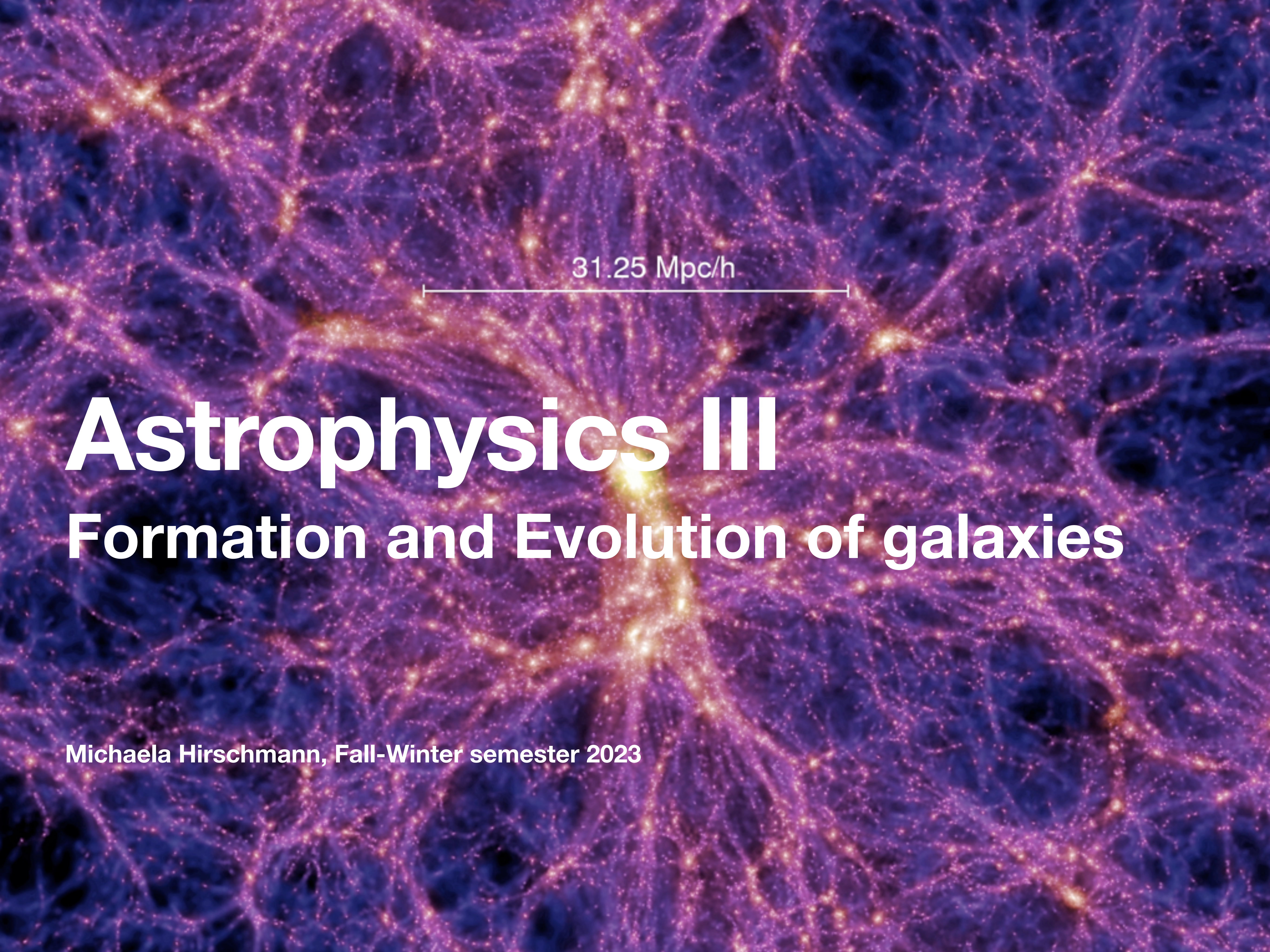


Astrophysics III

Formation and Evolution of galaxies

Michaela Hirschmann, Fall-Winter semester 2023

Lecture content and schedule

- *Chapter 1*: Introduction (galaxy definition, astronomical scales, observable quantities — repetition of Astro-I)
- *Chapter 2:* Brief review on stars
- *Chapter 3*: Radiation processes in galaxies and telescopes;
- *Chapter 4:* The Milky Way
- *Chapter 5*: The world of galaxies I
- *Chapter 6*: The world of galaxies II
- *Chapter 7:* Black holes and active galactic nuclei
- *Chapter 8:* Galaxies and their environment;
- *Chapter 9:* High-redshift galaxies
- *Chapter 10*:
    - Cosmology in a nutshell; Linear structure formation in the early Universe
- *Chapter 11*:
    - Dark matter and the large-scale structure
    - Cosmological N-body simulations of dark matter
- *Chapter 12*: Populating dark matter halos with baryons: Semi-empirical & semi-analytical models
- *Chapter 13:* Modelling the evolution of gas in galaxies: Hydrodynamics
- *Chapter 14*: Gas cooling/heating and star formation
- *Chapter 15*: Stellar feedback processes
- *Chapter 16*: Black hole growth & AGN feedback processes
- *Chapter 17*: Modern simulations & future prospects

Part I: Observational basics & facts of galaxies first 7 lectures

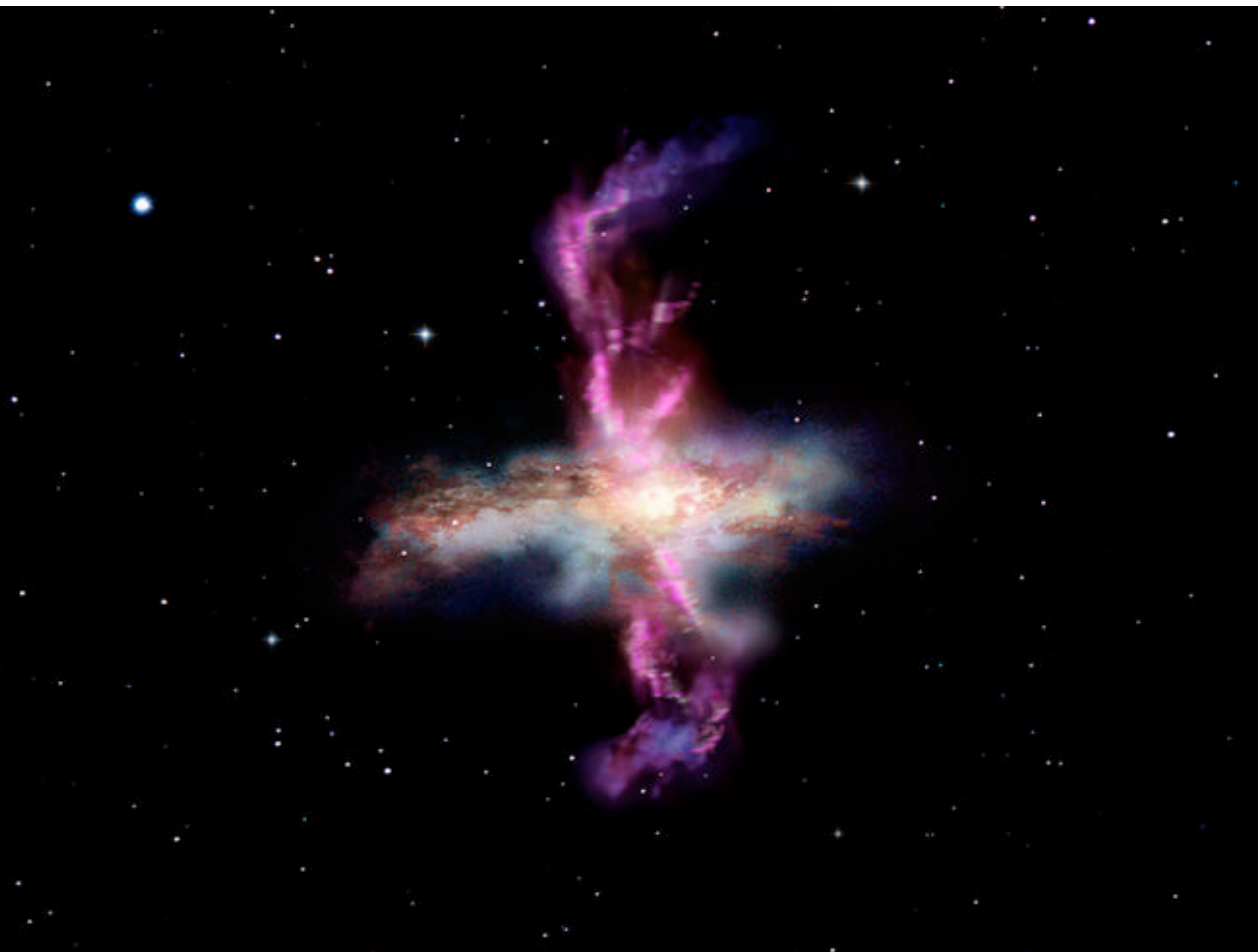
Part II: Theory & models of galaxy evolution processes second 7 lectures

Outline of this lecture

- Observational indications for stellar feedback processes
- Small-scale physical processes
  - SN explosions
  - Stellar winds
  - Ionising radiation/radiation pressure (radiation-hydrodynamics)
- Implementation of stellar feedback in cosmological simulations
  - Effect on galaxy properties
  - The formation of disk galaxies

Galactic-scale winds

- Galactic winds in nearby star-forming galaxies: Strong bi-polar outflows (200-500 km/s) at rates similar to the SFR in nearby starbursts up to z~1, also molecular outflows detected
- Winds in high-z (z~2-3) star-forming galaxies (via absorption lines)

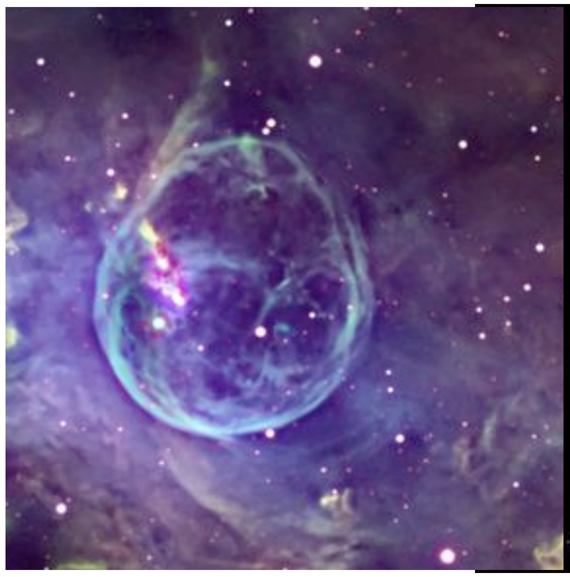
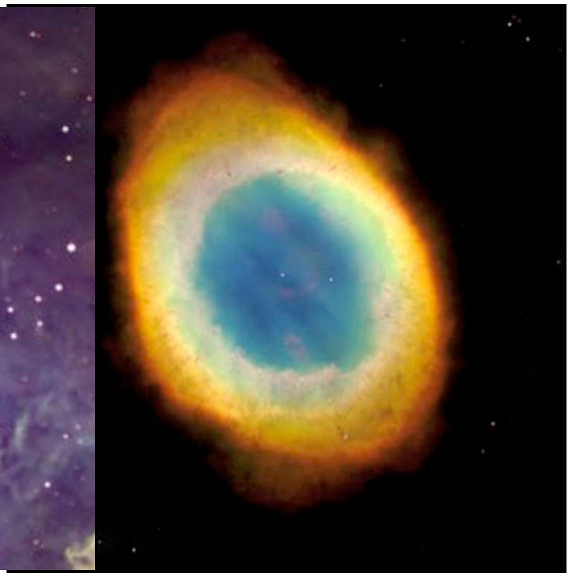


- Most likely a combination of different feedback processes from massive stars, relative contribution unknown

Feedback from different stages of stars

- **SNae explosions** and can not only enrich the interstellar medium with metals…
- …but also inject a lot of energy and momentum in the gas (observed velocities of 1000s of km/s driving shocks into the ISM)

- **Stellar winds** from
  - AGB stars, lot of metals, but slow winds (<10km/s)
  - Young OB stars, less mass loss, but high velocities (<2000km/s)

