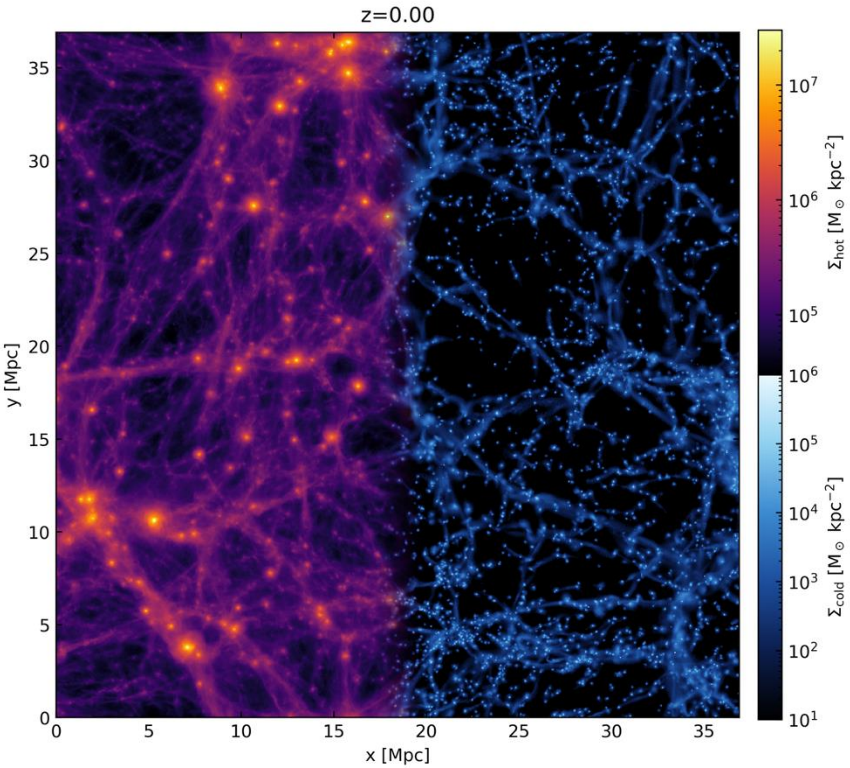
Leibniz-Institut für Astrophysik Potsdam

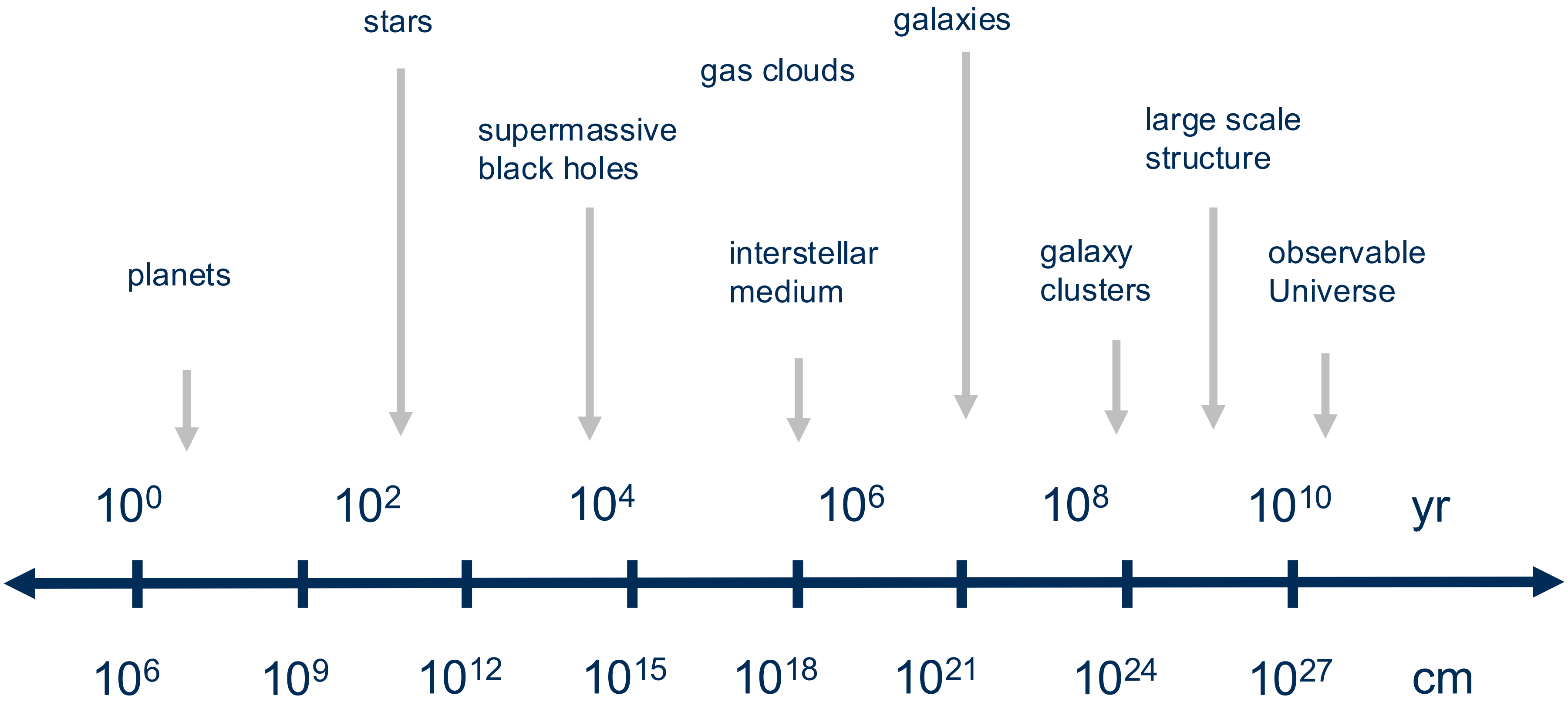
Overcoming the scale-problem in galaxy formation simulations using multi-fluid hydrodynamics

