Extreme Simulations of Starburst-Driven Galactic Winds

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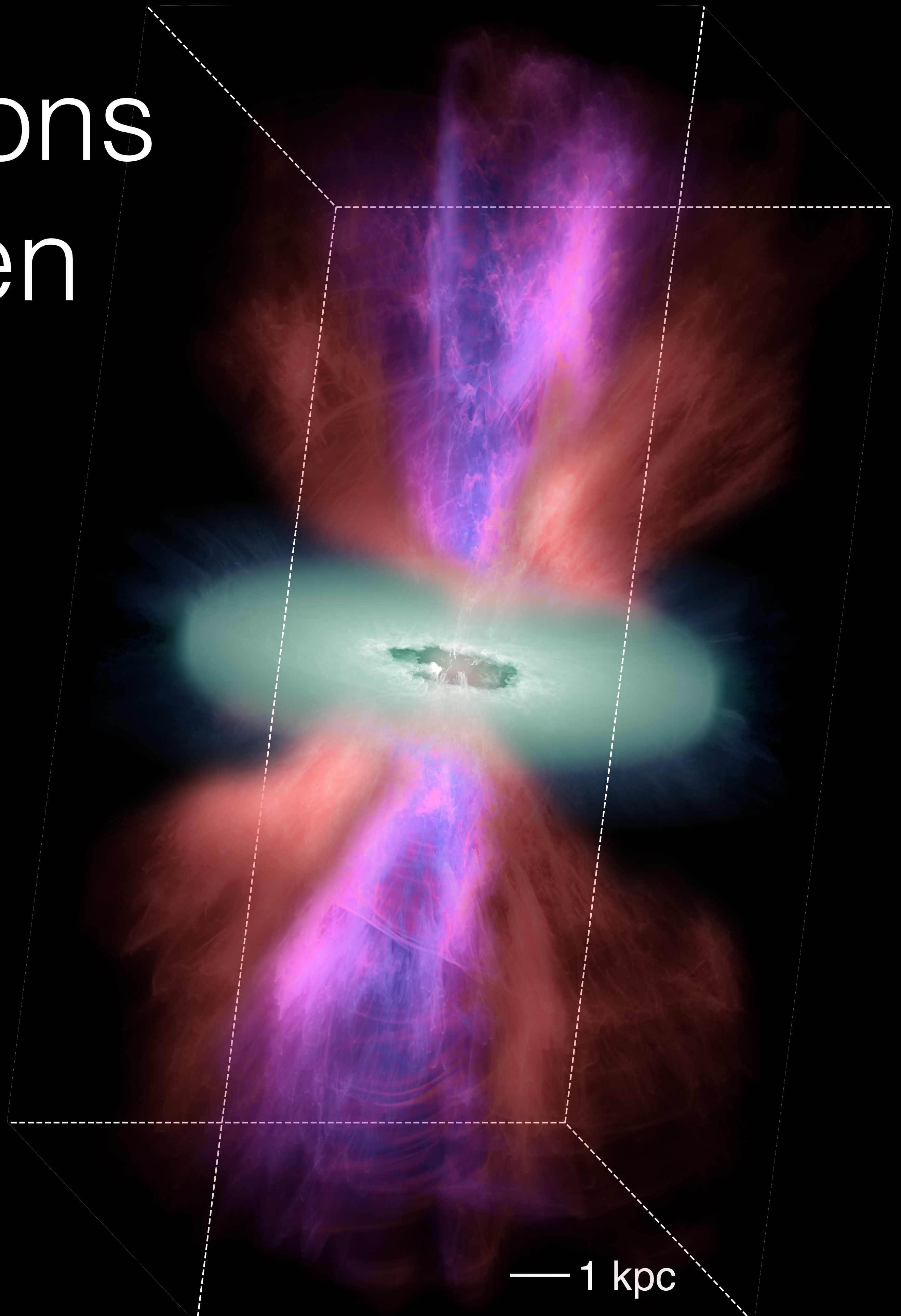

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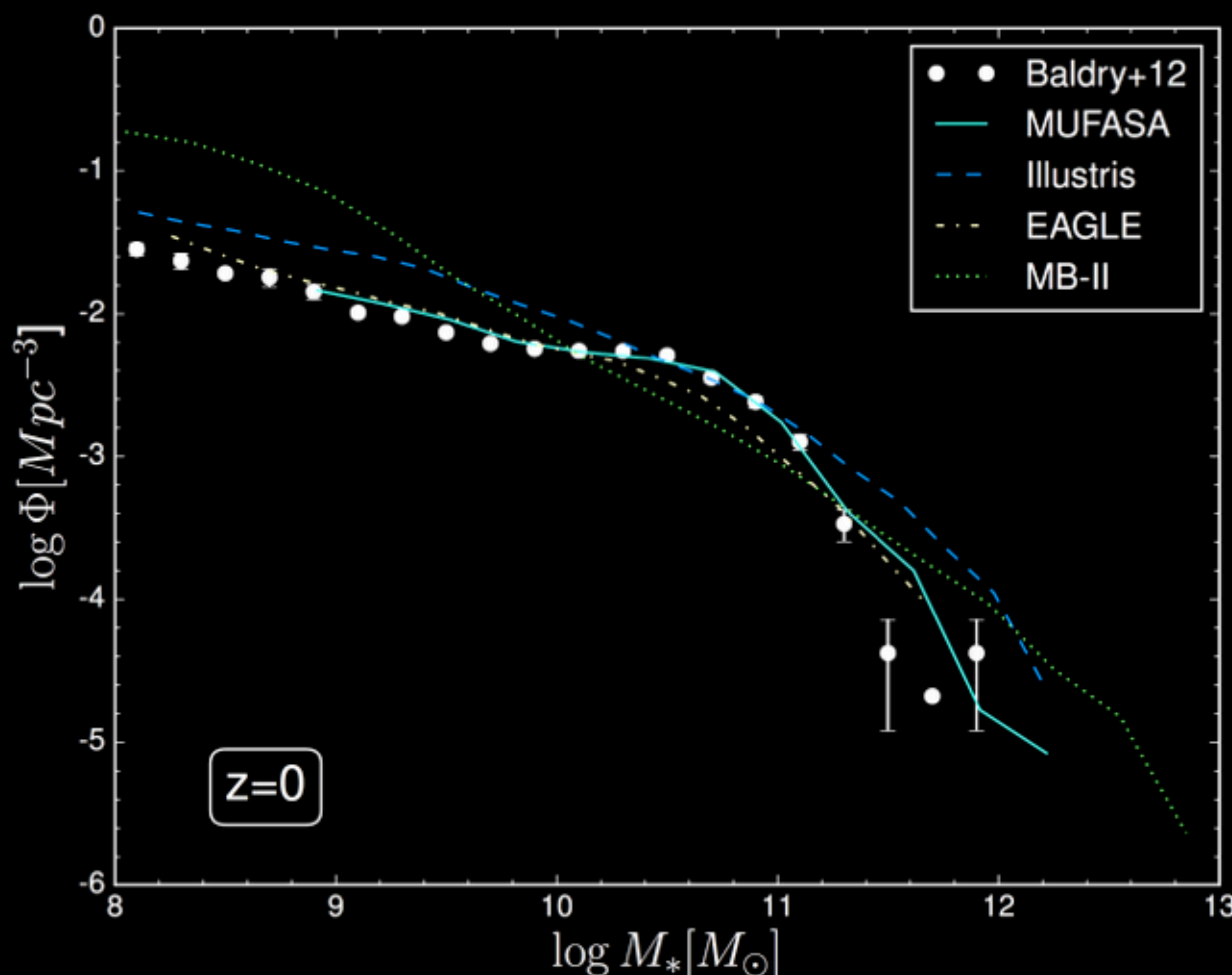
Project ID AST 125

Galactic Winds Are Necessary

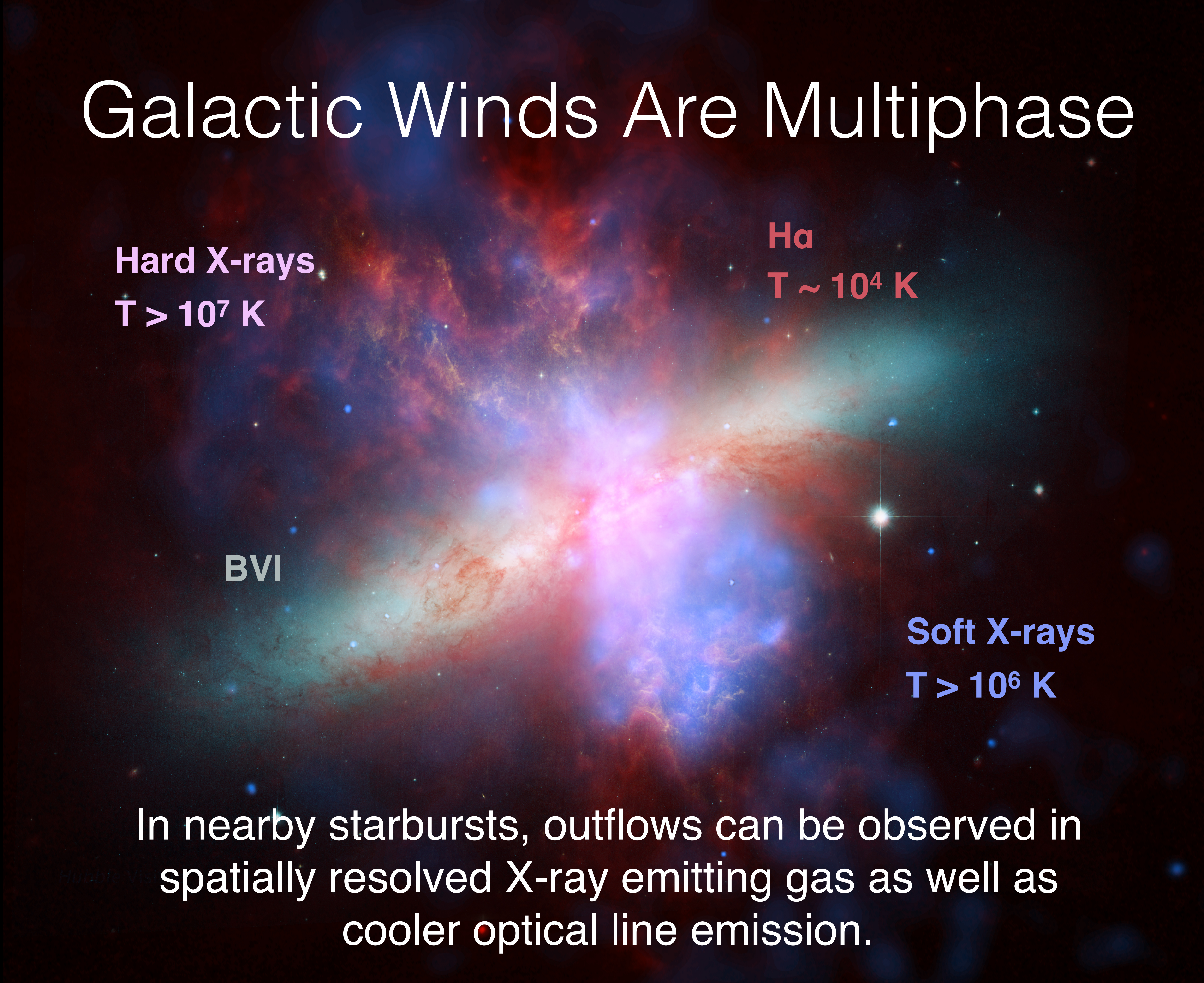
Our theories of galaxy formation require galactic winds to:

- regulate star formation in galaxies,
- reproduce the stellar mass function,
- enrich the circumgalactic medium (CGM) and intergalactic medium (IGM) with metals,
- and more.



Davé et al. (2016)

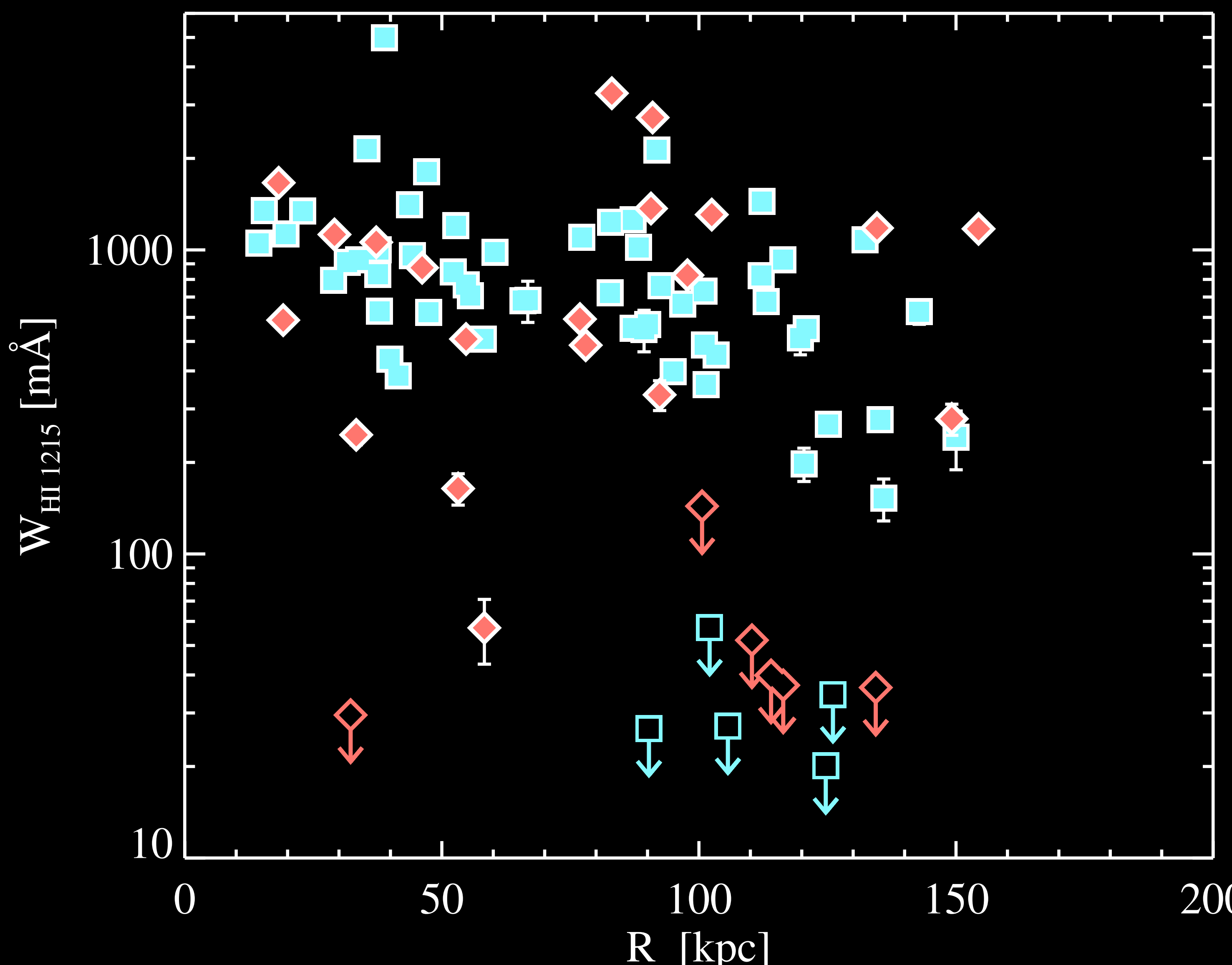
Galactic Winds Are Multiphase



In nearby starbursts, outflows can be observed in spatially resolved X-ray emitting gas as well as cooler optical line emission.

