Discussion:

From small to big scales

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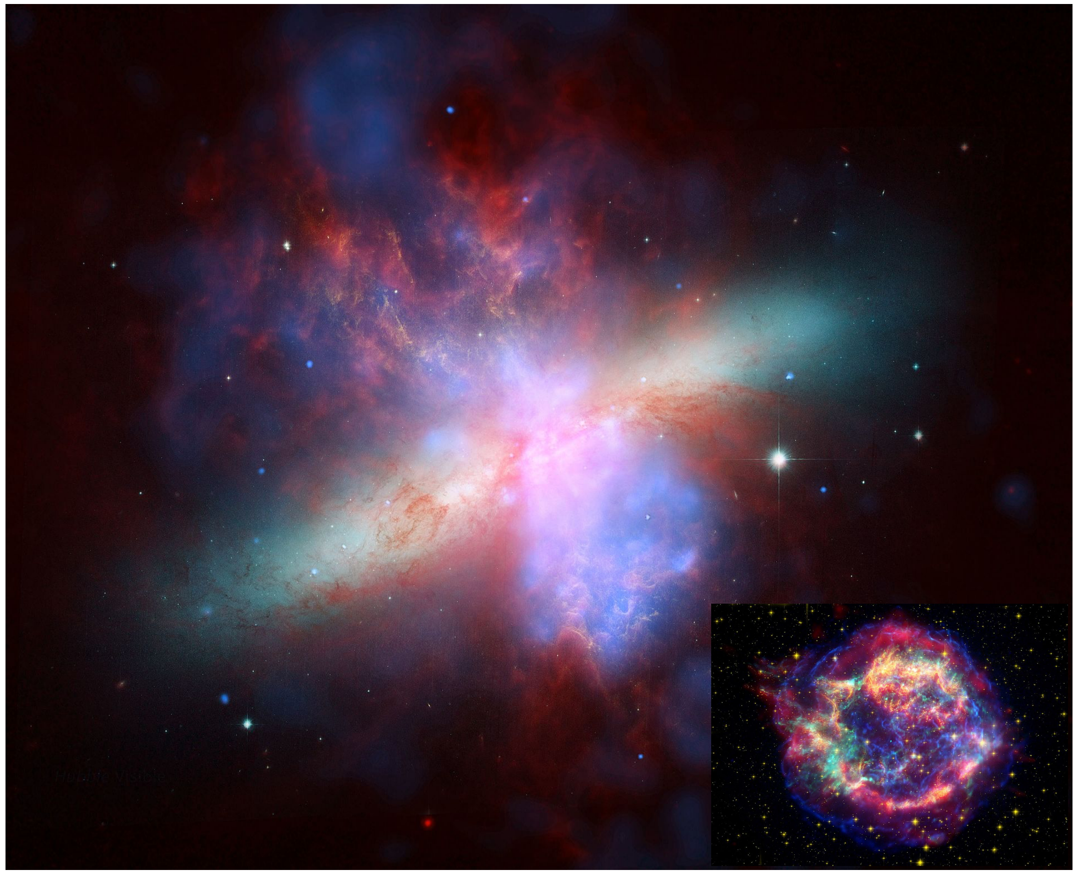
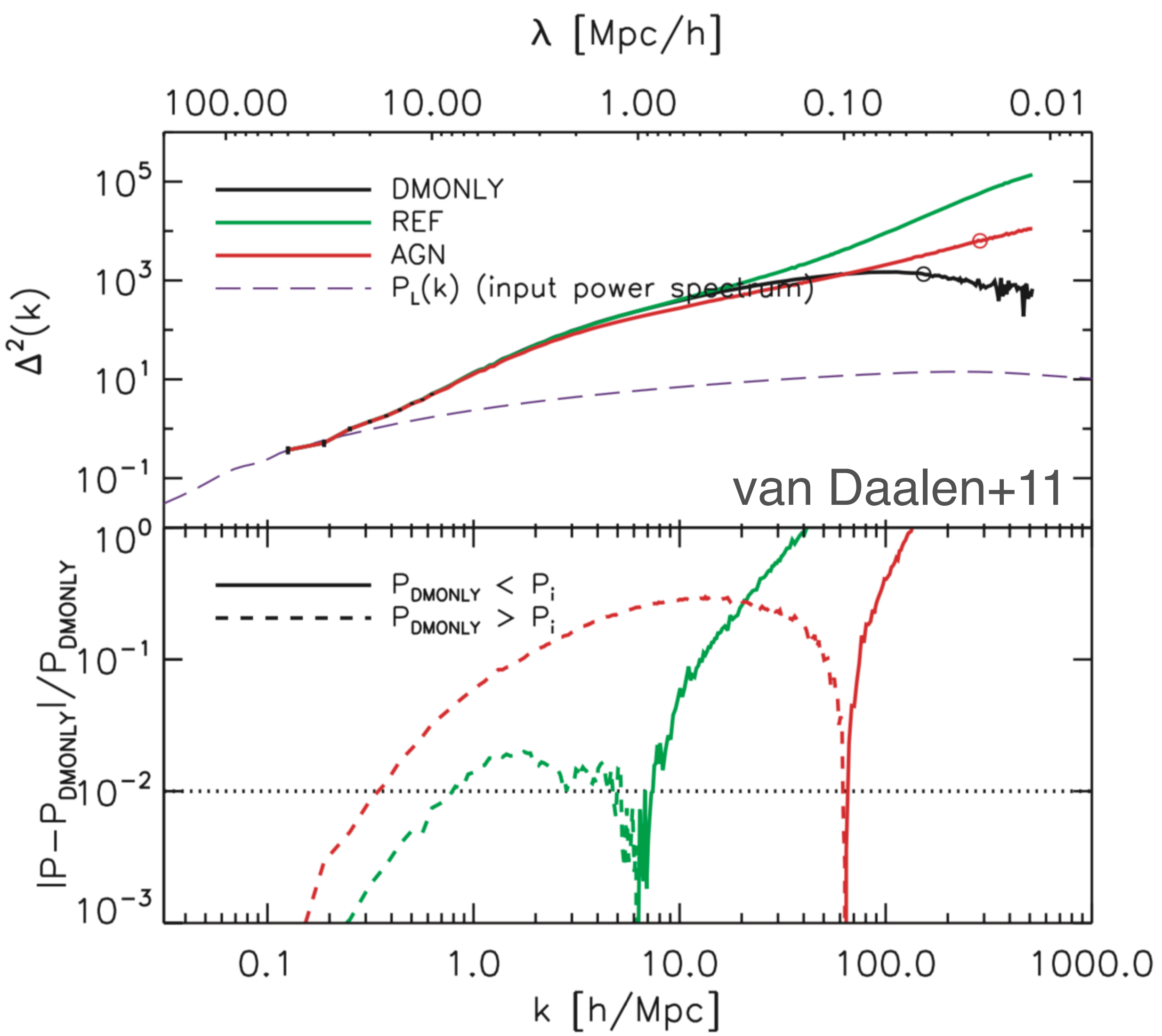
with input from Phil Hopkins

The multi-scale modeling program

- We would like simulations of large cosmic volumes (L~100 Mpc-1 Gpc) that, on the scales they resolve, correctly incorporate the net effects of all subgrid-scale physics
  - e.g., produce correct galactic winds, galaxy properties in kpc-resolution simulations without tuning
  - precision cosmology with LSST, Euclid, WFIRST will require modeling feedback in large volumes
- Idea: evolve a series of nested high-res "boxes" and coarse grain the results
- Many groups now working on aspects of this. How to do it? Will it be successful (T. Naab is skeptical)?





Lessons from SN feedback

- Must capture Sedov-Taylor momentum boost

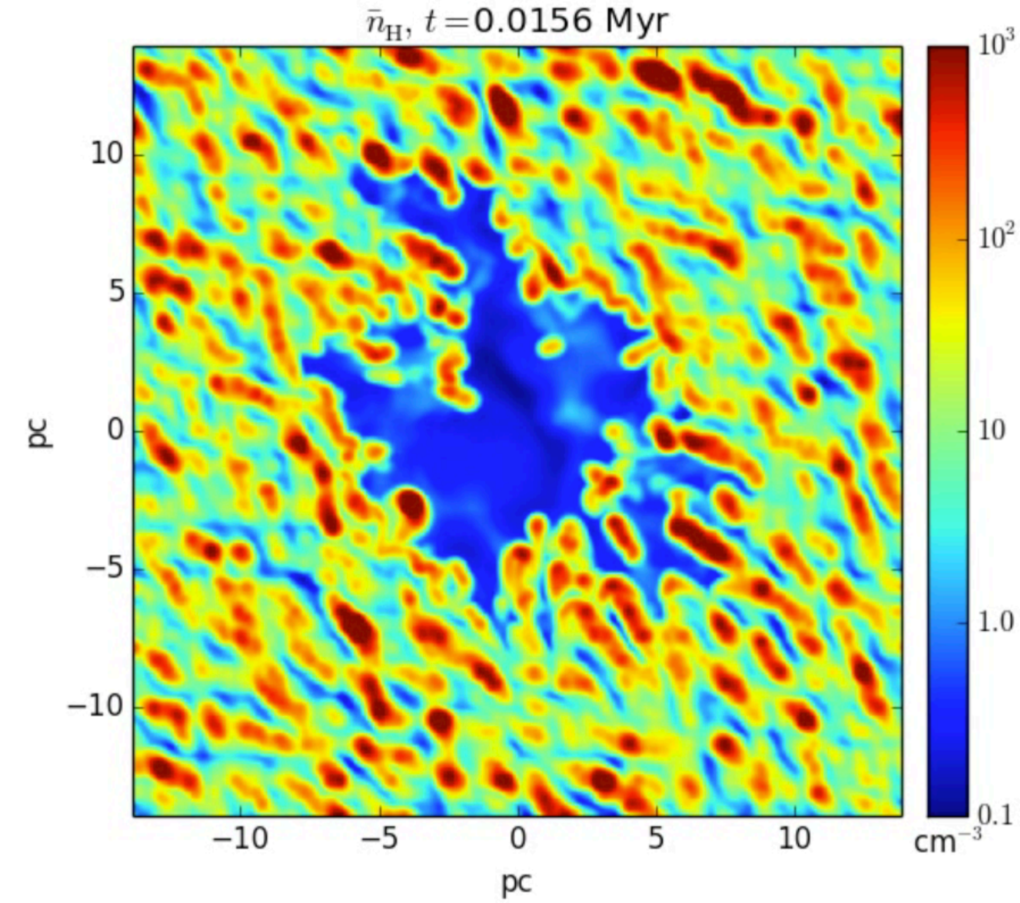
$$\frac{P_{\rm fin}}{P_{\rm ej}} \sim \left(\frac{M_{\rm cool}}{M_{\rm ej}}\right)^{1/2} \sim 5 - 15$$

