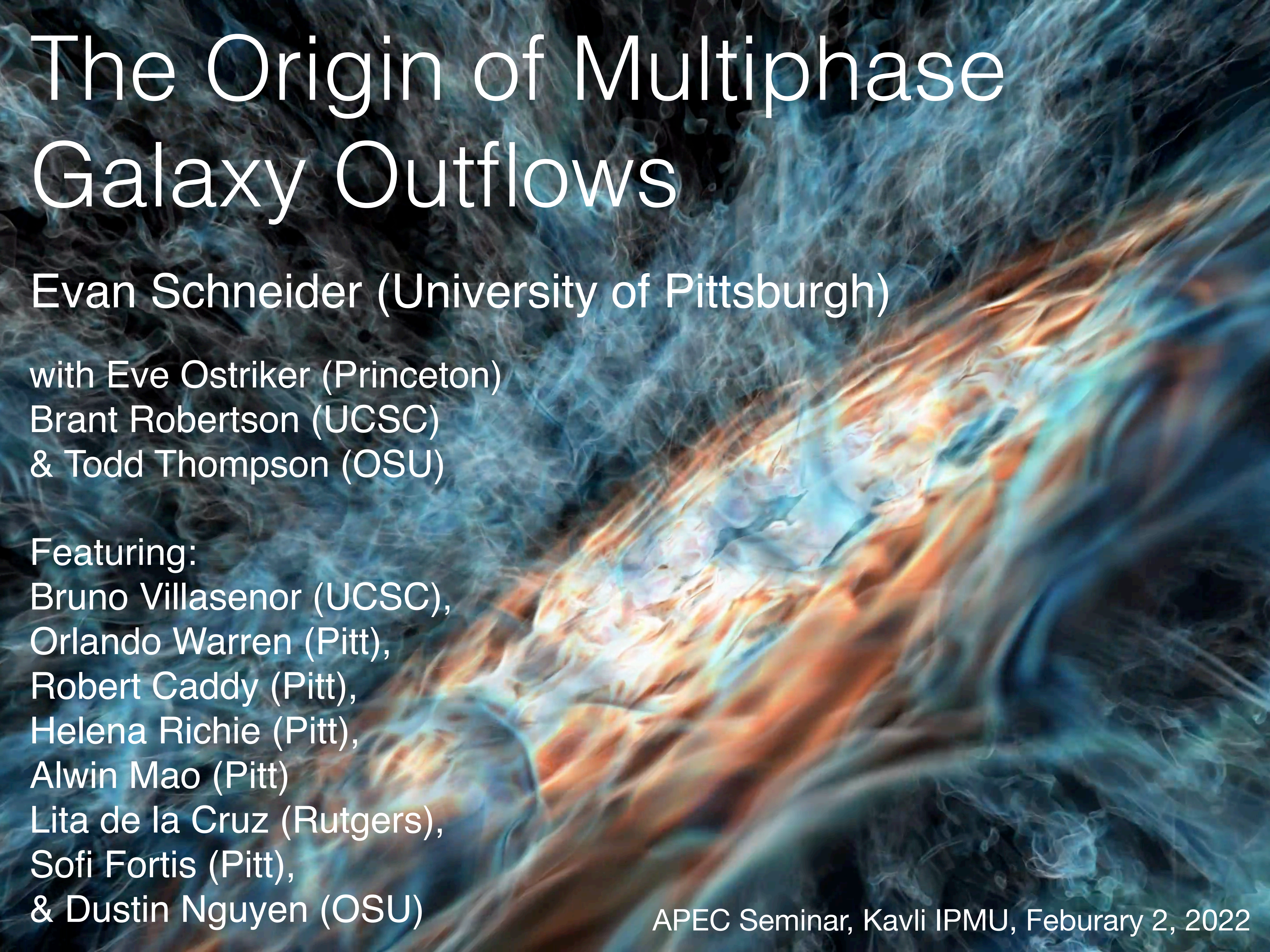


The Origin of Multiphase Galaxy Outflows

Evan Schneider (University of Pittsburgh)

with Eve Ostriker (Princeton)
Brant Robertson (UCSC)
& Todd Thompson (OSU)

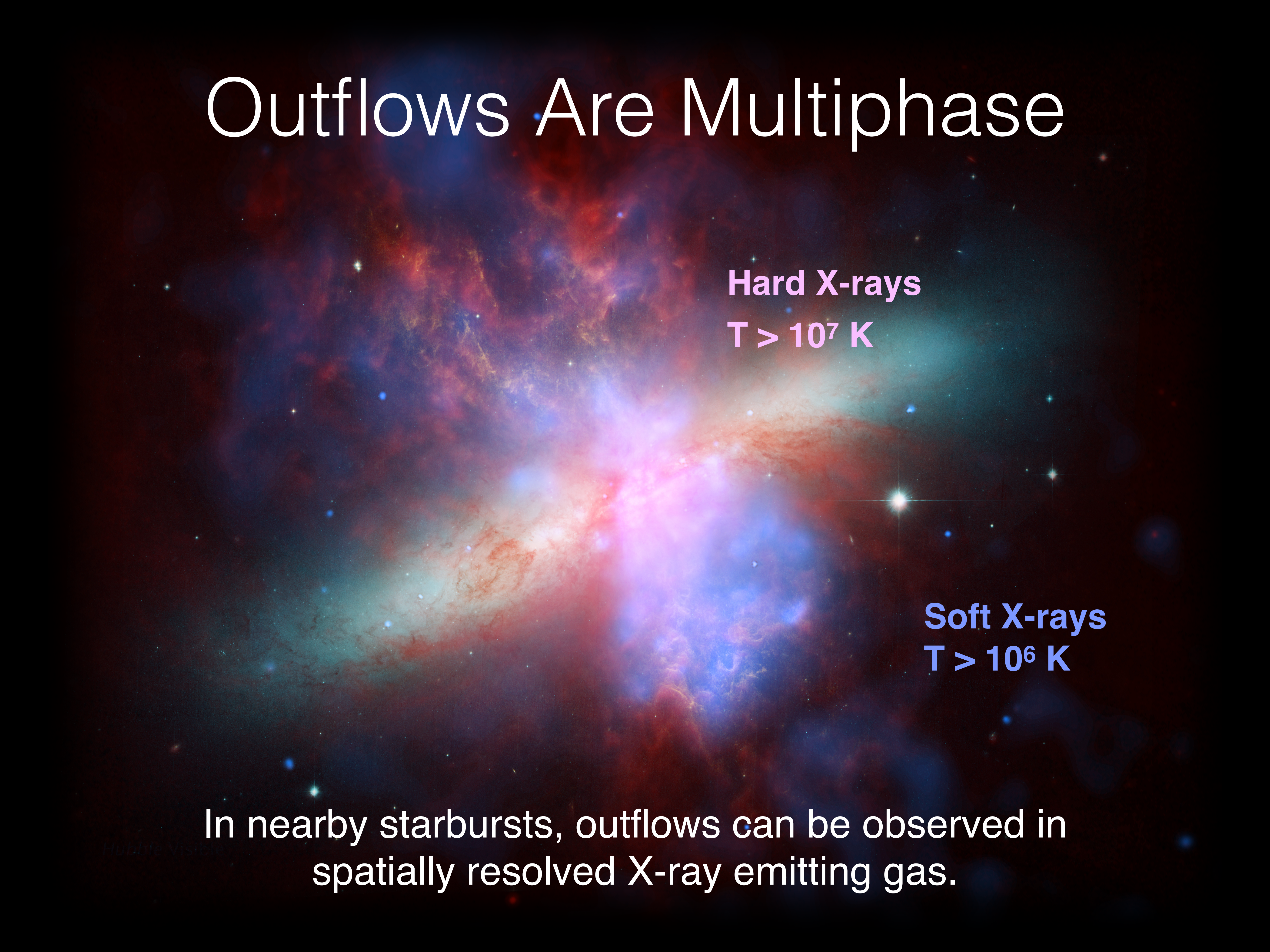
Featuring:
Bruno Villasenor (UCSC),
Orlando Warren (Pitt),
Robert Caddy (Pitt),
Helena Richie (Pitt),
Alwin Mao (Pitt)
Lita de la Cruz (Rutgers),
Sofi Fortis (Pitt),
& Dustin Nguyen (OSU)

APEC Seminar, Kavli IPMU, Feburary 2, 2022

Starburst Galaxy M82

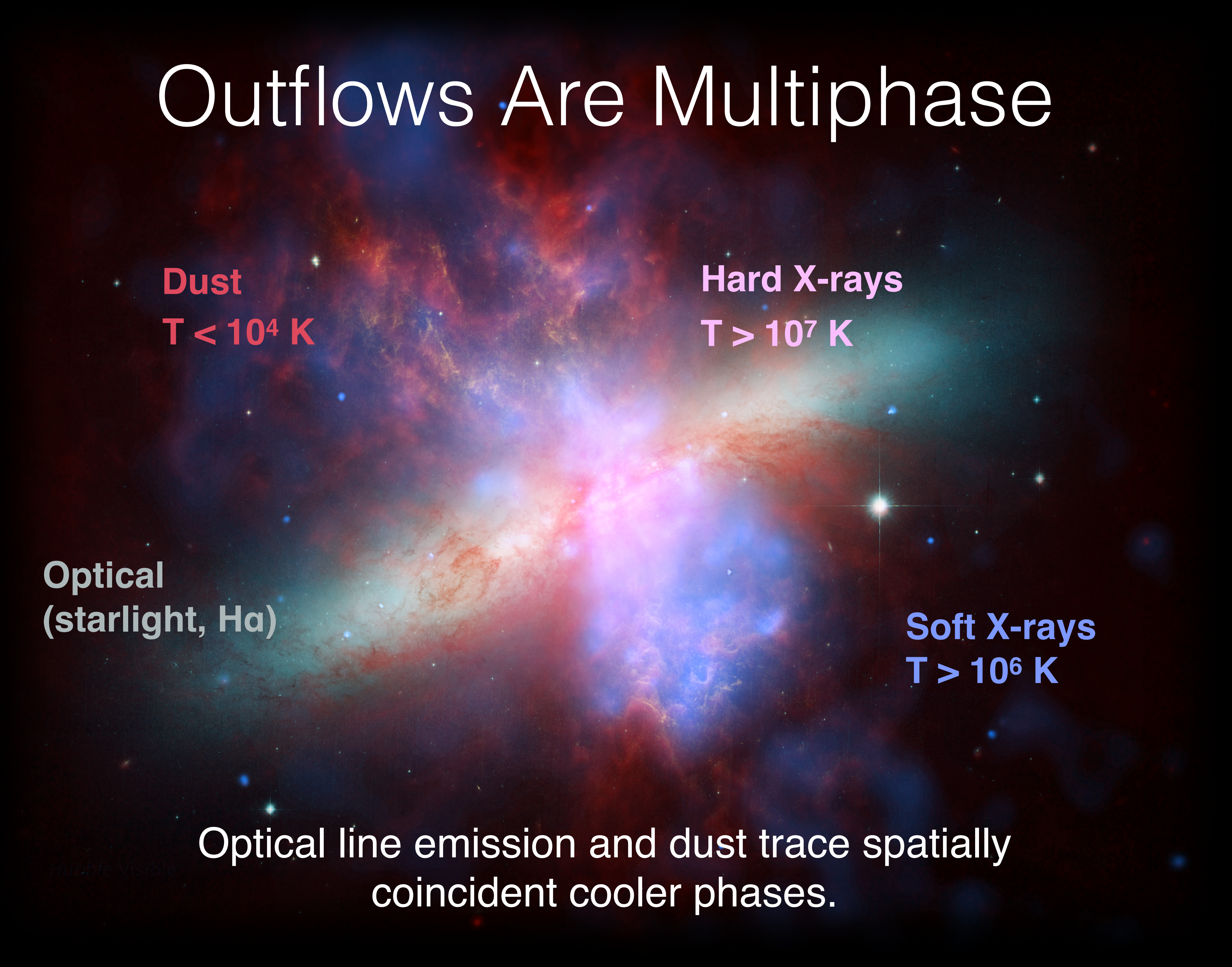
Image credit: NASA

Outflows Are Multiphase



In nearby starbursts, outflows can be observed in spatially resolved X-ray emitting gas.

Outflows Are Multiphase



Dust
$T < 10^4$ K

Hard X-rays
$T > 10^7$ K

Optical
(starlight, Hα)

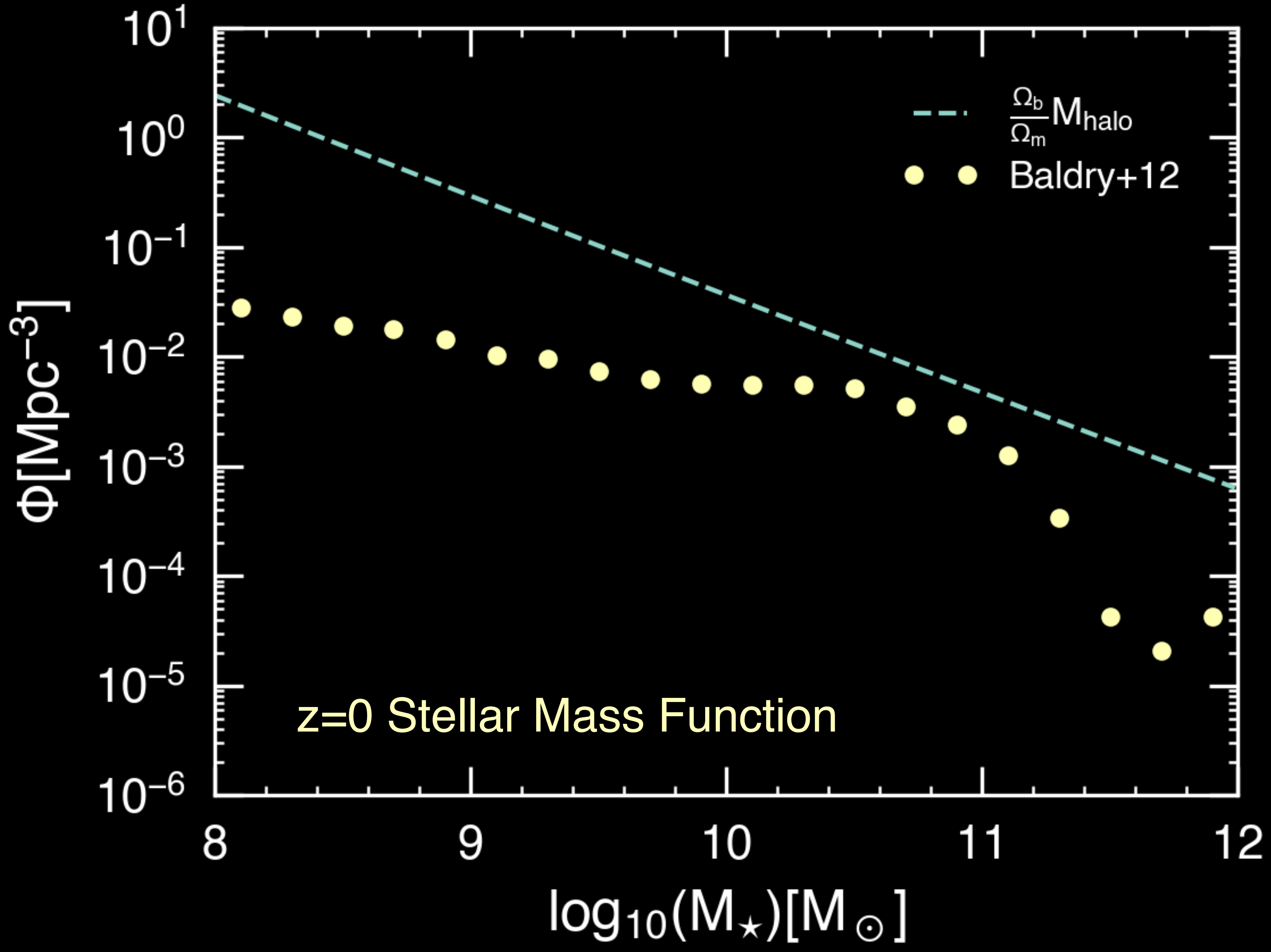
Soft X-rays
$T > 10^6$ K

Optical line emission and dust trace spatially coincident cooler phases.

Outflows Are Necessary

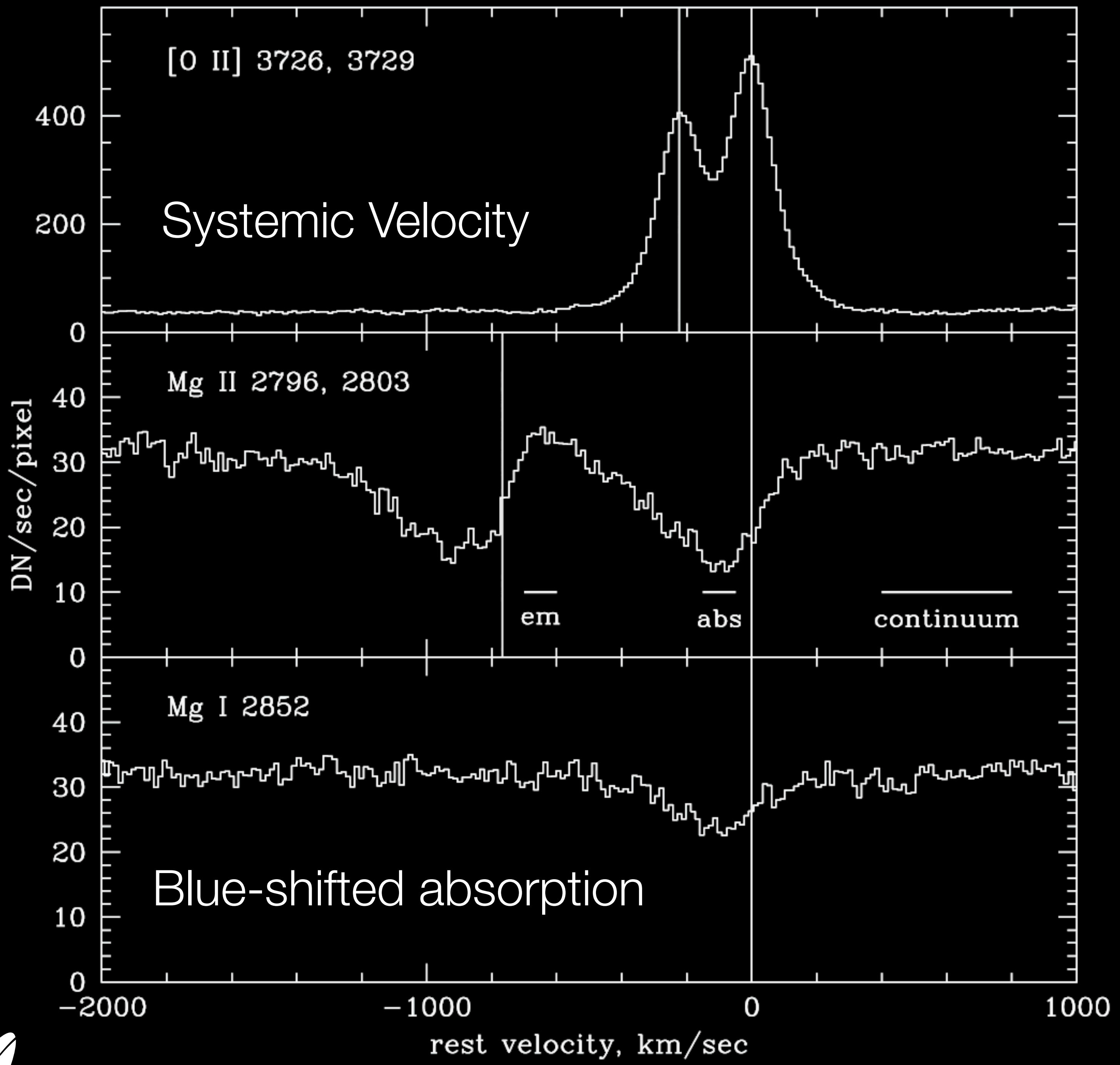
Cosmological simulations require stellar feedback to:

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

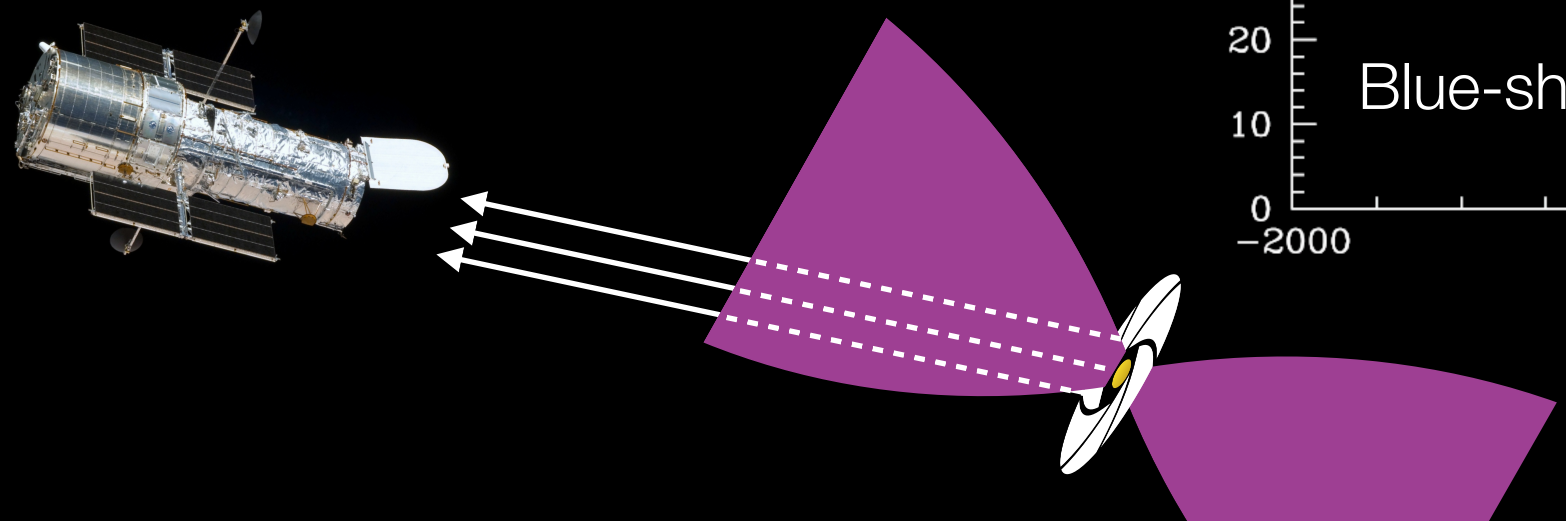


Cool Gas Exists In Outflows

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

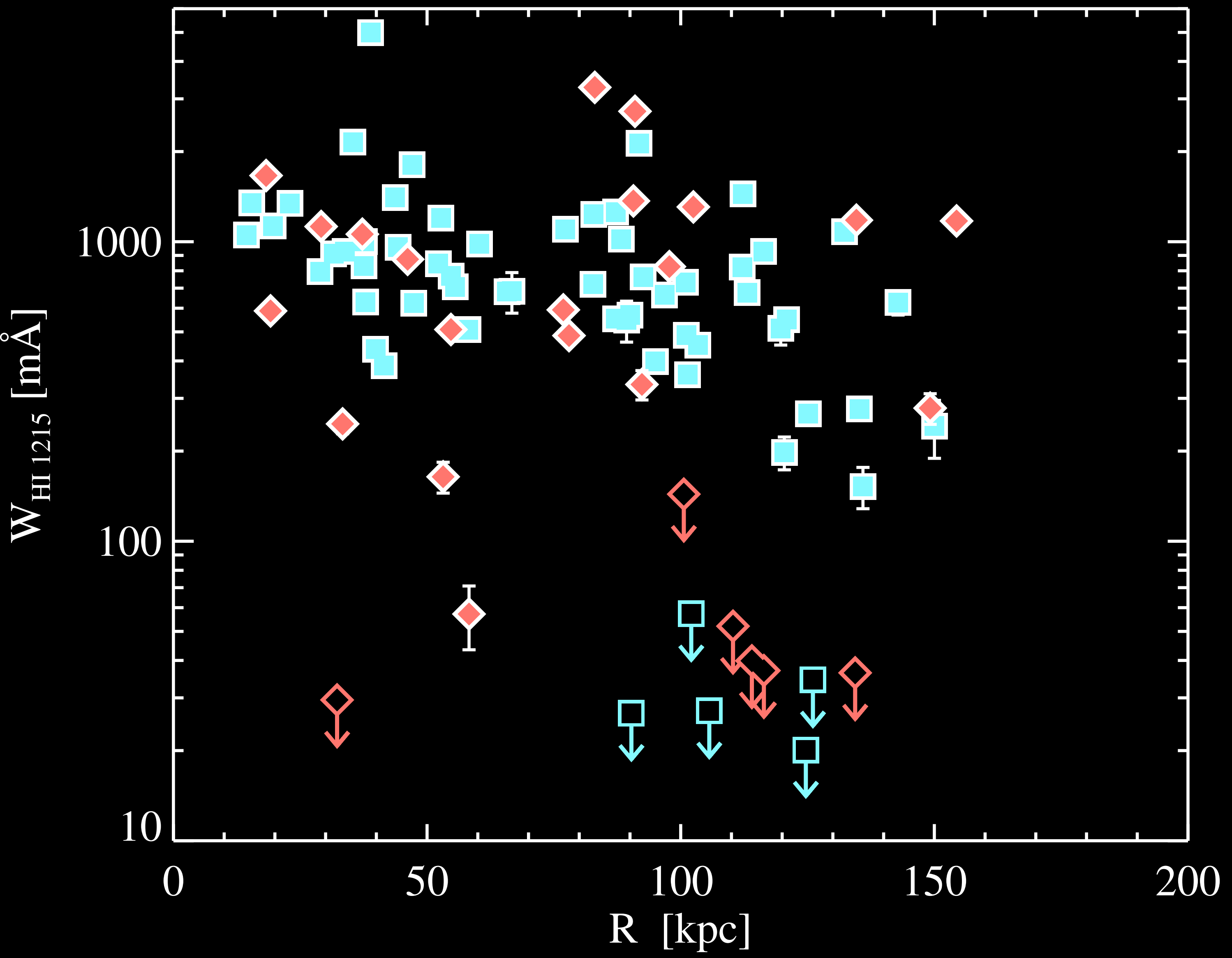


Weiner et al. (2009)

