The fate of heavy metals in galaxies
The role of mass and geometry

Chemical evolution in the Universe: The next 30 years

19.09.2013

Simone Recchi
G. Hensler, S. Plöckinger, E. Vorobyov – Department of Astrophysics, Vienna

Mon. Not. R. Astron. Soc. **322**, 800–820 (2001)

Dynamical and chemical evolution of gas-rich dwarf galaxies

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Astronomy
&
Astrophysics

Multiple starbursts in Blue Compact Galaxies

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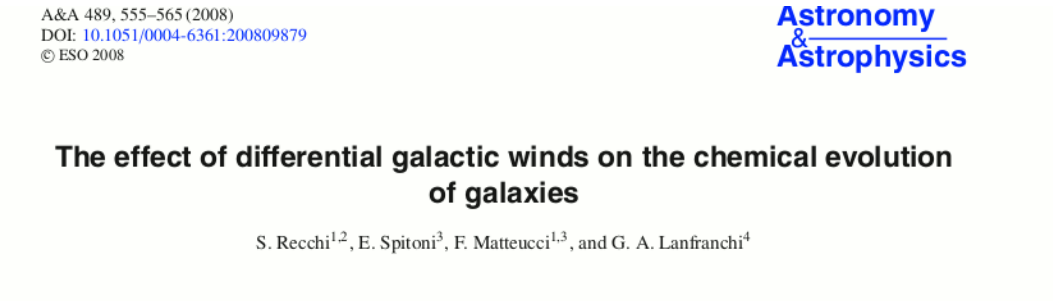

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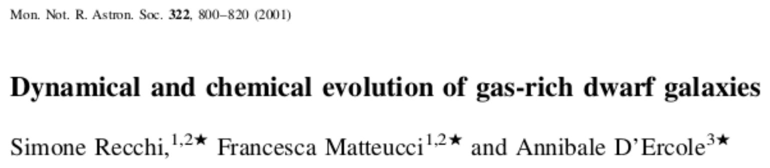
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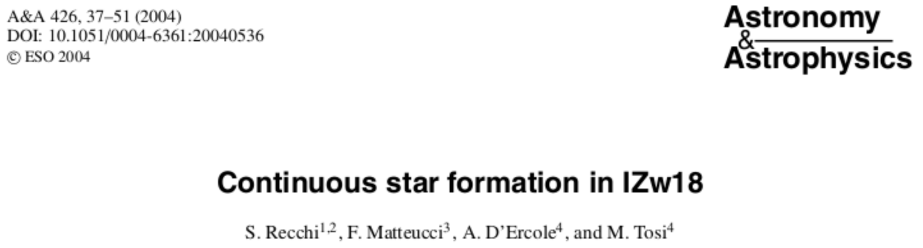
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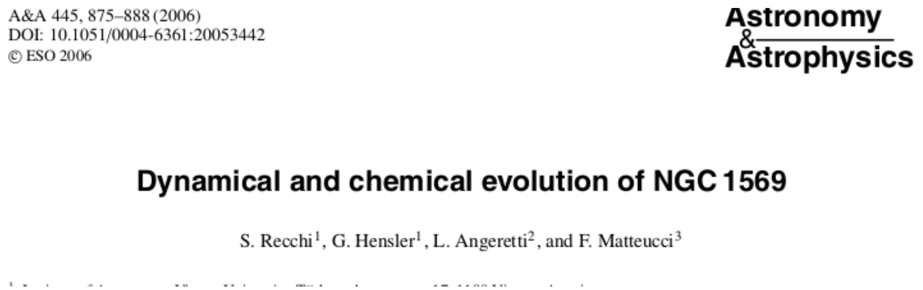
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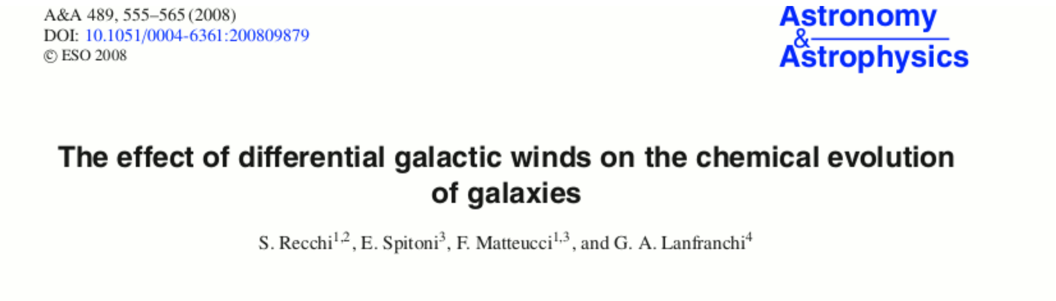
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Thanks so much Francesca for all I have learned from you!

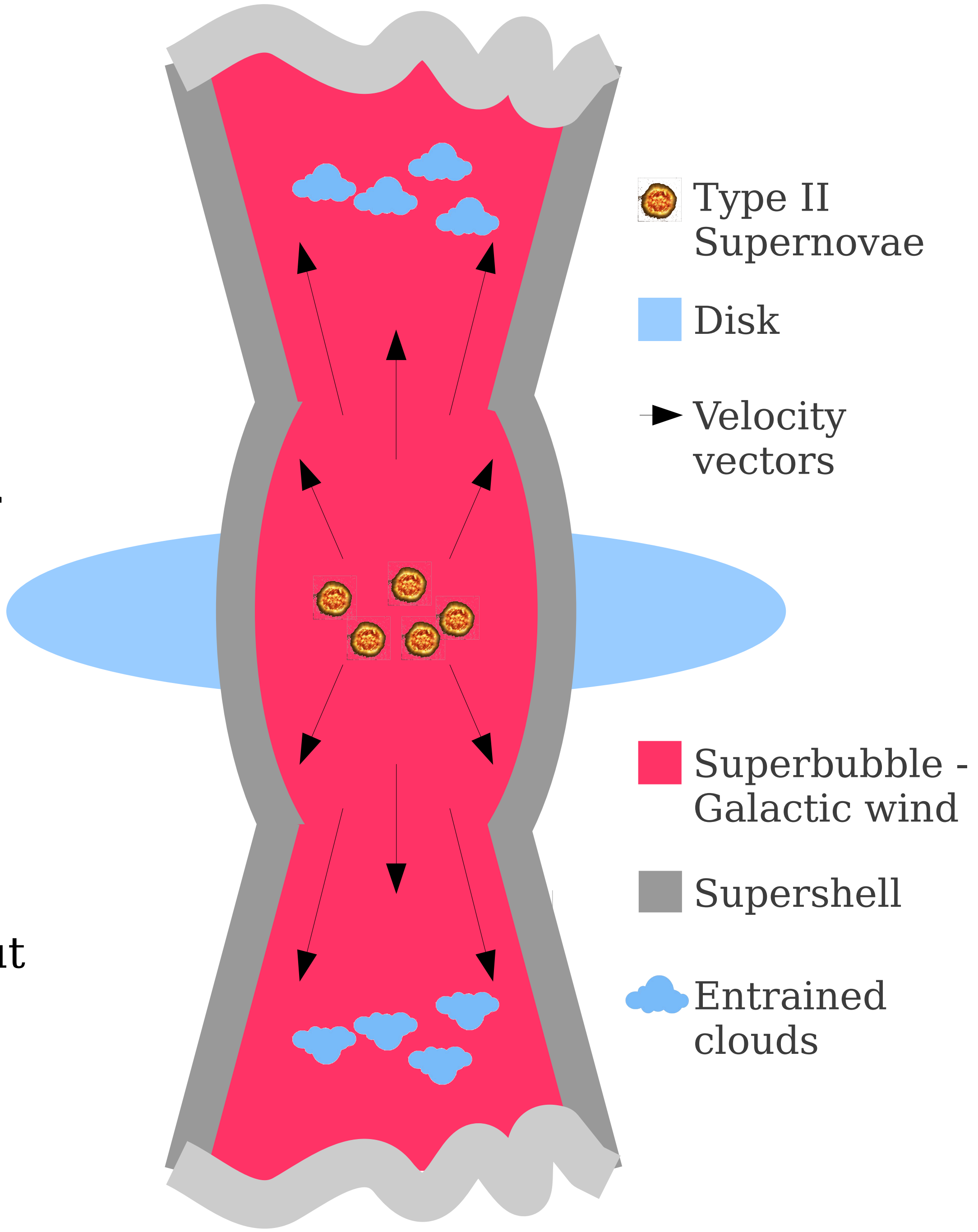
A proud "Matteucci boy"

Outline

- Introduction: motivation for this study and basic facts about galactic winds
- The role of geometry on the development of galactic winds
- The fate of heavy elements in dwarf galaxies and the mass-metallicity relation
- Conclusions and outlook

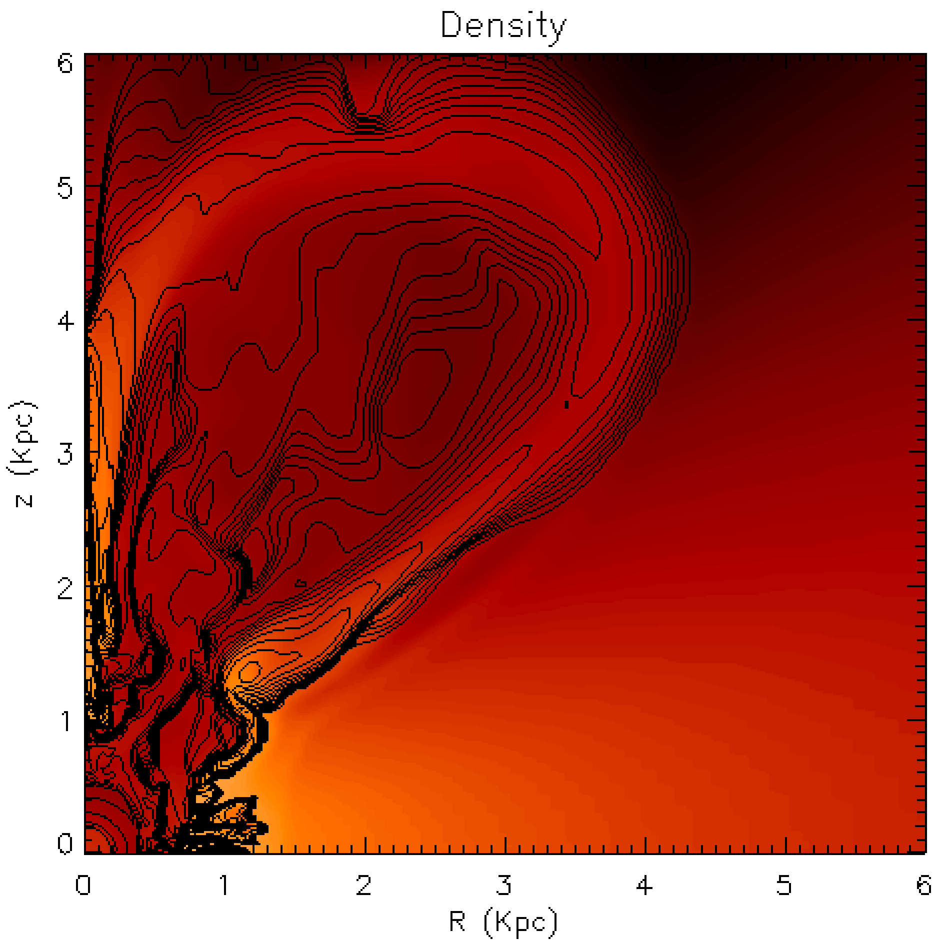
Galactic winds: the basics

- Type II SN explosions and stellar winds create a hot superbubble of metal-rich plasma.
- The gas is too hot and dilute to cool. Due to the lower pressure of the surrounding gas, it expands.
- If the galaxy is oblate, pressure gradient is steeper along the polar axis and bipolar outflows are formed.
- The ambient ISM is swept up in a thin, cold shell (supershell).
- At ~ 3 disk scale heights the supershell accelerates and fragments, allowing the venting out of the hot superbubble
- Mass-loading occurs during the expansion of the superbubble



Galactic winds: chemical consequences

- In disk galaxies galactic winds do not remove large fraction of pristine ISM (there is no much transport of gas along the equatorial plane)
- However, the outflow can direct metal-enriched ejecta from SNe out of the disk.
- This process, due to the shallower potential well, is more efficient for small objects. Low mass galaxies have therefore more difficulty retaining the heavy elements and their metallicity will stay low.
- The fate of metals, freshly produced during an intense episode of star formation depends thus on the mass of the parent galaxy and on the starburst luminosity



Red filled contours: total gas density distribution. Brightest colours – highest density

Black contours: isodensity contours of freshly produced oxygen

Galactic winds: chemical consequences

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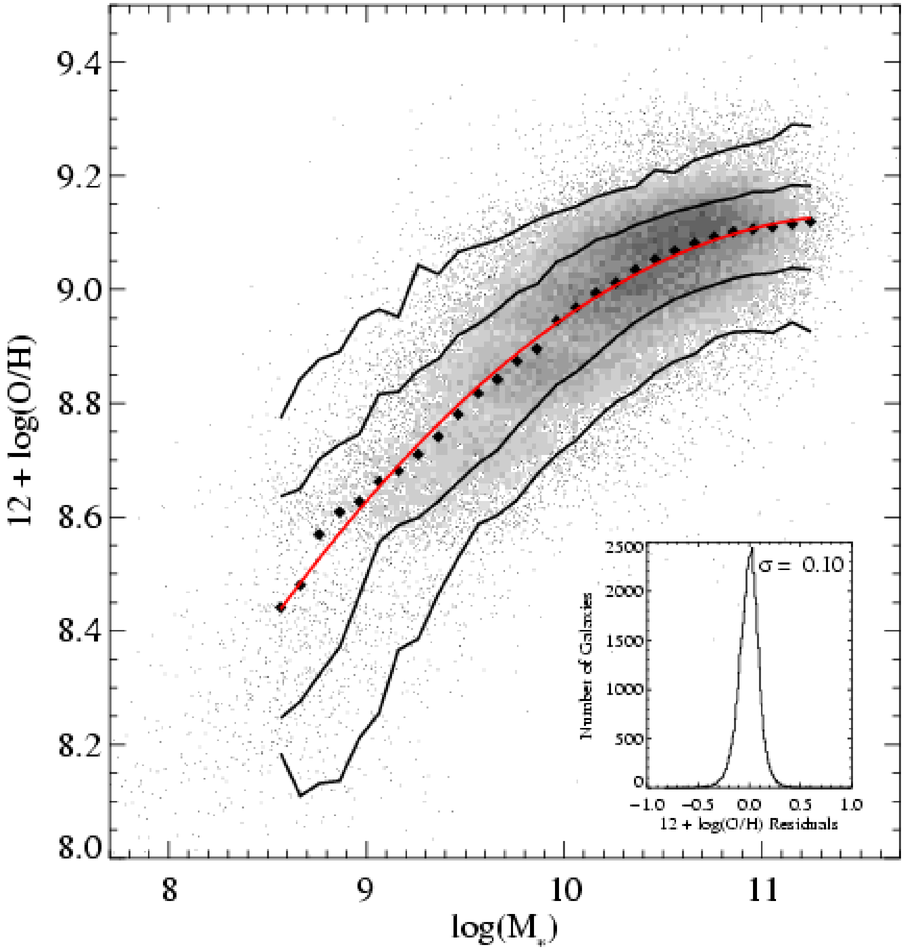
Differential galactic winds can explain the mass-metallicity relation



Tremonti et al. (2004)

Galactic winds: chemical consequences

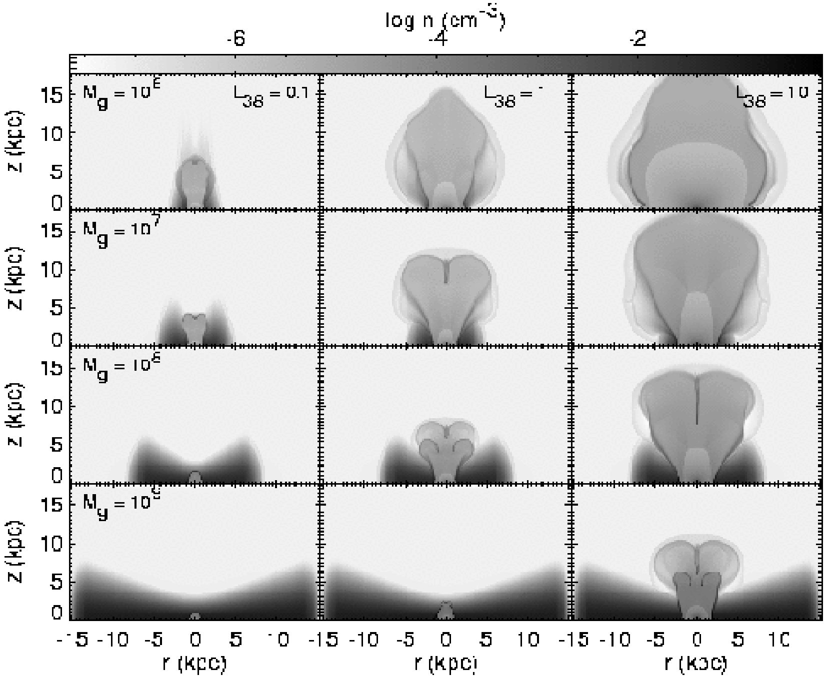
(MacLow & Ferrara 1999)