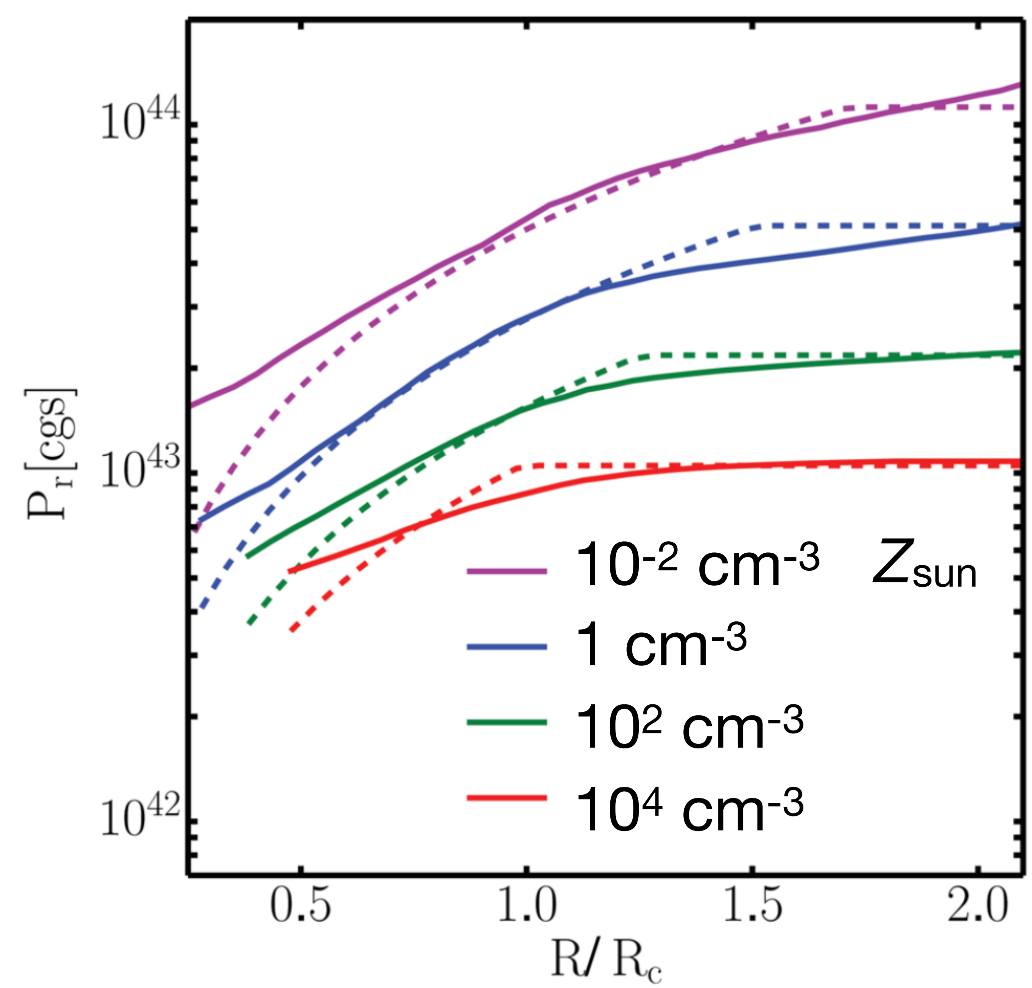
- Explicit requires resolving $M_{\rm cool}$~1,000 $M_{\rm sun}$

- <u>Subgrid model:</u>

  At resolution scale, inject P and $E_{\rm th}$ based on resolved SNR sims, for local $n_{\rm H}$, Z

  Good to ~20% for turb. energy, but misses hot phase when $M_{\rm cool}$ is not resolved

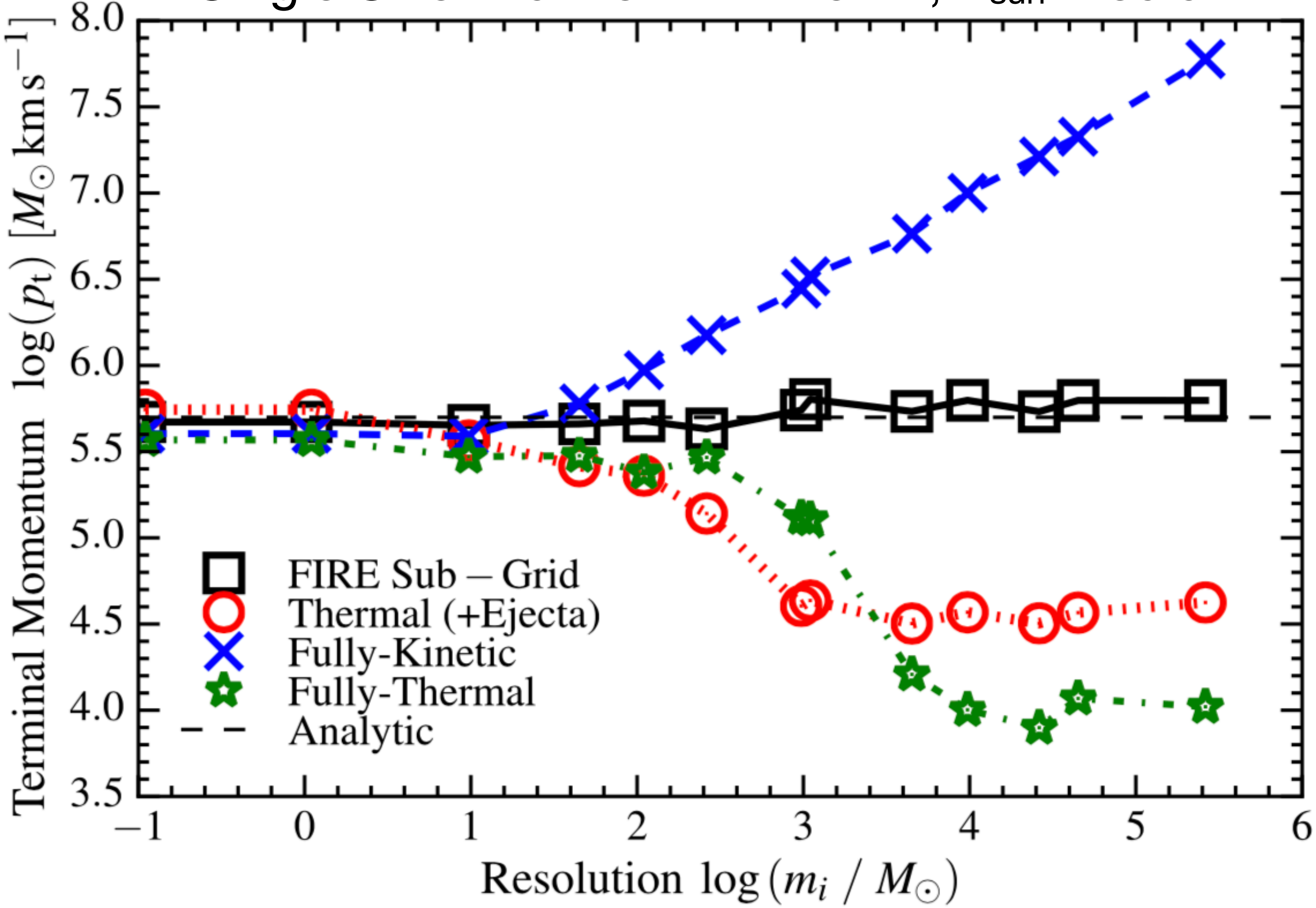




Martizzi, FG, Quataert+15 (also: Kimm & Cen 14; Kim & Ostriker 15; Walch & Naab 15; Simpson+15, …)

Version of this hybrid energy/momentum SN model used in FIRE: much more stable with resolution

Single SNe in uniform n=1 cm^{-3}, Z_{sun} medium



Compare different energy and momentum injection methods as a function of mass resolution m_i

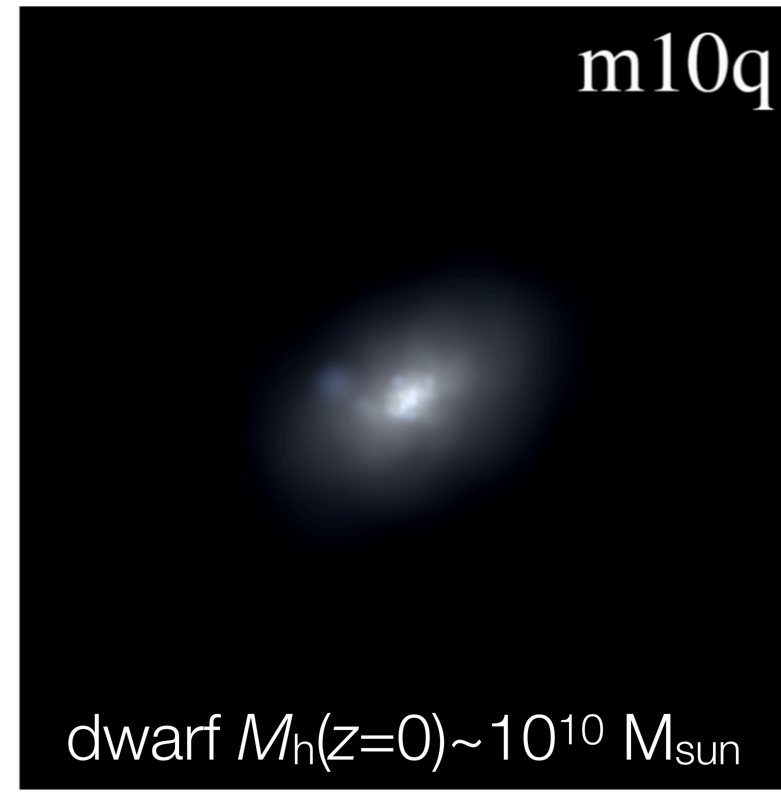
All methods converge for $m_i \ll M_{cool}$, but only the hybrid method accounting for momentum based on actual SNR models injects correct momentum at $m_i \gtrsim M_{cool}$

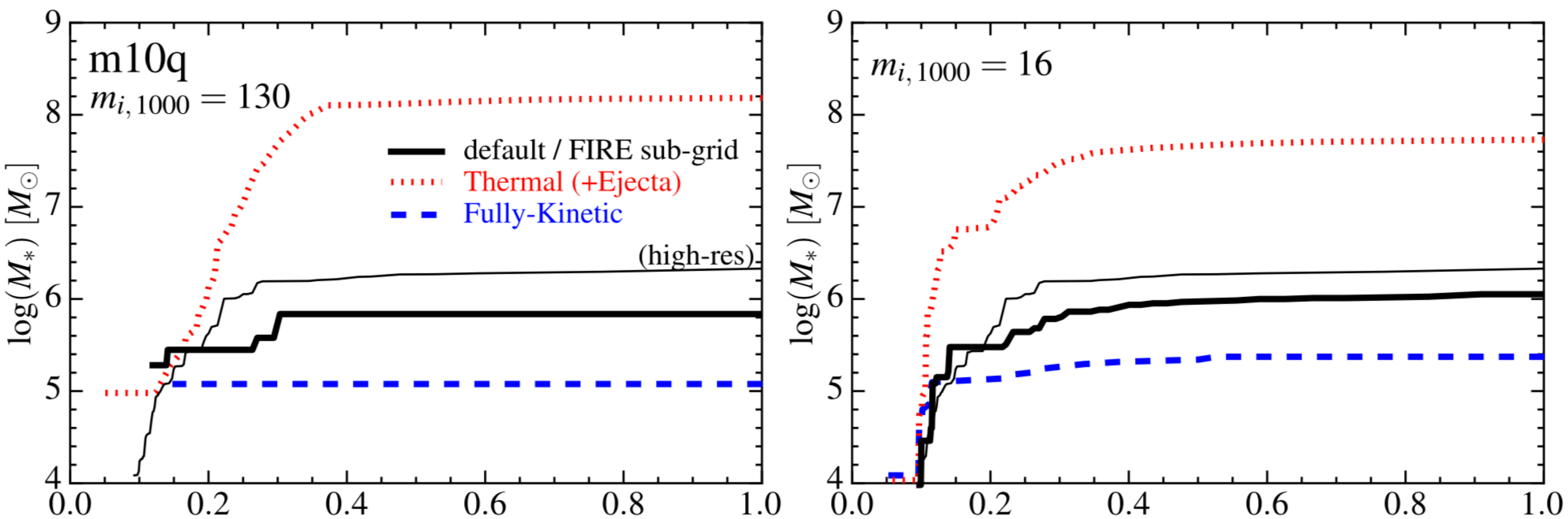
Hopkins, Wetzel, Keres, FG+18a

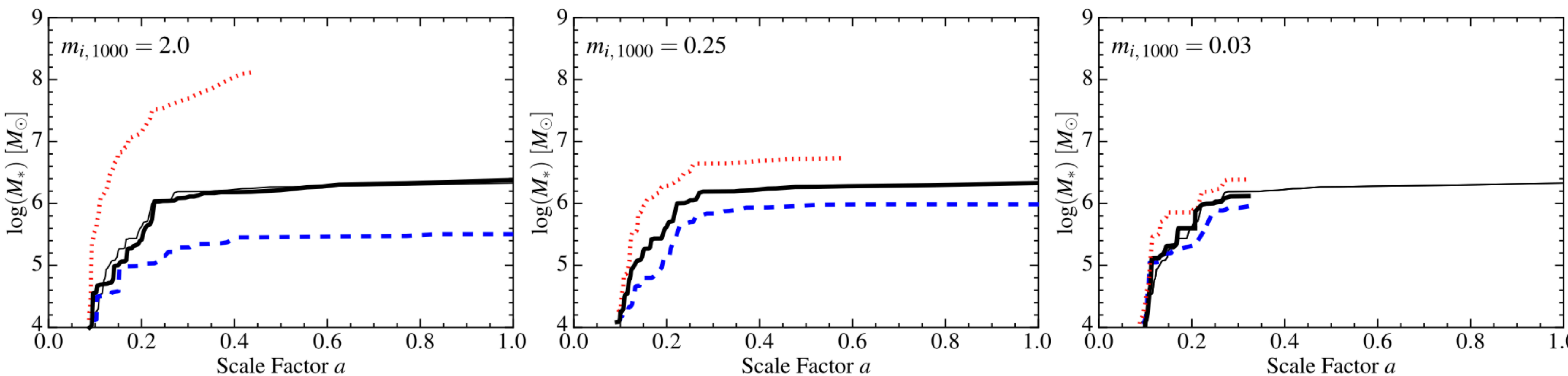
Resolution stability in cosmological zoom-ins

