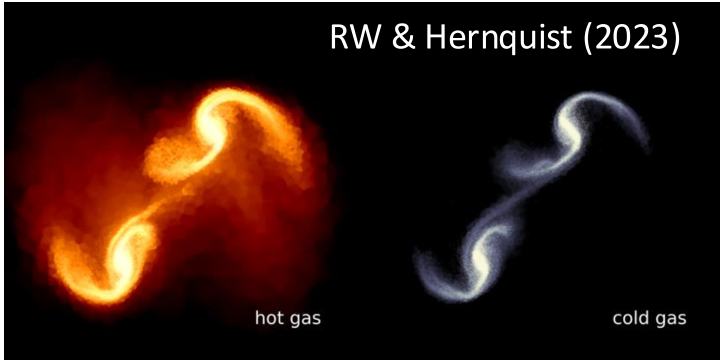
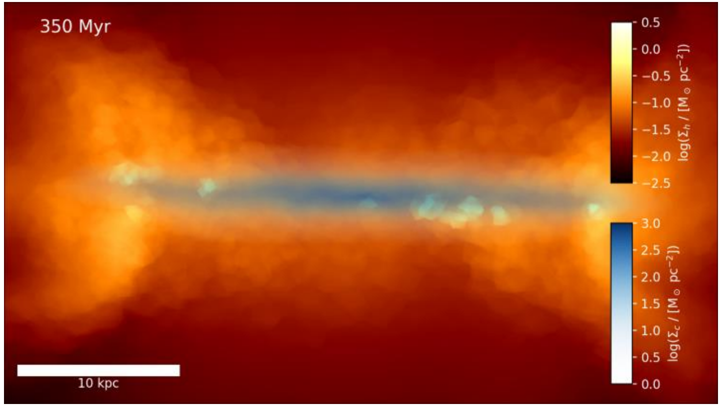
Leibniz-Institut für Astrophysik Potsdam



Multiphase gas

in cosmological

galaxy formation simulations

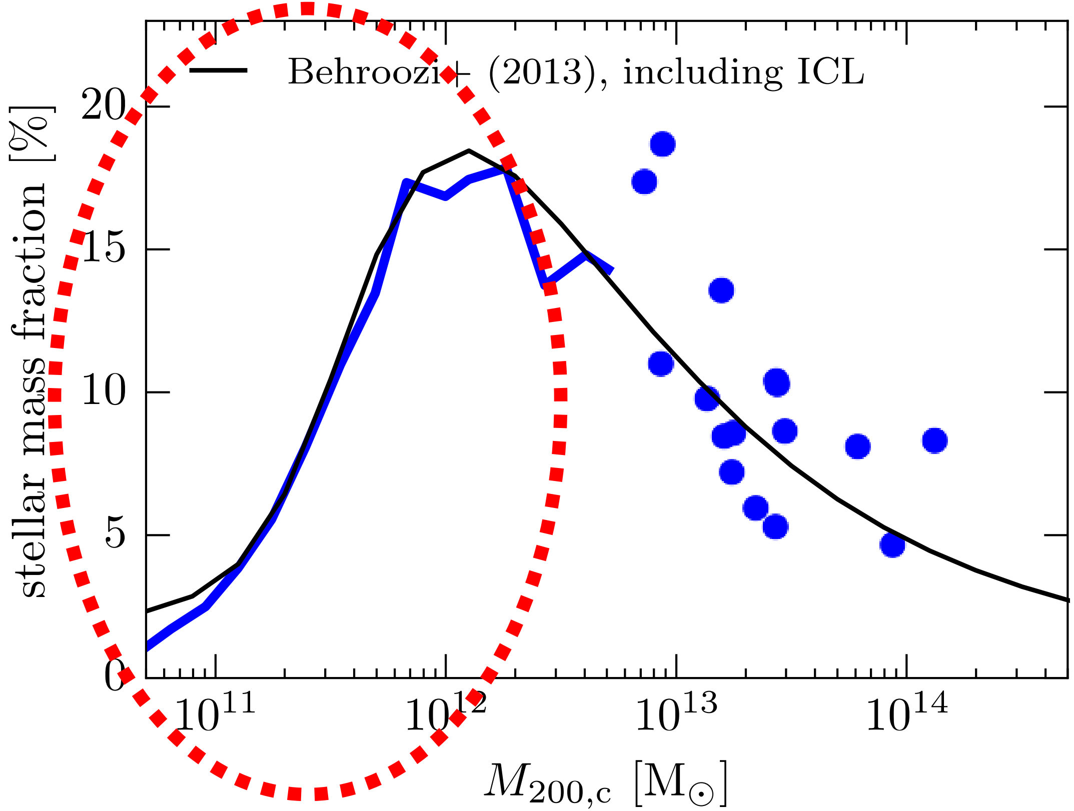


Stachlys, Bollati & RW (in prep)

Rainer Weinberger (AIP) / Potsdam Thinkshop 2025 / 15.07.2025

with: Francesco Bollati & Nele Stachlys (AIP)

