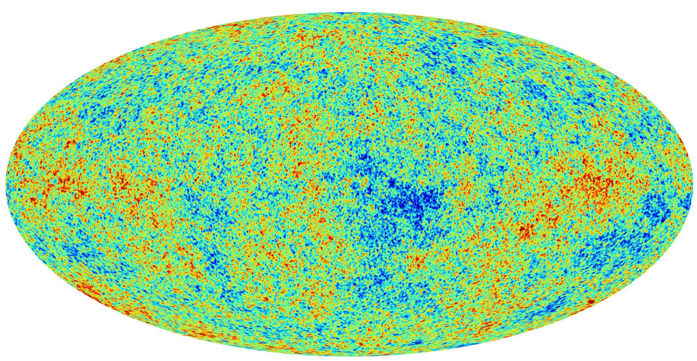
In a cosmological environment

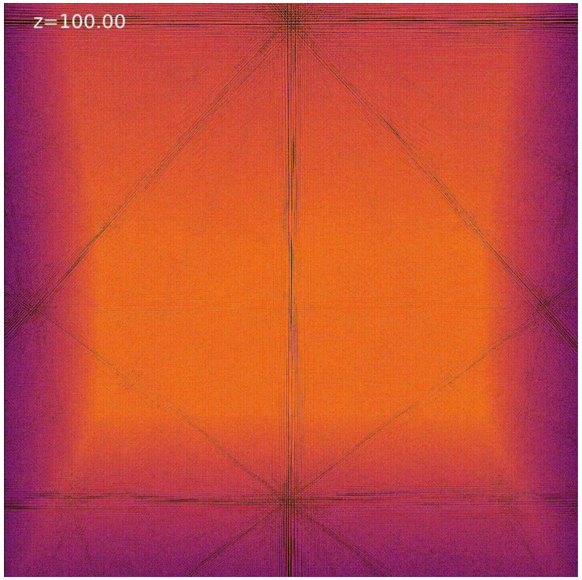


Cosmological Simulations









Initial conditions

Available random fields generators:

- original code from Ed Bertschinger : http://web.mit.edu/edbert/grafic2.101.tar.gz
- MPI version from Simon Prunet : http://www2.iap.fr/users/pichon/mpgrafic.html
- C++ MPI version from Doug Potter: http://sourceforge.net/projects/grafic/
- MUSIC: a new IC generator by Oliver Hahn: http://www.stanford.edu/~ohahn/

Cosmological inputs

- analytical power spectrum from Eisenstein & Hu, ApJ, 1998, 496, 605 (or your favorite function)
- cosmo parameters: omega_m, omega_lambda, omega_b, n_s, sigma_8
- run parameters: box size, grid size, noise random seed or external white noise file
- grafic format features 7 binary unformatted fortran files:

ic_velcx, ic_velcy, ic_velcz, ic_deltab, ic_velbx, ic_velby, ic_velbz

Expanding Universe and comoving coordinates

Expansion governed by Friedman-Lemaitre equations: $a(t)$ and $H(t)$

Define comoving coordinates: $\mathrm{x} = \dfrac{\mathrm{r}}{a(t)}$ $\quad \tilde{\rho}(\mathrm{x}, t) = \rho(\mathrm{r}, t)a(t)^3$

Define peculiar velocity: $\mathrm{v} = \mathrm{u} - H(t)\mathrm{r}$ $\quad \tilde{\mathrm{v}} = \mathrm{v}a(t)$

Define supercomoving time (Martel and Shapiro 1998): $\mathrm{d}\tau = \dfrac{\mathrm{d}t}{a(t)^2}$

Then magic happens ! Fluid equations are equal to the one without expansion.

The only difference being Poisson's equation: $\tilde{\phi} = \phi a(t)^2$

$$\tilde{\Delta}\tilde{\phi} = \frac{3}{2}a(t)\Omega_m \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

provided $p = 0$ or $p = (\gamma - 1)e$ with $\gamma = 5/3$ and $\tilde{p} = pa(t)^5$

Ingredients

Different fluids are modelled using different techniques.

1. **Dark matter** as a collisionless fluid (Vlasov equation)
2. **Gas** as a compressible ideal gas (Euler equations)
3. **Stars** as a collisionless fluid (Vlasov equation)
4. Various chemical species as passive scalars and associated reactions

Possible extra ingredients:

5. Metals and dust grains as passive scalars or as new fluids
6. Massive neutrinos as a quasi-relativistic fluid
7. Magnetic fields as a divergence free vector field
8. Supermassive black holes as individual accreting particles
9. Cosmic rays as an additional energy variables or as a new fluid

Dark Matter

(and stars)

Vlasov-Poisson equation

Collisionless limit of the Boltzmann equation:

$$\frac{Df}{Dt} = \frac{\partial}{\partial t} f(\mathbf{x}, \mathbf{v}, t) + \mathbf{v}\frac{\partial}{\partial \mathbf{x}} f + \mathbf{a}\frac{\partial}{\partial \mathbf{v}} f = 0$$

Liouville theorem: number of particle is conserve in phase-space The gravitational acceleration is given by **Poisson equation**:

$$\Delta\Phi(\mathbf{x}, t) = 4\pi G m \left(n(\mathbf{x}, t) - \bar{n}\right) \qquad n(\mathbf{x}, t) = \int f(\mathbf{x}, \mathbf{v}, t)\mathrm{d}^3\mathrm{v}$$

3 strategies:

- pure fluid on a 6D grid (Yoshikawa et al. 2013) or on a cold 3D manifold (Abel et al. 2012)
- pure N body using direct force computations or fast multipole methods (Barnes & Hut 1986; Bouchet & Hernquist 1988)
- mixture of the 2: the Particle-Mesh method (Hockney & Eastwood 1988)

N-body codes

N-body code : particle trajectory integrator coupled to your favorite gravity solver.

Displace the particles following their velocity

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{v}_p \quad \text{and} \quad \frac{d\mathbf{v}_p}{dt} = -\nabla_x \phi$$

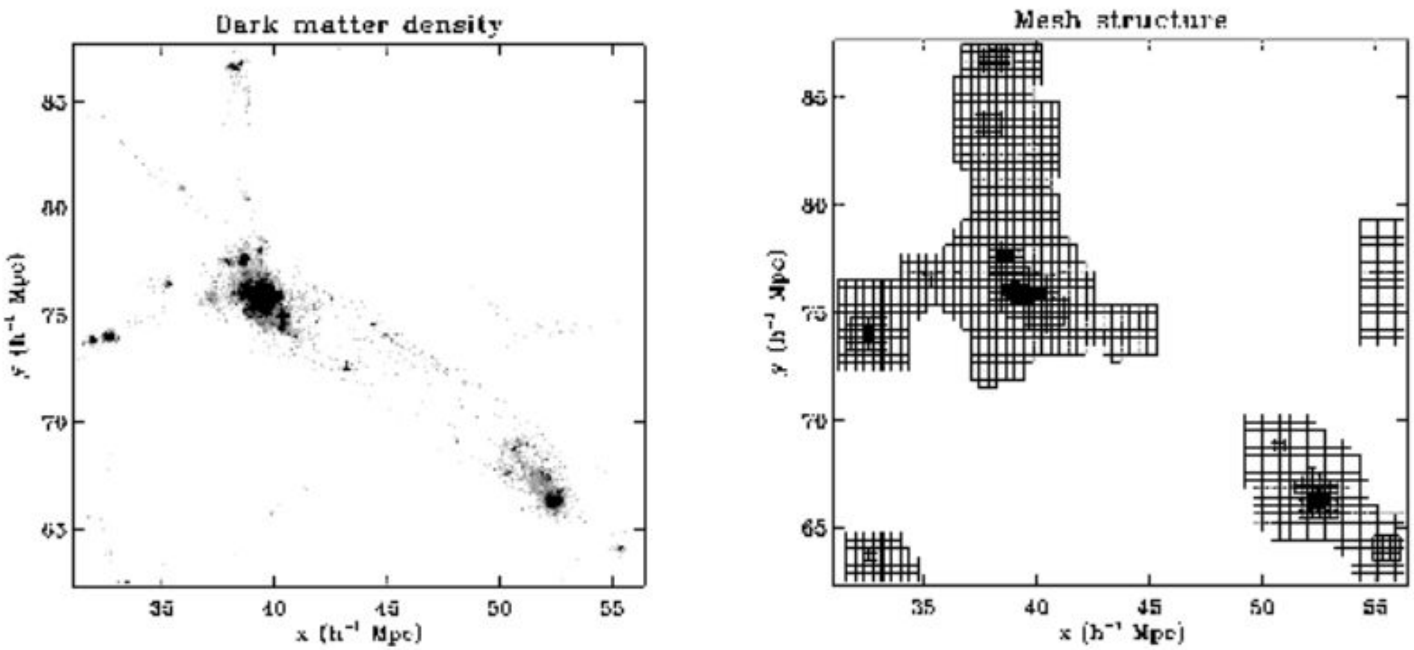
Then Update the velocity following their potential.

Some popular techniques:
(Scaling got better with time)

- Direct N body method, scales as N^2
- PM: Fast Fourier Transform on a grid, O(N log N), low resolution
- P3M (PP+PM): O(N log N) on large scales, N^2 on small scales, low resolution
- Tree codes, O(N log N), high resolution. Variant: Tree-PM
- **Adaptive Mesh Refinement (AMR)** with Multigrid solver, O(N), high resolution

Adaptive Mesh Refinement

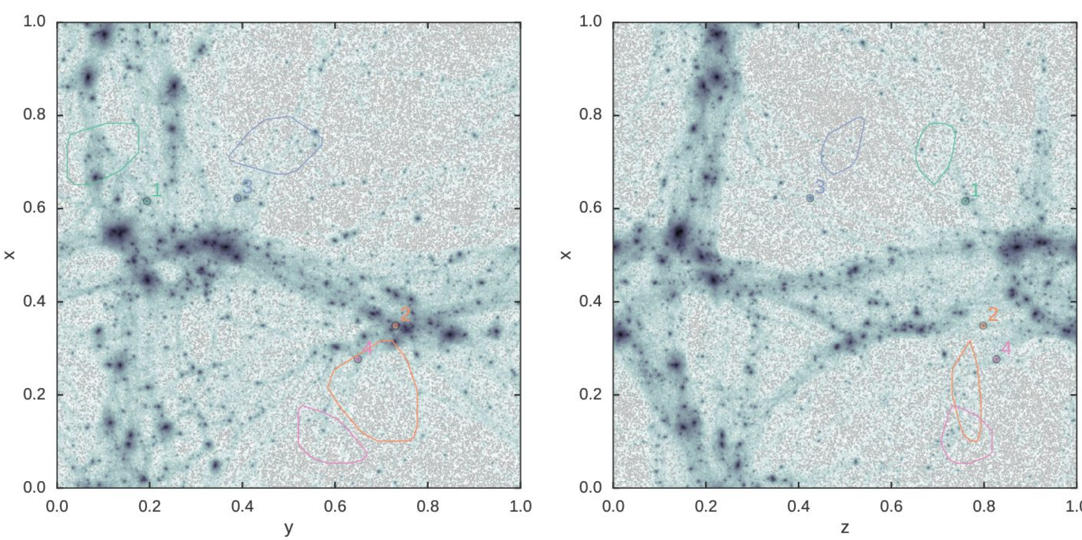
At each grid level, the force softening is equal to the local grid size. For pure dark matter simulations, using a quasi-Lagrangian strategy, the particle shot noise is kept roughly constant.



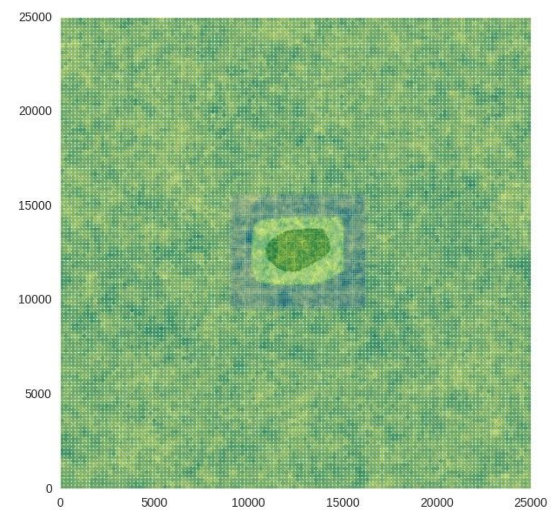
Popular codes based on this technique are ART (Kravtsov et al. 1997), FLASH (Fryxell et al. 2000), **RAMSES (Teyssier et al. 2002)**, ENZO (Bryan et al. 2014).

Zoom-in Simulations

1. detect one halo of interest in a cosmological simulation.
2. compute the Lagrangian volume in the low resolution IC
3. generate high-resolution IC by adding high frequency waves to the low resolution initial Gaussian random field
4. use the Lagrangian volume as a map to initialize high resolution particles.
5. do the high resolution simulation and check for contamination
6. eventually, compute a better initial Lagrangian volume and re-do the simulation



z=0



z=100

Gas

The Euler equations in conservative form

Gas is a highly collisional system with a Maxwell distribution function.

