Structure Formation: Bright side of the Universe

Anatoly Klypin
New Mexico State University

Also: Stefan Gottloeber (Astrophysikalisches Institut Potsdam)
Gustavo Yepes (UAM, Madrid)
Andrey Kravtsov (Chicago)

Cosmological n-body+hydro simulations

Codes:

- SPH + TREE
- AMR + shock capturing hydro

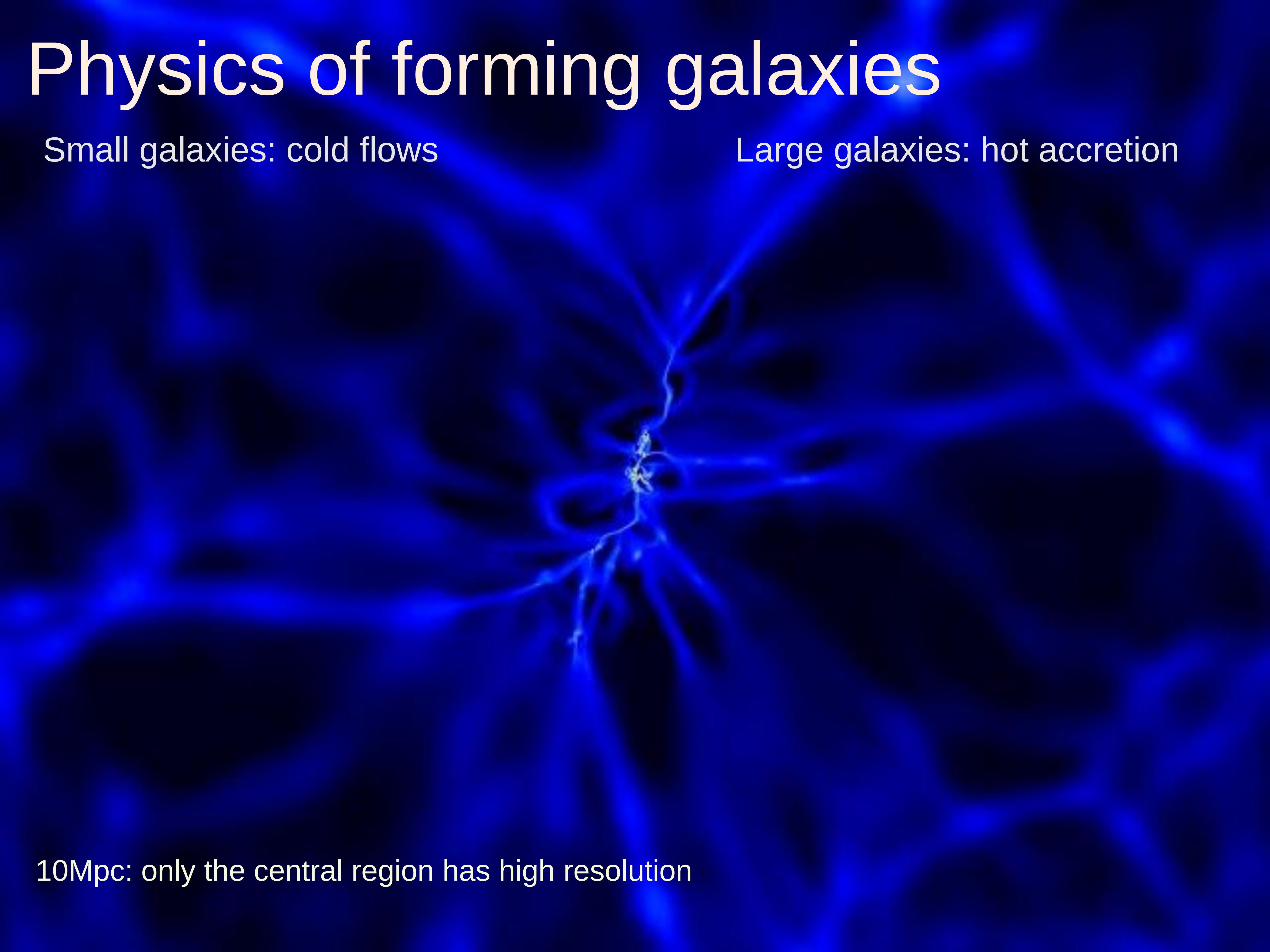
Physical processes:

- Compton cooling/heating on CMB
- Radiative gas cooling
- Star formation with simple approximations
- Metal enrichment
- Energy/momentum feedback from young stars and SN

Physics of forming galaxies

Small galaxies: cold flows

Large galaxies: hot accretion

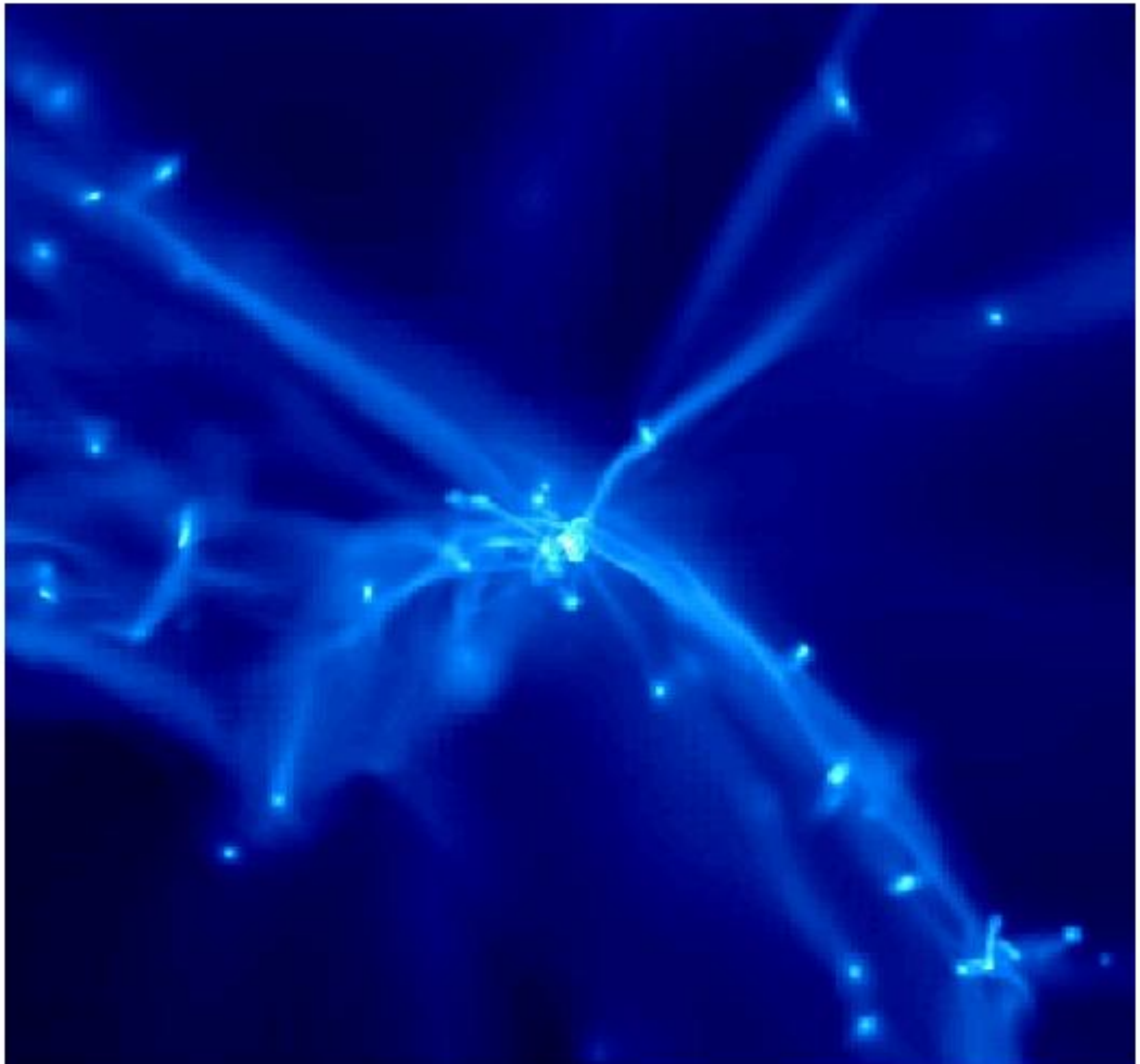


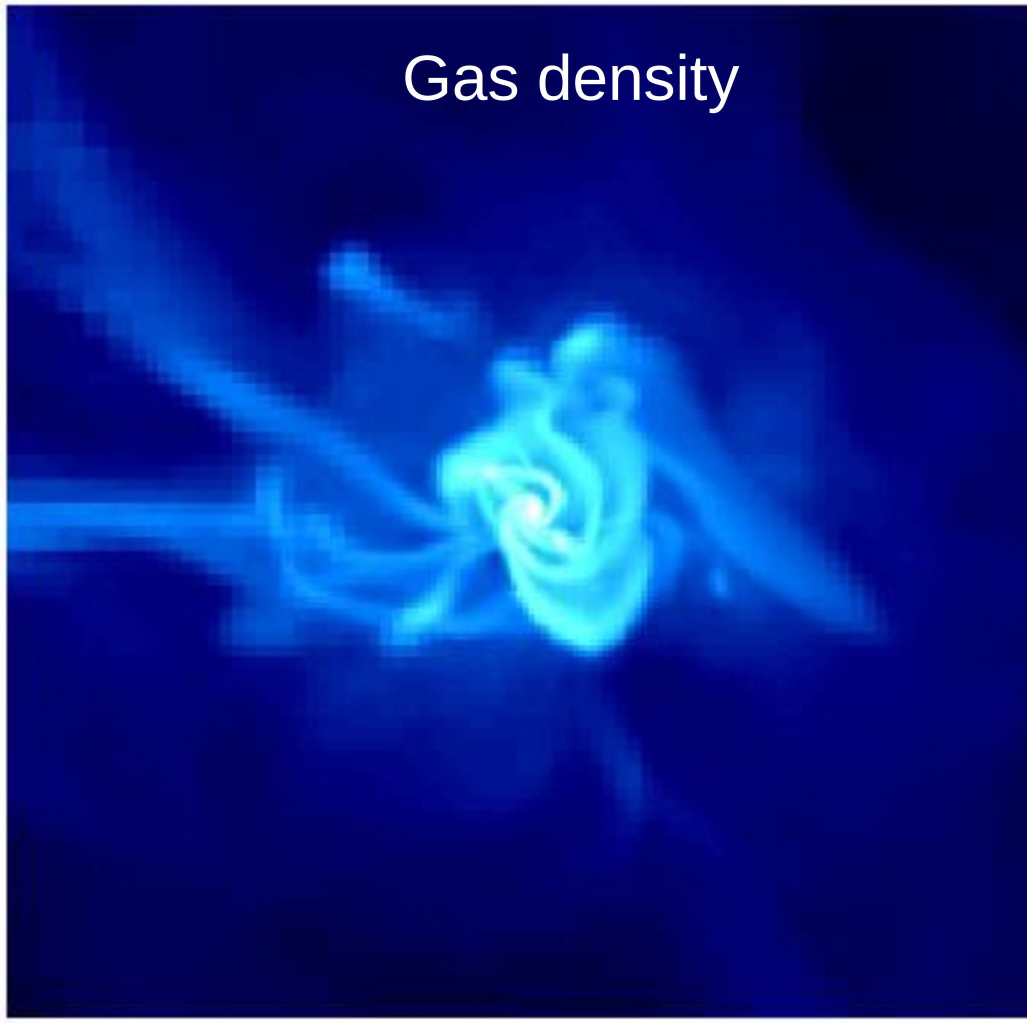
10Mpc: only the central region has high resolution

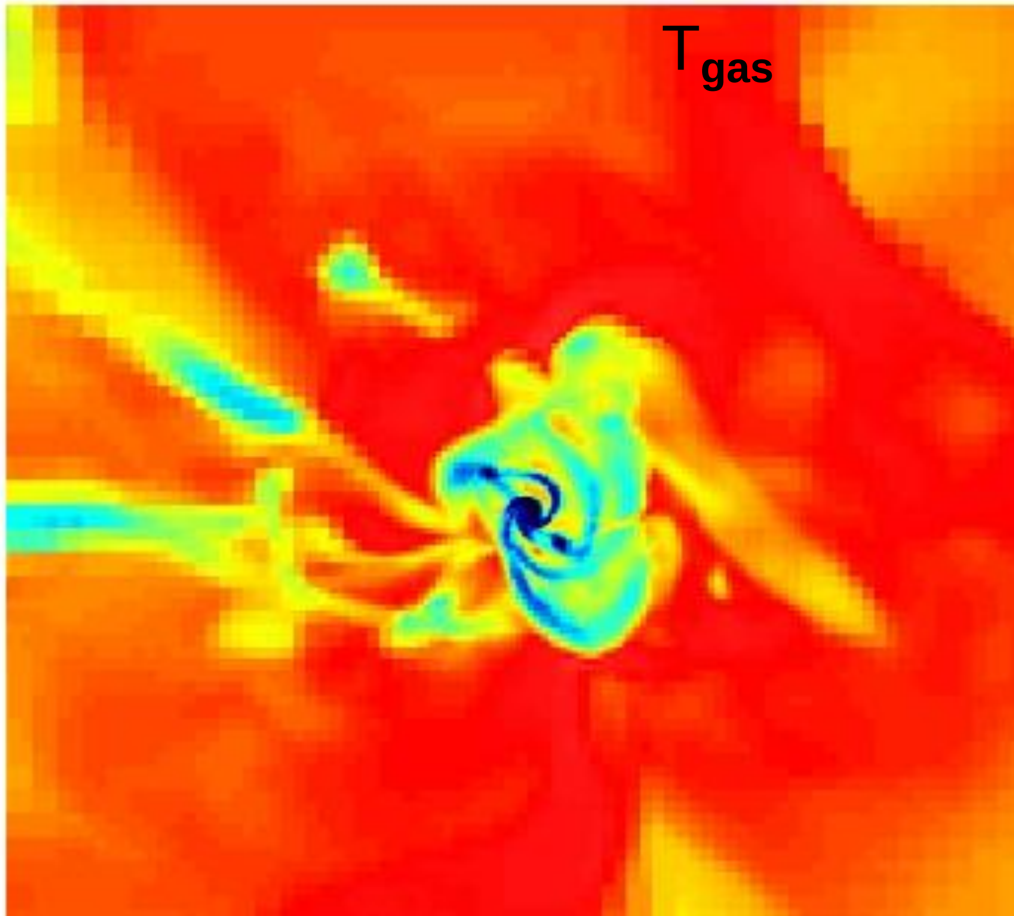
Credits: Kravtsov **100pc resolution Z=4** **100 kpc scale**

To model formation of galaxies we need to deal with "gastrophysics"...

