The role of STELLAR FEEDBACK in cosmological models of galaxy formation.

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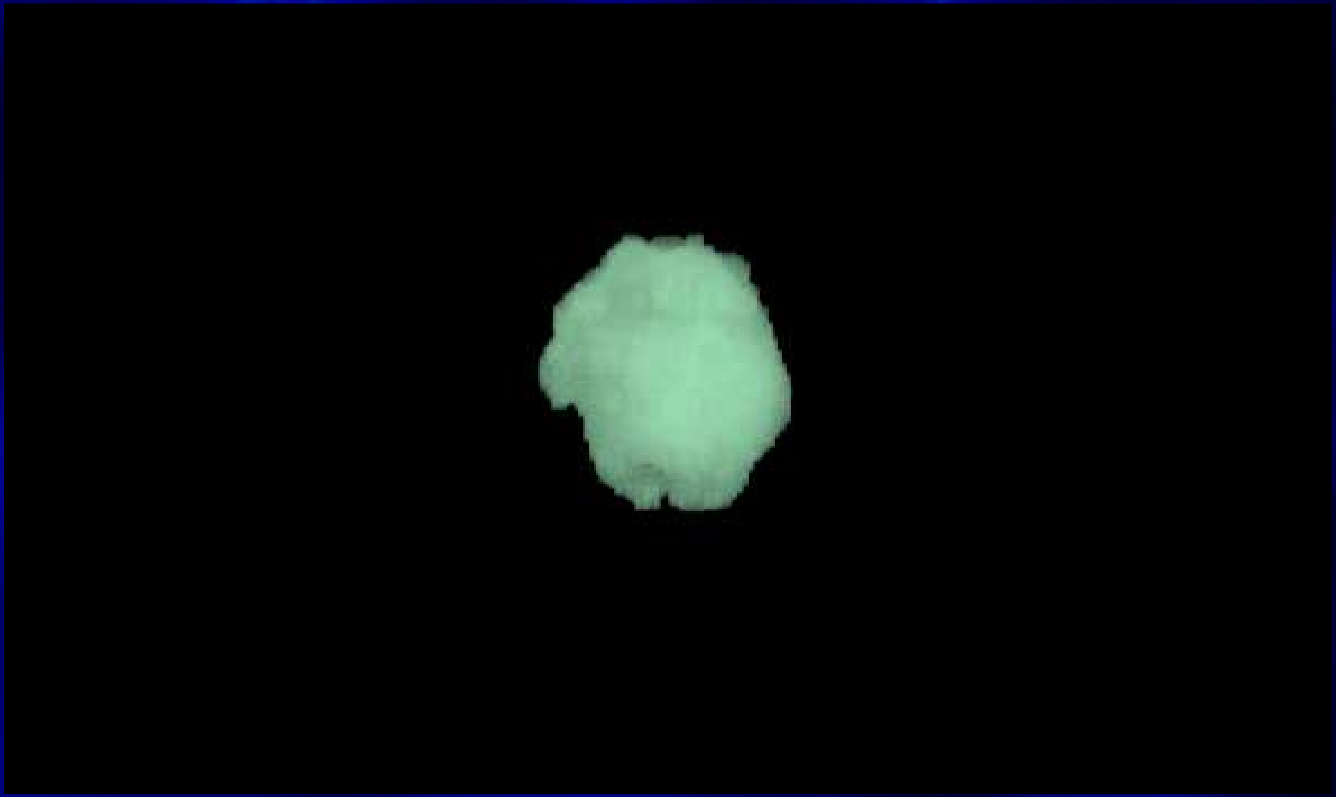
OUTLINE

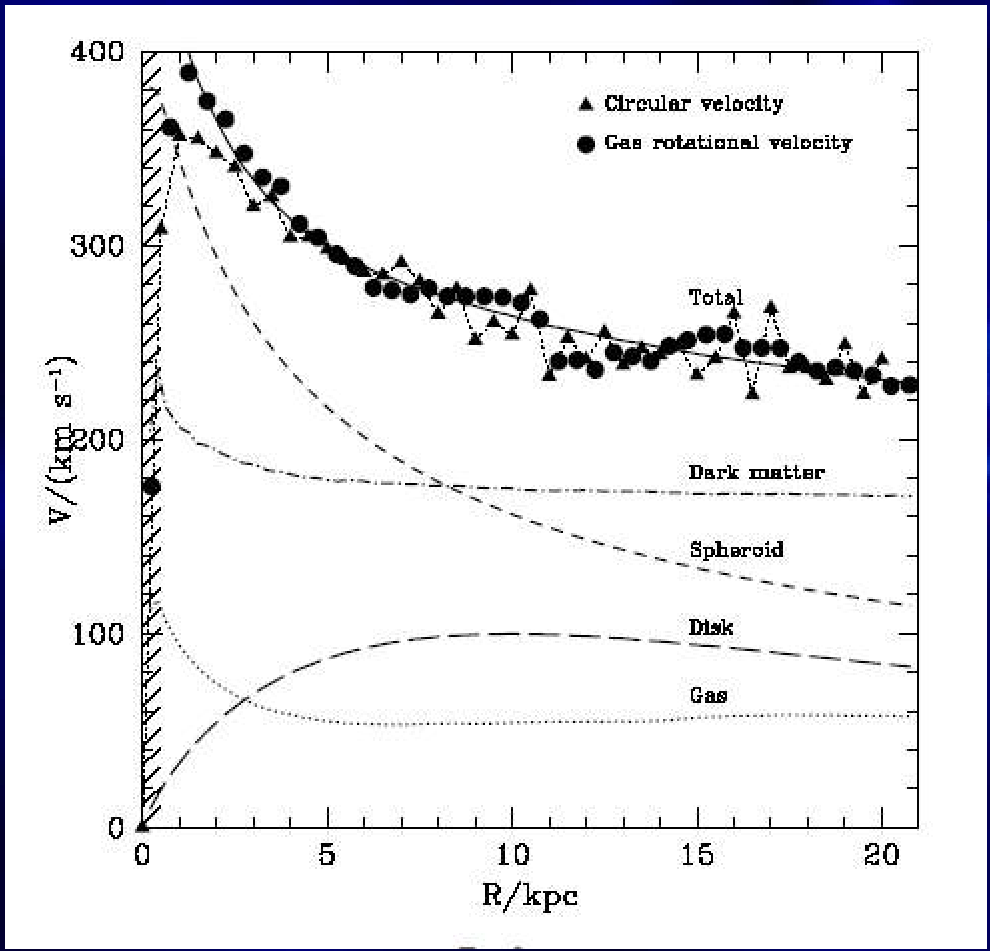
- Modeling of stellar feedback.
- A multiphase interstellar medium.
- Decreasing resolution.
- Formation of a galactic disk.