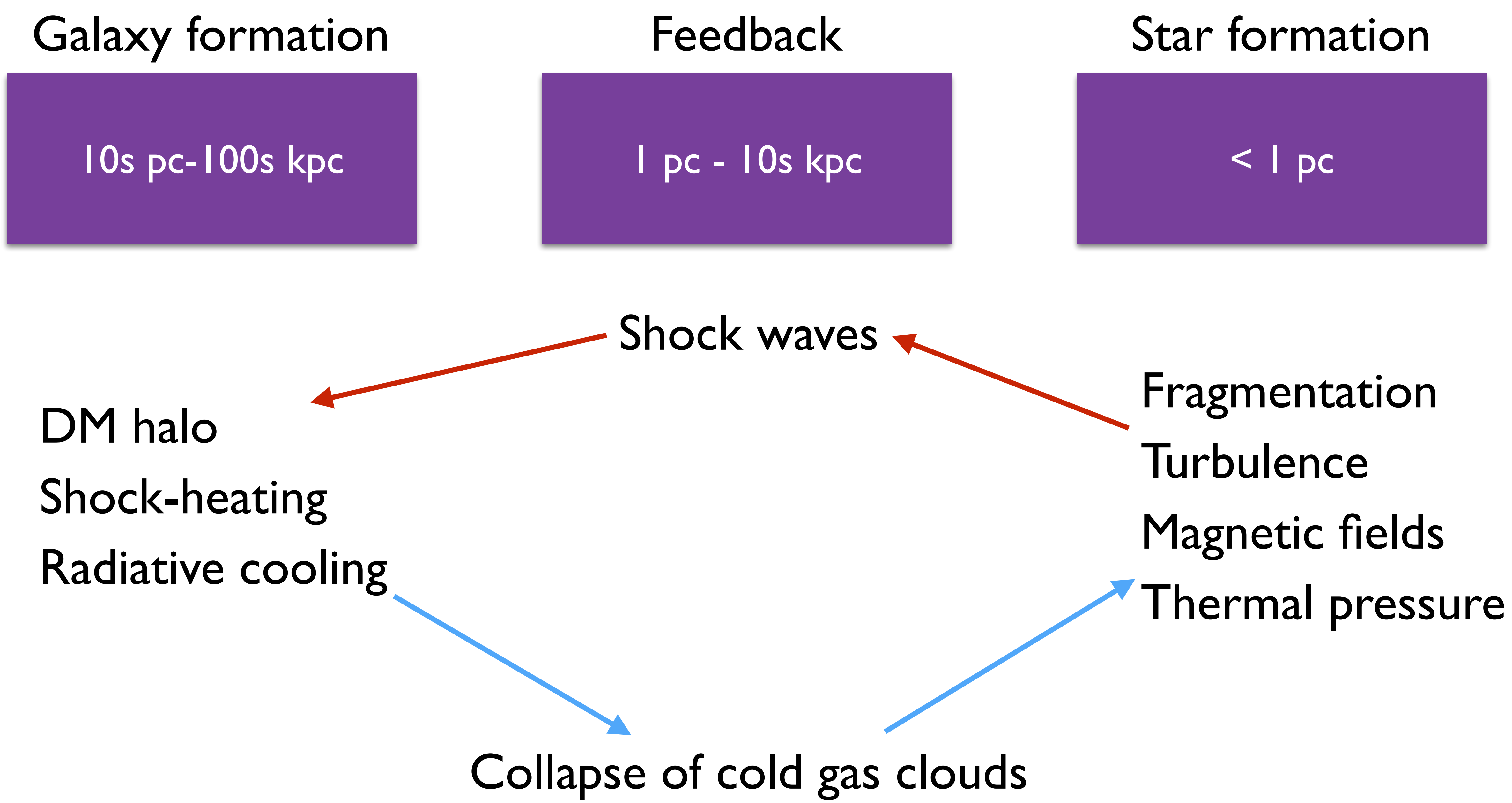



- Young massive (OB) stars may also affect their surrounding gas by **ionising (UV) radiation** (radiation pressure and photo-ionization heating)

Stellar feedback processes

- What stellar feedback processes exist?
    - SN explosions of massive stars
    - Radiation from young stars
    - Stellar winds from young and old stars
- Why should we account for these processes in simulations?
    - Directly effecting ISM
    - Mass, metallicity, momentum and energy injection
    - Leading to gas heating, outflows and chemical enrichment
    - Likely impact on galaxy properties

Scales involved in stellar feedback



- Sub-resolution models needed since cosmo sims cannot resolve scales much below few tens parsec (large cosmological boxes even 700 parsec)
- Before looking at different models in simulations, **how do the different small-scale physical processes work**?

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Small-scale physics: SN explosion

- During SNae explosions, typically 2-5 $M_\odot$ of gas are ejected at supersonic velocities v_{eject}~6000-7000km/s driving a shock (blast wave) into the ambient medium, an energy of E_{exp}~10^{51} erg is released
- The three phases of a blast wave in a homogeneous medium
  - Momentum conserving Free expansion phase: The wave front expands rapidly, and the speed of the expansion is constant because the mass of the ejected material is much larger than the mass of the ambient medium. This phase lasts u*ntil the mass of the swept-up material becomes comparable to the mass of the ejecta.*
  - Then, the remnant enters the energy conserving Sedov-Taylor phase; in this phase, the shock wave slows down but conserves energy (adiabatic expansion) and about three orders higher ambient gas mass than SN ejecta can be heated to high T (>1e6K).
  - As soon as radiative losses become dominant, a cooling shell forms behind the shock front and the amount of hot gas decreases rapidly —> Snow-Plow phase, shock wave slows further down and transforms into a sound wave.

Small-scale physics: SN explosion

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- The three phases of a blast wave in a homogeneous medium (Free expansion, Sedov-Taylor, Snowplow)

- The end of a SN: merging with the external medium

$$v_S(t_{merge}) = c_S$$

- Efficiency of SN depends on the stage at which the blast wave merges with the external ISM

- For a homogeneous medium (no external pressure), analytical, self-similar solutions exist for the adiabatic Sedov-Taylor phase

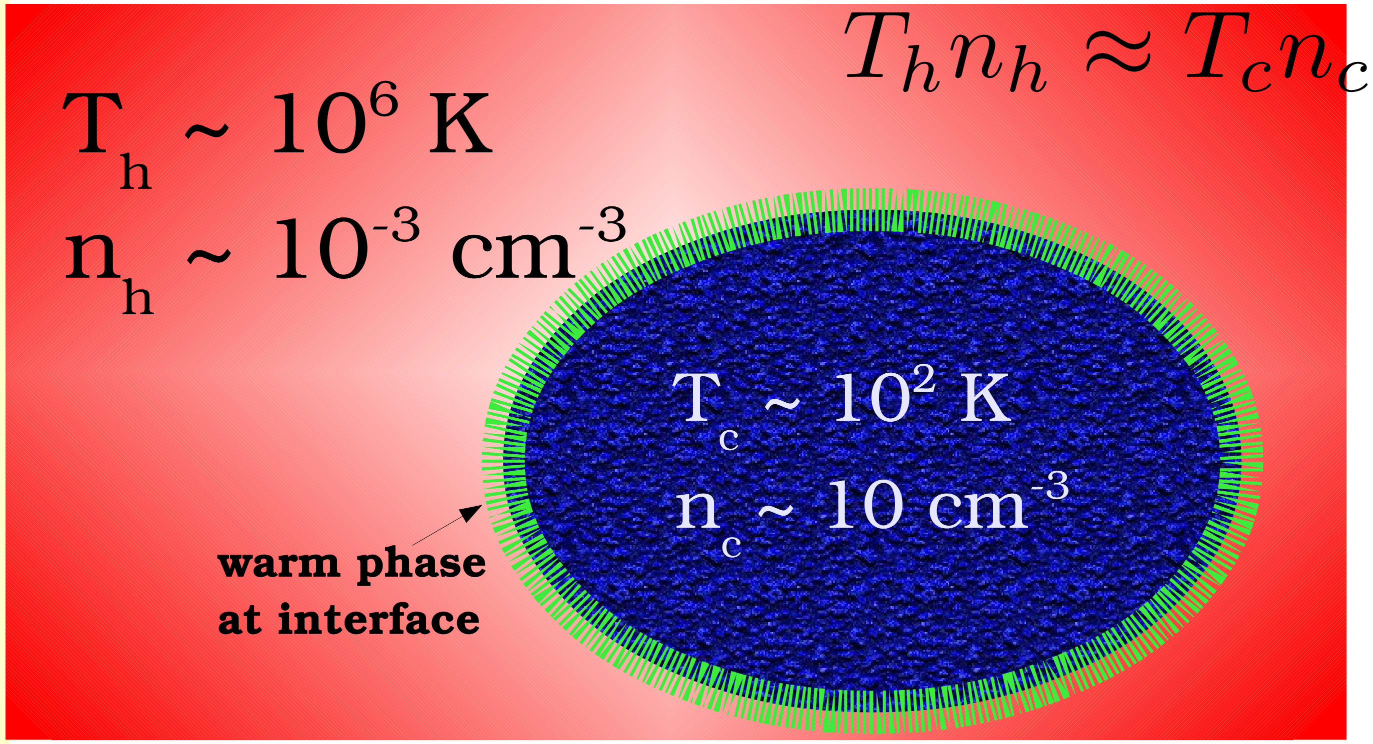
$$R_s(t) = 84.8 \left(\frac{E_{51}}{\mu_0 n_0} \right)^{1/5} t_6^{2/5} \, pc$$

Small-scale physics: Multi-phase ISM

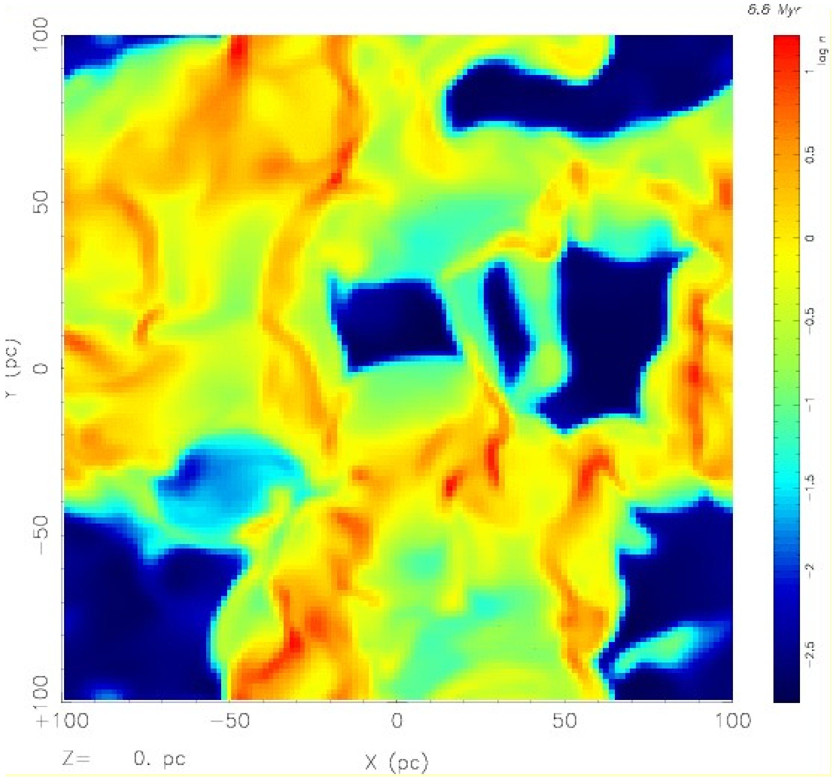
- These analytic considerations were for a homogeneous medium, while in reality: MULTIPHASE MEDIUM

McKee & Ostriker (1977):

- **diffuse hot ($T \sim 10^6$ K) phase**
- **cold ($T \sim 10^2$ K) clouds in rough pressure equilibrium**
- **warm ($T \sim 10^4$ K) phase formed at the interface**



