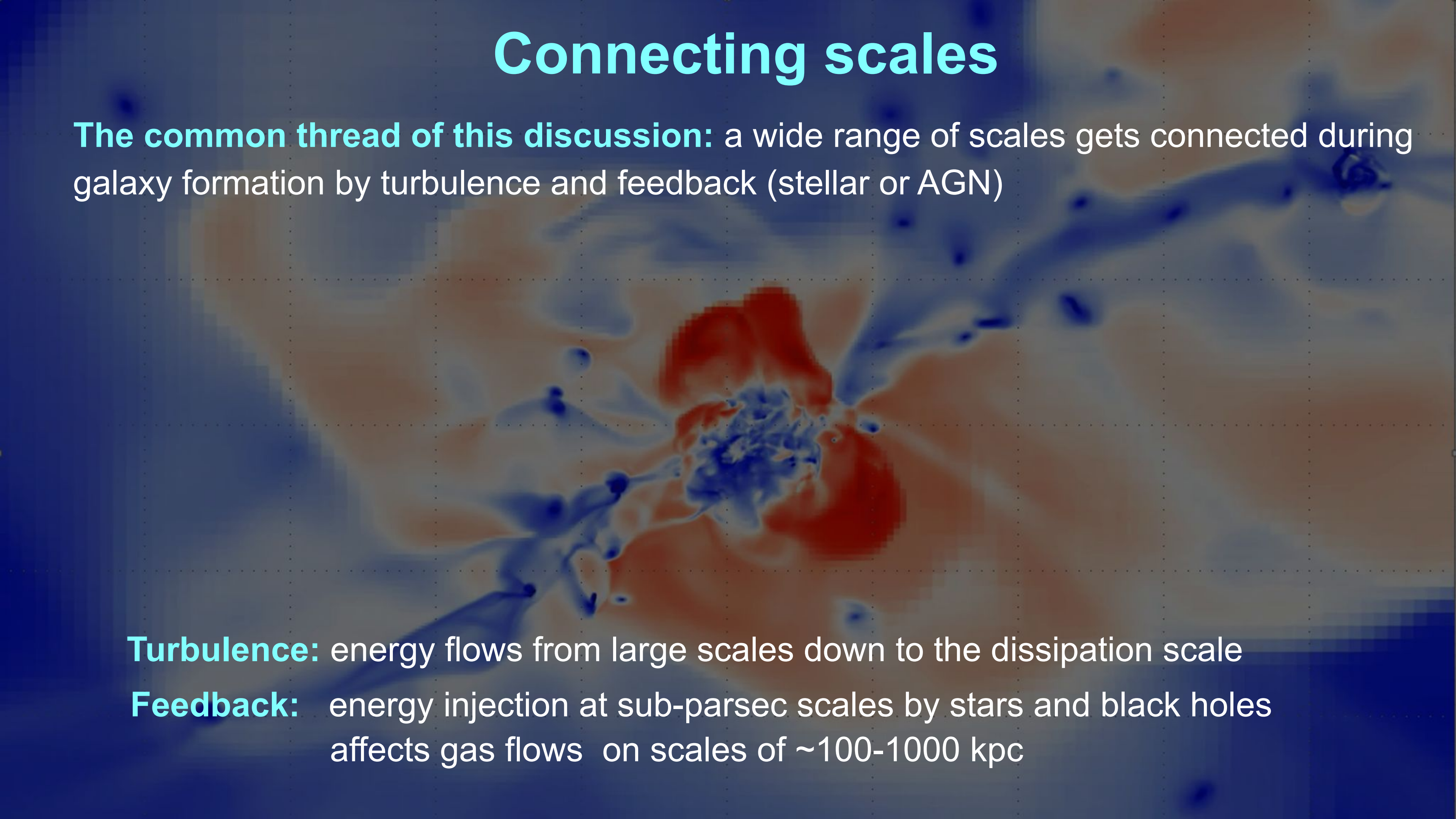
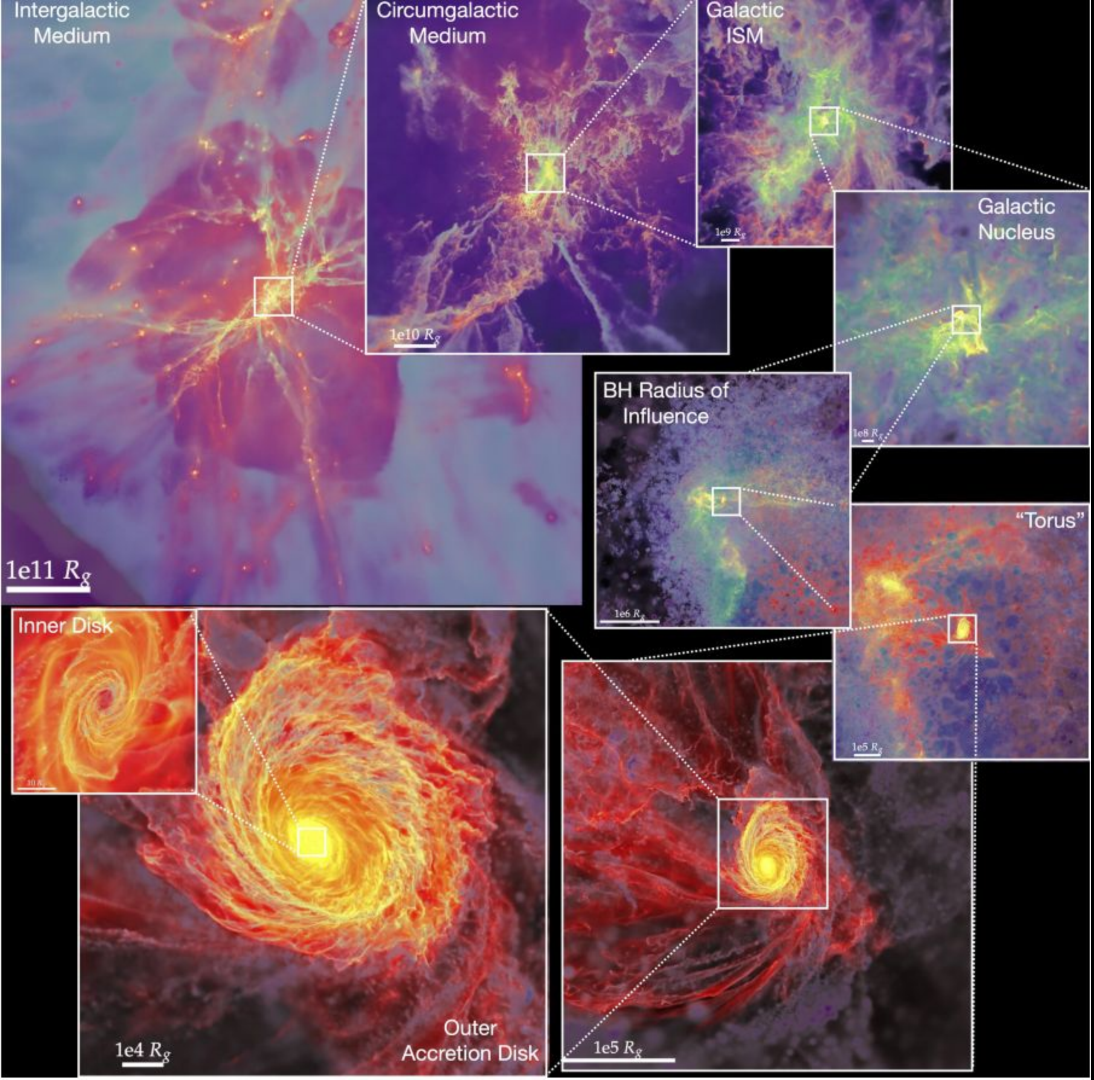
Connecting scales

The common thread of this discussion: a wide range of scales gets connected during galaxy formation by turbulence and feedback (stellar or AGN)



Turbulence: energy flows from large scales down to the dissipation scale

Feedback: energy injection at sub-parsec scales by stars and black holes affects gas flows on scales of ~100-1000 kpc



Example: magnetized turbulent gas flows from large-scales down to accretion disk around central supermassive black hole

(e.g., Hopkins+ 2024, 2025)

Example: depletion time of galaxies

Global depletion time in galaxies is connected to the small-scale depletion time in star-forming regions by turbulence and feedback (Semenov+ 2017, 2018)

local depletion time
In star forming regions

typical time an ISM atom spends outside star-forming regions (large-scale motions/turbulence)

