Subgrid Models for Next-generation Cosmological Simulations of Galaxy Formation

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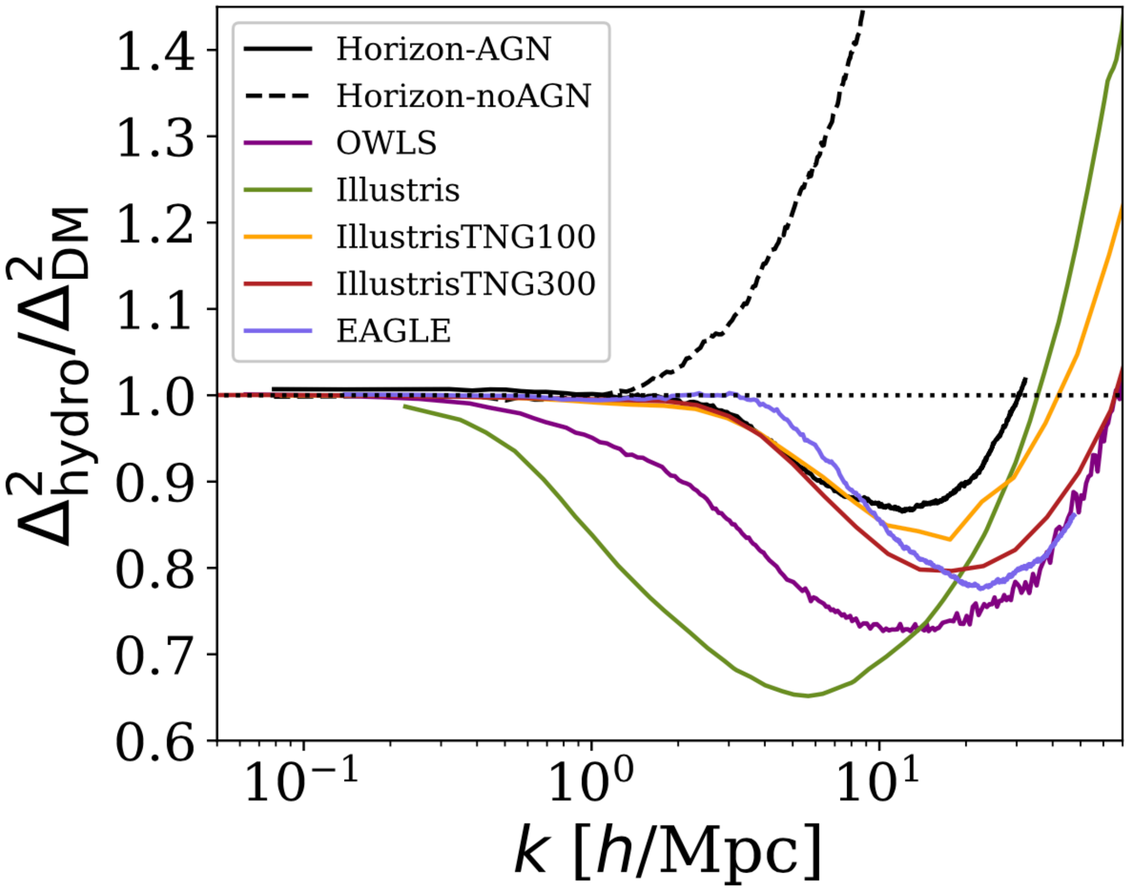
Why Should We Care About Baryonic Physics?

- Predictions for the CMB sufficiently robust
  - Growth of dark matter structure and halo abundance (at least in ΛCDM) relatively well understood via analytical techniques and N-body simulations.
- On small scales ($\lesssim$10 Mpc), baryons cannot be assumed to trace dark matter.
- Crucial to accurately account for baryonic effects to understand
  - Galaxy properties
  - Cosmic shear, spatially resolved X-ray and SZ observations of clusters from upcoming surveys (e.g., Schaye et al. 2023)



Chisari et al. (2018)

Galaxy formation is challenging due to its intrinsic multiphysics character

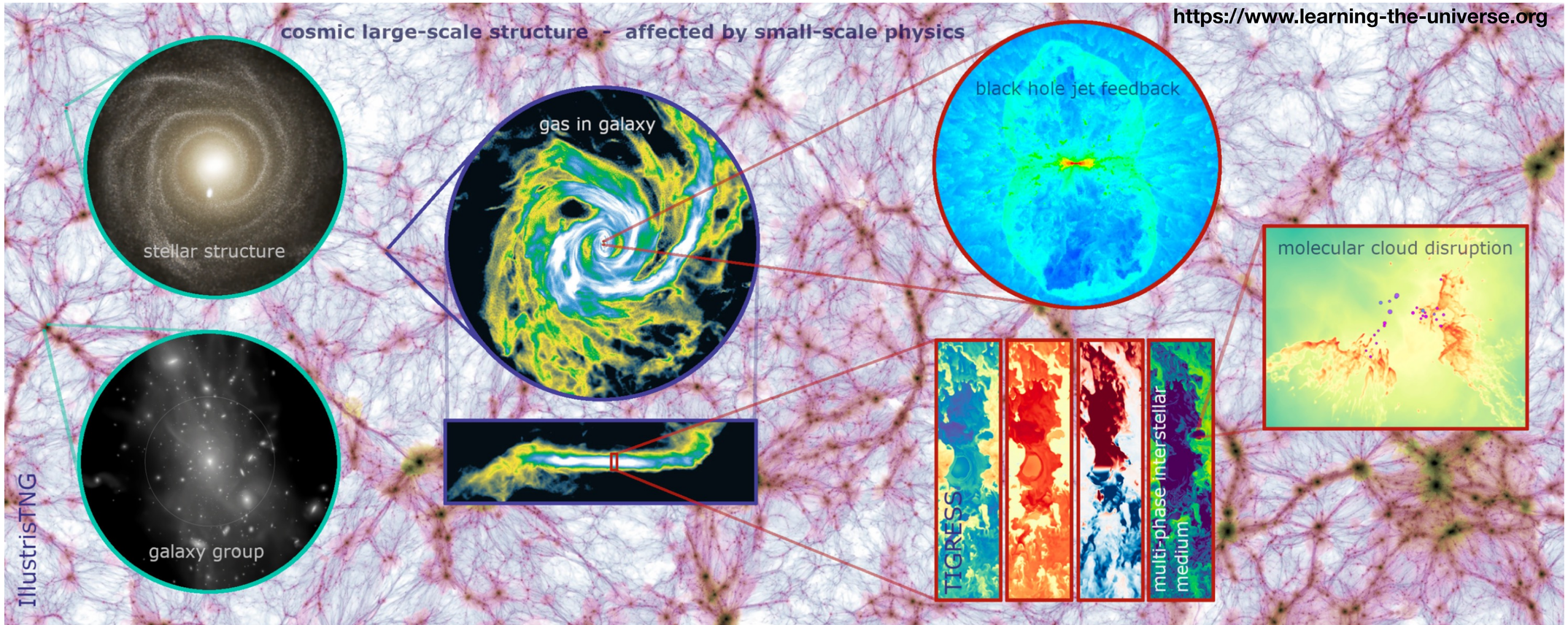
Most important astrophysical processes

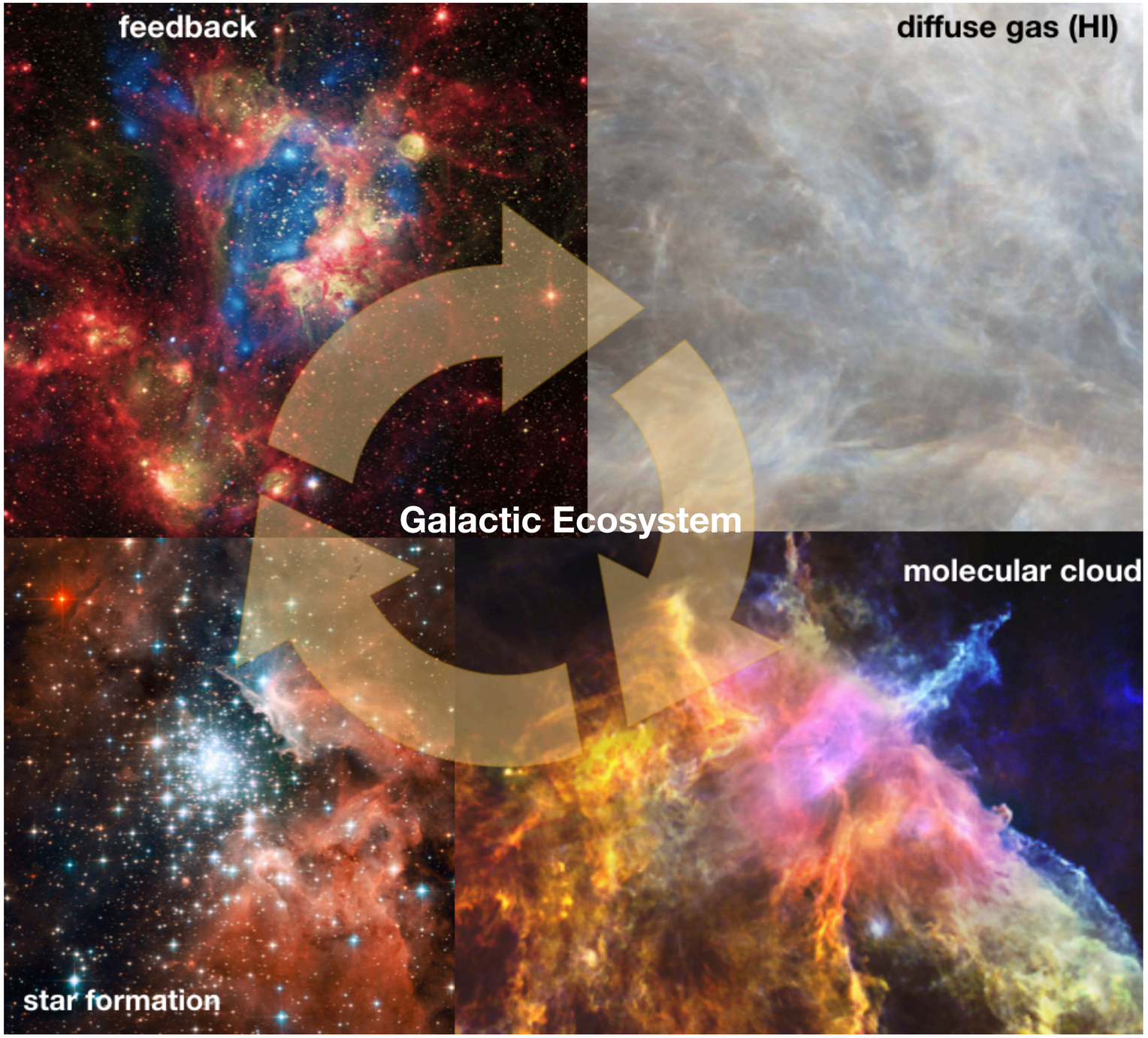
Gas cooling	Interstellar medium	Star formation	Stellar feedback	Supermassive black holes	Active galactic nuclei	Magnetic fields	Radiation fields	Cosmic rays
Atomic/ molecular/ metals/ tabulated network	Effective equation of state/ multiphase	Initial stellar mass function/ probabilistic sampling/ enrichment	Kinetic/ thermal/ variety of sources from stars, supernovae	Numerical seeding/ growth by accretion prescription/ merging	Kinetic/ thermal/ radiative/ quasar model radio mode	Ideal MHD/ cleaning schemes/ constrained transport	Ray tracing/ Monte Carlo/ moment based	Production/ heating/ anisotropic diffusion/ streaming