Again, hybrid energy/momentum (FIRE) SN subgrid model is much more stable with resolution

and gives the solution to which all subgrid models converge at $m_i \ll M_{cool}$







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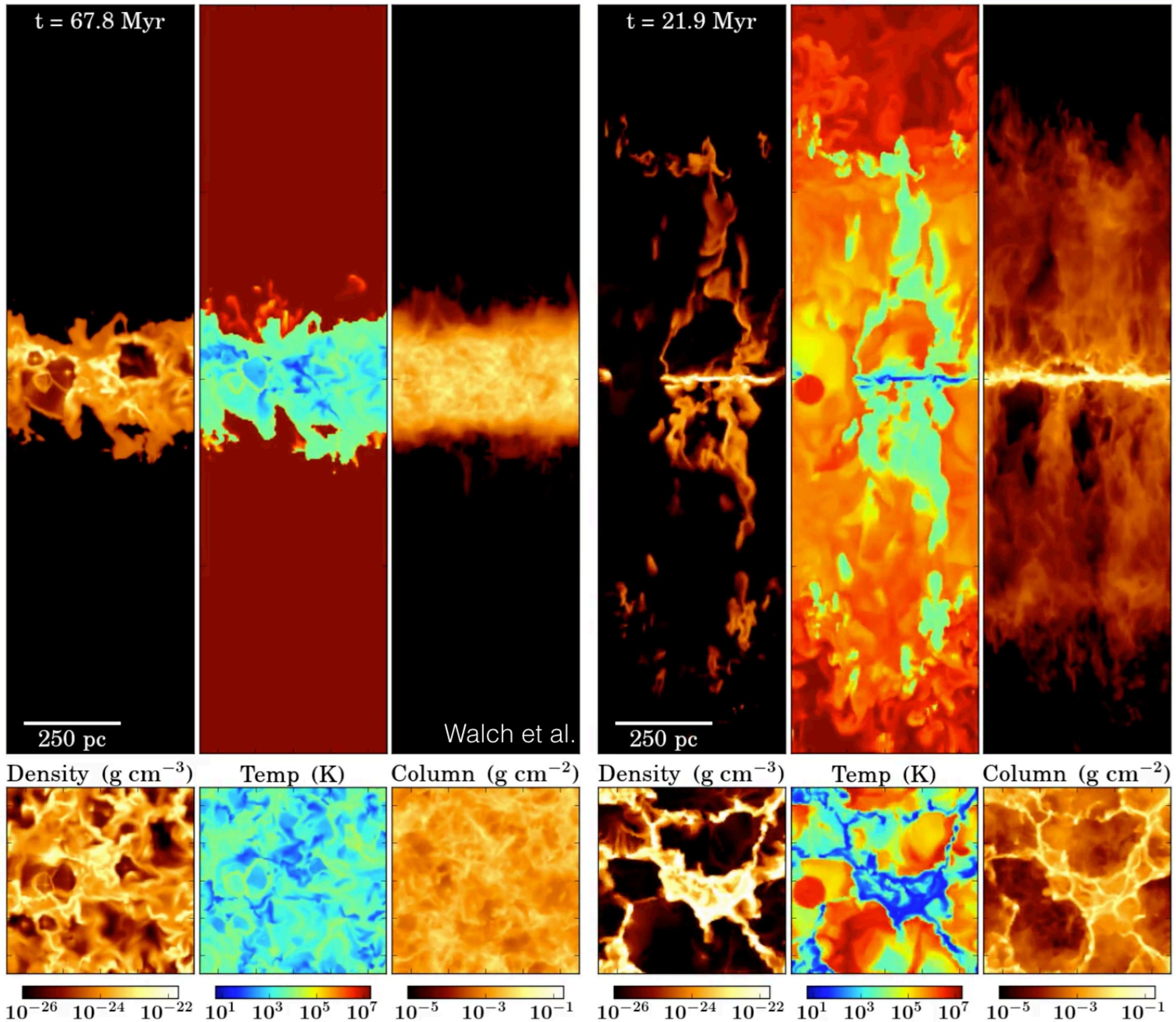
SN clustering is critical: need realistic ISM/SF model

SNe explode in peaks



SNe clustered & explode off-peak

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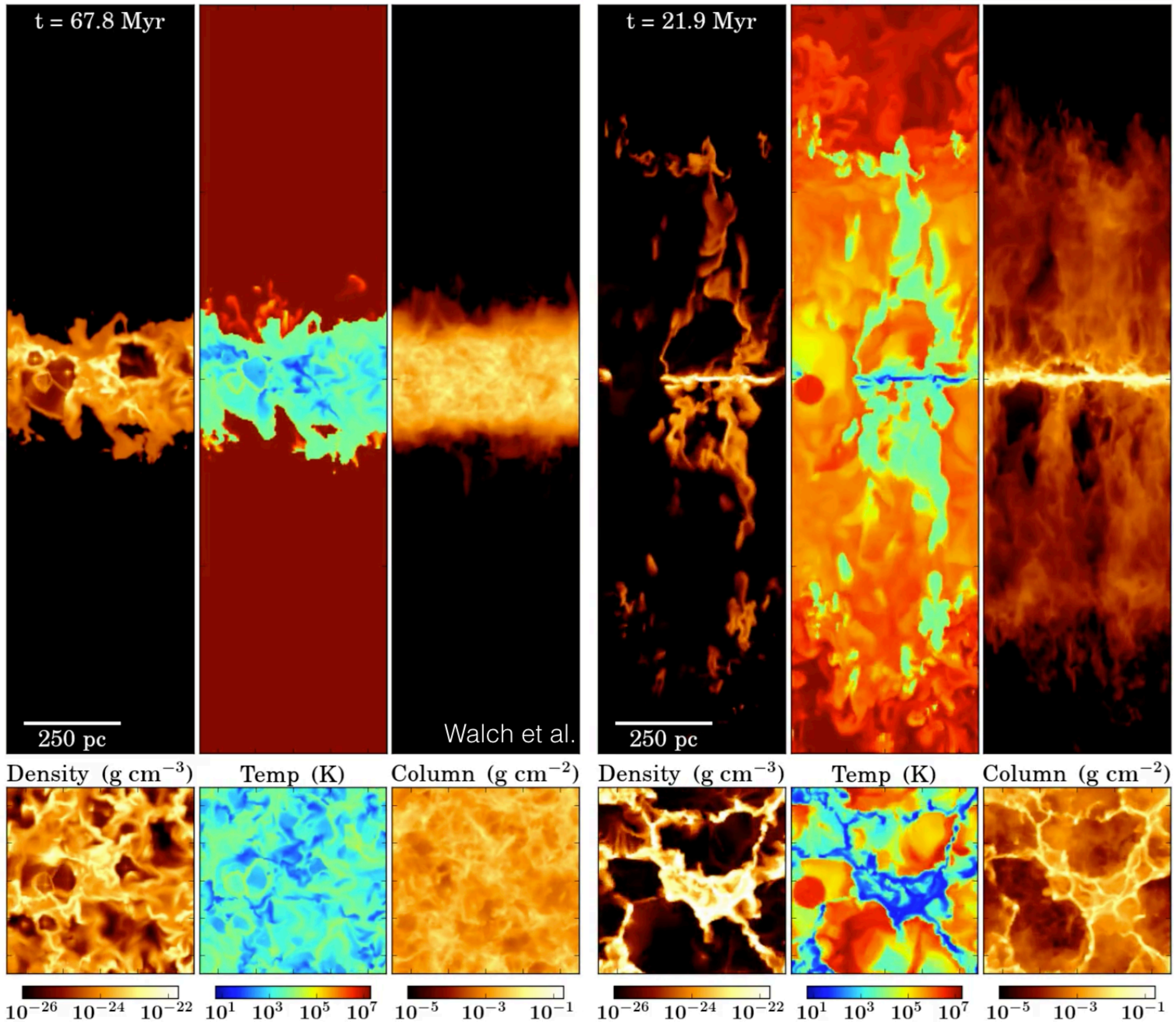
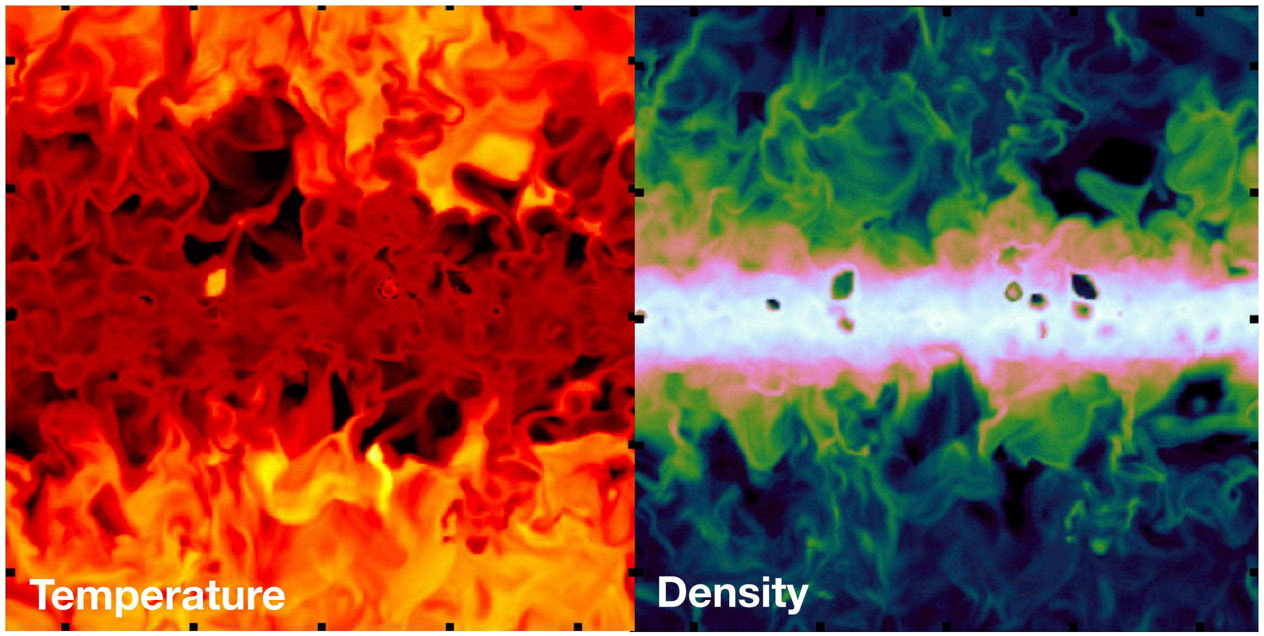