Luminosity (10^{38} erg s^{-1})

Mass ($M_\odot$)	0.1	1	10
10^6	0.18 1	1 0.99	1 1
10^7	3.5e-3 1	8.4e-3 1	4.8e-2 1
10^8	1.1e-4 0.8	3.4e-4 1	1.3e-3 1
10^9	0 0	7.6e-6 0.69	1.9e-5 0.97

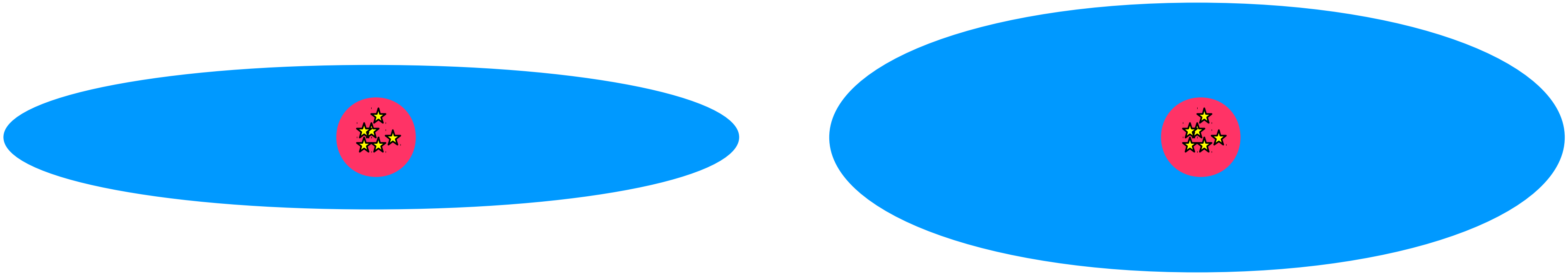
Mass ejection efficiencies

Metal ejection efficiencies



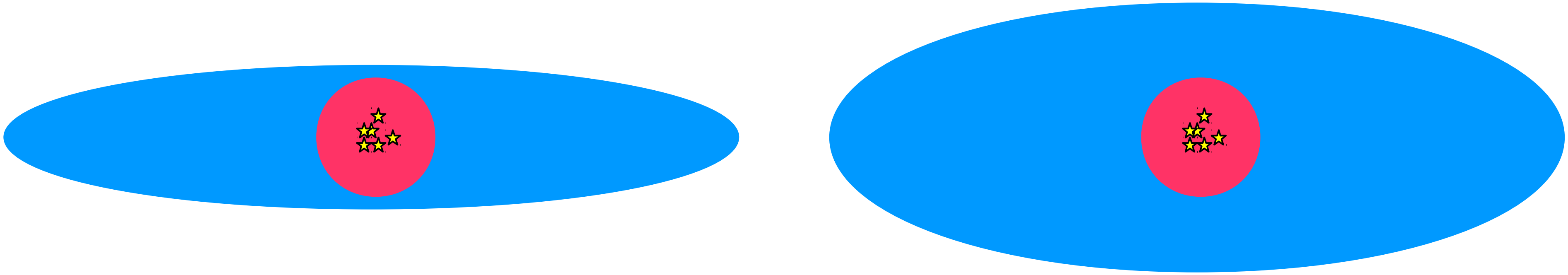
- The majority of models experiences blowout and expels almost all the metals
- The majority of models retains all the initially present gas

Galactic winds: changing the disk thickness



- As a consequence of the energy feedback, a hot superbubble is created and it begins to expand

Galactic winds: changing the disk thickness



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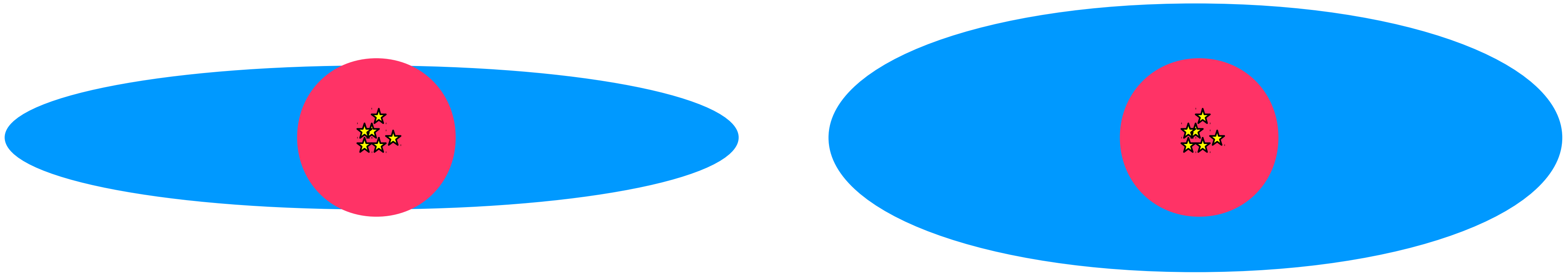
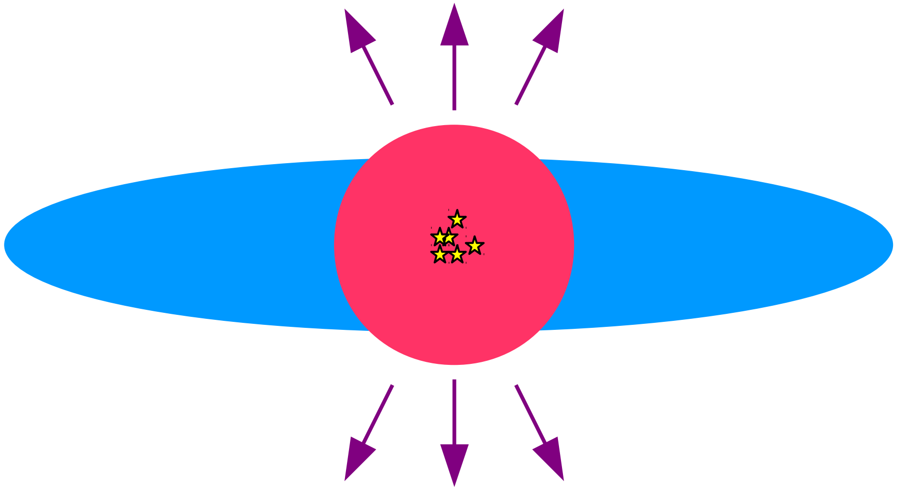
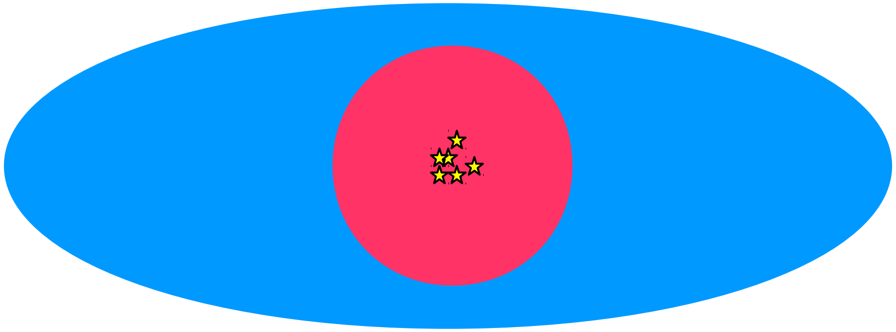


Galactic winds: changing the disk thickness



$R_{SB} > H_{disk}$ => blowout



$R_{SB} < H_{disk}$ => confinement

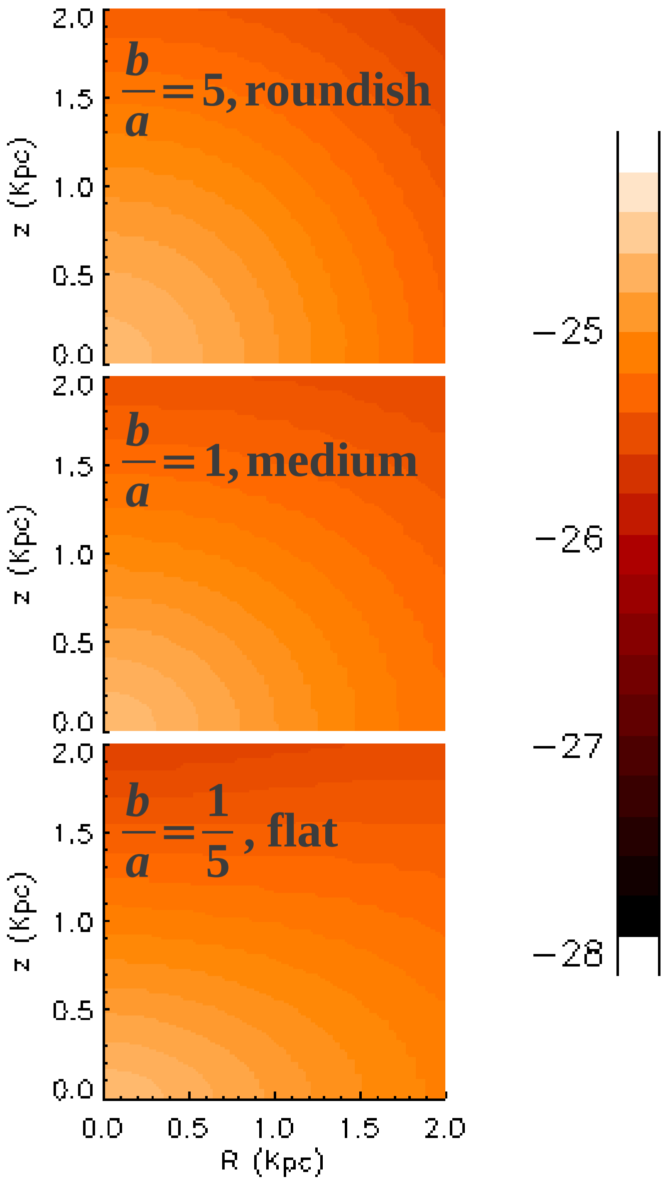
- The flatter the galaxy, the easier the blowout (and the larger the fraction of escaping metals!)
- The idea is simple but it has never been numerically explored in the past. In particular, in MacLow & Ferrara's simulations the degree of flattening is always the same (but see Strickland & Stevens 2000, Silich & Tenorio-Tagle 2001, Dubois & Teyssier 2008, Schroyen et al. 2011).

The goal

- Perform a more complete study of the fate of gas and freshly produced metals after an episode of star formation.
- In particular, study the effect of the initial gas distribution on the evolution of galactic winds and on the ejection efficiencies of gas and metals.

The set-up

- 2-D axisymmetric models. Typical resolution 4 pc
- Detailed feedback and chemical enrichment by SNeII, SNeIa, low-and intermediate mass stars
- 3 components: gas, disk and dark matter halo. The gas is set in hydrostatic equilibrium with the centrifugal potential and the potential generared by dark matter and disk (i.e. no gas self-gravity!)
- Disk follows a Miyamoto-Nagai potential with variable ratio b/a. If b/a<<1 → flat distribution; b/a>>1 → roundish distribution.
- Models with different b/a have the same gas mass within 0.5 r_{vir}.
- Ejection efficiencies: fraction of material found outside r_{vir}
- The star formation is constant for 500 Myr



Basic parameters

- Baryonic masses: 10^7 , 10^8, 10^9 $M_\odot$.
- Degrees of flattening: b/a=0.2, 1, 5.
- Gas-to-baryon ratios: 0.6, 0.9

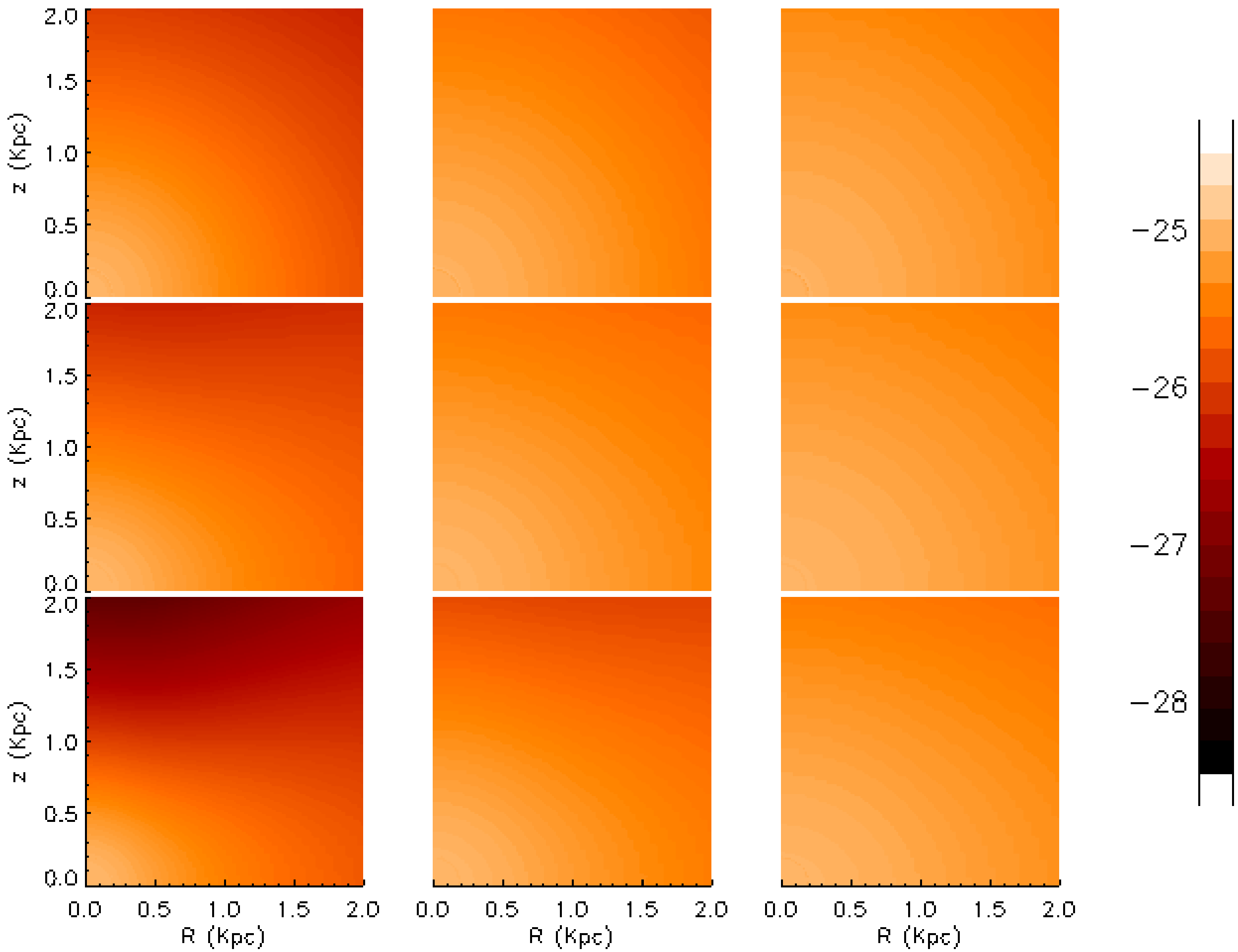
Results

$M_b = 10^7$ $M_b = 10^8$ $M_b = 10^9$

$\frac{b}{a} = 5$, roundish

$\frac{b}{a} = 1$, medium

$\frac{b}{a} = \frac{1}{5}$, flat



- Models with 90% of gas, as a function of mass and degree of flattening. Constant star formation for 500 Myr. First 200 Myr of evolution. Gas density distribution