Vogelsberger et al. (2020)

Importance of Feedback

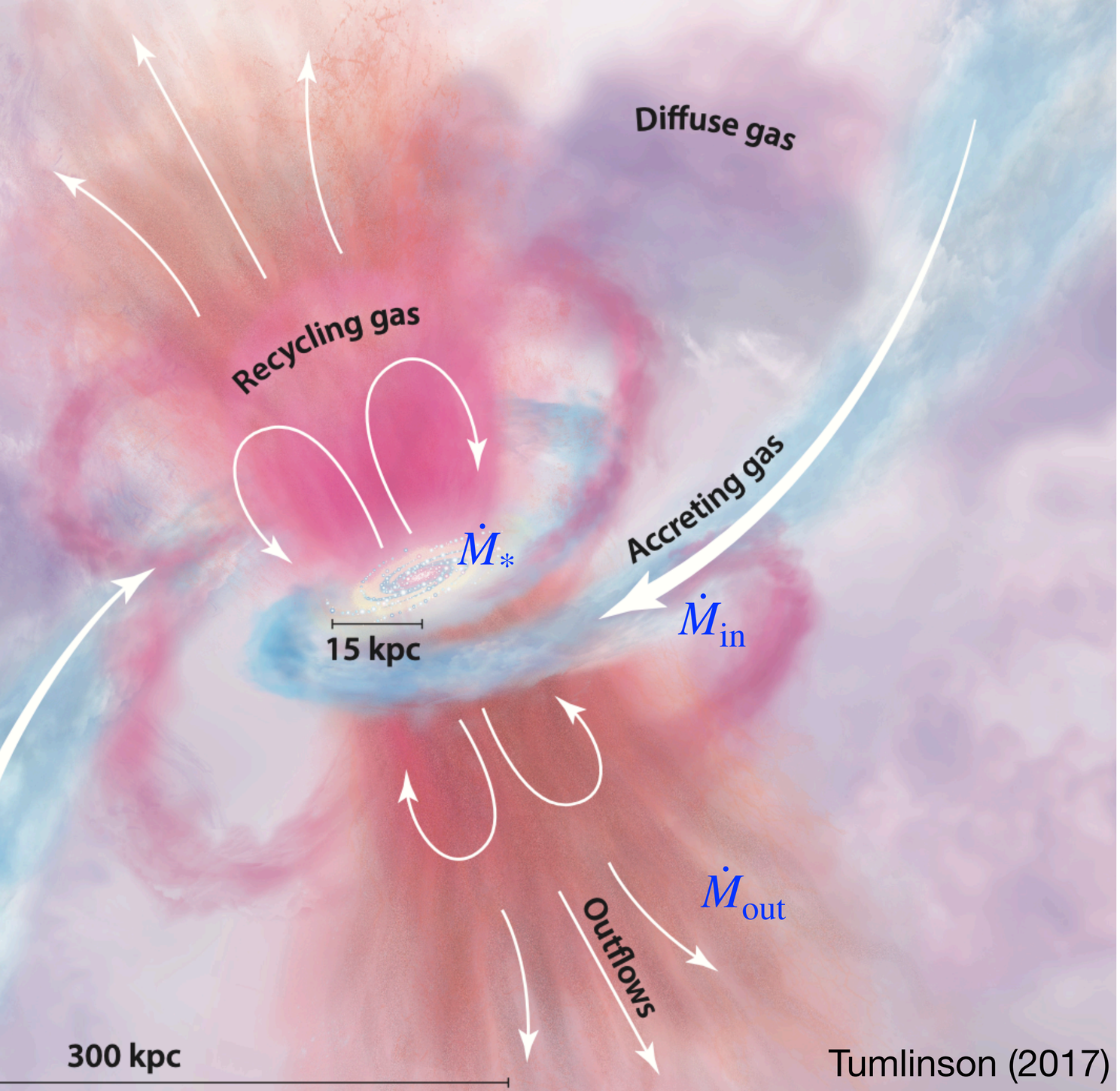
- Arguably the single most important lesson in the last ~30 years of understanding the origin of structure in the universe…**stars and massive black holes, dramatically alters how most other astronomical objects form**."
  - ASTRO2020 White Paper
- Energy produced by stars vs. BHs comparable: $E_*/E_{\rm BH} \sim \dfrac{(\epsilon_{\rm nuc}/10^{-4})}{(\epsilon_{\rm BH}/0.1)} \times \left(\dfrac{1/10^3}{M_{\rm BH}/M_*} \right)$





Role of (Stellar) Feedback

- **Regulation of multiphase structure and star formation rate within ISM**
- $\dot{M}_* \ll M_{\rm gas}/t_{\rm dyn}$
- Reduces star formation efficiency by
  - Turbulence driving by SNe (balanced by dissipation)
  - Heating by UV radiation (balanced by cooling)



Tumlinson (2017)

Role of Outflow Feedback

- $\dot{M}_{\rm ISM} = \dot{M}_{\rm in} - \dot{M}_* - \dot{M}_{\rm out}$
- **Ejective feedback**

  Reduces the available reservoir of star-forming material and enriches the circumgalactic medium (CGM)

  $\dot{M}_{\rm out} = \eta_M \dot{M}_*$

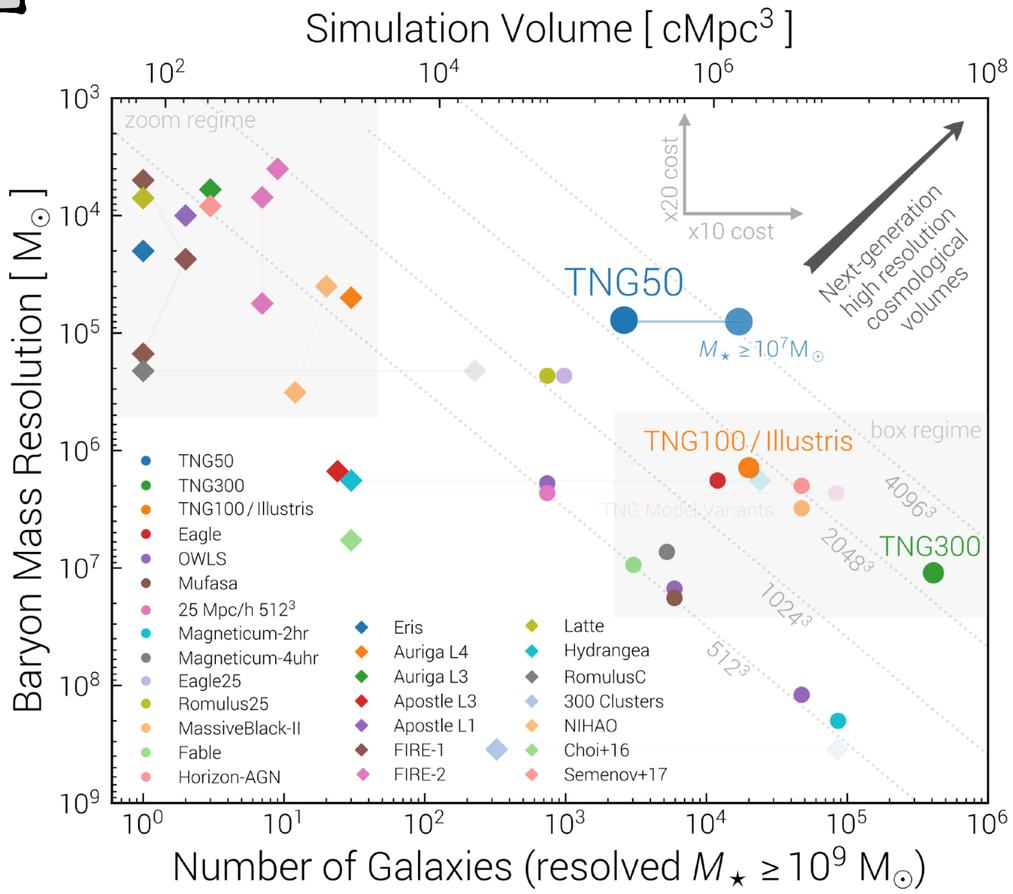
  adopted by most existing cosmological simulations to reproduce galaxy observables

- **Fundamental question**: how does the mass loading factor $\eta_{\rm M}$ in different thermal phases change with galactic conditions?

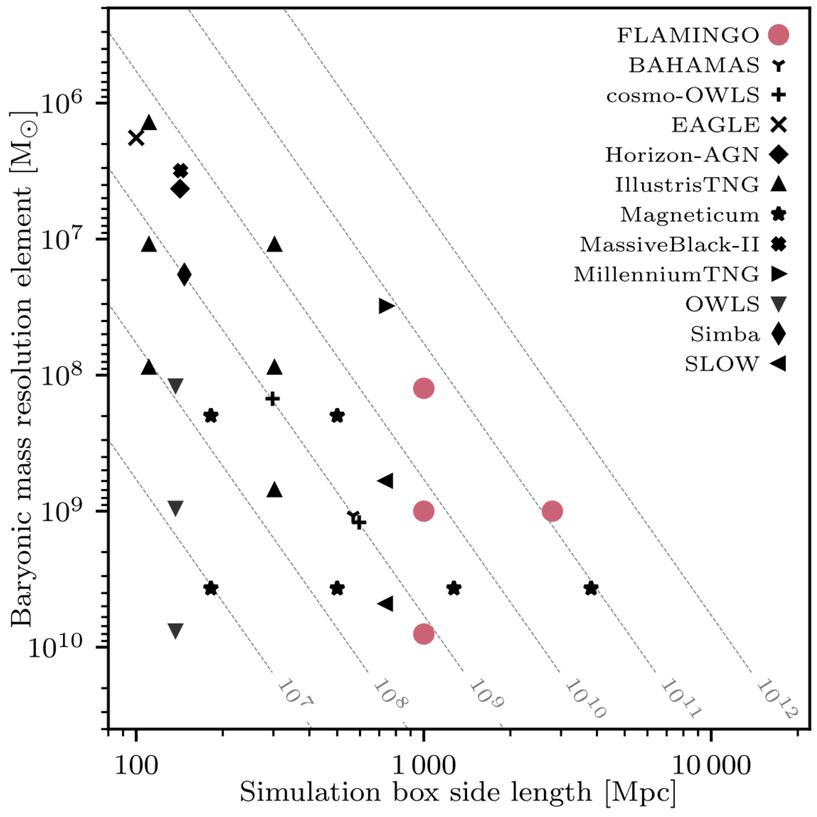
Resolution is the Elephant in the Room

- Large-volume cosmological simulations of galaxy formation are forced to adopt subgrid models for small-scale baryonic processes.

