Max-Planck-Institut für
Astrophysik

MAX-PLANCK-GESELLSCHAFT

Simulations of the multi-phase interstellar medium

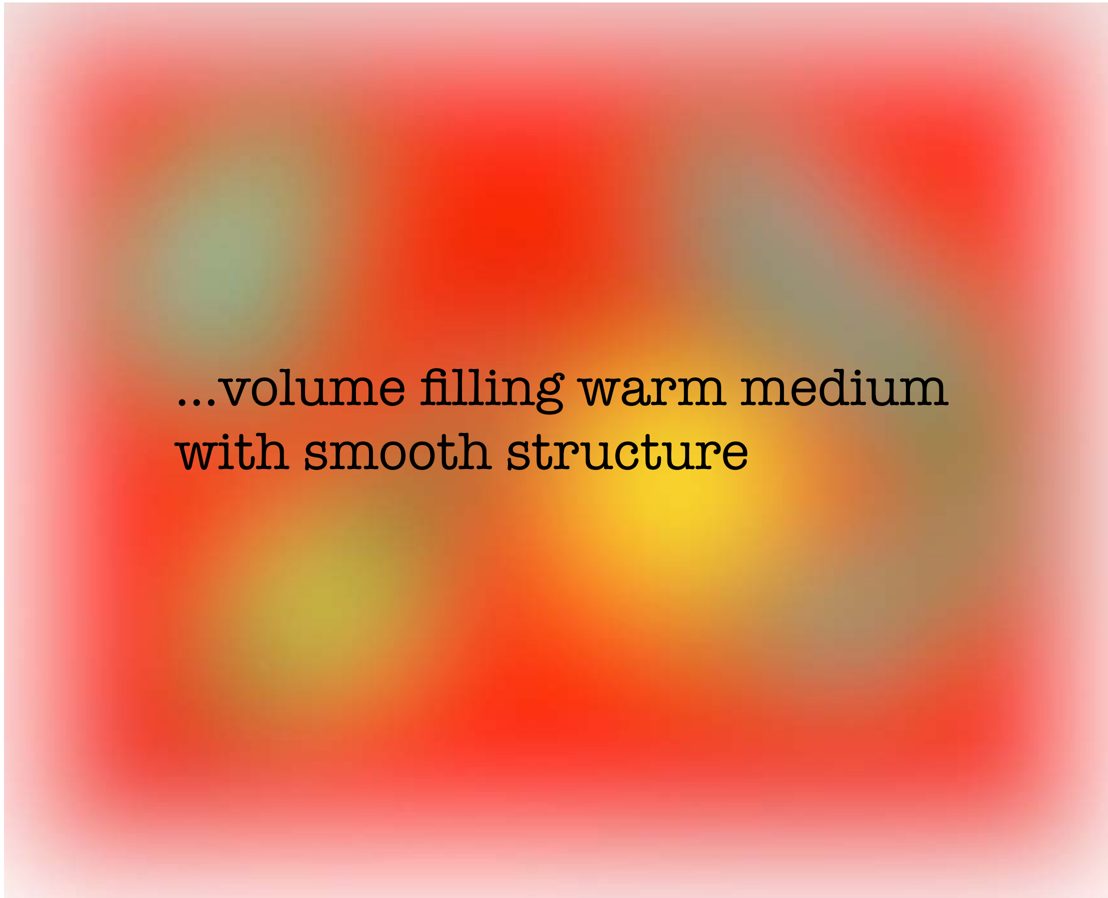
Thorsten Naab
MPA, Garching

S. Walch, P. Girichidis, T. Peters, C.-Y. Hu, A. Gatto, R Klessen, S. Glover, R. Wunsch etc.

Carving through the codes
Davos, February 14th, 2017

The multi-phase ISM drives galaxy evolution

500 pc



...the ISM in cosmological galaxy formation simulations

The multi-phase ISM drives galaxy evolution

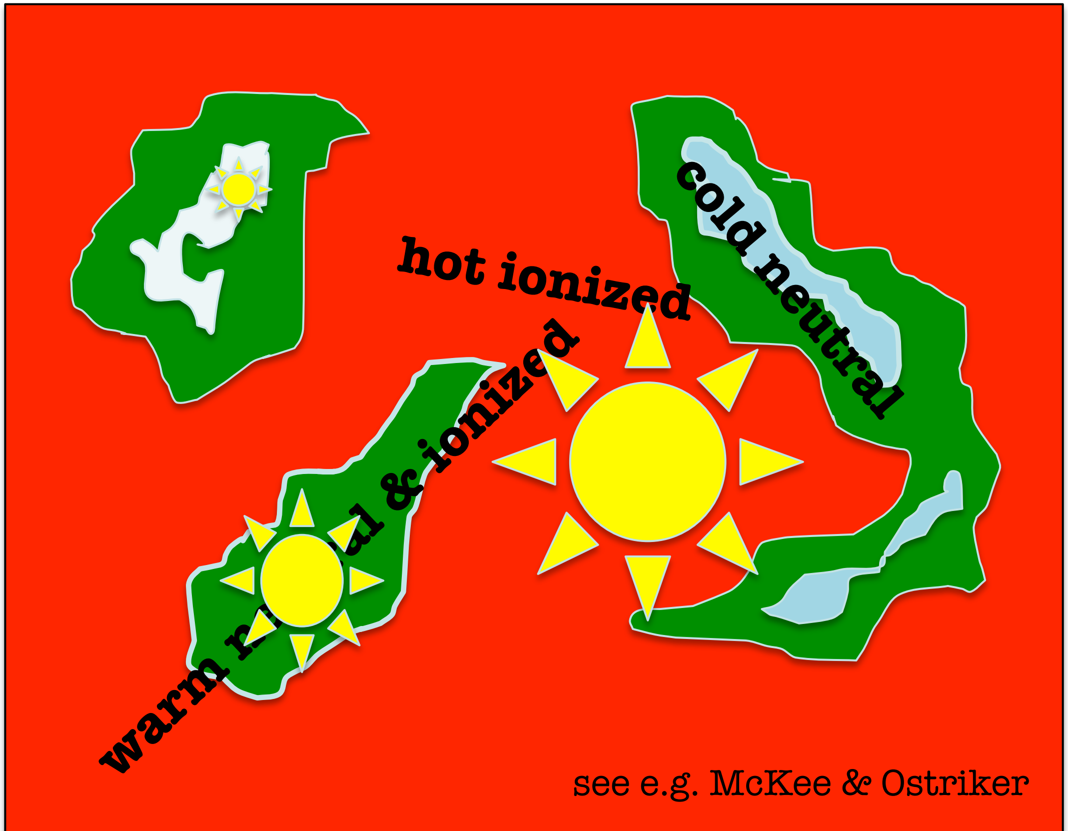
[CII]

X-rays

CO

γ-rays

500 pc



[OIII]

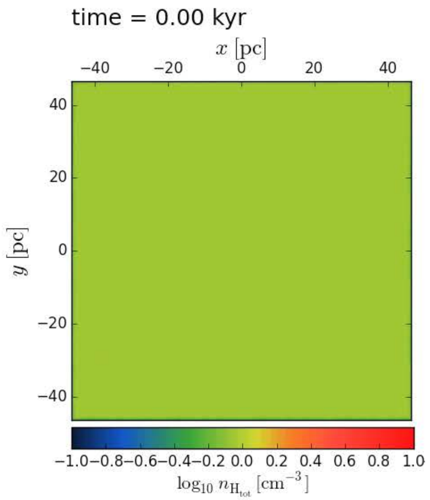
[NII]

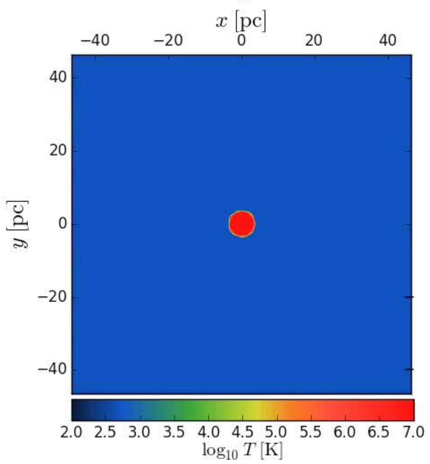
H_α

H_β

- Volume in the ISM is filled with hot ionized, warm ionized & neutral gas
- Mass is mostly in warm/cold & molecular medium
- Ambient density of supernova explosions determines their impact
- Stable hot volume filling phase drives outflows