Rainer Weinberger / AG 2026 / 9. September 2026

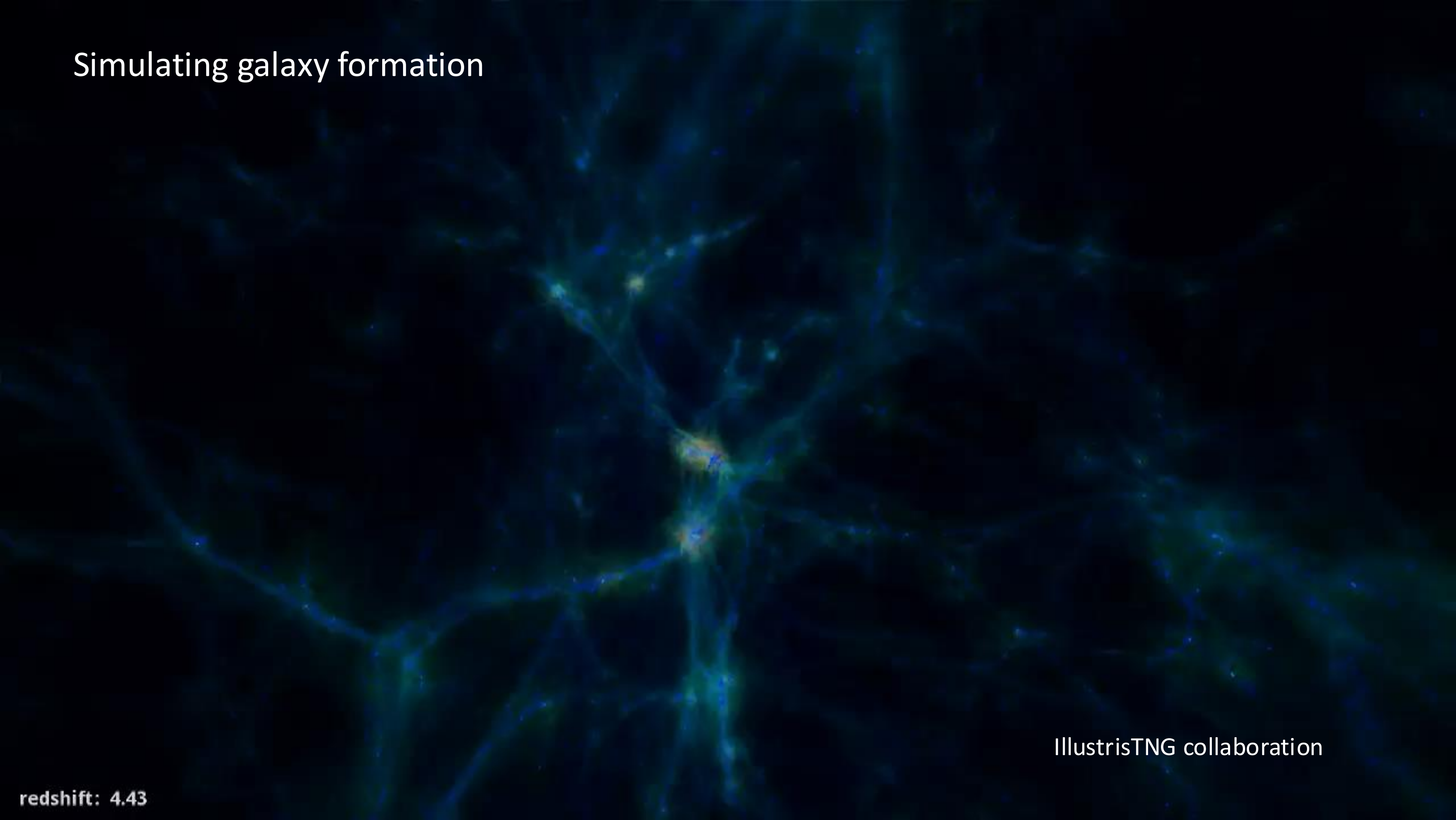


RW et al. (in prep)