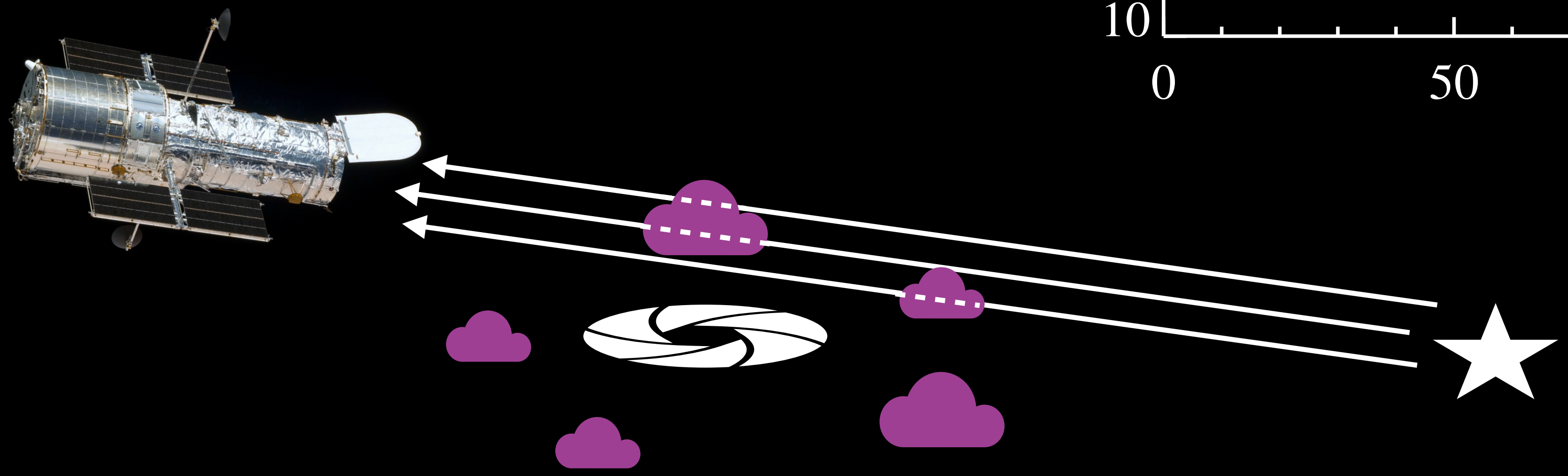


… And Around Galaxies …

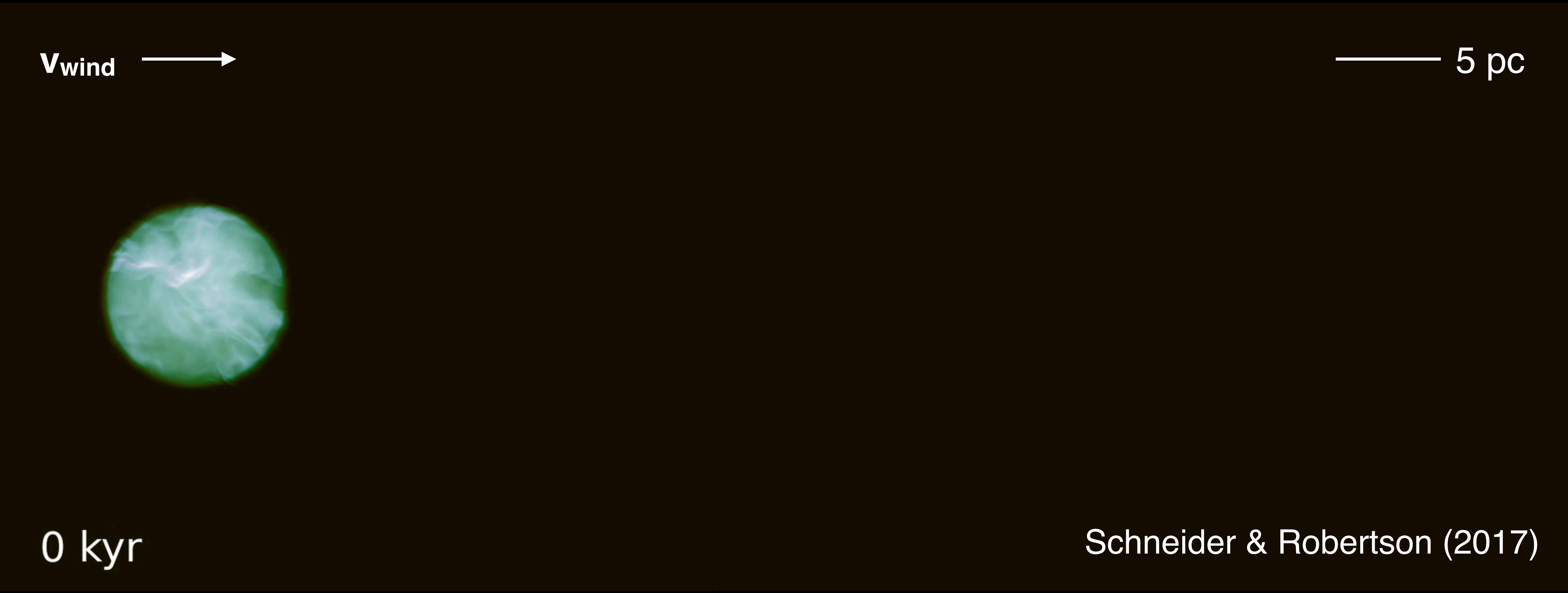
Recent surveys have found abundant neutral hydrogen in the halos of both star-forming and passive galaxies at low and high redshift.



Bordoloi et al. (2017)



… But Cool Gas Is Difficult To Accelerate.



Schneider & Robertson (2017)

See also: Cooper+09; Scannapieco+15; McCourt+15; Brüggen+16,20; Banda-Barragán+16,18,19,20,21; Gronke+18,19; Forbes+19; Sparre+19,20; Li+20; Kanjilal+20; Abruzzo+21; Farber+21

Can we build a physically-motivated model that explains the observed nature of galaxy outflows?

Simulating Outflows Is Challenging

~10 kpc (galactic disk)

~1 kpc (winds generated)

~100 kpc (CGM)

The scales involved in galactic wind evolution range from ~1-10 pc (cooling radius of supernova bubbles) to ~100 kpc (virial radius of halo).

Cholla:

Computational hydrodynamics on || architectures

Cholla are also a group of cactus species that grows in the Sonoran Desert of southern Arizona.

- A GPU-native, massively-parallel, grid-based hydrodynamics code (publicly available at github.com/cholla-hydro/cholla)
- Available physics includes:
  - Unsplit 3D compressible hydrodynamics
  - Optically thin radiative cooling and photoionization heating
  - Static gravity
  - Passive Scalar Tracking
  - Self gravity (FFT based or relaxation method)
  - Particles
  - Cosmology

Schneider & Robertson (2015, 2017); Schneider+20; Villasenor+21

Cholla:

Computational
hydrodynamics
on
||
architectures

Cholla are also a group of cactus species that grows in the Sonoran Desert of southern Arizona.

- A GPU-native, massively-parallel, grid-based hydrodynamics code (publicly available at github.com/cholla-hydro/cholla)
- Features in development:
    - Star formation and stellar feedback models (Orlando Warren)
    - MHD (Robert Caddy)
    - Dust (Helena Richie)
    - Radiative Transfer
    - Automated testing and continuous integration (Robert Caddy)

Cholla takes advantage of the world's most powerful supercomputers.

Summit:

Fastest Open Science Supercomputer in the US

- 200 petaflops
- 4600 nodes
- 27,600 NVIDIA V100 GPUs

Cholla takes advantage of the world's most powerful supercomputers.

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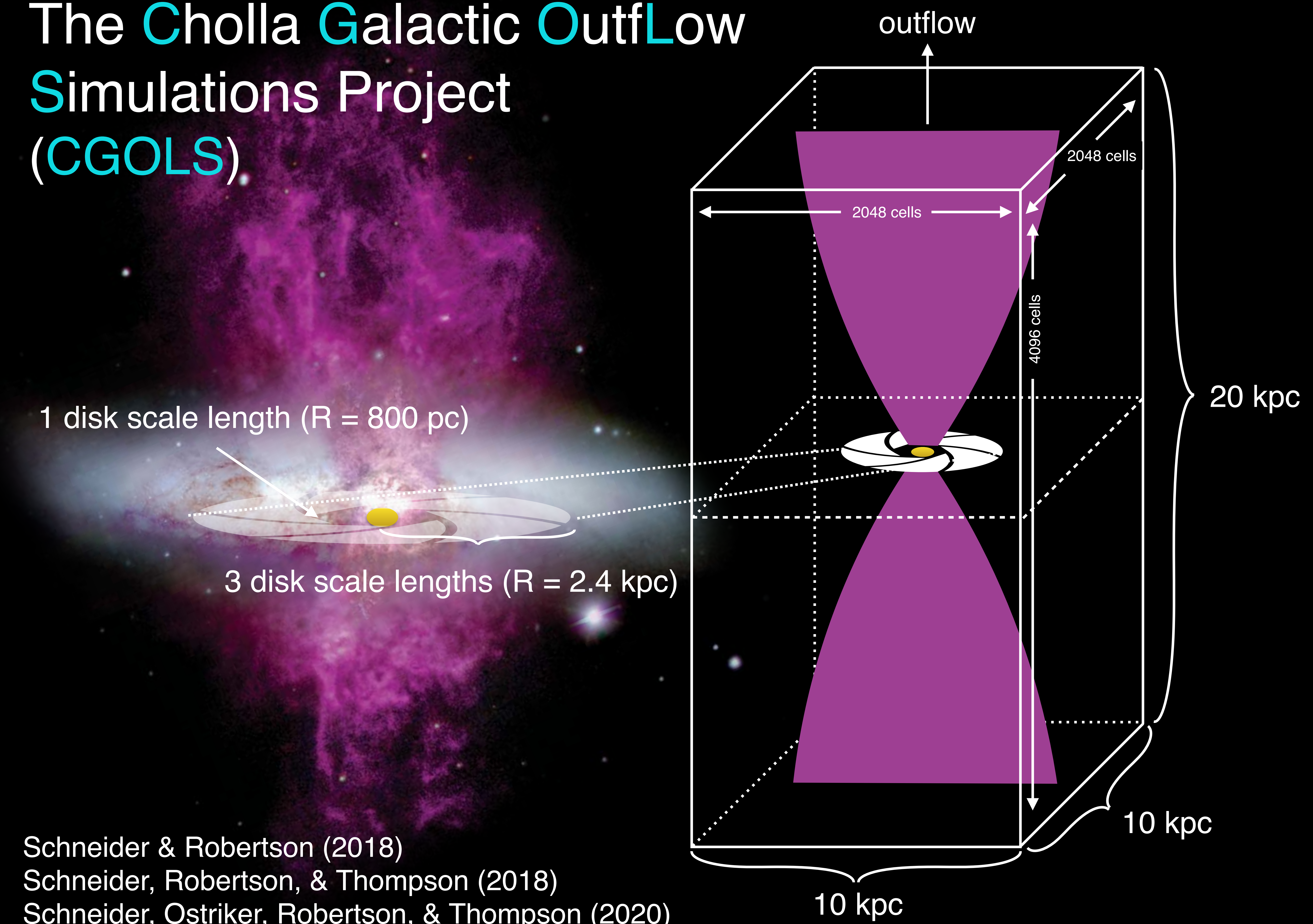
Cholla takes advantage of the world's most powerful supercomputers.

Frontier: The first US exascale supercomputer

See https://www.olcf.ornl.gov/caar/frontier-caar/

The Cholla Galactic OutfLow Simulations Project (CGOLS)



outflow

2048 cells

2048 cells

4096 cells

20 kpc

1 disk scale length (R = 800 pc)

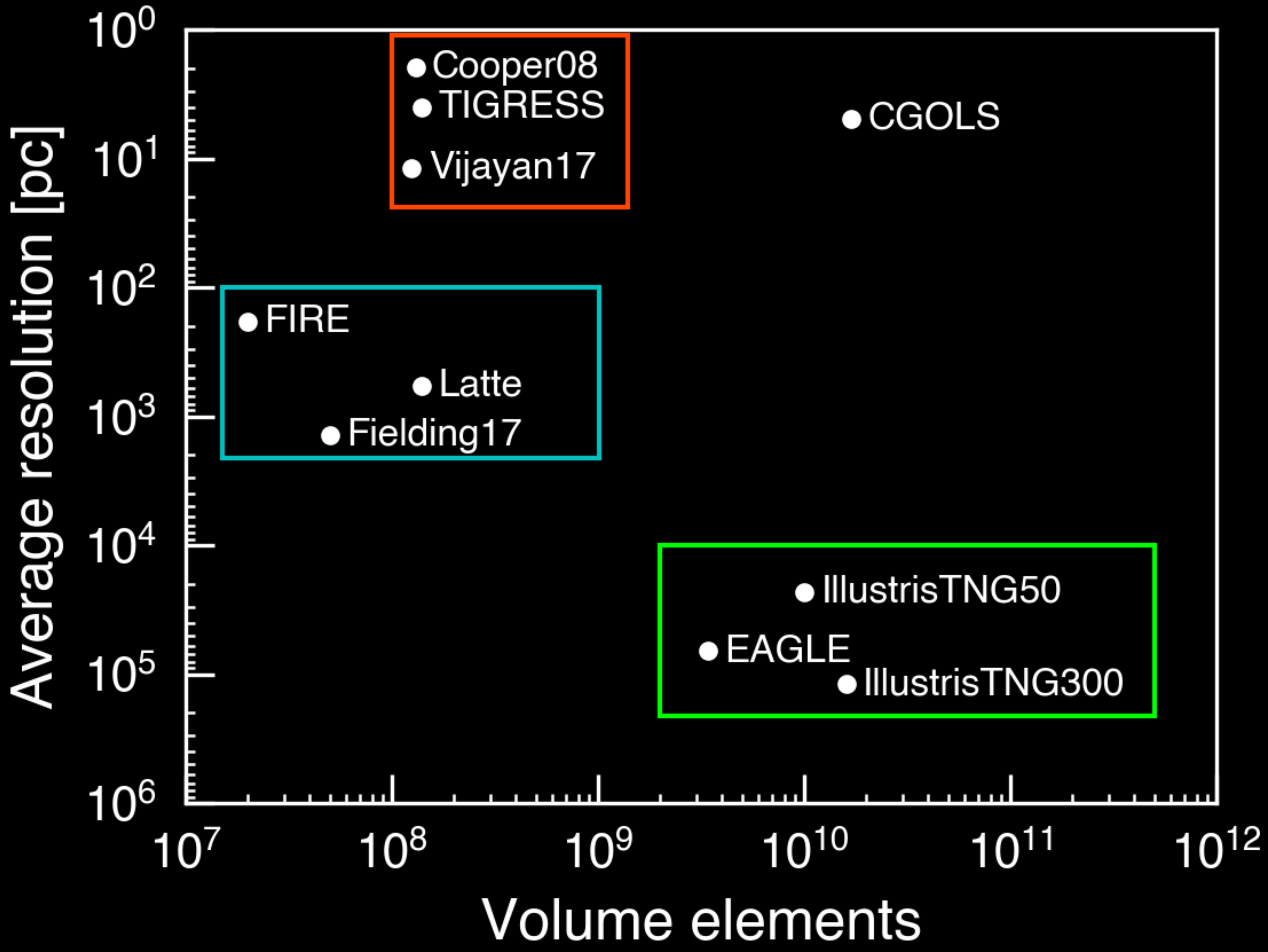
3 disk scale lengths (R = 2.4 kpc)

10 kpc

10 kpc

Schneider & Robertson (2018)
Schneider, Robertson, & Thompson (2018)
Schneider, Ostriker, Robertson, & Thompson (2020)

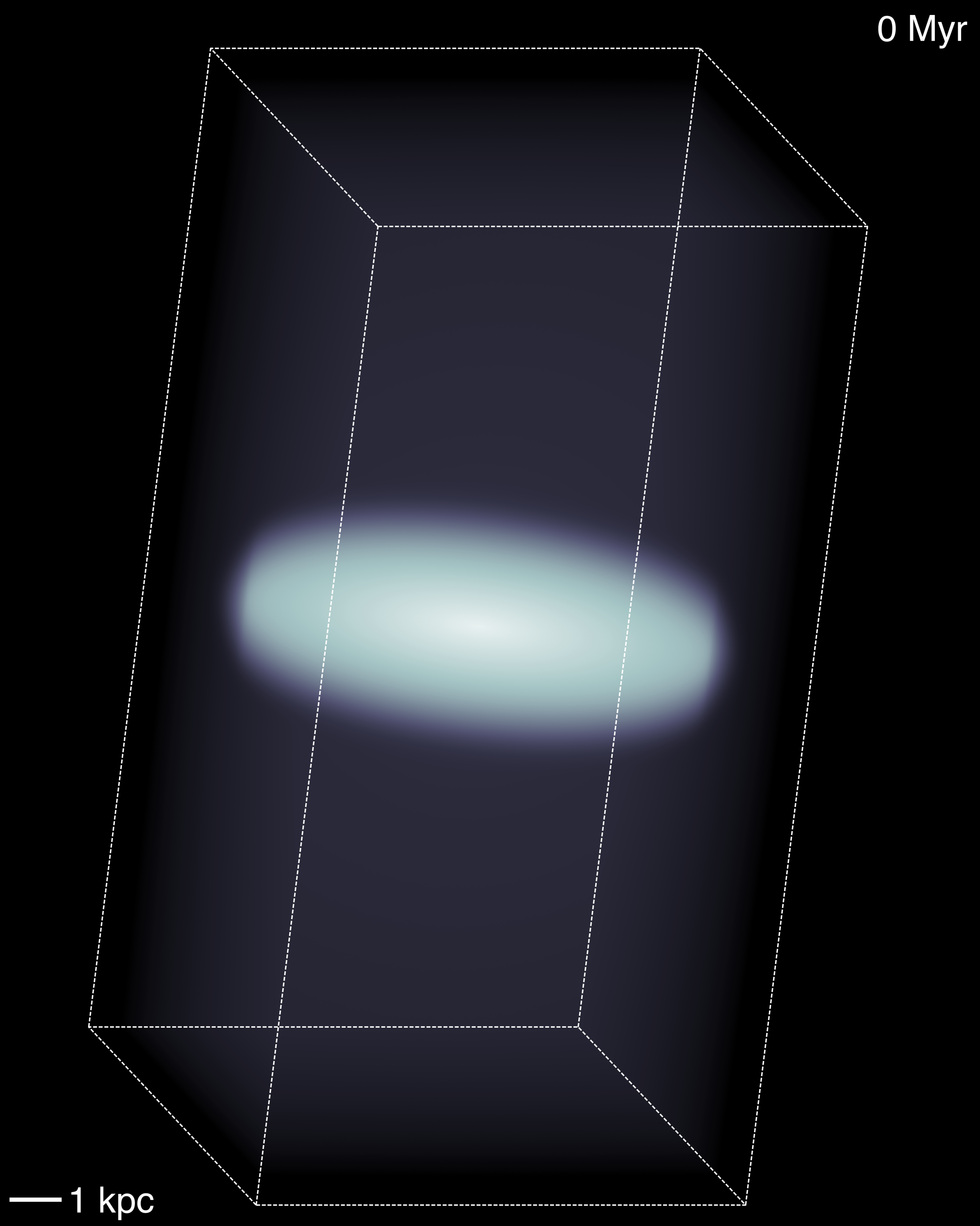
What's unique about CGOLS?



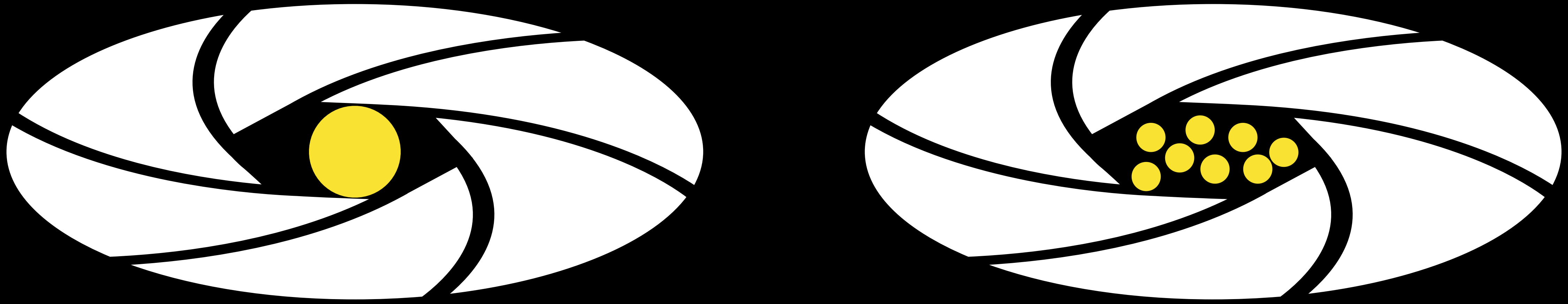
Schneider & Robertson 2018

CGOLS 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 $M_{DM} = 10^{11}\ M_\odot$
- All simulations run at three resolutions: Δx = 5pc, 10pc, and 20pc, in a 10 kpc x 10 kpc x 20 kpc box



CGOLS Simulation Features
Feedback Models



Feedback is either central or clustered, with varied mass loading, energy loading, and “SFR”.