A system of three conservation laws + EoS

$$\partial_t \rho + \nabla \cdot \mathbf{m} = 0$$ (mass)

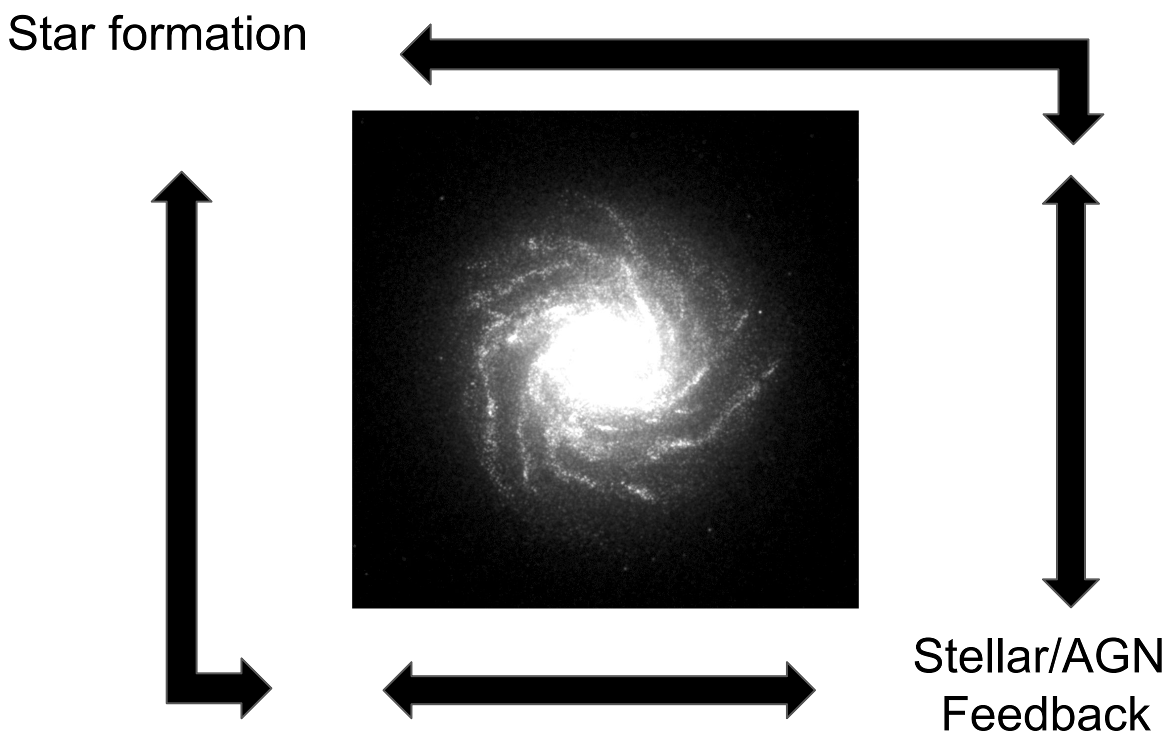
$$\partial_t \mathbf{m} + \nabla \cdot (\rho \mathbf{u} \times \mathbf{u}) + \partial_x P = 0$$ (momentum)

$$\partial_t E + \nabla \cdot \mathbf{u}(E + P) = 0$$ (energy)

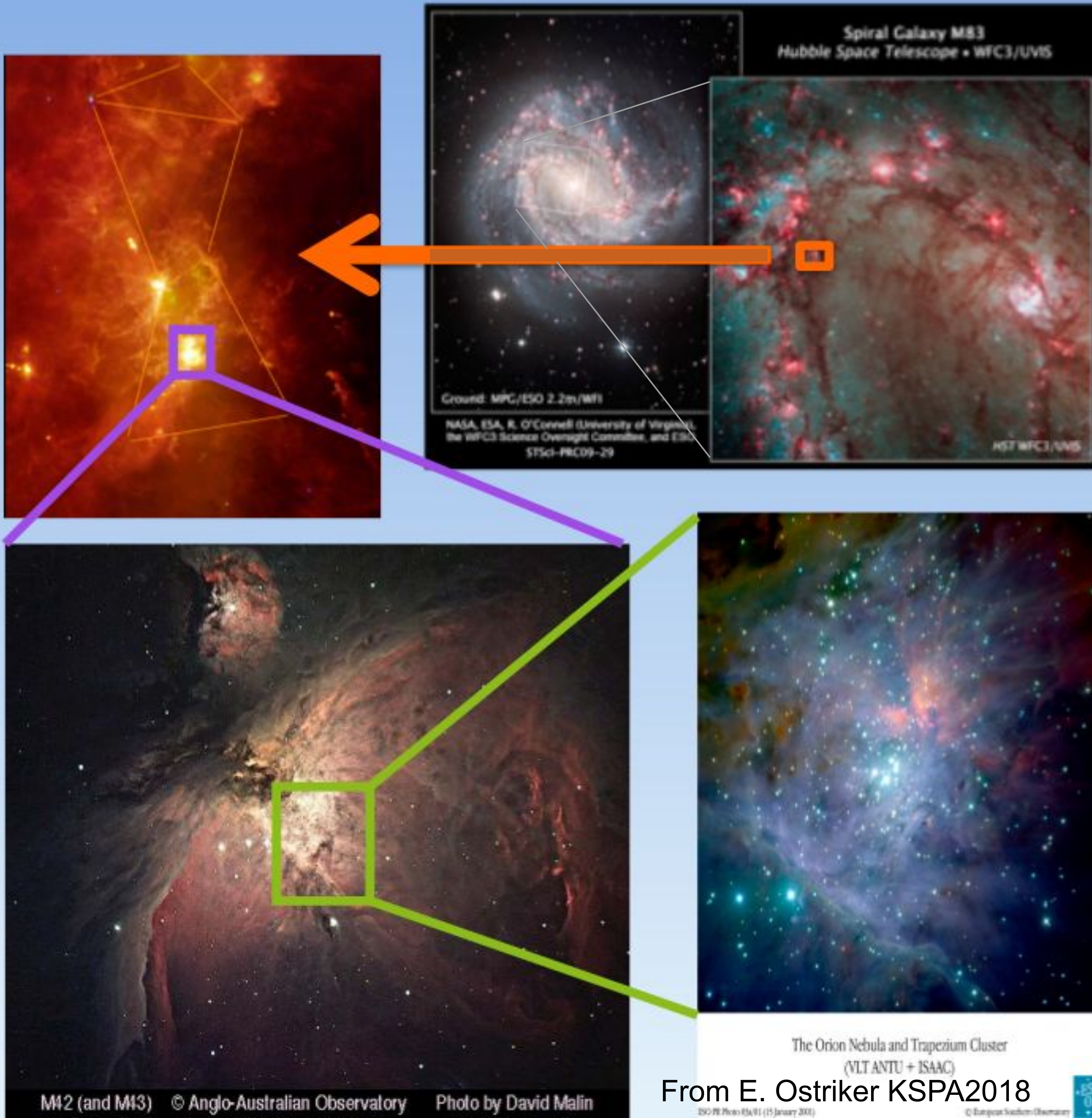
For cosmological simulations one need to add source terms to these conservation laws:

- Gravity
- Radiative processes
- Star formation and feedback

Galaxies



Some old problems: angular momentum, disc size, stellar to halo mass ratio, equilibrium between SF and feedback



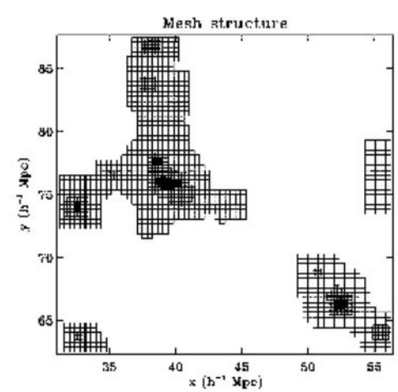
From E. Ostriker KSPA2018

This processes happen in a huge dynamical range (24 orders of magnitude in density)

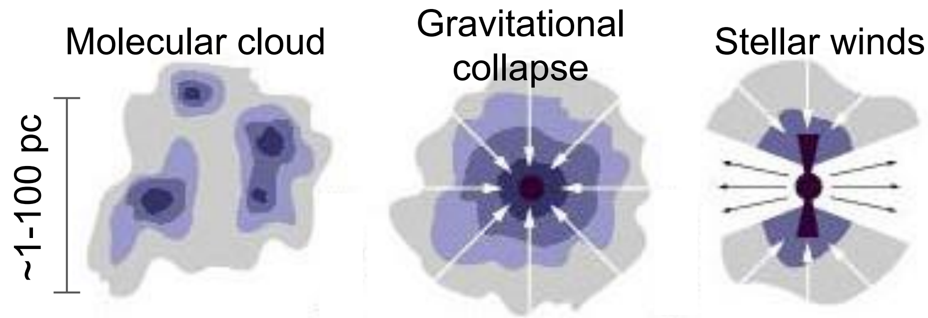
Simulations have to be divided in:

- Diffuse ISM
- Molecular clouds
- Core collapse

So how to model this for cosmological simulations?



Star formation



Fixed global eff

(KS-law)

$$\epsilon_{\rm ff} = \text{constant}$$

vs

local turbulent eff

(Mff$_\epsilon$)

$$\epsilon_{\rm ff} = \epsilon_{\rm ff}(\textit{hydro})$$

Schmidt law for star formation:

$$\dot{\rho}_\star = \epsilon_{\rm ff} \frac{\rho_g}{t_{\rm ff}} \quad for \quad \rho_g > \rho_\star$$

Krumholz & Tan (2007).

From Federrath & Klessen (2012)

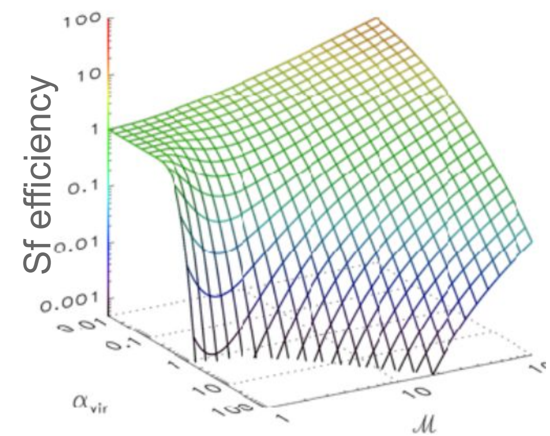
Multi-freefall (Mff$_\epsilon$): calculated efficiency

$$p(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{\left(s + \frac{1}{2}\sigma_s^2\right)^2}{2\sigma_s^2}\right)$$

models we use: Krumholtz & McKee (2005)

$$\sigma_s^2 = \ln\left(1 + b^2 \mathcal{M}^2\right) \qquad \mathcal{M} = \frac{\sigma_{\rm T}}{c_s} \quad \text{Mach number}$$

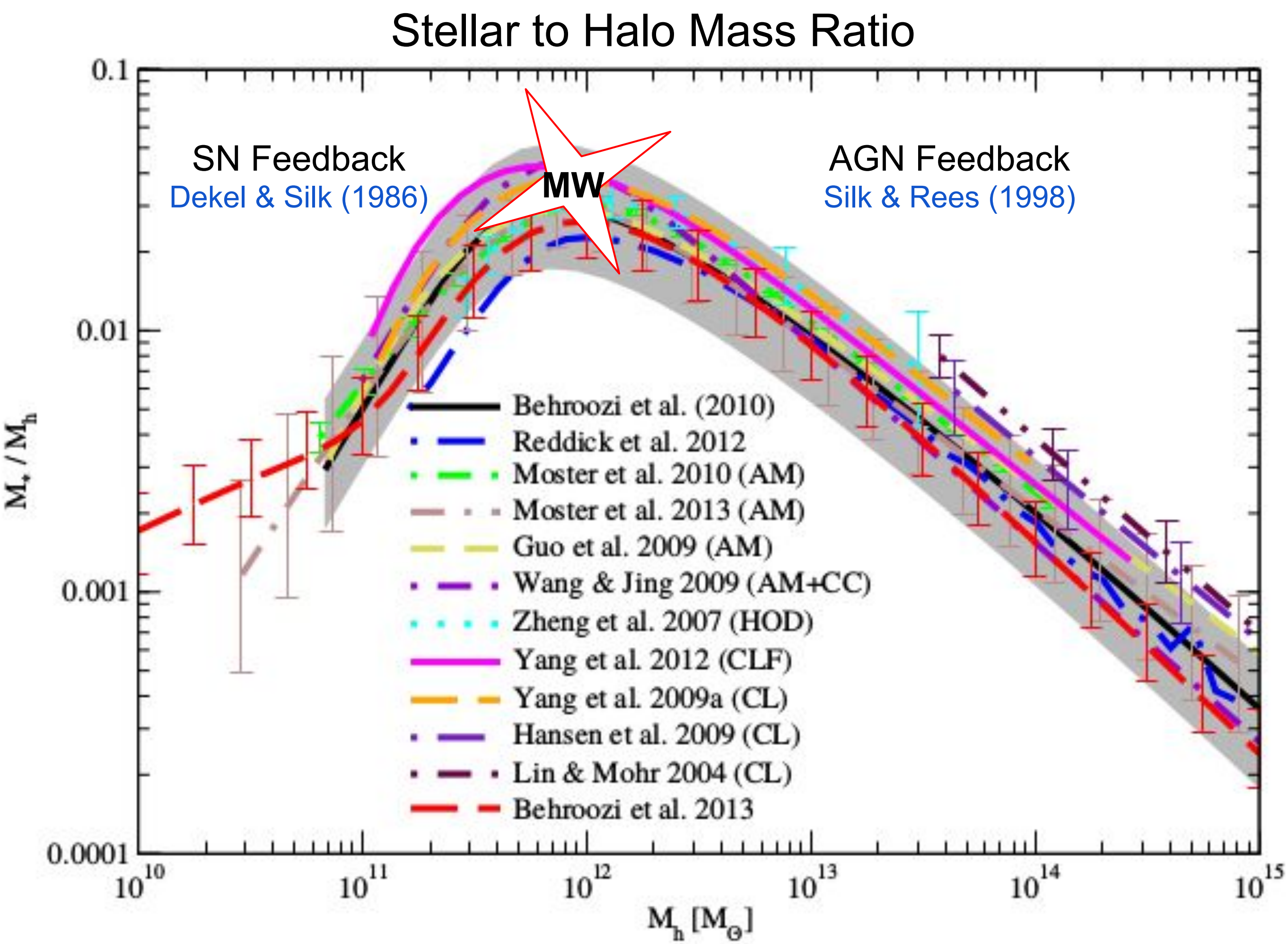
$$\rho_{\rm crit} \propto \alpha_{\rm vir} \mathcal{M}^2 \qquad \alpha_{\rm vir} = \frac{\sigma_{\rm T}^2}{G\rho_0 \Delta^2} \quad \text{Virial parameter}$$



$$\epsilon_{\rm ff} = \frac{\epsilon}{2\phi_t} \exp\left(\frac{3}{8}\sigma_s^2\right) \left[1 + \text{erf}\left(\frac{\sigma_s^2 - s_{\rm crit}}{\sqrt{2\sigma_s^2}}\right)\right]$$