Resolved ISM Sims (TIGRESS)



Nelson et al. (2019)

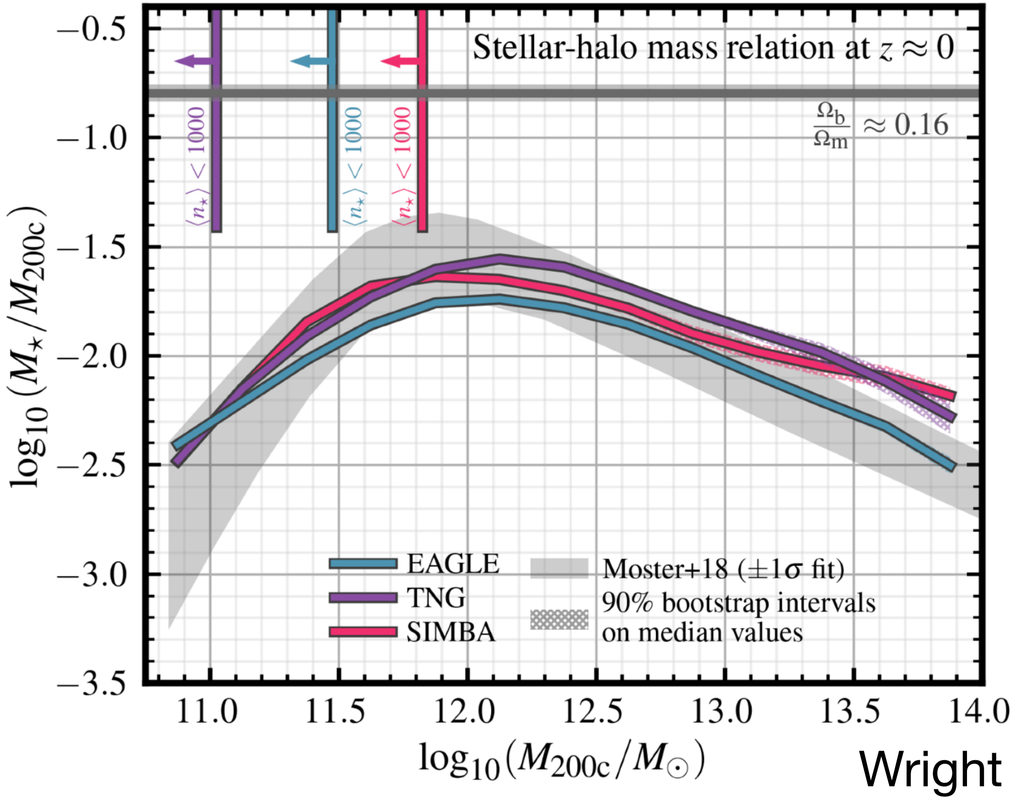


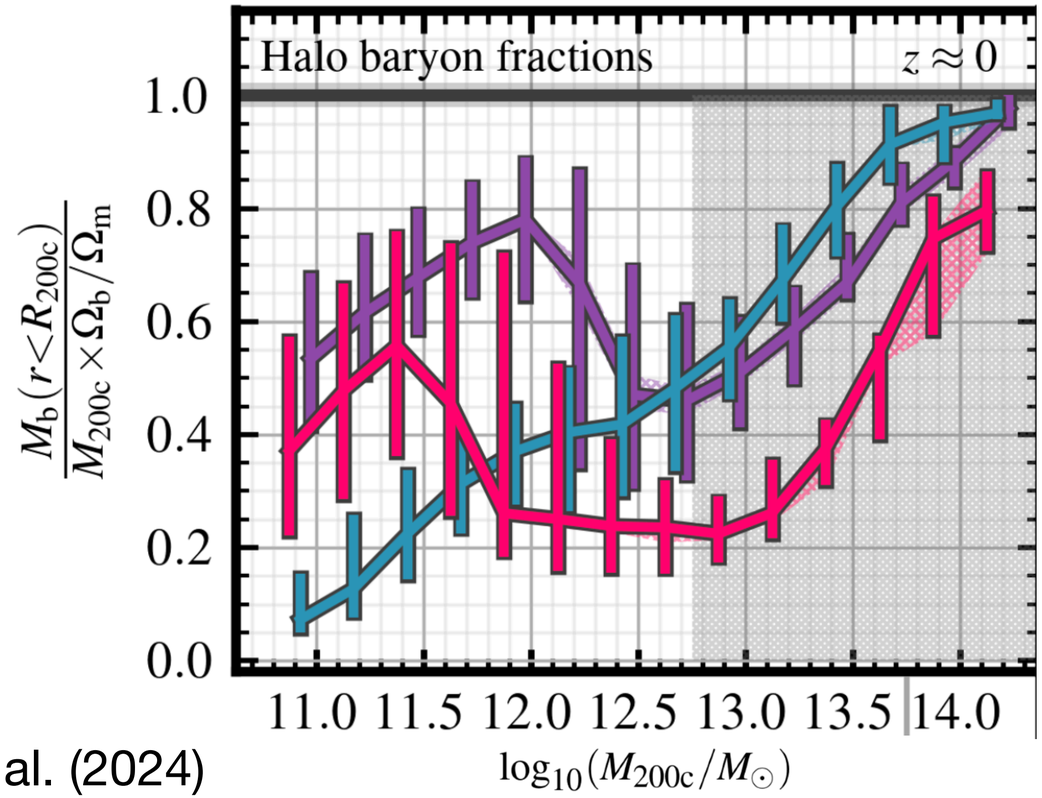
Schaye et al. (2023)

Subgrid models: Major Source of Uncertainty in Galaxy Formation Theory

- Subgrid models are **empirical** (e.g., star formation rate; wind velocity); free parameters tuned to match global observations; limited predictive power (Crain & van de Voort 2023)
- Different choices of sub-grid recipes may lead to different predictions.
- We could **get the right answer for the wrong reasons** for quantities that were not calibrated.

Need to learn from small-scale simulations that resolve key physical processes
→ physics-based subgrid models

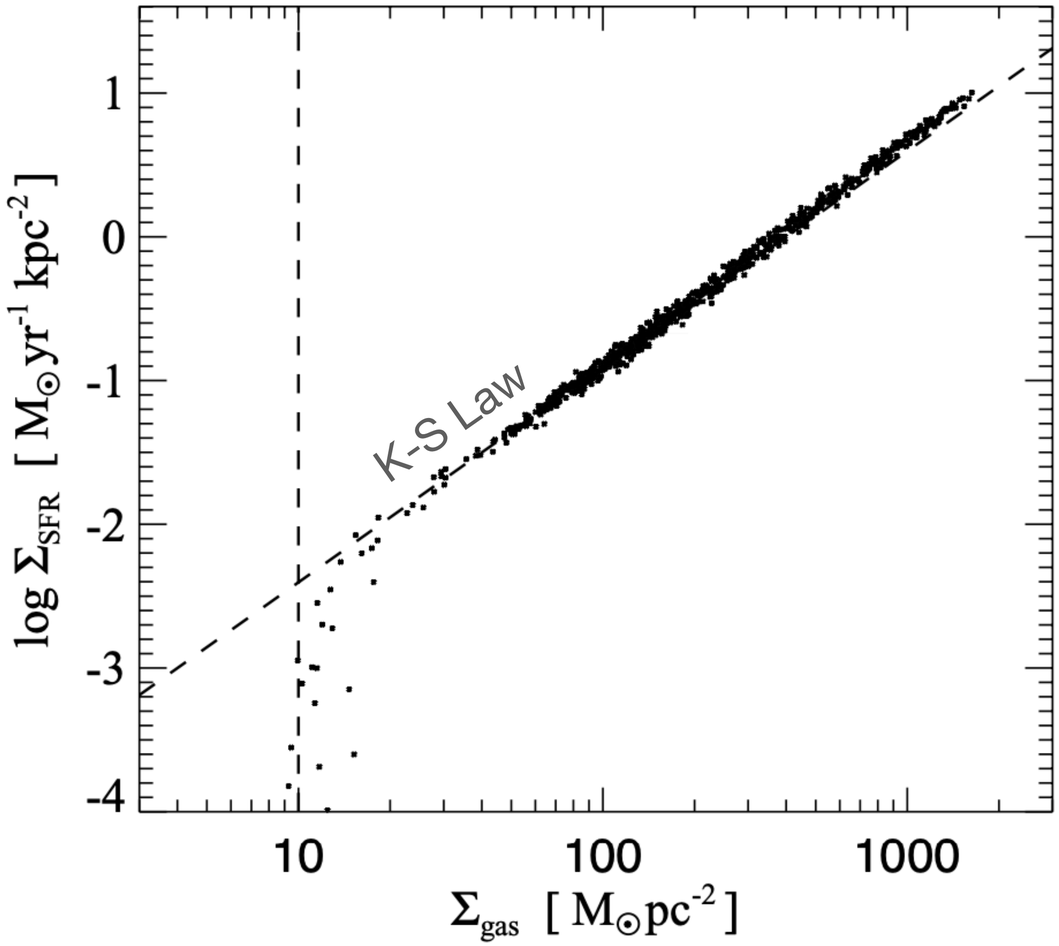




Wright et al. (2024)

Star Formation Prescription Example

- In the Illustris/IllustrisTNG, the star formation timescale t_* follows a free-fall scaling with gas density: $\dot{m}_g = (1-\beta) m_g / t_*$ with $t_*(\rho) \approx 2.2\,\mathrm{Gyr}\,(\rho/0.1\,\mathrm{cm}^{-1})^{-1/2}$



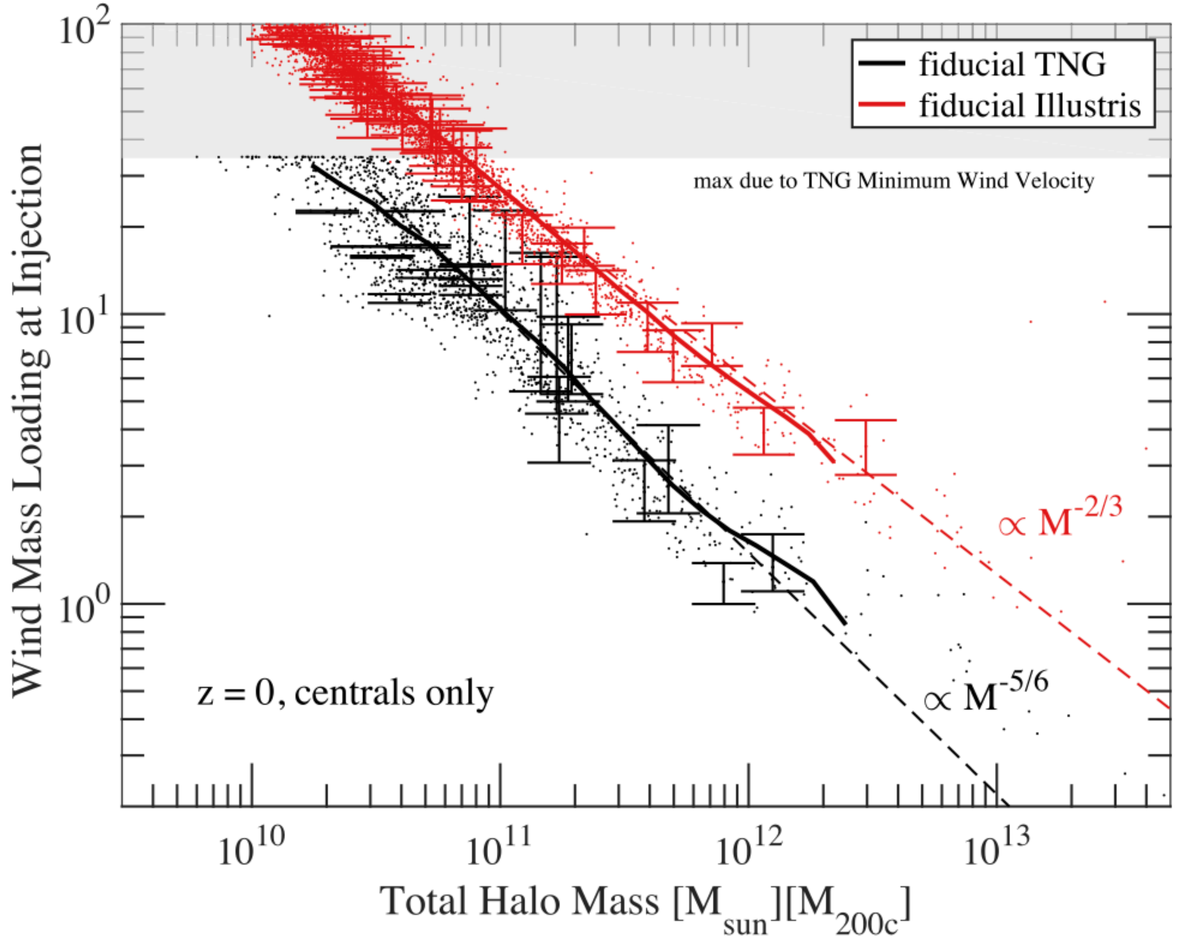
Springel & Hernquist (2003)

