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A multiscale view of galaxy formation

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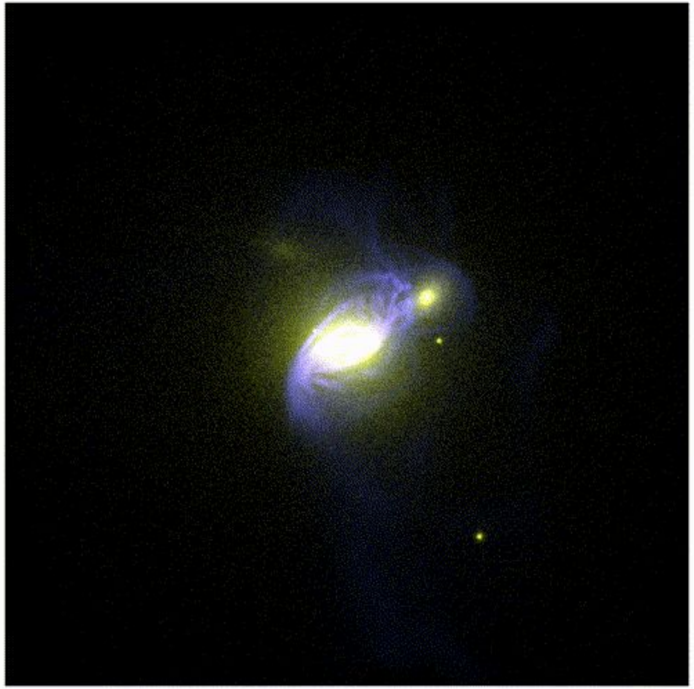
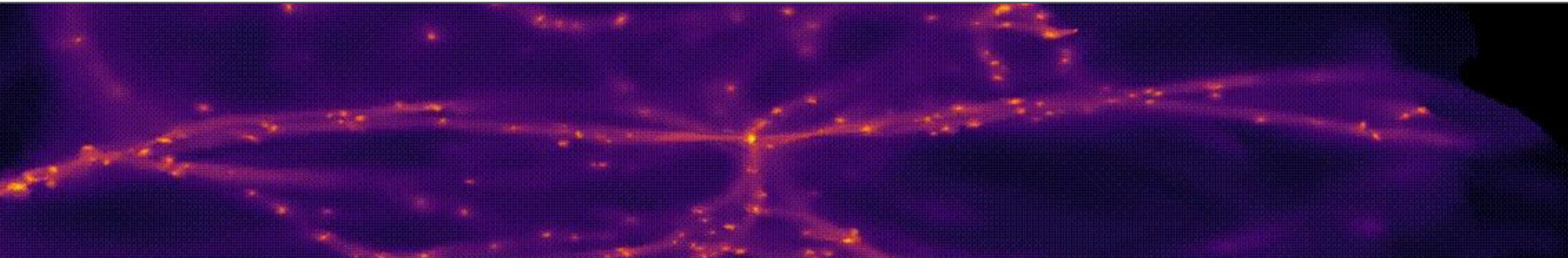
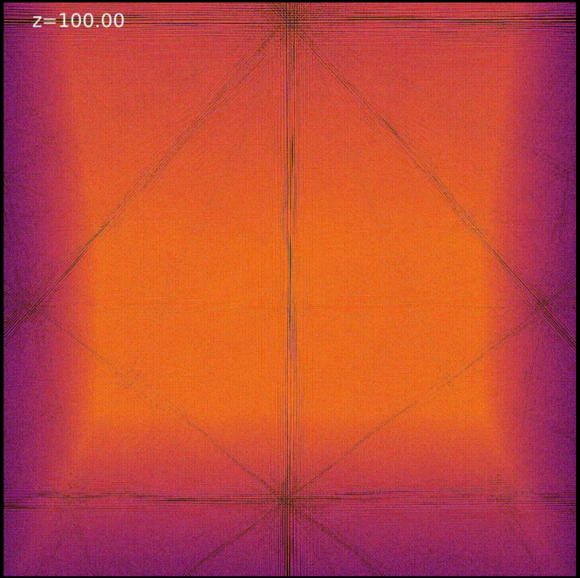
DE LA RECHERCHE À L'INDUSTRIE cea





What is a Galaxy and how to simulate it

Cosmological initial conditions and the right ingredients can help the understanding of galaxy formation



What are the right ingredients?

