Max-Planck-Institut für
Astrophysik

MAX-PLANCK-GESELLSCHAFT

Simulations of interstellar medium and star formation

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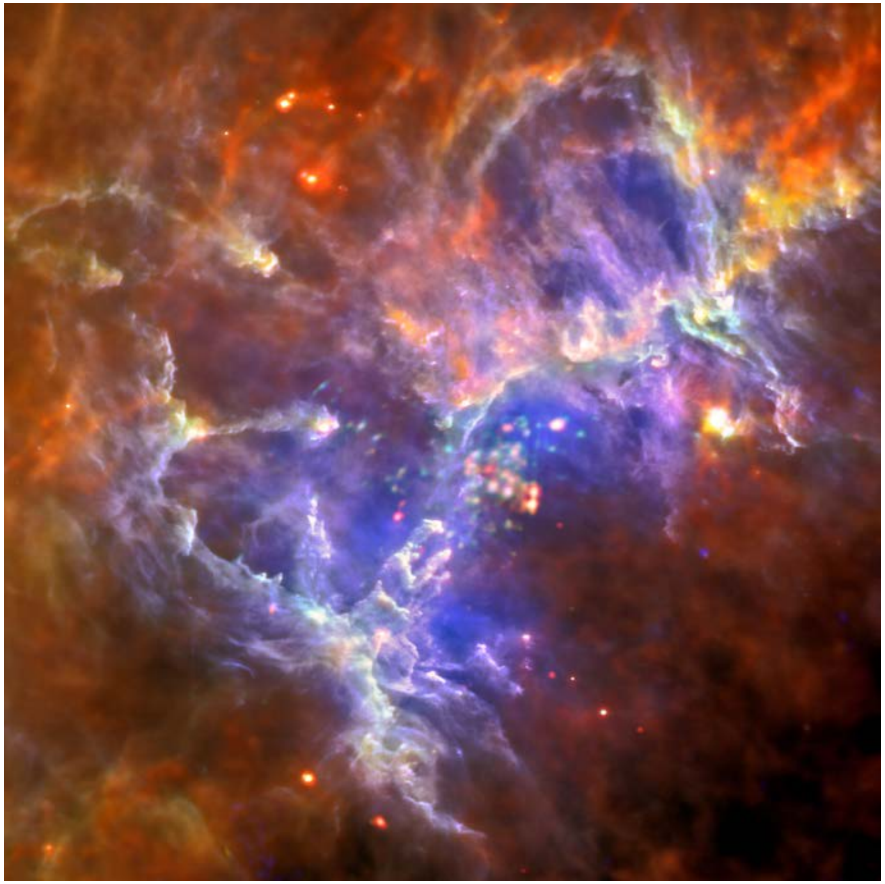
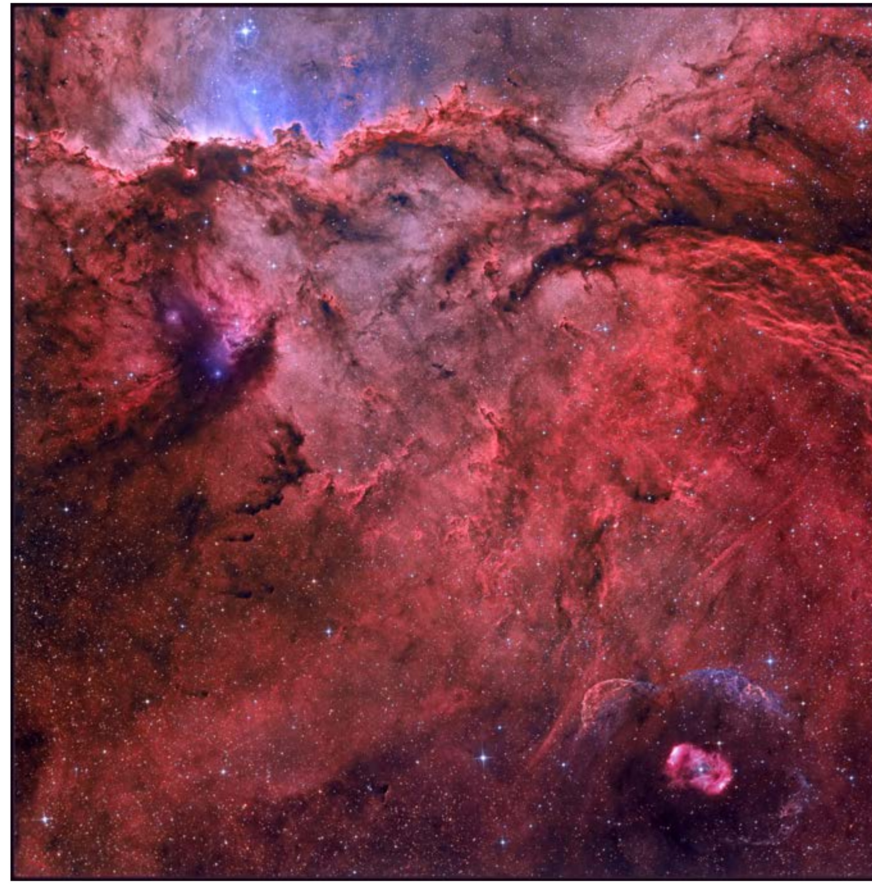
the SILCC collaboration