Results

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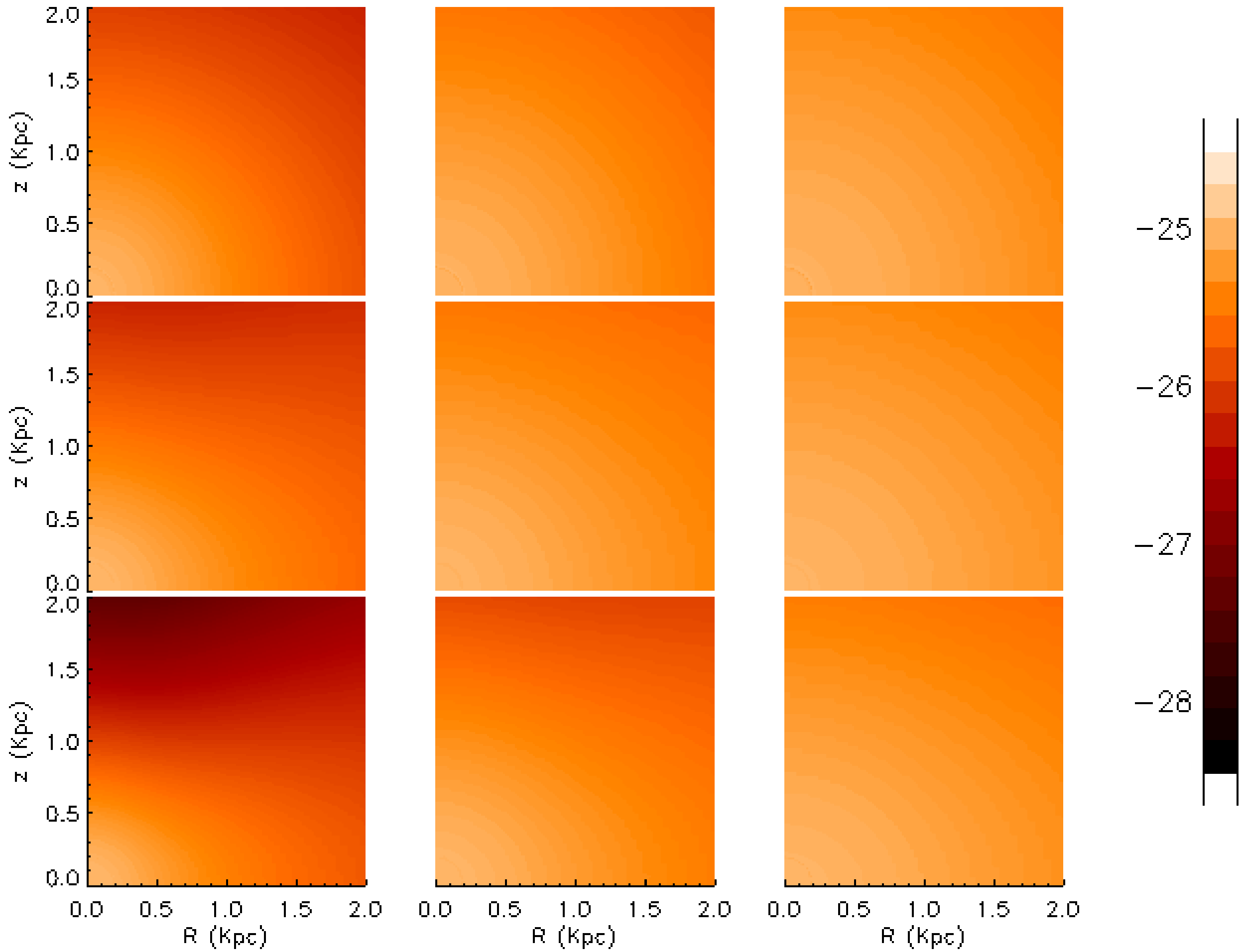

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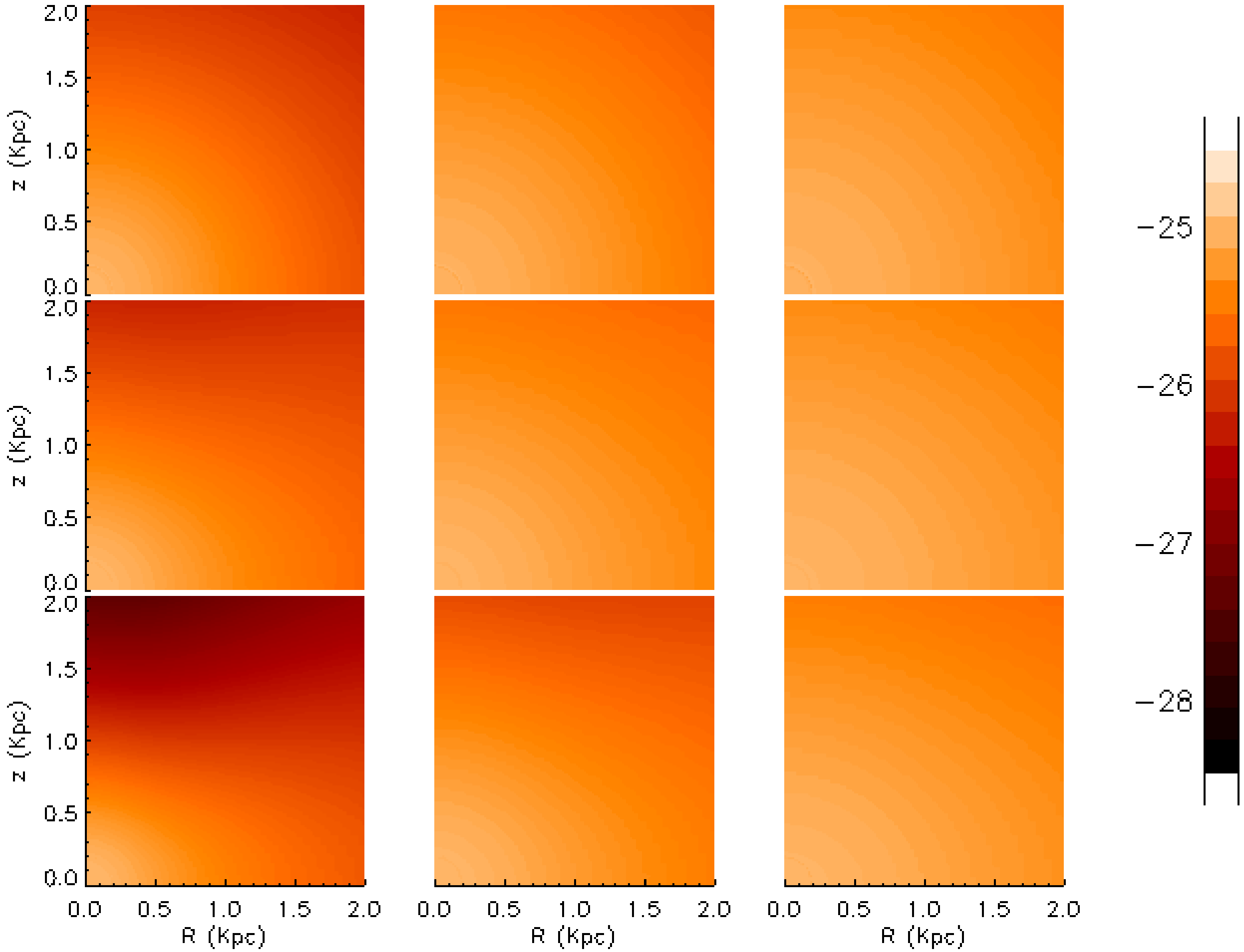

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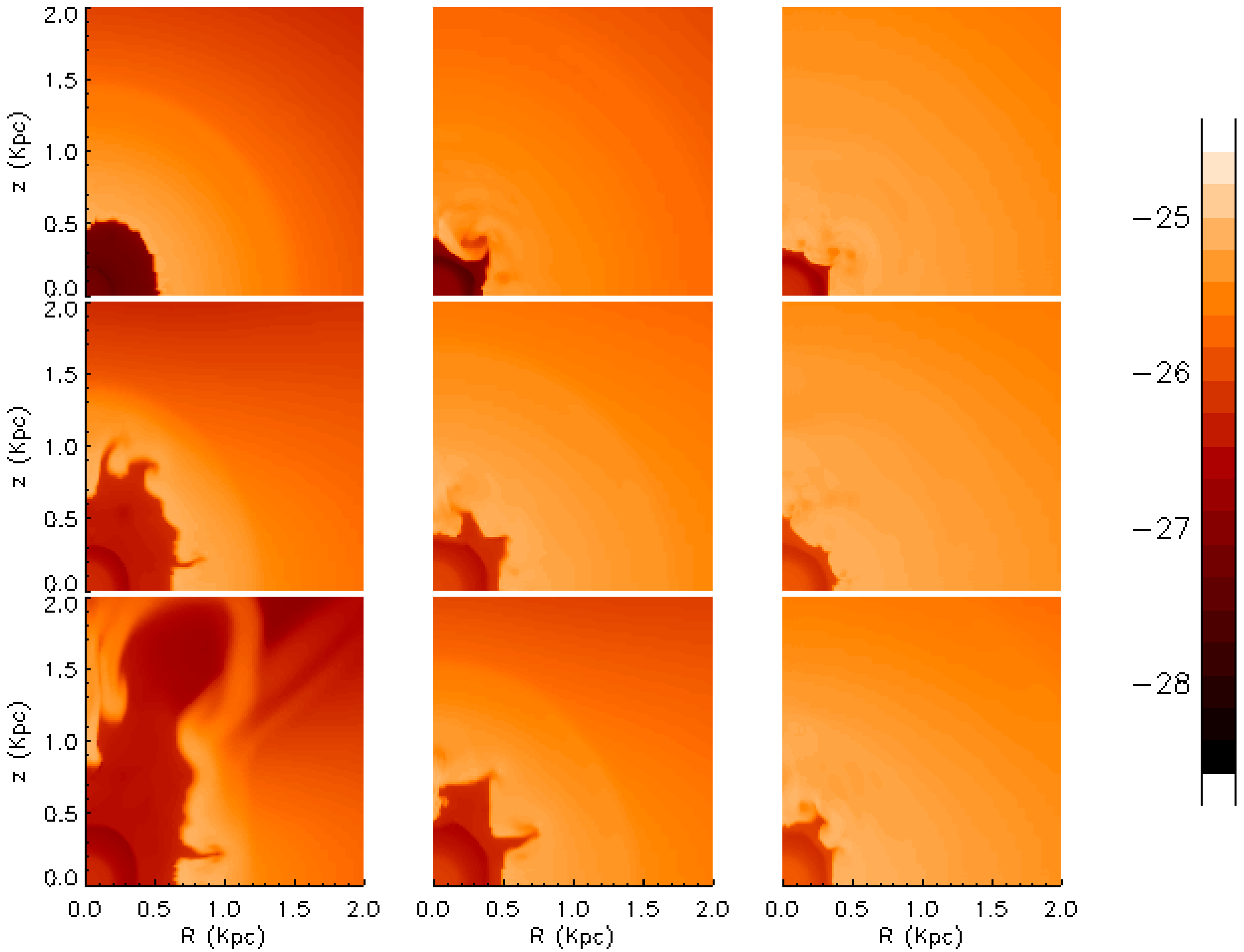


- Models with 90% of gas, as a function of mass and degree of flattening. Constant star formation for 500 Myr. First 200 Myr of evolution. Gas density distribution

Results

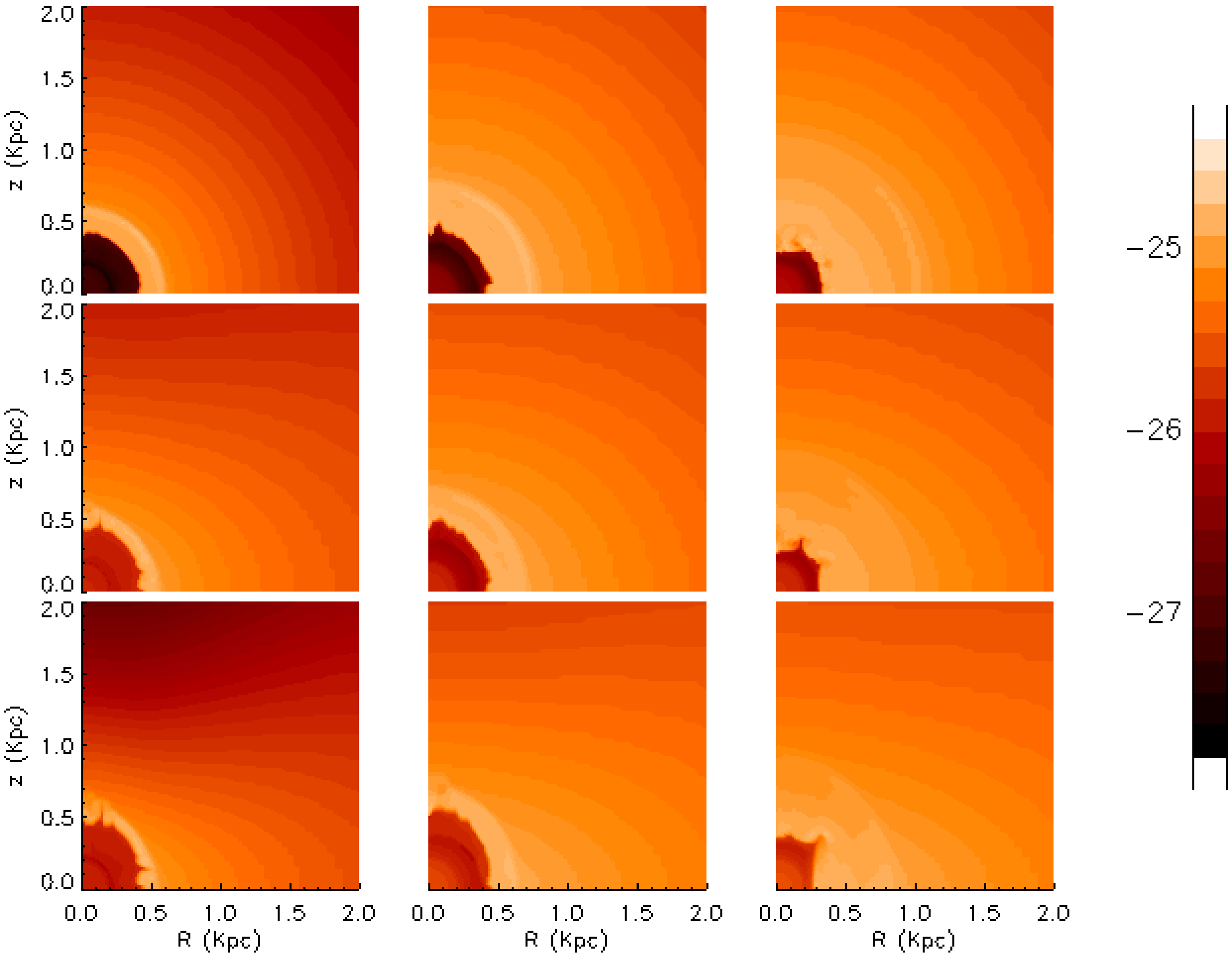
Models with 60% of gas. Gas distribution after 50 Myr