1 Mpc scale







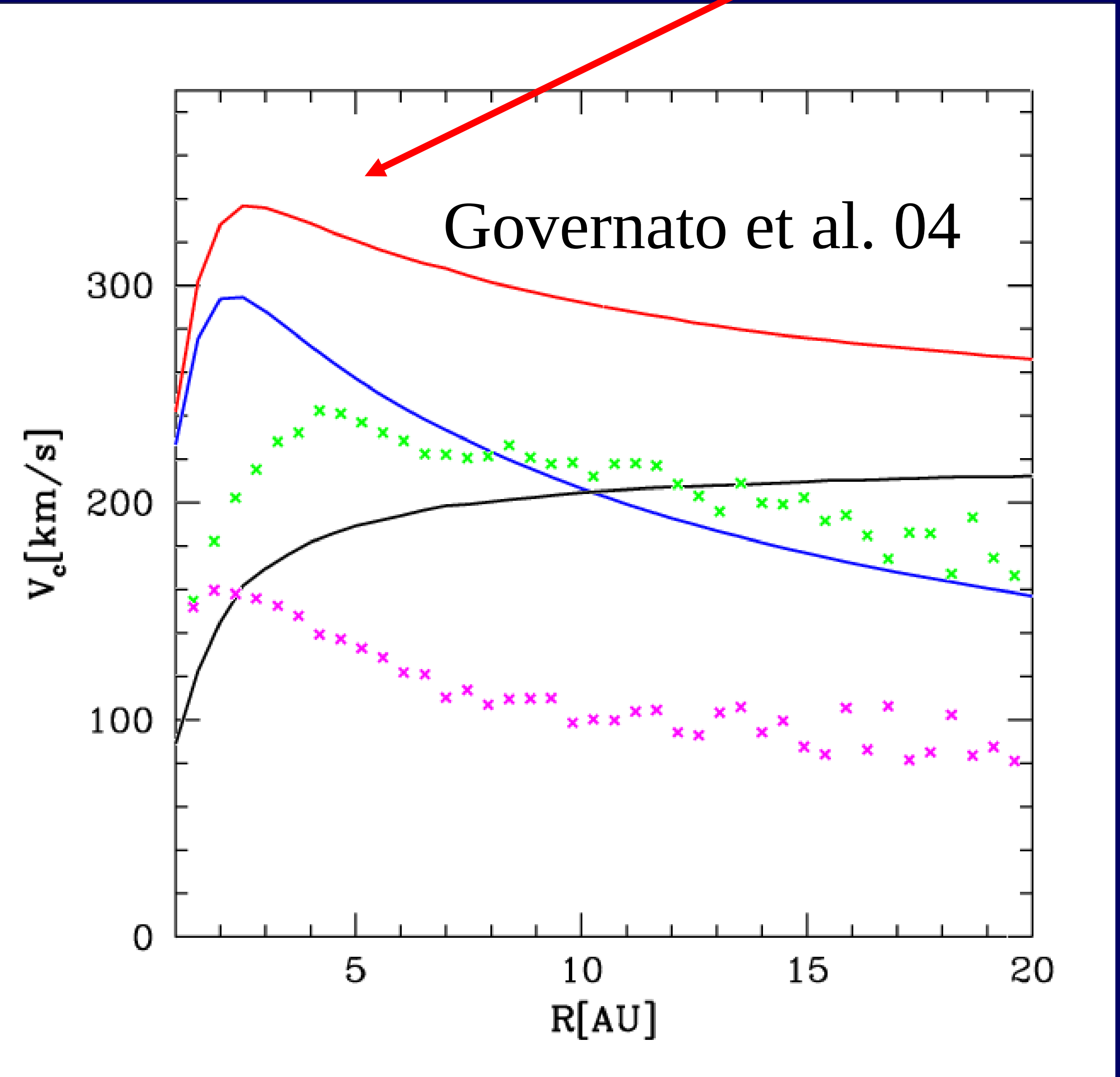
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

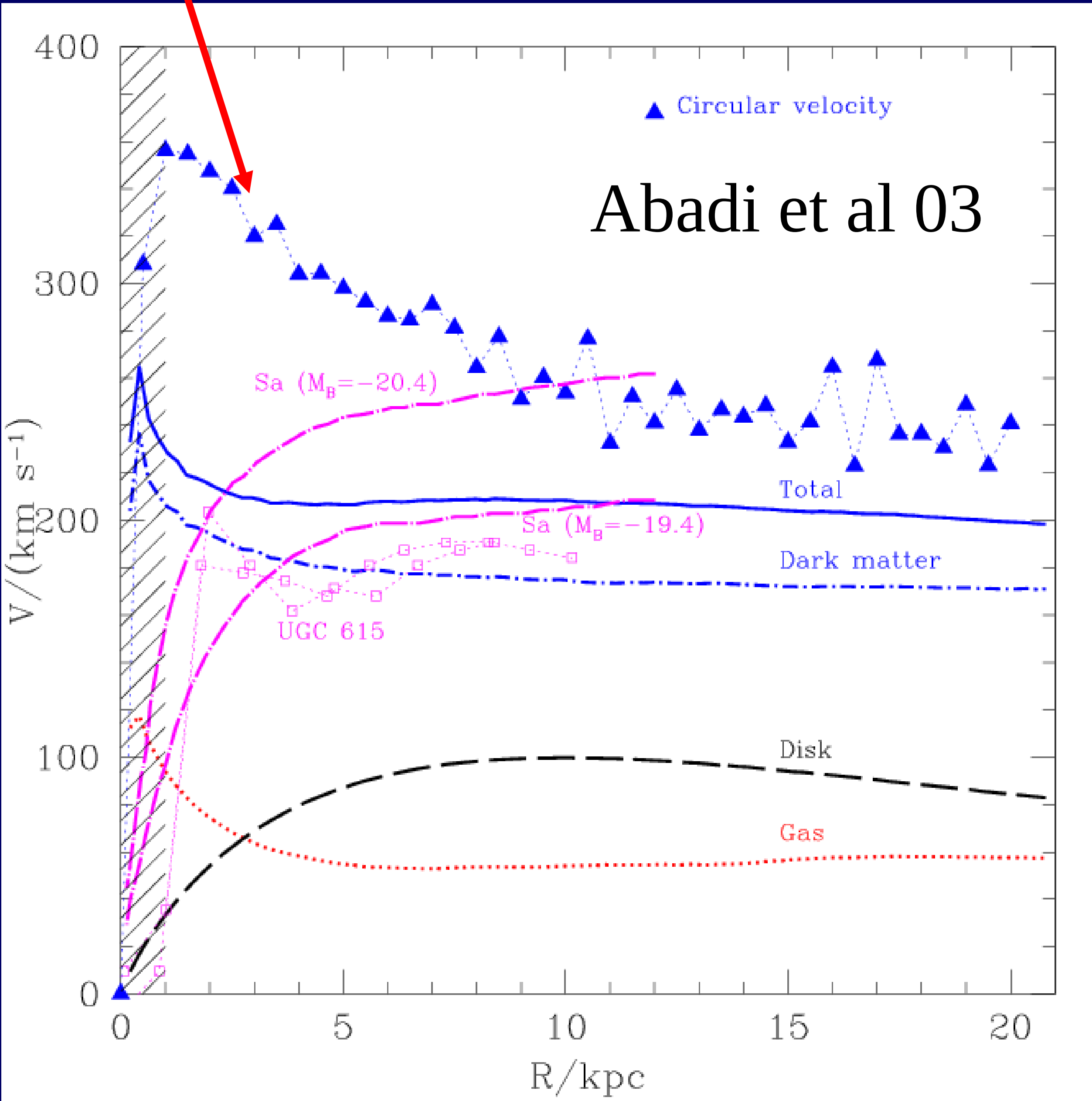
Galaxies too concentrated. Bulge/Disk 1:3 or higher.

Governato

3 10^12 solar

8 10^11 solar masses



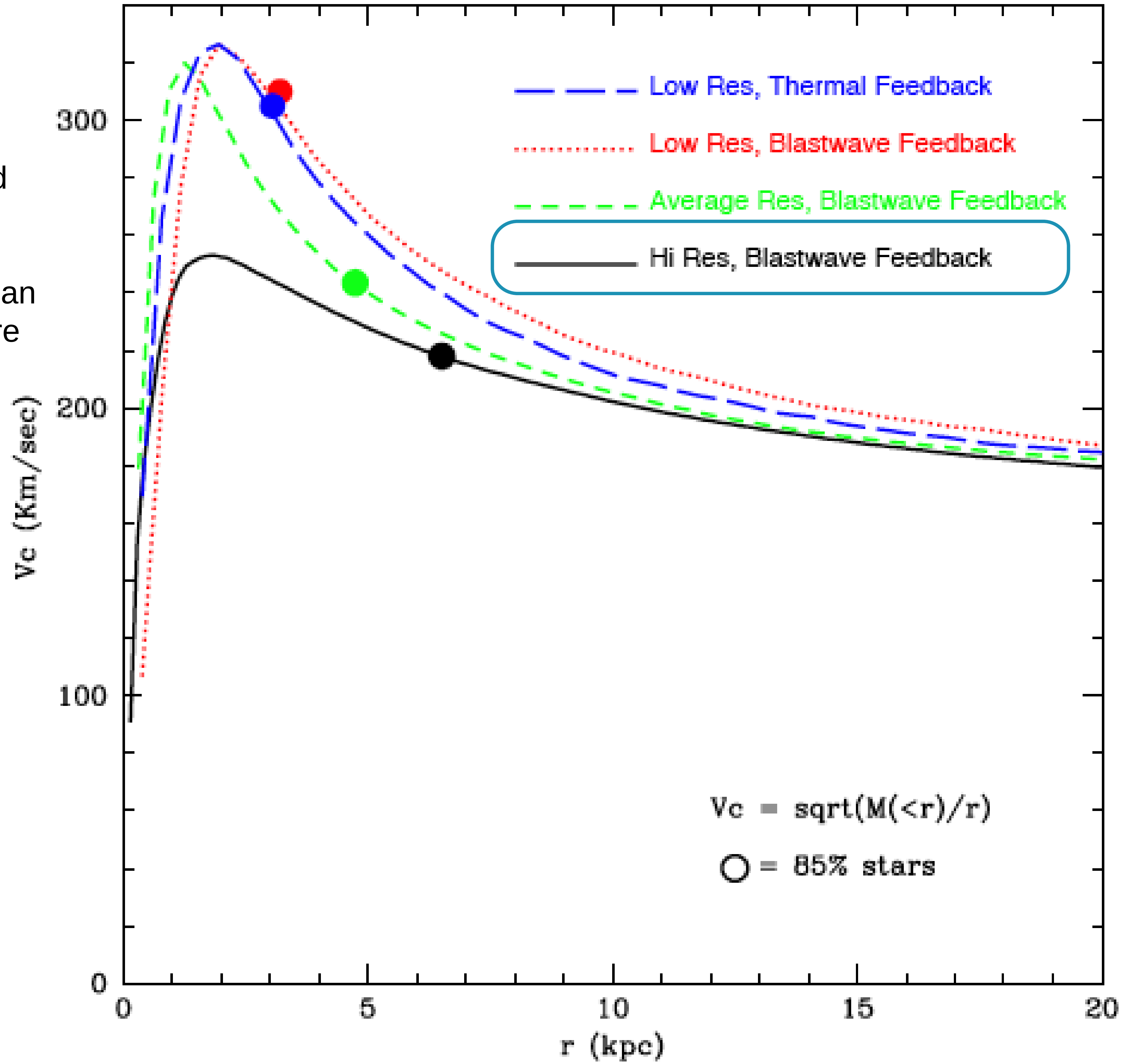


Peak velocity higher than in the real Milky Way. No realistic feedback yet!

Improved resolution and more realistic stellar feedback makes more realistic galaxy models.

Main test: rotation curves should be flat.

Models on the right are better than they used to be, but still there are some defects in the central regions



Governato, Mayer, Brook 2008

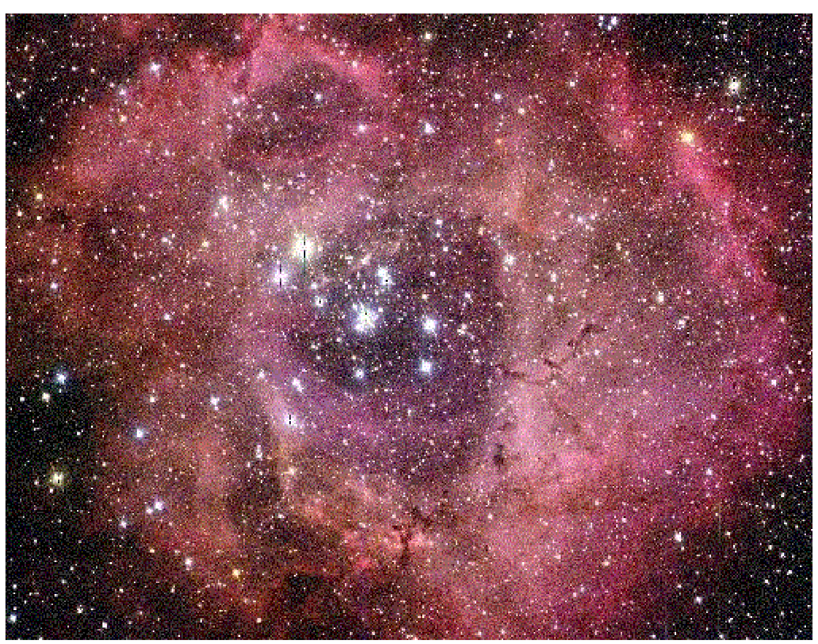
Outflows: physics

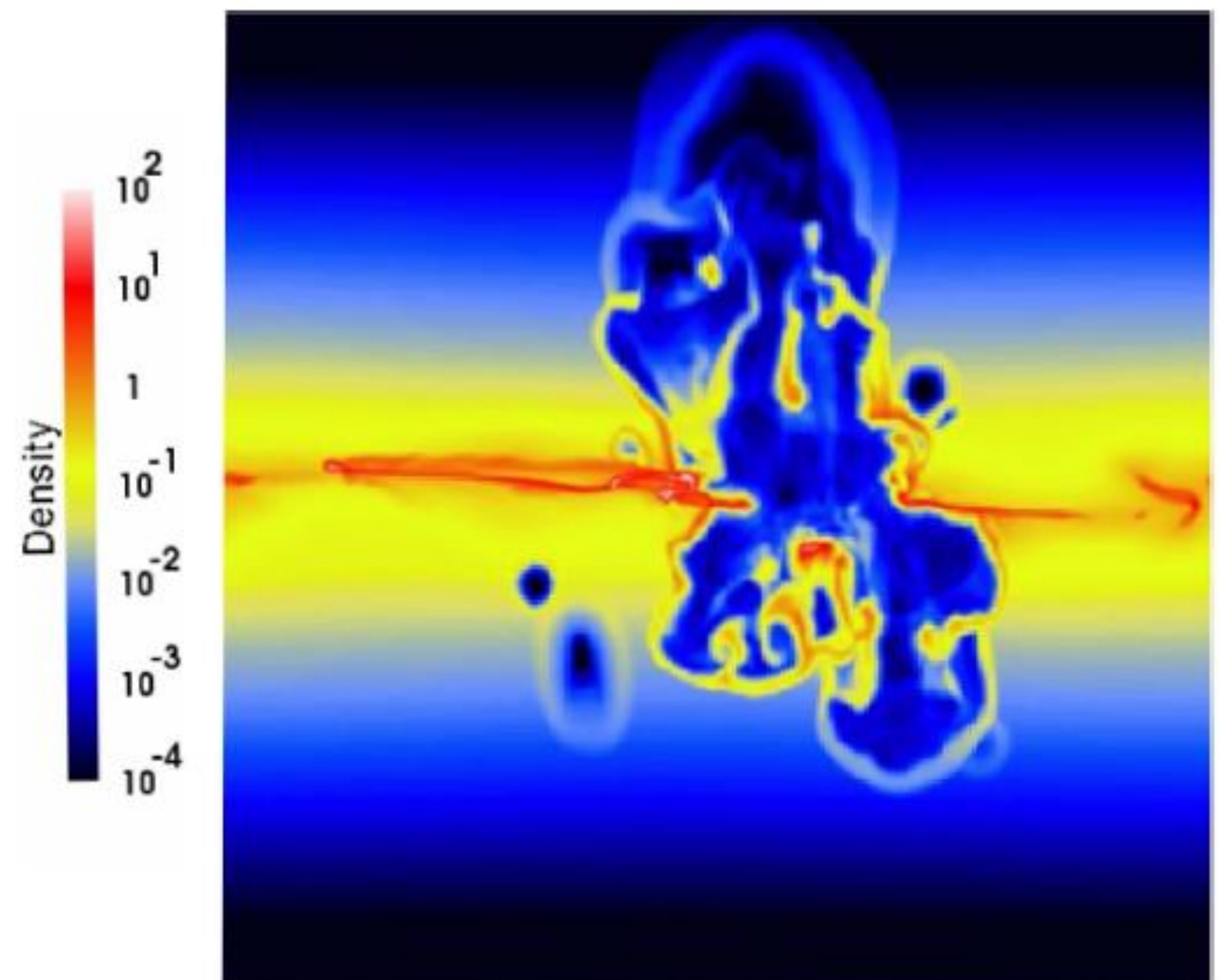
High velocities are not created inside the regions of star formation: rms velocity in molecular clouds is 1-10 km/s