Stars, Planets, and Galaxies
Berlin, April 13th, 2018

HII & wind regions in the Milky Way





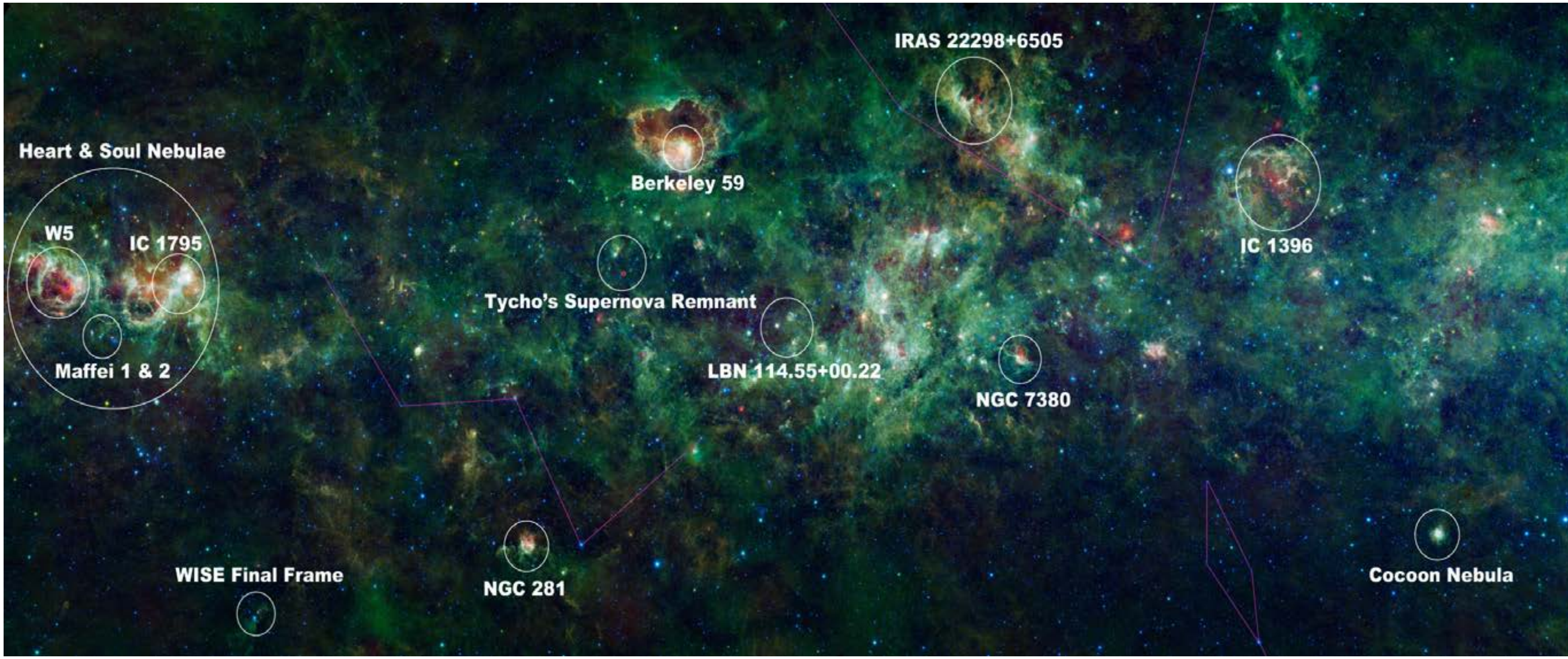
- Ionization and winds from massive stars heat and shape the ISM – deposition of energy and momentum

SN remnants in the Milky Way

- SN expel gas at 1000 – 6000 km/s and drive shocks into the ISM
- Particles are accelerated to relativistic energies (Krymsky 1977; Axford et al. 1977; Bell 1978a,b; Blandford & Ostriker 1978) – mostly protons

Ackermann et al. 2013, Nikolic et al. 2013

Feedback in the Milky Way



Can we better understand how massive stars impact the ISM and regulate galaxy formation by heating, enrichment, outflows etc.?