Global depletion time

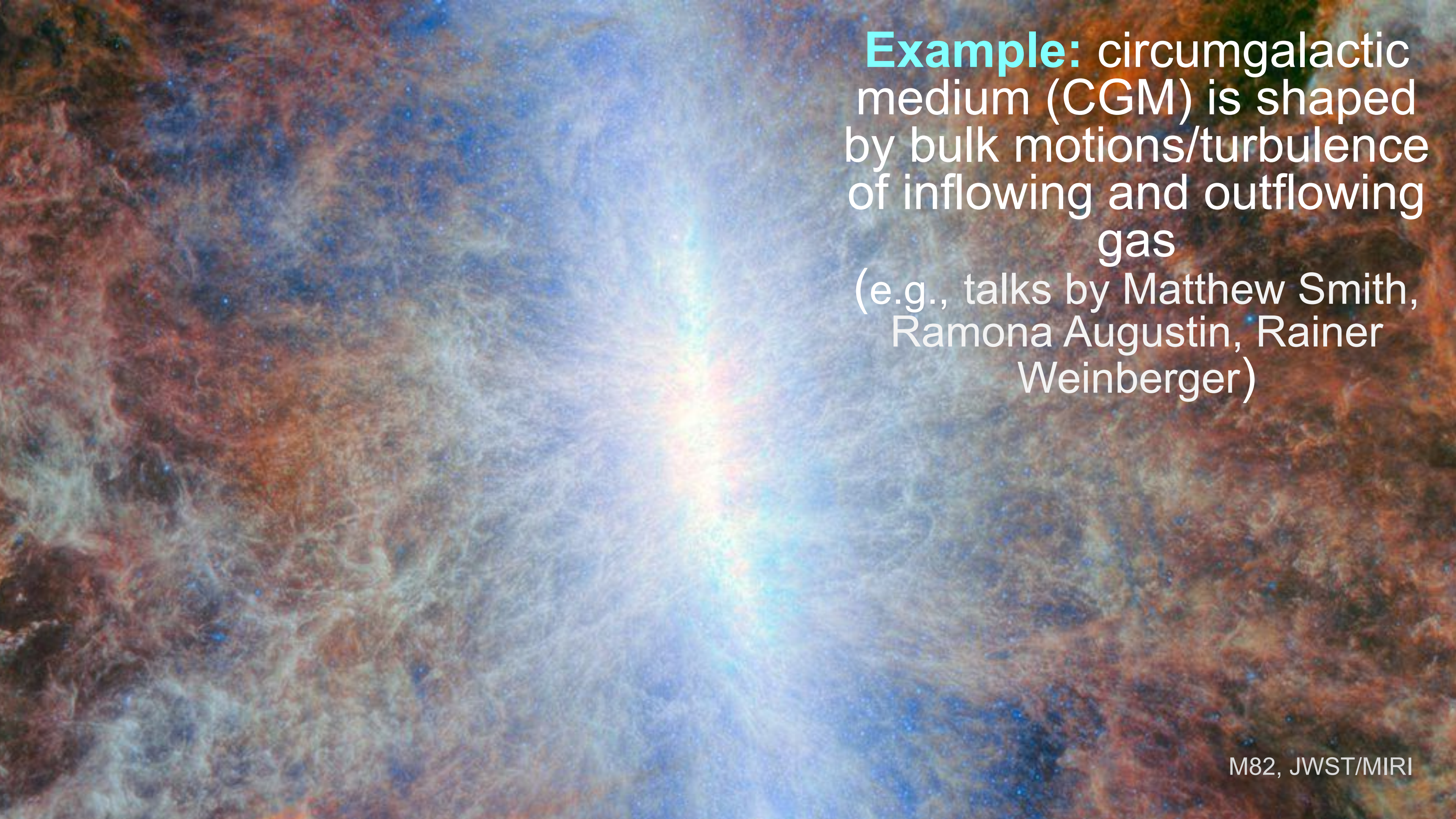
$$\tau_{\rm dep} = \frac{M_{\rm gas}}{\dot{M}_\star} = \tau_{\rm dep,sf}\left(1 + \frac{t_{\rm nsf}}{t_{\rm sf}}\right)$$

typical time an ISM atom spends in star-forming regions (feedback)

NGC 628, JWST/NIRCam and HST, NASA/ESA/CSA/STScI, Janice Lee (STScI), Thomas Williams (Oxford) and PHANGS Team
https://webbtelescope.org/contents/media/images/2024/105/01HM9S5Y93HVHGEX645E96WFG4

Example: circumgalactic medium (CGM) is shaped by bulk motions/turbulence of inflowing and outflowing gas

(e.g., talks by Matthew Smith, Ramona Augustin, Rainer Weinberger)

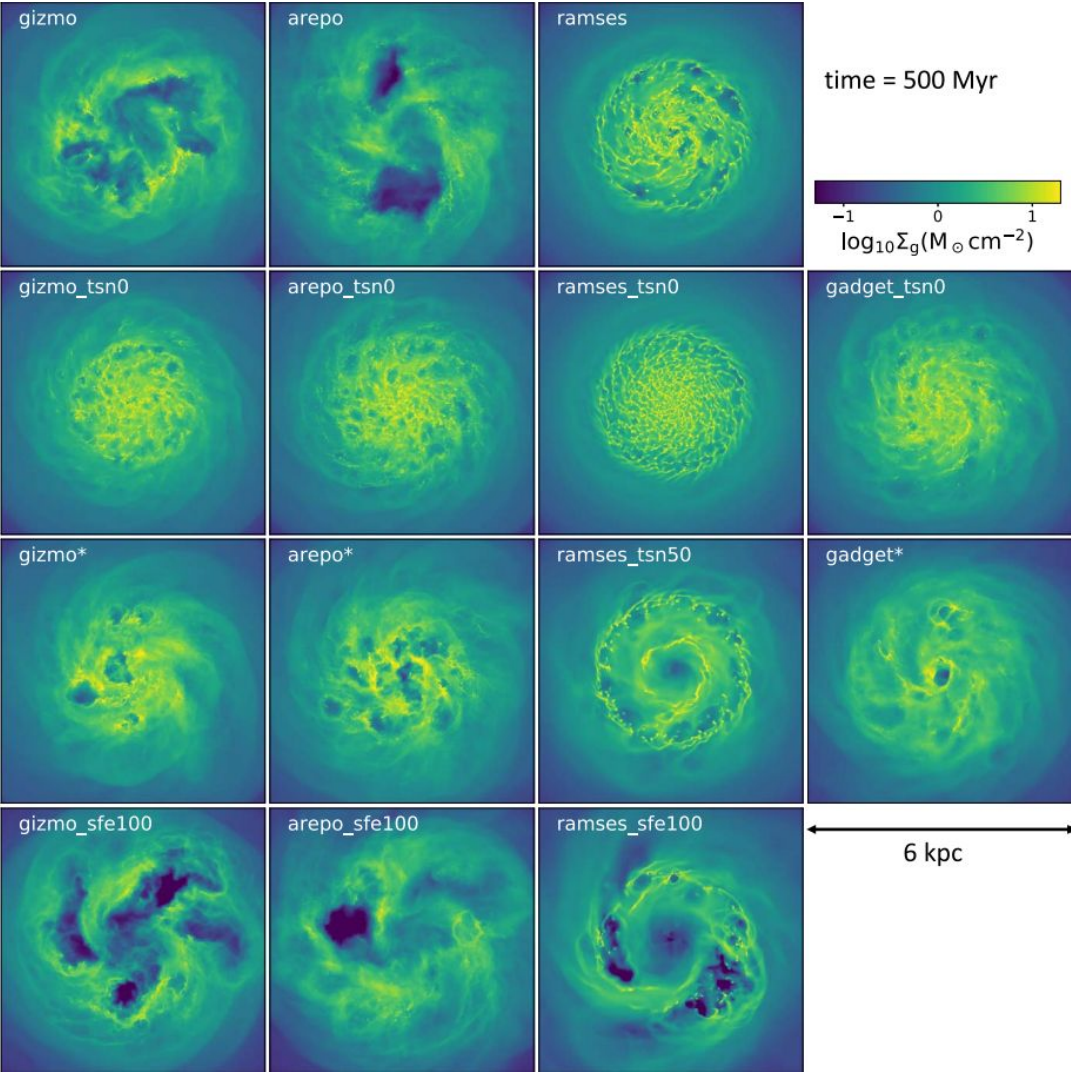


M82, JWST/MIRI

Coupling of scales presents distinct challenges to modeling galaxy formation

because it makes large-scale distribution of gas in simulations sensitive to

- numerical effects near resolution scale (e.g., the “butterfly effect”; Genel+ 2019)
- details of modeling star-formation and feedback

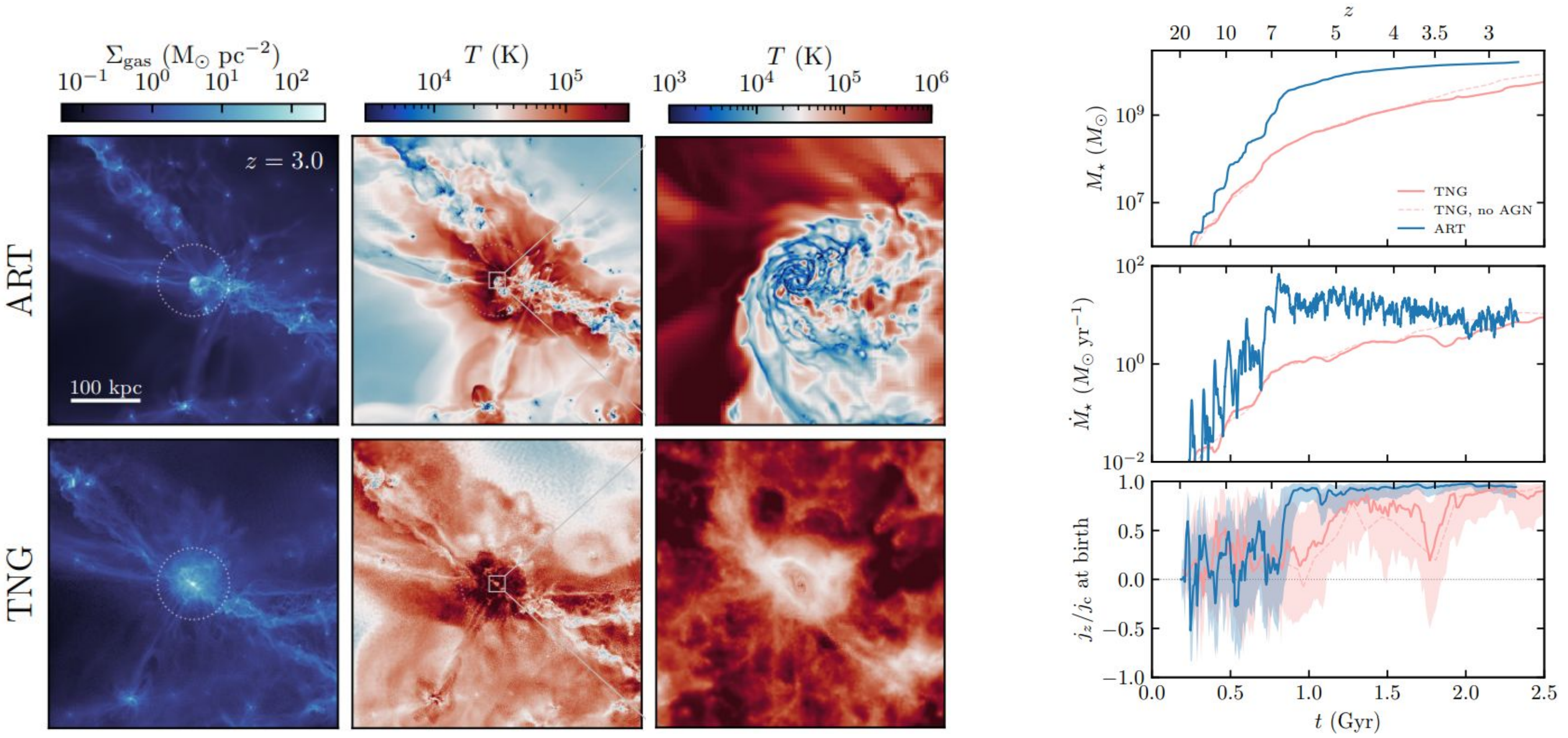


Gas surface density in idealized simulations of a dwarf galaxy with different codes but the same model for heating/cooling, star formation and feedback (modeling individual SN explosions)