Young stellar cluster -> superbuble -> **accelerated shock**

4 kpc

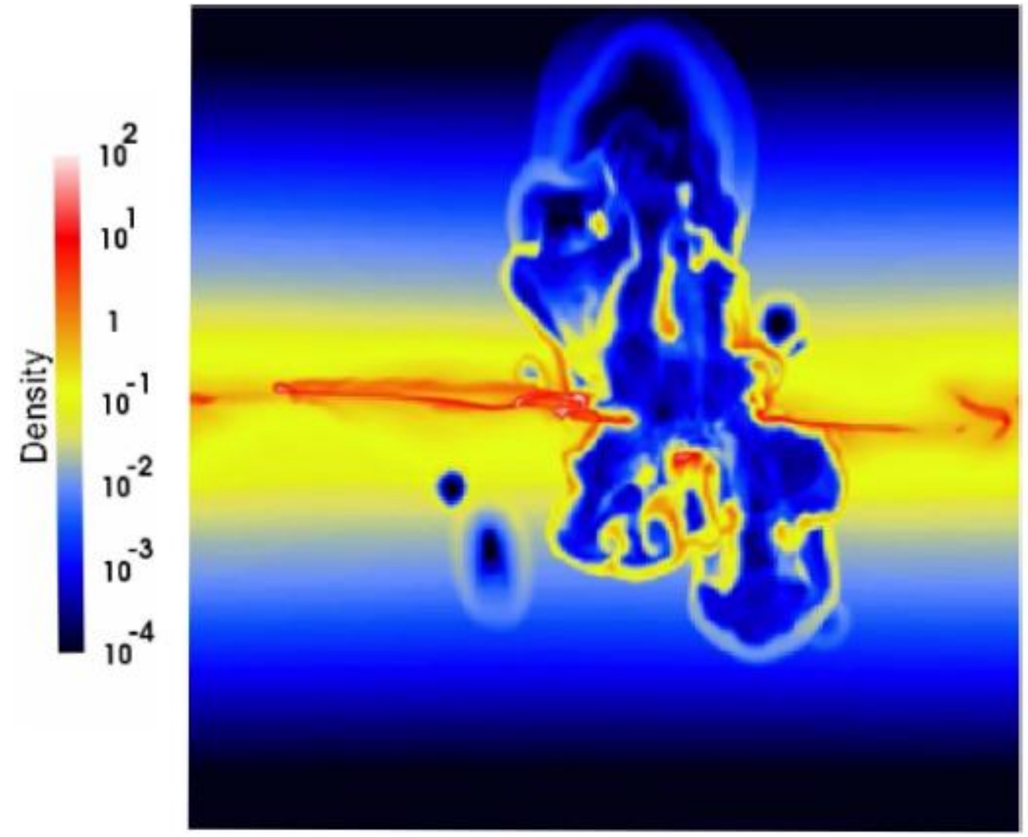
10 pc



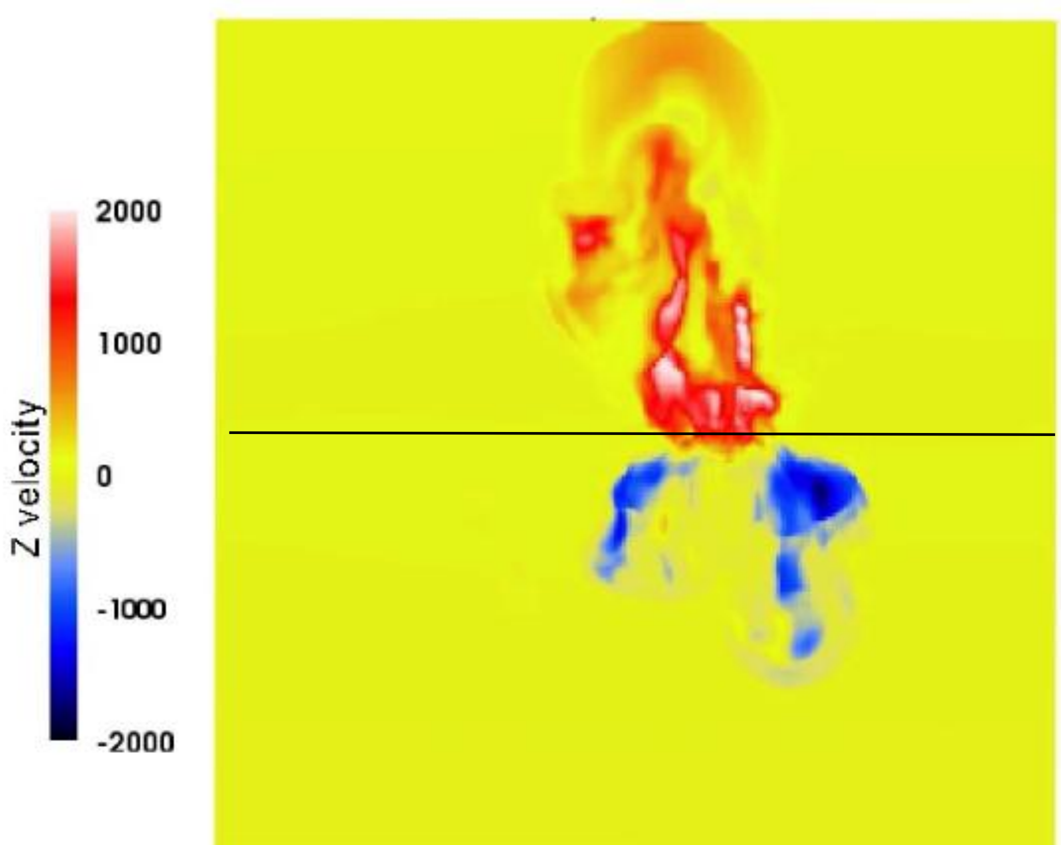


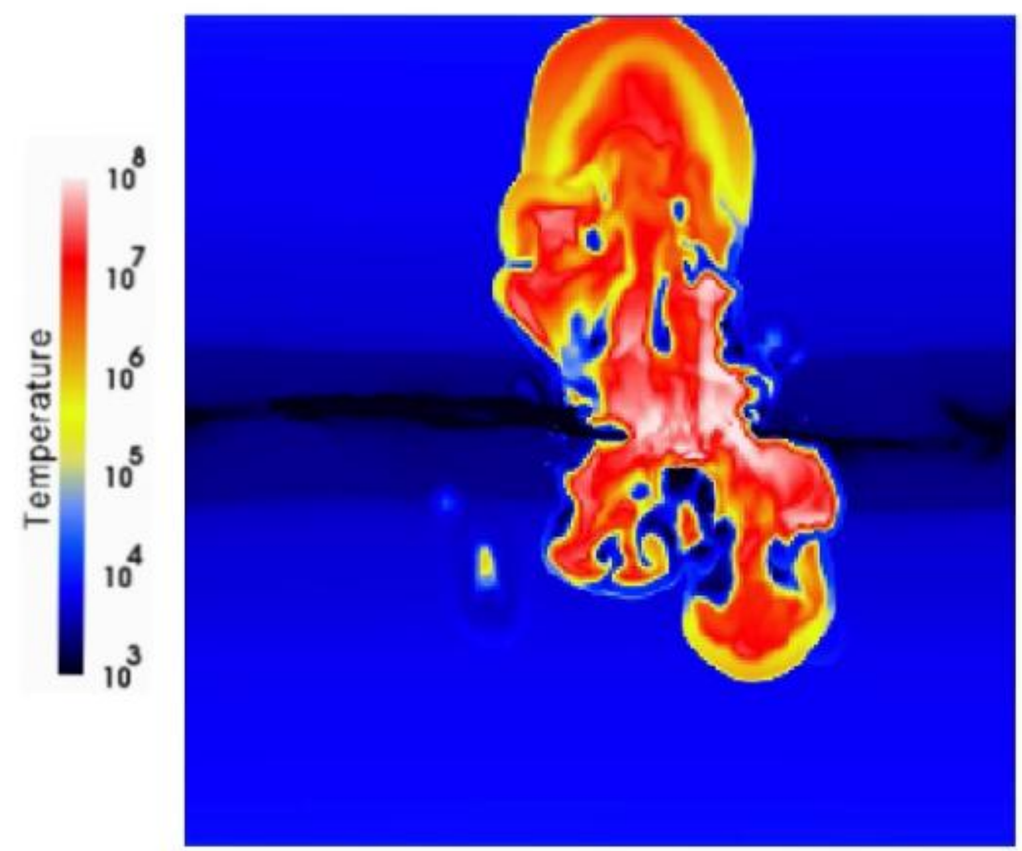
Modeling ISM: 12 pc resolution

Early stages of evolution: first star cluster dumps its energy



Wave accelerates on declining density

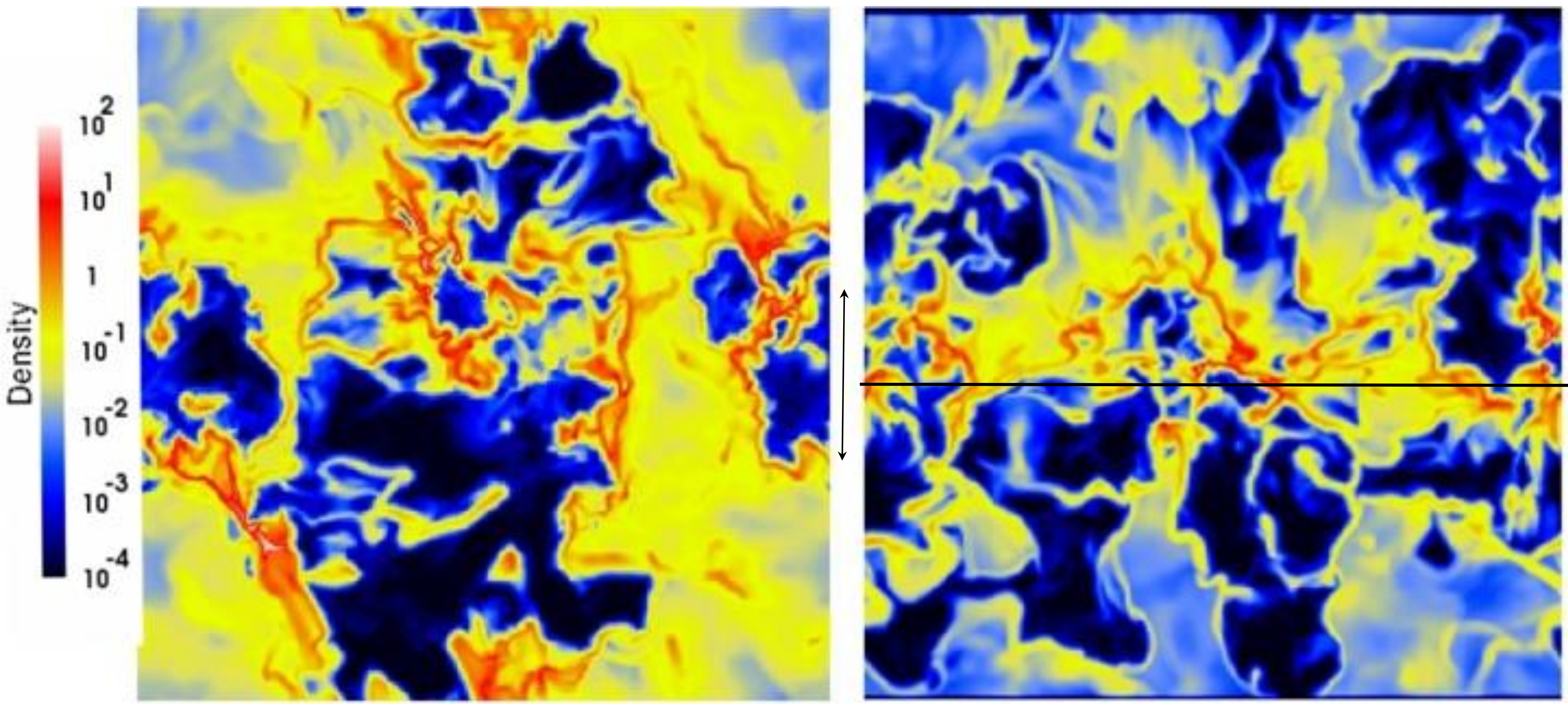




4 kpc. 12pc resolution Ceverino & Klypin 2007

Simulations of a Fragment of ISM Thin slices

Plane of disk 1 kpc Orthogonal to the Disk plane



Tasker & Bryan 2008: Isolated MW. 50 pc resolution 210 kpc

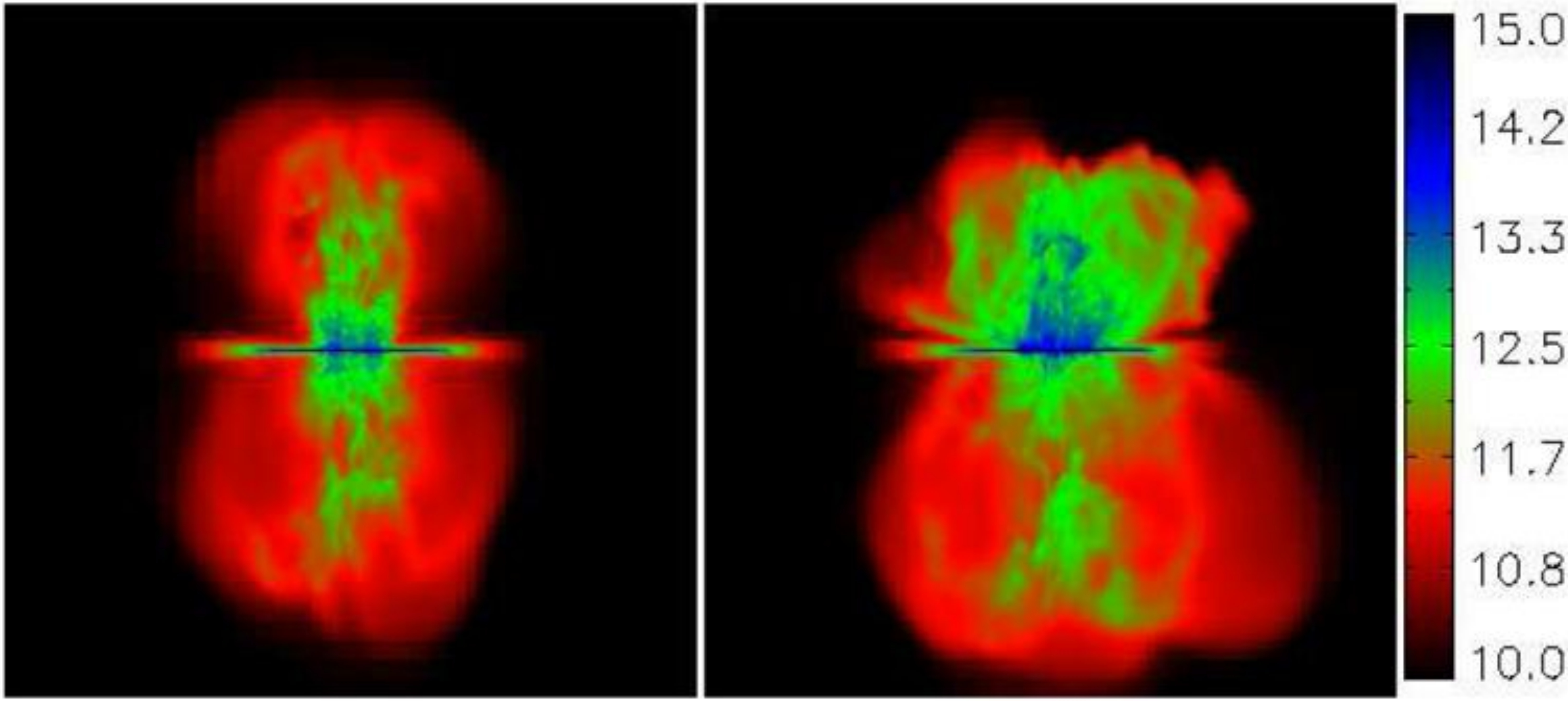


FIG. 4.— Edge-on projections of the baryon density in the CFDBCK and DFDBCK simulations after 142 Myrs. Images are $\sim$ 210 kpc across. Both simulations include feedback and radiative cooling, but the left-hand image (CFDBCK) has a low density cut-off and low efficiency for star formation whereas the right-hand image shows the disk with a high density cut-off and high star formation efficiency.