Cosmological N-body + gas-dynamics simulations of galaxy formation



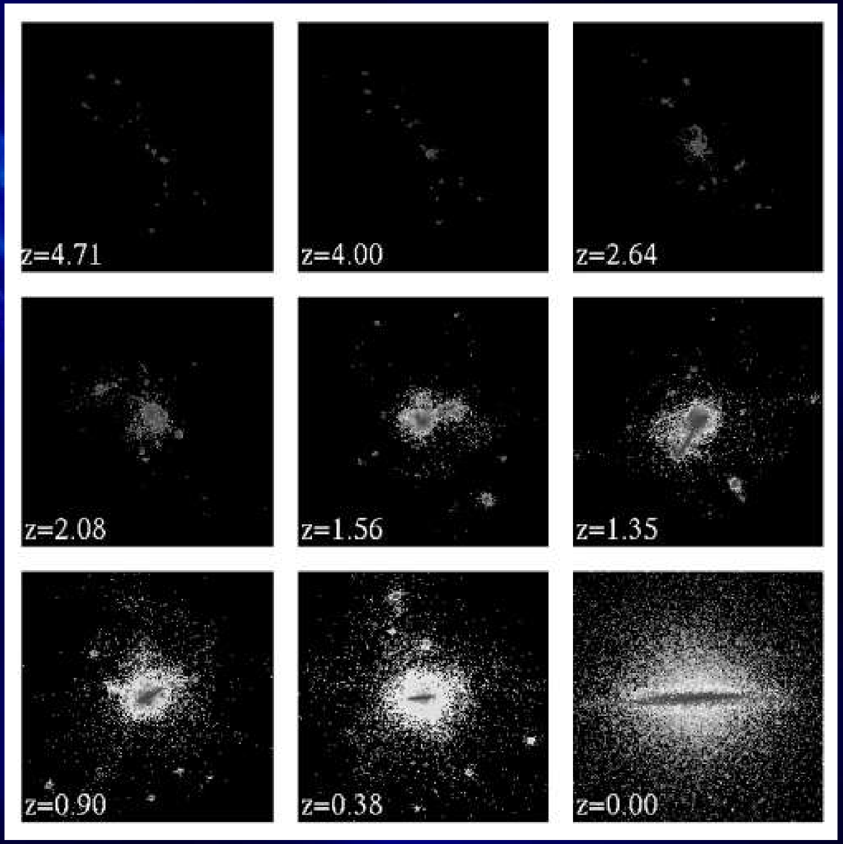
Governato et al 2006

The problem: A strong spheroid

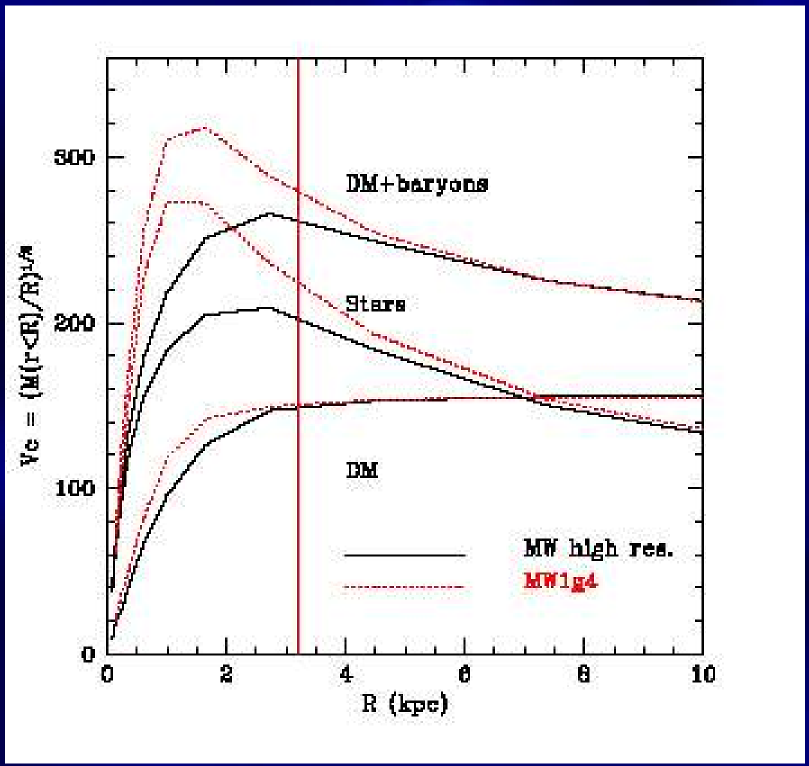


Abadi et al. 2003

500 pc force resolution (Plummer softening scale)
100,000 particles.

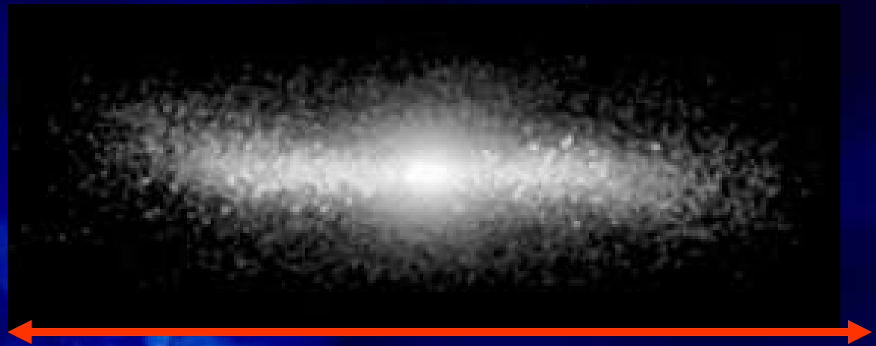


Better models of feedback are needed… and better resolution



300 pc resolution.
4M particles.

Governato et al. 2006
Stinson et al. 2006



30 Kpc

20 Kpc

Key physics for galaxy formation:

- Radiative processes.
- Star formation.
- Stellar feedback.

Adaptive Refinement Tree (ART) N-body + Eulerian gasdynamics code (Kravtsov et al 1997, Kravtsov 2003).

Stellar Feedback

- Thermal energy from stellar winds and supernova explosions.
- Injection of mass and heavy elements.
- Radiative heating, ionization and dissociation.

Gasdynamical equations

$$\frac{\partial}{\partial t} + \nabla(\quad \vec{u}) = \left(\frac{\partial}{\partial t} \right)$$

Star
formation

$$+ \left(\frac{\partial}{\partial t} \right)$$

Stellar
mass
looses
Star
formation
Stellar
mass
looses
Star
formation
Stellar
mass
looses

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u}\nabla)\vec{u} = -\nabla - \frac{\nabla P}{} + \left(\frac{\partial \vec{u}}{\partial t}\right) + \left(\frac{\partial \vec{u}}{\partial t}\right) \frac{\partial E}{\partial t} + \nabla\left[E + P\right]\vec{u} = - \quad \vec{u}\nabla \quad + \quad -L + \left(\frac{\partial E}{\partial t}\right) + \left(\frac{\partial E}{\partial t}\right) \nabla^2 \quad = 4G(\quad {}_{Tot} + 3P_{Tot}/c^2) - \quad E = \quad (\quad + \frac{u^2}{2}) \quad = \frac{1}{-1}\frac{P}{}$$

Gasdynamical equations

$$\frac{\partial}{\partial t}+\nabla(\ \vec{u})=\left(\frac{\partial}{\partial t}\right)_{\text{Star formation}}$$