One free parameter $\longrightarrow \epsilon$

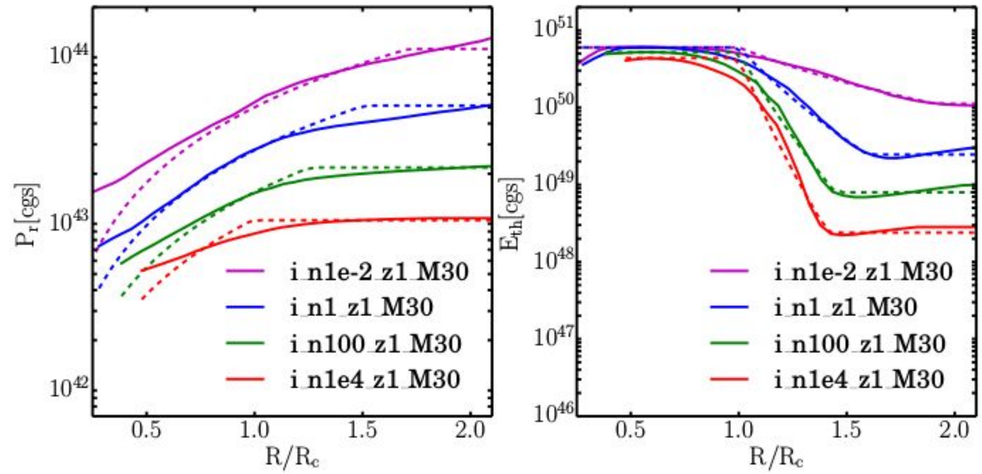
Feedbacks



Behroozi et al. (2013)

Martizzi et al. (2015)

SN Feedback



The end of the life of a massive star

$$M < 8\mathrm{M}_\odot$$

~ 10 Myr

How to model it :

Delayed Cooling (DCool) vs **Mechanical Feedback (MecFB)**

Inject directly a non-thermal energy corresponding to the SN explosion

Model the two phases of the SN explosion and inject the corresponding momentum

$$p_{\mathrm{SN,snow}} \approx 3 \times 10^5\,\mathrm{km\,s^{-1}}\,\mathrm{M}_\odot\, E_{51}^{16/17} n_{\mathrm{H}}^{-2/17} Z'^{-0.14}$$

$$\rho \frac{D\epsilon_{turb}}{Dt} = \dot{E}_{inj} - \frac{\rho\epsilon_{turb}}{t_{\mathrm{diss}}}$$

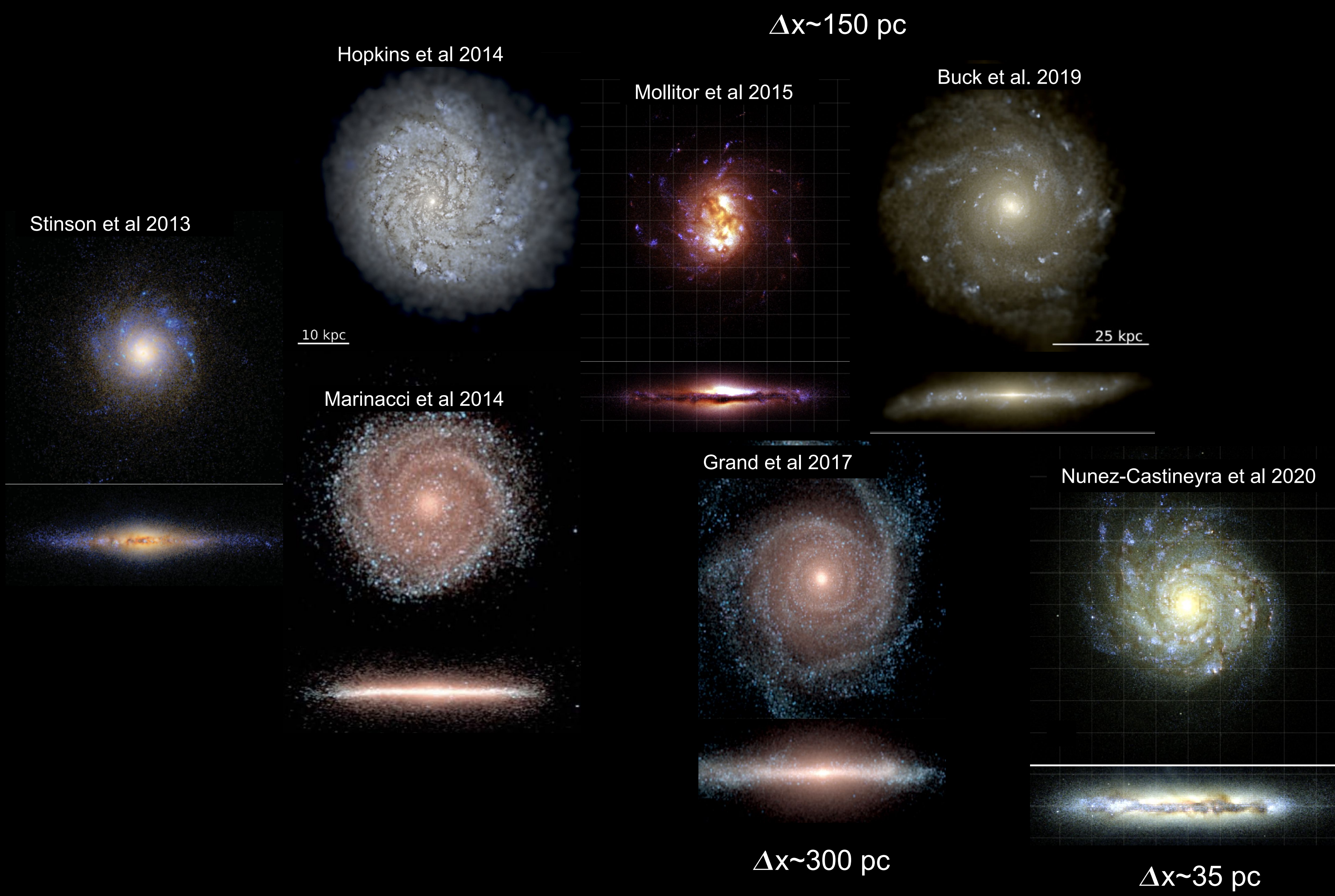
$$p_{\mathrm{SN}} = \begin{cases} p_{\mathrm{SN,ad}} = \sqrt{2\chi\, M_{\mathrm{ej}}\, f_e\, E_{\mathrm{SN}}} & (\chi < \chi_{\mathrm{tr}}) \\ p_{\mathrm{SN,snow}} & (\chi \geq \chi_{\mathrm{tr}}) \end{cases}$$

Teyssier et al. 2013, Dubois et al. 2015.

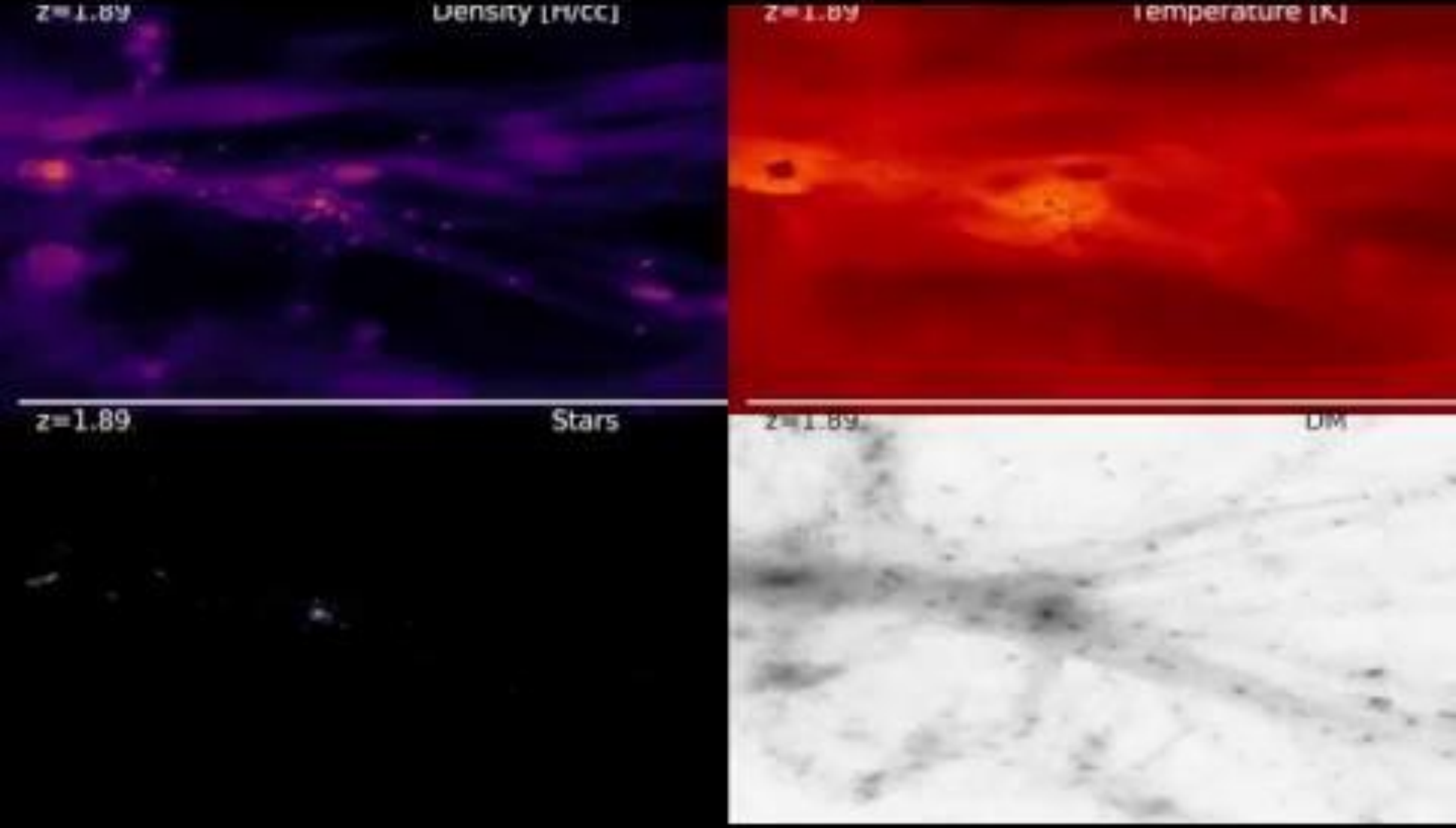
$$\chi \equiv dM_{\mathrm{swept}}/dM_{\mathrm{ej}} \qquad \chi_{\mathrm{tr}} \equiv 69.58\, E_{51}^{-2/17} n_{\mathrm{H}}^{-4/17} Z'^{-0.28}$$

Kimm & Cen 2014. Kimms et al. 2015.

