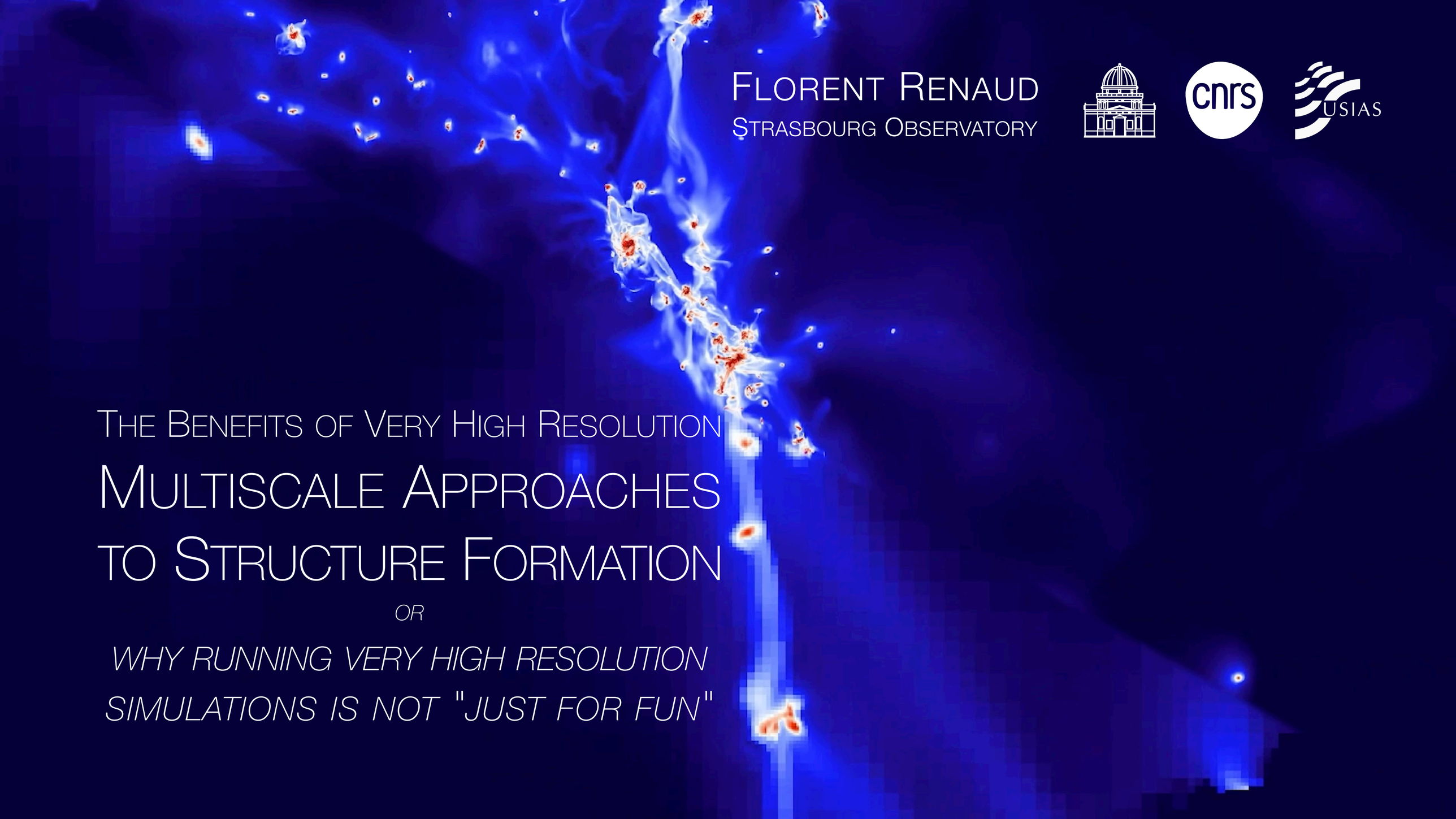


Florent Renaud
Strasbourg Observatory

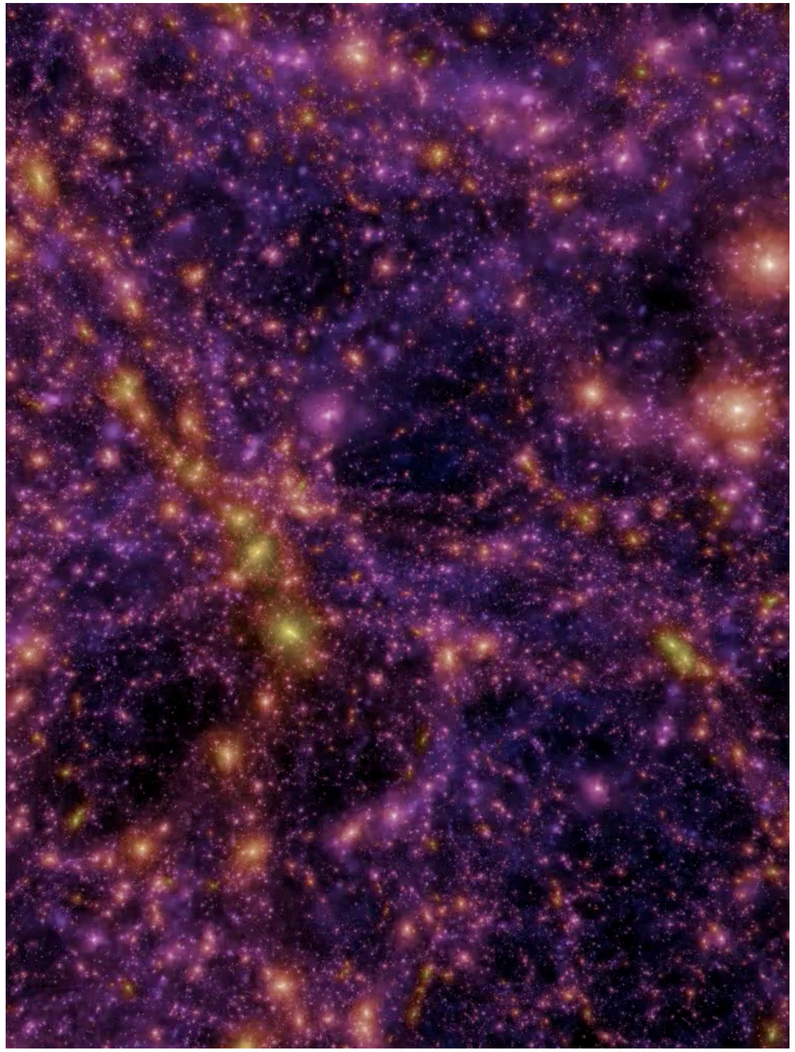
The Benefits of Very High Resolution

Multiscale Approaches to Structure Formation

or

Why running very high resolution simulations is not "just for fun"

TENSIONS WITH WHAT?



Sales et al. (2022)

No tension	Uncertain	Weak tension	Strong tension
Missing satellites	$M_\star$-$M_{\rm halo}$ relation	Too big to fail	Diversity of rotation curves
	Core-cusp	Diversity of dwarf sizes	Satellite planes
		Quiescent fractions	

Historical "tensions" between:

Reality
measurements from luminous matter

ΛCDM
dark-matter only simulations

this is not LCDM

here is your problem!