SNe clustered & explode off-peak

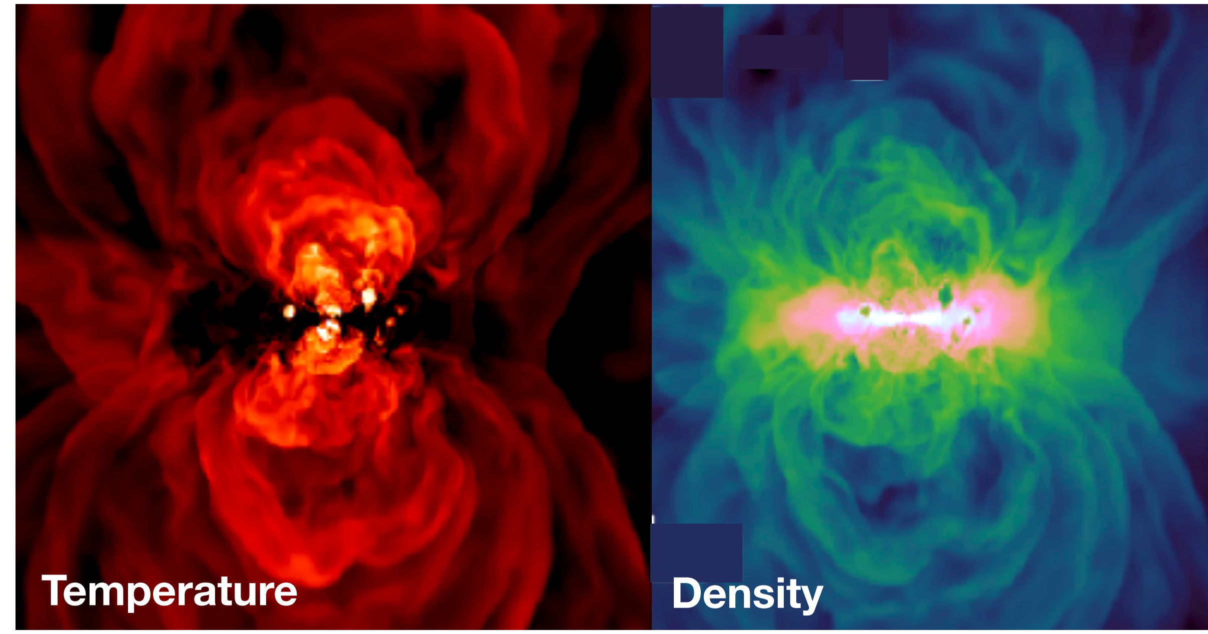
➔ same algorithm for injecting SN energy/momentum will produce very different results in simulations with “pressurized” subgrid ISM than in simulations with multiphase ISM shaped by gravity, cooling, local feedback, …

Local vs. global simulations

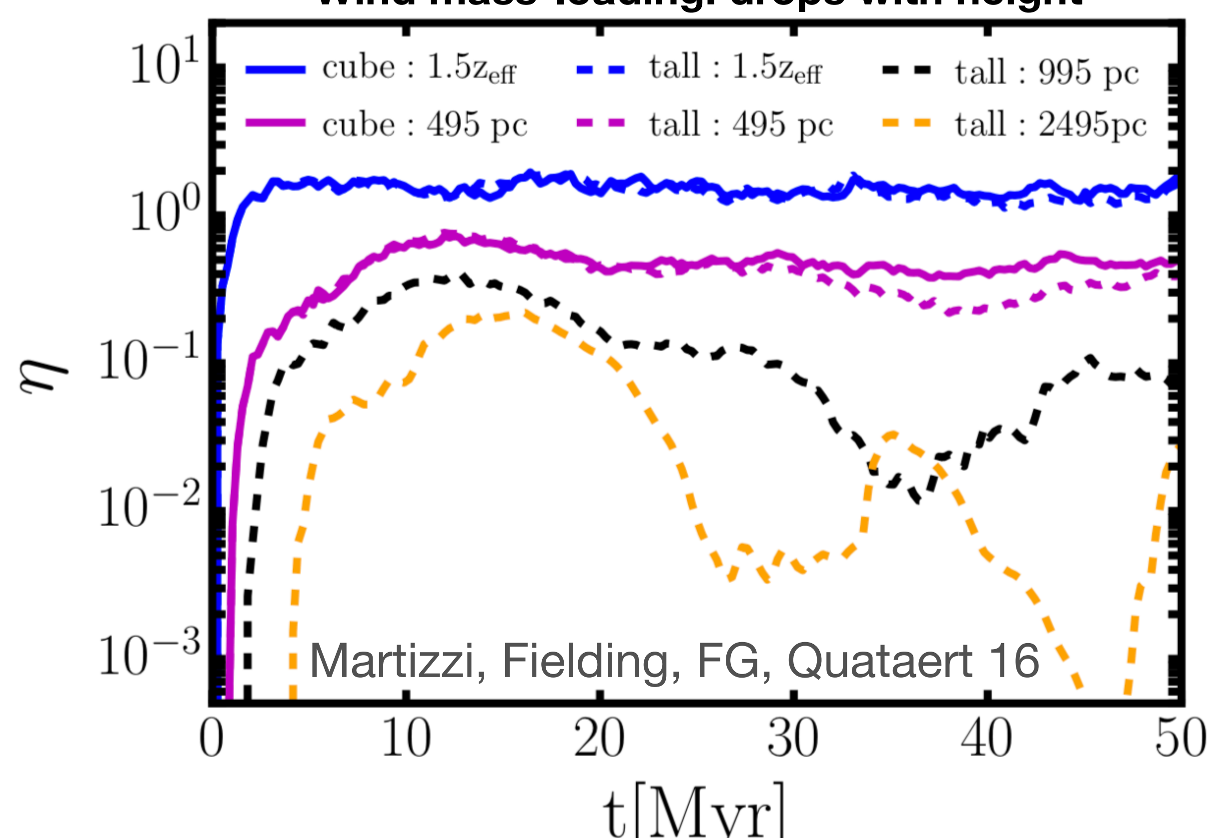
Local vertically stratified box



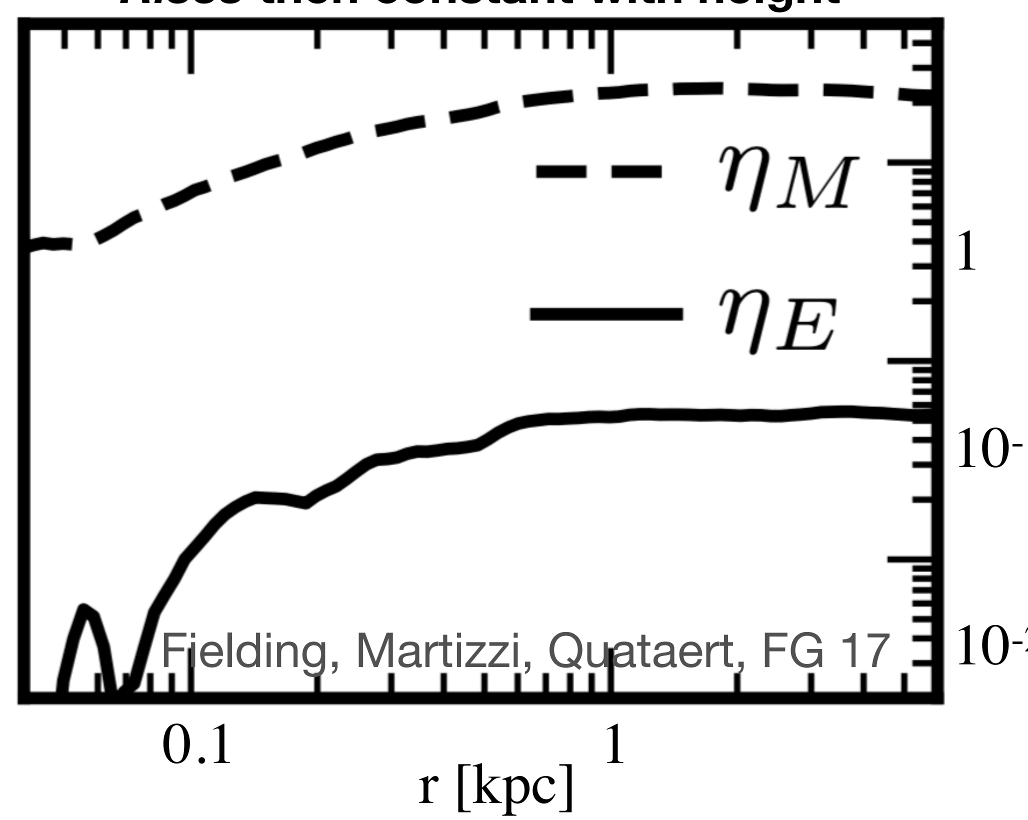
Global disk simulation



Wind mass-loading: drops with height



***Rises* then constant with height**



identical SN physics and disk properties

Local vs. global simulations

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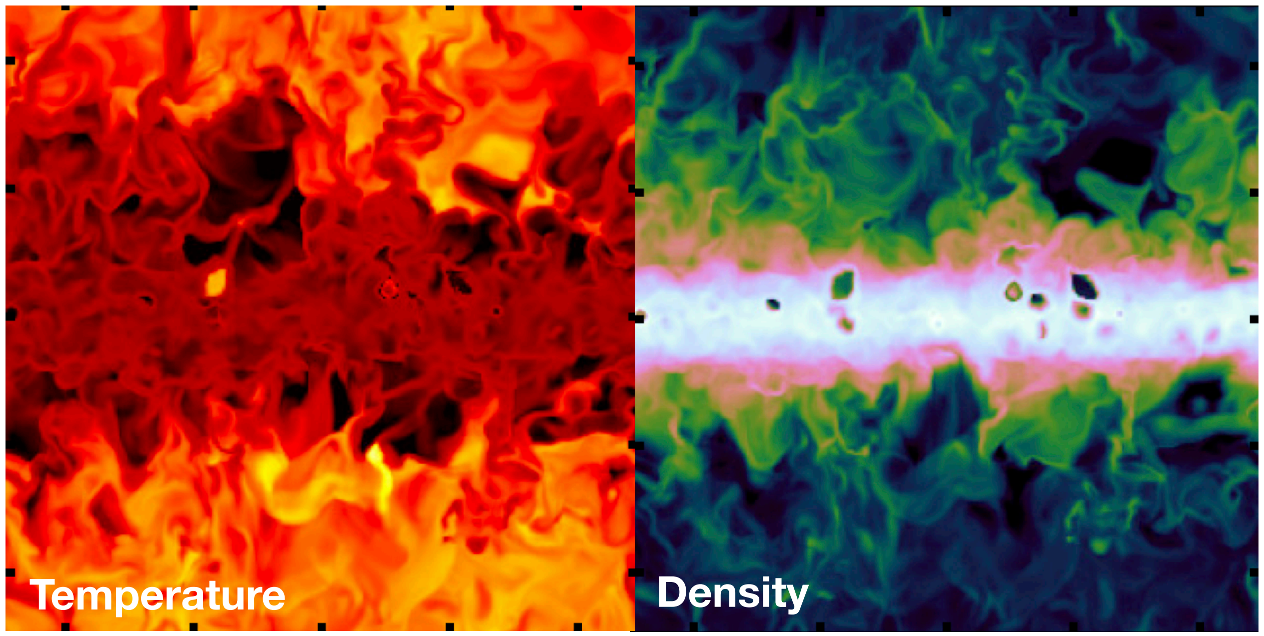

