A physically motivated model of the Interstellar Medium

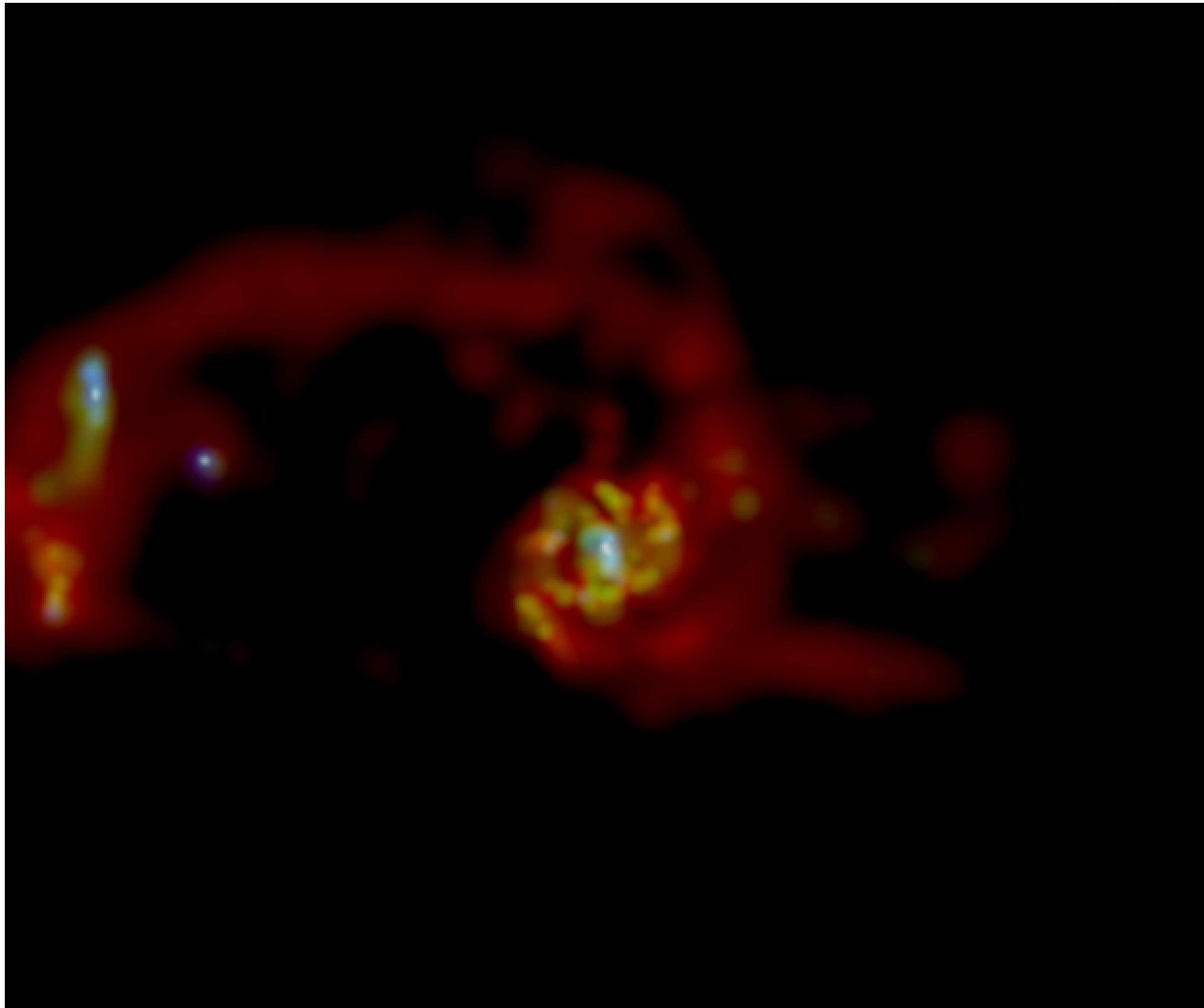
Towards a macroscopic view of the ISM

Josh Borrow, Durham University, Supervisor: Prof. Richard Bower
@JBorrow

Motivation and Background

State of the art cosmological simulations

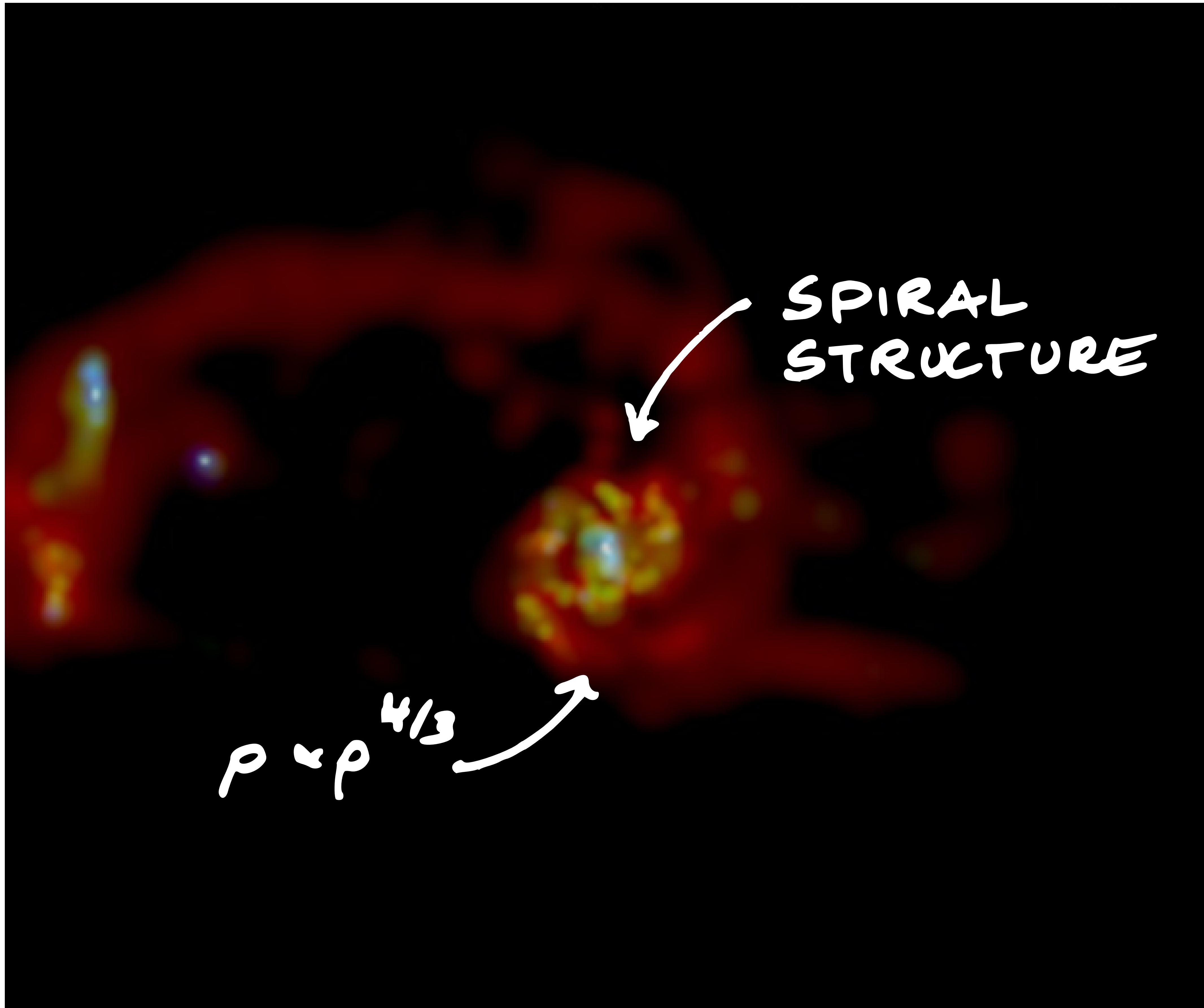
- Simulations have limited resolution
- In EAGLE, a mass resolution of 10^6 solar masses is achieved
- However, a large number of physical processes take place on smaller scales…
- How do we include them in the simulation?