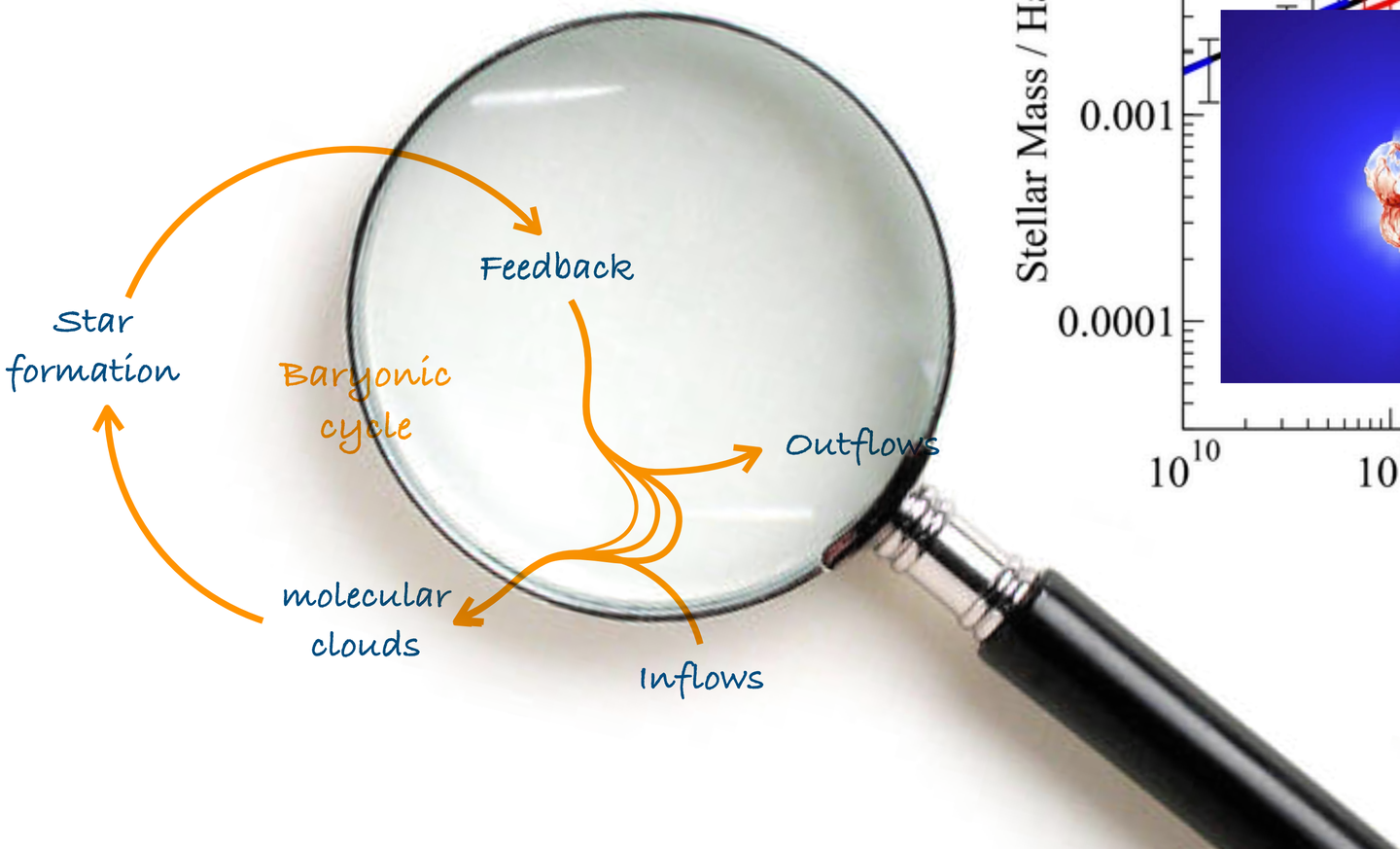
Many improvements by including baryonic physics

But need (uncertain) sub-grid recipes in cosmological volumes

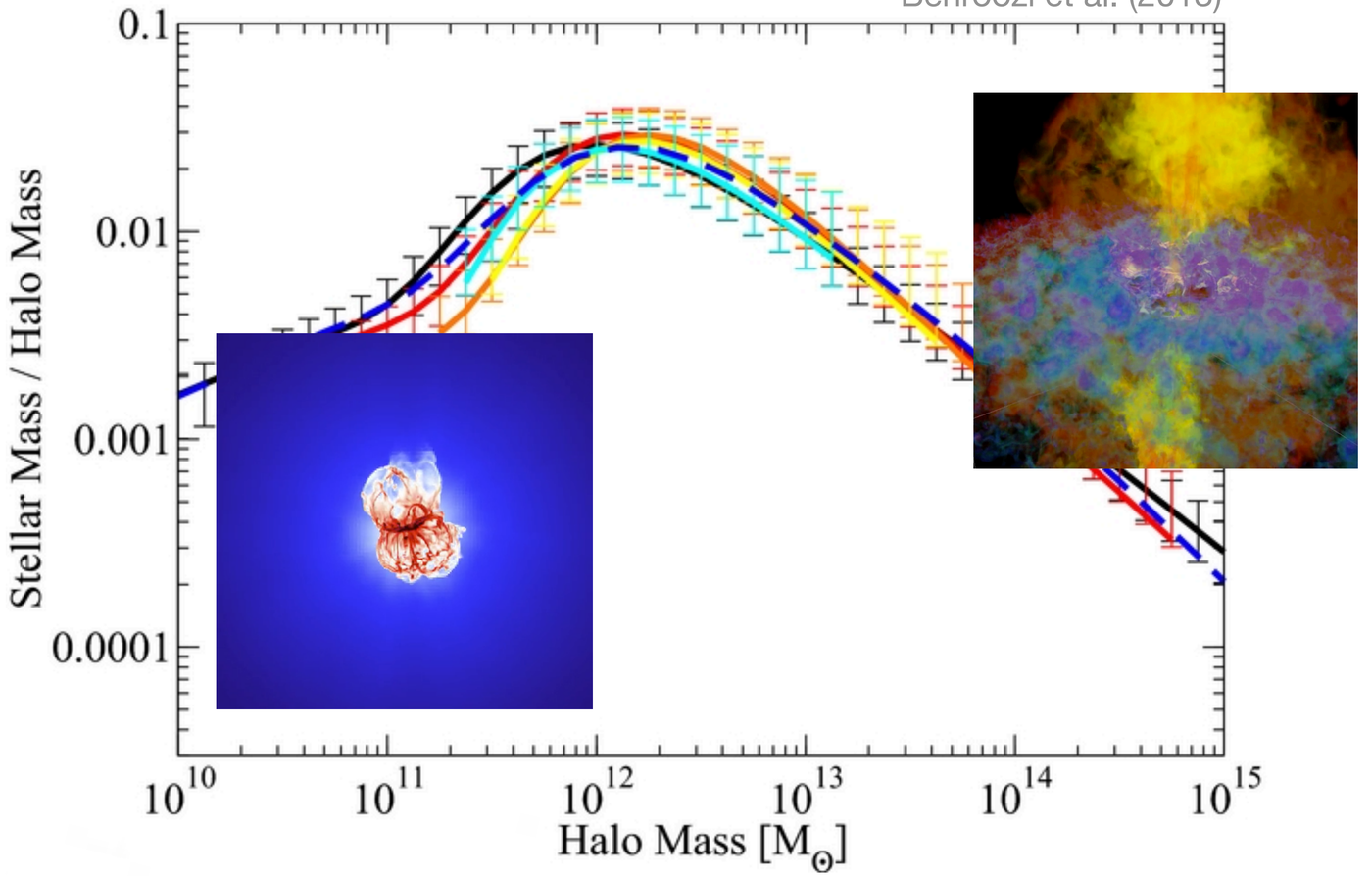
INEFFICIENCY OF GALAXY FORMATION

Low baryonic fraction in galaxies

→ feedback (stellar + AGN)

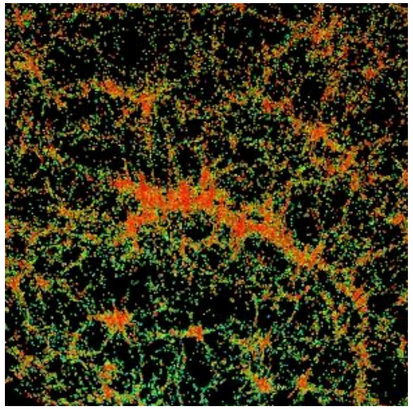


Behroozi et al. (2013)



Movies by O. Agertz and V. Gaibler

MULTI-SCALE IMPLIES MULTI PHYSICS





toward planet formation

cosmological structures — *galaxy formation* — *galactic dynamics* — *star formation* — *star cluster evolution*

