Galactic Winds at Exascale

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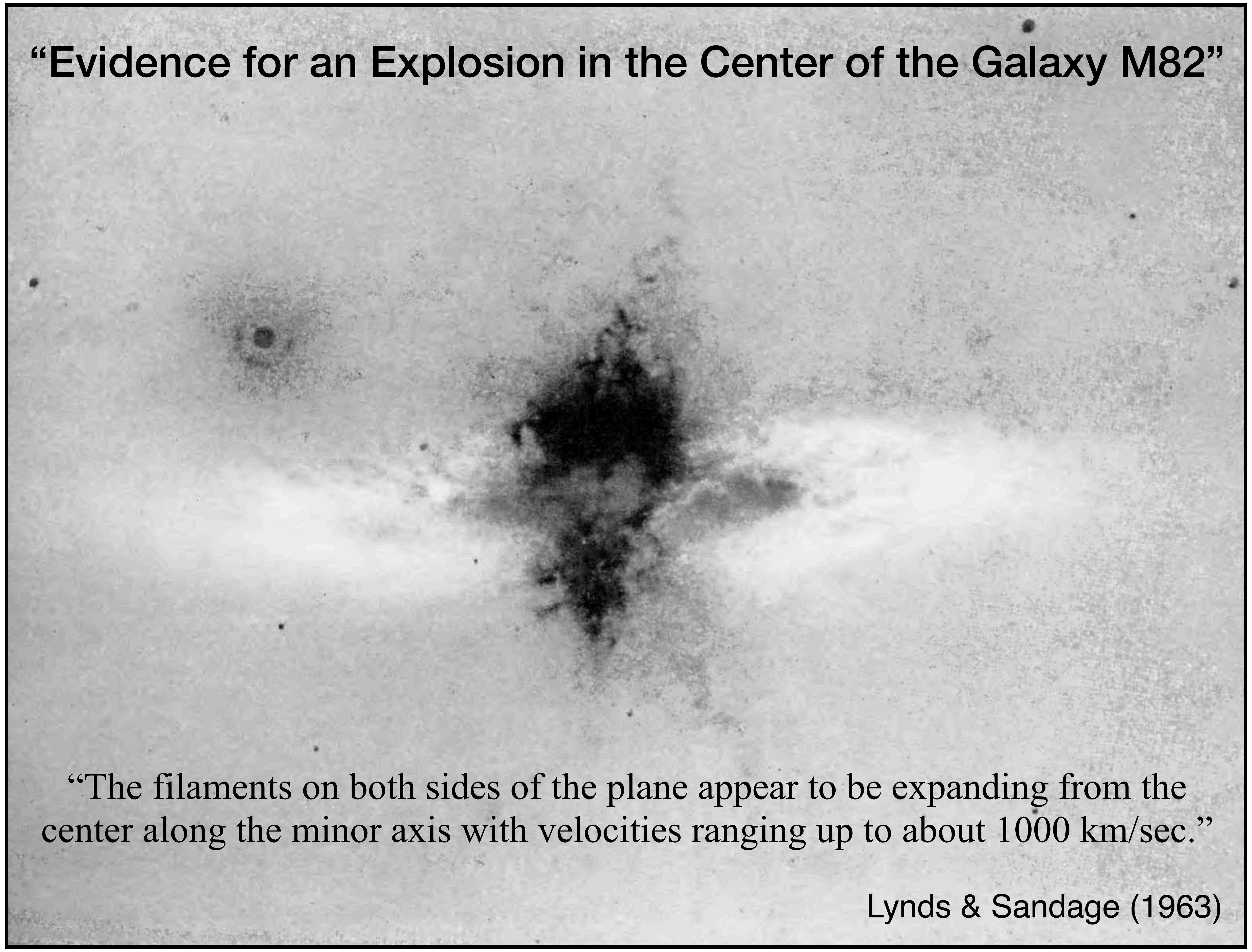
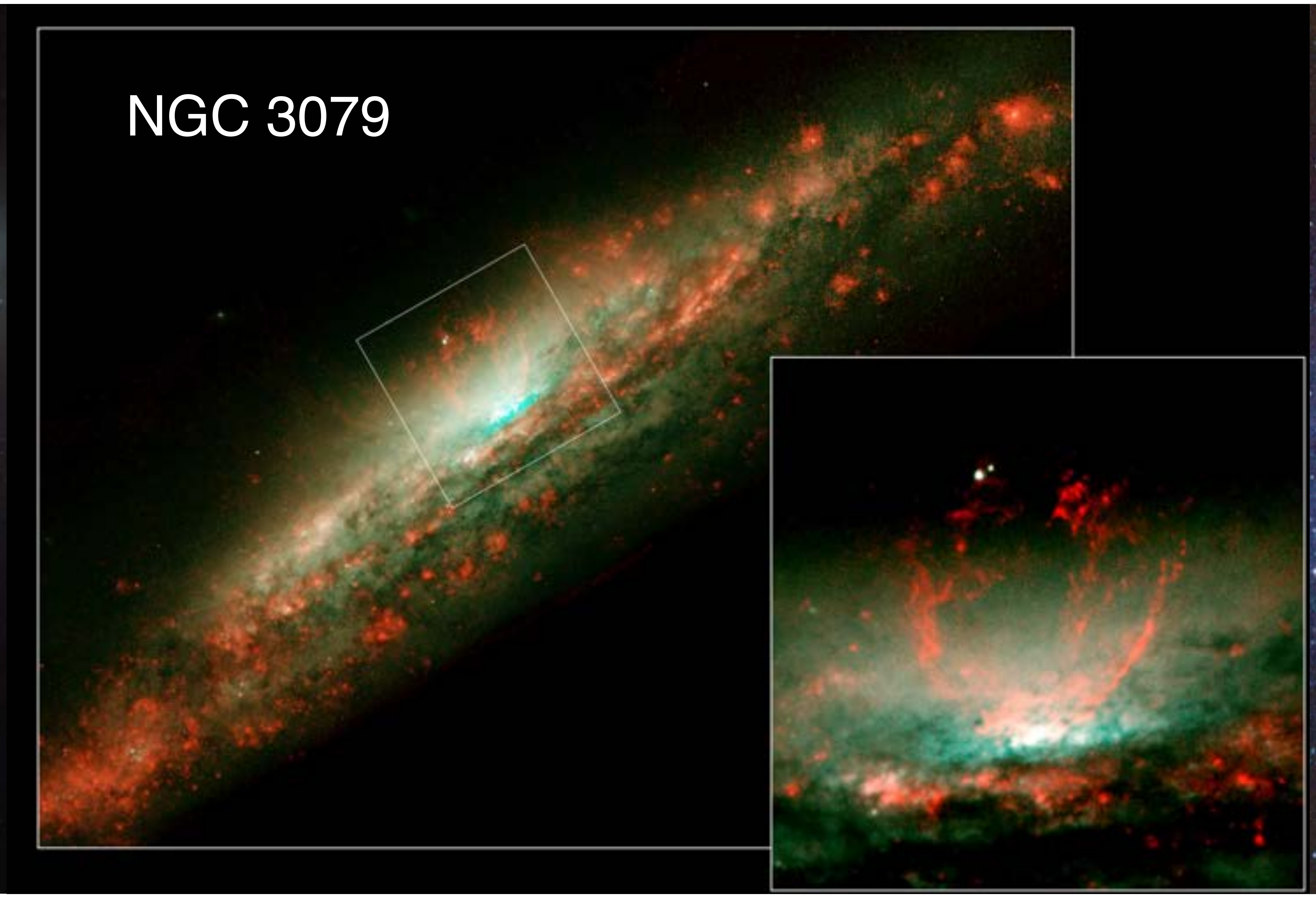
Observations of outflows

- Galactic outflows have been observed for ~80 years.
- Spectroscopy shows gas moving out of galaxies at high speeds (hundreds of km/sec).
- In many cases, speeds exceed the escape velocity — a “wind”.
- Proposed as a mechanism to self regulate star formation in galaxies.