$M_b = 10^7$ $M_b = 10^8$ $M_b = 10^9$

$\frac{b}{a} = 5$

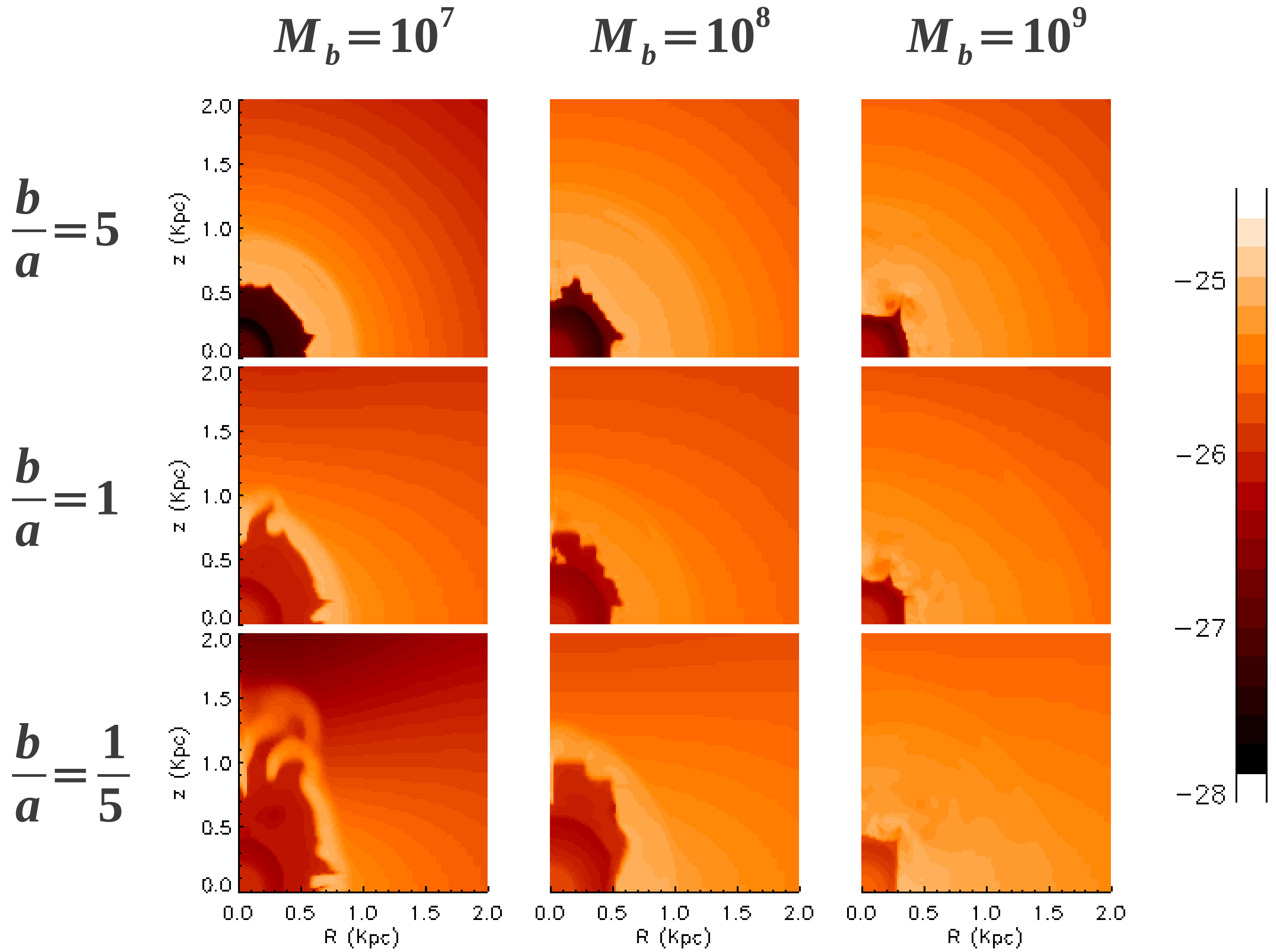
$\frac{b}{a} = 1$

$\frac{b}{a} = \frac{1}{5}$



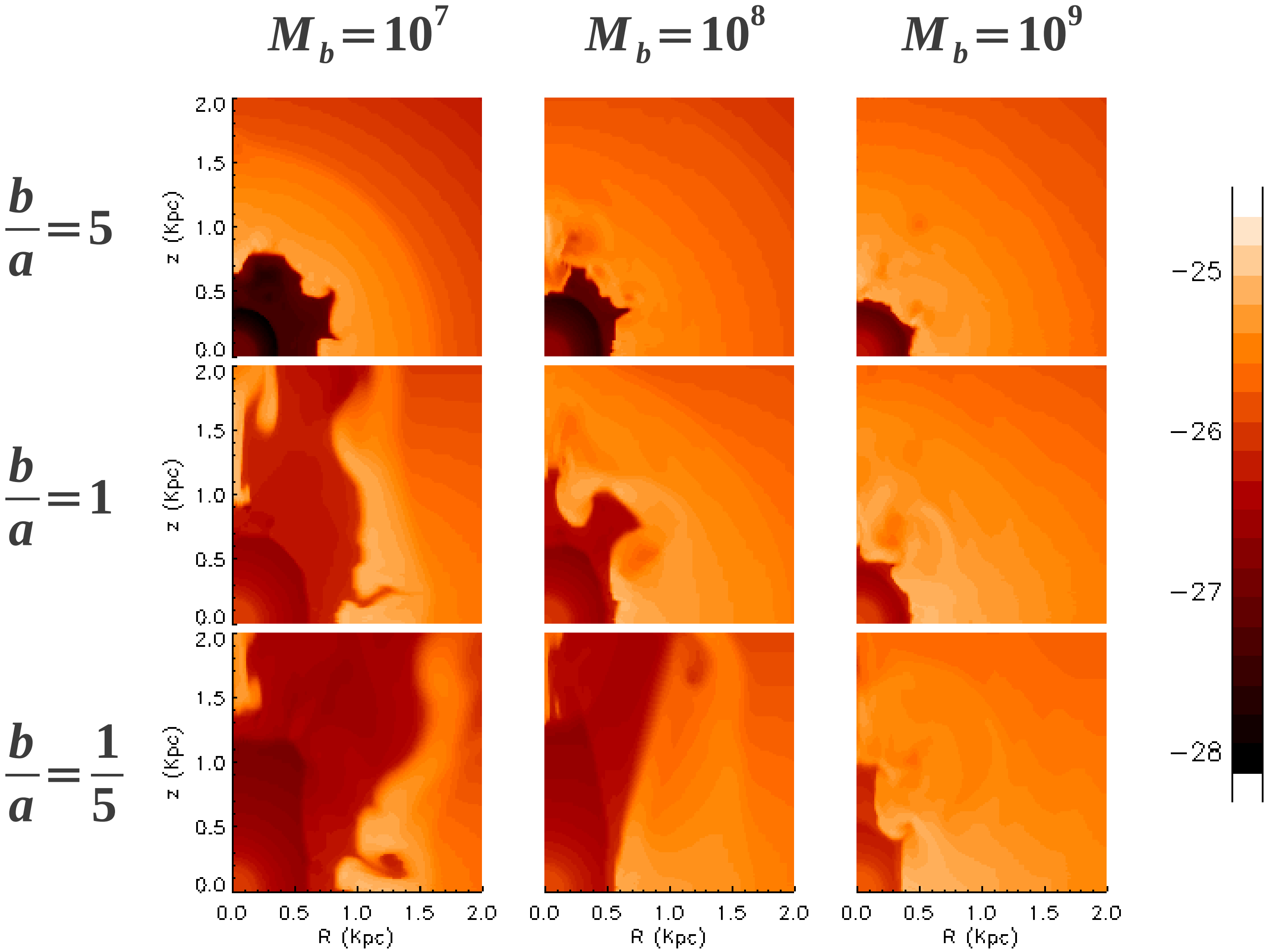
Results

Models with 60% of gas. Gas distribution after 100 Myr



Results

Models with 60% of gas. Gas distribution after 200 Myr



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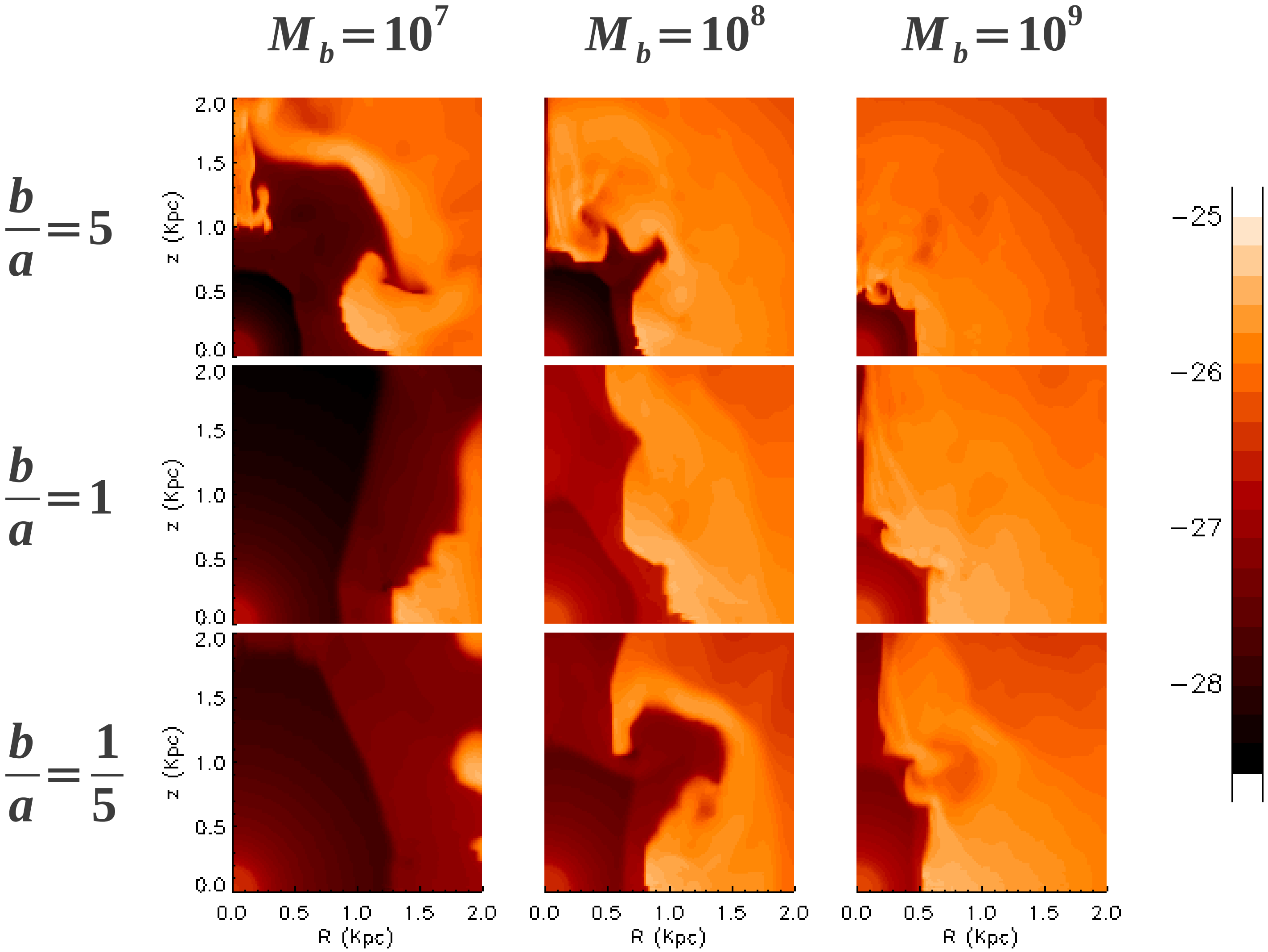
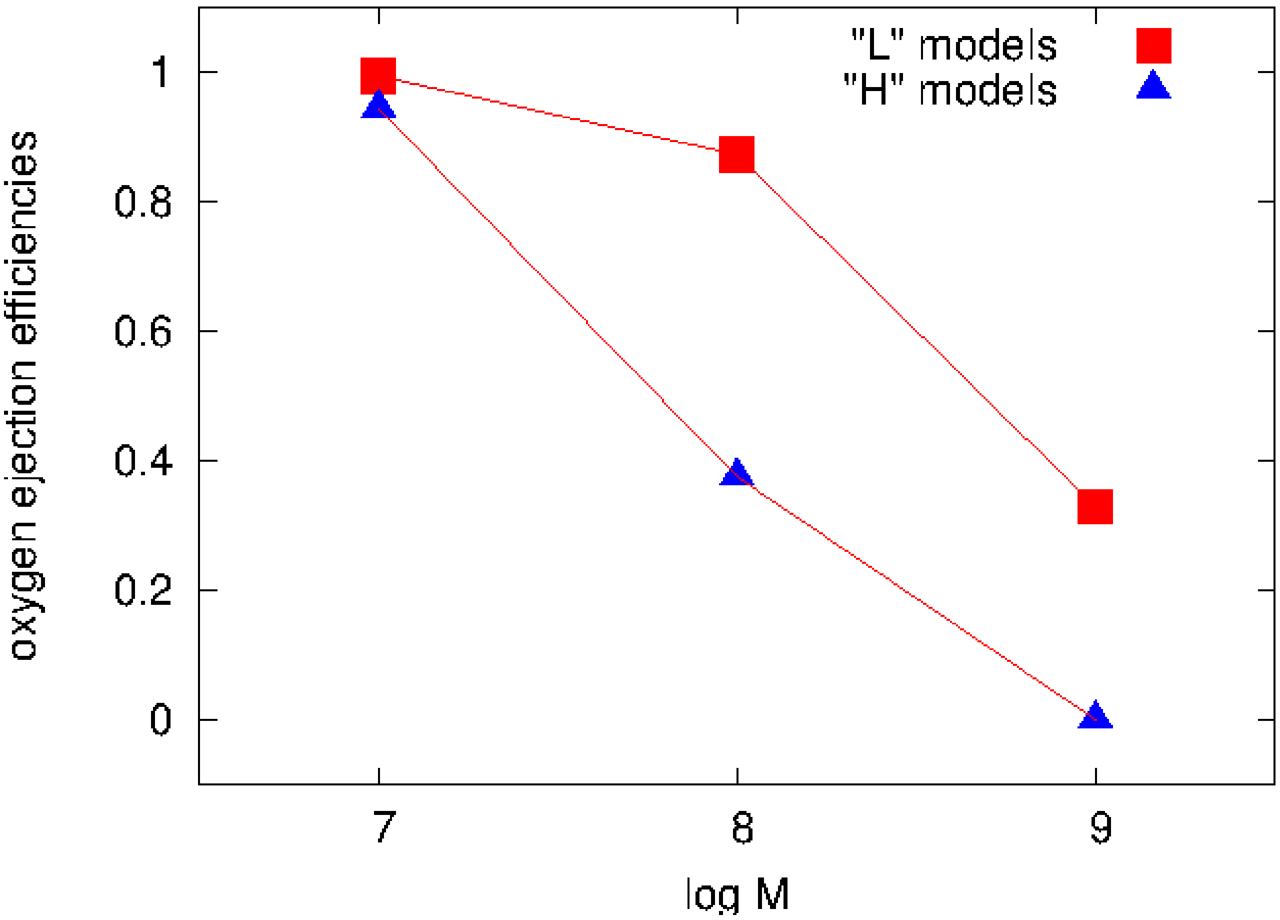
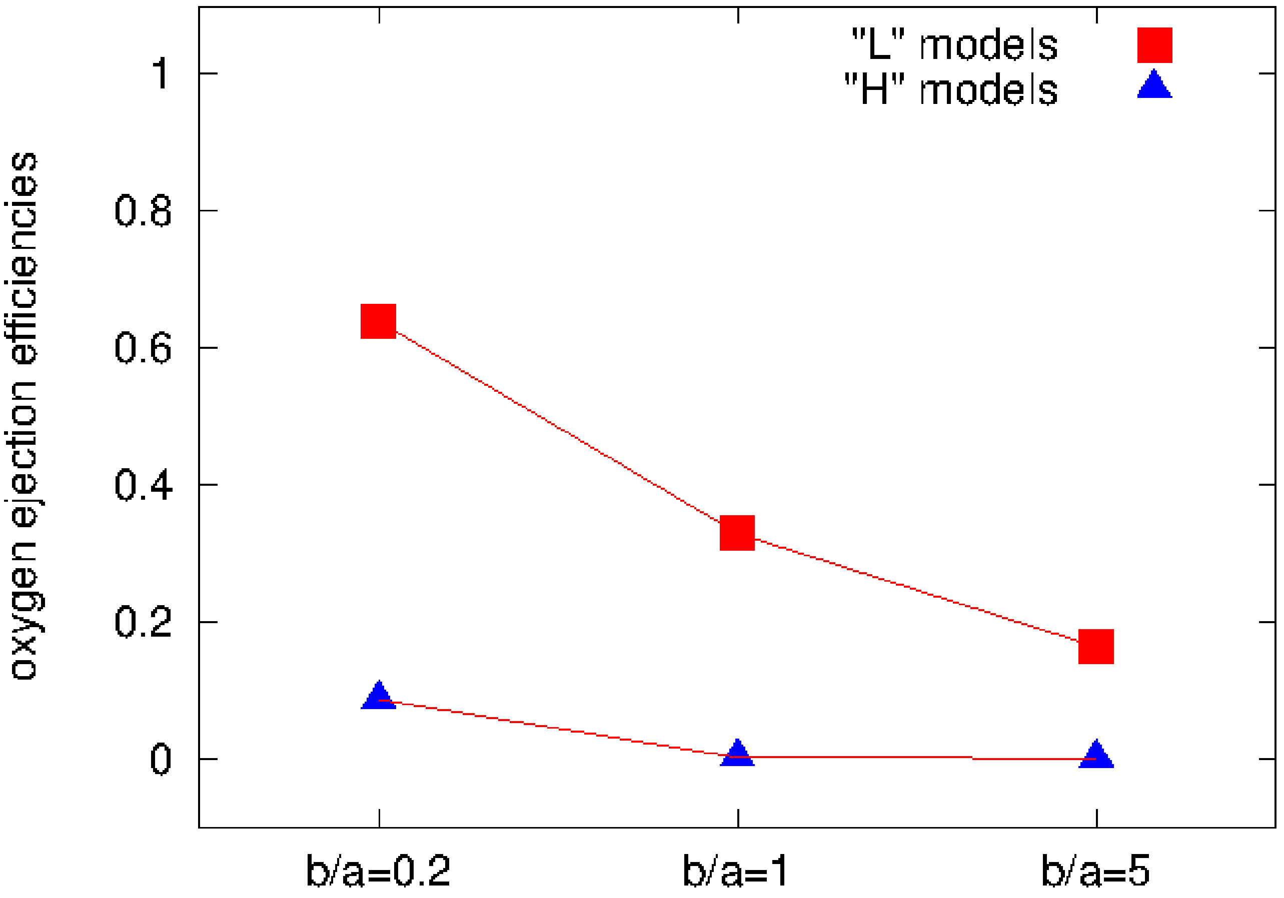