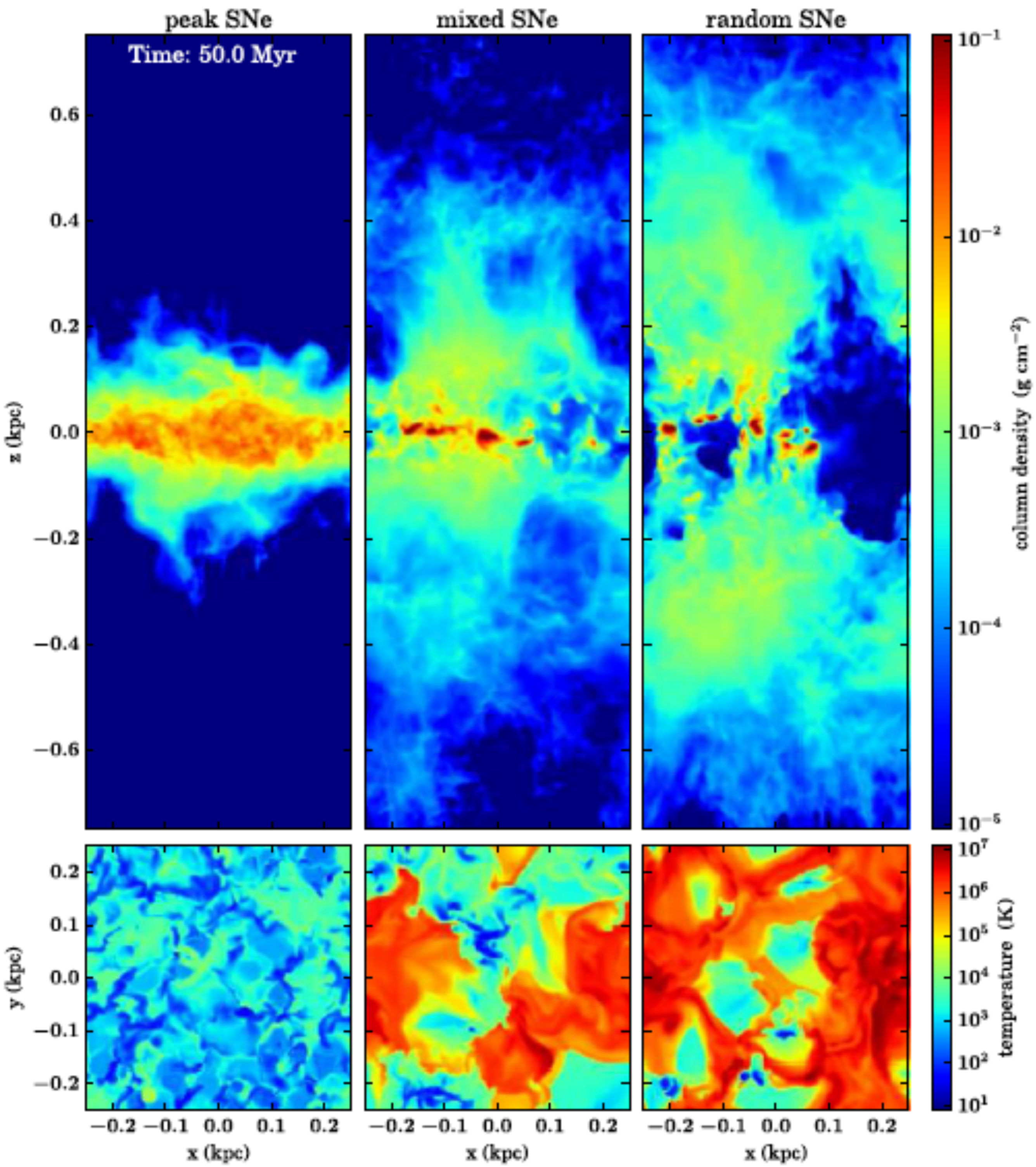
- Turbulence complicates the ISM:
  - No well-defined phases, but broad peaks in T distribution
  - Cold clouds are transient (can collapse)



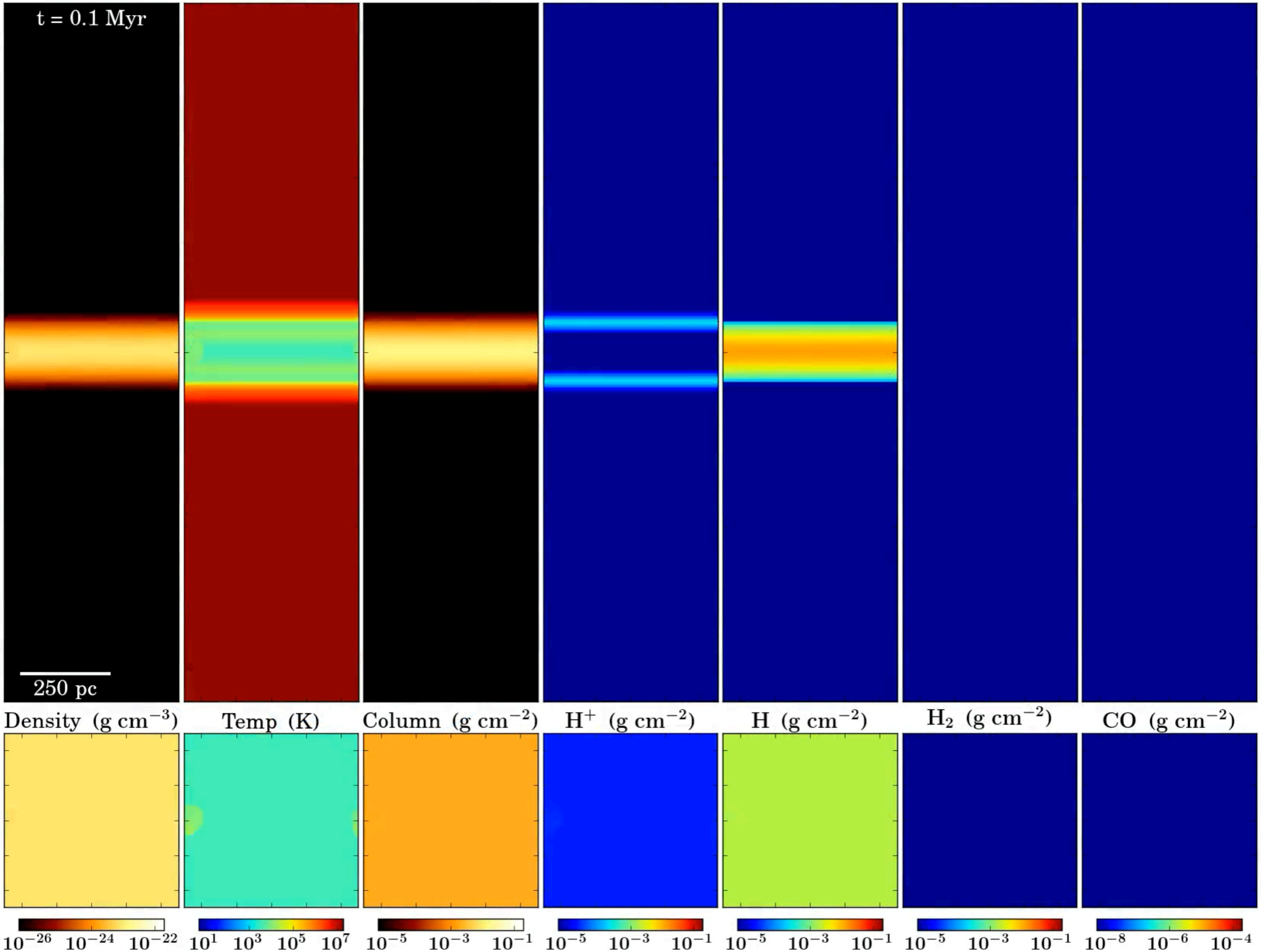
- Use numerical **small-scale simulations** to study complex impact of SN explosions in a multi-phase medium

Small-scale physics: SN explosion

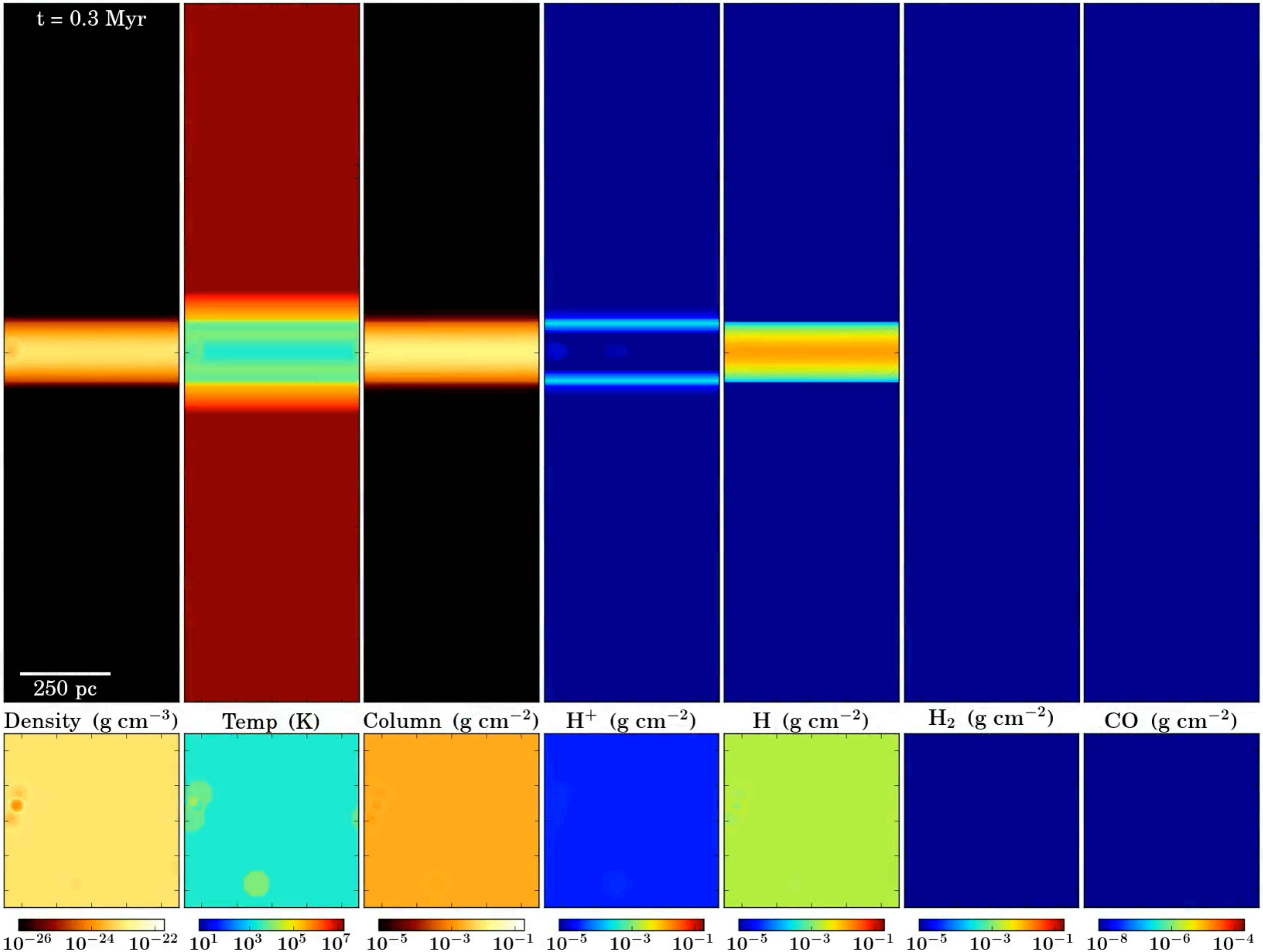
- SILCC project (Walch et al.): Snapshots of vertical gas column density distribution (top) and mid-plane panels (bottom) for three simulations (500pc box) stratified galactic disk shaped by SN exploding at constant rate
- Left: Each SN explodes at current density peak —> no outflows, no hot gas
- Middle: 50% of SN explode at random (less dense) positions
- Right: All SN explode at random positions —> hot gas becomes volume filling and strong outflows are driven



Small-scale physics: SN explosion



Small-scale physics: SN explosion

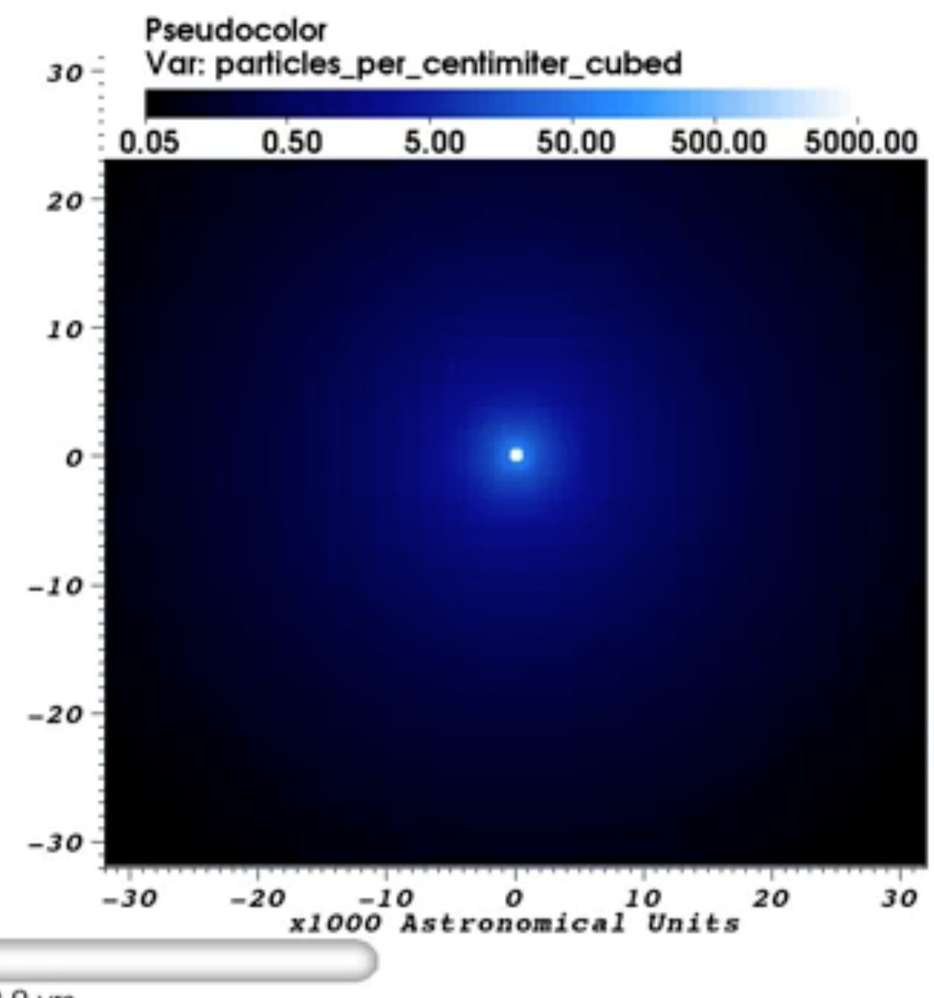


Small-scale physics: Stellar winds

- Radiation-driven stellar winds from O- and B-stars create bubbles of low-density gas around the stars (contribute to the superbubbles!)
- Typical B-stars have mass loss rates of 1e-9$M_\odot$/yr, and wind velocities of ~2000km/s and an integrated wind energy of ~10^{47} erg, very massive stars can even reach ~10^{50} erg
- Energetically less important than SN, but they can significantly reduce the gas densities around massive stars and increase the impact of a SN