Cool Gas Exists Around Galaxies

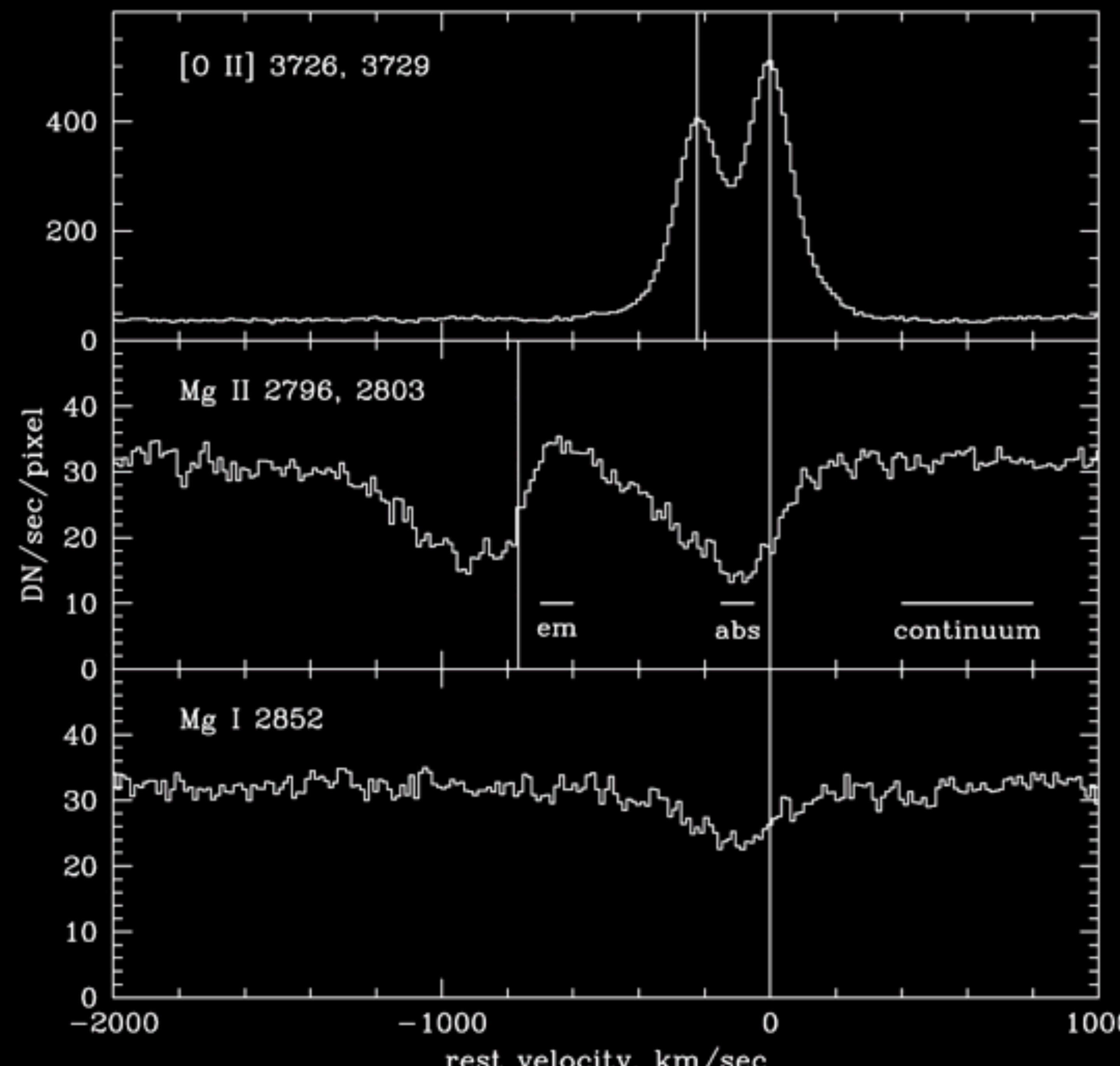
COS-Halos and other CGM surveys have found abundant neutral hydrogen in the halos of both star-forming and passive galaxies in the nearby universe.



Bordoloi et al. (2017)

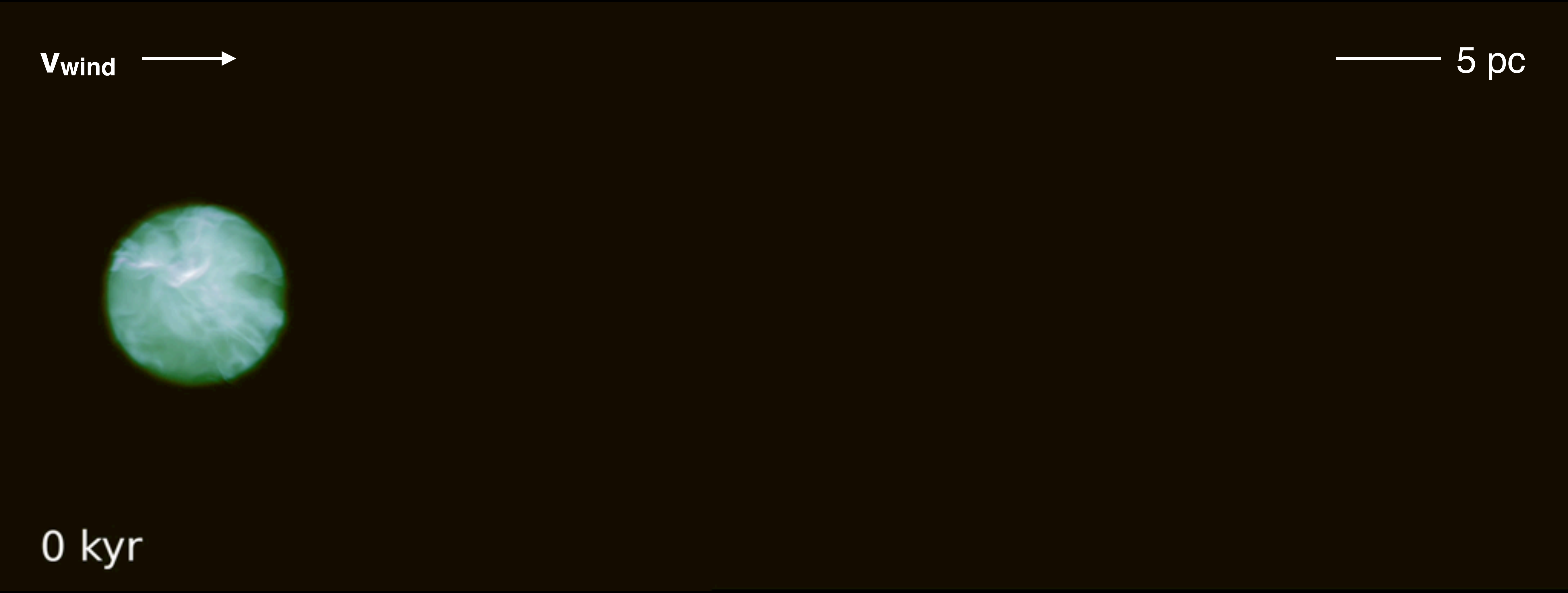
… And In Outflows…

Low-ionization, blue-shifted metal lines are frequently observed when looking “down the barrel” at star-forming galaxies, indicating cool, outflowing material.



Weiner et al. (2009)

… But Cool Gas Is Difficult To Accelerate.



Schneider & Robertson (2017)

Can we build a coherent theory of outflows that explains the observations?

We want a physically-motivated model that:

- Reproduces the multiphase nature of outflows
- Explains the velocity structure of outflows
- Efficiently transports metals out of galaxies to enrich the CGM and beyond
- Ideally, can explain observations of the multiphase CGM

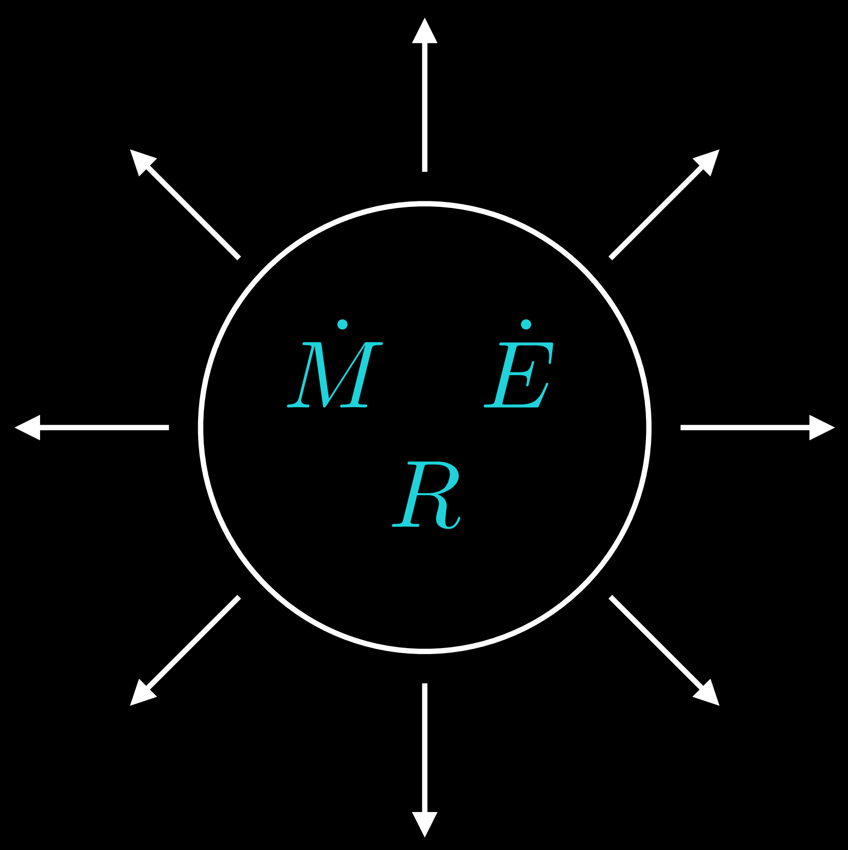
The Chevalier & Clegg Model

The Chevalier & Clegg outflow model assumes spherical symmetry and its solution is governed by three parameters:

$\dot{M}$: mass injection rate

$\dot{E}$: energy injection rate

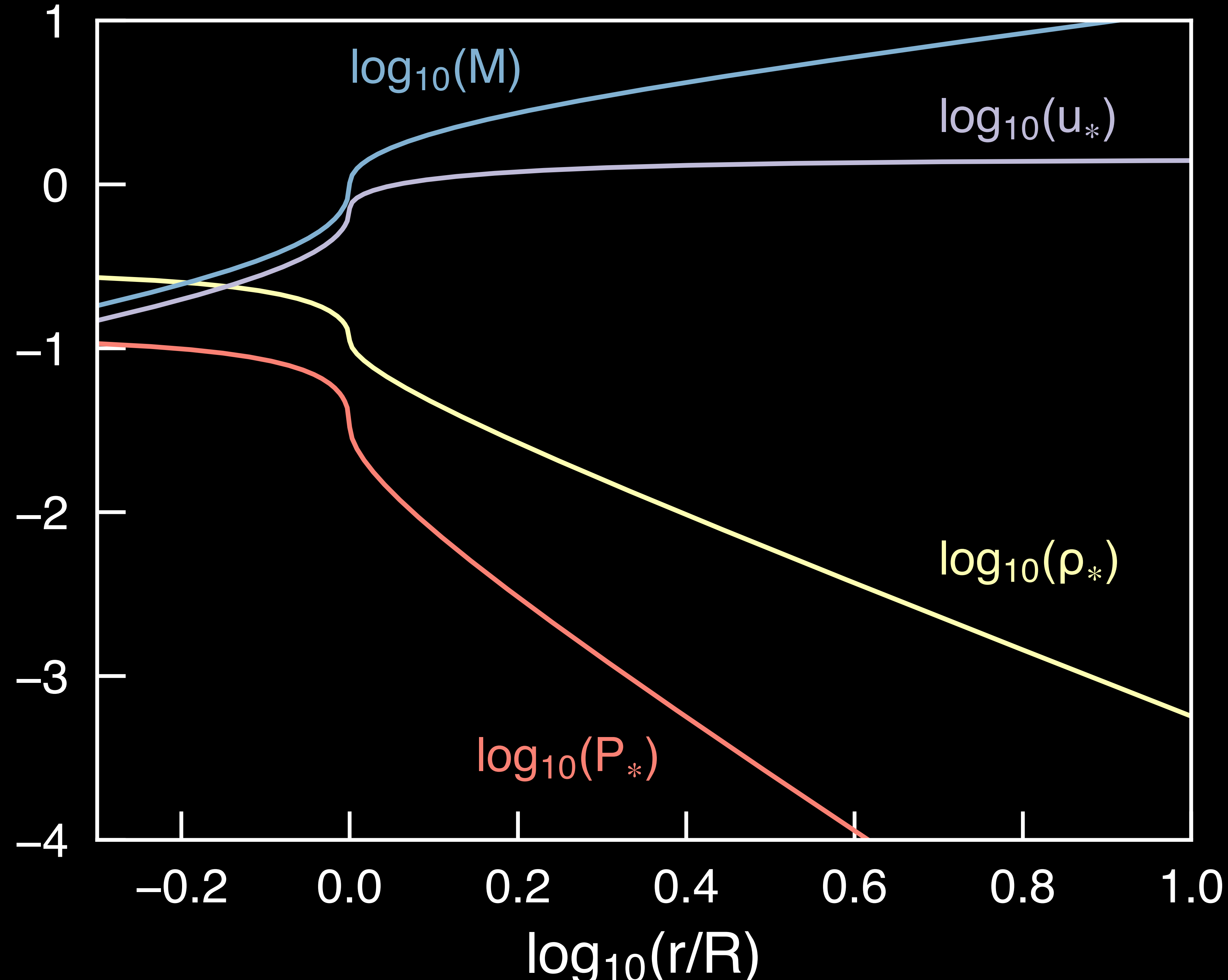
R : injection radius



See also Bustard et al. (2016)

The Chevalier & Clegg model neglects gravity, radiative cooling, and additional sources of momentum.