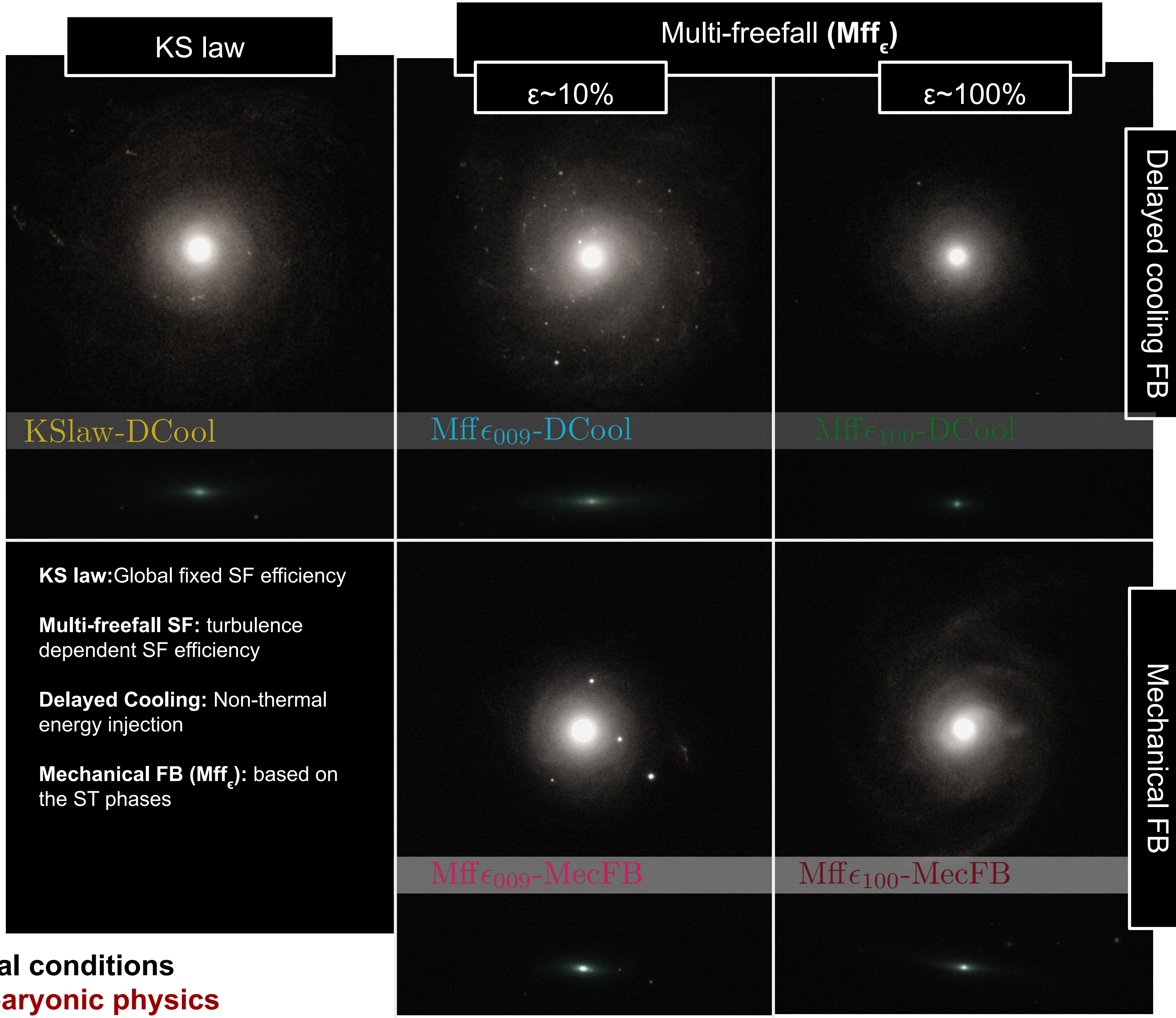
Some recent Zoom-in MW-like simulations



Mochima


z=1.89
Density [H/cc]
z=1.89
Temperature [K]
z=1.89
Stars
z=1.89
DM

MOCHIMA

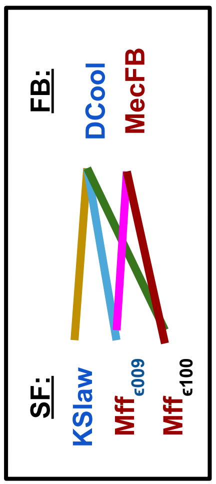


KS law: Global fixed SF efficiency

Multi-freefall SF: turbulence dependent SF efficiency

Delayed Cooling: Non-thermal energy injection

Mechanical FB (Mff$_\epsilon$): based on the ST phases

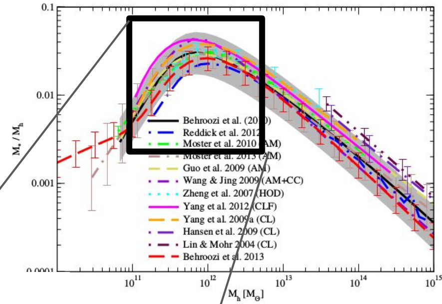


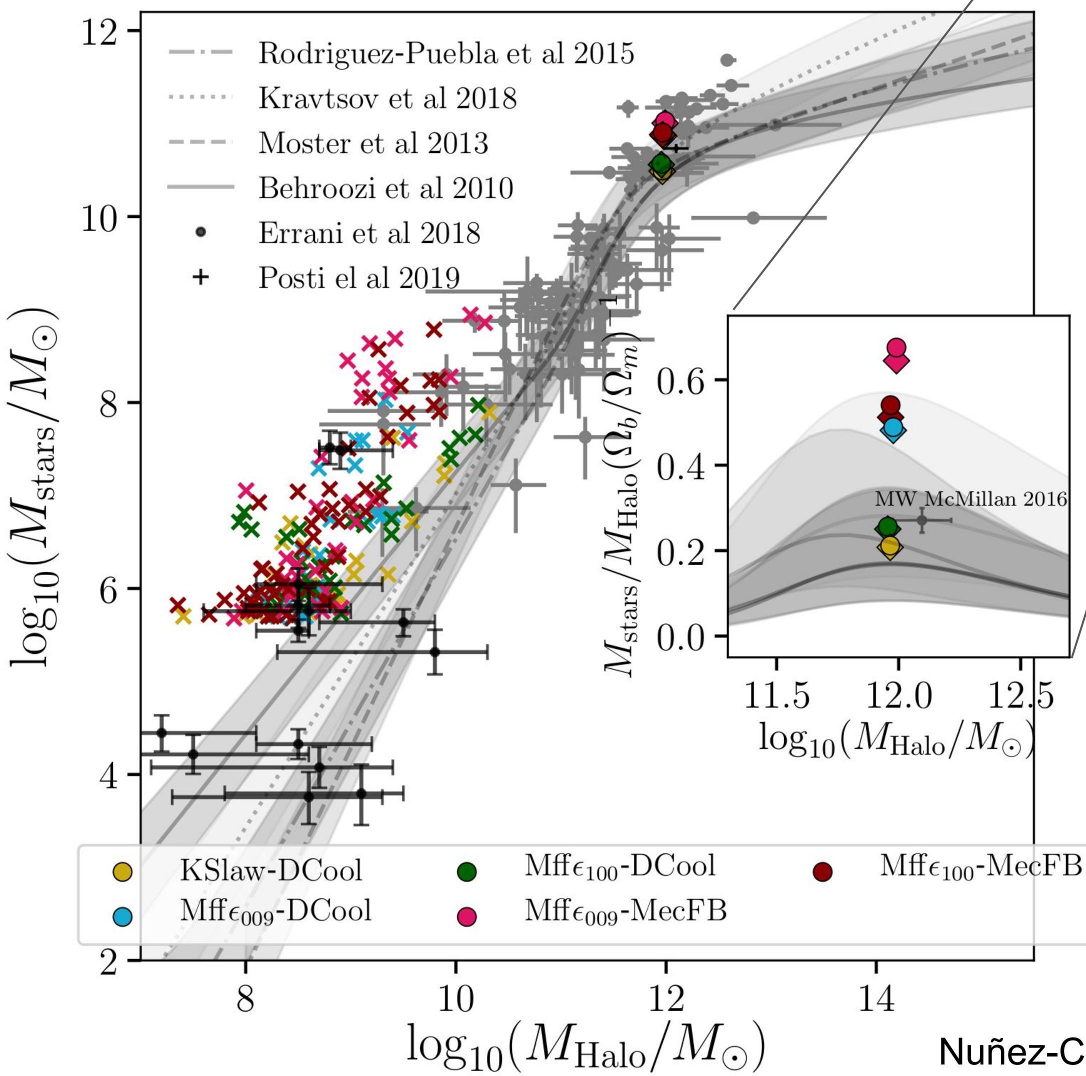
Same initial conditions
different baryonic physics

