Learning the Universe

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

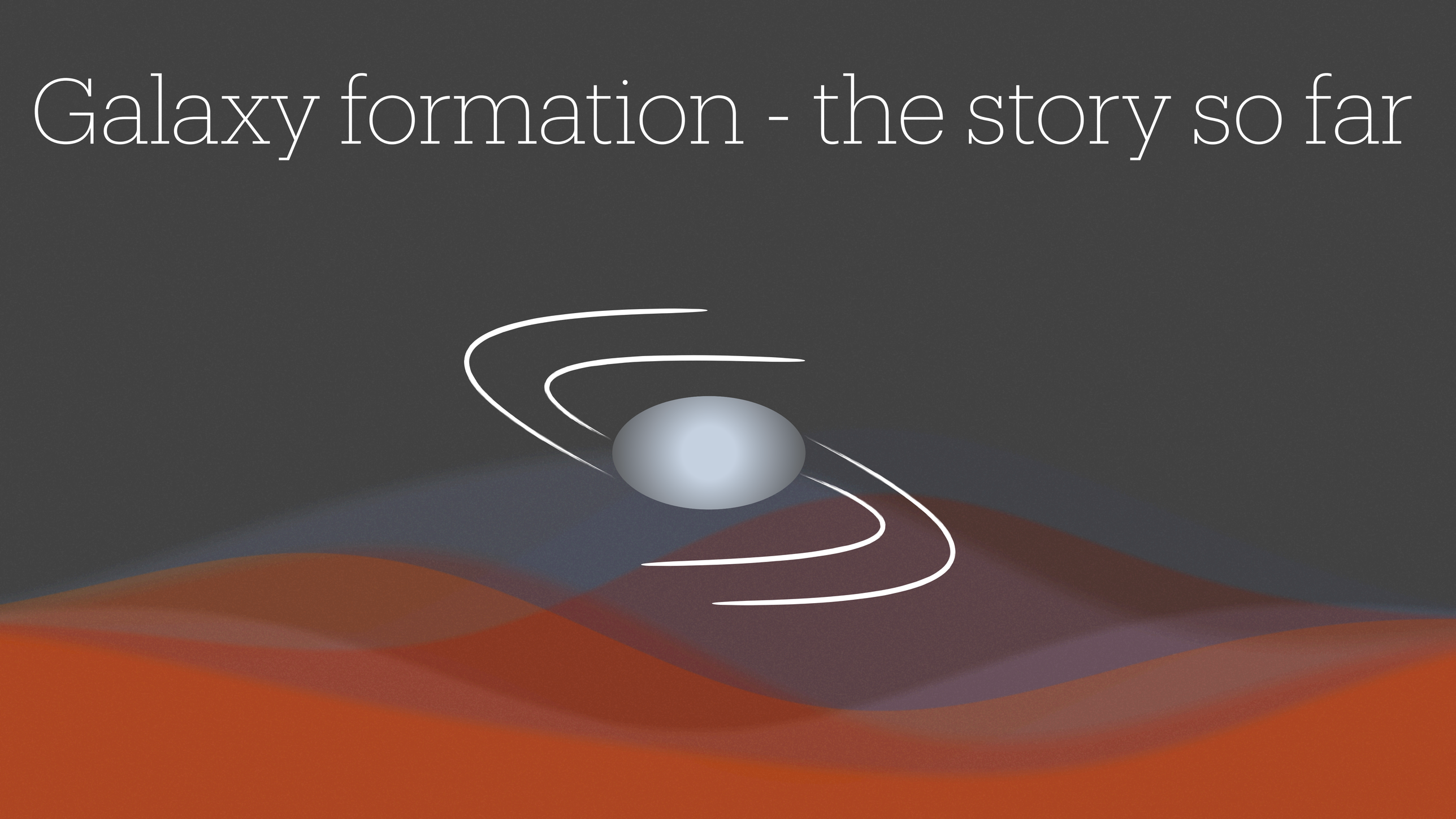
Prevention is better than cure?

High specific energy, low mass loaded winds and their impact

Jake Bennett
Matthew Smith, Drummond Fielding, Greg Bryan,
Chang-Goo Kim, Volker Springel, Lars Hernquist, Rachel Somerville, Laura Sommovigo

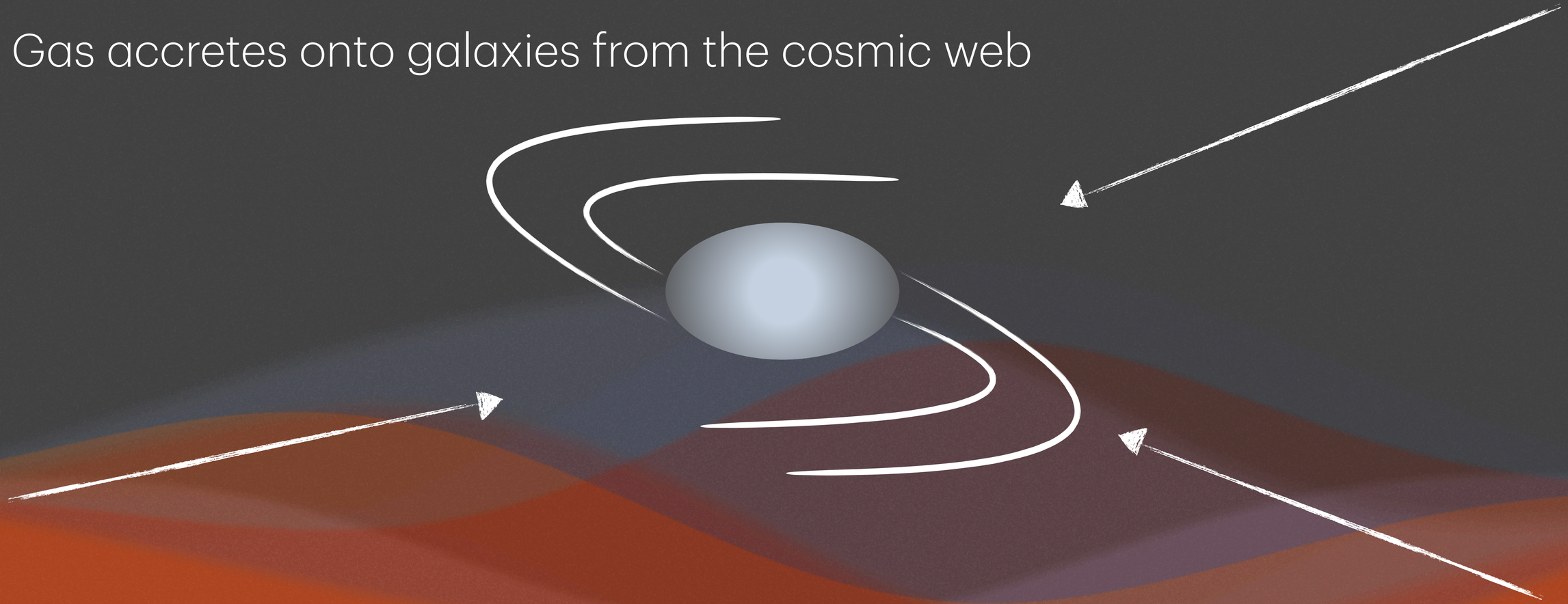
Learning the Universe Fellow — Potsdam Feedback Thinkshop — 17/07/25

Galaxy formation - the story so far



Galaxy formation - the story so far

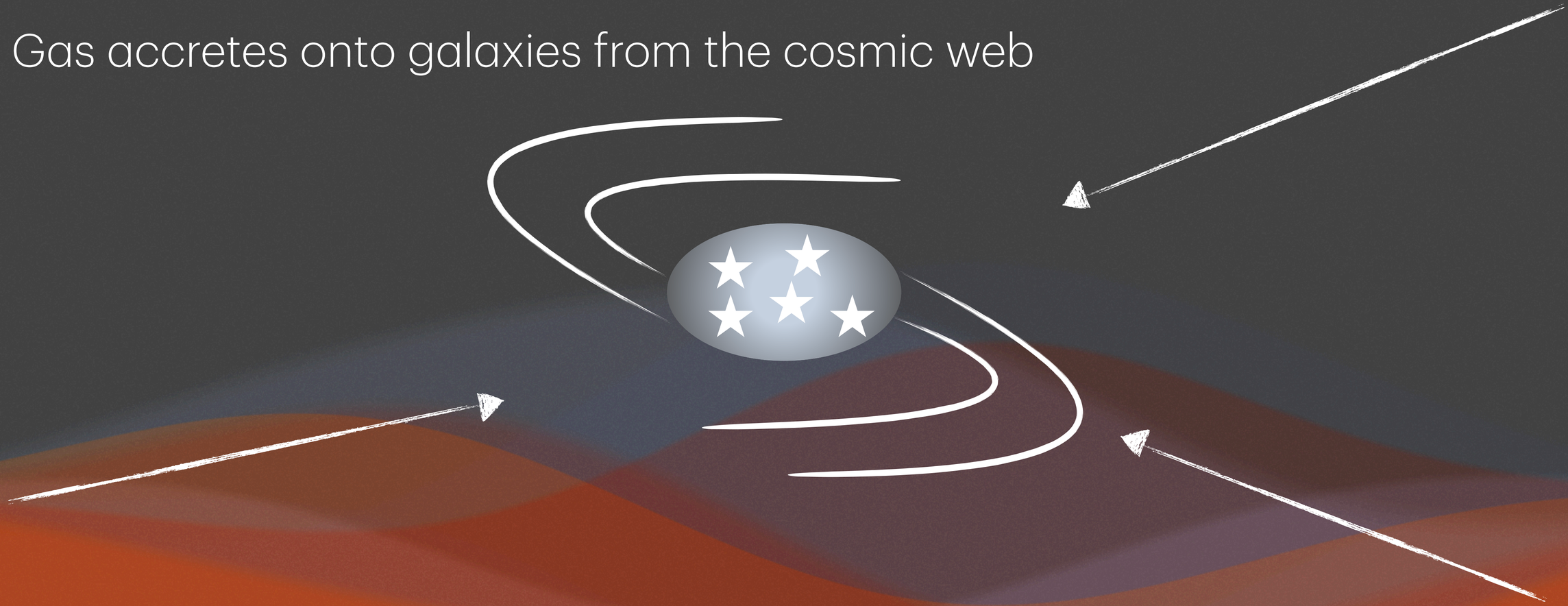
Gas accretes onto galaxies from the cosmic web