Galactic Wind Prescription Example

- In the IllustrisTNG, wind velocity scales with the local, 1D DM velocity dispersion

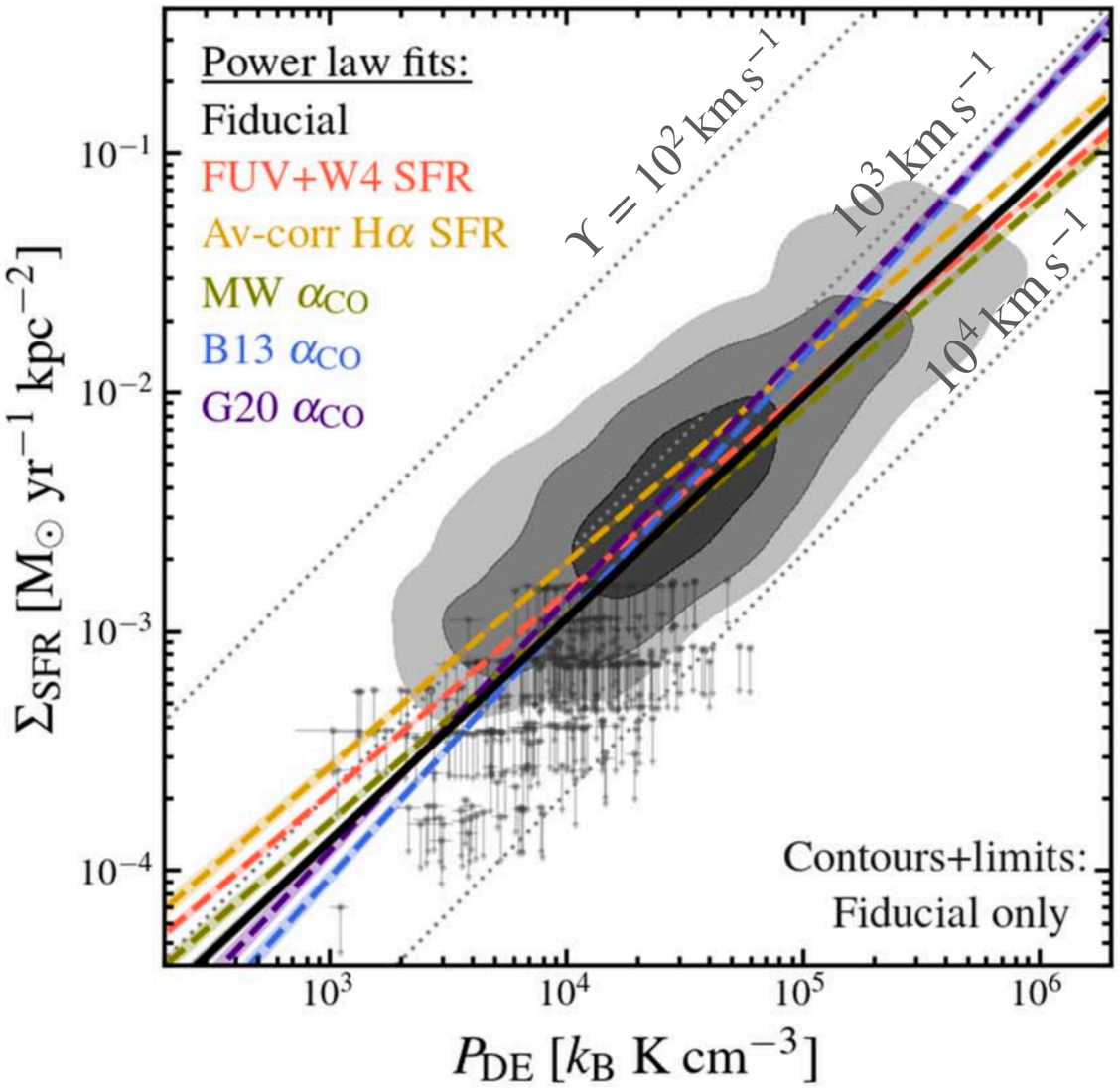
$$v_w = \max\left[\kappa_w \sigma_{\rm DM}(H0/H(z))^{1/3}, v_{w,\rm min}\right]$$

- Mass loading factor: $\eta_M = \dfrac{\dot{M}_w}{\dot{M}_*} = \dfrac{2}{v_w^2}\varepsilon_{\rm w}(1 - f_{\rm therm})$ with specific energy for wind ε_w and thermal energy fraction $f_{\rm therm}$



Pillepich et al. (2018)

Pressure-regulated Feedback-Modulated Star Formation



Sun et al. (2023)

- Star formation (feedback) as a source of energy and momentum (Ostriker & KimCG 2022):

$$\Sigma_{\rm SFR} = \frac{1}{\Upsilon} P_{\rm DE}$$

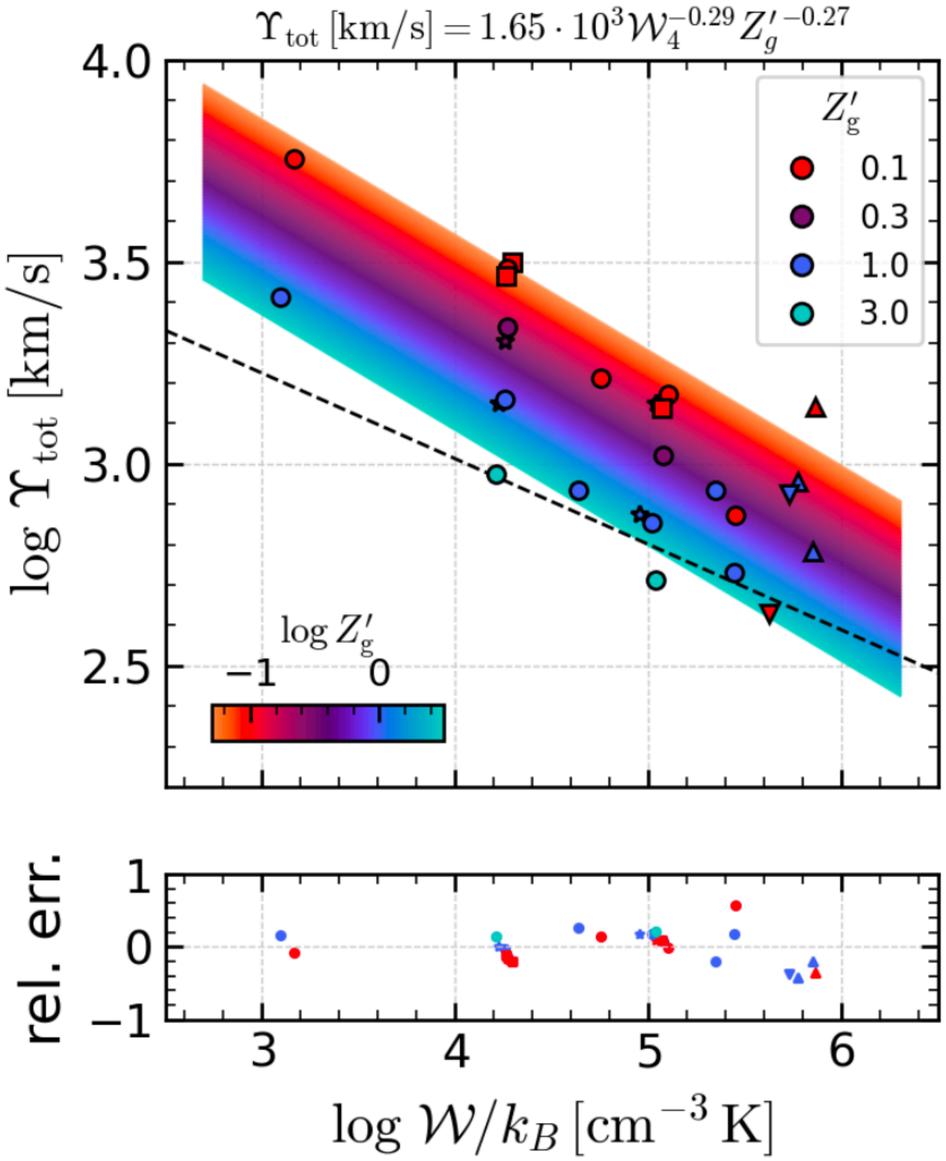
- Star formation required to keep the ISM in a long-term equilibrium is ultimately set by **the weight or the dynamical equilibrium pressure**:

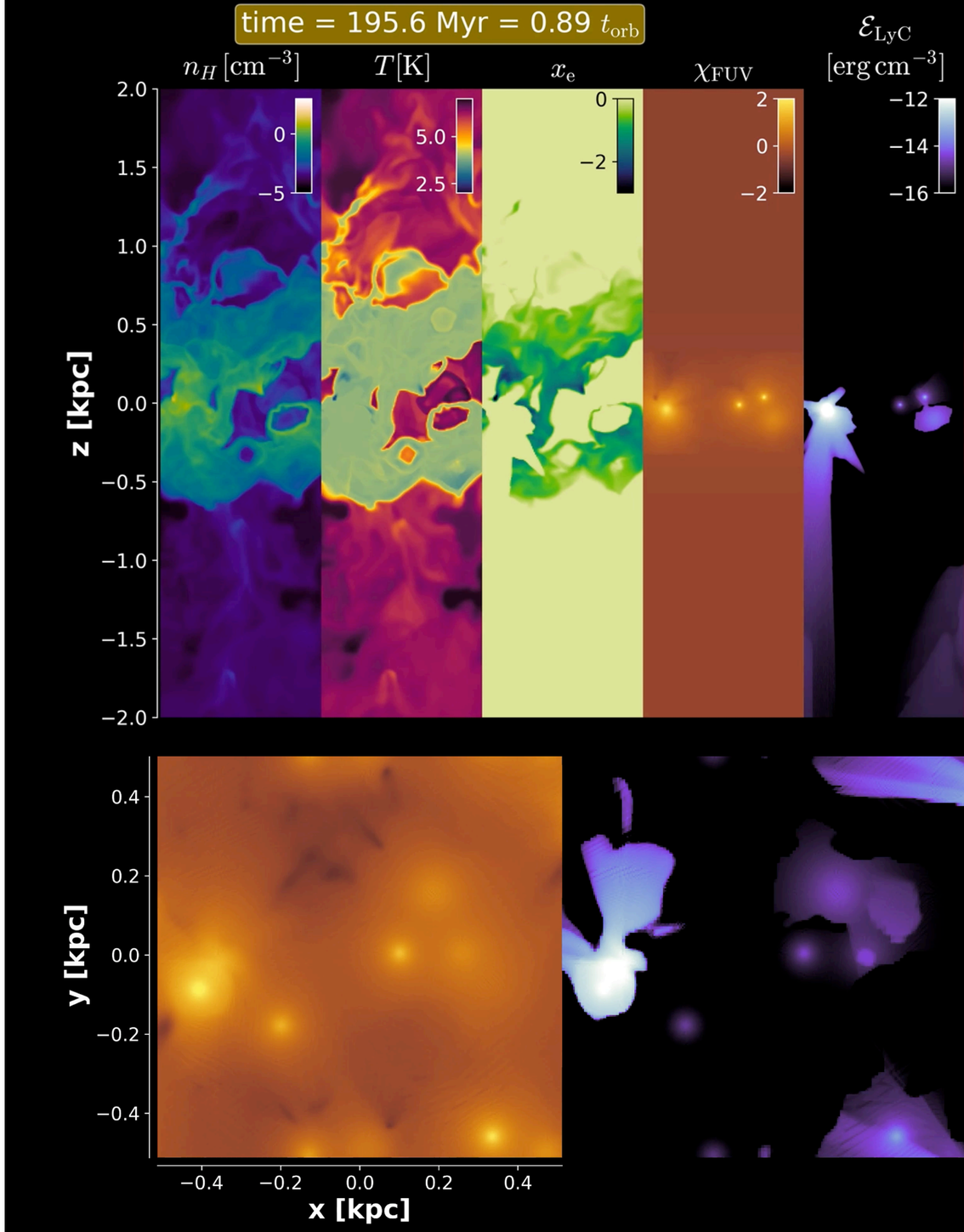
$$P_{\rm DE} = \mathscr{W} \approx \frac{\pi G \Sigma_{\rm gas}^2}{2} + \Sigma_{\rm gas} (2 G \rho_{\rm sd})^{1/2} \sigma_{\rm eff}$$