Gas in a typical EAGLE galaxy (Schaye et. al 2015).
Image courtesy of J. Borrow, S. Bancroft, and Richard Bower.

State of the art cosmological simulations

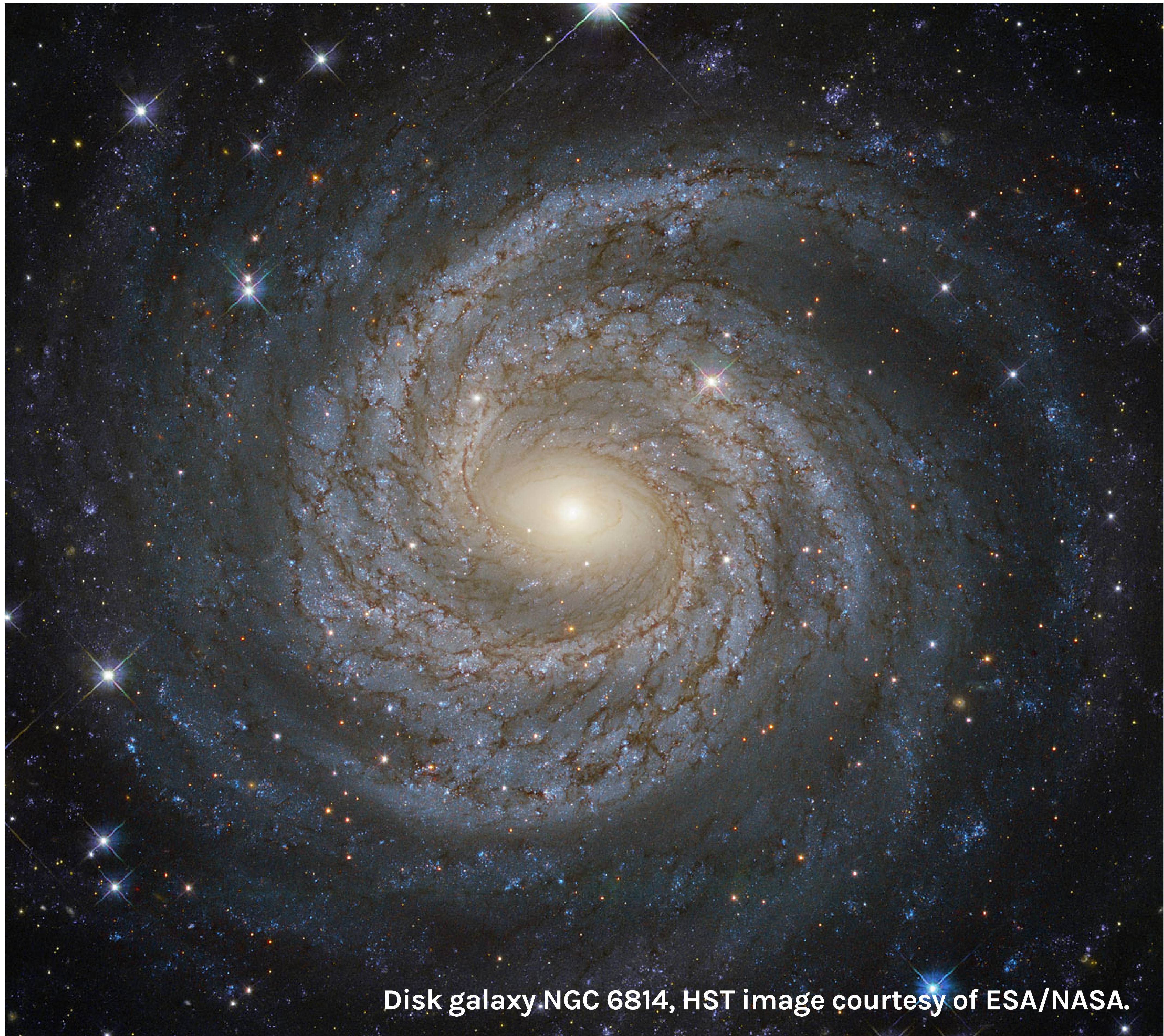
- Simulations have limited resolution
- In EAGLE, a mass resolution of 10^6 solar masses is achieved
- However, a large number of physical processes take place on smaller scales…
- How do we include them in the simulation?



Gas in a typical EAGLE galaxy (Schaye et. al 2015).
Image courtesy of J. Borrow, S. Bancroft, and Richard Bower.