The inefficiency of star formation

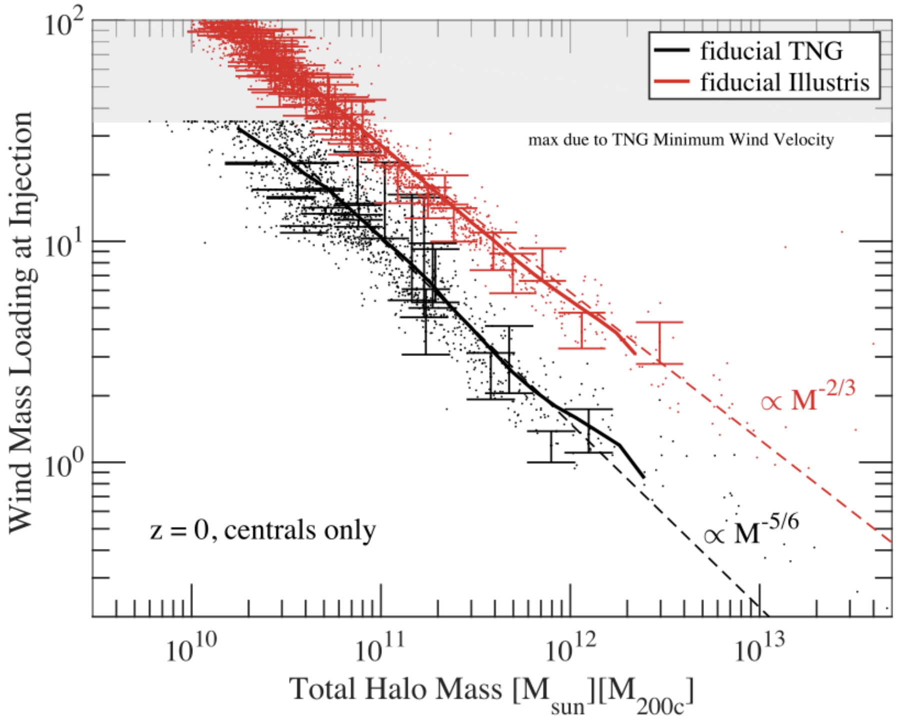


RW et al. (2017)

Stellar feedback driven galactic outflows moderate the star formation efficiency

Efficient stellar feedback driving galactic winds

- Mass loading factors exceeding unity
- Increasing toward lower masses
- This mass-loading scaling is an input parameter
- Comparisons to observations are problematic

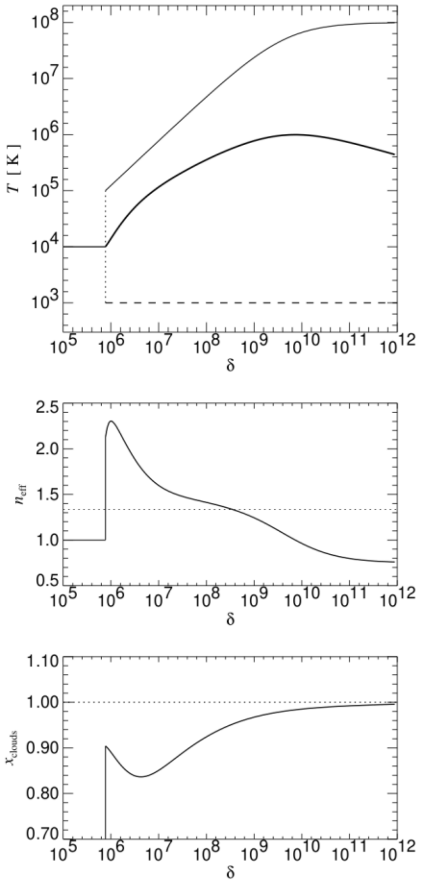


Pillepich et al. (2018)