Nuñez-Castiñeyra, Nezri, Devriendt, Teyssier 2020

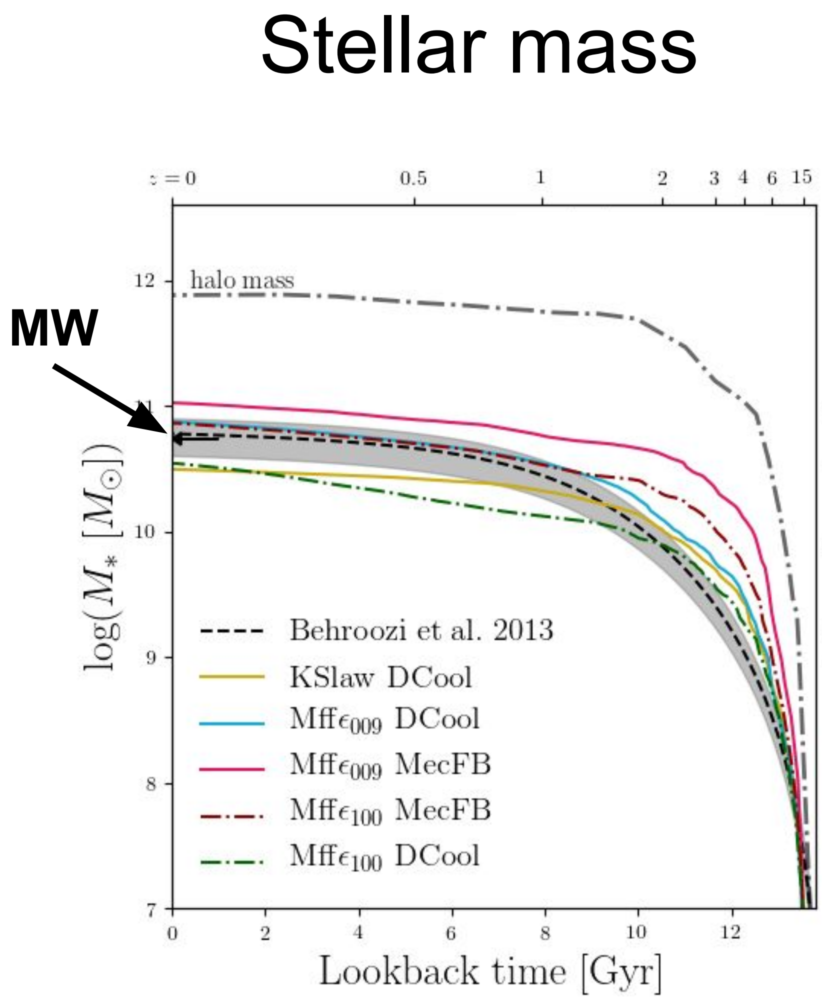
Comparisons with observations

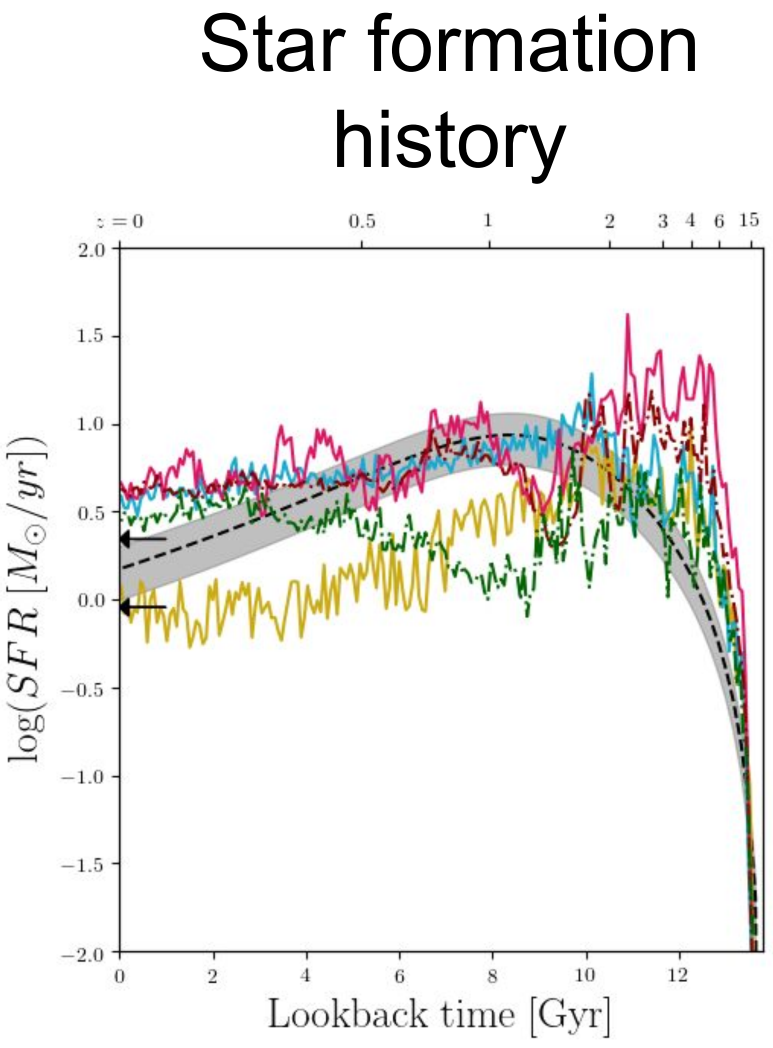
Comparison with observation
SHMR





Nuñez-Castiñeyra et al. 2020

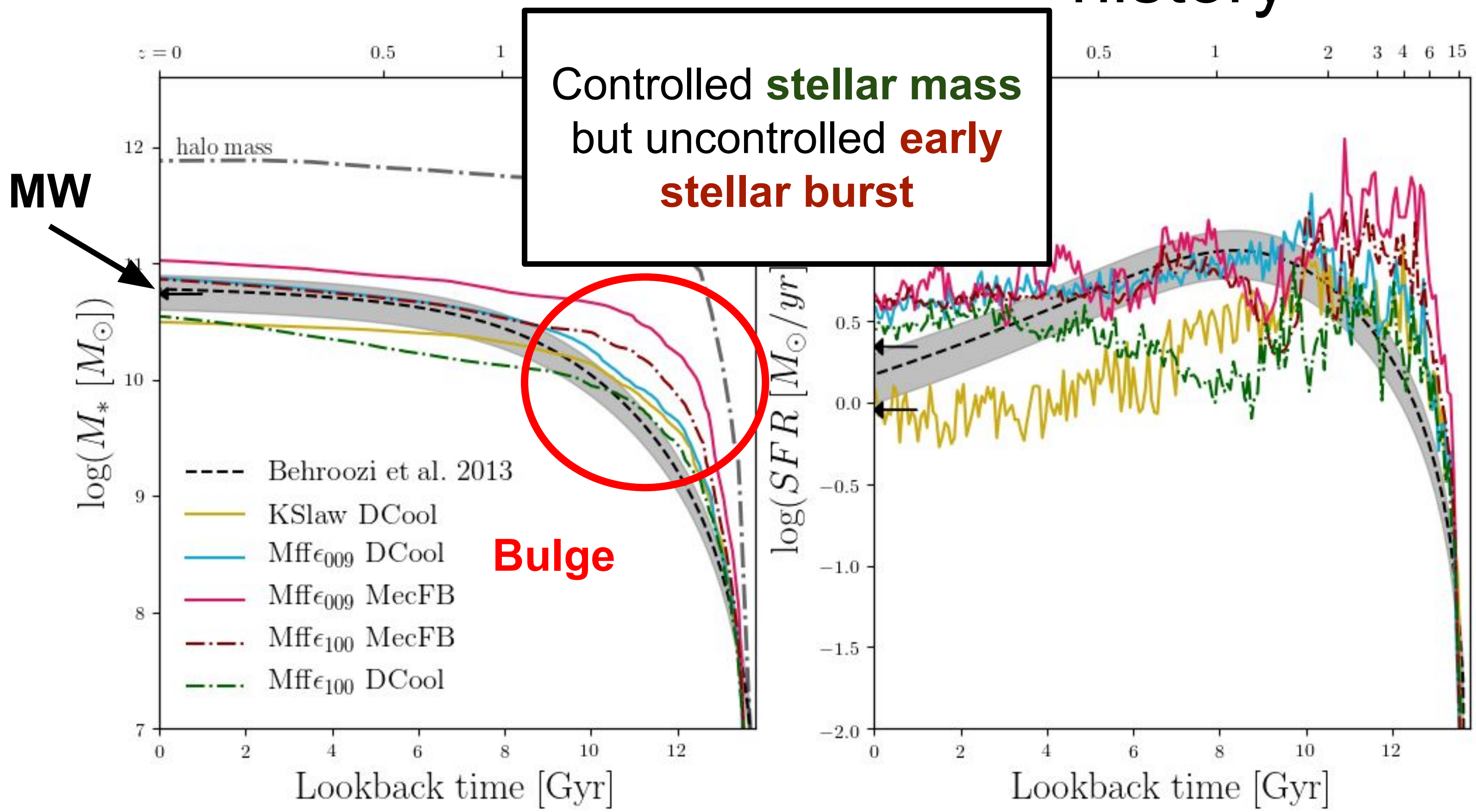




Nuñez-Castiñeyra et al. 2020

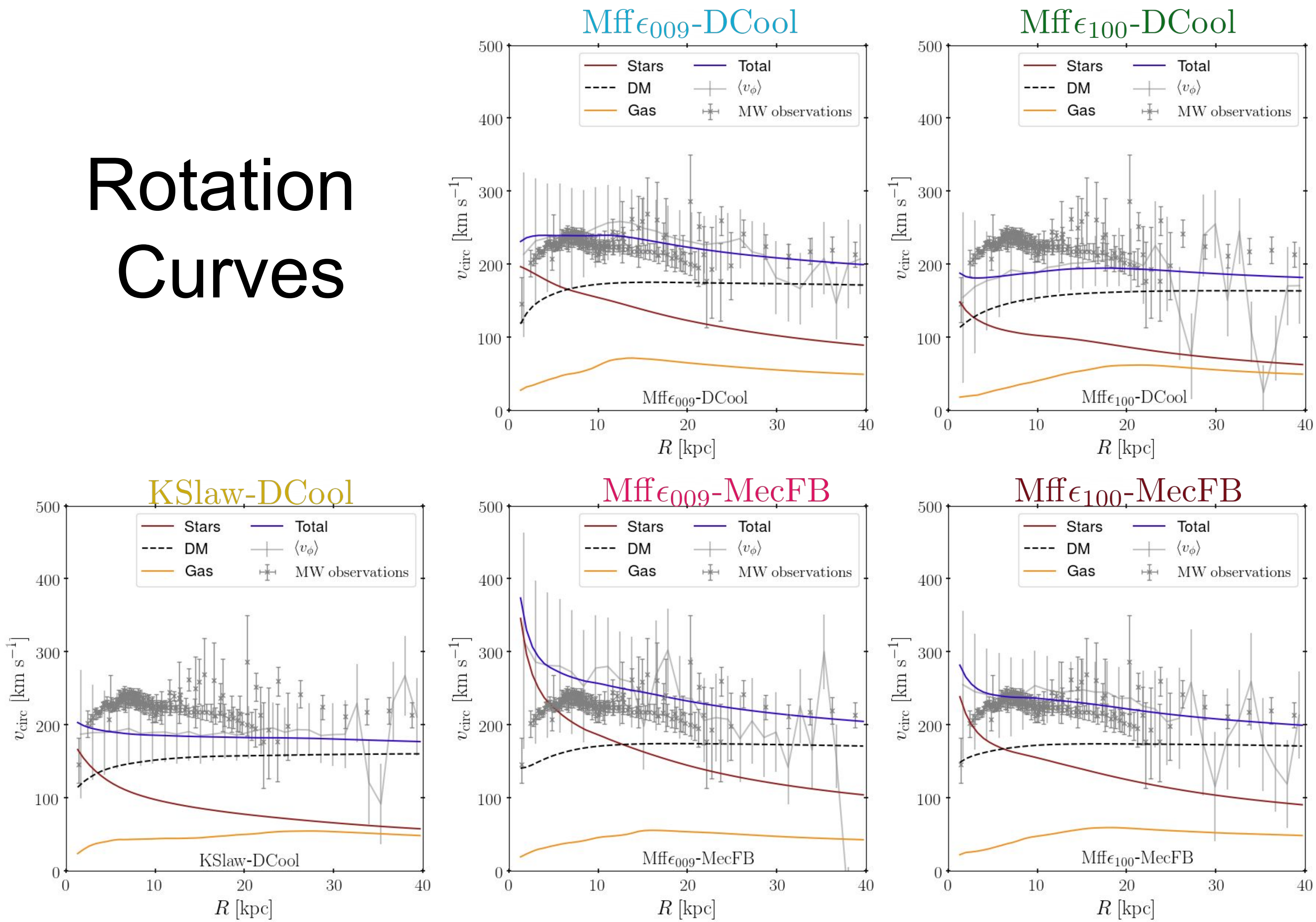
Stellar mass

Star formation history



Nuñez-Castiñeyra et al. 2020

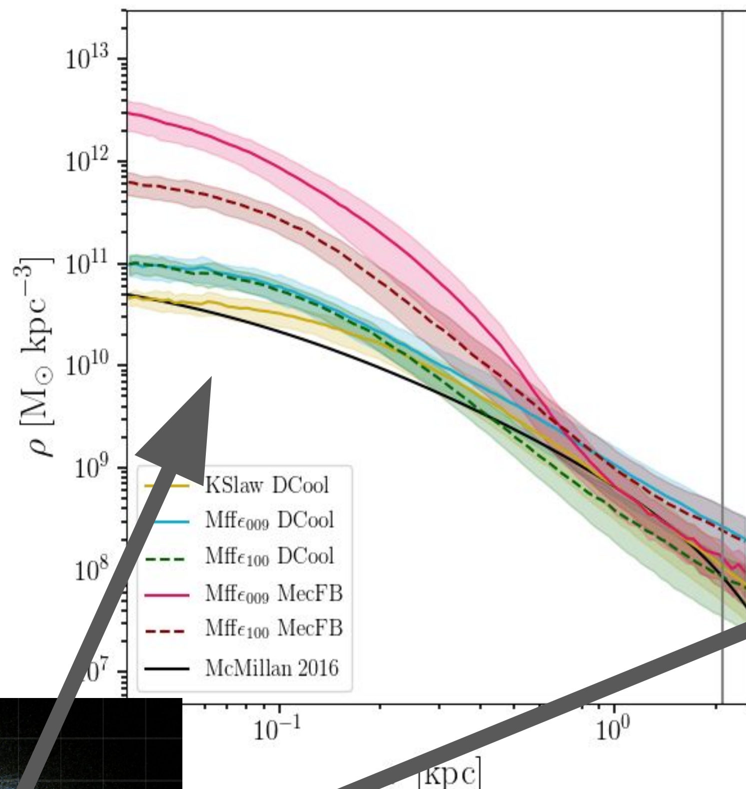
Rotation Curves



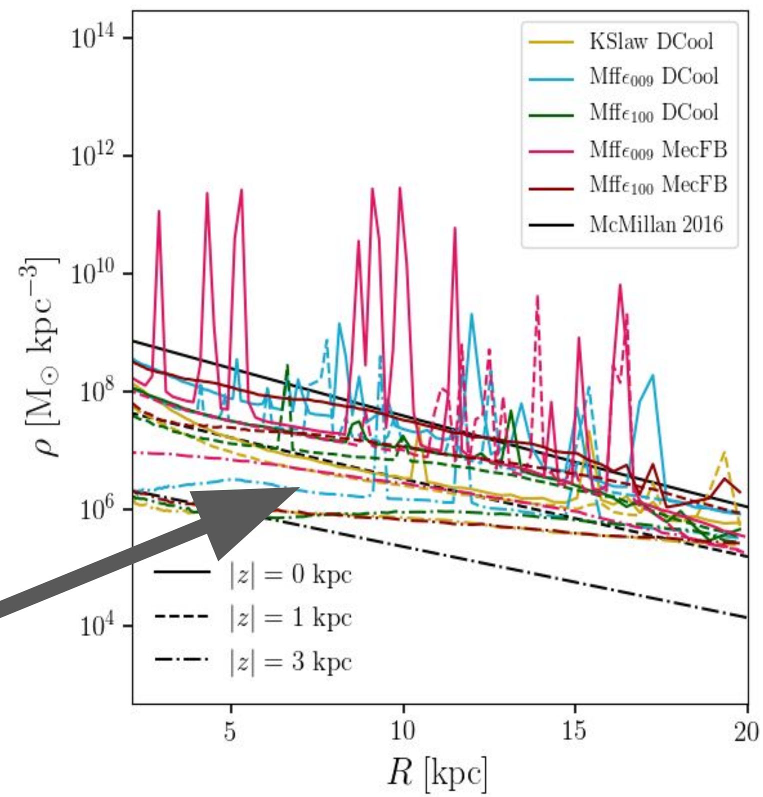
Nuñez-Castiñeyra et al. 2020

MW-mass models

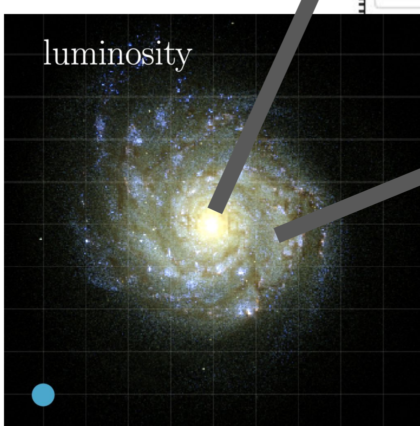
Successful disc but bright bulge!!!
Restraining bar formation??



Bulge



Disc



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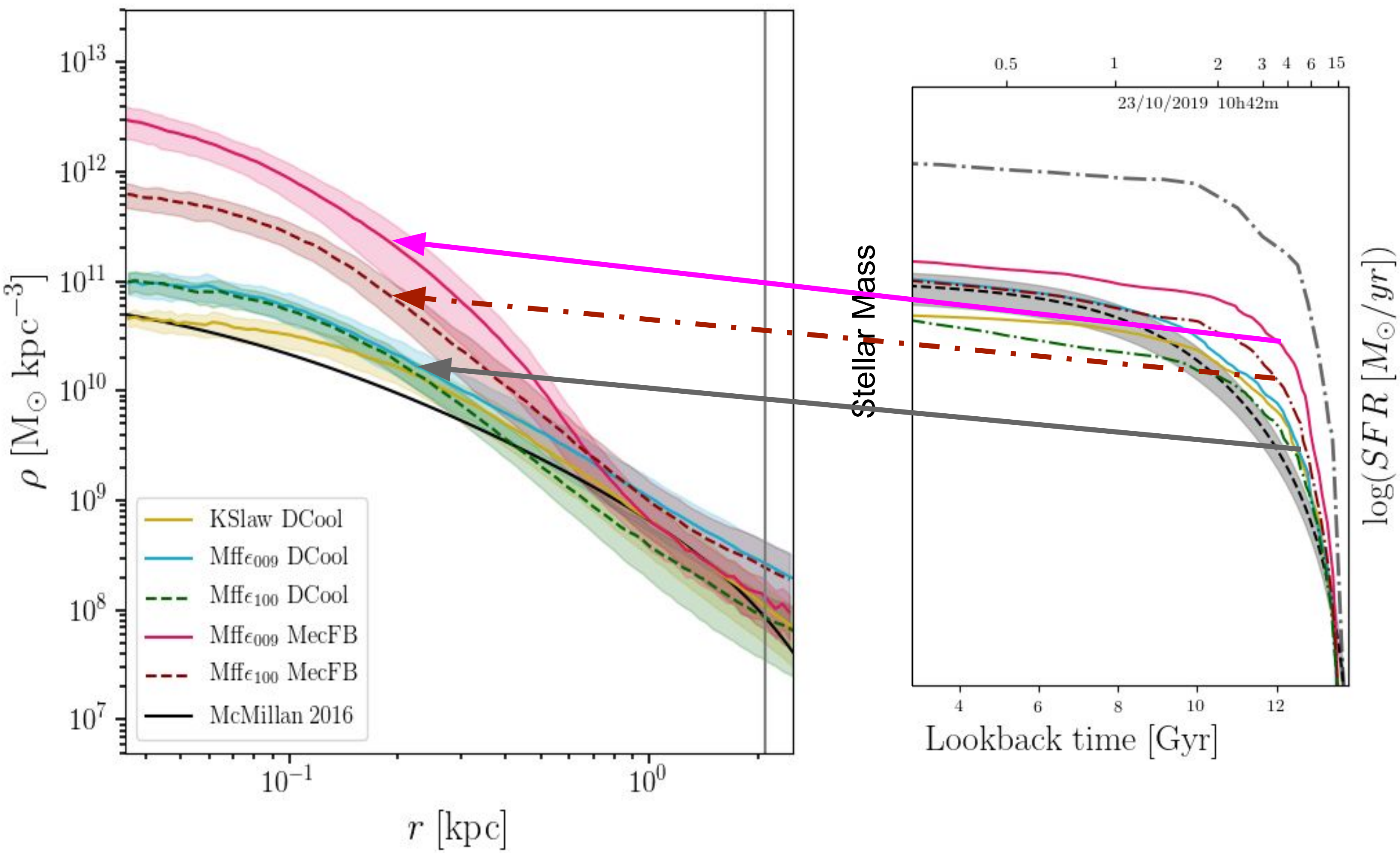
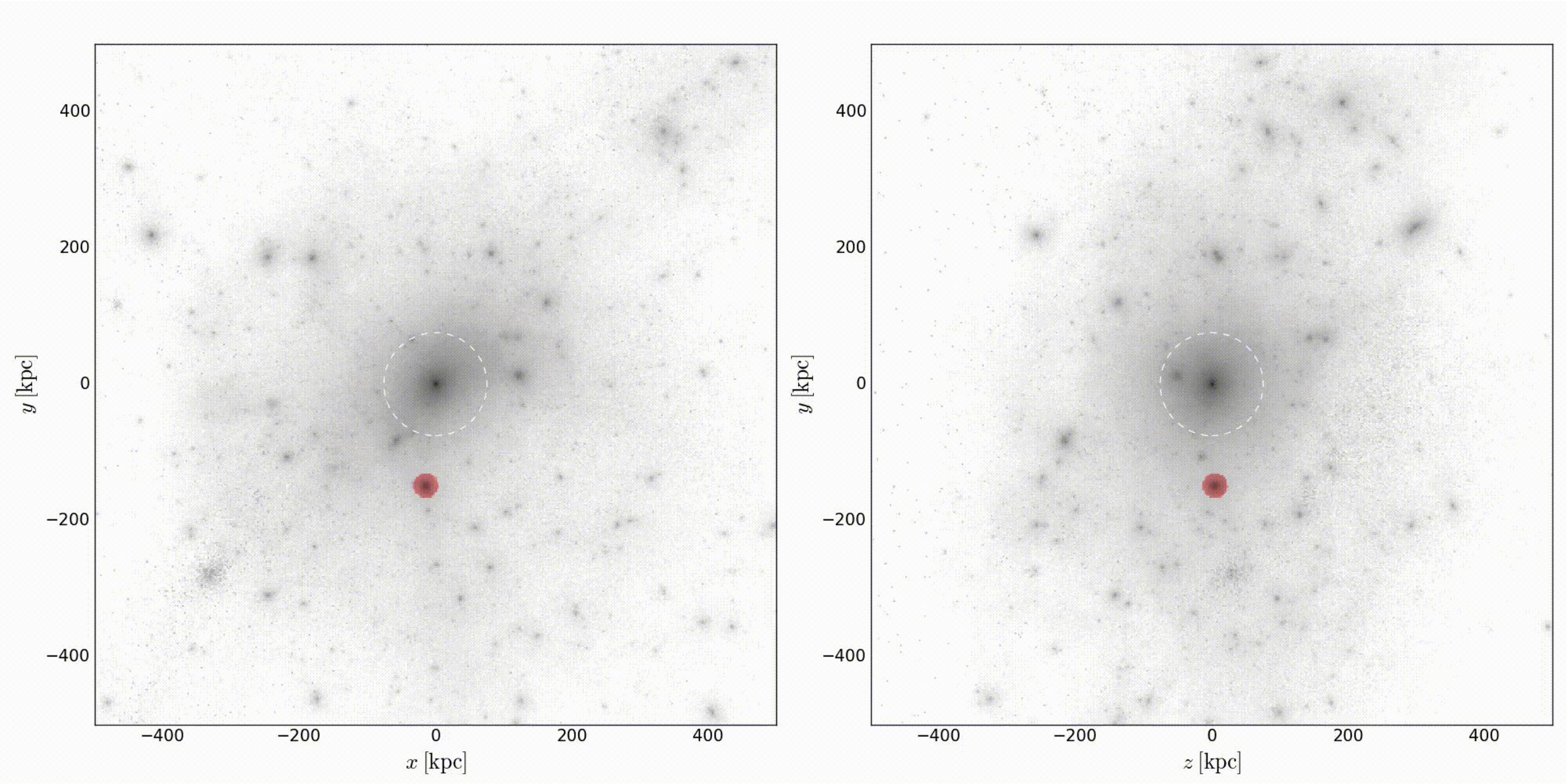