- Might be a strong regulator of star formation in forming star clusters

- Also these processes are modelled in small-scale hydro simulations



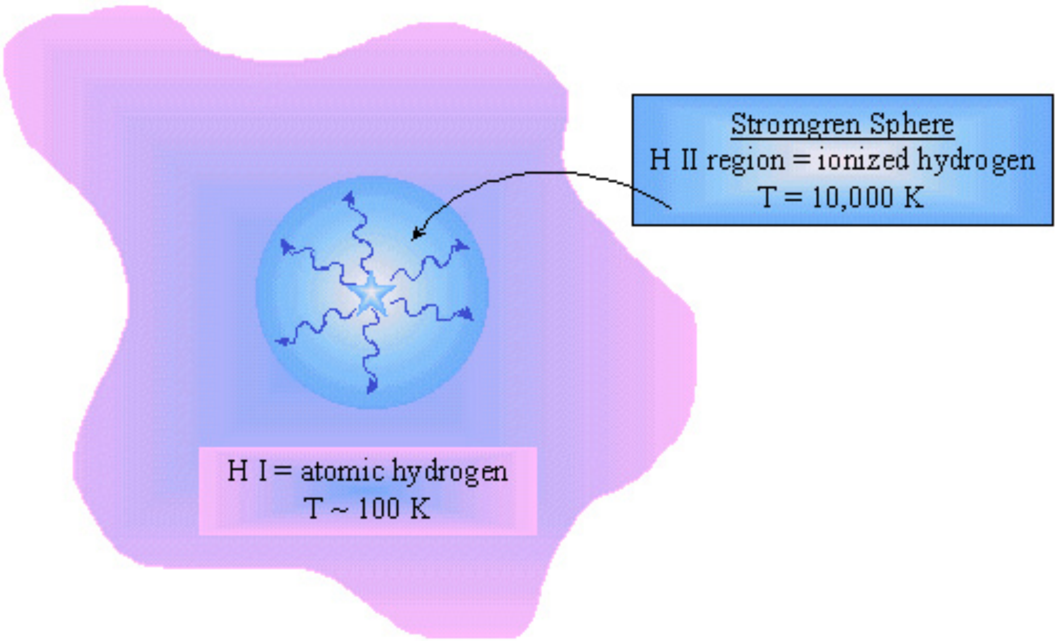
Small-scale physics: Radiation

- Total energy released by newly formed stellar populations is dominated by stellar radiation. By the time the first star exploded as SN, the star would have released already ~10^{53} erg as radiation and ~10^{50} erg in stellar winds
- **Photo-ionisation heating**: UV photons create HII regions around young massive stars by heating the parental cloud from <100K to ~10^4K
  - Full radiative transfer treatment of ionising radiation is challenging
  - Often approximated using the Stroemgren approach: ISM within the Stroemgren sphere (homogeneous, spherically symmetric medium) is ionised and heated to ~10^4 K
  - At Stroemgren radius recombination rate equals the ionisation rate, one can derive

$$R_S = \left(\frac{3}{4\pi}\frac{S_*}{n^2\beta_2}\right)^{1/3}$$

  - n is the density
  - β is the total recombination rate and has an approximate value of

$$\beta_2(T_e) \approx 2 \times 10^{-16} T_e^{-3/4} [m^3/s]$$

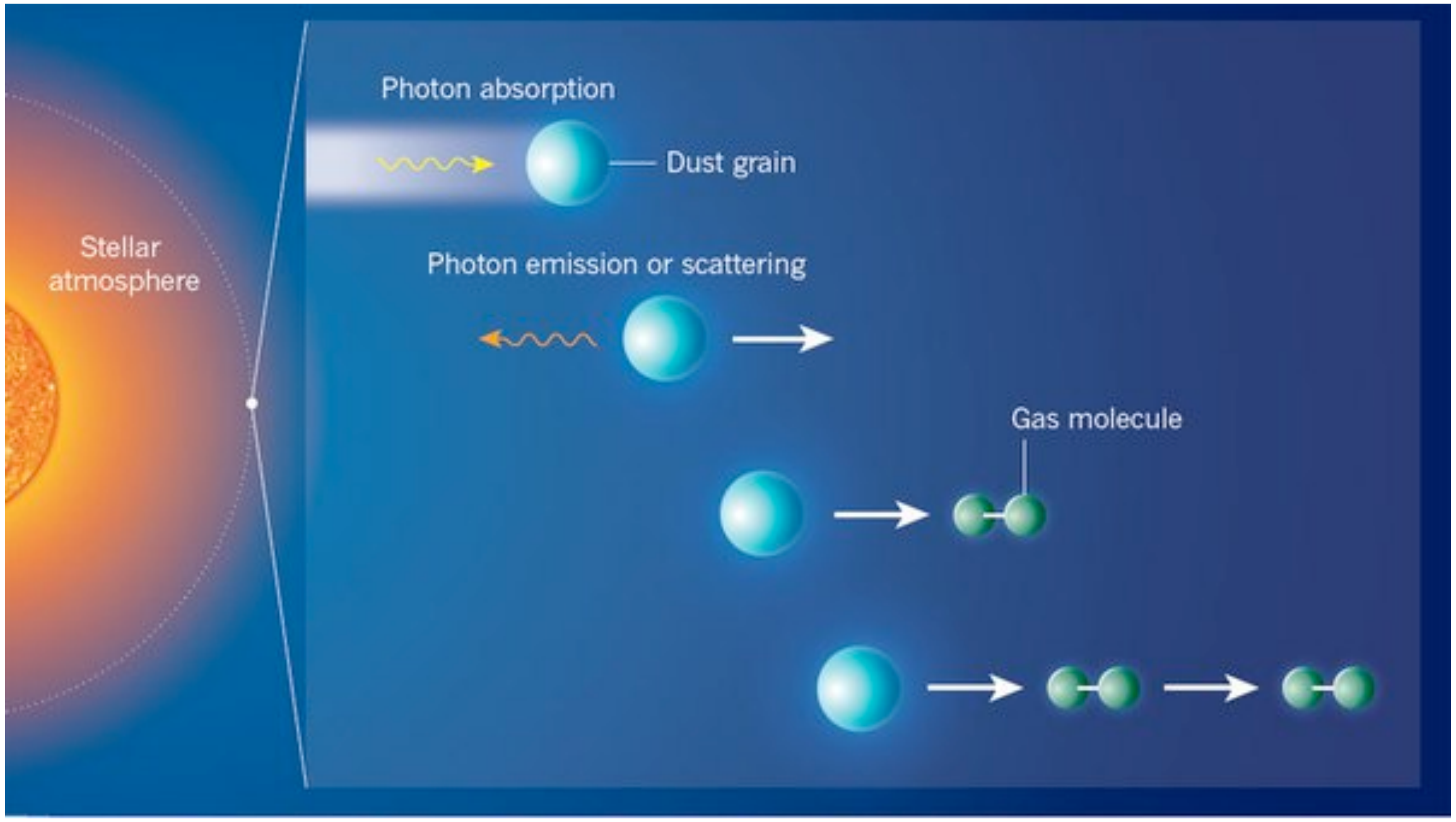


Small-scale physics: Radiation

- Total energy released by newly formed stellar populations is dominated by stellar radiation. By the time the first SN exploded, stars would have released already $\sim 10^{53}$ erg as radiation and $>10^{50}$ erg in stellar winds
- **Radiation pressure**: on gas (direct) and dust (indirect) of re-emitted infrared radiation can result in a significant momentum input into the ISM

$$\dot{P}_{\rm rad} \approx (1 + \tau_{IR}) L/c$$

  - Efficiency of this process depends on $\tau_{\rm IR}$, which is the optical depth to the re-radiated IR emission of the dust, i.e. on the details of scattering in optically thick regions
  - It is still not clear to what extent these processes can help to drive winds

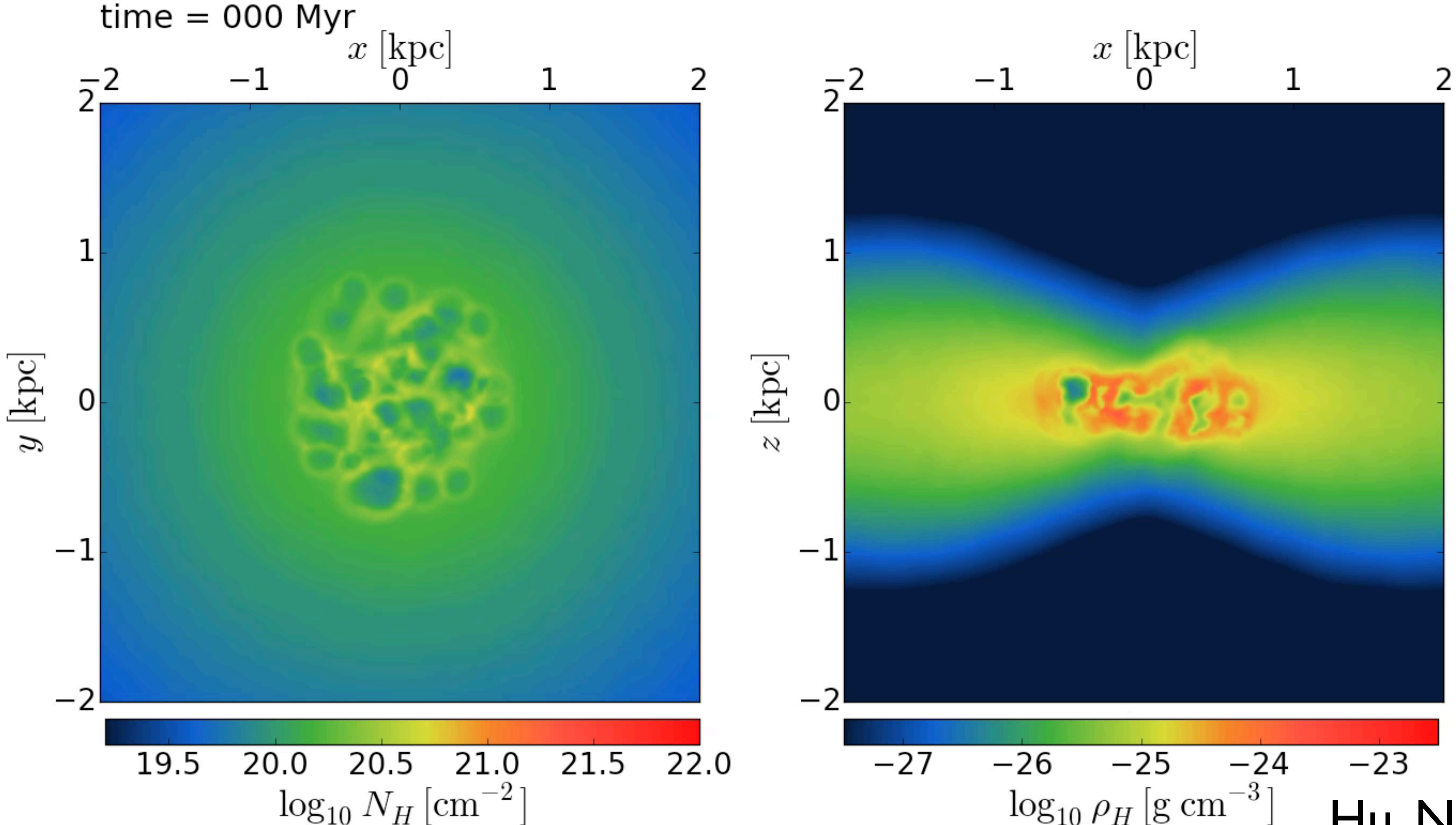


Stellar radiation, winds & SN explosions

- High-resolution simulation of an isolated dwarf galaxy (1e7 Msolar)
- Sample individual stars, i.e. individual SN explosions, stellar winds, and radiation as a Stroemgren approach

➡ The latter two processes alone cannot drive outflows, but they are responsible ISM heating (less dense) —> efficient SN explosion