10 Mpc — 100 kpc — 1 kpc — 10 pc — 0.1 pc

1 Gyr — 100 Myr — 10 Myr — 1 Myr — 0.1 Myr

gas inflows

mergers

outflows, galactic winds

turbulence

shear

magnetic fields

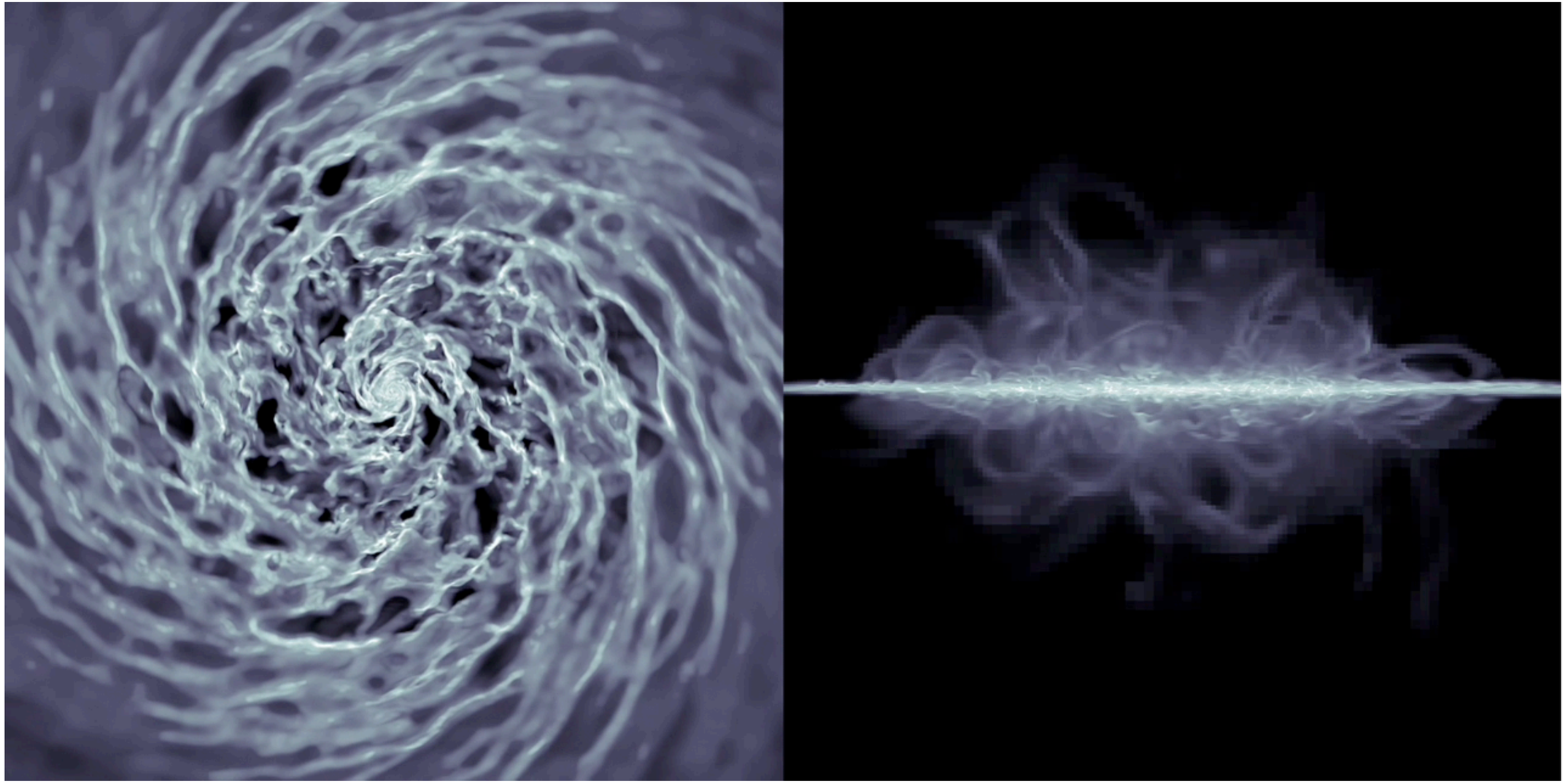
stellar evolution

stellar feedback

gravitation, tides

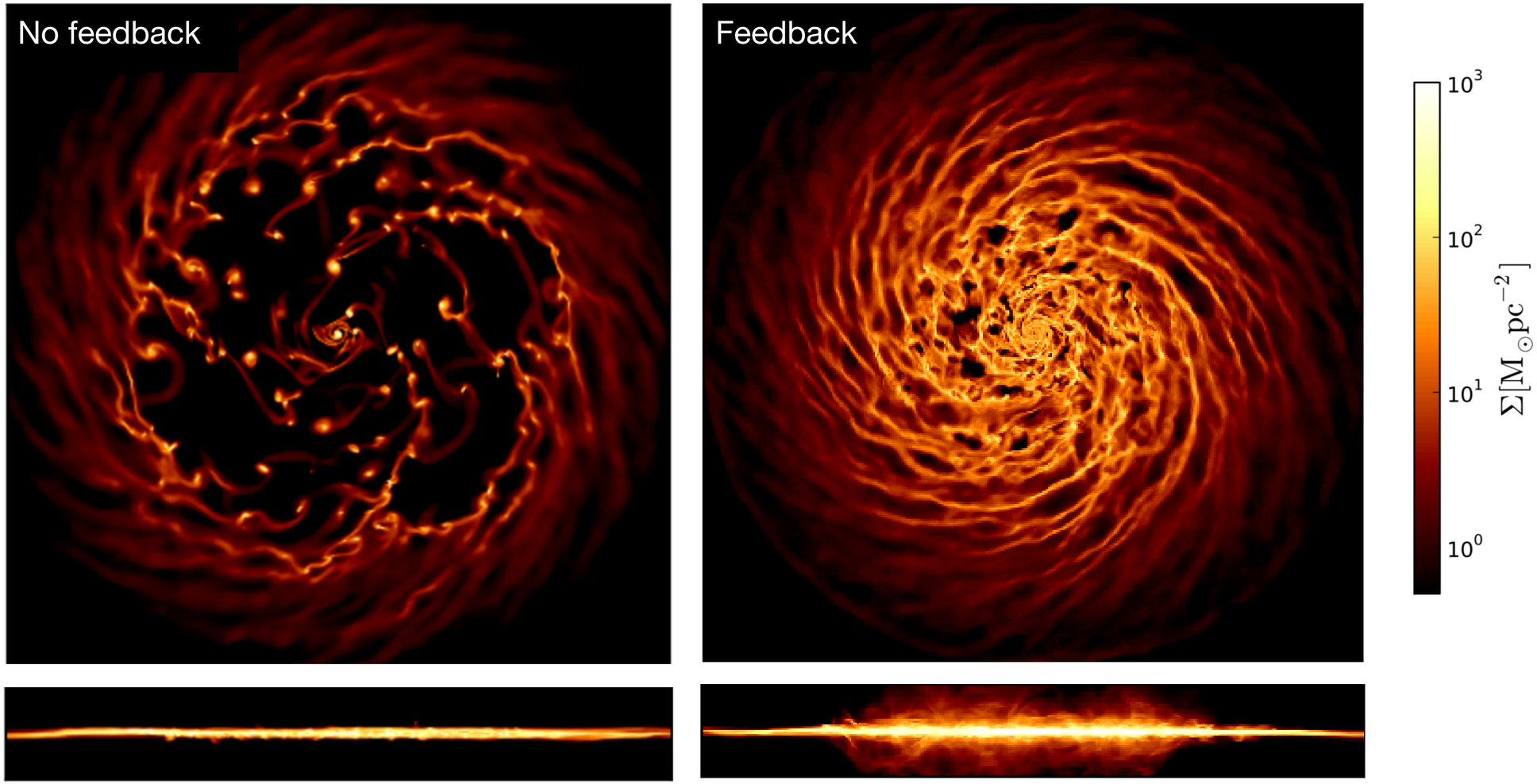
FEEDBACK NEEDED TO REGULATE THE GALACTIC STRUCTURE

Grisdale et al. (2017)



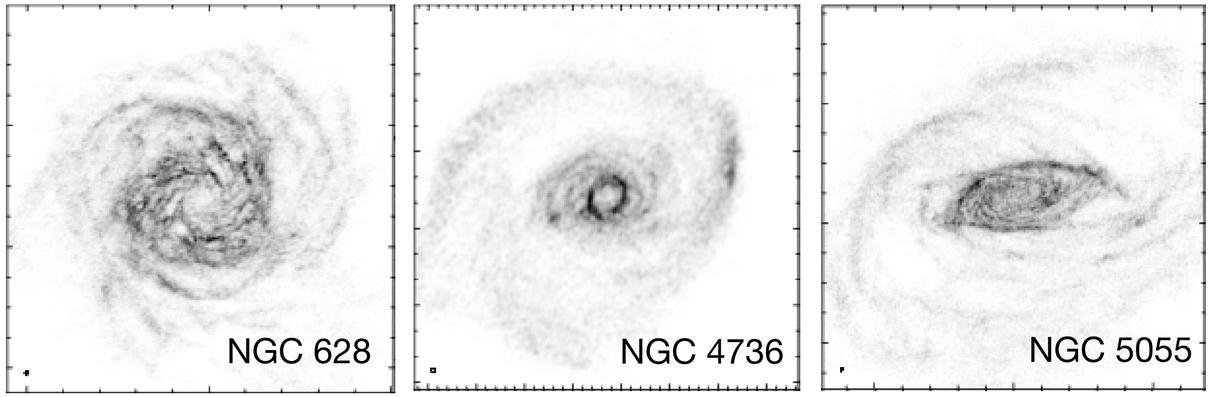
FEEDBACK NEEDED TO REGULATE THE GALACTIC STRUCTURE

Grisdale et al. (2017)