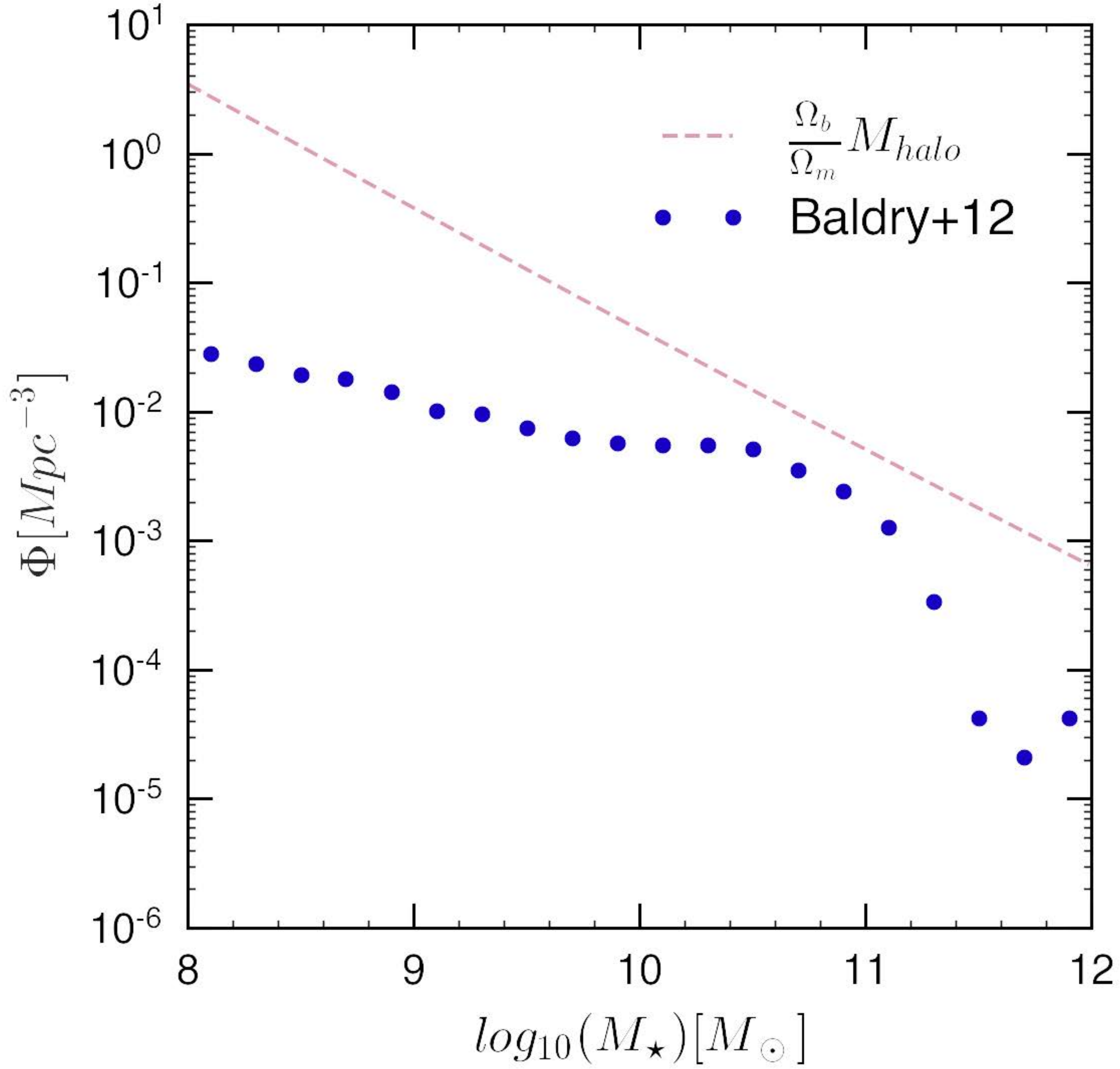
Outflows are ubiquitous

- Many local star-forming galaxies are observed to host modest outflows.
- At higher redshift, the incidence rate of observed outflows increases (Rubin 2014).
- Data are consistent with all galaxies driving outflows at various points in their lives.



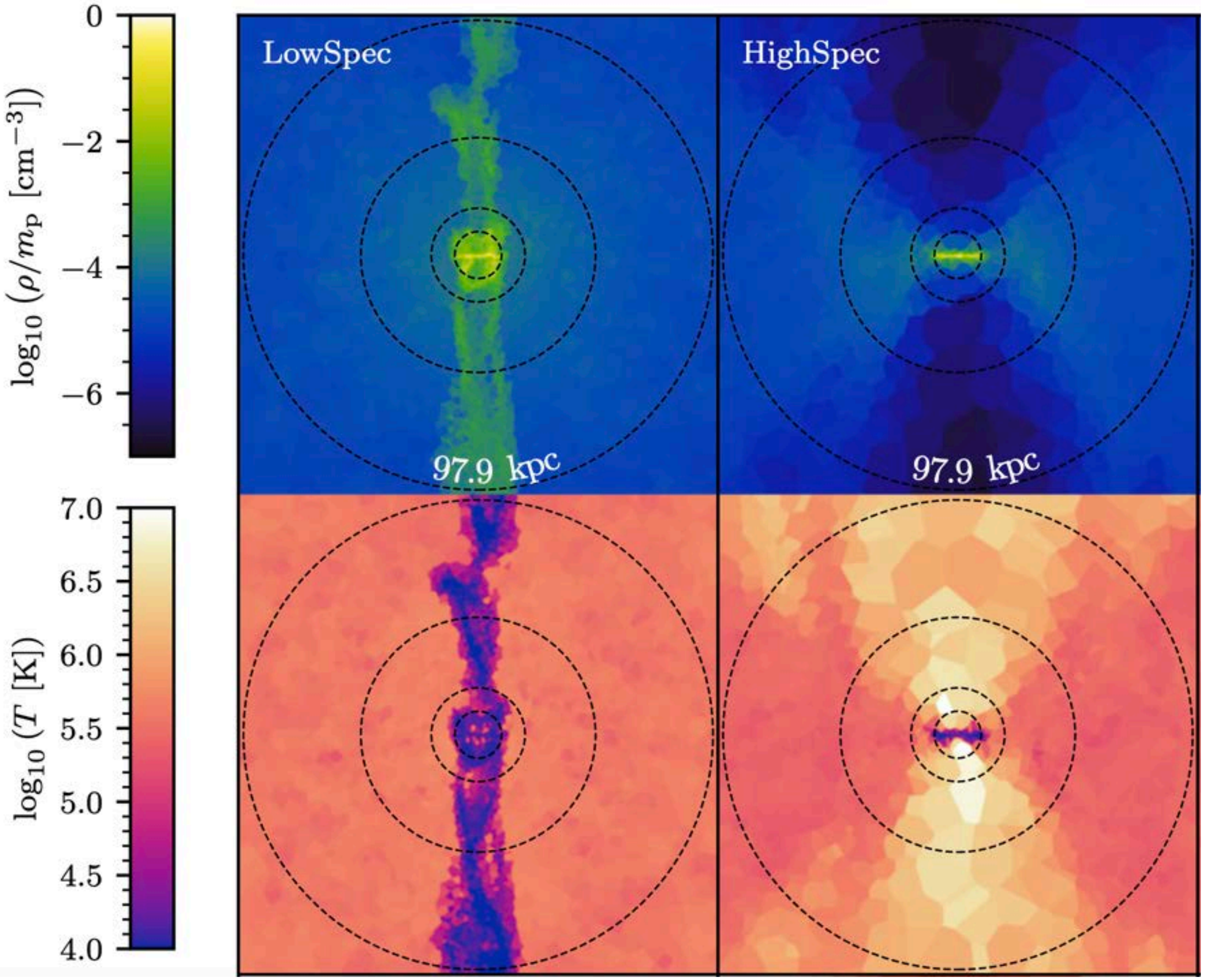
Outflows are necessary

- The stellar mass function of galaxies does not follow the halo mass function.
- Cosmological simulations cannot reproduce the galaxy population without significant outflows.
- Winds in these simulations are “prescribed” in the sense that they are not generated self-consistently, but rather tuned to produce correct galaxies.
- Different simulations use very different prescriptions — what’s going on?



Mass versus energy ejection

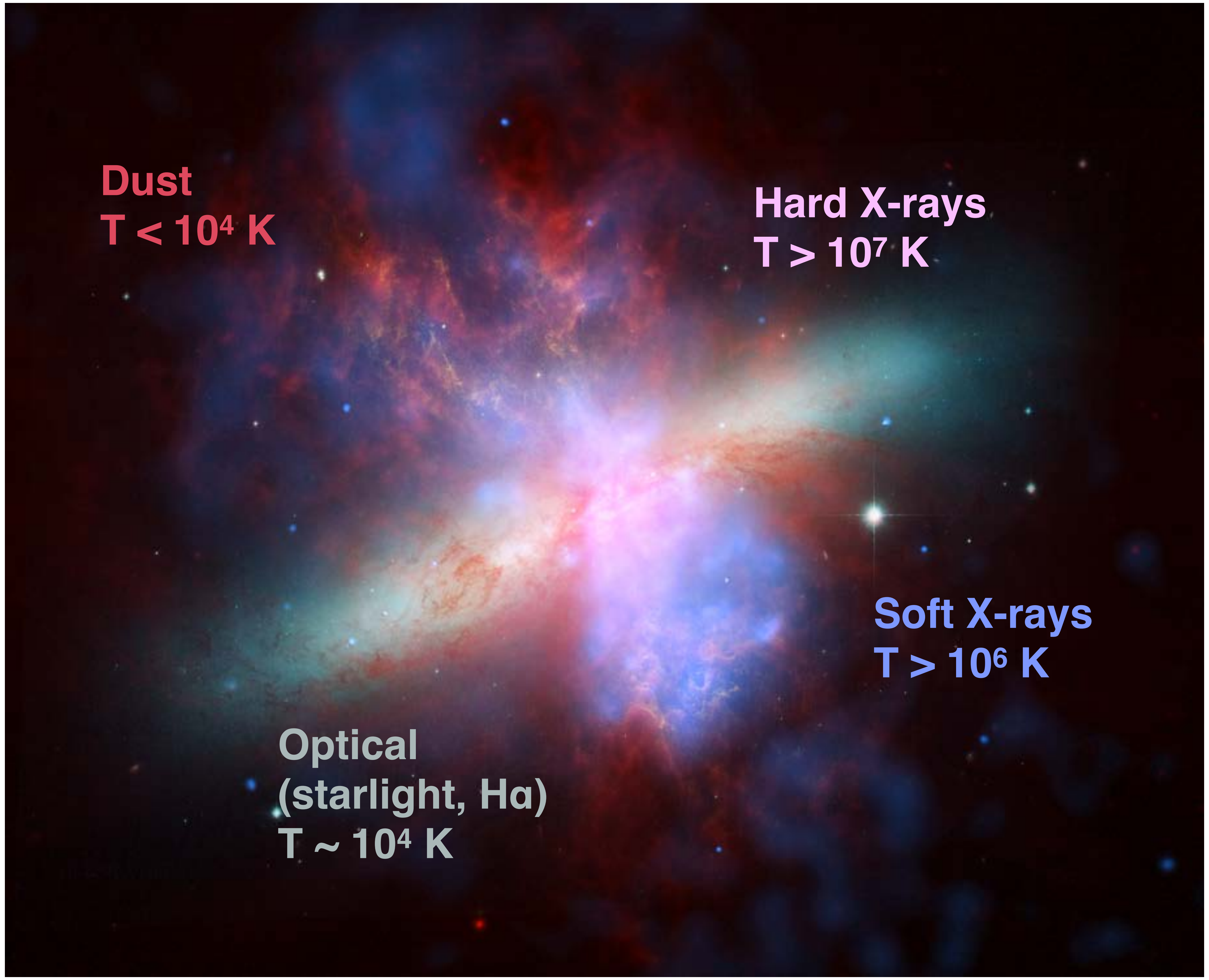
- Cosmological simulations require outflow properties that change with galaxy mass, for example, different "mass loading" factors, $\eta_m = \dot{M}_{\rm outflow}/\dot{M}_{\rm SFR}$.
- However, it is not clear which mode of feedback is most important: kicking out lots of mass ("ejective" feedback, high η_m), versus high specific energy outflows ("preventative" feedback, high η_E).