The Chevalier & Clegg Model



The Radiative Wind Model

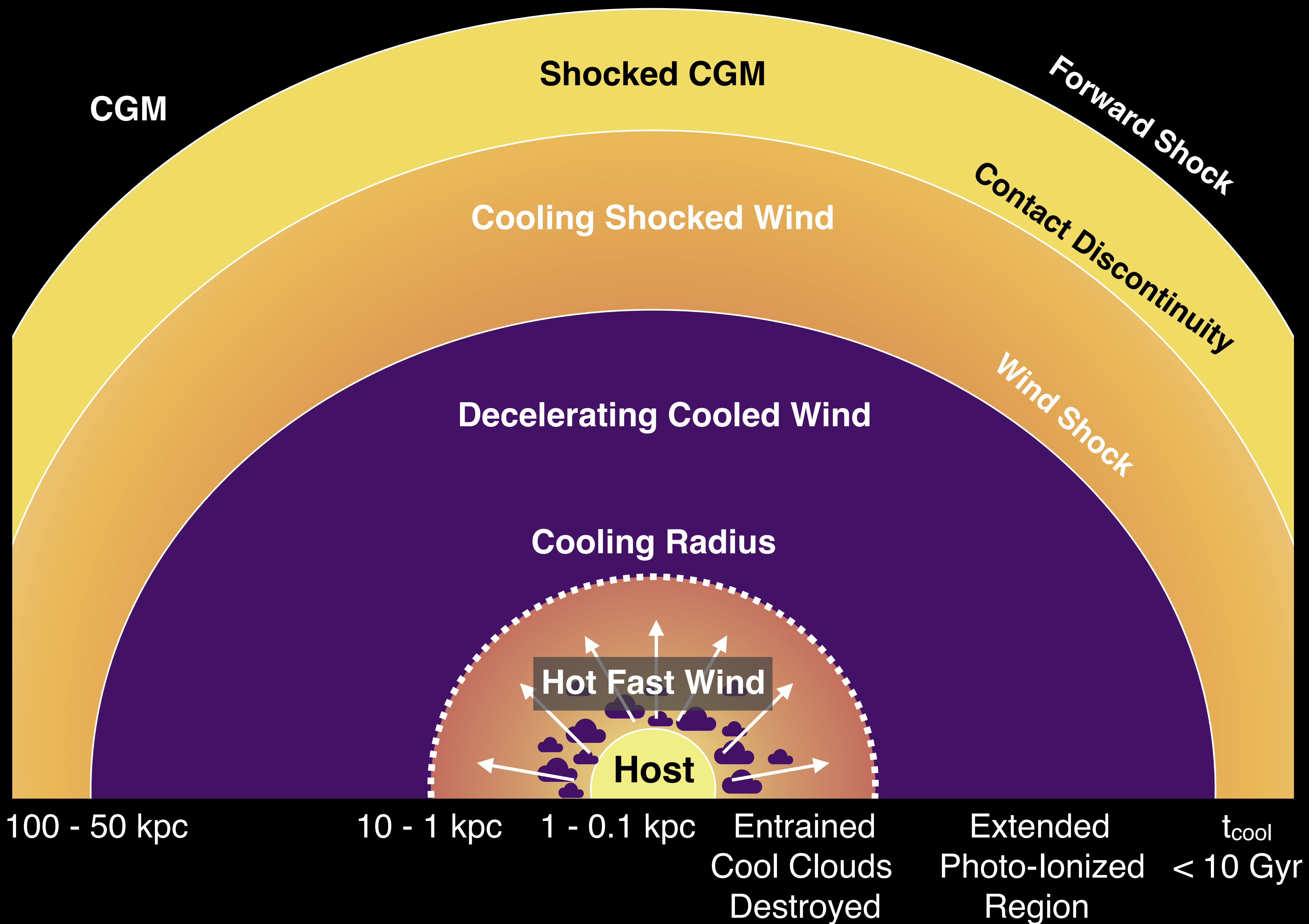
$$\dot{M}_{\rm wind} = \beta \dot{M}_{\rm SFR}$$

Mass-loading factor

$$\dot{E}_{\rm wind} = 3 \times 10^{41}\,{\rm erg\,s^{-1}}\,\alpha \dot{M}_{\rm SFR}$$

Energy-loading factor

The Radiative Wind Model

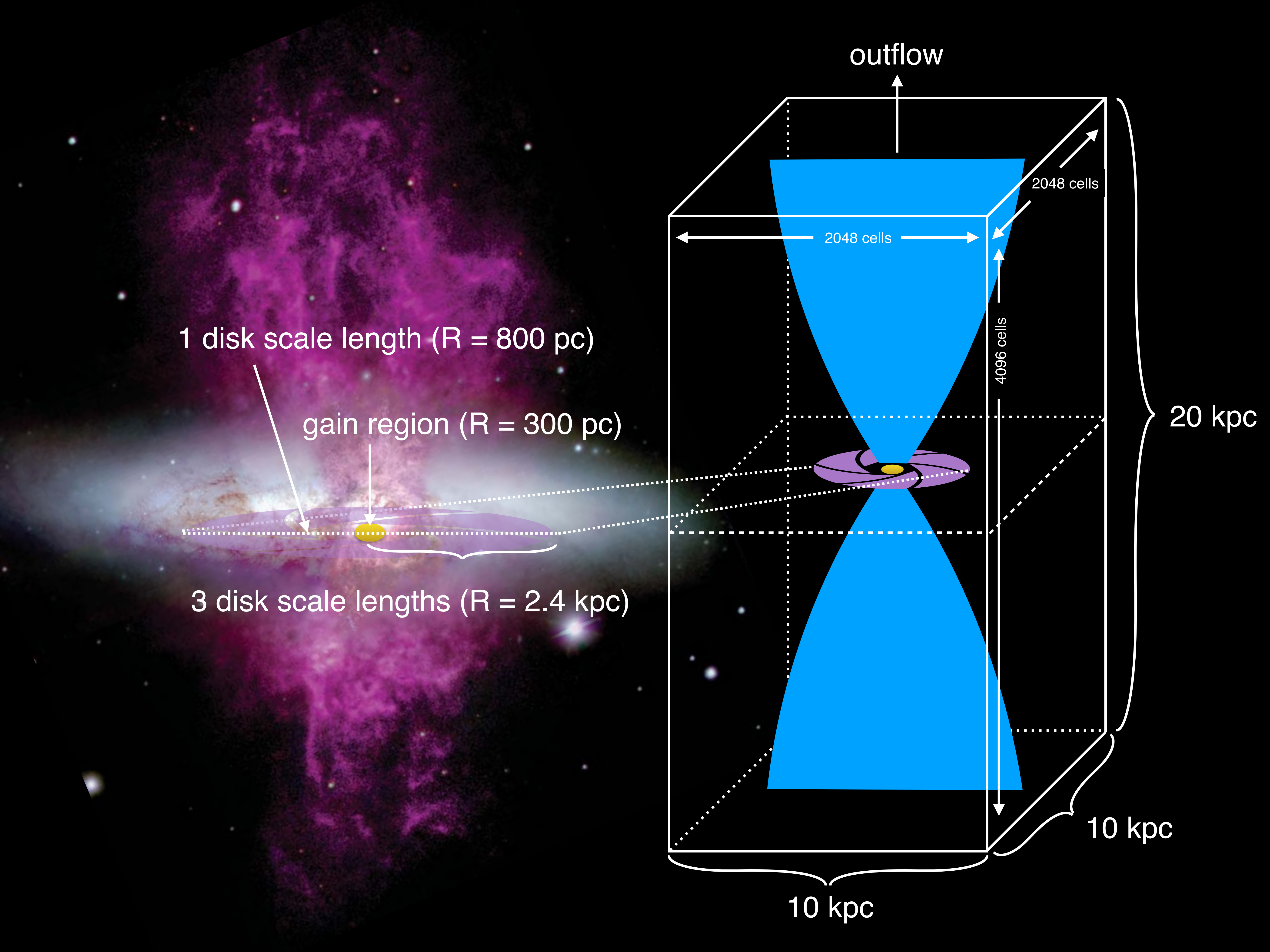


Thompson et al. (2016)

Introducing the CGOLS project

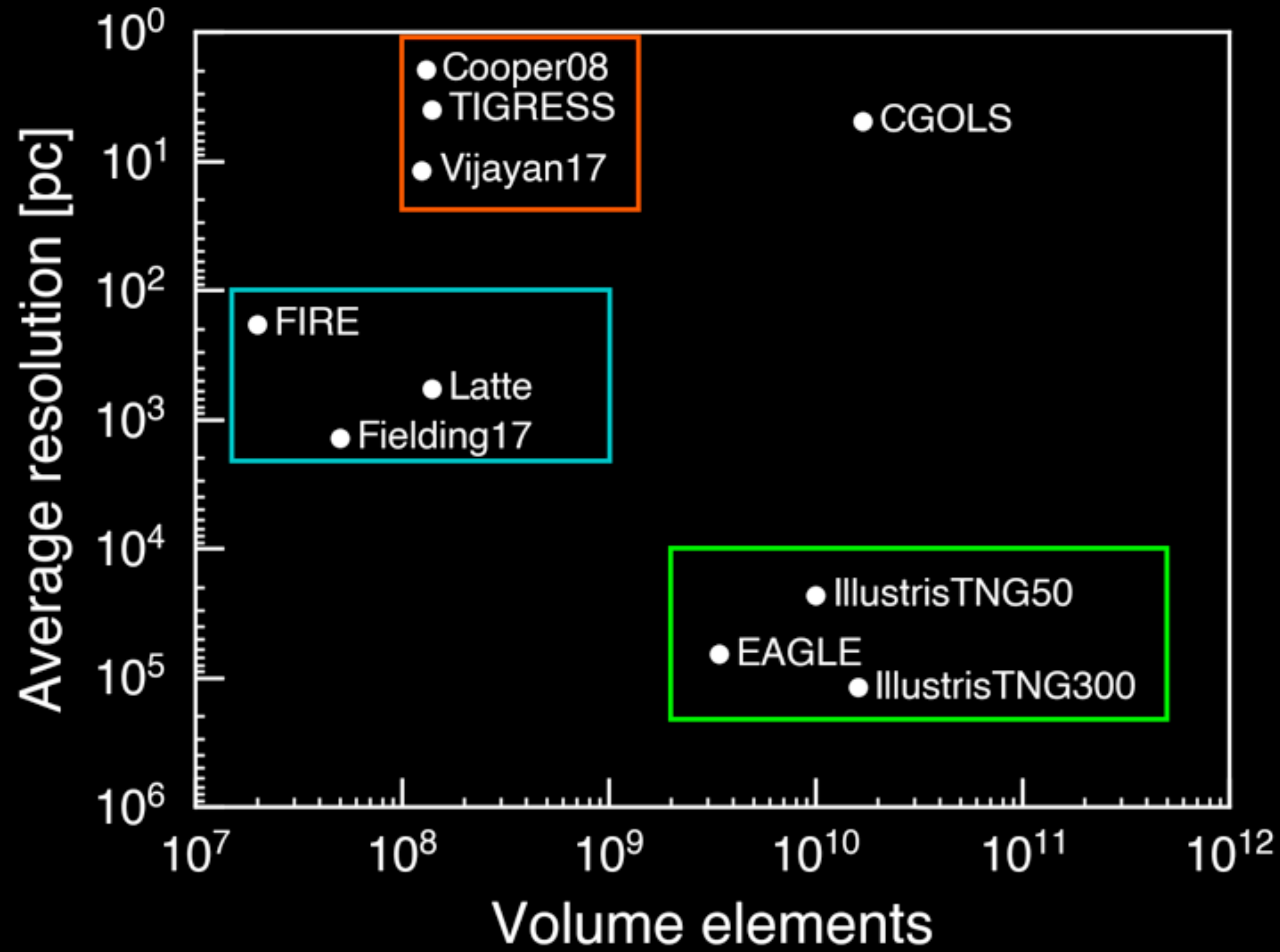
- Via the INCITE program (AST 125), we have received ~100 million core-hours on Titan (over 2 years) to tackle the challenge of simulating galactic winds.
- We are running a series of high resolution simulations to develop a theory of winds in a systematic manner.
- We call this project CGOLS (Cholla Galactic OutfLow Simulations).

Arxiv No. 1803.01008 & 1803.01005



outflow
2048 cells
2048 cells
4096 cells
20 kpc
10 kpc
10 kpc
1 disk scale length (R = 800 pc)
gain region (R = 300 pc)
3 disk scale lengths (R = 2.4 kpc)

How does CGOLS compare?



