Impact of Star Formation on the Growth of Galaxies in Numerical Simulations

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The 11th KIAS workshop on Cosmology and Structure Formation

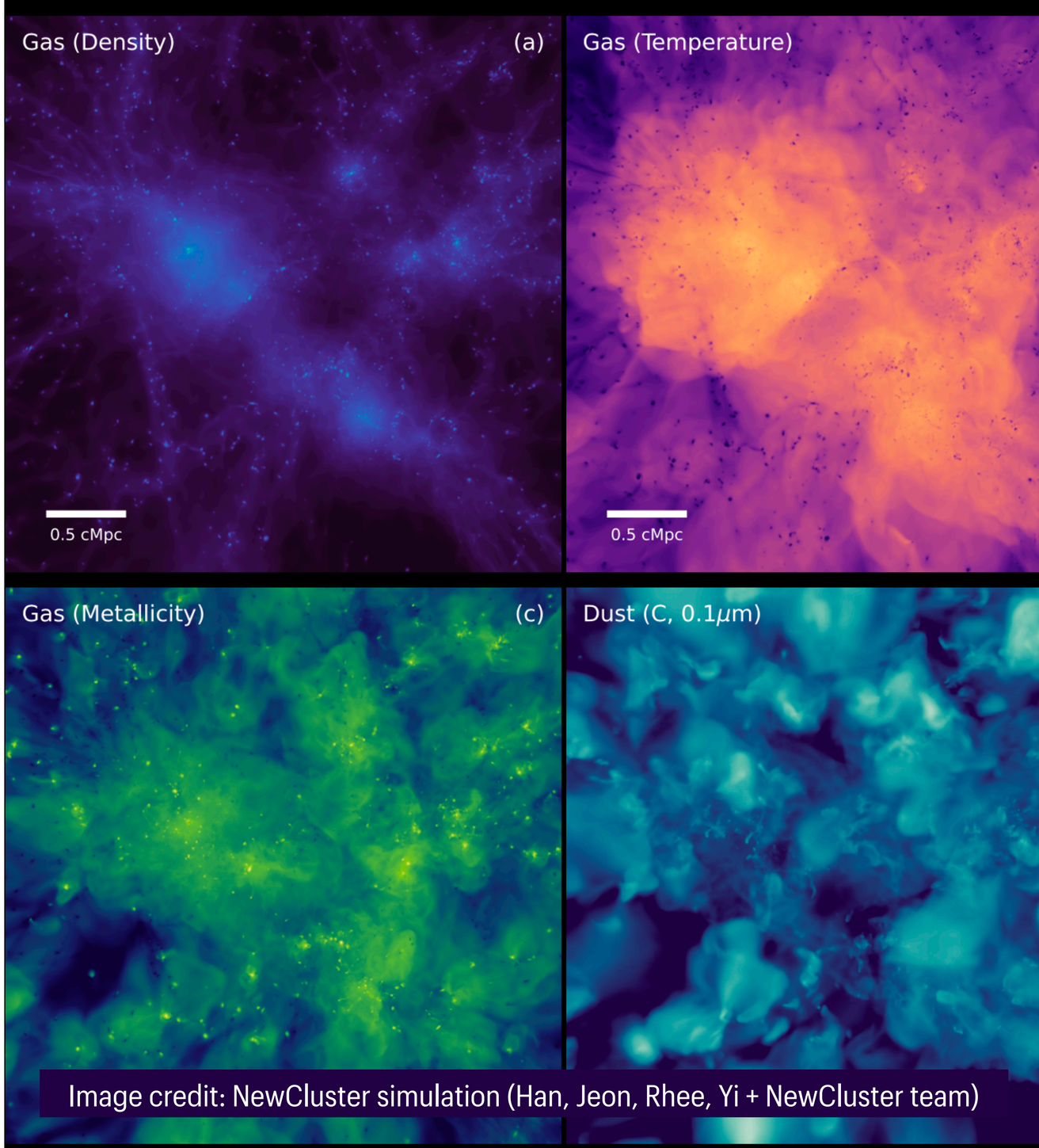
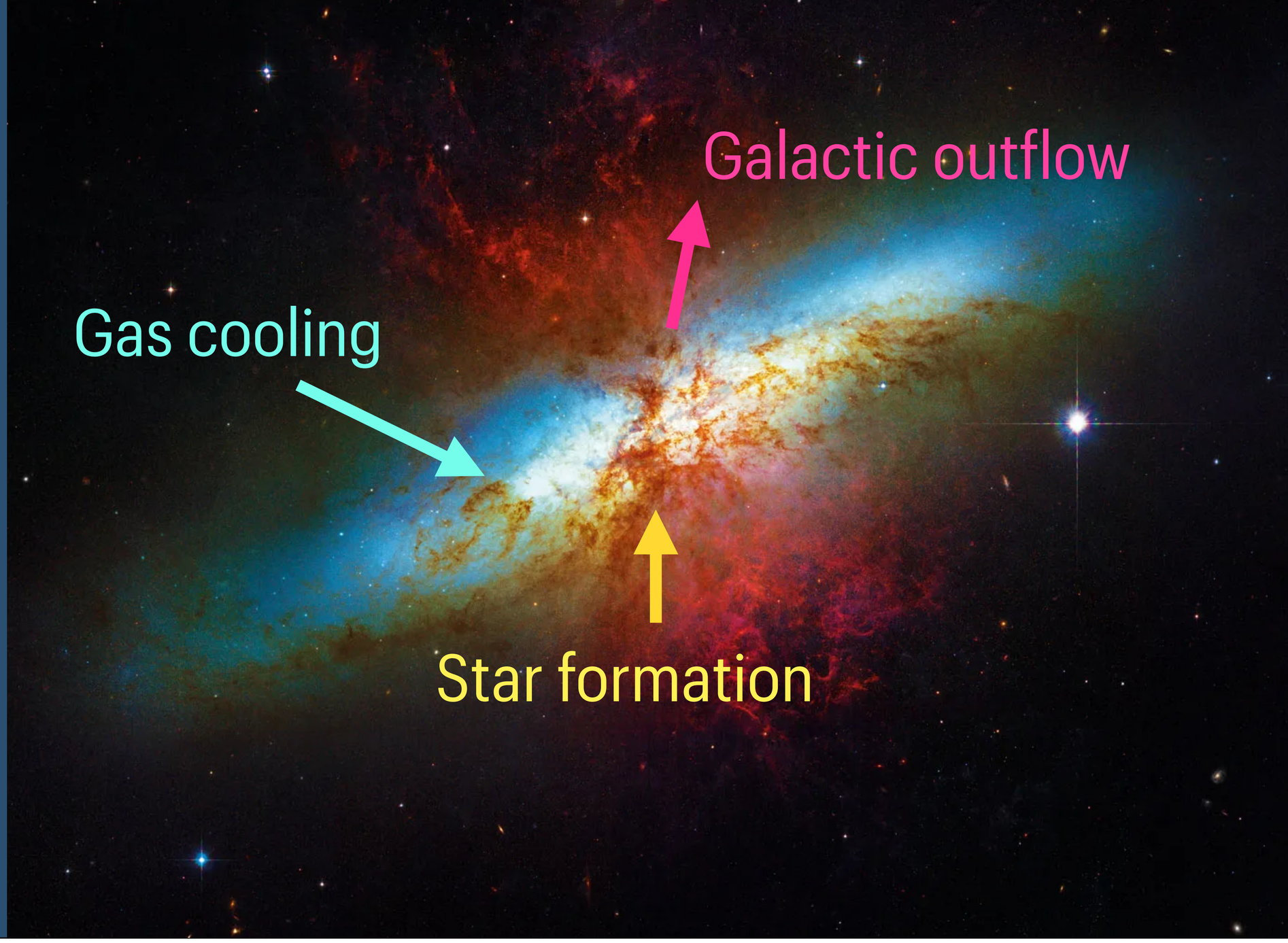


Image credit: NewCluster simulation (Han, Jeon, Rhee, Yi + NewCluster team)

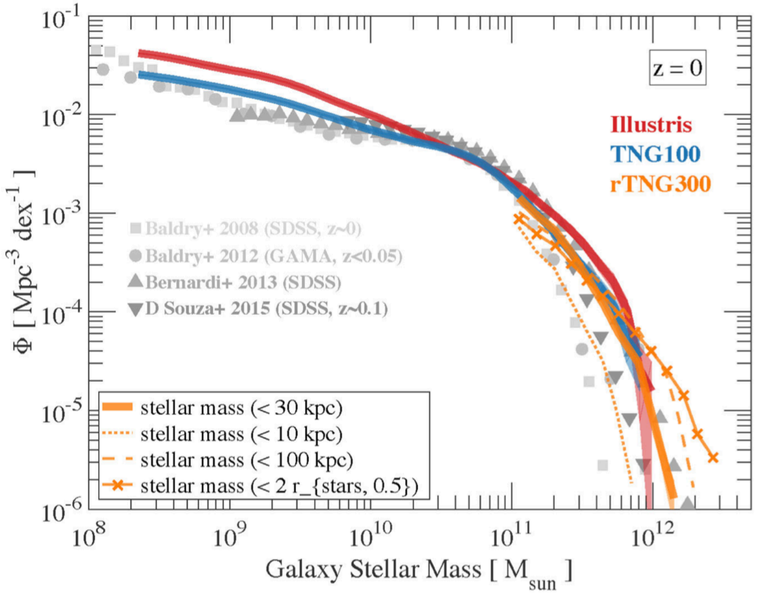
Galaxy Formation
~
Baryon Cycle



Theoretical models have been successful in several ways

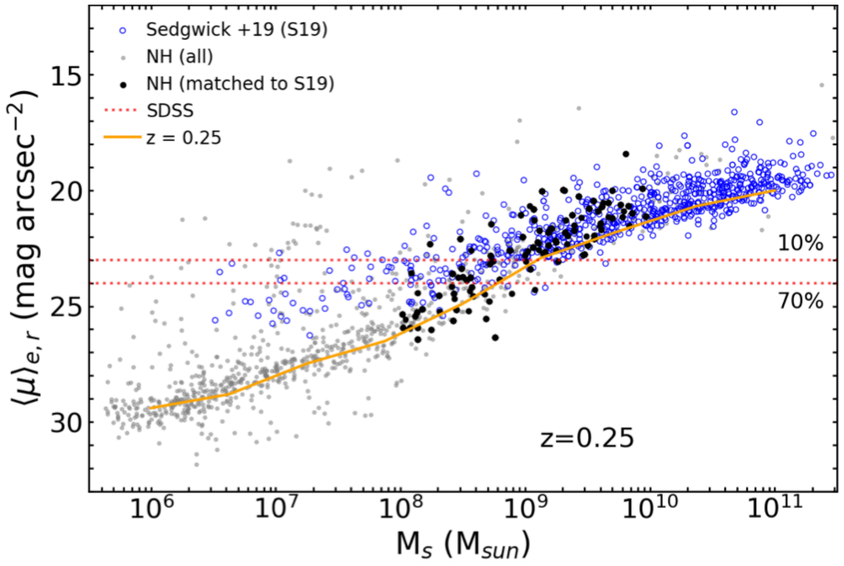
Illustris-TNG

(Pillepich+18)