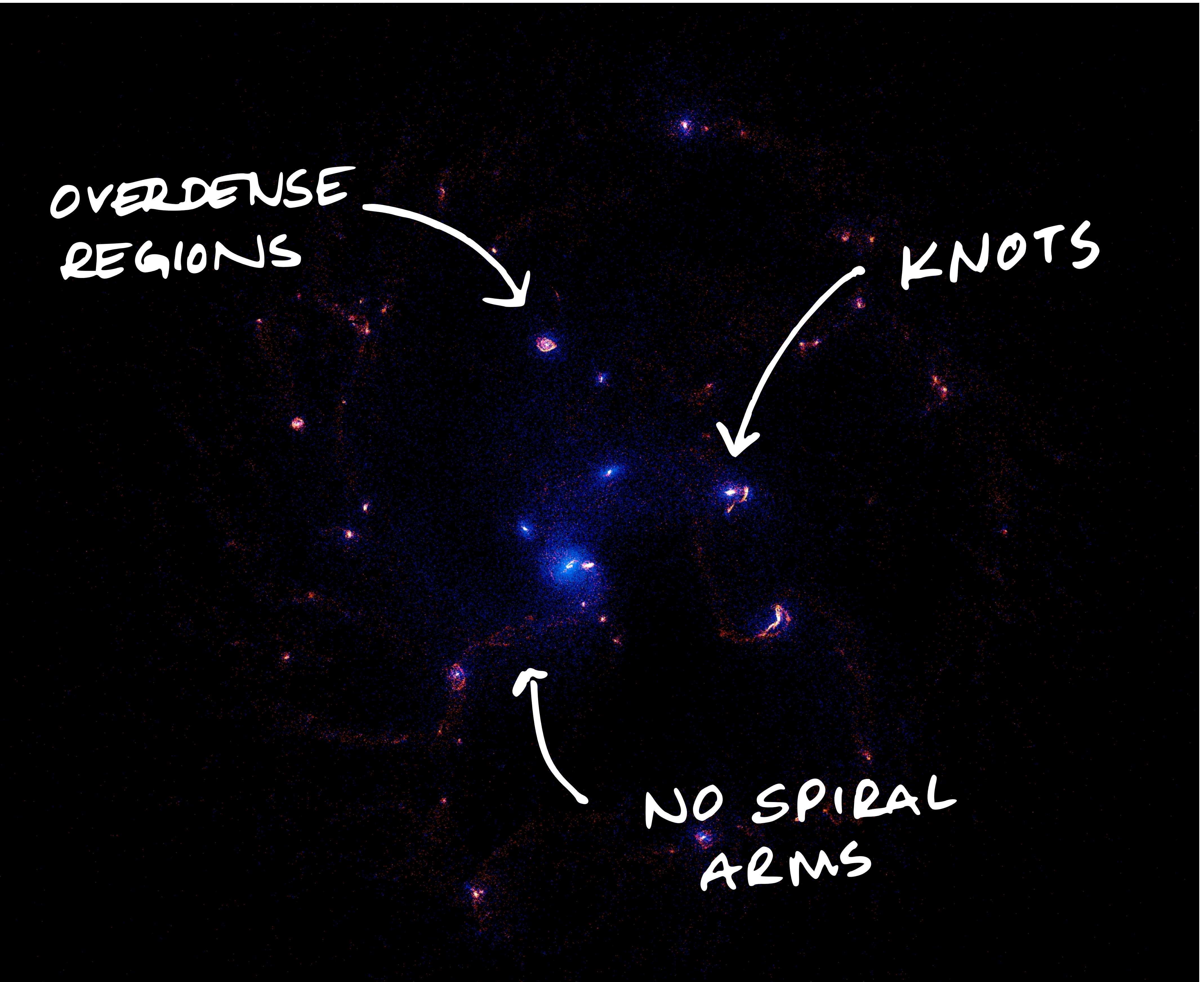
Simulations and observations of disk galaxies

Simulation of a disk galaxy using InterstellarGadget, a modified version of the GADGET-2 SPH code. 100'000 gas particles, 100'000 star particles, and a fixed NFW halo using an isothermal equation of state.



Disk galaxy NGC 6814, HST image courtesy of ESA/NASA.

Simulations and observations of disk galaxies

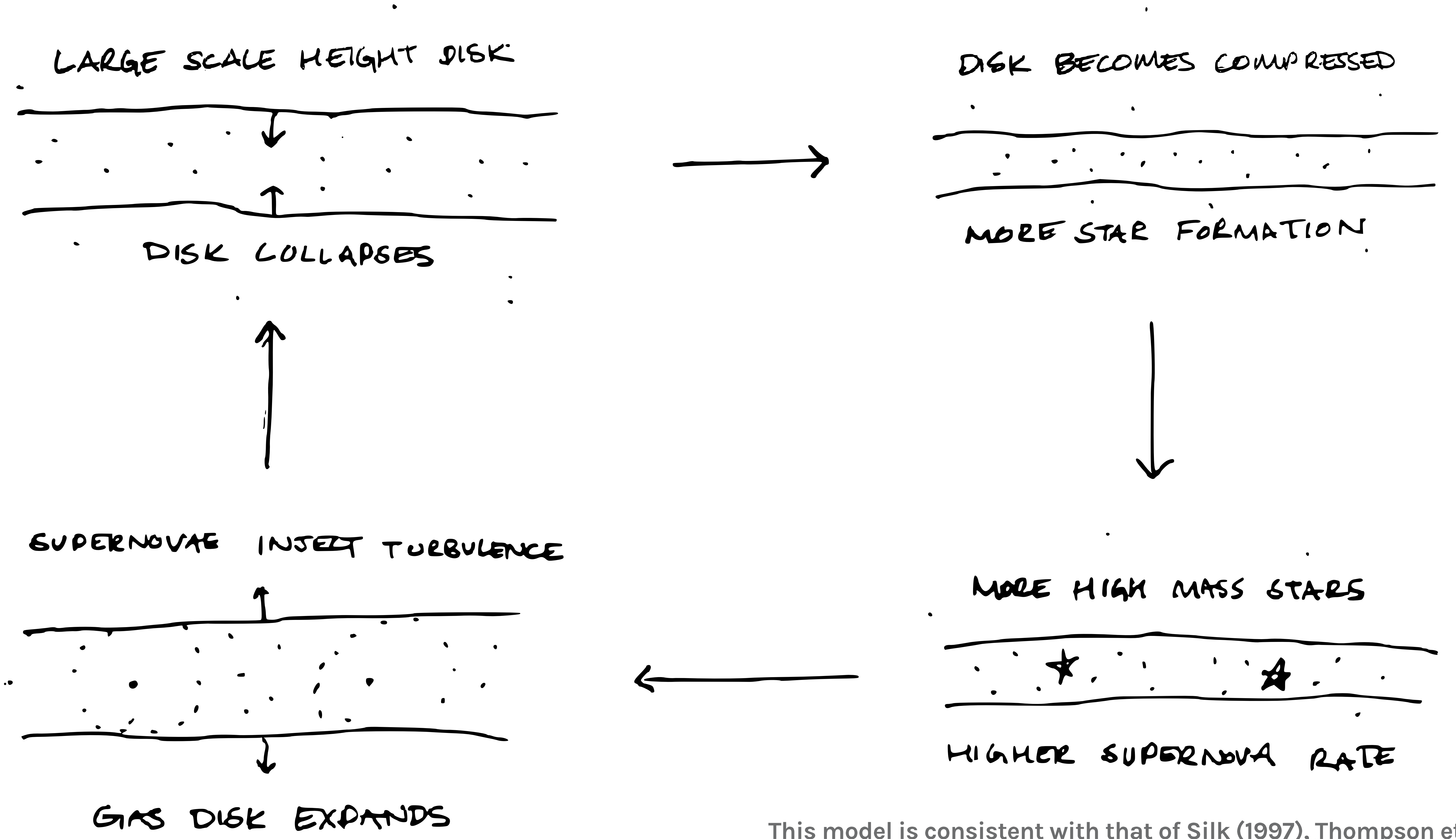


Simulation of a disk galaxy using InterstellarGadget, a modified version of the GADGET-2 SPH code. 100'000 gas particles, 100'000 star particles, and a fixed NFW halo using an isothermal equation of state.