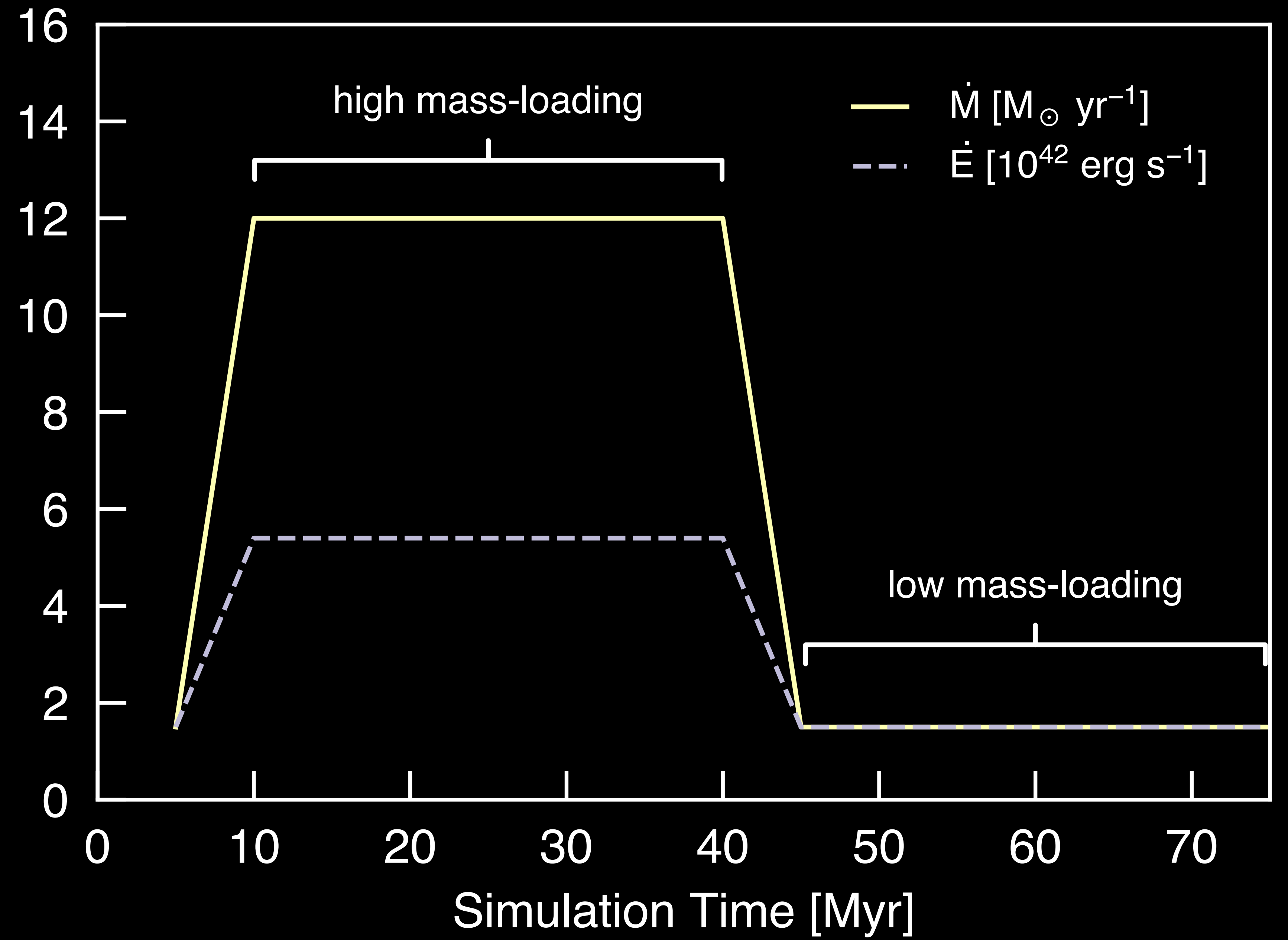
CGOLS Year 1 Simulation Features

- Isothermal gas disk, $T = 10^4$ K in vertical hydrostatic and rotational equilibrium
- Static potential with a stellar disk + NFW dark matter halo, $M_{stars} = 10^{10}\ M_{\odot}$ and $M_{DM} = 5 \times 10^{10}\ M_{\odot}$
- All simulations run at 3 resolutions: 5pc, 10pc, and 20pc, in a 10 kpc x 10 kpc x 20 kpc box
- Starburst feedback is either “central” or “clustered”, with varied mass-loading, energy-loading, and SFR

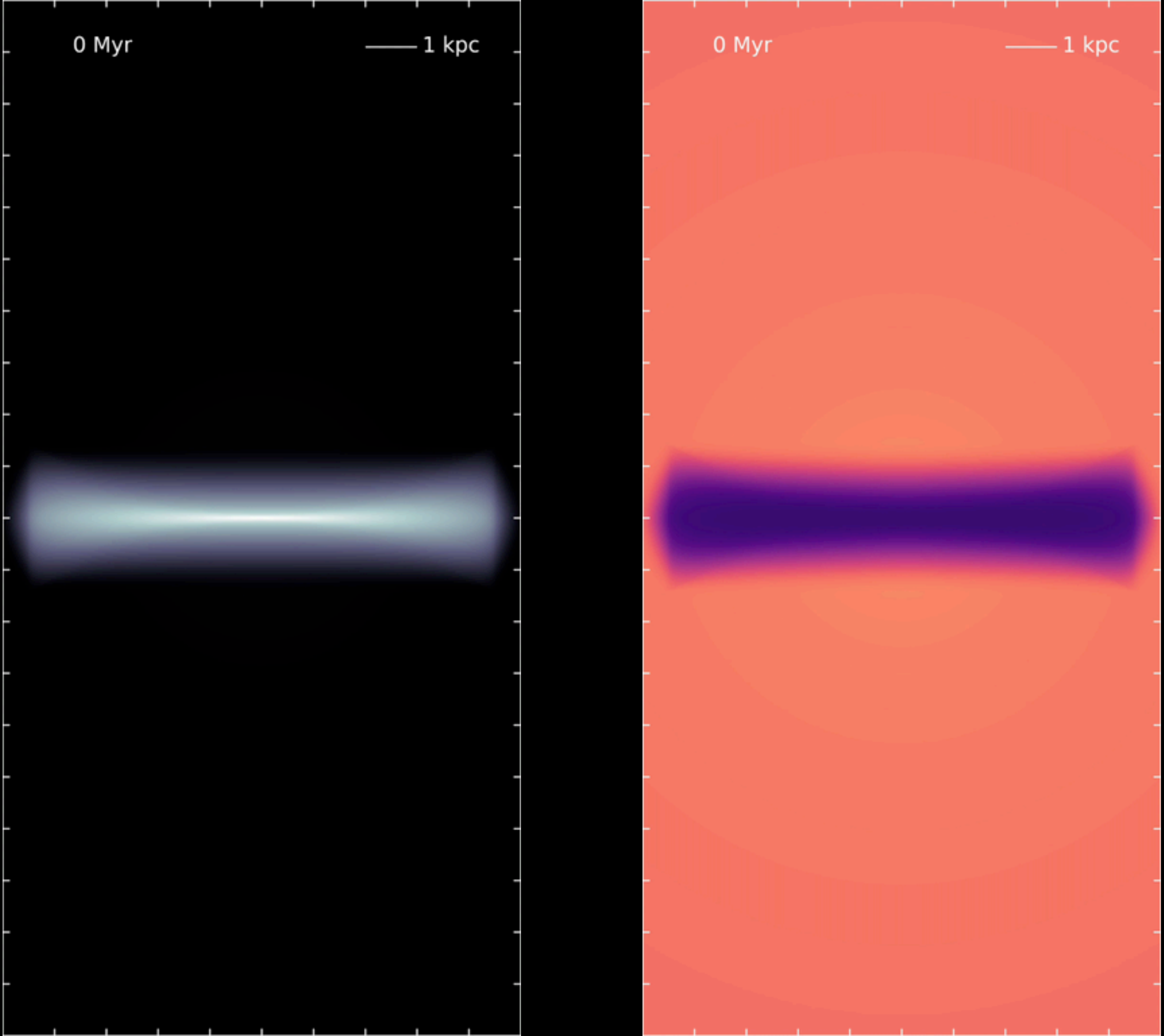
CGOLS Year 1 Simulation Features

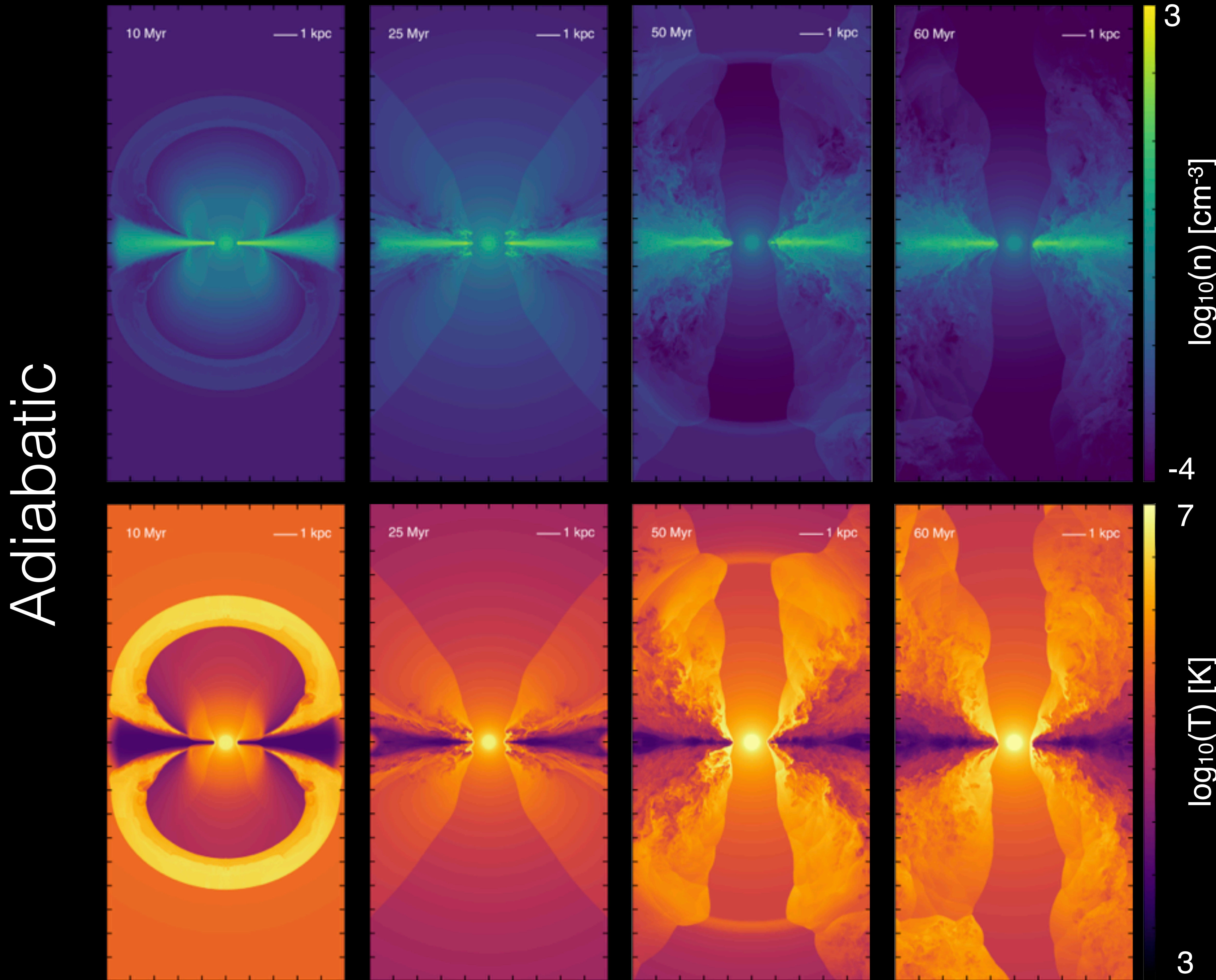
High mass-loading:
$\alpha = 0.9$,
$\beta = 0.6$,
SFR = 20 $M_{\odot}$/yr

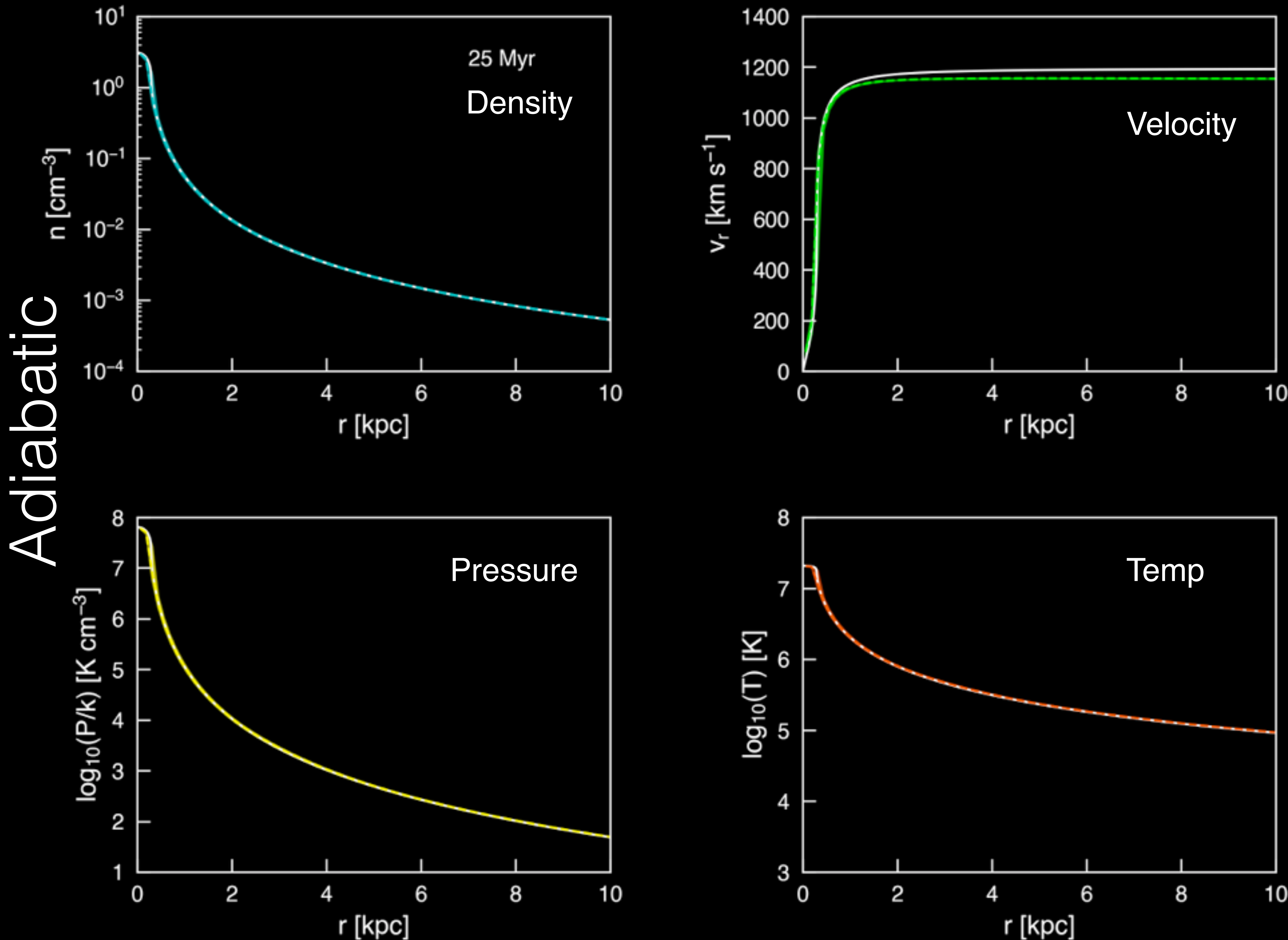
Low mass-loading:
$\alpha = 1.0$,
$\beta = 0.3$,
SFR = 5 $M_{\odot}$/yr