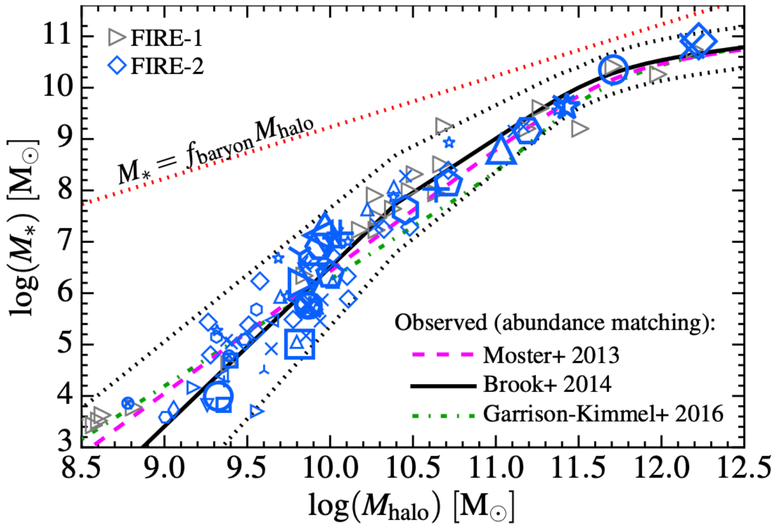
NewHorizon

(Dubois+21)



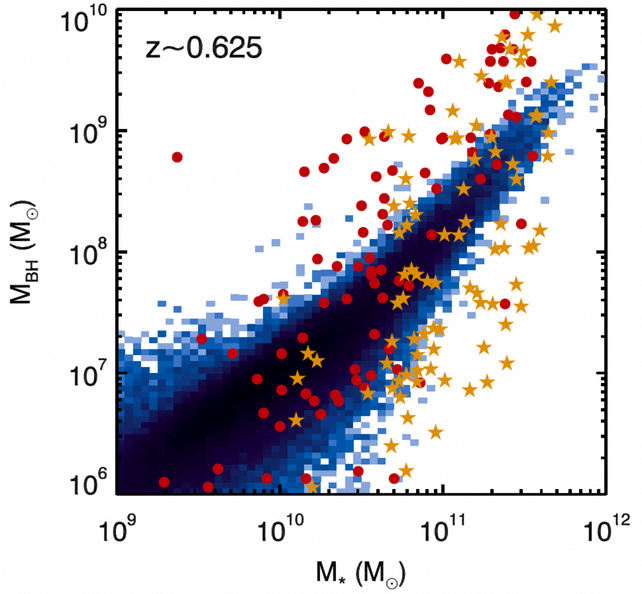
FIRE-2

(Hopkins+18)

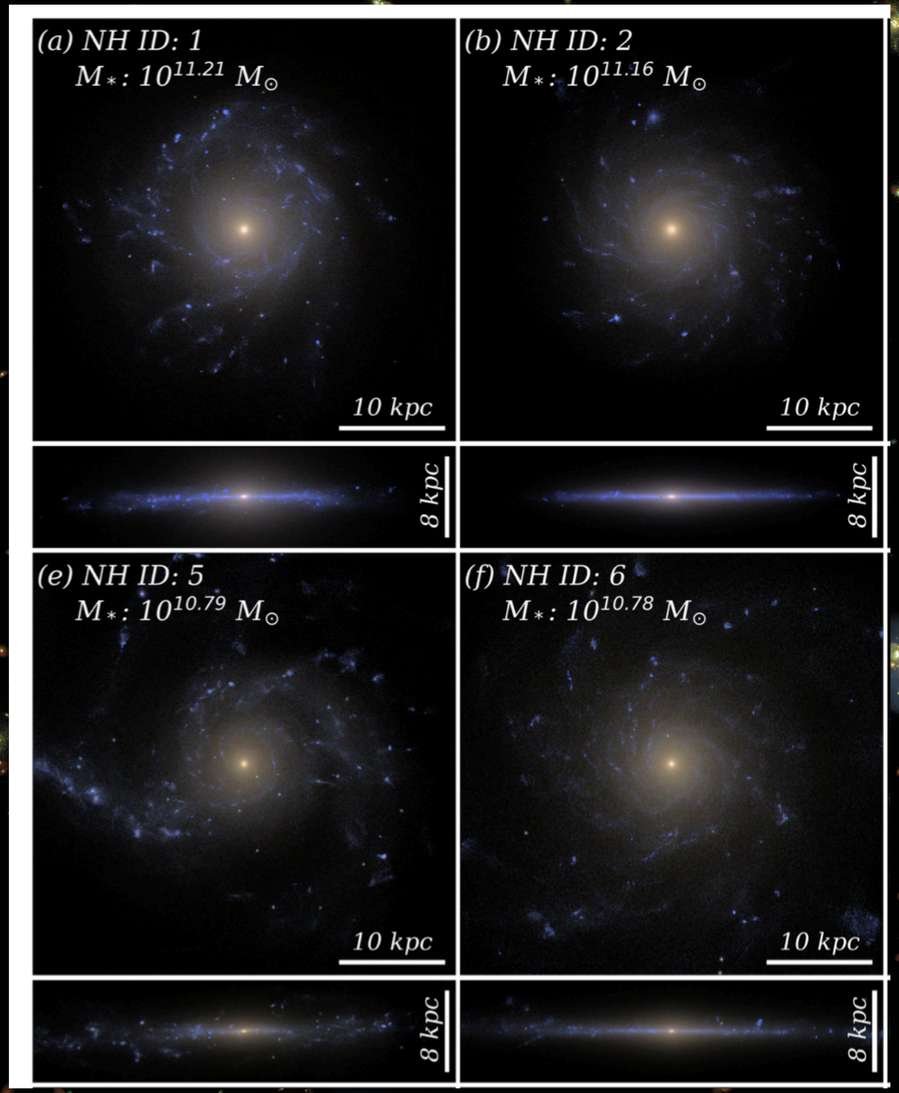


Horizon Run 5

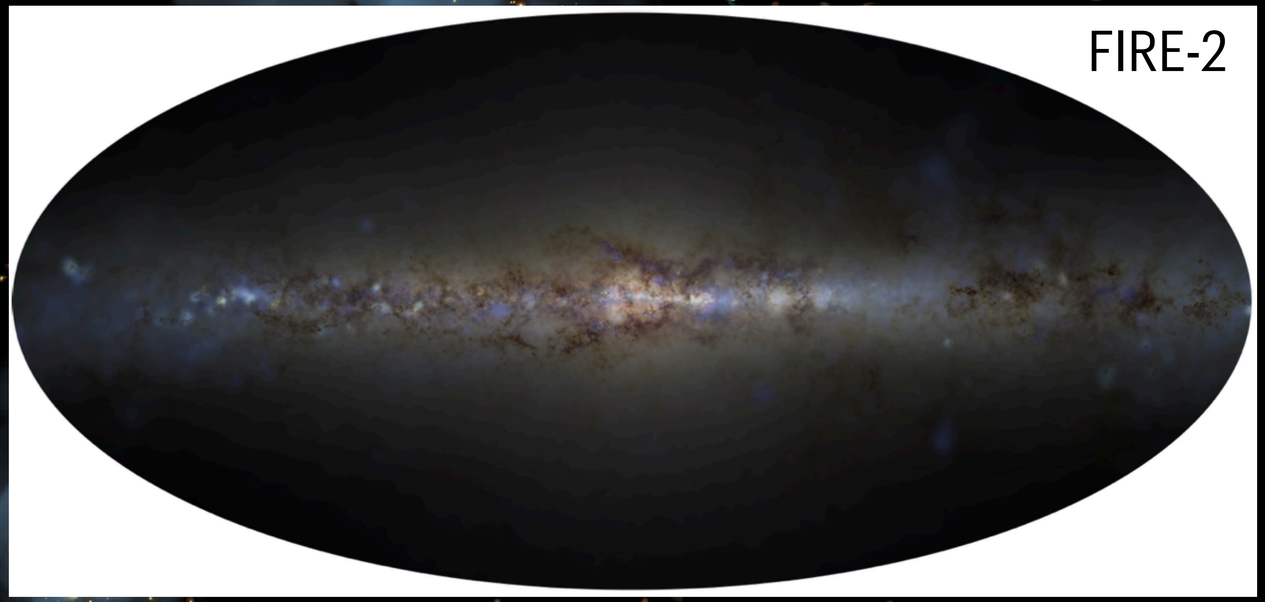
(Lee JH+21)



Predictions are becoming more realistic: zoom-in simulations



NewHorizon, NH2 (Yi et al. 23)



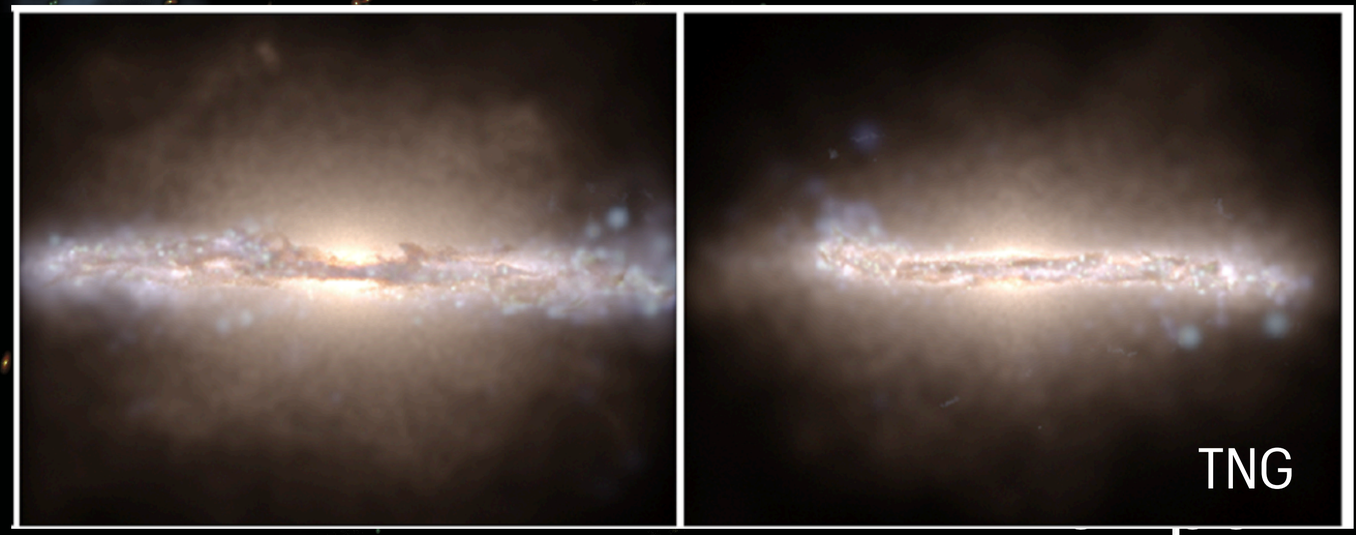


Image credit: Jaehyun Lee & HR5 collaboration

Uncertainties in numerical modeling of galaxy formation

Gas cooling

- Fully coupled photo-chemistry (uncertainties in metal yields, stellar IMF)
- Unstable cold filamentary accretion, recycling of galactic fountains
- Gas accretion on to the DMH in the presence of strong magnetic fields