Oxygen ejection efficiency vs. mass



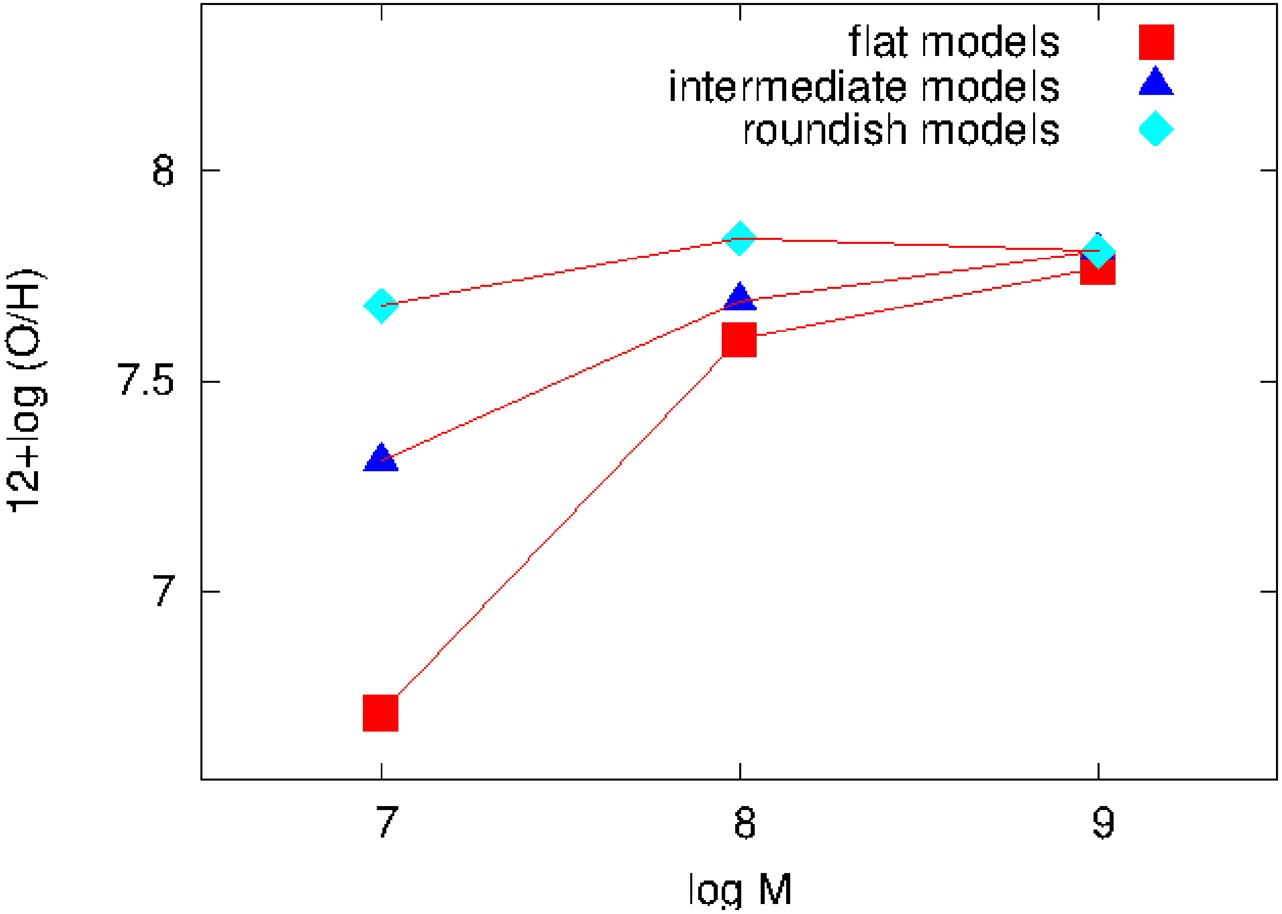
- Models with b/a=1
- Confirms previous results (MacLow & Ferrara 1999)

Oxygen ejection efficiency vs. degree of flattening



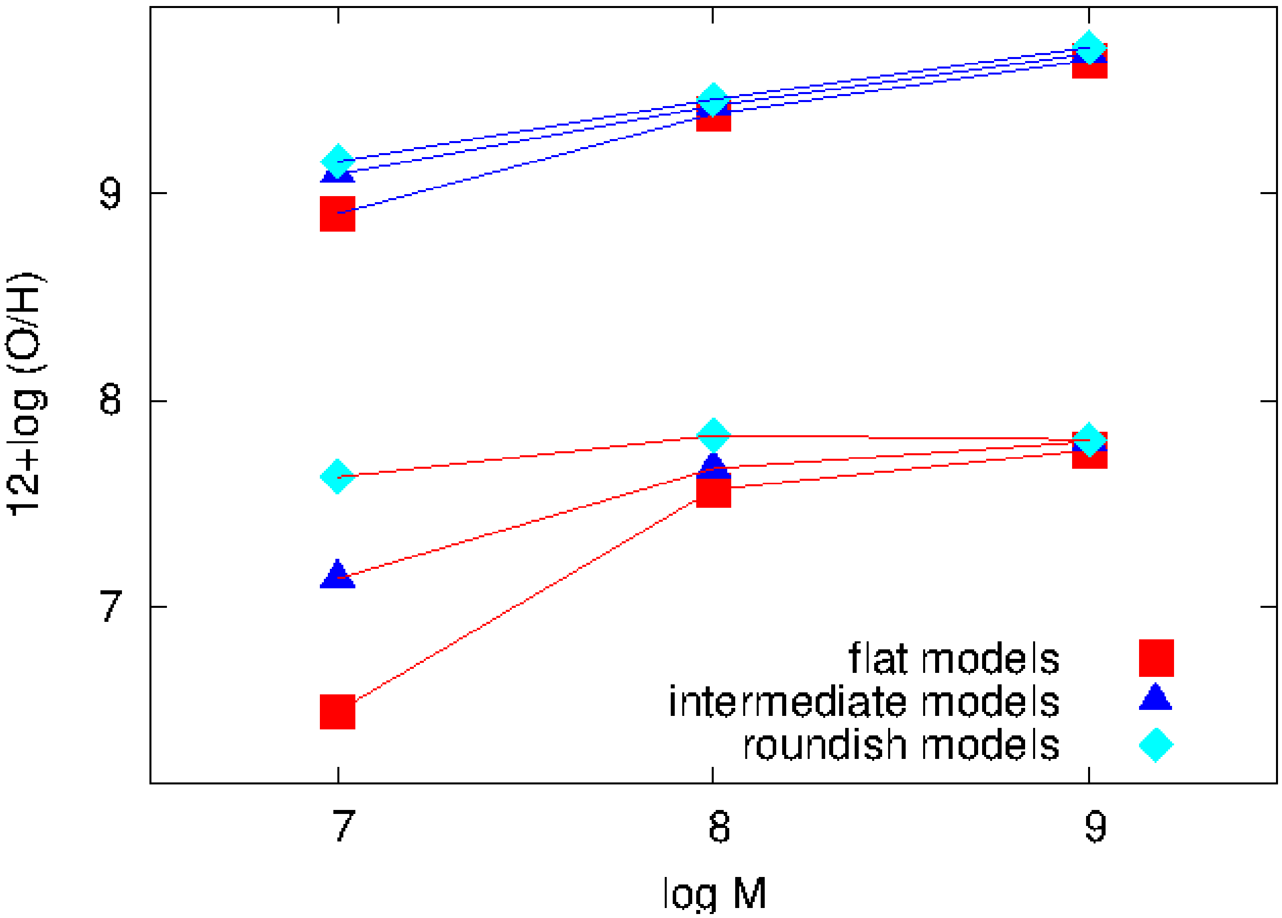
- Models with $10^9\ M_{\odot}$.
- Oxygen ejection efficiencies can vary by one order of magnitude. Notice that the total gas ejection efficiencies do not vary significantly with b/a!

The mass-metallicity relation



- Low-mass models show large variations of the final O/H as a function of the degree of flattening
- The models predict a spread in the mass-metallicity relation, particularly at low masses.

Hot- and cold-phase abundances



- Threshold temperature $2*10^4$ K.
- We have checked that a variation of this threshold temperature has a negligible effect.

Concluding remarks

- We confirm that the ejection efficiencies of metals is larger (often much larger) than the ejection efficiency of pristine gas.
- However, this does not hold for spherical or quasi-spherical galaxies.
- The degree of flattening of a galaxy can change the fraction of ejected metals by up to one order of magnitude
- On the other hand, the ejection efficiency of pristine gas is much less dependent on the degree of flattening.
- Consequently, the degree of flattening can change the final metallicity of a galaxy by up to one dex.
- High-mass galaxies retain a much larger fraction of metals than low-mass ones (confirming many previous studies).

Outlook

Stellar hydrodynamics (Vorobyov, Hensler, Mitchell, SR)

In a grid-based simulation stars can be described as a fluid! The moments of the collisionless Boltzmann equation

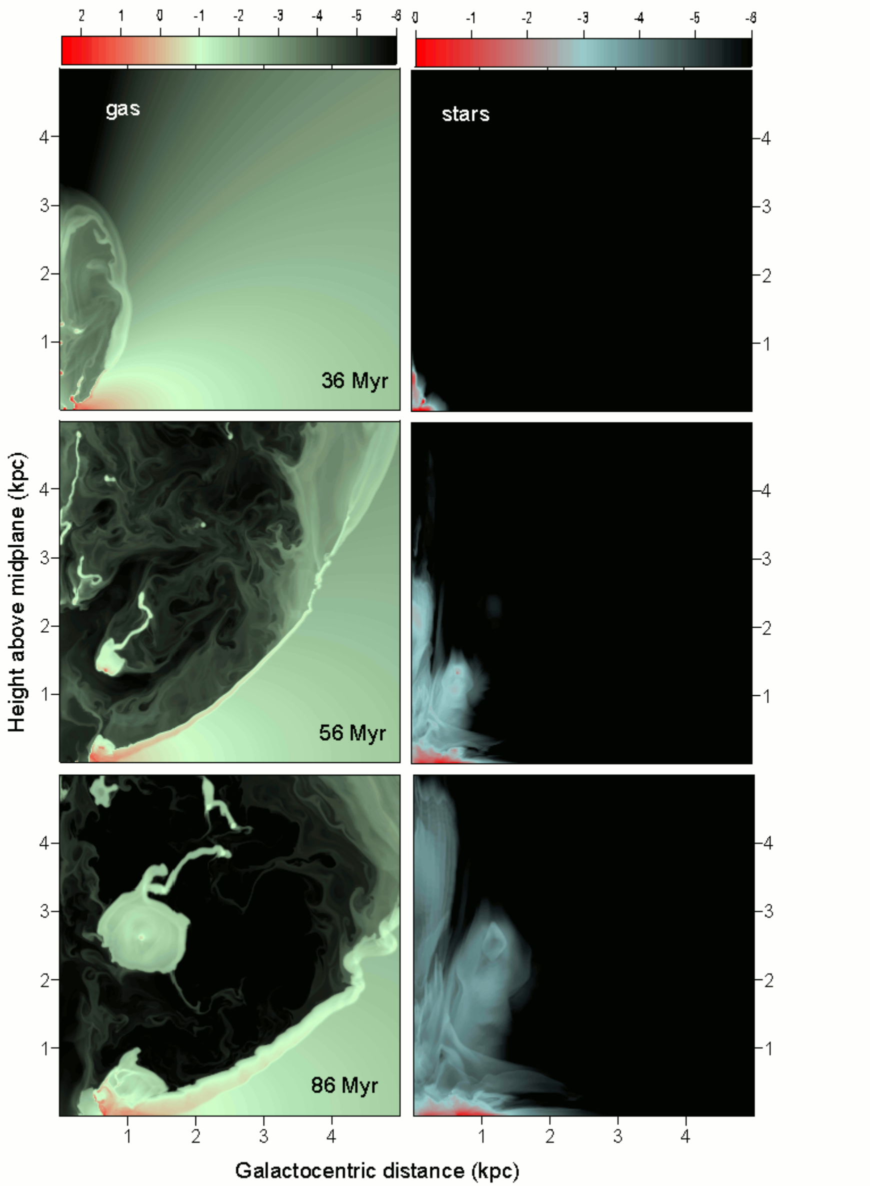
$$\frac{\partial f}{\partial t}+v_i\frac{\partial f}{\partial x_i}+\frac{\partial \Phi}{\partial x_i}\frac{\partial f}{\partial v_i}=0$$

are calculated until the second-order moments (third order moments are set to zero), f being the distribution function

$$f(t, x_i, v_i)=A\exp\left[-\sum_i v_i^2/\sigma_i^2\right]$$

A set of equations similar to the Euler equation is thus obtained.

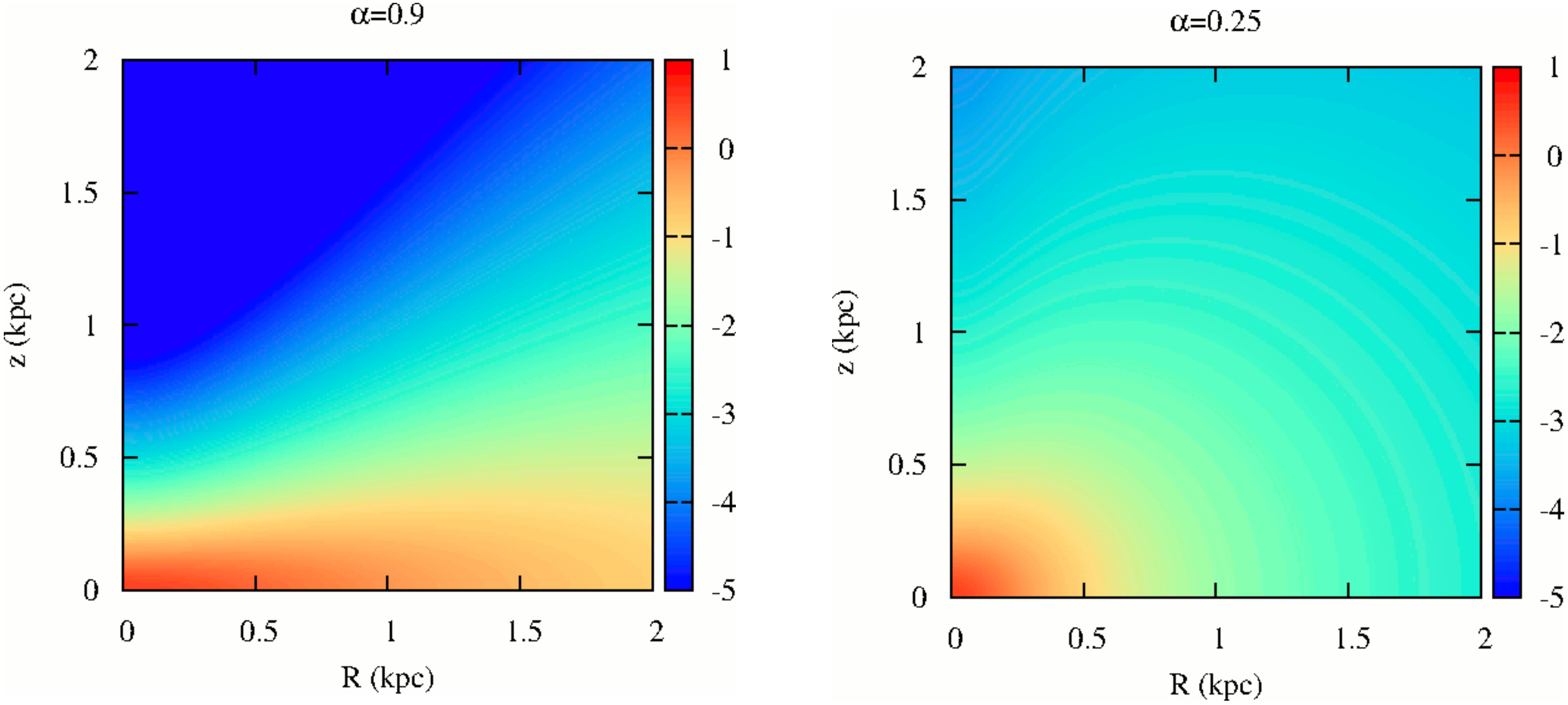
We are currently performing chemo-dynamical simulations of dwarf galaxies with stellar hydrodynamics included



Outlook

Initial conditions including self-gravity (Vorobyov, Hensler, SR).