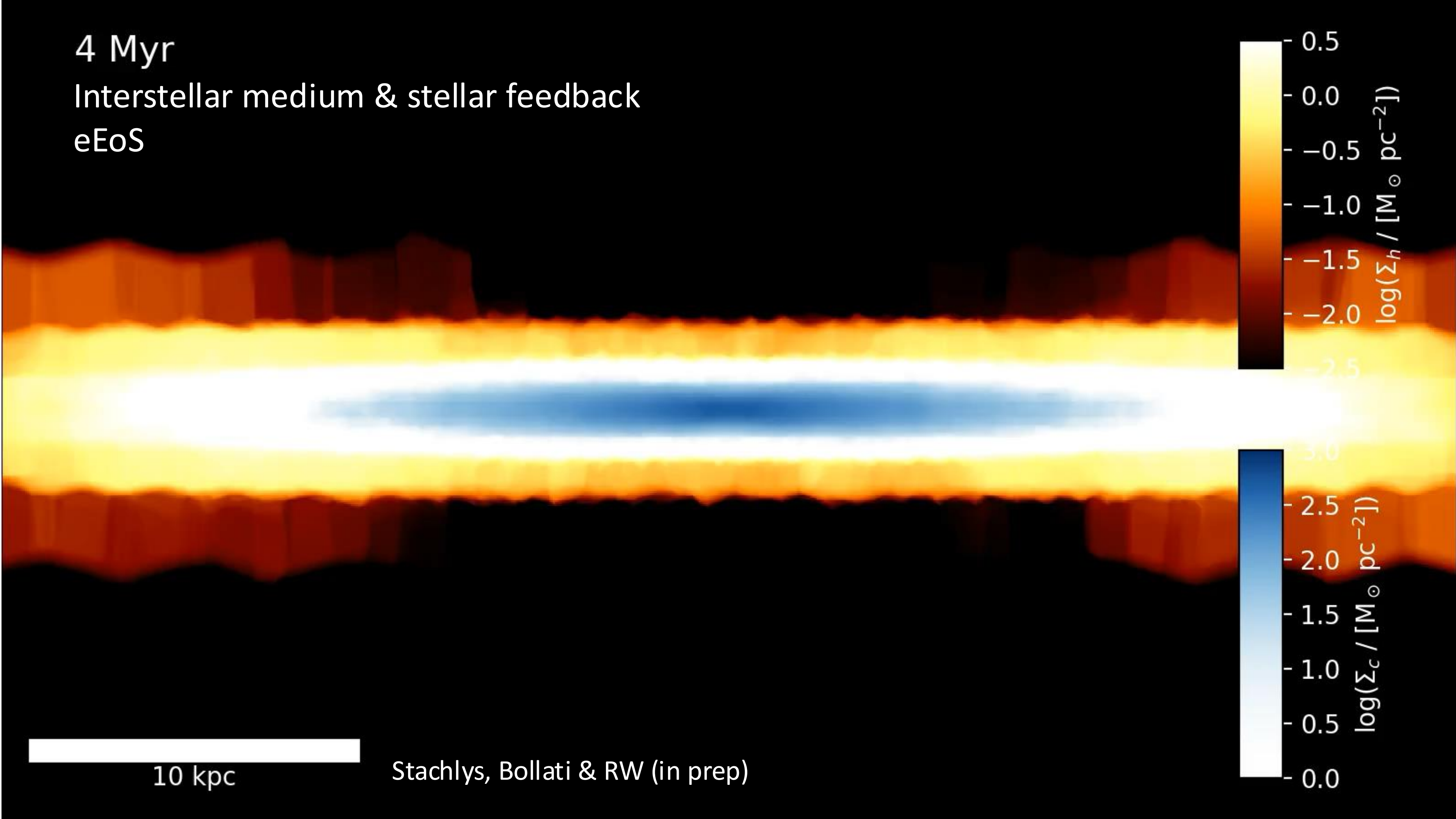
The effective equation of state

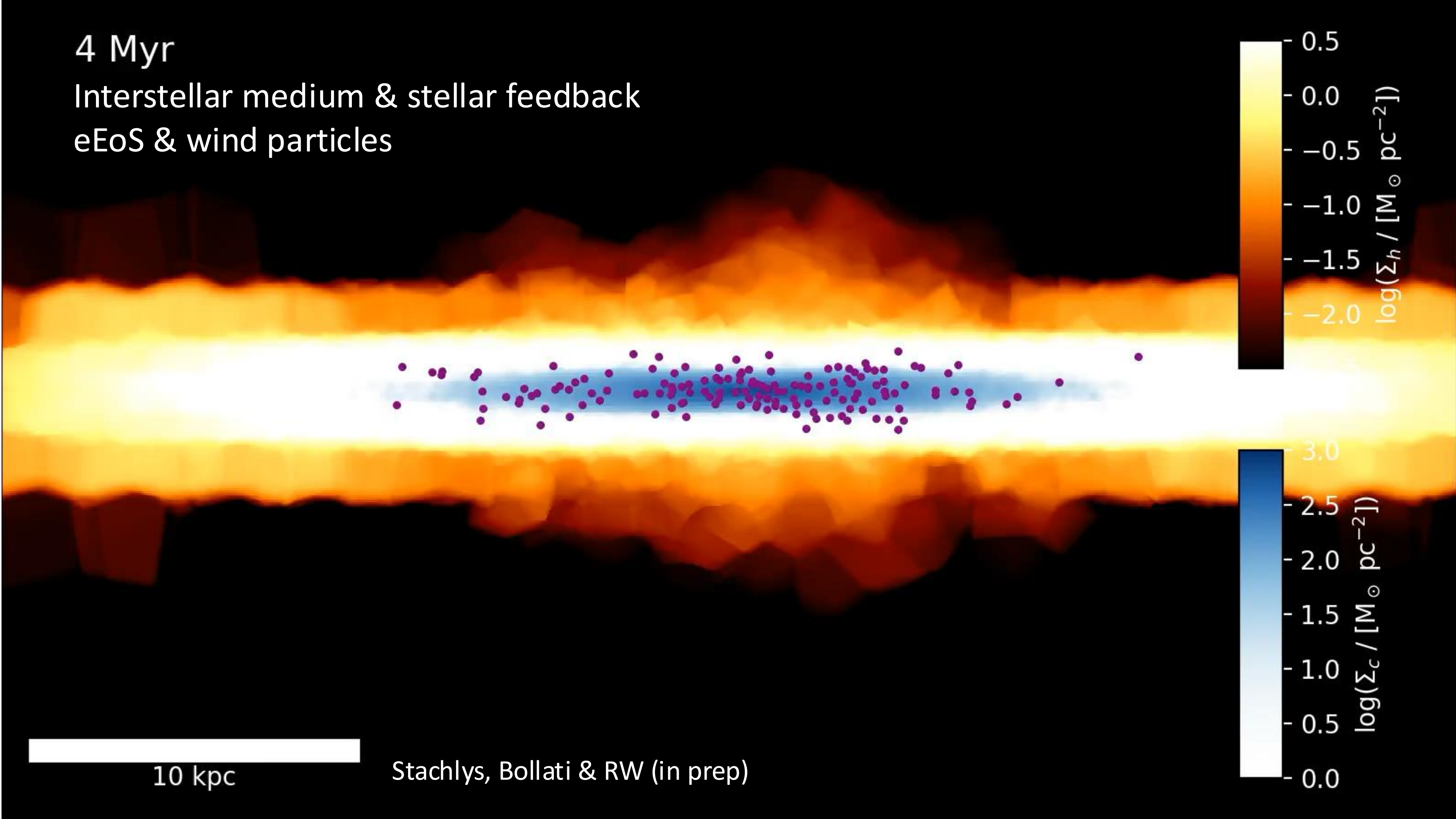
Stabilize the ISM and
launch galactic winds out of it