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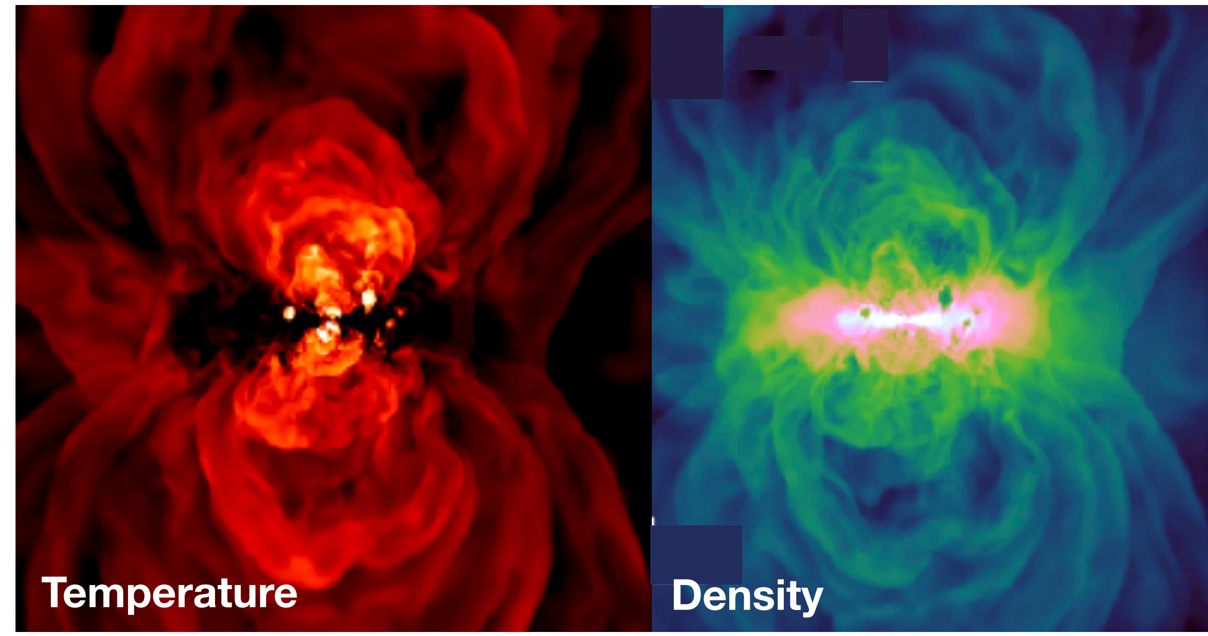

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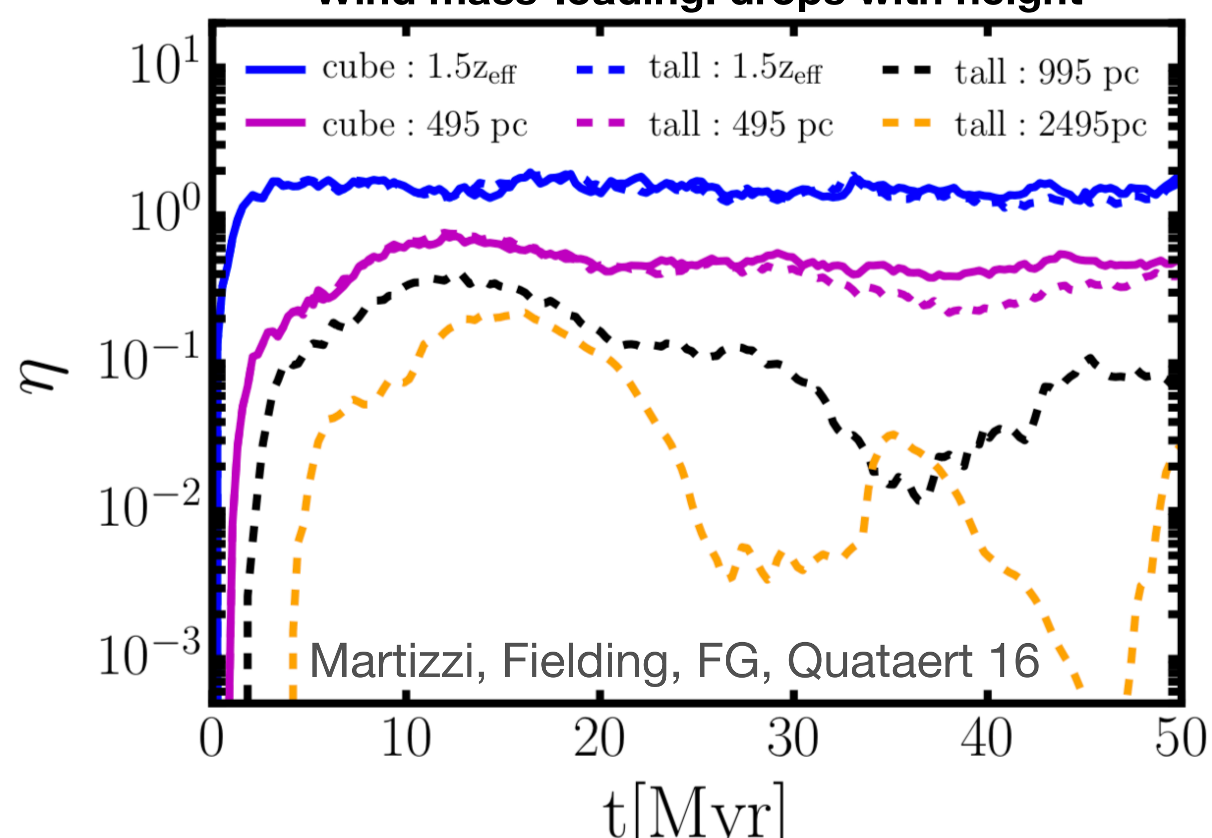

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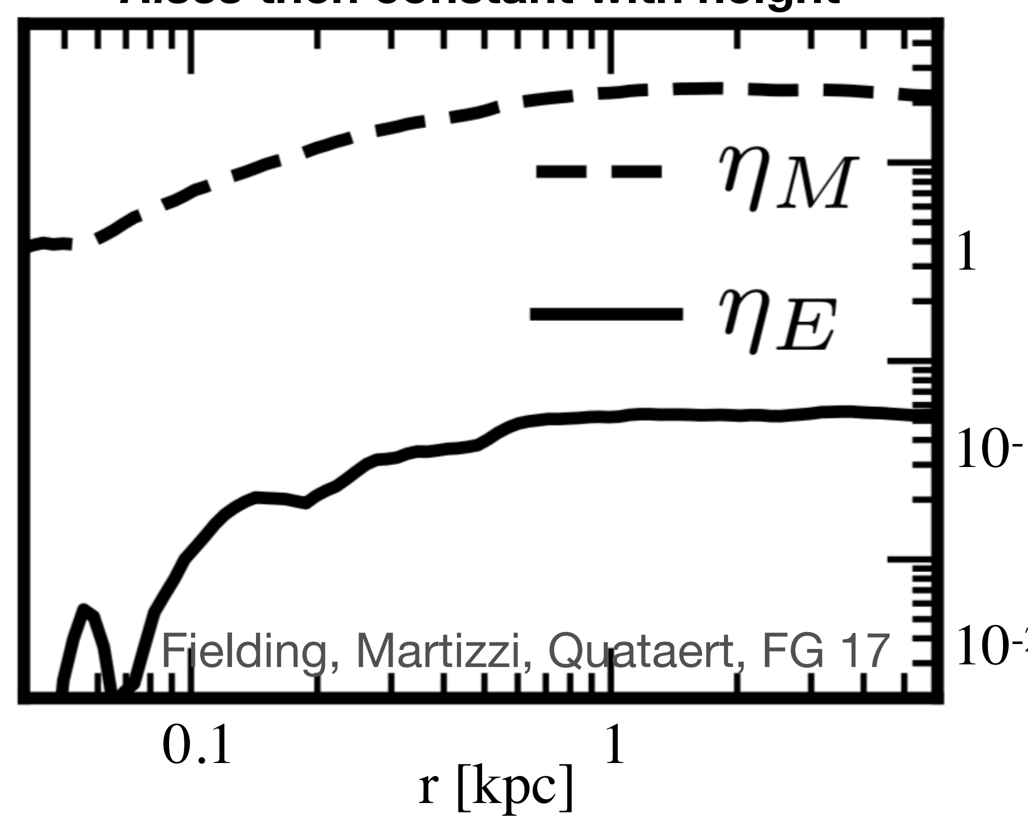
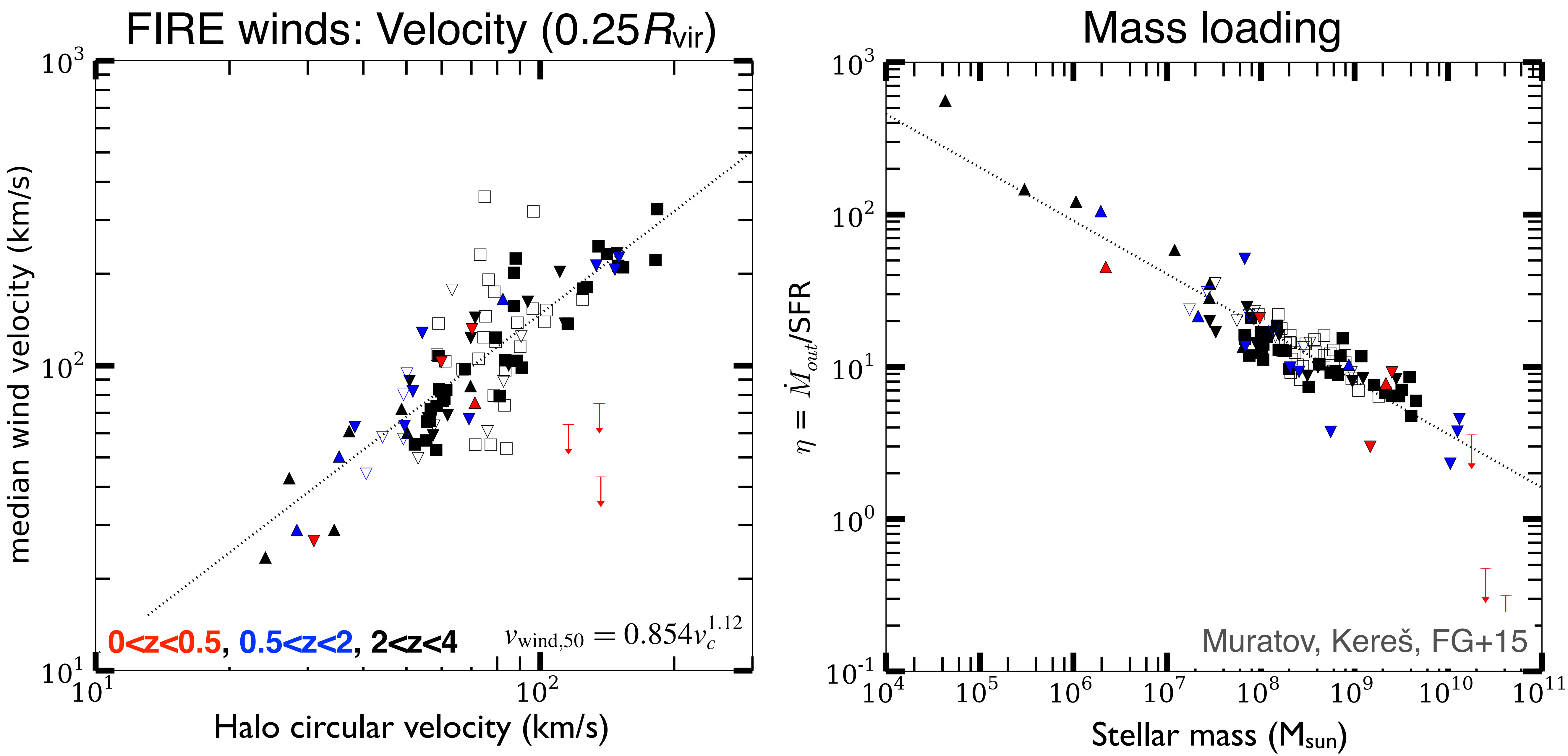


identical SN physics and disk properties

➔ BCs of local (high-res) models can make qualitative difference for large-scale outcome