What is a Galaxy and how to simulate it

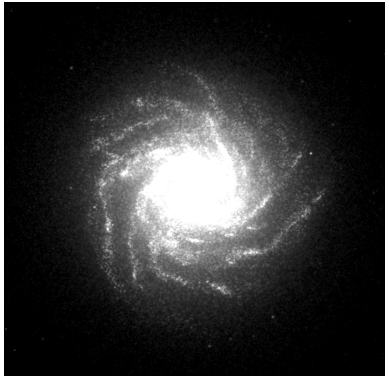
DM

Collisionless limit of the Boltzmann equation:

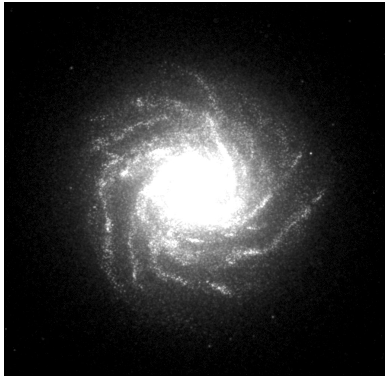
$$\frac{Df}{Dt} = \frac{\partial}{\partial t} f(\mathbf{x}, \mathbf{v}, t) + \mathbf{v} \frac{\partial}{\partial \mathbf{x}} f + \mathbf{a} \frac{\partial}{\partial \mathbf{v}} f = 0$$

Liouville theorem: number of particles is conserved in phase-space. The gravitational acceleration is given by **Poisson equation**:

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



What is a Galaxy and how to simulate it



Gas

DM

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

Hydro. 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)

What is a Galaxy and how to simulate it

Gas — DM

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

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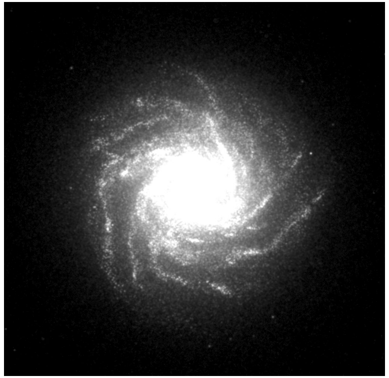
Add gravity and heating and cooling rates. (this can be expanded to include magnetic fields as well)



Turbulence

Grav Collapse

What is a Galaxy and how to simulate it

Gas
DM
Stars

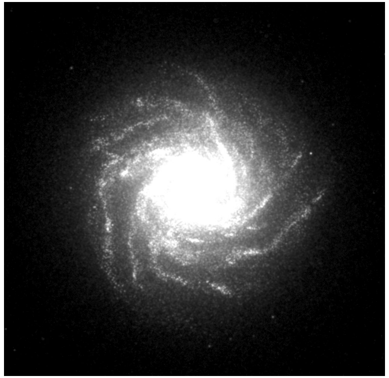
We need an effective model at the scale of the spatial resolution:

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

Ruled by the star formation efficiency

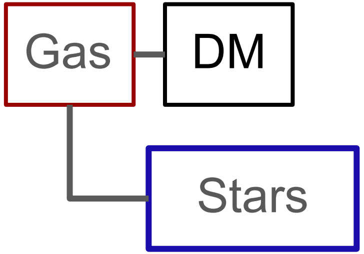
Star formation

Grav Collapse



Turbulence

What is a Galaxy and how to simulate it



We need an effective model

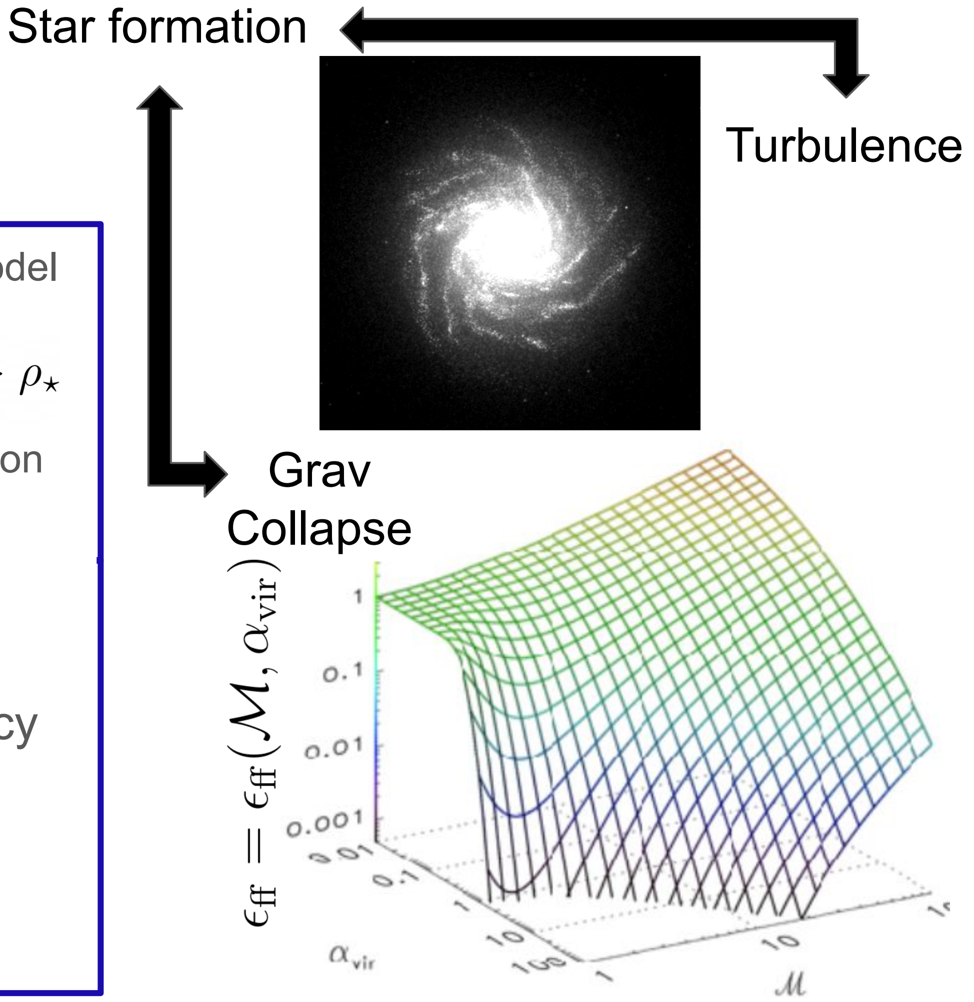
$$\dot{\rho}_\star = \epsilon_{\rm ff}\frac{\rho_g}{t_{\rm ff}} \quad for \quad \rho_g > \rho_\star$$

Ruled by the star formation efficiency

- Constant efficiency galaxy wide
- Environmental dependent efficiency

$$\epsilon_{\rm ff} = \epsilon_{\rm ff}(\mathcal{M}, \alpha_{\rm vir})$$

Multi-freefall star formation (Federrath & Klessen (2012))



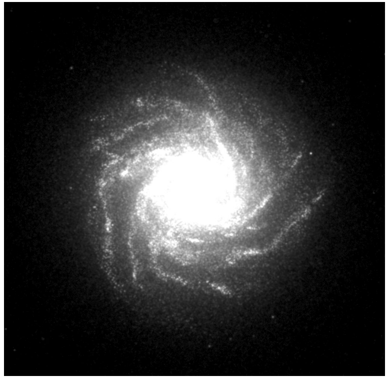
What is a Galaxy and how to simulate it

Gas — DM

Stars

SN explosions
Cosmic rays

Star formation



Turbulence

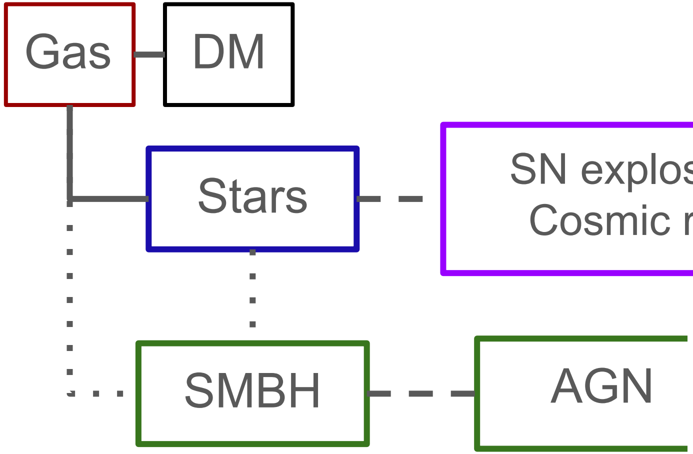
Feedback

Grav Collapse

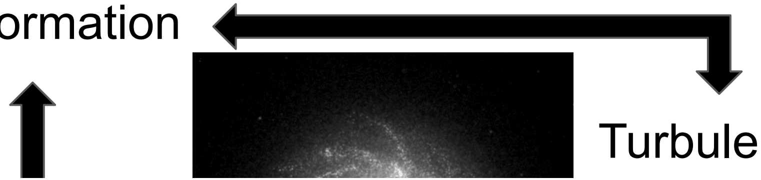
We need effective models:

- **SN** : thermal or kinetic energy injections, delayed local cooling, mechanical Sedov taylor phases.(Teyssier et al. 2013, Dubois et al. 2015.Kimm & Cen 2014. Kimms et al. 2015.)
- **Cosmic rays**: relativistic fluid that provides and effective pressure (Low energy GeV) (Dubois & Commerçon 2016)