A stable hot phase with supernovae – wind driving





simulation: Hu et al. 2016

After the formation of a dense shell
the SN remnants cool rapidly

$$t_{\rm sf} = 4.4 \times 10^4 yr E_{51}^{0.22} n_0^{-0.55}$$

$$r_{\rm sf} = 22.6 pc\, E_{51}^{0.29}\, n_0^{-0.42}$$

Expectation value for a SN exploding in a
previous bubble – condition for a stable hot phase

$$N_{\rm hot} = S \frac{4\pi}{3} r_{sf}^3 t_{sf}$$

$$N_{\rm hot} = S 2.13 \times 10^{-6} kpc^3 Myr E_{51}^{1.09} n_0^{-1.81}$$

$S = 280\ \mathrm{kpc^{-3}\ Myr^{-1}}$

solar neighborhood: $n_0 = 1\ \mathrm{cm^{-3}}$; $N_{hot} = 0.005$

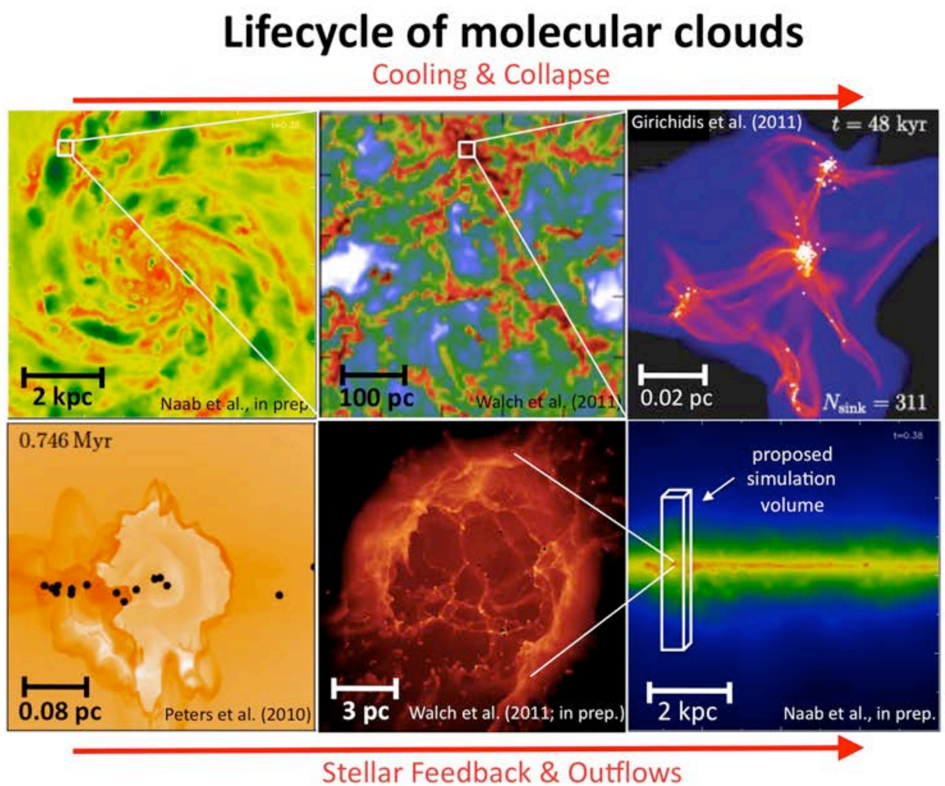
$n_{0,hot} \leq 0.015\ \mathrm{cm^{-3}}$; $N_{hot} = 1$

Naab & Ostriker 2017

The SILCC Project

SImulating the LifeCycle of Molecular Clouds

S. Walch, T. Naab, P. Girichidis, R. Klessen, S. Glover, T. Peters,
R. Wünsch, A. Gatto



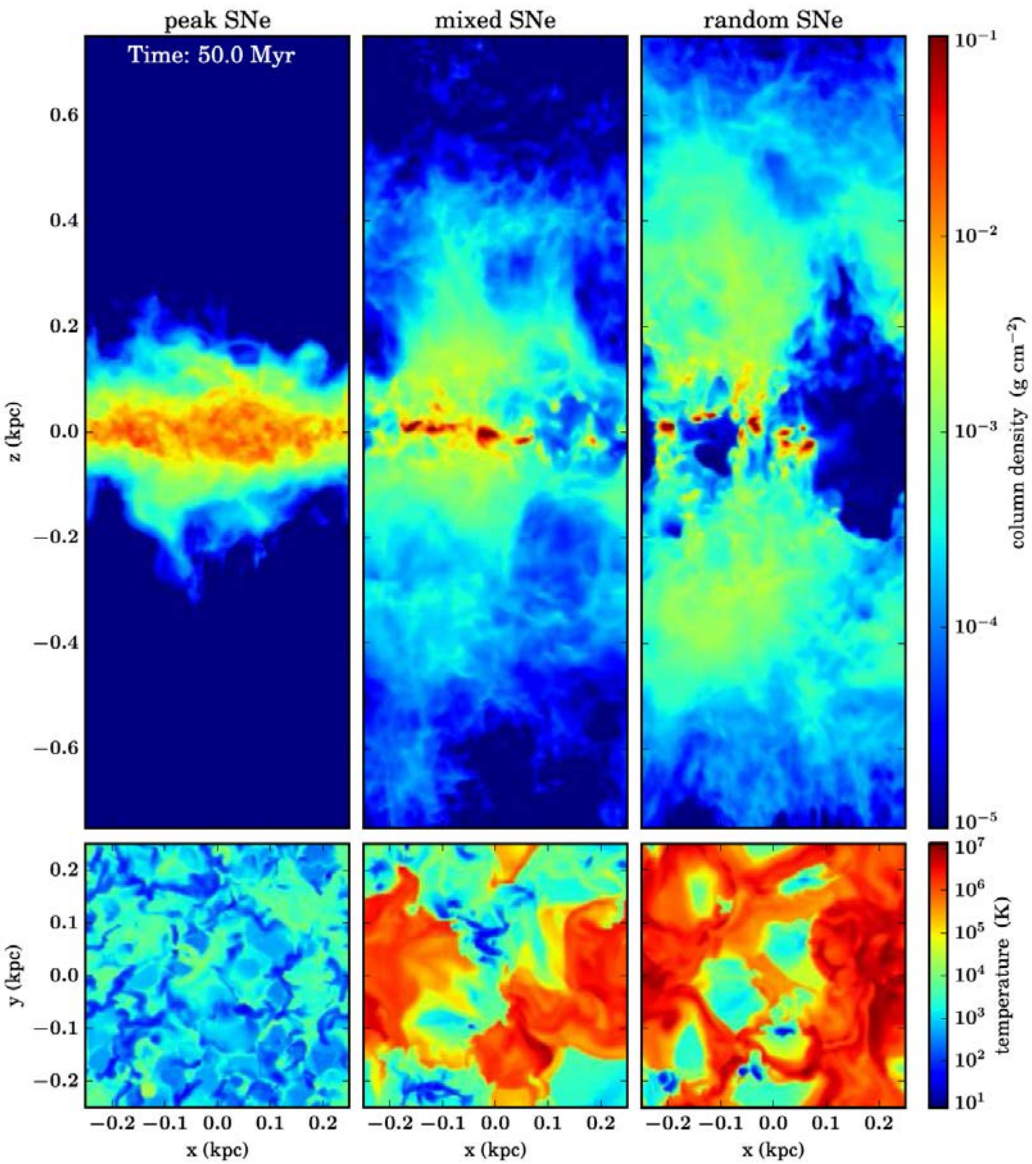
AMR code FLASH 4 with...

- tree self-gravity
- external potential
- ideal MHD
- heating & cooling
- molecule formation
  TreeCol – RT
- sink particles with subgrid cluster/star model
- ionization, wind, and supernova feedback

Physical processes followed in SILCC

- MHD followed with adaptive mesh refinement grid code FLASH
- Simplified non-equilibrium chemical network with detailed heating and cooling, X-ray/cosmic ray/UV background (Glover et al. 2011, Walch et al. 2015)
- Formation H_2 and CO by direct conversion of C+ to CO (no neutral carbon) and photo-dissociation including self-shielding (Nelson & Langer 1997, Glover 2011)
- Star formation/SN models at increasing level of complexity: fixed rates (Walch et al. 2015, Girichidis et al 2016), sink-based algorithm for star cluster formation sampling massive stars (Gatto et al. 2016)
- Feedback from OB stellar winds (Gatto et al. 2016) and radiation with module FERVENT (Baczynski et al. 2016, Peters et al. 2016)
- Four energy bins to account for: photo-electric heating, H_2 photo-dissociation, H photo-ionization, H_2 photo-ionization and recombination
- Test differential effects!

The impact of SN location on ISM properties

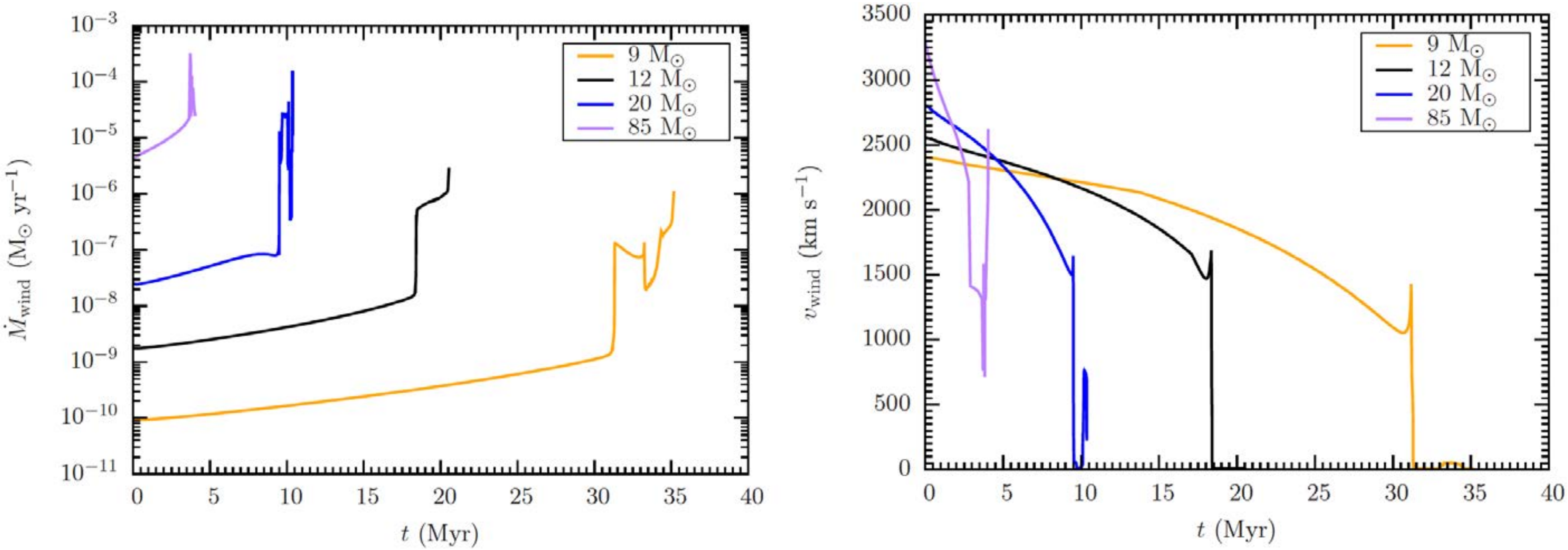


Naab & Ostriker 2017; SILCC papers

The ambient density of supernova explosions determines the fate of the ISM and outflows (Walch et al. 2015, Girichidis et al. 2016, Gatto et al. 2016, SILCC I, II & III)

Various physical processes impact ISM structure & ambient densities of SNe: walkaway/runaway OB stars, stellar winds, radiation, clustered SNe (Mac Low+, Hennebelle+, Ostriker+, Martizzi+ etc.)