Smith et al. (2023)

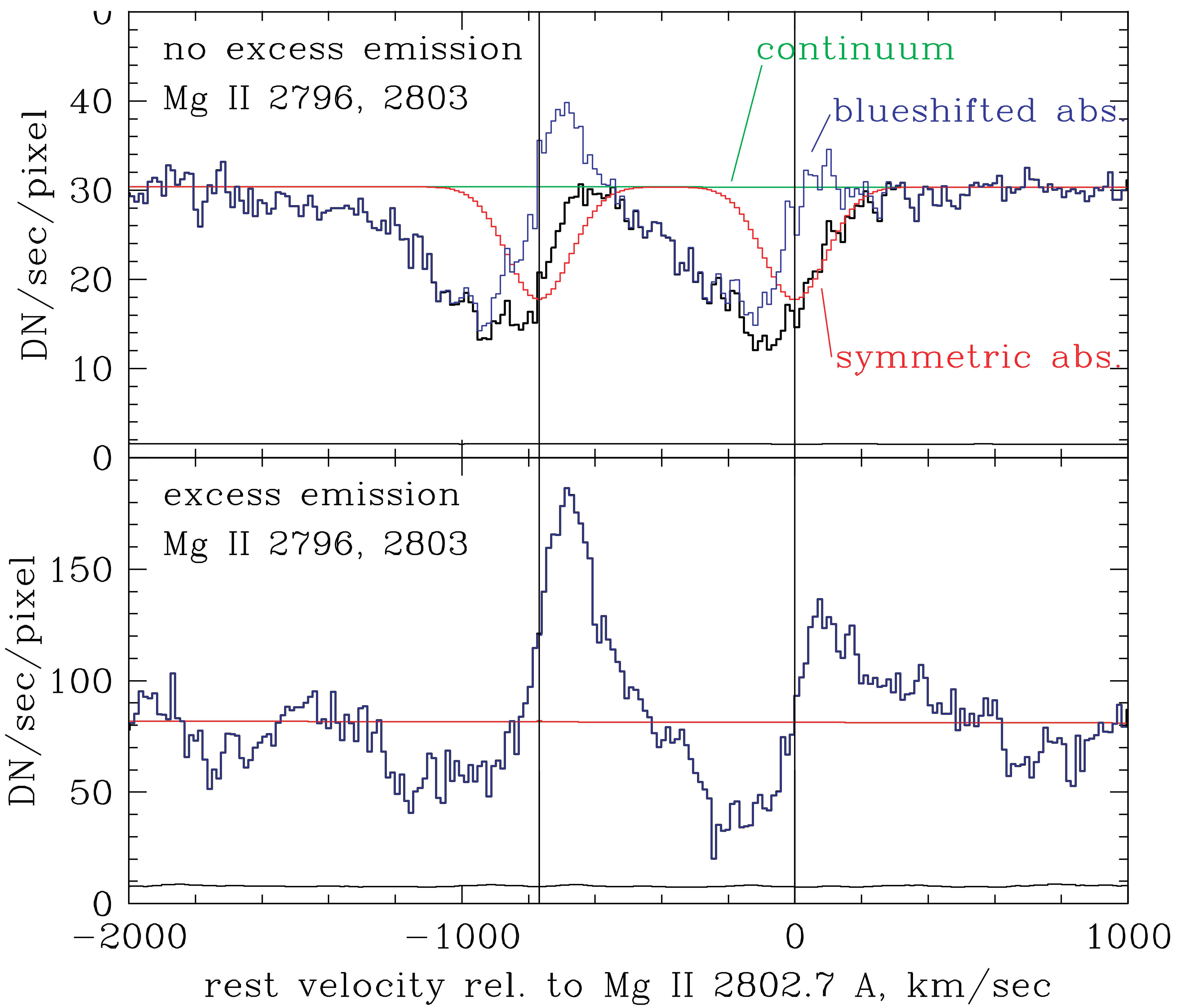
Why not just observe the answer?

- In nearby galaxies, outflows can be observed in spatially-resolved X-ray emitting gas, while optical line emission traces spatially coincident, cooler phases.
- Outflowing molecular gas and dust are also routinely detected.
- This multiphase nature of outflows makes them difficult to fully characterize observationally.
- The hot phase can only be characterized for the closest systems.



Outflow kinematics

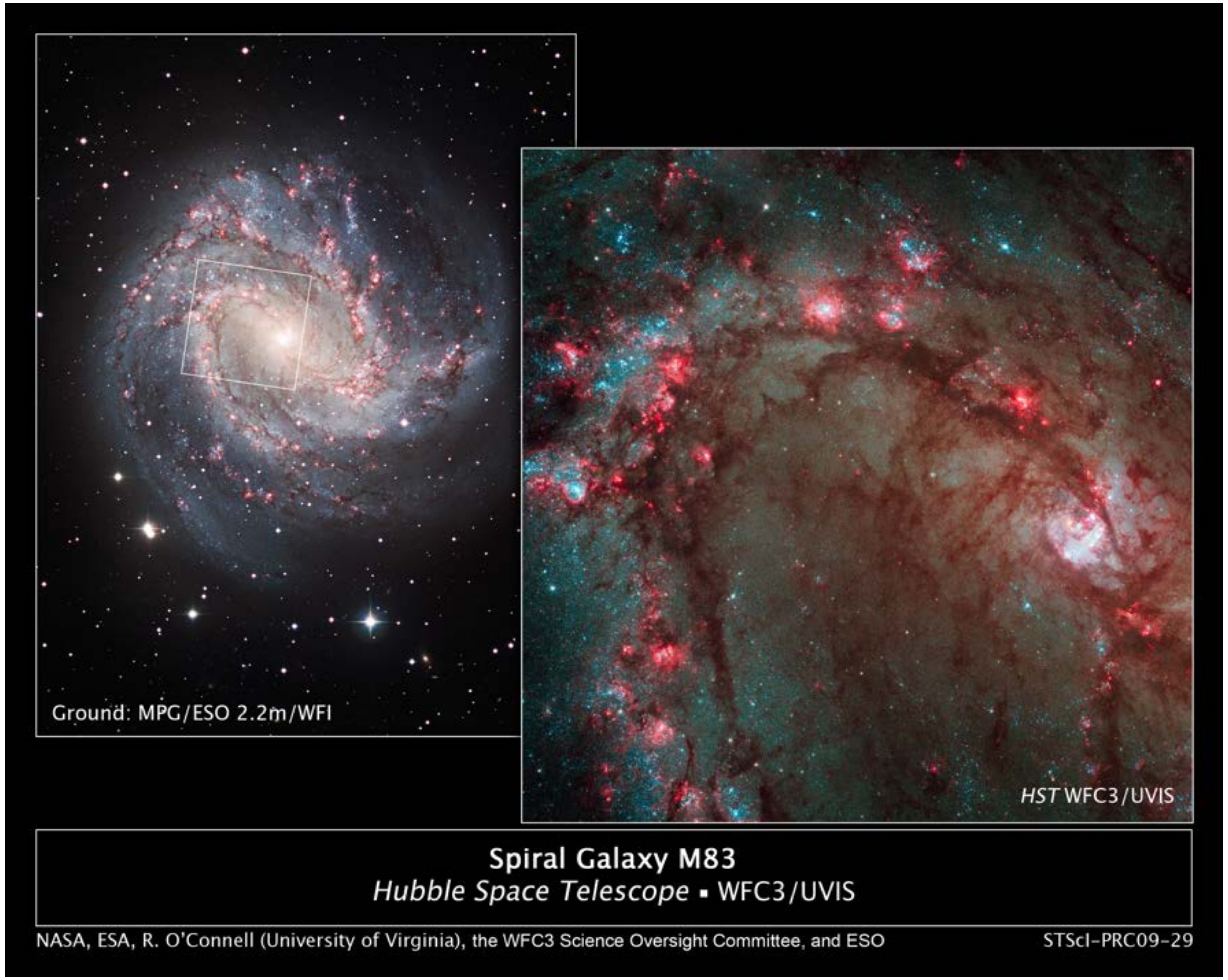
- Cool gas (10^4 K) in absorption-line studies is observed to have a wide range of velocities.
- Constraining the location of the outflowing gas can be challenging.
- Observations of outflows in emission can help, but most are not bright enough to see.
- This leads to large uncertainties in mass / energy / metal outflow rates for any given system.