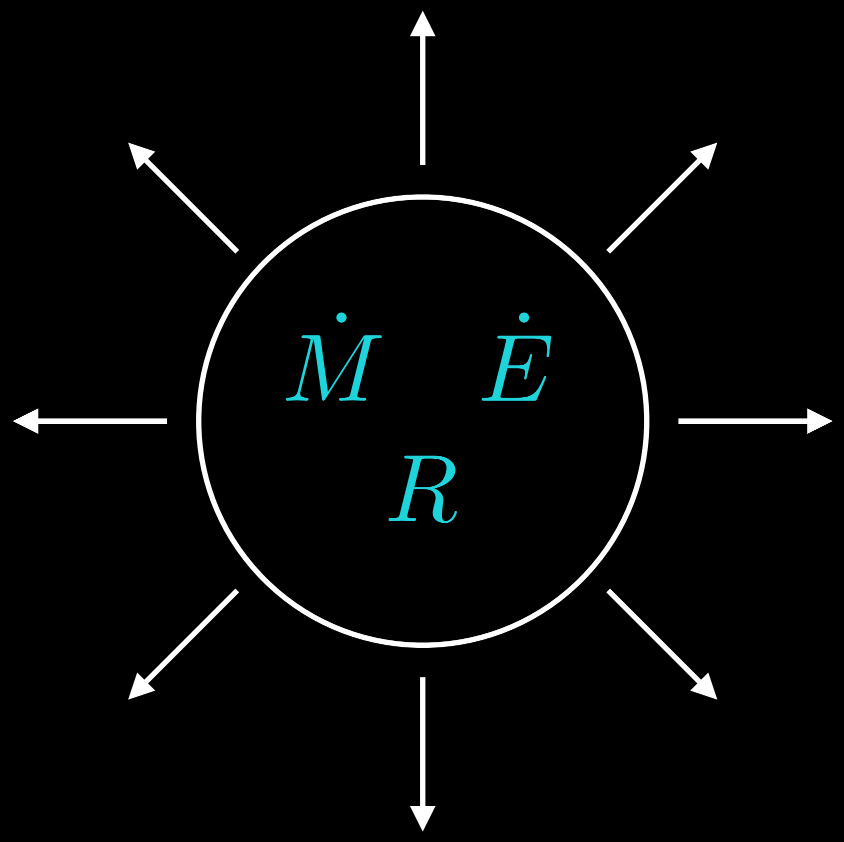
The Adiabatic Wind Model

The Chevalier & Clegg (1985) 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



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

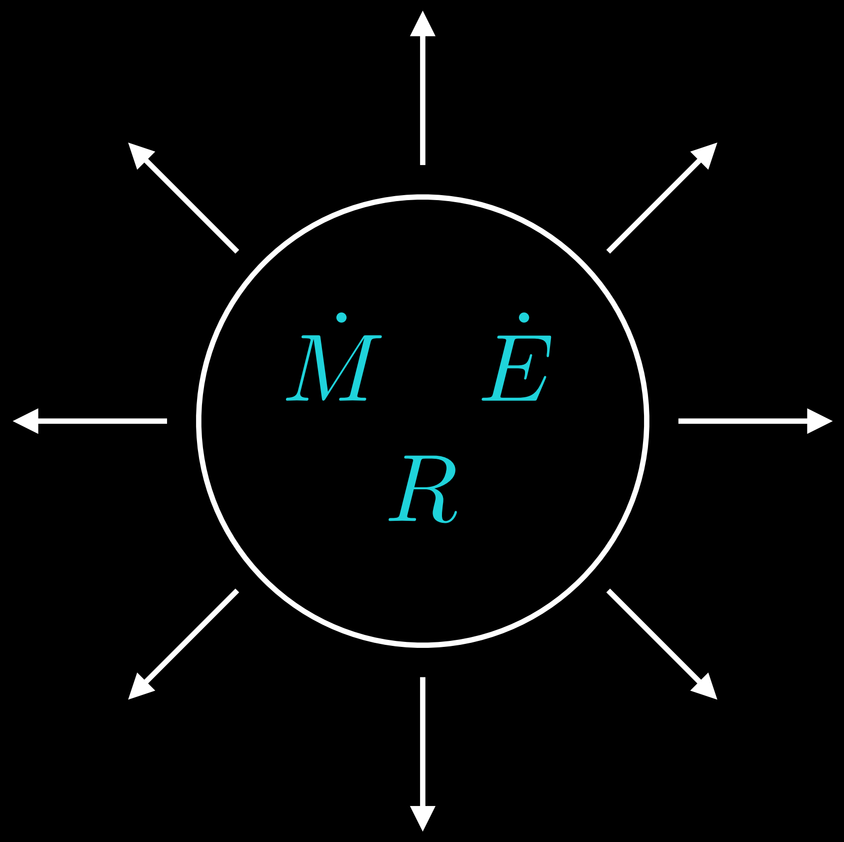
The Adiabatic Wind Model

The Chevalier & Clegg (1985) outflow model assumes spherical symmetry and its solution is governed by three parameters:

$\dot{M}$: mass injection rate

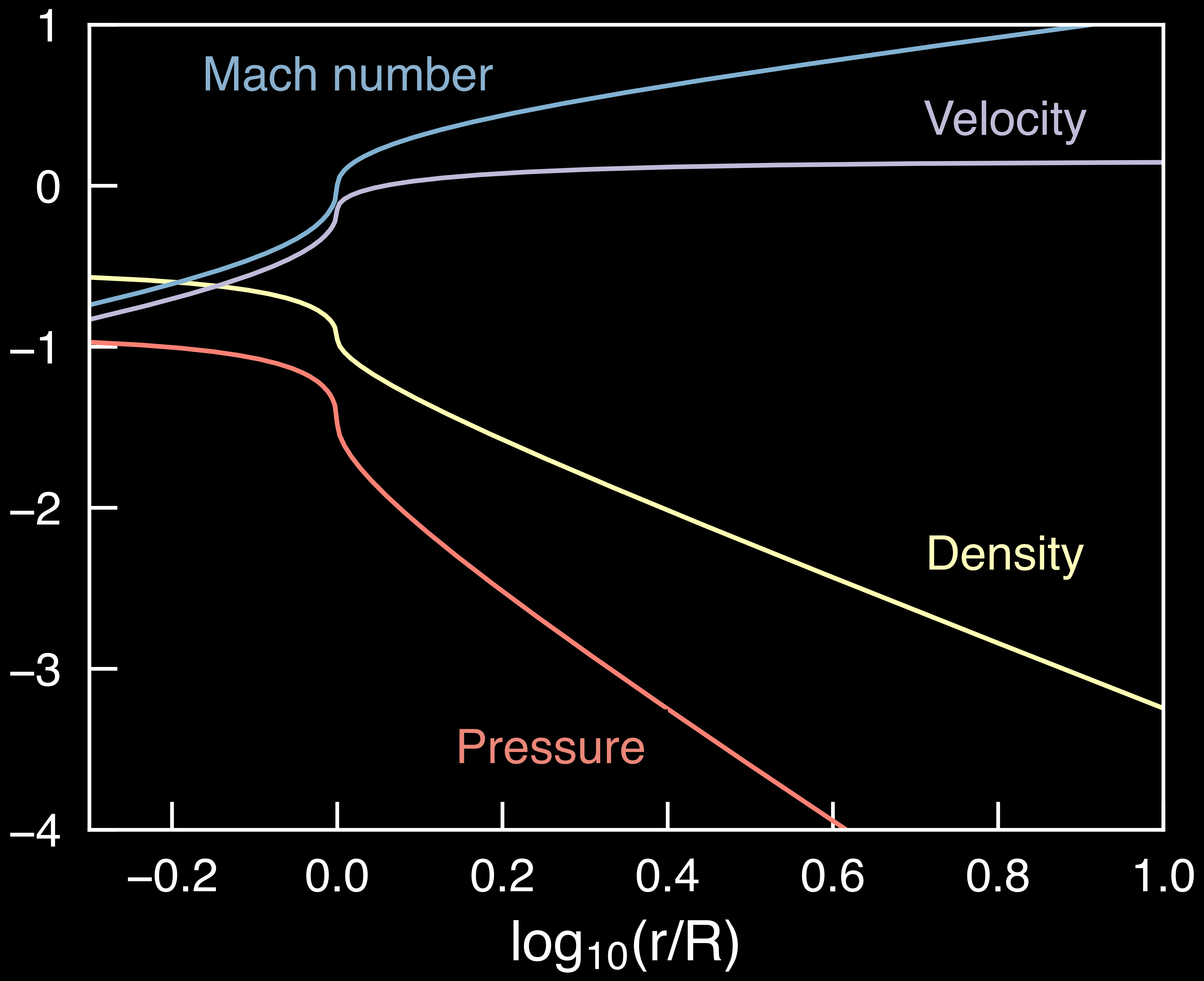
$\dot{E}$: energy injection rate

R : injection radius

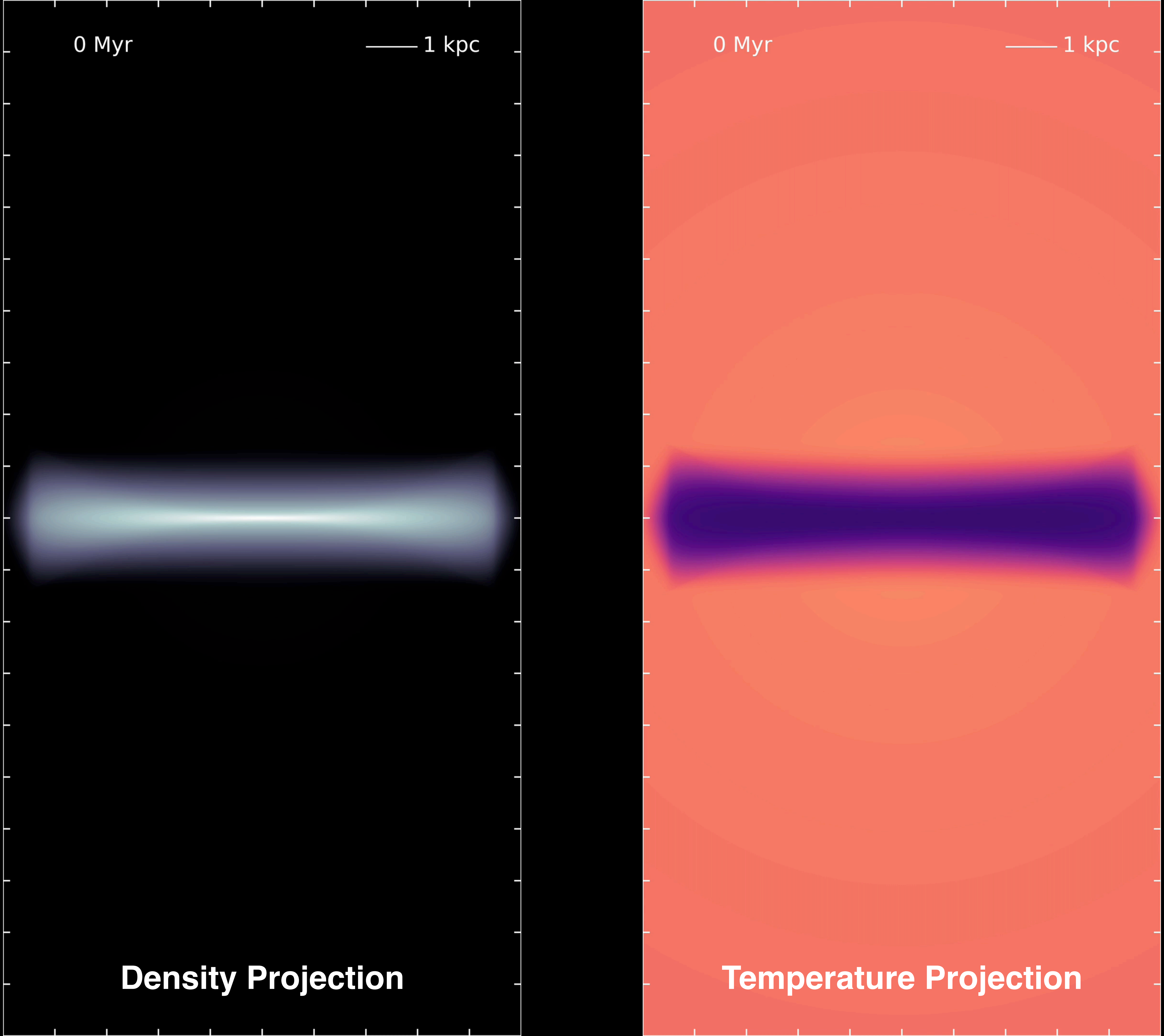


$$\dot{M}_{\mathrm{wind}} = \underset{\substack{\uparrow \\ \text{Mass-loading factor}}}{\beta}\dot{M}_{\mathrm{SFR}} \qquad \dot{E}_{\mathrm{wind}} = 3 \times 10^{41}\,\mathrm{erg\,s^{-1}}\,\underset{\substack{\nwarrow \\ \text{Energy-loading factor}}}{\alpha}\dot{M}_{\mathrm{SFR}}$$

The Adiabatic Wind Model

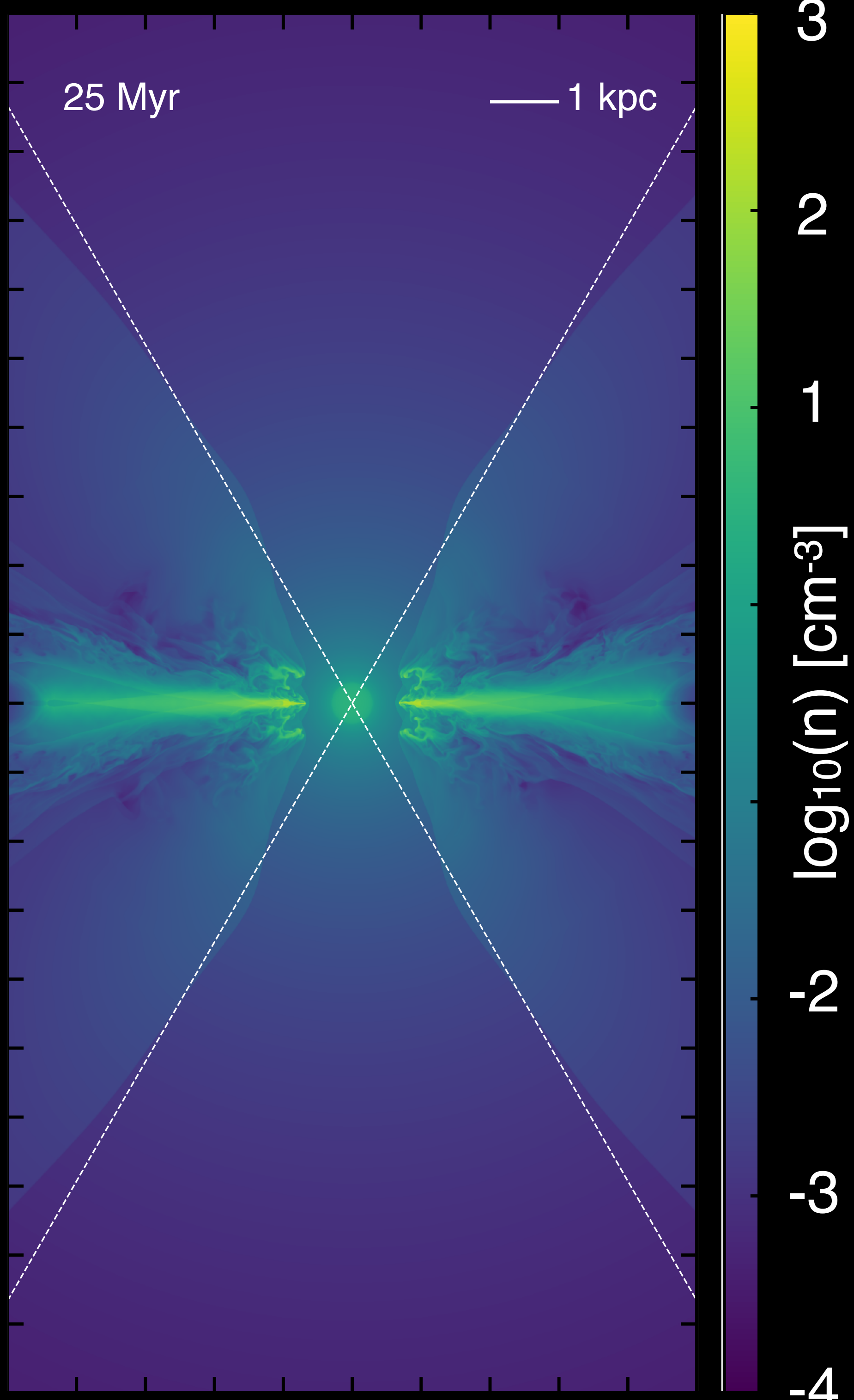


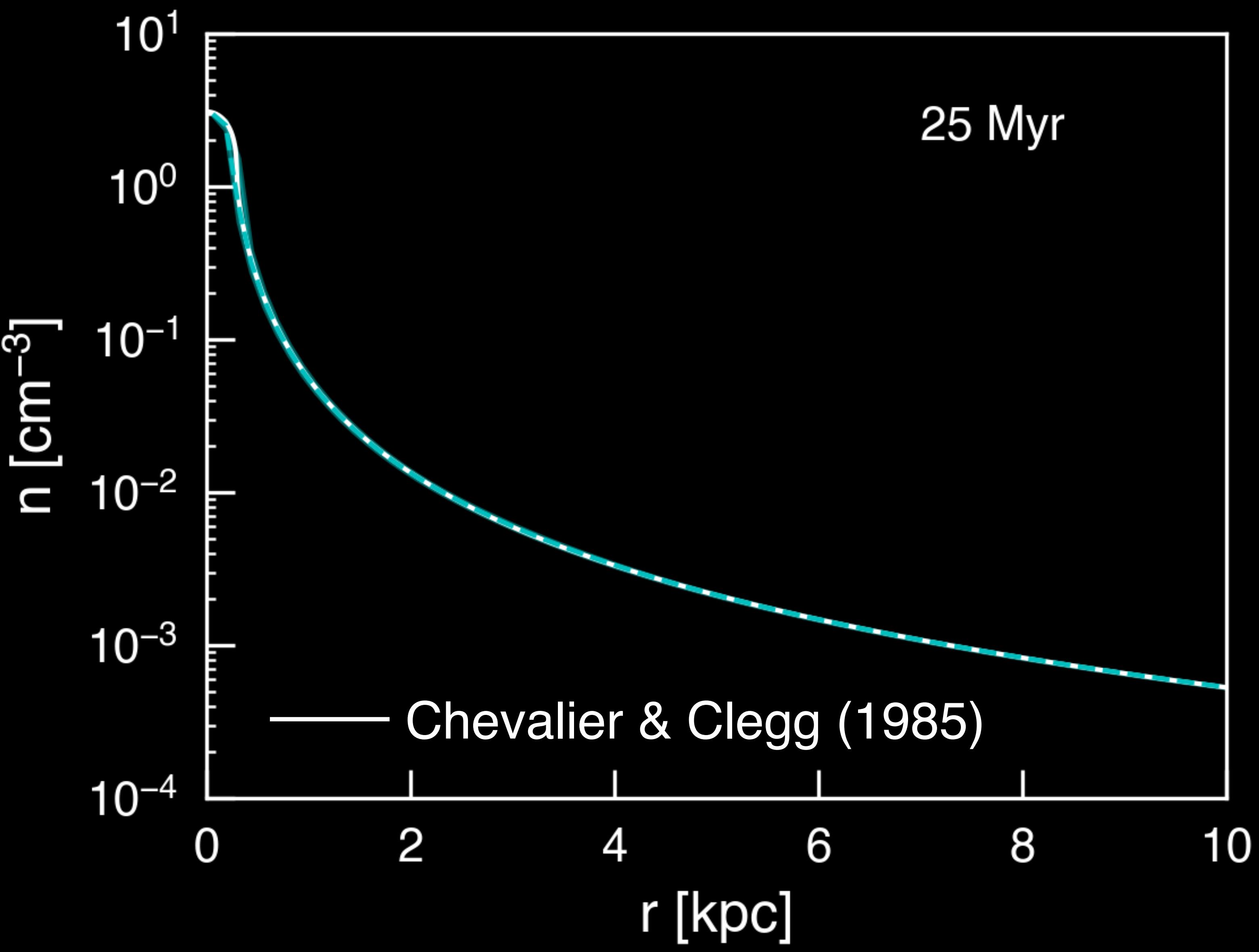
Adiabatic Simulation - Central Feedback



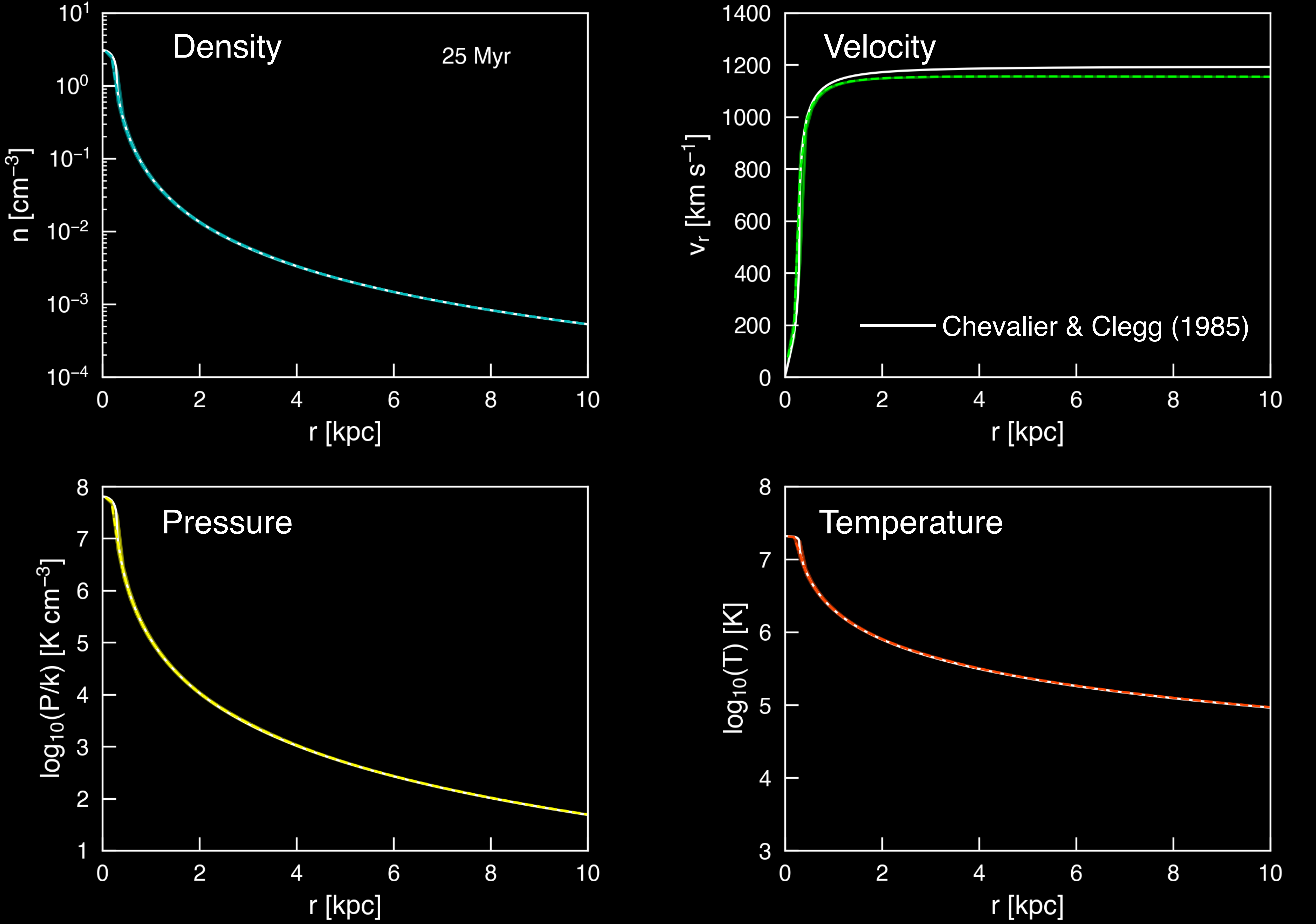
Schneider & Robertson (2018) Arxiv No. 1803.01008

Within the free wind zone, the analytic model provides a good fit to the simulation results.