A small fraction of this gas forms stars

Galaxy formation - the story so far

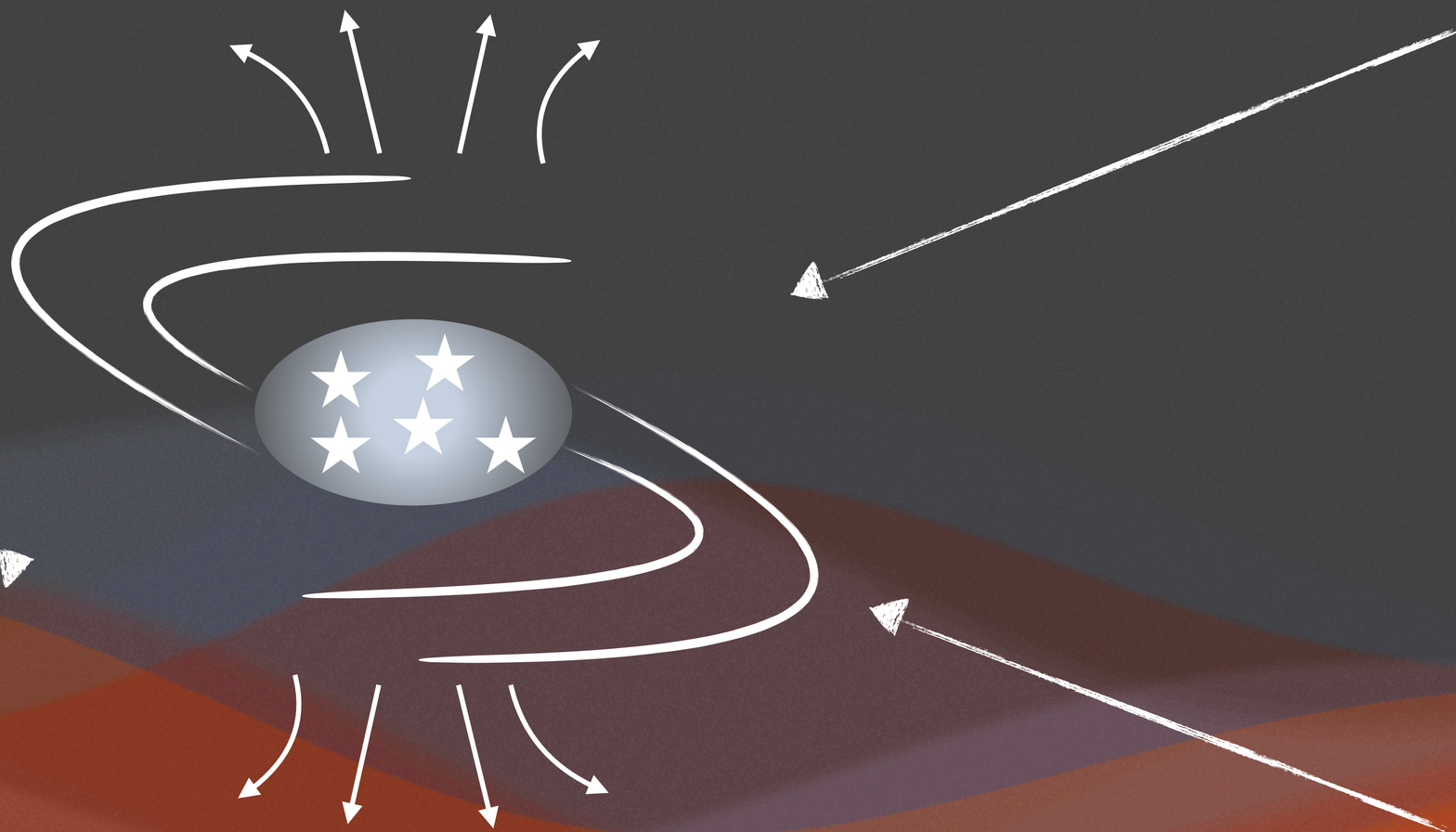
Gas accretes onto galaxies from the cosmic web



A small fraction of this gas forms stars

Galaxy formation - the story so far

$$\eta_{\mathrm{M}} = \dot{M}_{\mathrm{out}} / \dot{M}_{\star}$$
$$\eta_{\mathrm{E}} = \dot{E}_{\mathrm{out}} / \dot{E}_{\star}$$



Feedback from this star formation launches outflows

Outflows characterised by mass and energy loadings

Galaxy formation - the story so far

$$\eta_{\rm M} = \dot{M}_{\rm out}/\dot{M}_\star$$
$$\eta_{\rm E} = \dot{E}_{\rm out}/\dot{E}_\star$$

- In (most) models these loadings are tuned so result reproduces observables (e.g. stellar mass function).
- They often have quite high mass and energy loadings $\eta_{\rm M} > 1$, $\eta_{\rm E} > 1$, especially at low masses

→ Ejective *feedback*

Galaxy formation - the story so far

$$\eta_{\mathrm{M}} = \dot{M}_{\mathrm{out}}/\dot{M}_{\star}$$
$$\eta_{\mathrm{E}} = \dot{E}_{\mathrm{out}}/\dot{E}_{\star}$$

- Hints from idealised models and observations point to a hot, diffuse phase *without much mass* being important (e.g. Kim et al. 2020, Carr et al. 2023, Voit et al. 2024a,b).
- Hot winds heat and deplete the CGM, halting further inflow.

→ Preventative feedback

Galaxy formation - the story so far

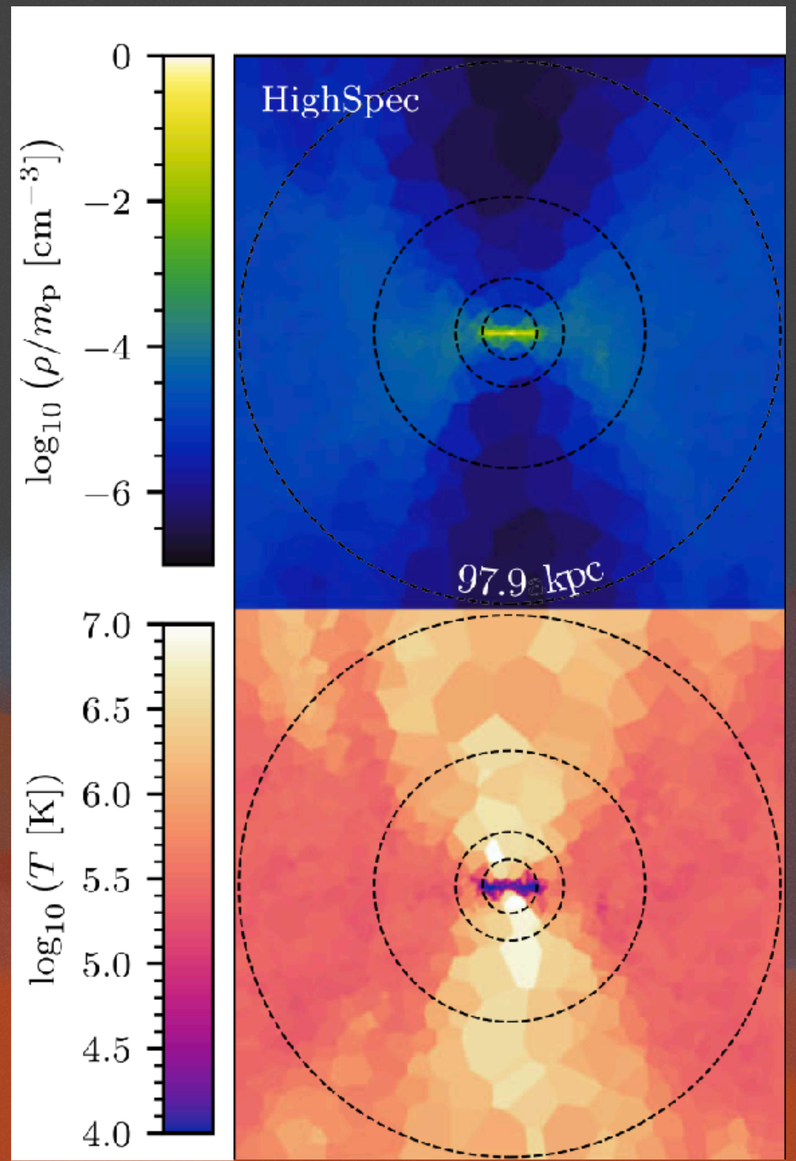
$$\frac{\eta_{\mathrm{E}}}{\eta_{\mathrm{M}}}$$ → Specific energy

- Hints from idealised models and observations point to a hot, diffuse phase *without much mass* being important (e.g. Kim et al. 2020, Carr et al. 2023, Voit et al. 2024a,b).
- Hot winds heat and deplete the CGM, halting further inflow.