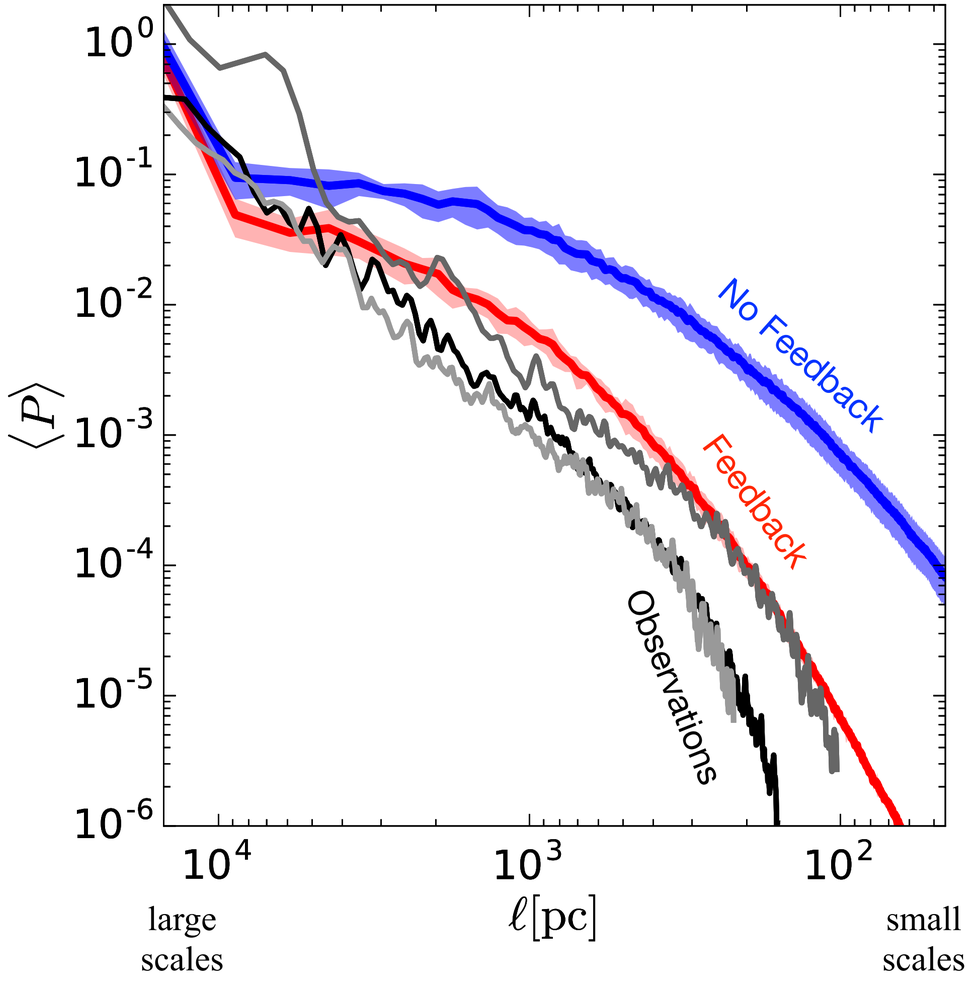


GALACTIC POWER SPECTRUM

THINGS survey: Walter et al. (2008)



Grisdale et al. (2017)

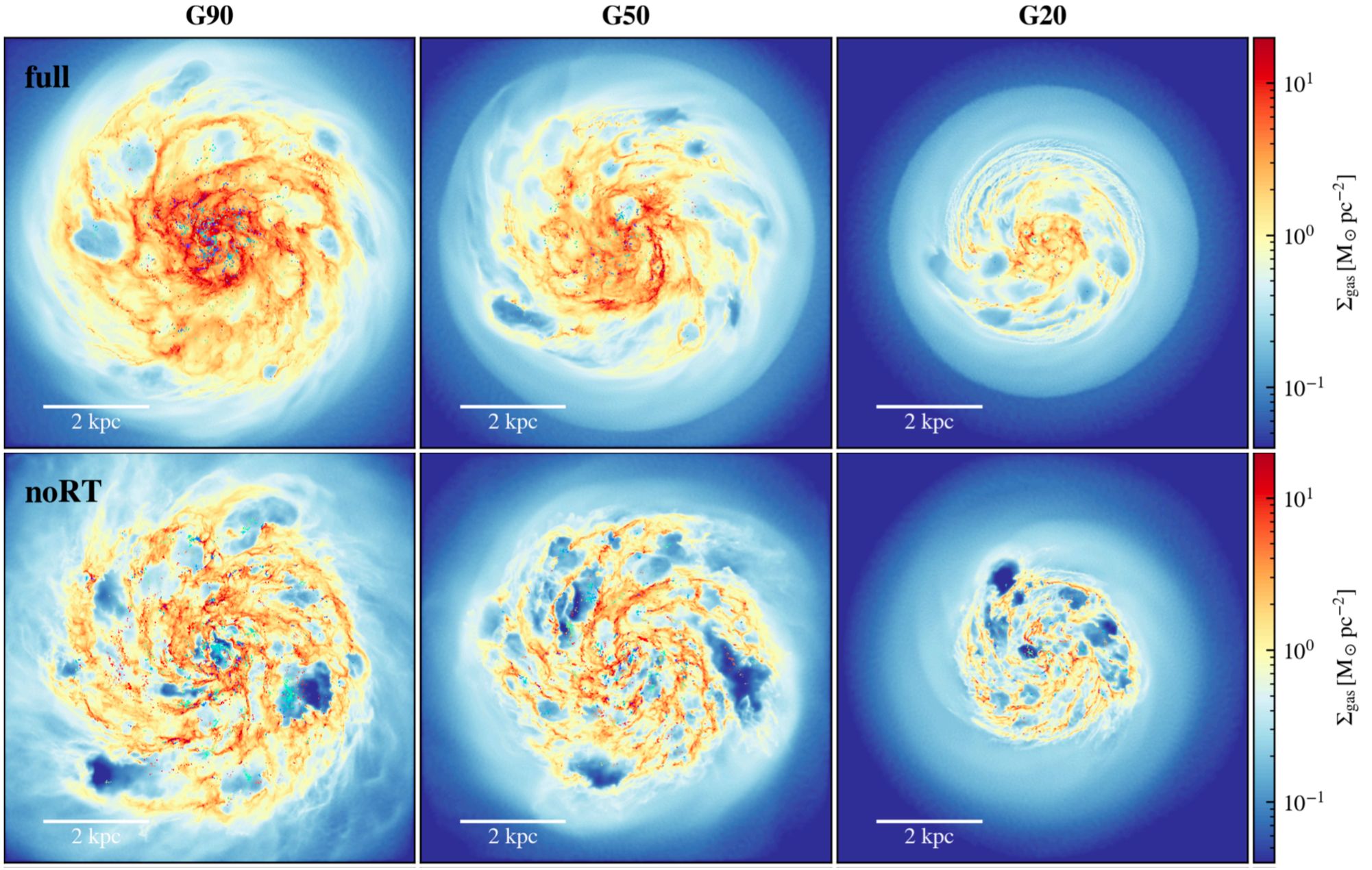


No feedback: highest discrepancies at small scales

→ Need feedback to *statistically* match real galaxies

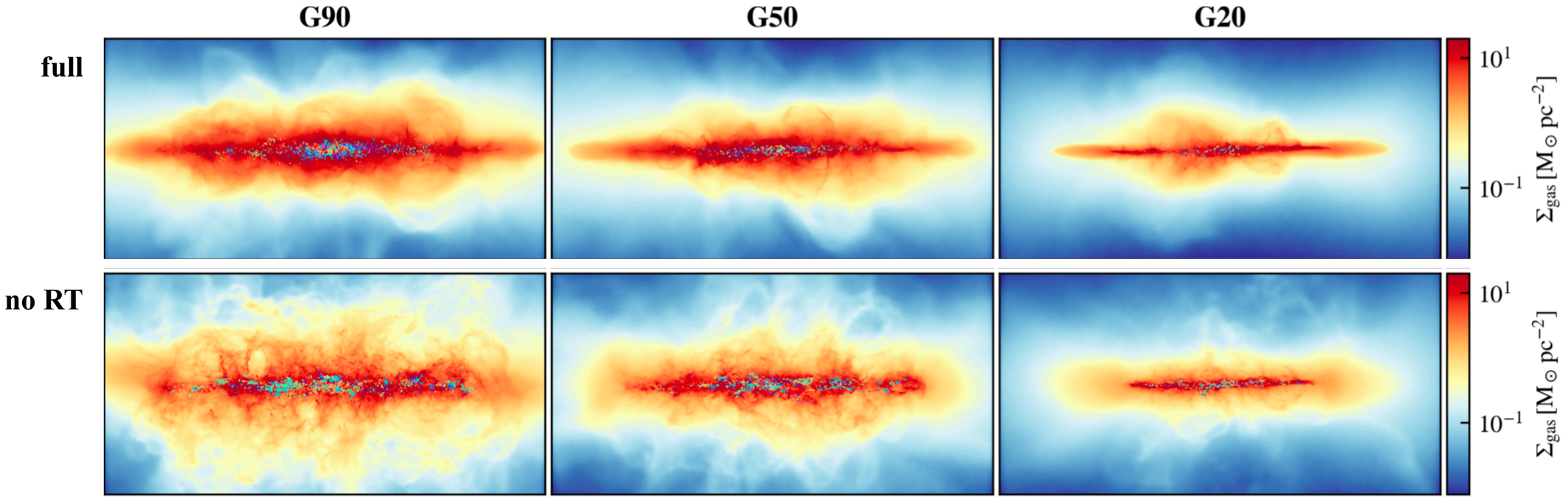
EARLY (= BEFORE SUPERNOVAE) FEEDBACK

Li et al. (in prep.)