Star formation

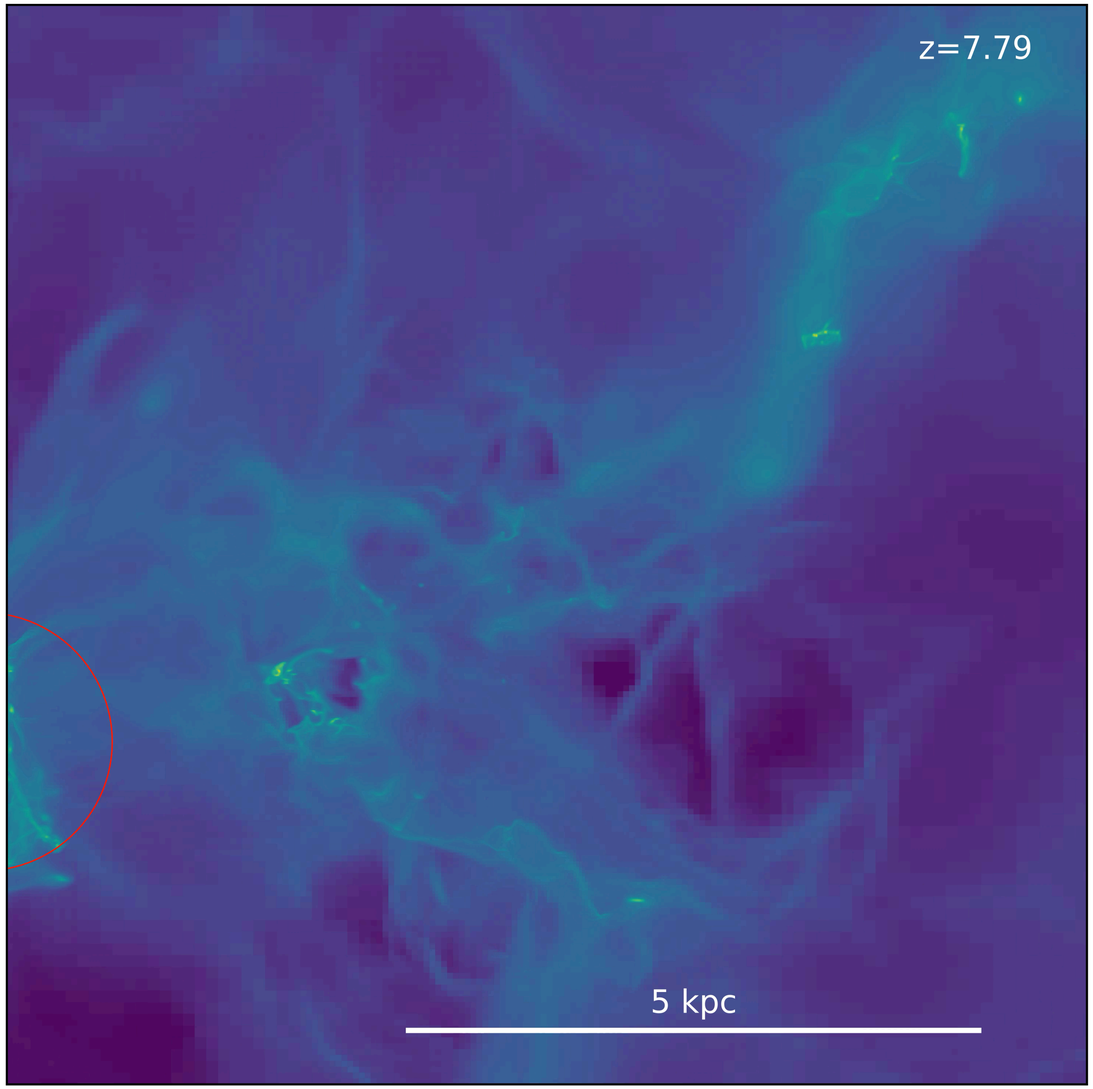
- Star formation efficiency per free-fall time
- Runaways, pre-stellar feedback, magnetic fields



Stellar feedback

- Uncertainties in stellar physics: stellar IMF, hypernovae
- Unknown feedback processes (CR pressure, line-driven winds etc)
- Different entrainment due to gas clumping/fragmentation
- Clustering of star formation

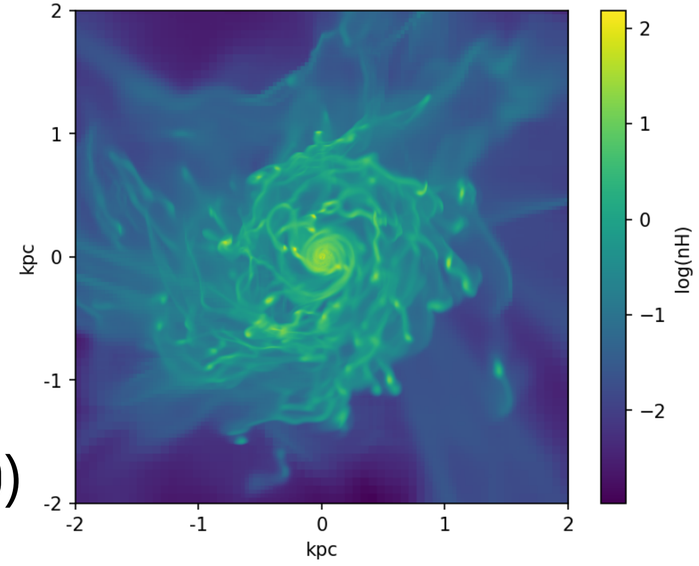
How do we know if a model fails? Overcooled features



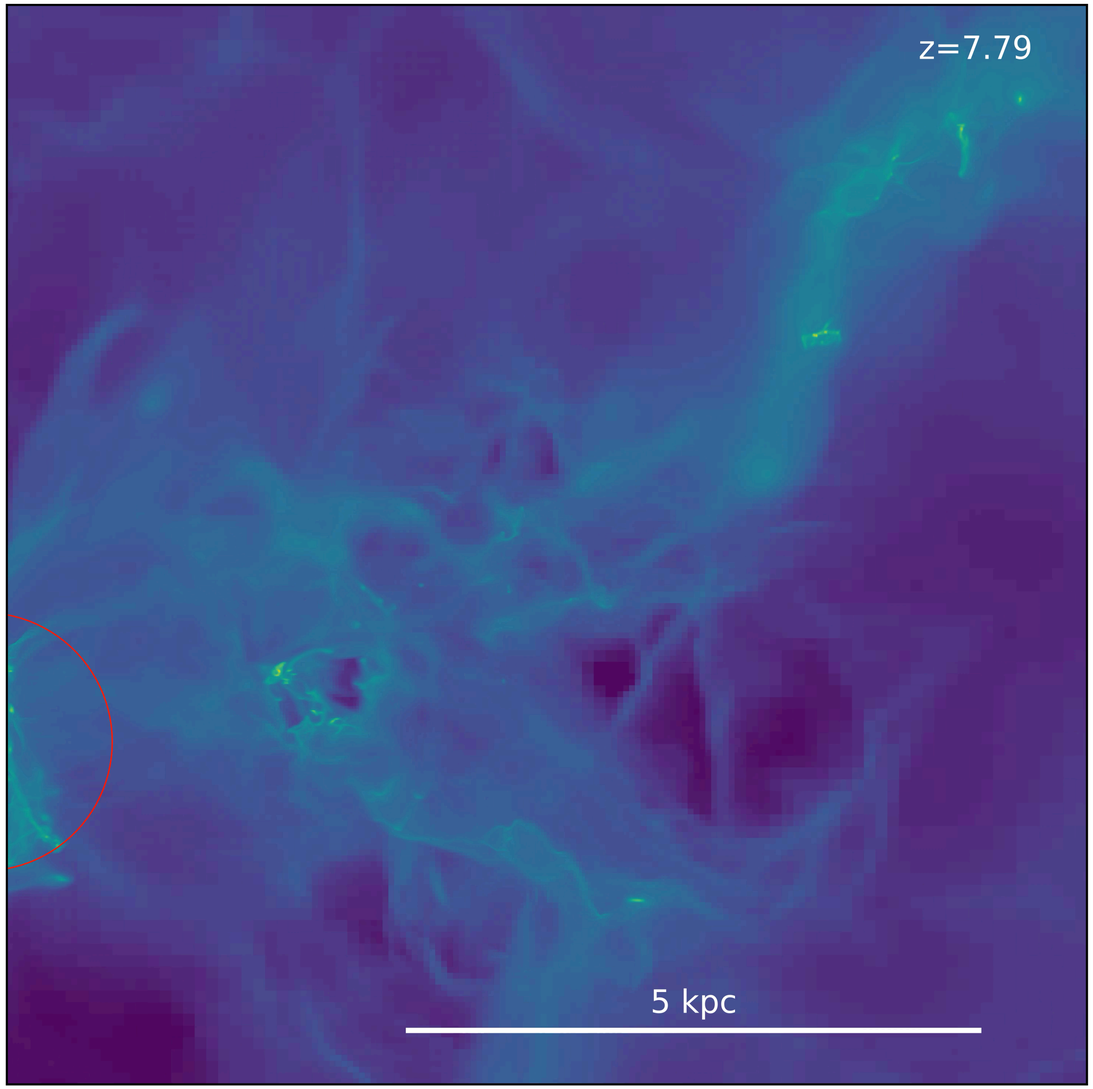
Kang et al. (in prep)

- RAMSES-RT (Rosdahl & Teyssier 15)
- Initial condition: GenetIC (Stopyra+20) <- More accurate IC
- M_{halo} ~ 10^{10} $M_\odot$ at $z = 6$
- Radiation + mechanical SN feedback <- More accurate fb
- Δx_{min} ~ 7 pc

Δx_{min} ~ 1 pc (z~10)



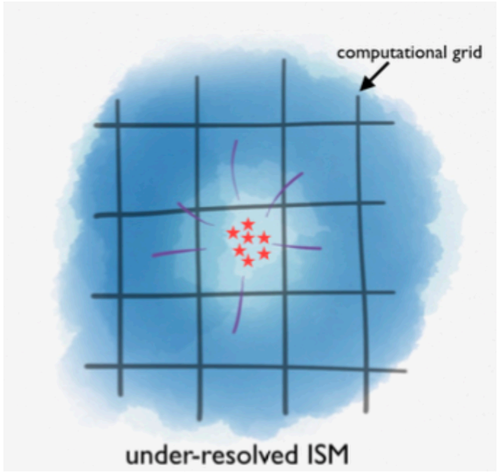
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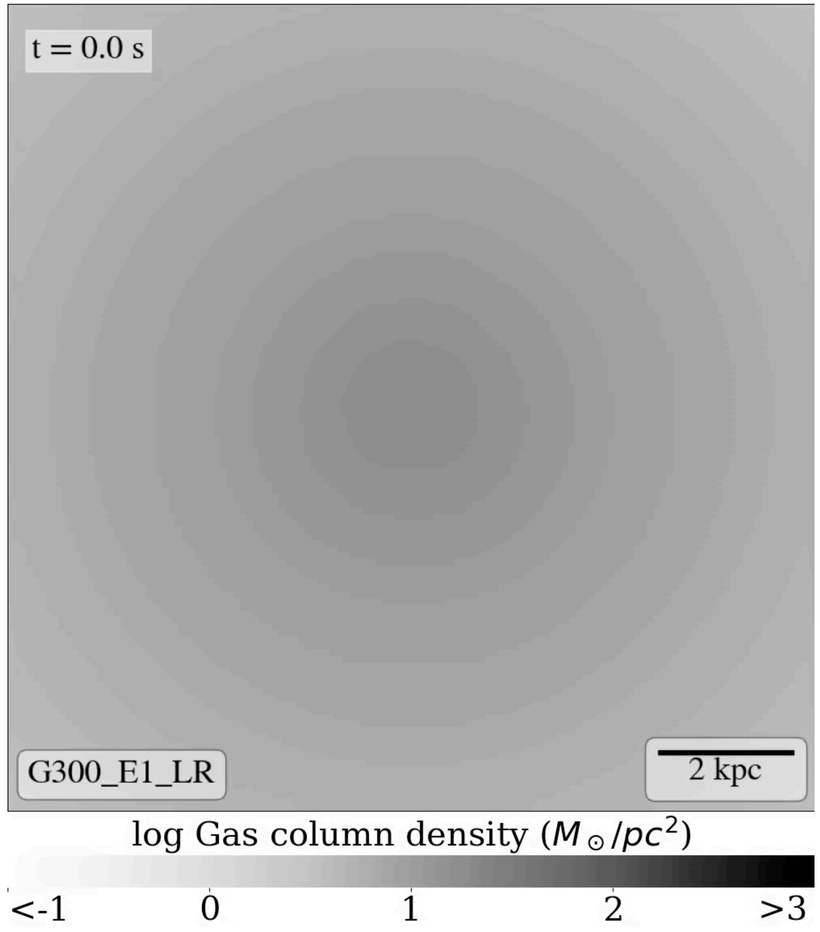
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- Δx_{min} ~ 7 pc
- Star formation: Multi-freefall ($\epsilon_{ff} = f(\alpha_{vir}, \mathcal{M}) \sim 0.2$)