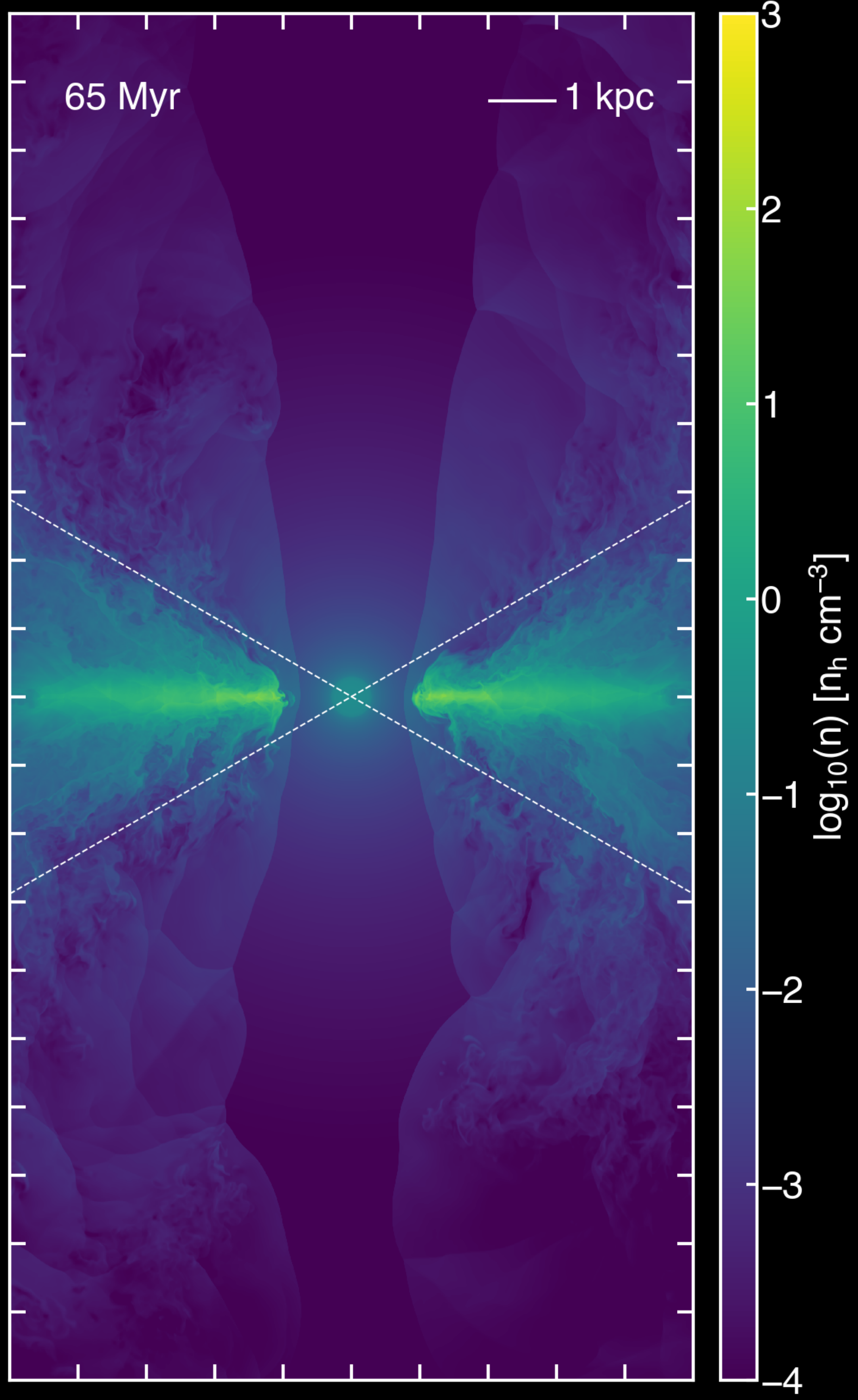


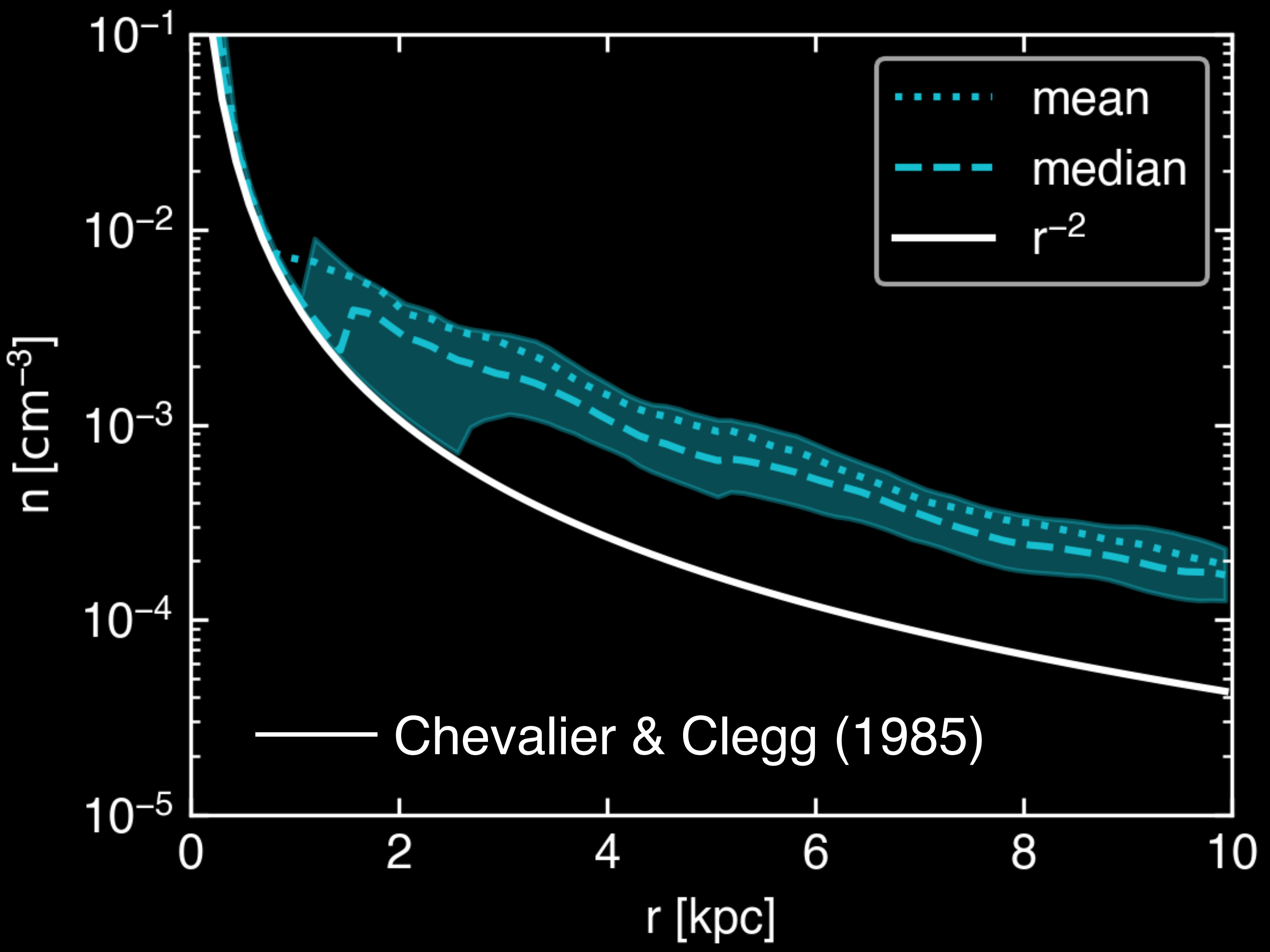
Schneider & Robertson (2018)



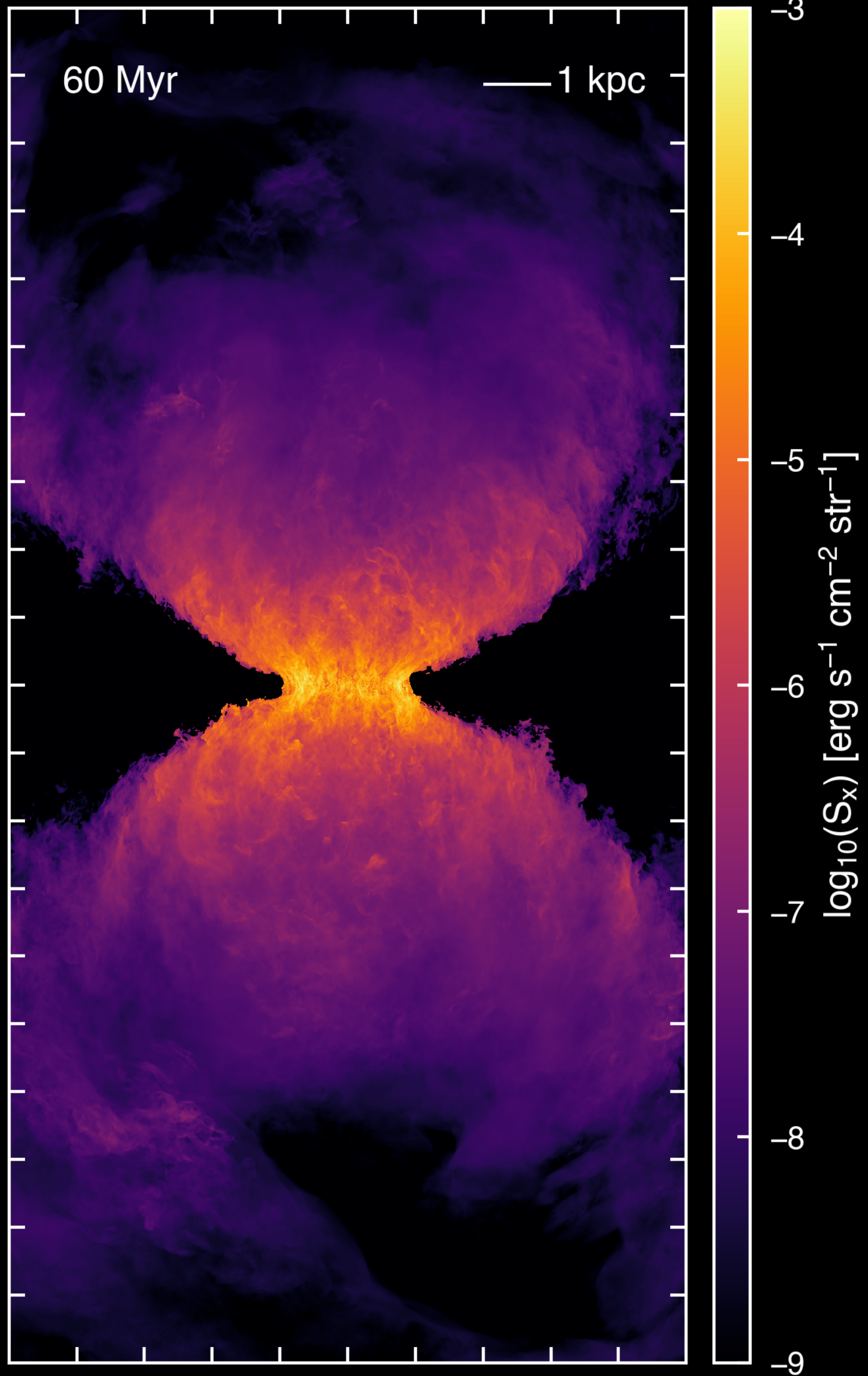
Schneider & Robertson (2018)

Outside, the wind is significantly mass-loaded.

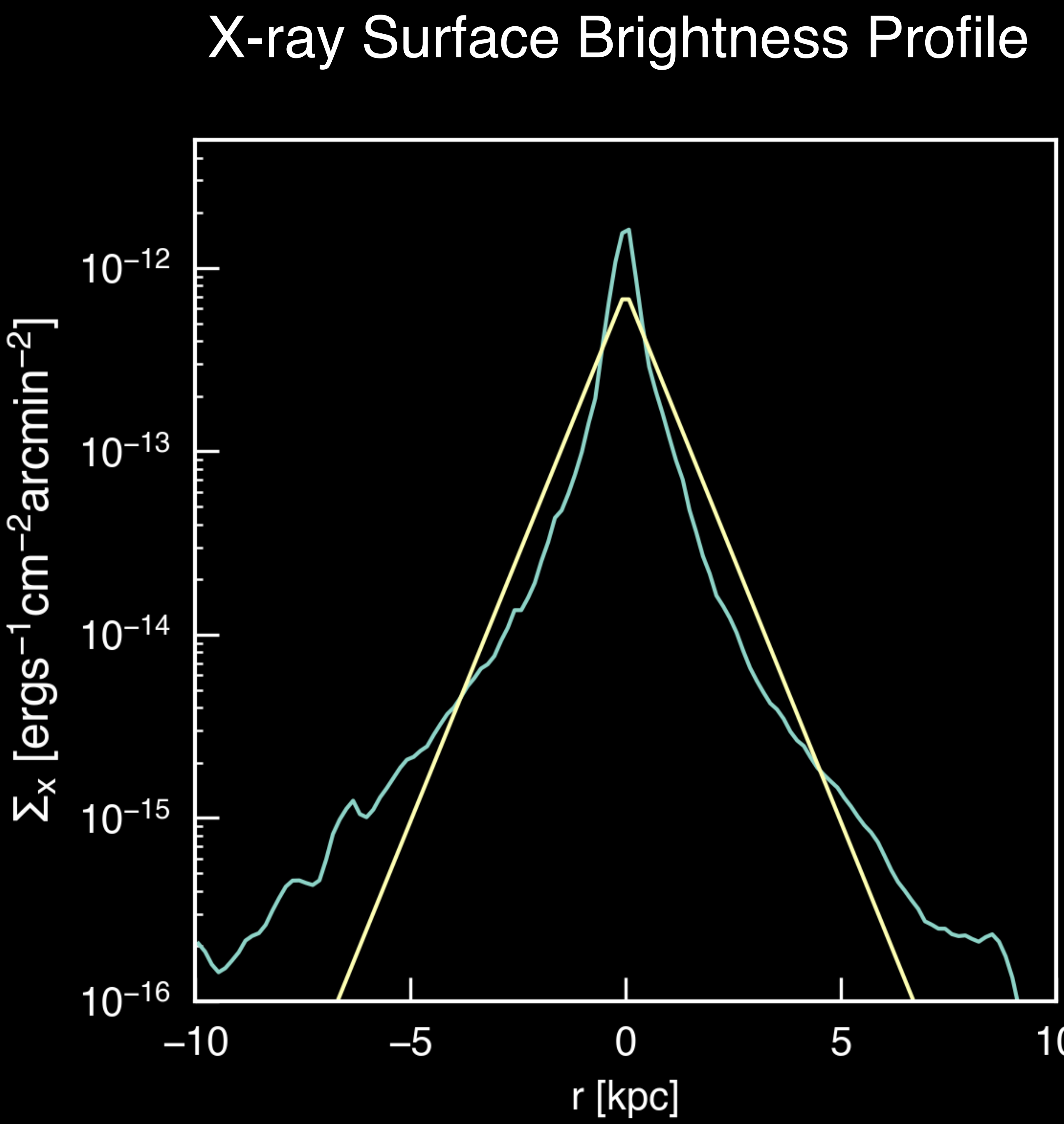




Comparison to X-ray Observations



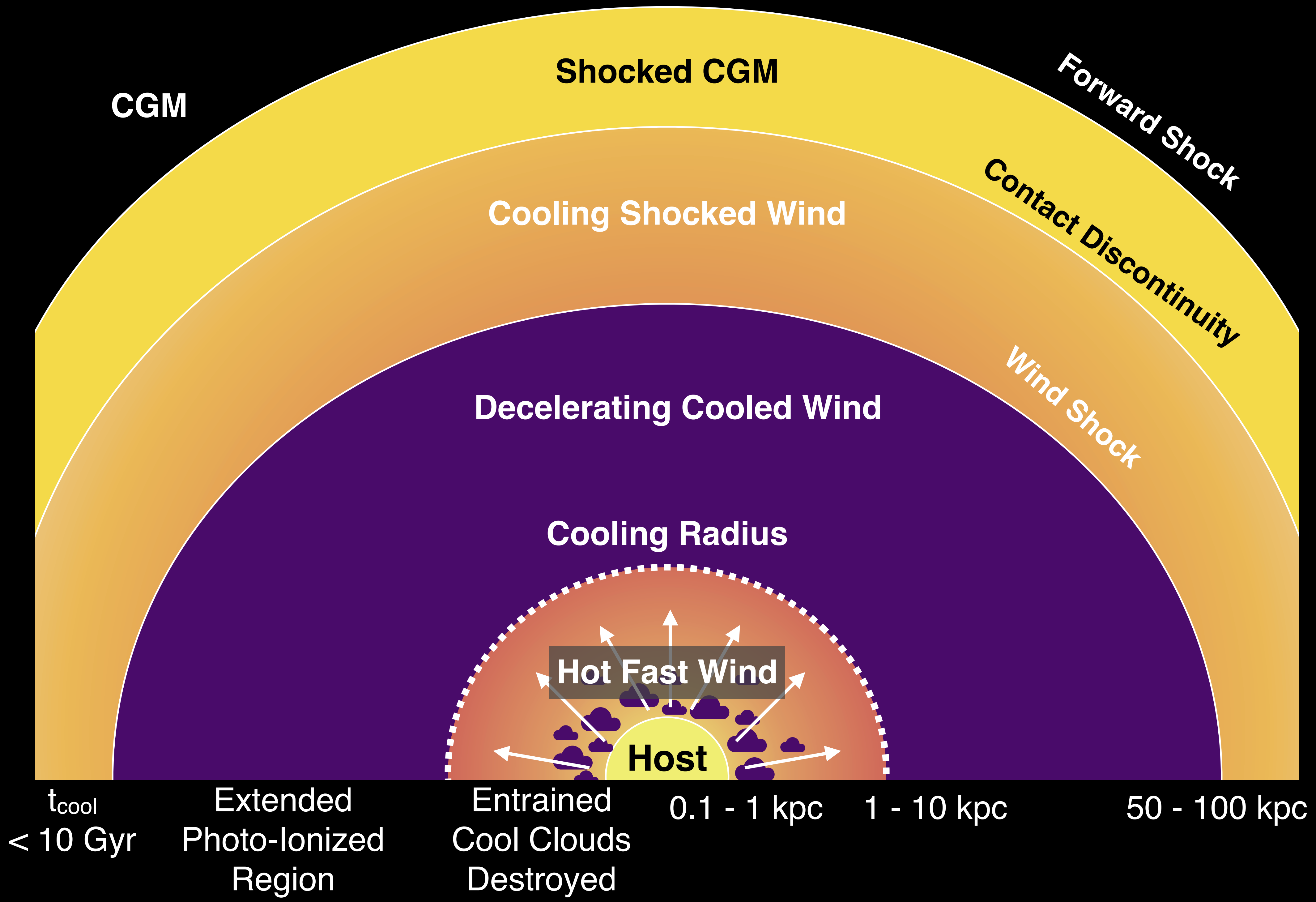
Schneider & Robertson (2018)



Total luminosity sim: 1.9 x 10^{40} erg s^{-1}

Total luminosity obs: 4.3 x 10^{40} erg s^{-1}

The Radiative Wind Model



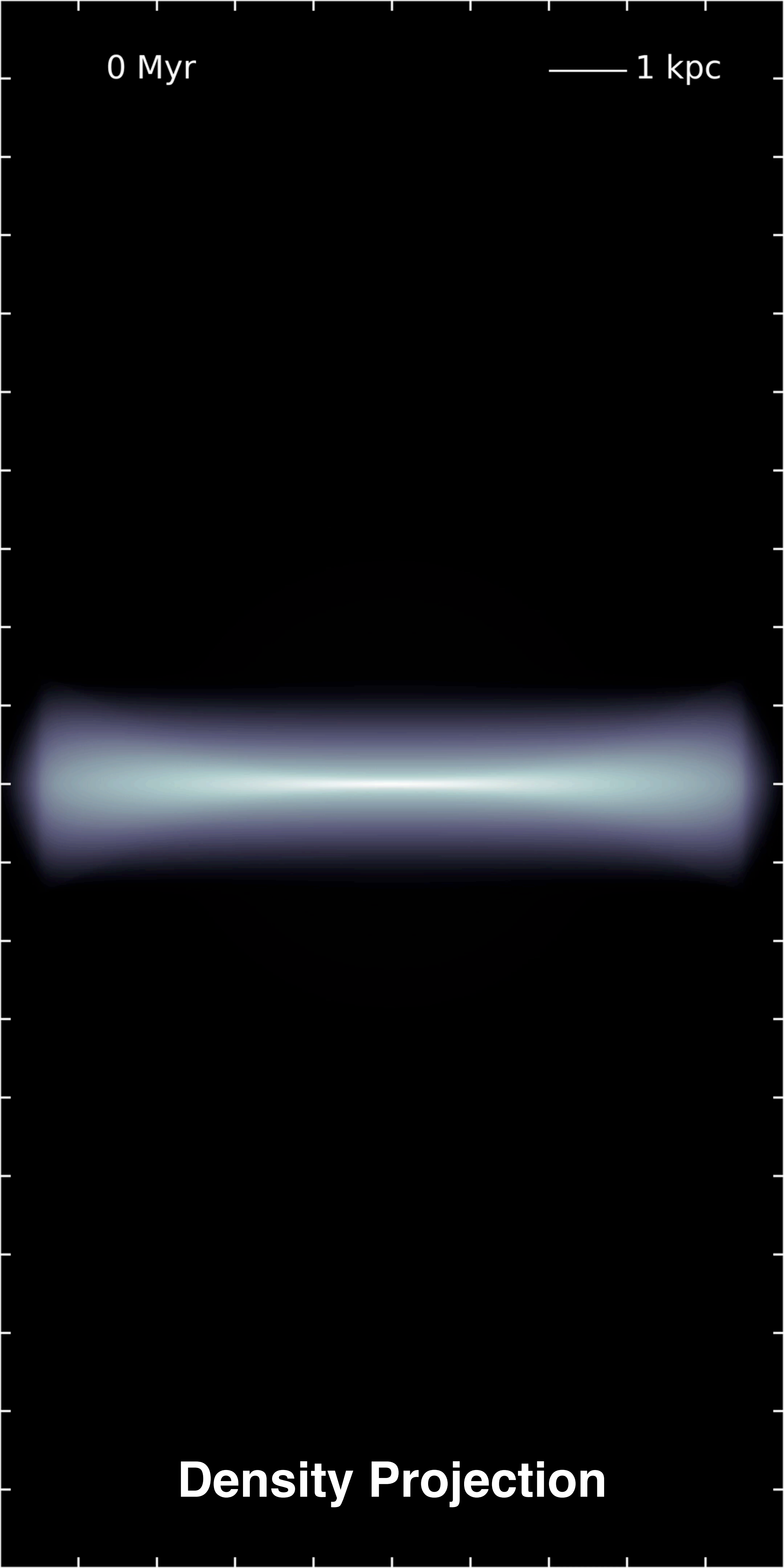
$$t_{\rm cool} \propto \frac{\alpha^{2.2}}{\beta^{3.2}}$$

$$t_{\rm adv} \propto \left(\frac{\beta}{\alpha}\right)^{\frac{1}{2}}$$

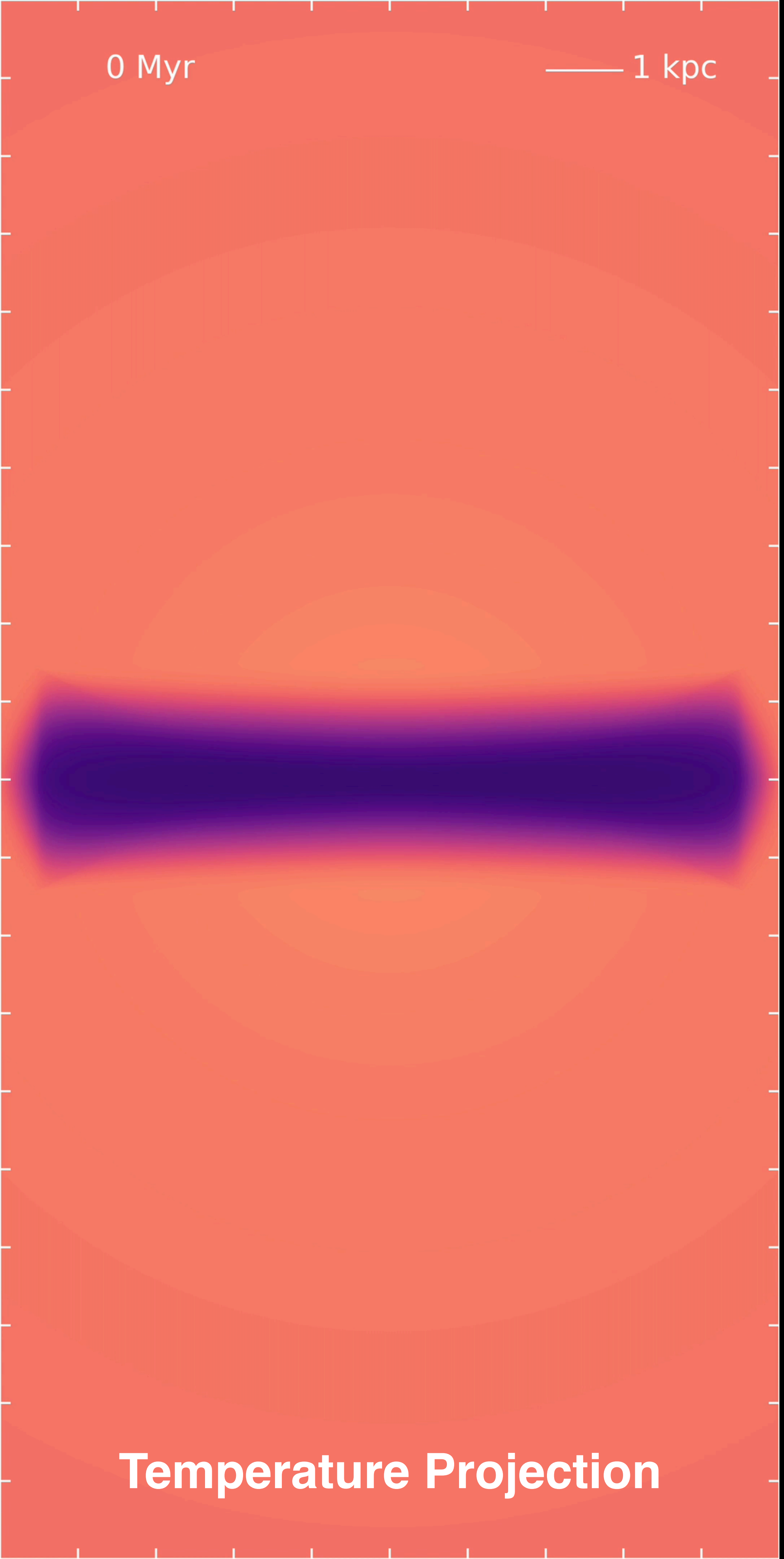
$$r_{\rm cool} \sim 4{\rm kpc}\frac{\alpha^{2.13}}{\beta^{2.92}}$$

Thompson et al. (2016)