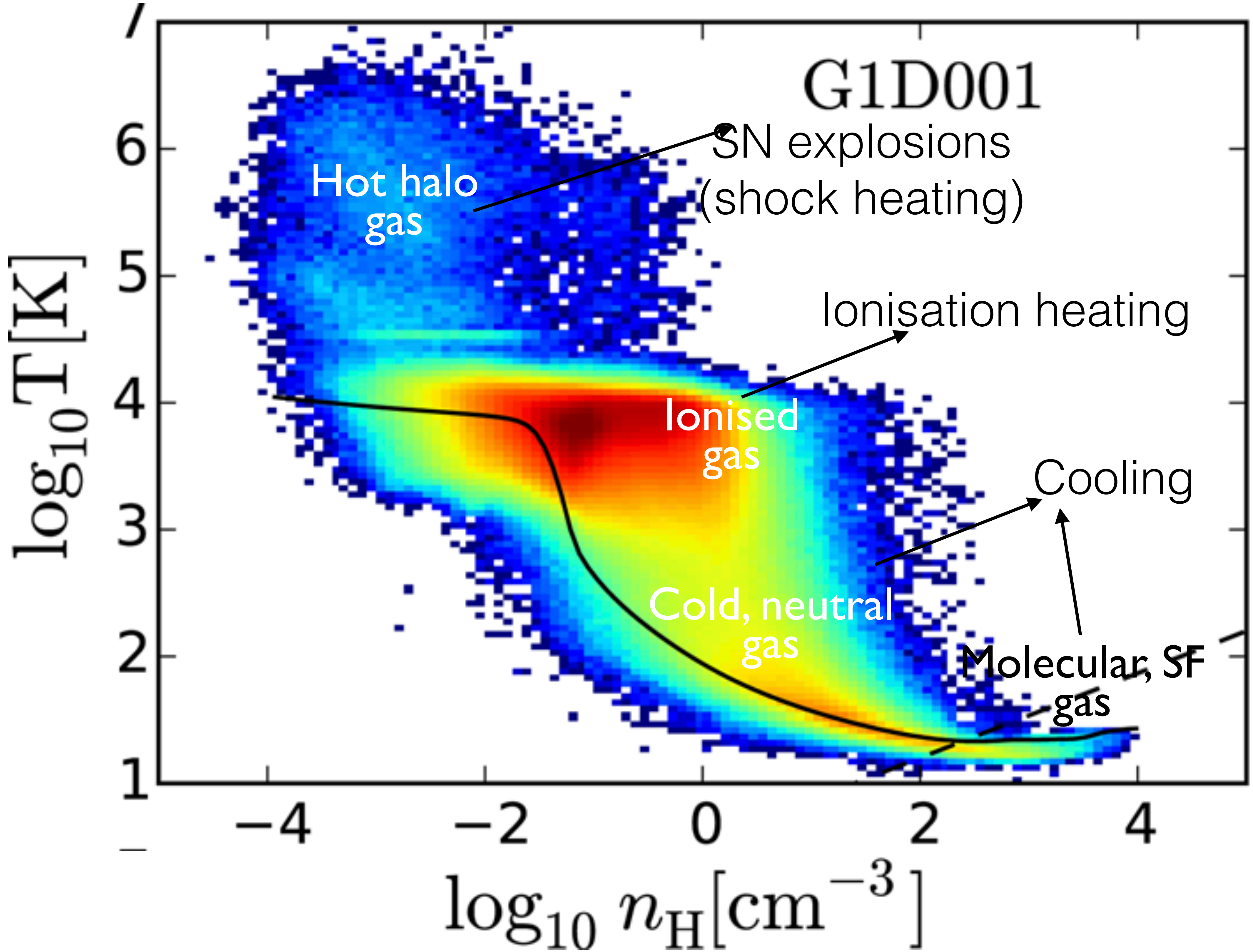
➡SN explosions seem to ultimately important for driving galaxy scale outflows as observed!



Hu, Naab et al. 2016

Phase diagram of gas

Phase diagram = Temperature-density diagram for a simulated dwarf galaxy



Summary — Stellar feedback processes

- With only gas cooling, shock and adiabatic heating and SF, simulated galaxies are not realistic —> Feedback?
- Stellar feedback refers to mass, metal, momentum and energy injection due to different evolutionary stages of massive stars
  - SN explosions/superbubbles (1e51 erg per SN)
  - Stellar winds
  - Radiation (Photo-ionisation, heating, radiation pressure)
- Stellar feedback can lead to gas heating and gas outflows, and is important for creating a realistic multi-phase ISM in a galaxy
- Depending on where SN explode changes the gas heating and outflows

Outline of this lecture

- •Observational indications for stellar feedback processes
- •Small-scale physical processes
    - •SN explosions
    - •Stellar winds
    - •Ionising radiation/radiation pressure (radiation-hydrodynamics)
- •Implementation of stellar feedback in cosmological simulations
    - •Effect on galaxy properties
    - •The formation of disk galaxies

Stellar feedback in a cosmological context

How can we model these complex feedback processes on larger scales > 100pc-1kpc in cosmological simulations?

- Problem 1: we do not have the resolution to capture these small-scale processes in cosmological simulations (a few 100-10s pc)
- Problem 2: we do not have (yet) a full prescription coming from small-scale simulations.

Implementation: Thermal feedback model

- Idea: simply dump thermal energy from massive stars/SN into surrounding gas particles (or cells), i.e. assuming ~10% of stars explode as SN…
- Problem: at possible resolution: thermal energy is radiated away too quickly so that no efficient stellar feedback with galactic-scale outflows is possible (*system cannot hydro-dynamically respond to the energy input due to the larger sound crossing time of the gas compared to the cooling time —> no conversion of thermal into kinetic energy*)
- Until ca 10-15 years ago, simulations repeatedly failed to generate strong outflows (and realistically looking low-mass/spiral galaxies)!

Use numerical "tricks" to mimic efficient stellar feedback and galactic-scale outflows in cosmological simulations

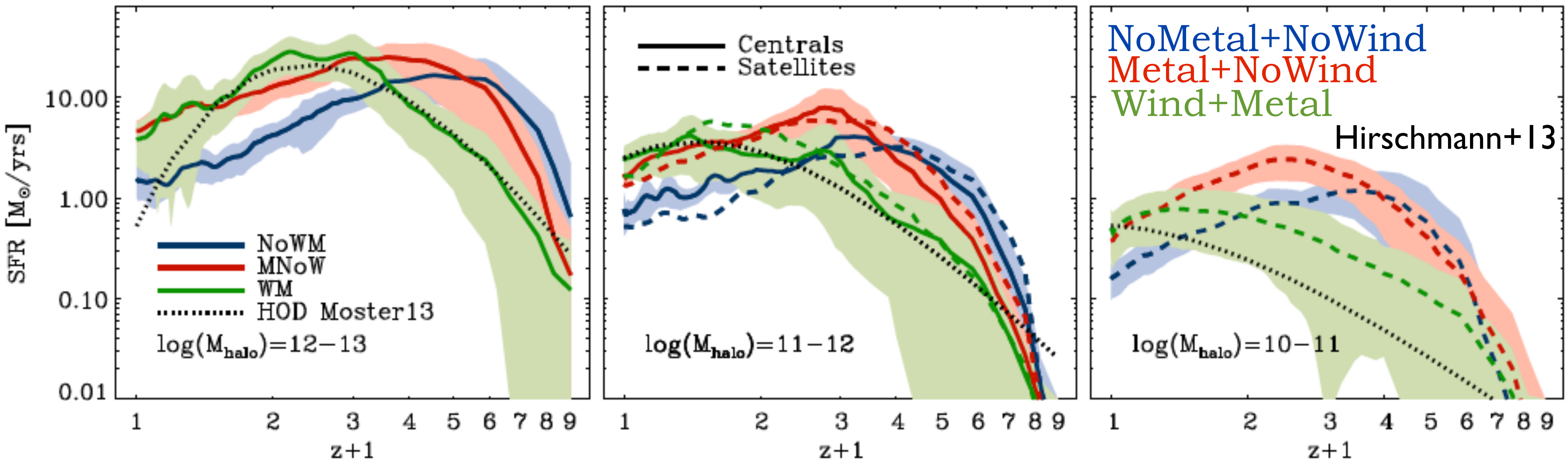
Implementation: Efficient stellar fb models

How to overcome inefficient thermal feedback?

- **Introduce mechanical (kinetic) feedback for galactic winds, gas particles get a "velocity kick"**
  - Ejected gas mass rate is proportional to SFR: $\dot{M}_w = \eta \dot{M}_\star$
    η is called the mass-loading factor, typically η =2 is assumed
  - Wind carries fixed fraction of SN energy wind velocity is constant $\frac{1}{2}\dot{M}_w v_w^2 = \chi \epsilon_{SN} \dot{M}_\star$
- **Delayed cooling model should mimic the effect of SNII blast wave**
  - In each SNII explosion, a fraction of the SN energy is added to the ISM distributed to the surrounding gas
  - Disable cooling in these neighbouring gas particles for a specific t
- **Stochastic thermal feedback:**
  - Ensure that the heated gas responds hydrodynamically to the temperature increase before the thermal energy is radiated away
  - Energy released from SNII in thermal way, however, a "Temperature threshold" is introduced
- **Two-phase feedback model:**
  - Thermal energy only injected in neighbouring hot gas cells

Implications: Star formation rates

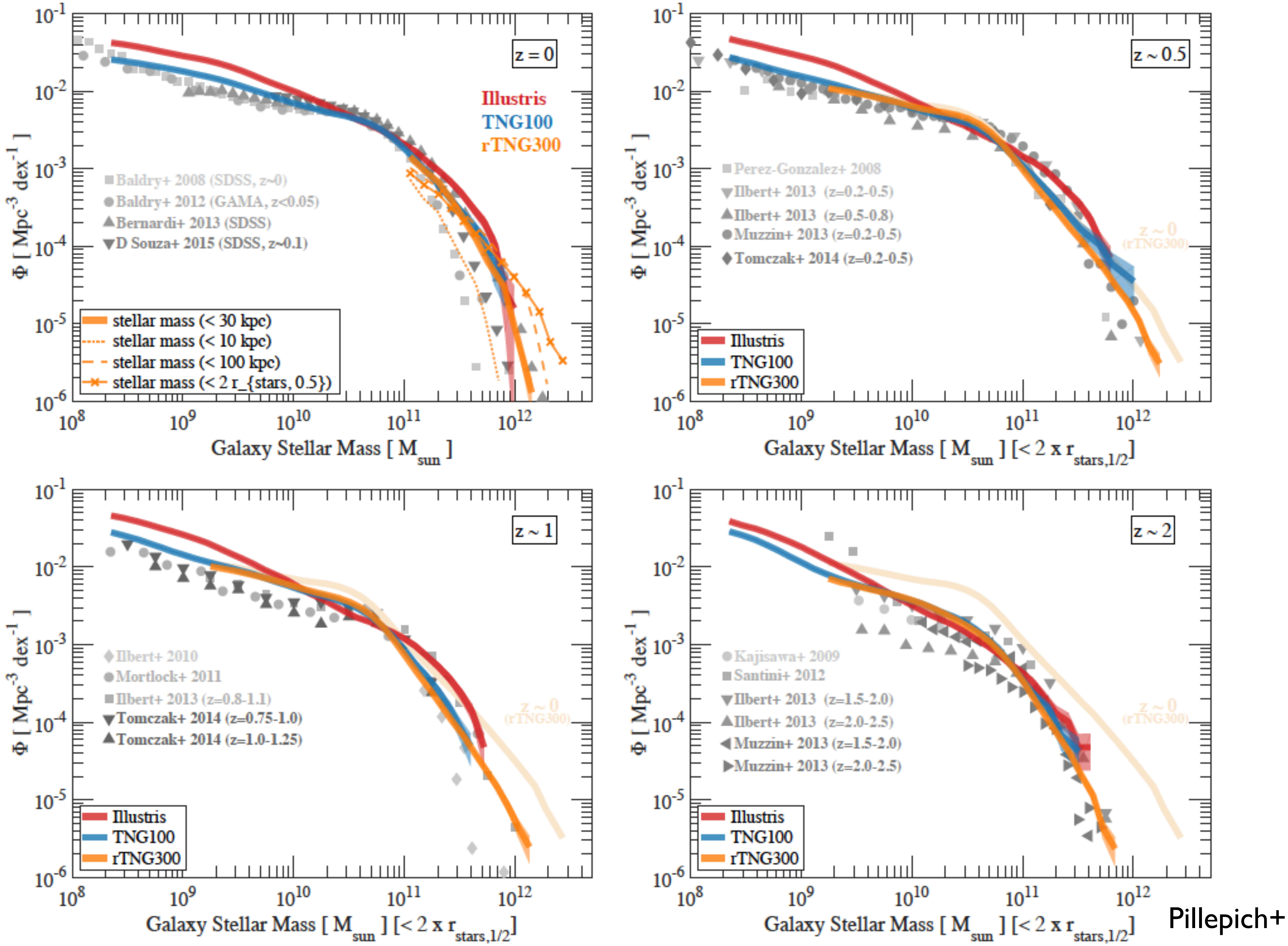
- Model for kinetic feedback



- Stellar-driven outflows significantly suppress early SF and delay it towards later times
- SFR of less massive galaxies peak at later times than that of massive galaxies —> anti-hierarchical trend
- Consistent with stellar baryon conversion efficiencies from abundance matching predictions (Lecture 8)
- Consequence: delayed metal enrichment and higher cold gas fractions (see exercise of Lecture 8)
- Same conclusions drawn from SAMs (Lecture 8)