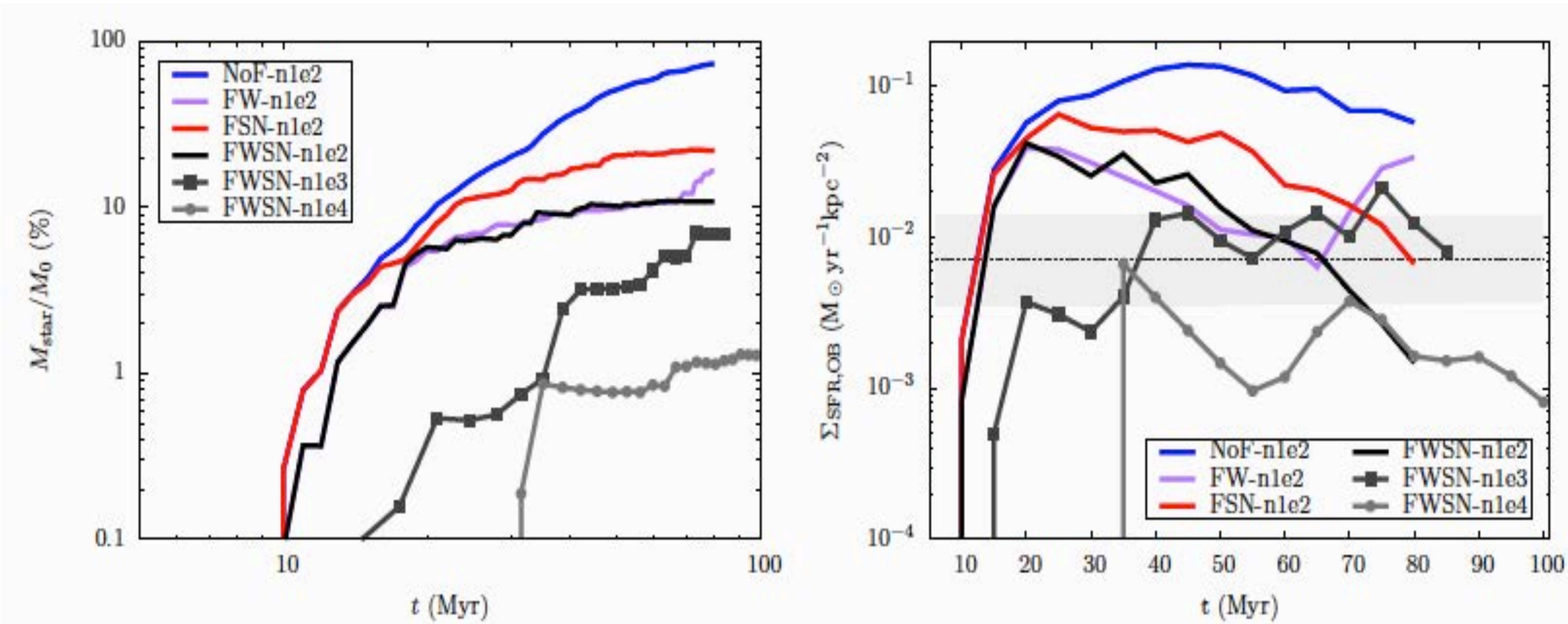
Stratified disk – cluster sinks with stellar winds



- Star formation is modeled with accreting sink particles representing star clusters
- Massive stars (drawn from IMF) have stellar winds depositing mass and momentum into the surrounding ISM (Puls et al. 2008)
- At the end of their respective lifetime massive stars explode as SNII

Gatto et al. 2017 (SILCC III)

Supernovae can launch outflows

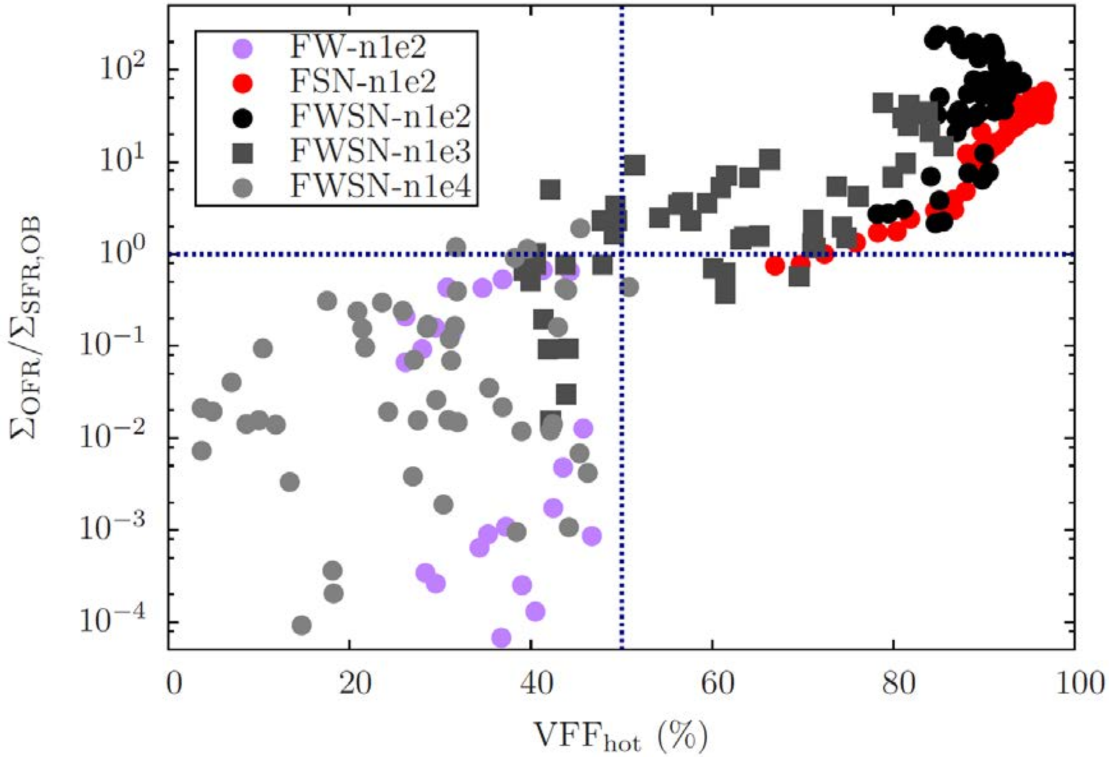


Stellar winds regulate sink formation – star formation more than supernova feedback

Star formation rates are empirically regulated with varying density threshold – towards realistic values

Gatto et al. 2017 (SILCC III)

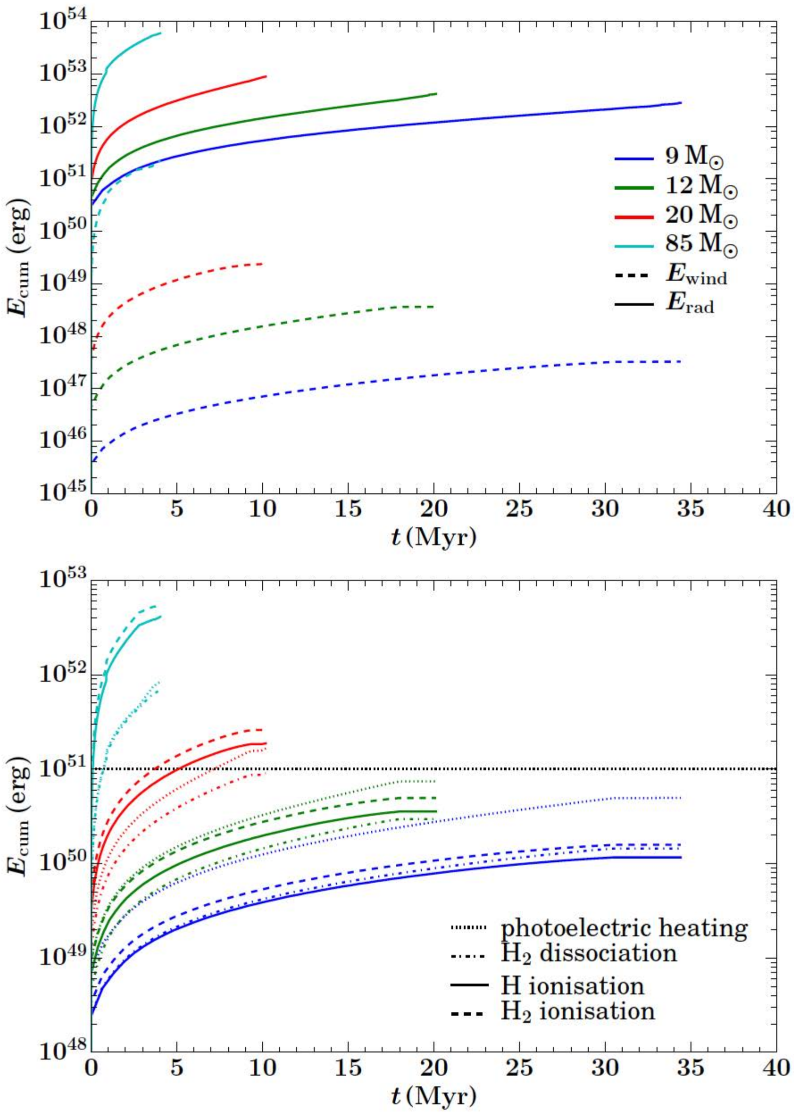
Hot volume filling ISM drives outflows



- Models with high star formation rates generate volume filling hot gas
- Volume filling hot gas drives outflows with significant mass loading
- This process is mainly driven by star formation rate which is regulated by supernovae and winds