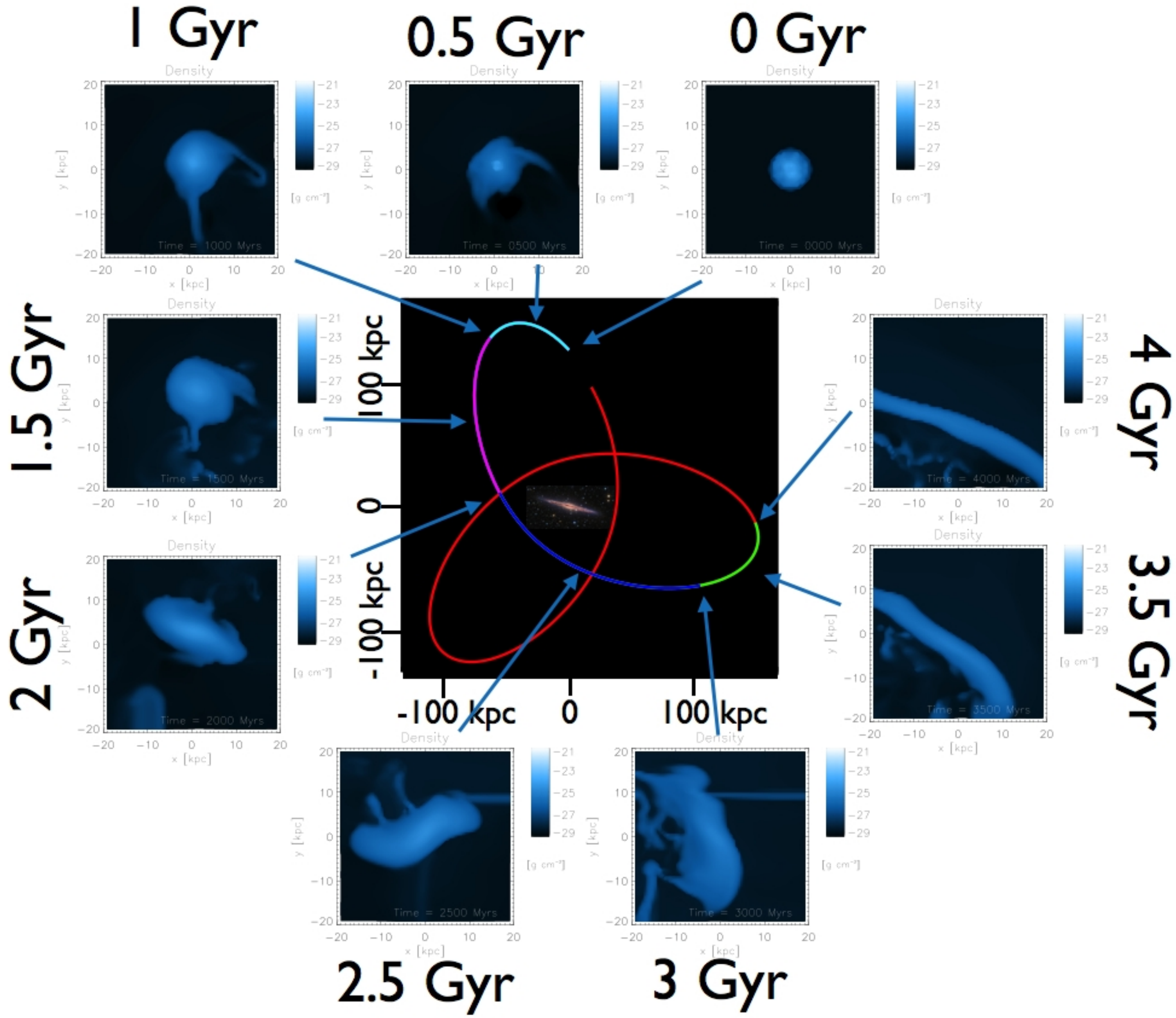
The gas is initially set in equilibrium also with the gas self-gravity. The Poisson equation and the equation of hydrostatic equilibrium are simultaneously solved by means of an iterative procedure. Different degrees of centrifugal support are parametrized by α.



Vorobyov, SR & Hensler 2012

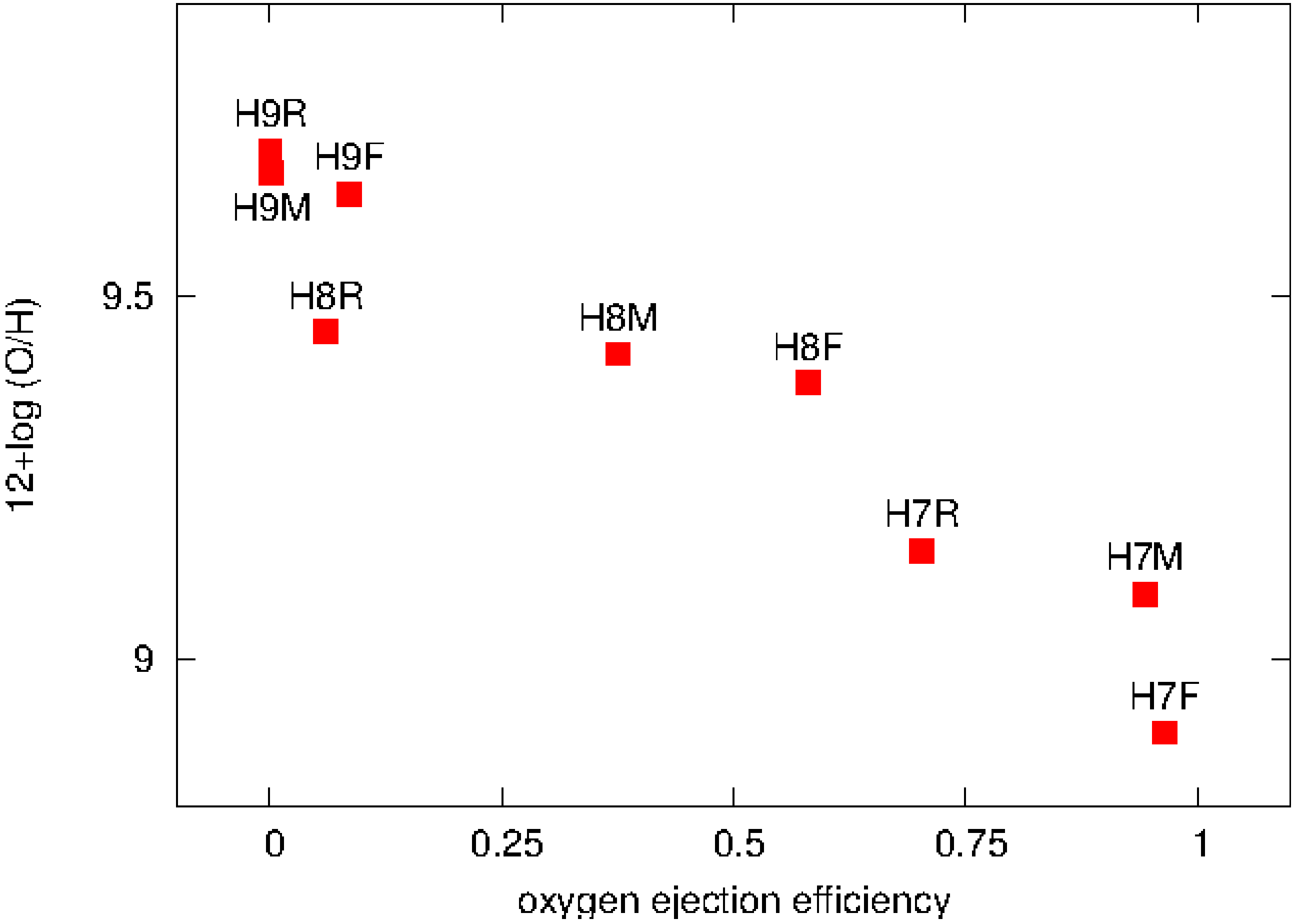
Outlook

Dynamical and chemical evolution of dwarf galaxies orbiting a massive galaxy (S. Plöckinger, Hensler, SR)



Thank you for the attention!

Hot-phase abundances and ejection efficiencies

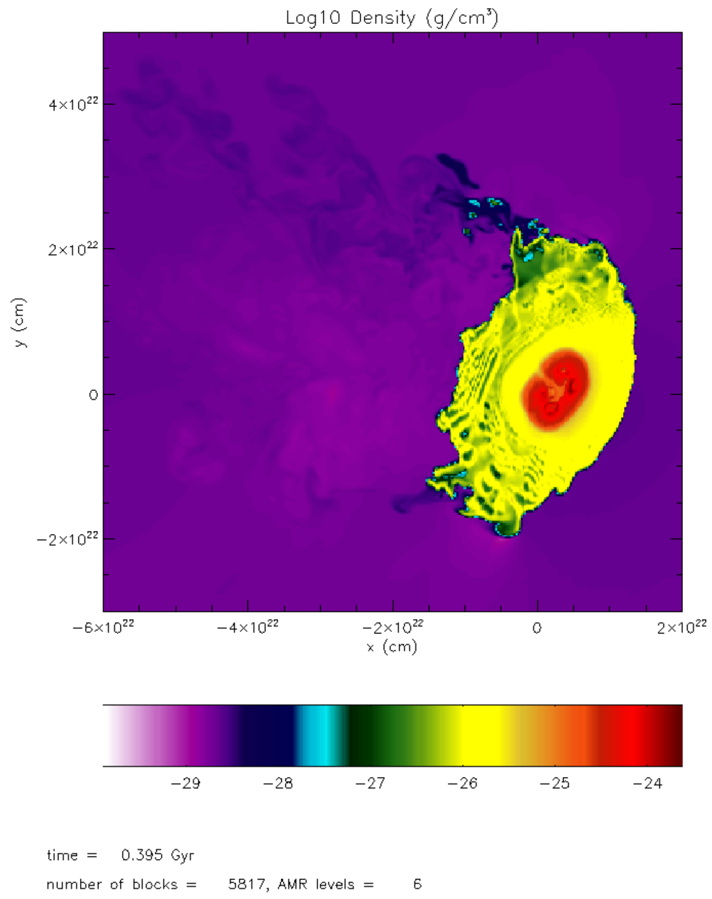


- Correlation mainly due to mass loading of the outflow

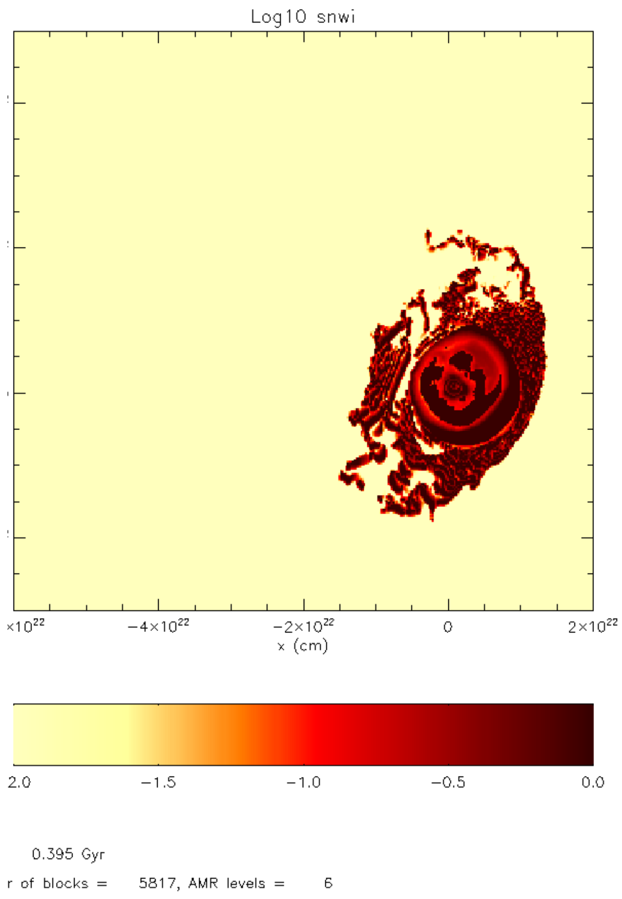
Outlook

Dynamical and chemical evolution of dwarf galaxies orbiting a massive galaxy (S. Plöckinger, Hensler, SR)