- **Feedback yield** $\Upsilon(P_{\rm DE}; Z) = P_{\rm DE}/\Sigma_{\rm SFR} \sim 10^3\,{\rm km\,s^{-1}}$ **measures the efficiency with which feedback recovers the ISM pressure**.

TIGRESS-NCR Simulations

KimJG+23, KimCG+23, 24, Linzer+24

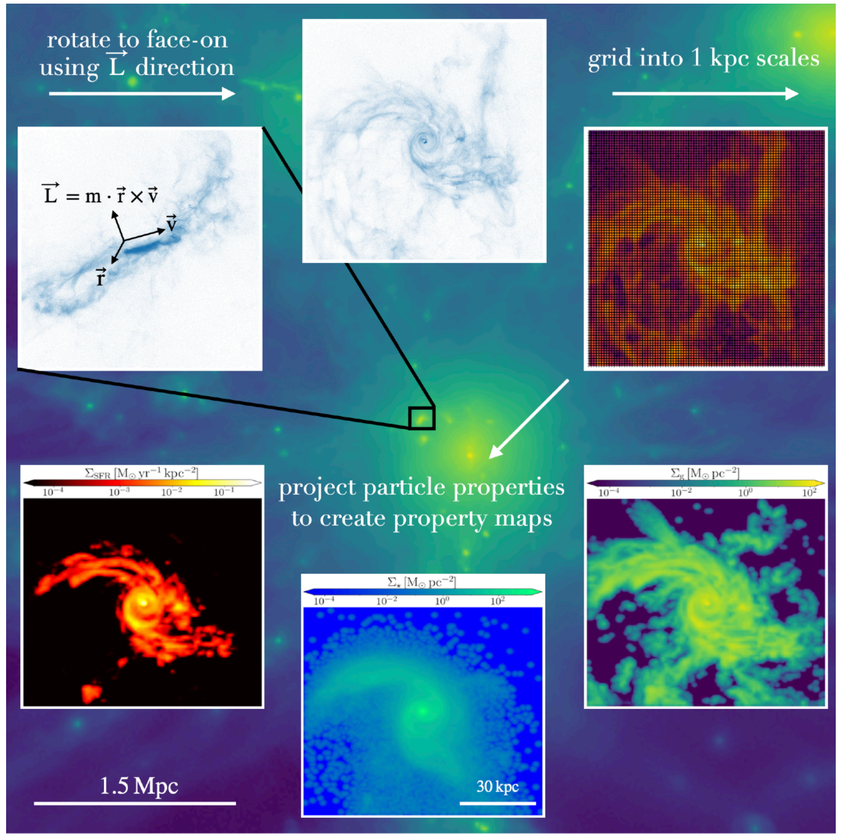


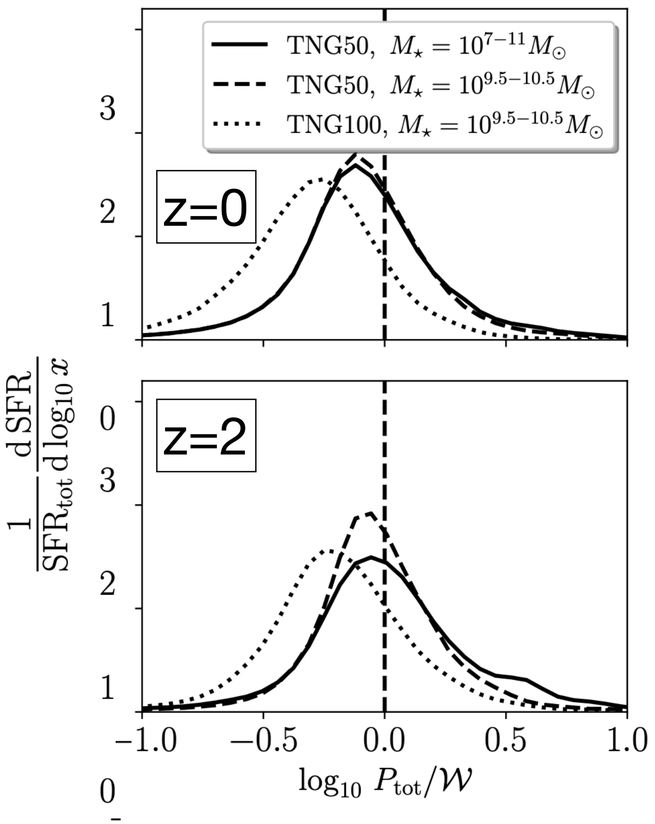


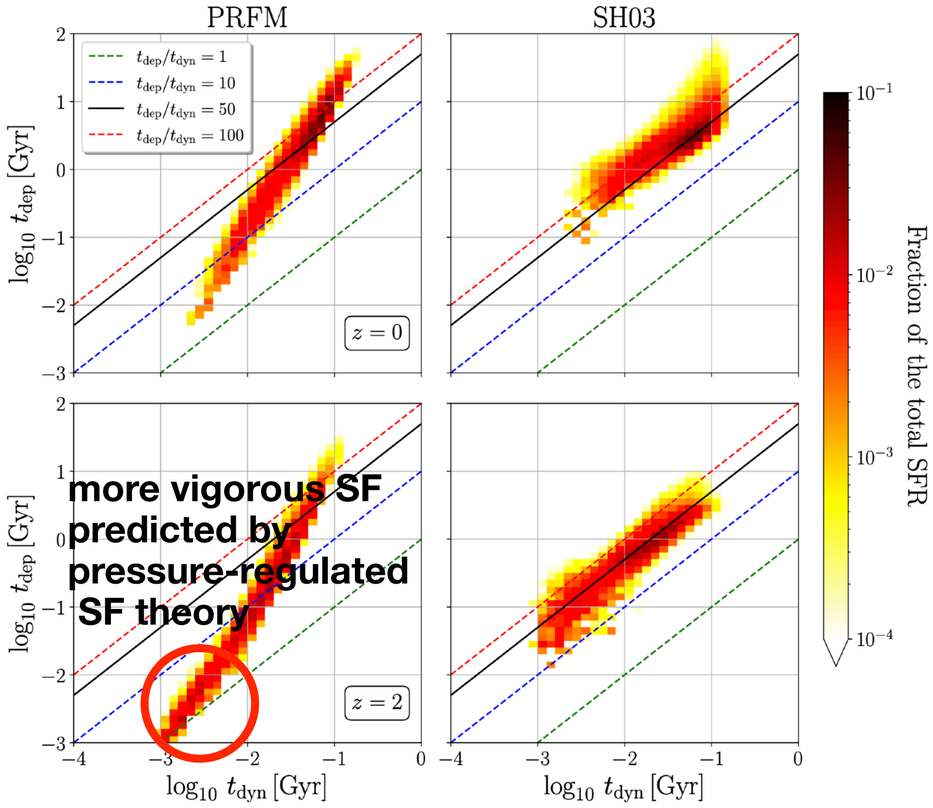
Towards Implementation of the Pressure-Regulated, Feedback-Modulated Model of Star Formation in Cosmological Simulations: Methods and Application to TNG

Sultan Hassan [1,2,3,*] Eve C. Ostriker [4,5] Chang-Goo Kim [4] Greg L. Bryan [6,2] Jan D. Burger [7]
Drummond B. Fielding [2,8] John C. Forbes [2,9] Shy Genel [2,10] Lars Hernquist [11]
Sarah M. R. Jeffreson [11] Bhawna Motwani [6] Matthew C. Smith [7] Rachel S. Somerville [2]
Ulrich P. Steinwandel [2] and Romain Teyssier [4,12]

Hassan et al. (2024)







- New recipe for the star formation rate of a gas cell/particle:

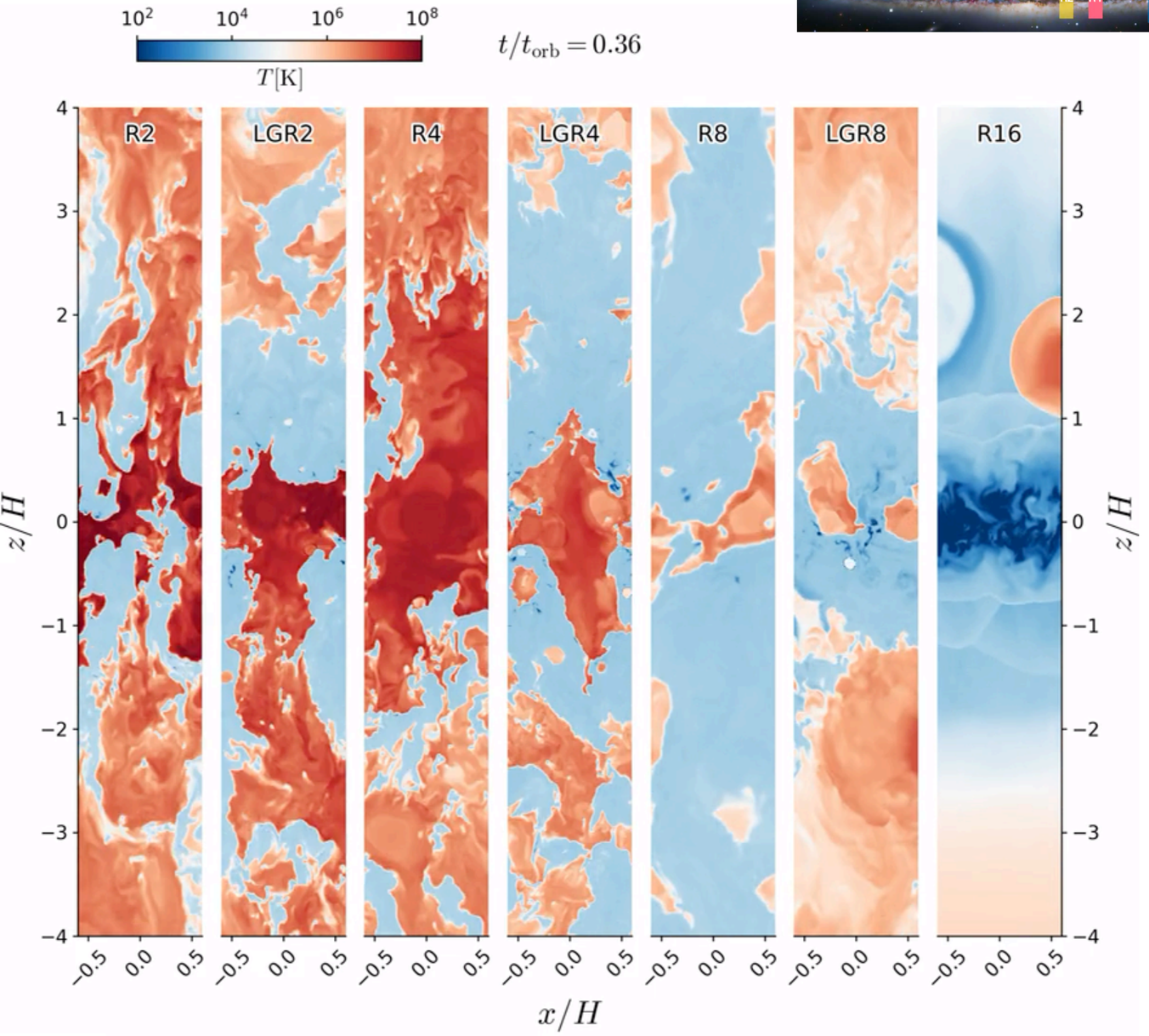
$$\dot{m}_* = \frac{m_{\rm gas}}{t_{\rm dep}} = \frac{\sigma_{\rm eff}}{\Upsilon_{\rm tot}} \frac{m_{\rm gas}}{t_{\rm dyn}} \quad \textbf{with} \quad t_{\rm dep} = \frac{2\Upsilon_{\rm tot}}{\langle g_z \rangle} = \frac{\Upsilon_{\rm tot}}{\sigma_{z,\rm eff}} t_{\rm dyn}$$