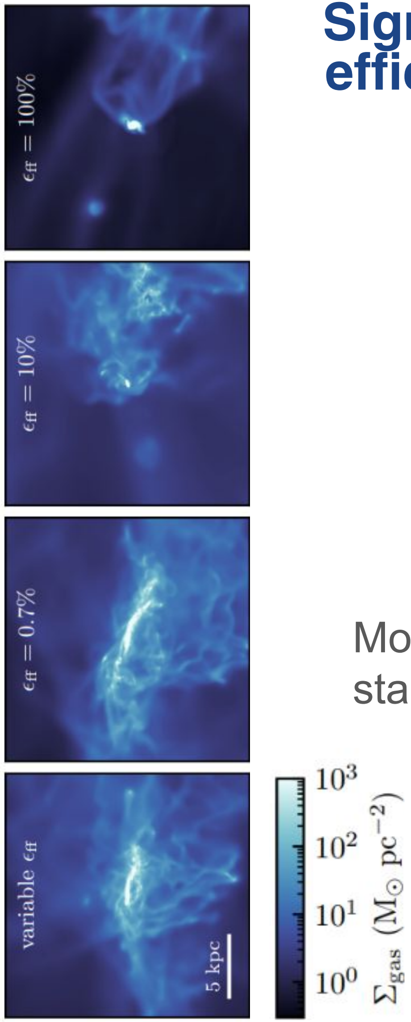
Hu+ 2023, ApJ 950, 132; arXiv/2409.18173
cf. also Matthew Smith' talk yesterday

Large differences in thermodynamic structure of the ISM will translate to large differences in predicted ISM spectra

Zoom-in simulations of MW progenitor from the same initial conditions using star formation and feedback physics in the Illustris TNG and ART simulations (Semenov+2024, arXiv/2409.18173)



Significant effects of different modeling of the star formation efficiency of on the smallest scales on the bulk properties of galaxies even when everything else is kept fixed



(Semenov+, arXiv/2410.09205)

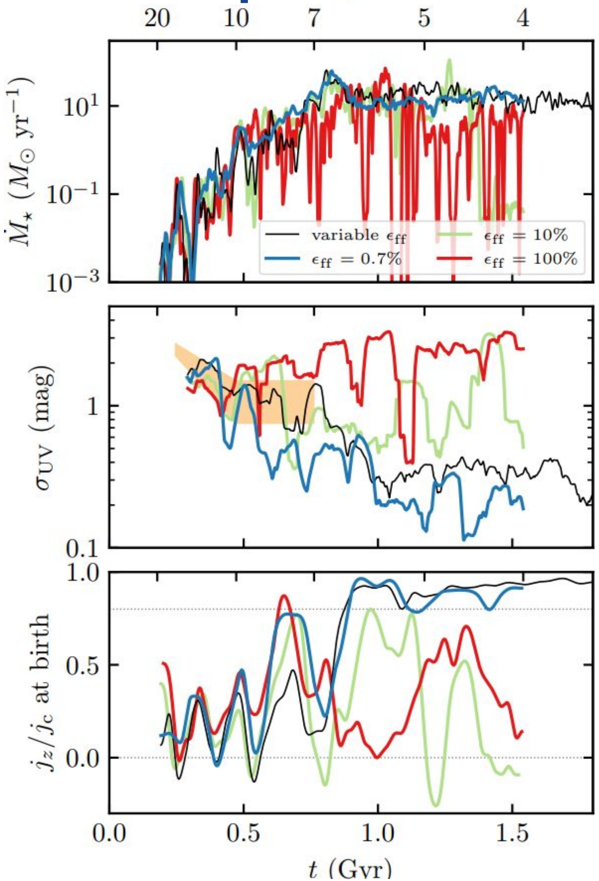
$$\dot{\rho}_\star = \epsilon_{ff} \frac{\rho}{t_{ff}}$$

$$t_{ff} = \sqrt{3\pi/32G\rho}$$

Model motivated by simulations of turbulent star-forming regions (Semenov+ 2016):

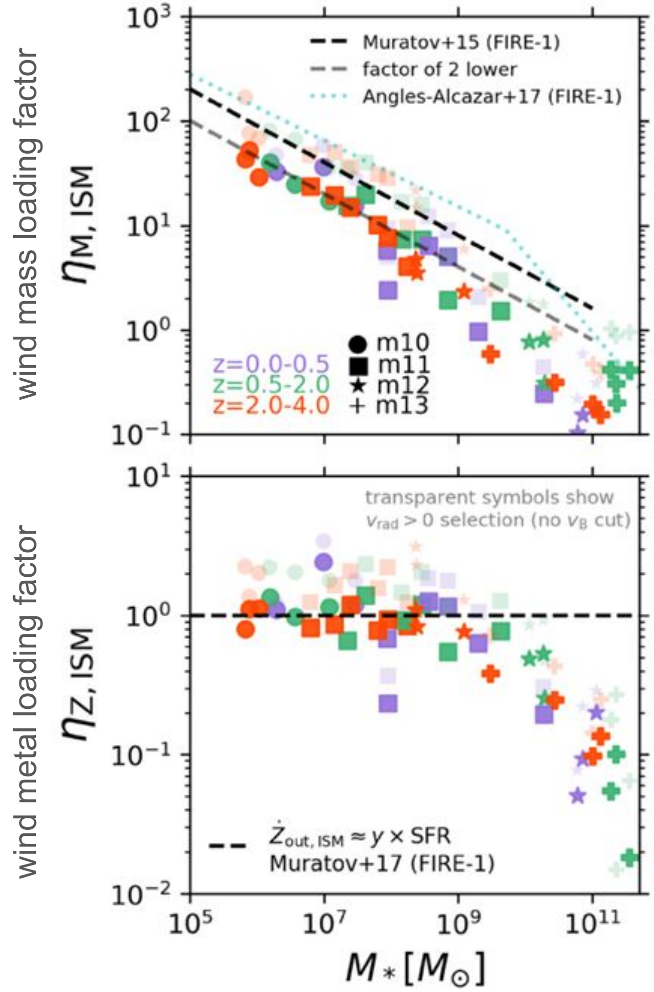
$$\epsilon_{ff} = 0.9 \exp\left(-\sqrt{\alpha_{vir}/0.53}\right)$$

$$\alpha_{vir} \equiv \frac{5\sigma_{tot}^2 R}{3GM}$$

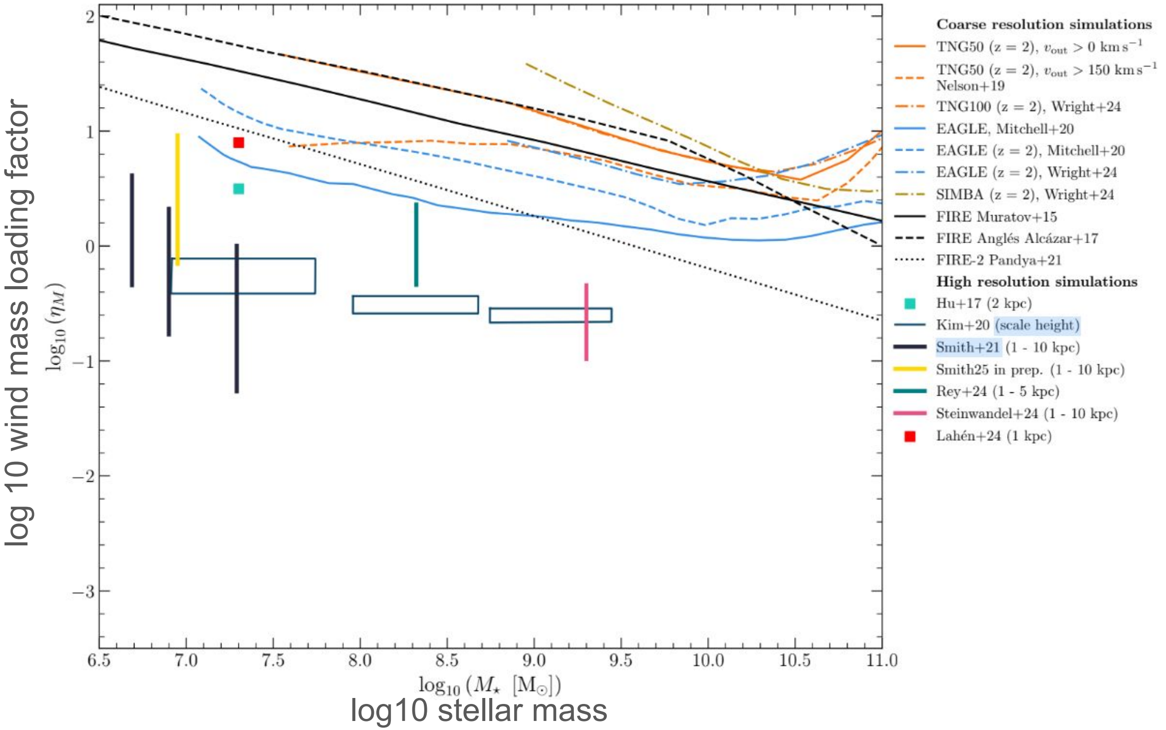


Wind mass loading factor depends on the operational definition and details of star formation and feedback modeling