The multi-scale problem

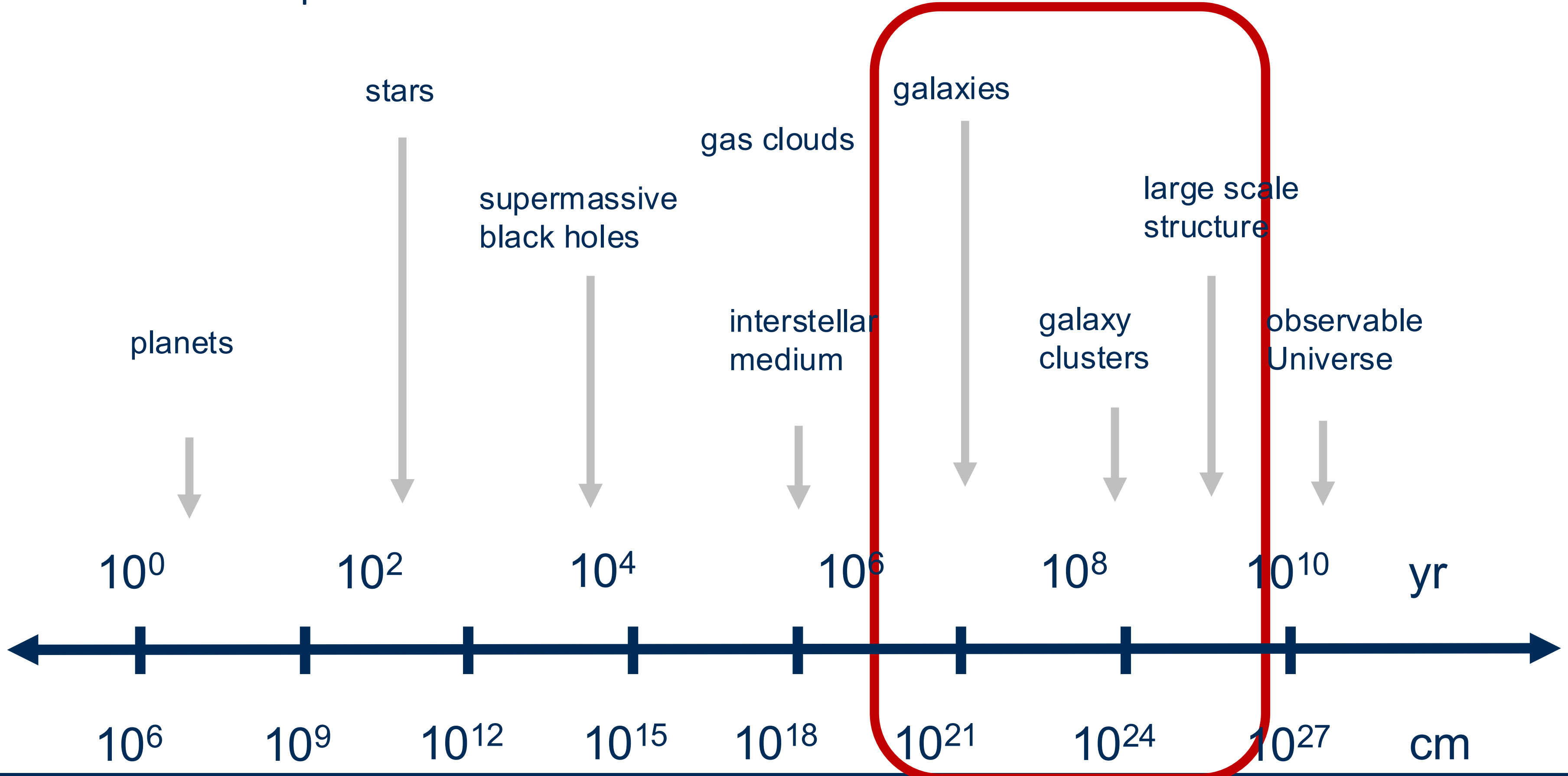


Simulating galaxy formation

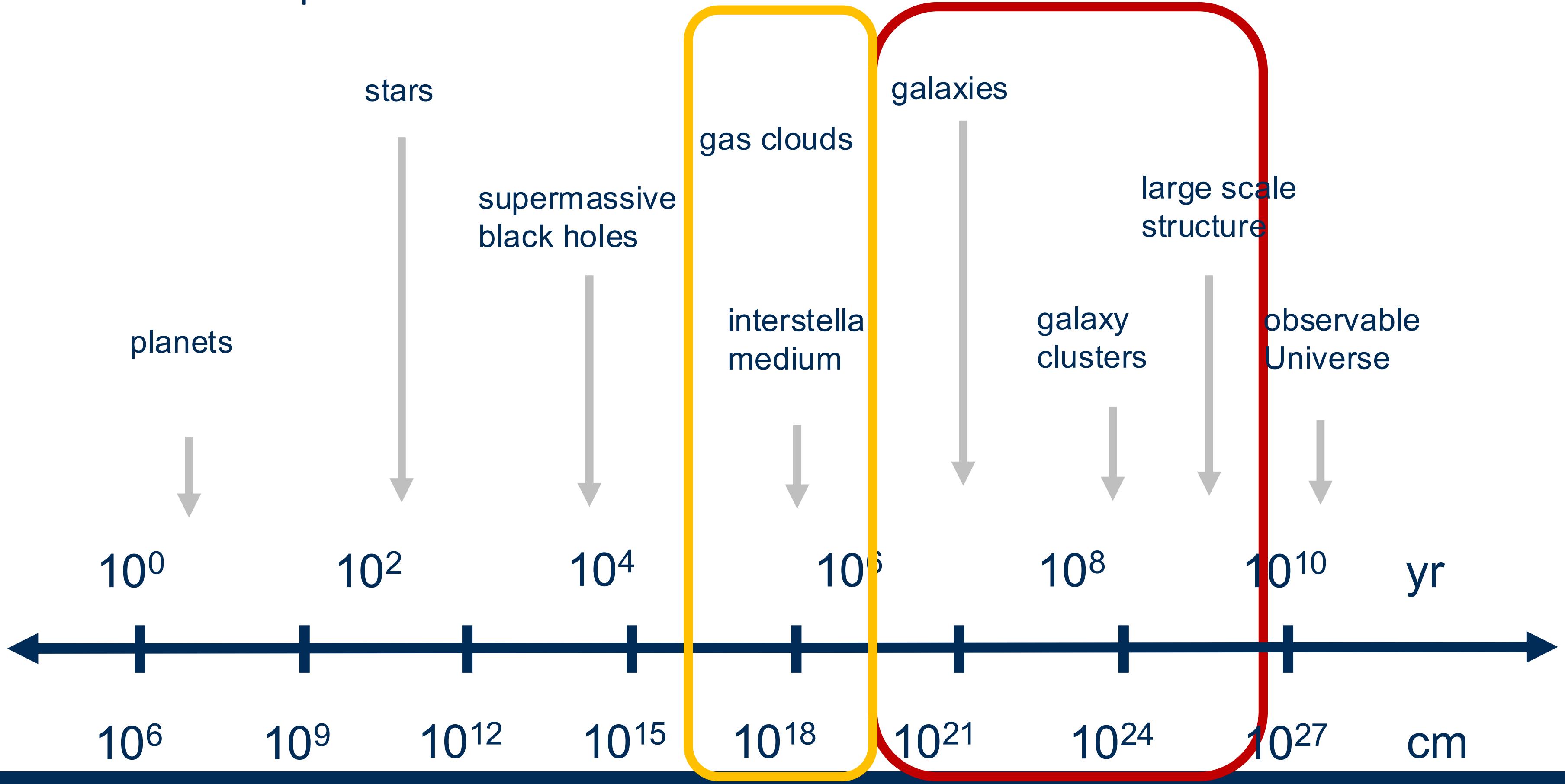


IllustrisTNG collaboration

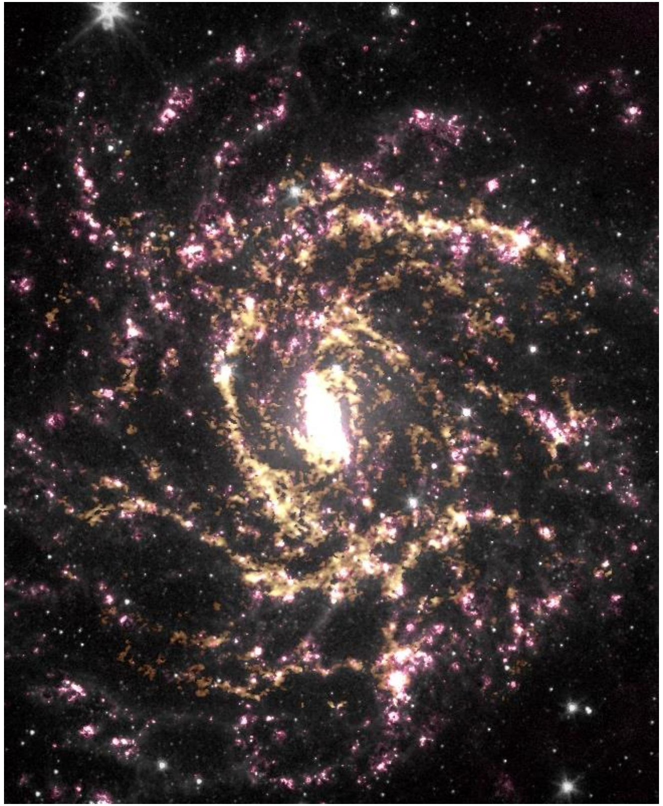
The multi-scale problem



The multi-scale problem



Multi-phase media in observations– few kpc scales



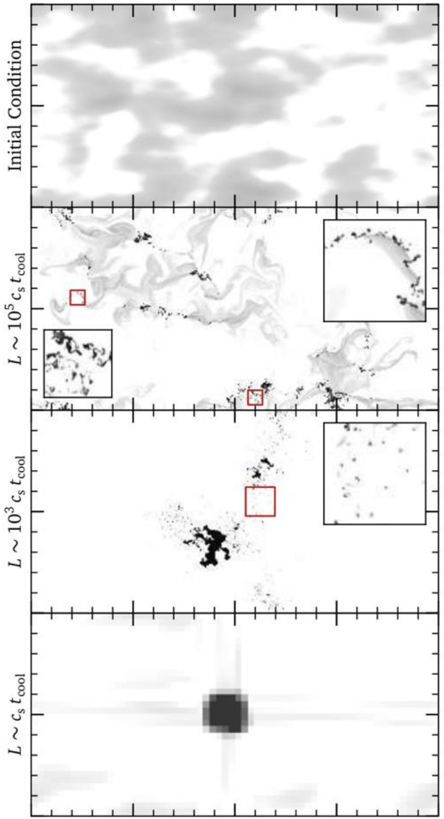
IC 342 – multi-phase interstellar medium