Star formation Stellar mass looses

$$\left(\frac{\partial}{\partial t}\right)_{\text{Stellar mass looses}}$$

$$\frac{\partial E}{\partial t}+\nabla\left[(E+P)\vec{u}\right]=-\quad \vec{u}\nabla \quad -L+\left(\frac{\partial E}{\partial t}\right)_{\text{Star formation}}+\left(\frac{\partial k}{\partial t}\right)_{\text{Stellar mass looses}}$$

$$E = \left(\ +\frac{u^2}{2}\right) = e + k$$

$$\frac{\partial k}{\partial t}+\nabla\left[(E+P)\vec{u}\right]=-\quad \vec{u}\nabla \quad +\left(\frac{\partial E}{\partial t}\right)_{\text{Star formation}}+\left(\frac{\partial k}{\partial t}\right)_{\text{Stellar mass looses}}$$

$$\frac{\partial e}{\partial t}= \quad -L$$

$$\frac{\partial \vec{u}}{\partial t}+(\vec{u}\nabla)\vec{u}=-\nabla\ -\frac{\nabla P}{\ }+\left(\frac{\partial \vec{u}}{\partial t}\right)+\left(\frac{\partial \vec{u}}{\partial t}\right)$$

$$\nabla^2 \ = 4G(\ _{Tot}+3P_{Tot}/c^2)-$$

$$=\frac{1}{\ -1}\frac{P}{\ }$$

$\frac{\partial E}{\partial t} + \nabla[(E+P)\vec{u}] = -$ $\vec{u}\nabla$

Star formation Stellar mass looses

$+\left(\frac{\partial E}{\partial t}\right)$

Heating rate: =

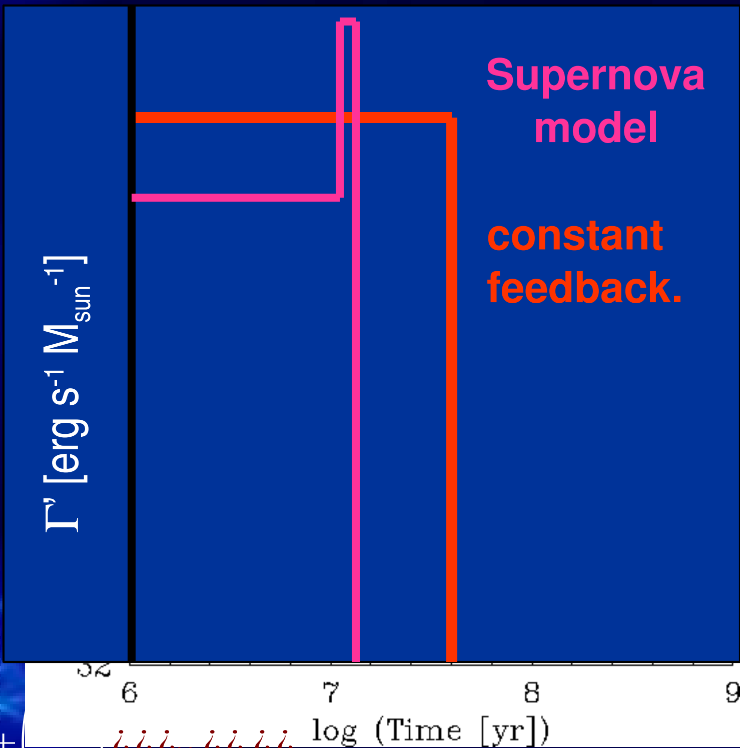
Stars

Star formation Stellar mass looses

$E =$ Cooling rate: $L = n_H^2 L'$ $=$ e + k

$\frac{\partial k}{\partial t} + \nabla[(E+P)\vec{u}] = -$ $\vec{u}\nabla$ $+\left(\frac{\partial k}{\partial t}\right)$

$+\left(\frac{\partial E}{\partial t}\right)$



Leitherer et al.1999

$\frac{\partial e}{\partial t} =$ Heating regime: $n_H^2 L' \leq$

Stars

Condition for heating:

$$\frac{n_H}{10^{-57} M_{Sun}} L' \leq \frac{M_{\text{Young stars}}}{M_{Gas}}$$

Radiative cooling bellow 10^4 K is a crucial process for stellar feedback.

Two regimes:

$$T = 10^4\text{-}10^5 K \Rightarrow L' \approx 10^{-22} \text{ erg s}^{-1} \text{ cm}^3 \Rightarrow n_H \leq 0.1 \text{ cm}^{-3}$$

$$T = 10^2 K \Rightarrow L' \approx 10^{-25} \text{ erg s}^{-1} \text{ cm}^3 \Rightarrow n_H \leq 100 \text{ cm}^{-3}$$

Shortcuts I: Stop cooling…

Governato et al. 2006

- Dwarf galaxy (V_{max}=130 km/s)
- Multi-phase ISM.
- Filaments with T~10^4 K.
- Cavities full with 10^5 K gas.

Shortcuts II: Sub-resolution multiphase model.

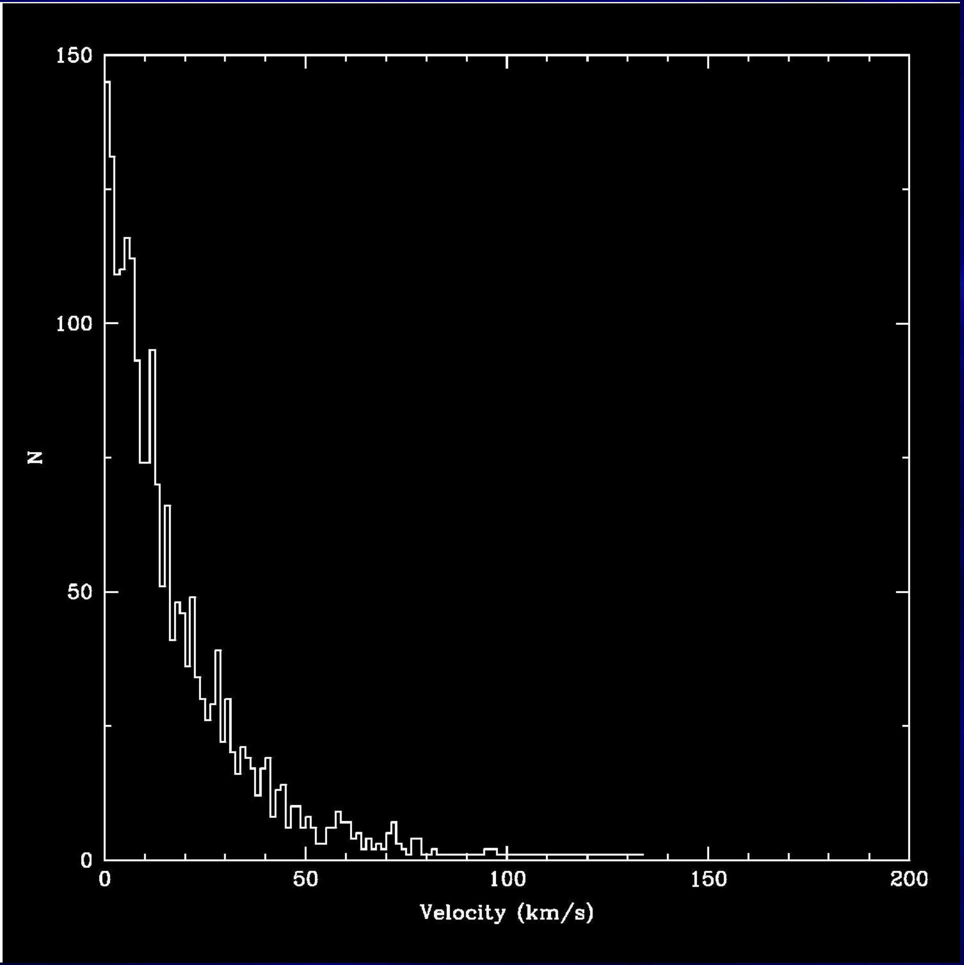
- Hot and cold phases coexist in the same resolution element (Yepes et al. 1997; Springel et al. 2004, 2005).

Our model

- No sub-grid physics. No shutdown of cooling.
- High resolution: Resolving molecular clouds.
- Cooling bellow 10^4 K.
- Right spatial distribution of the energy sources.

RUNAWAY STARS

Runaway stars



- 20%-30% of massive stars are found in the field rather than in clusters (Gies, 1987)
- 10 % have high velocities (v> 40 km/s)
- Exponential distribution of peculiar velocities (v_{Scale}=17 km/s)

The effect of stellar feedback in the ISM:

A 3-phase medium.