Adiabatic

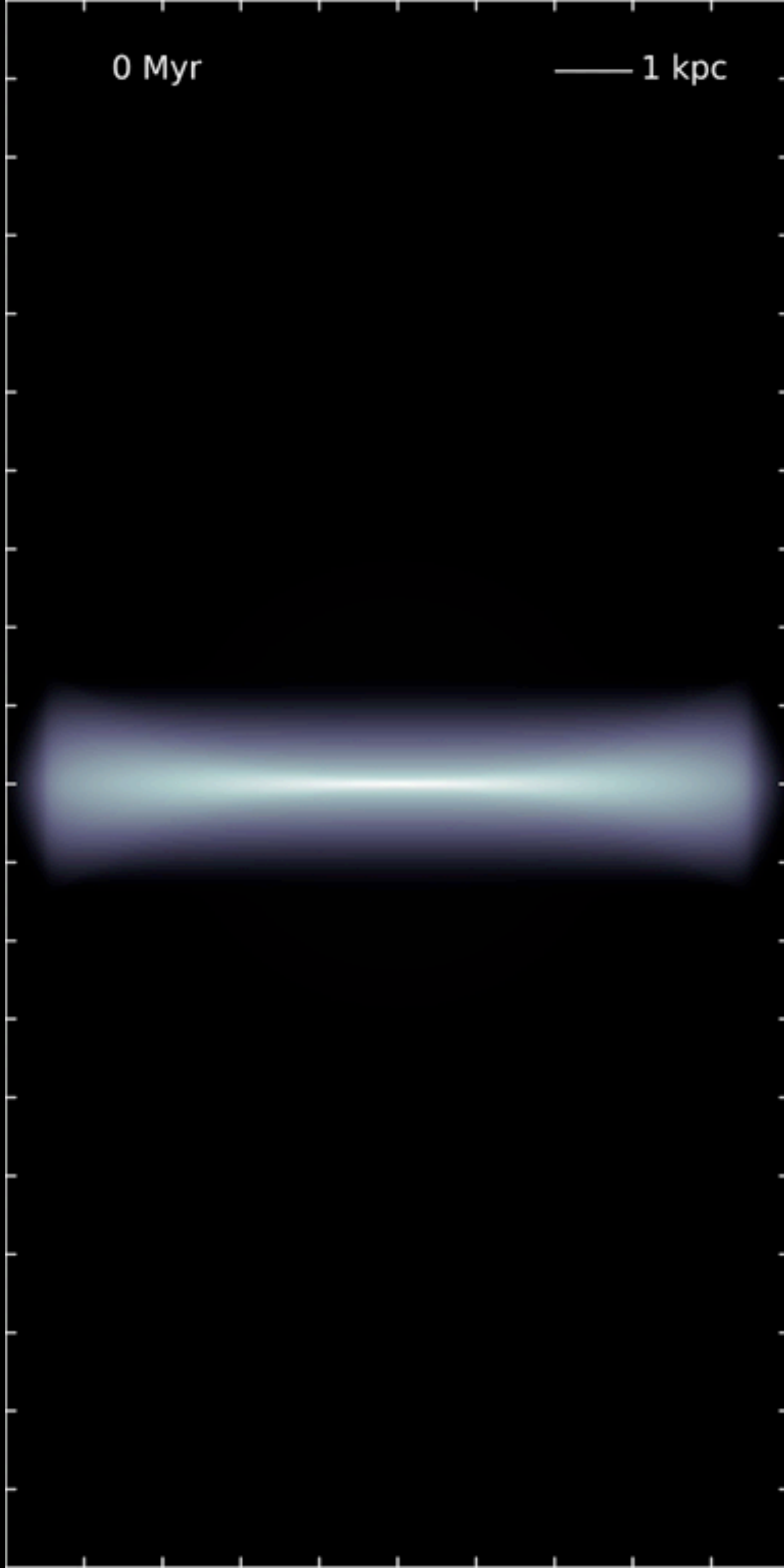



Adiabatic
10 Myr
25 Myr
50 Myr
60 Myr
1 kpc
3
-4
log10(n) [cm-3]
7
3
log10(T) [K]



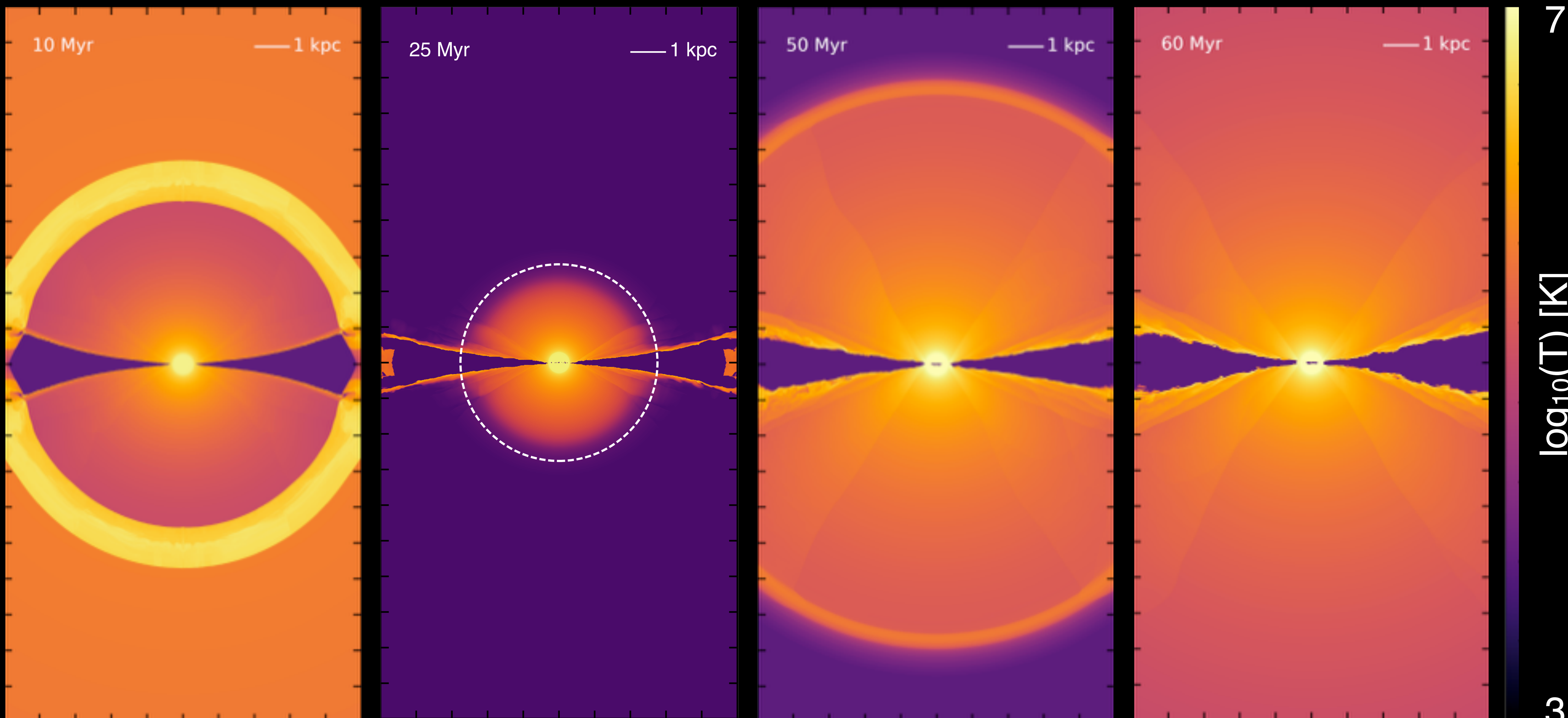
Adiabatic
25 Myr
Density
n [cm⁻³]
r [kpc]
Velocity
v_r [km s⁻¹]
r [kpc]
Pressure
log₁₀(P/k) [K cm⁻³]
r [kpc]
Temp
log₁₀(T) [K]
r [kpc]