Nuñez-Castiñeyra et al. 2020

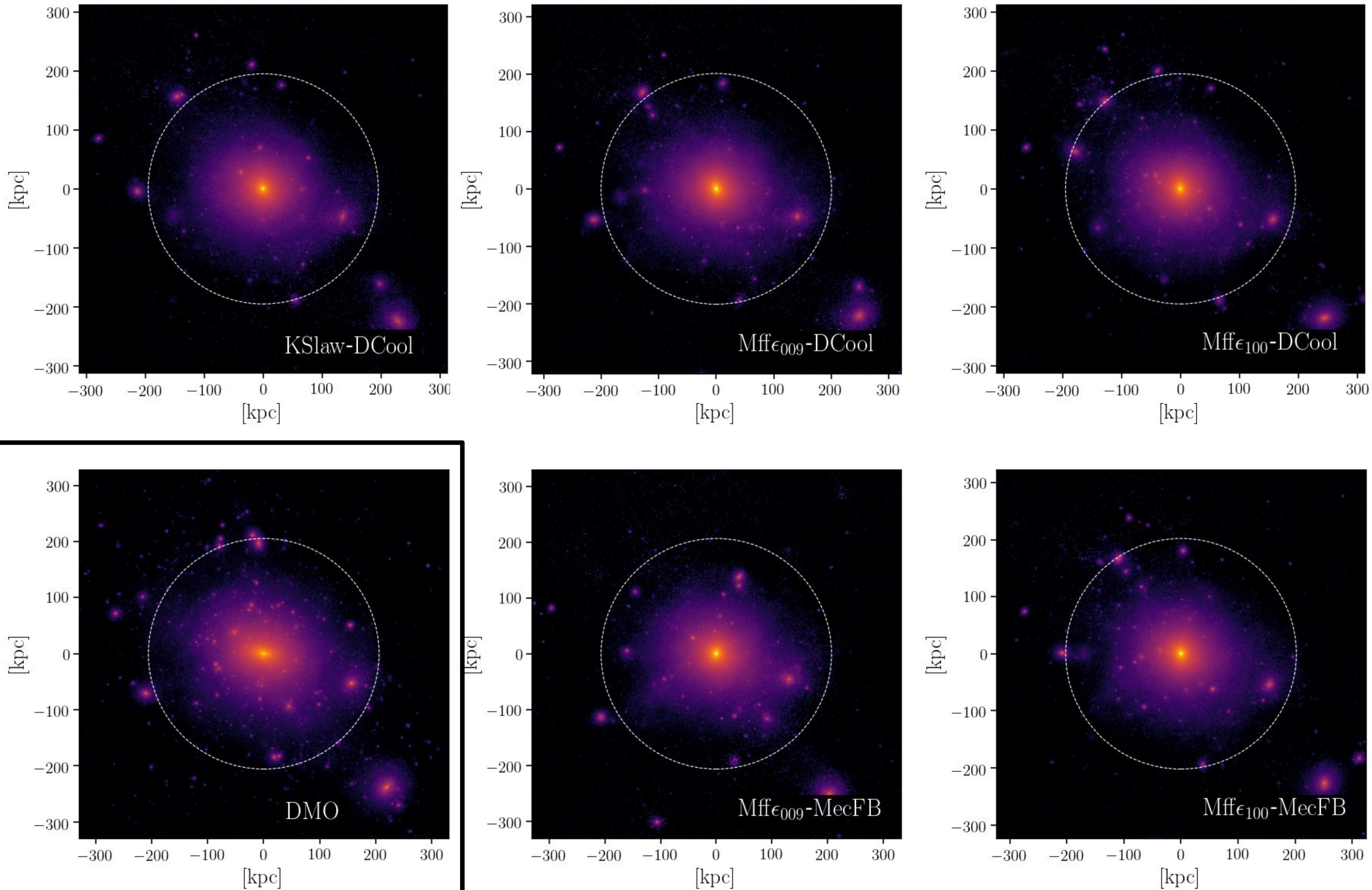
The Dark Matter connection

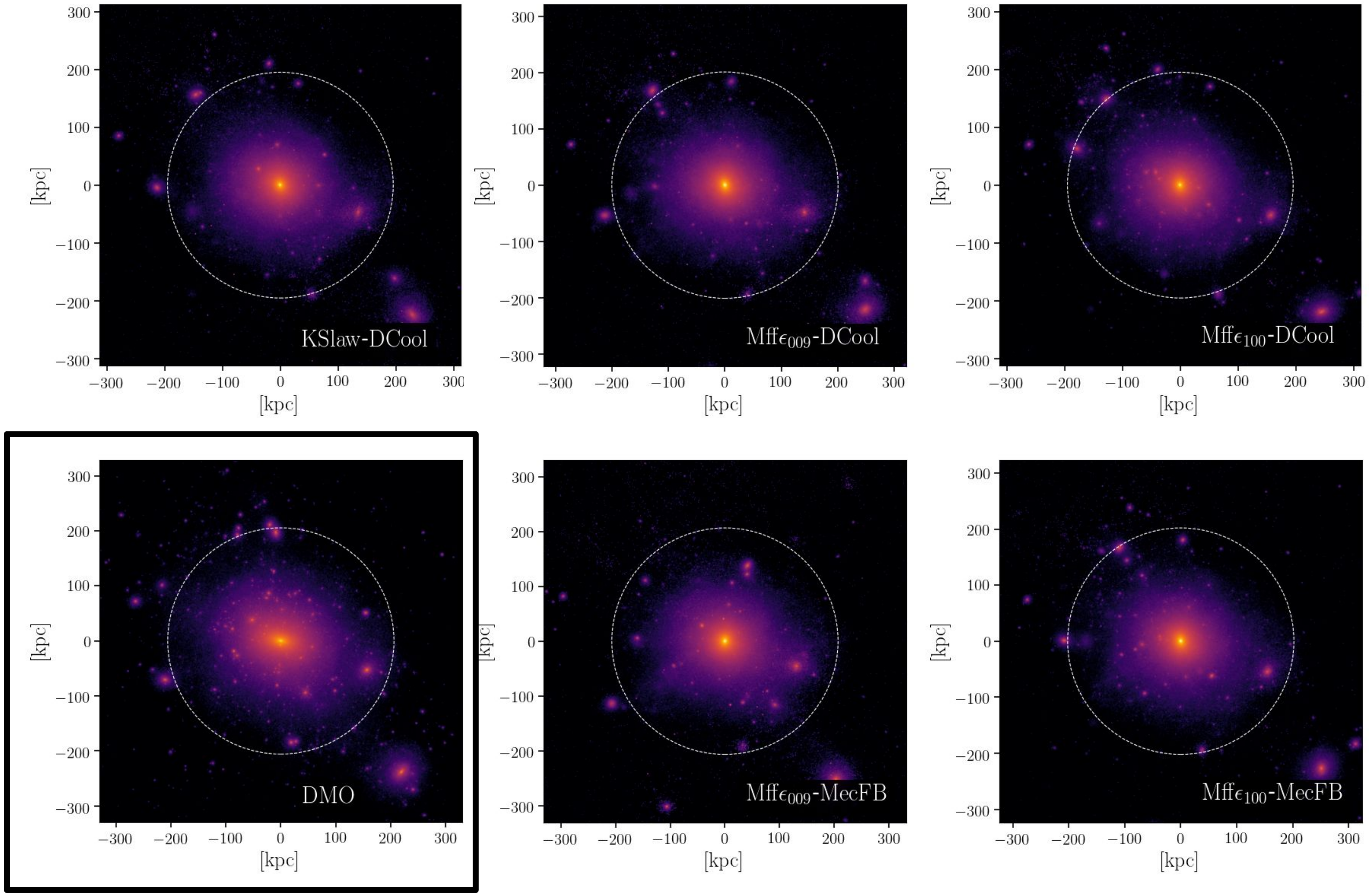


"Milky Way like " simulation are the great lab of DM dynamics:

- Phase space distribution
- Indirect/Direct Dark Matter detection
- Sub-structure mass spectrum, spatial distributions and phase space features
- DM mass distributions

Dark Matter Halos



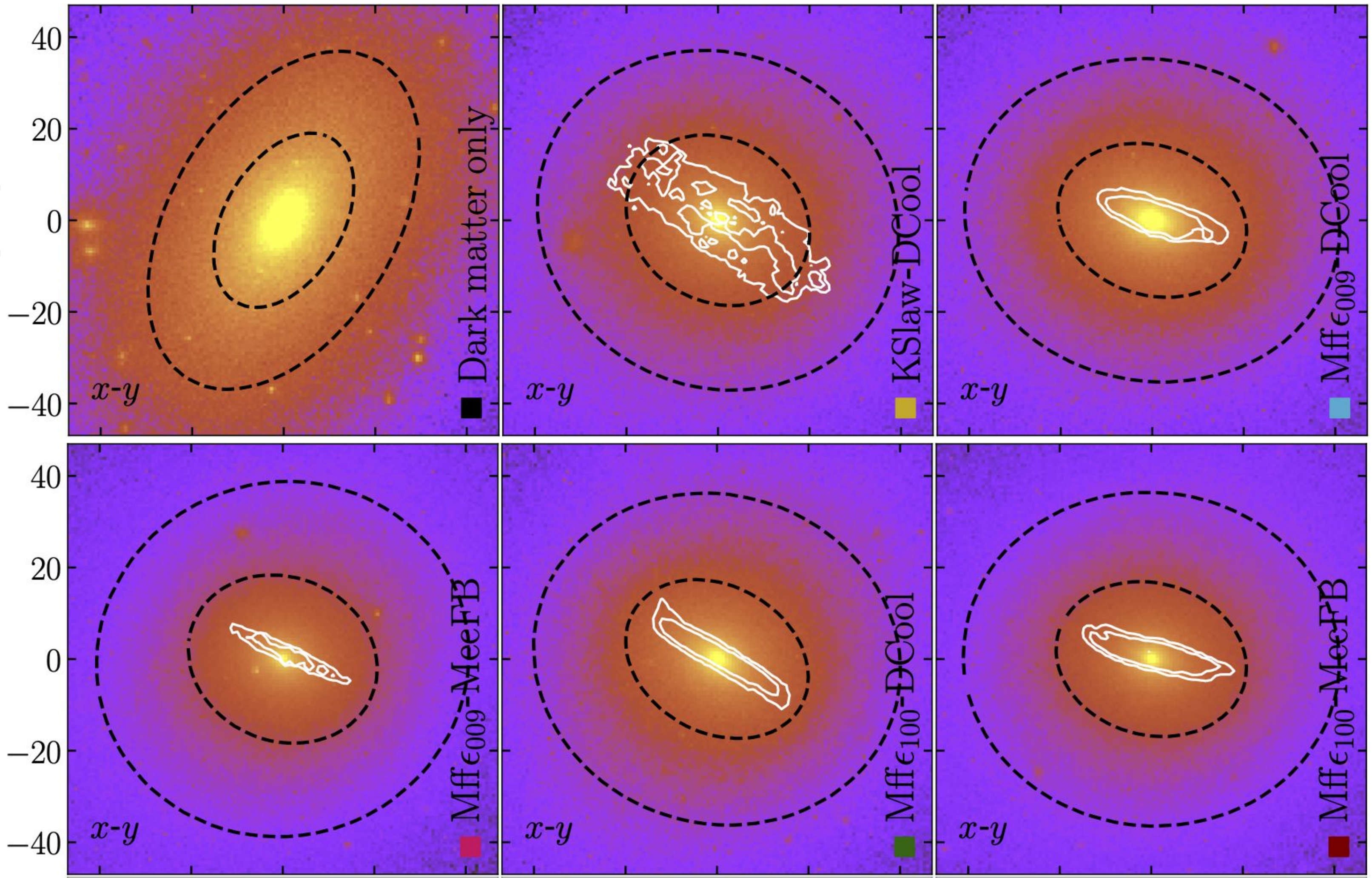


What is the impact of baryonic physics ?

- DM **profile**
- Shape of halo
- **Dark Disc**
- **Phase space** distribution
- ...