Gatto et al. 2017 (SILCC III)

Cluster sinks with supernovae, winds and ionisation

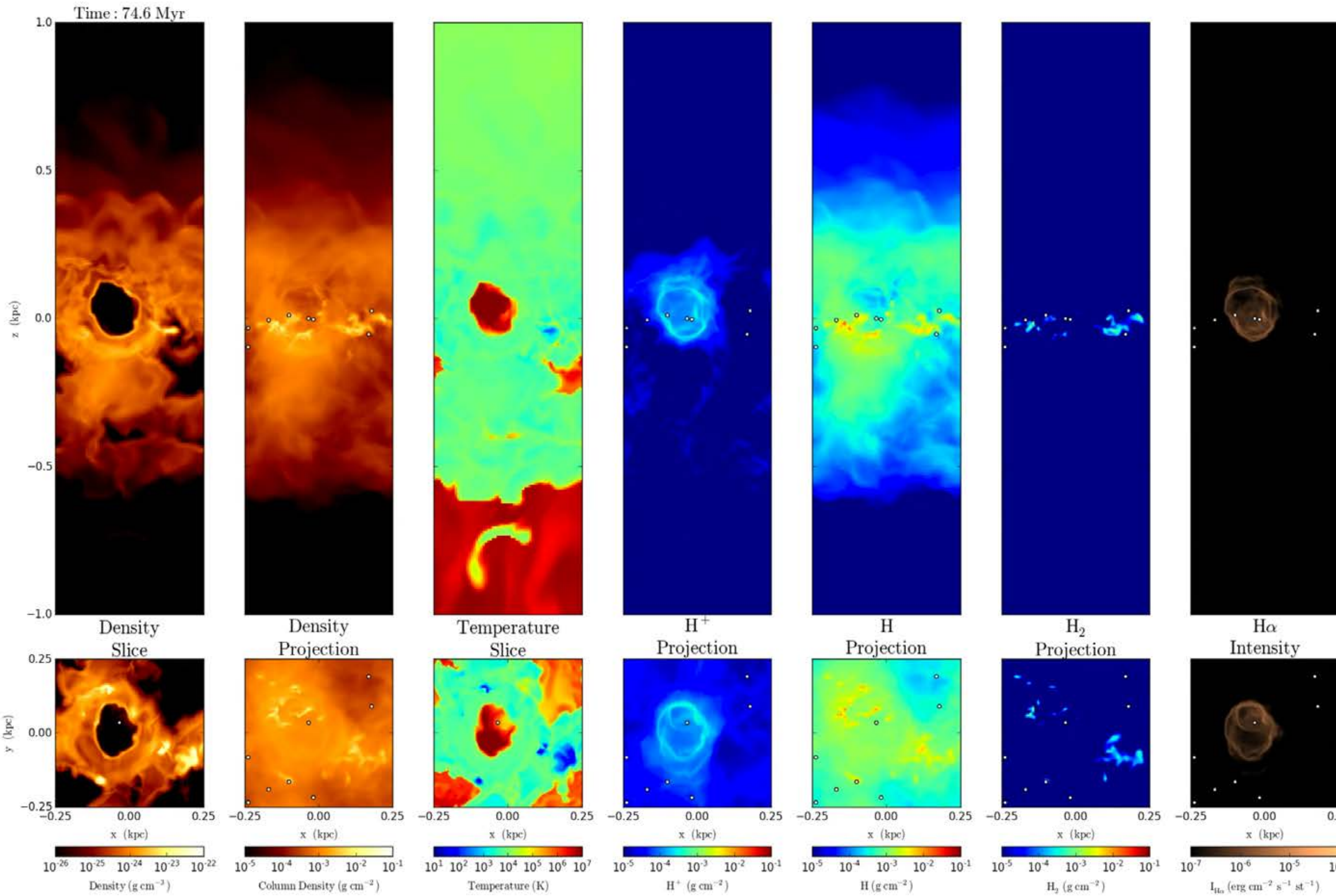


- Star formation is modeled with accreting sink particles representing star clusters
- Massive stars (drawn from IMF) have stellar winds depositing mass and momentum into the surrounding ISM (Puls et al. 2008)
- Radiation from massive stars is followed with the ray-tracing code FERVENT for photoelectric heating, H_2 photo-dissociation, and photo-ionization of H and H_2 (Baczynski et al. 2016)
- At the end of their respective lifetime massive stars explode as SNII

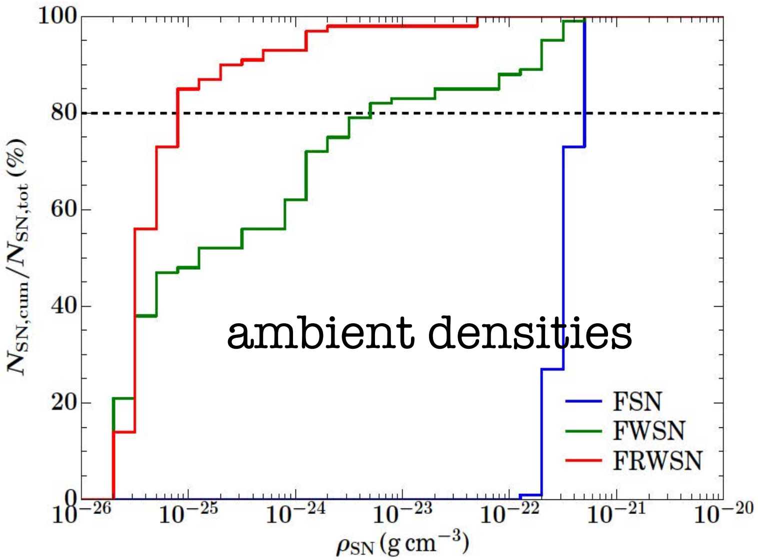
Peters et al. 2017 (SILCC IV)

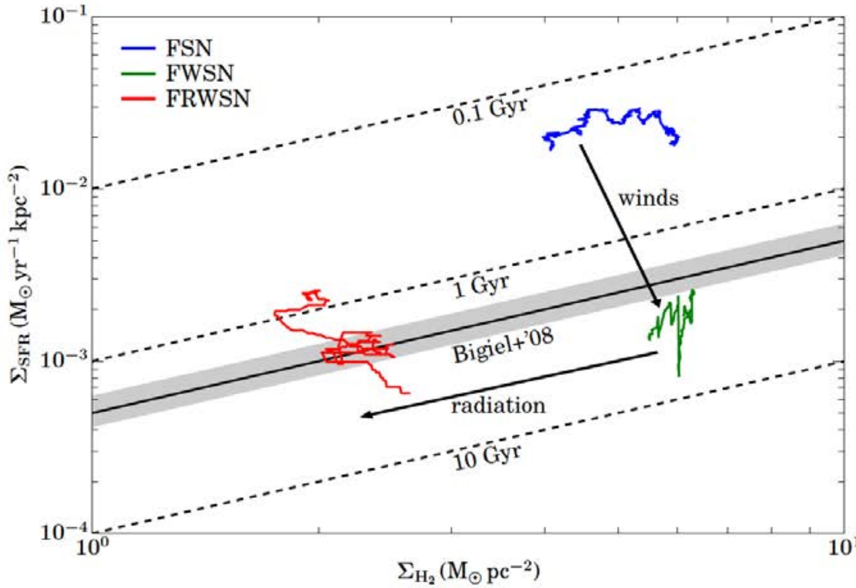
Cluster sinks with supernovae, winds and ionisation

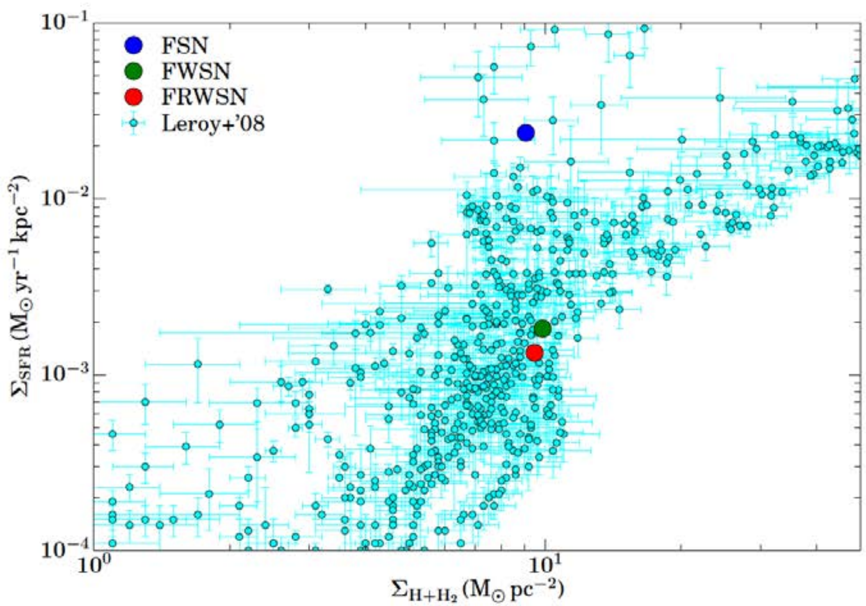
(Peters et al. 2017)