Radiative Cooling



Schneider, Robertson, & Thompson 1803.01005

Temperature Evolution in the Radiative Model



Early wind expansion

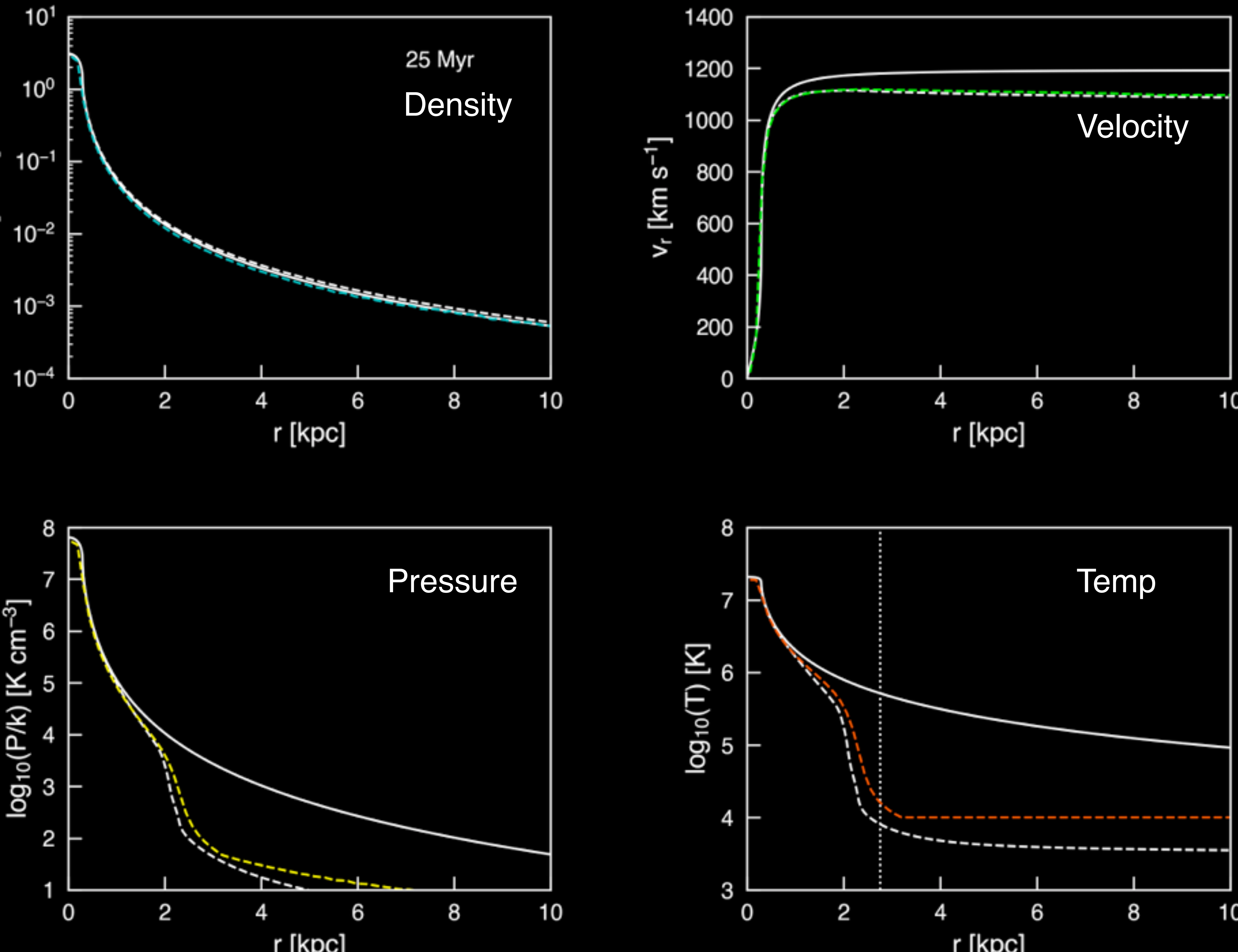
High mass-loading cooled wind state

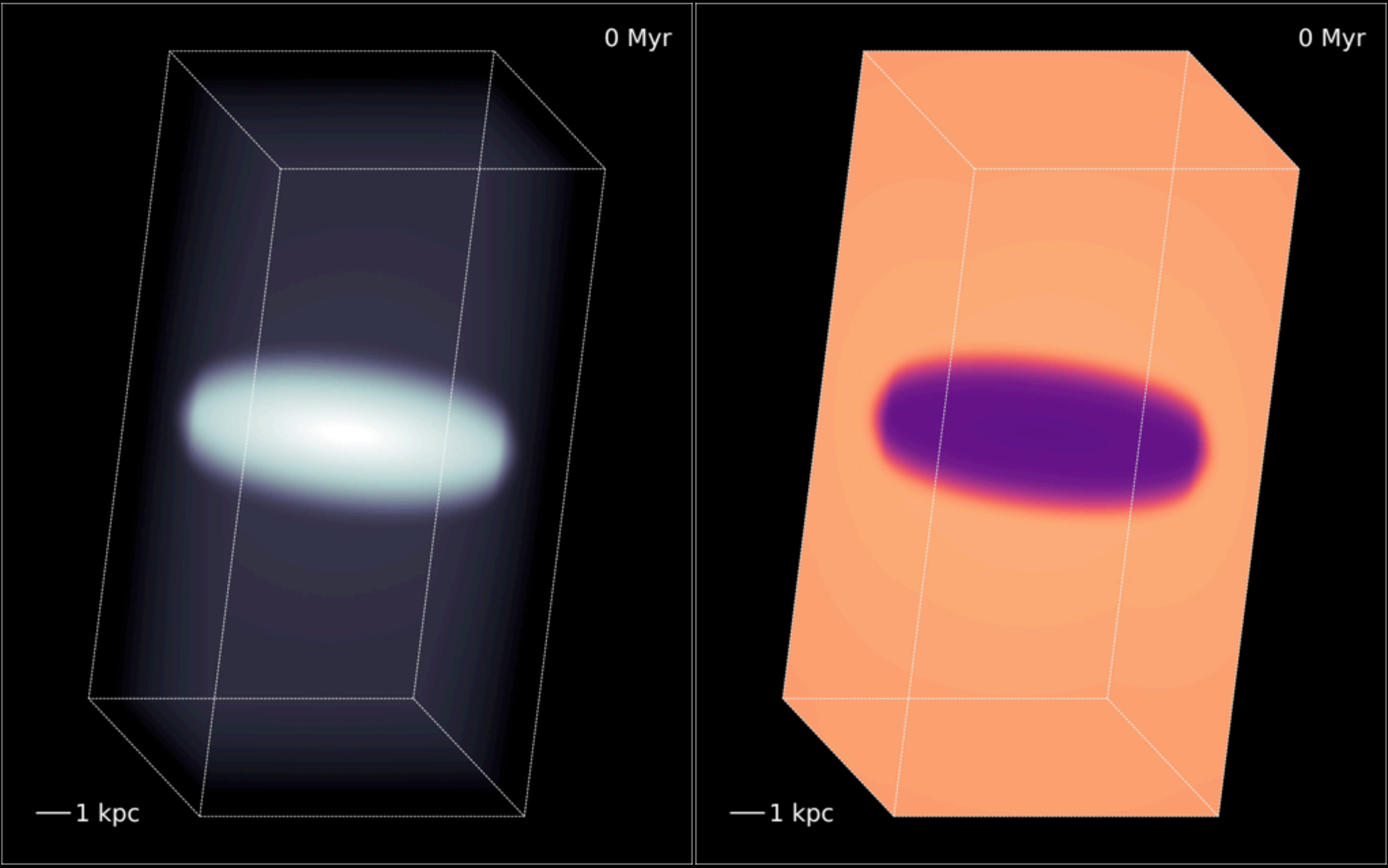
Low mass-loading wind expansion

Late-time smooth flow

Schneider, Robertson, & Thompson 1803.01005

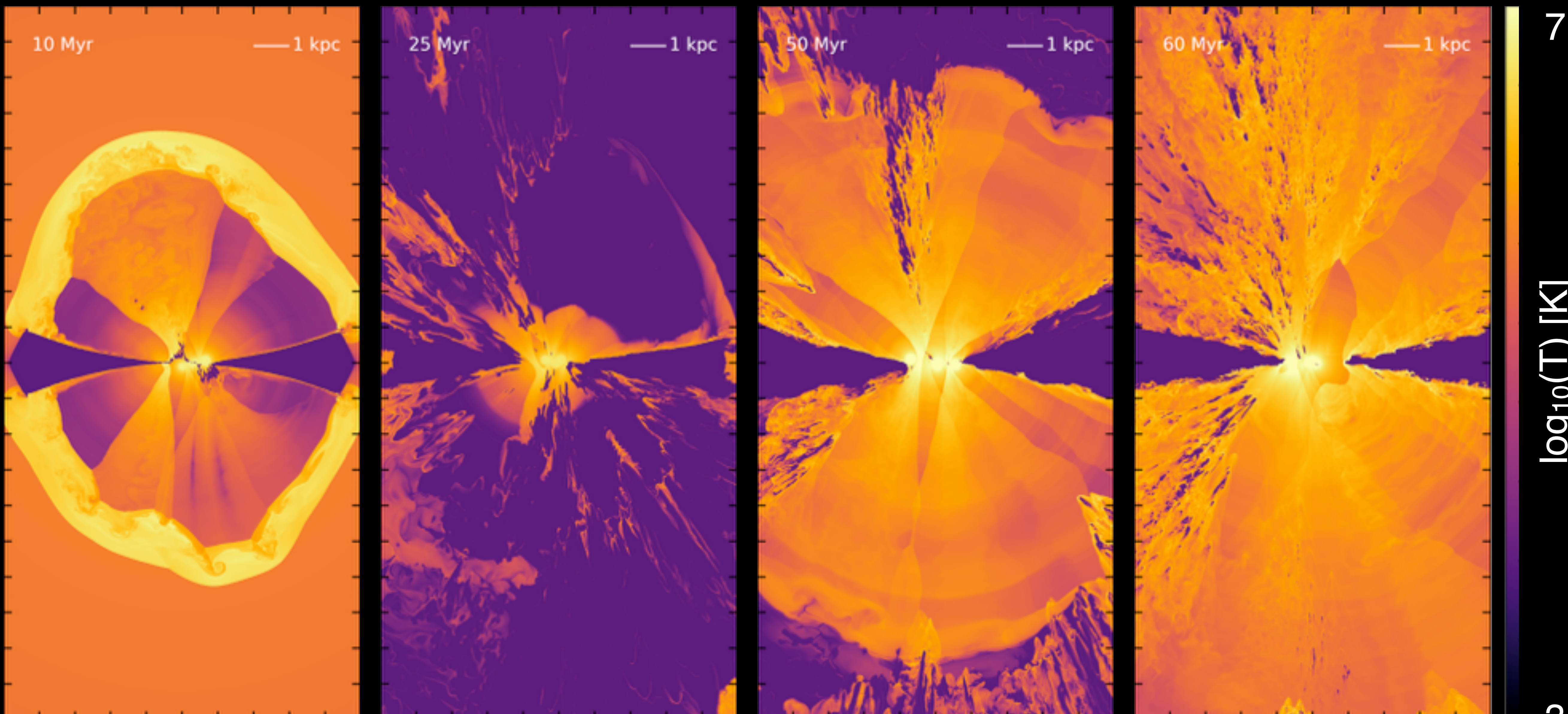
Radiative Cooling





0 Myr
1 kpc
0 Myr
1 kpc

Temperature Evolution in the Clustered Model