→ Preventative feedback

High specific energy winds

$$\frac{\eta_E}{\eta_M}$$ → Specific energy

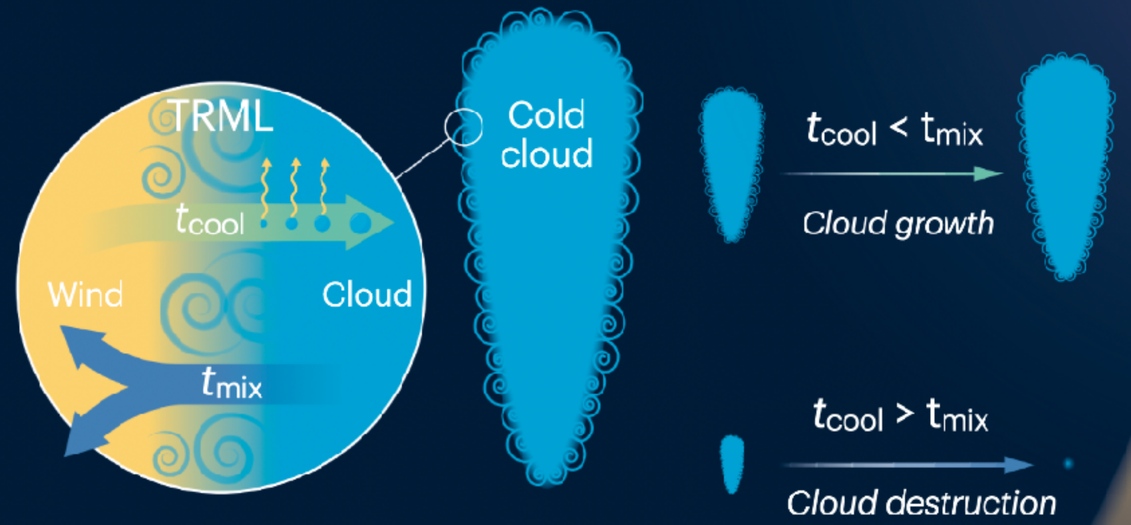


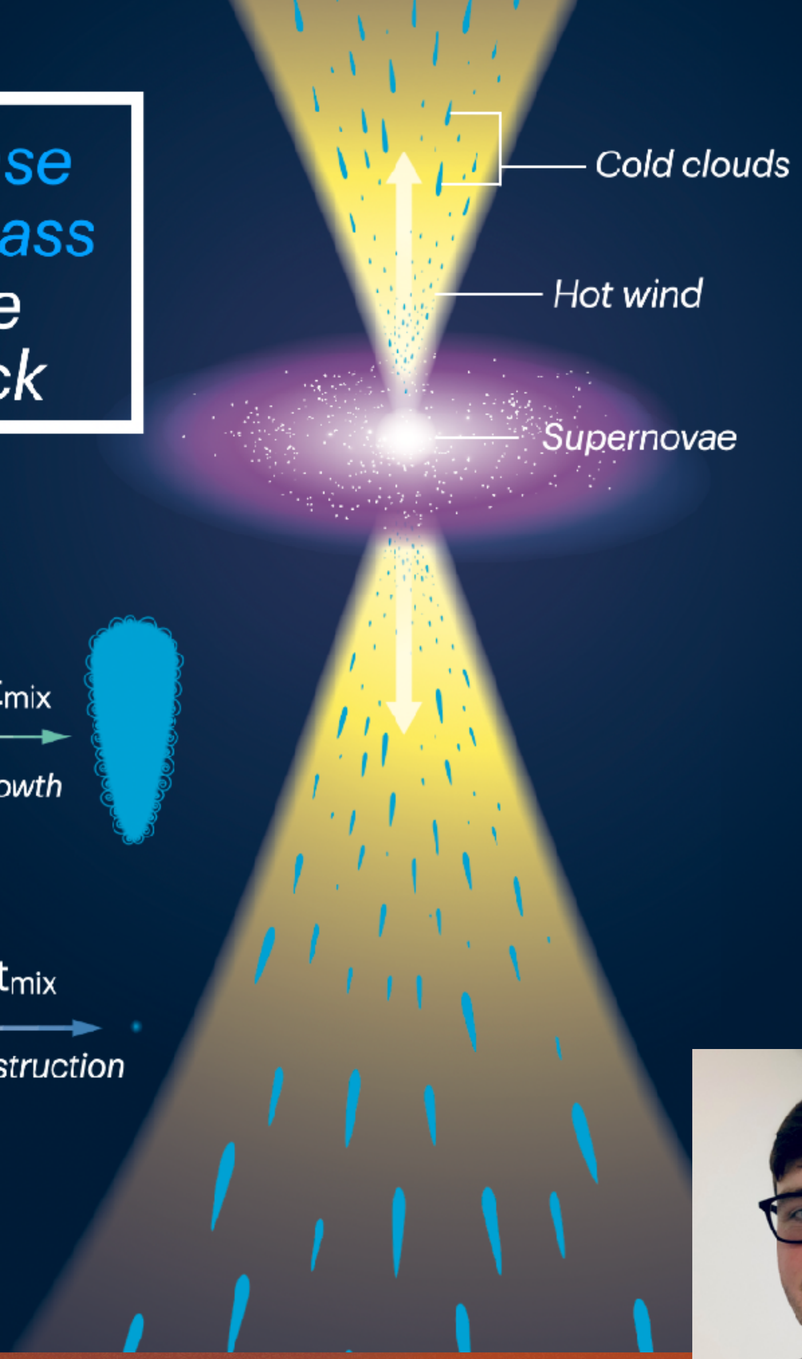
Smith et al. 2024a

Arkenstone Multiphase Galactic Winds

hot phase carries energy *preventative feedback*

cold phase carries mass *ejective feedback*





Cold ↔ Hot

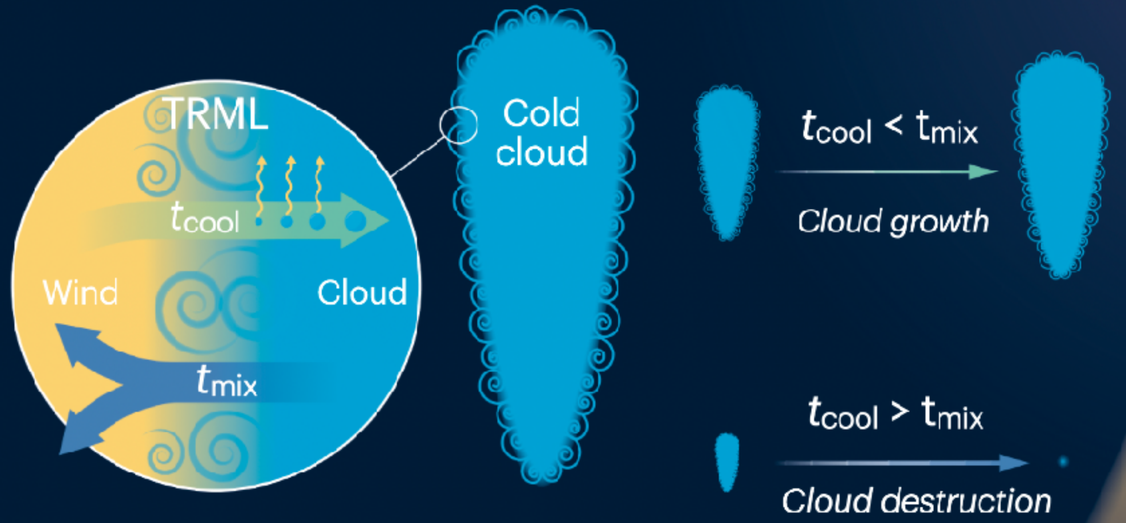
phases interact on the fly via
the ***T**urbulent **R**adiative **M**ixing **L**ayer* model

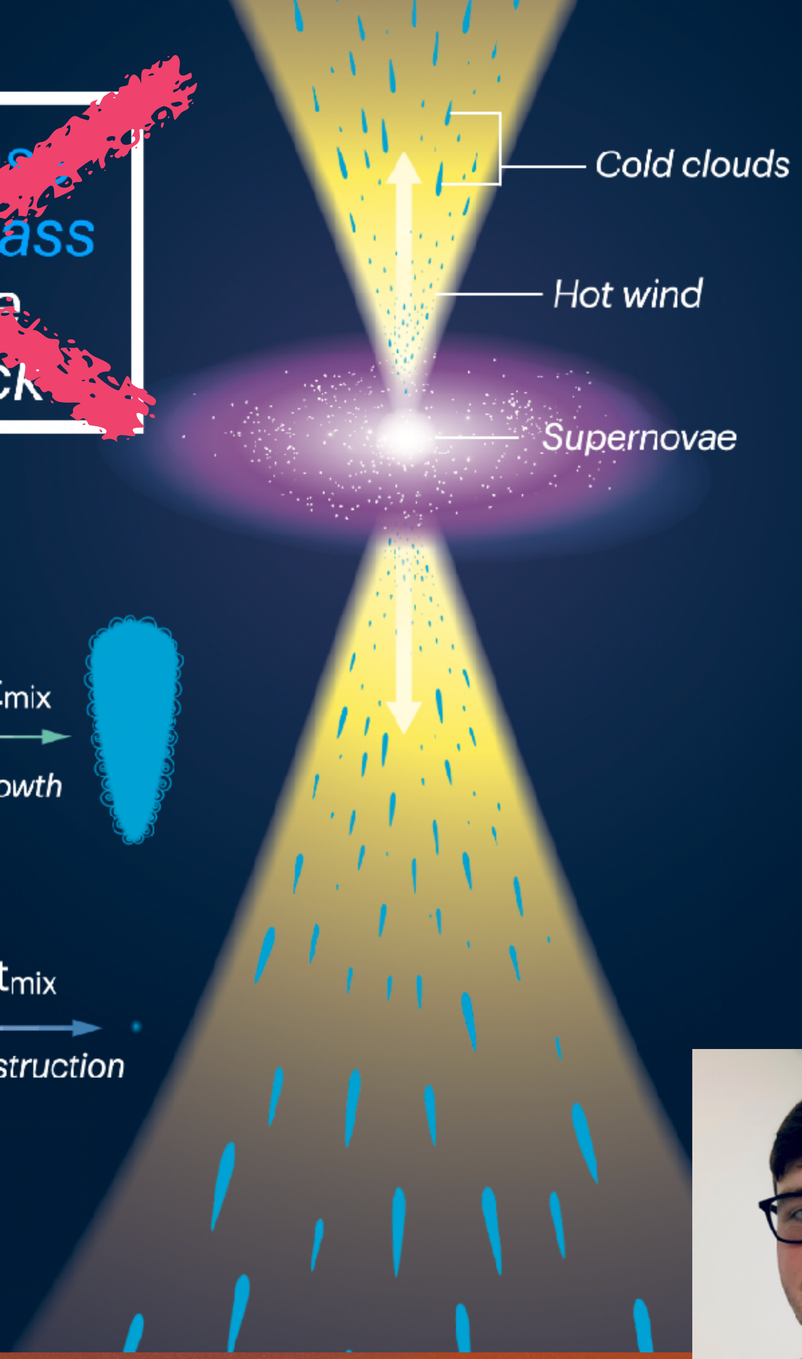
Smith et al. 2024a,b; Bennett et al. 2024

Arkenstone Multiphase Galactic Winds

hot phase carries energy preventative feedback

~~*cold phase carries mass ejective feedback*~~





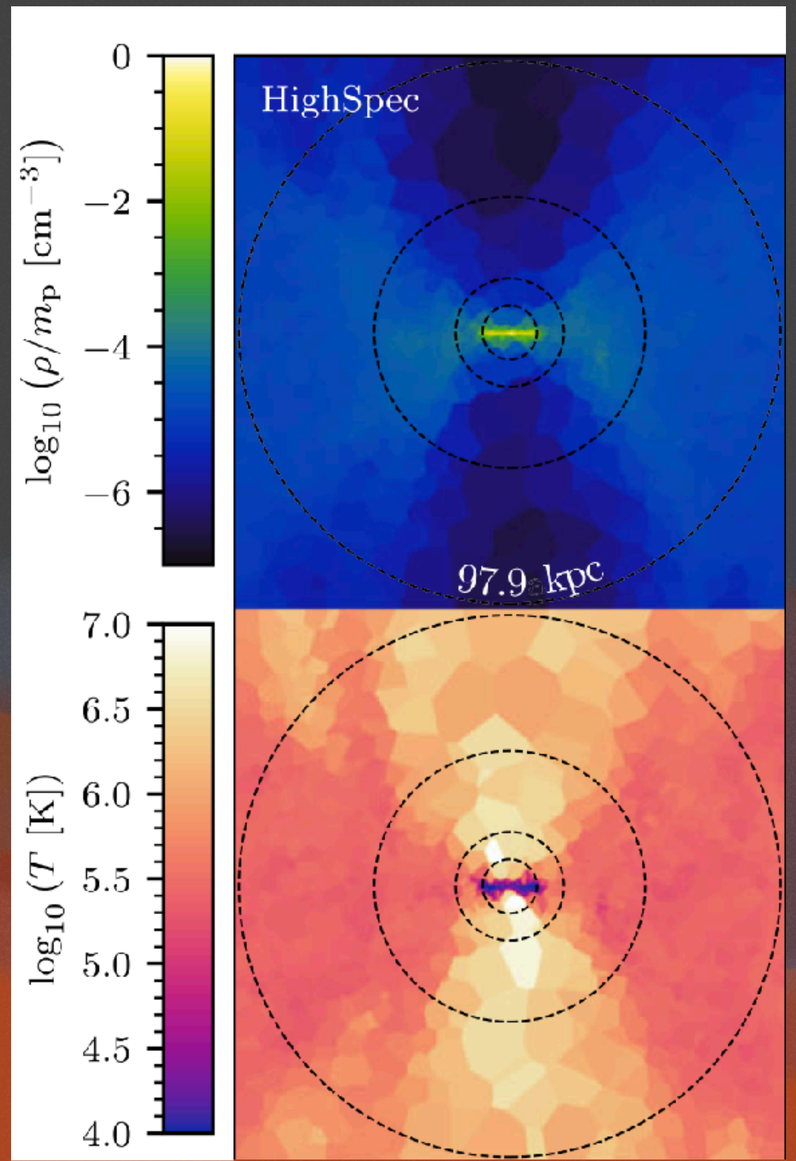
Cold ↔ Hot

phases interact on the fly via
the ***T**urbulent **R**adiative **M**ixing **L**ayer* model