from turbulent box simulations
e.g. Federrath & Klessen (12)



$$\frac{dM_\star}{dt} = \epsilon_{\rm ff}\frac{M_{\rm gas}}{t_{\rm ff}}$$

Different view of the over-cooling in an isolated galaxy simulation





- Code: RAMSES-RT
- RHD simulation of a NGC300-like galaxy (isolated)
- DMH mass: $3\times10^{11}\ M_{sun}$
- Type II SNe + Radiation feedback
- Max resolution: 8-16 pc
- Star formation: Multi-freefall

GMCs are often (unrealistically) long-lived -> **problem**!

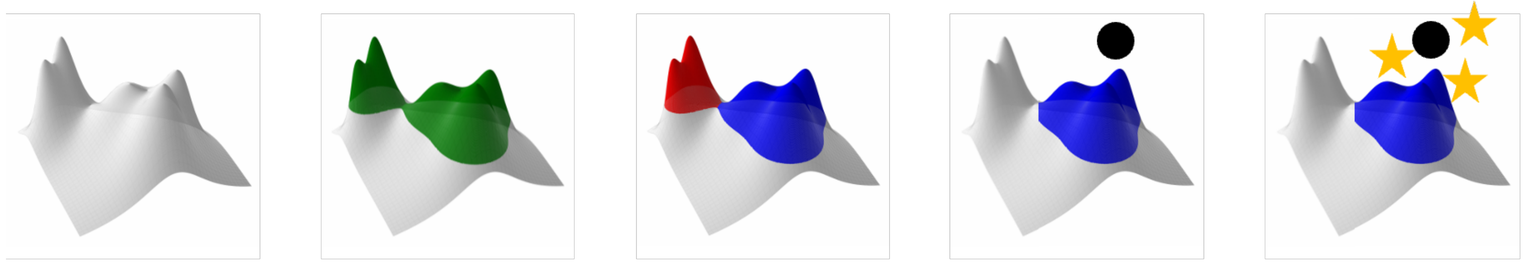
(c.f. disruption time scale in GMC simulations or observations is on the order of 5-10 Myr)

How can we model star formation more accurately? sink particle!

(1) create a seed of sink particles in locally Jeans unstable regions

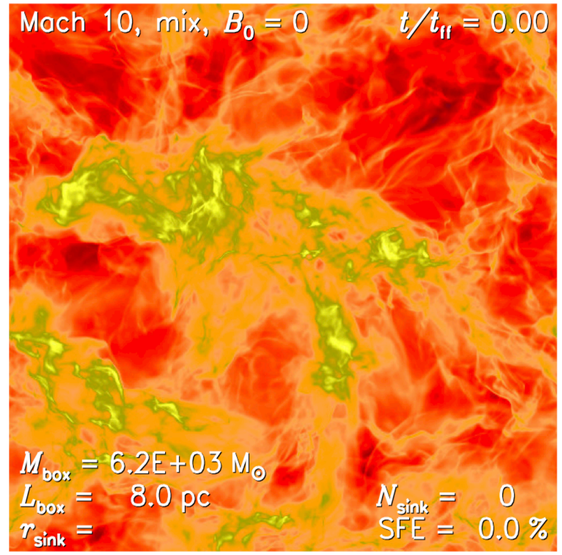
(2) sink particles accrete based on the Bondi/Flux accretion scheme

(3) convert a sink mass into a star



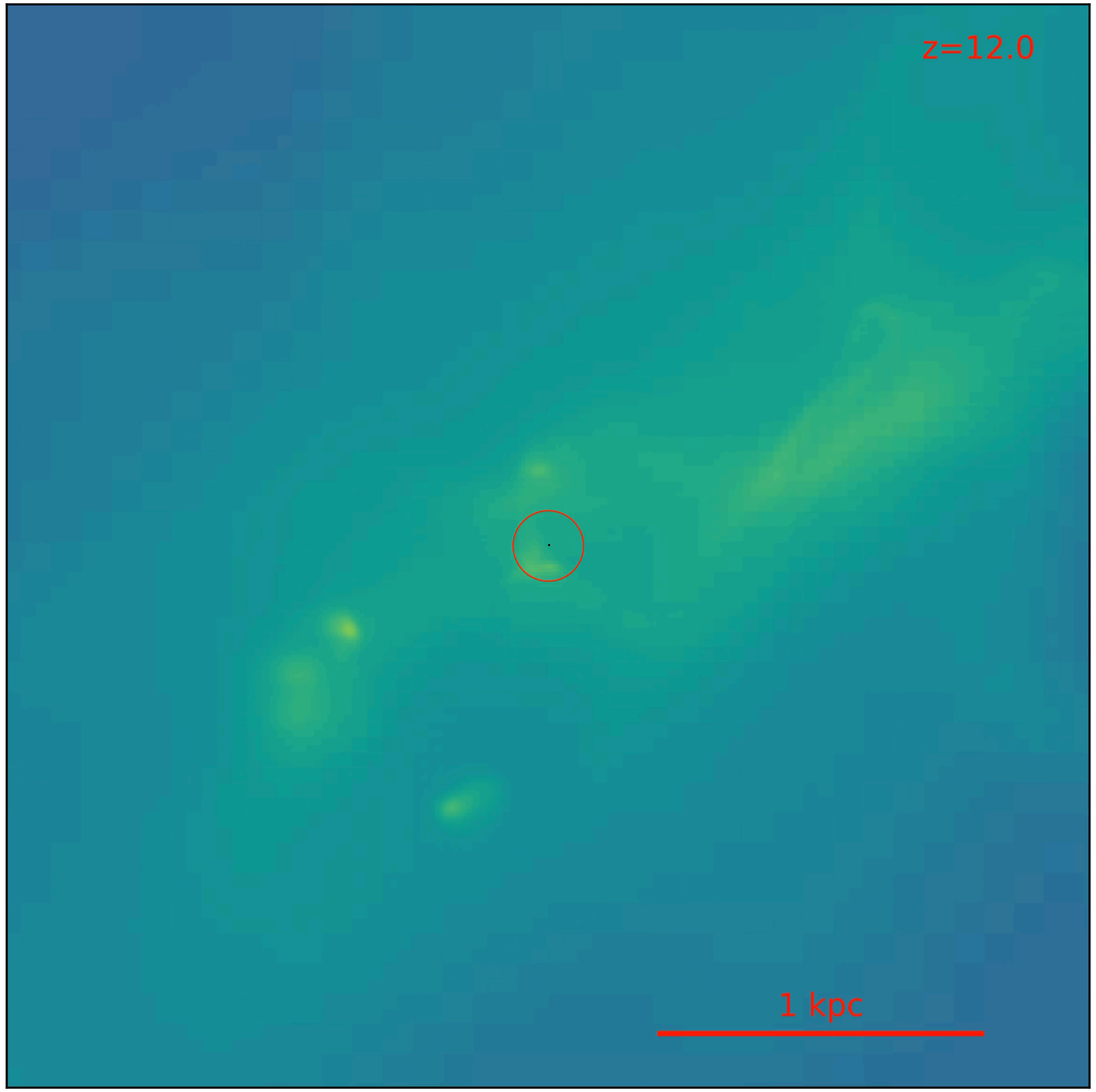
(e.g. Bate 1995; Krumholz 2004; Gong & Ostriker 2013; Bleuler & Teyssier 2014; 2015)

Example of the use of sink particles:
turbulent box SF sims



Federrath & Klessen (12)

Application of the sink particle-based SF to a cosmological sim



Kang et al. (24)

- RAMSES-RT (Rosdahl+ 13, Rosdahl & Teyssier 15)
- Initial condition: MUSIC (Hahn & Abell 2011)
- M_{halo} ~ 10^9 $M_\odot$, M_{star} ~ 2×10^6 $M_\odot$ at z = 6
- Radiation feedback + mechanical type II SN feedback
- Δx_{min}= 0.7 $(z/6)^{-1}$ pc
- Star formation: Multi-freefall

vs. SINK particle algorithm

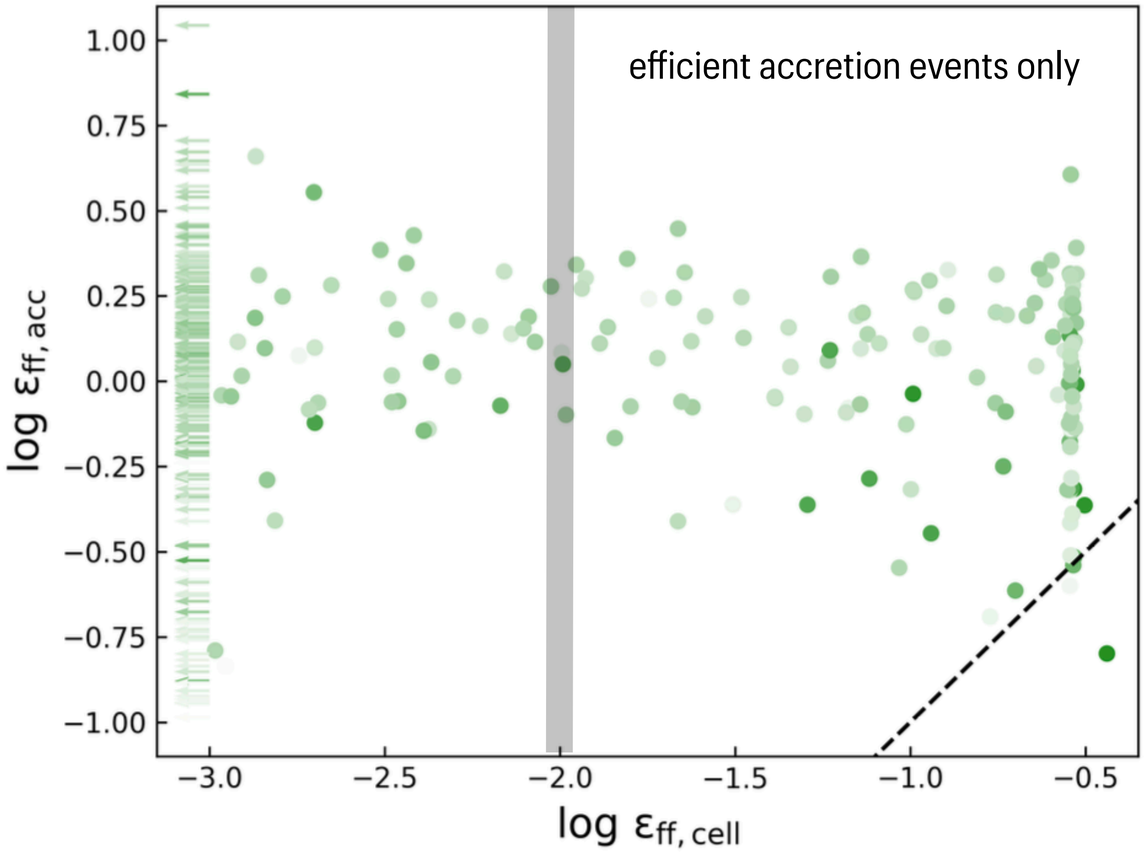
Different $\epsilon_{\rm ff}$ between two different star formation models

$$\epsilon_{\rm ff,acc} \equiv \frac{\dot{M}_{\rm acc}}{M_{\rm gas}/t_{\rm ff}}$$

measure of how rapidly
a sink particle accretes

(not $\epsilon_{\rm ff}$ measured on GMC scales)