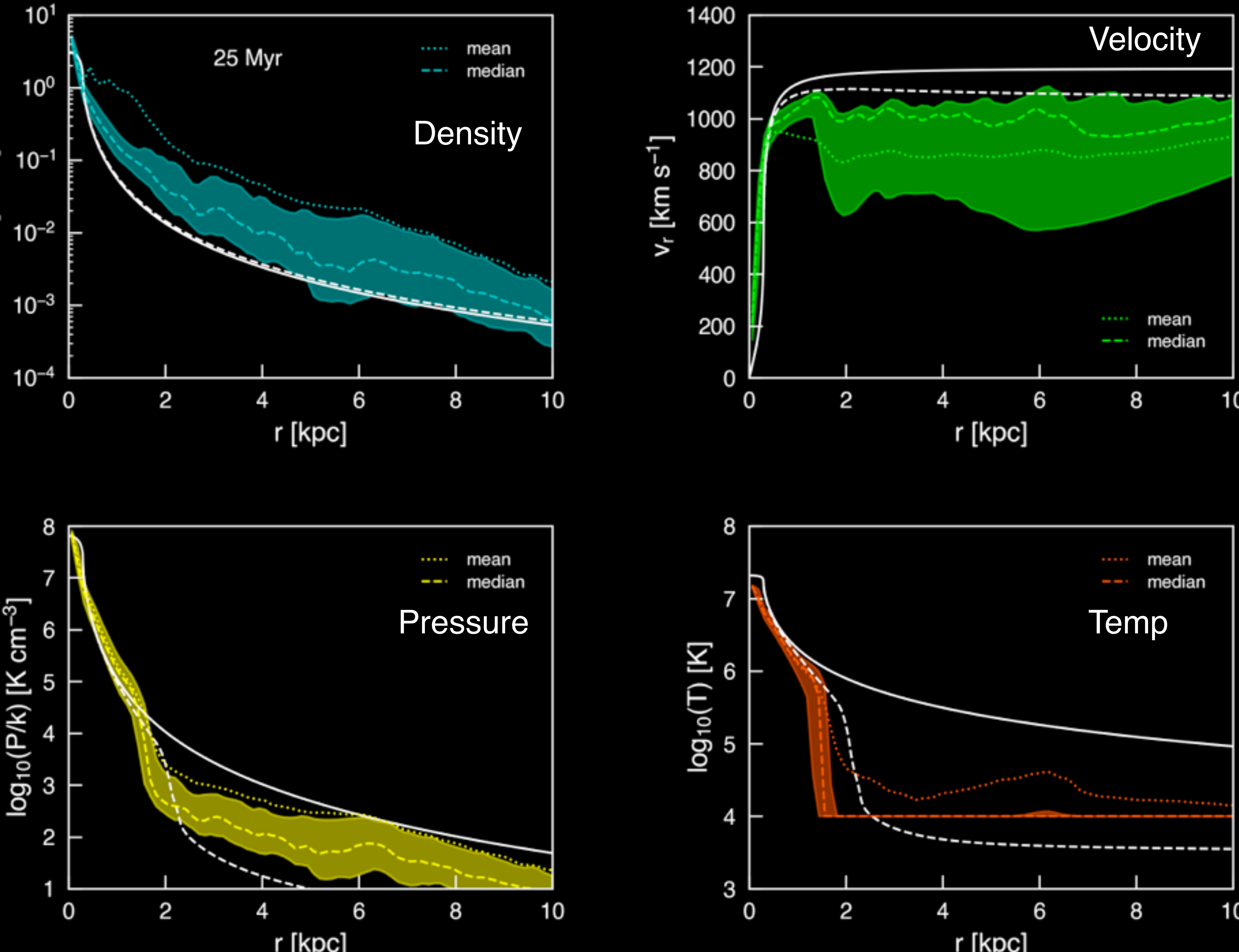
Early wind expansion

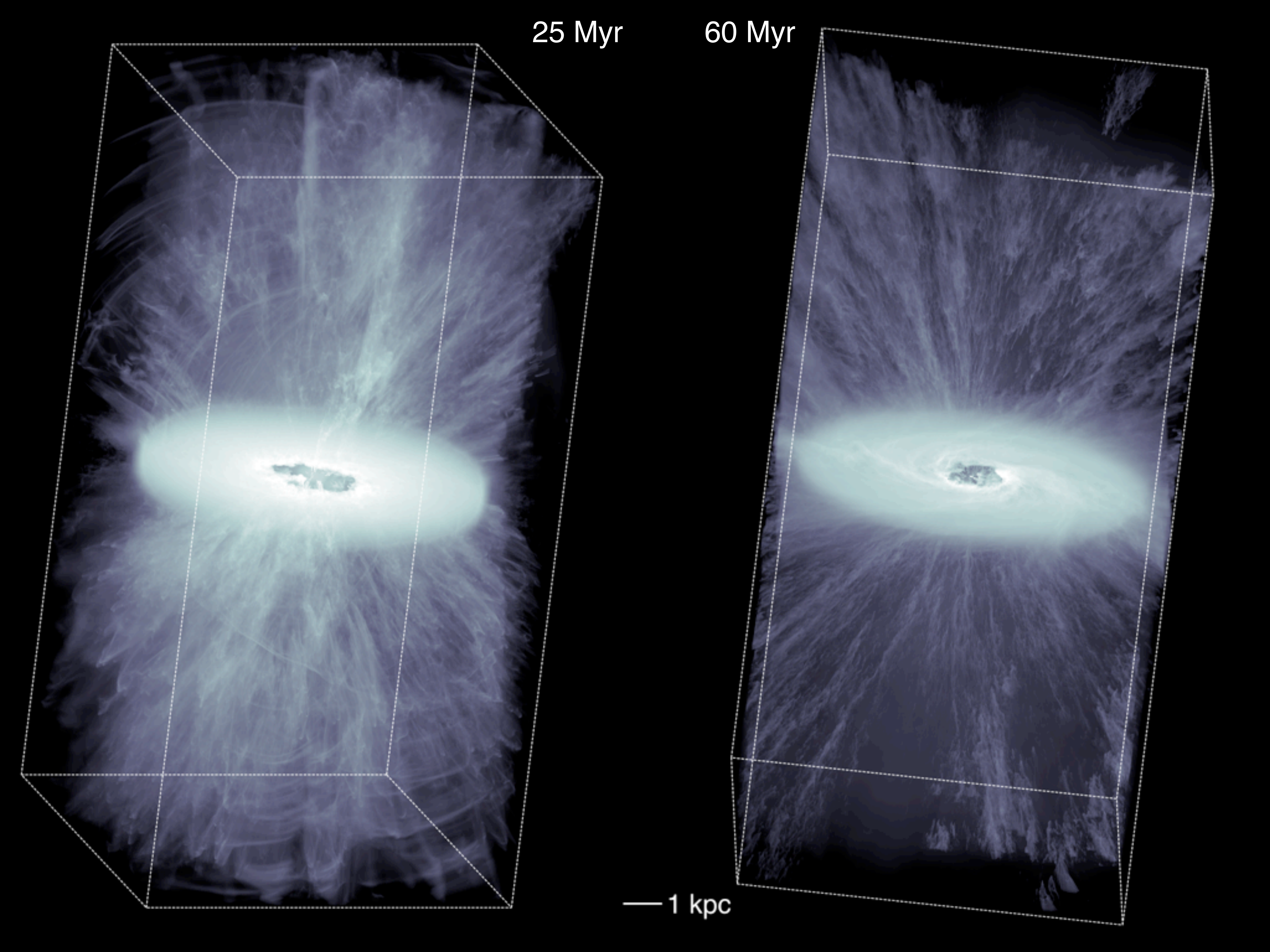
High mass-loading cooled wind state

Low mass-loading wind expansion

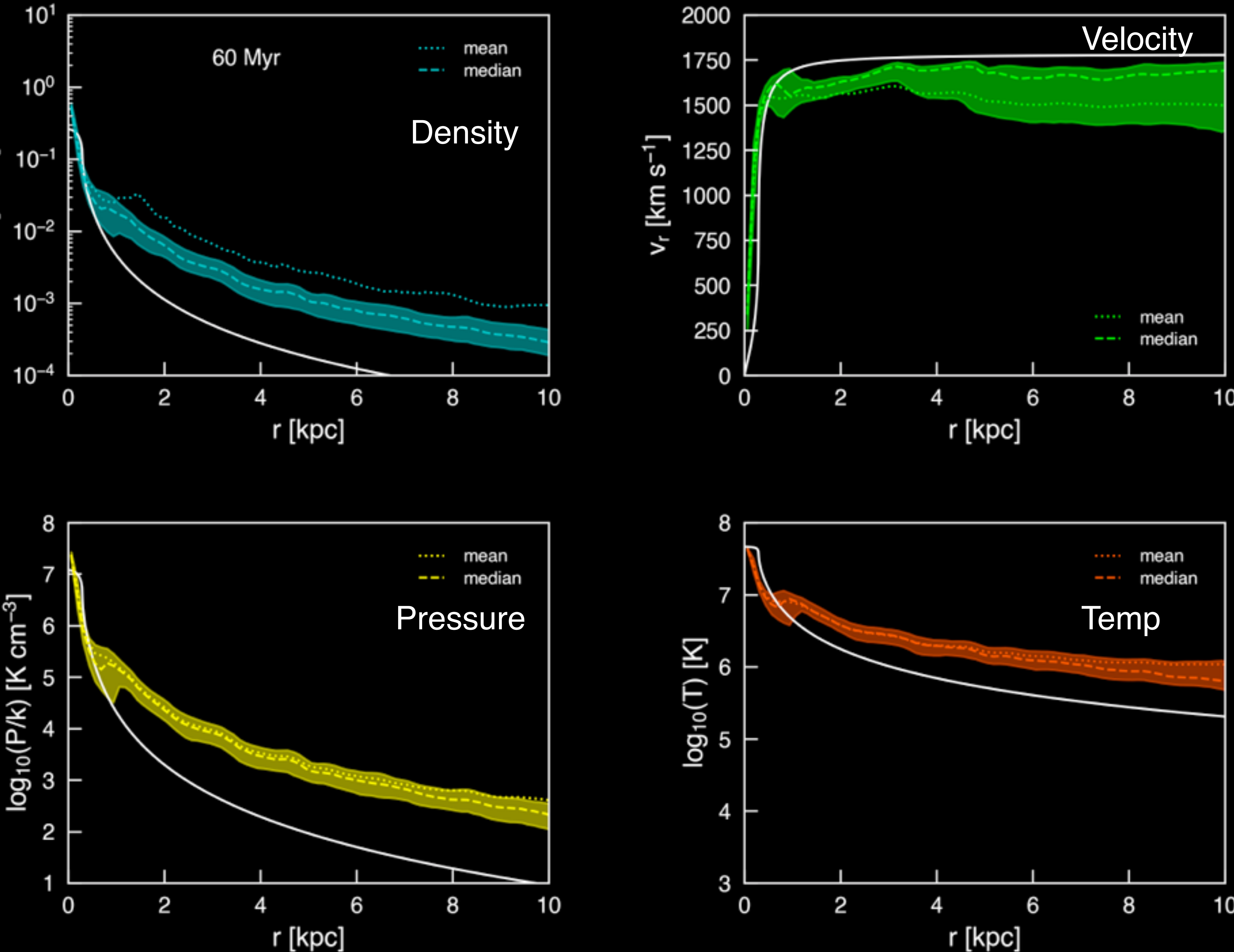
Late low mass-loading state

Radiative + Clustered FB: high state

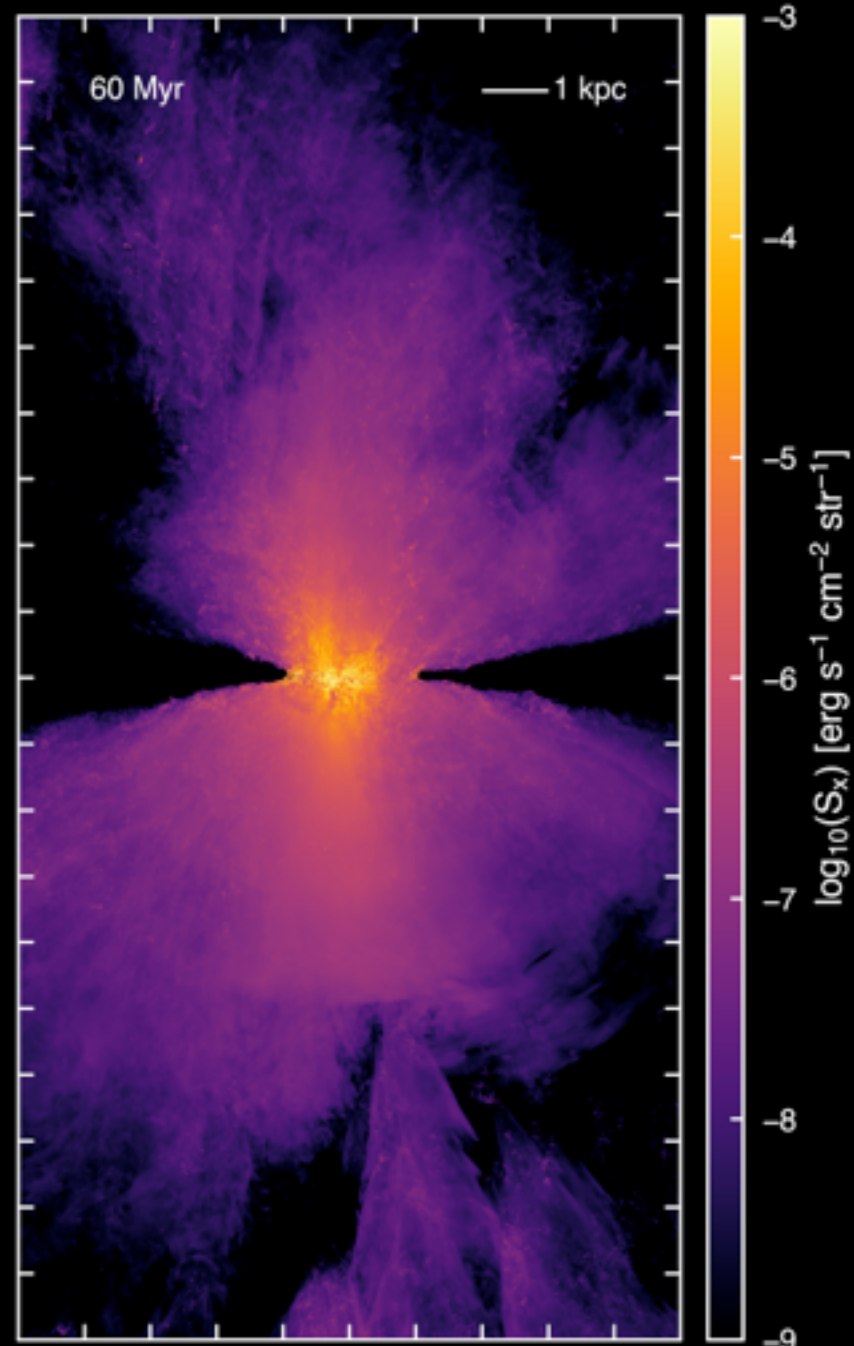



25 Myr
60 Myr
1 kpc

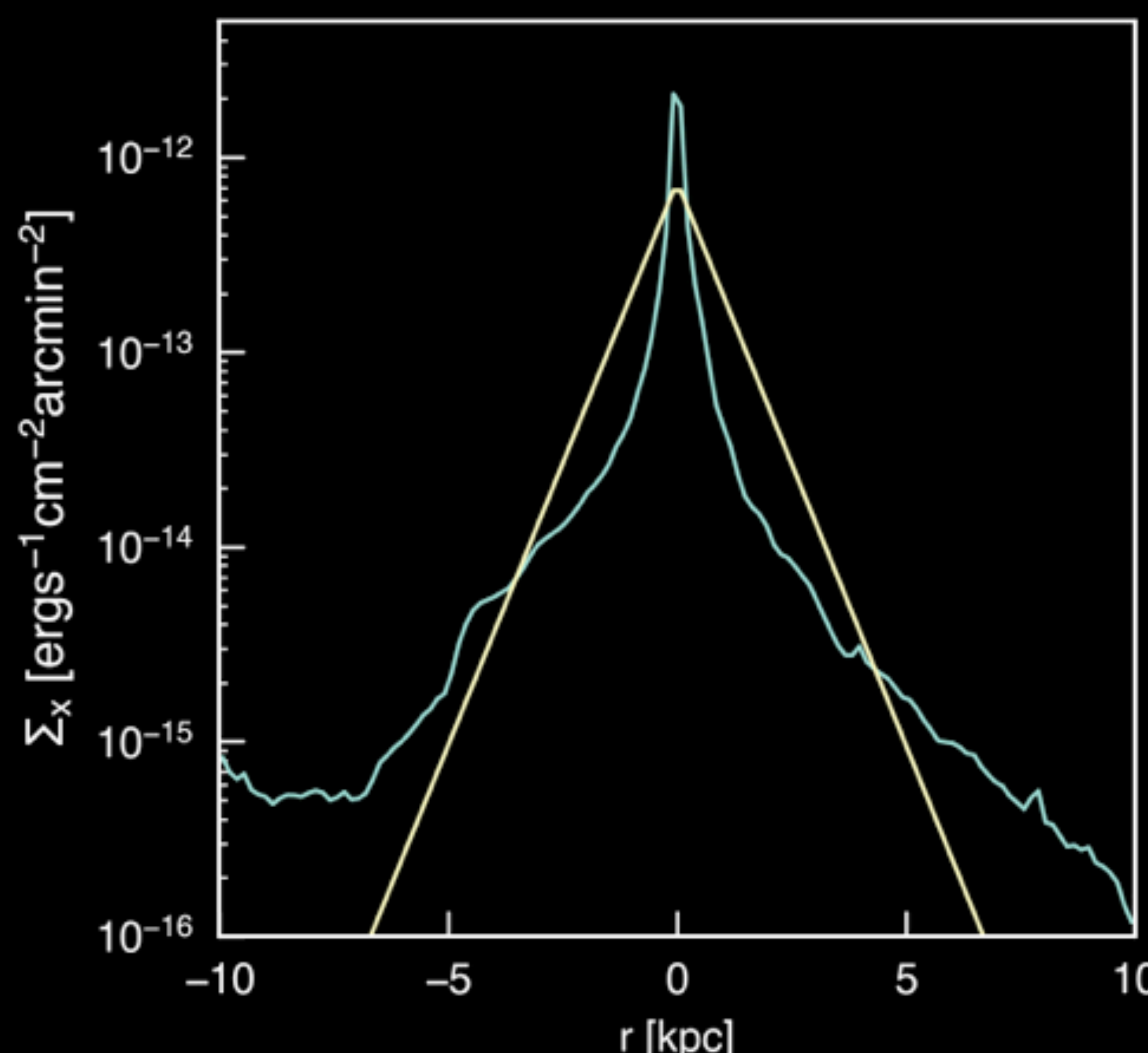
Radiative + Clustered FB: Low state



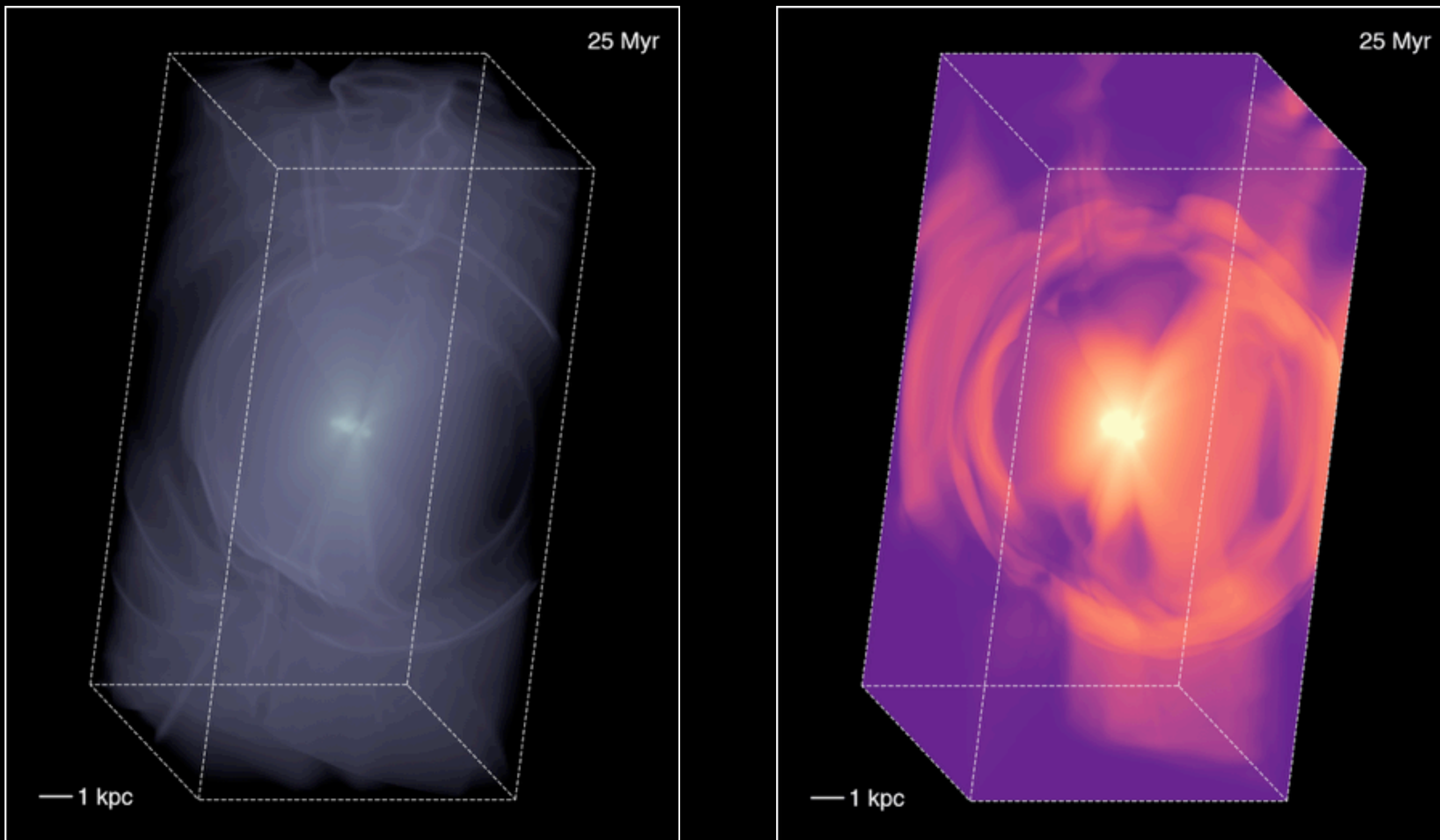
Comparison to X-ray Observations