Smith et al. 2024a,b; Bennett et al. 2024

High specific energy winds

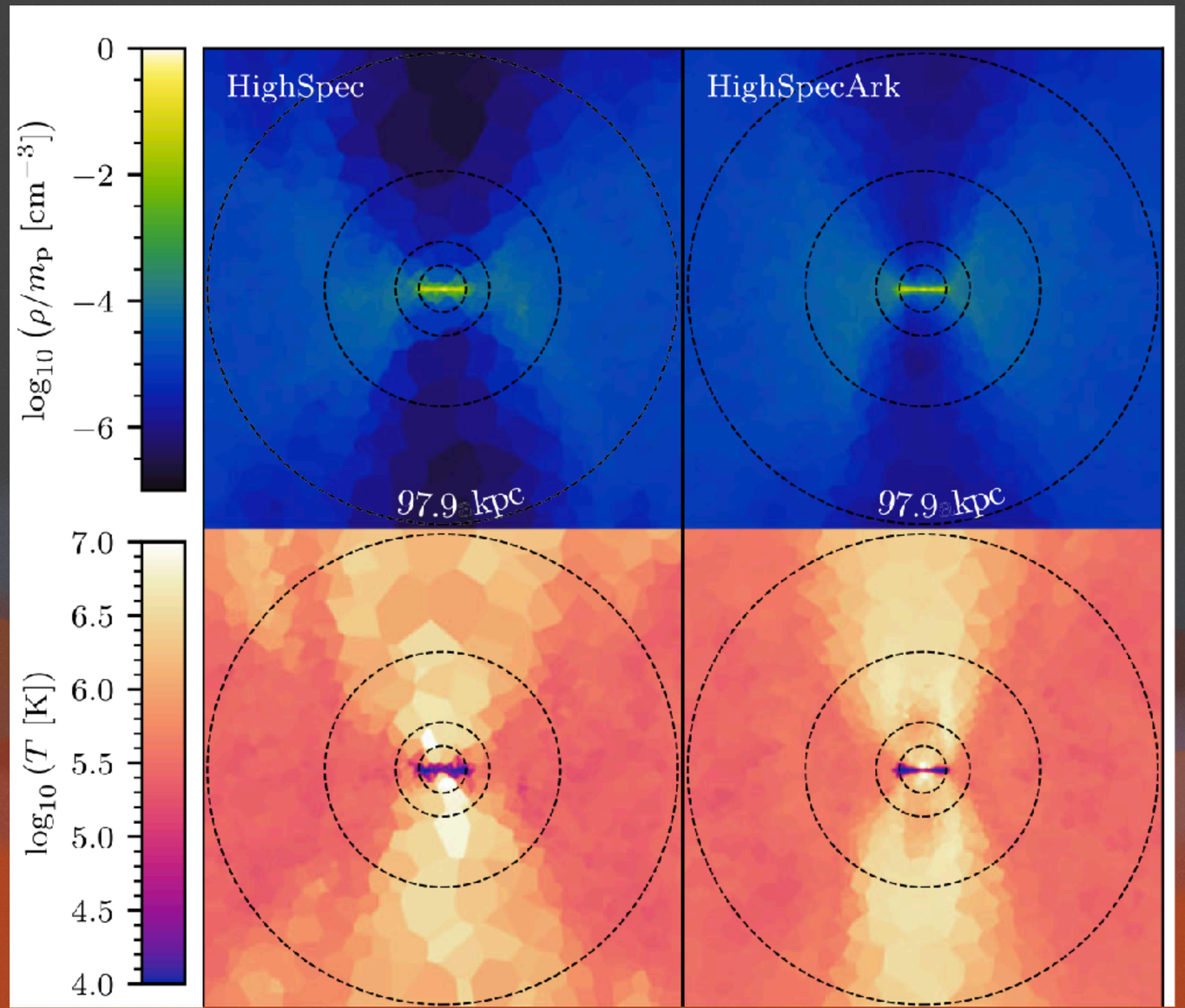
$$\frac{\eta_E}{\eta_M}$$ → Specific energy