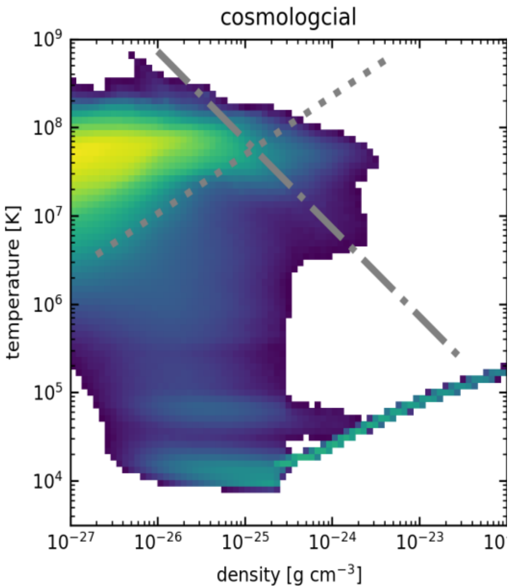
Spitzer IRAC 4.5µm (grey) - NASA/JPL-Caltech/J. Turner; NOEMA CO(1-0) (orange) - IRAM/A. Schruba & J. Pety; Mayall Hα (pink) - NOAO/K. Herrmann

Multi-phase galactic outflow

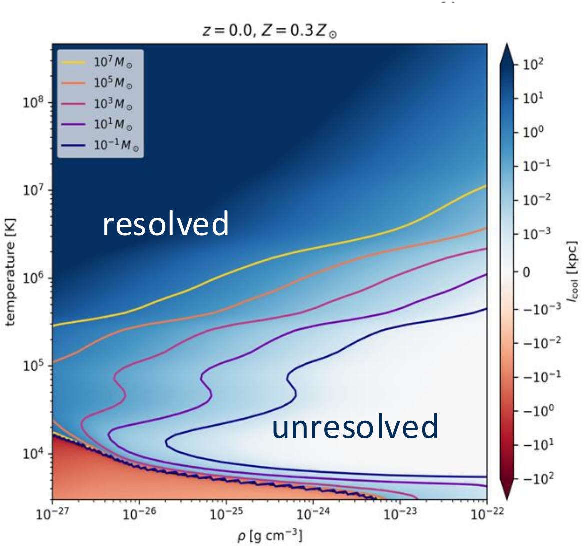
Image: NASA/JPL-Caltech/STScI/CXC/UofA/ESA/AURA/JHU

The smallest scales – shattering and turbulent mixing layers



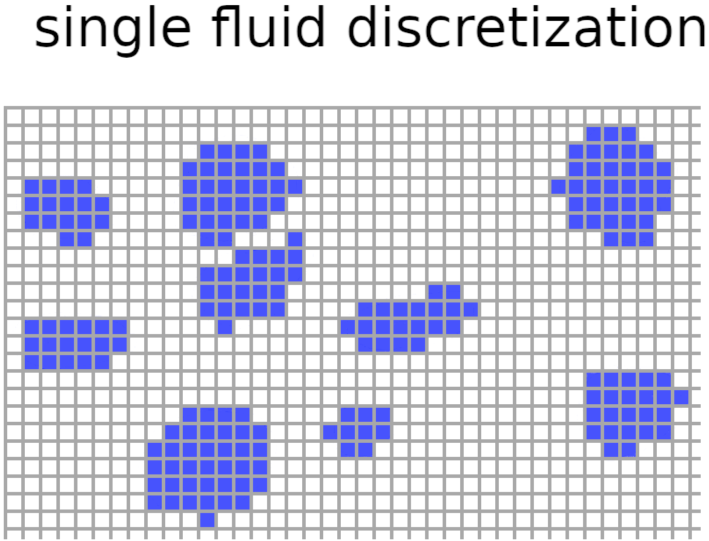


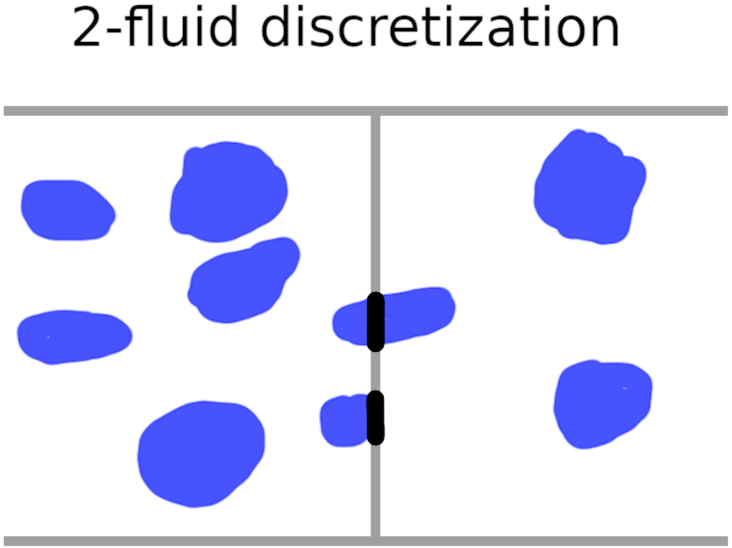
McCourt et al. (2016)



RW et al. (in prep.)

Multi-fluid hydrodynamics





Multi-fluid hydrodynamics

fluid 1

$$\boxed{\partial_t (\alpha_1 \rho_1) + \nabla \cdot (\alpha_1 \rho_1 \mathbf{v}_1)} = \boxed{\dot{m}} \quad (2)$$

$$\boxed{\partial_t (\alpha_1 \rho_1 \mathbf{v}_1) + \nabla \cdot \left(\alpha_1 \rho_1 \mathbf{v}_1 \mathbf{v}_1^T + \alpha_1 p_1 \mathbf{I}\right)} =$$

$$\boxed{p_i \mathbf{I} \nabla \alpha_1} + \boxed{\dot{m} \mathbf{v}_i + \mathbf{F}_d} \quad (3)$$

$$\boxed{\partial_t (\alpha_1 E_1) + \nabla \cdot (\alpha_1 \mathbf{v}_1 (E_1 + p_1))} =$$

$$\boxed{p_i \mathbf{v}_i \nabla \alpha_1} + \boxed{\dot{m} E_i + \mathbf{F}_d \cdot \mathbf{v}_i + Q} \quad (4)$$

fluid 2

$$\partial_t (\alpha_2 \rho_2) + \nabla \cdot (\alpha_2 \rho_2 \mathbf{v}_2) = -\dot{m} \quad (5)$$

$$\partial_t (\alpha_2 \rho_2 \mathbf{v}_2) + \nabla \cdot \left(\alpha_2 \rho_2 \mathbf{v}_2 \mathbf{v}_2^T + \alpha_2 p_2 \mathbf{I}\right) =$$

$$p_i \mathbf{I} \nabla \alpha_2 - \dot{m} \mathbf{v}_i - \mathbf{F}_d \quad (6)$$

$$\partial_t (\alpha_2 E_2) + \nabla \cdot (\alpha_2 \mathbf{v}_2 (E_2 + p_2)) =$$

$$p_i \mathbf{v}_i \nabla \alpha_2 - \dot{m} E_i - \mathbf{F}_d \cdot \mathbf{v}_i - Q \quad (7)$$

volume filling fraction

$$\partial_t \alpha_1 + \mathbf{v}_i \nabla \cdot \alpha_1 = \dot{\alpha} \quad (8)$$

$$\alpha_1 + \alpha_2 = 1. \quad (9)$$

RW & Hernquist (2023)