Kennicutt-Schmidt relation

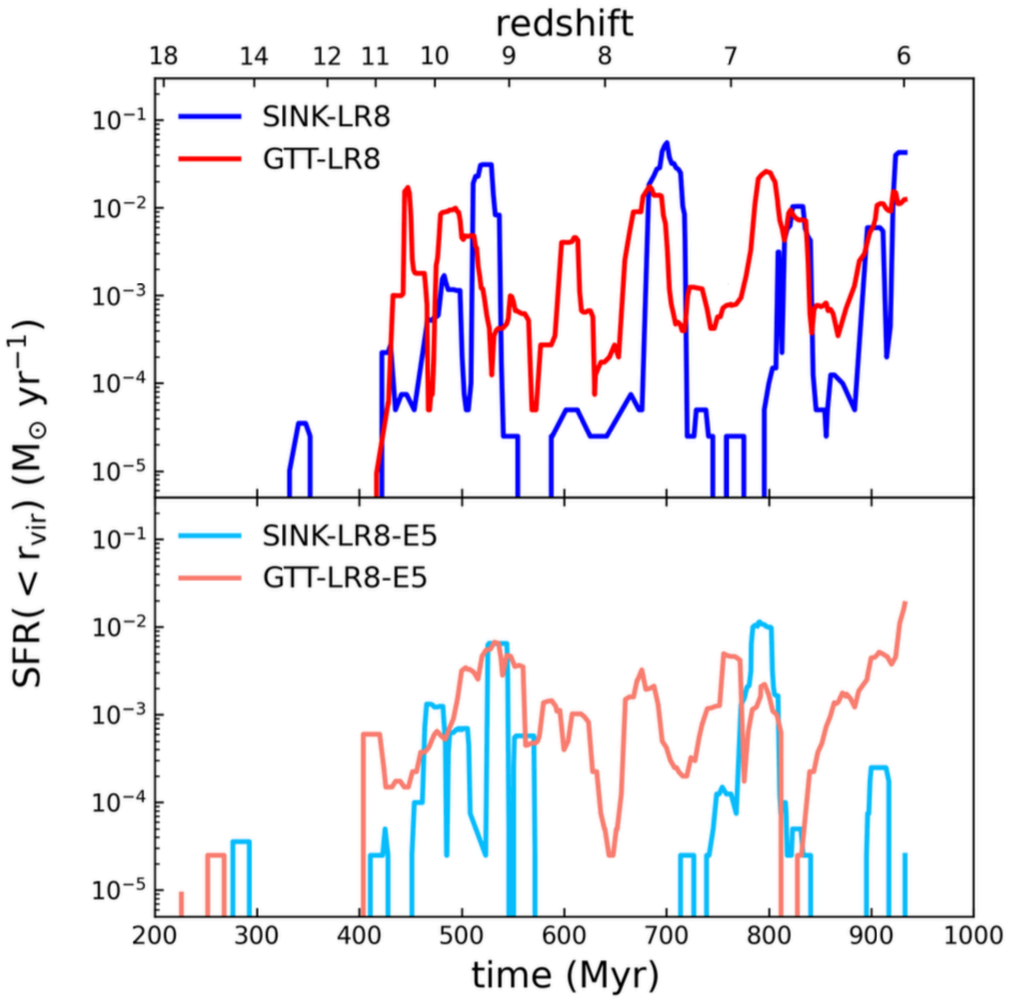


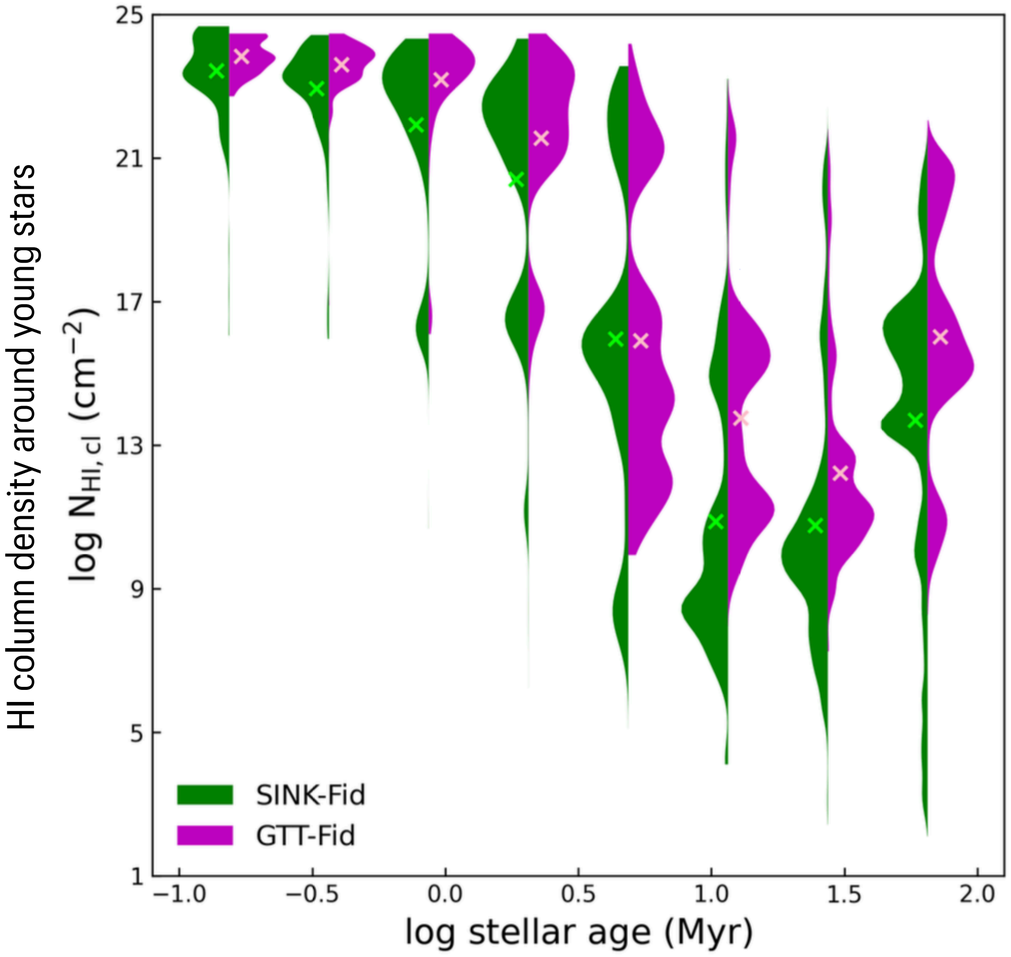
1:1 relation

$\epsilon_{\rm ff}$ expected from local thermo-turbulent conditions
(aka multi-freefall model)

Kang et al. (24)