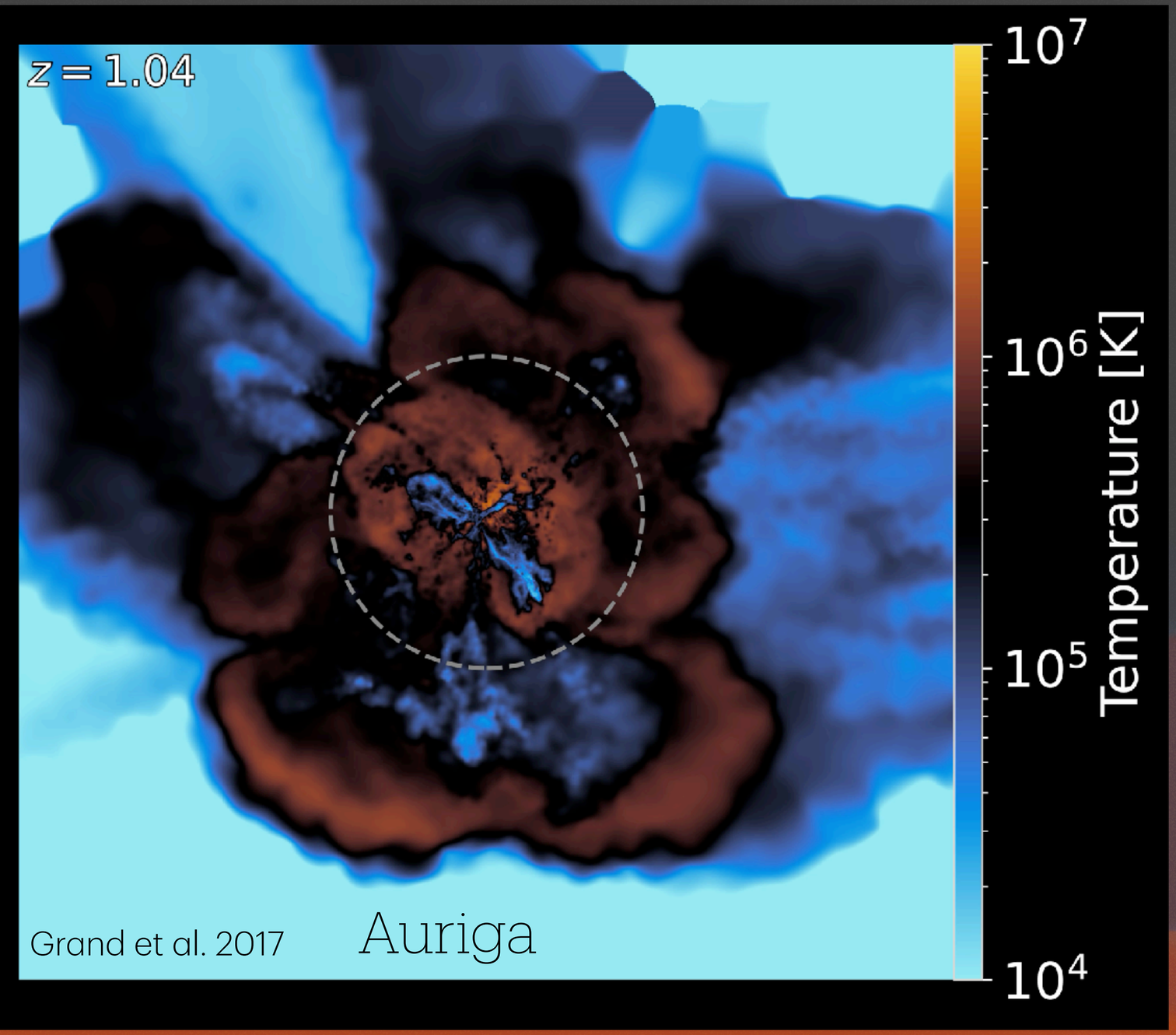
Smith et al. 2024a

High specific energy winds

$$\frac{\eta_E}{\eta_M}$$ → Specific energy



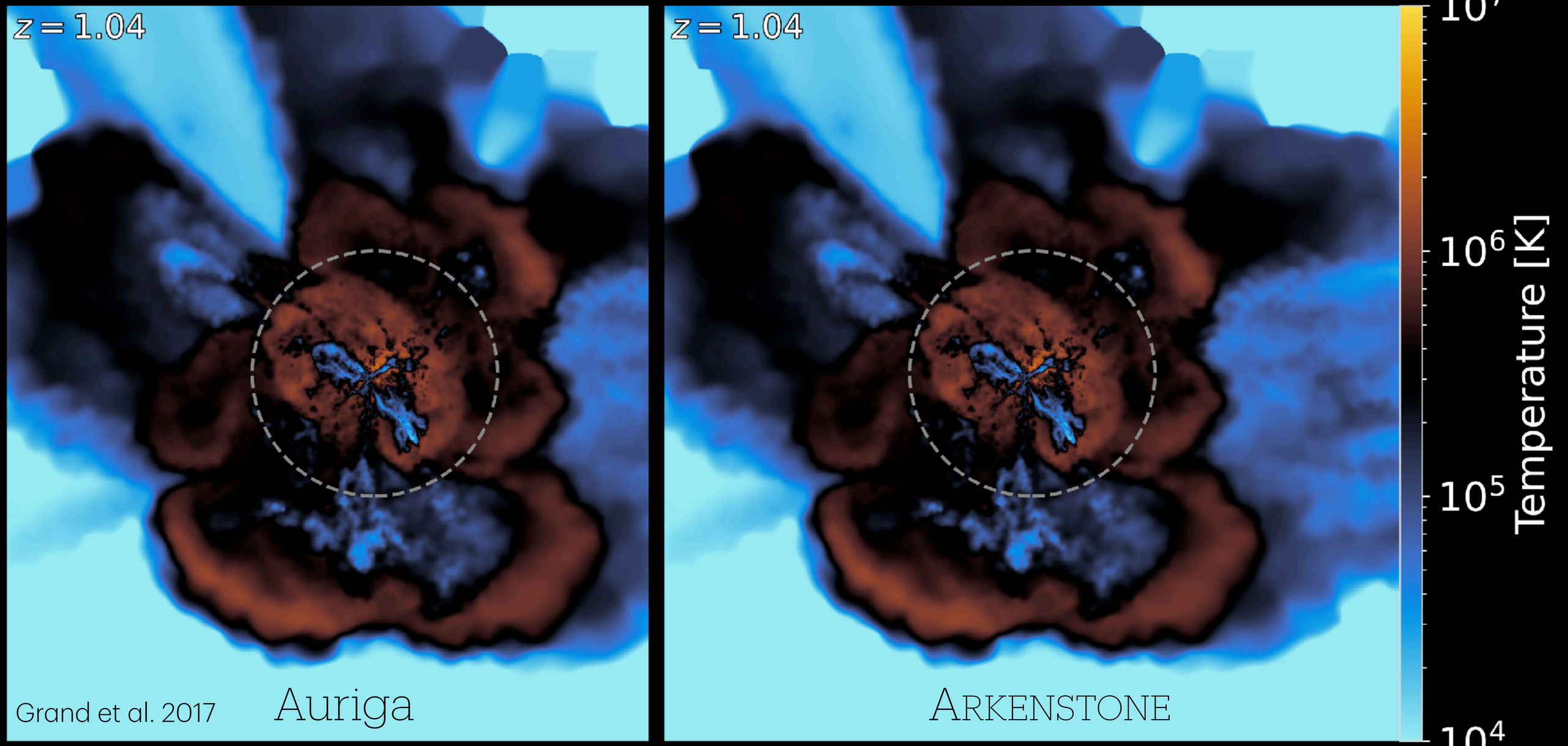
Smith et al. 2024a



Grand et al. 2017

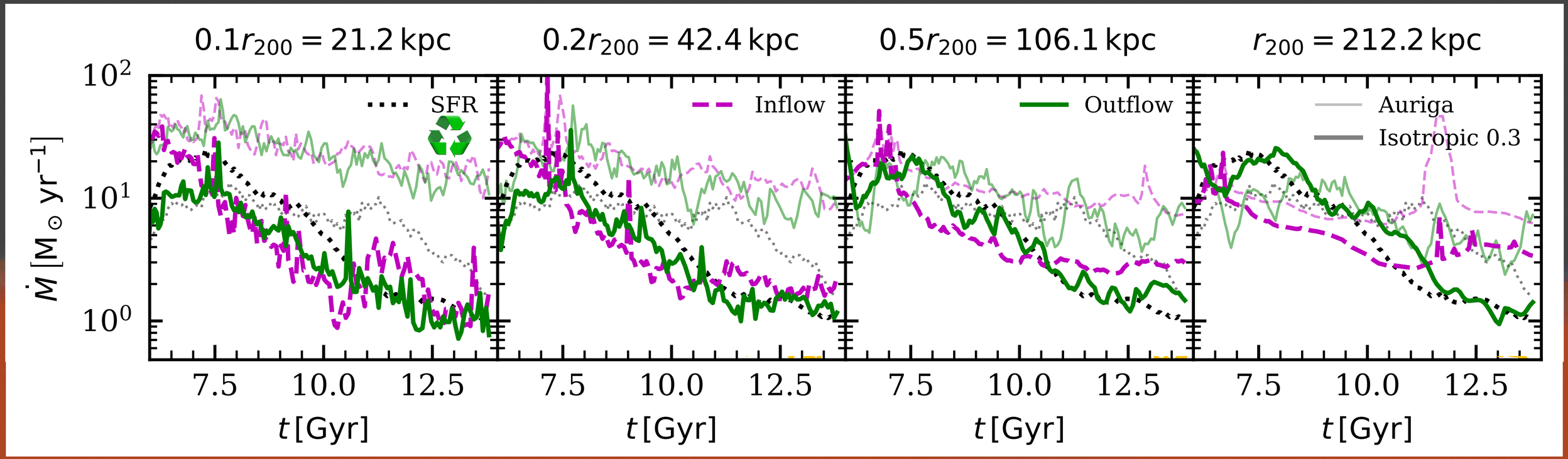
Auriga

Arkenstone

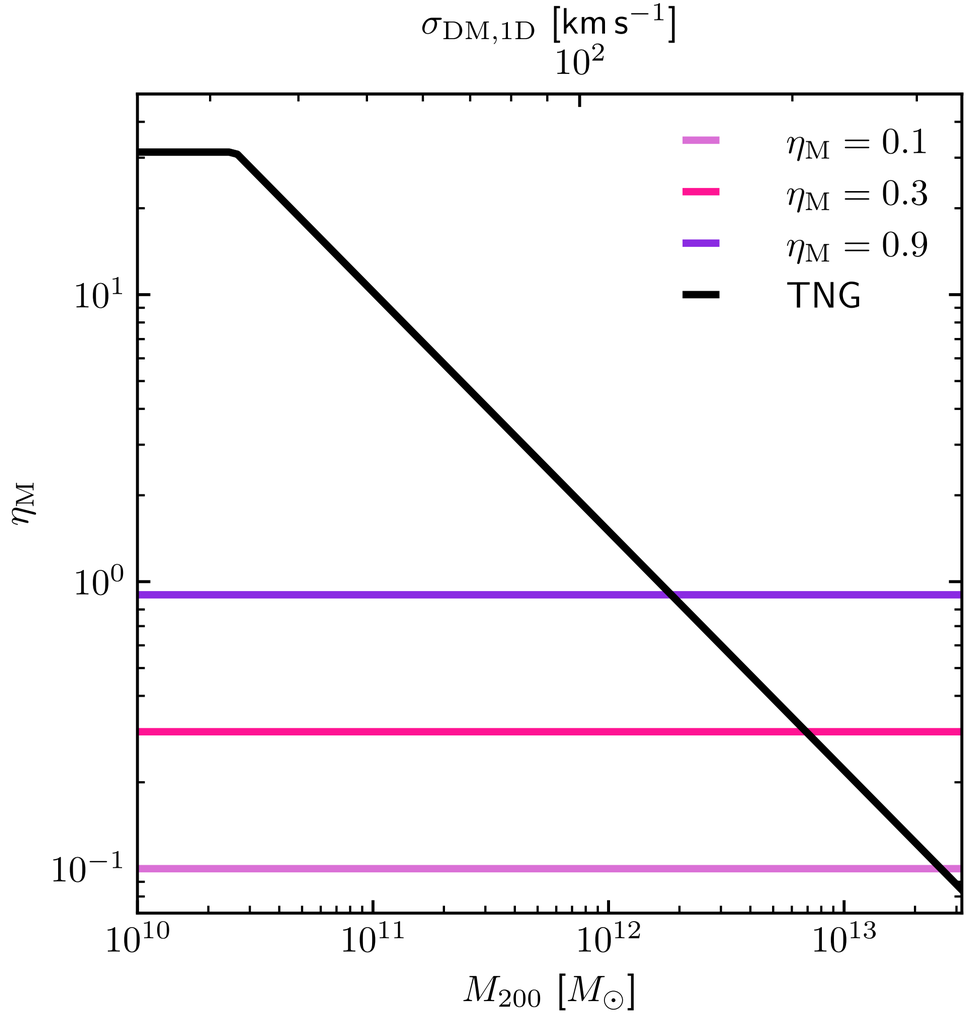

$z = 1.04$
$z = 1.04$
10^7
10^6
10^5
10^4
Temperature [K]
Grand et al. 2017
Auriga
ARKENSTONE
$\eta_E = 0.9, \eta_M = 0.3$

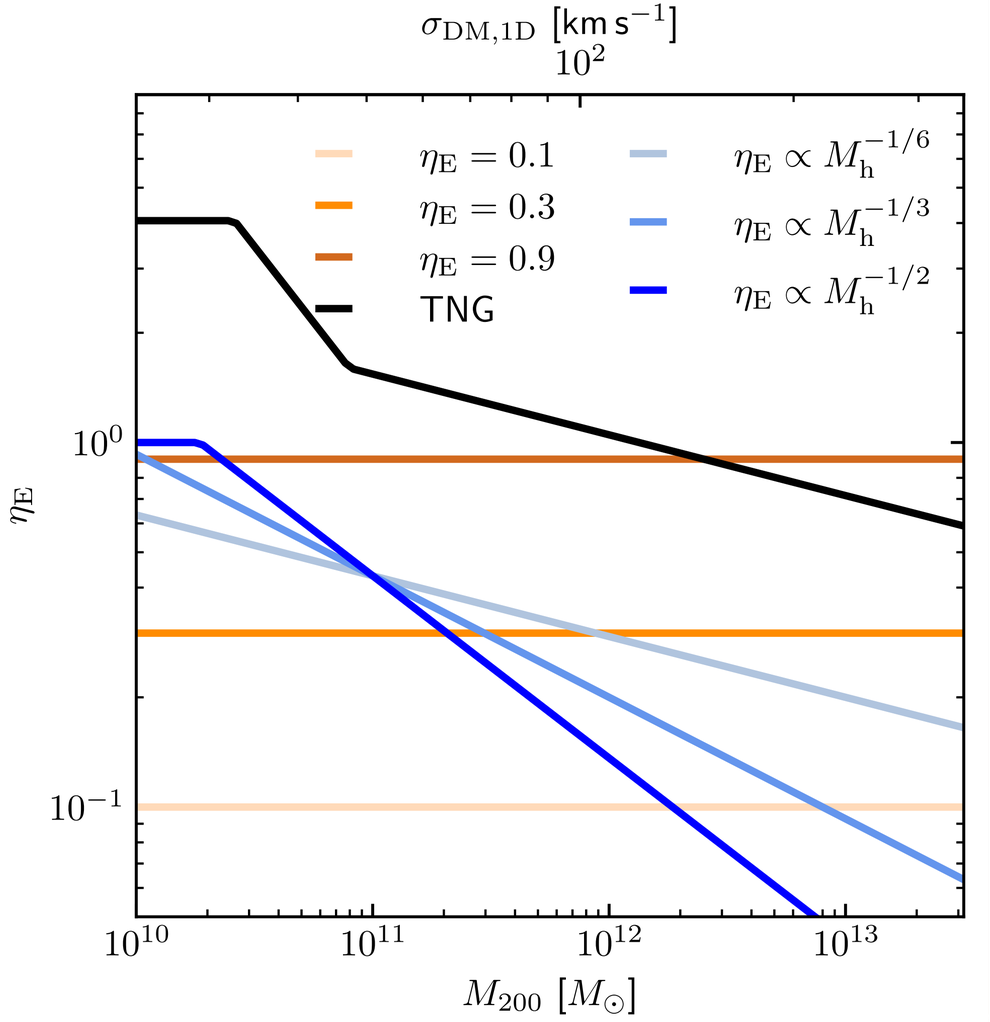
Preventative Feedback

- Cosmological zoom of $10^{12}\,\mathrm{M}_\odot$ halo
- ARKENSTONE ($\eta_\mathrm{E} = 0.3$, $\eta_\mathrm{M} = 0.3$) switched on at $z = 1$
- Inflowing and outflowing mass fluxes plummet