- To calculate $\dot{m}_*$, use eEOS to set $P_{\rm tot}$ and then $\Upsilon_{\rm tot}$ calibrations with $t_{\rm dyn} \approx 2/\left[2\pi G\rho_g + 4\pi G\rho_*/(1 + H_*/H_g)\right]^{1/2}$

Galactic Winds are Multiphase

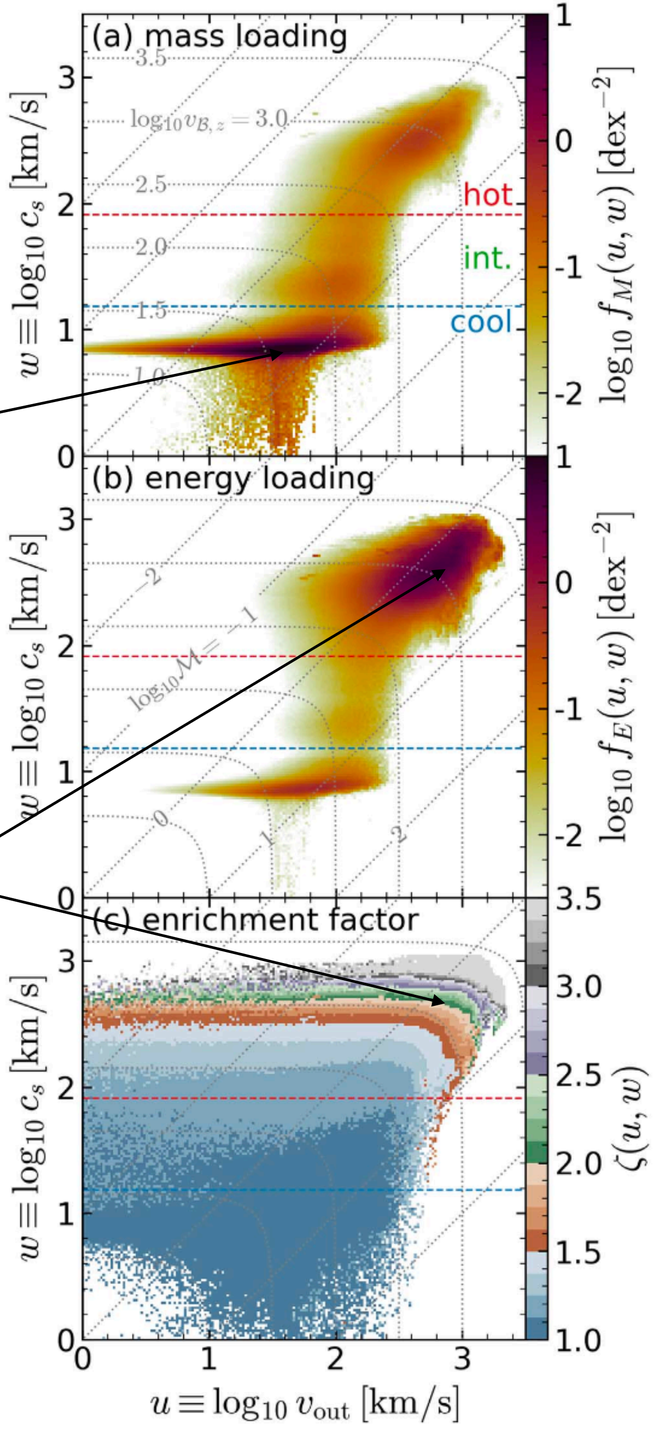
KimCG et al. (2020ab)

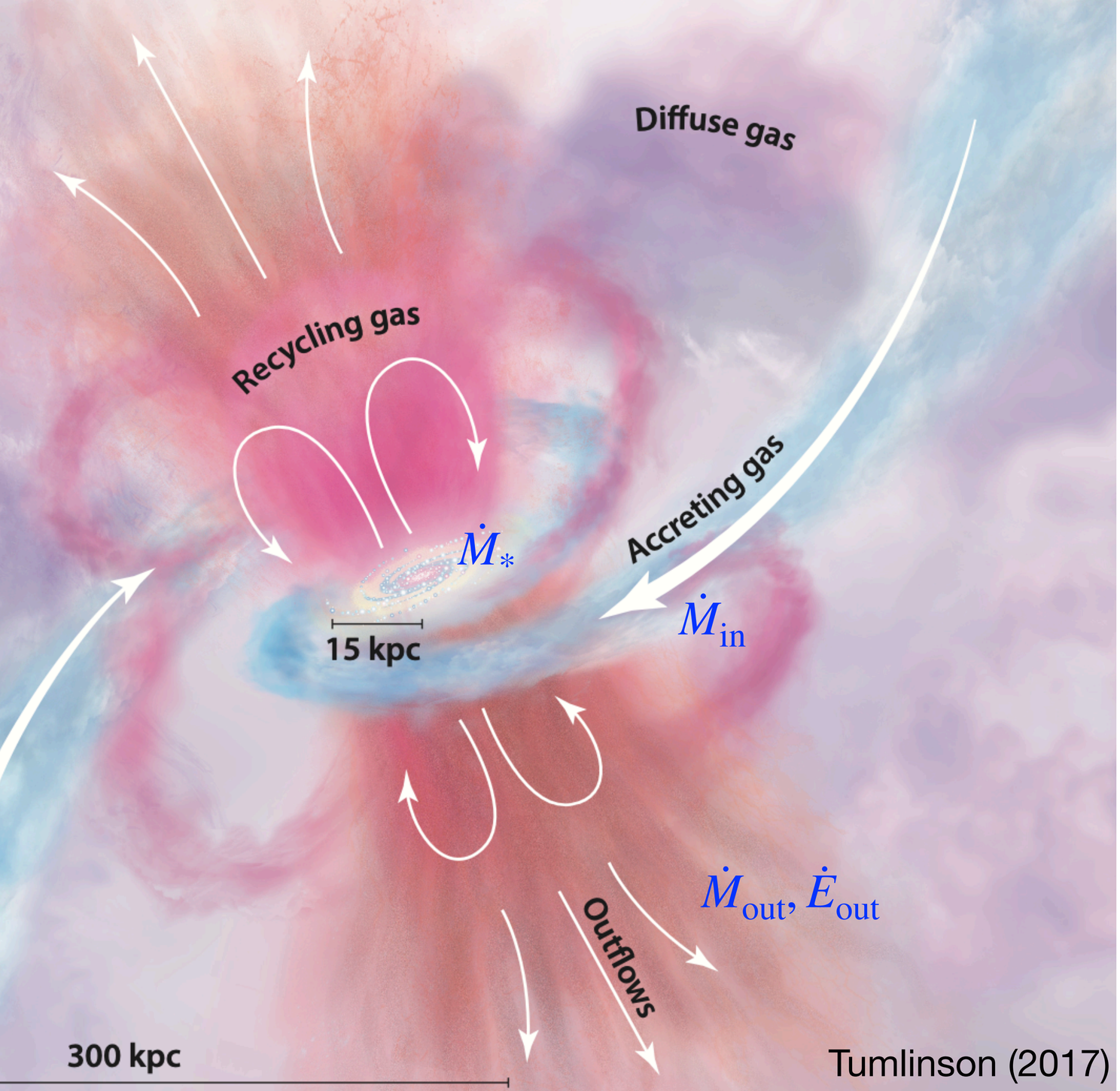




most mass carried by cool phase

most energy and metals carried by hot phase





Tumlinson (2017)

Role of Outflow Feedback (Revisited)

$$\dot{M}_{\rm ISM} = \dot{M}_{\rm in} - \dot{M}_* - \dot{M}_{\rm out}$$

- **Ejective feedback**

  Reduces the available reservoir of star-forming material and enriches the circumgalactic medium (CGM)

  $$\dot{M}_{\rm out} = \eta_M \dot{M}_*$$

- **Preventive feedback**

  The prevention of fresh inflows of gas from reaching the galaxy from the intergalactic medium (IGM) via the CGM