Stratified flow model

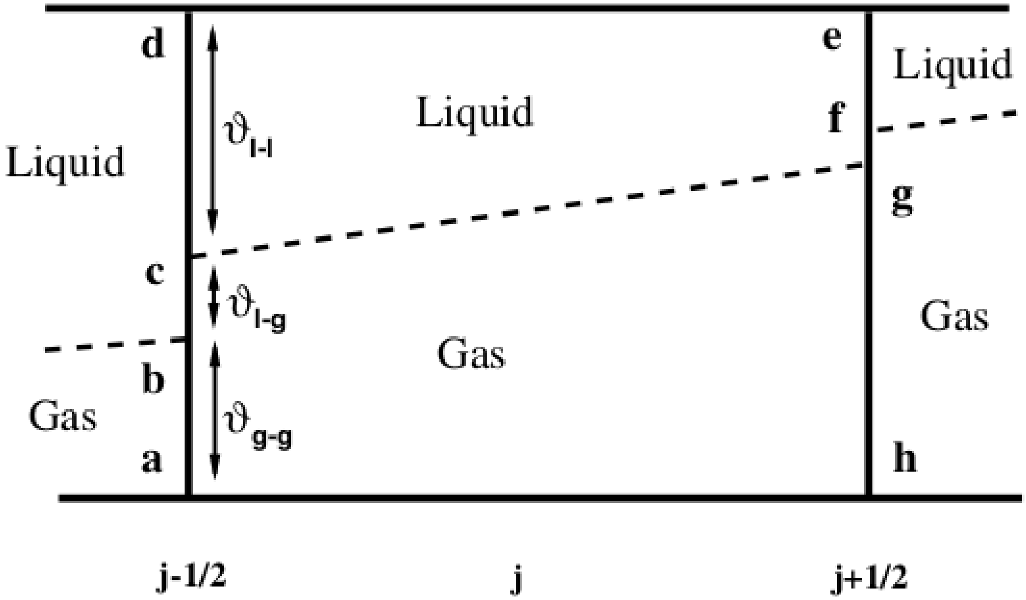
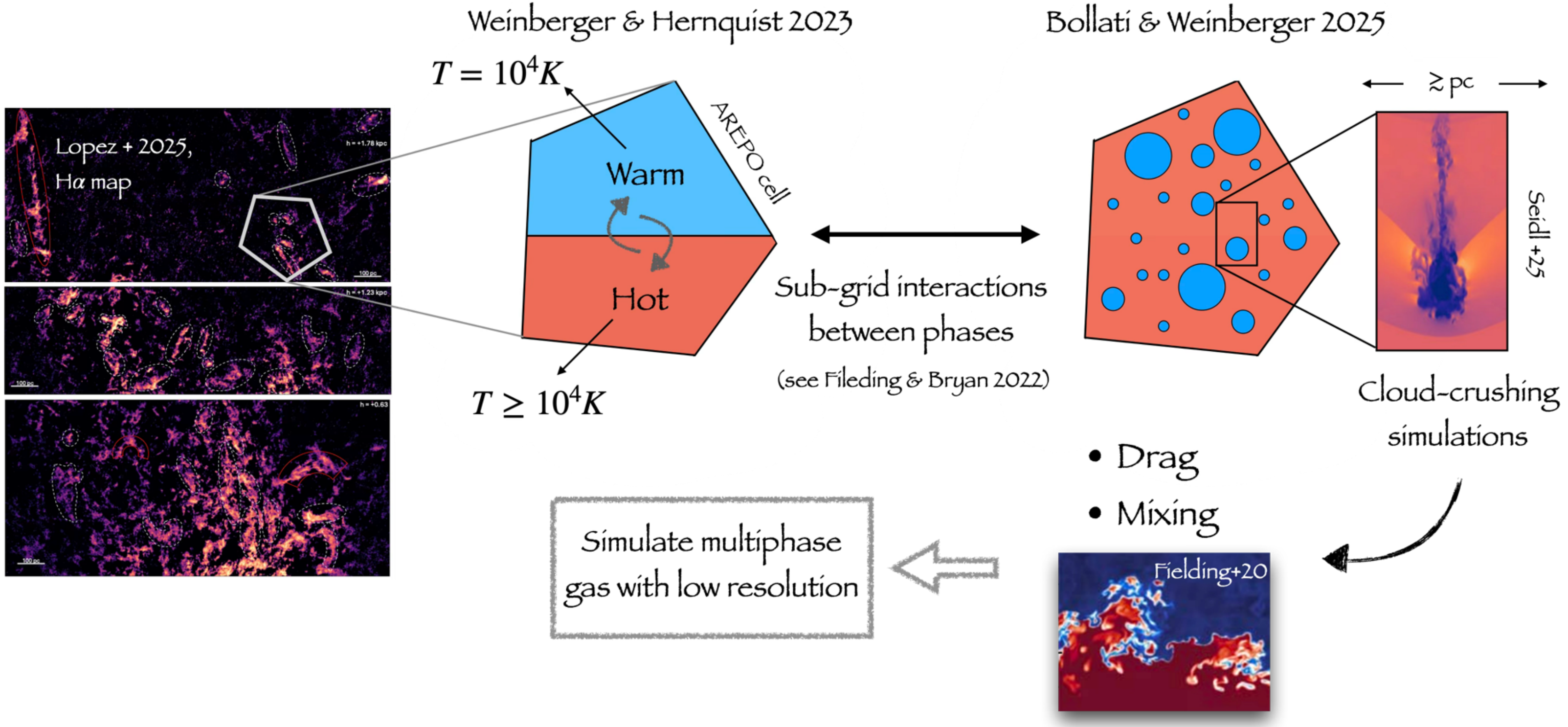


Fig. 3. Illustration of the one dimensional stratified flow.