Disk galaxy NGC 6814, HST image courtesy of ESA/NASA.

Building a stellar feedback based model of the ISM

A stellar feedback model



This model is consistent with that of Silk (1997), Thompson et al. (2005), Ostriker and Shetty (2011), Faucher-Giguère et al. (2013), and Martizzi et al. (2016).

Building a star formation model

- Turbulent pressure injected from star formation

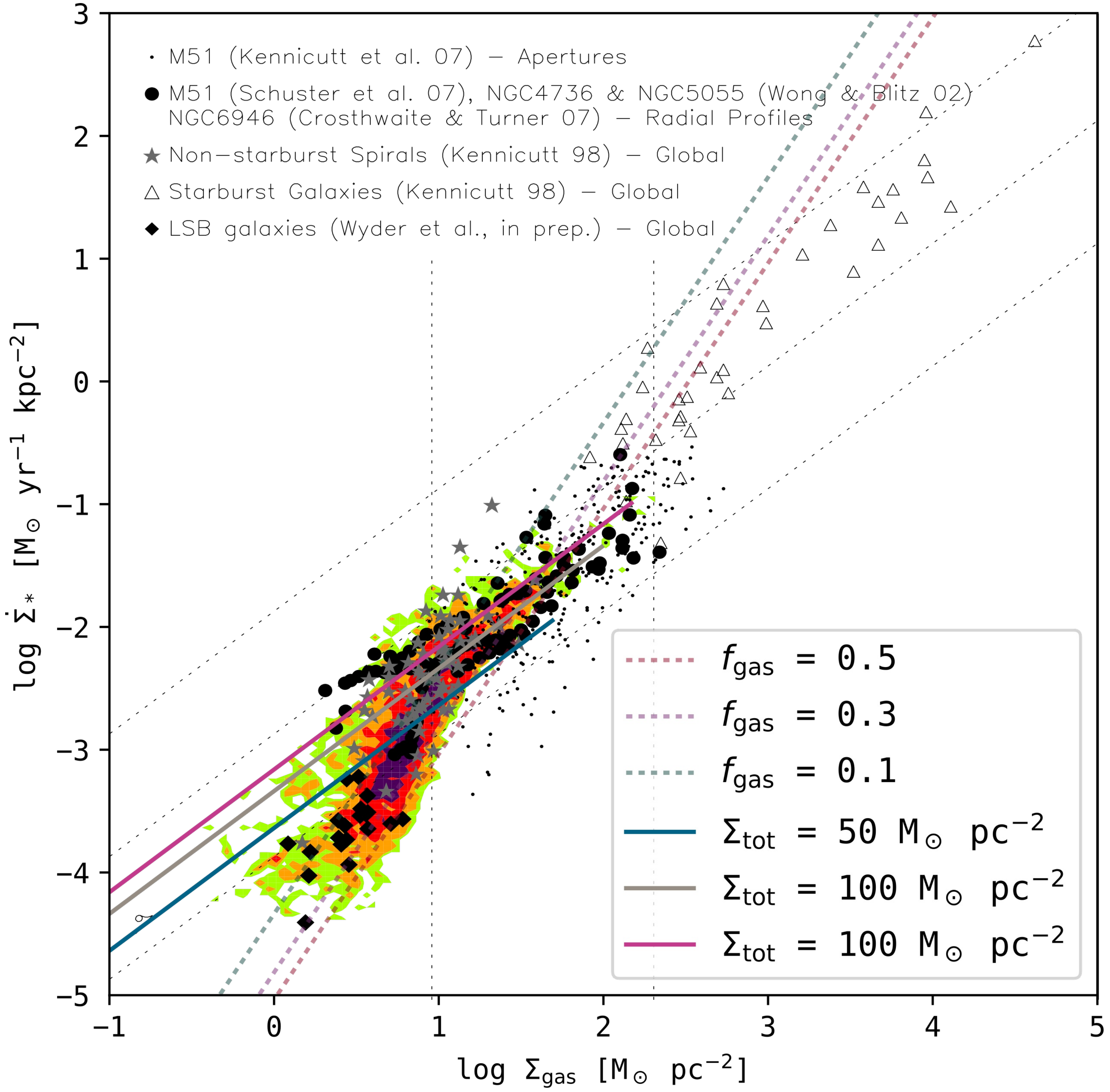
$$p_T = F\dot{\Sigma}_* \left(\frac{P_{fin}}{m_*}\right)$$

- A disk in hydrostatic equilibrium has (vertically)

$$p_H \approx \pi G \Sigma_g \Sigma_{tot}$$

- Equating these leads to

$$\dot{\Sigma}_* = \frac{\pi G}{F\left(\frac{P_{fin}}{m_*}\right)} \Sigma_g \Sigma_{tot}$$



This model is consistent with that of Silk (1997), Thompson et al. (2005), Ostriker and Shetty (2011), Faucher-Giguère et al. (2013), and Martizzi et al. (2016).

Plot adapted from Bigiel et al. (2008).

Building a 'Zoom-Out' model

- Traditional 'Zoom-In' simulation: large-scale with follow up high resolution runs on smaller scales.
- Instead, run the small-scale simulations first and extract macroscopic parameters.
- Here: dispersion injected by supernovae (Martizzi, 2015):

$$\sigma = 1.8 \left(\frac{f}{F}\right)^{3/5} G^{2/5} P_{fin}^{1/5} f_{gas}^{-2/5} \Sigma_g^{1/5} \ .$$