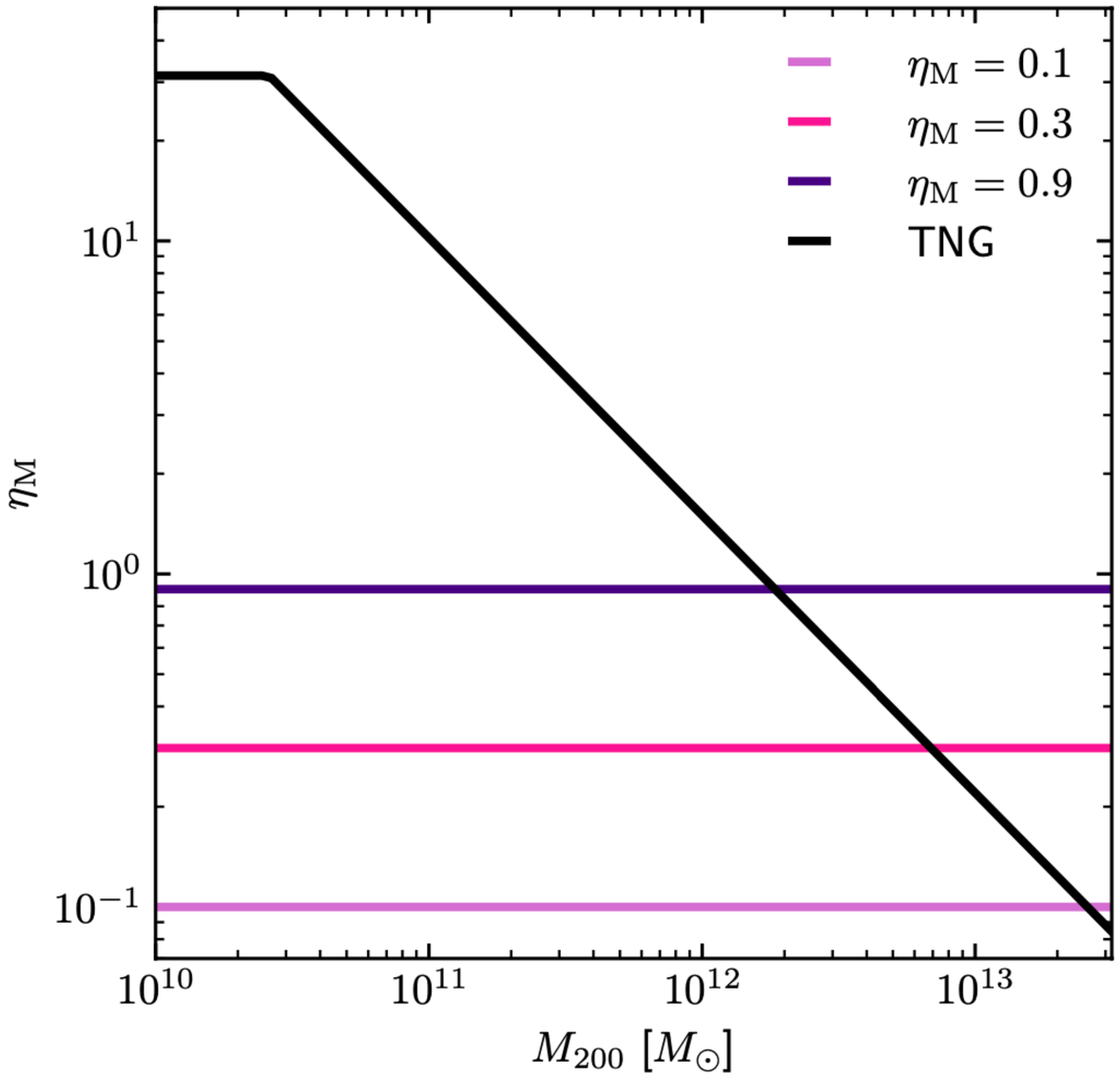
  $\dot{E}_{\rm out} = \eta_E \varepsilon_{\rm SN} \dot{M}_*$ with

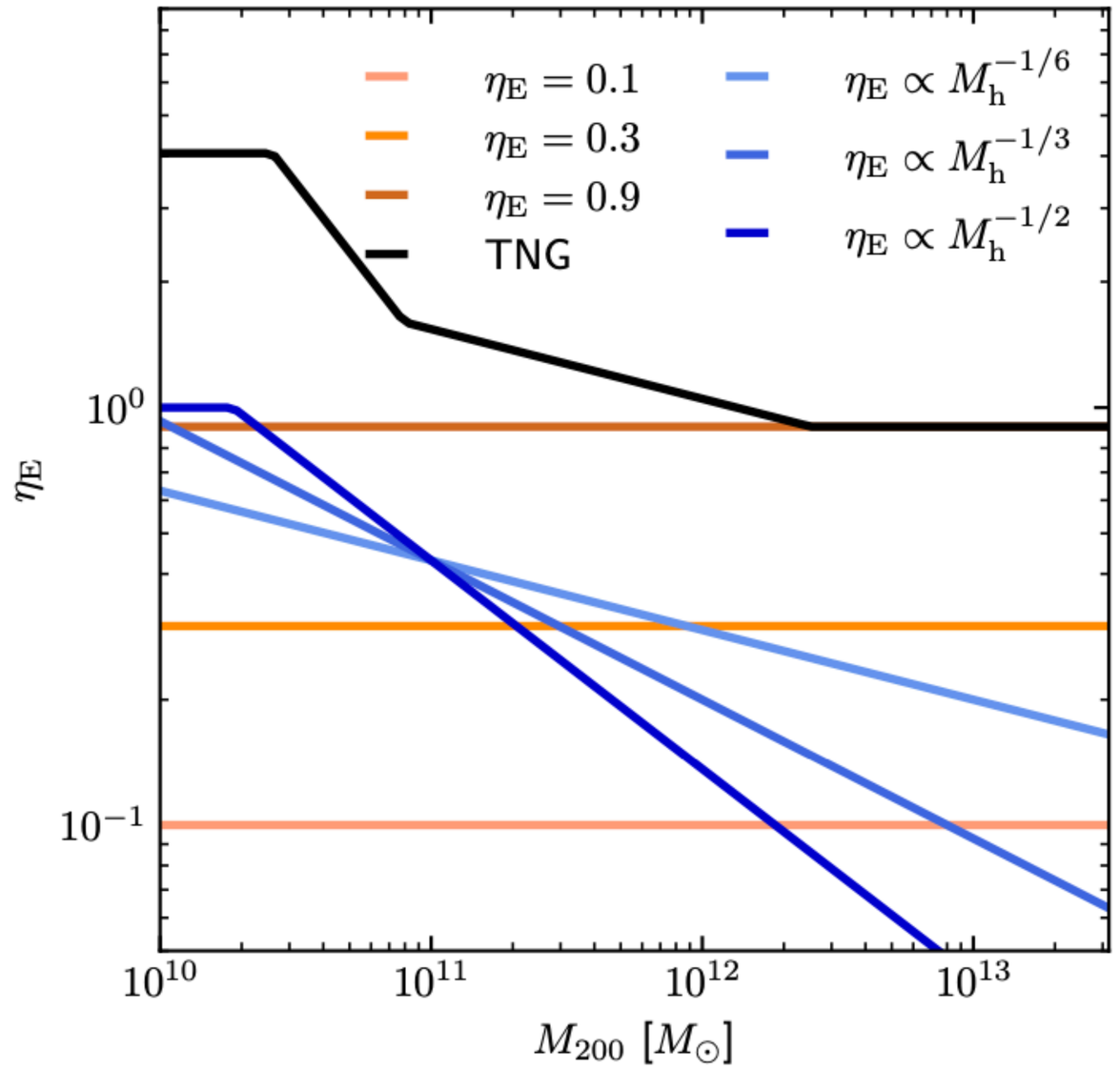
  $$\varepsilon_{\rm SN} \approx 10^{51}\,{\rm erg}/(10^2\,M_\odot) \sim (770\,{\rm km\,s^{-1}})^2$$

- **Outstanding question**: how does $\dot{E}_{\rm out}$ control $\dot{M}_{\rm in}$ and $\dot{M}_{\rm acc}$? Need to consider CGM energetics (e.g., Voit et al. 2024ab):

  $$\dot{E}_{\rm CGM} = \dot{M}_{\rm acc}\varepsilon_{\rm acc} - \dot{M}_{\rm in}\varepsilon_{\rm loss} + \eta_E \varepsilon_{\rm SN} \dot{M}_*$$

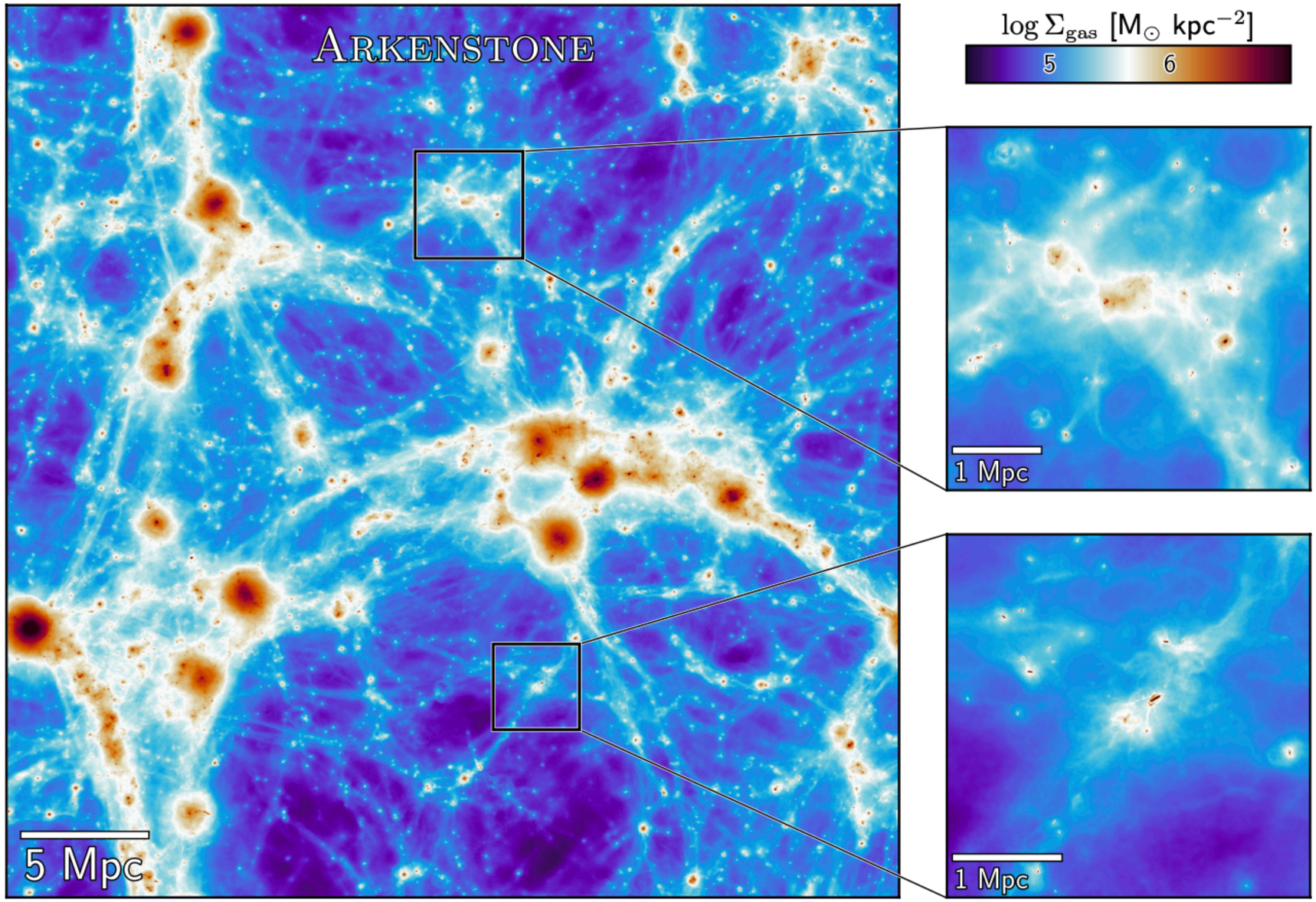
Cosmological Simulations with Hot High Specific Energy Winds





Bennett et al. (2024)

Cosmological Simulations with Hot High Specific Energy Winds



Bennett et al. (2024)