Superbubbles and isolated bubbles

The effect of the stellar feedback in the ISM:

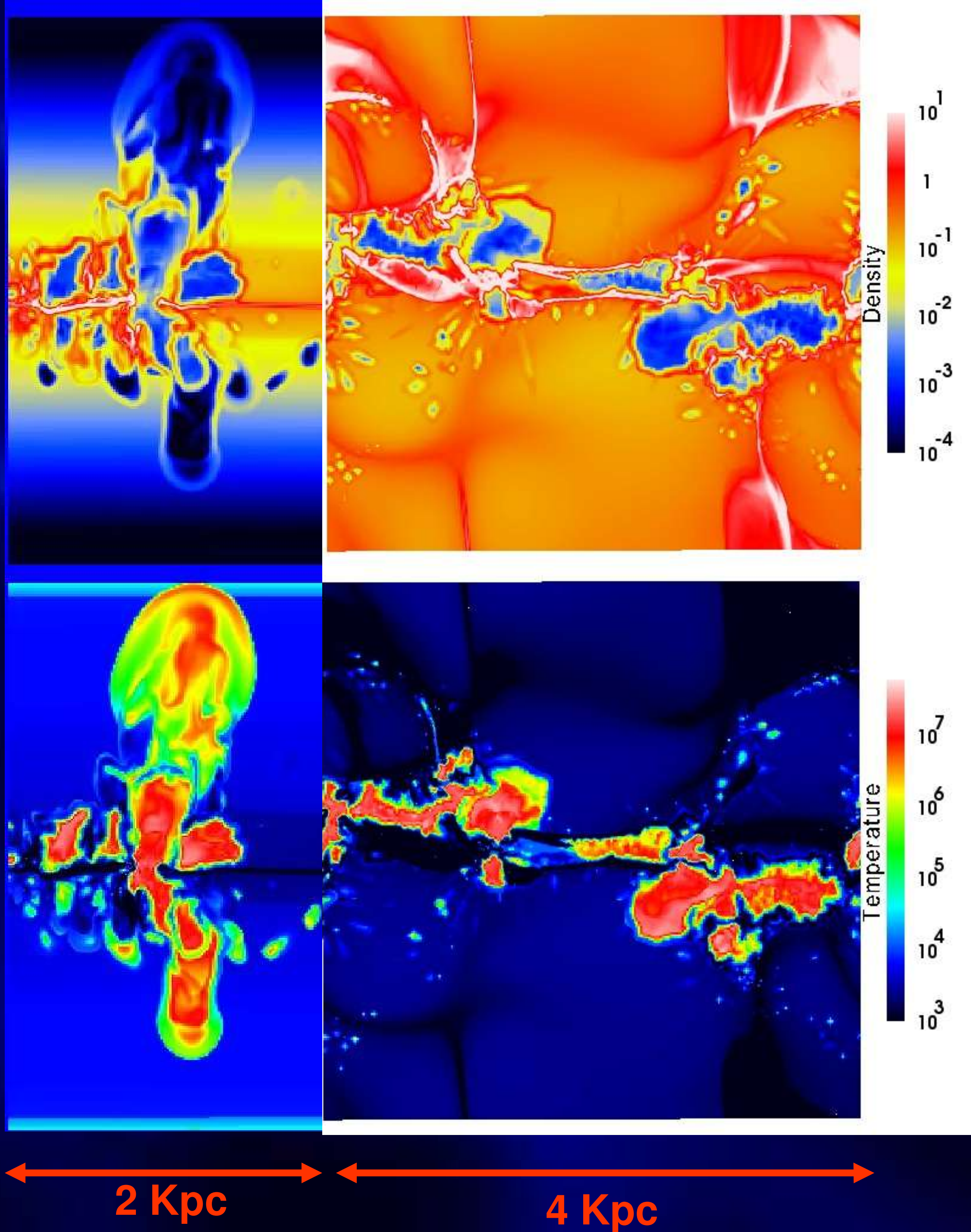
Multiphase medium.

Cold ($T<10^3$ K) gas

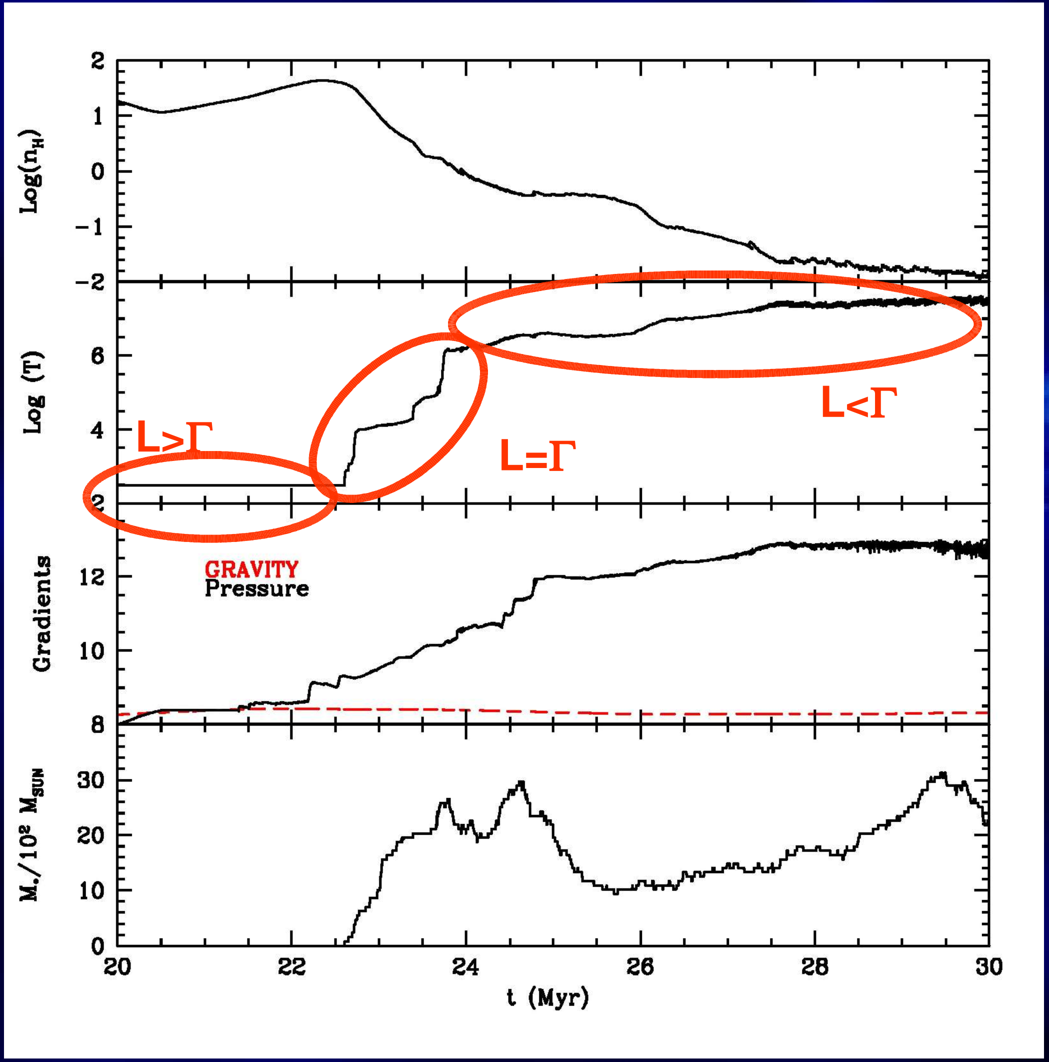
Warm ($10^3 < T < 10^4$ K)

Hot ($T> 10^4$ K) gas.