Weiner et al. 2009

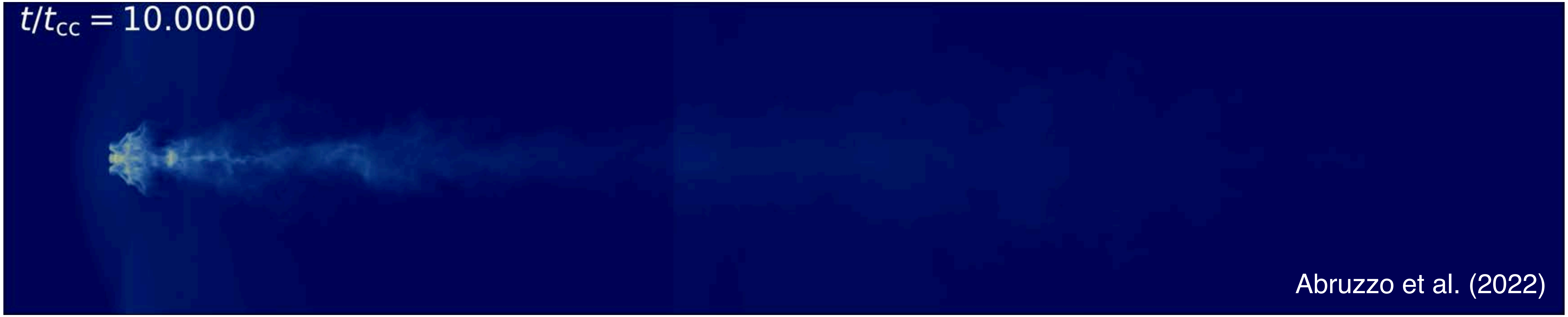
Why not just simulate the answer?

- Outflows are driven from small-scale regions with complex ISM interactions (i.e. stellar winds and supernovae), which are difficult to resolve in full-galaxy simulations.
- As winds expand out of galaxies, interactions between phases continue to play a major role.
- In addition, the physical drivers of outflows are still debated (hot gas vs. radiation pressure vs. cosmic rays, etc.)



Insight from small-scale simulations

In recent years, a number of simulations have shown that depending on the cloud and wind properties, the cool gas phase in outflows may gain or lose mass (Gronke & Oh 2018, etc.).



Density contrast $\chi = 100$; $T_{\rm cl} = 10^4\,\rm K$; $t_{\rm cc}/t_{\rm cool} = 1/9$

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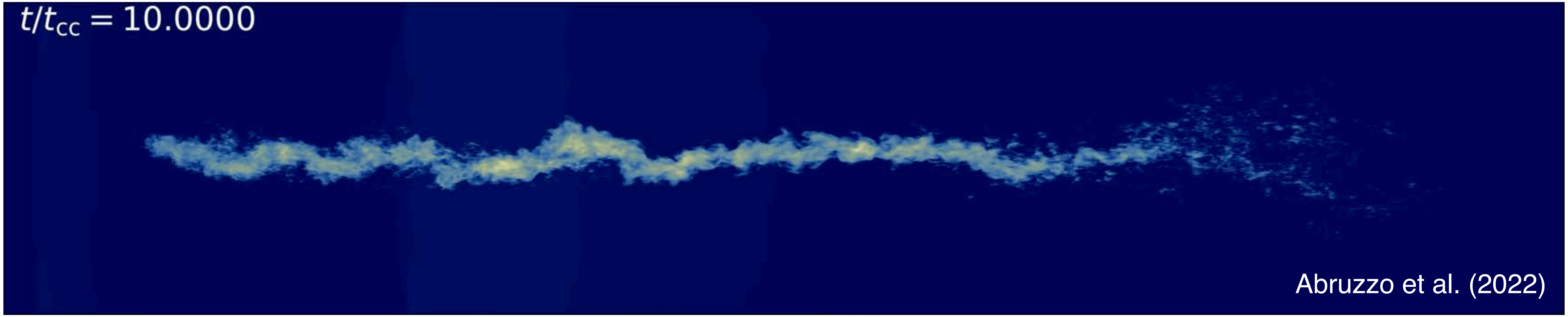


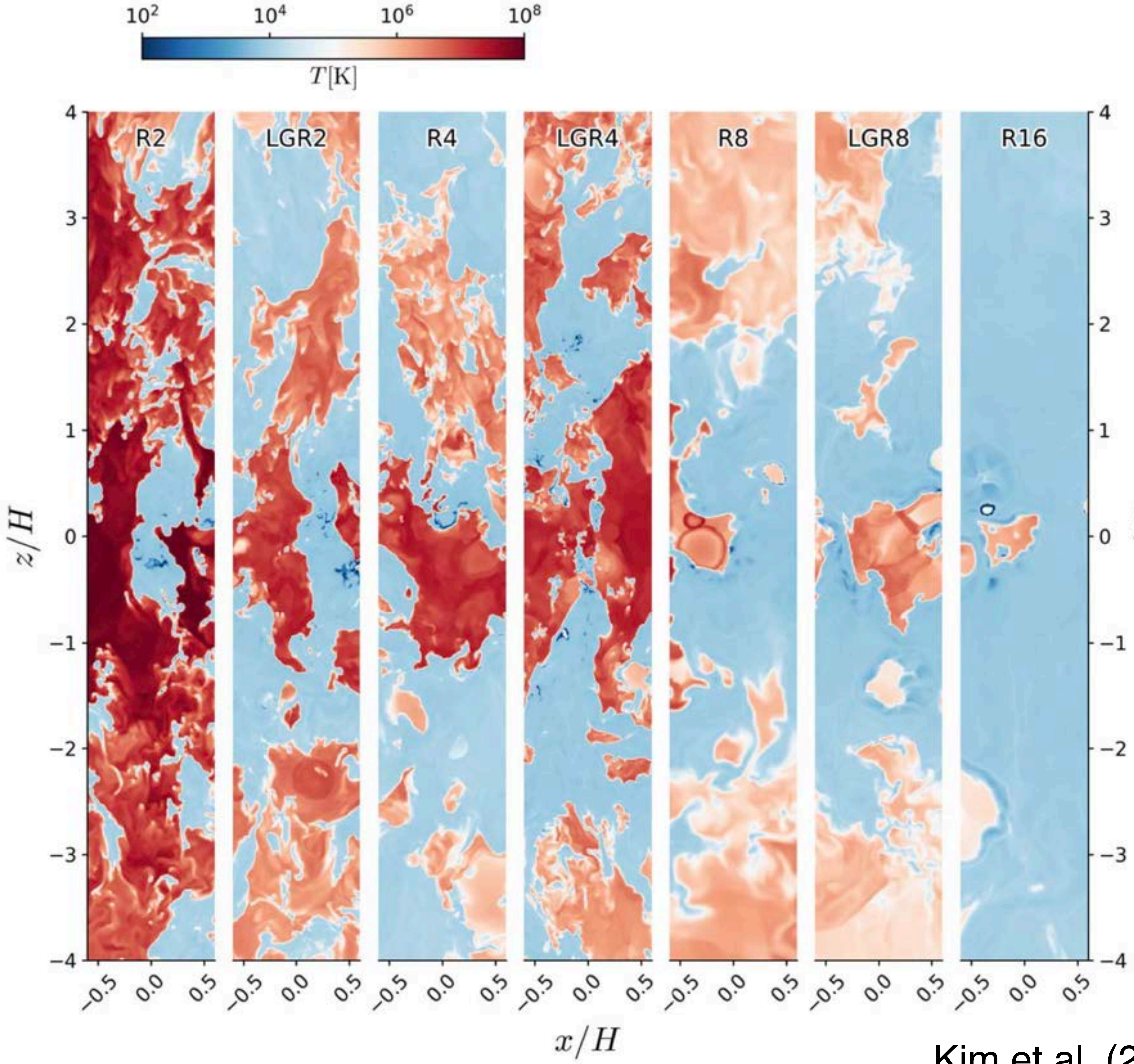
Density contrast $\chi = 100$; $T_{cl} = 10^4$ K; $t_{cc}/t_{cool} = 5$

Bridging scales as a next step

- Small-scale ISM simulations can resolve these interactions between phases, and show some trends with galaxy properties, e.g. star formation surface density.

- It is not clear whether the results from small-scale simulations agree with those from even the highest resolution cosmological zooms (Pandya et al. 2021).