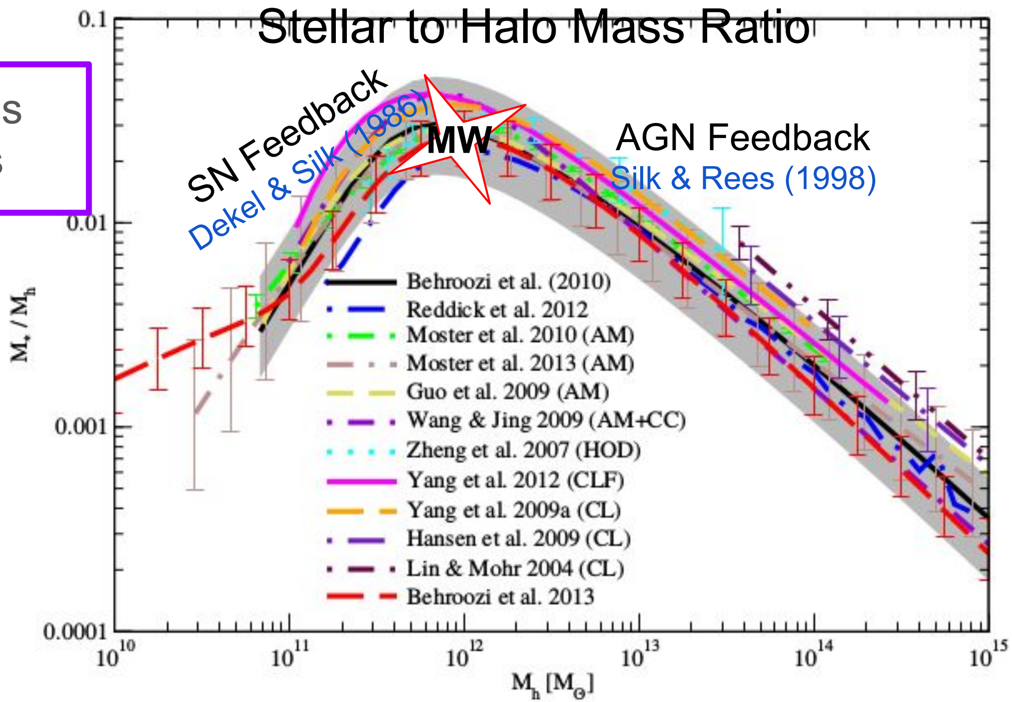
What is a Galaxy and how to simulate it



Star formation

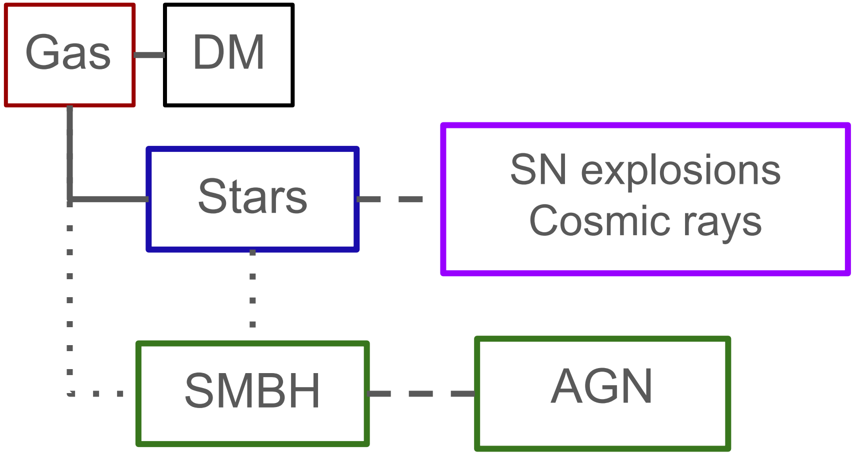


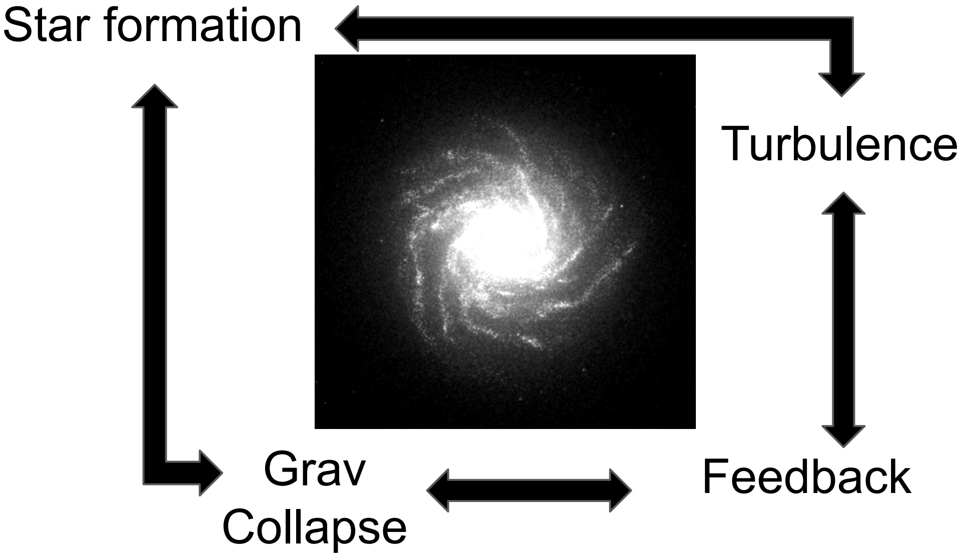
Turbulence



Behroozi et al. (2013)

What is a Galaxy and how to simulate it



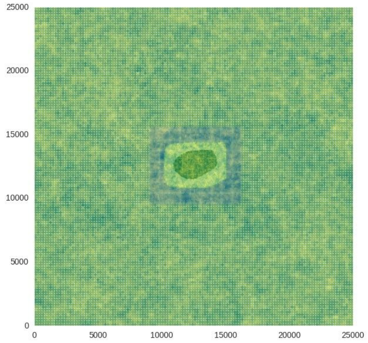


At the end, with these ingredients.. You have a nonlinear environment