Multi-scale and complex-physics problem: heating/cooling, massive star evolution, radiation, magnetic fields, cosmic rays

more than 5000 IR bubbles identified in the 'Milky Way project' based on Spitzer imaging

The multi-phase ISM drives galaxy evolution

[CII]

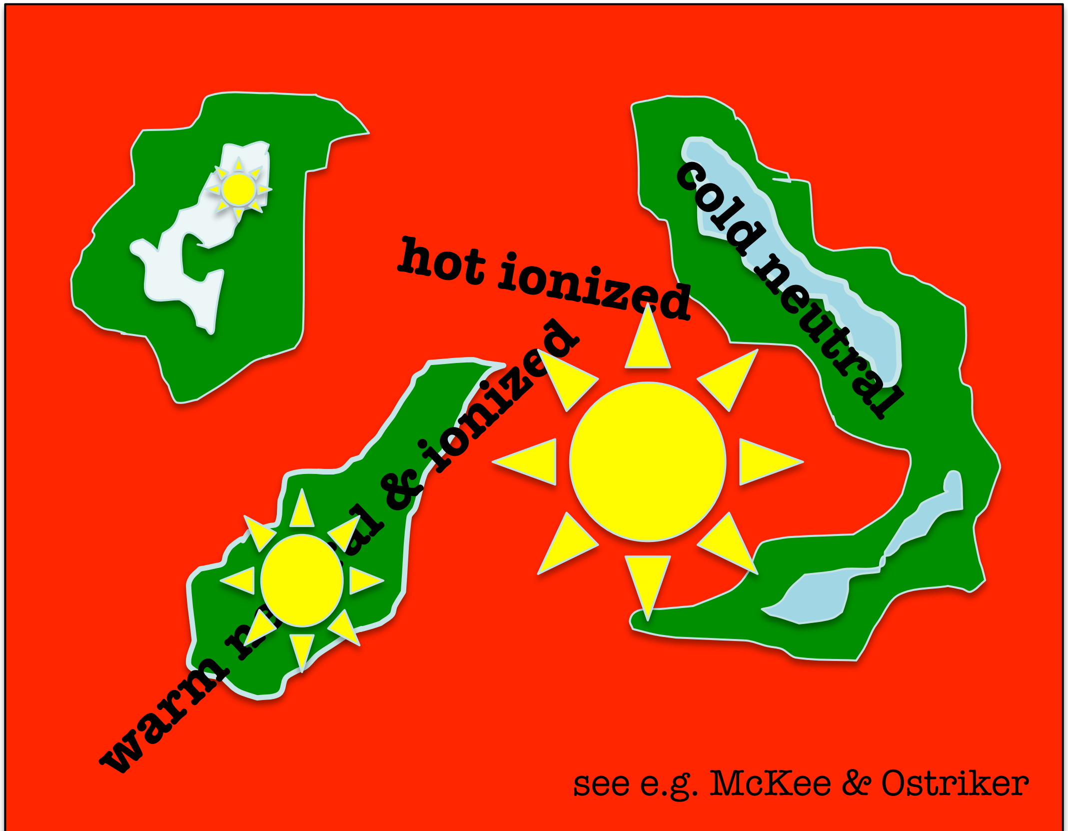
X-rays

CO

γ-rays

synchroton

500 pc



[OIII]

[NII]