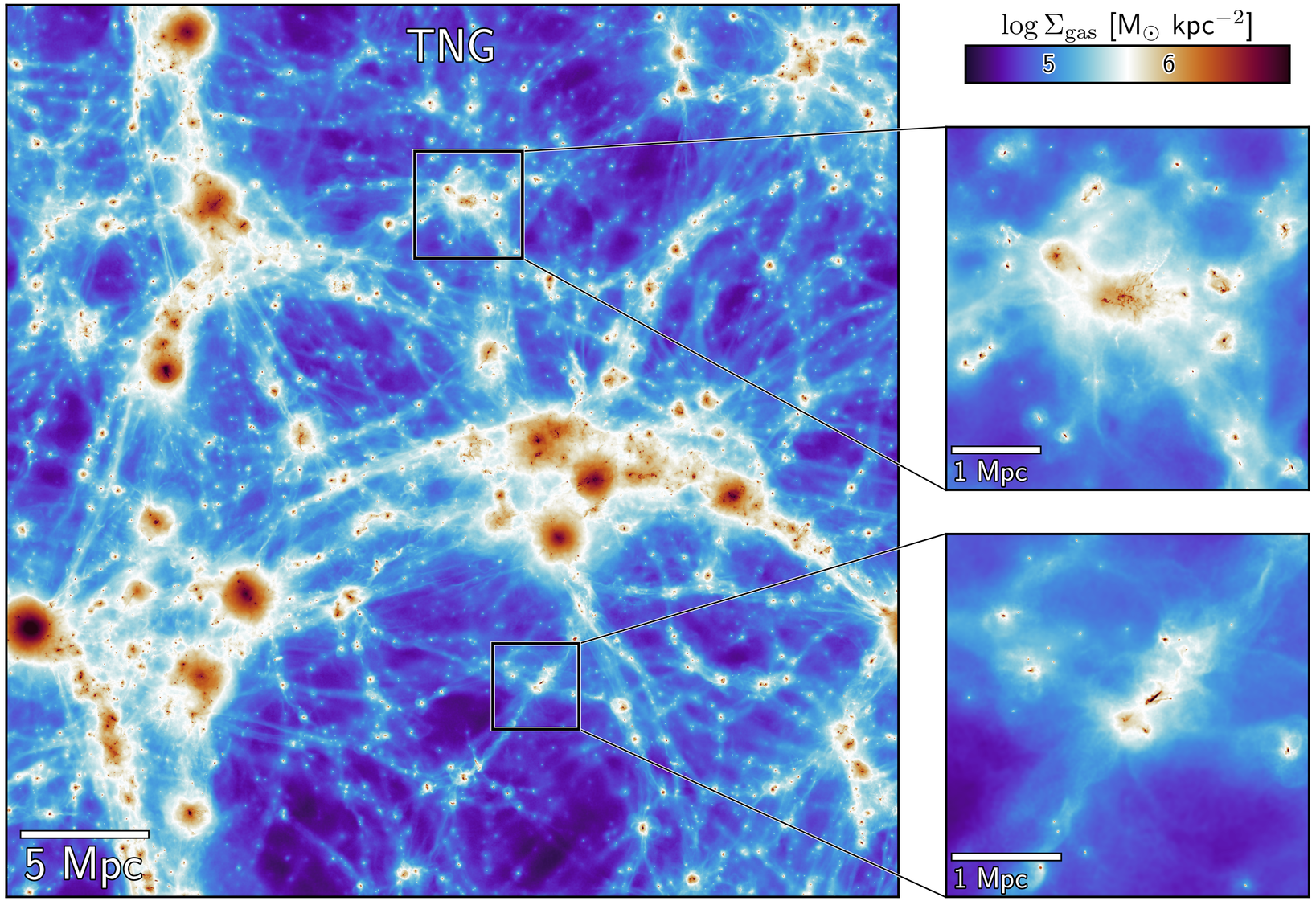
Cosmological Box - Loading Tests





Bennett et al. 2024

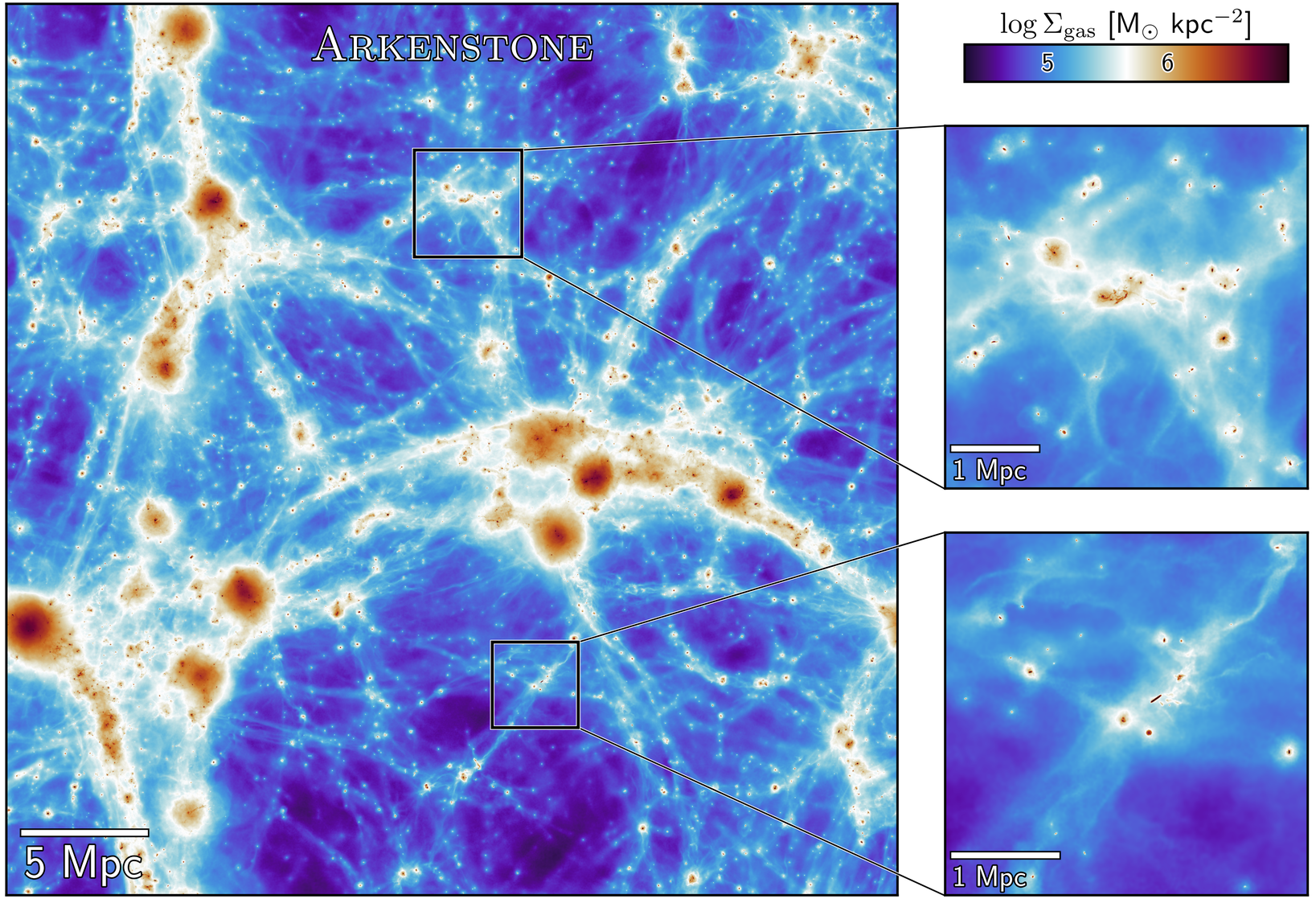
Cosmological Box - TNG



- 25 Mpc/h box
- 2 x 512^3 particles
- $m_{\rm gas} = 2 \times 10^6\ \mathbf{M}_\odot$

Bennett et al. 2024

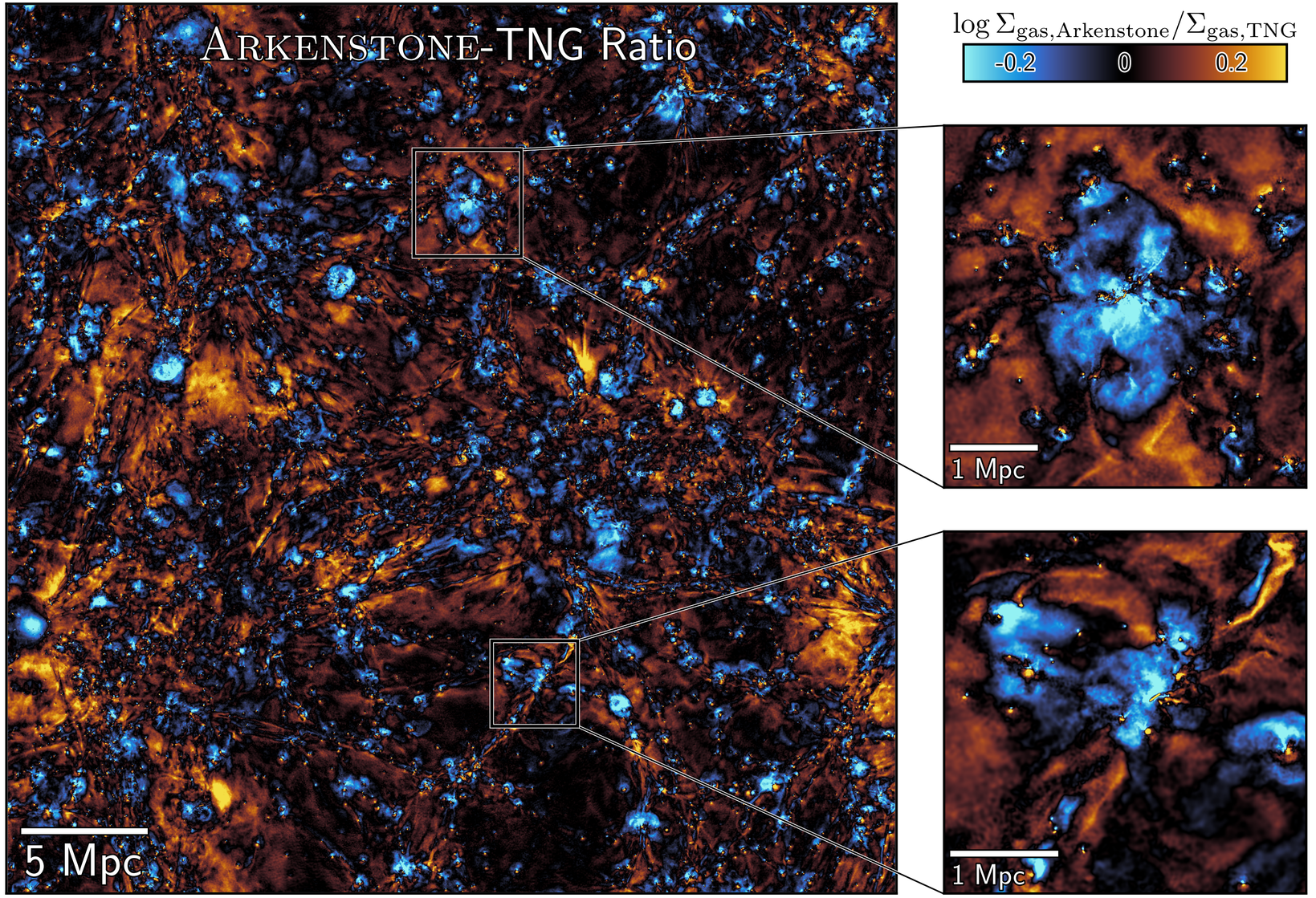
Cosmological Box - $\eta_E \propto M_h^{-1/3}$, $\eta_M = 0.3$