that evolves with time and can be compared with observation (?)...
giving us information on:

- Galaxy formation
- Galactic dynamics
- Dark matter distribution

Cosmological simulations

Zoom in

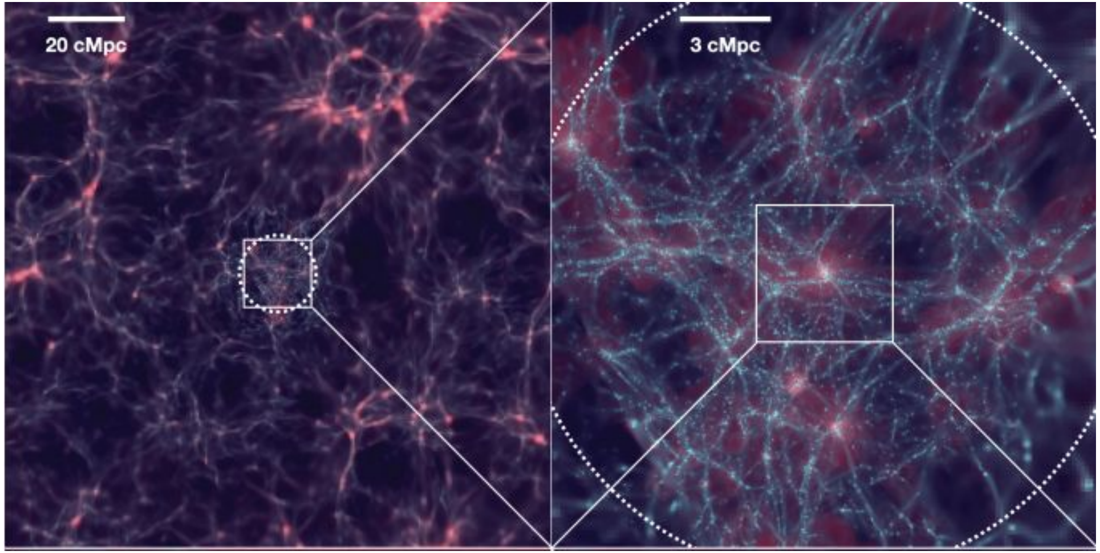


- 1 galaxy
- High resolution
- Short running time

Isolated simulations of one galaxy without a cosmological environment are also possible.