- Use an effective equation of state above a “star formation threshold“ density
- Apply a star formation law matching scaling relations
- According to a mass and energy loading launch “galactic winds“
  - Hydrodynamically decoupled wind particles
  - With prescribed mass, metal and energy loading
  - Decouple at a distance outside star forming region



Springel & Hernquist (2003)


4 Myr
Interstellar medium & stellar feedback
eEoS
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
log(Σ_h / [$M_\odot$ pc^{-2}])
3.0
2.5
2.0
1.5
1.0
0.5
0.0
log(Σ_c / [$M_\odot$ pc^{-2}])
10 kpc
Stachlys, Bollati & RW (in prep)



4 Myr
Interstellar medium & stellar feedback
eEoS & wind particles
0.5
0.0
−0.5
−1.0
−1.5
−2.0
log(Σ_h / [M_⊙ pc^−2])
3.0
2.5
2.0
1.5
1.0
0.5
0.0
log(Σ_c / [M_⊙ pc^−2])
10 kpc
Stachlys, Bollati & RW (in prep)

Beyond the effective equation of state – 2-fluid treatment

2-phase interstellar medium

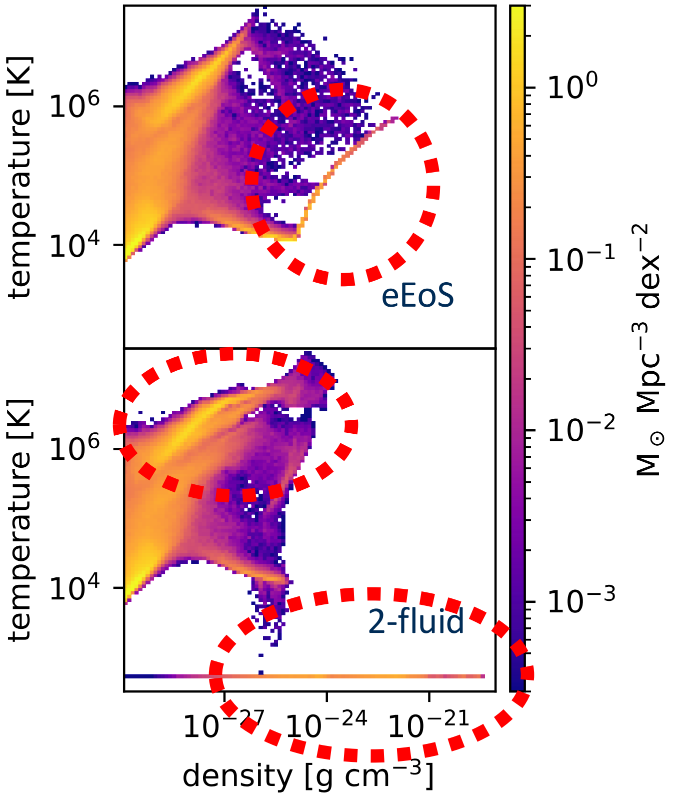
equations following Springel & Hernquist (2003)

- Cold gas formation via thermal instability
- Star formation proportional to cold gas
- Evaporation and heating by supernova energy injection

➢ **Replaces effective equation of state**

➢ **Non-equilibrium of rates possible**

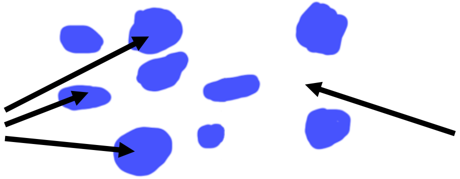
➢ **Allows independent movement of phases**



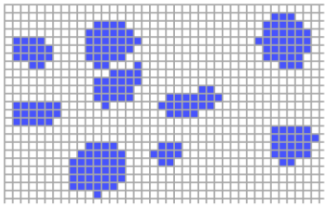
RW & Hernquist (2023)