Pandya, V. et al. 2021, MN 508, 2979

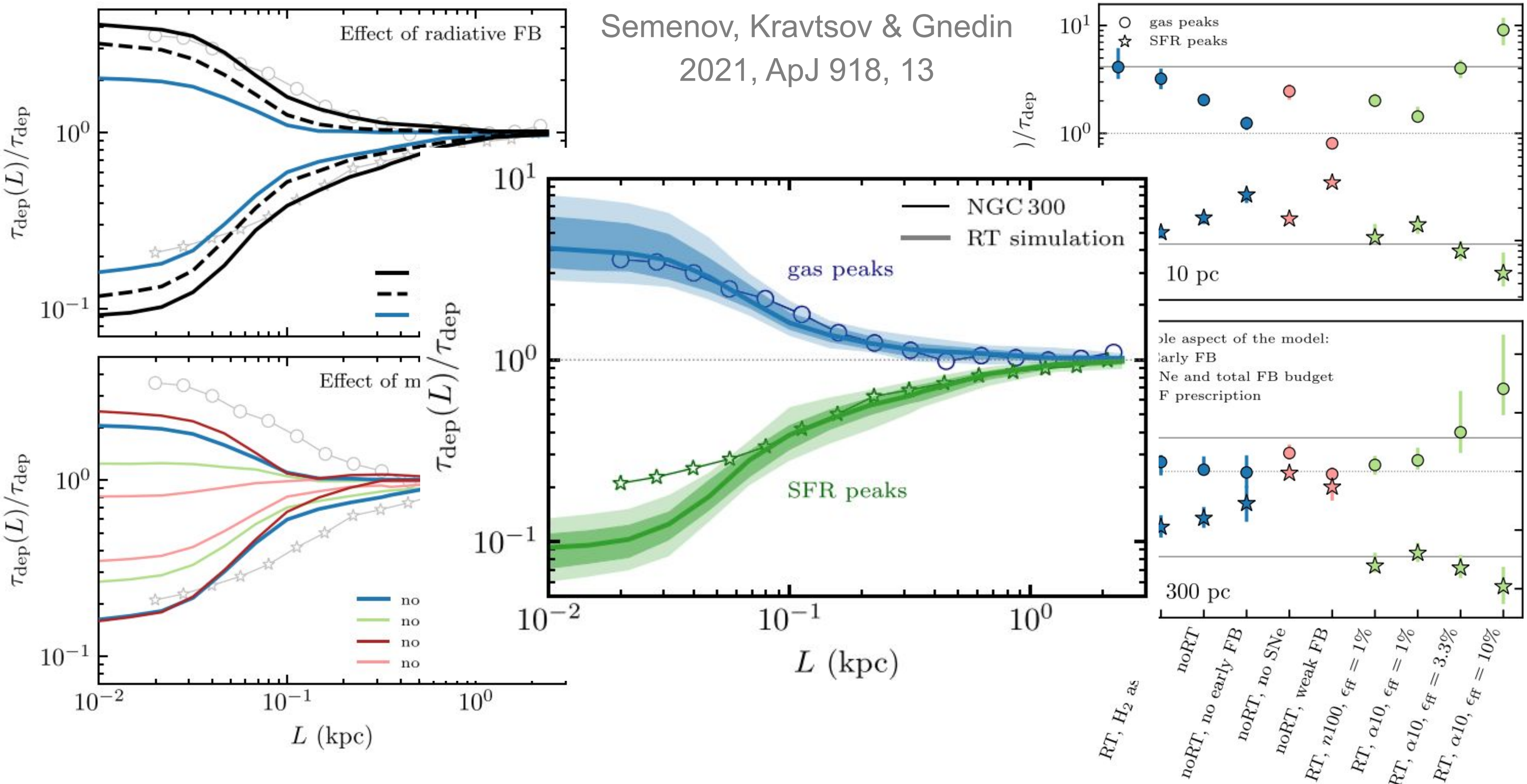


Stellar mass vs wind mass loading factor in different simulations from Matthew Smith's talk yesterday



Can star formation and feedback treatment be "calibrated" using observations, such as star formation "tuning fork"?

Semenov, Kravtsov & Gnedin 2021, ApJ 918, 13



Summary

1. **Turbulence and feedback couple small and large scales during galaxy formation.**

2. **This coupling of scales makes galaxy formation a formidable and fascinating problem, but also presents many challenges:**

   - the “butterfly effect” due to numerical effects: ~5-25% variation in bulk properties of galaxies simulated with the same code from nearly identical ICs (Genel et al. 2019)

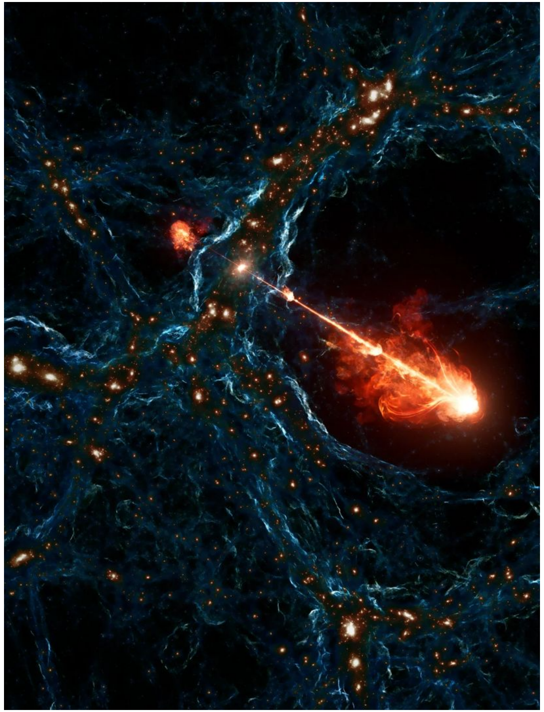
   - different treatment of star formation (SF) and feedback significantly affects bulk properties of high-z galaxies (stellar mass, SFR, …) and their morphology

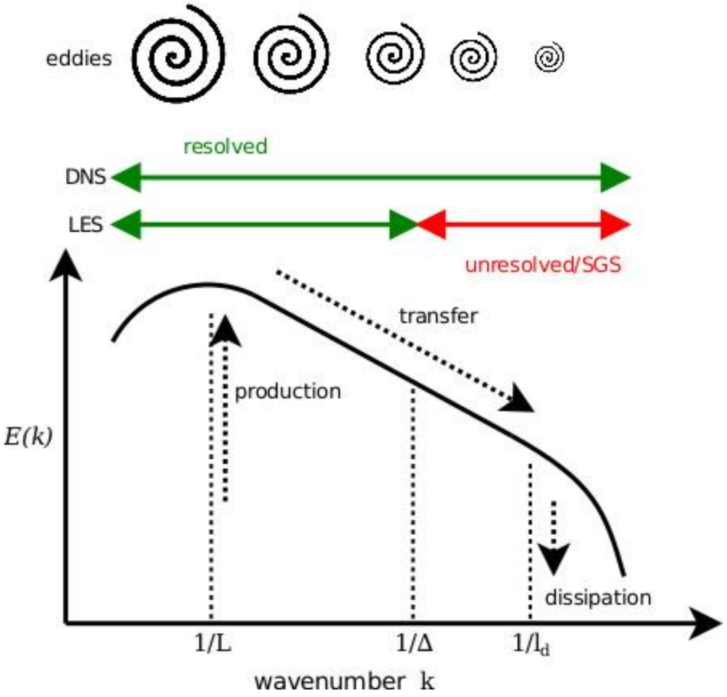
   - even different modeling of SF efficiency in star-forming regions in simulations with identical star formation and feedback prescription, can affect these galaxy properties

   - outflow mass loading factor calibrations are different even for the same simulation for different definitions of the outflow rate, they are significantly different in simulations with different prescriptions of star formation and feedback.