Radiative Simulation - Central Feedback



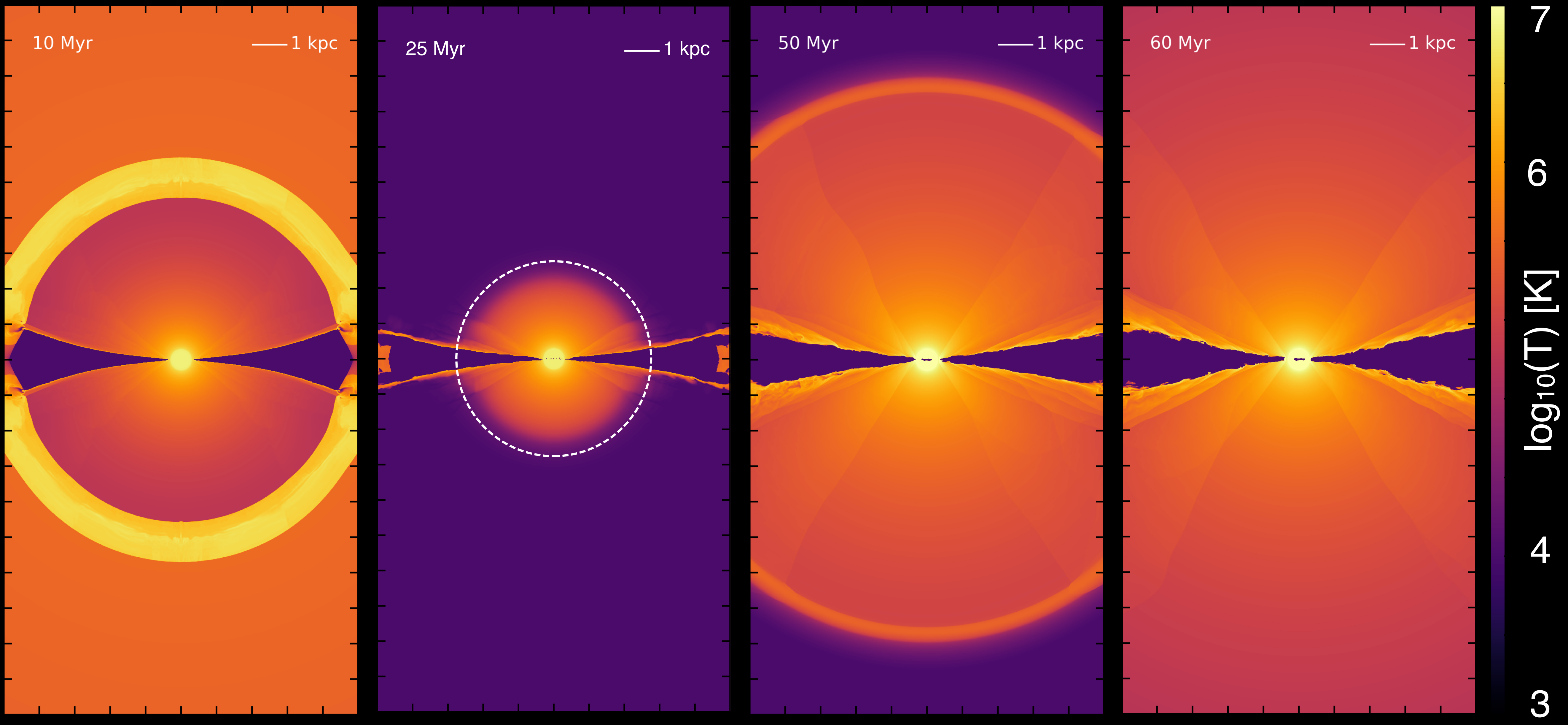
Density Projection



Temperature Projection

Schneider, Robertson & Thompson (2018) Arxiv No. 1803.01005

Temperature Structure in the Radiative Model



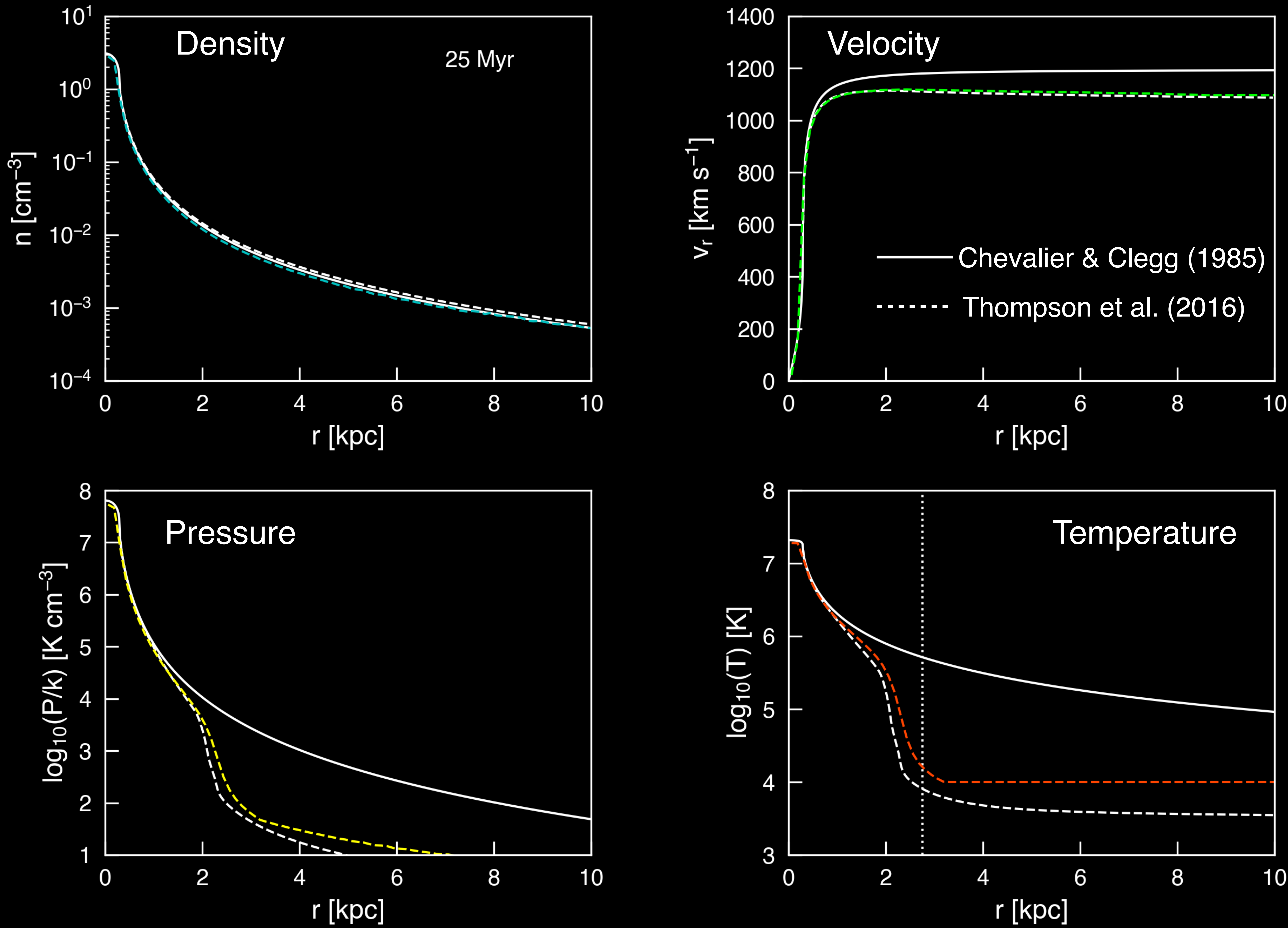
Early wind expansion

High mass-loading cooled wind state

Low mass-loading wind expansion

Late-time smooth flow

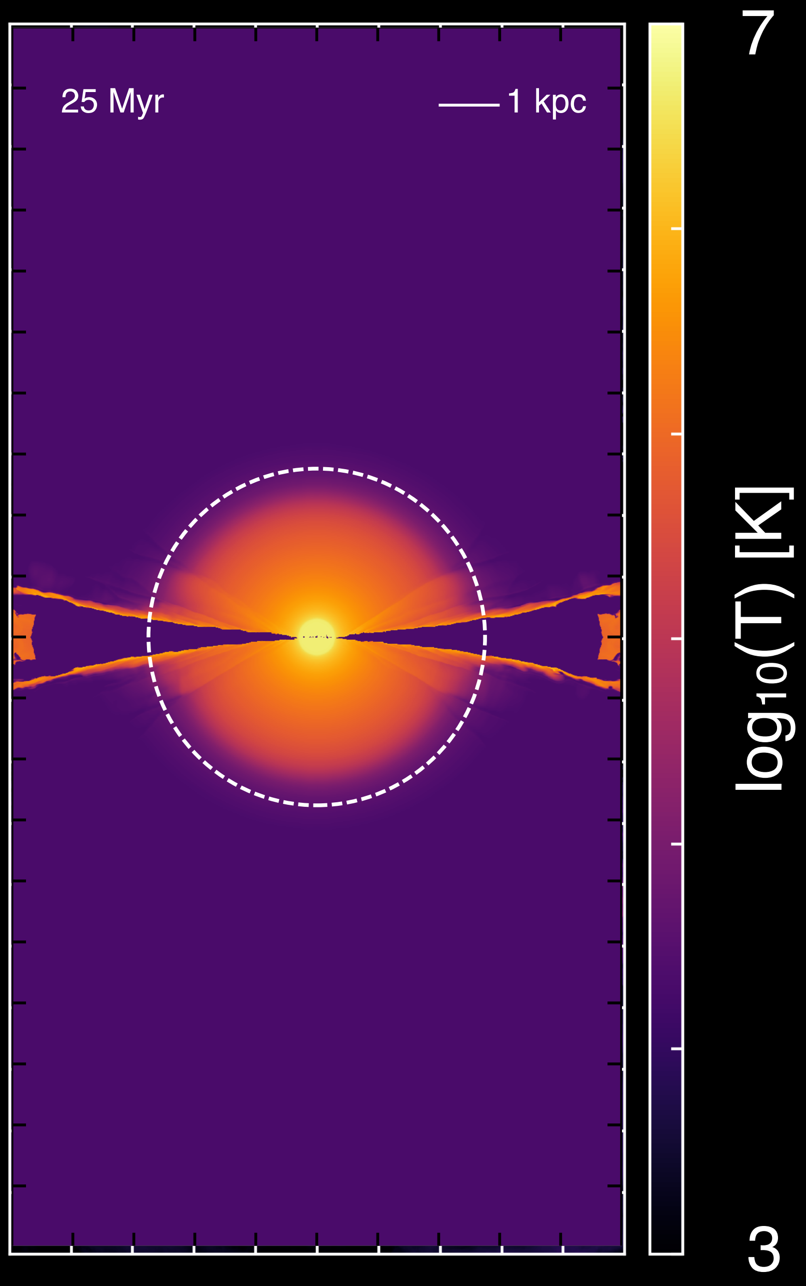
Schneider, Robertson, & Thompson (2018)



Schneider, Robertson, & Thompson (2018)

Where do we stand?

- The adiabatic model does a good job reproducing the X-ray observations, but can’t explain the cool gas.
- The radiative model produces fast-moving, cool gas, but lacks a true multiphase structure.

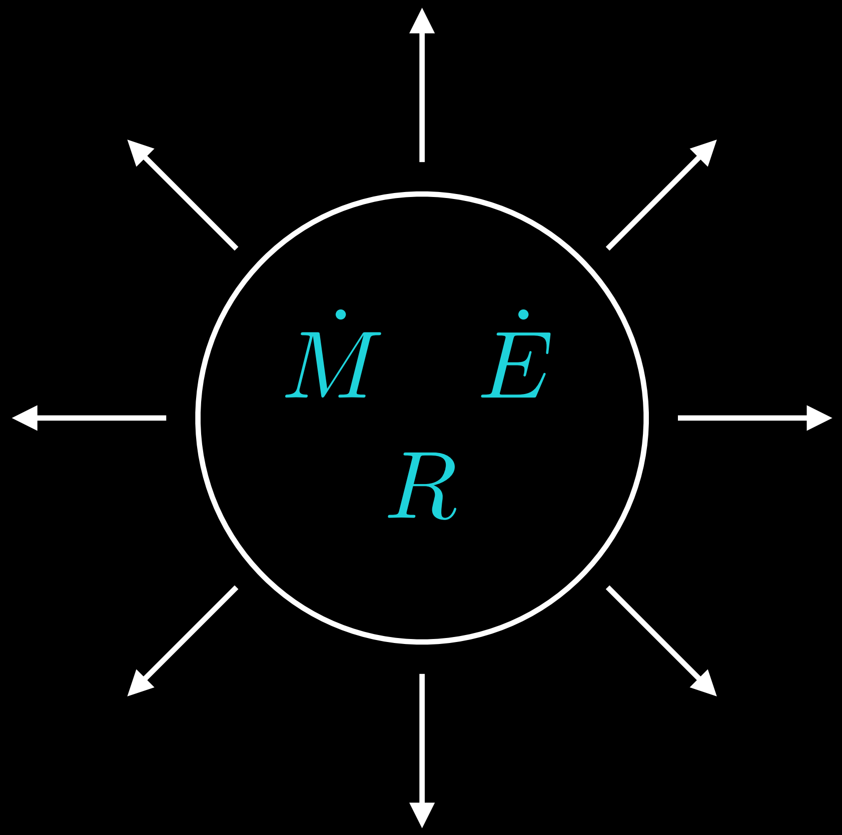


Neither model accounts for multiphase structure *at a single radius* in the outflow.

Assumptions in the Model

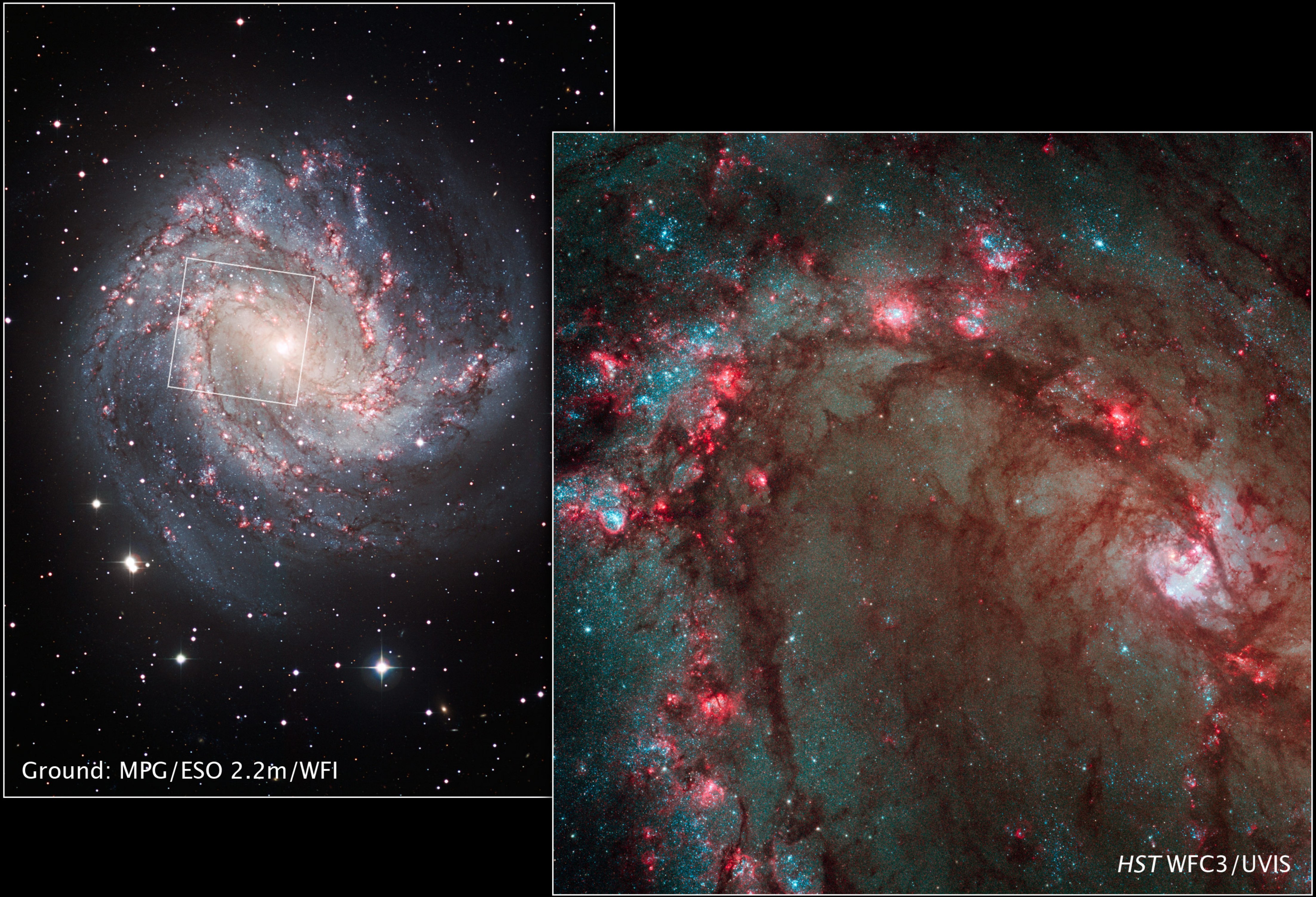
These simple models involved some big assumptions, namely:

- The **radius** within which feedback is deposited
- The **spherically symmetric** nature of the feedback
- The **arbitrary** (though not un-motivated) values for the mass and energy loading factors



Some (relevant) facts about star formation

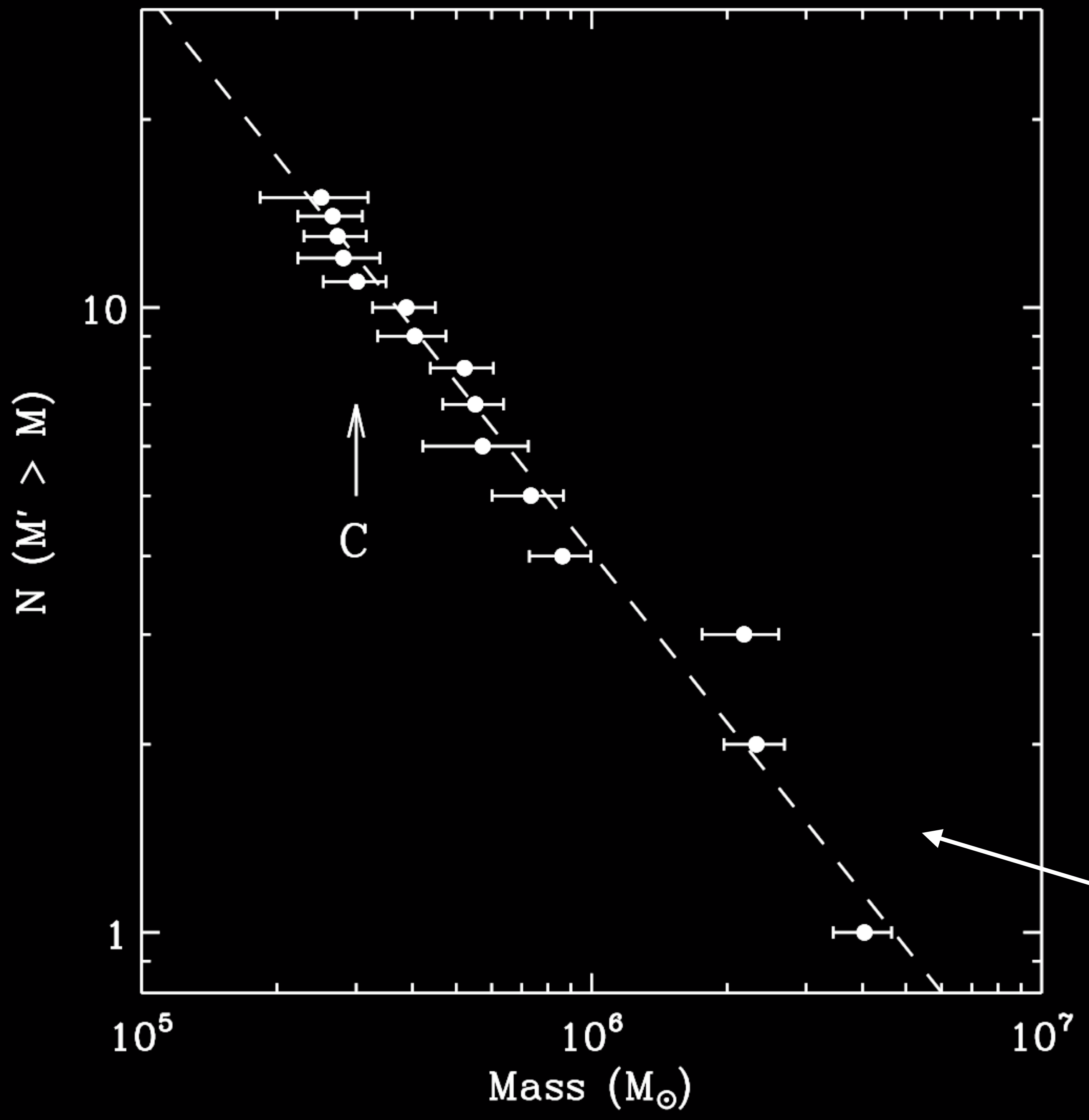
1. Stars form in clusters. Bigger stars form in bigger clusters.

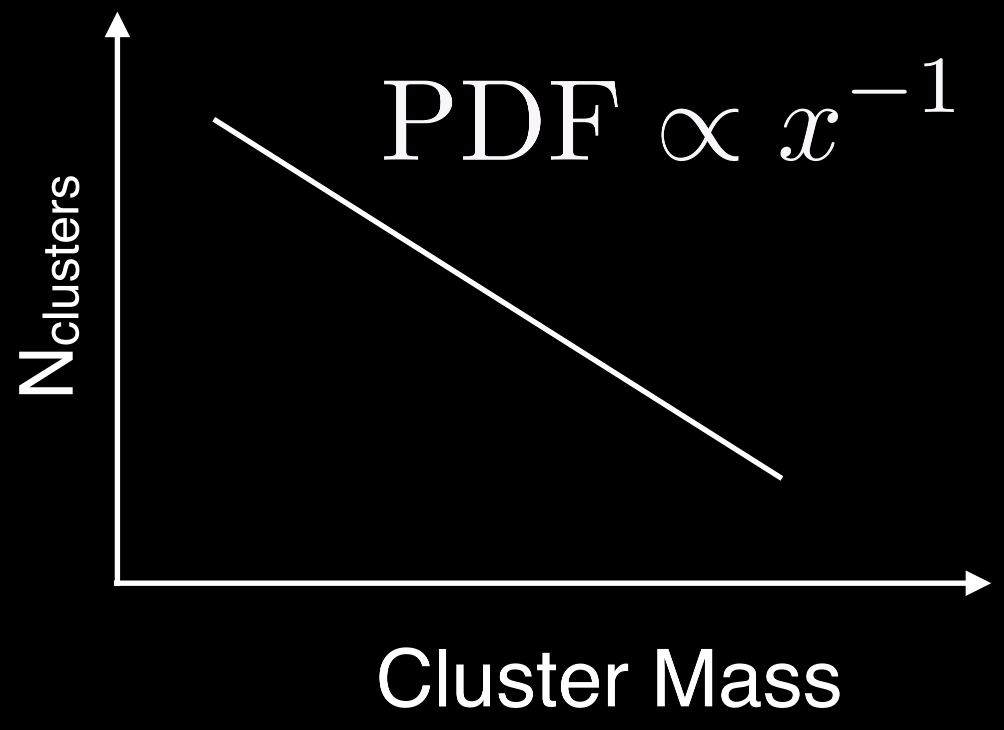


Spiral Galaxy M83
Hubble Space Telescope ▪ WFC3/UVIS

NASA, ESA, R. O’Connell (University of Virginia), the WFC3 Science Oversight Committee, and ESO STScI-PRC09-29

2. The cluster mass function is fairly shallow → at least half, or more, of all the stellar mass forms in the biggest clusters.