Mochima, FIRE, Auriga, NIHAO

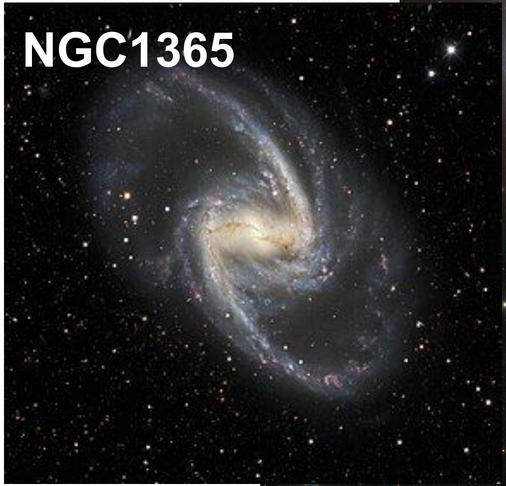
Cosmo box

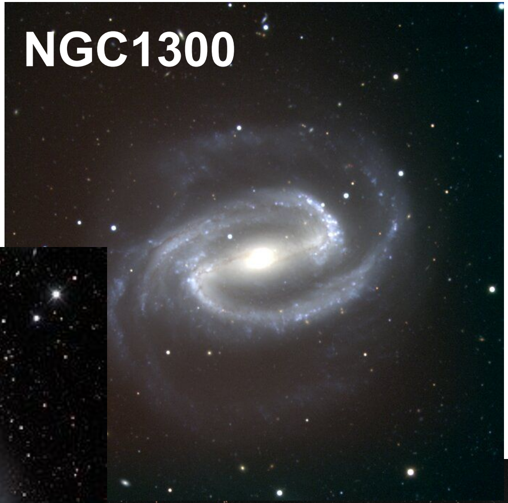


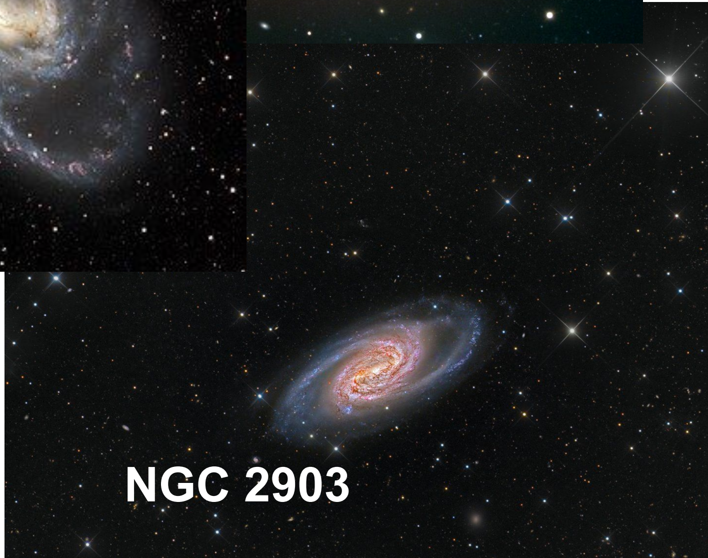
- \+ galaxies
- \- resolution
- Long running time