M82, JWST/MIRI

Jet Feedback in Groups and Clusters

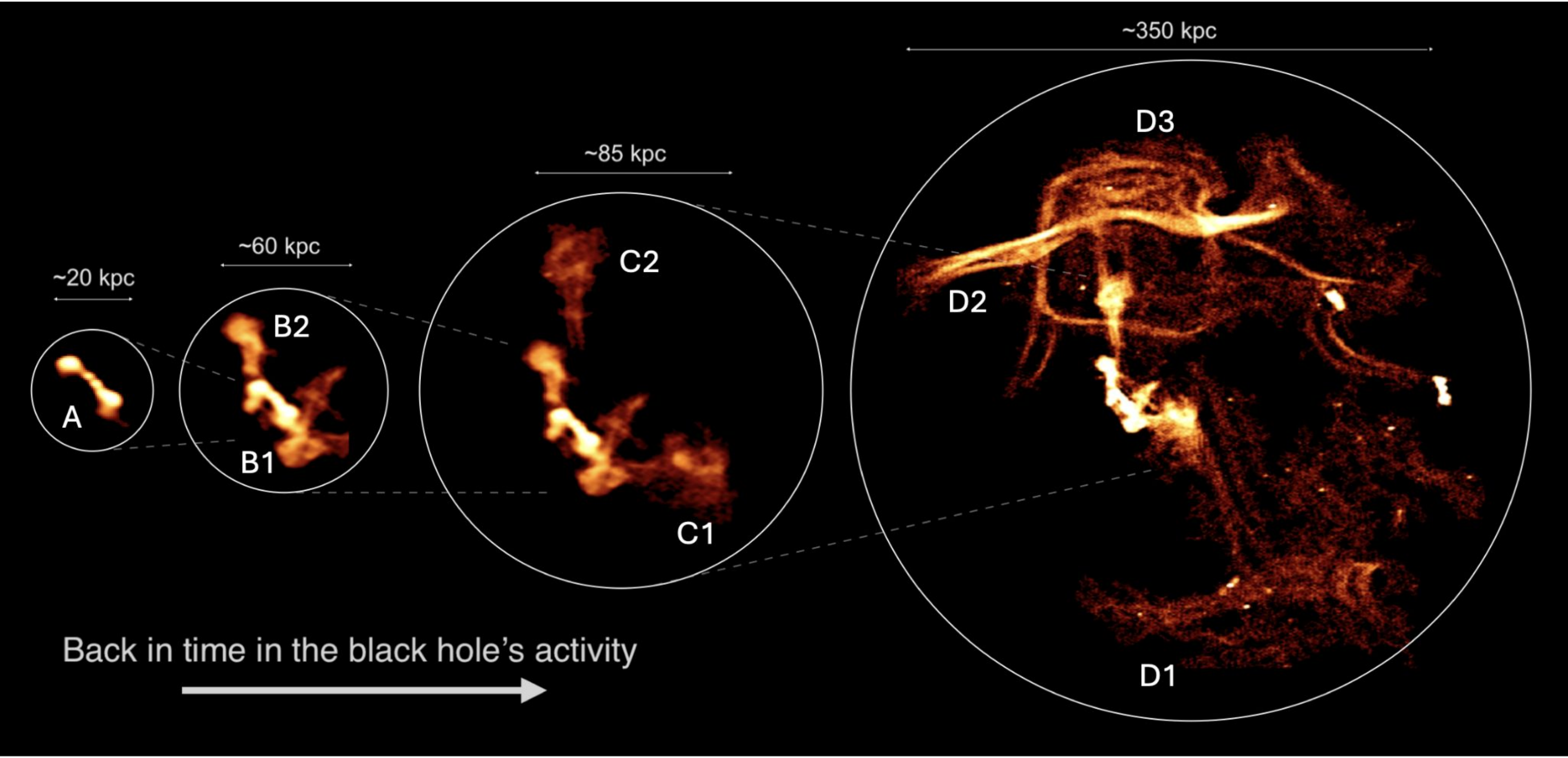




Grete+ 23

Energy to bigger scales

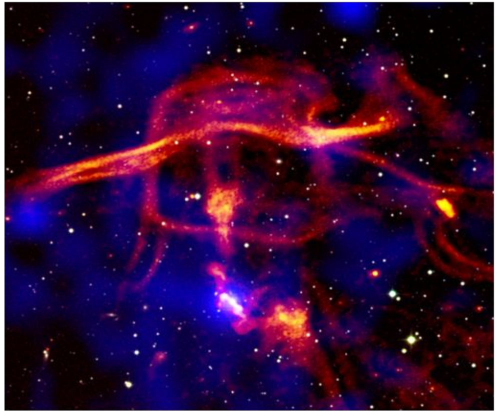
Energy to smaller scales



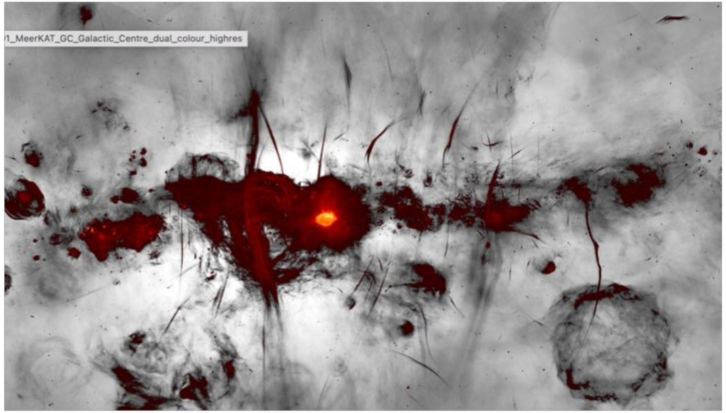
Majumder+ 25, Brienza+ 21

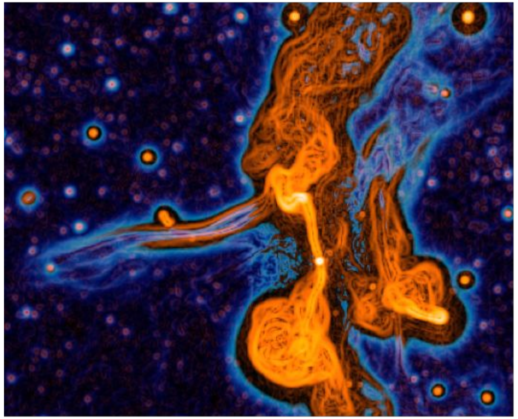
GALAXY CLUSTER

RADIO GALAXY IN GROUP

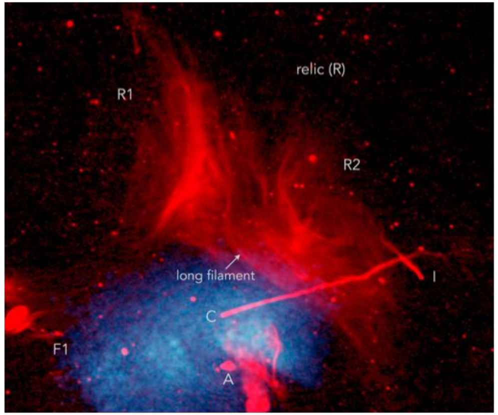


GALACTIC CENTRE

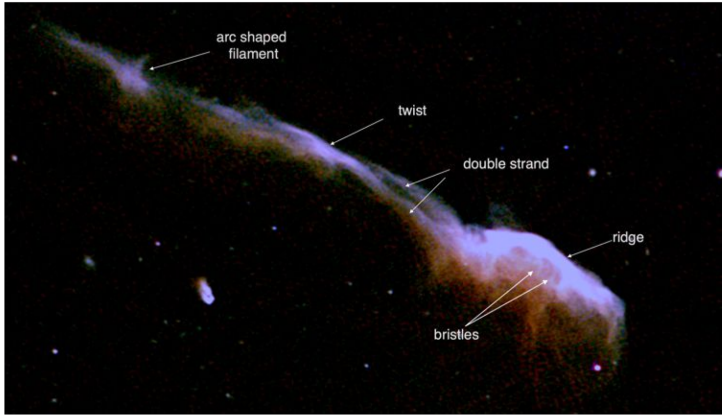




RADIO GALAXY IN CLUSTER