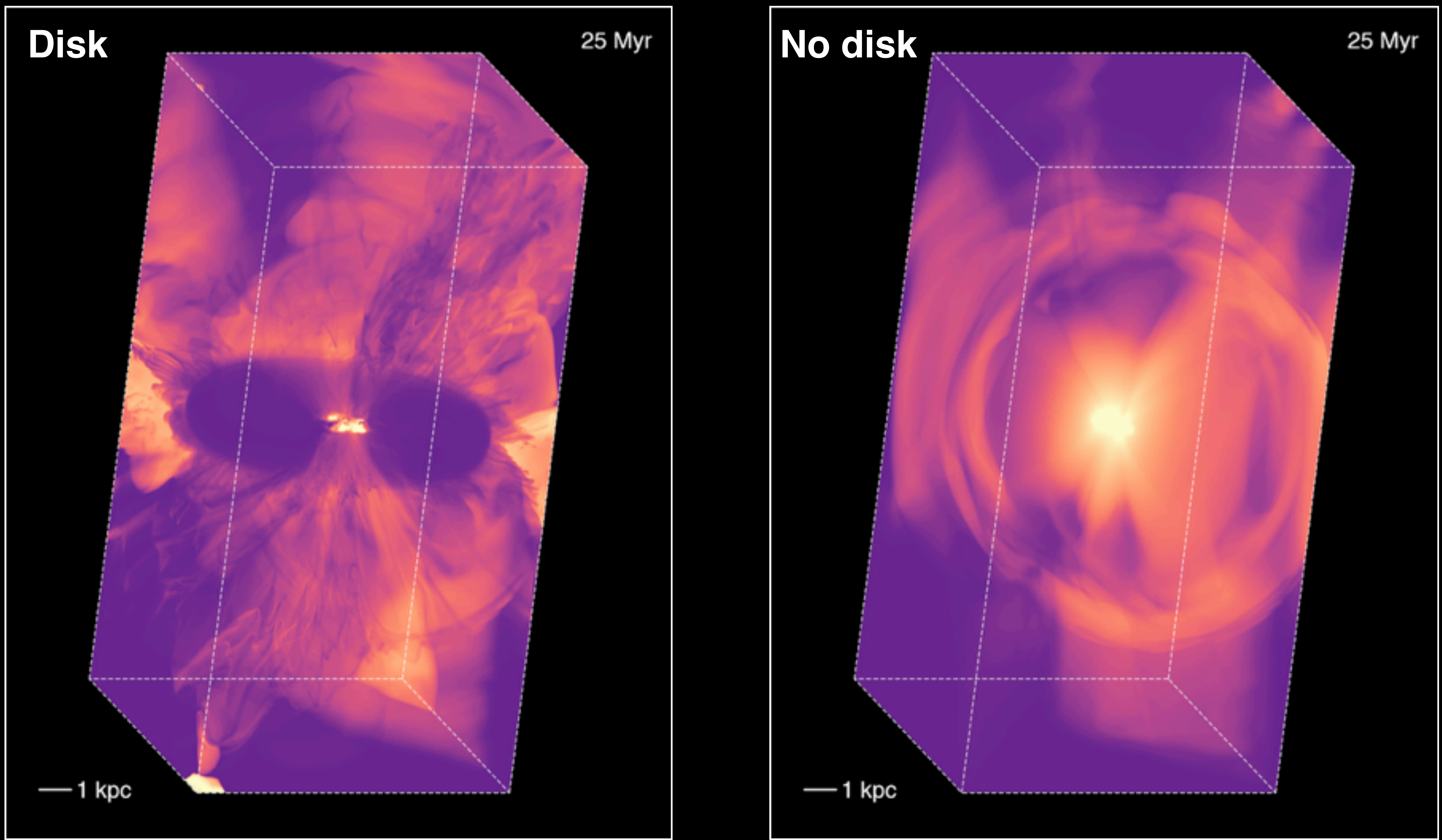
Total luminosity sim: 1.4×10^{40} erg s^{-1}
Total luminosity obs: 4.3×10^{40} erg s^{-1}



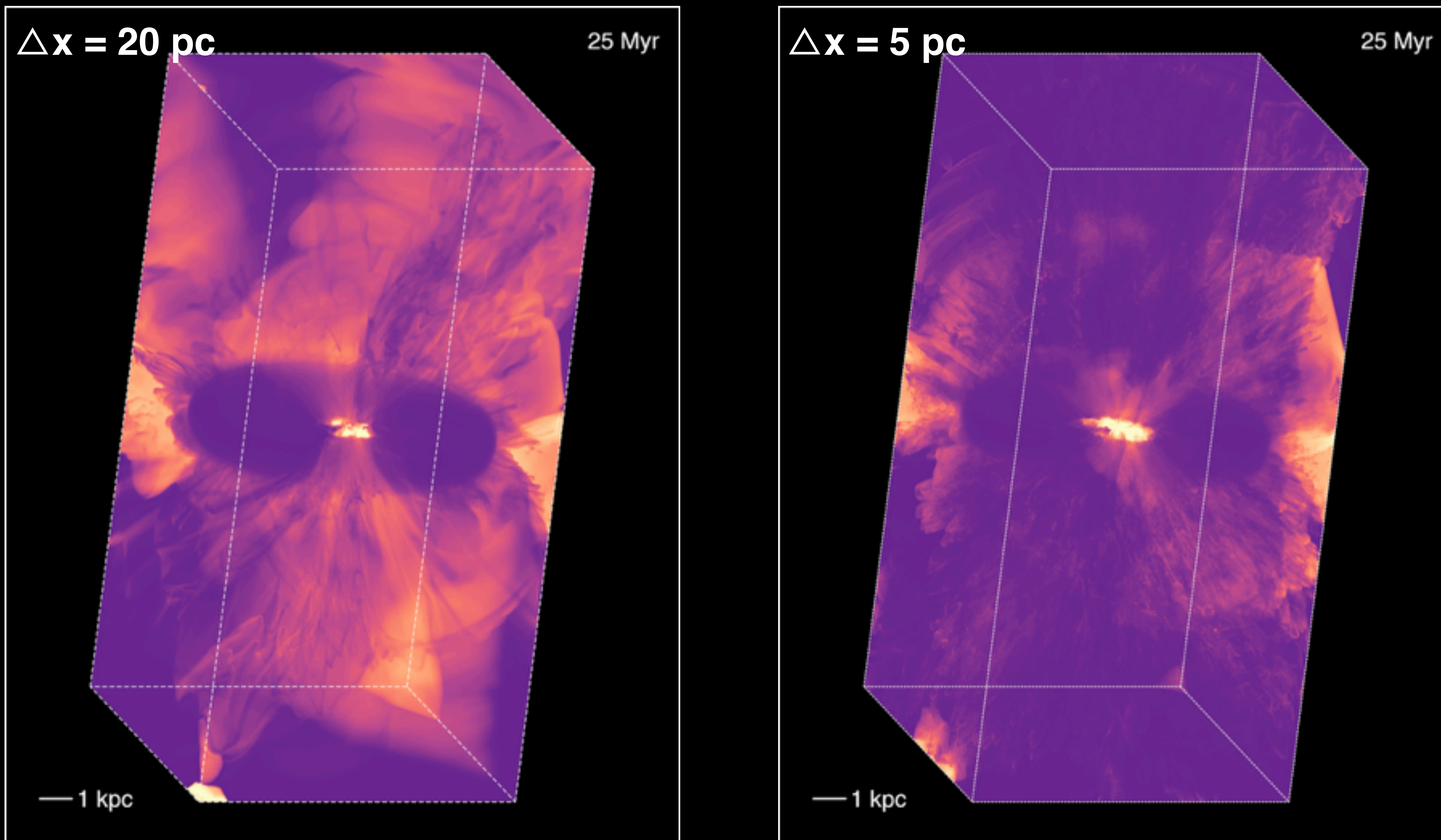
How is the multiphase structure generated?



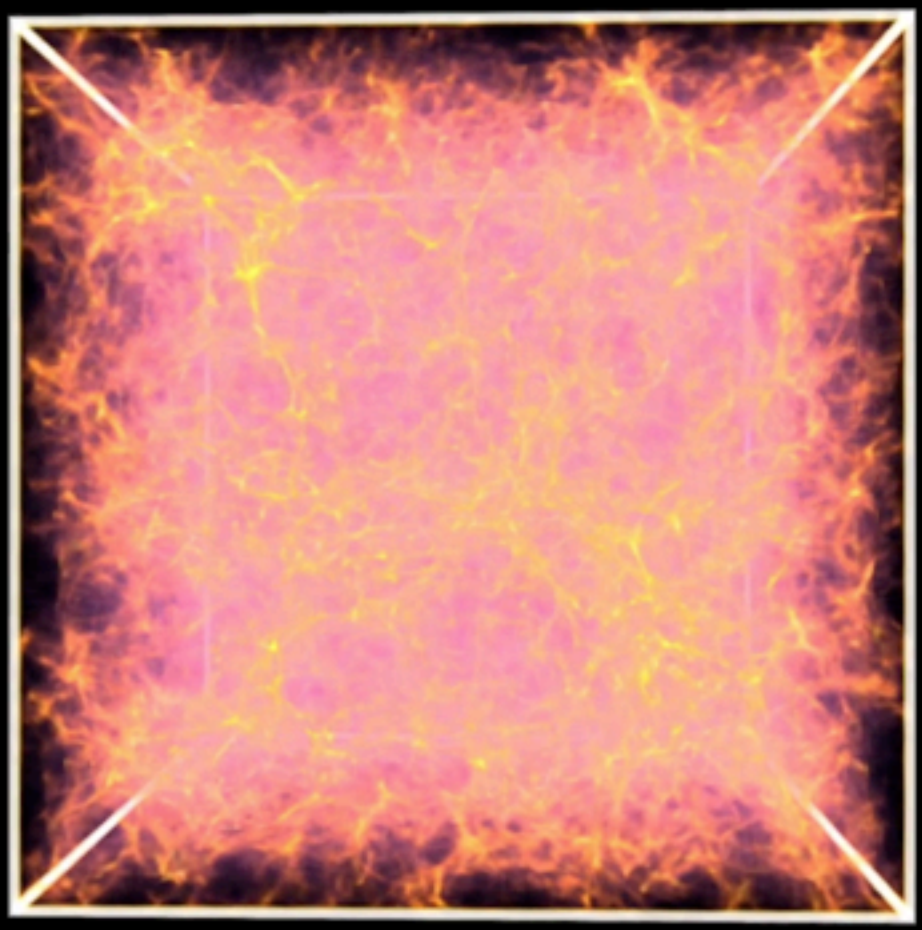
How is the multiphase structure generated?

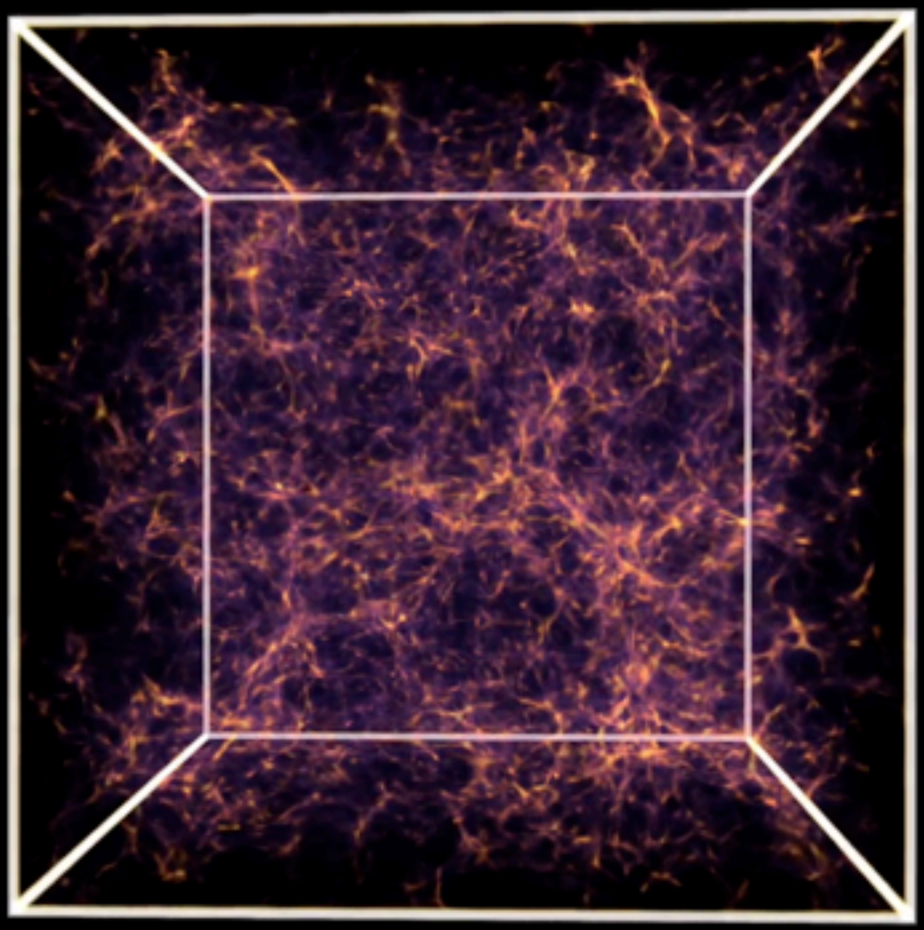


And what is the effect of resolution?



Cosmological Simulations with Cholla





Villasenor, Schneider, and Robertson (in prep)