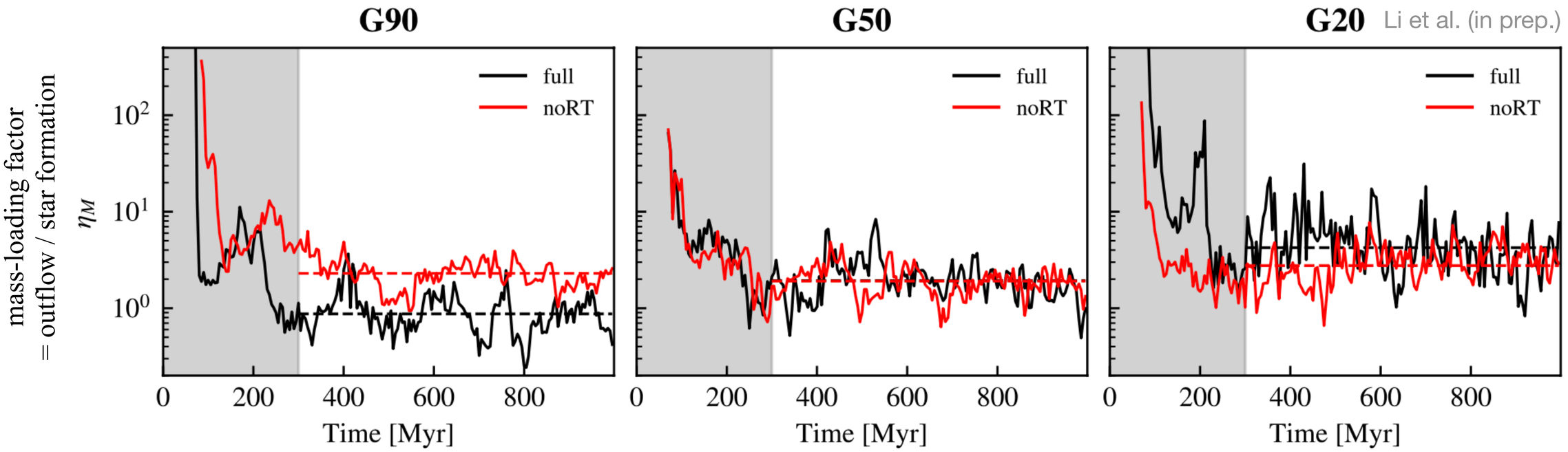


EARLY (= BEFORE SUPERNOVAE) FEEDBACK

Li et al. (in prep.)



FROM STELLAR TO GALACTIC SCALE

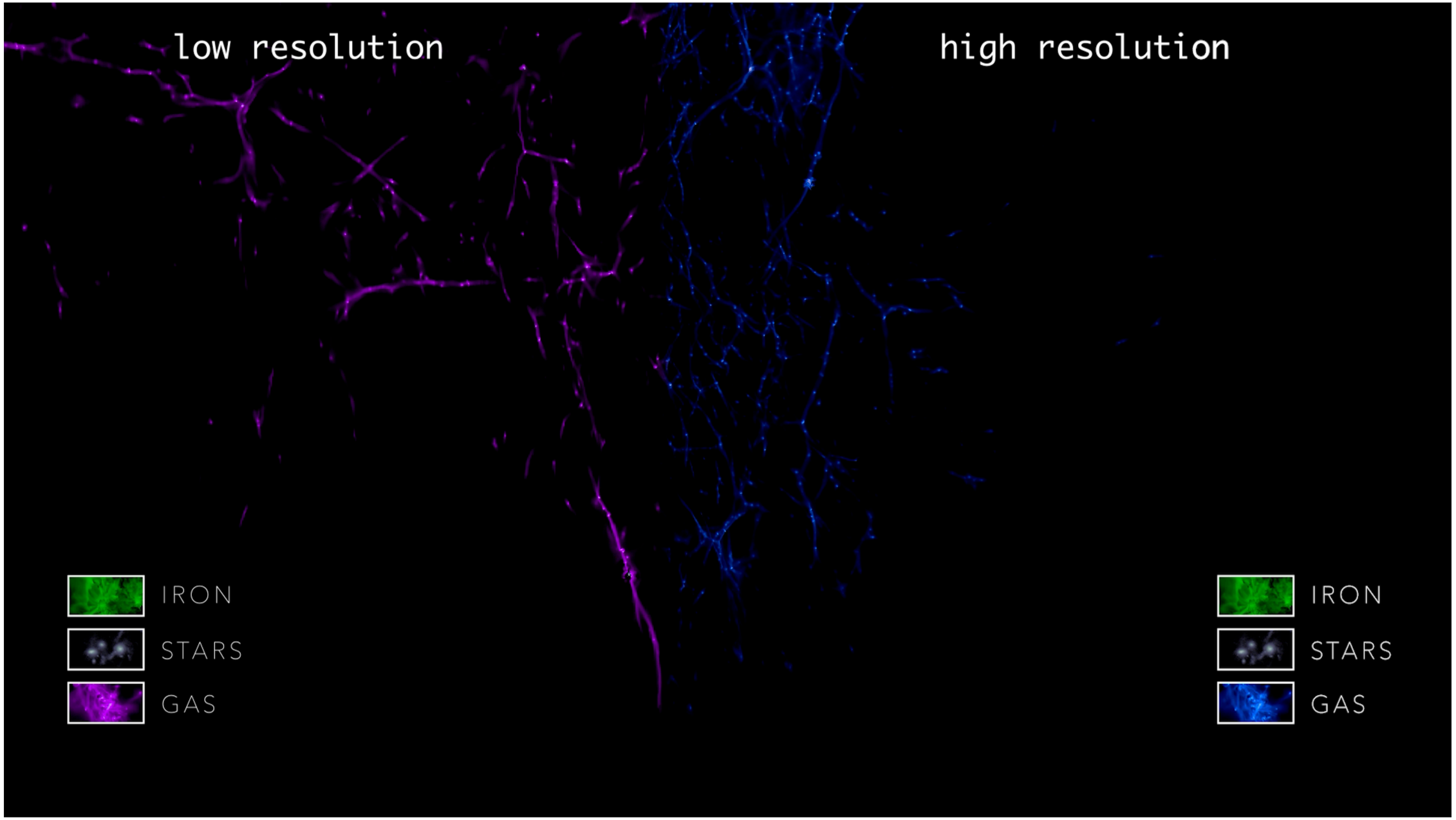


The efficiency of removing gas from the galaxy depends on

- the strength of the wind (SFR, feedback local efficiency...)
- the potential of the host
- the coupling between the wind and the interstellar and circum-galactic media

we still don't know how to do this

IN COSMOLOGICAL SIMULATIONS



SUPERNOVA FEEDBACK IN TURBULENT MEDIUM

Ohlin, Renaud & Agertz (2019)