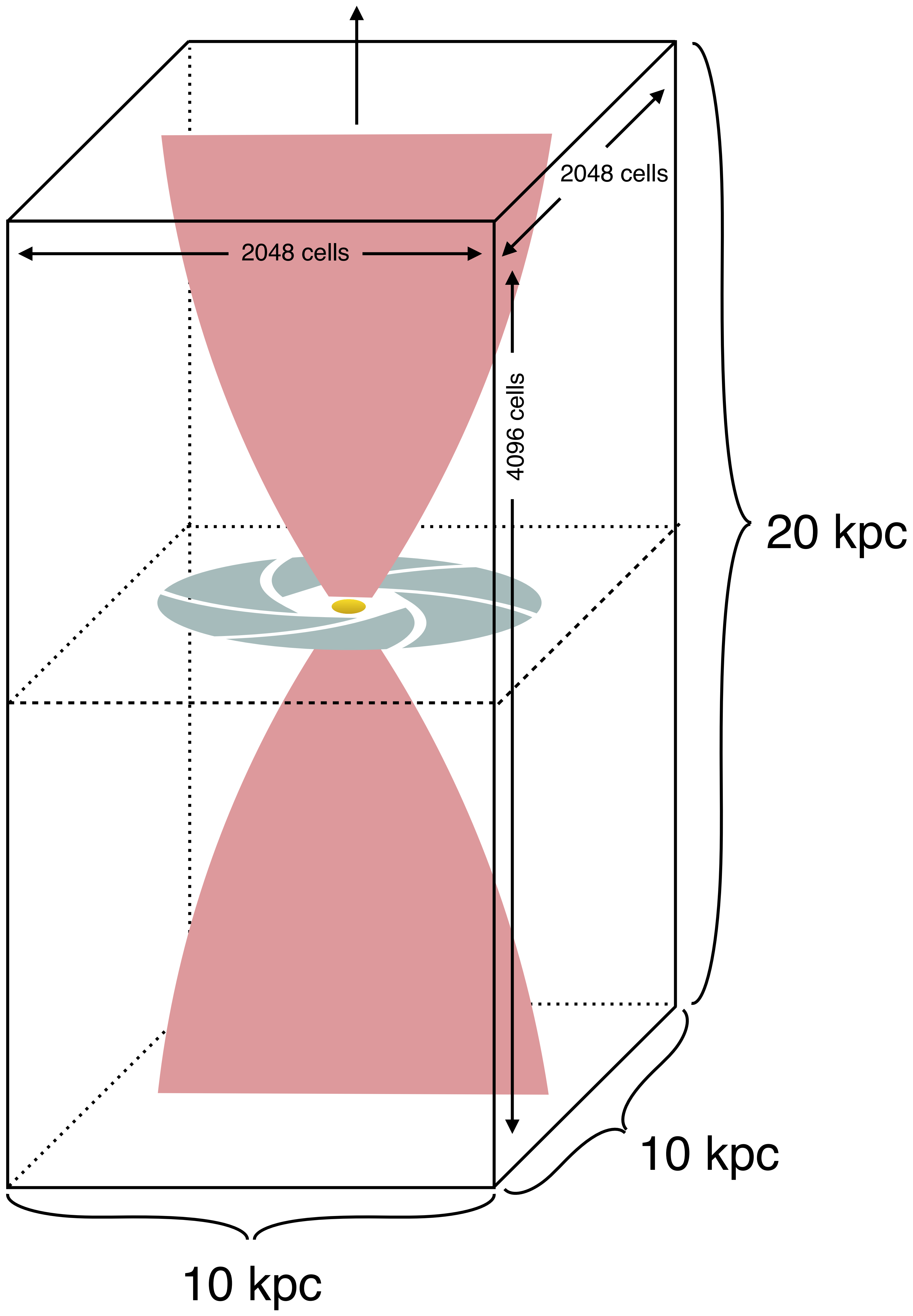
- We need high-res simulations on galaxy scales to fill in the gap.



Kim et al. (2020)

The Cholla Galactic OutfLow Simulations (CGOLS) project

- A set of isolated galaxy simulations designed to study outflows, particularly mixing between hot ($T > 10^6$ K) and cool ($T \sim 10^4$ K) phases.
- Our fiducial galaxy is roughly modeled after the nearby starburst, M82.
- The main advantage of CGOLS is resolution — each simulation has approximately 2×10^{10} cells, comparable to the resolution of a cosmological simulation.



Schneider+18a, 18b, 20, 23 (*submitted*)

Cholla:

Computational
hydrodynamics
on
ll
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 features include:
  - Unsplit 3D compressible magnetohydrodynamics
  - Optically thin radiative cooling and photoionization heating from 10 - 10^9 K
  - Static gravity with custom analytic functions
  - Passive scalar tracking
  - Self gravity (FFT based or relaxation method)
  - Particles
  - Cosmology

Schneider & Robertson (2015, 2017); Villasenor+21; Caddy & Schneider, *in prep*

CGOLS: Global Simulations of Outflows

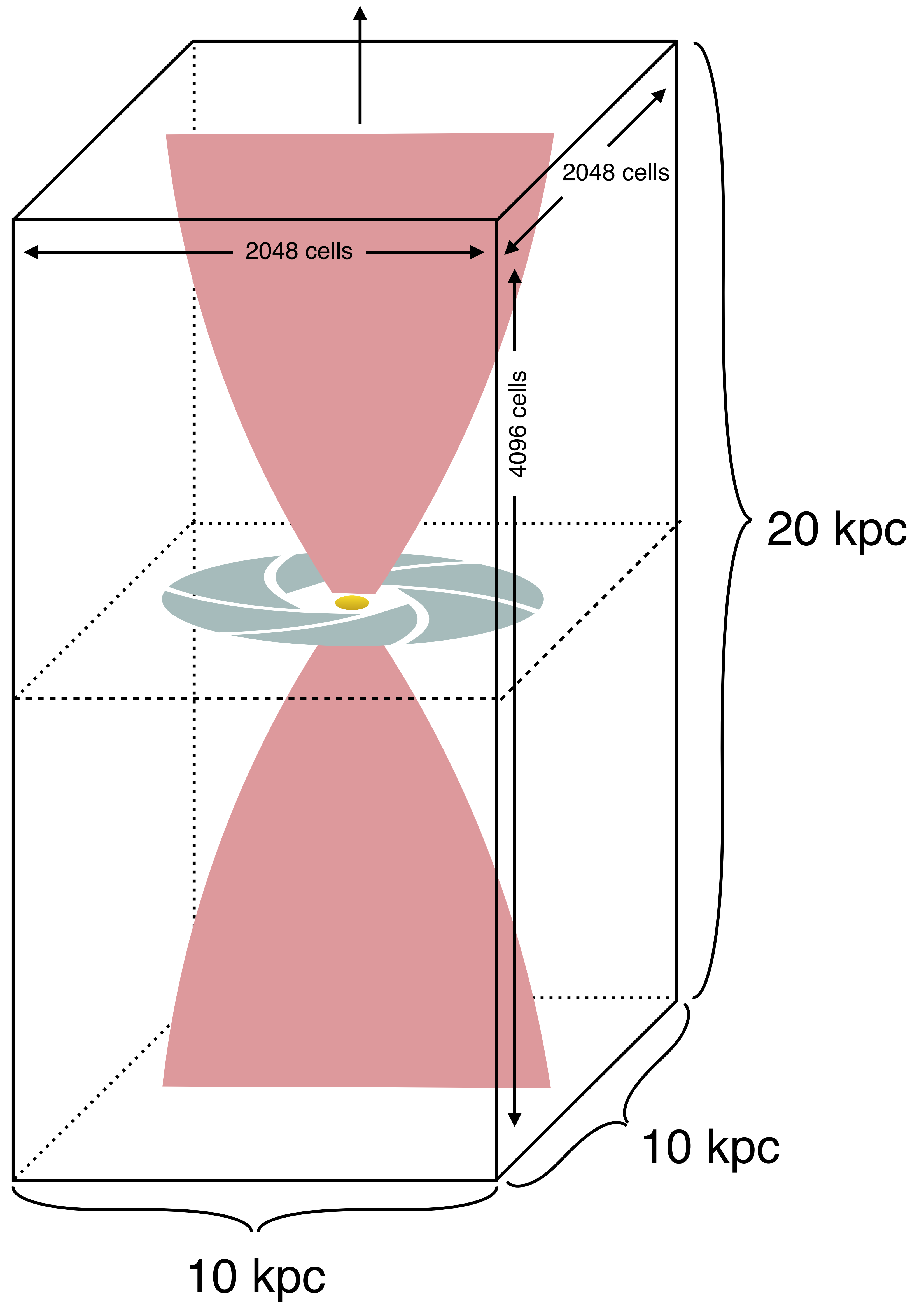
- ICs: Isothermal gas disk ($M_{gas} = 2.5 \times 10^9\ M_\odot$) at $T = 10^4$ K in vertical and rotational equilibrium

- Static gravitational potential with a stellar disk ($M_{stars} = 10^{10}\ M_\odot$) and NFW halo ($M_{DM} = 5 \times 10^{10}\ M_\odot$)

- All simulations are run at 3 resolutions: Δx = 5, 10, 20 pc

- Supernova feedback is applied in a "resolved" fashion via clusters

- No star formation model; No cold ISM (yet)