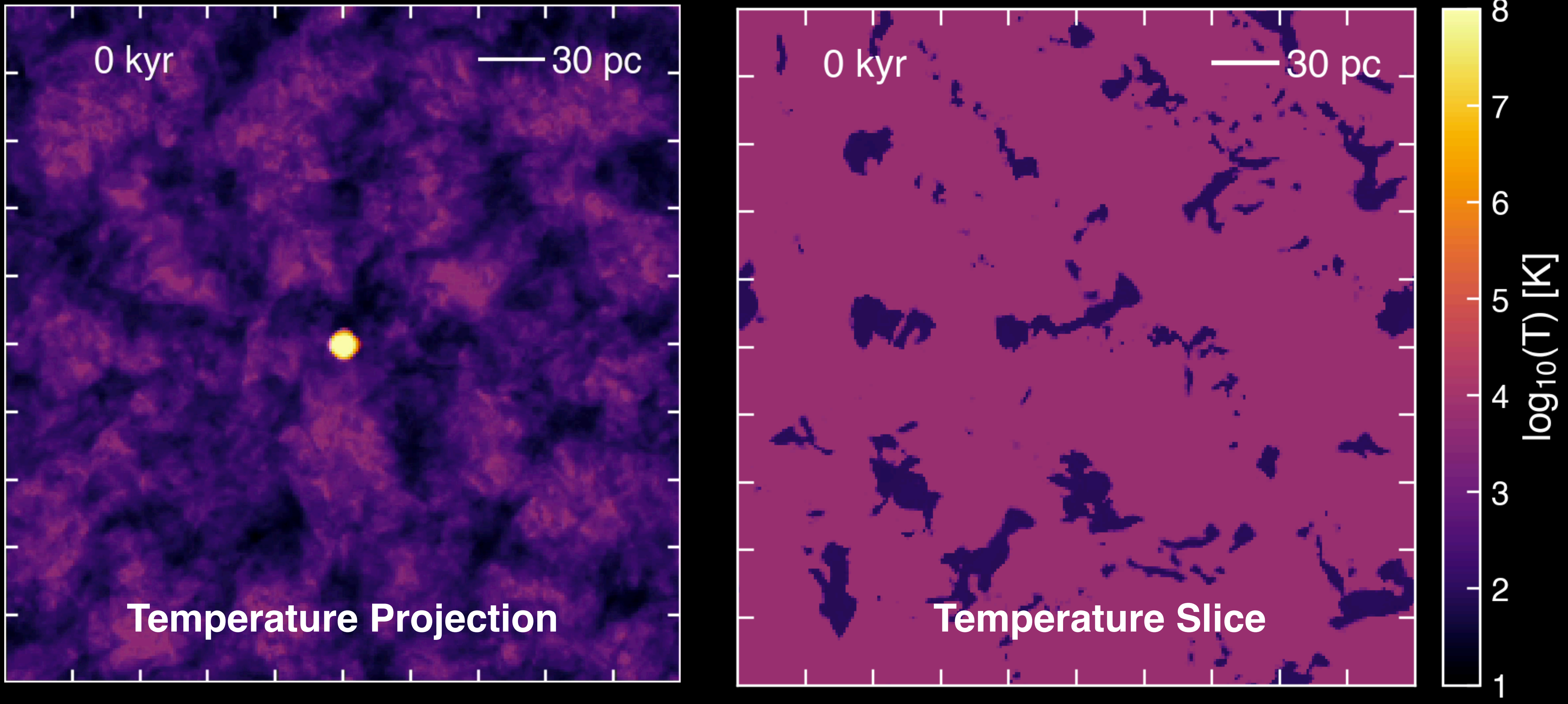


Ex: In M82, 60% of the mass of the nuclear starburst is in the three largest clusters.

McCrady et al. (2007)

Superbubble Simulations

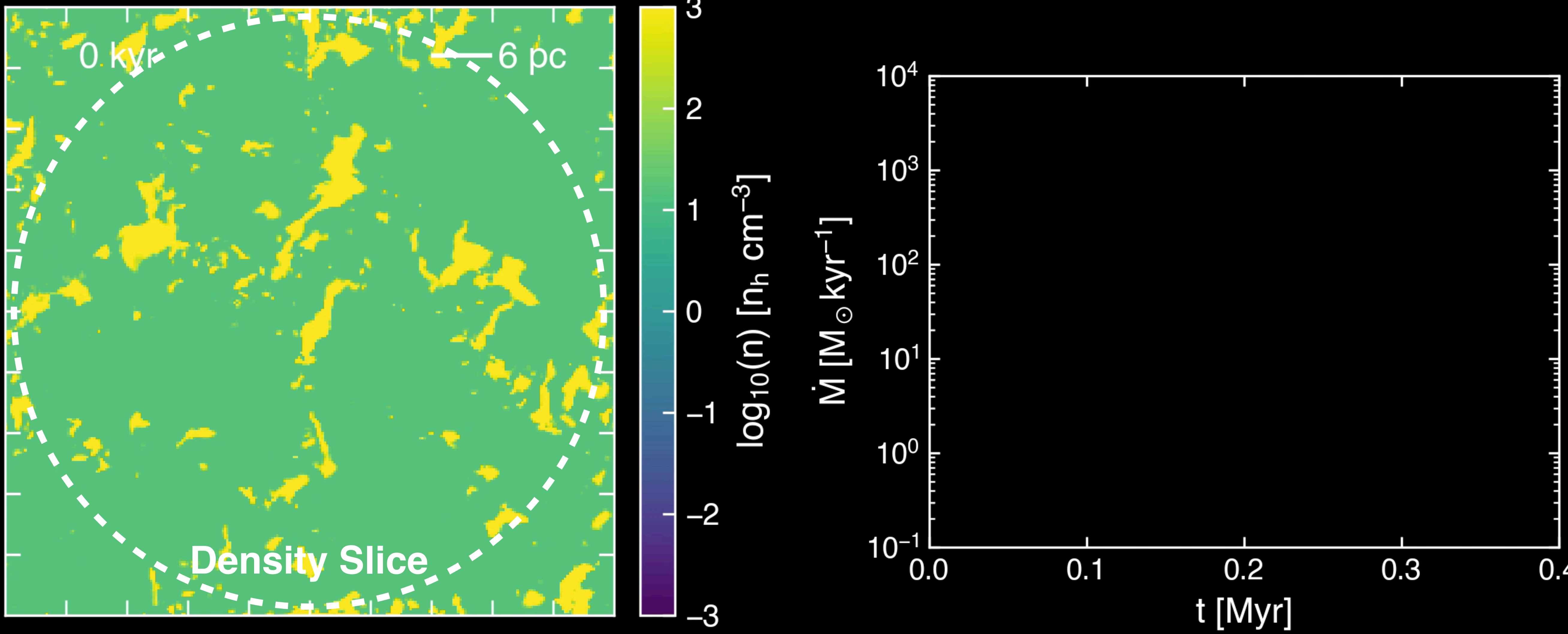
Using well-resolved simulations of a multi-phase ISM, we can capture the processes that are unresolved in our global galaxy simulations (CGOLS).



See also Kim+17, Fielding+18, Lancaster+21a,b

Schneider et al. *in prep*

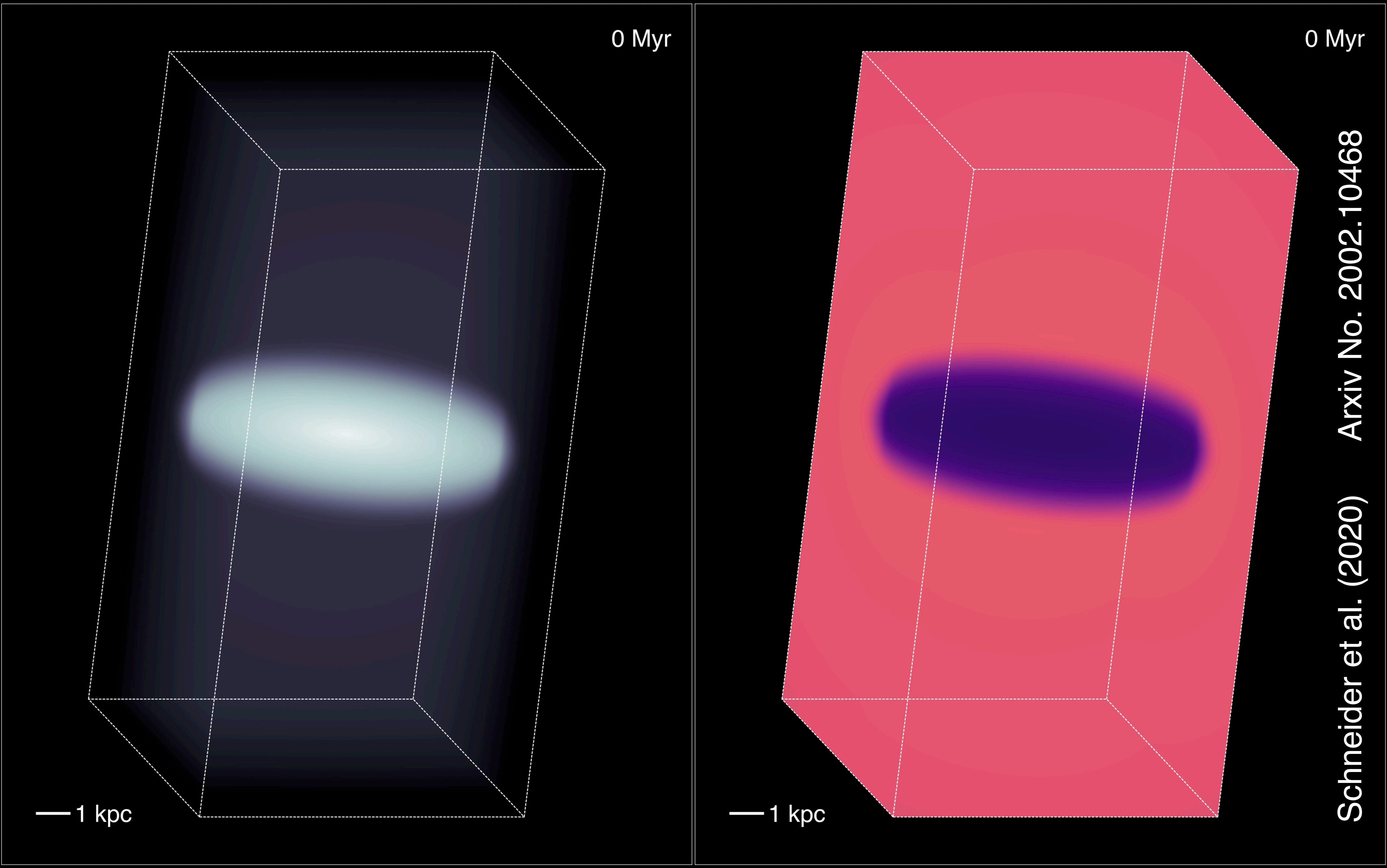
What should the mass and energy loading be?



Using these simulations, we can directly measure mass and energy loading rates for individual clusters.

Schneider et al. *in prep*

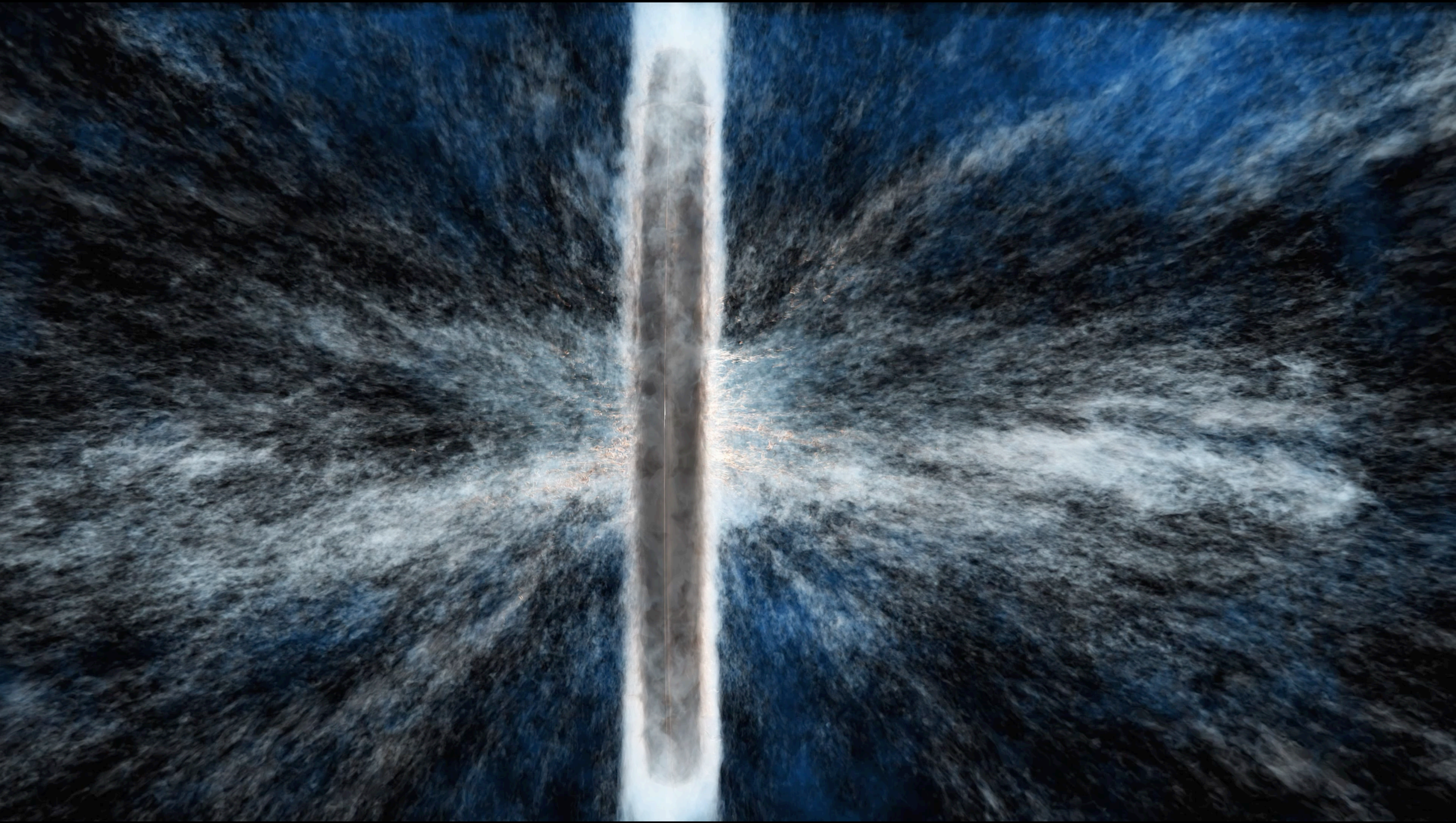
Radiative Simulation - Time-Variable Clustered Feedback



Schneider et al. (2020) Arxiv No. 2002.10468

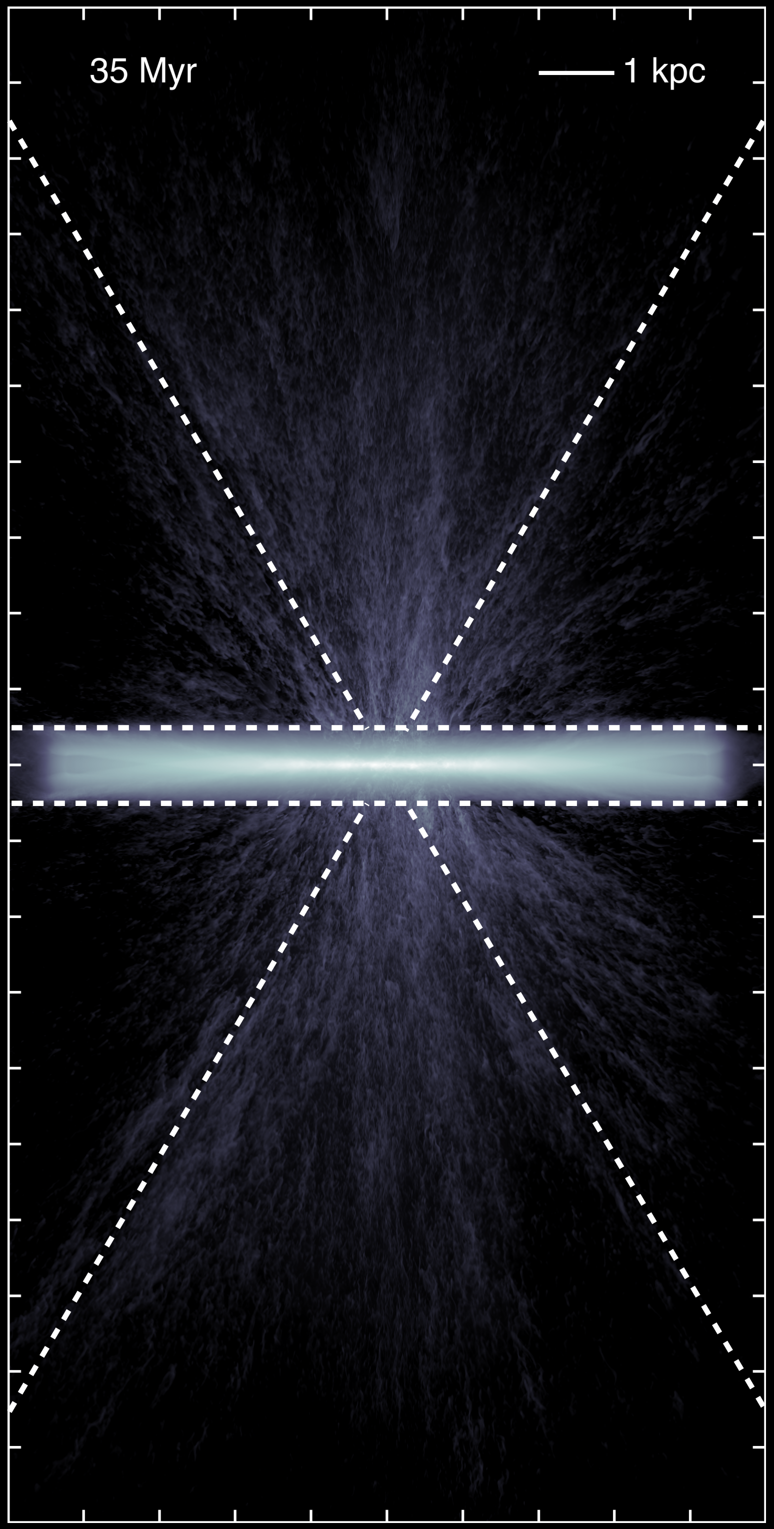
Density Projection **Temperature Projection**

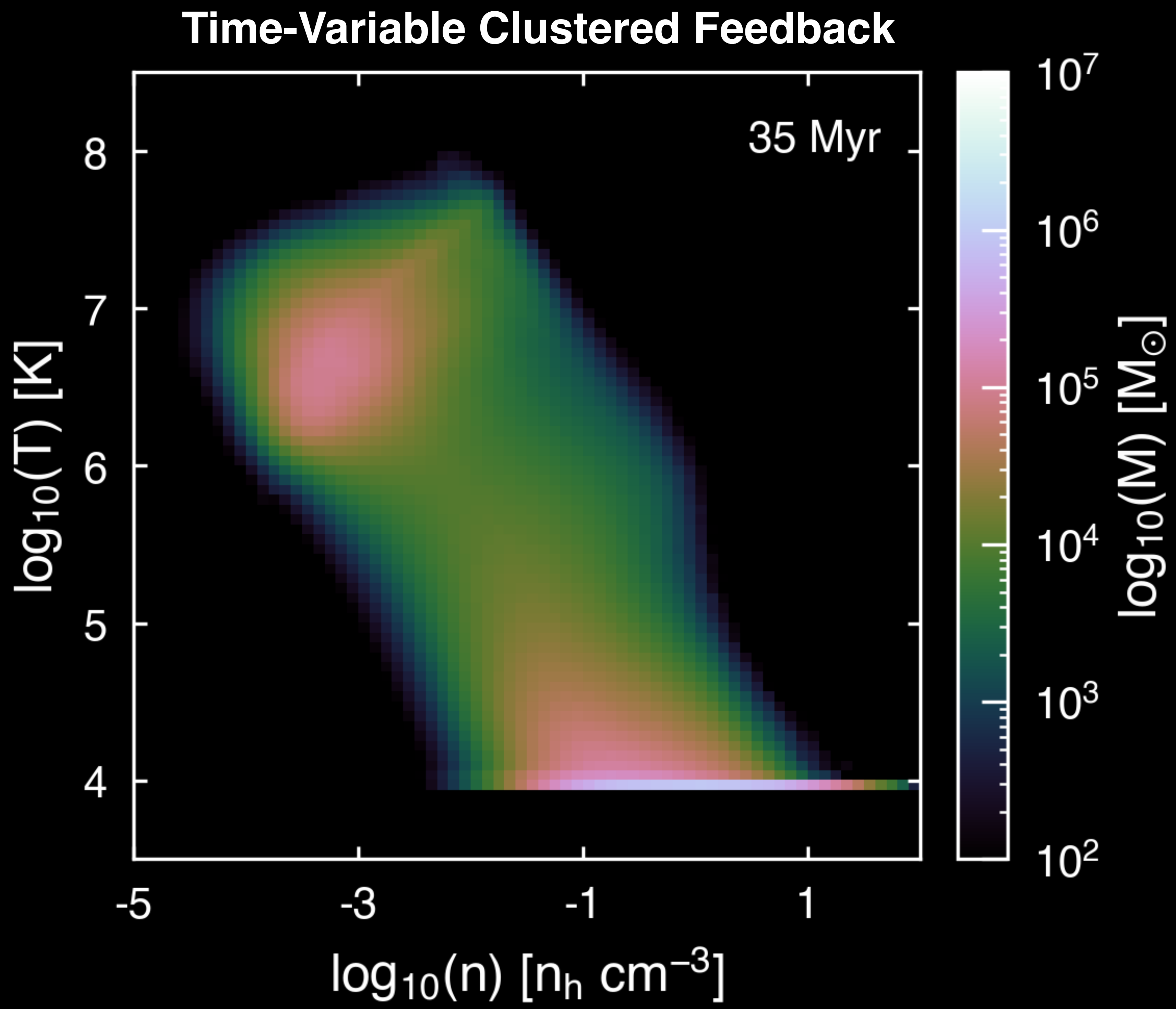
CGOLS Simulation - Time-Variable Clustered Feedback



NVIDIA IndeX Rendering of Density Field   Schneider et al. (2020)   Arxiv No. 2002.10468

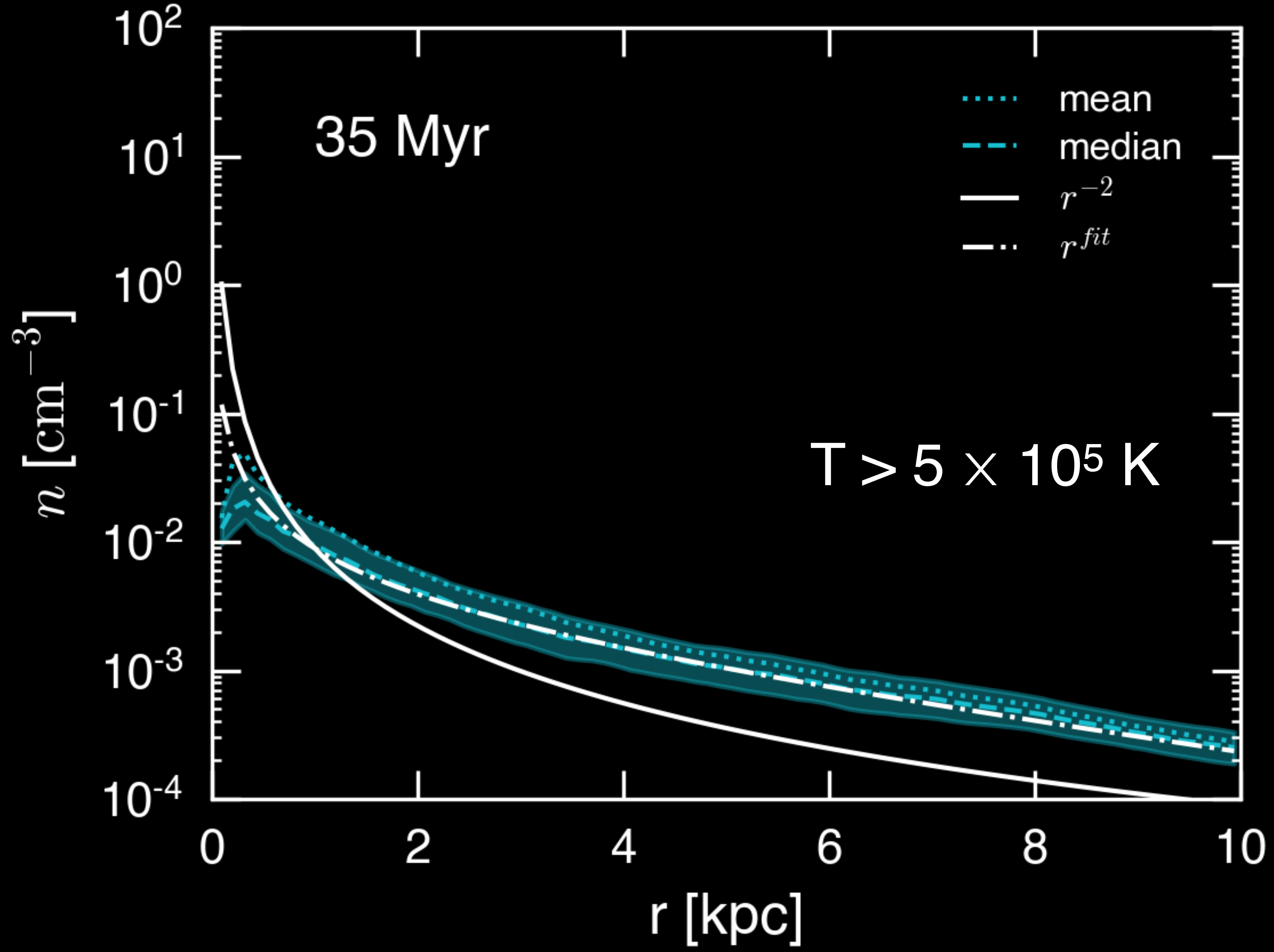
How is the mass distributed?