More bursty star formation with a more accurate model

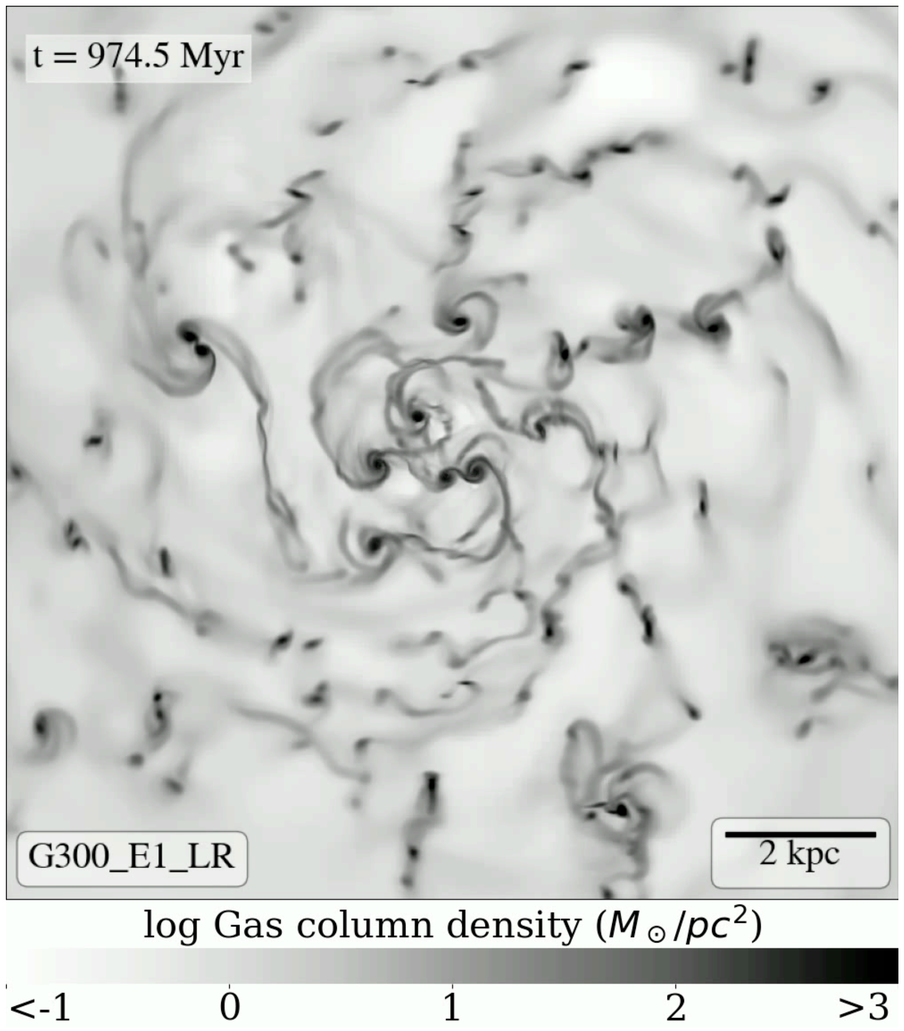


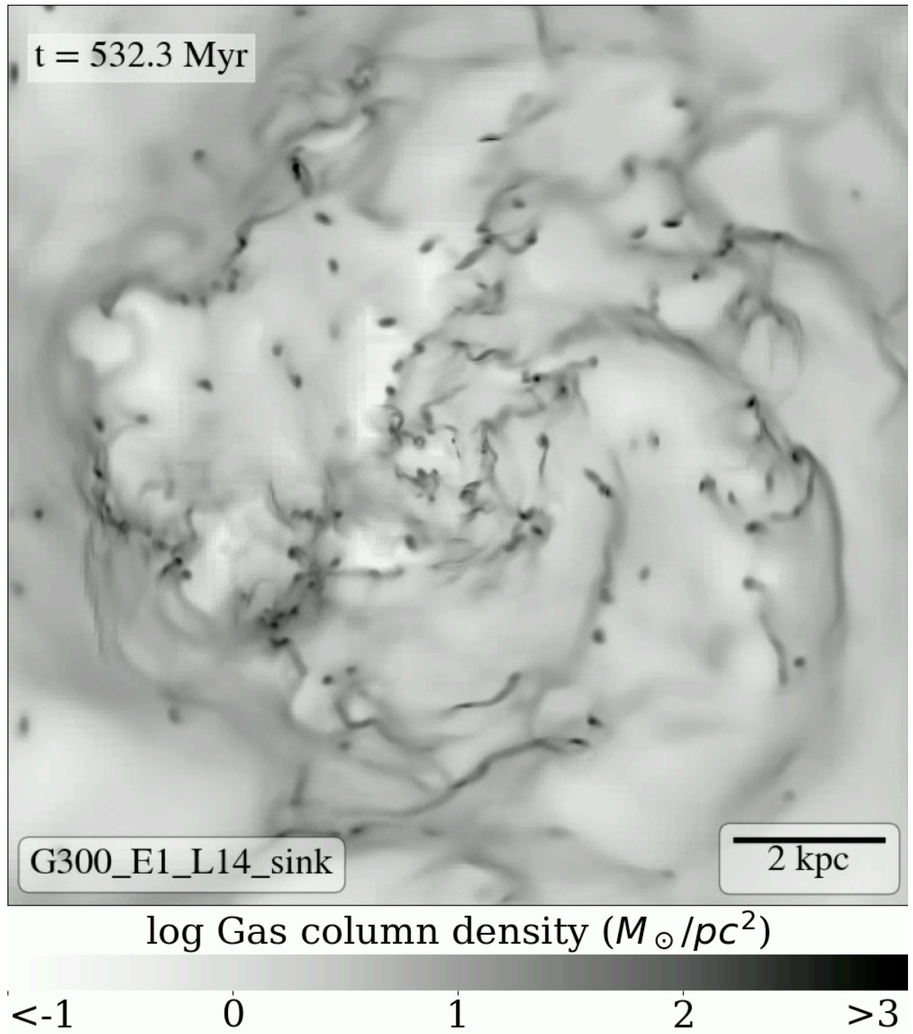


Kang et al. (24)

Feedback becomes more coherent and stronger

GMCs are quickly destroyed in an isolated disk





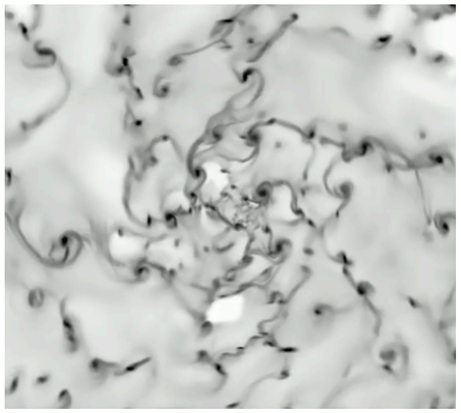
Han+ (in prep)

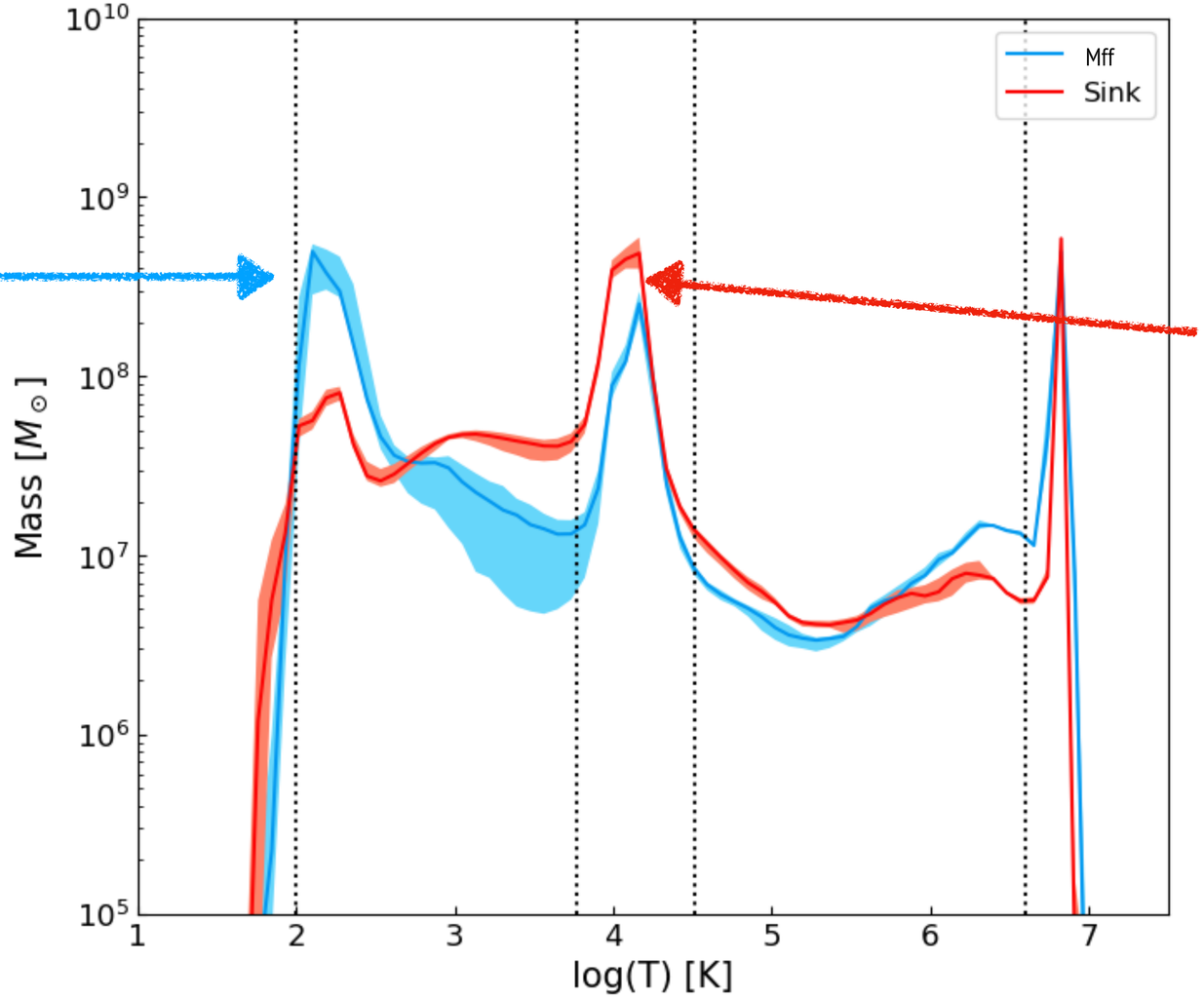
No GMCs are long-lived if SFEs are locally very high

(see also Kim & Ostriker 17)

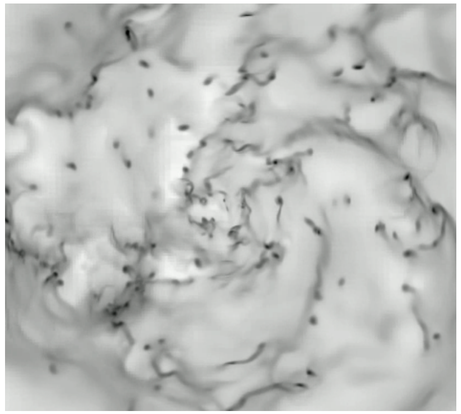
Pressure support for the ISM

The ISM is mostly cold
in the Multi-freefall model





The ISM is mostly warm
in the sink model

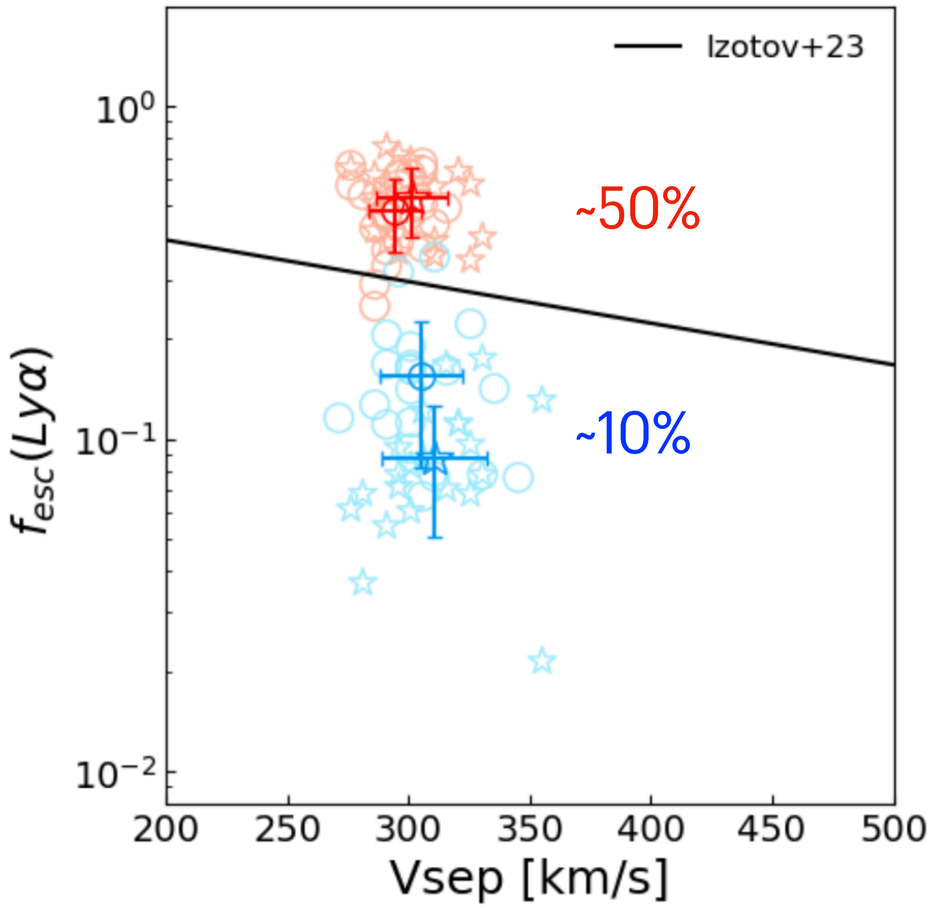


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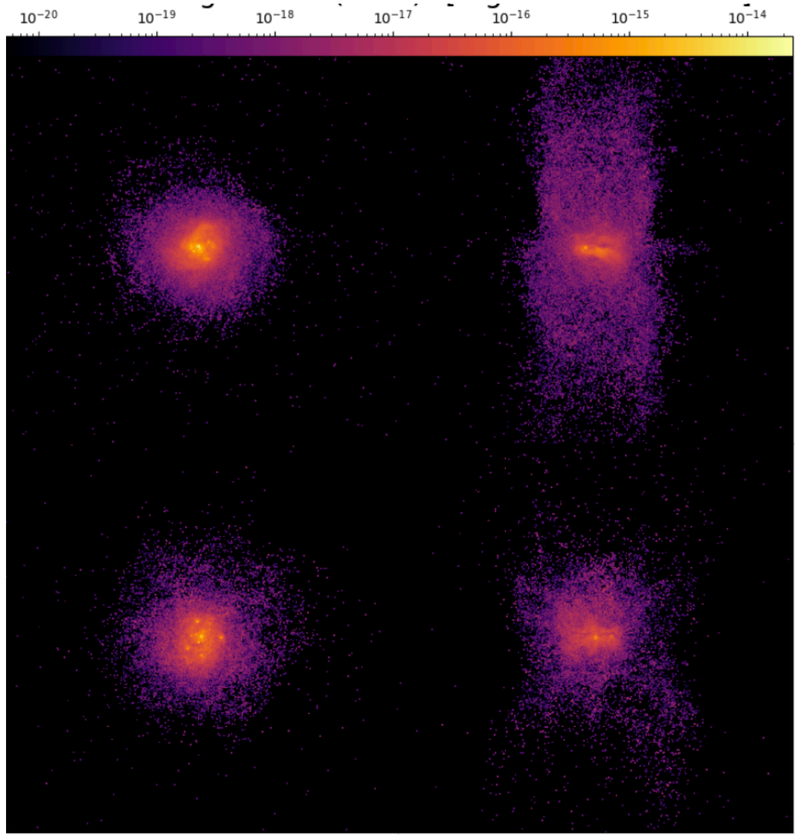
Very different predictions for observables