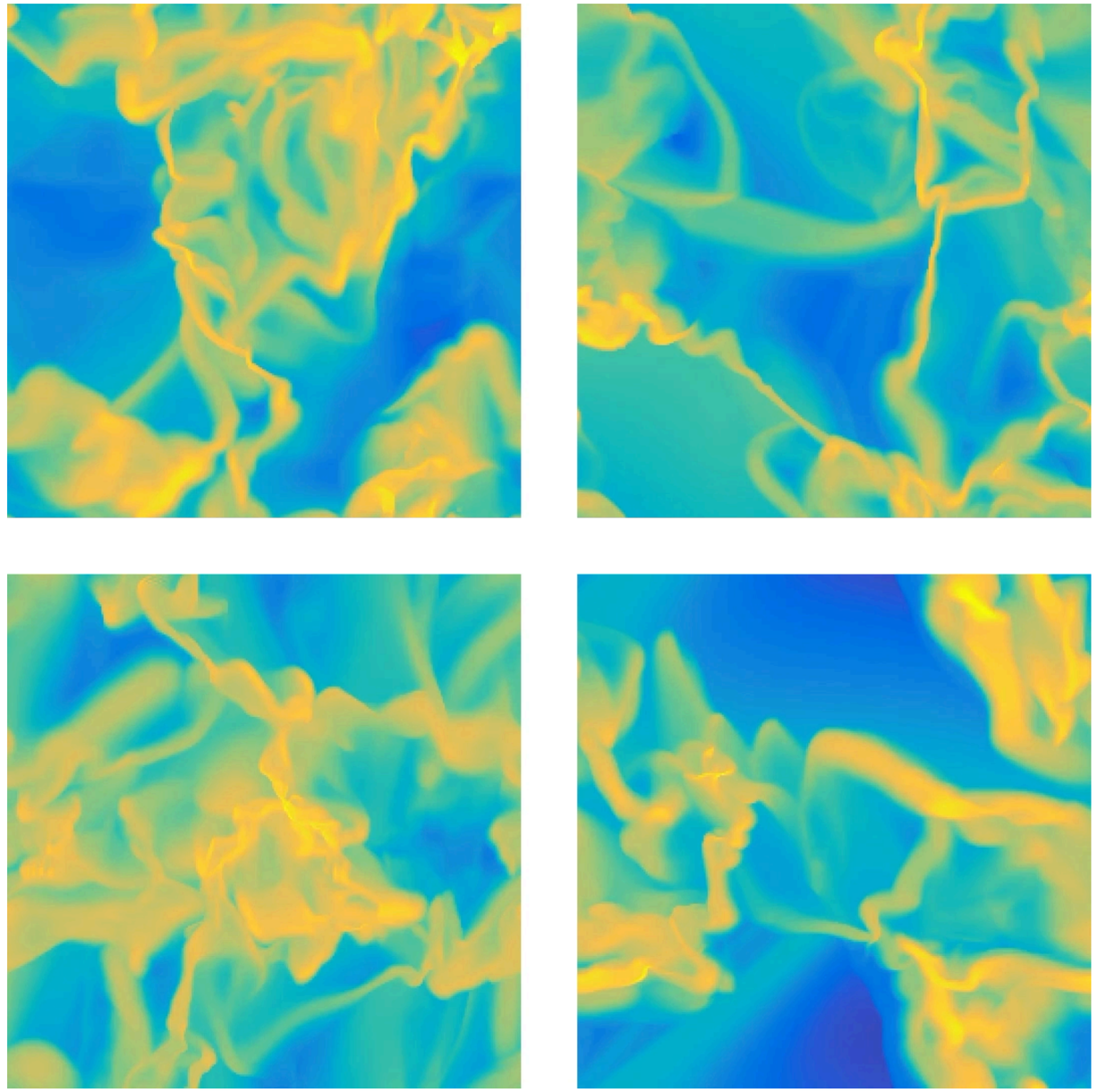
Different statistical realizations
of the same medium

- same average density
- same turbulence spectrum

→ strictly identical if *not* resolved
(typically in cosmo simulations)

1 supernova at the center

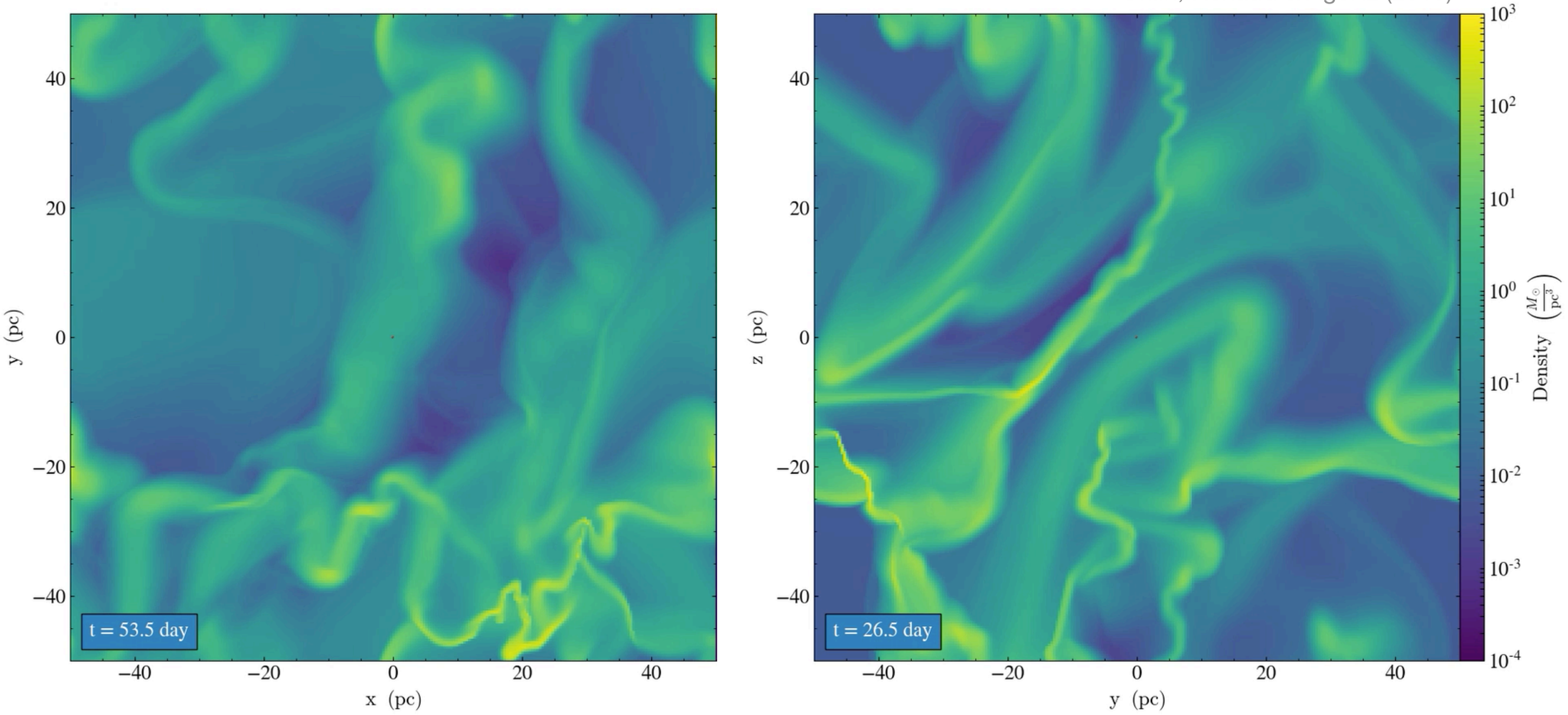
Different coupling scales and efficiencies
with the ISM



see also Martizzi et al. 2015, Kim & Ostriker 2015

SUPERNOVA FEEDBACK IN TURBULENT MEDIUM

Ohlin, Renaud & Agertz (2019)



◯ : in homogeneous medium

EXPANSION RATE AND VOLUME OF SN BUBBLES

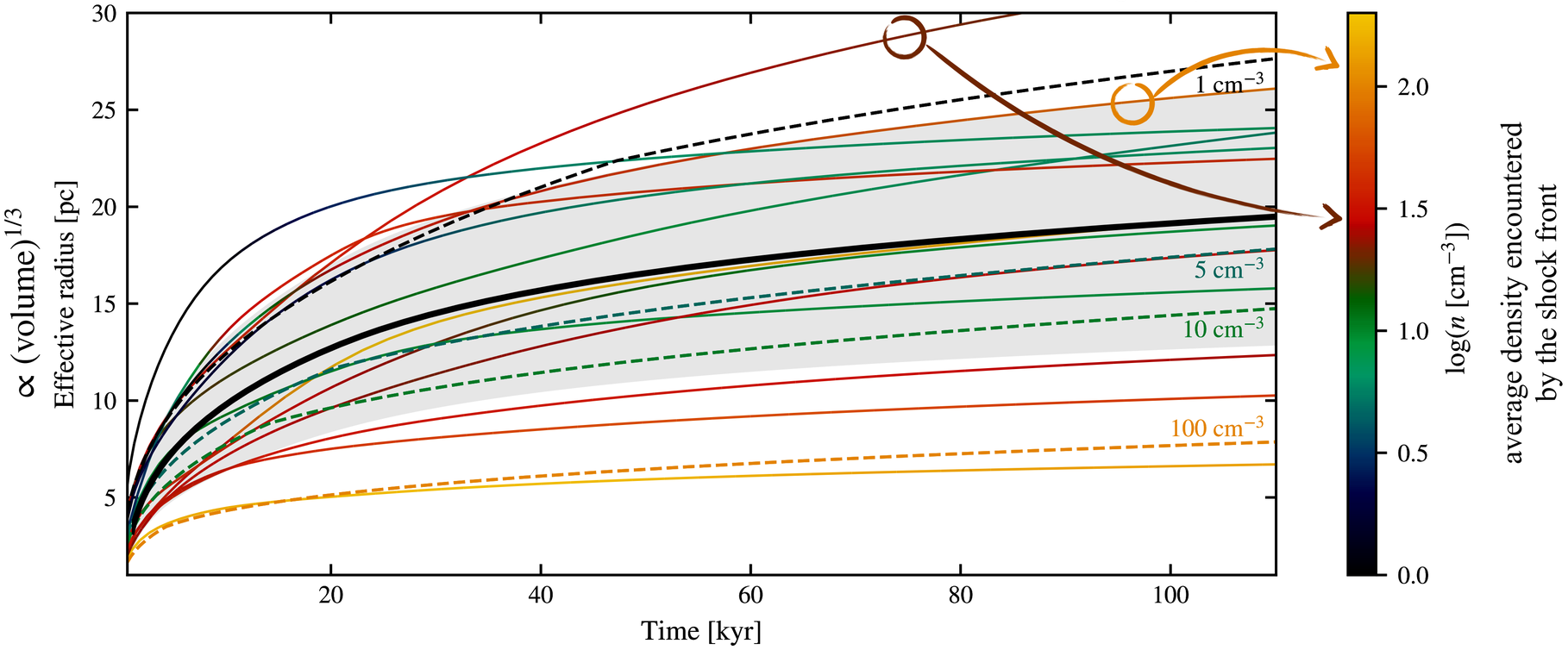
- - - - - in homogeneous medium

In turbulent medium:

——— individual realizations with box density of $100\ \mathrm{cm}^{-3}$

▬ average and std. deviation

Ohlin, Renaud & Agertz (2019)

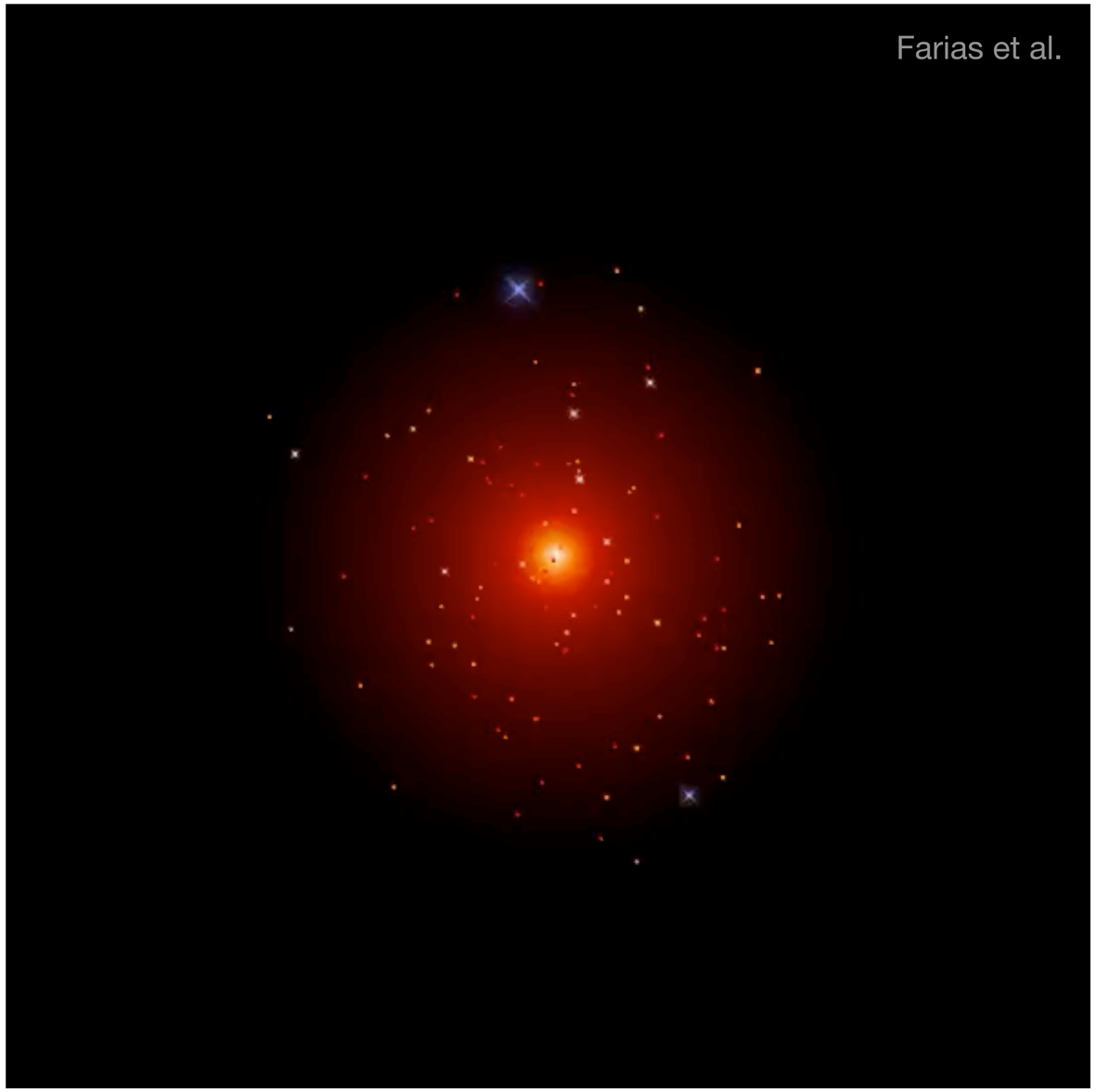


The (semi-)analytical solutions are incorrect

Need to resolve the structure of the ISM around the injection of feedbak

> 12 orders of magnitudes in cosmo simulations ...

STELLAR DYNAMICS MATTERS (A LOT!) AT GALACTIC SCALE



Star cluster mass-loss is caused by

- stellar evolution
- tides
- relaxation (collisional dynamics)

} stars escape the cluster

In binary/multiple systems, the ejection can be early and/or fast

velocity kicks → runaway stars

Need star-by-star dynamics to capture this

~10% of the stars are runaways

Mean traveling distance for SNII progenitors = 100 pc

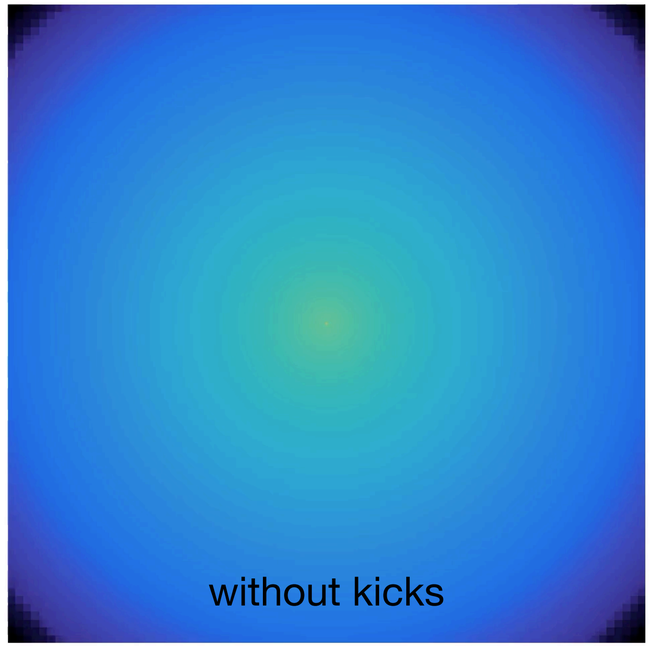
RUNAWAY STARS

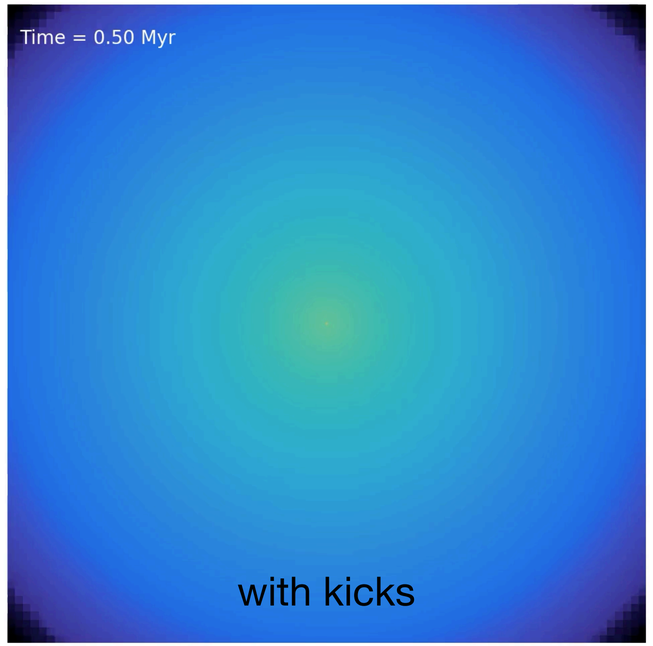
Andersson, Renaud & Agertz (2021)

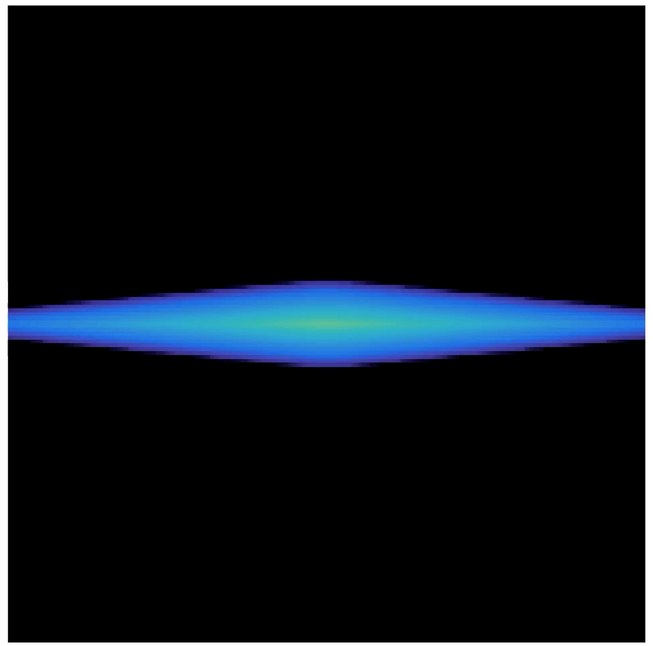
Runaways stars inject feedback
far from their formation sites