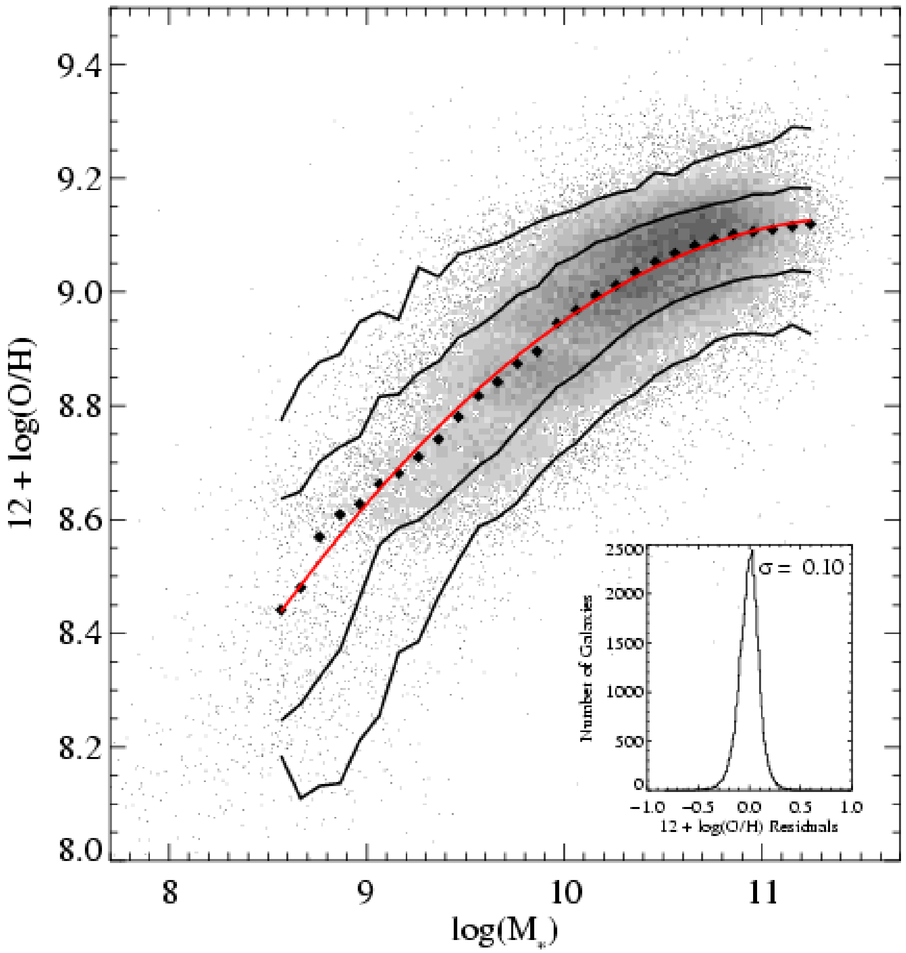
Density



Metallicity

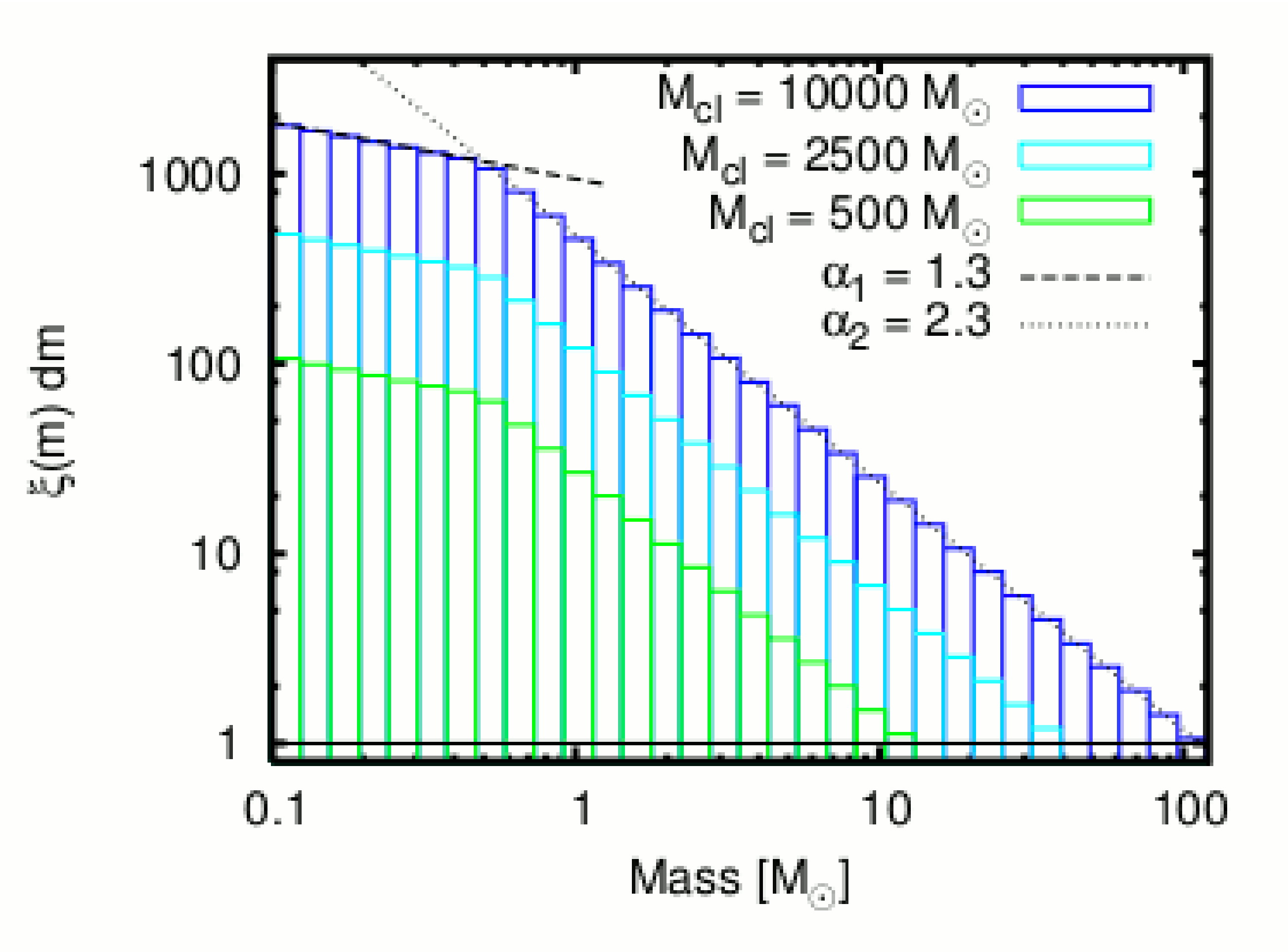


The mass-metallicity relation



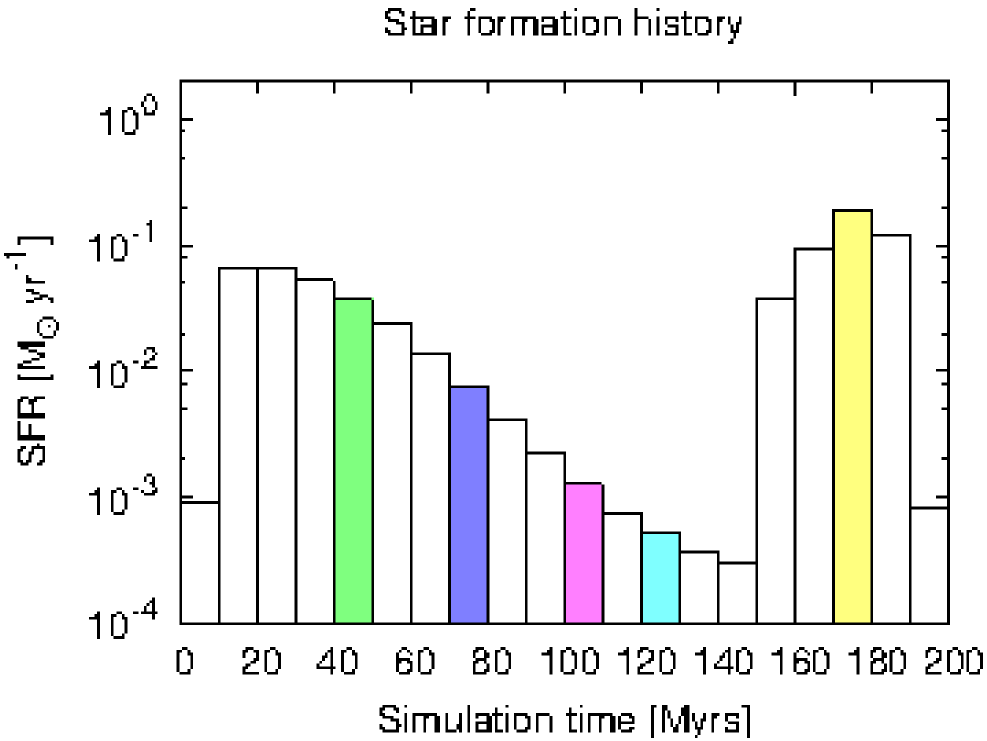
- From Tremonti et al. (2004)
- Spread largest for low-mass objects?

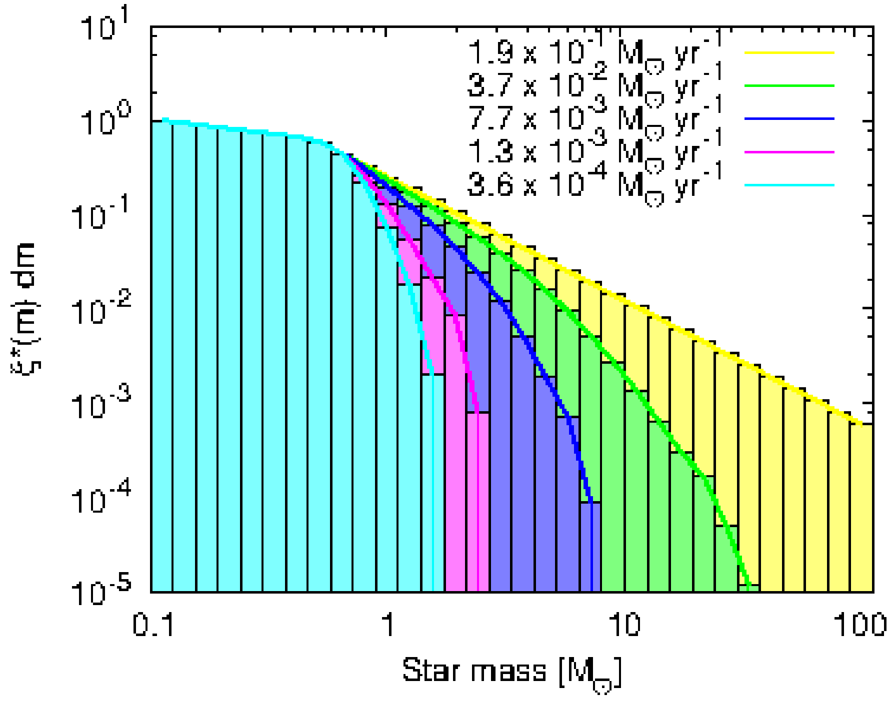
Chemodynamical evolution of Satellite galaxies



- IMF for each stellar cluster is truncated if the number of stars per mass bin becomes equal to 1.
- Maximal lifetime of star cluster: 10 Myr → if the SFR is low, most of the clusters will be small and the IMF will be truncated at low masses

Chemodynamical evolution of Satellite galaxies

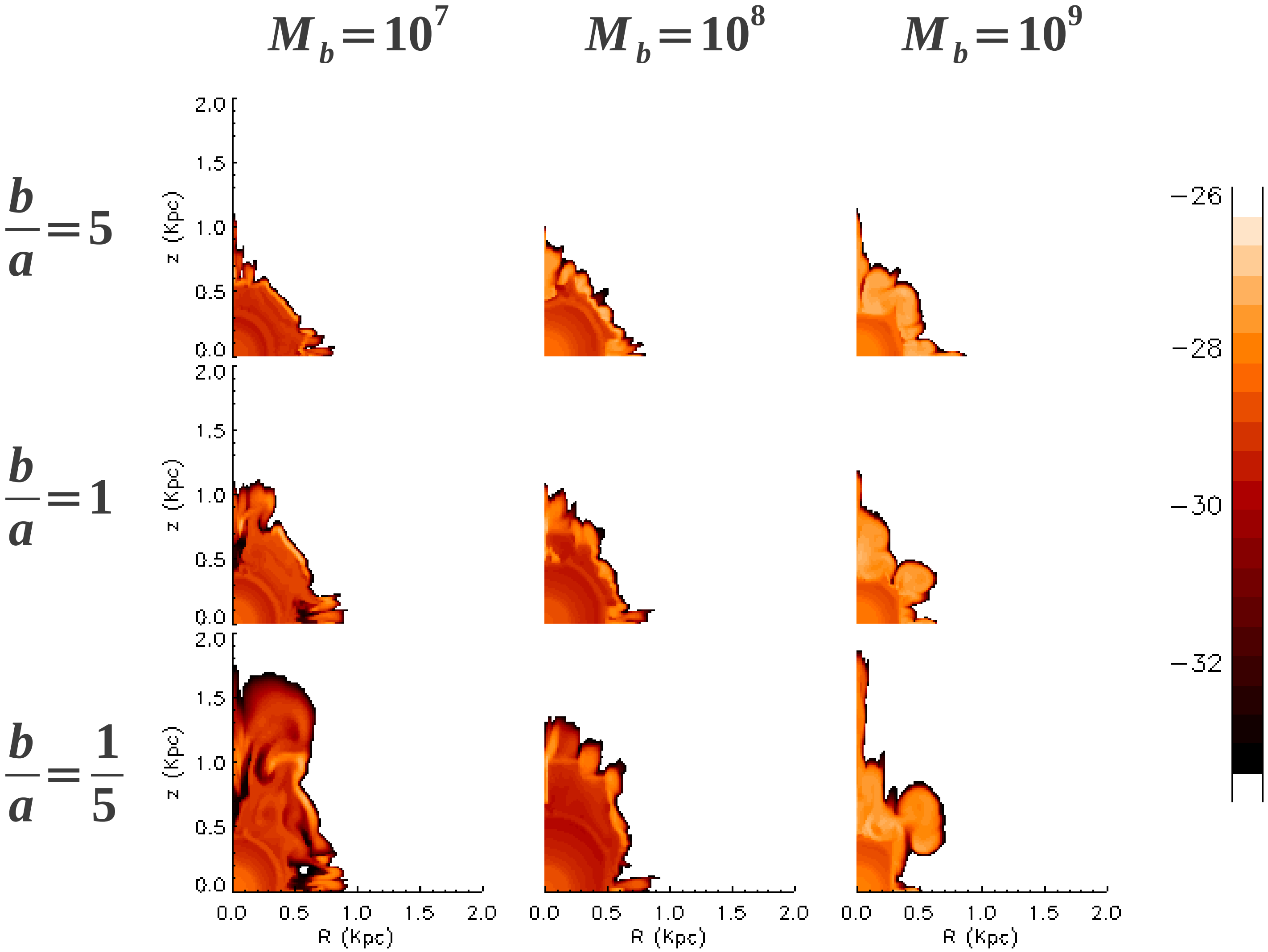




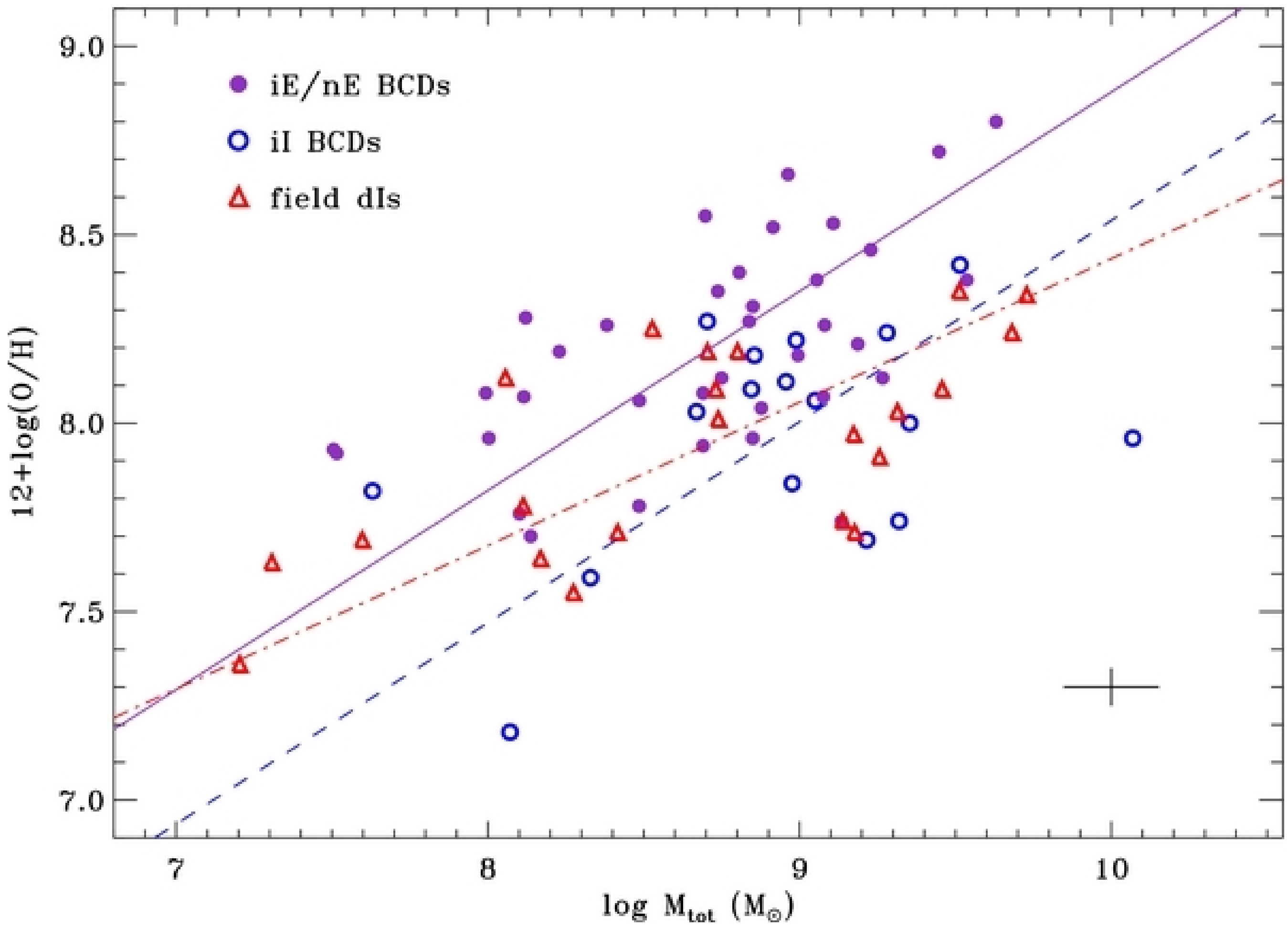
- That resembles the IGIMF formulation!

The fate of freshly produced oxygen

Oxygen distribution after 100 Myr



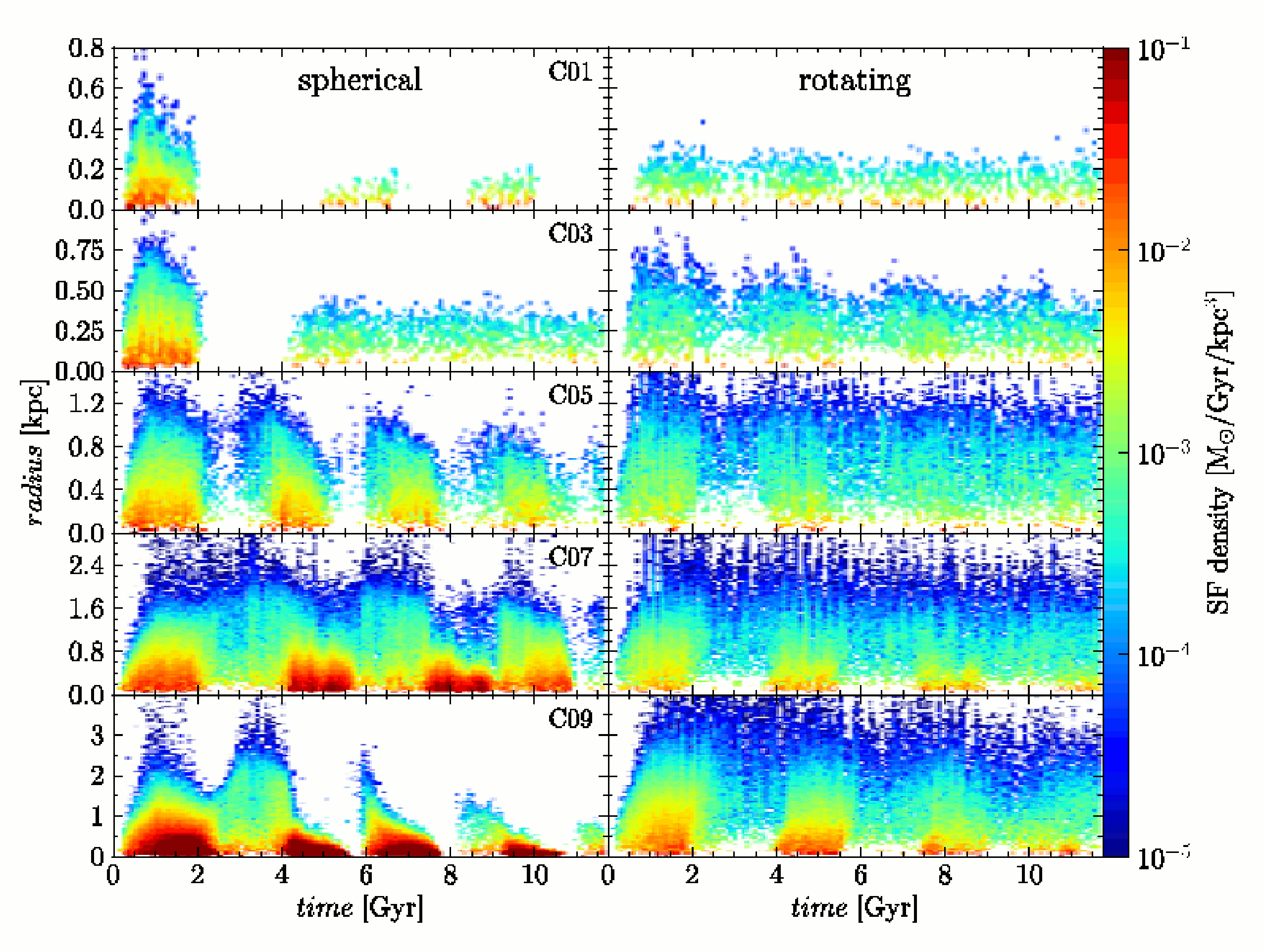
The mass-metallicity relation



- From Zhang et al. (2013)
- Spread largest for low-mass objects?