Horizons, FIRE 2, Ilustris TNG, DEUS, SIMBA

Galactic centers: unbarred and barreds







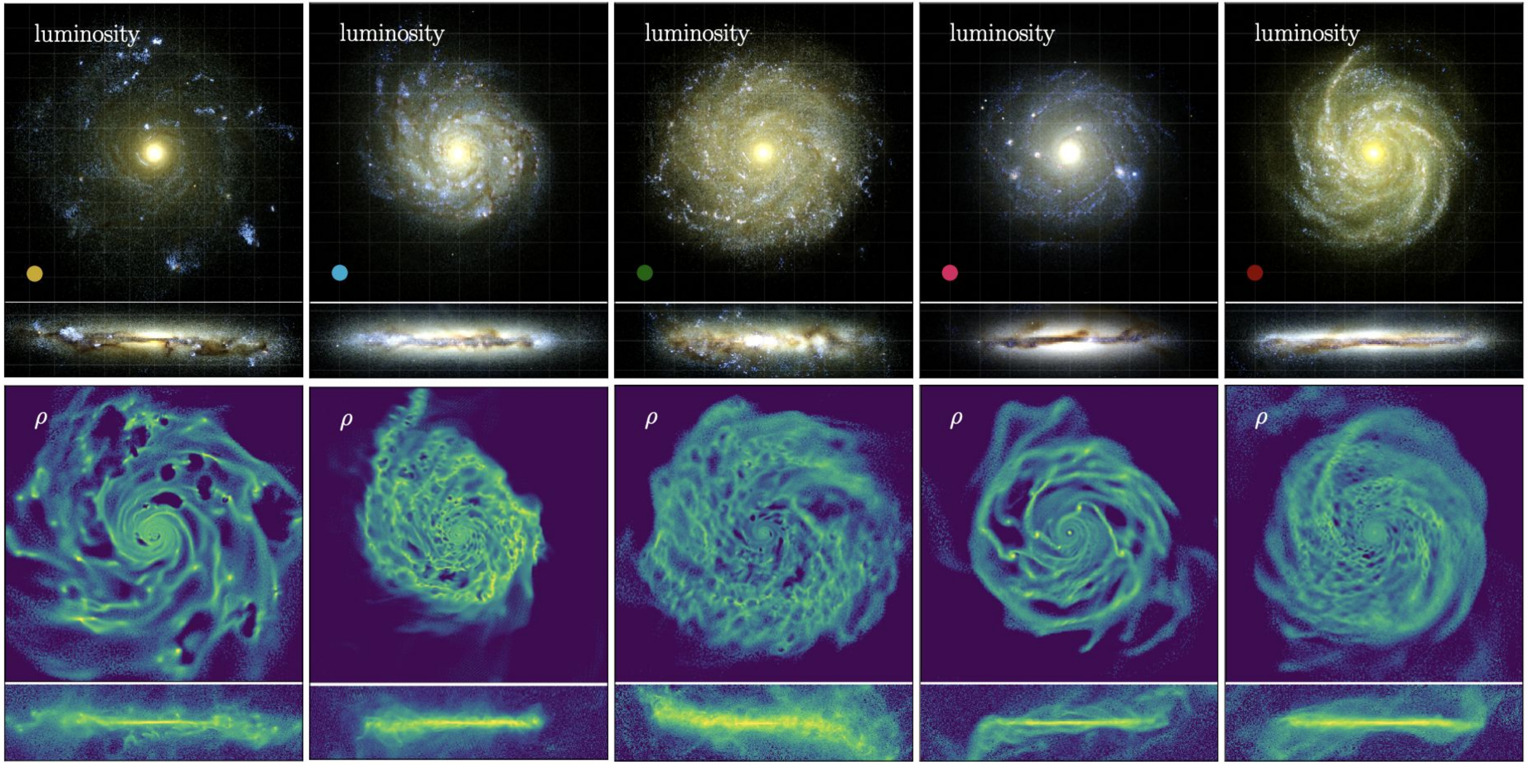
The Mochima simulation

Delayed Cooling
(Dubois et al 2015)

Mechanical FB
(Kimm et al. 2015)

Kennicutt-Schmidt
SF

Turbulent SF
(multi-ff KN Hennebelle & Chabrier 2011)



Nunez-Castineyra et al. 2020

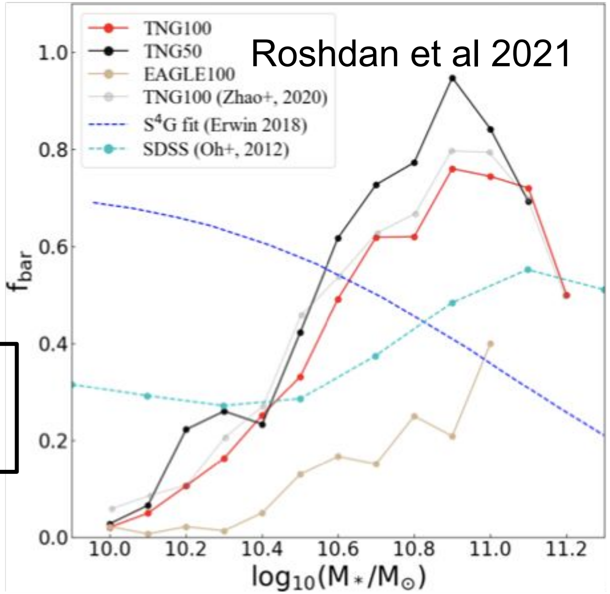
Some tensions between simulations and observations

(that I am interested in lately)

- Too few galactic bars in cosmological simulations

Bar growth is suppressed in CS (Reddish et al 2022)
Too slow and too short (Roshdan et al 2021)
Too short maybe not that slow (Frenkel et al 2022)

Possible exceptions:
Auriga simulation



Bar have been claimed to be **shortlived** or not a permanent feature:

Bournaud, F., & Combes, F. (2002)
Bournaud, F., Combes, F., & Jog, C. J. (2004).
Bournaud, F., Combes, F., & Semelin, B. (2005)