14 pc resolution

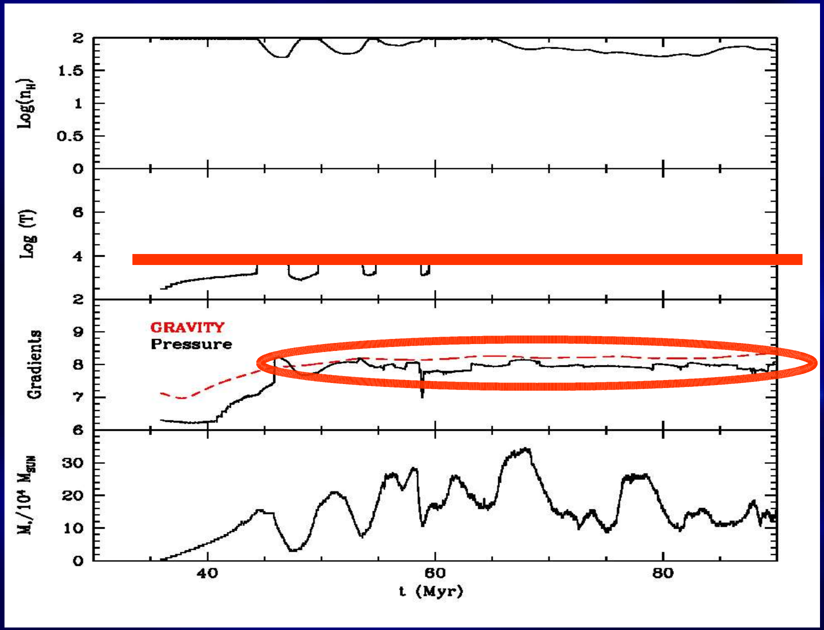


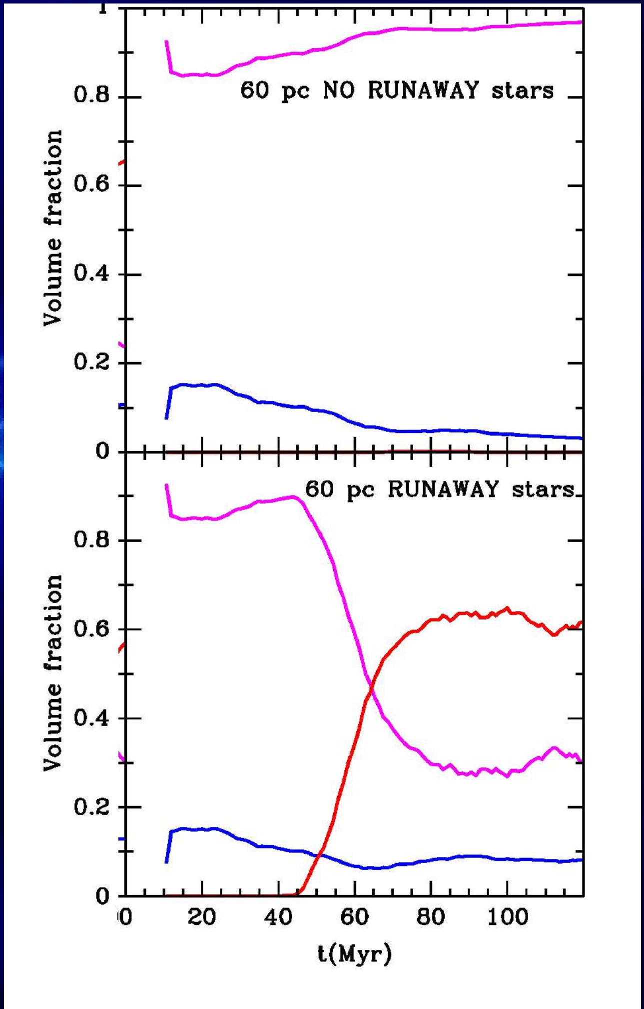
Bubble expansion



- Cooling dominates.
- Balance between radiative cooling and stellar heating.
- Heating dominates.

Lower resolution: the importance of runaway stars





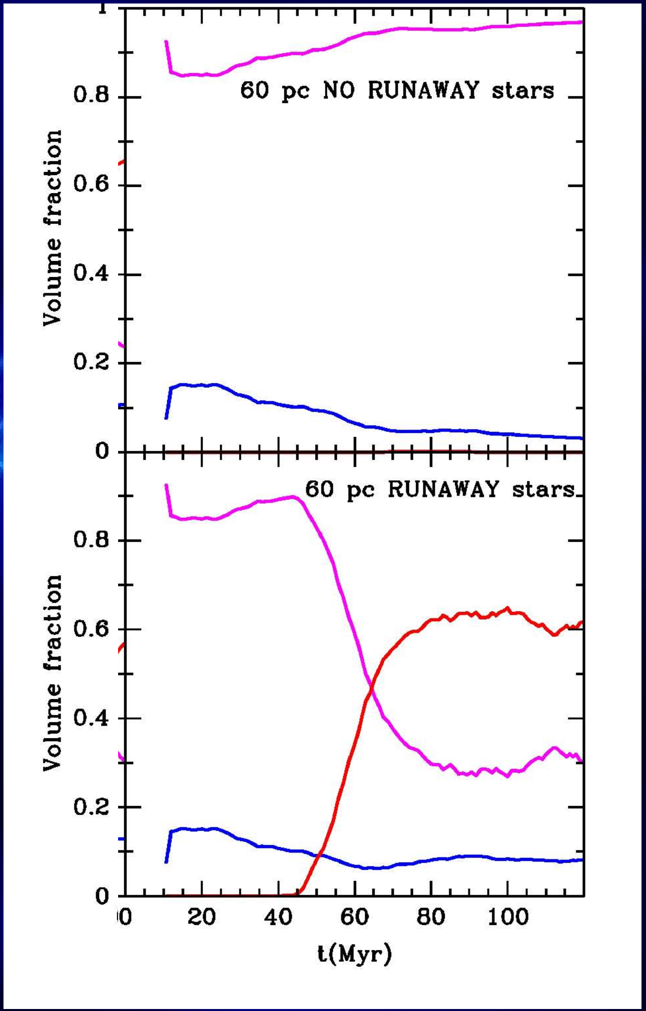
Cold (T<10³ K) gas

Warm (10³ < T < 10⁴ K)

Hot (T> 10⁴ K) gas.

Lower resolution: the importance of runaway stars

A 3-phase medium is resolved when runaway stars are included.



Cold ($T<10^3$ K) gas

Warm ($10^3 < T < 10^4$ K)

Hot ($T> 10^4$ K) gas.

Results on the formation of galactic disks.

- Preliminary runs.
- Rotation curves.
- The effect of stellar feedback.