Time-Variable Clustered Feedback

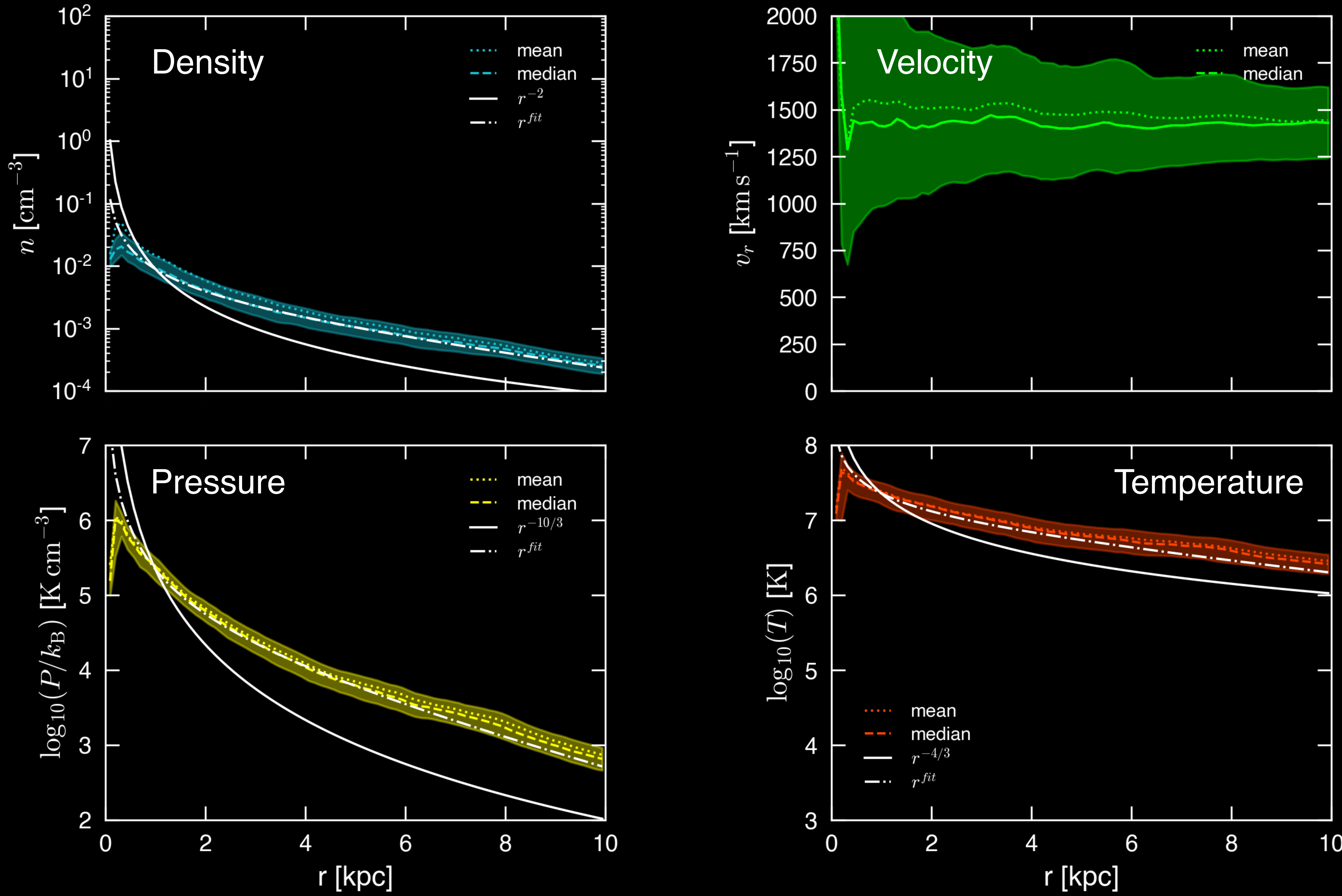
Schneider et al. (2020)

Hot Gas Radial Profiles



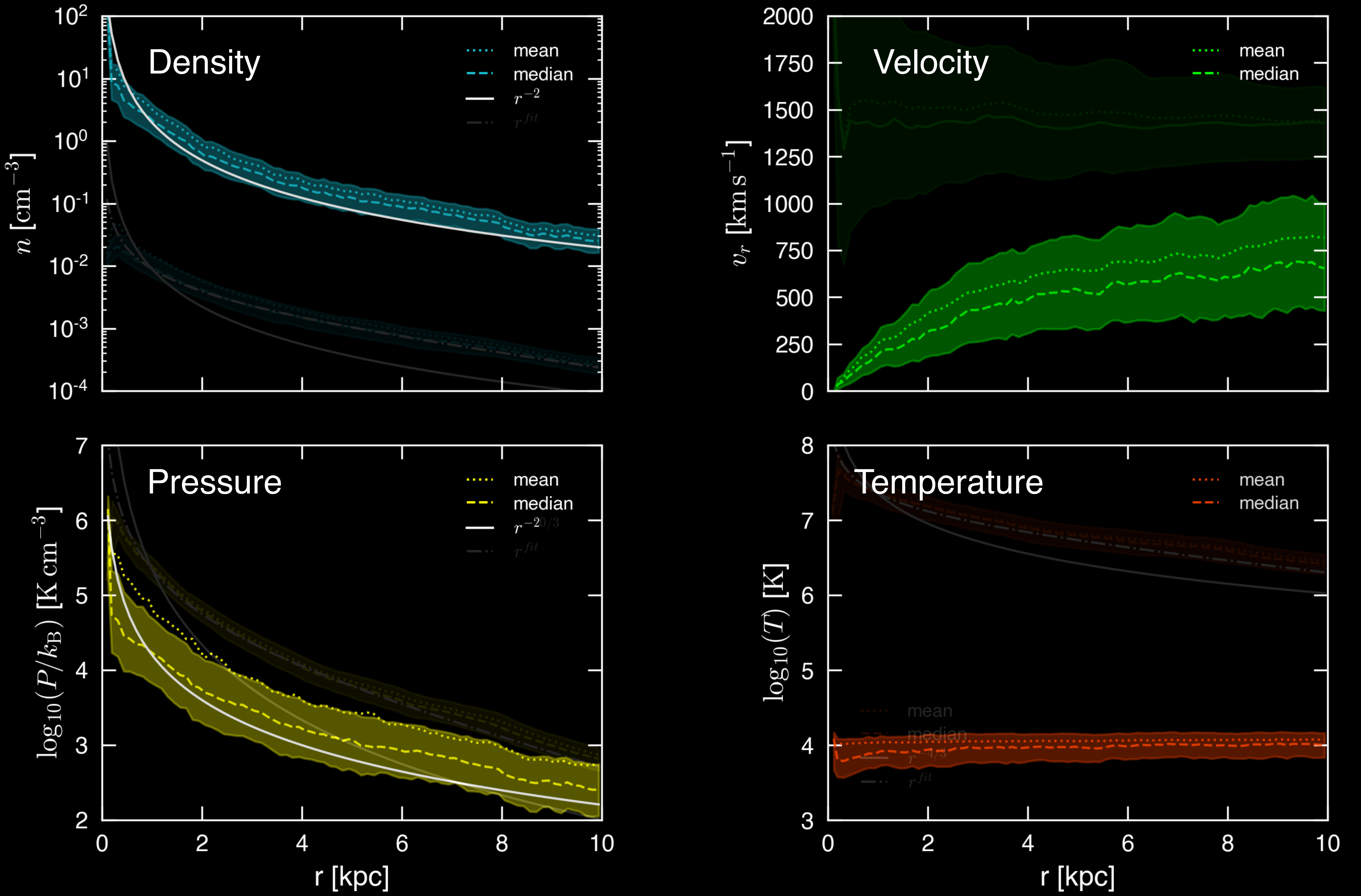
Schneider et al. (2020)

Hot Gas Radial Profiles



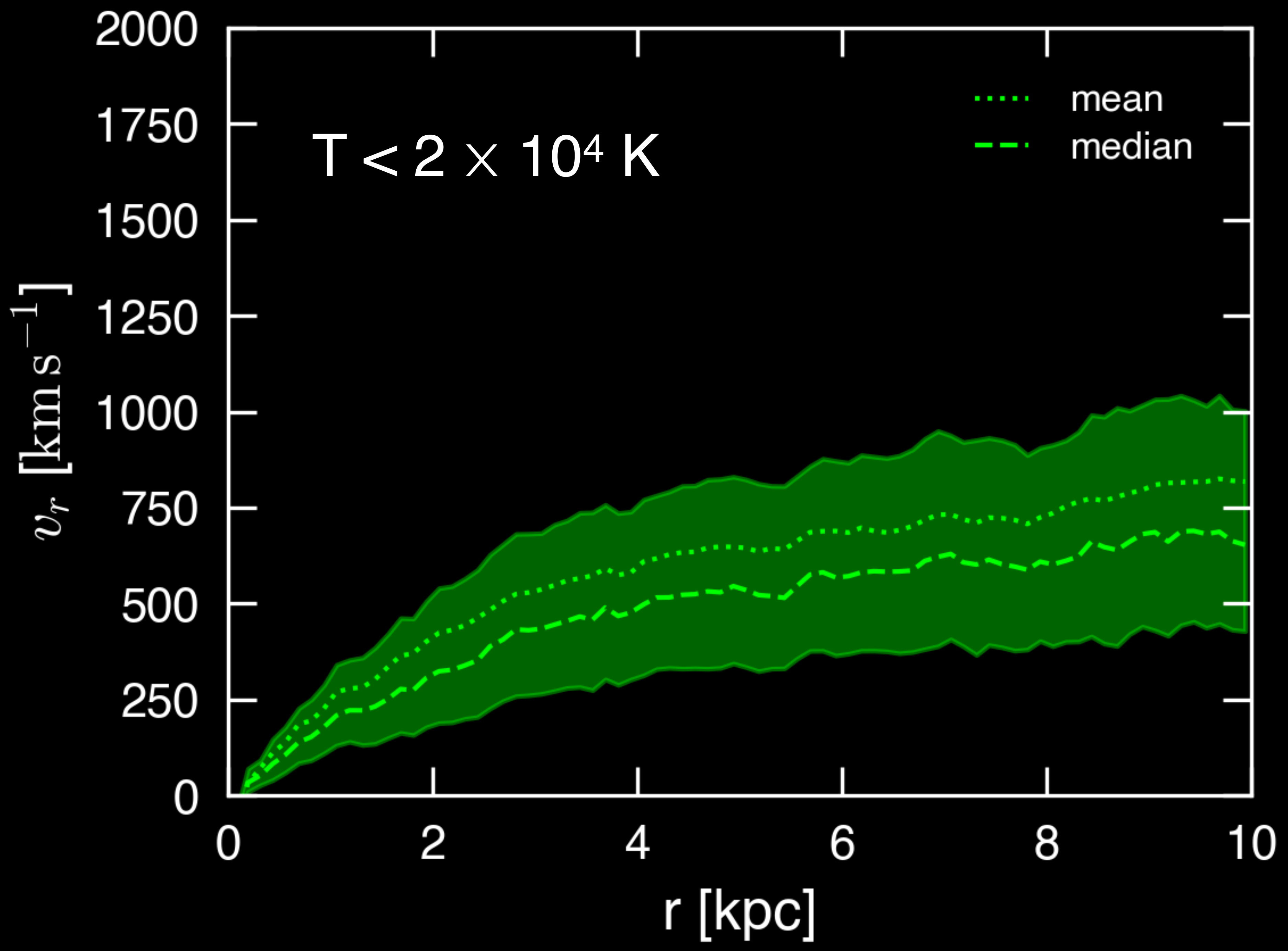
Schneider et al. (2020)

Cool Gas Radial Profiles



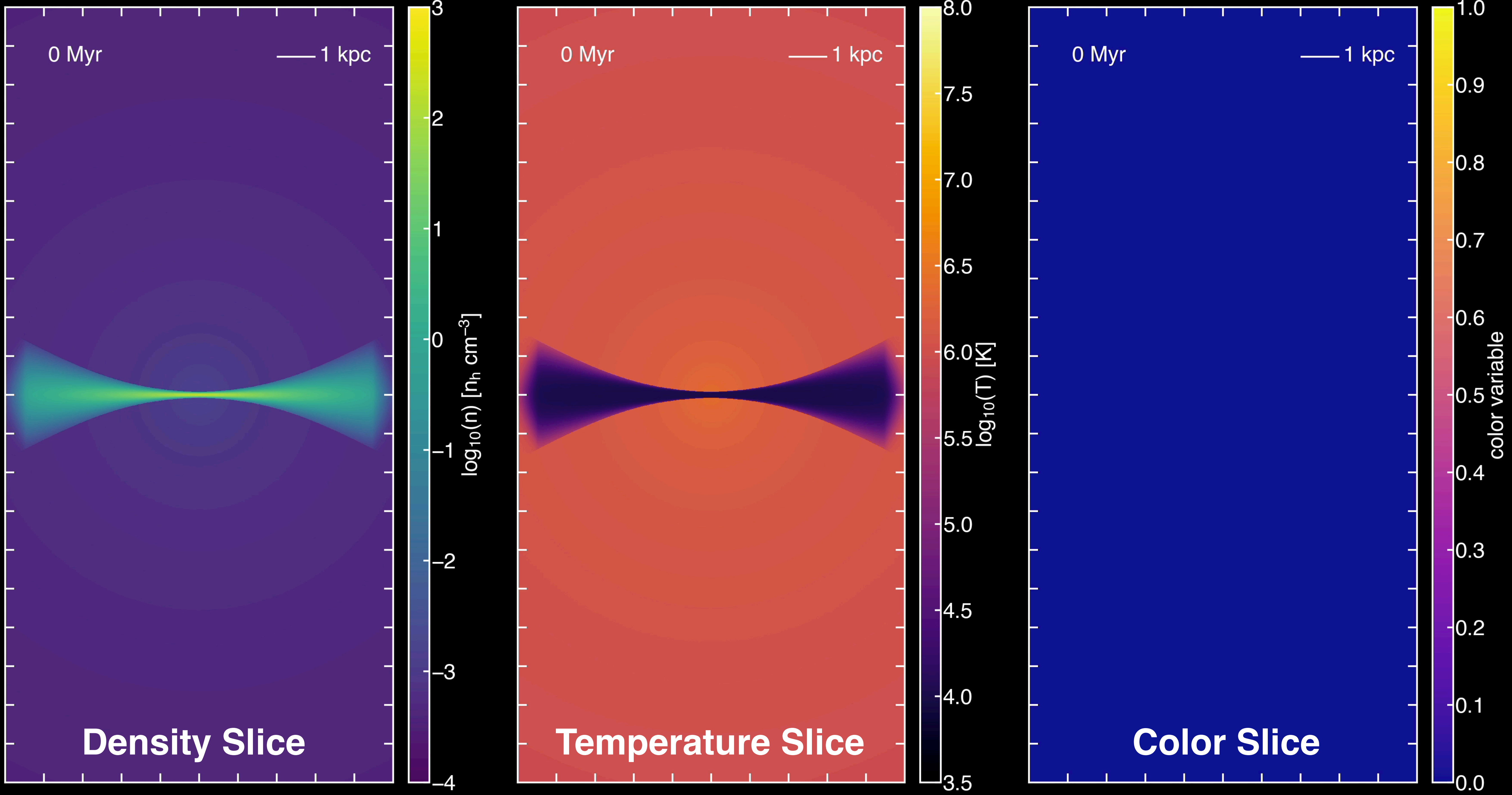
Schneider et al. (2020)

How fast is the gas moving?



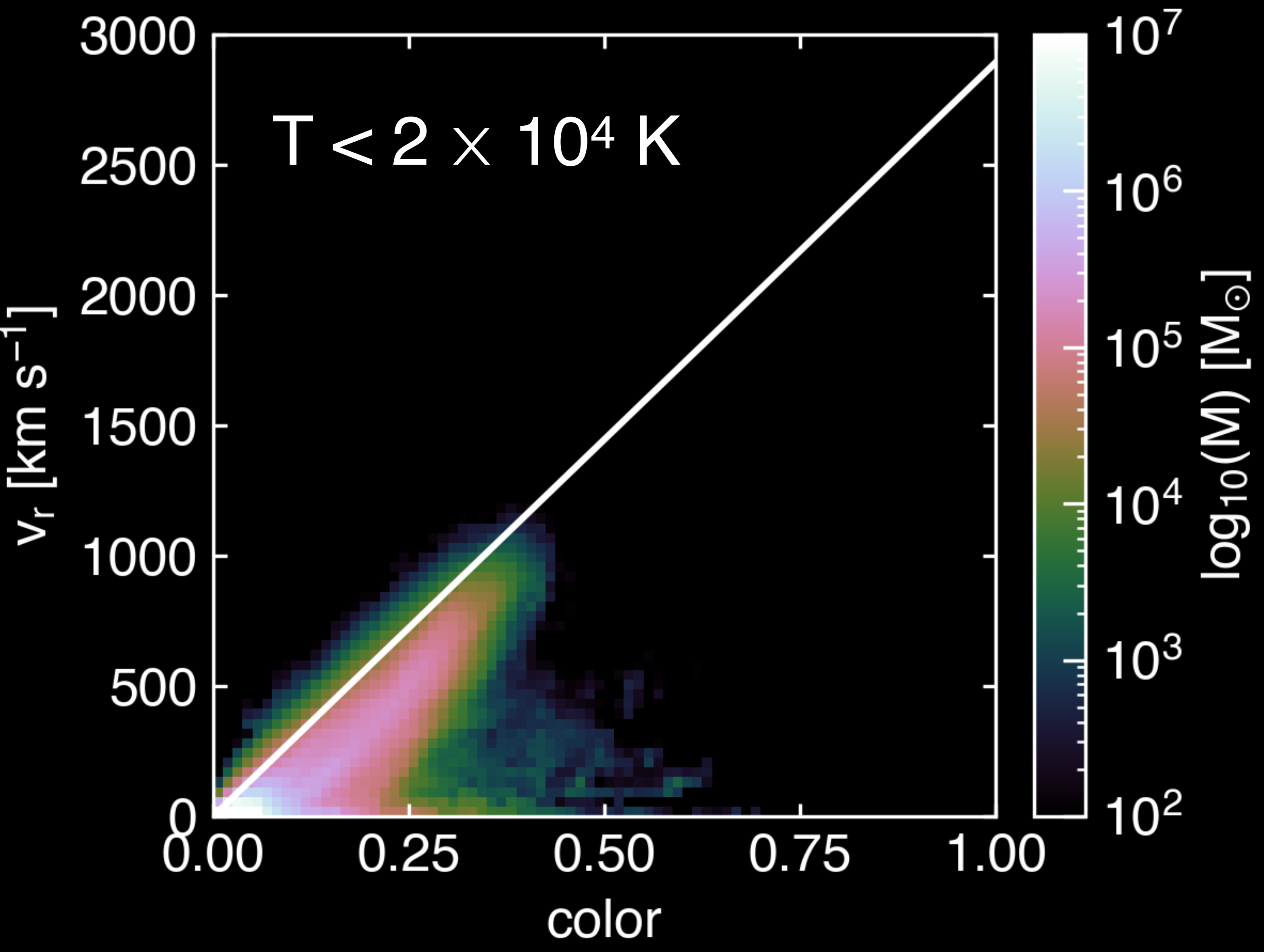
Schneider et al. (2020)

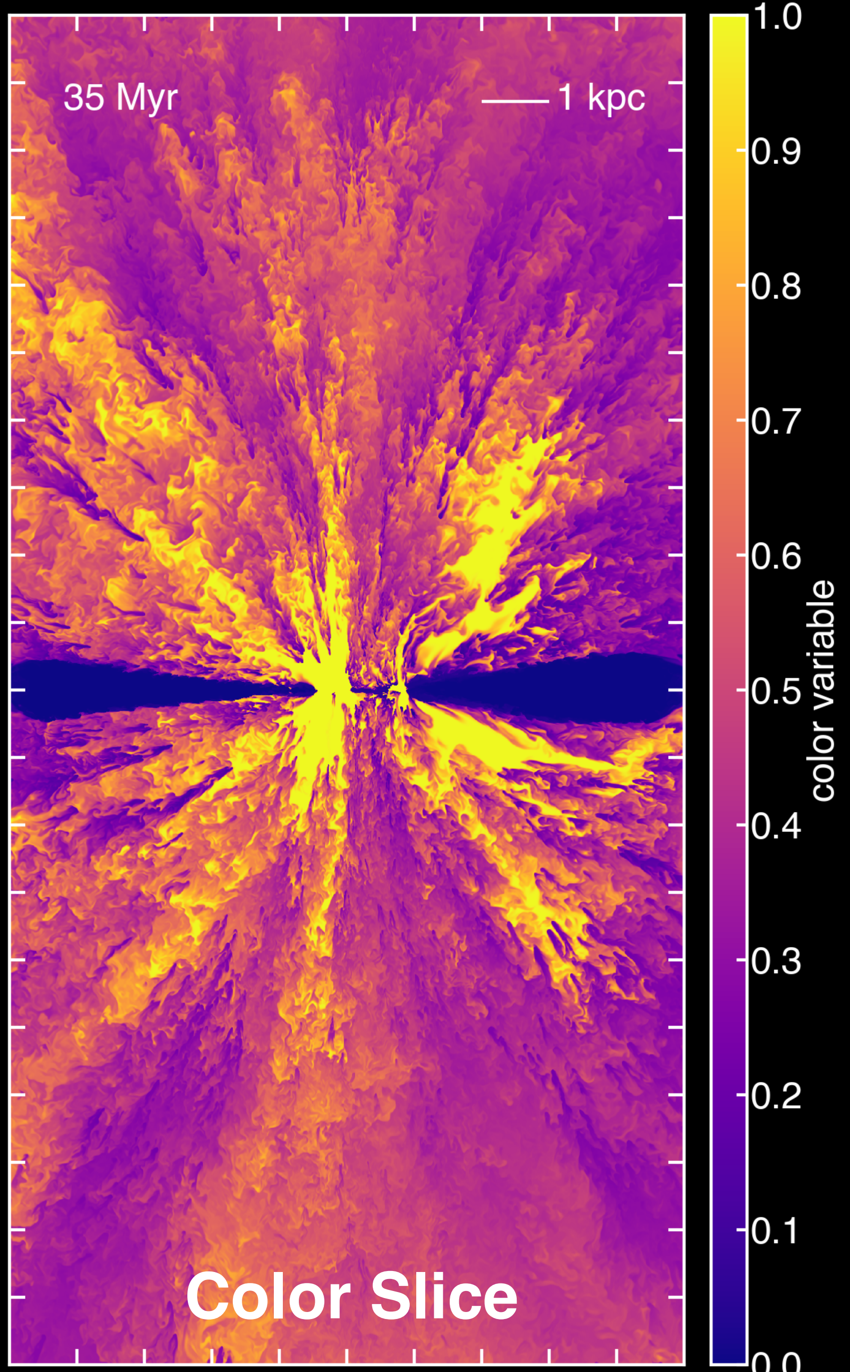
How does the cool gas form?



Schneider et al. (2020)

How is the cool gas accelerated?

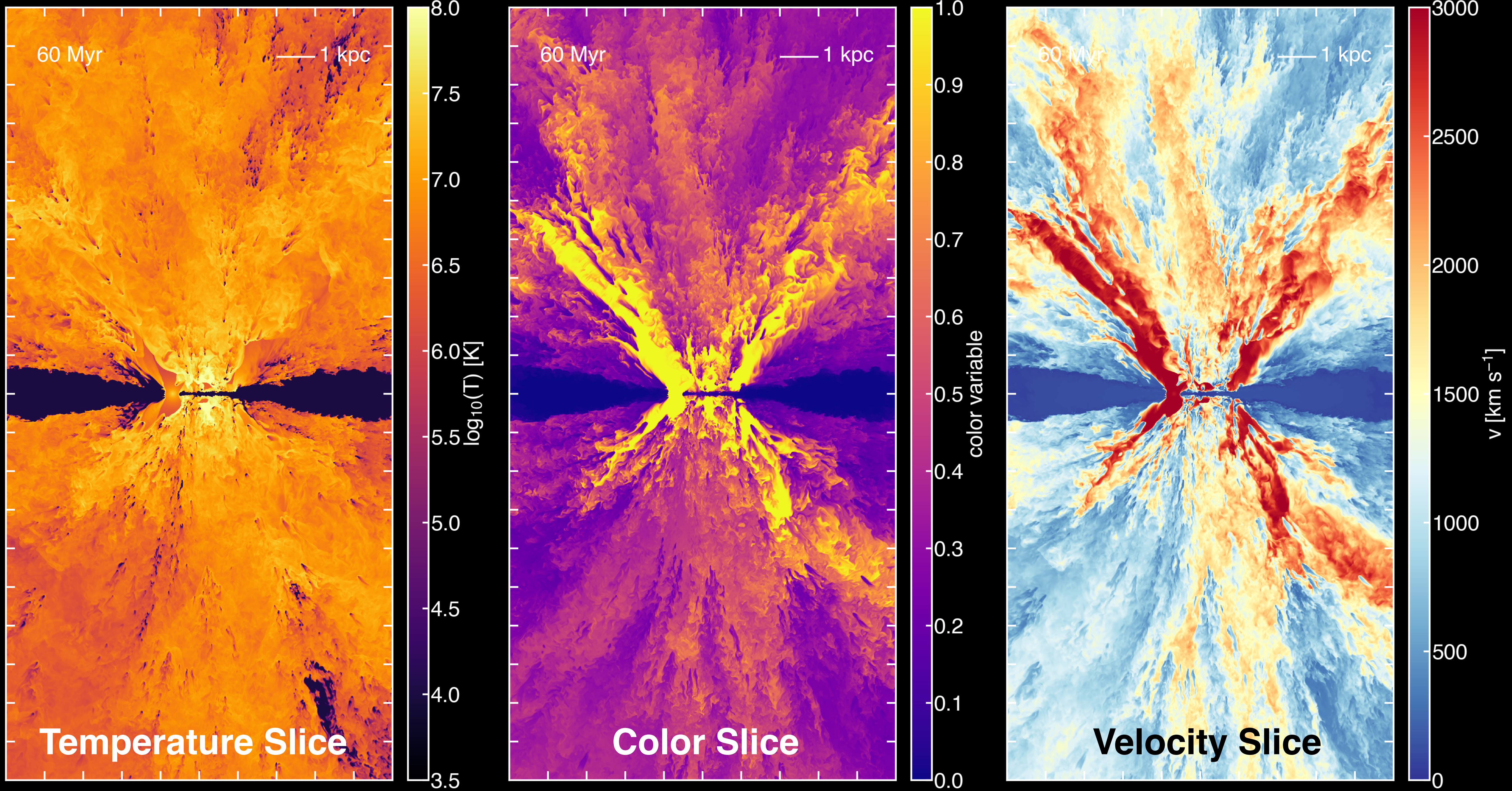




See also Armillotta+16,17; Gritton+17; Gronke+18,19; Fielding+18,21; Melso+19;

Schneider et al. (2020)

Where do the metals go?