ISM and galaxy formation

- Efficiency of star formation: mass consumption should be low
- Efficiency of star formation: energy release should be high
- Angular momentum: flat rotation curves + thin stellar disks
- Observed vis. modeled Outflows of gas from galaxies: velocities, metallicites, QSO absorption lines

Implementation of different physical processes

Ceverino & Klypin 2007

Kravtsov's ART hydro code: Physical processes included:

- AMR shock capturing hydro
- metallicity-dependent cooling + UV heating (Haardt & Madau). CLOUDY. Compton cooling
- Temperature range for cooling: 10^2K -10^8K
- Jeans length resolved with 4 cells
- Energy release from stellar winds+ SNII +SNI
- Thermal feedback: most * form at T< 1000K n>10cm^{-3}
- Runaway stars: massive stars move with exp(-v/17km/s)

$$\frac{d\rho_{*,\mathrm{young}}}{dt} = \frac{\rho_{\mathrm{gas}}}{\tau}$$

τ=2-20 Myrs

Effective τ=150-1000 Myrs

Mass consumption rate per free-fall time averaged over gas "molecular" gas (n>30cm^{-3}) is 0.03

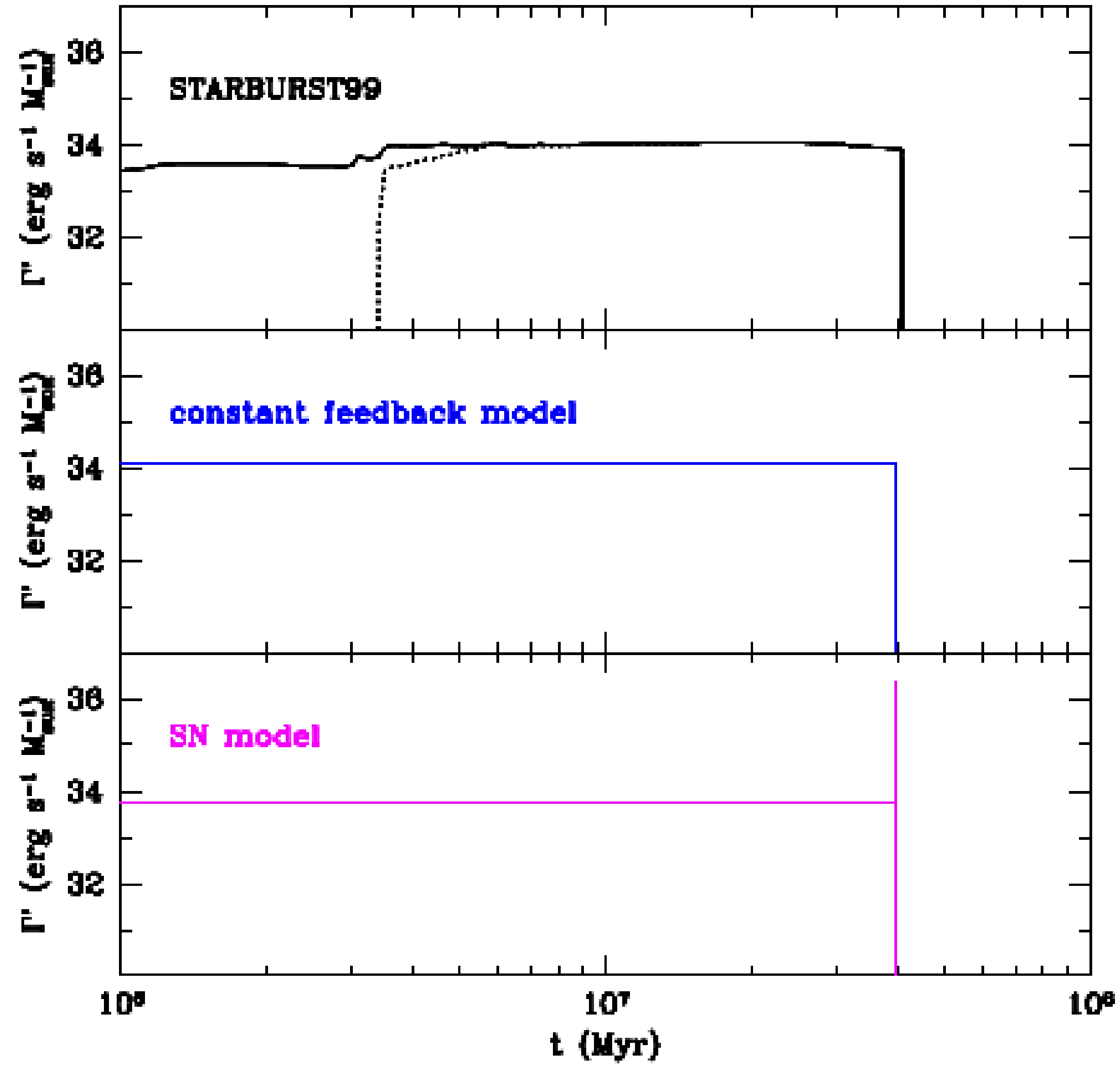


Fig. 1.— Rate of energy losses per unit mass from a single stellar population. Top panel shows the results from the STARBURST99 code, assuming a Miller-Scalo IMF for a mass range $(0.1 - 100)$ $M_{\odot}$.

Cosmology: formation of MW galaxy

z=3.5 Major progenitor. 45 pc resolution

Face-on view SFR =10Msun/year

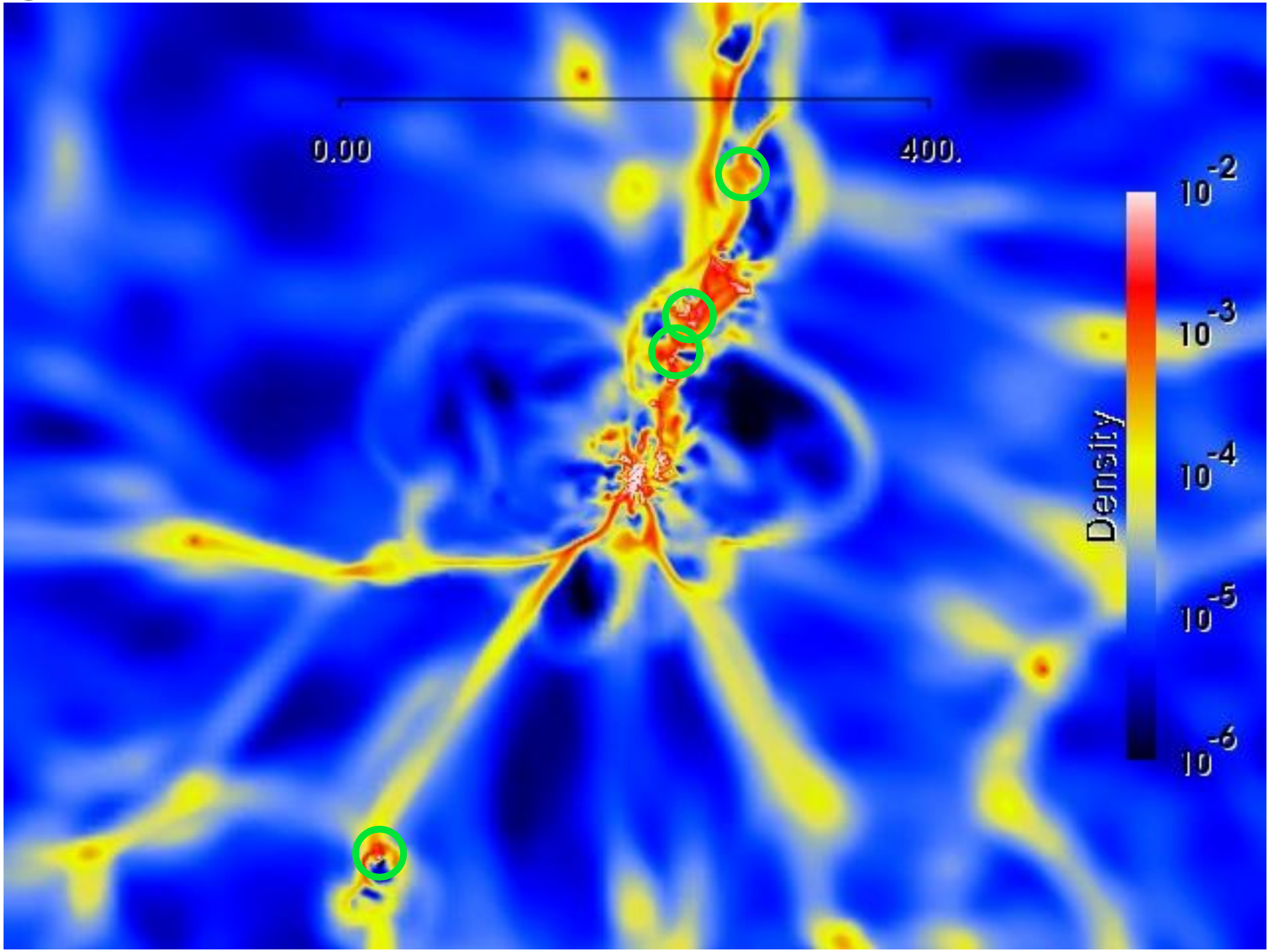
Ceverino & Klypin 2007

ART N-body+hydro code (Kravtsov)