Chang et al. 2007, JCoPh 225, 840

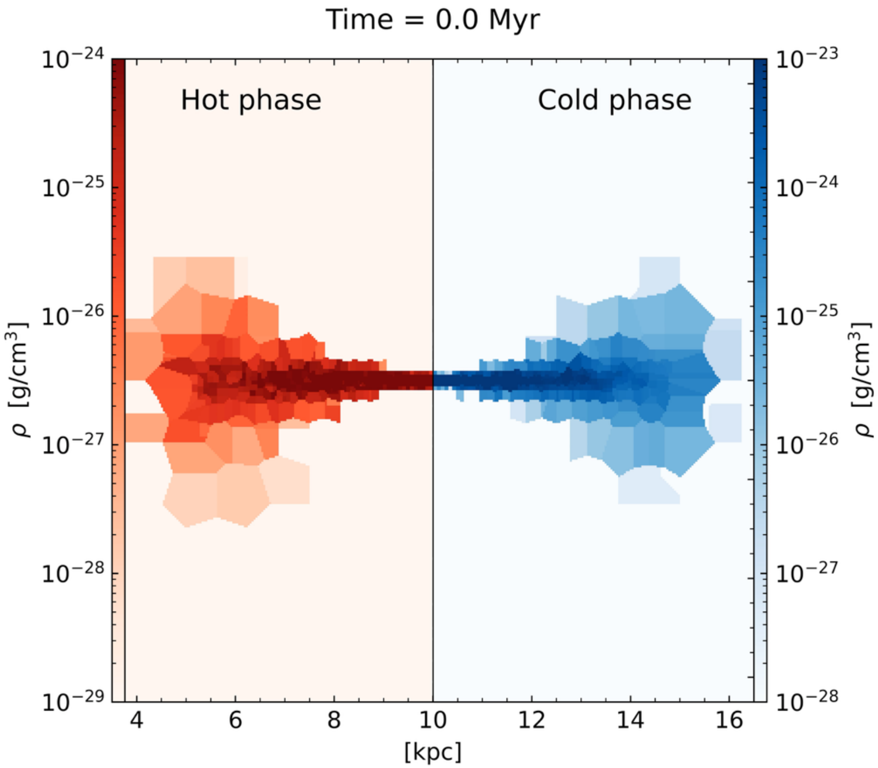
Multi-fluid galactic outflow model



slide: F. Bollati

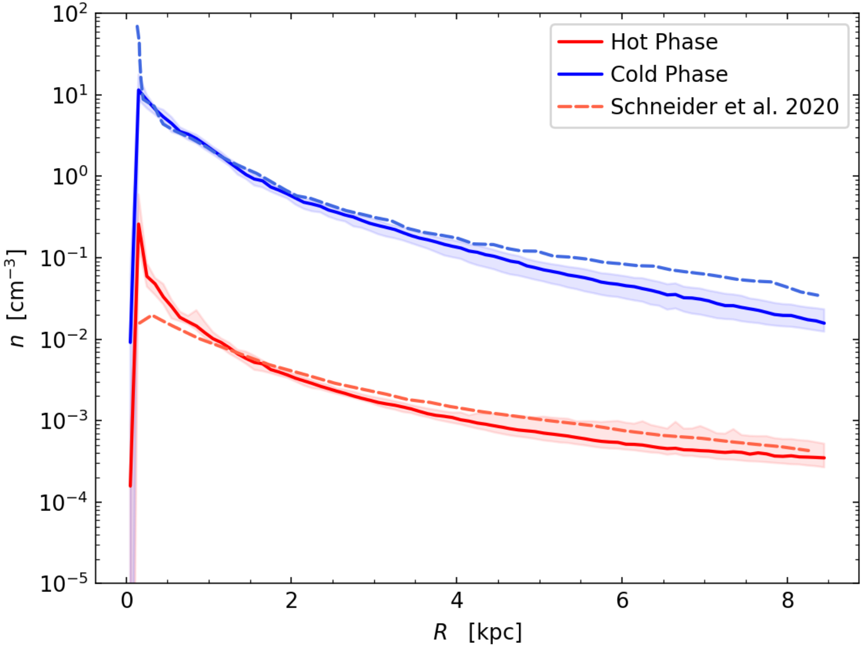
M82 like outflow

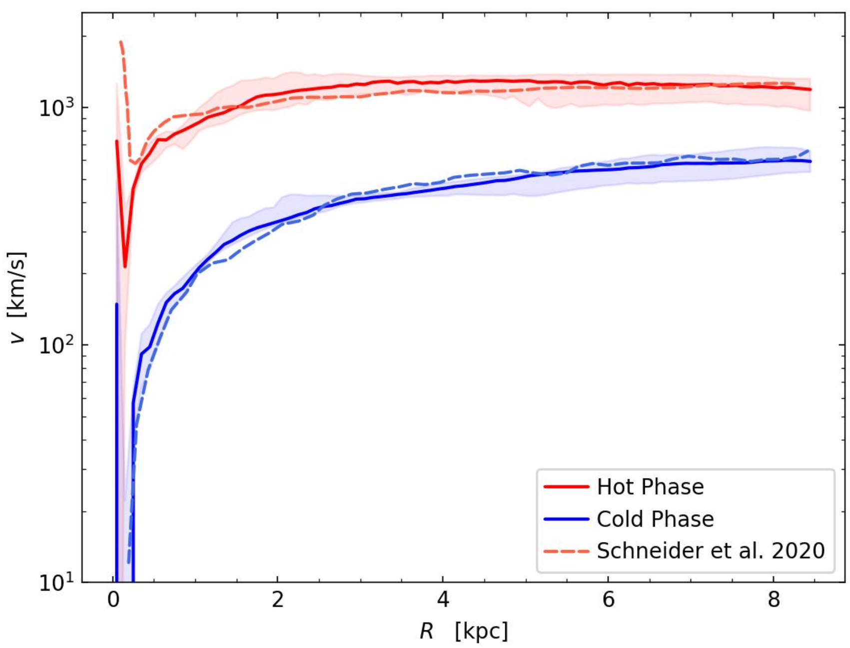
Multi-phase galactic outflow
Image: NASA/JPL-Caltech/STScI/CXC/UofA/ESA/AURA/JHU



Bollati & RW (2026)