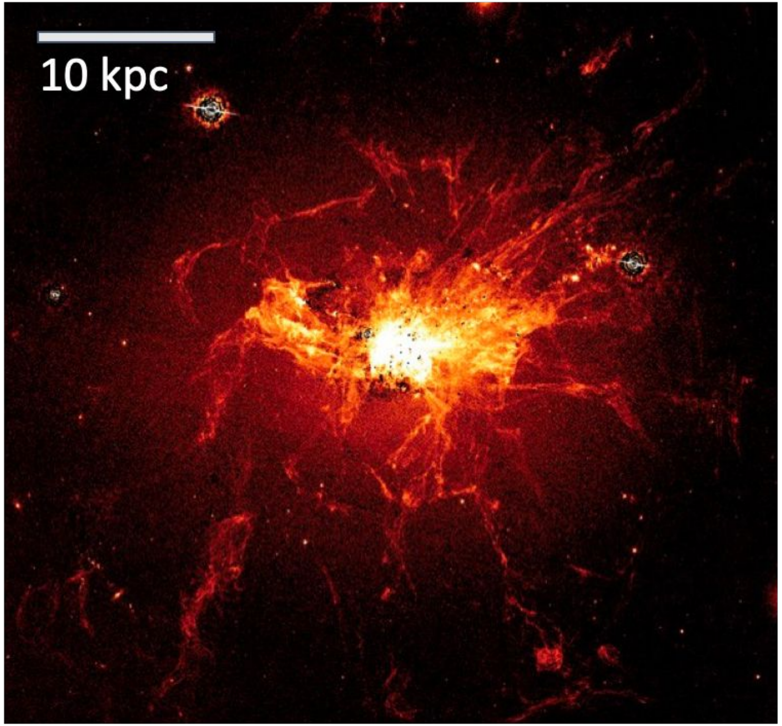


GALAXY CLUSTER/RELIC



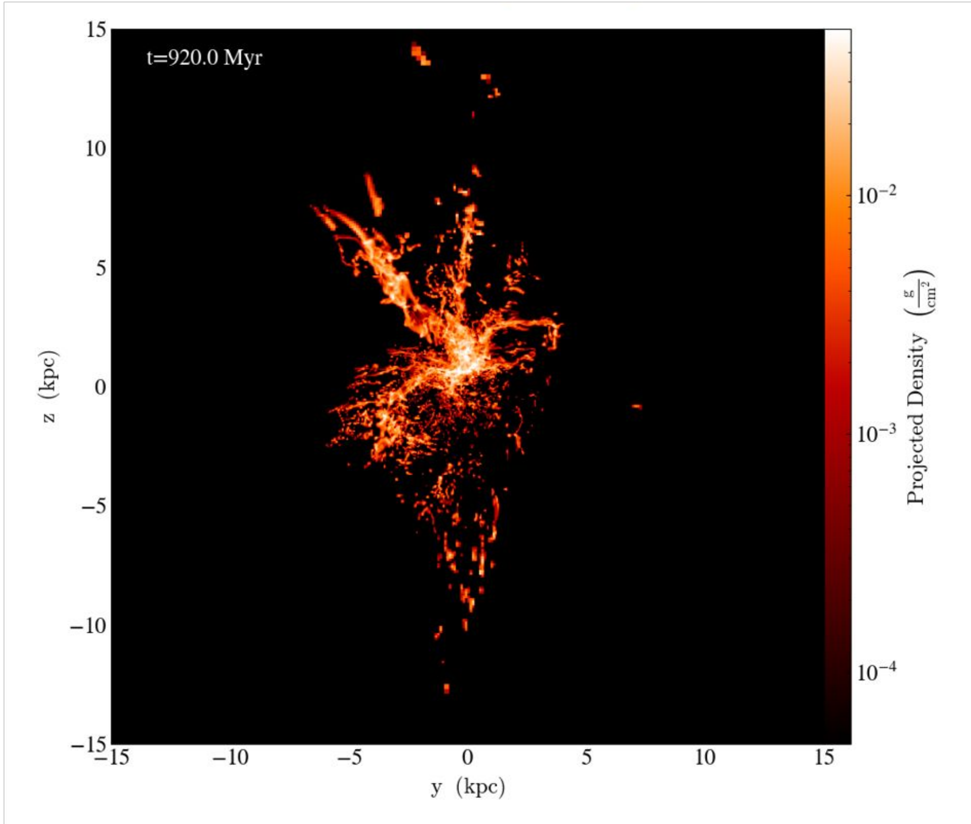
GALAXY CLUSTER/RELIC

NGC1275



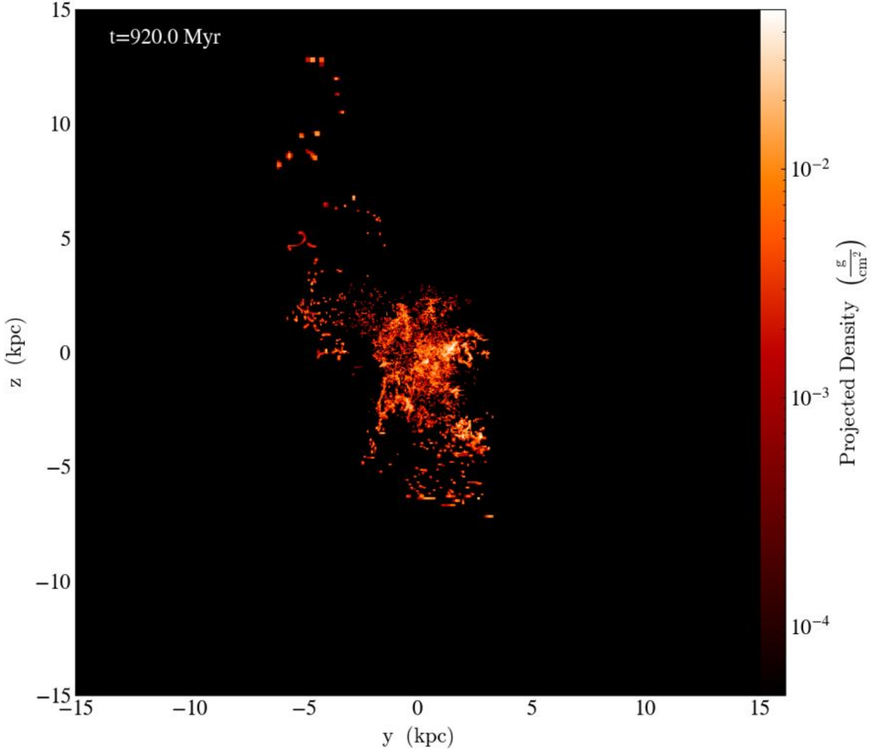
Fabian+ 2008

SIMULATION (MHD)

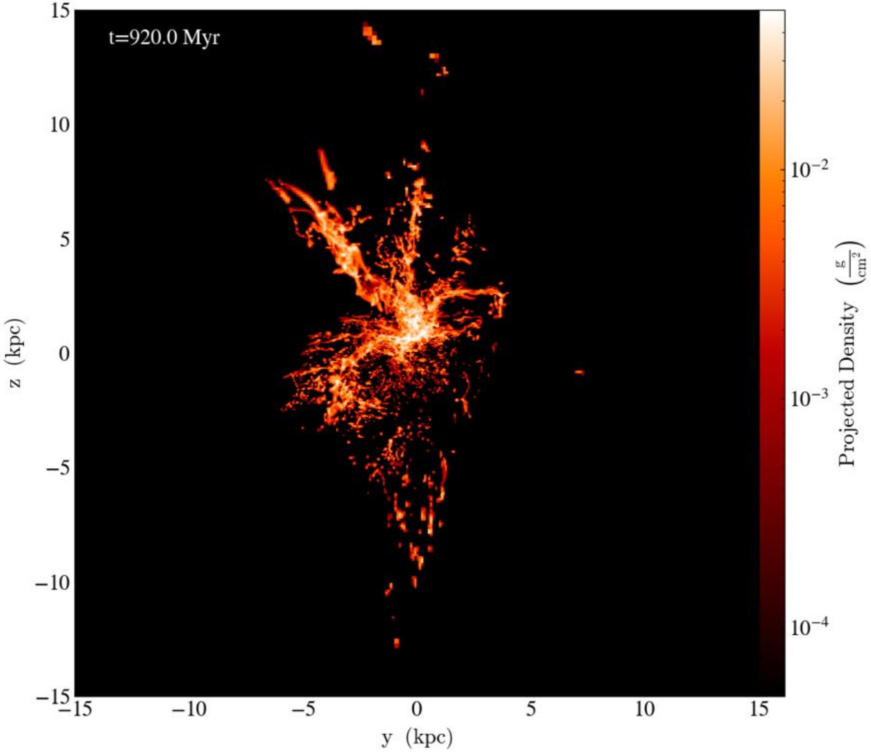


Fournier, MB+ 2024

HYDRO

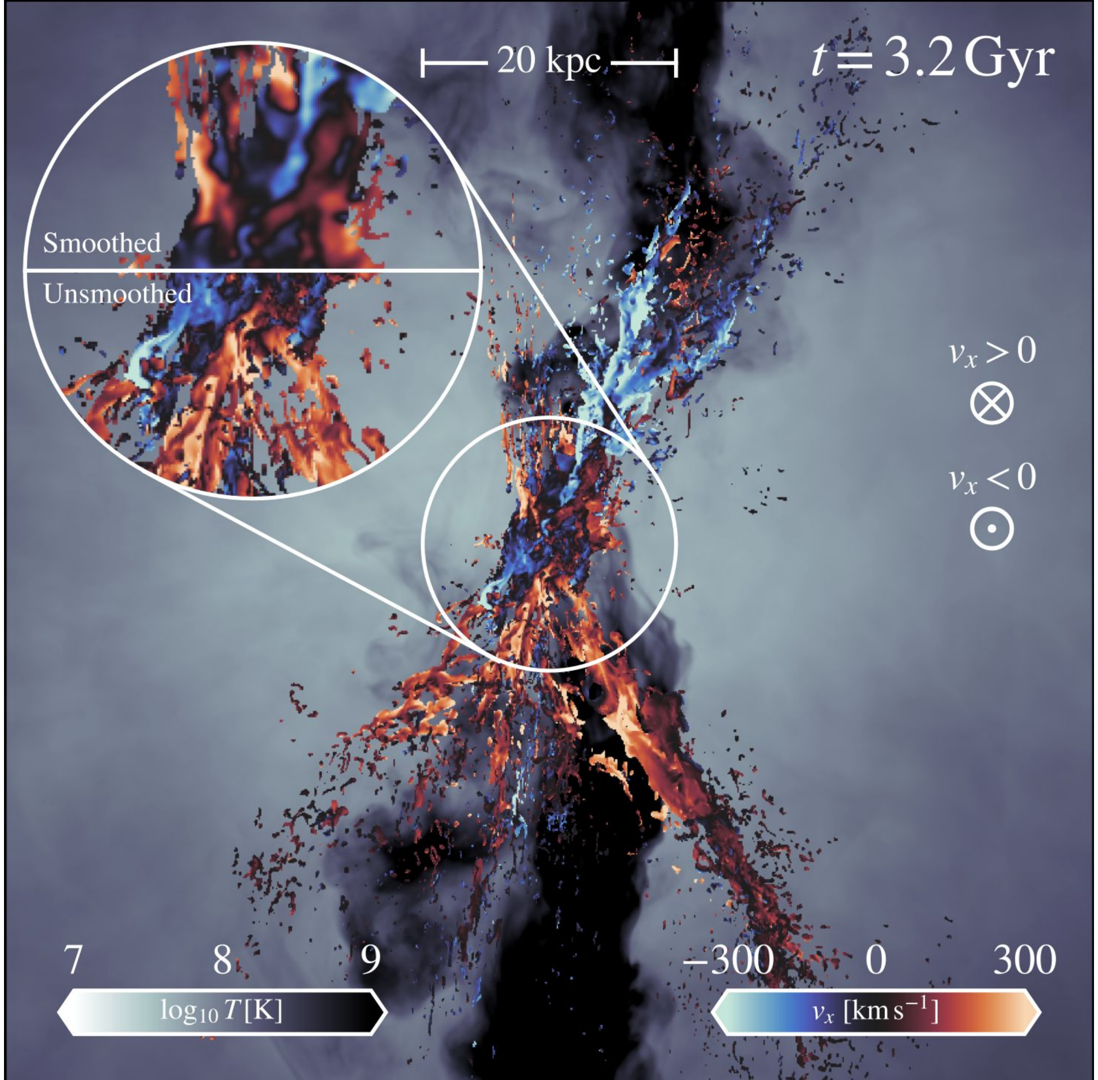


MHD



Magnetic fields favor filaments over tiny clumps no clear correlation between the behavior of the hot (10^6 K ≤ T ≤ 10^8 K) and cold (T ≤ 10^5 K) phase VSFs.