The effect of rotation

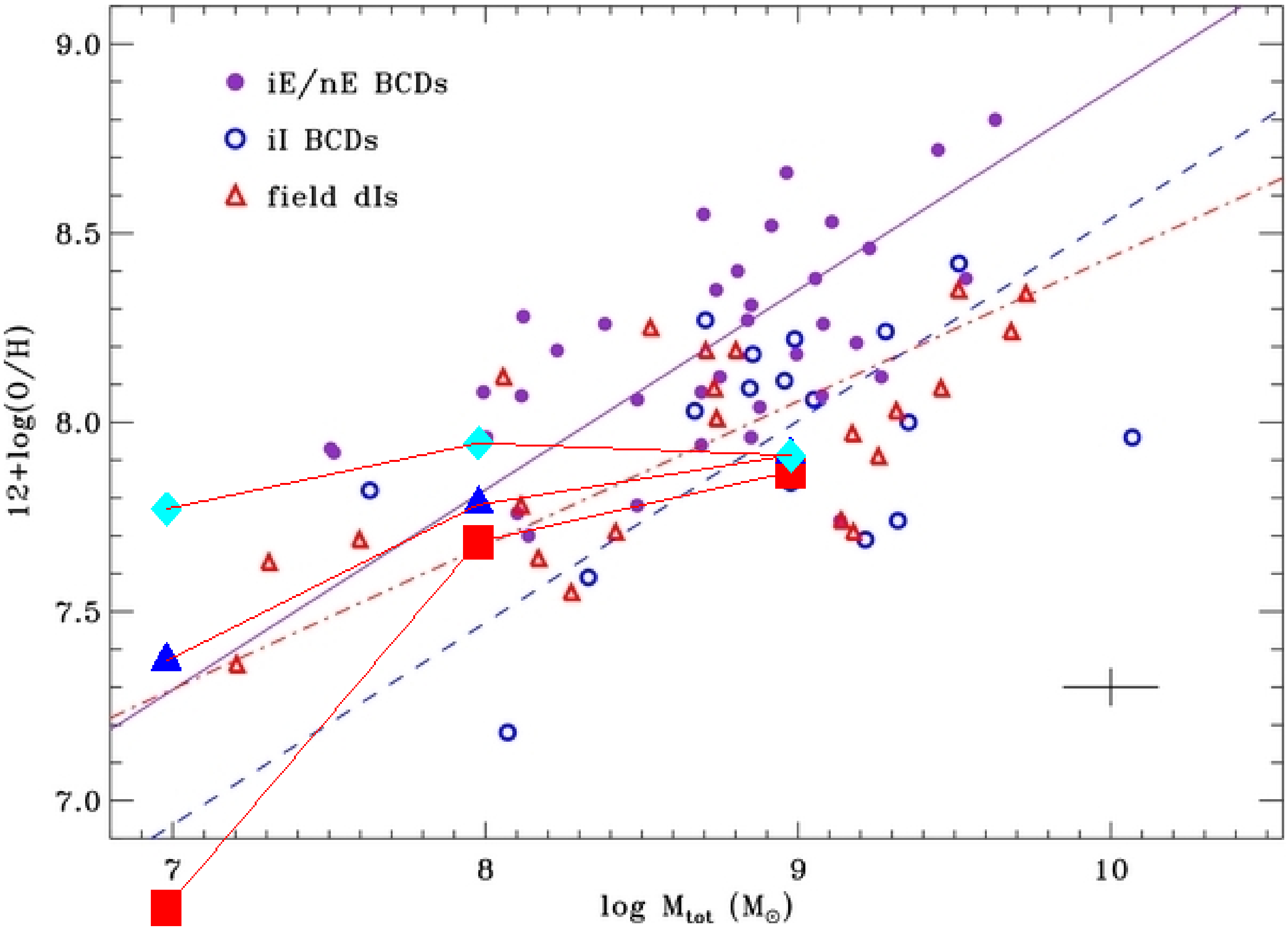
(Schroyen et al. 2011)



- Rotating galaxies allow for a more evenly distributed star formation density. Metallicity gradients turn out to be flatter

- Usually these models do not develop galactic winds

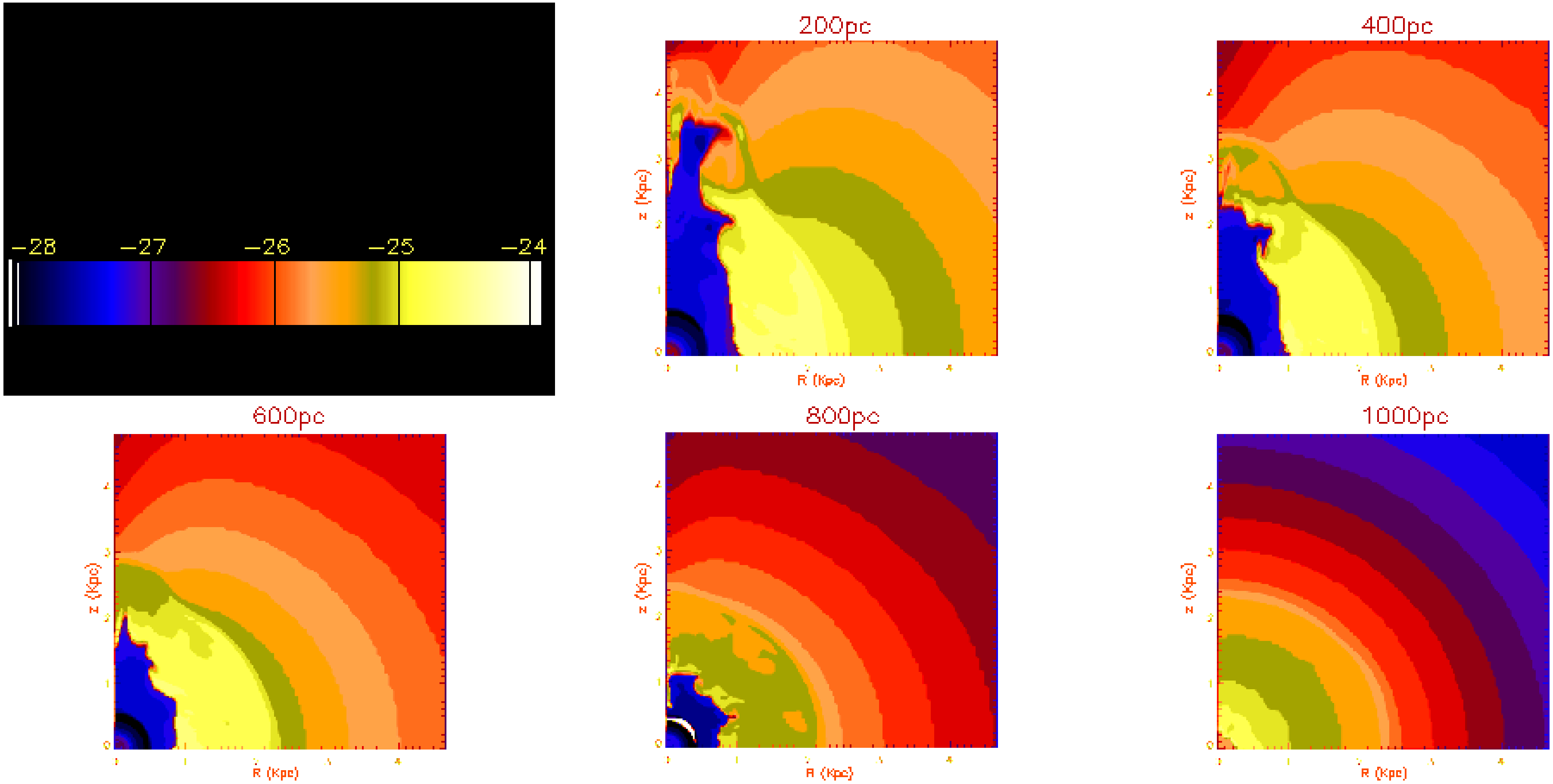
The mass-metallicity relation



- Data from Zhang et al. (2013)
- The models predict a spread in the mass-metallicity relation

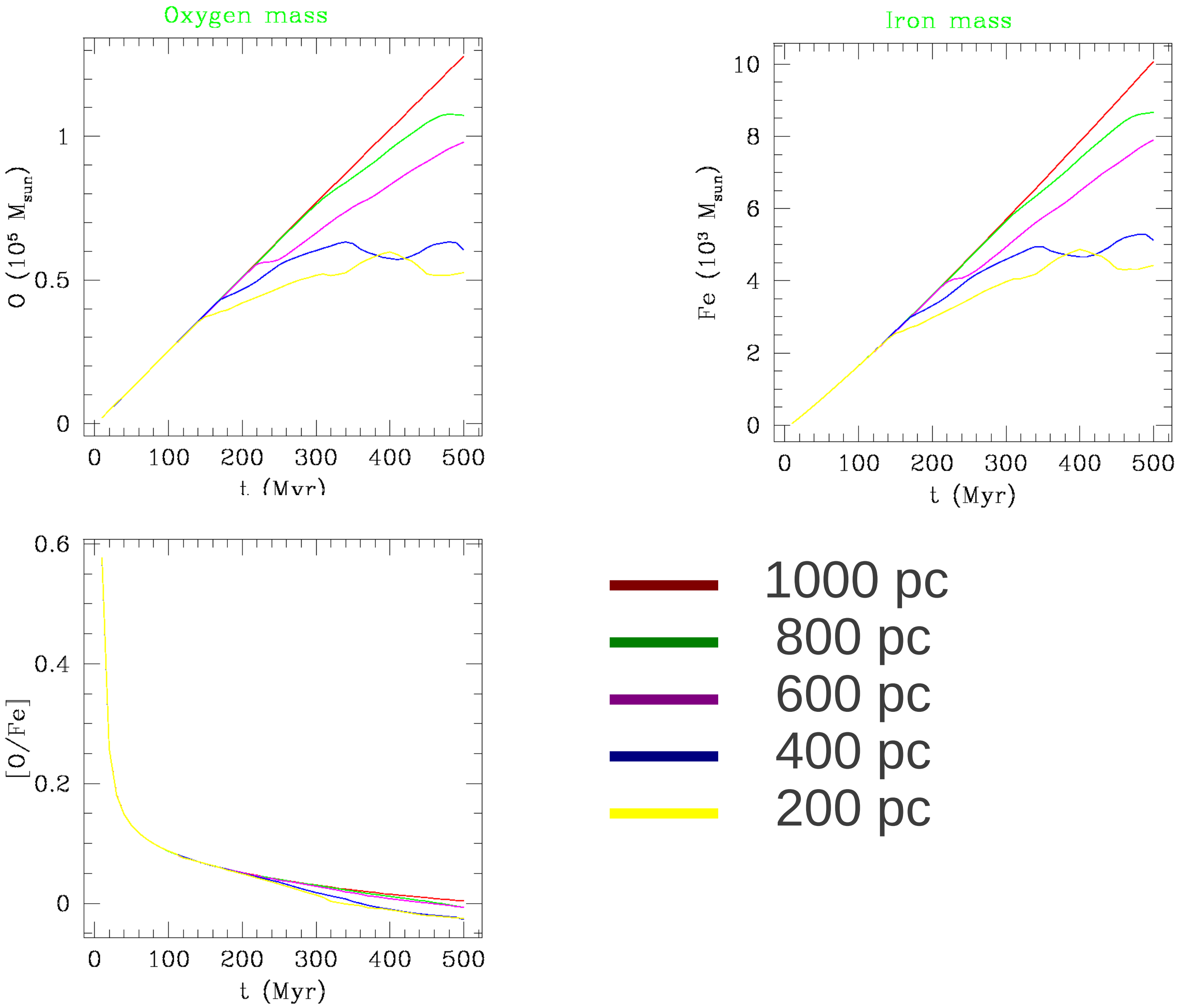
Galactic wind development vs. flattening

Star formation constant for 500 Myr. Gas semi-mayor axis: 1000 pc. Variable gas semi-minor axis. Gas density distribution.

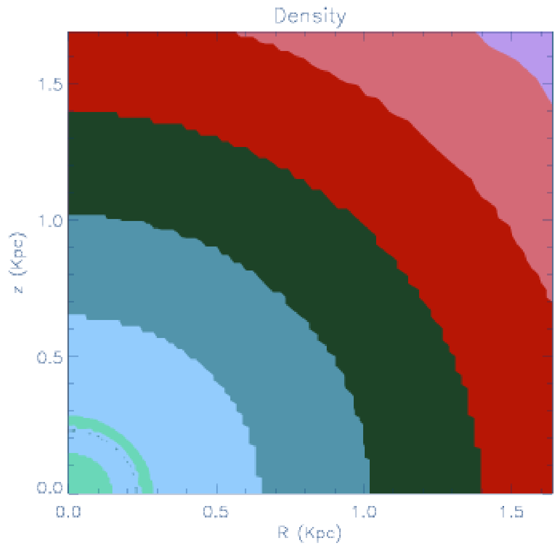


Galactic wind development vs. flattening

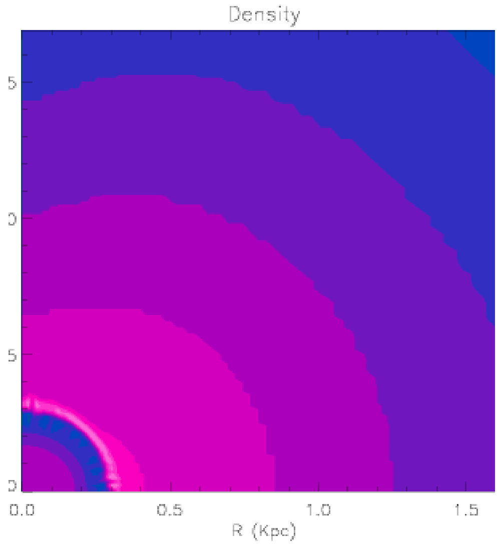
Star formation constant for 500 Myr. Gas semi-mayor axis: 1000 pc. Variable gas semi-minor axis. Evolution of abundances.



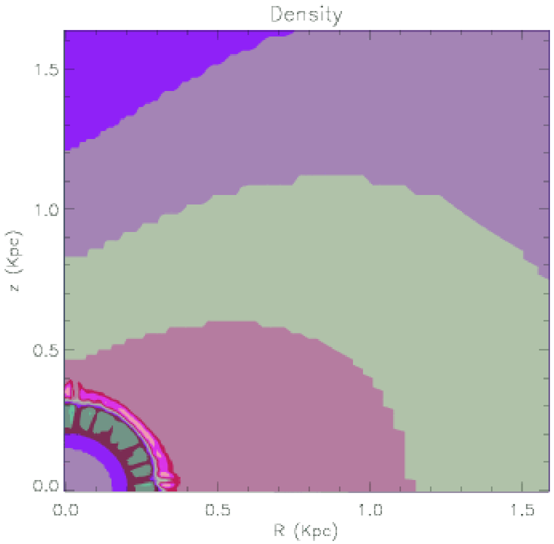
Semi-major axis: 1 Kpc. Variable semi-minor axis



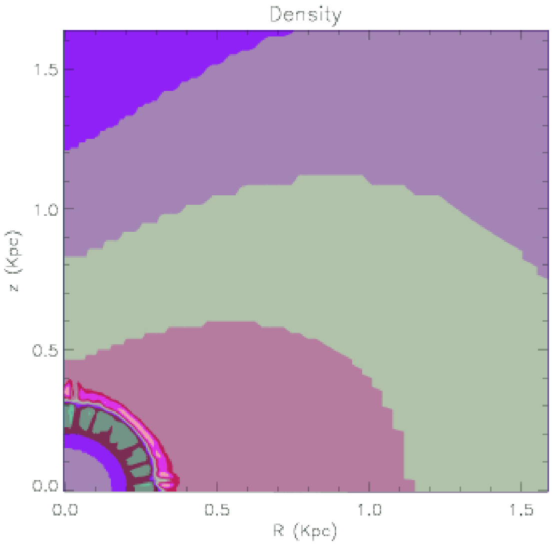
1000 pc



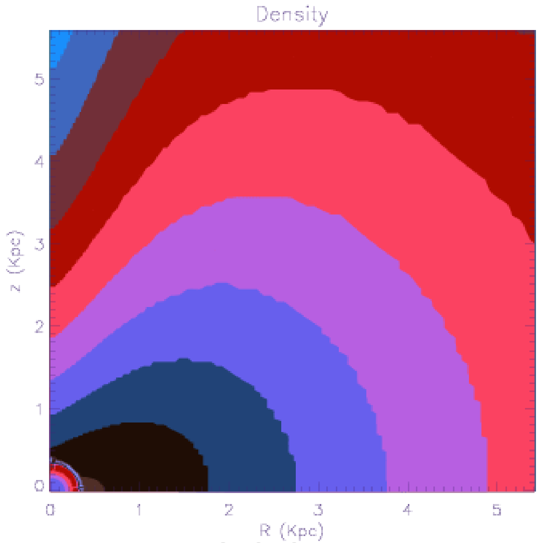
800 pc



600 pc



400 pc



200 pc

Future work

- Run self-consistent chemo-dynamical simulations of galaxies within the IGIMF theory.