The issue of numerical mixing

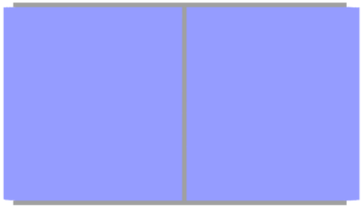
Cold, dense gas clouds



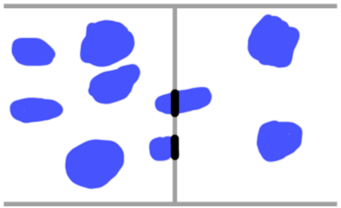
Embedded in a hot, dilute medium



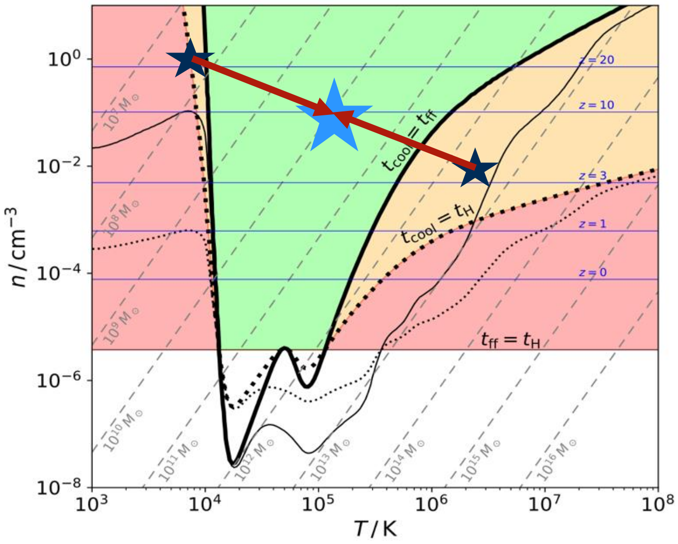
Spatially resolving



Numerical mixing



2-fluid



RW & Hernquist (2023)

Laursen (2023)

Multi-fluid hydrodynamics

fluid 1

$$\partial_t \left(\alpha_1 \rho_1\right) + \nabla \cdot \left(\alpha_1 \rho_1 \mathbf{v}_1\right) = \dot{m}$$

$$\partial_t \left(\alpha_1 \rho_1 \mathbf{v}_1\right) + \nabla \cdot \left(\alpha_1 \rho_1 \mathbf{v}_1 \mathbf{v}_1^T + \alpha_1 p_1 \mathbf{I}\right) = p_i \mathbf{I} \nabla \alpha_1 + \dot{m} \mathbf{v}_i + \mathbf{F}_d$$

$$\partial_t \left(\alpha_1 E_1\right) + \nabla \cdot \left(\alpha_1 \mathbf{v}_1 \left(E_1 + p_1\right)\right) = p_i \mathbf{v}_i \nabla \alpha_1 + \dot{m} E_i + \mathbf{F}_d \cdot \mathbf{v}_i + Q$$

fluid 2

$$\partial_t \left(\alpha_2 \rho_2\right) + \nabla \cdot \left(\alpha_2 \rho_2 \mathbf{v}_2\right) = -\dot{m}$$

$$\partial_t \left(\alpha_2 \rho_2 \mathbf{v}_2\right) + \nabla \cdot \left(\alpha_2 \rho_2 \mathbf{v}_2 \mathbf{v}_2^T + \alpha_2 p_2 \mathbf{I}\right) = p_i \mathbf{I} \nabla \alpha_2 - \dot{m} \mathbf{v}_i - \mathbf{F}_d$$

$$\partial_t \left(\alpha_2 E_2\right) + \nabla \cdot \left(\alpha_2 \mathbf{v}_2 \left(E_2 + p_2\right)\right) = p_i \mathbf{v}_i \nabla \alpha_2 - \dot{m} E_i - \mathbf{F}_d \cdot \mathbf{v}_i - Q$$

volume filling fraction

$$\partial_t \alpha_1 + \mathbf{v}_i \nabla \cdot \alpha_1 = \dot{\alpha}$$

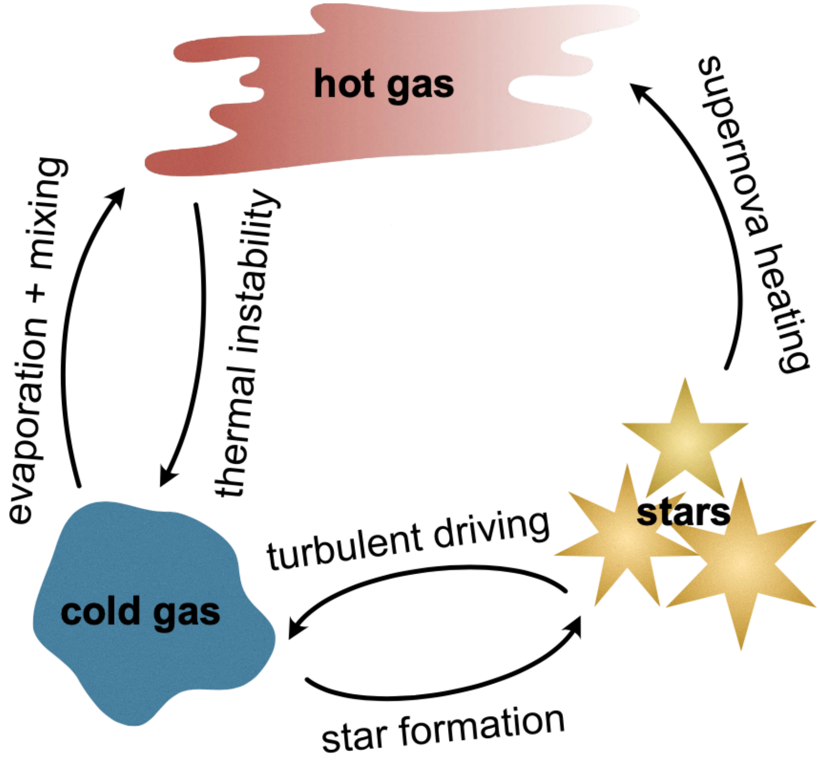
$$\alpha_1 + \alpha_2 = 1.$$

RW & Hernquist (2023)

A new interstellar medium & stellar feedback model (preliminary!)