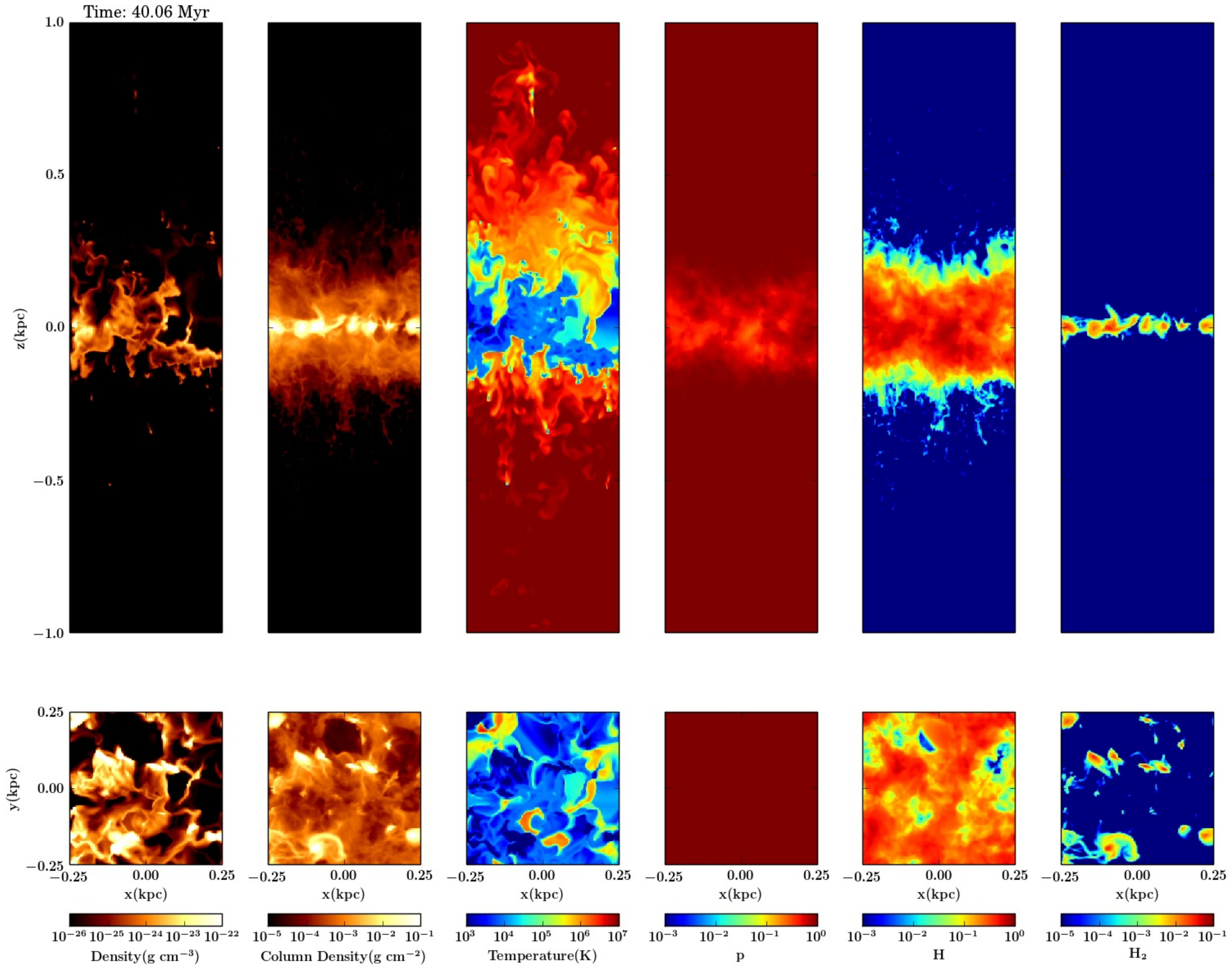


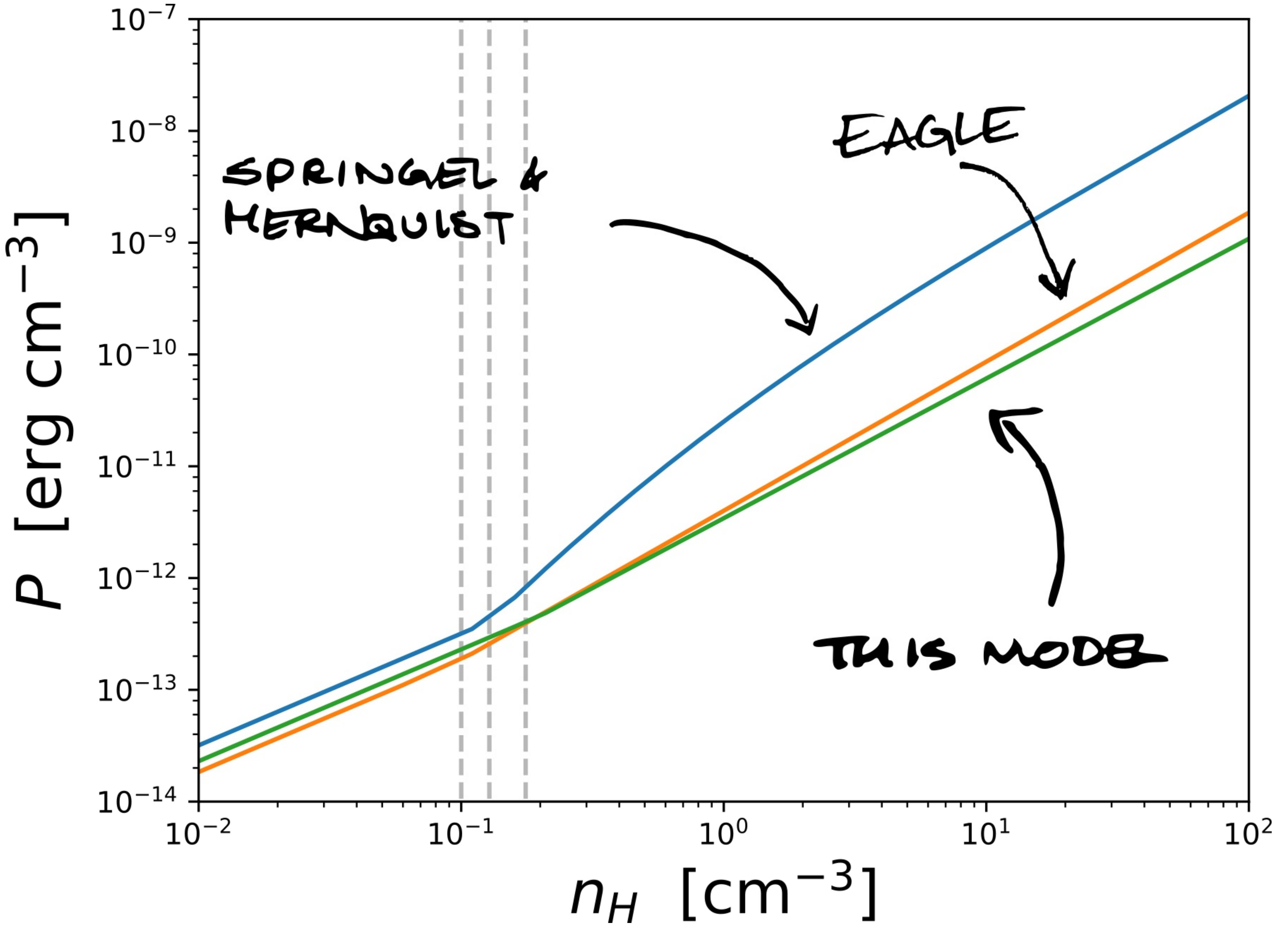
Figure from the Silcc Collaboration website (https://hera.ph1.unikoeln.de/~silcc/).