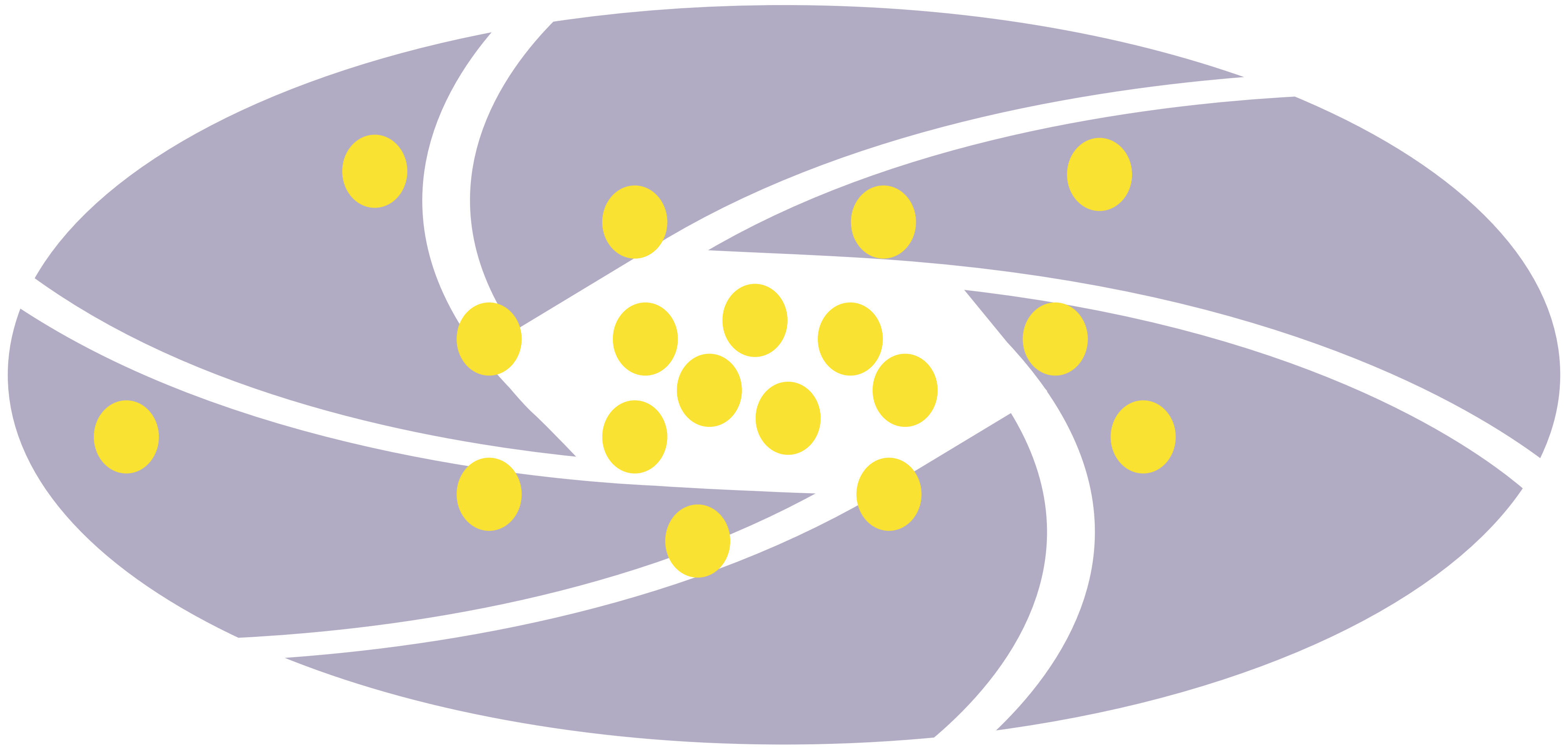


A little more about the feedback model

- “Clusters” are sites of mass and energy injection, R_{cl} = 30 pc
- Two models for cluster distribution: “central”, with clusters placed within the central kpc, and “distributed”, with clusters sprinkled throughout the disk
- Clusters turn on in accordance with the “star formation rate”, 20 $M_{\odot}$ yr^{-1}

Central

Distributed



CGOLS V: a distributed starburst simulation

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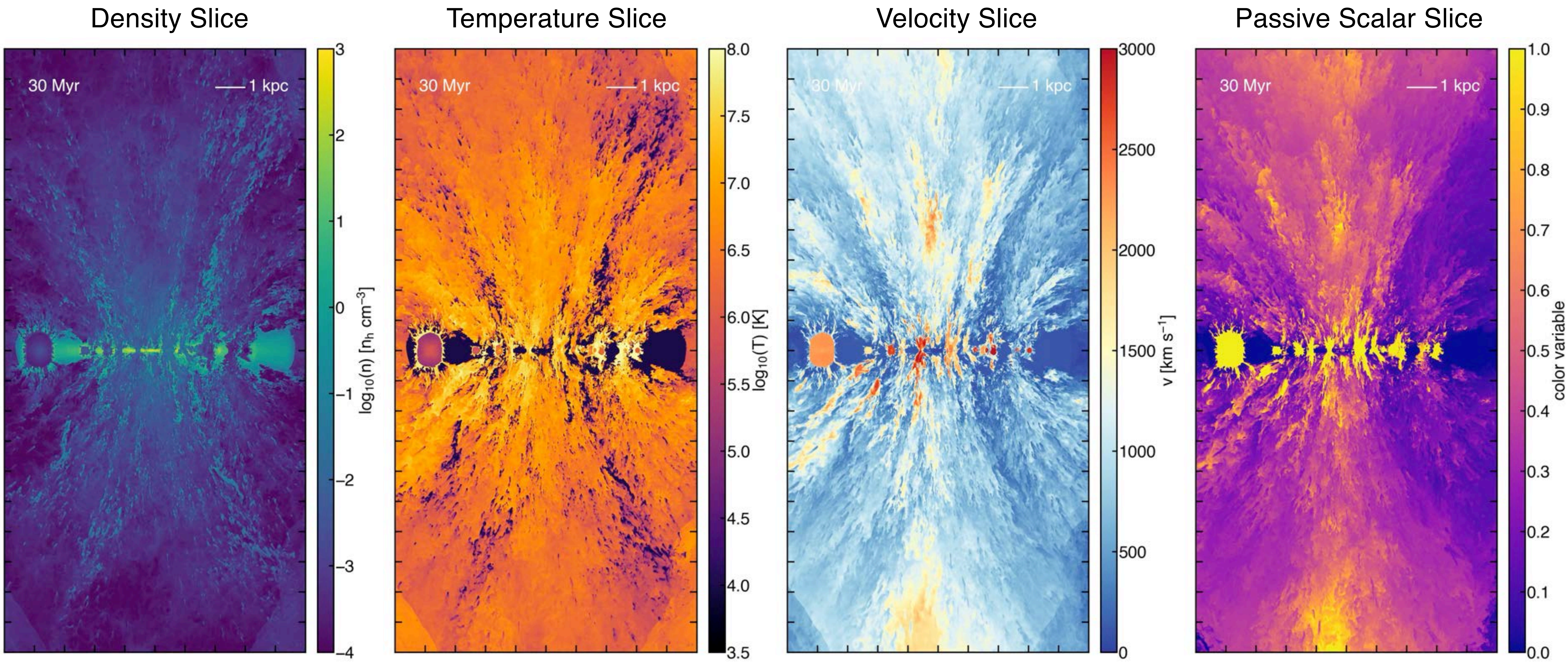
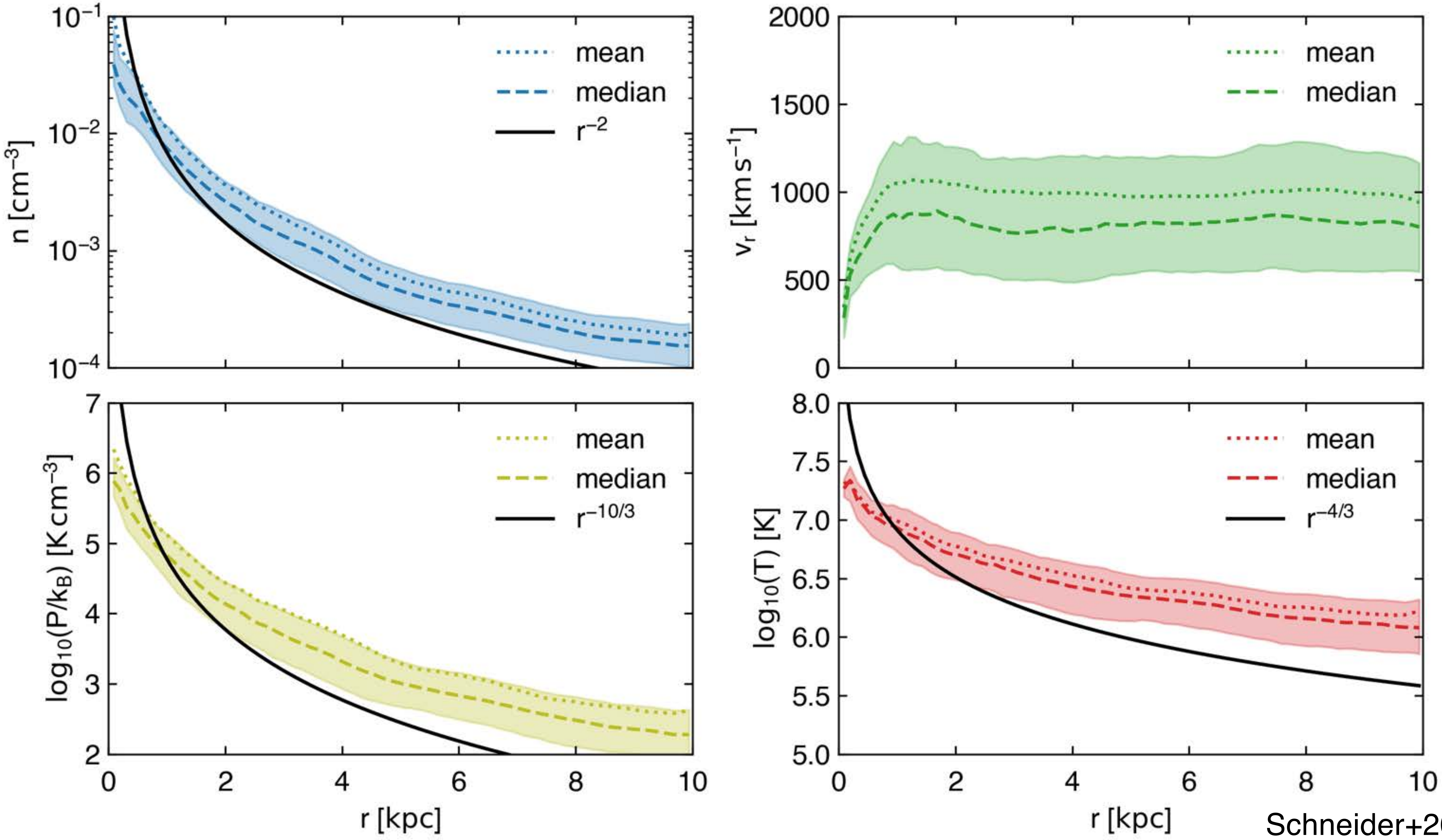