Lyman-α escape fraction



Lya escape more efficiently
in the model with more accurate
star formation,
more consistent with
high f_{esc} in observations

Lya Surface Brightness

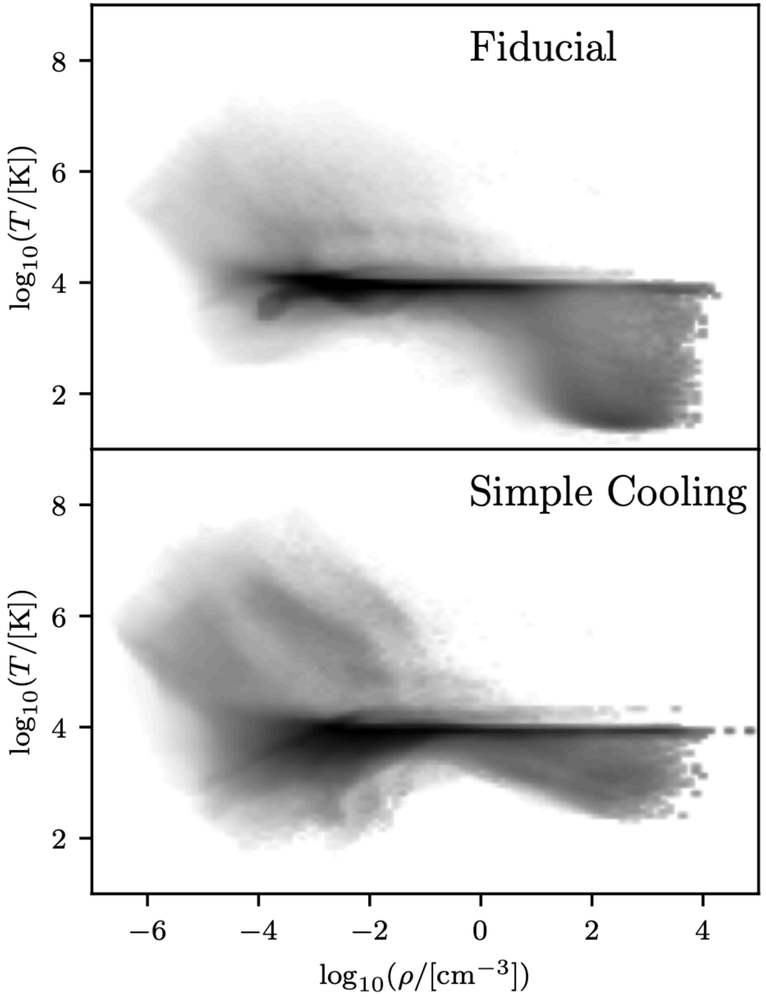


- DMH mass: 10^{10} M_{sun}
- Stellar mass: 10^{8} M_{sun}

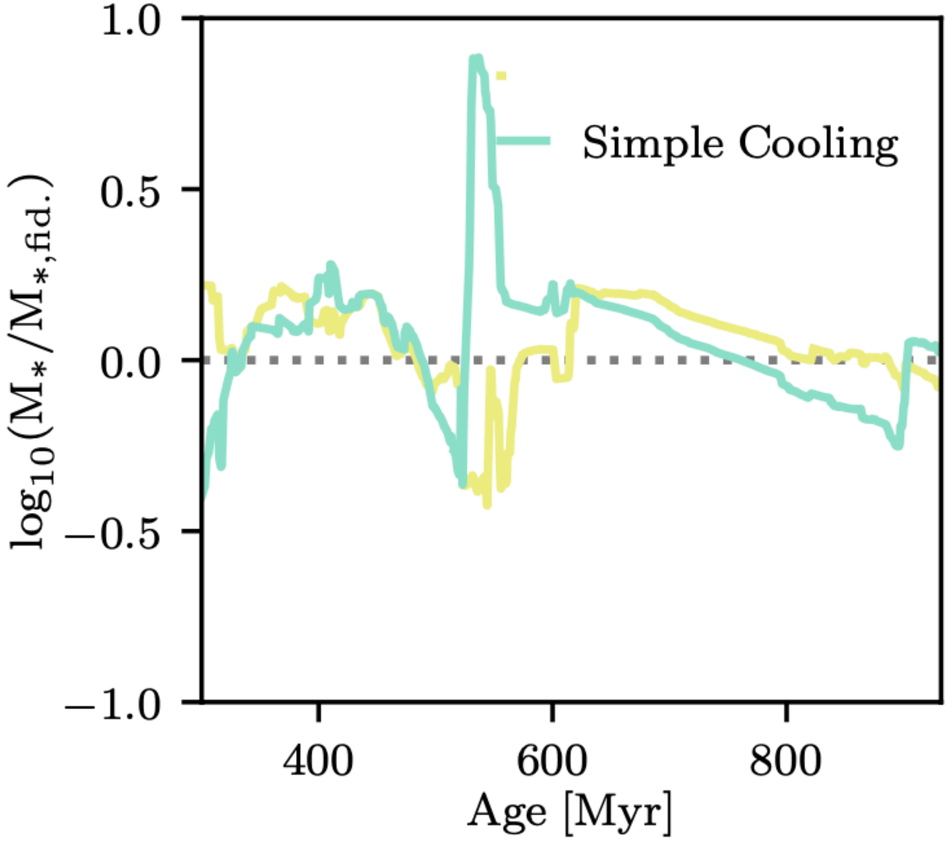
Koh+ (in prep)

More complex cooling/heating model?

w/ complex cooling/heating network (aka PRISM model)



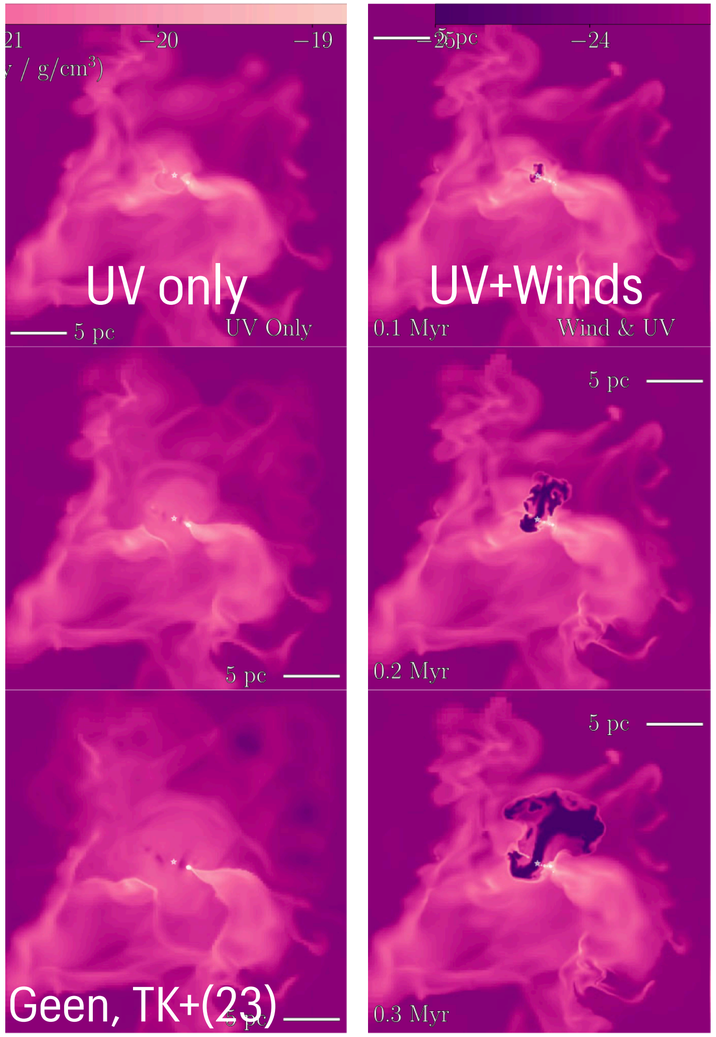
Katz+ (to be submitted)

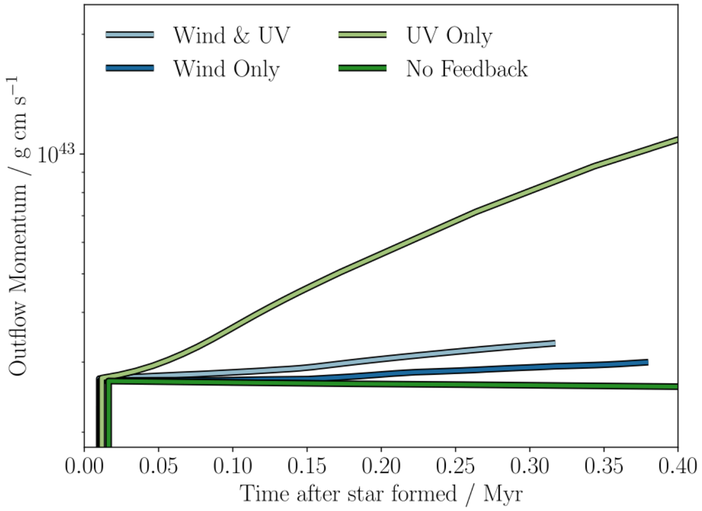


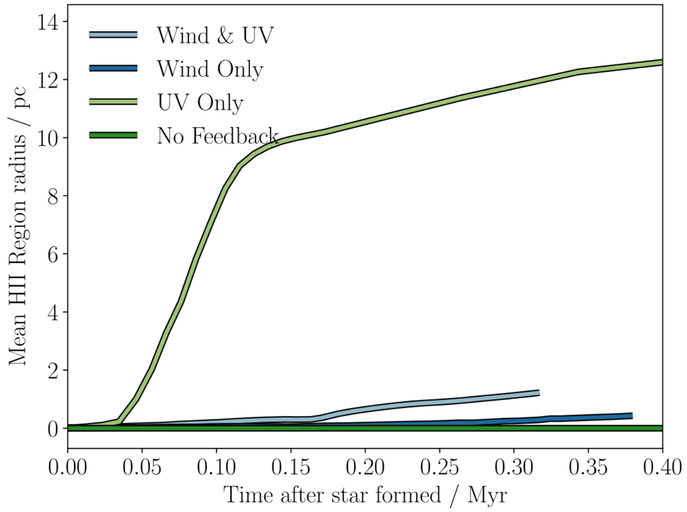
Accurate cooling/heating model does not appear to systematically suppress star formation

Are we missing any important feedback process?