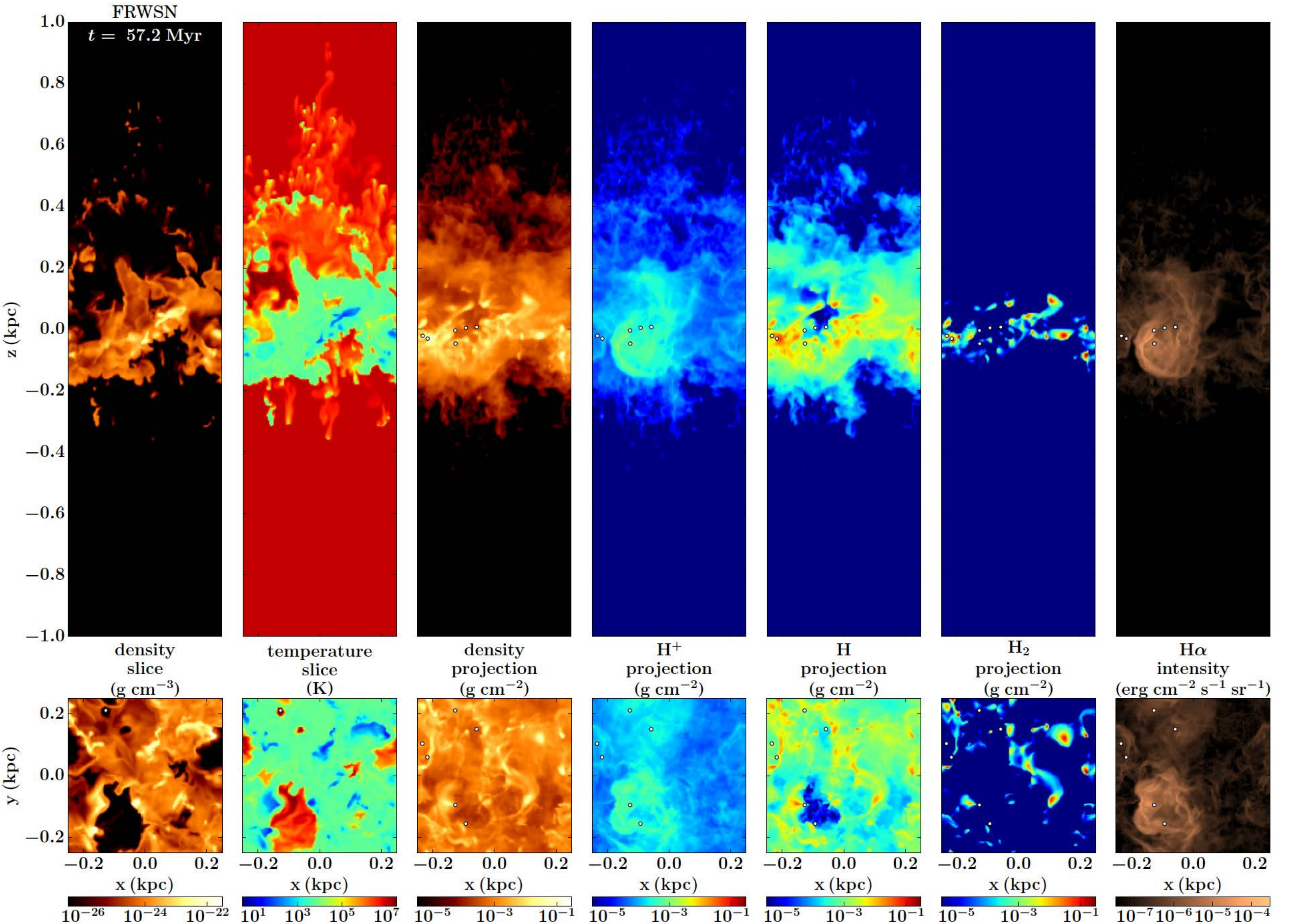
Star formation and ambient densities







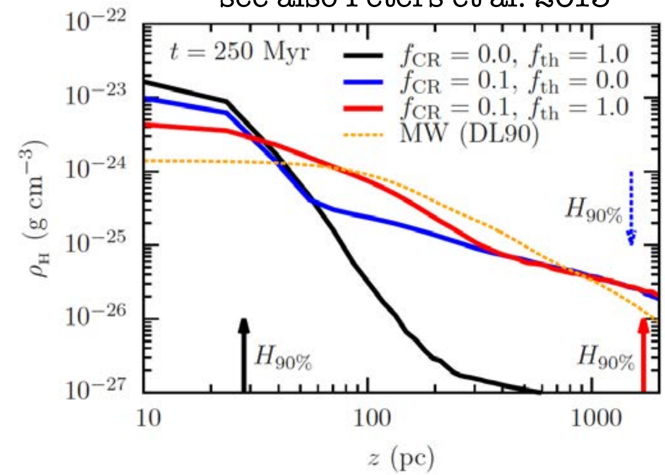
- Winds and radiation significantly change ambient SN densities
- H_2 depletion timescales of about 2 Gyr
- Location on the KS is regulated by feedback (see Hopkins+)



FRWSN
$t =$ 57.2 Myr
z (kpc)
y (kpc)
x (kpc)
density slice (g cm^{-3})
temperature slice (K)
density projection (g cm^{-2})
H^+ projection (g cm^{-2})
H projection (g cm^{-2})
H_2 projection (g cm^{-2})
Hα intensity (erg cm^{-2} s^{-1} sr^{-1})
10^{-26} 10^{-24} 10^{-22}
10^{1} 10^{3} 10^{5} 10^{7}
10^{-5} 10^{-3} 10^{-1}
10^{-7} 10^{-6} 10^{-5} 10^{-4}

Magnetic fields and cosmic rays?

see also Peters et al. 2015

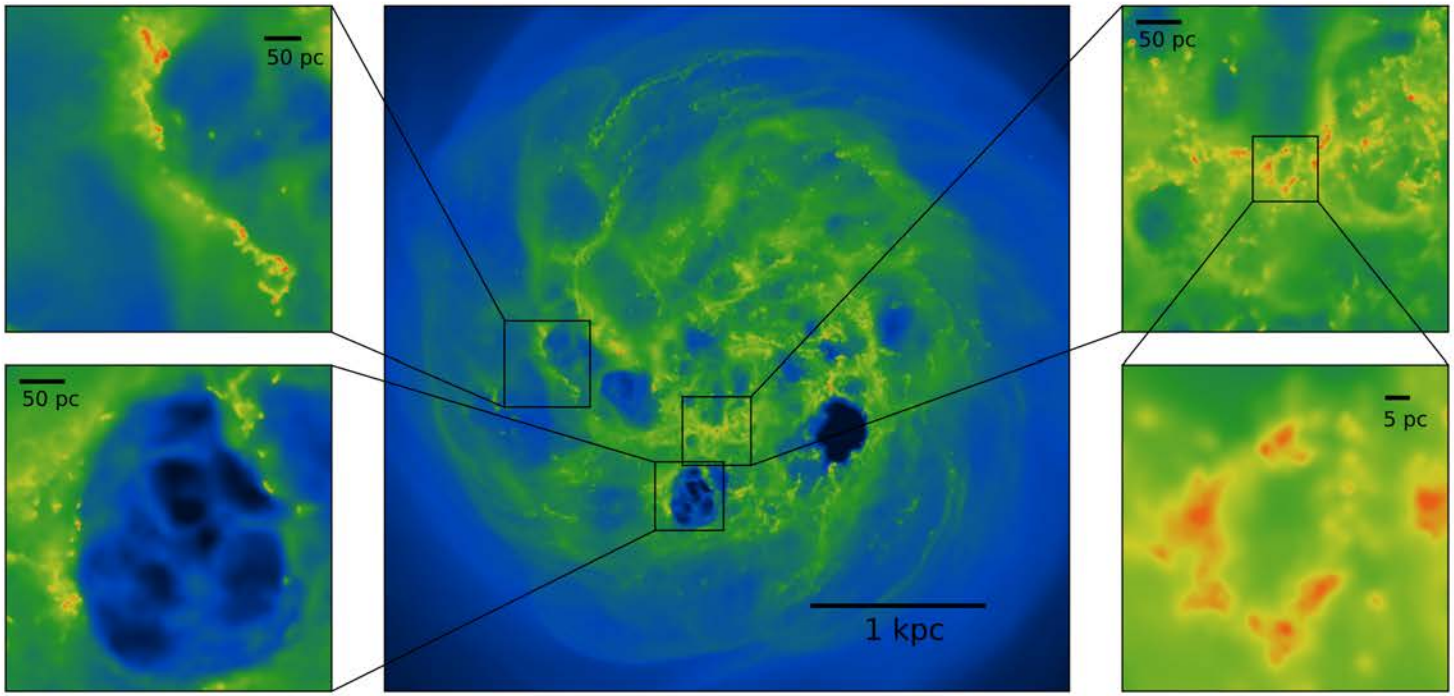


implementation for cosmic rays (Girichidis et al. 2016)

- Diffusion coefficient κ = 10^{28} cm^2/s
- CR driven pressure gradient drives gas out of the disk in a slow (colder)wind (Girichidis et al. 2016, see Peters et al. 2016, Simpson et al. 2016)

galaxy scales see: Yang et al. 2012, Hanasz et al. 2013, Booth et al. 2013, Salem & Bryan et al. 2014, Ruszkowski et al. 2016