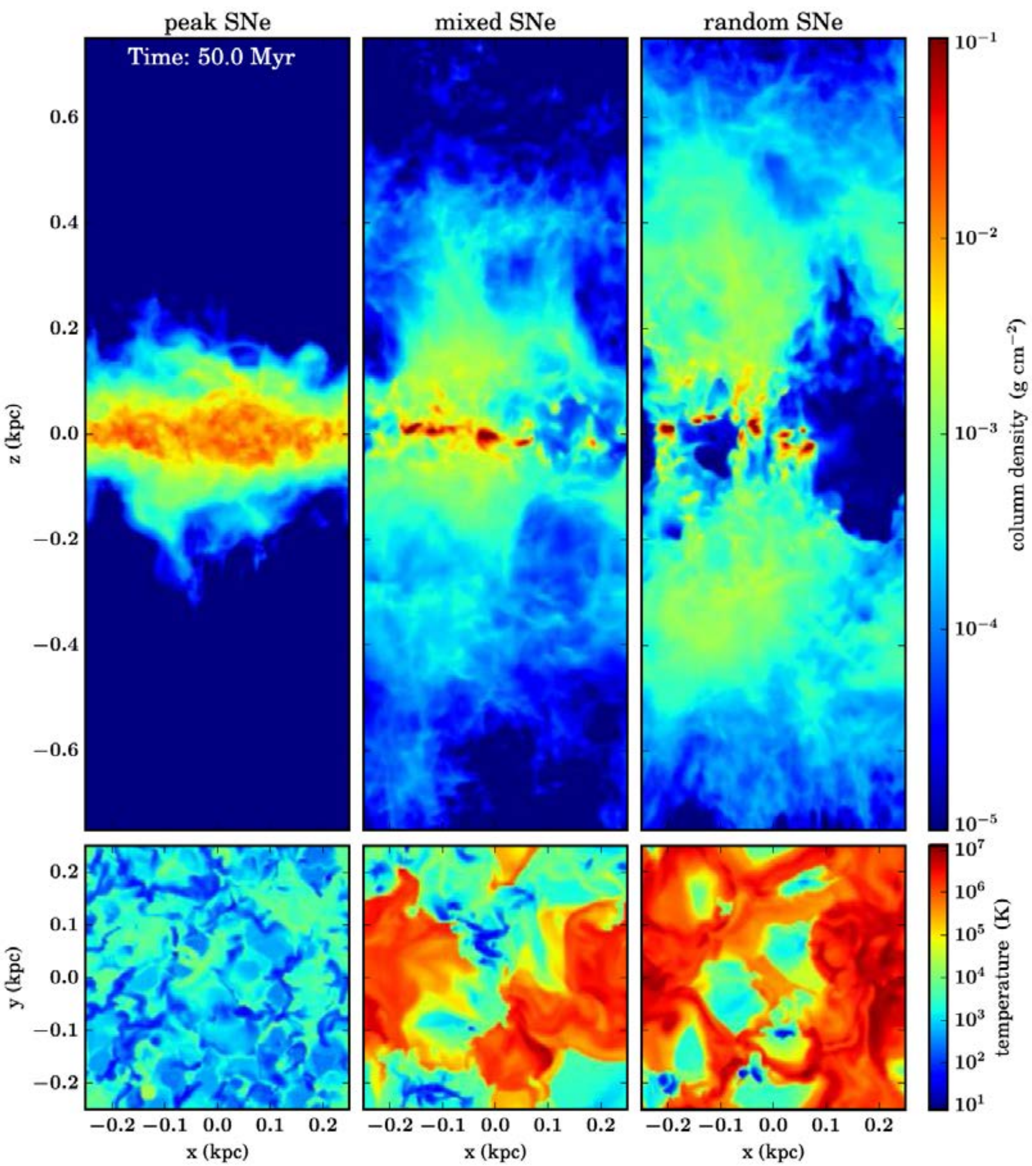
H_α

H_β

FIR

- 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

The impact of SN location on ISM properties (SILCC)



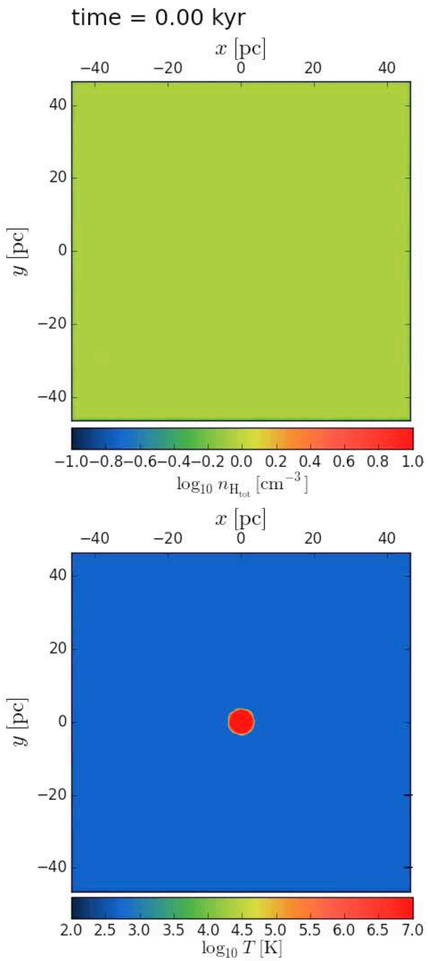
Walch et al. 2015, figure from Naab & Ostriker 2017

The ambient density of supernova explosions determines the fate of the ISM and outflows (Girichidis et al. 2016, Gatto et al. 2016)

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.)

Kim, Kim & Ostriker 2011, Hennebelle & Iffrig 2014, Walch et al. 2015, Girichidis et al. 2016, Naab & Ostriker 2017, Gatto et al. 2016, Li et al. 2016