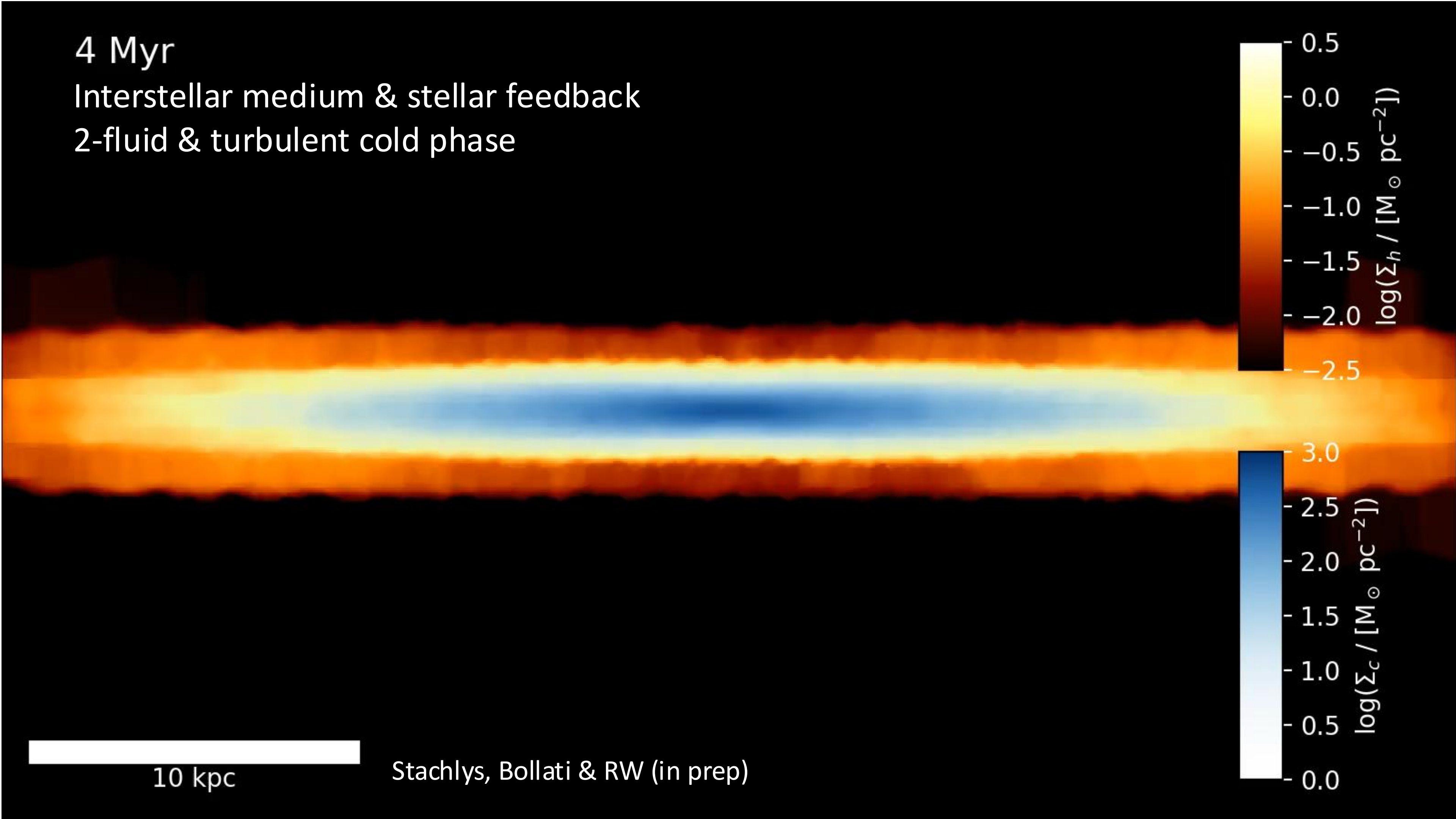
Similar to Springel & Hernquist (2003), but

- Lower evaporation factor
- Turbulent pressure support of cold phase
- (more to come)



Stachlys, Bollati & RW (in prep.)

see poster!