400 kpc proper

Cold Flow regime

Slice of gas density



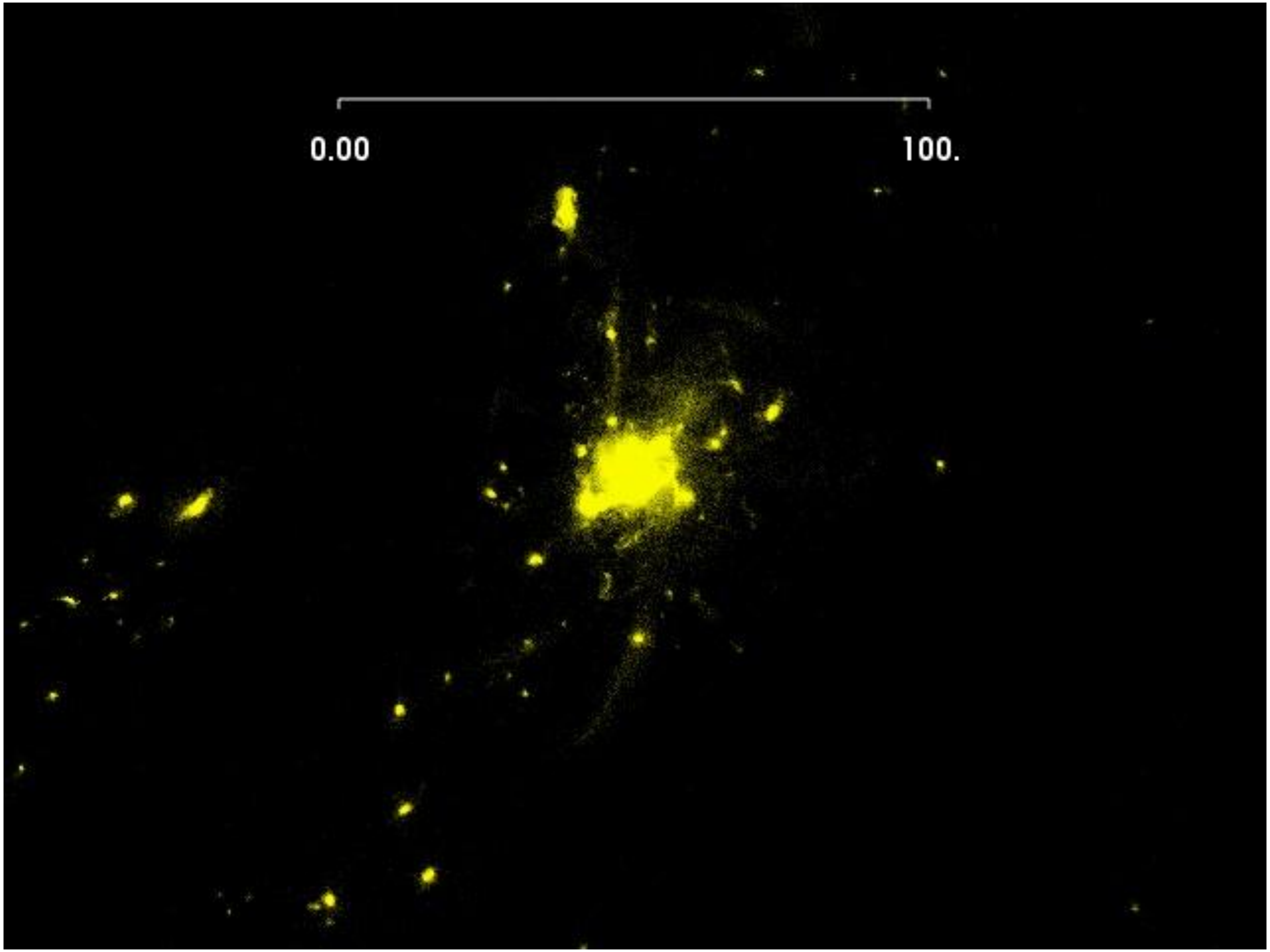
Ceverino & Klypin 2007

z=3.5 Major progenitor of MW. 45 pc resolution

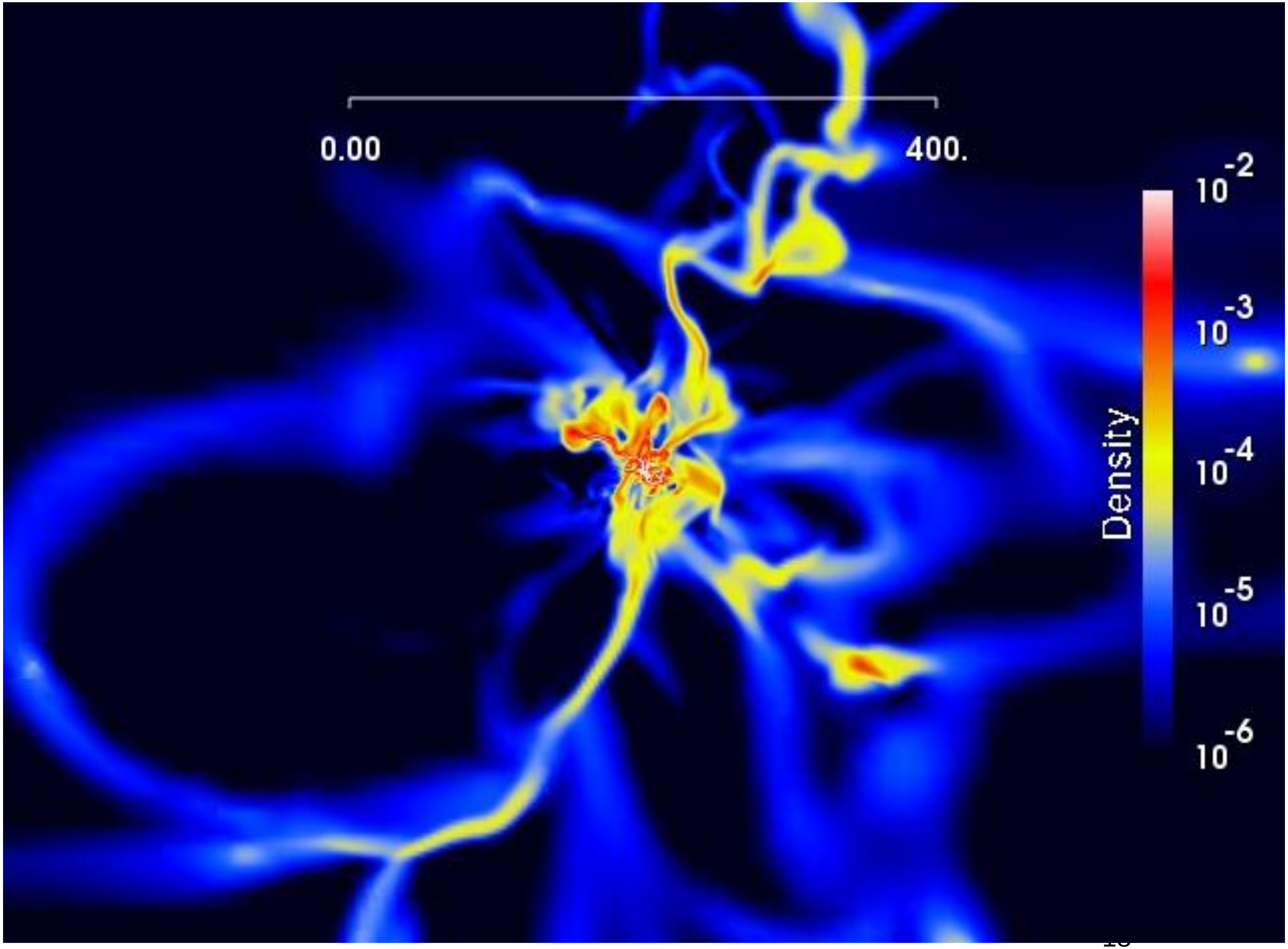
Face-on view

100 kpc proper

Stars



z=1.3 Major progenitor of MW. 45 pc resolution Face-on view



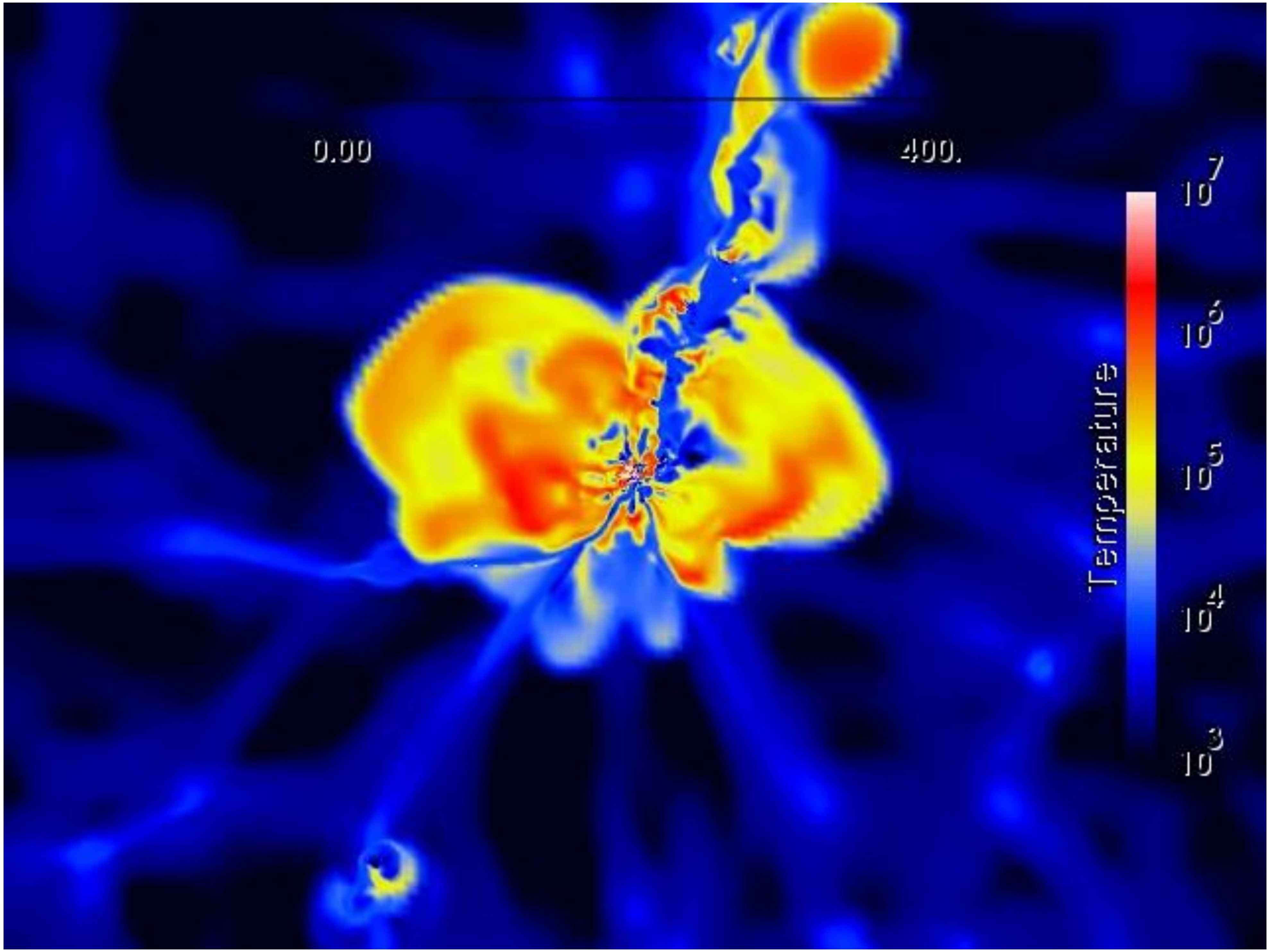
Ceverino & Klypin 2007

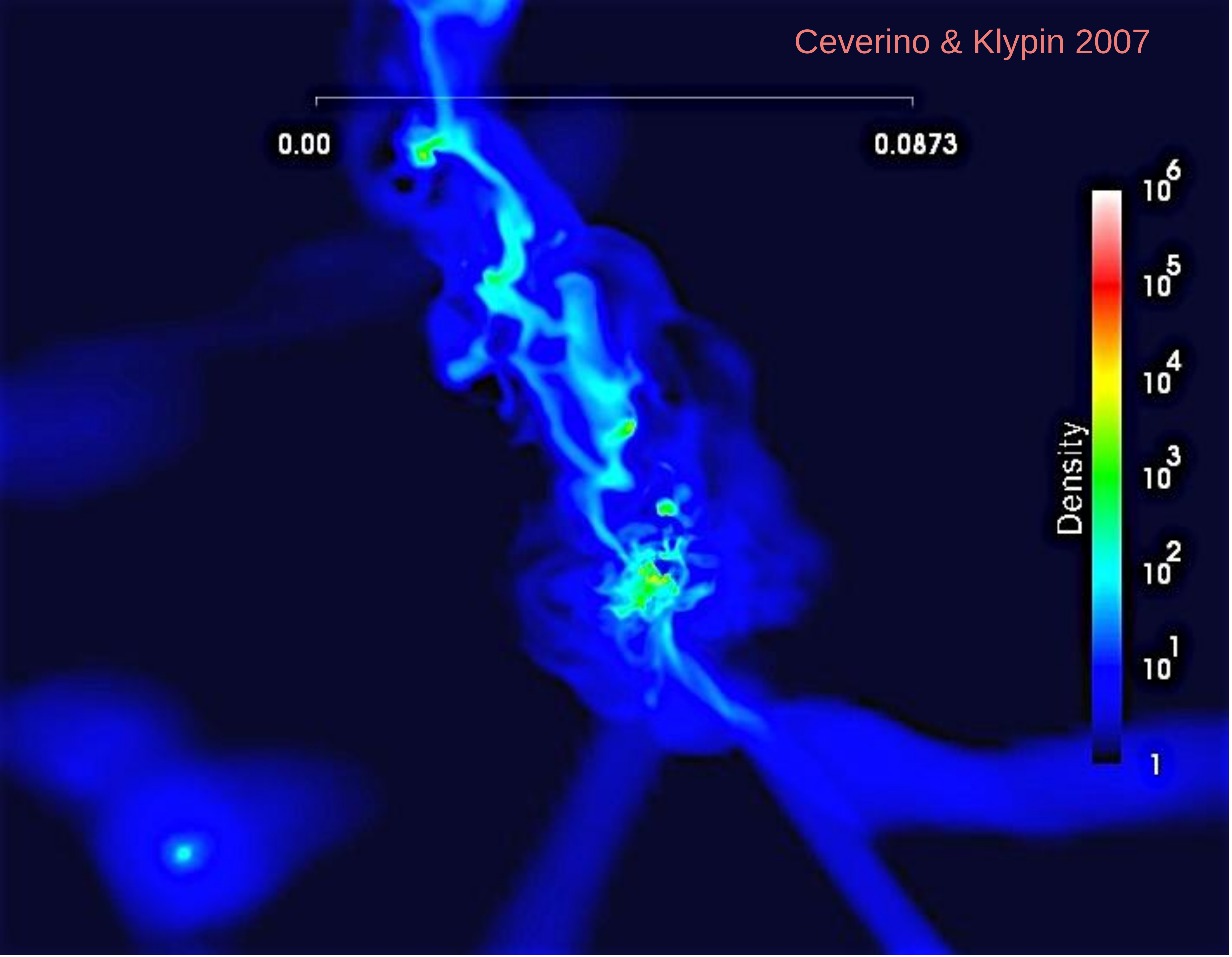
z=3.5 Major progenitor of MW. 45 pc resolution
Face-on view

400 kpc proper

Cold Flow regime

Slice of
temperature





350kpc

Z=2.5

40pc resolution. Mvir(z=0)=1.e12Msun. Ndm=400K

Ceverino & Klypin 2007

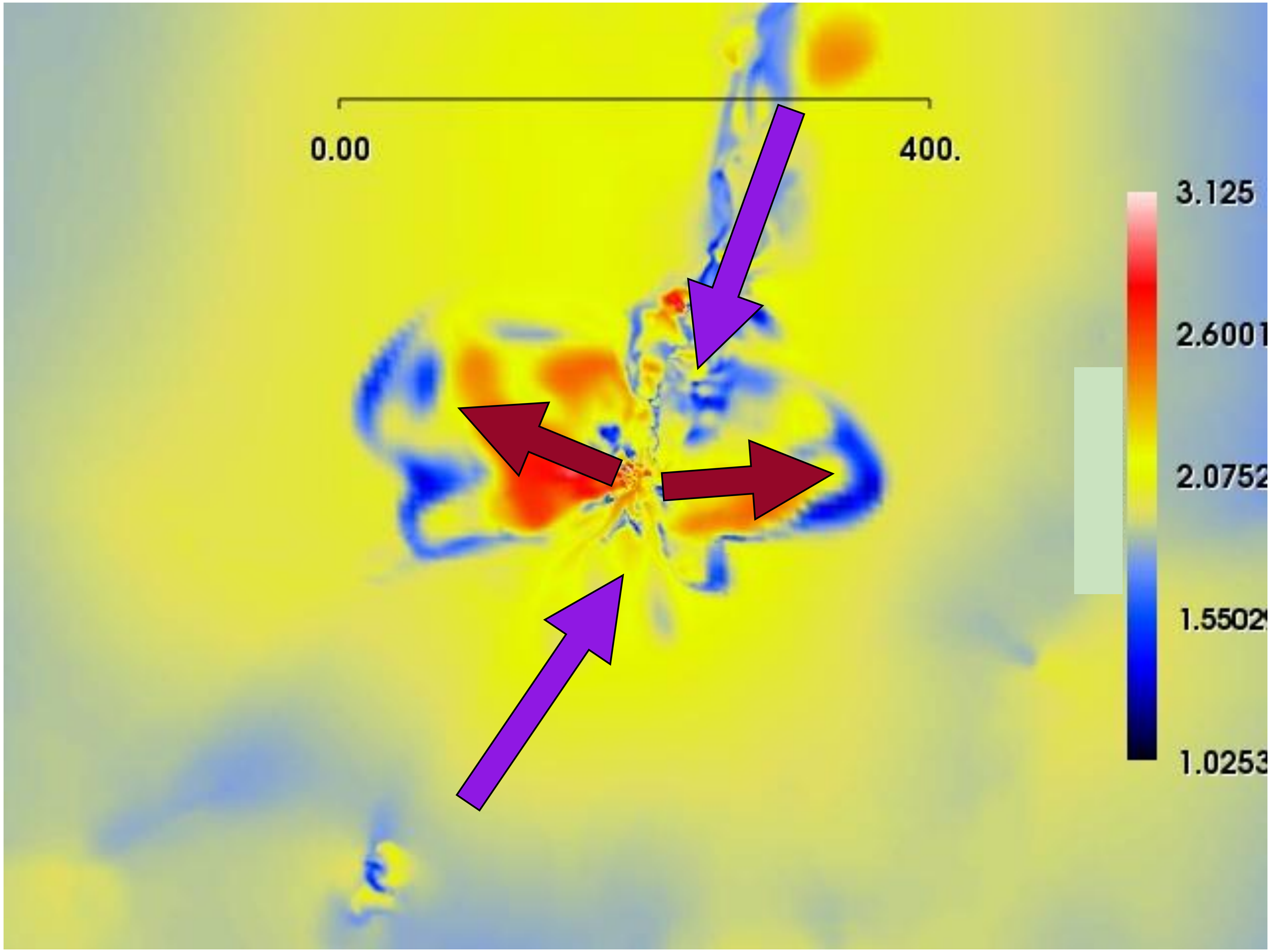
z=3.5 Major progenitor of MW. 45 pc resolution
Face-on view