Application to simulations

- Really, what is required is an equation of state
- When the disk is in equilibrium, the jeans length is of order the scale height, and we use small scale simulations to calibrate dispersion
- This leads to

$$p_T = 4.5 \left(\frac{f}{F}\right)^{3/2} G^{3/4} P_{fin}^{1/2} f_{gas}^{-1} \rho_g^{5/4}$$

See Schaye (2001) for the original derivation, and Schaye (2007) for a recent use of this. Martizzi (2015)'s small scale simulations were used to calibrate the velocity dispersion in this model.

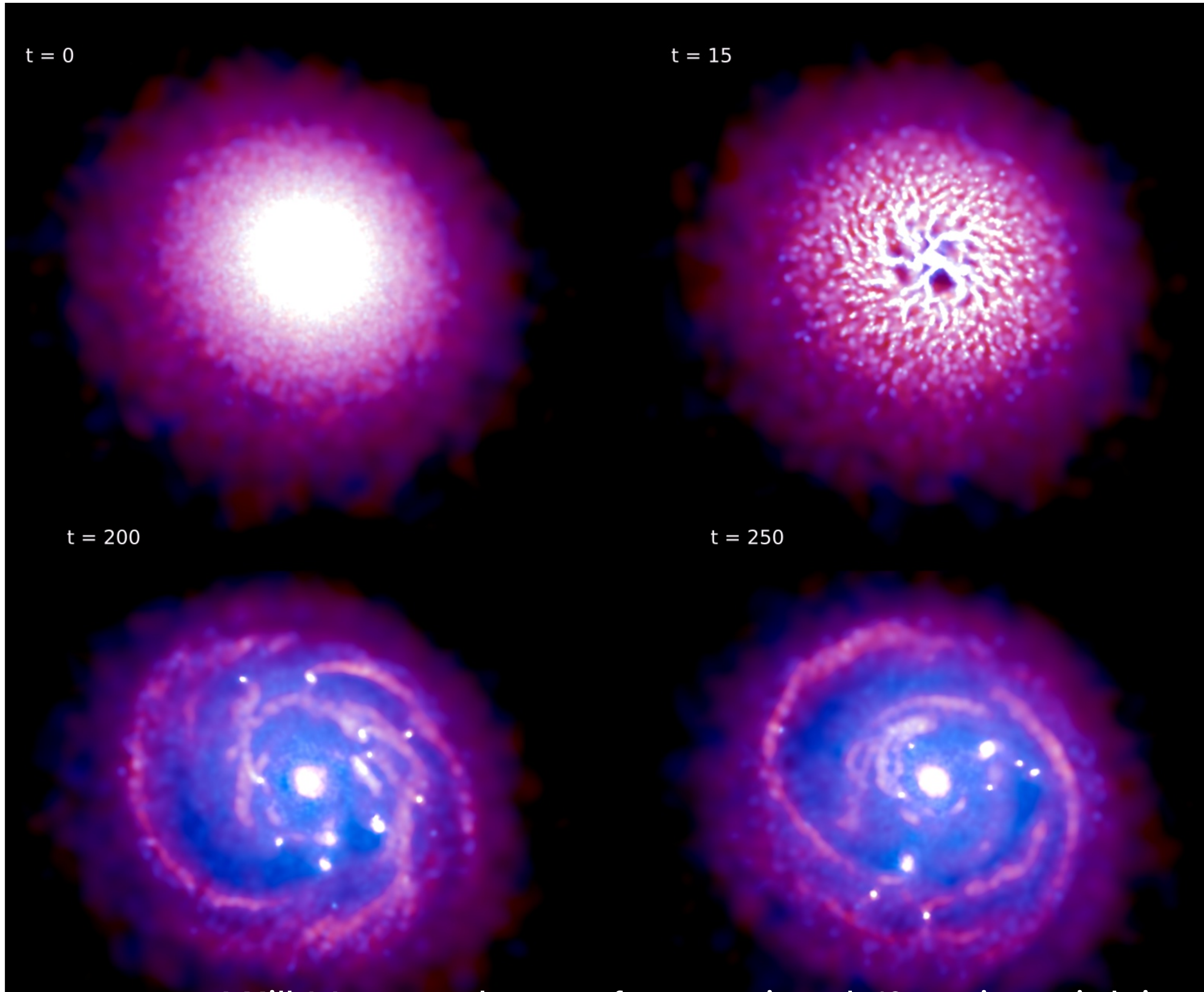


Fit of Springel & Hernquist (2003) from Robertson et al. (2004).

Testing a subgrid model

Running simulations with GADGET-2

- Runs of isolated disk galaxies to test for stability
- Modified version of GADGET-2 (InterStellarGadget) with a custom EOS & fixed NFW profile
- Why GADGET-2? Relatively easy to modify for this purpose.



A Milk Way-type galaxy ran after approximately 10 rotation periods in InterStellarGadget, a modified version of the GADGET-2 SPH code.

The original references for the GADGET-2 code can be found in Springel (2005). For more infromation, please see the project website (http://wwwmpa.mpa-garching.mpg.de/gadget/)