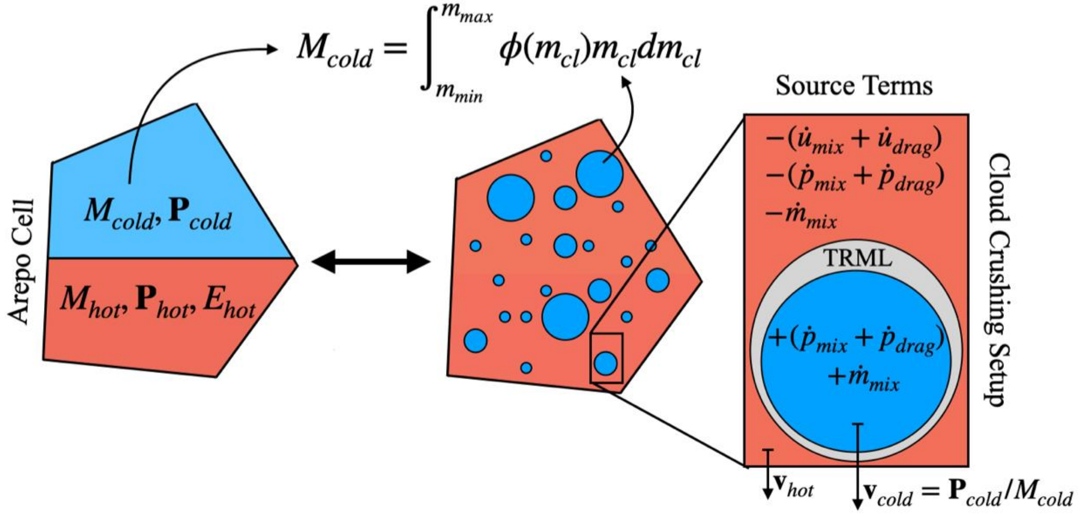


4 Myr
Interstellar medium & stellar feedback
2-fluid & turbulent cold phase
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
$\log(\Sigma_h$ / [$M_\odot$ pc^{-2}])
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$\log(\Sigma_c$ / [$M_\odot$ pc^{-2}])
10 kpc
Stachlys, Bollati & RW (in prep)

Multi-phase galactic outflow modelling

Model for the unresolved colder cloud population

- Cloud mass function
- Analytic mixing and drag terms (population averaged)
- Similar to Fielding & Bryan (2022)



Bollati & RW (in prep.)

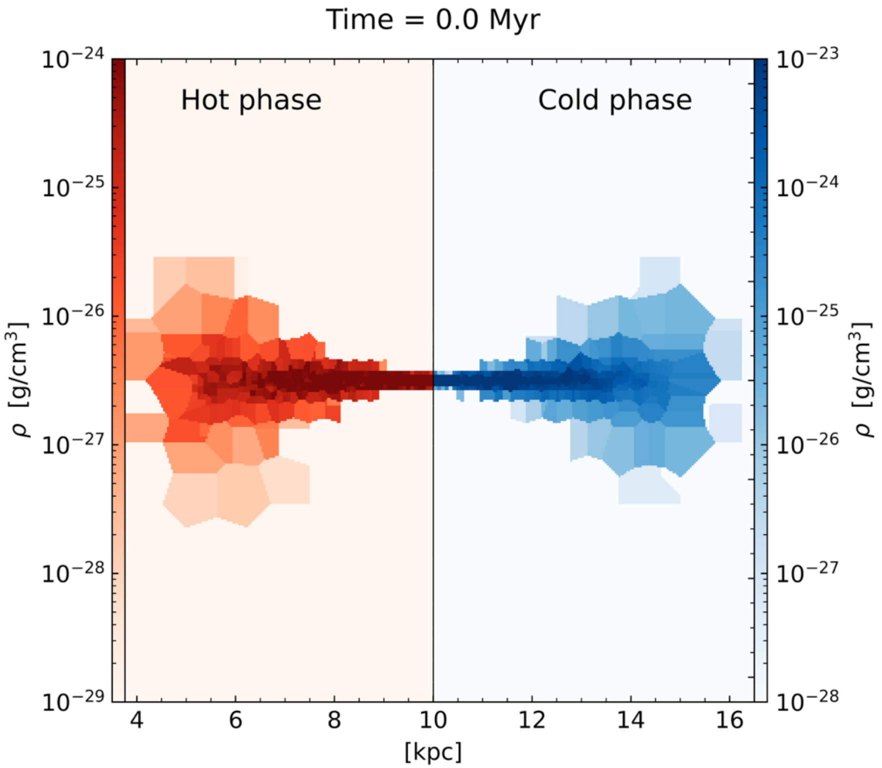
see poster!

Multi-phase galactic outflow modelling

- Chevalier & Clegg like hot wind injection
- Cold gas in disk
- Interaction between hot and cold phase:
  - Drag forces
  - Mass exchange via
    - Cloud crushing
    - Stimulated condensation

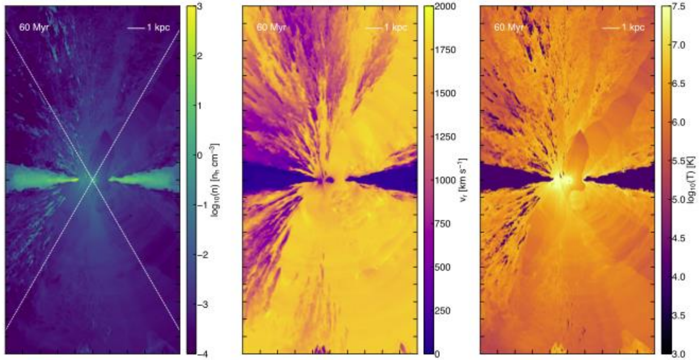
➢ **No need to resolve individual clouds**