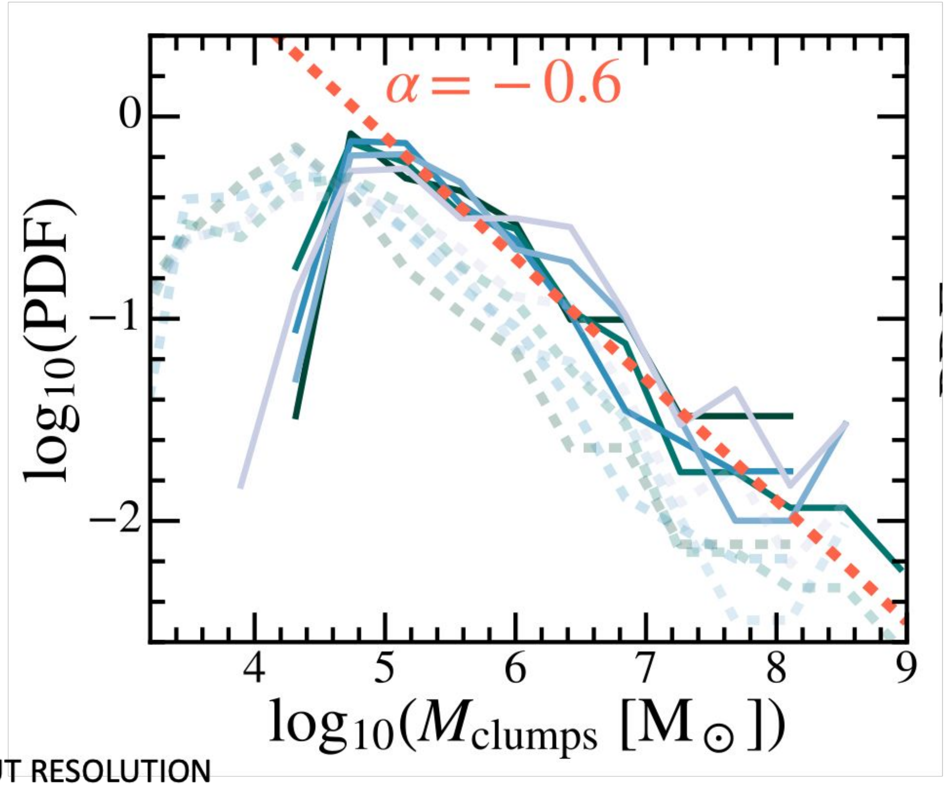
Grete+ 25, Fournier+ 25



FILAMENTS ARE CLUMPY

DOMINATED IN NUMBER BY LIGHT CLUMPS AND BY MASS BY MASSIVE CLUMPS

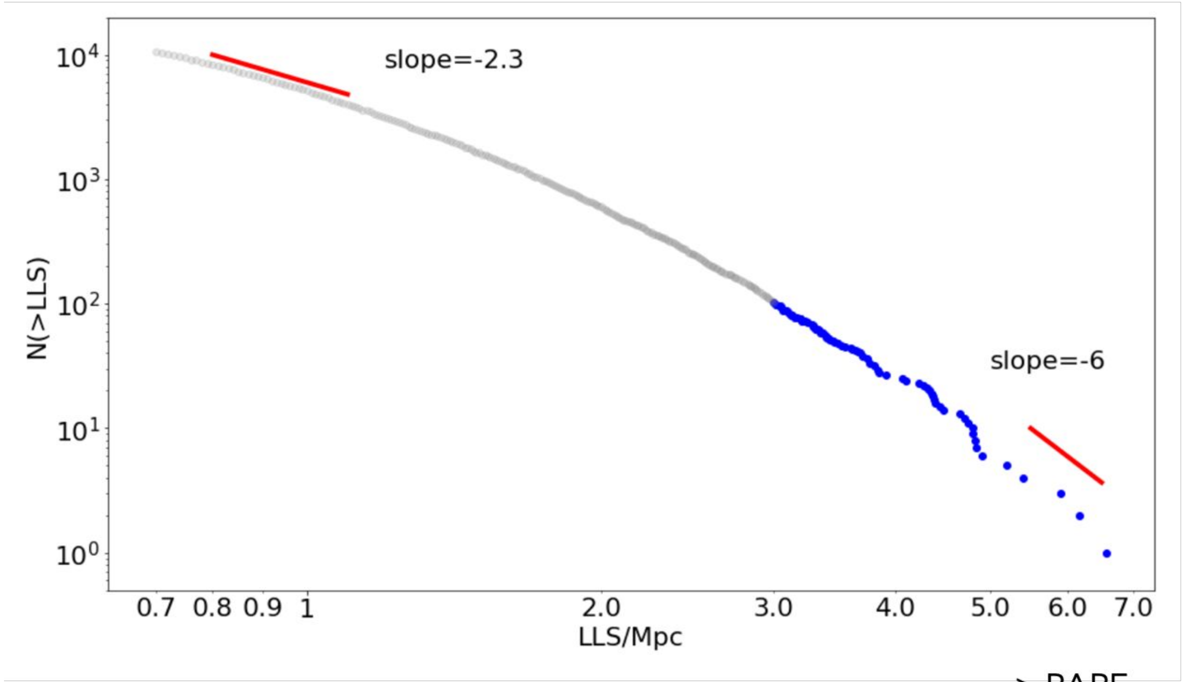
RESULT OF CLUMP-FINDING



BUT NEED TO WORRY ABOUT RESOLUTION

Fournier, MB+ 2024

NEW: 140 GRGs > 3 Mpc



-> RARE

18% IN CLUSTERS !

Andernach & MB 2025

Questions to discuss

1. **When can we trust quantitative or even qualitative predictions of simulations?**

Two types of simulations: reliable quantitative results or only trustworthy qualitative results

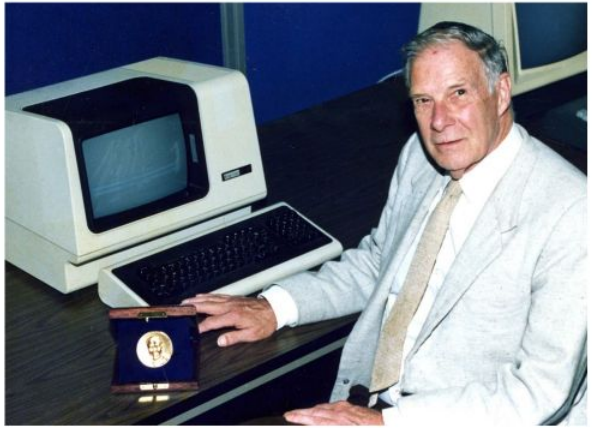
Current examples of the need for predictions and potential interpretation of observations:

- Observed CGM properties
- Level of burstiness of SF at z>9
- Timing of disk formation (both in general and for the Milky Way)
- Modeling/interpreting observed highly clustered star formation in high z galaxies
- Modeling/interpreting JWST spectra of high z galaxies

2. **Is there too much freedom in modeling relevant physics in current simulations?**

   Can models of star formation and feedback be calibrated to give reliable results on large-scales using observations like the star formation “tuning fork”? What tests/calibrations are best for specific problems? Detailed comparisons to observed gas distribution? Clustering of young massive stars?

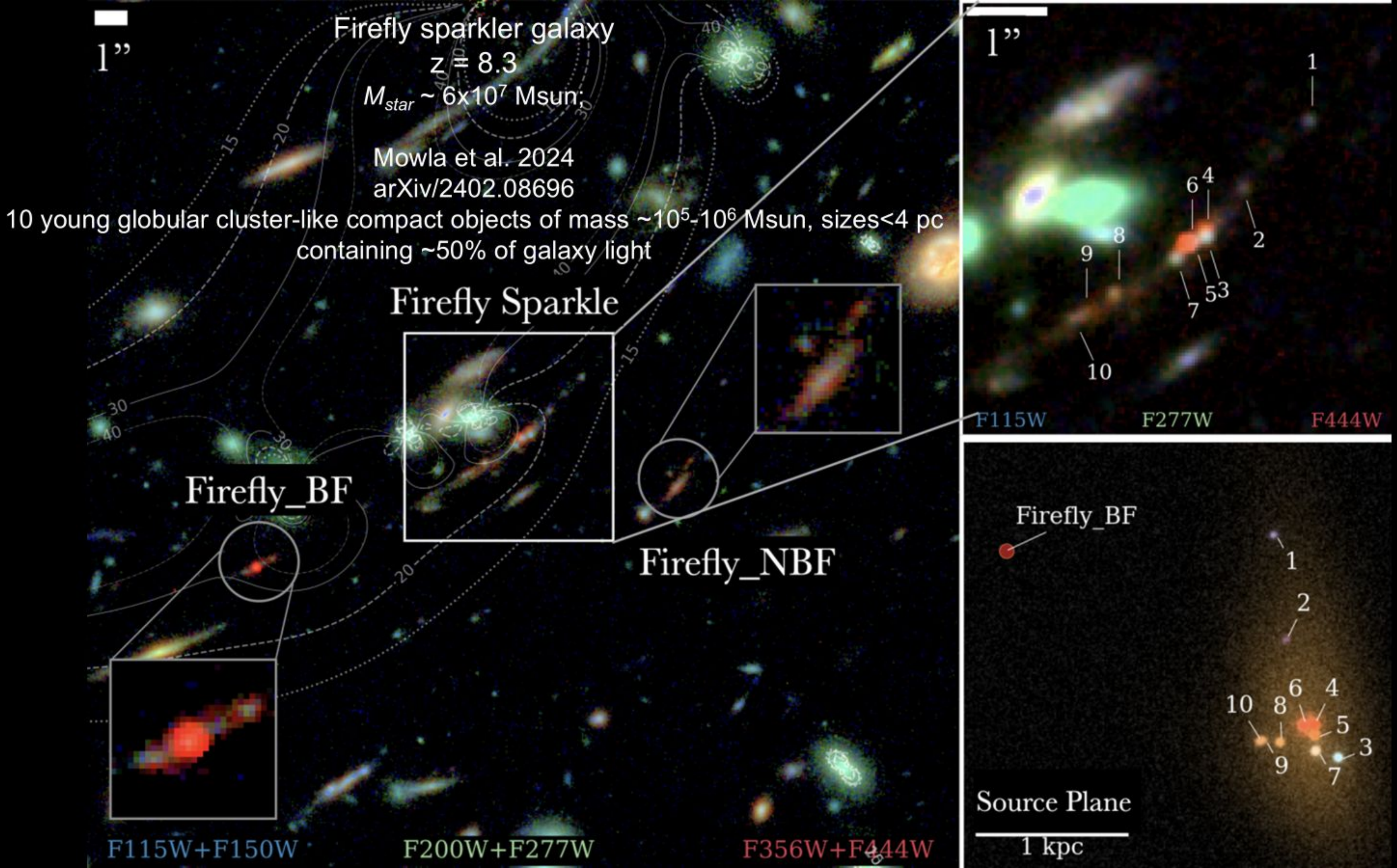
3. **What aspects of turbulencem B-fields, and feedback are most important for coupling different scales?**