Implications: Galaxy stellar mass function

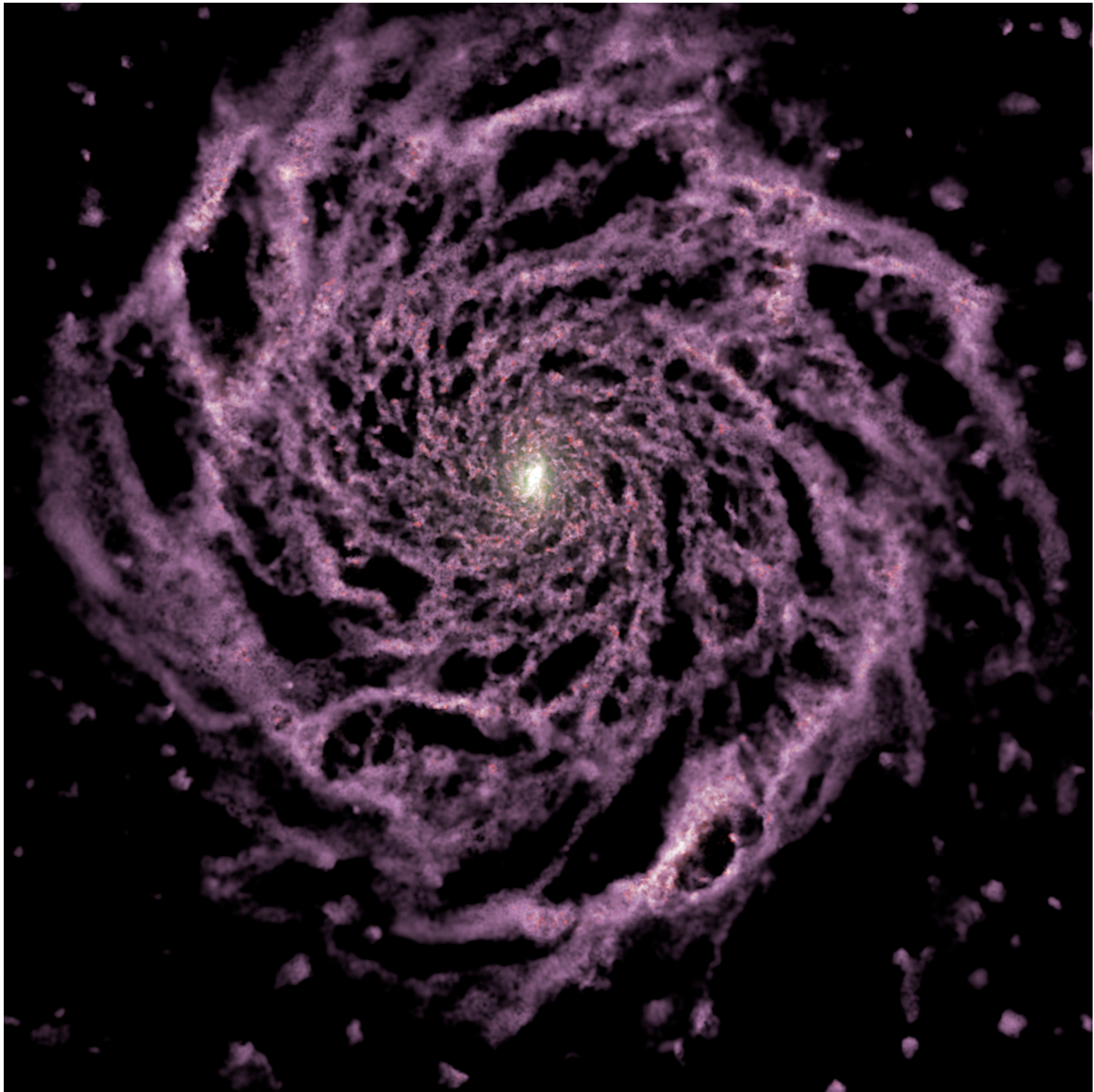
- Weak vs kinetic stellar feedback in Illustris and TNG100



Pillepich+17

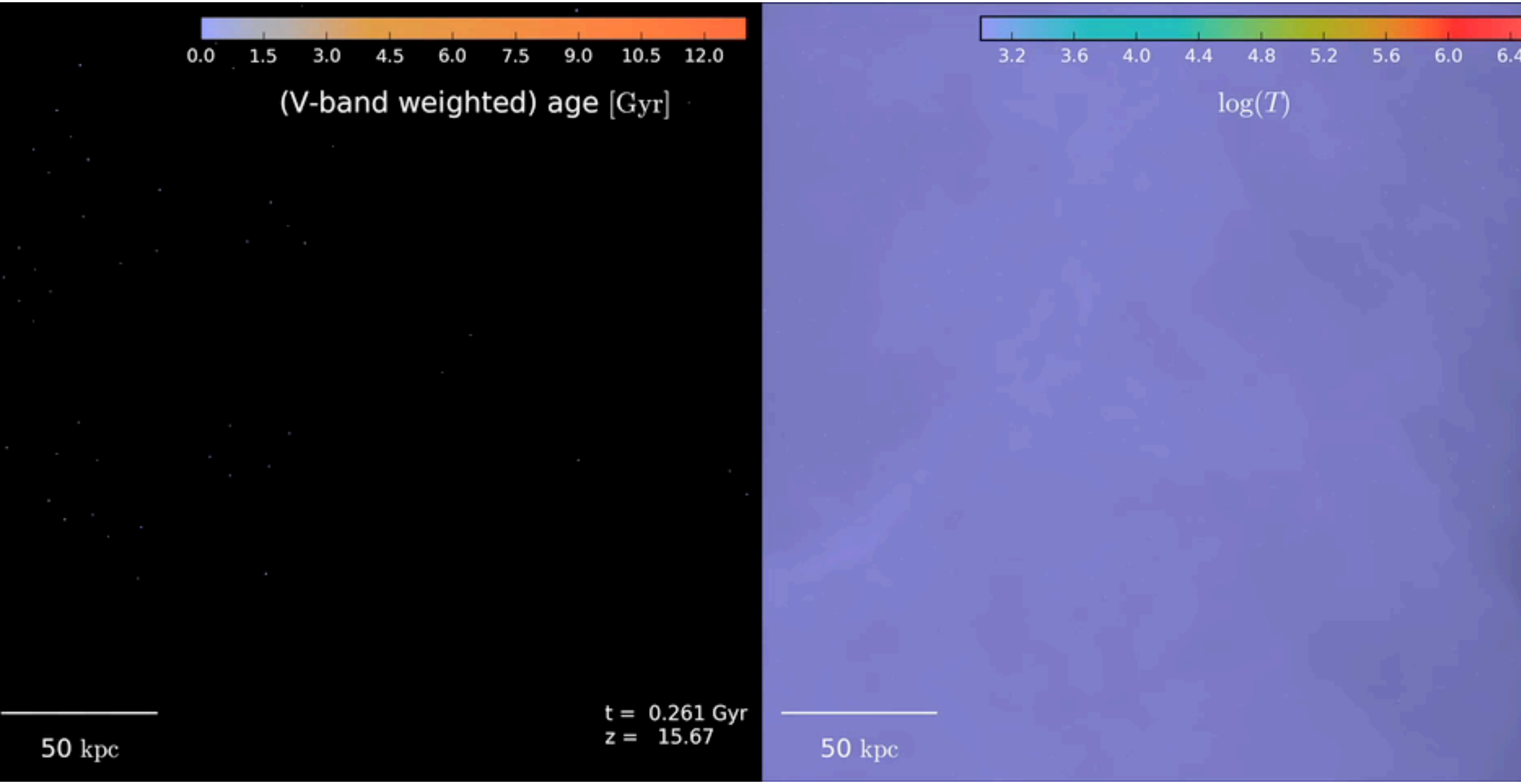
Formation of disk galaxies

- 2011: Eris simulation (efficient stellar feedback via a delayed cooling model, high resolution and high SF threshold)



- First simulation of a realistically looking spiral MW type galaxy!
- However, this galaxy still contains too many stars!
- Add "early" stellar feedback: accounting for additional energy release from massive stars (before they explode) —> realistic stellar contents in halos (Stinson et al. 2014)
- Movie link: https://www.youtube.com/watch?v=VQBzdcFkB7w