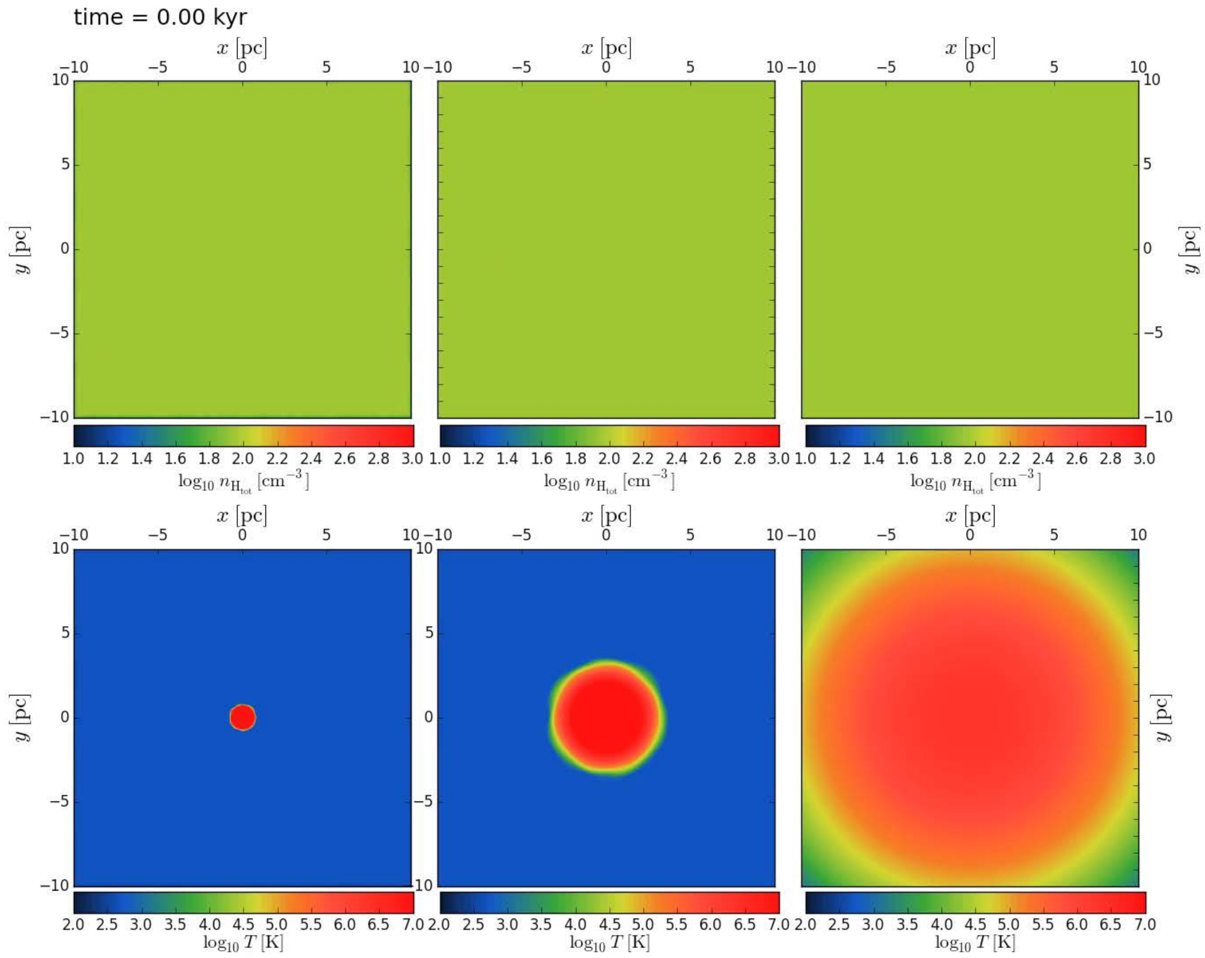
Star formation in dwarf galaxies



Simulation of idealized dwarf ($10^8 M_\odot$) with improved mixing (Gadget-based (SPHgal), Hu et al. 2014), $4M_\odot$ and 2pc resolution, chemical network (Nelson & Langer 1997), TreeCol (Clark et al. 2013), 1 SN explosion every $100M_\odot$ of stars formed (25 particles)

Hu, Naab et al. 2016

Resolving blast waves in the ISM of galaxies



M_{gas}=1$M_{\odot}$ M_{gas}=10 $M_{\odot}$ M_{gas}=100 $M_{\odot}$

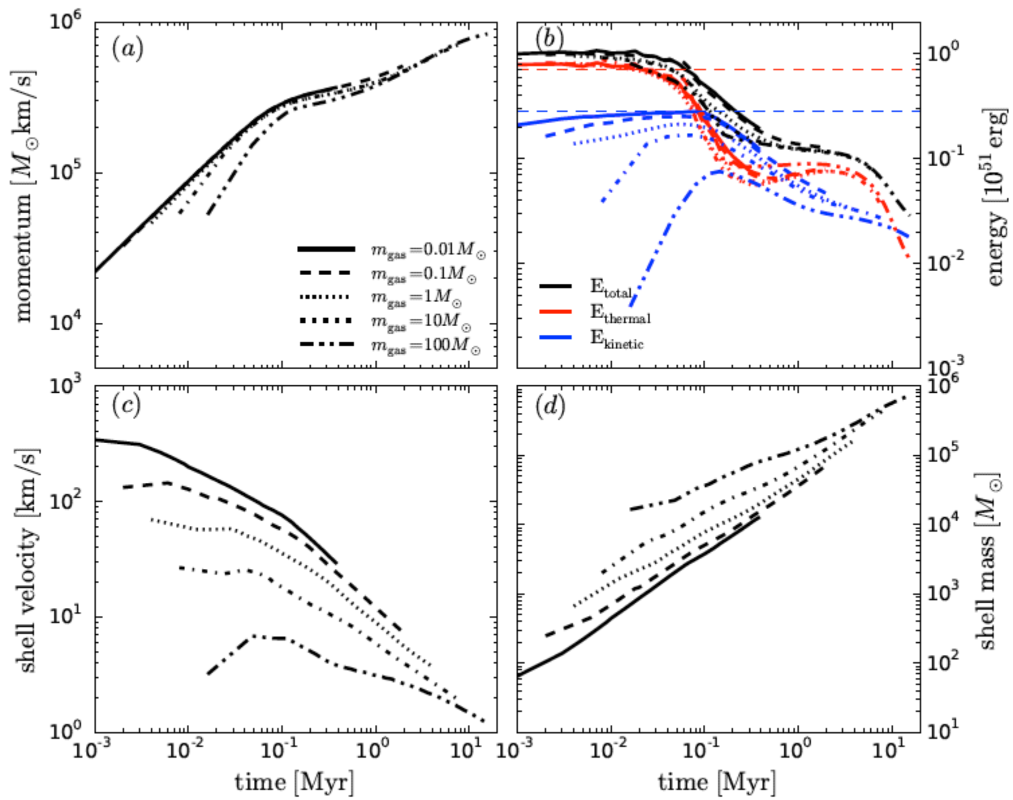
SN blast waves are typically unresolved in galaxy-scale simulations - many phenomenological models

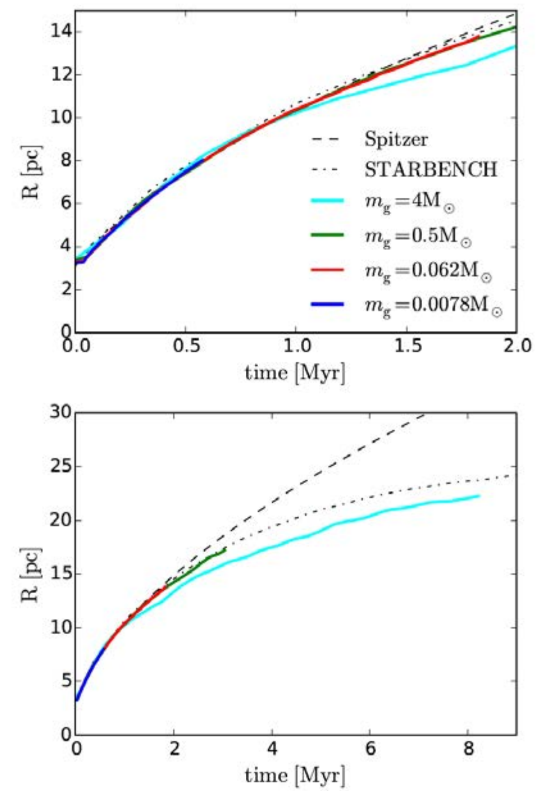
Cooling time shorter than sound crossing time – no proper blast wave evolution (della Vechia & Schaye 2012)

This problem also exists for high resolution galaxy simulations if mass resolution in the stellar phase and gas phase is comparable!