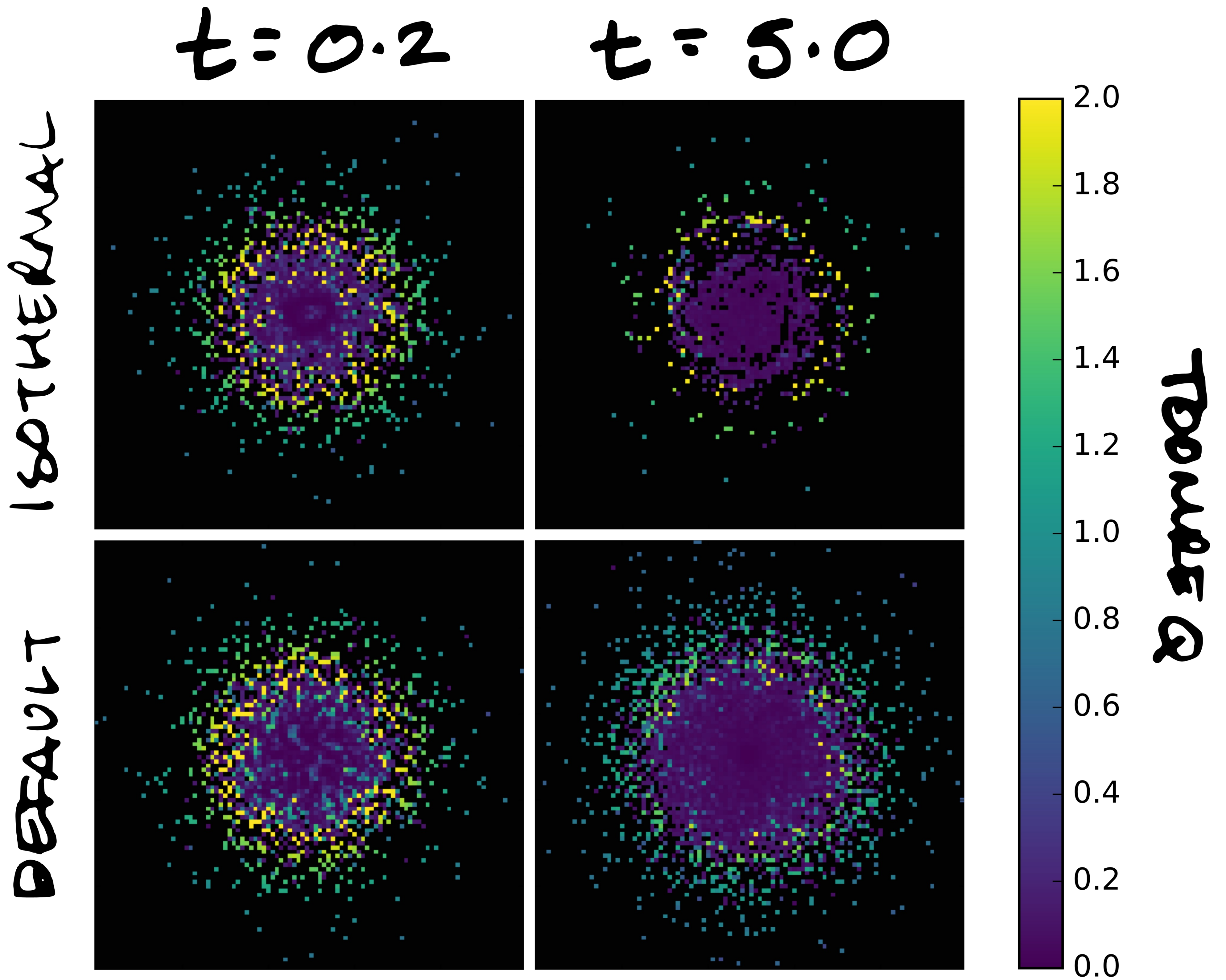
Testing a subgrid model

- A useful check for stability is the Toomre (1964) Q parameter, which is given by (for gas)

$$Q_{\text{gas}} \equiv \frac{c_s \kappa}{\pi G \Sigma}$$

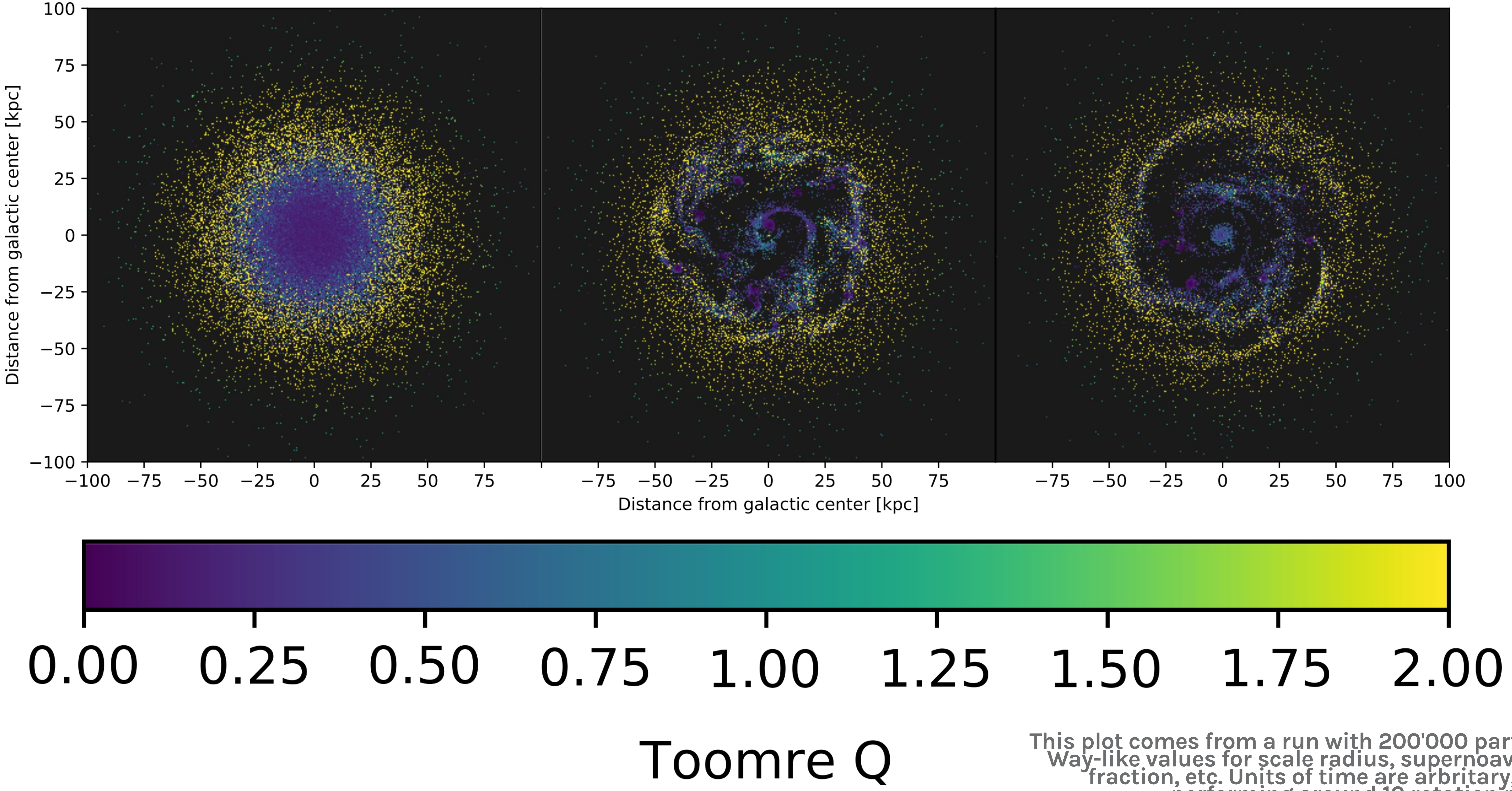
- A disk is considered stable where Q > 1.
- An isothermal disk has an EOS of $p = c_s^2 \rho_g$

CONSTANT!