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

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

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

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

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

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

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

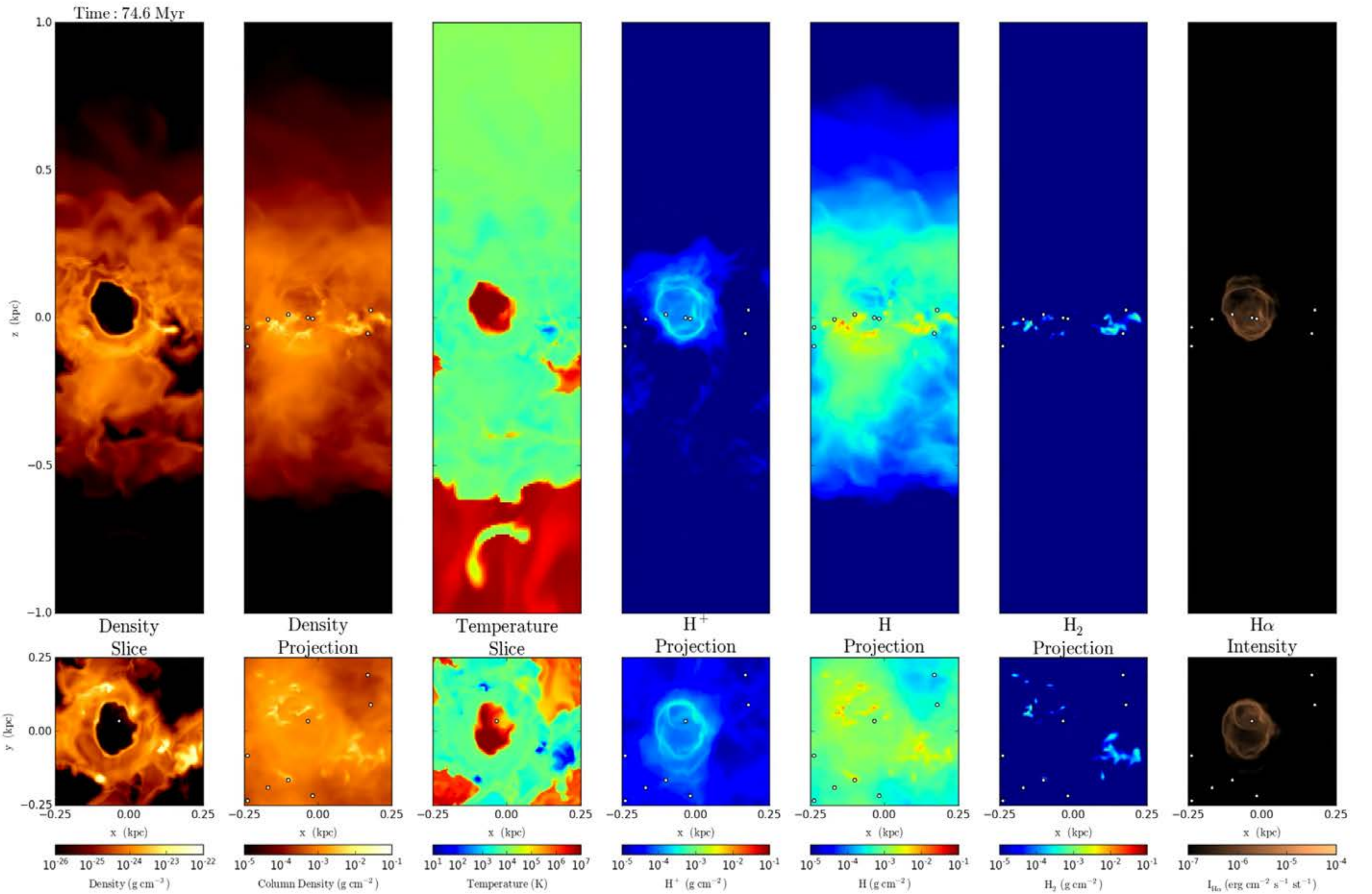
solar neighborhood: $n_0 = 1$ cm^{-3}; $N_{\rm hot} = 0.005$