Hu et al. 2016

Star formation in dwarf galaxies



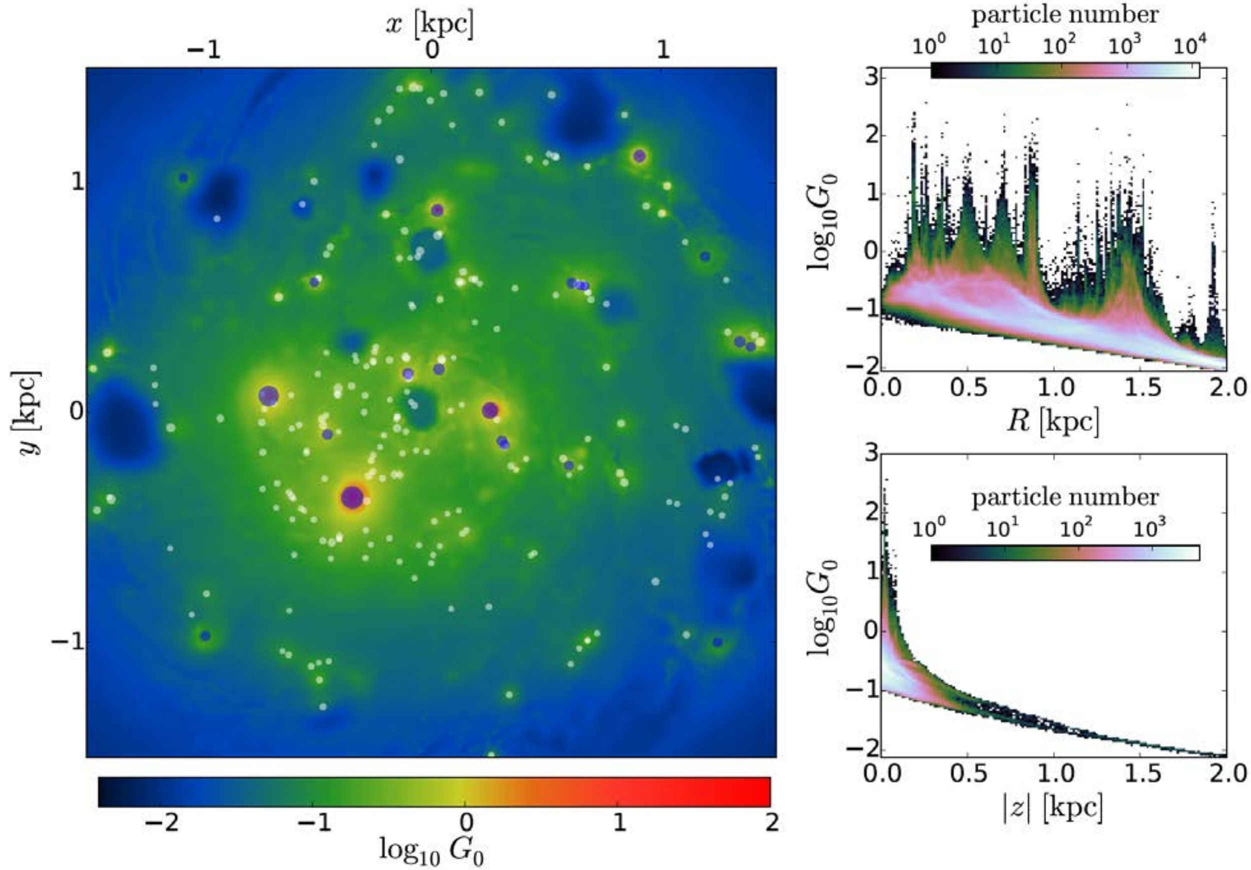


How well do we resolve blast waves and ionization fronts in the simulations?

Typically, shell velocities are underestimated

Hu et al. 2016/2017

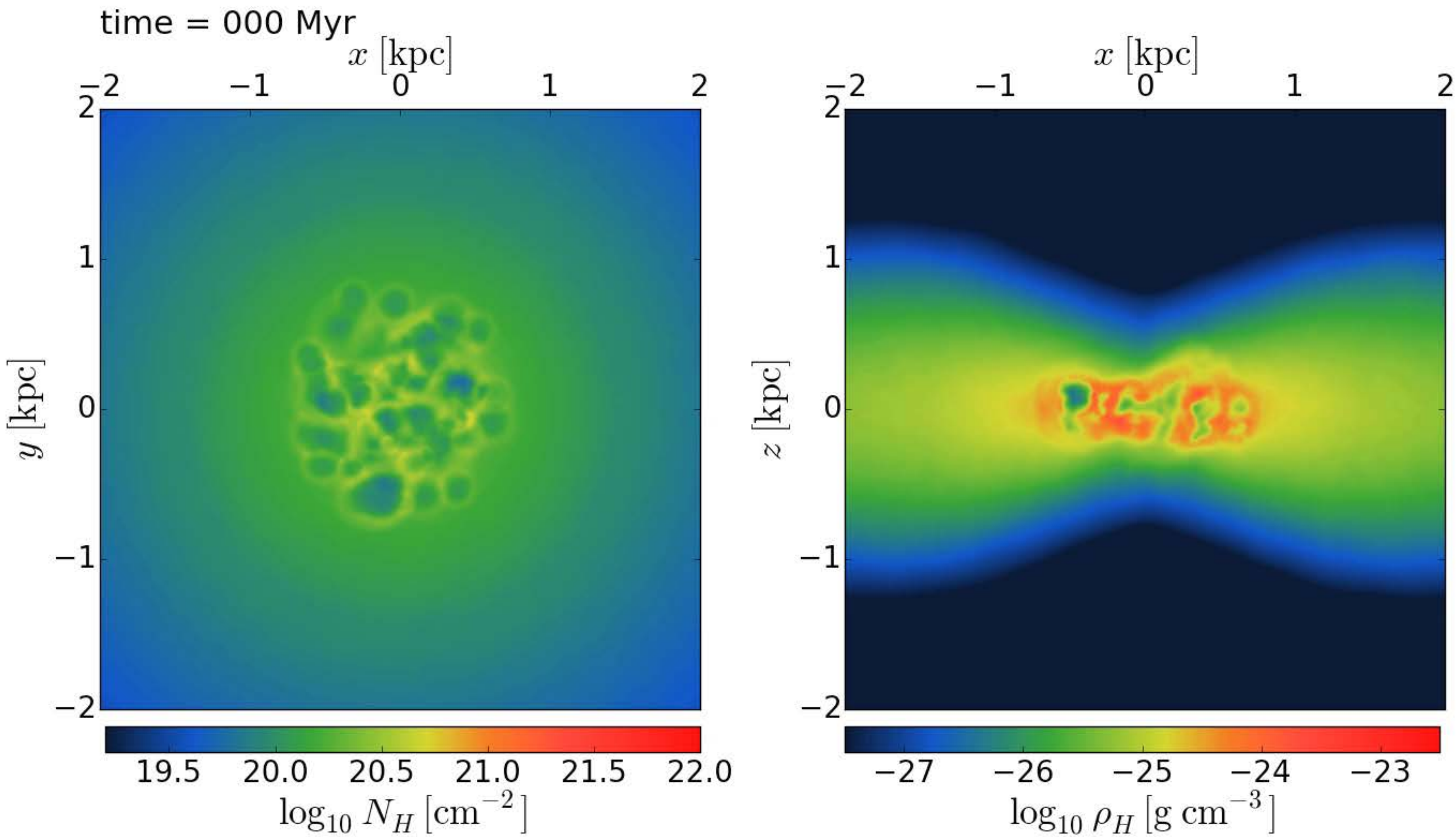
Star formation in dwarf galaxies



- Stars are randomly sampled from IMF – conversion of gas particles to star particles is adjusted accordingly
- Radiation field from massive stars approximated in the optically thin limit (low dust-to-gas ratios)
- Photoionization approximated (see Hopkins, Quataert & Murray 2012)