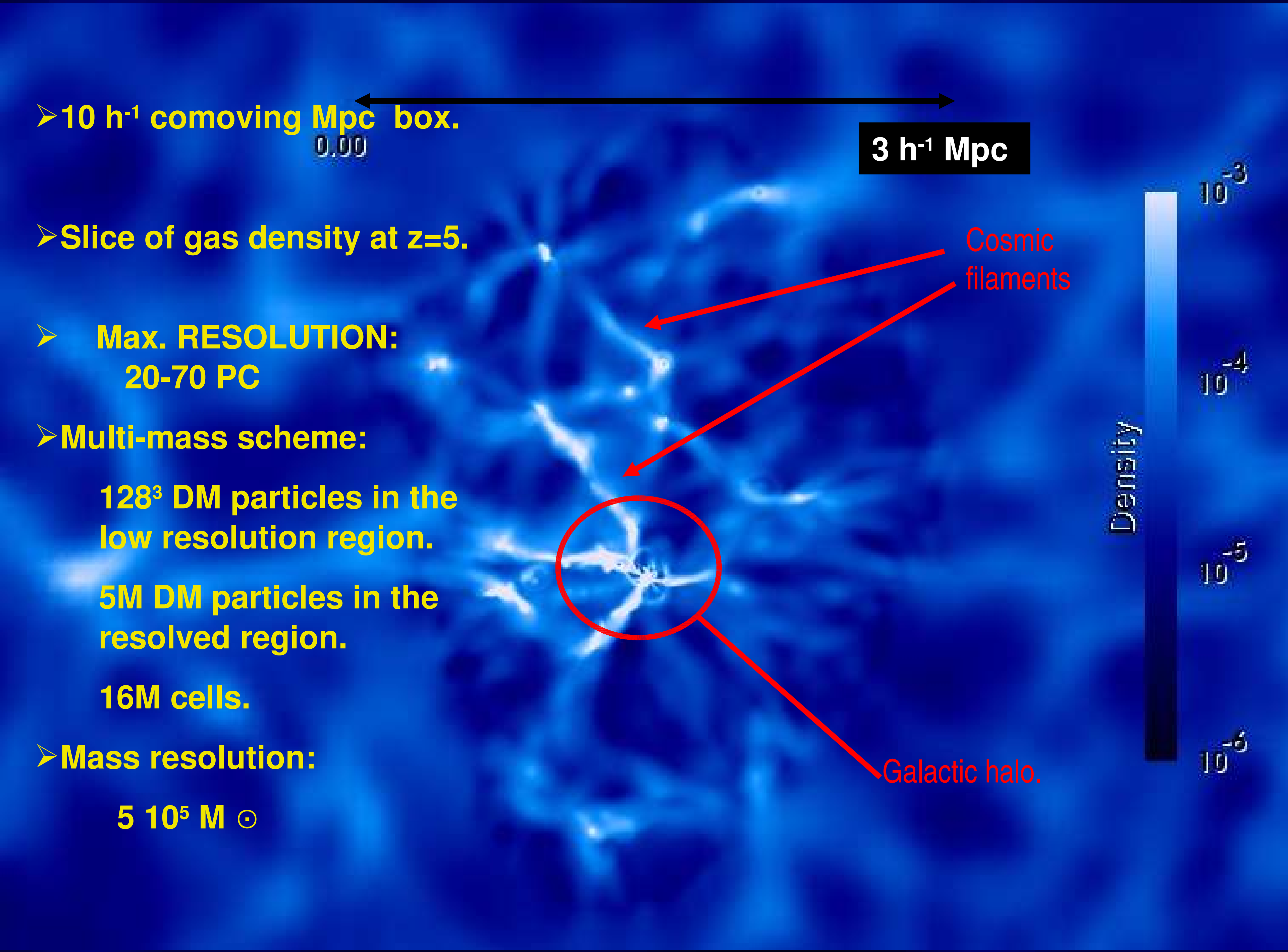
- 10 h^{-1} comoving Mpc box.
- Slice of gas density at z=5.
- Max. RESOLUTION:
  20-70 PC
- Multi-mass scheme:

  128^3 DM particles in the low resolution region.

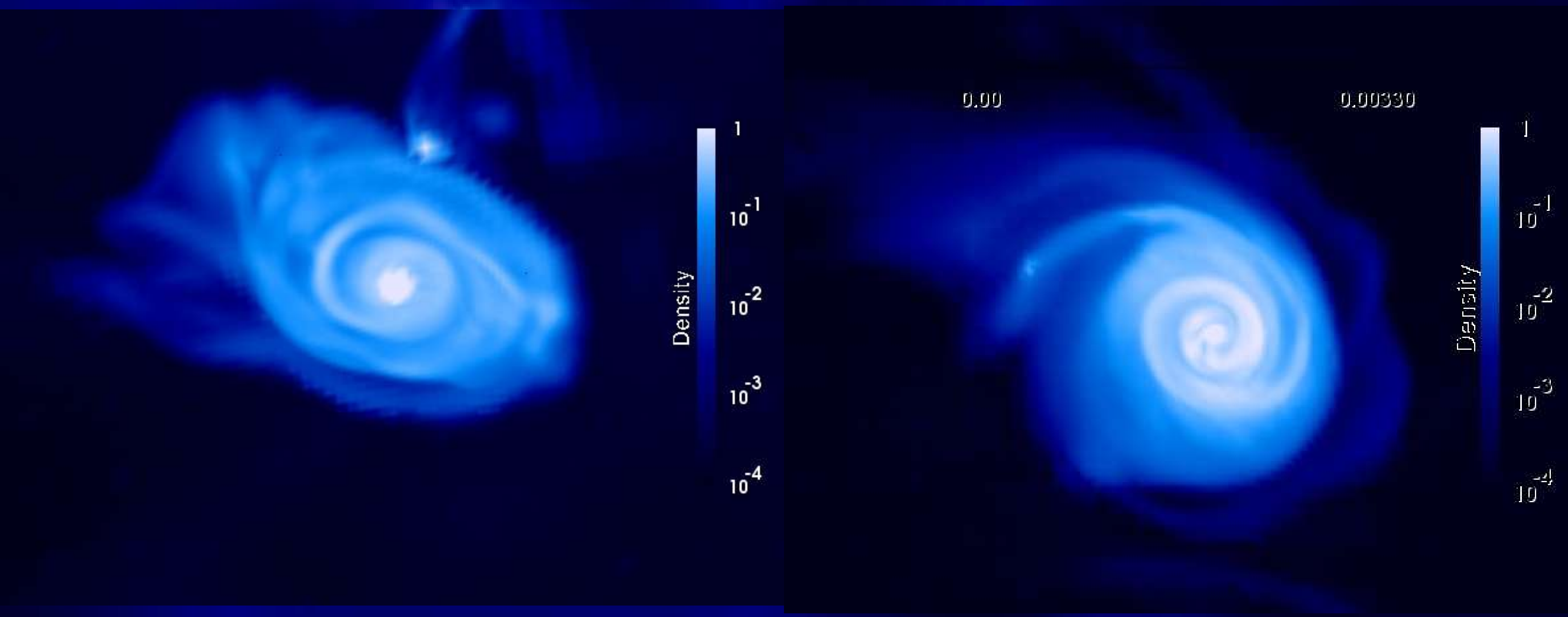
  5M DM particles in the resolved region.