"The purpose of computing is insight, not numbers"

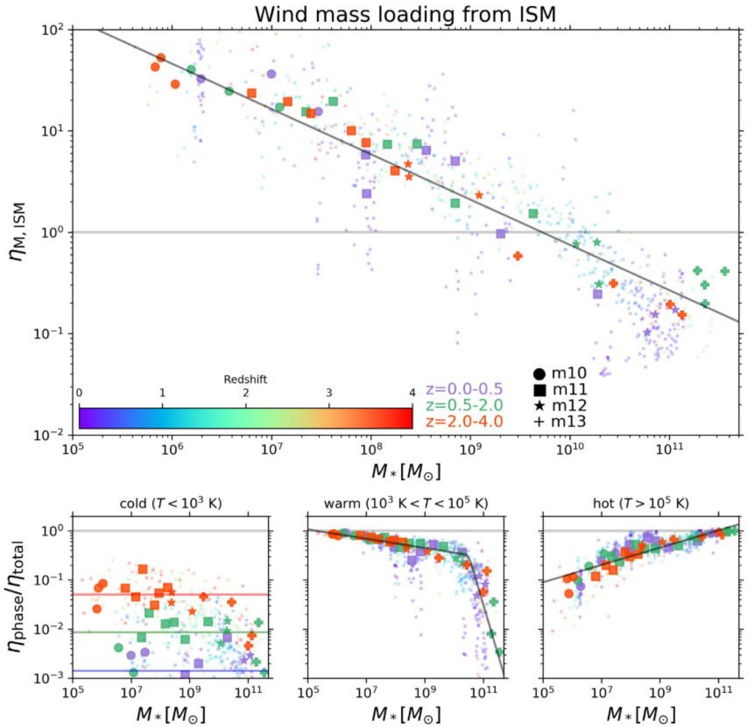
- Richard Hamming

Extra slides

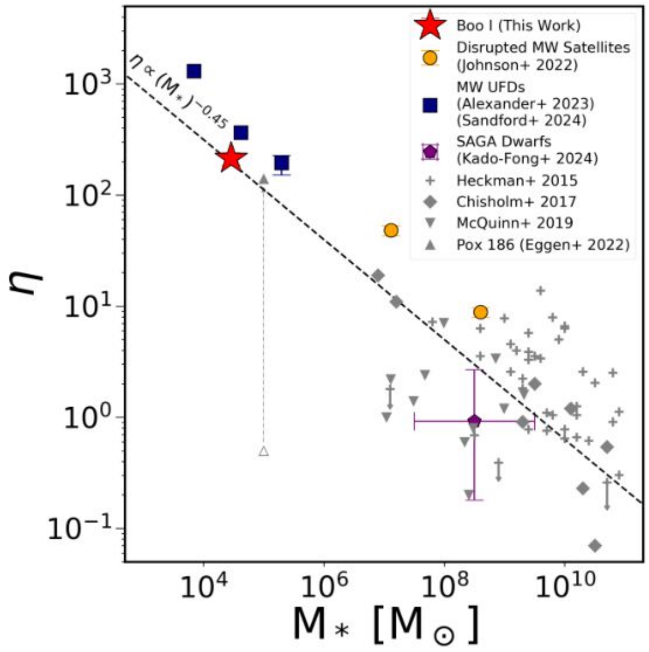


1”
Firefly sparkler galaxy
z = 8.3
M_{star} ~ 6x10^7 Msun;
Mowla et al. 2024
arXiv/2402.08696
10 young globular cluster-like compact objects of mass ~10^5-10^6 Msun, sizes<4 pc
containing ~50% of galaxy light
Firefly Sparkle
Firefly_BF
Firefly_NBF
F115W+F150W
F200W+F277W
F356W+F444W
1”
1
2
3
4
5
6
7
8
9
10
F115W
F277W
F444W
Firefly_BF
Source Plane
1 kpc

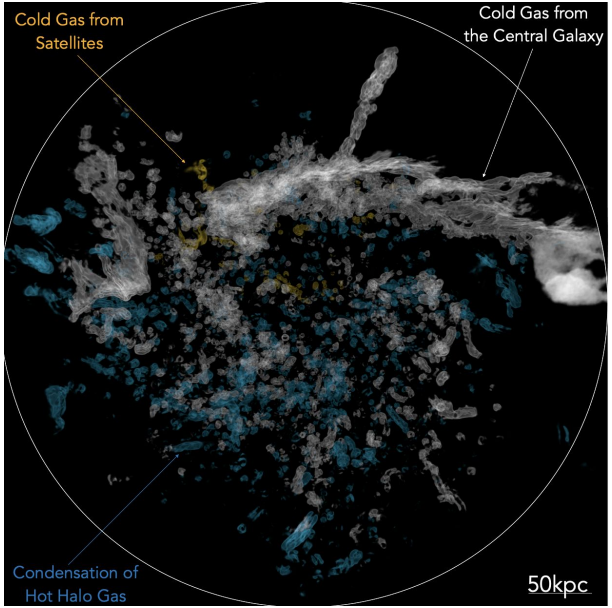
Outflow mass loading factors in simulations and observations



Pandya, V. et al. 2021, MN 508, 2979

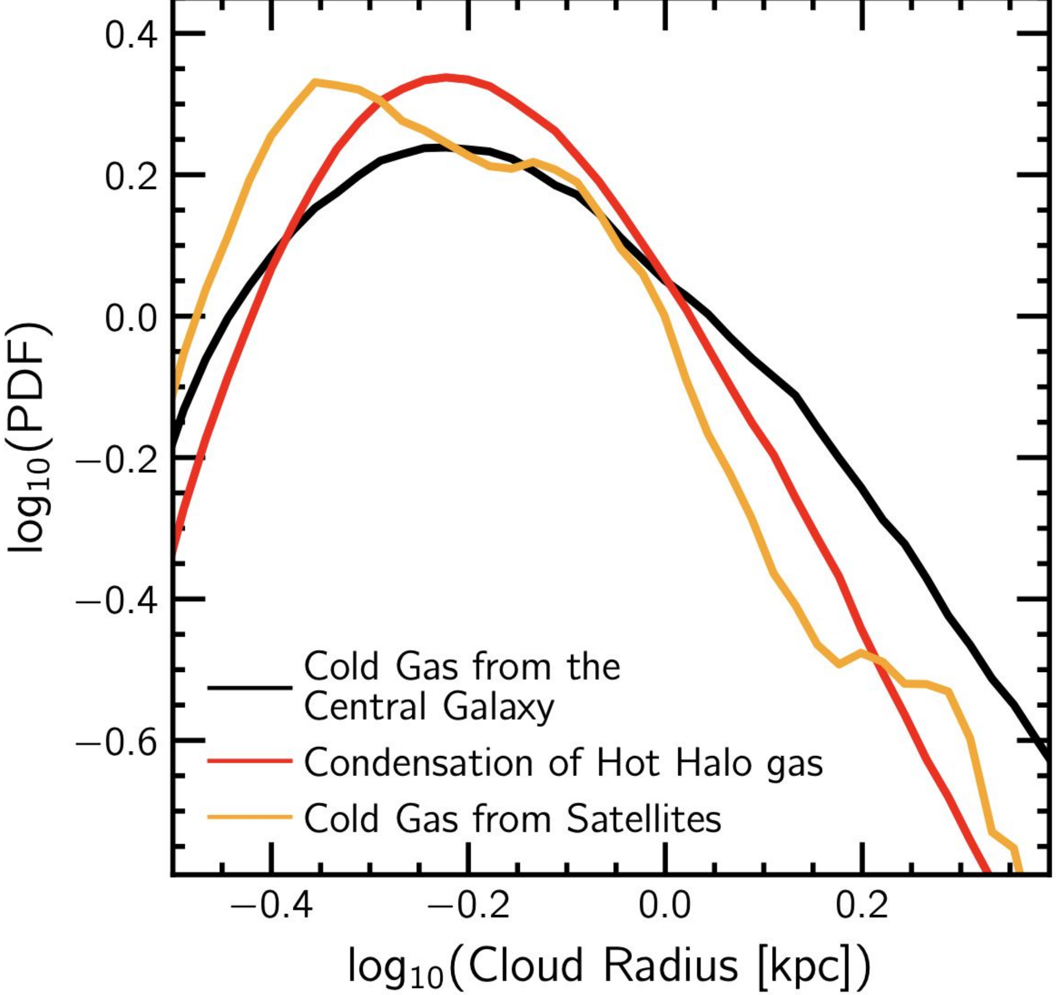


Credit: Nathan Sandford (U Toronto)



Cold Gas from
Satellites
Cold Gas from
the Central Galaxy
Condensation of
Hot Halo Gas
50kpc

Rahul+ 24



0.4
0.2
0.0
−0.2
−0.4
−0.6
log10(PDF)
−0.4
−0.2
0.0
0.2
log10(Cloud Radius [kpc])
Cold Gas from the
Central Galaxy
Condensation of Hot Halo gas
Cold Gas from Satellites

Questions to discuss

1. **Spatial scales:** Ion Larmor radius, turbulent dissipation scale, Alfven scale, cooling scale, injection scale, accretion scale

   Relevance for feedback and observational/theoretical accessibility?

2. **Temporal scales:** free-fall, cooling, …?

Opportunities of exascale computing? What next for subgrid modelling? ML?