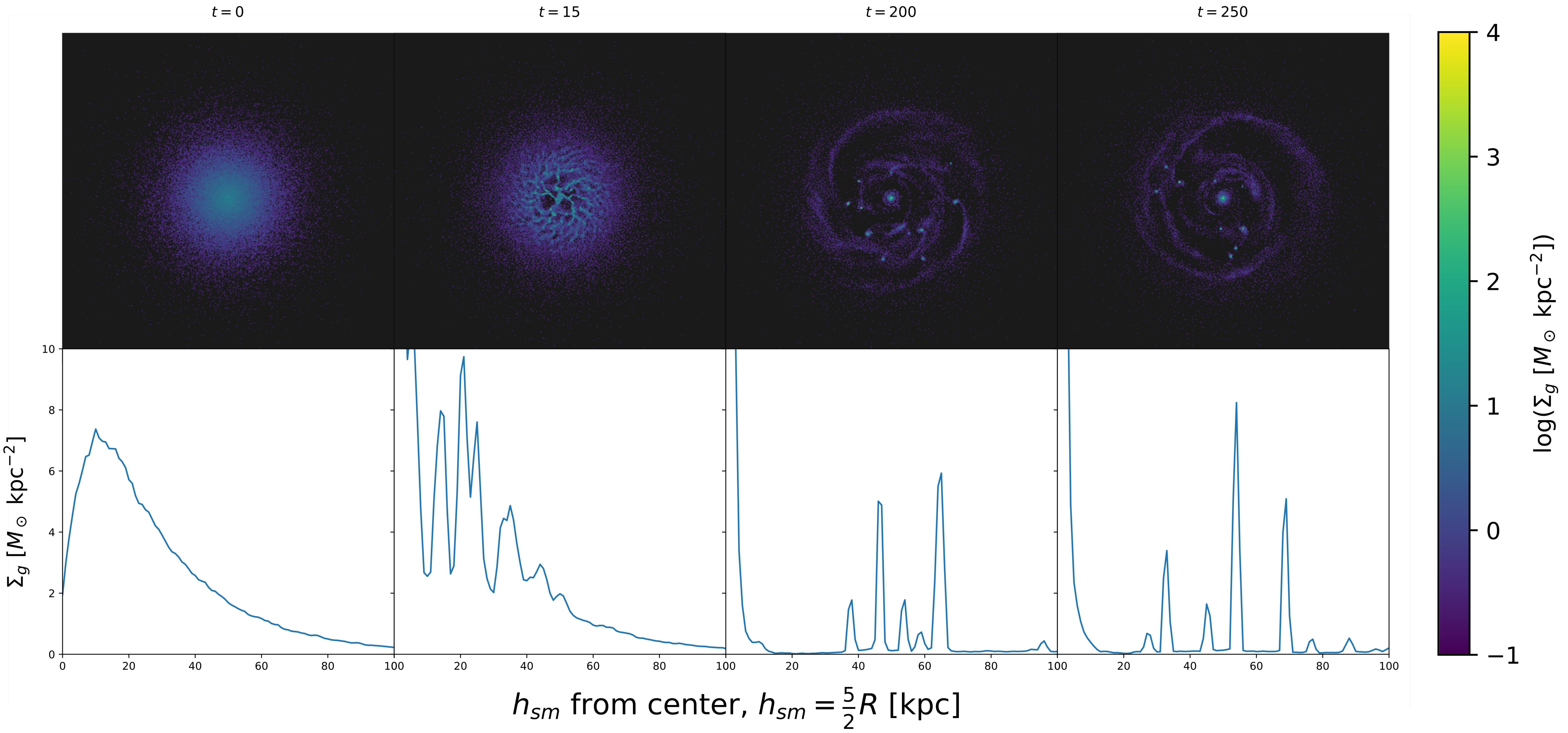
Plot generated with SurVis, a custom python module used to visualise the Toomre Q parameter of an isolated disk galaxy. InterstellarGadget was used to simulate the galaxy, which has a mass resolution similar to EAGLE with 20'000 particles.

The evolution of the Toomre parameter with time



This plot comes from a run with 200'000 particles with MIlky Way-like values for scale radius, supernoave efficiency, gas fraction, etc. Units of time are arbitrary, with the galaxy performing around 10 rotation periods at t=200.

The evolution of surface density with time



Successes so far and ongoing issues

- Able to reproduce an equation of state very similar to the one used in EAGLE
- Galaxies end up in a quasi-stable state
- Galaxies also stabalised by mass flow into the central region (Krumholz and Burkhart, 2016)

- Low surface density
- Some regions completely devoid of gas
- Not enough simulation data yet to make confident conclusions.

Future work & Repositories

- Run more simulations using InterStellarGadget
- Analyse using current pipeline
- More measures of success?

- Modified GADGET-2:
  github.com/JBorrow/InterStellarGadget
- Custom initial conditions generator:
  github.com/JBorrow/GoGoGadget
- Toomre Q visualisation:
  github.com/JBorrow/SurVis

Contact information available at dur.ac.uk/joshua.borrow

Appendix: Pressure generation from supernovae

At first glance, it may seem that the equation

$$p_T = F\dot{\Sigma}_* \left(\frac{P_{fin}}{m_*}\right)$$

is unreasonable, however performing some quick dimensional analysis:

$$[p_T] = \frac{[M][L]}{[T]^2[L]^2}$$

$$\left[\frac{P_{fin}}{m_*}\right] = \frac{[L]}{[T]} \qquad [\dot{\Sigma}_*] = \frac{[M]}{[L]^2[T]}$$

It can also be seen that F comprises three factors

$$p_T = \frac{K_1 K_3}{K_2}\dot{\Sigma}_* \left(\frac{P_{fin}}{m_*}\right)$$

- K1: supernova rate compared to star formation rate
- K2: mass ratio of SN star to mean star
- K3: efficiency of momentun injection from SNe.

Appendix: Useful information about GMCs

Component	Fractional Volume	Scale Height (pc)	Temperature (K)	Density (atoms/cm3)
Molecular clouds	< 1%	80	10–20	10^2–10^6
Cold Neutral Medium (CNM)	1–5%	100–300	50–100	20–50
Warm Neutral Medium (WNM)	10–20%	300–400	6000–10000	0.2–0.5
Warm Ionized Medium (WIM)	20–50%	1000	8000	0.2–0.5
H II regions	< 1%	70	8000	10^2–10^4
Hot Ionized Medium (HIM)	30–70%	1000–3000	10^6–10^7	10^{-4}–10^{-2}

Data adapted from Ferriere (2001) who compiled it from various sources.

The evolution of the Toomre parameter with time

- Difficulty: some areas of the galaxy are swept clean of gas and so have highly uncertain values for the Toomre parameter.
- Initial turbulence is injected through velocity dispersion of the particles.