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

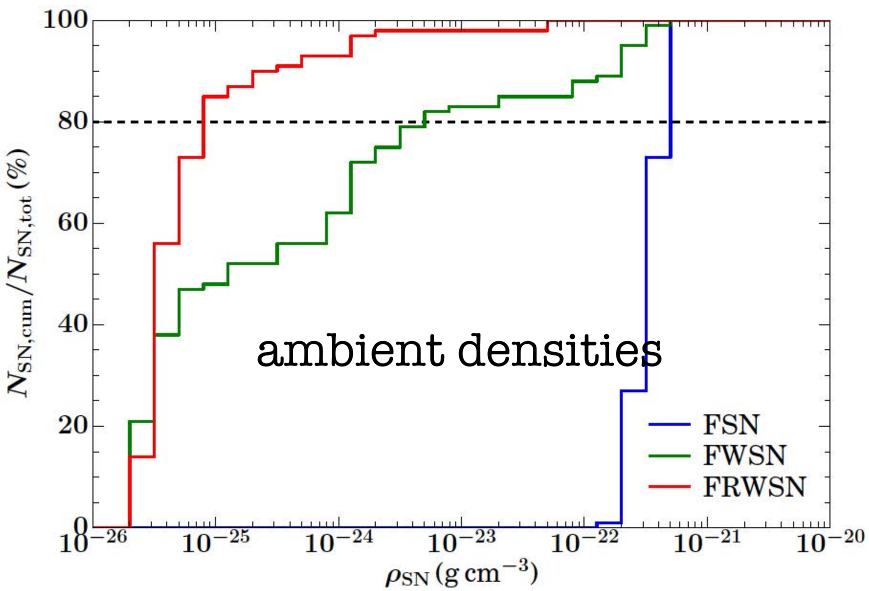
Naab & Ostriker 2017, ARA&A

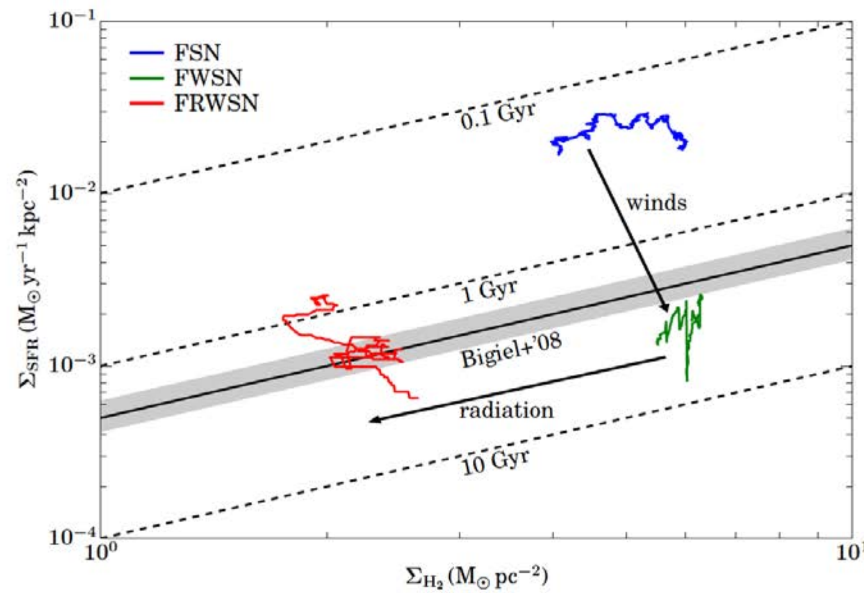
Cluster sinks with supernovae, winds and ionisation

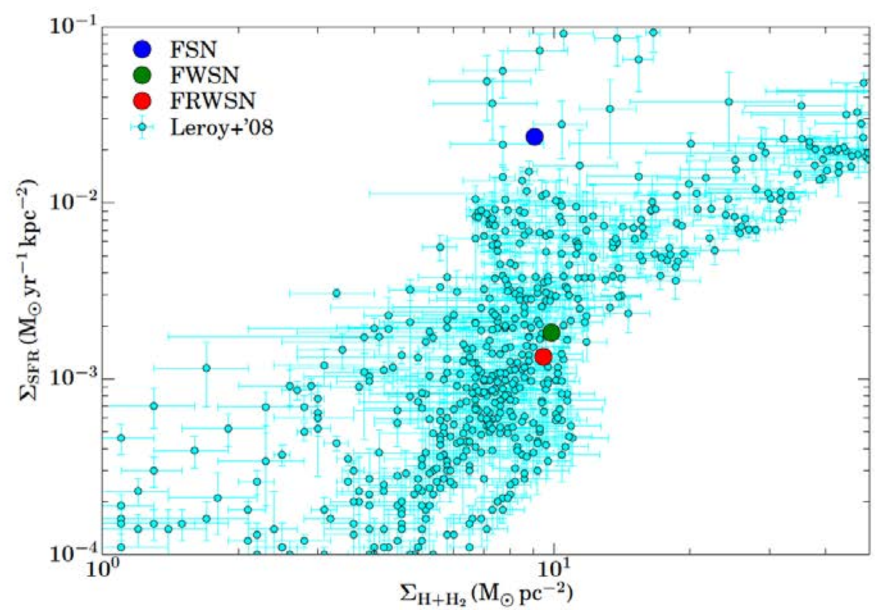
(Peters et al. 2017)