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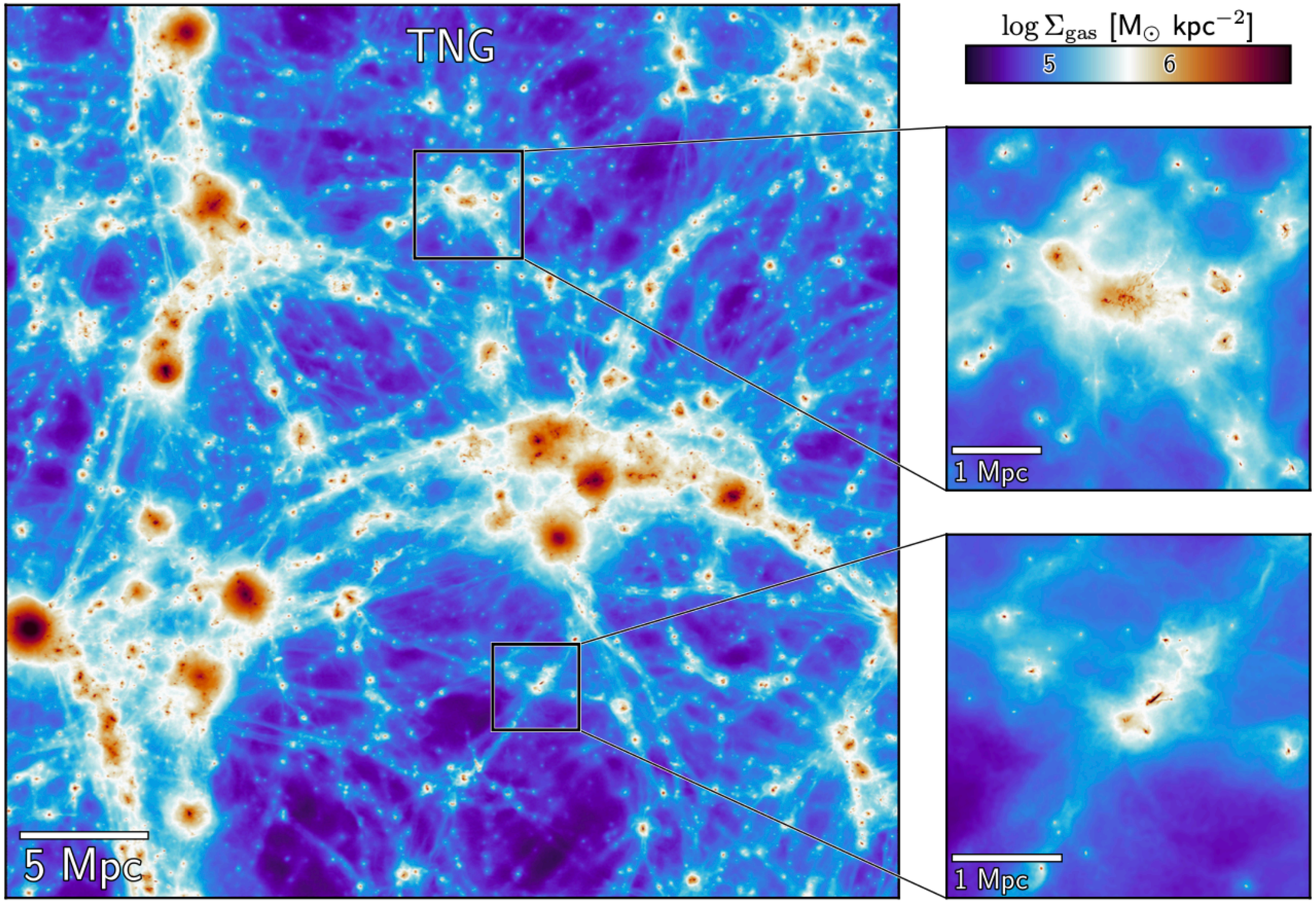

Bennett et al. (2024)

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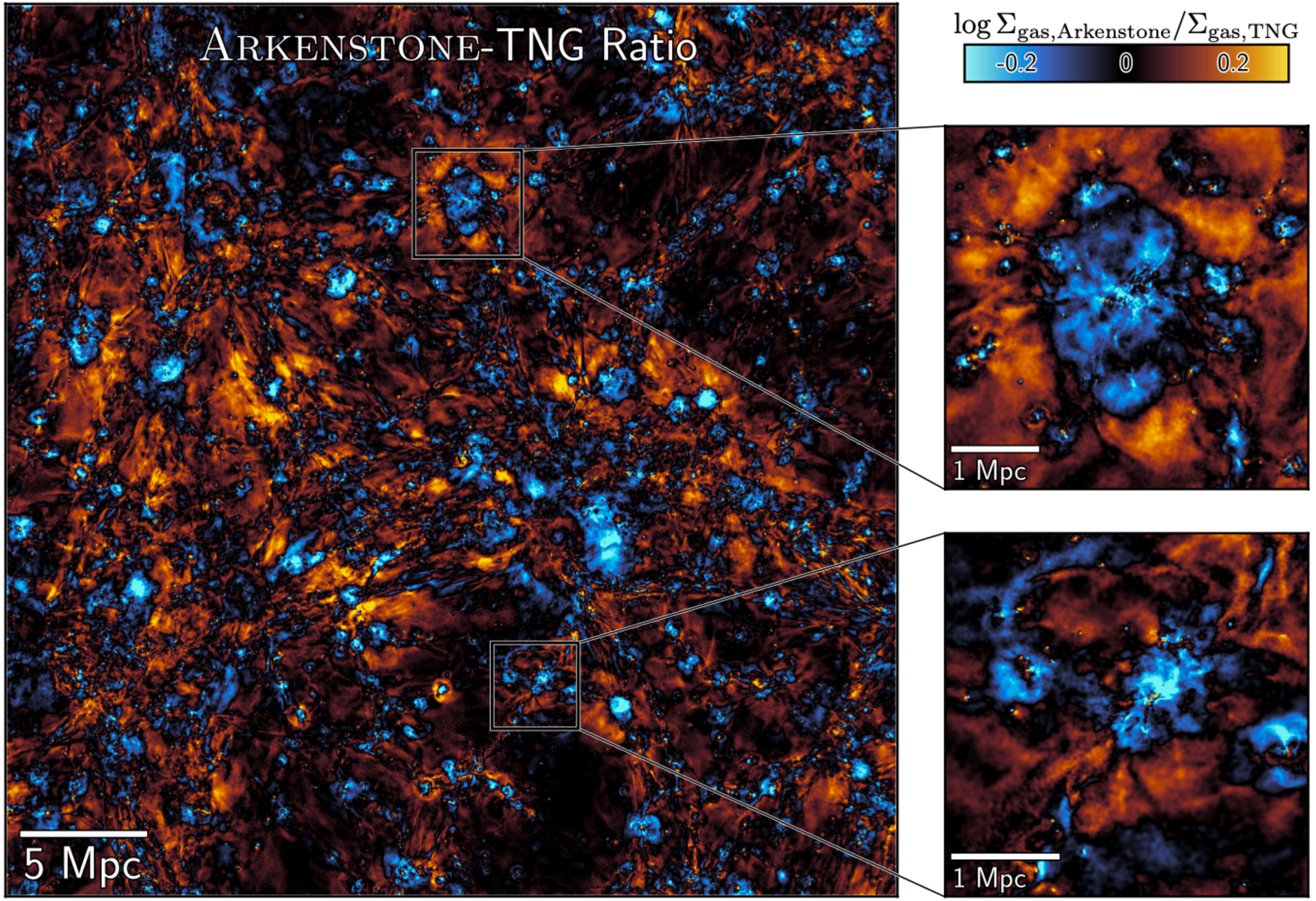


Bennett et al. (2024)

observations

fixed energy loading η_E

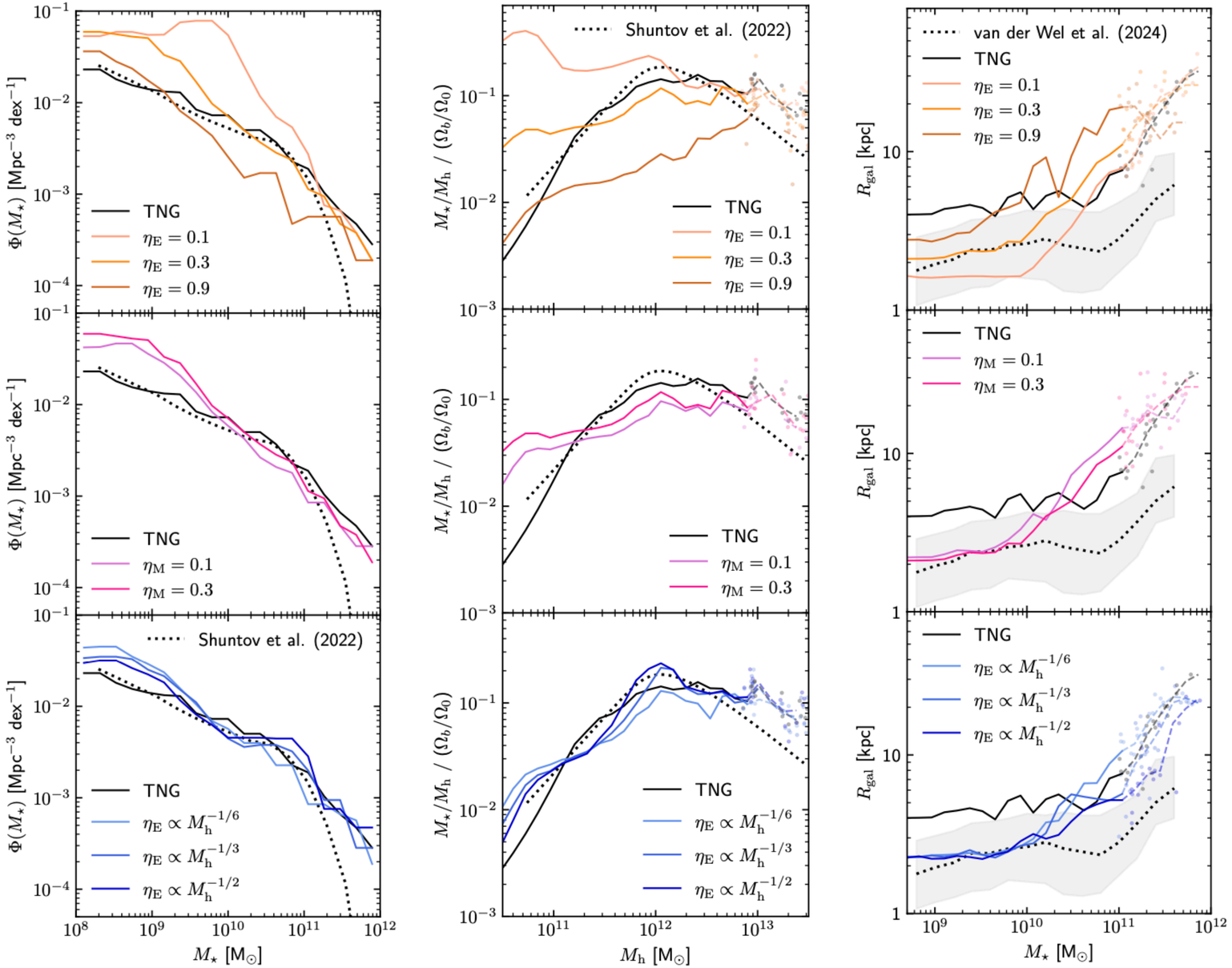
fxied mass loading η_M

variable energy loading η_E

stellar mass function

stellar mass halo mass relation

galaxy size



Bennett et al. (2024)

Summary

- Cosmological simulations of galaxy formation have had many successes, but contain empirically-calibrated subgrid treatments that limit their accuracy and predictive power.
- Future:
  - Learn from controlled small-scale simulations that resolve key physical processes.
    - Pressure-regulated star formation
    - Multiphase outflows, cloud-wind interaction
    - Black hole accretion flows, feedback, movement
  - Derive and calibrate subgrid models that are robust to numerical resolution, free from tunable parameters
- Another challenge:
  - Developing and maintaining software that runs effectively across diverse platforms