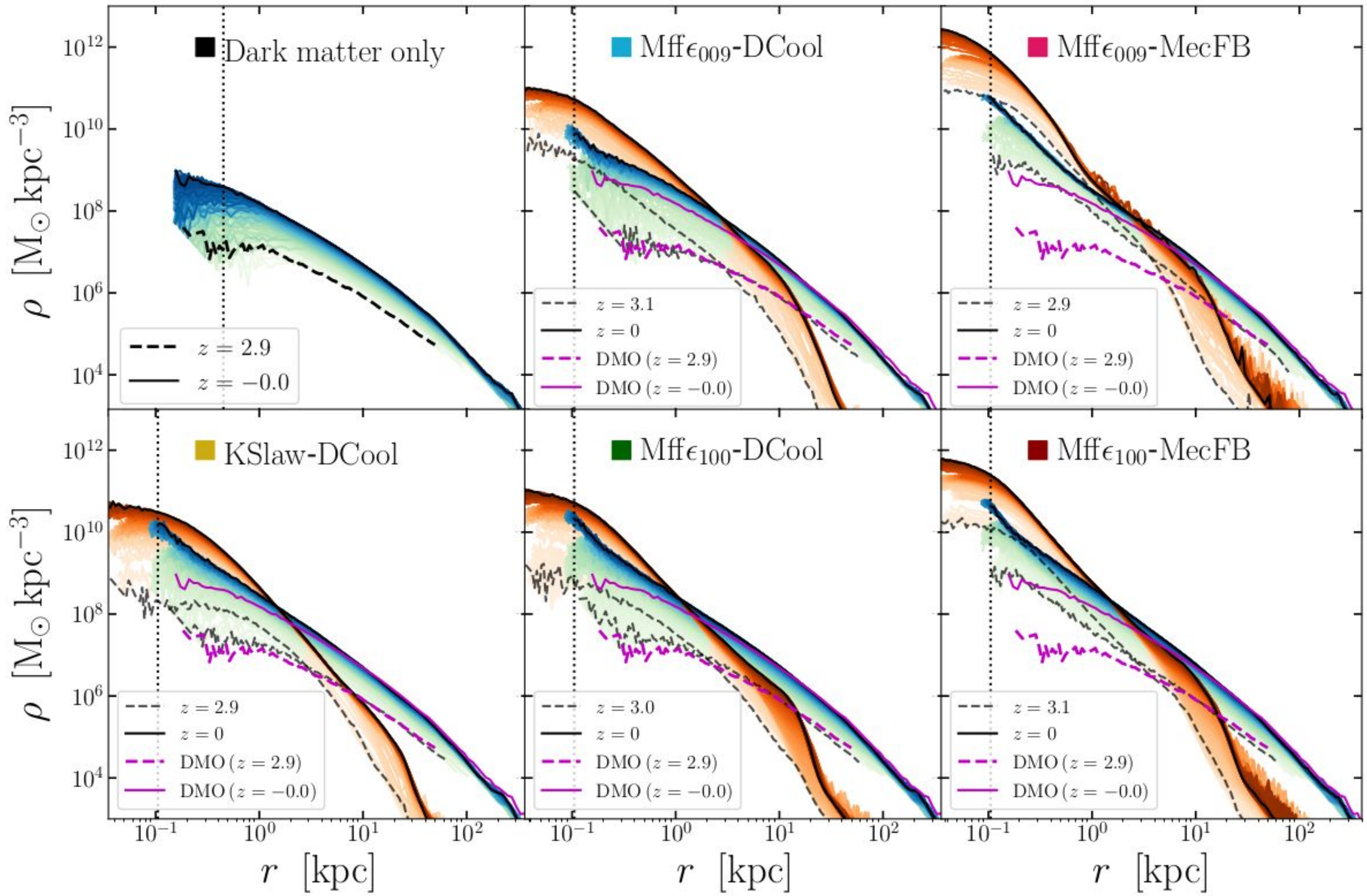
- **Substructures**:
  - **Mass and spatial distribution**
  - Tidal effects
  - **Resilience**
  - ...

The galaxy and the halo



Nuñez-Castiñeyra et al. in prep

The evolution of the halo



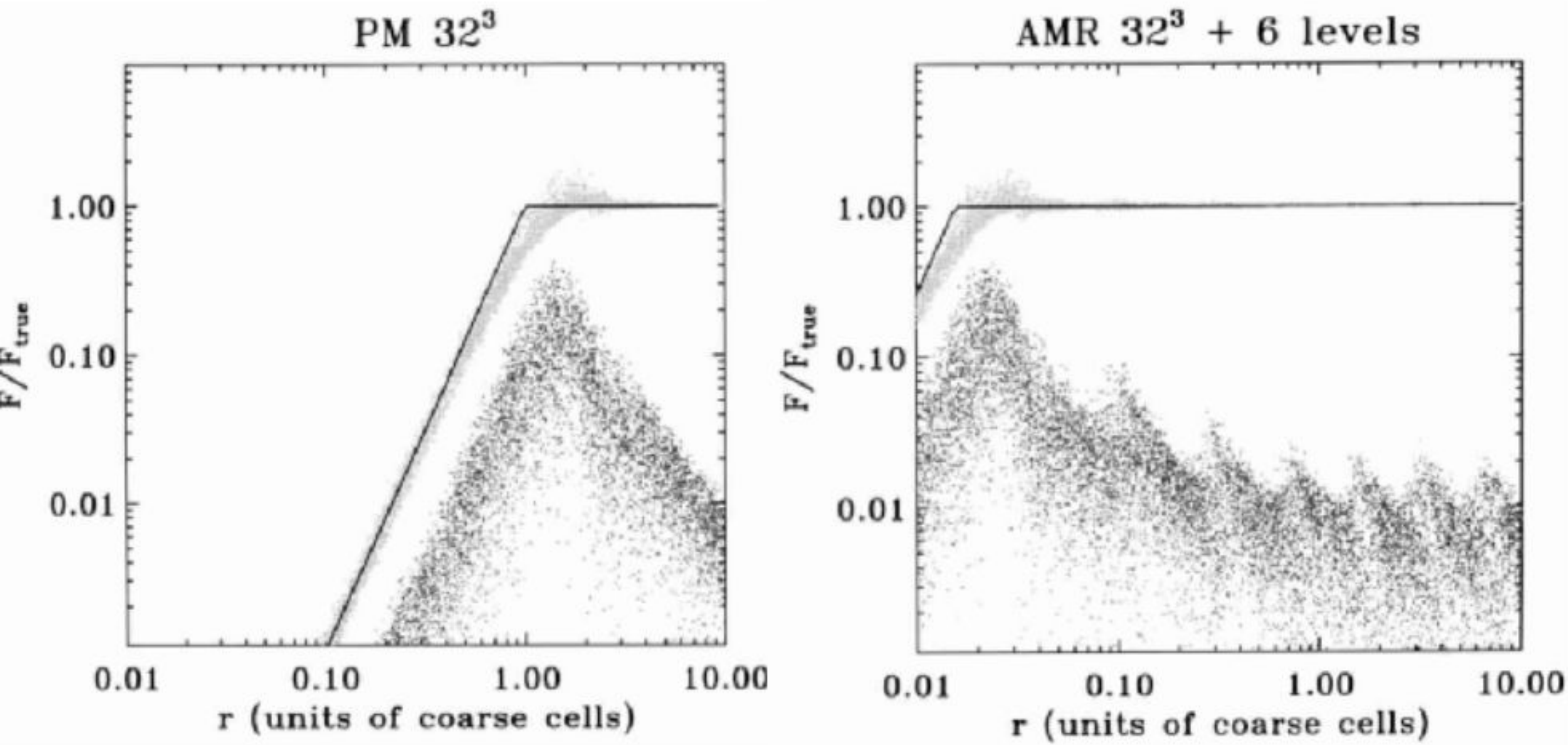
- DMO and hydro runs agree in the outer halo
- **Inner profile** is **modified** by the baryonic distribution
- **Different concentrations** as a result

Nuñez-Castiñeyra et al. in prep

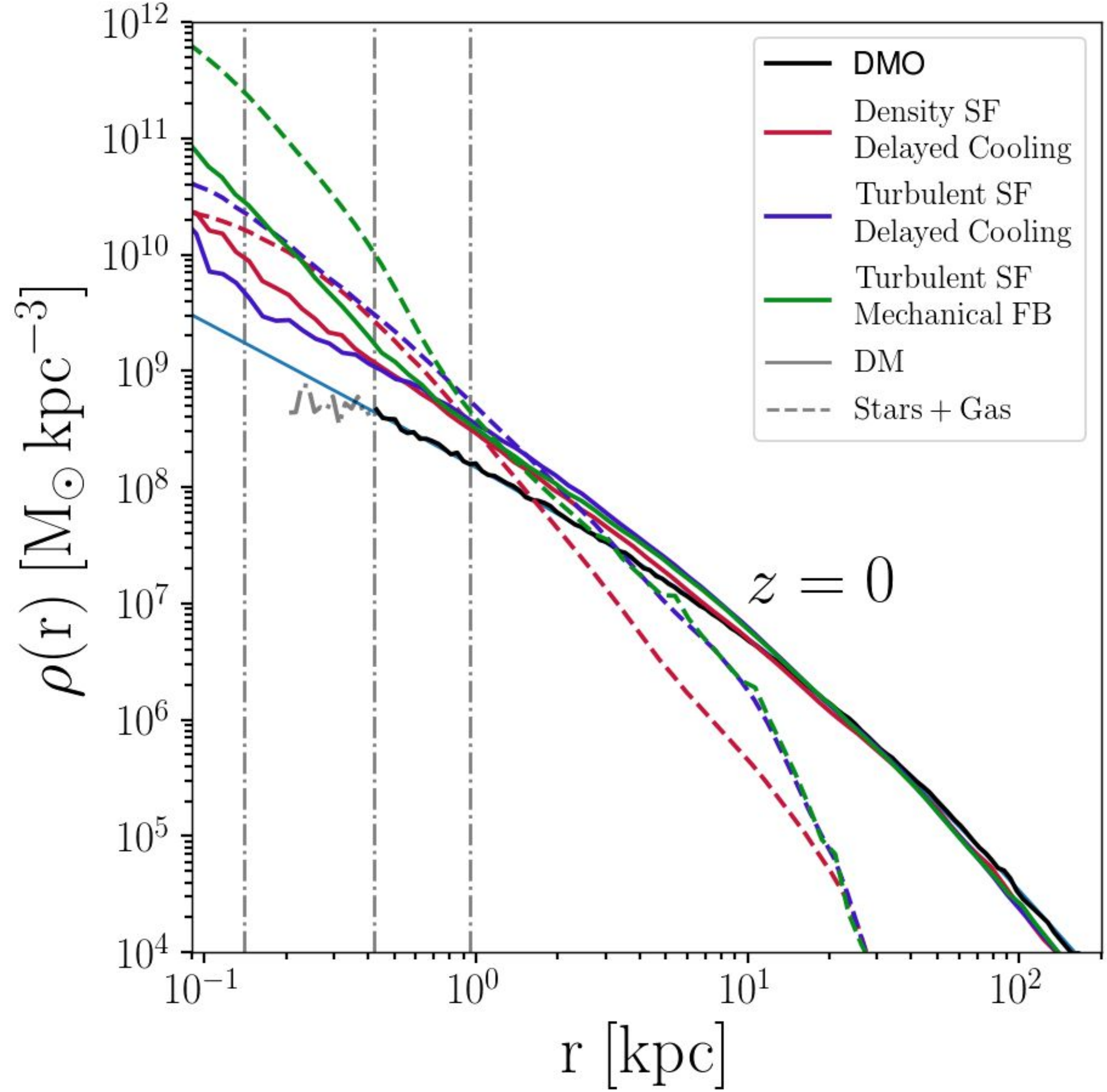
Open questions

- What is the effect of baryonic physics on DM distributions
- What is the effect of baryonic physics on DM phasespace distributions
- Where is cold gas entering the galactic disc from
- Is the shape of the DM halo in a DMO simulation related on the shape of the galaxy in the hydro simulation
- What about sub halos?
- Is there a more consistent way of describing the scaling of subgrid physics with resolutions
- other sources of feedback : stellar wind, cosmic rays
- equilibrium between SF and feedbacks on all scales (dwarfs -> clusters) remains to be found
- Much more question..

Gracias

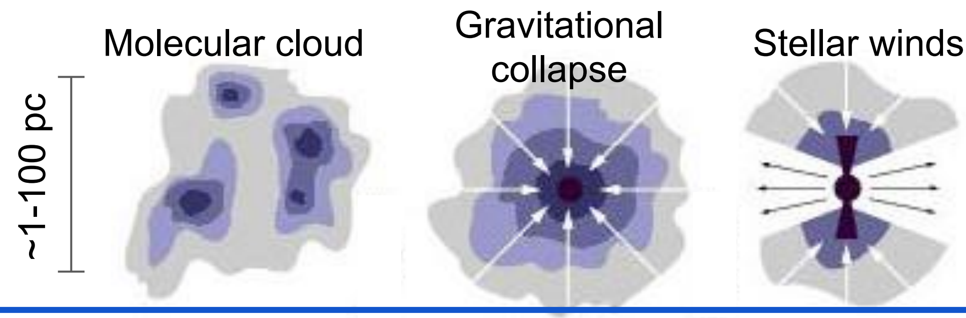


PM 32^3
AMR 32^3 + 6 levels
F/F$_{true}$
1.00
0.10
0.01
0.01
0.10
1.00
10.00
r (units of coarse cells)



DMO
Density SF
Delayed Cooling
Turbulent SF
Delayed Cooling
Turbulent SF
Mechanical FB
DM
Stars + Gas
$z = 0$
$\rho(\mathrm{r})$ [$\mathrm{M}_\odot$ kpc^{-3}]
r [kpc]

Star formation



Fixed global eff
(KS-law)
$\epsilon_{\rm ff} = \text{constant}$

vs

local turbulent eff
(Mff$_\epsilon$)
$\epsilon_{\rm ff} = \epsilon_{\rm ff}(\textit{hydro})$

Schmidt law for star formation:

$$\dot{\rho}_\star = \epsilon_{\rm ff} \frac{\rho_g}{t_{\rm ff}} \quad for \quad \rho_g > \rho_\star$$

Krumholz & Tan (2007).
From Federrath & Klessen (2012)

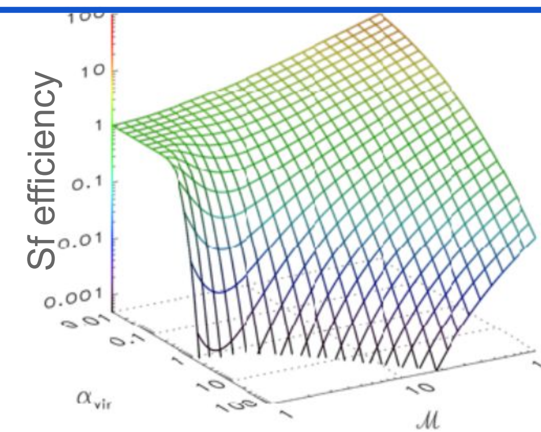
Multi-freefall (Mff$_\epsilon$): calculated efficiency

$$p(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{\left(s + \frac{1}{2}\sigma_s^2\right)^2}{2\sigma_s^2}\right)$$

models we use: Krumholtz & McKee (2005)

$\sigma_s^2 = \ln\left(1 + b^2 \mathcal{M}^2\right)$ $\quad \mathcal{M} = \frac{\sigma_{\rm T}}{c_s}$ Mach number

$\rho_{\rm crit} \propto \alpha_{\rm vir} \mathcal{M}^2$ $\quad \alpha_{\rm vir} = \frac{\sigma_{\rm T}^2}{G\rho_0\Delta^2}$ Virial parameter



$$\epsilon_{\rm ff} = \frac{\epsilon}{2\phi_t} \exp\left(\frac{3}{8}\sigma_s^2\right)\left[1 + \text{erf}\left(\frac{\sigma_s^2 - s_{\rm crit}}{\sqrt{2\sigma_s^2}}\right)\right]$$