Comparison to observations at different wavelengths



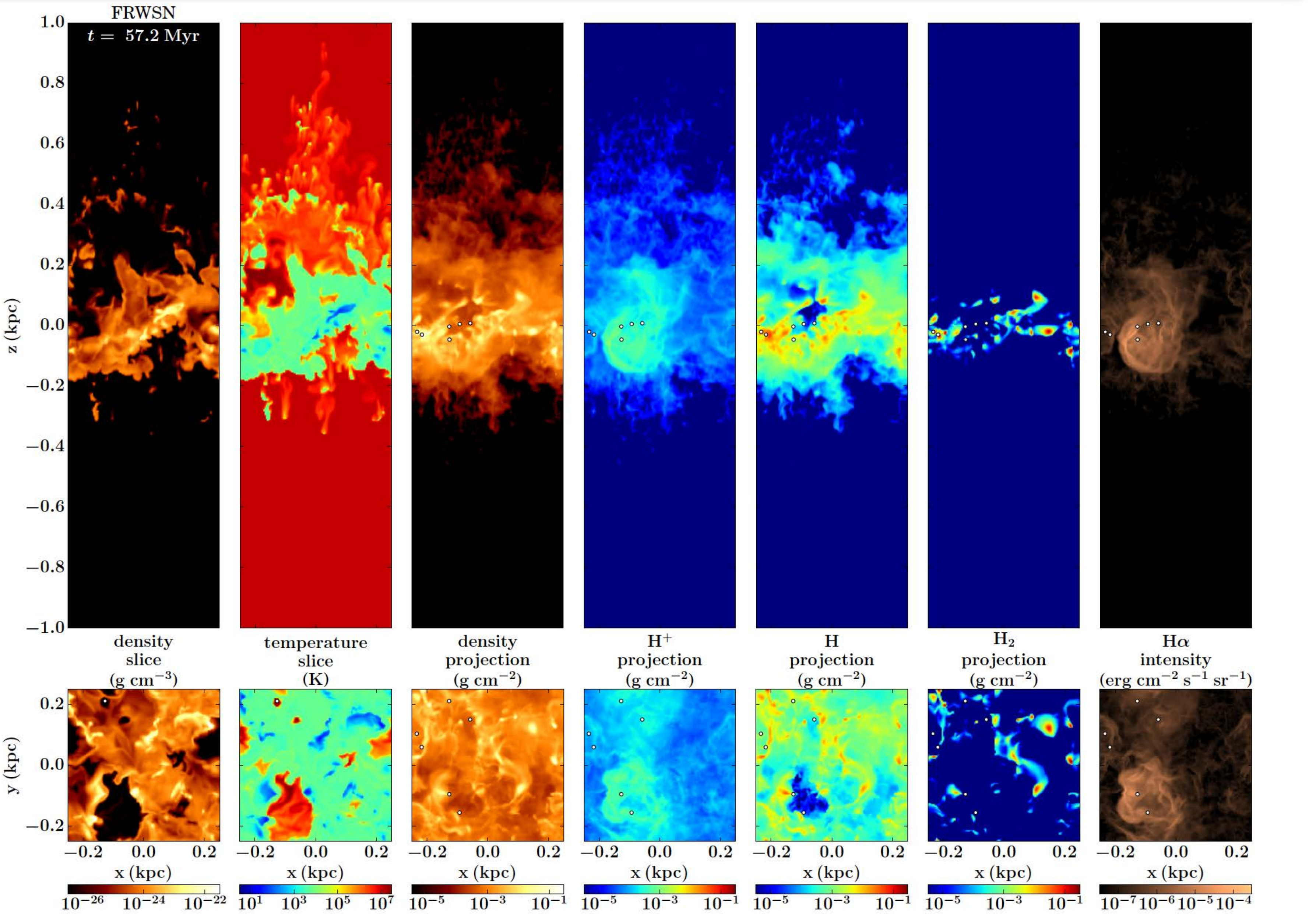




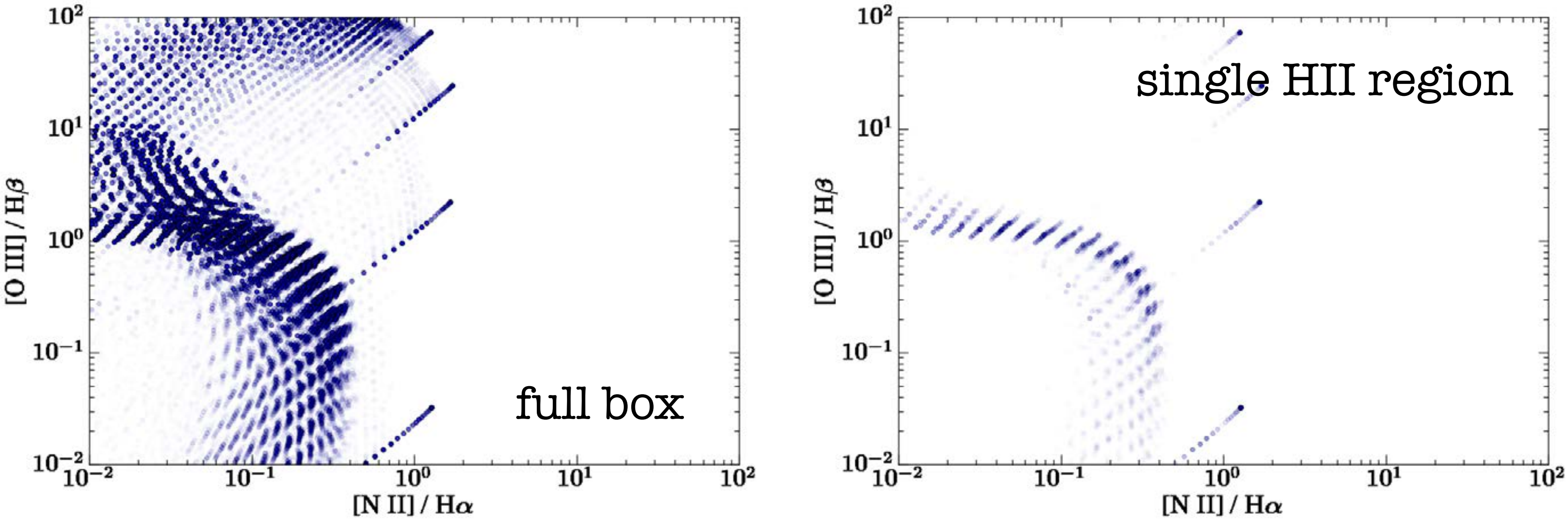
- Pre-supernova feedback impacts ambient densities
- H_2 depletion timescales of about 2 Gyr
- Location on the KS is regulated by feedback (see Hopkins+)