- 25 Mpc/h box
- 2 x 512^3 particles
- $m_{gas} = 2 \times 10^6\ M_\odot$

Bennett et al. 2024

Cosmological Box - $\eta_E \propto M_h^{-1/3}$, $\eta_M = 0.3$

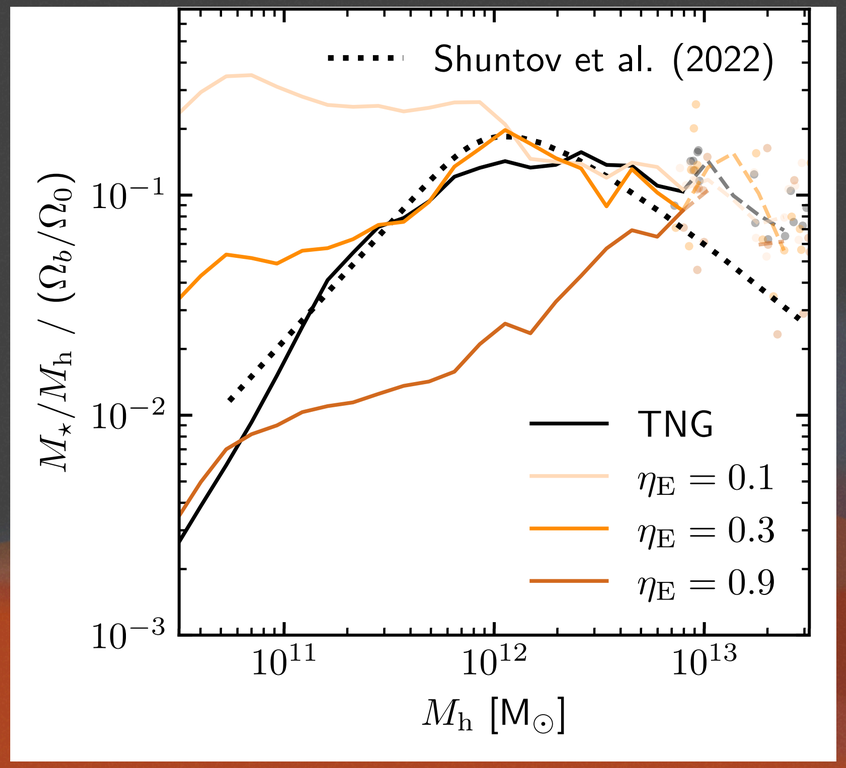


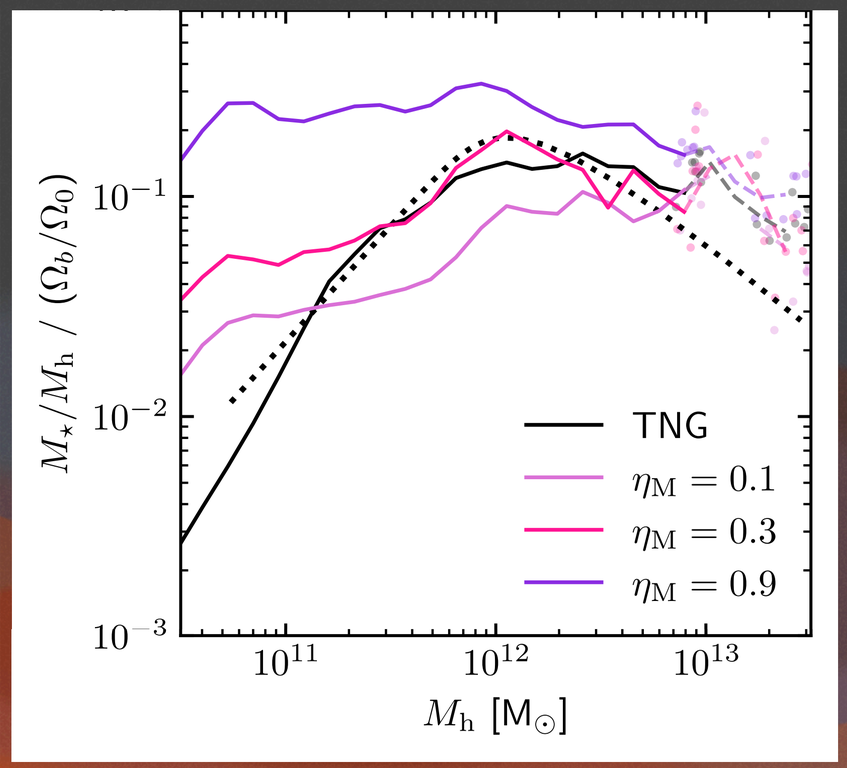
- 25 Mpc/h box
- 2 x 512^3 particles
- $m_{\rm gas}$ = 2 x 10^6 $\mathbf{M}_\odot$
- Gas is redistributed to large radii.
- IGM is heated.
- Potentially relevant for observables from FRBs to Lyα forest to SZ effect.

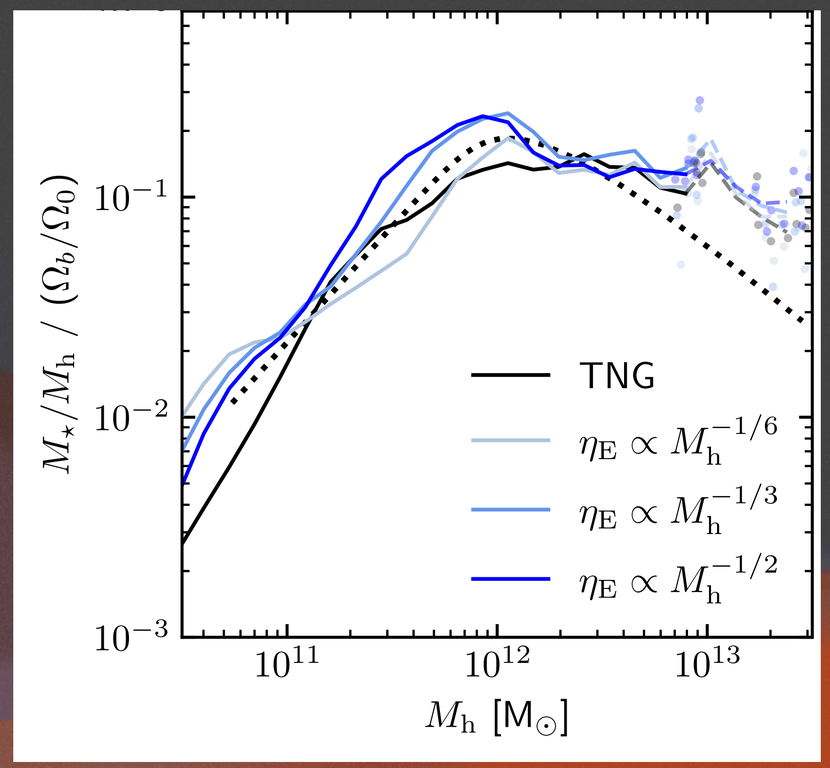
Bennett et al. 2024

Energy loading as king

The $z = 0$ stellar to halo mass relation - 25 Mpc/h box





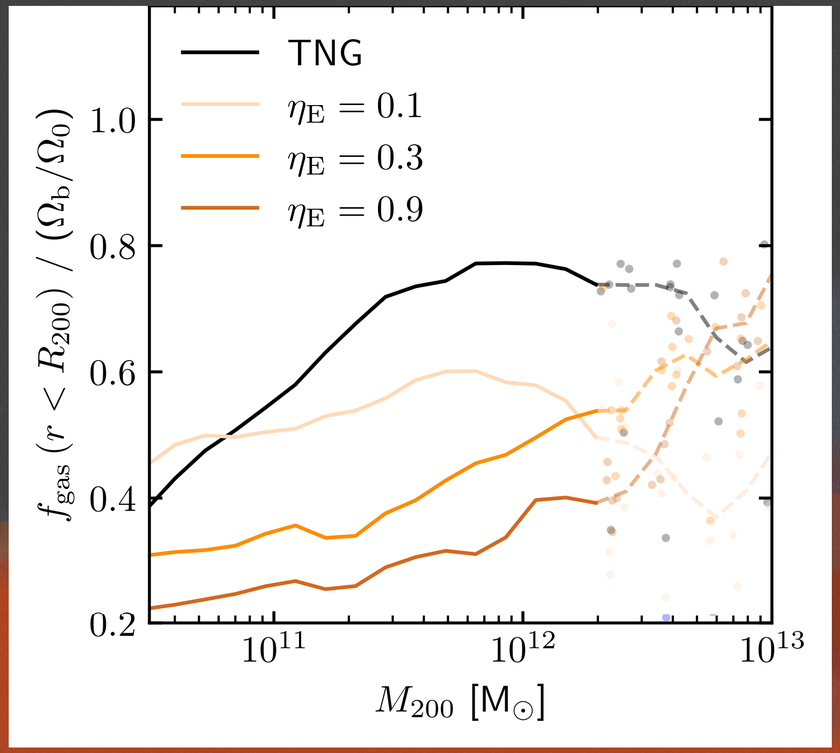


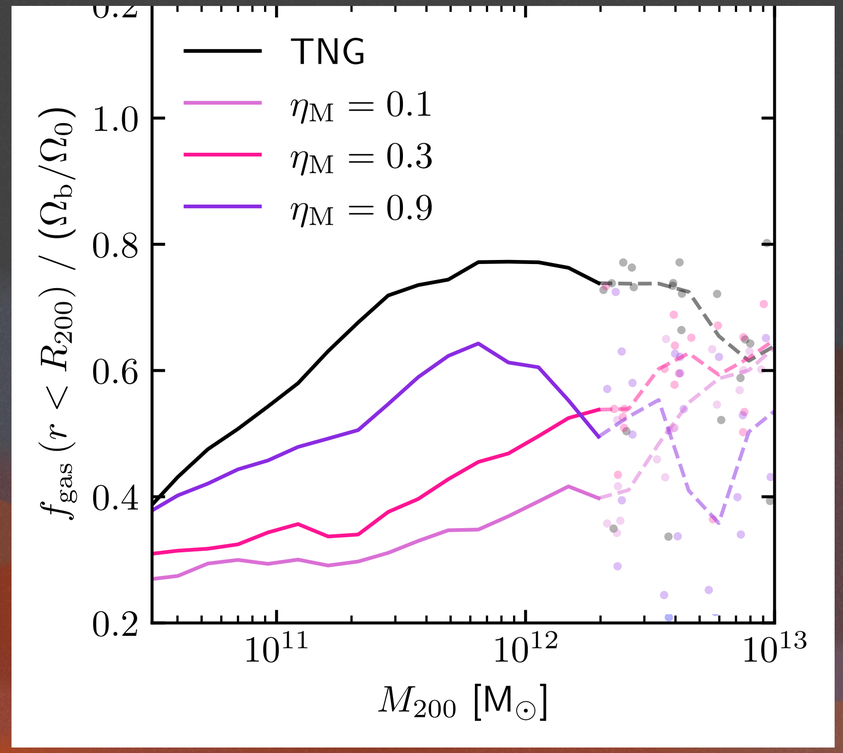
TNG Model: Weinberger et al. 2017; Pillepich et al. 2018 — but without B fields

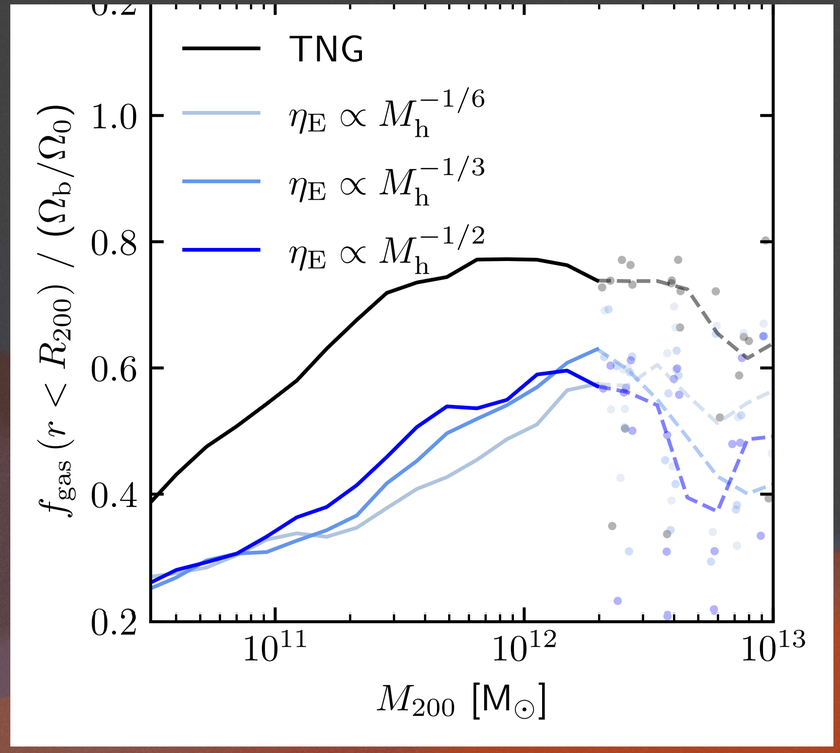
Bennett et al. 2024

How is star formation regulated?