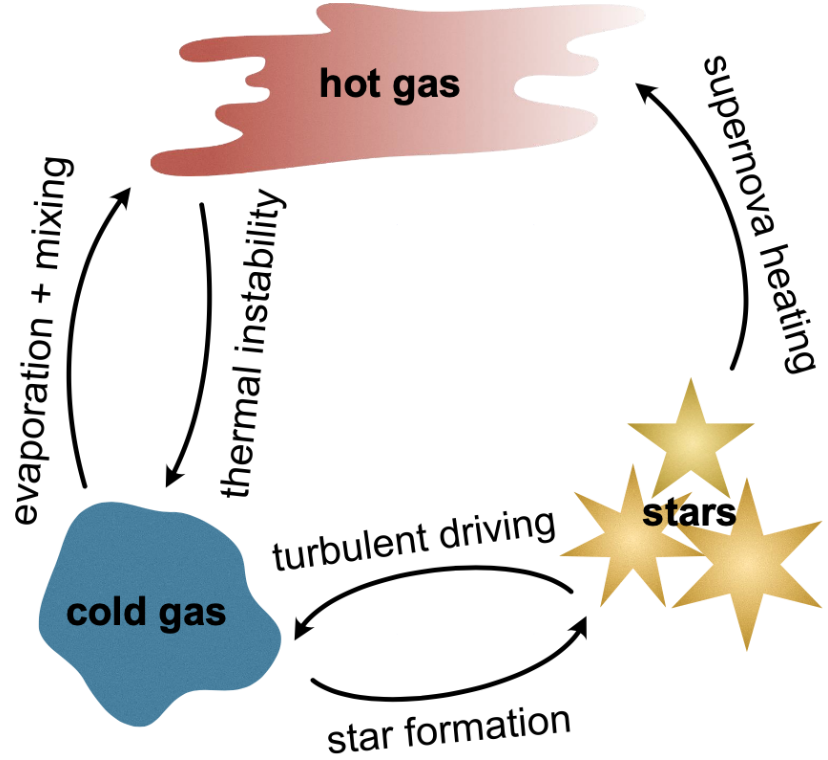
Überschrift lorem ipsum



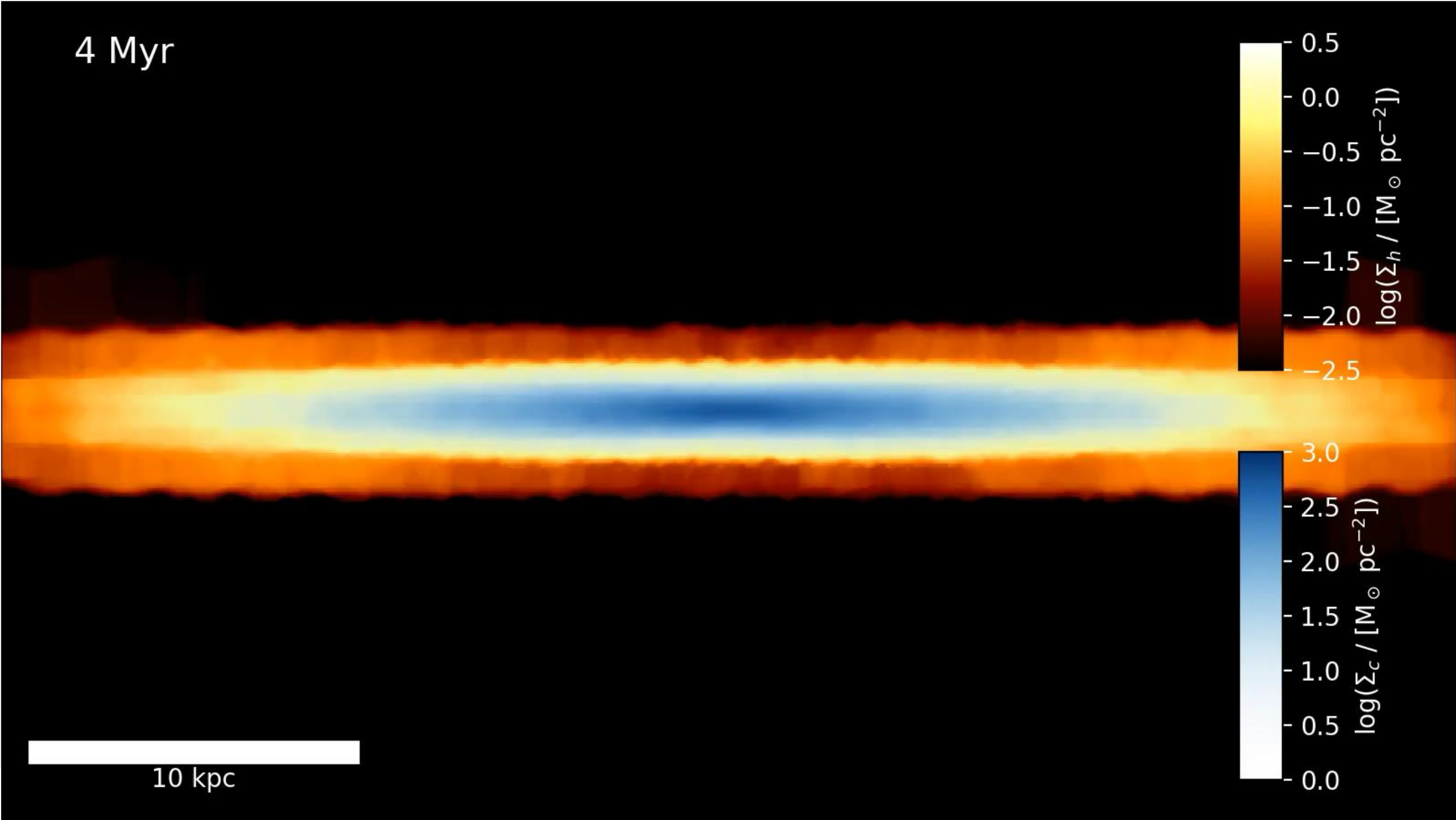


Bollati & RW (2026)

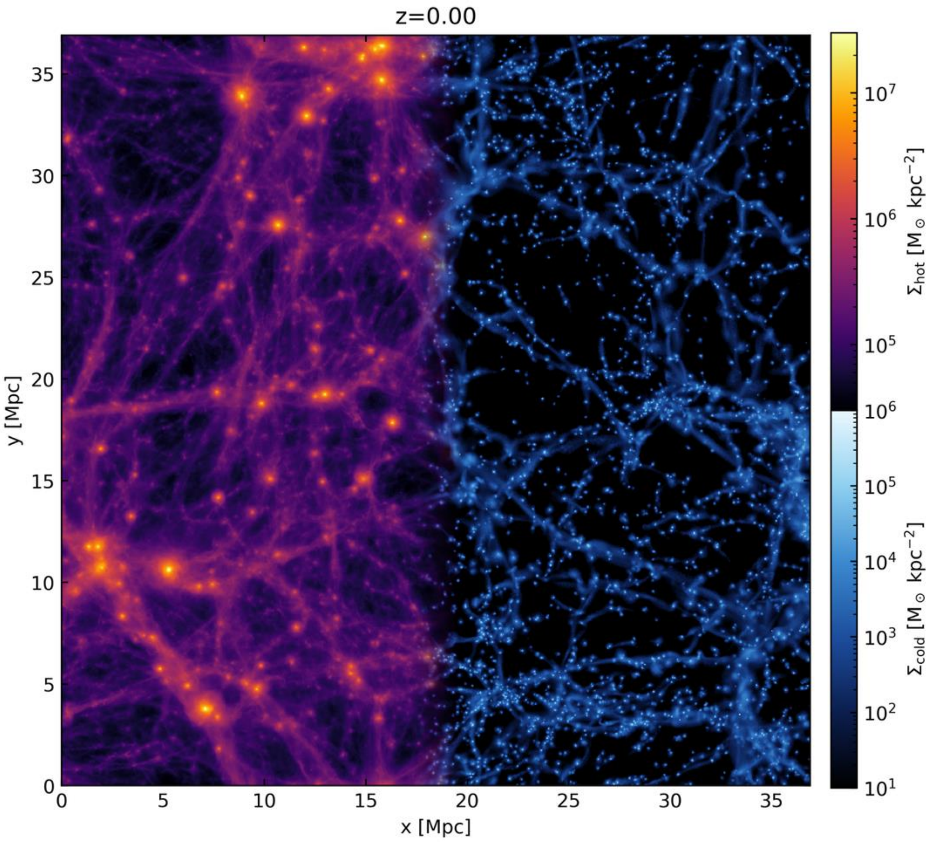
Driving outflows – the interstellar medium



Stachlys+ (in prep.)