Stellar winds





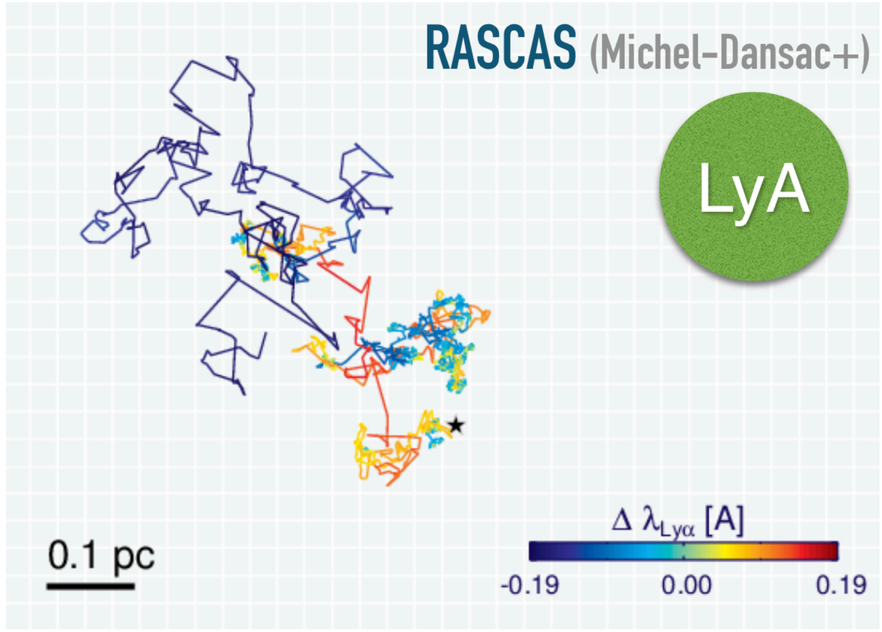


Inclusion of stellar winds creates dense shells that effectively absorb ionizing radiation

-> Winds weaken the radiation feedback

Are we missing any important feedback process?

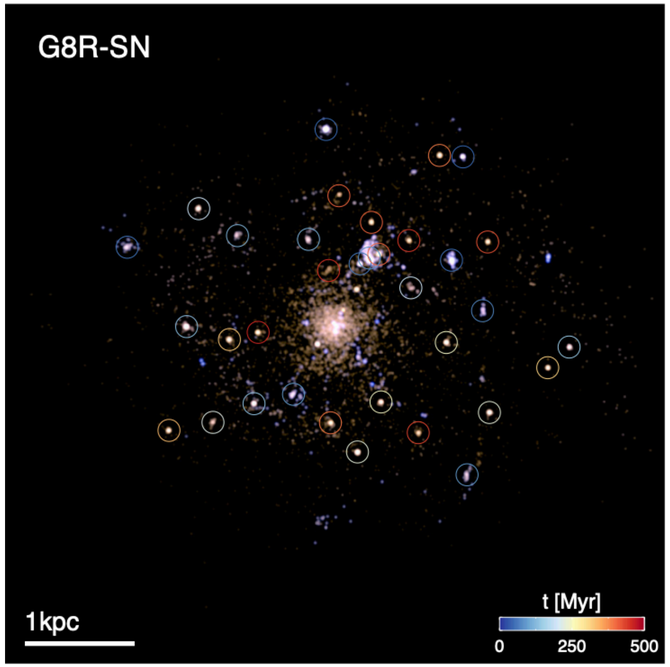
Lya pressure



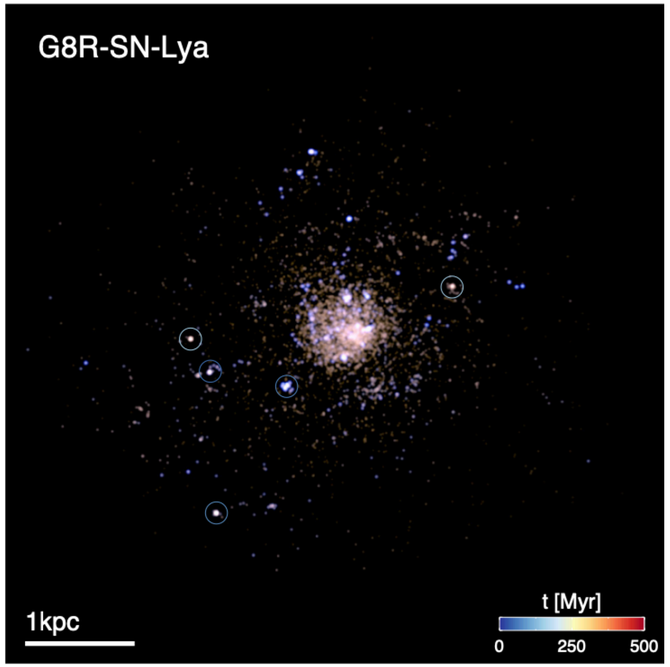
Multi-scattering nature of Lya photons can transfer boosted momentum to the surrounding

(Dijkstra+08; Smith+17)

Radiation+SN



Radiation+SN+Lya pressure



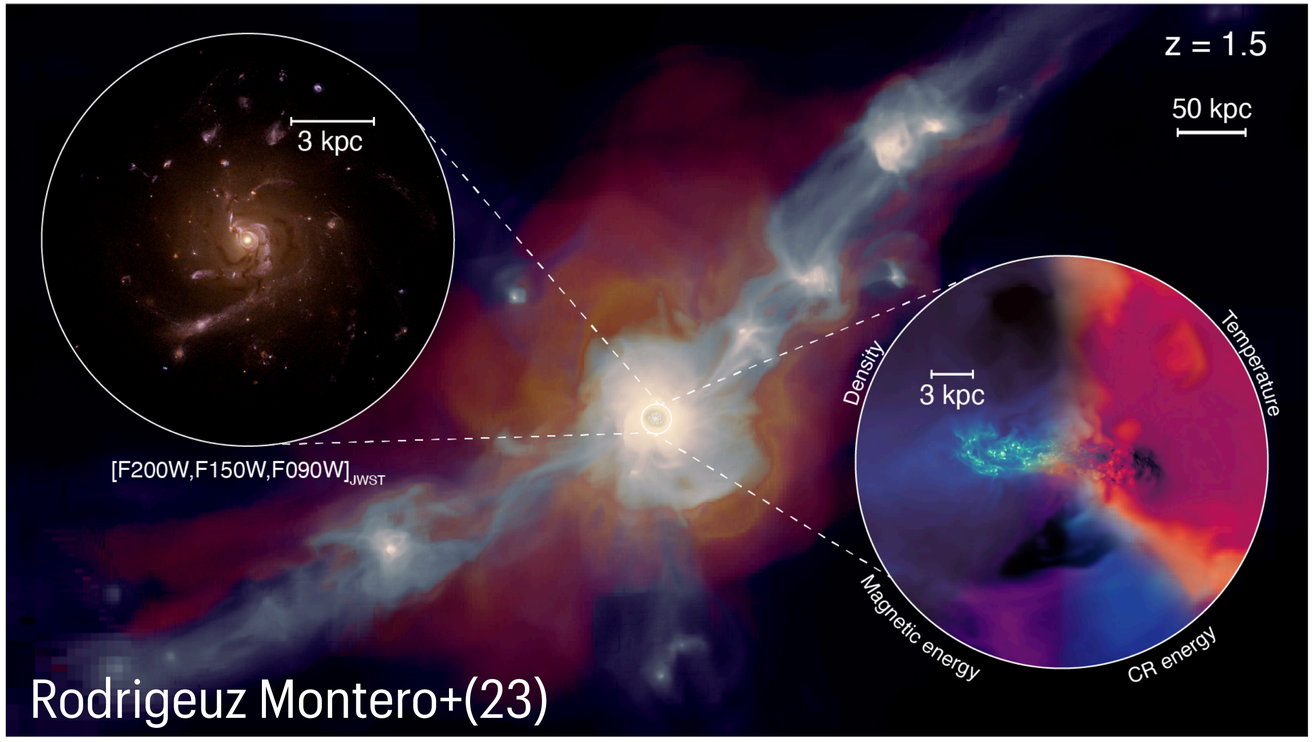
(Kimm+18; see also Han+22)

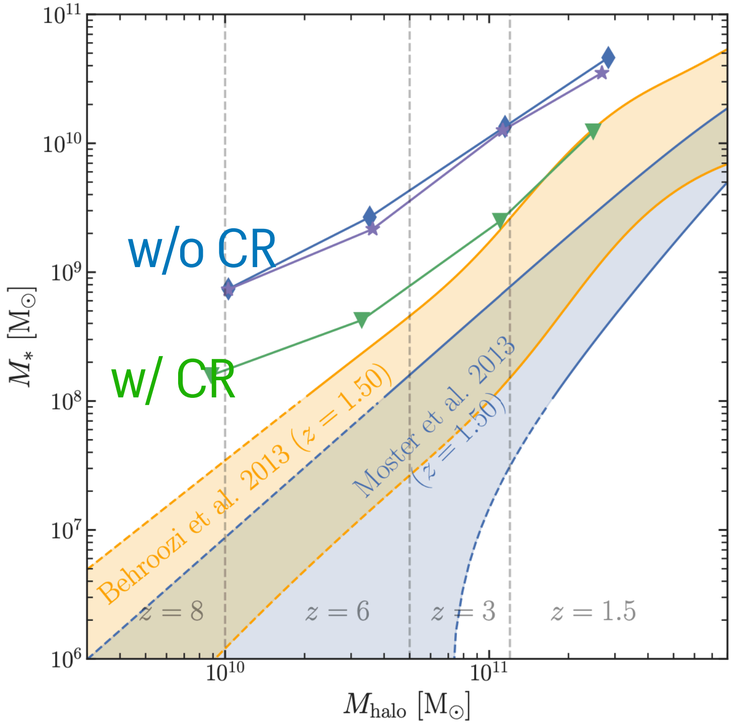
Lya suppresses formation of star clusters,
but its effect is expected to diminish in metal-rich environments
-> perhaps not a stable solution?

Are we missing any important feedback process?

Cosmic ray pressure

- Cosmic rays: relativistic particles formed via diffusive shock acceleration in supernova remnants
- Relativistic -> adiabatic cooling is slower than non-relativistic gas
- Extra pressure near the galactic plane -> drives warm/cold outflows & **suppress inflow** onto the disk
- MW: $P_{CR} \sim P_B \sim P_{turb}$ (e.g. Beck 16, Zweibel 17)





Summary

- More accurate model of star formation leads to bursty star formation, which can better self-regulate SF
- GMCs are destroyed more quickly, allowing Lya/other photons to escape more efficiently
- Simulated ISM is supported by warm gas
- Perhaps together with CR pressure, we may be able to solve the long-standing problem of over-cooling and make more realistic predictions for galaxy formation and evolution