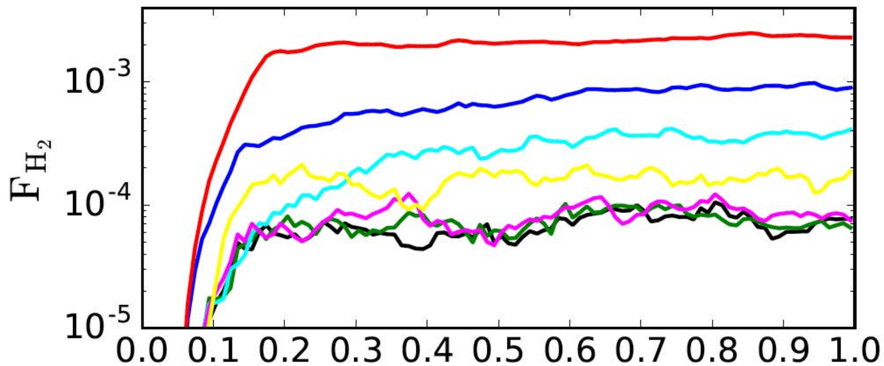
Hu et al. 2017

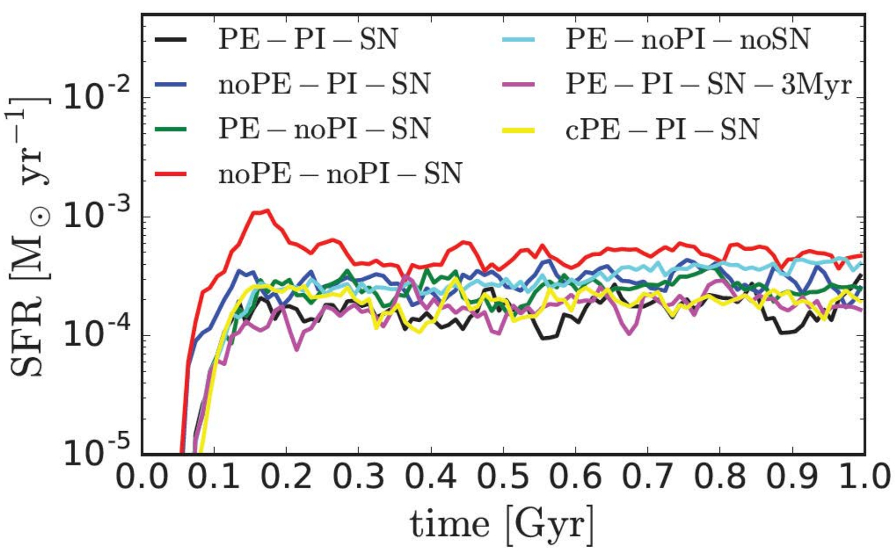
Star formation in dwarf galaxies

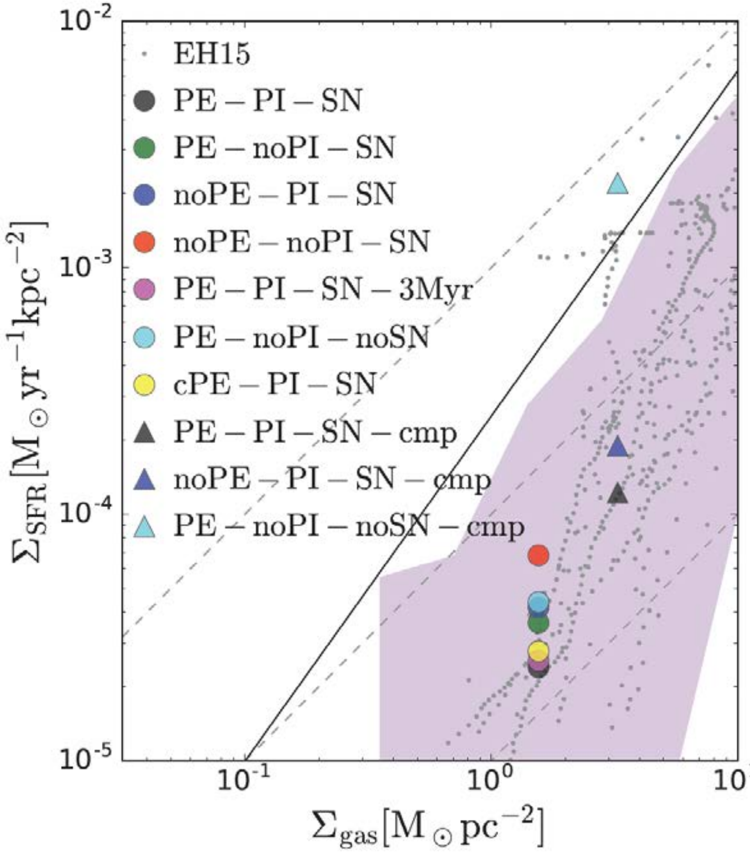


Hu, Naab et al. 2017

Star formation in dwarfs is regulated by SNe



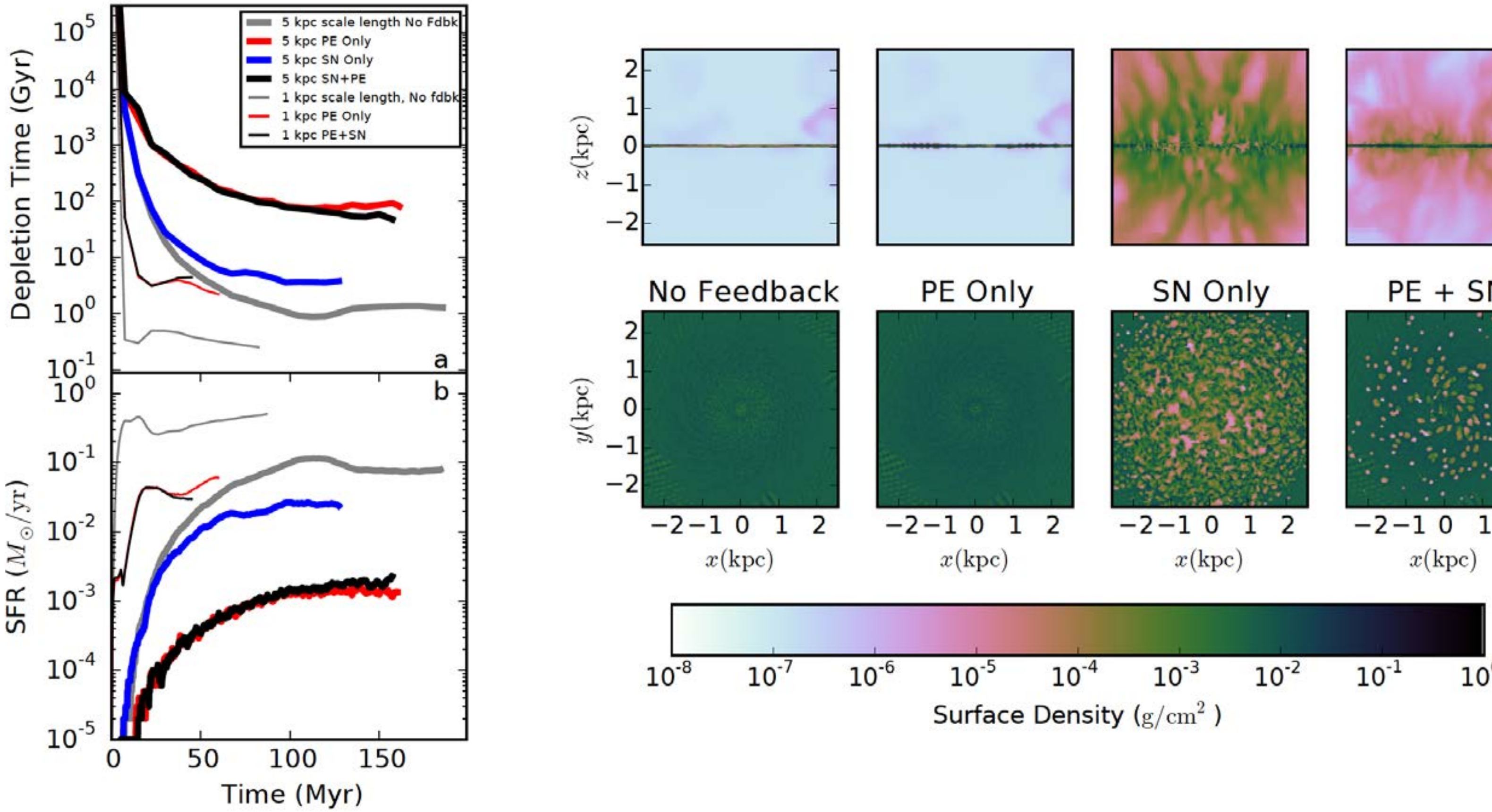




- Galaxy structure is determined by SN feedback
- PE heating has a big effect on H2 formation but a small effect on star formation
- Star forming gas is mainly HI - no H_2 star formation regulation

Hu et al. 2017

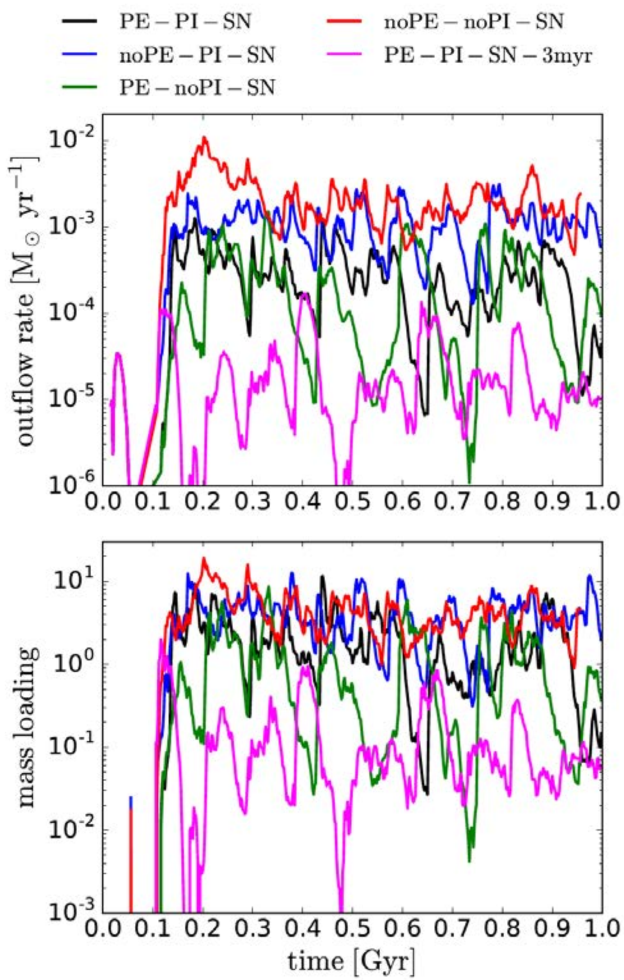
Really?

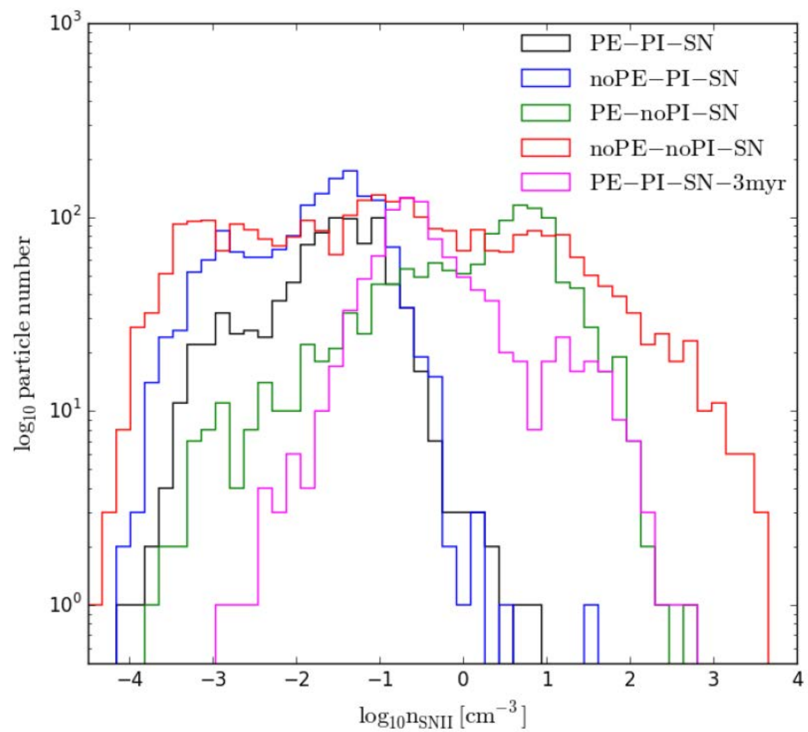


- Forbes et al. claim an order of magnitude suppression from PE heating
- Problem: PE heating turned off for self-shielded gas, but cooling not (fractional ionization due to UV background)

Forbes, Krumholz, Goldbaum & Dekel, 2016

Ambient densities of SNe are important





- Ambient densities are not only regulated by ‘feedback’ but also by ‘walkaways’
- Lower ambient densities – higher outflow rates

Conclusion

- The ISM drives galaxy evolution! A major challenge in theoretical galaxy formation is understanding the physical processes setting the multi-phase structure of the ISM and driving mechanisms of outflows

- Models of physical processes setting the gas phase distribution make simulations directly comparable to observations at all wavelengths

- Ambient densities of supernova explosions really matter! Stellar winds, radiation, clustering walkaway/runaway stars strongly impact the ISM structure – it's all about massive stars

- A number of problems: code accuracy, resolution limits, sub-resolution models, idealized tests of physical processes, convergence tests, code comparisons

- Is there a relevant scale? Maybe resolving the impact of individual massive stars on 0.1-1 pc scales with a well defined star formation model

- Make codes public