ARKENSTONE depletes the CGM (here at $z = 2$)

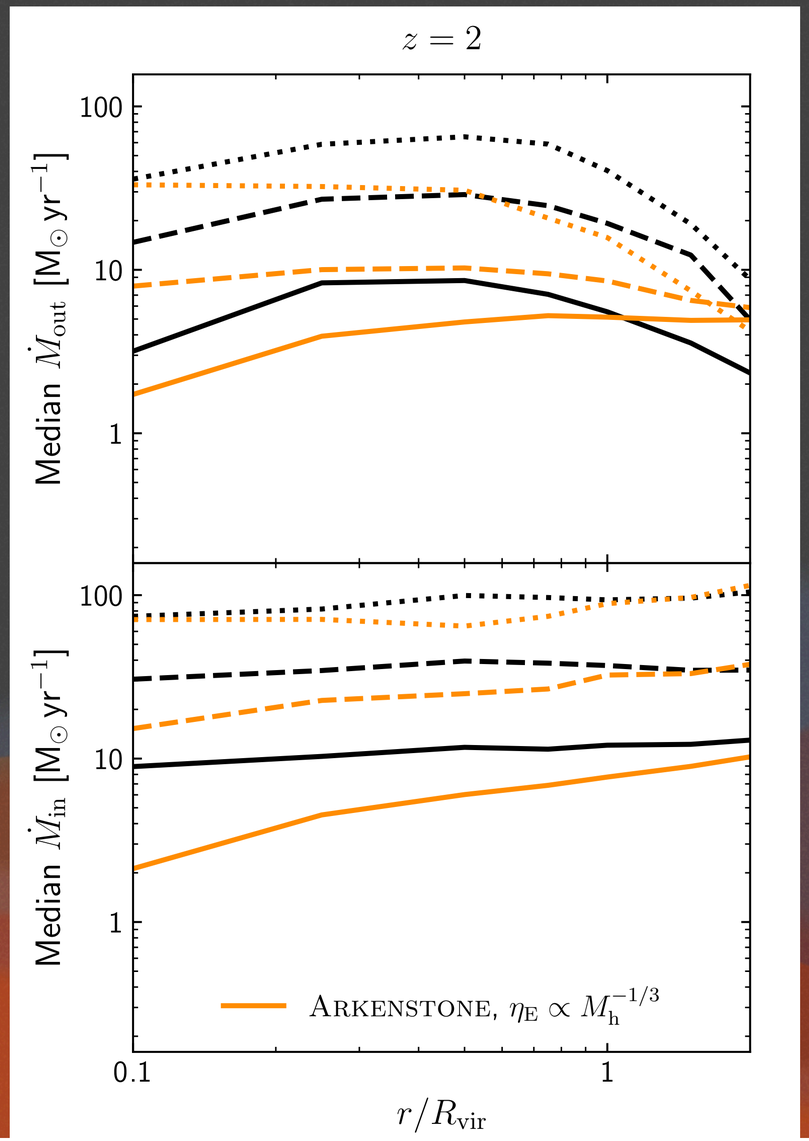






Bennett et al. 2024

How is star formation regulated?



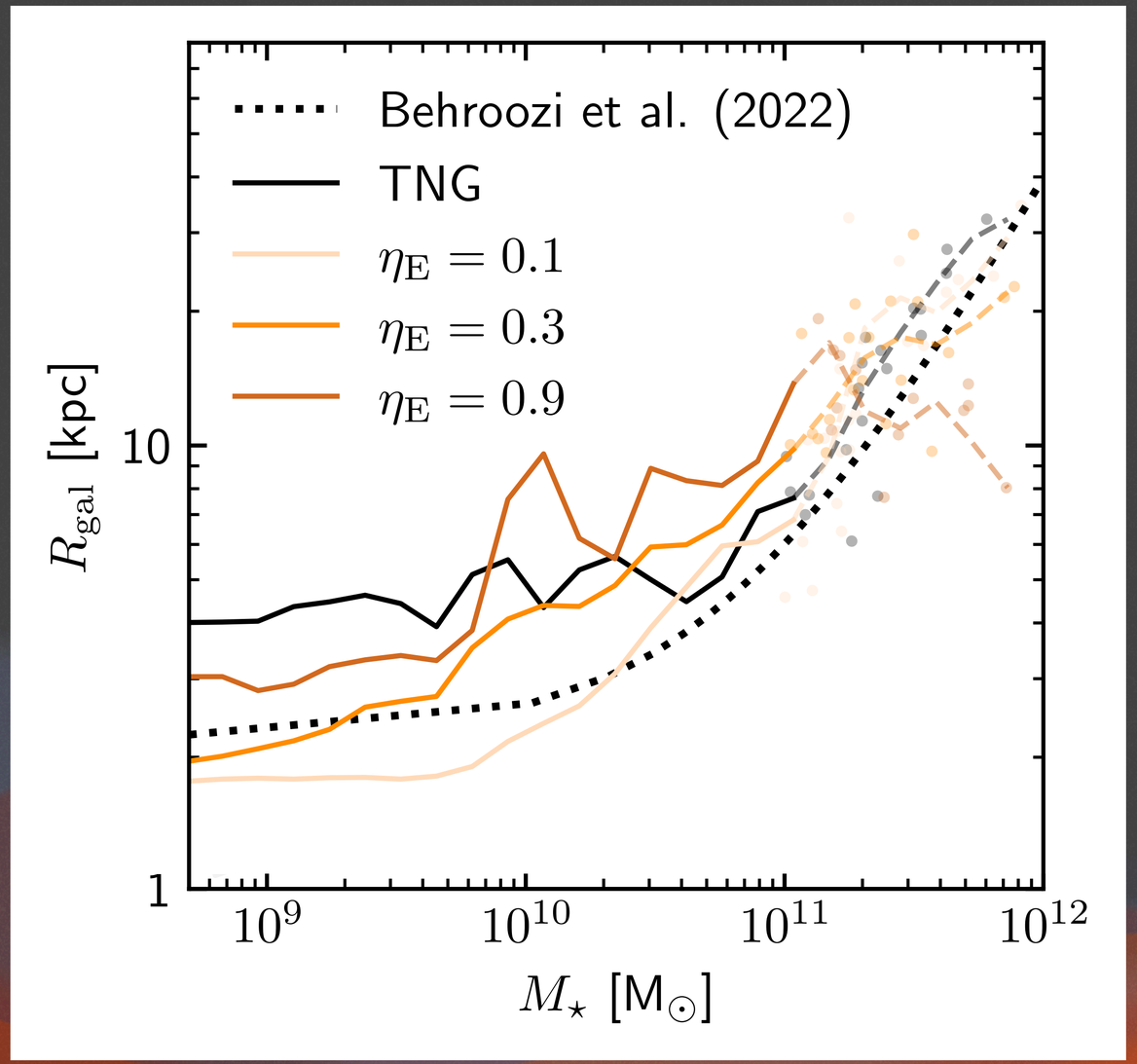
$11 < \log(M_{\rm h}/{\rm M}_\odot) < 11.5$ $11.5 < \log(M_{\rm h}/{\rm M}_\odot) < 12$ $12 < \log(M_{\rm h}/{\rm M}_\odot) < 12.5$

- Inflowing (and outflowing) mass fluxes are reduced.
- Clear signatures of prevention at $z = 2$.

Bennett et al. 2024

Galaxy sizes

- Galaxy stellar size seems to have a dependence on the energy loading.
- All Arkenstone runs have smaller low-mass galaxies than TNG.

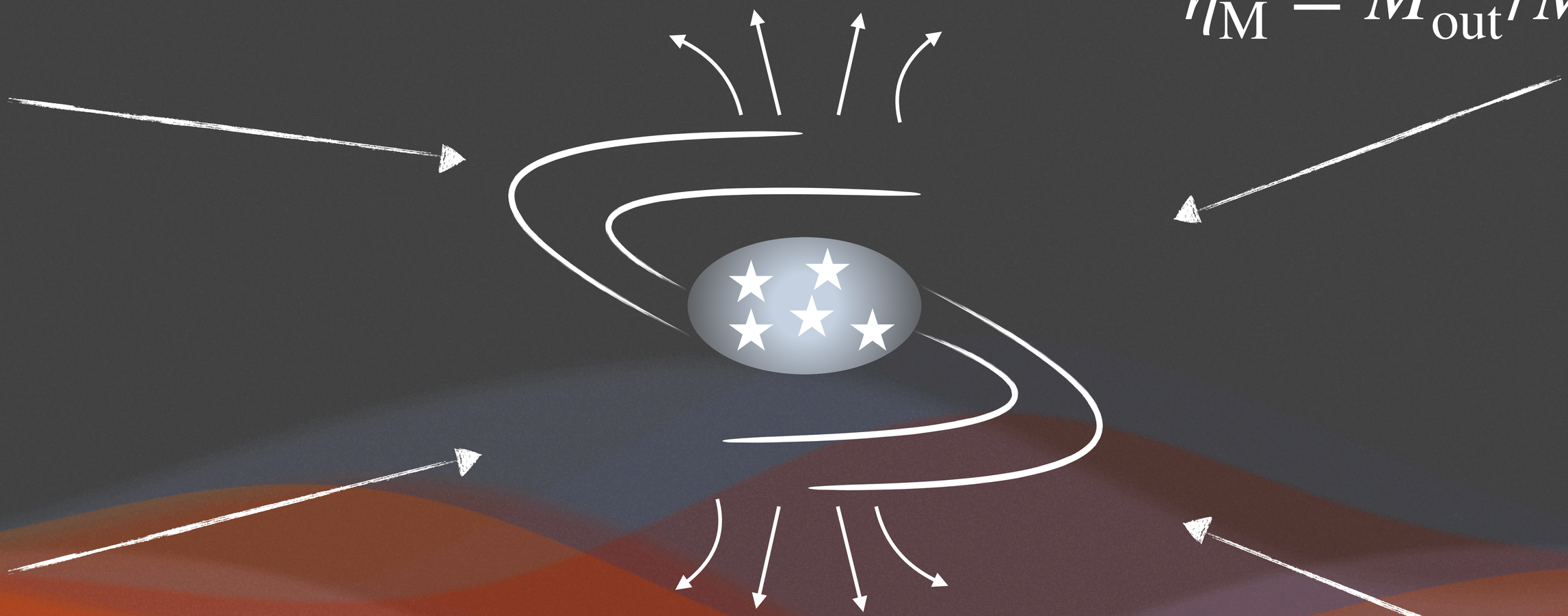


Bennett et al. 2024

Conclusions

$$\eta_{\mathrm{E}} = \dot{E}_{\mathrm{out}} / \dot{E}_{\star}$$

$$\eta_{\mathrm{M}} = \dot{M}_{\mathrm{out}} / \dot{M}_{\star}$$



Out with the (c)old (but not literally)

Conclusions

$$\eta_E = \dot{E}_{out}/\dot{E}_\star$$

$$\eta_M = \dot{M}_{out}/\dot{M}_\star$$

- High specific energy winds can regulate via <u>preventative</u> feedback.
- We have explored this for the first time in cosmological simulations.
- The content of the CGM is key, but many interesting secondary properties!

ARKENSTONE:

Smith et al. 2024a,b

Bennett et al. 2024b

Out with the (c)old (but not literally)

And in with the η_Ew...

“But what about metals?”