➢ **No numerical mixing between phases**

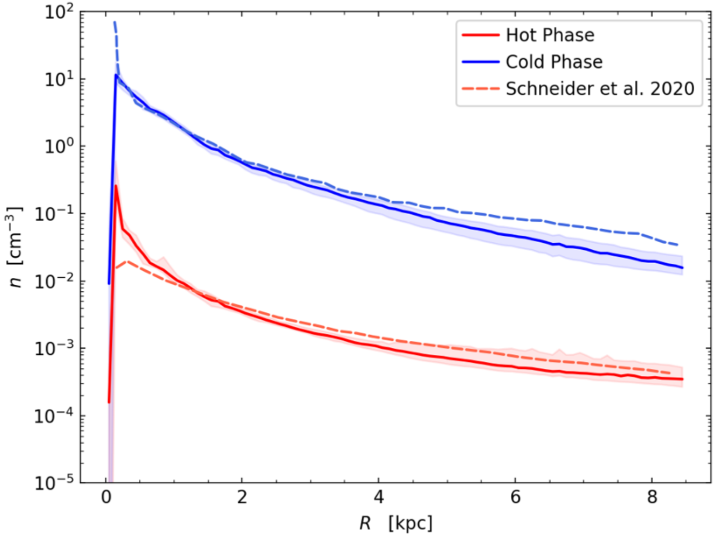


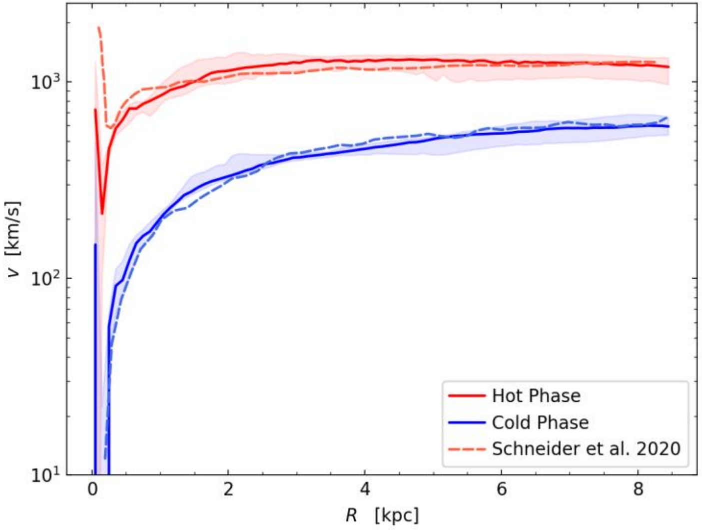
Bollati & RW (in prep)

2-fluid galactic outflows
as coarse-grained high-resolution simulations



Schneider et al. (2018)

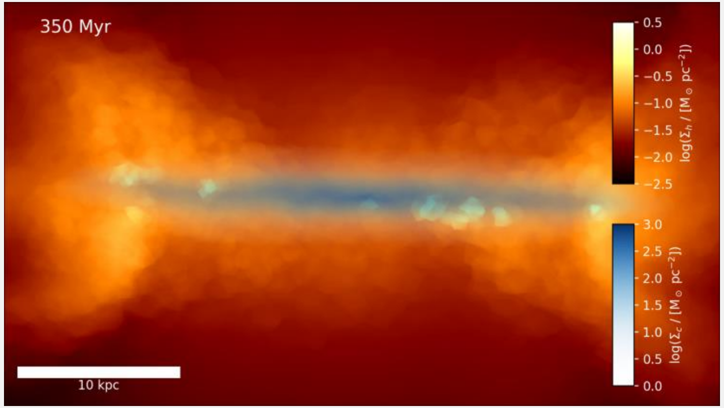




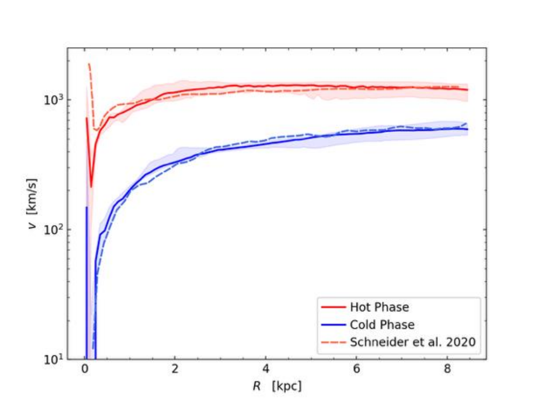
Bollati & RW (in prep)

Summary

- Multi-phase gas is a key obstacle for accurate gas modelling in cosmological simulations
- Multi-fluid approach allows a representation without spatially resolving the cold gas structure
- **Multi-phase interstellar medium**
    - ➢ *see poster Nele Stachlys*
    - – No need for decoupled wind particles
    - – Or other numerical tricks
- **Starburst driven multi-phase outflows**
    - ➢ *see poster Francesco Bollati*
    - – Coarse-graining of high-resolution simulations
    - – Explicit solution of the interaction terms facilitates interpretation
- **The required resolutions are reachable in large cosmological volumes**



Stachlys, Bollati & RW (in prep)



Bollati & RW (in prep)