400 kpc proper

Cold Flow regime

Vmax =1000km/s

Slice of gas velocity:
Log scale in km/s

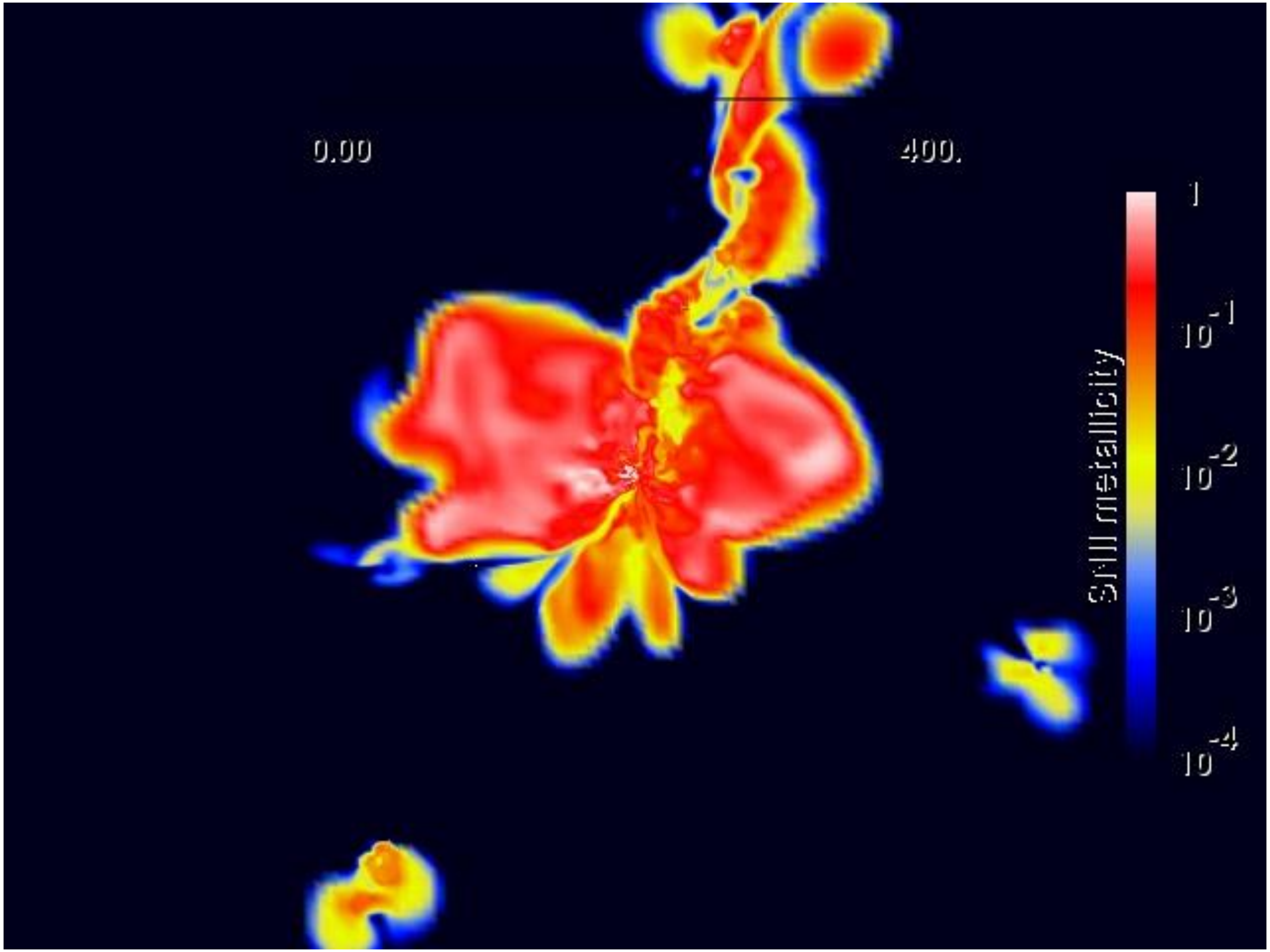


Ceverino & Klypin 2007

z=3.5 Major progenitor of MW. 45 pc resolution
Face-on view

400 kpc proper

Cold Flow regime



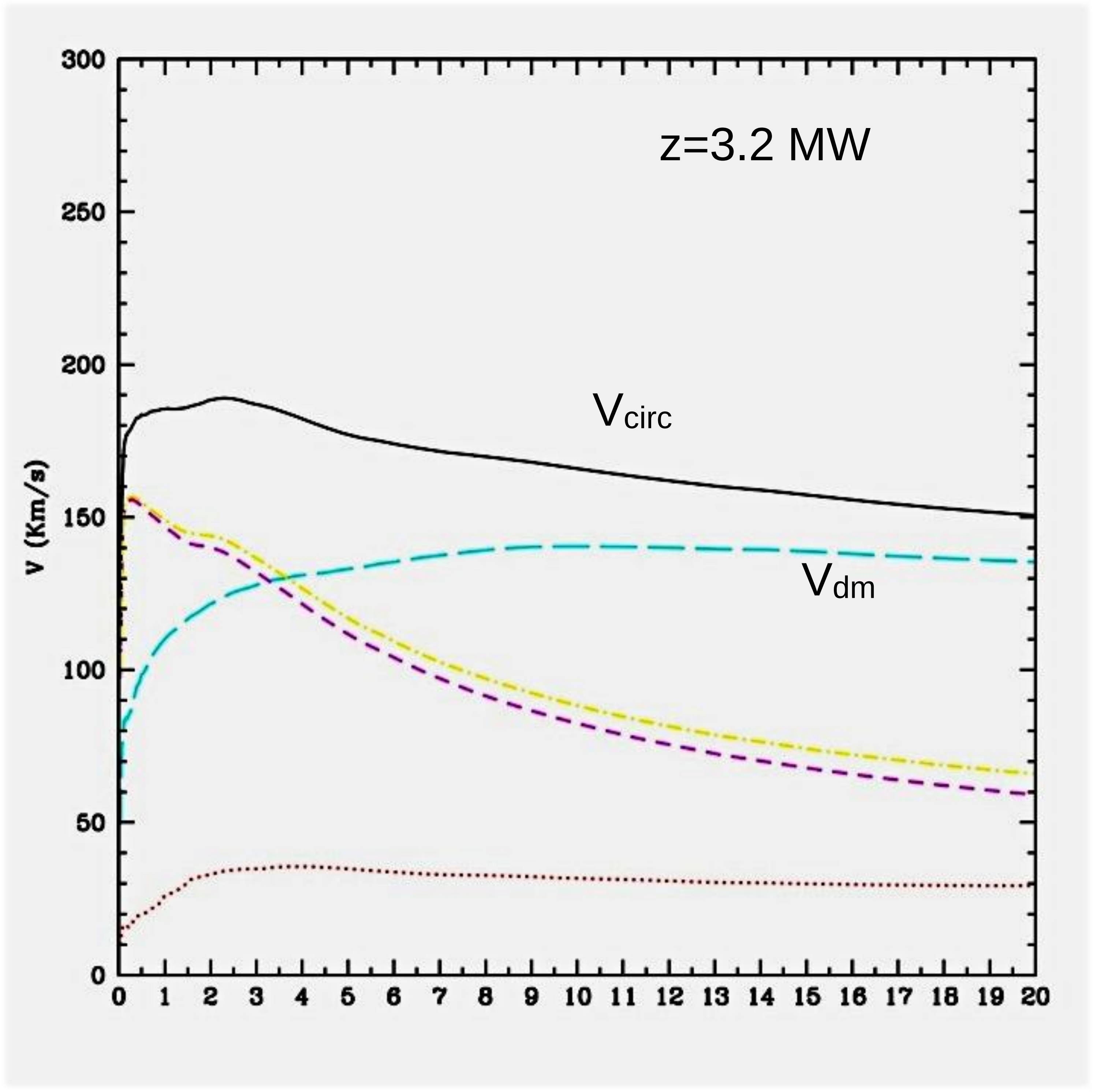
Slice of gas metallicity

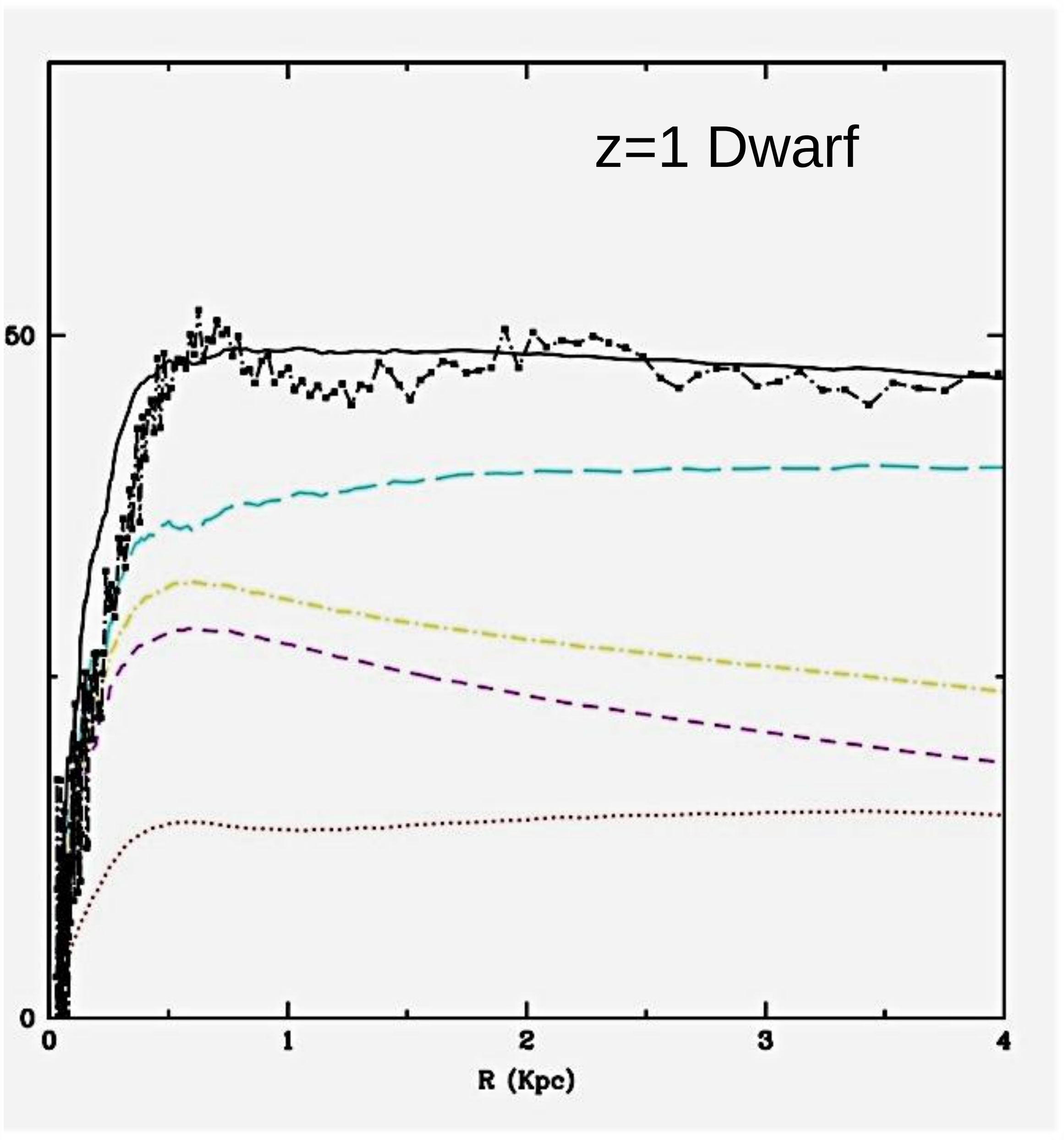
Flat rotation curves are still the most sensitive test for feedback models

Combination of resolution and feedback improves the rotation curves

Ceverino & Klypin 2007

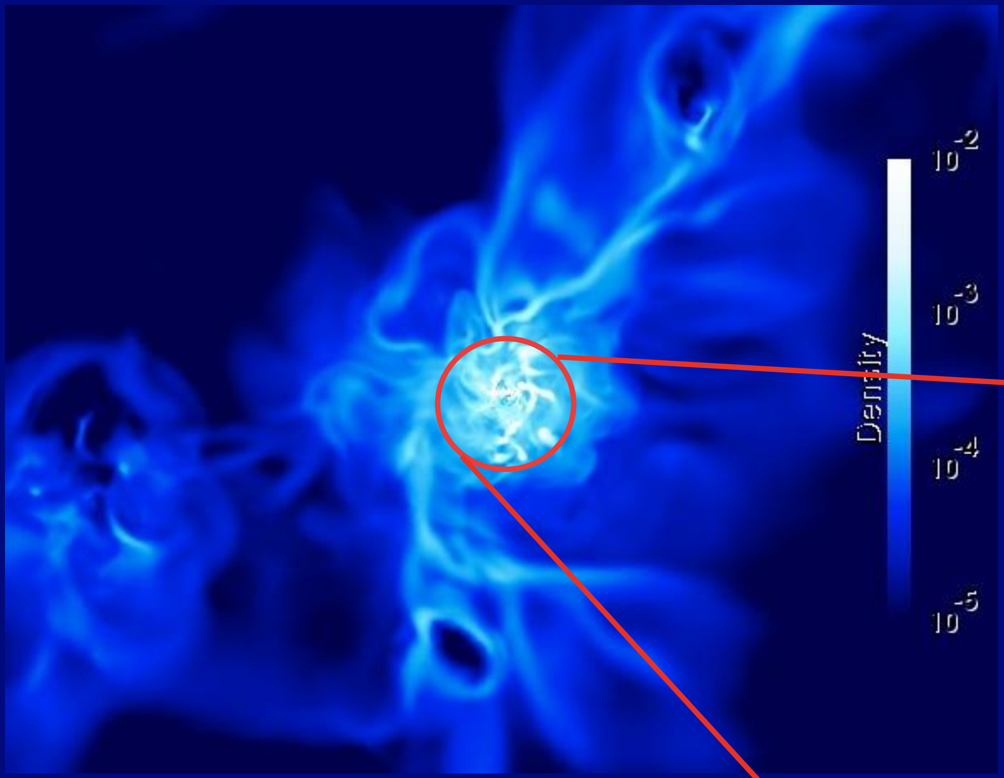
Resolution 45 pc. Thermal stellar feedback + runaway stars