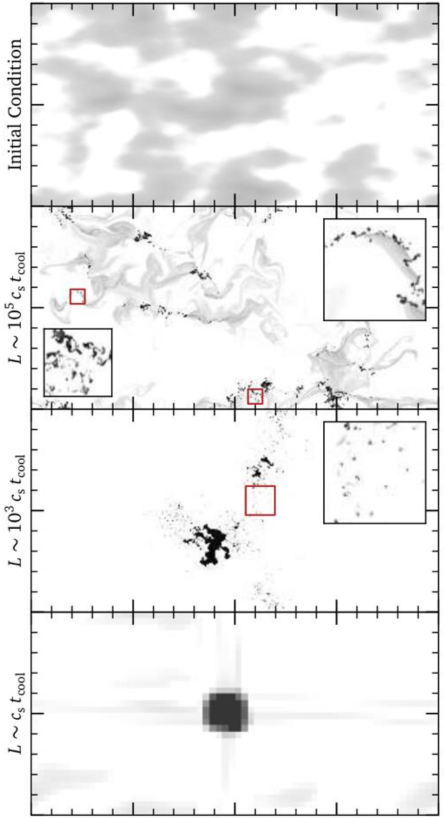

4 Myr
10 kpc
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
log(Σ_h / [M_⊙ pc^−2])
3.0
2.5
2.0
1.5
1.0
0.5
0.0
log(Σ_c / [M_⊙ pc^−2])

Back to cosmological simulations

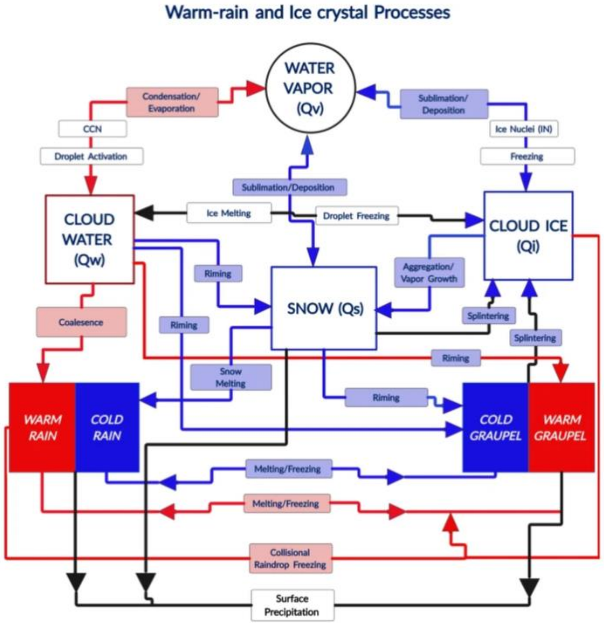


RW et al. (in prep)

Open questions – **precipitation / thermal instabiltiy**



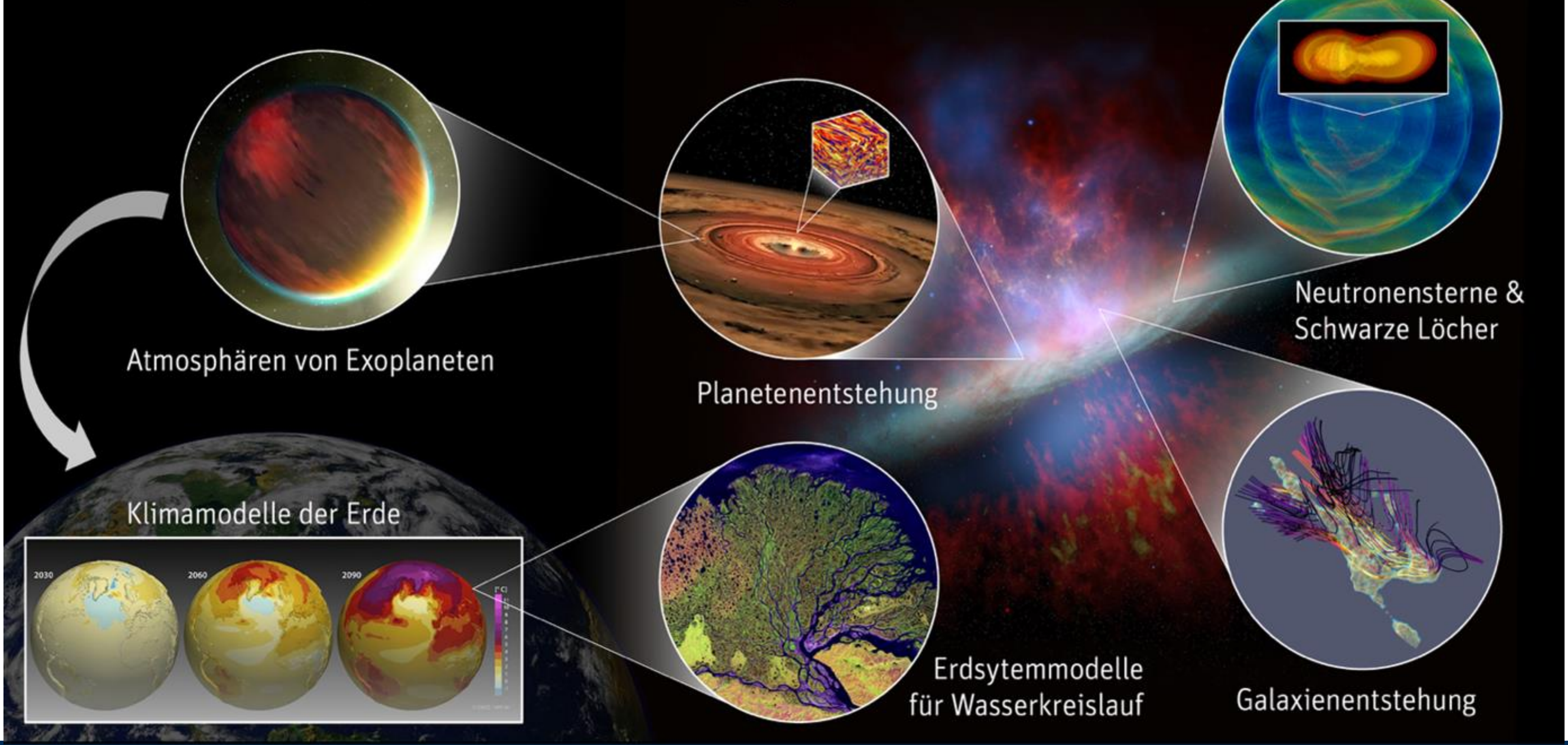
McCourt et al. (2016)



Gupta et al. (2023)

Communications Earth&Environment 4, 226

Leibniz WissenschaftsCampus | Multiskalen Herausforderungen: Von der Astrophysik bis zur Klimaforschung



Summary

- Galaxy formation is a multi-scale problem
  - Computational cutoff around the scale of gas clouds
  - Drastic impact on galactic gas cycle
- Represent multi-phase gas as multi-fluid system
  - Spatially resolved, hot phase
  - Spatially unresolved cool gas clouds with volume filling fraction
- Get multi-component outflows cheaply
- In ISM, need to model spatially unresolved turbulenc via SGS turbulence model
- Full cosmological context in progress – stay tuned