One free parameter $\rightarrow \epsilon$

Resources

Usual pipeline

1 **DMO** no Zooms

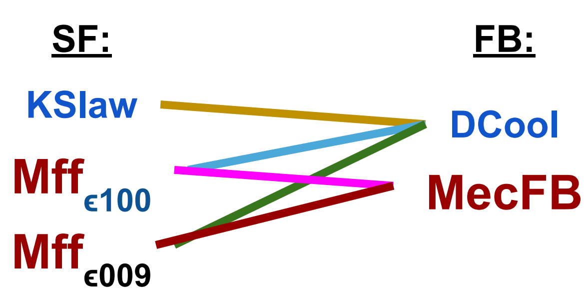
1 **DMO** Zooms

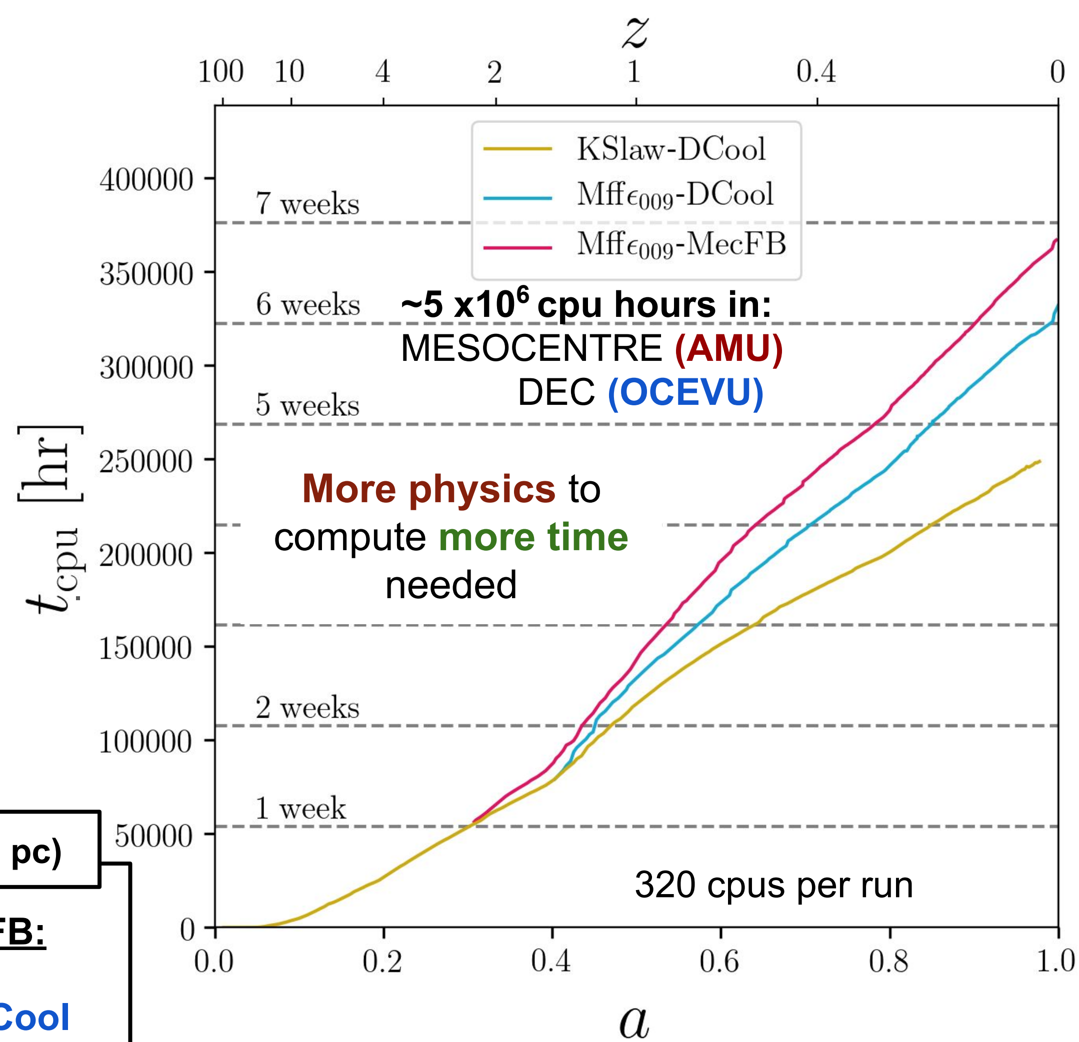
1 **DMO** decontaminated

1 **hydro** low resolution **(~400 pc)**

If disc:

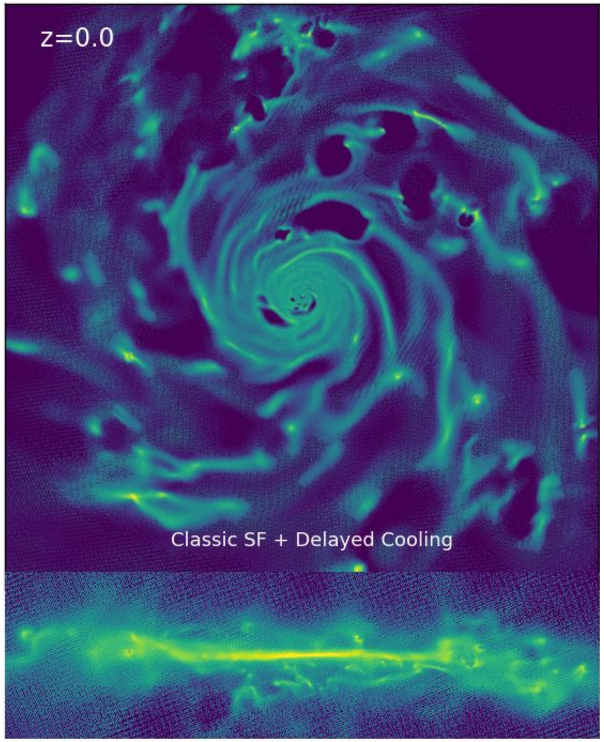
5 hydro high-resolution (~35 pc)

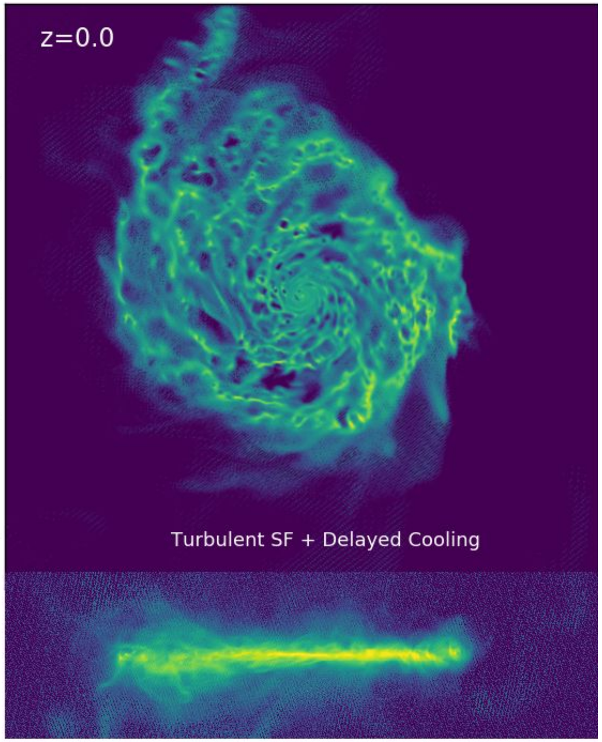


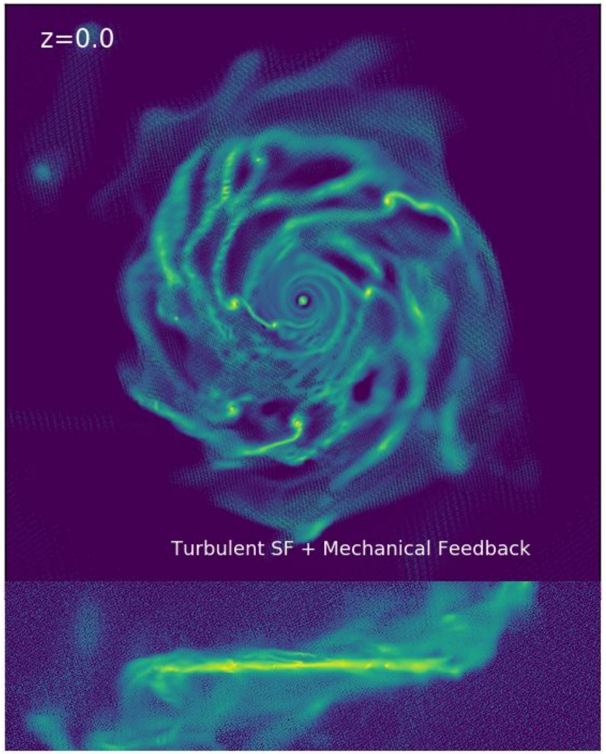


All the analyses have been performed with an original python library **(WKBL)** and based on the **unsio package**

Mochima (Boxsize: 36 Mpc, M_H= 0.9x 10^{12} M_{sun}, M_{dm}=1.8x 10^5, Δx=35 pc)
Gas





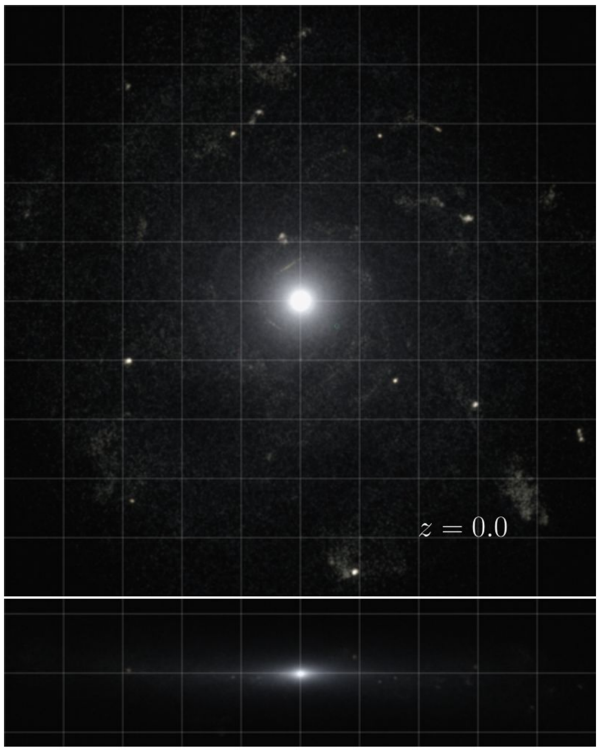


SF: Schmidt law (KT13)
FB: Delayed Cooling(T13)

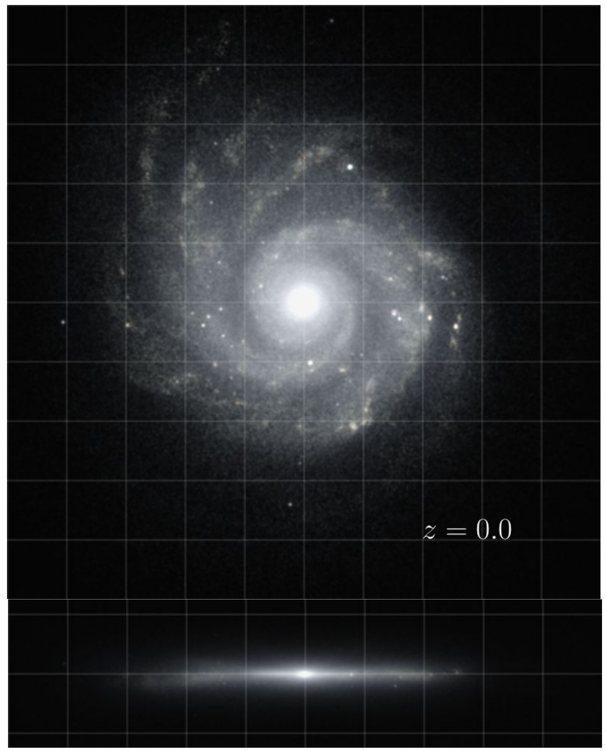
SF: Turbulent SF (KM05)
FB: Delayed Cooling (T13)

SF: Turbulent SF (KM05)
FB: Mechanical Feedback (K15)

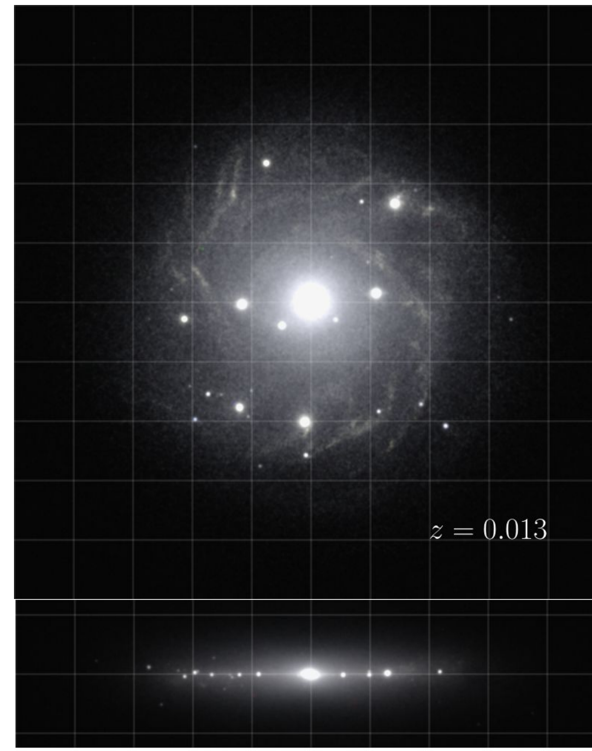
Mochima (Boxsize: 36 Mpc, M_H= 0.9x 10^{12} M_{sun}, M_{dm}=1.8x 10^5, Δx=35 pc)
Stars



SF: Schmidt law (KT13)
FB: Delayed Cooling(T13)



SF: Turbulent SF (KM05)
FB: Delayed Cooling (T13)



SF: Turbulent SF (KM05)
FB: Mechanical Feedback (K15)

Star formation

Schmidt law for star formation:

$$\dot{\rho}_* = \epsilon_* \frac{\rho_g}{t_{\rm ff}} \text{ for } \rho > \rho_*$$

Krumholz & Tan (2007).

Option 1: constant efficiency

The aim is to **calibrate parameters** to reproduce Kennicutt (1998) relation:

$$\Sigma_{\rm SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{\rm gas}}{\rm M_\odot pc^{-2}} \right)^{1.4}$$

Daddi et al. (2010)