Higher gas fraction -> weaker bars (but)
Cuspy DM halos -> weaker bars

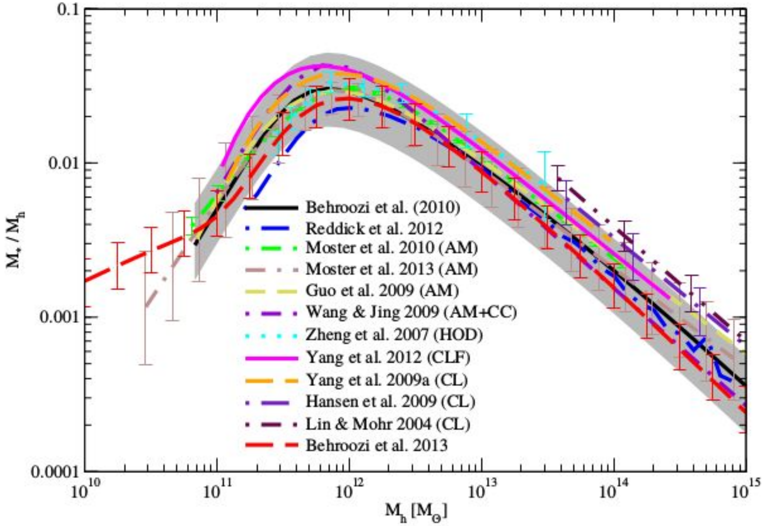
Gas fractions can also impact the formation of the bar:

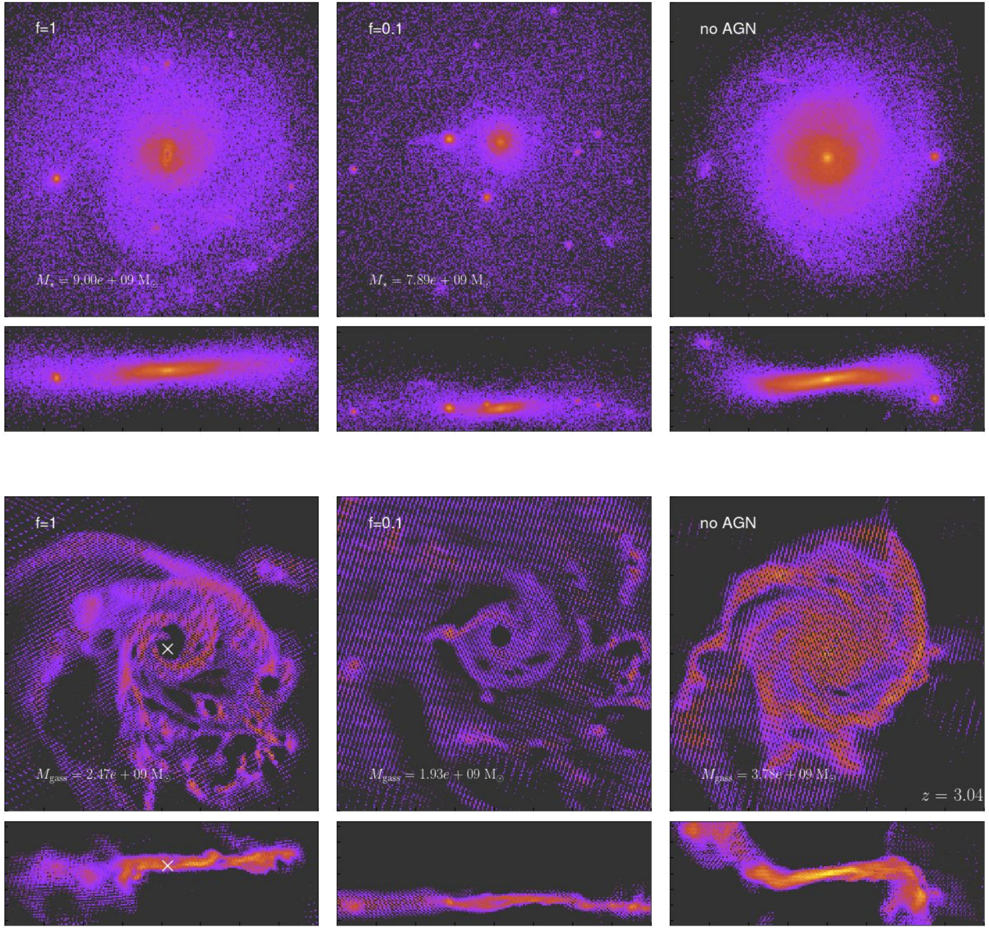
Athanassoula, E., Machado, R. E. G., & Rodionov, S. A. (2013).
Villa-Vargas, J., Shlosman, I., & Heller, C. H. (2010)
Sheth, K., Vogel, S. N., Regan, M. W., Thornley, M. D., & Teuben, P. J. (2005)

The **Dark Matter halo** will impact the fate of the bar as well:

Weinberg & Katz (2007)
Athanassoula (2002, 2003)
Debattista & Sellwood (2000)

The AGN addition and a bar?





The AGN addition and a bar?

Why is this bar here?

- A flyby?
- The right gas fraction?
- A cored DM halo?

What do we need to approach this question?

Some Python skills in data visualization and data analysis.