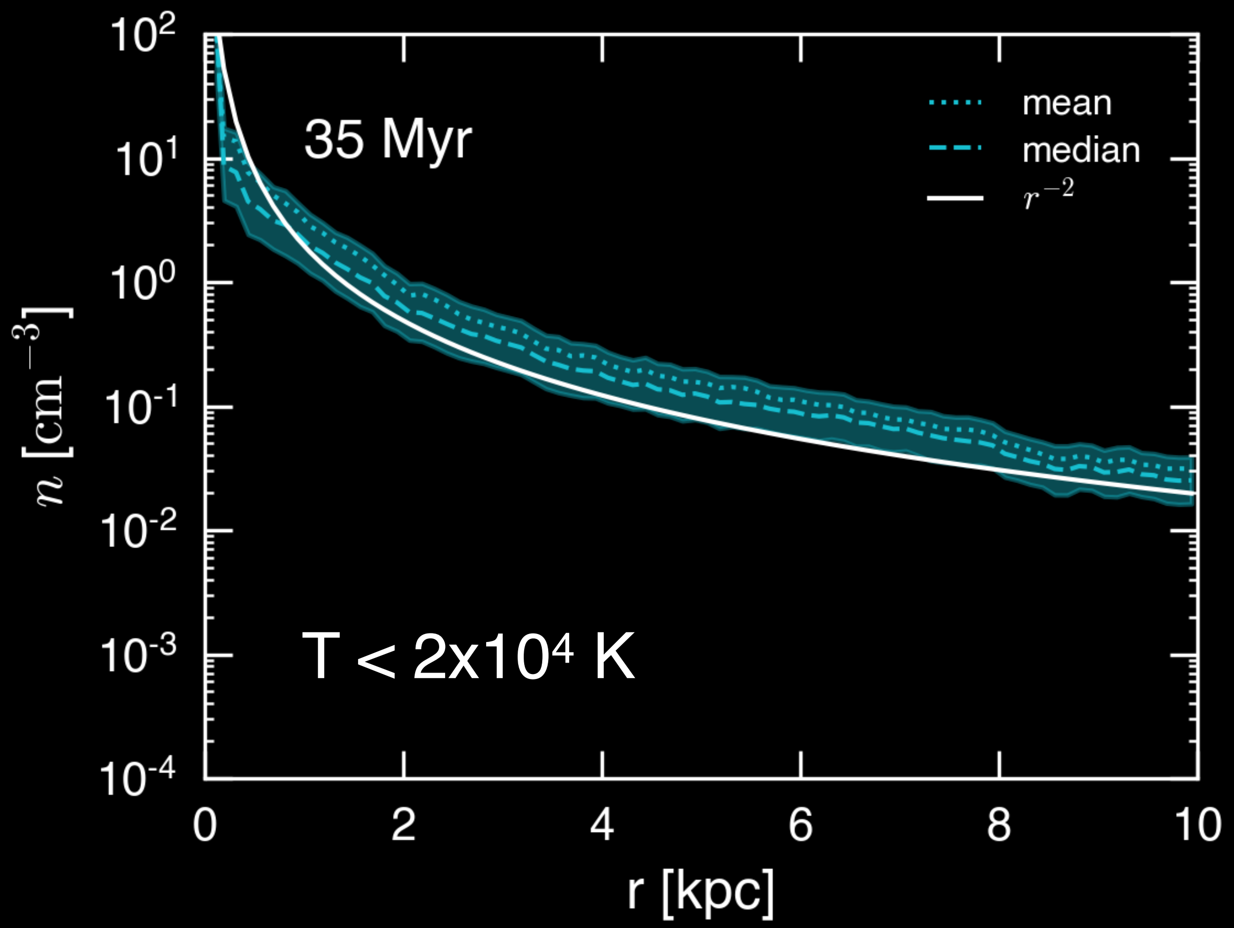
Schneider et al. (2020)

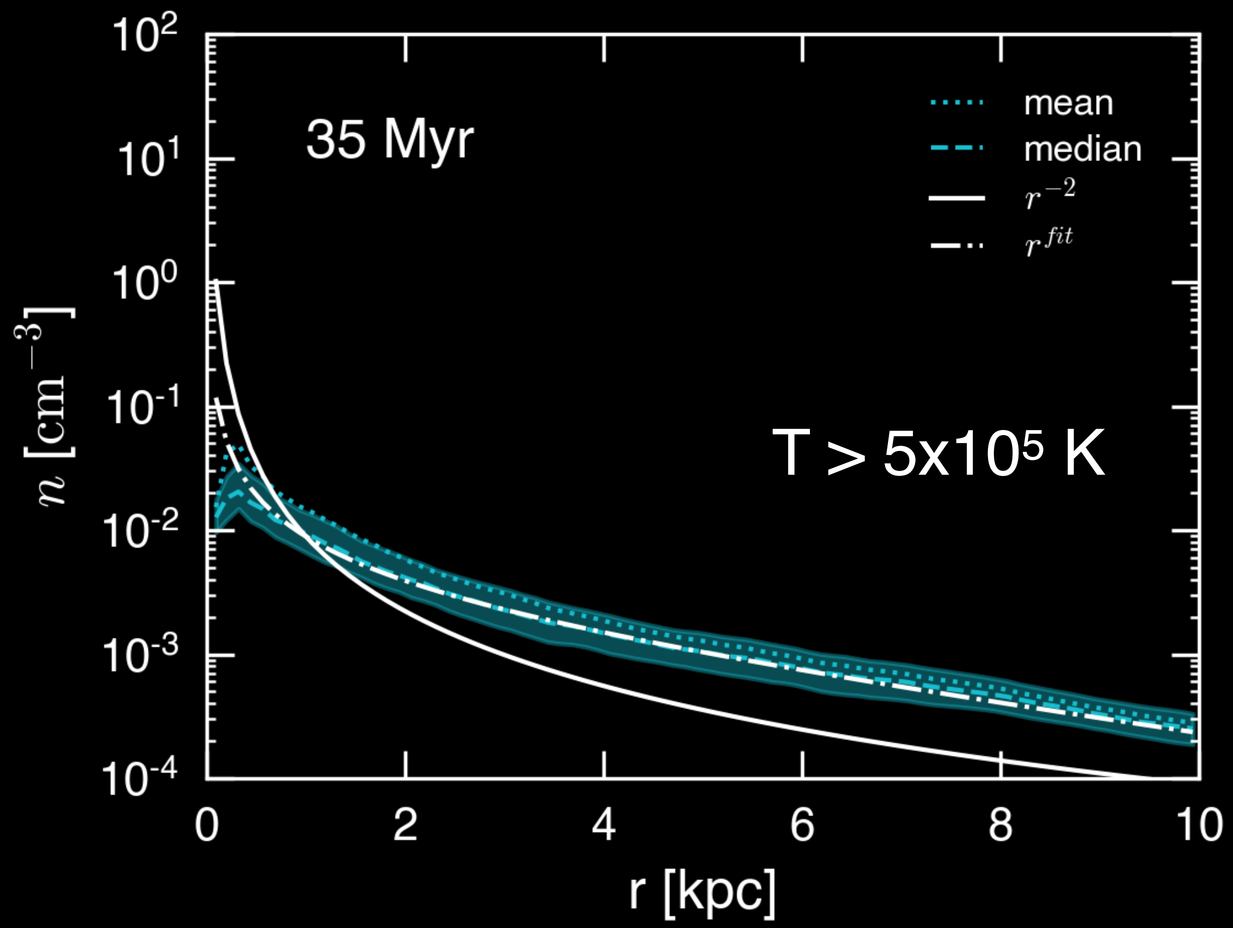
Summary: Can we build a physically-motived model that explains observed nature of galaxy outflows?

- Reproduces the multiphase nature of outflows ✓
- Explains the velocity structure of outflows ✓
- Efficiently transports metals out of galaxies to enrich the CGM and beyond ✓

What's Next for CGOLS?

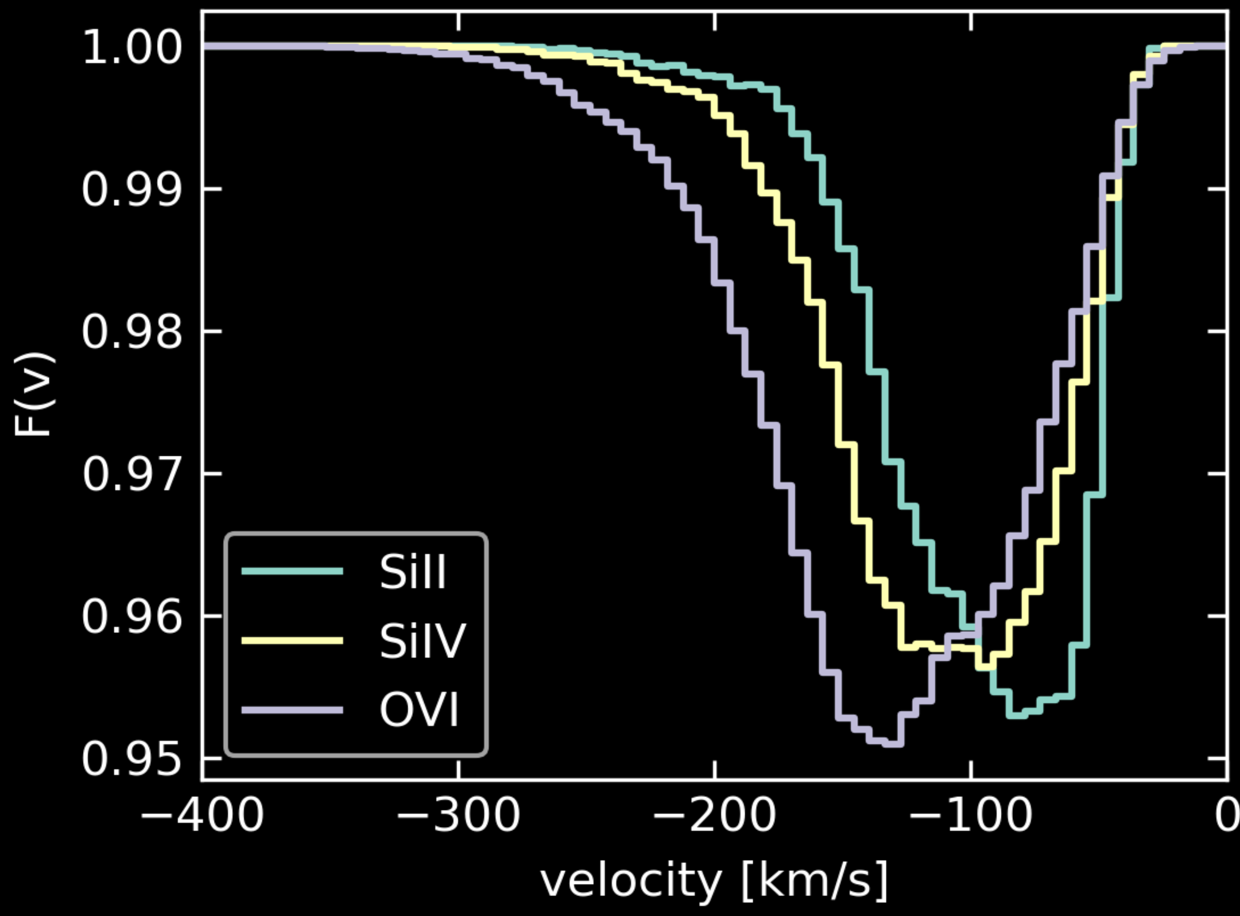
We are refining our two-phase analytic models for outflows - see work by Dustin Nguyen at OSU!

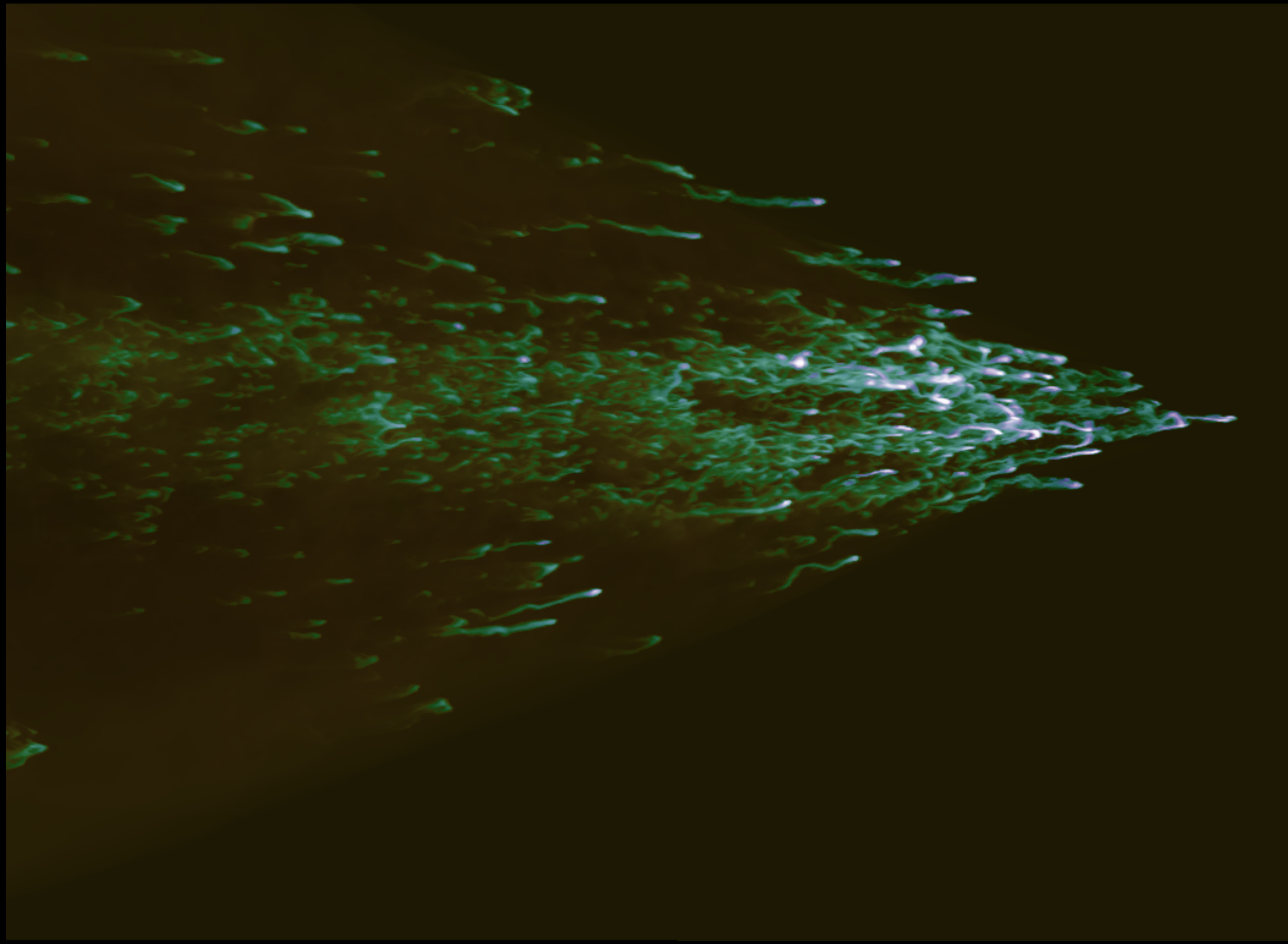




What’s Next for CGOLS?

Further progress in differentiating between models will come by improving our comparisons to observations.



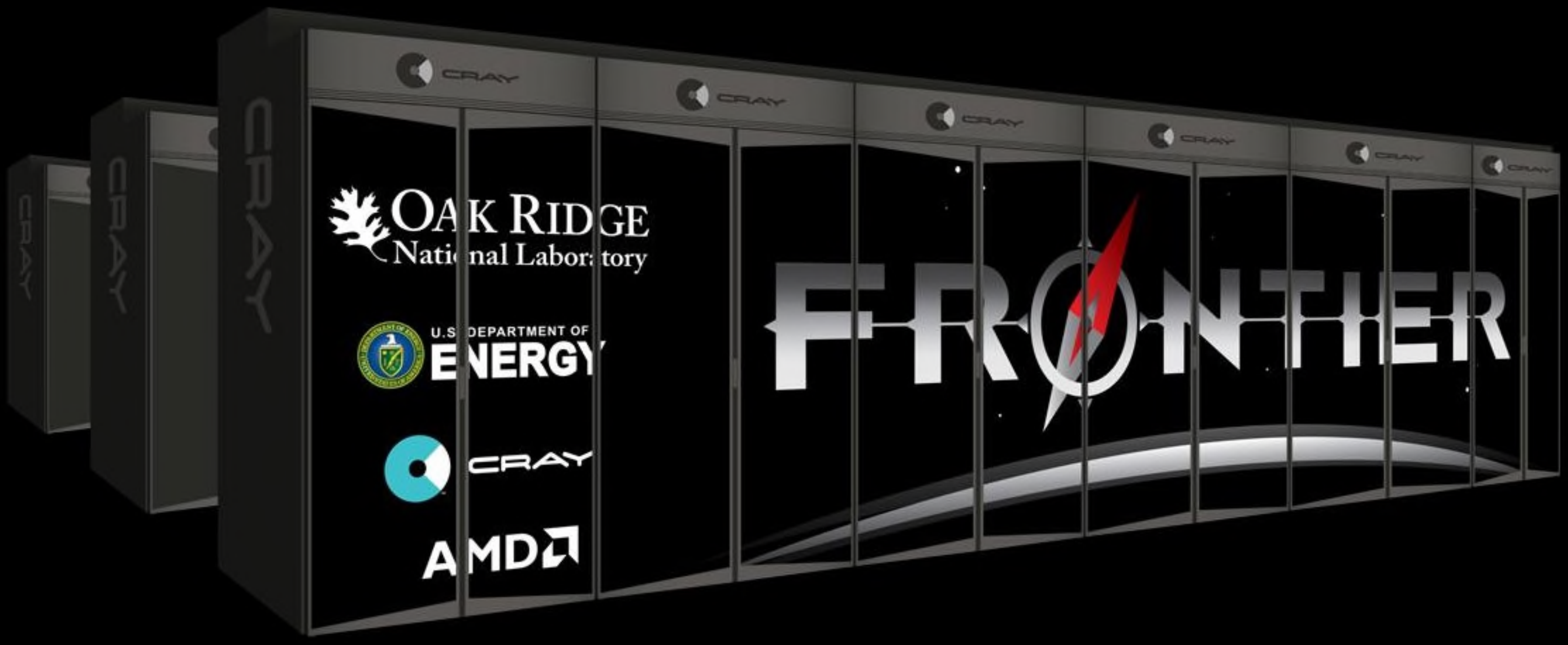


Mock absorption-line profiles will enable us to compare to observables directly (de la Cruz, Schneider & Ostriker, 2021, Fortis+ *in prep*.).

What’s Next for CGOLS?

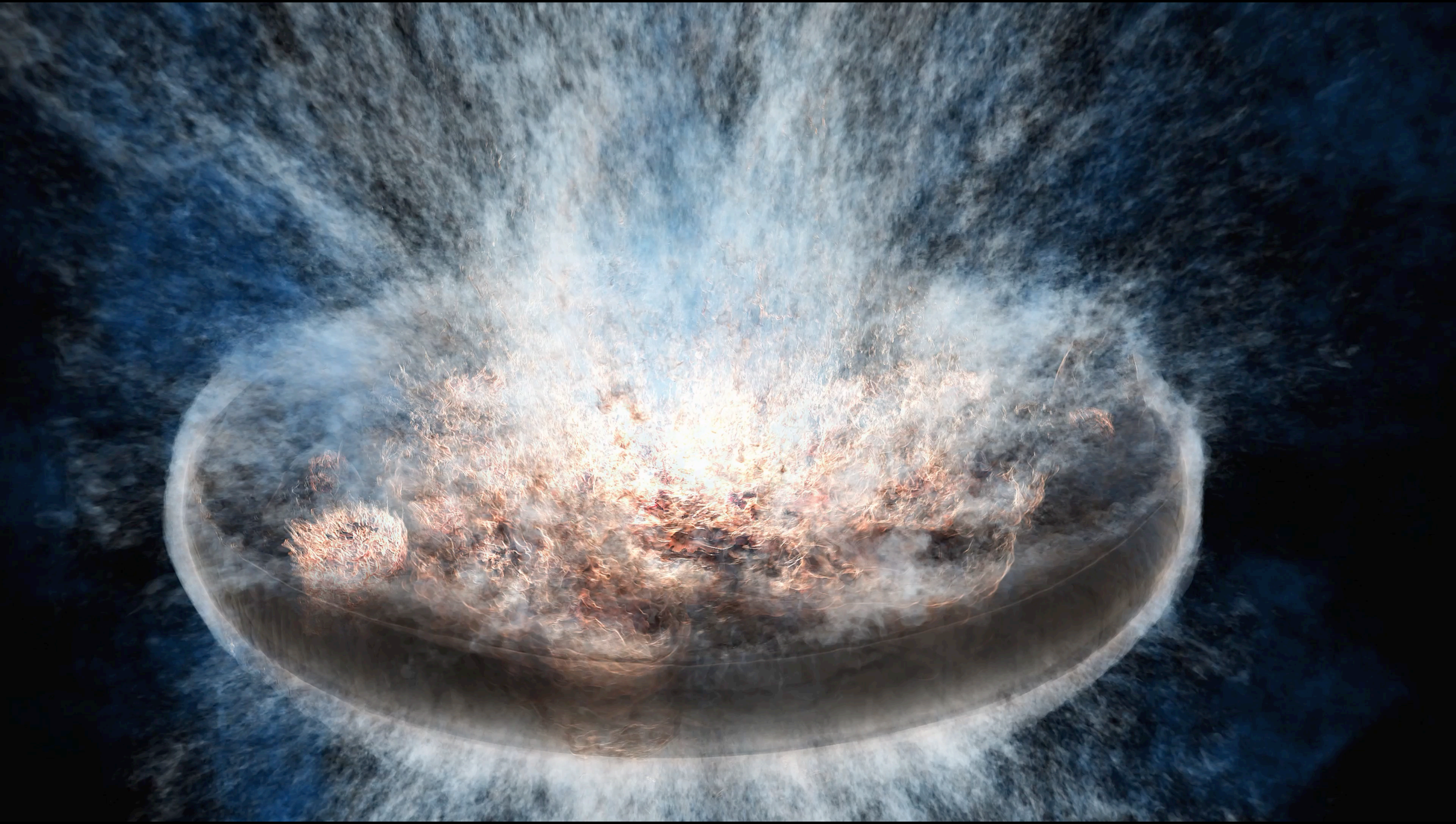
The Cholla CAAR team will produce an exascale Milky Way Galaxy simulation: over 10^{12} cells, with self-gravity, self consistent star formation and stellar feedback (Orlando Warren + CAAR team).

Team members: Reuben Budiardja (OLCF), Robert Caddy (Pitt), Nicole Drakos (UCSC), Alwin Mao (Pitt), Damon McDougal (AMD), Brant Robertson (UCSC), Bruno Villasenor (UCSC), Orlando Warren (Pitt), Trey White (Cray/HPE)



We still have more simulations to analyze (and run)!

CGOLS Simulation - Time-Variable Distributed Feedback



Visualization produced using the Nvidia IndeX software package.

Thanks!