  16M cells.
- Mass resolution:

  $5\ 10^5\ M_\odot$

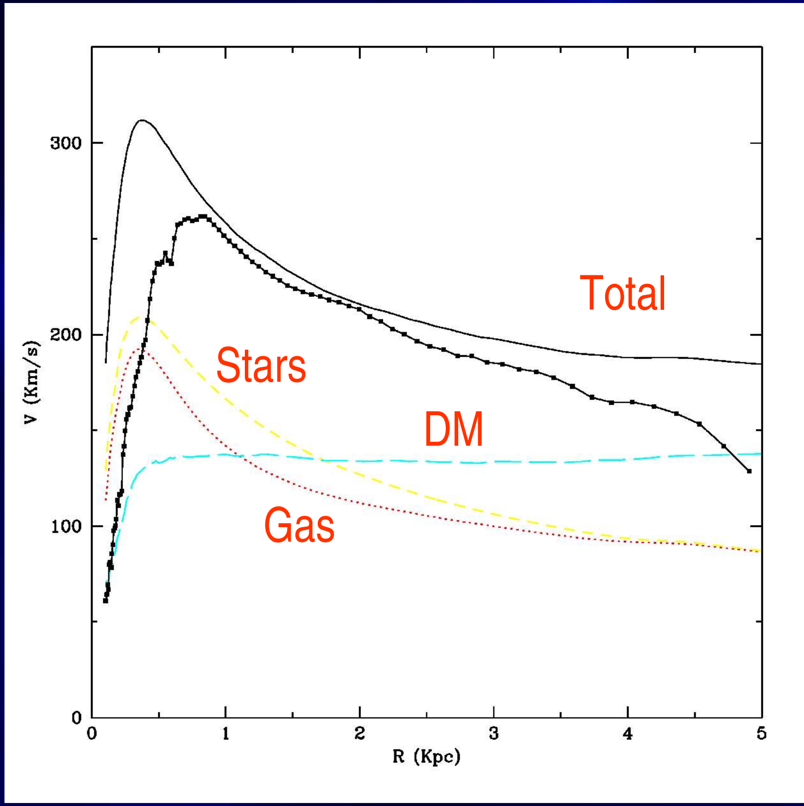


Galactic disks?



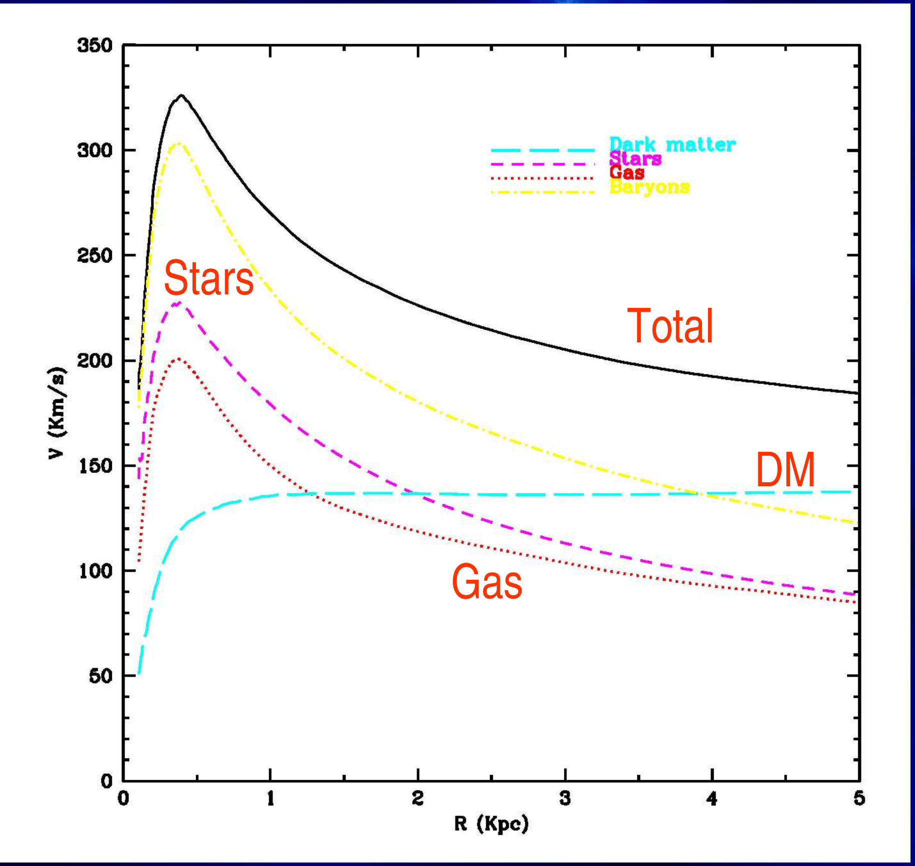
20 Kpc at z=0.6

Rotation curve at z=3



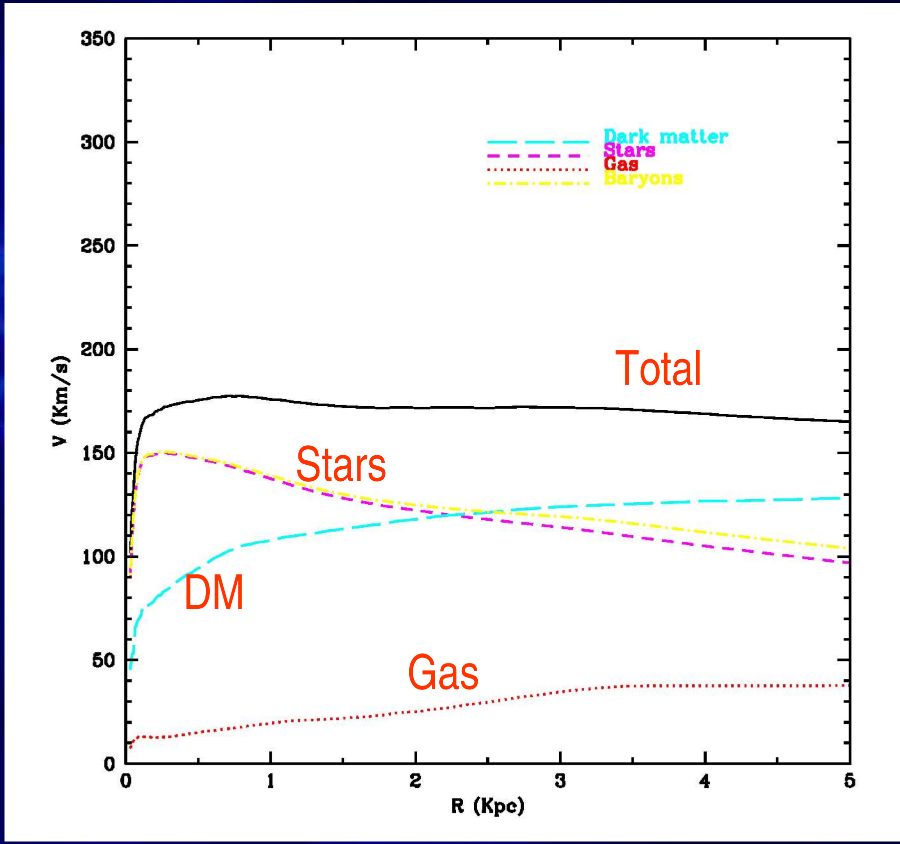
180 pc resolution

Stellar feedback needs a ~50 pc resolution to be fully operational.