Cosmological zoom-in simulation

only technique that can presently simultaneously model SN clustering, multiphase ISM, “correct” ICs/BCs — use to predict galactic wind properties

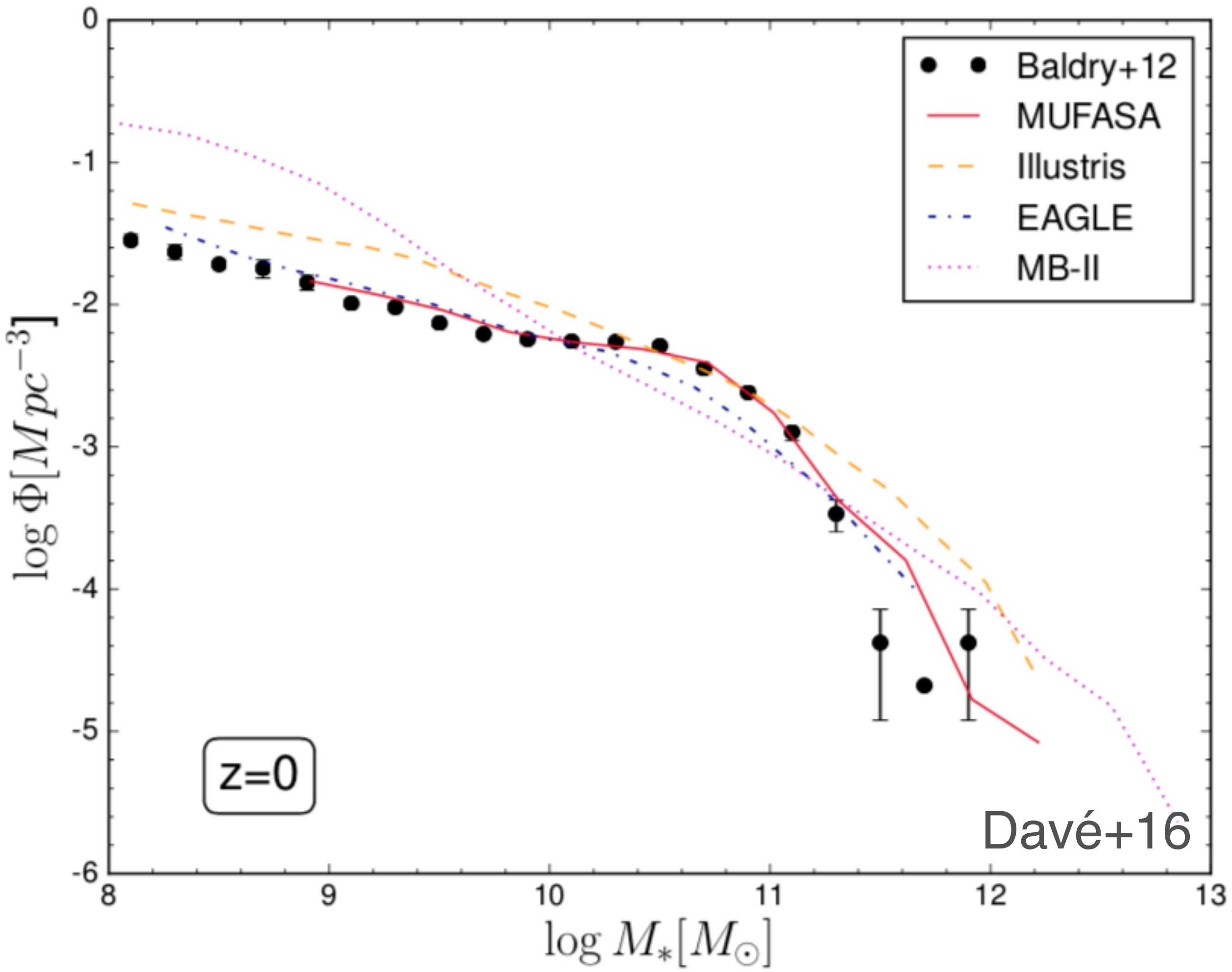


Main limitations: relatively small samples, usually don’t cover all important environments (e.g., groups and clusters), don’t always resolve hot phase

Going to full cosmological volumes: MUFASA

Uses FIRE scalings to set velocity and mass loading for “hydrodynamically decoupled” kinetic winds

➔ excellent match to observed GSMF



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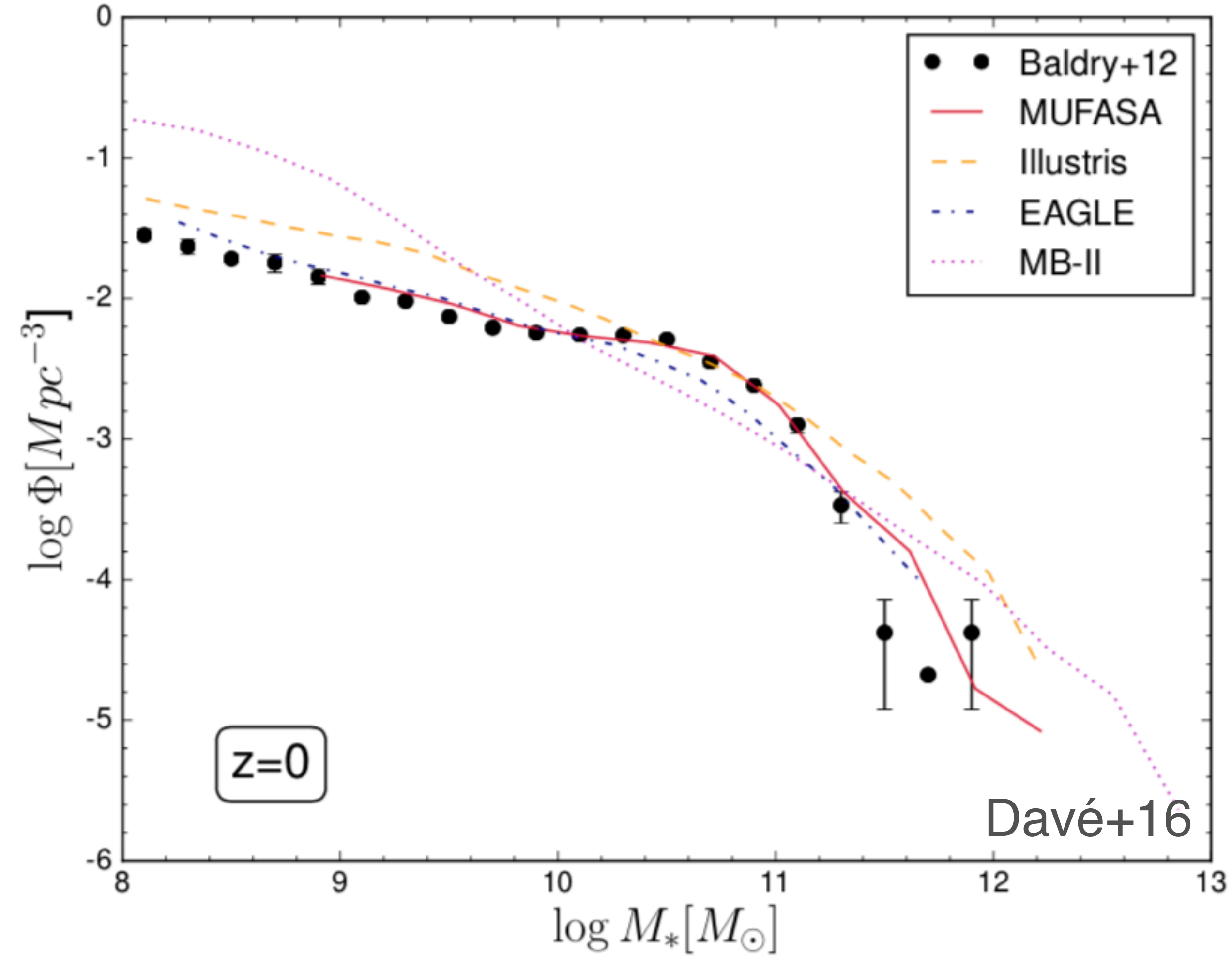
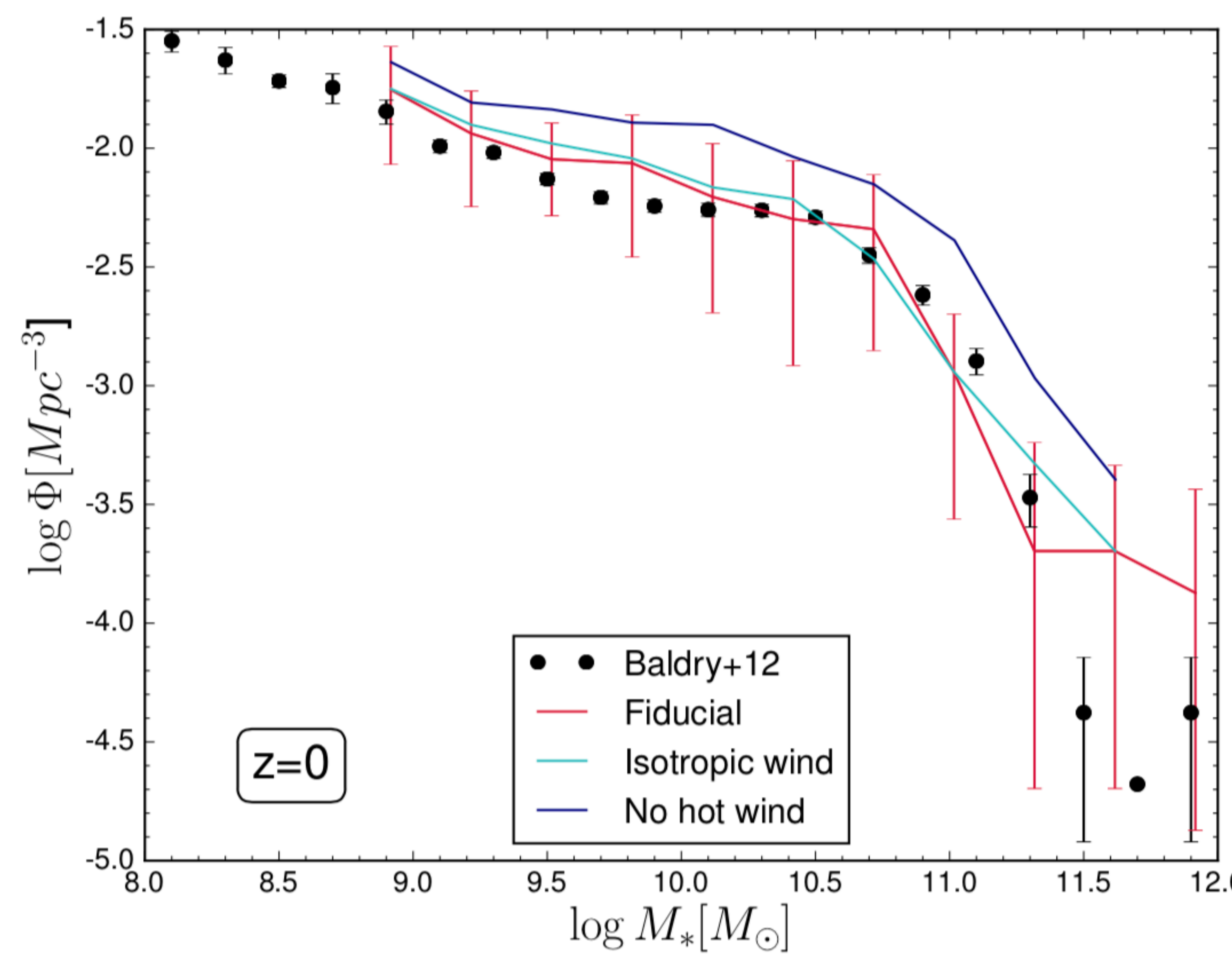


But, this required some tweaking/ augmenting of the FIRE scalings:

- adjust $v_{\rm wind}$ to account for the fact that MUFASA winds are launched at $R<R_{\rm FIRE}$
- include ‘hot’ wind component



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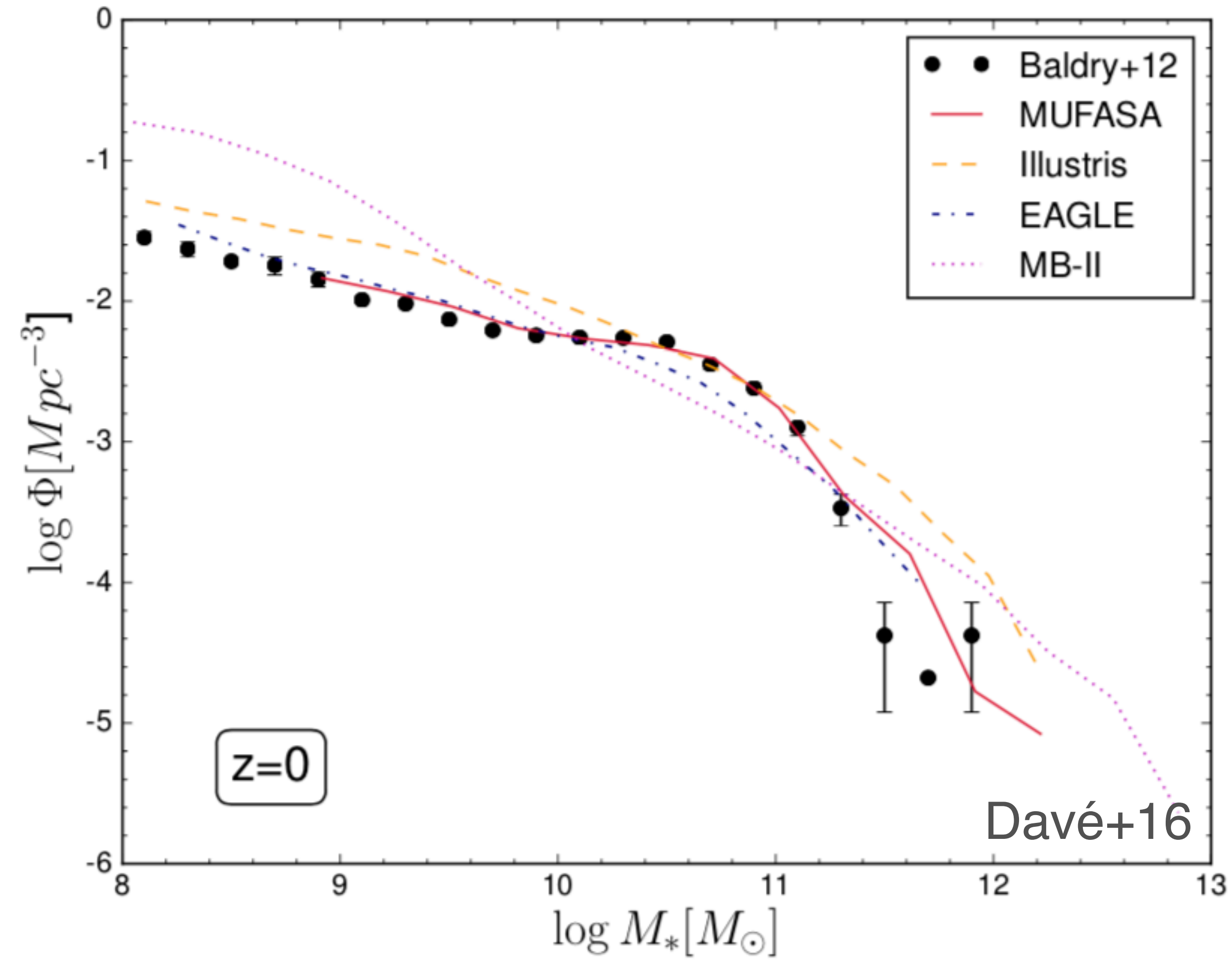

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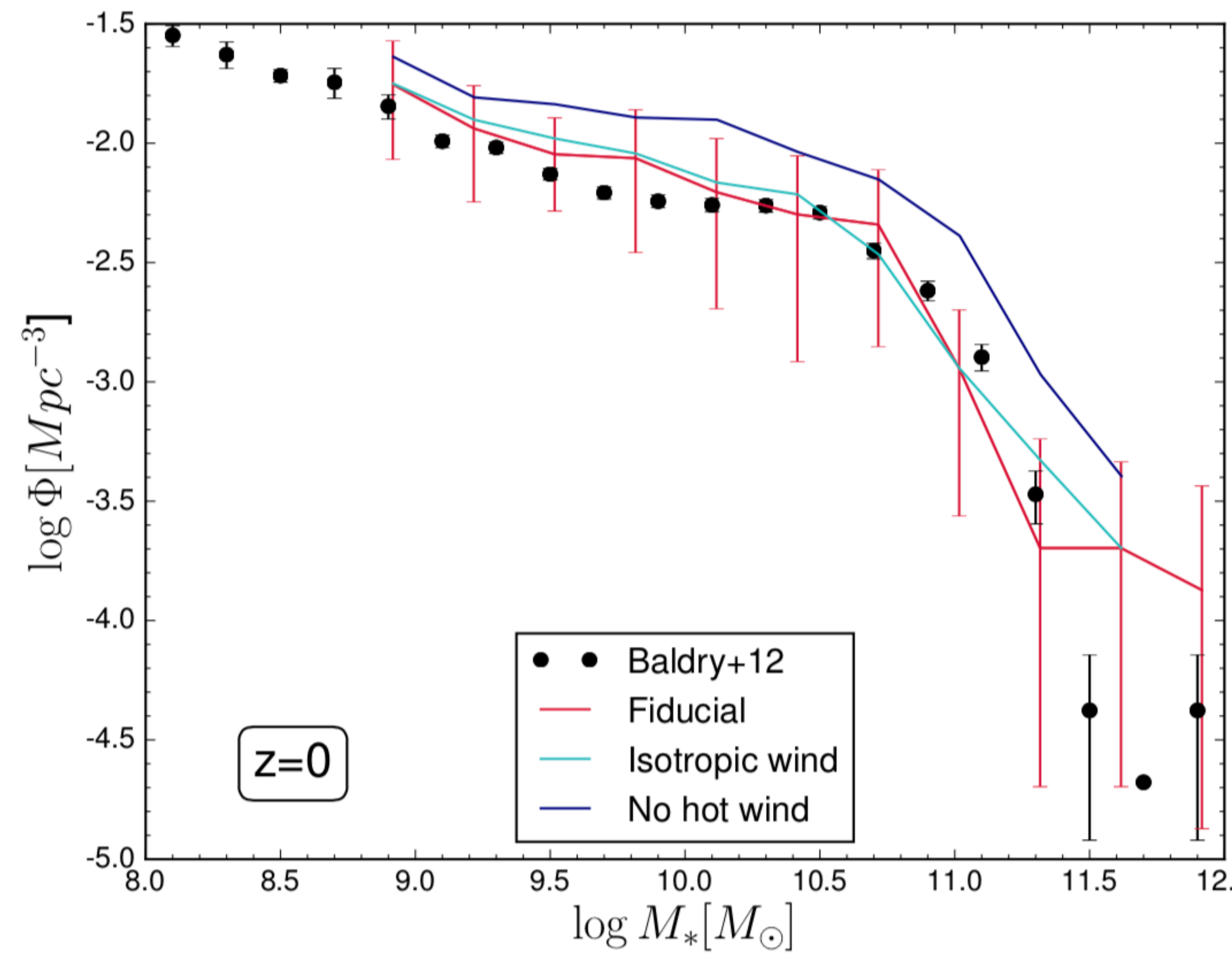

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Some other limitations:

- does not capture full velocity, density, temperature distributions of the zooms
- does not capture wind time variability

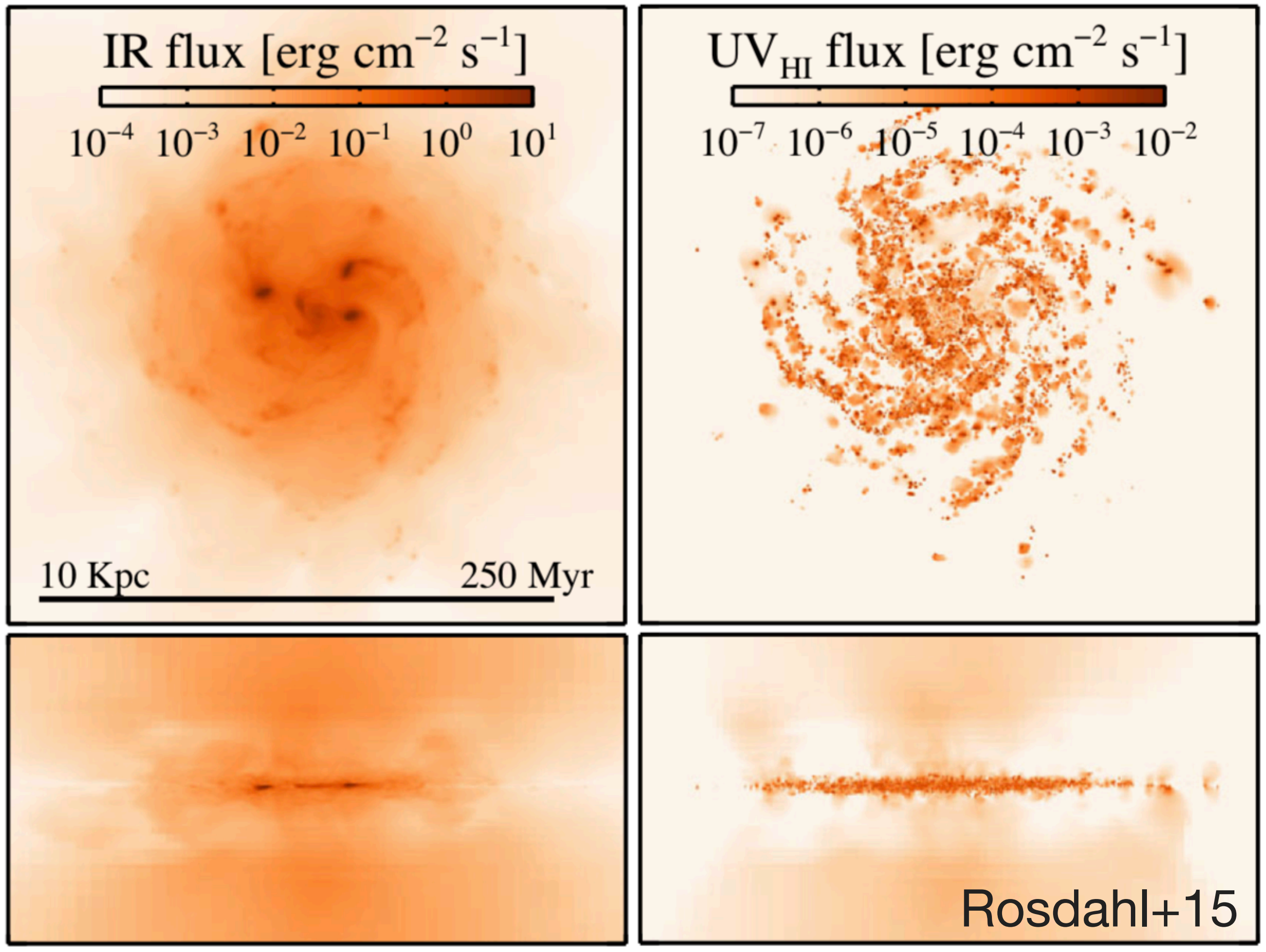
Subgrid models for radiation and CRs?