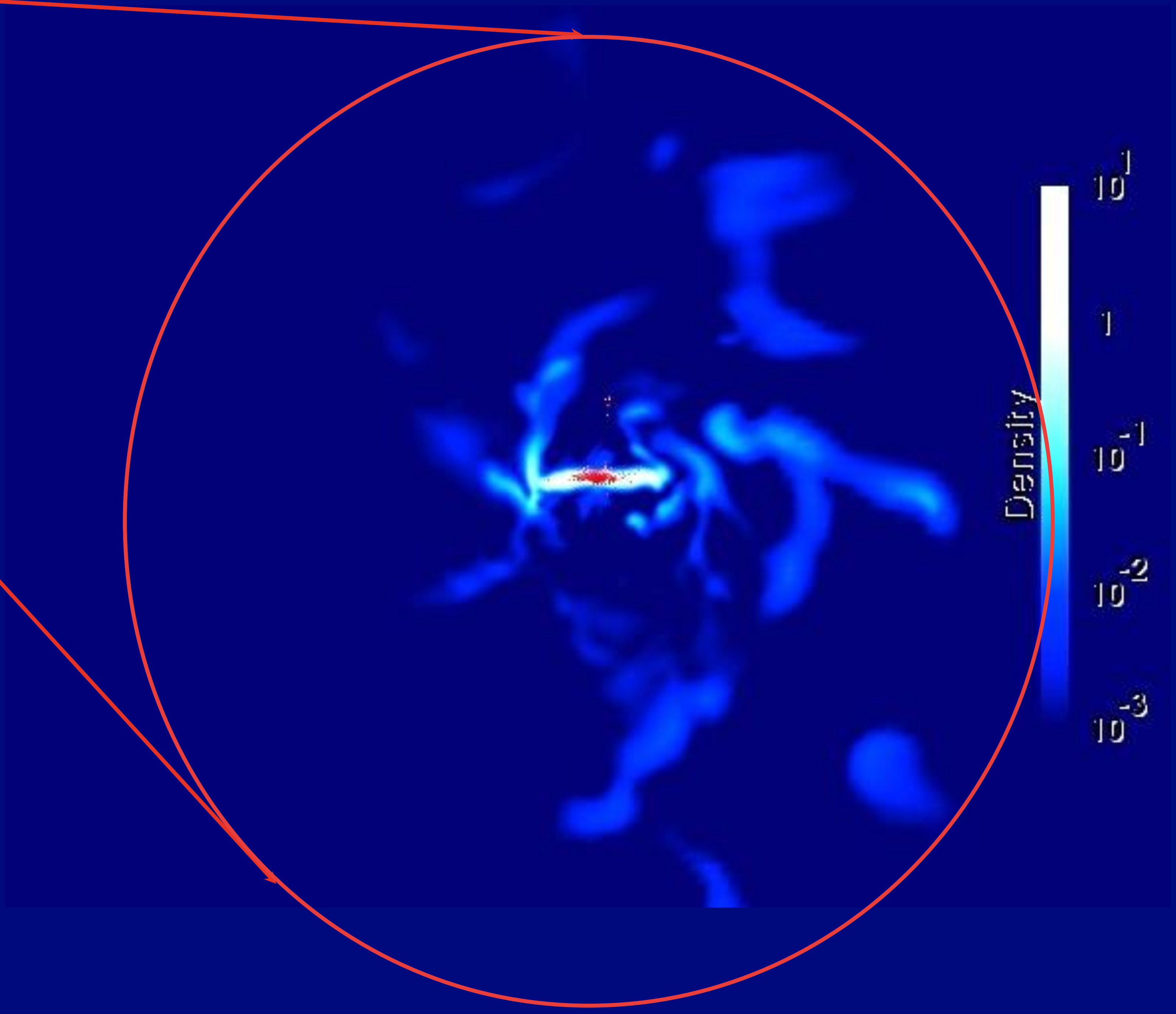


600kpc

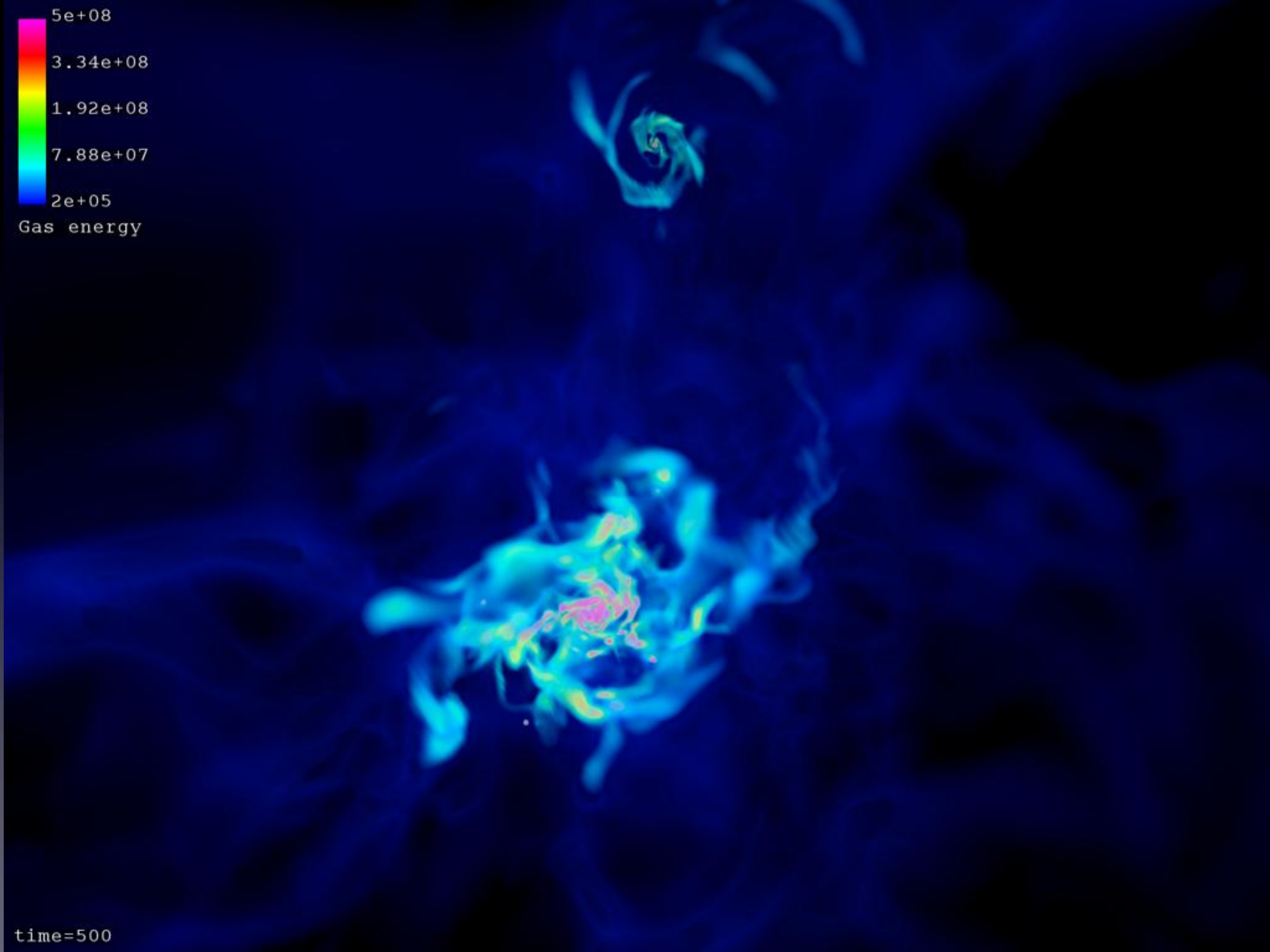
z=1

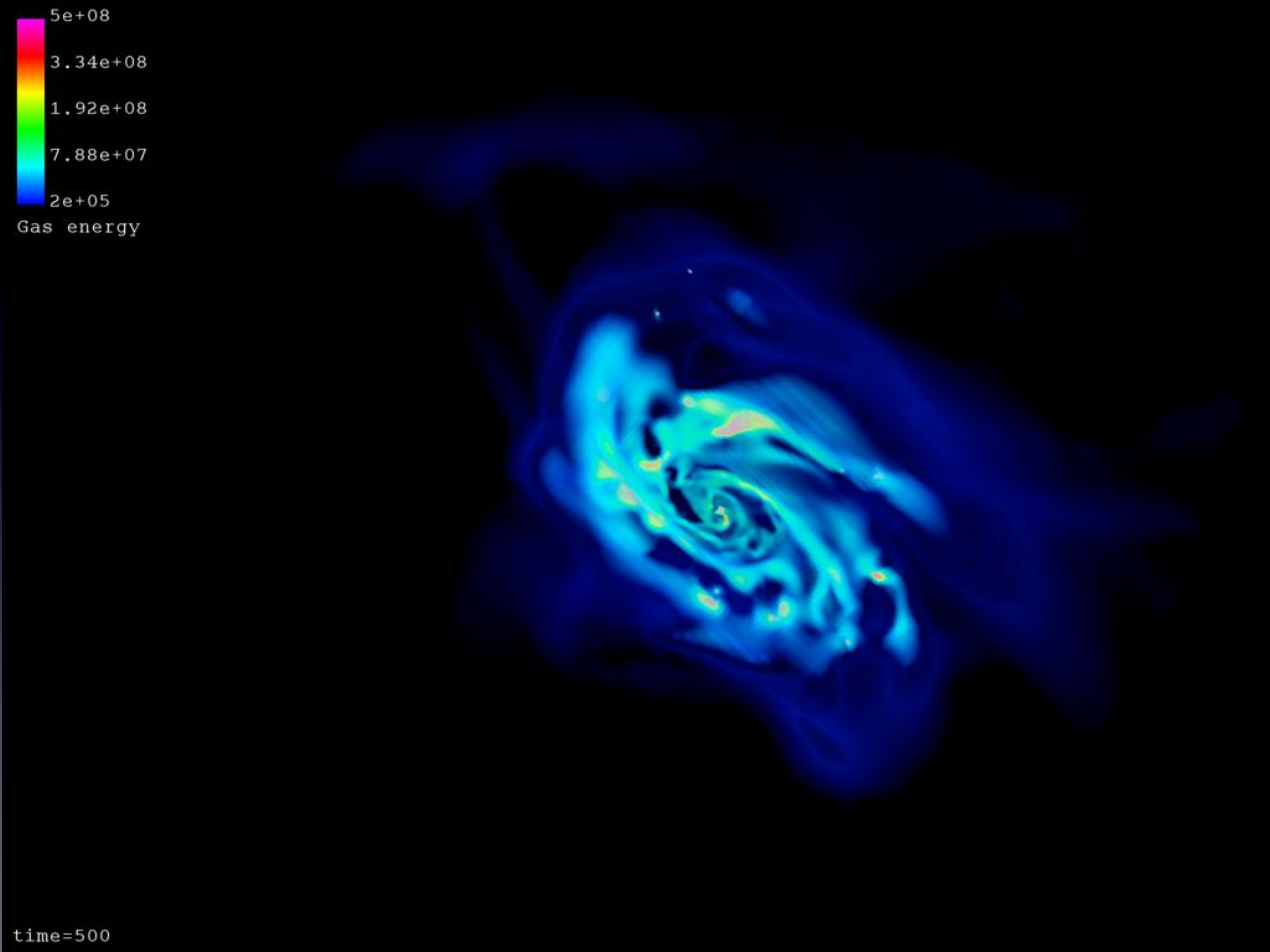


70kpc

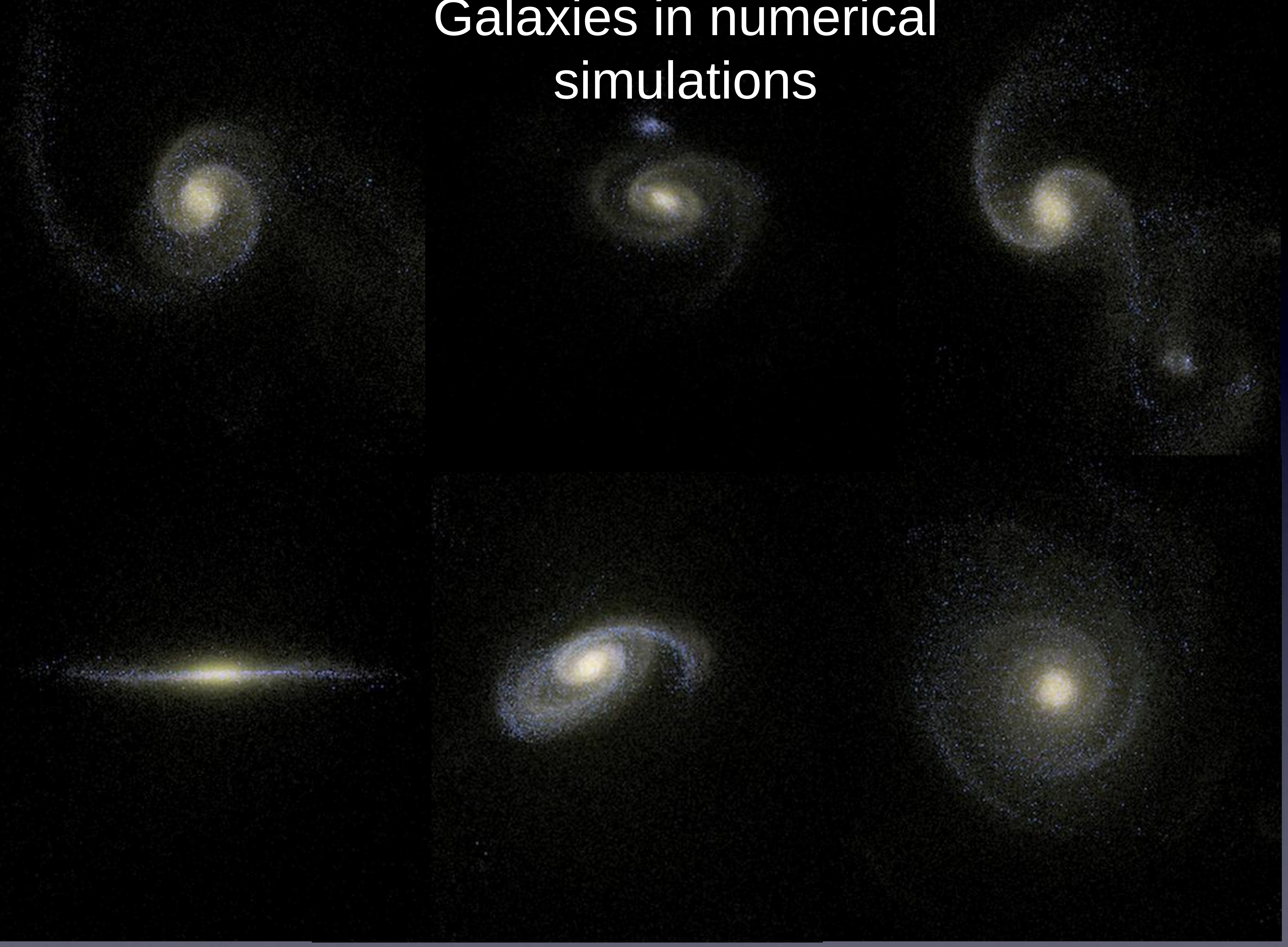


Disk galaxy:
edge-on


5e+08
3.34e+08
1.92e+08
7.88e+07
2e+05
Gas energy
time=500


5e+08
3.34e+08
1.92e+08
7.88e+07
2e+05
Gas energy
time=500

Galaxies in numerical simulations



High-Redshift Clumpy Disks & Bulges in Cosmological Simulations

Daniel Ceverino[1*], Avishai Dekel[1†] and Frederic Bournaud[2‡]

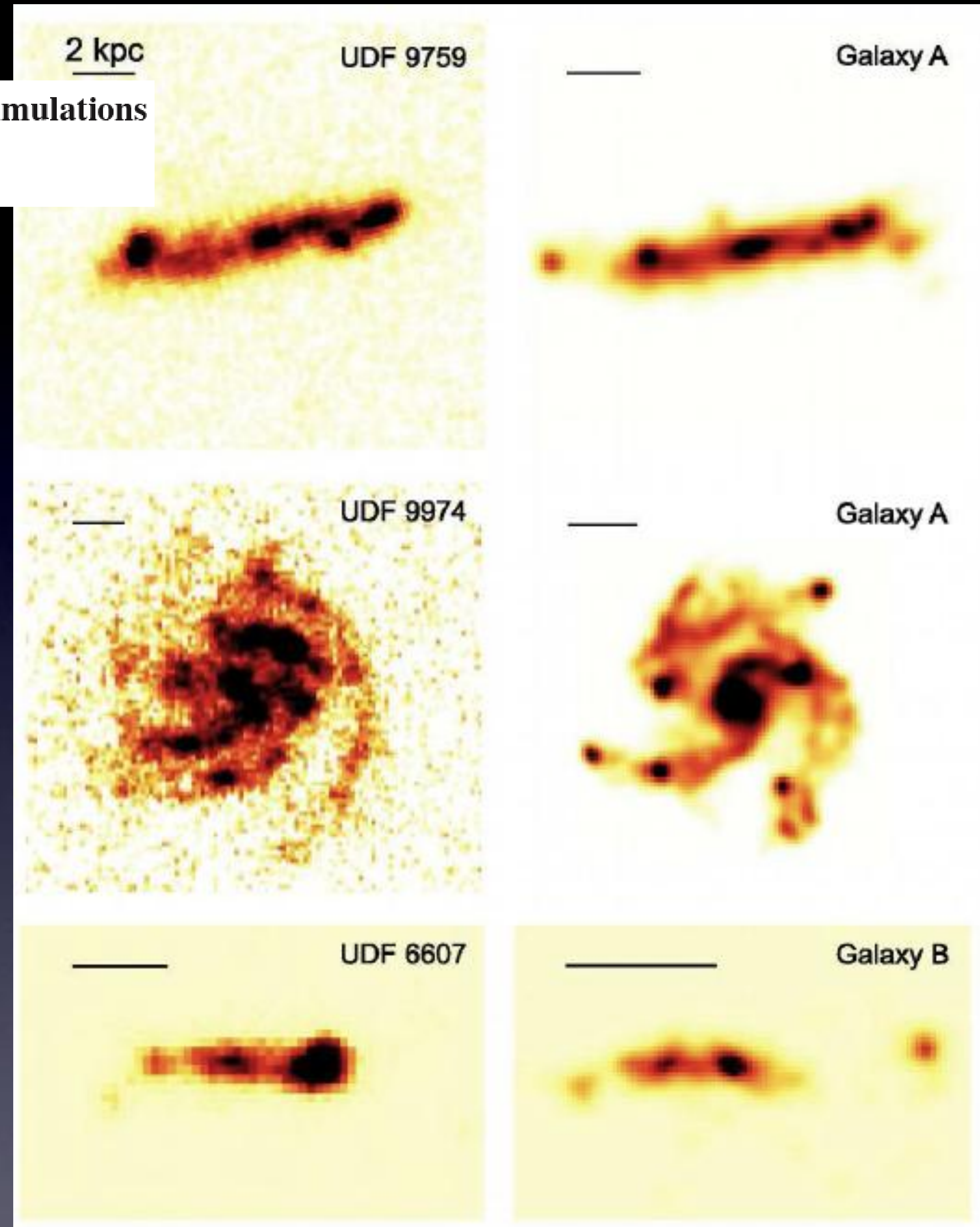


Figure 7. A qualitative comparison of observed and simulated clumpy discs at high redshift. Shown are V-Band images (UV rest-frame) of three galaxies from the Hubble Ultra Deep Field, representing the different appearances of the clumpy disks depending on the viewing angle: a "chain" galaxy (UDF 9974 at $z = 1.3$), a face-on "clump cluster" (UDF 9759 at $z = 1.2$), and a "tadpole" galaxy (UDF 6607 at $z = 1.6$). The simulations are viewed with about the same resolution, using as a proxy for the UV emission the stars younger than 200 Myr (top panel), 100 Myr (medium panel) and 10 Myr (bottom panel). The