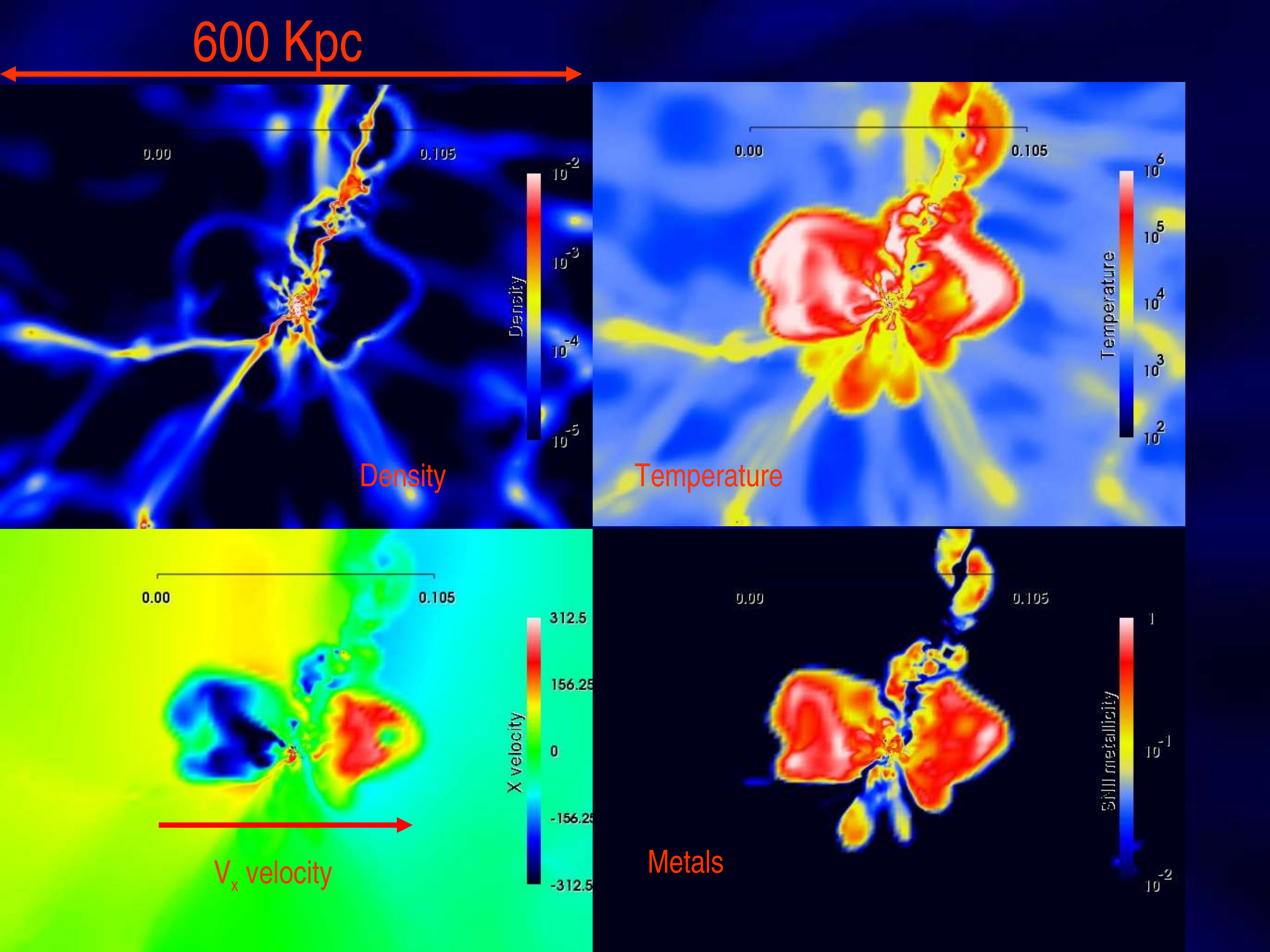


180 pc resolution

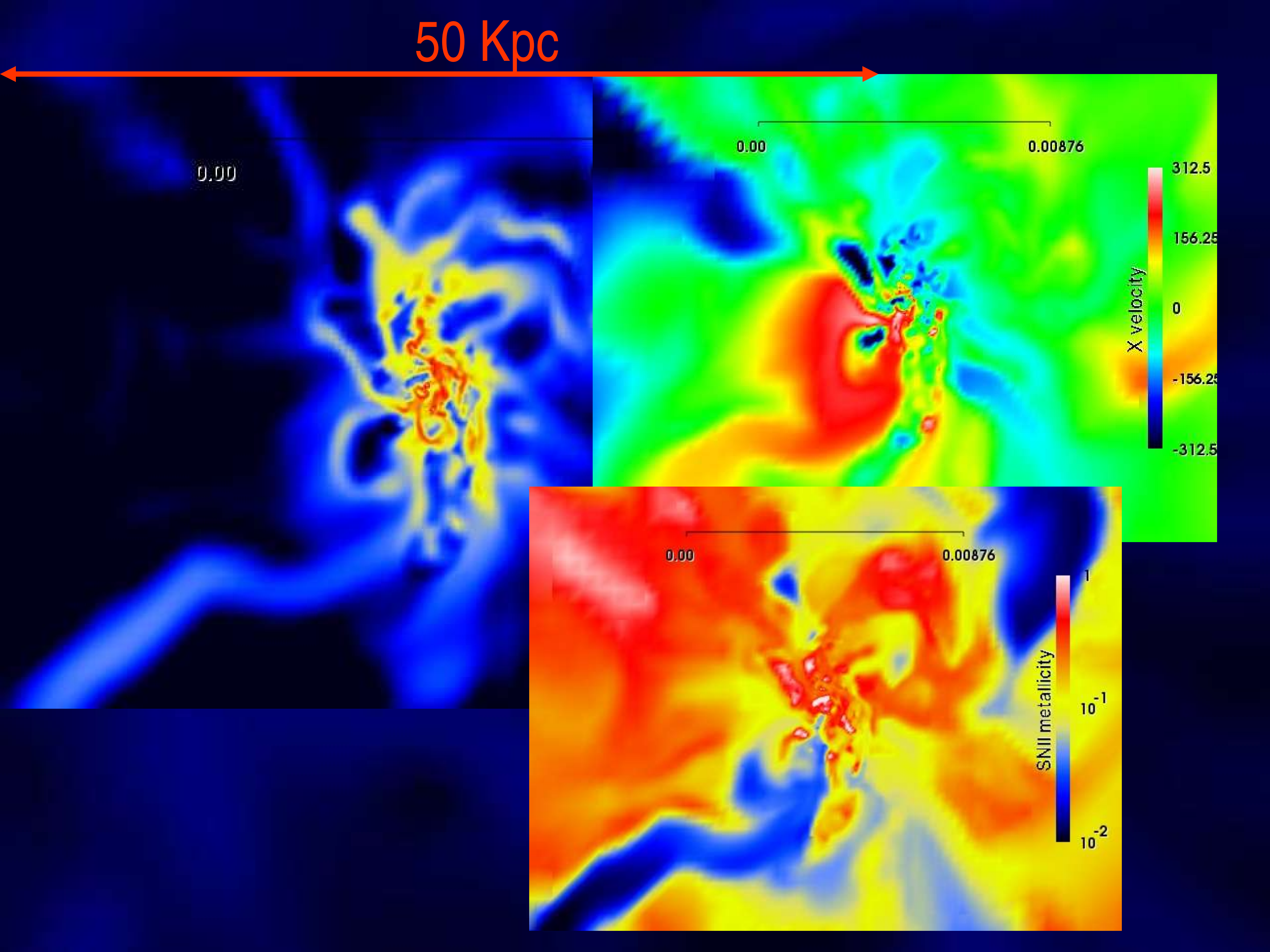
Z=3



45 pc resolution



600 Kpc
0.00
0.105
Density
10^-2
10^-3
10^-4
10^-5
Temperature
10^6
10^5
10^4
10^3
10^2
X velocity
312.5
156.25
0
-156.25
-312.5
V_x velocity
SiIII metallicity
1
10^-1
10^-2
Metals



50 Kpc
0.00
0.00
0.00876
312.5
156.25
0
-156.25
-312.5
X velocity
0.00
0.00876
1
10^-1
10^-2
SNII metallicity

Conclusions

- Stellar feedback maintains a 3-phase ISM.
- Hydro-simulations of the ISM show gas outflows or galactic "fountains".
- They can be used to check multi-phase models.
- A minimum of 50-pc resolution plus runaway stars are crucial for stellar feedback.
- Stellar feedback regulates the formation of the bulge and shapes the inner part of the rotation curve.

THE END