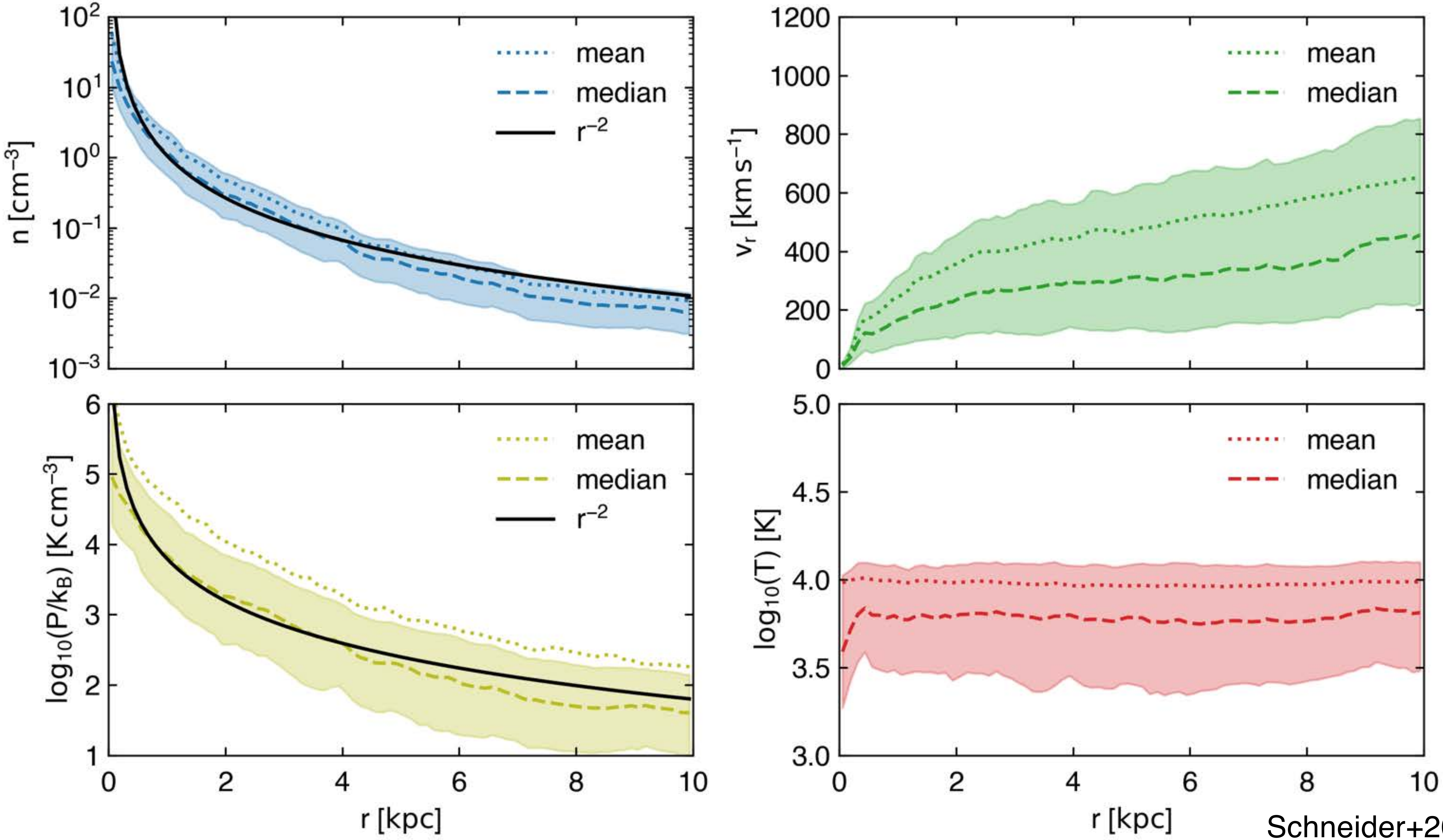
Schneider+2023, *submitted*

Radial gas profiles: hot gas ($T > 5 \times 10^5$ K)



Schneider+2023, *submitted*

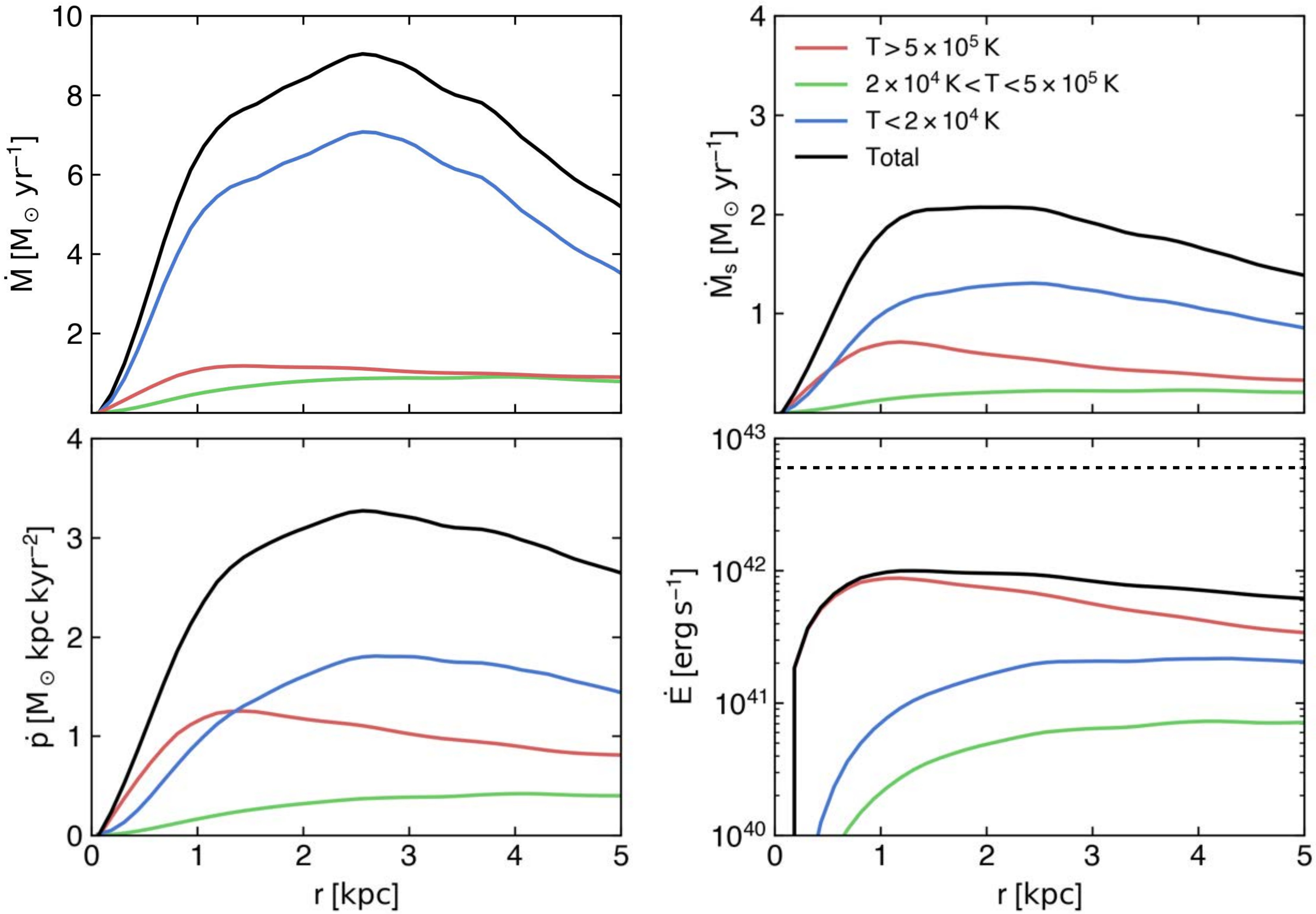
Radial gas profiles: cool gas ($T < 2 \times 10^4\,\mathrm{K}$)