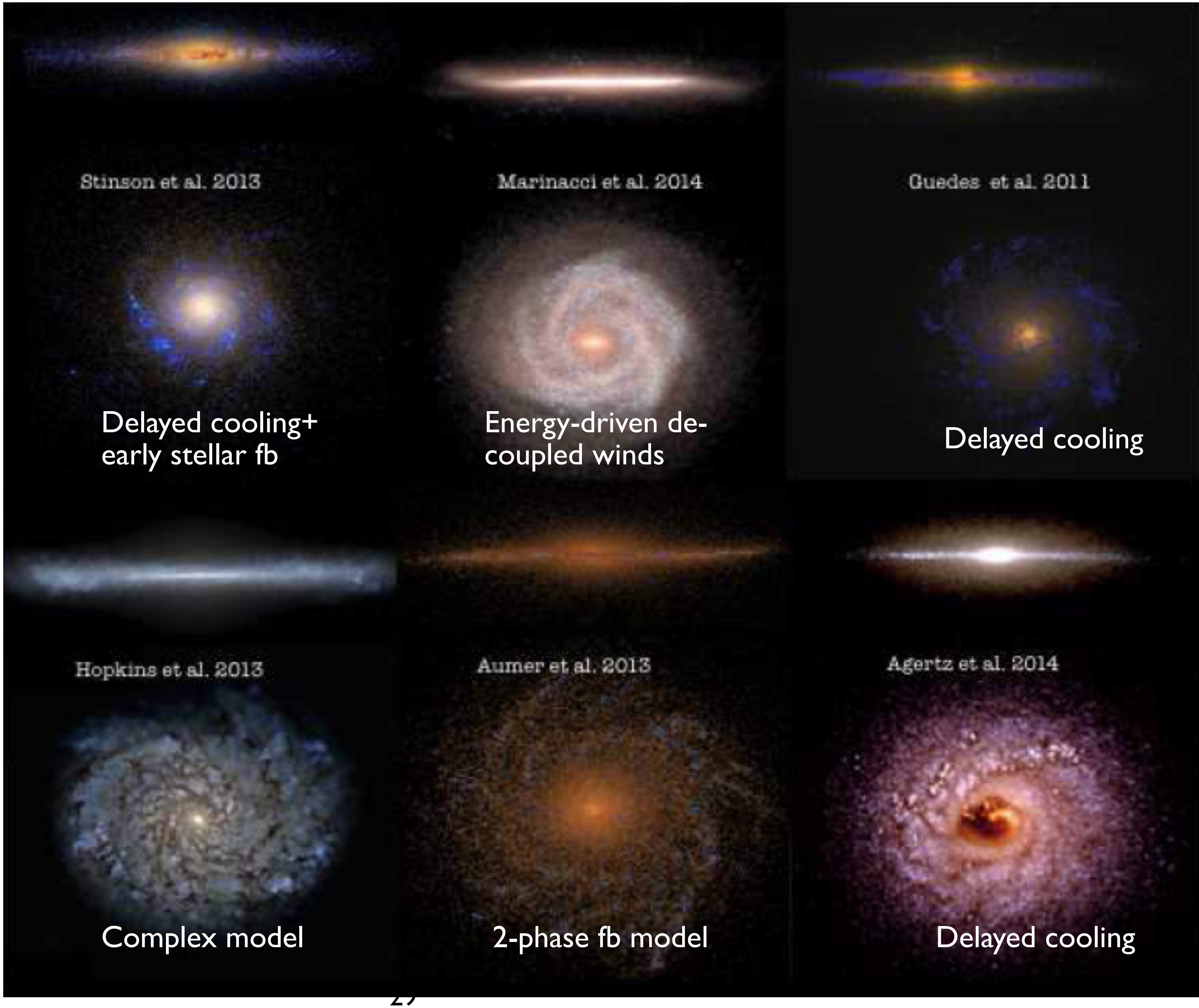
Implementation: Kinetic model



- Realistic spiral galaxies and realistic low stellar content

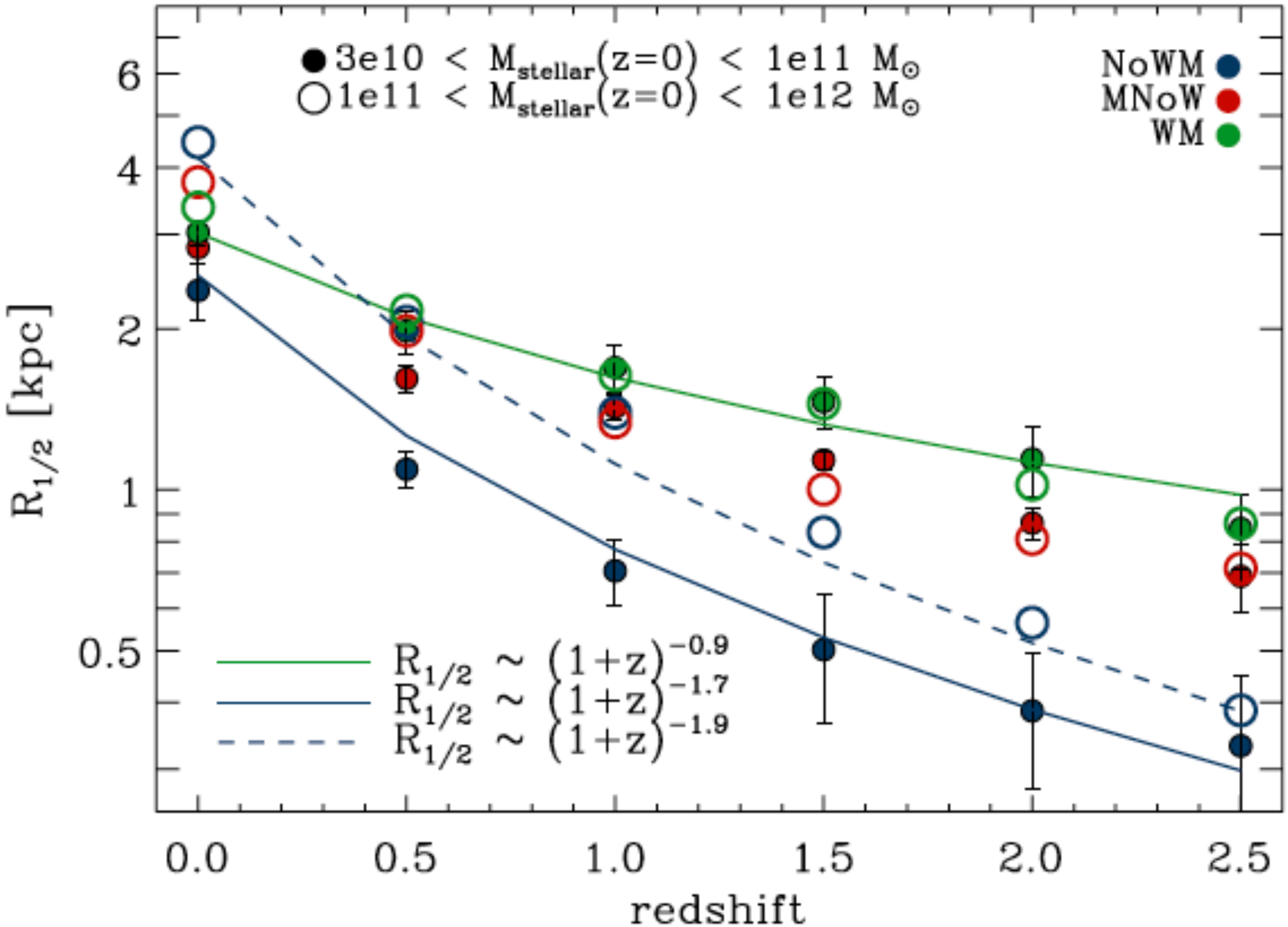
Implications: Formation of disk galaxies

- Key process for generating disk galaxies:
- Efficient out-flows at high z to remove low-angular mo-mentum gas
- Re-accreted with higher angular mo-mentum at late times
- and other minor points
- Different sub-resolution models were successful



Implications: Galaxy sizes

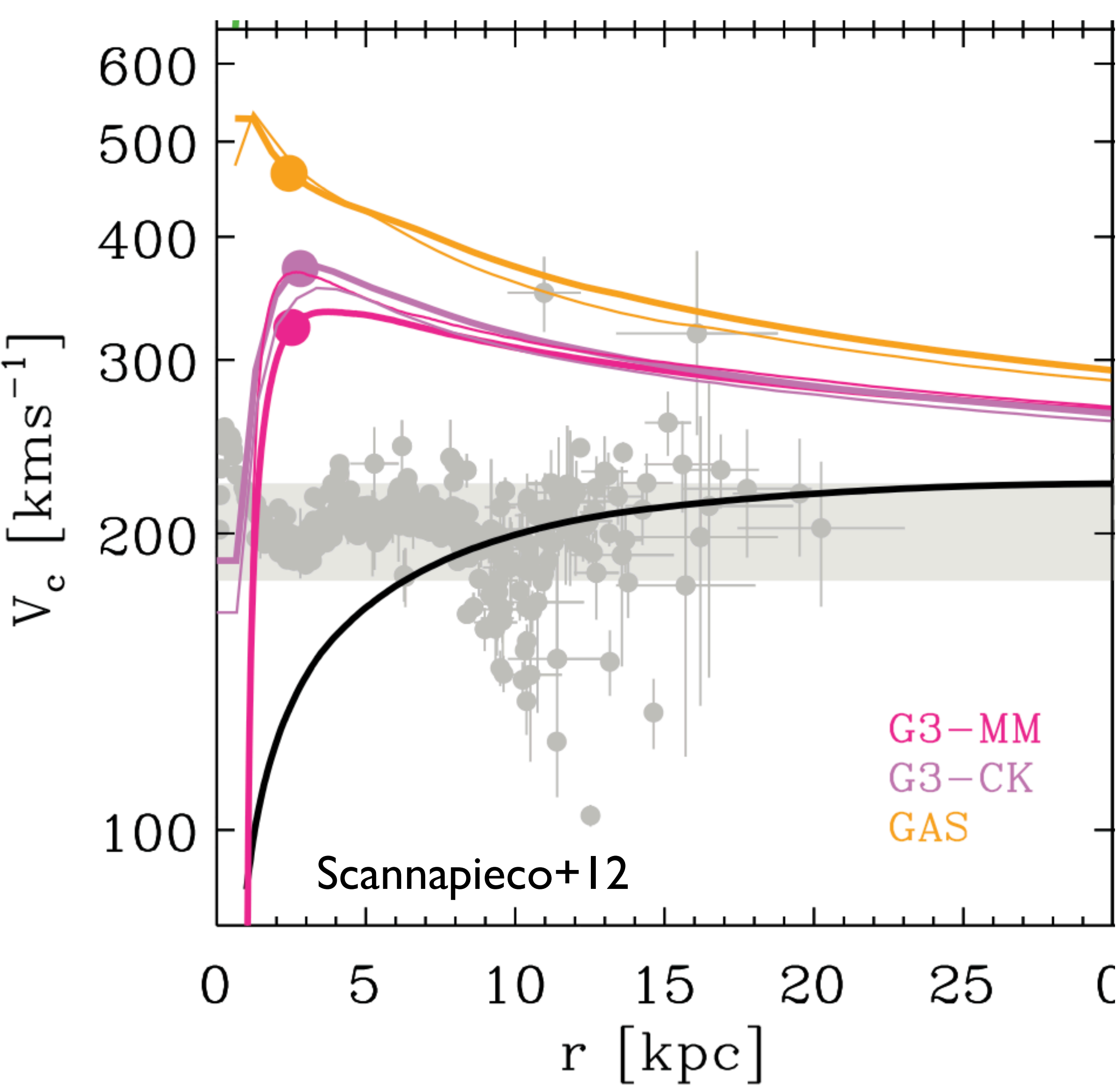
- Stellar feedback leads to larger sizes due to late re-accretion of high-angular momentum gas
- More consistent with observations

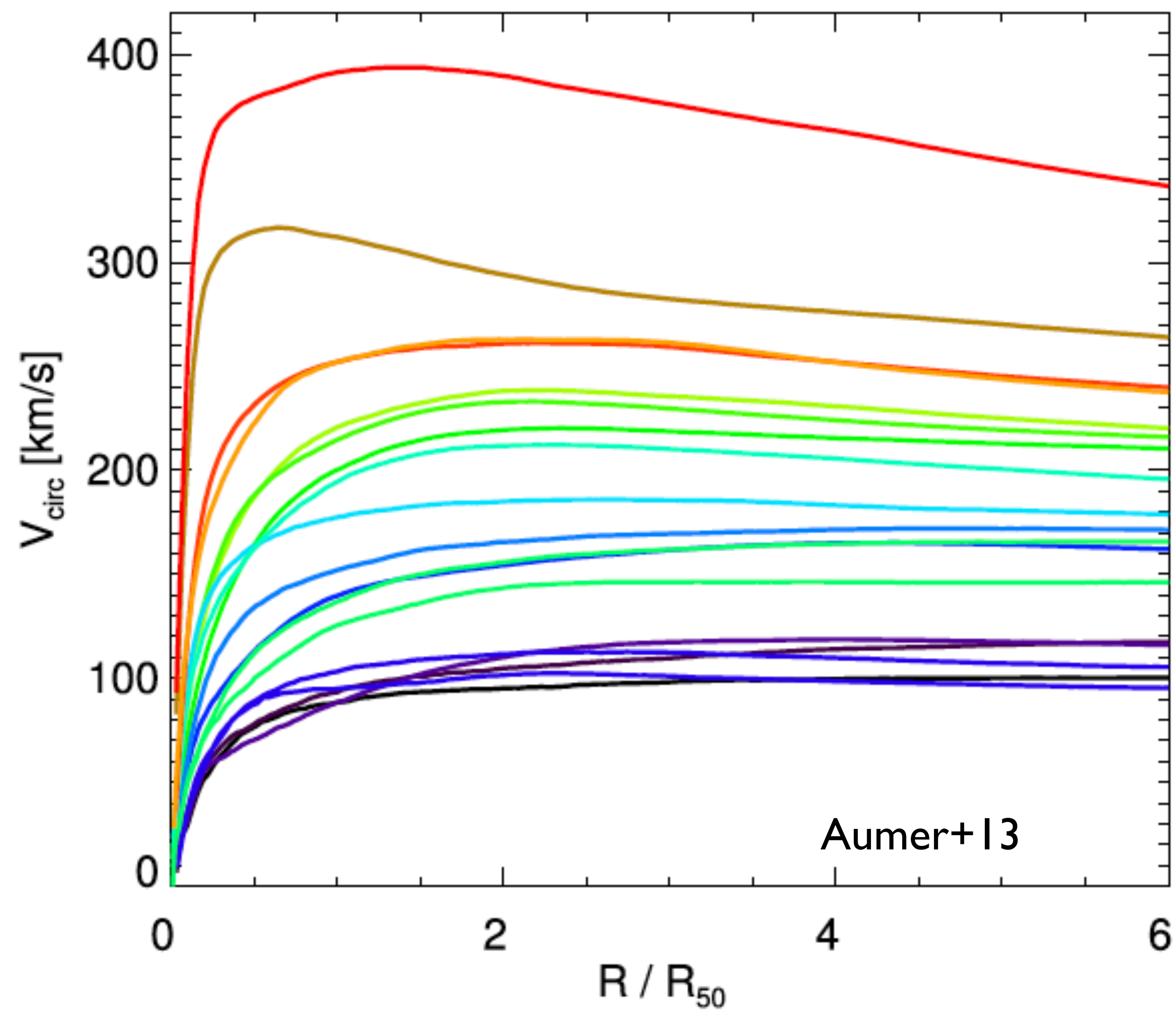


Hirschmann+13

Implications: Flat rotation curves

$$V_{\rm circ} = \sqrt{GM_{\rm tot}(< r)/r}$$





- Weak stellar fb
- too “peaked”