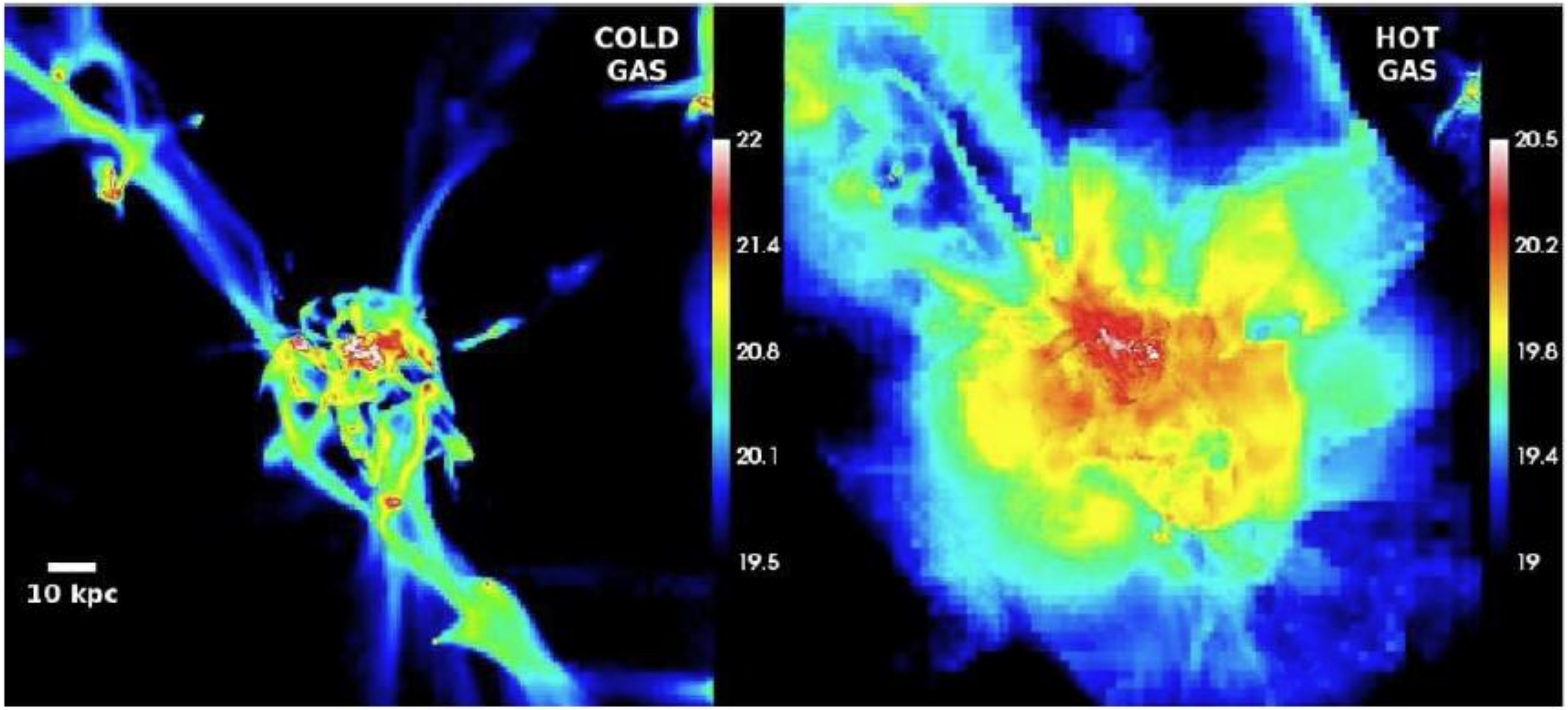
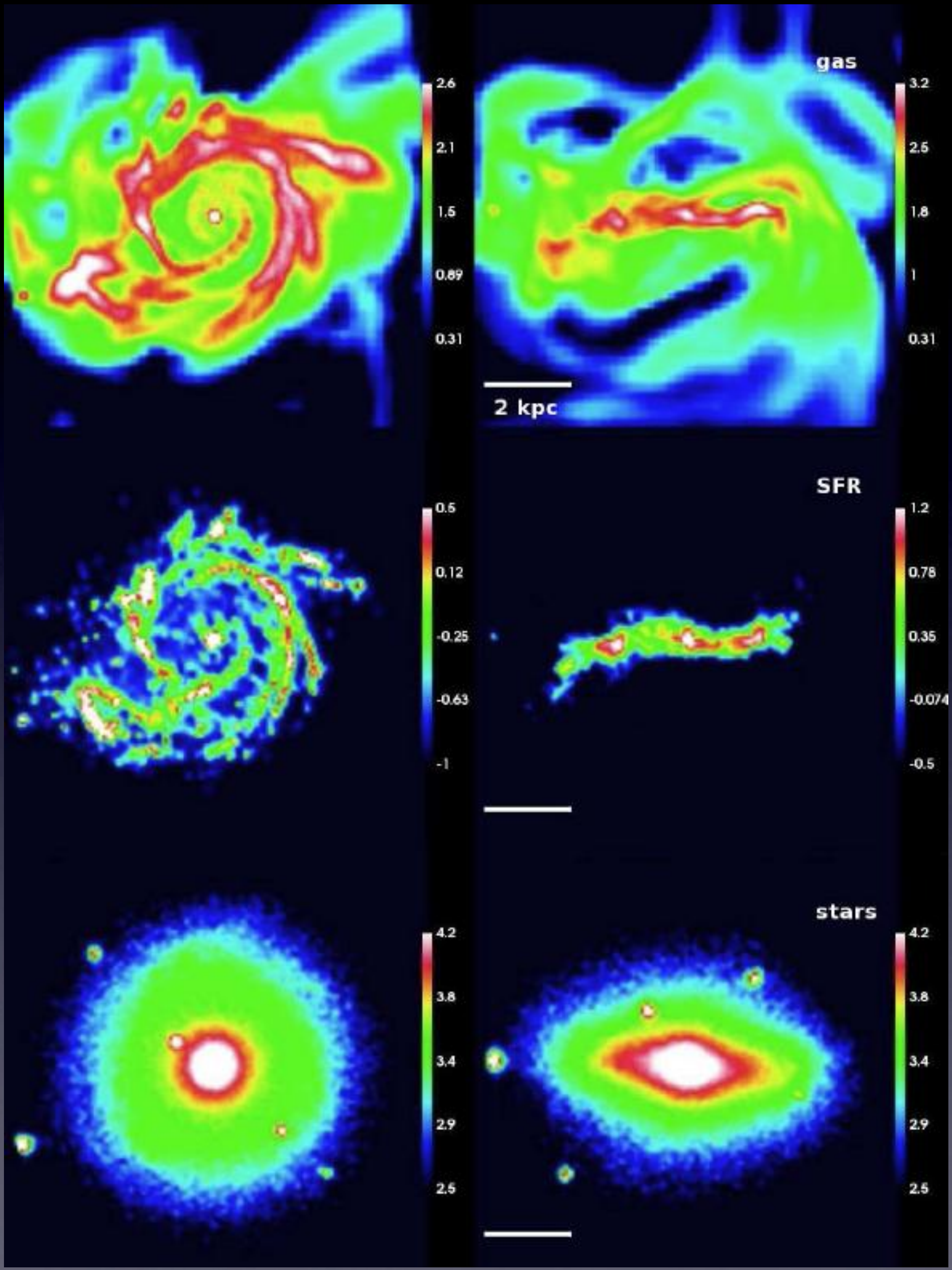
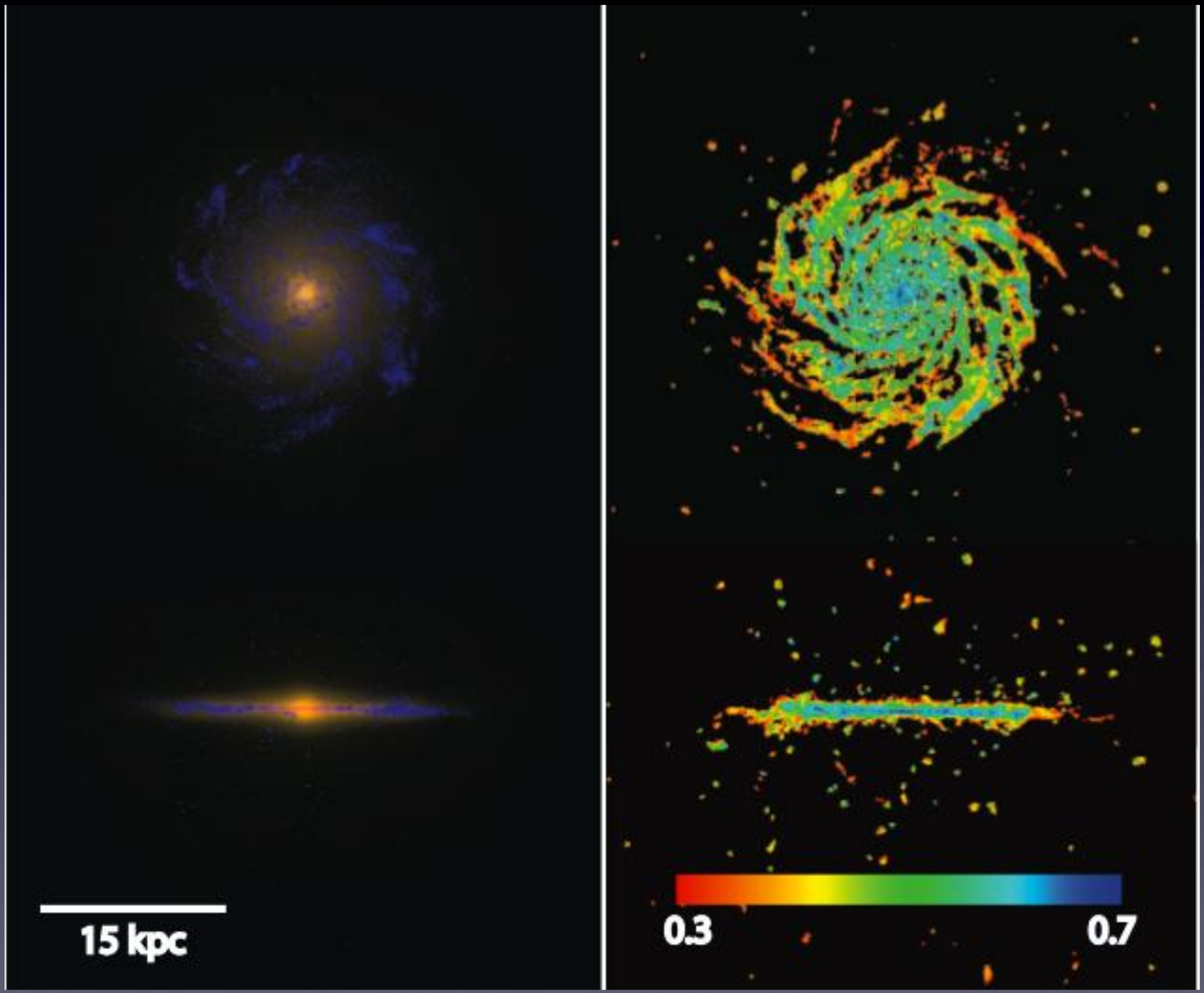


Figure 3. A zoom-out gas surface-density maps showing the streams feeding galaxy A. Left: cold gas ($T < 5 \times 10^4$ K). Right: hot gas ($T > 3 \times 10^5$ K). The box size is $160 \times 160\,\mathrm{kpc}$, covering the whole virial sphere. The color refers to log gas surface density in units of H atoms cm^{-2}. Two major narrow streams carry the gas from well outside the virial radius to the inner $\sim 20\,\mathrm{kpc}$ halo core, where they break into a multi-stream turbulent core before joining the inner disc of radius $\sim 6\,\mathrm{kpc}$, seen nearly edge-on at the box centre (mostly in white).

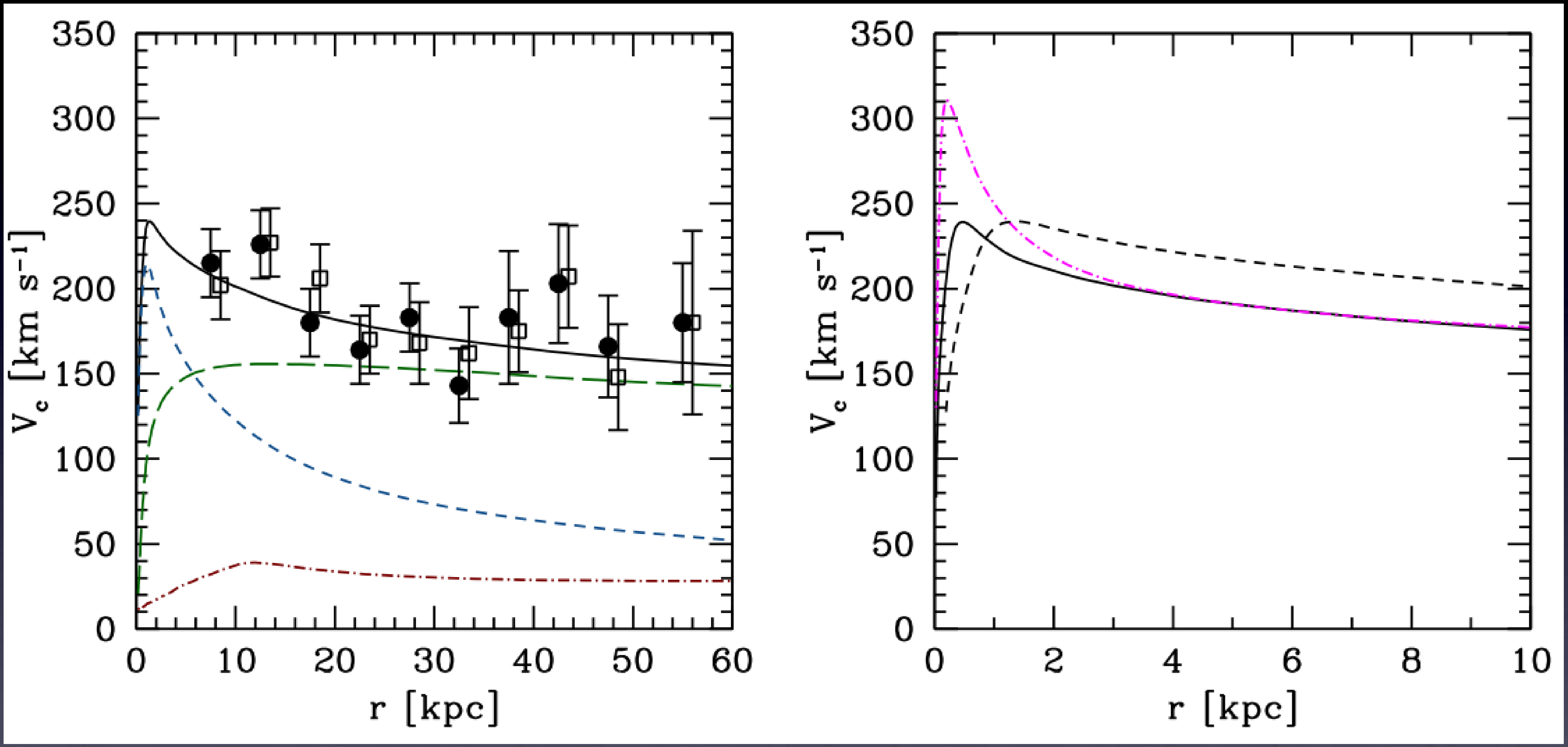

gas
2.6
2.1
1.5
0.89
0.31
3.2
2.5
1.8
1
0.31
2 kpc
SFR
0.5
0.12
-0.25
-0.63
-1
1.2
0.78
0.35
-0.074
-0.5
stars
4.2
3.8
3.4
2.9
2.5
4.2
3.8
3.4
2.9
2.5

Guedes et al 2011: Milky Way model

Optical/UV Neutral H



Guedes et al 2011: Milky Way model



Guedes et al 2011: Milky Way model

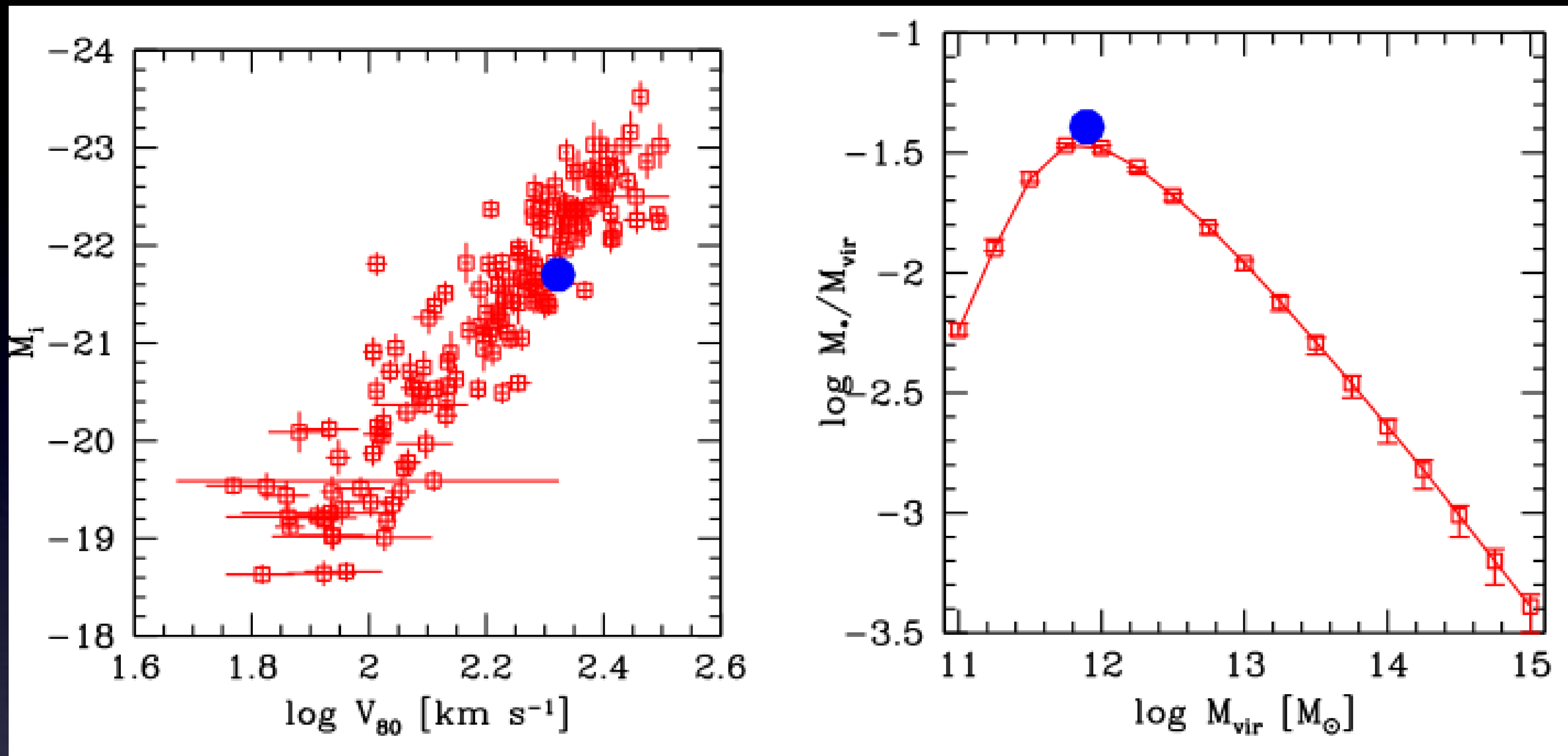


FIG. 4.— *Left panel:* The i-band Tully-Fisher relation for the Pizagno et al. (2007) galaxy sample (*empty squares with error bars*). *Filled circle:* The Eris simulation. Here V_{80} denotes the circular velocity at the radius containing 80% of the i-band flux, as defined by Pizagno et al. (2007). *Right panel:* The stellar mass - halo mass relation at $z = 0.1$ from Behroozi et al. (2010), modified for a Kroupa IMF (*empty squares with error bars*). Errors bars include only statistical uncertainties. *Filled circle:* The Eris simulation with a photometric stellar mass of $\mathcal{M}_* = 3.2 \times 10^{10}$ $M_\odot$ and a virial mass of $M_{vir} = 7.9 \times 10^{11}$ $M_\odot$ (see text for details).

Recent progress:

- “galaxies” lay on the Tully-Fisher relation: no problems with angular momentum
- Merging of two spiral galaxies (may) produce a spiral galaxy with very large disk.
- Barred “galaxies” are typical.

Physics and numerics:

- *typical resolution is 100-300pc - still too low. Requires subgrid physics: reduced cooling rates in places of star formation*
- *Goals: get to 20-50pc and to include some physics of molecular clouds. No subgrid physics (on its way: Kravtsov & Gnedin(Chicago), Ceverino (NMSU)*
- *Correct physics of ISM is important for forming realistic galaxies*

Conclusions

- Galactic Outflows are produced by forming galaxies: put it in right regime, it flies like a bird
- Velocities: 300-500 km/s are typical at z=2-3. Large (1000-2000 km/s) outflows happen frequently.
- Direction of outflows:
  - perpendicular to disk at small distances (10~kpc);
  - uncorrelated with disk at larger distances. Not random: outflows find holes in density field)
- Small galaxies tend to have larger velocities given sufficient SFR (Dekel & Silk again)
- Do not violate laws of physics simulating outflows. It is tempting, but do not do it.
- Need to fulfill two conditions to have feedback efficient to produce out flows:
  - overheating regime
  - high resolution: better 50 pc
- Mechanism for efficient feedback has important bottleneck: young stellar cluster => superbubble
- Accelerating shocks

- Two important tests for any design of feedback:
  - Flat rotation curves of galaxies (thin disks in spirals)
  - QSO absorption lines