Schneider+2023, *submitted*

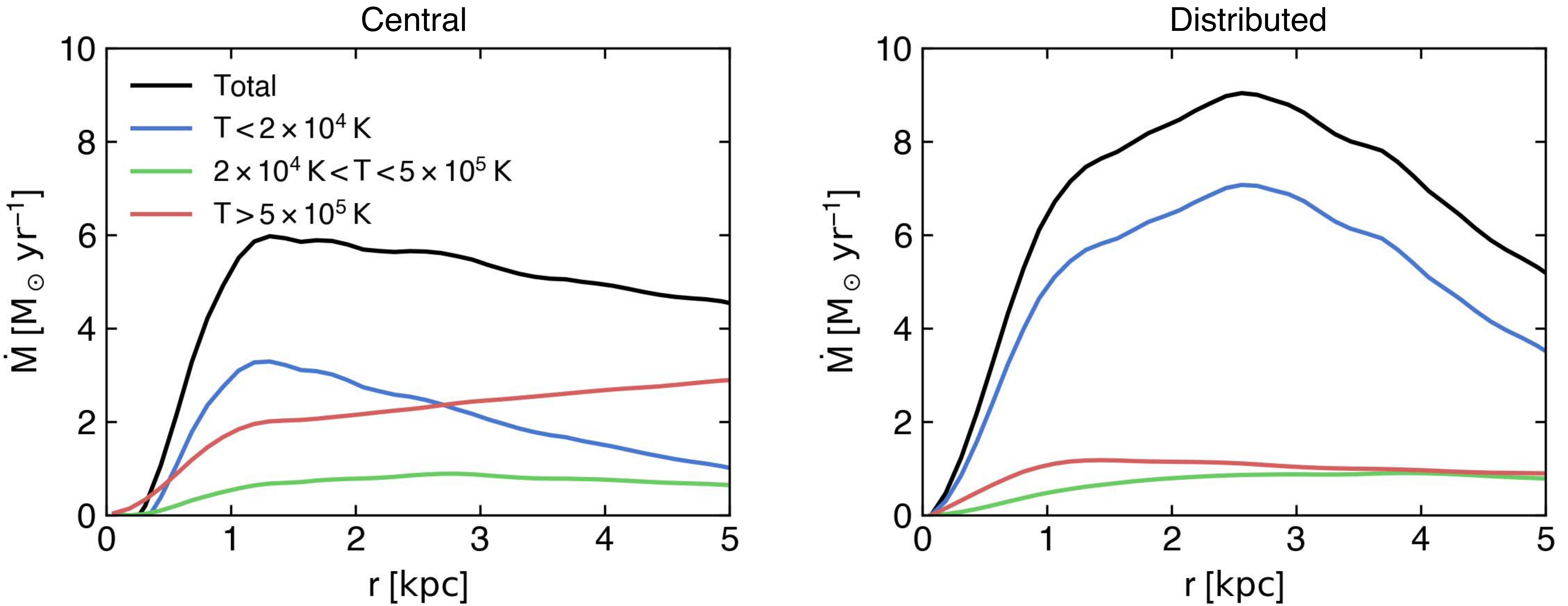
Outflow rates

- Outflow rates are computed in spherical shells, excluding the disk.
- Total mass-loading ($\dot{M}_{\rm outflow}/\dot{M}_{\rm SFR}$) never exceeds ~0.5.
- *Scalar* mass-loading reaches 1.
- Energy loading is ~0.1 at 5 kpc.



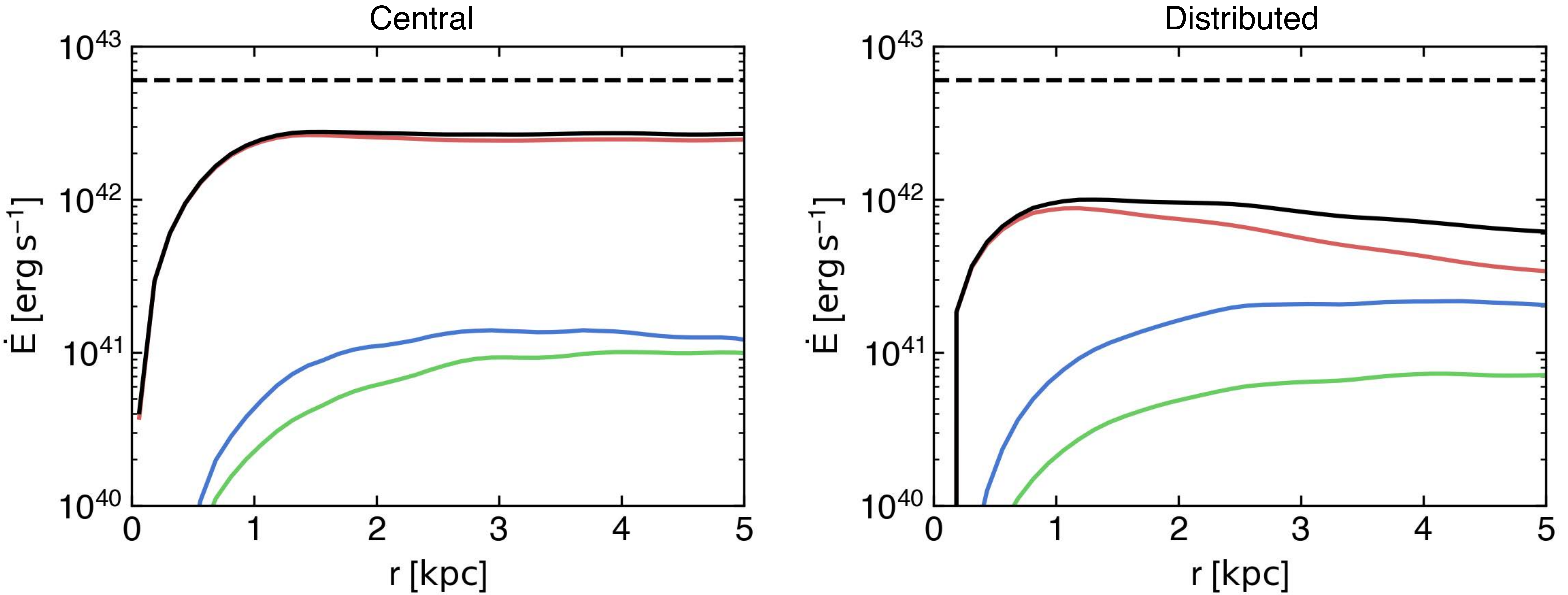
Model dependence - mass loading

Outflow properties look qualitatively different between the central and distributed models, though they wind up with similar total mass outflow rates at 5 kpc ($\eta_m \sim 0.25$).



Model dependence - energy loading

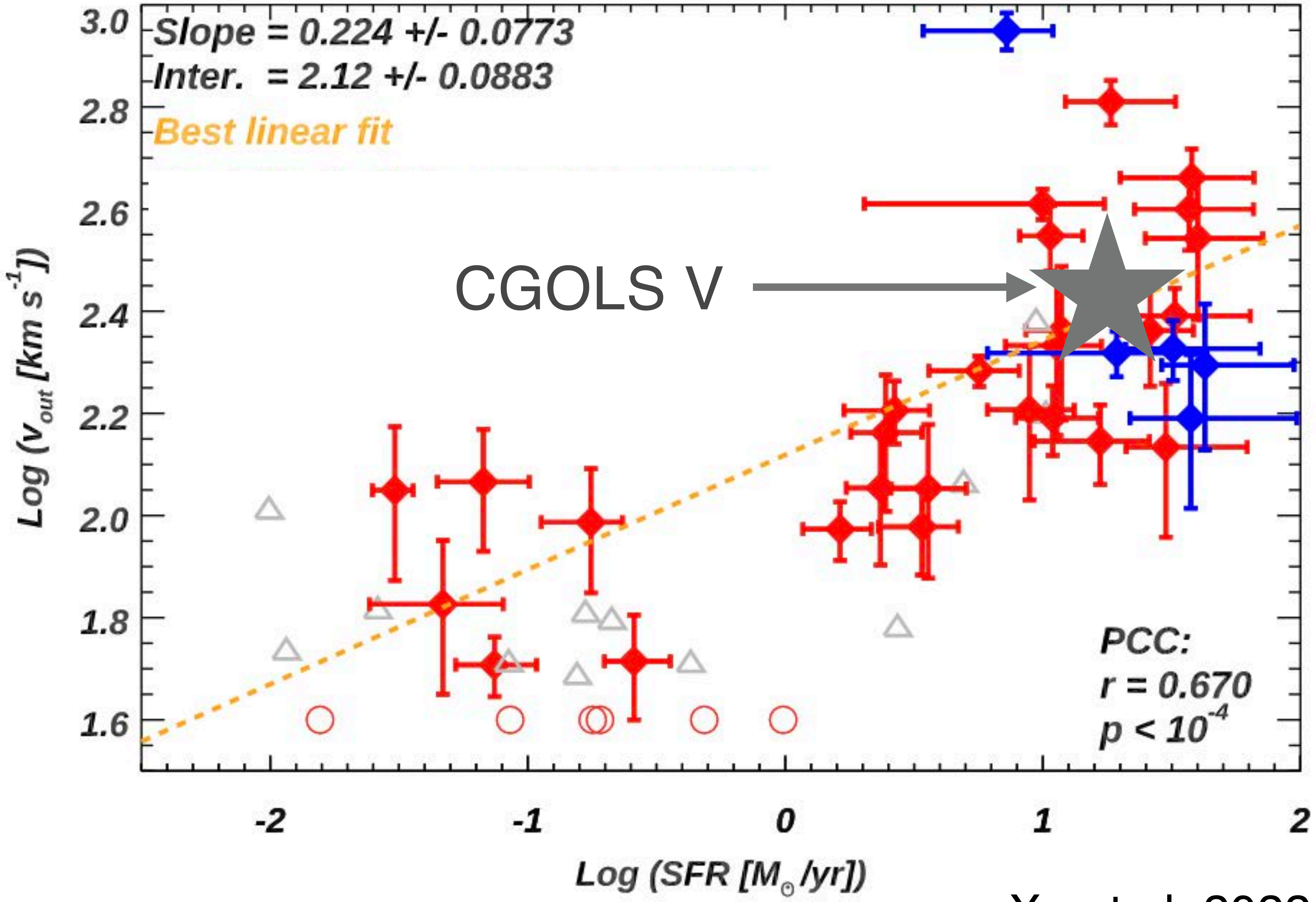
The same is not true of the energy loading. The central model is much more effective at transporting energy out in the hot phase.



How consistent is this model with observations?

- Comparing to the low-*z* starburst sample explored in Xu et al. 2022, for an M82-like galaxy with our adopted star formation rate:
    - Mass loading should be 0.3 - 0.6
    - Wind velocity should be 260 - 360 km/s at ~3 kpc
    - Kinetic energy flux in the cool phase should be ~5%
- The distributed model fits the data better than the central burst

Outflow velocity versus galaxy star formation rate



Xu et al. 2022

Conclusions

- Clustered supernovae are effective at driving multiphase outflows.
- The spatial distribution of clusters can have qualitative and quantitative impacts on the resulting outflow.
- In the CGOLS models, a more centrally-concentrated burst:
  - has higher energy loading
  - has faster winds
- A more distributed burst:
  - has more cool gas
  - has higher mass loading

What's next?

We've entered a new era in supercomputing — exascale.

CGOLS-MW will be done soon!