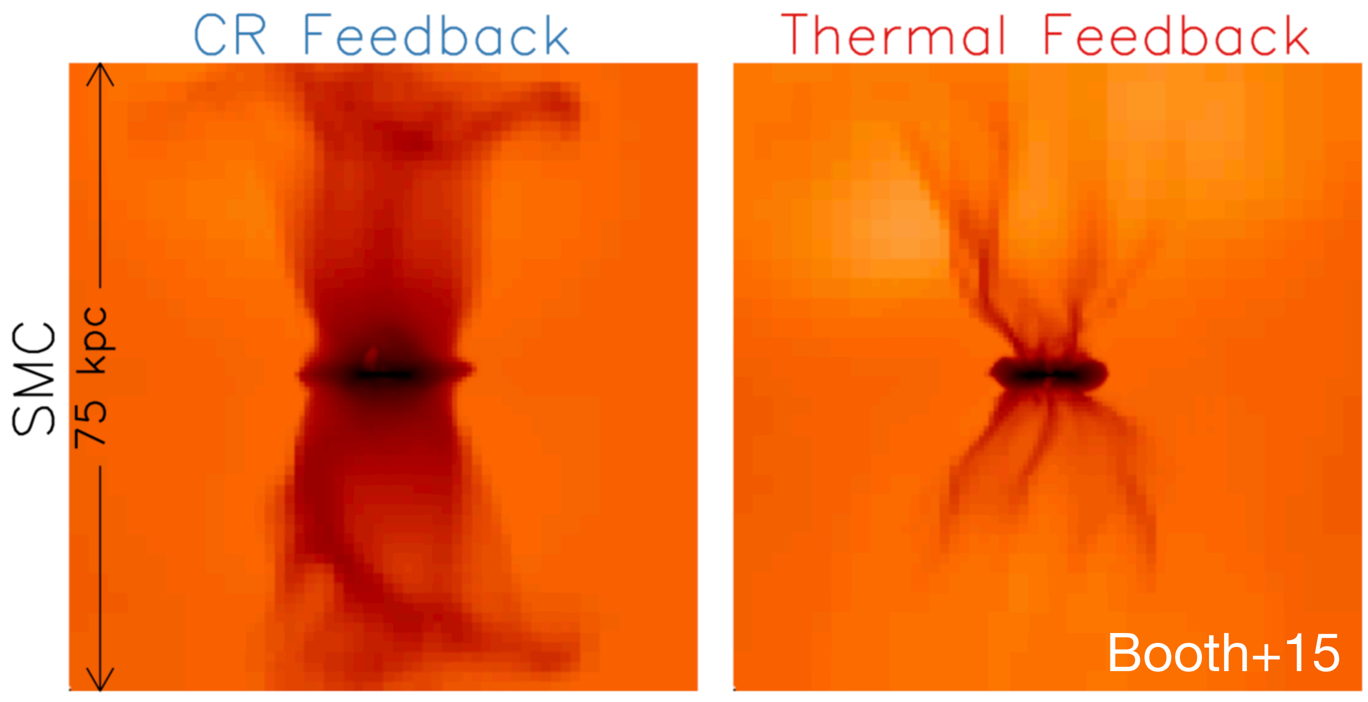
For SNe, some success in developing “resolution-stable“ subgrid model

Can we do the same for other feedback processes?

I.e., capture correct macro results without doing full transport, e.g. at ~100 pc-1 kpc resolution in pure hydro codes

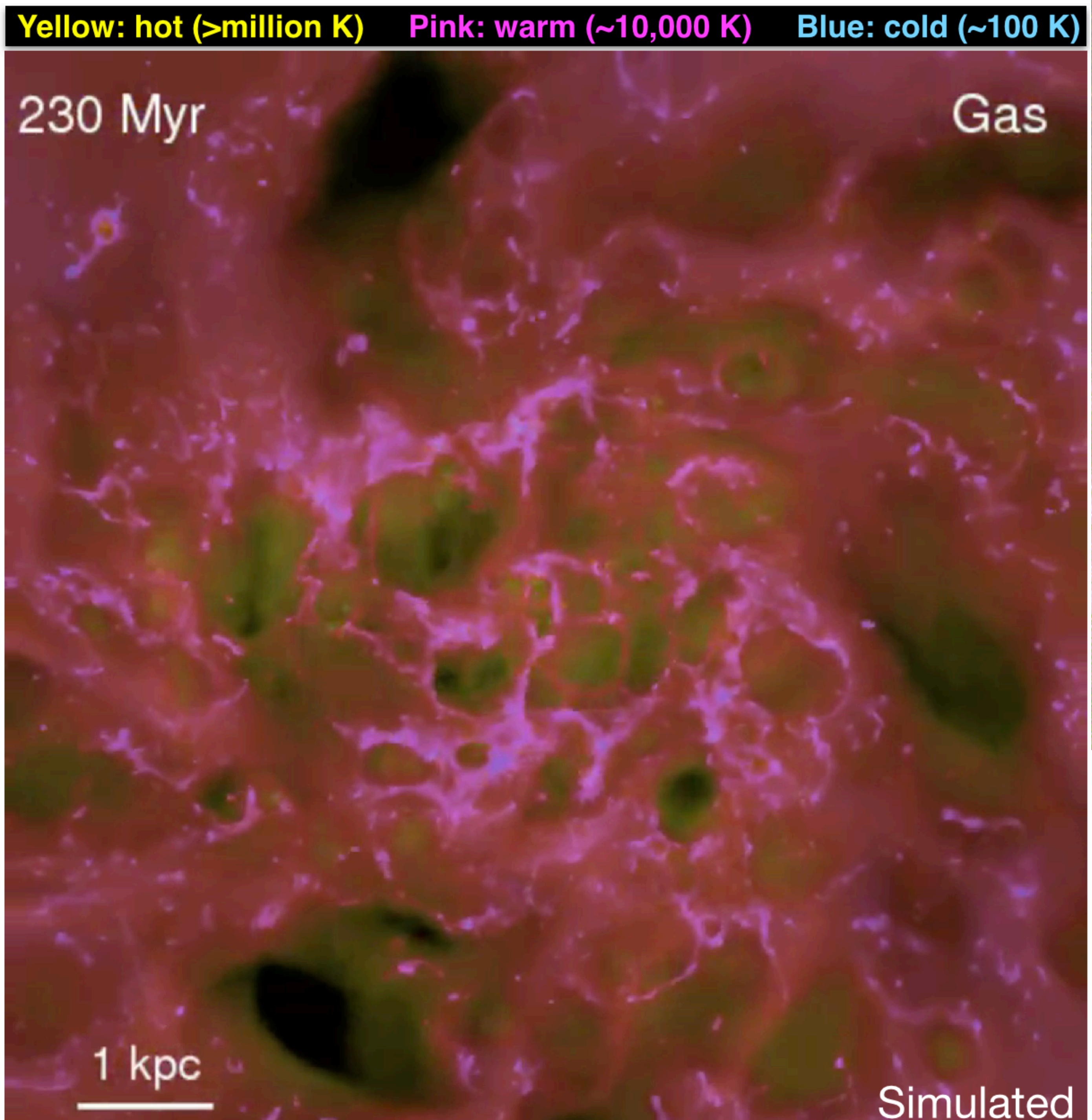
R. Kannan (this morning) suggested SN-like model including rad. in $P_{\rm terminal}$

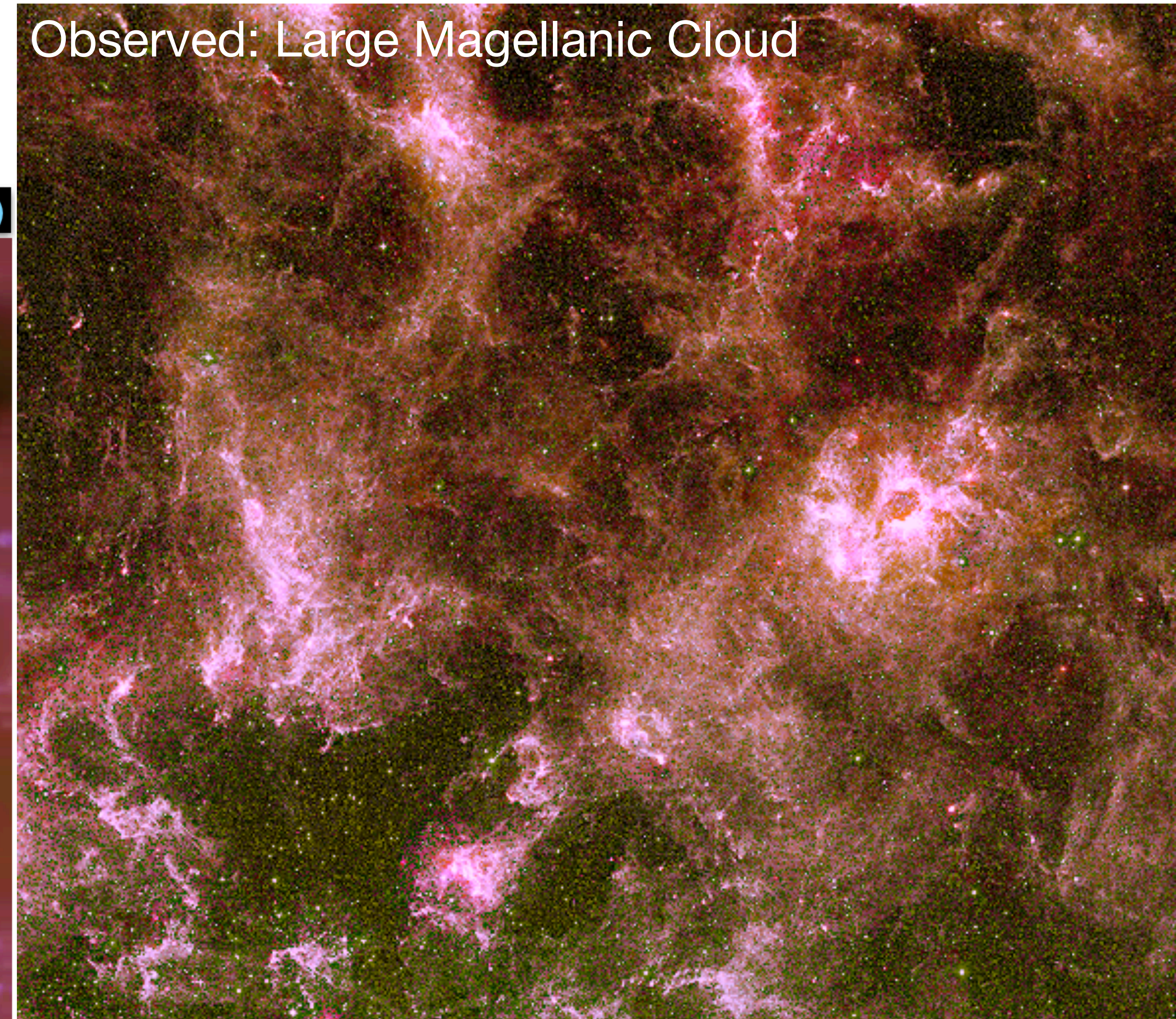




Where should we start from? Lots of ISM physics!

if we are to "coarse grain" physics from the bottom up, what scales do we need to start with in order to get correct "macro" results?





- Gravity & cool/chemistry
- Turbulence (Mach~10-100)
- Magnetic fields
- Cosmic rays
- Radiation & winds from stars
- Supernovae

Other questions

1. Is there a better, more well-defined approach to coarse graining galaxy formation?

2. "Natural divides for subgrid models" (introduced by V. Springel yesterday). E.g., stellar evolution, molecular clouds. What are others?

3. What observations would be most helpful in directly informing subgrid models?

4. Are there things we take for granted in galaxy formation that may be wrong? E.g., are SNe really as important as assumed?

5. Are we missing some fundamental ingredients in current theories? Things that observers see but theorists are ignoring.
   [ΛCDM, gravity, cooling, (M)HD, star formation, SNe, stellar winds, radiation, cosmic rays, AGN]

6. What are our metrics for success (what is good enough)?

Other questions #2

7. What about AGN feedback -- does it quench galaxies at the massive end?

Extra slides

Pretty FIRE Galaxies