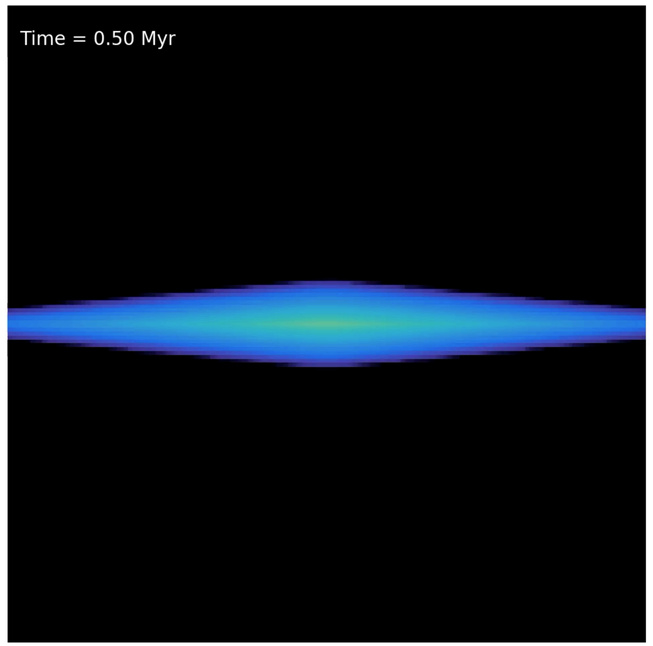
- Less feedback in the star-forming cloud
  - → different energy budget
  - → less efficient (slower?) regulation of star formation
  - → different chemical enrichment

- Feedback in lower density medium
  - → less resistance from the ISM
  - → coupling to larger scales
  - → stronger galactic winds (speed and mass-loading factor)

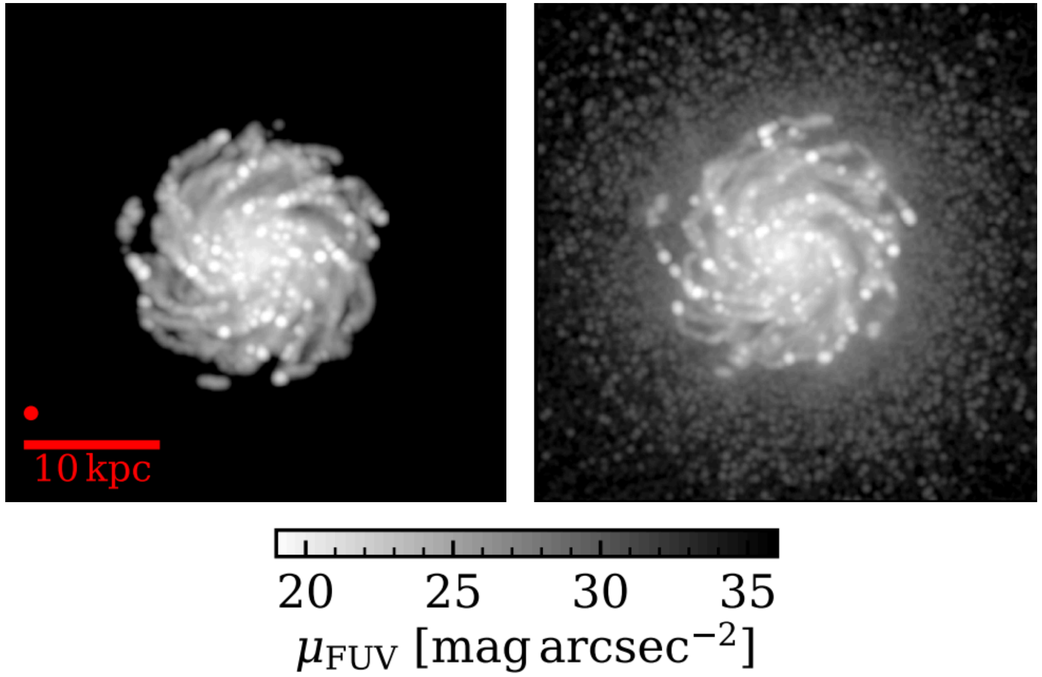




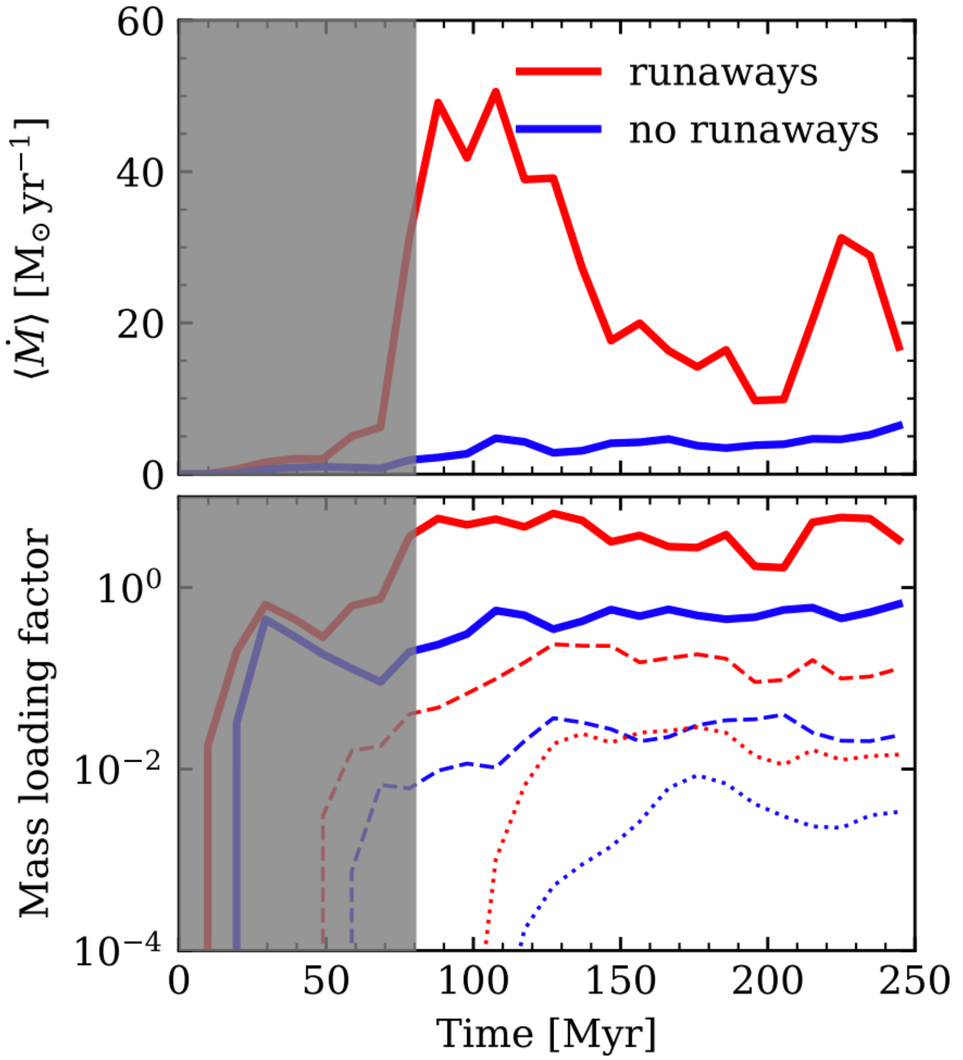




RUNAWAY STARS



Andersson, Renaud & Agertz (2020, 2021)



Significant differences in the mass and size of galaxies initially caused by star-star interactions!

Specially important in dwarfs (shallow potential)

What do the properties of the kicks depend on?
(compactness, mass segregation, binary fraction, relaxation time ...?)

Conclusions

Florent Renaud | Strasbourg Observatory / CNRS
florent.renaud@astro.unistra.fr

Simulations at low resolution with highly incomplete physics do not match observations

This should not be mistaken with tensions with cosmo models

Feedback is key for galaxy formation

but details remain poorly understood

- clustering
- coupling to larger scales
- runaway effects

Detailed effects propagate to large scales (quenching, outflows, enrichment,...)

Sub-grid recipes cannot always properly replace high resolution