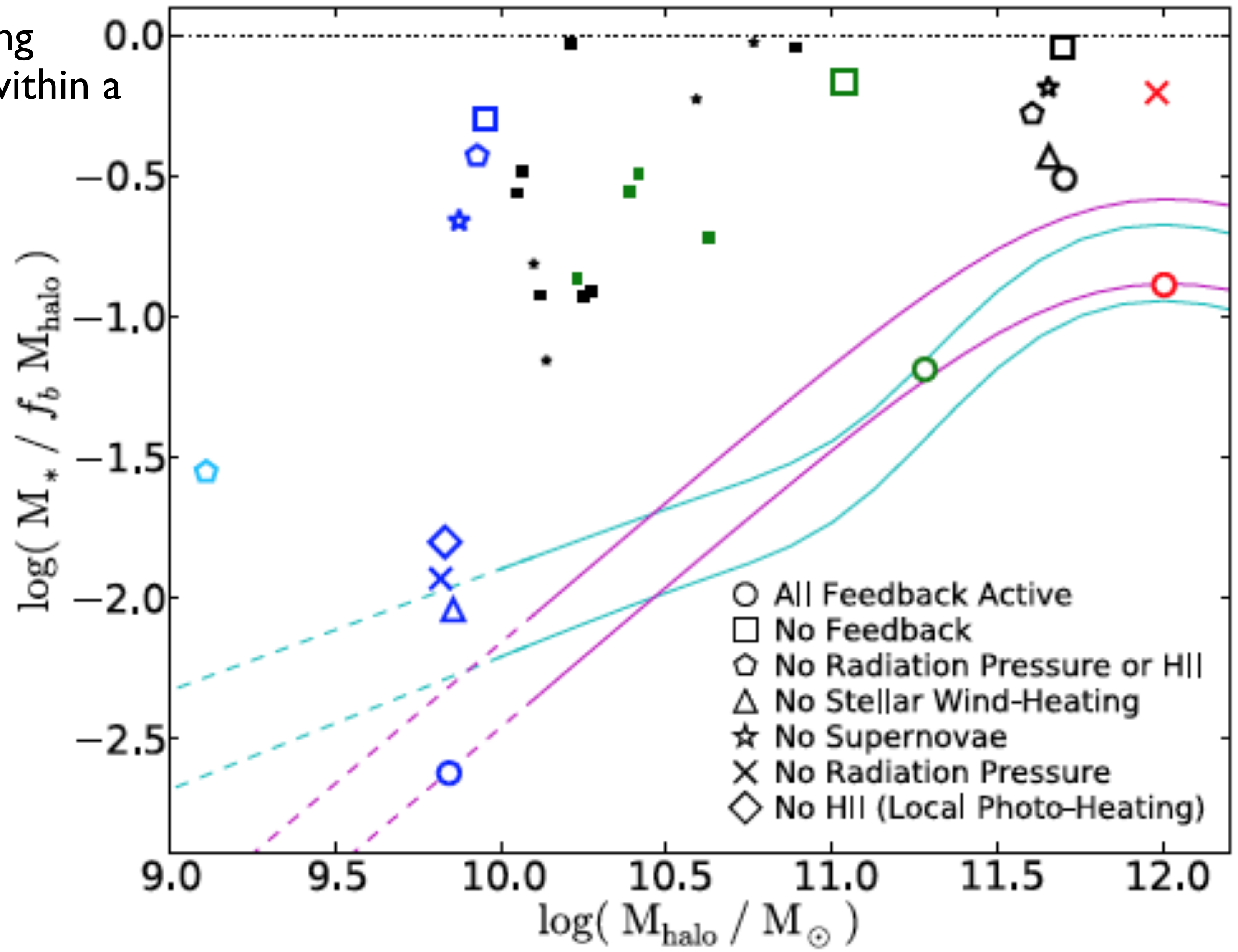
- “Two-phase” stellar fb
- more relastic

Towards more realistic feedback models…

FIRE (=Feedback in realistic environments) model (see Hopkins+14):

- Radiation pressure: gas illuminated by stars feels a momentum flux $\dot{P}_{\rm rad} \propto L_{\rm incident}/c$
- Supernova feedback: Use tabulated SN rates as a function of age and metallicity, stochastic determination whether a SN event occurs for a star particle, thermal energy and radial momentum is injected in gas particles in the kernel (+mass and metal yield)
- Stellar winds: injection of wind momentum, metals and mass as a continuous function of metallicity and age into the gas within a smoothing length
- Photo-Ionisation: calculate the ionising photon-flux from each star particle, heating within a Stroemgren sphere

- One of the main conclusions is that the FIRE simulations indicate that all these different mechanisms are necessary in order to get realistically low stellar contents…



Towards more realistic feedback models…

- Latte simulations: Milky Way-like halos with the FIRE feedback model may solve the "missing satellite" and "too-big-to-fail" problem (Wetzel+16, Garrison-Kimmel+19) —> no tension with LambdaCDM!

Towards more realistic feedback models…

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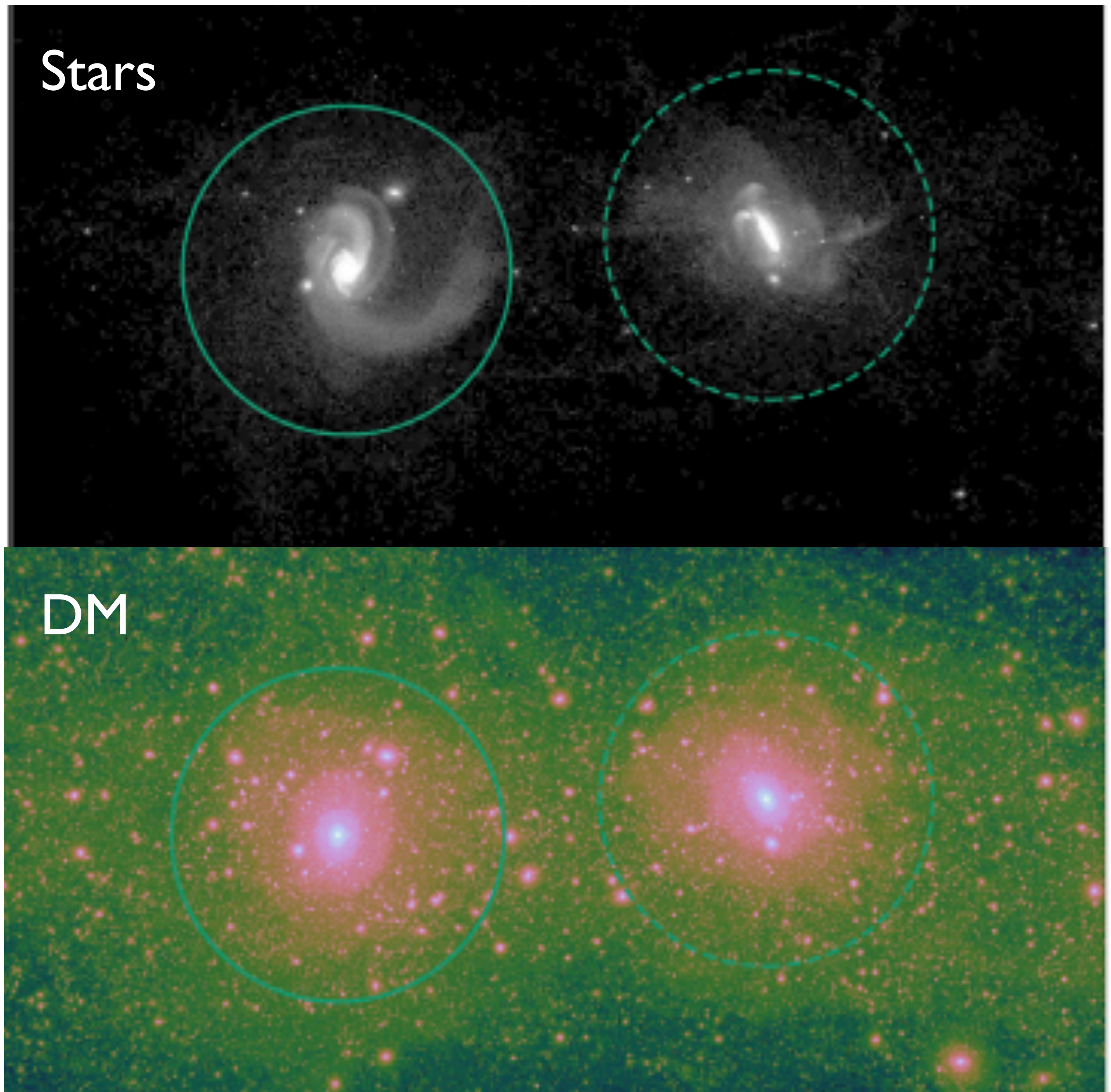

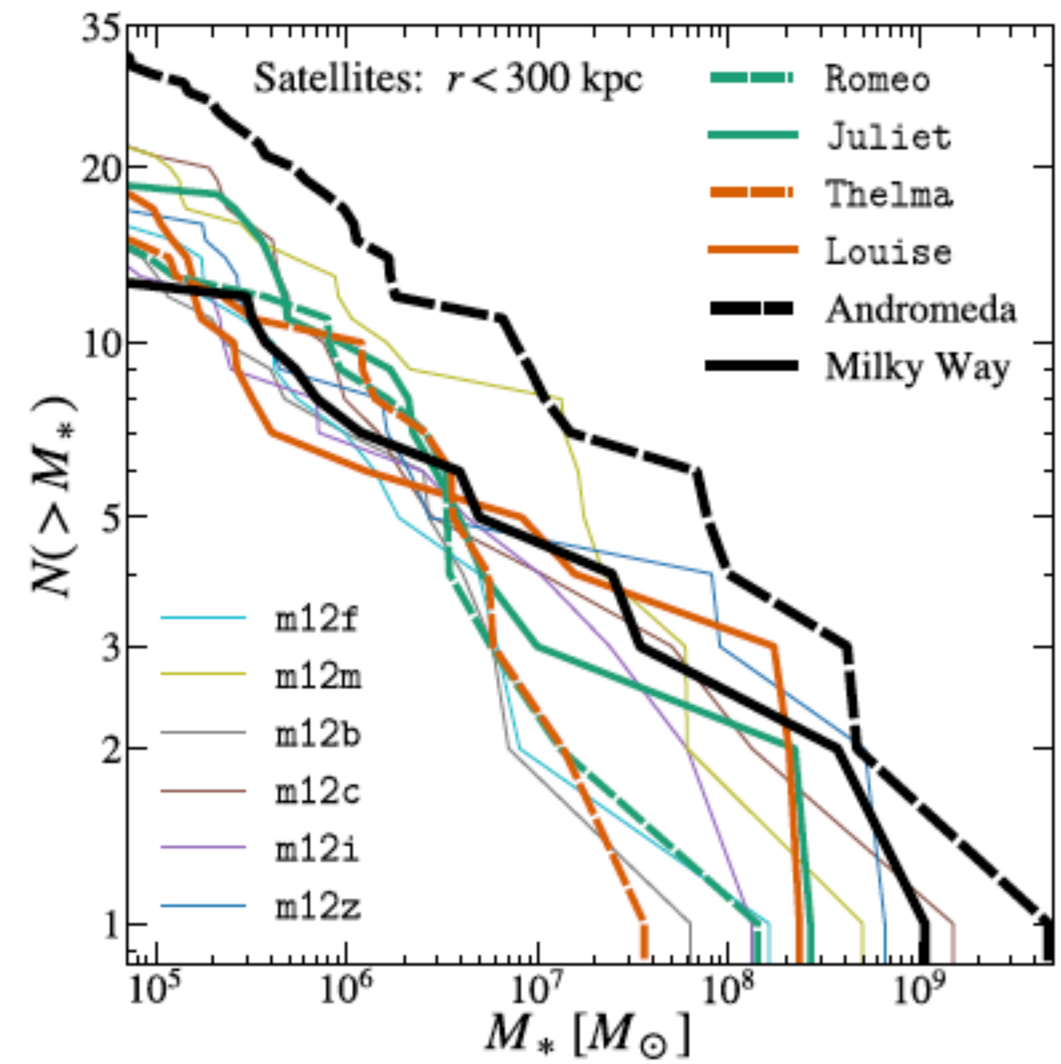

+ realistically low circular velocities (galaxies are less dense)

Can stellar fb fix failures of LambdaCDM?

- In principle yes!
- Regarding possible failures of CDM model: stellar-driven outflows are found to be a potential solution for:
    - realistically low stellar content in low mass halos
    - realistically reduced low-mass end of the stellar stellar mass fct
    - flatter rotation curves of MW-like galaxies
    - low number of luminous satellites around MW with lower maximum circular velocity (Missing satellite, too-big-too fail)
    - can alleviate cusp-core problem
- However, some form of warm dark matter may have a similar effect as strong stellar fb (still debated)
- Thus, it is unclear whether a contribution from a potential warm dark matter is needed, and if yes, which one!
    - To decide on that, small-scale physical processes are still not elaborated enough, ON-GOING RESEARCH

Summary -- Chapter 15

- Stellar feedback processes comprise mass, metal, momentum and energy injection into the ambient medium via SN explosions, ionising radiation and stellar winds.
- Due to dynamic range problem in cosmological simulations, empirically motivated sub-resolution models for stellar feedback have to be adopted.
- Stellar feedback primarily affects MW-like and lower-mass galaxies:
    - it delays their SFRs, reduces their stellar content and leads to the build-up of a spiral-like structure (because of early ejection of low-angular mom gas, which re-accreted later on)
    - this also leads to a reduced low-mass end of the galaxy stellar mass function, higher cold gas fractions and delayed chemical enrichment
- Stellar feedback is a possible candidate to solve several tensions between observations and LambdaCDM simulations

Only stellar feedback?

- Is stellar feedback sufficient to predict realistic galaxy populations?
- No, massive galaxies still problematic
    - overcooling problem in massive halos
    - too large stellar mass at given halo mass
    - massive end of stellar mass function over estimated
    - too high SFR, too young stellar ages
    - too small in size

Energy release from accreting supermassive BHs, i.e. AGN feedback

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first 7 lectures

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