similar conclusion recently by Butler et al. 2017

Emission line diagnostics...



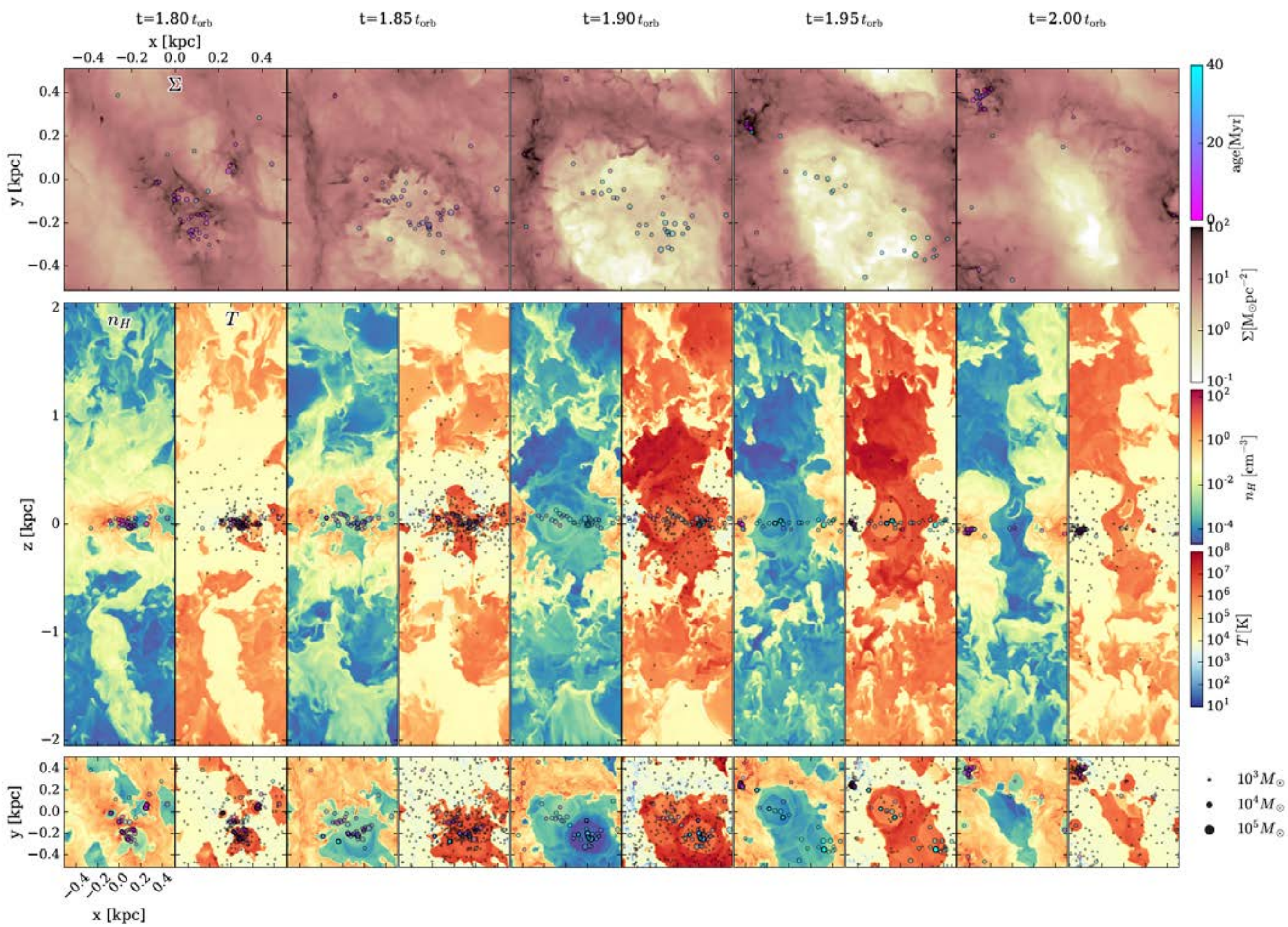
Emission line diagnostics...



First attempts on emission line diagnostics from ISM simulations including star formation, stellar winds, radiation transfer and supernova explosions

E. Pellegrini & T. Peters et al.

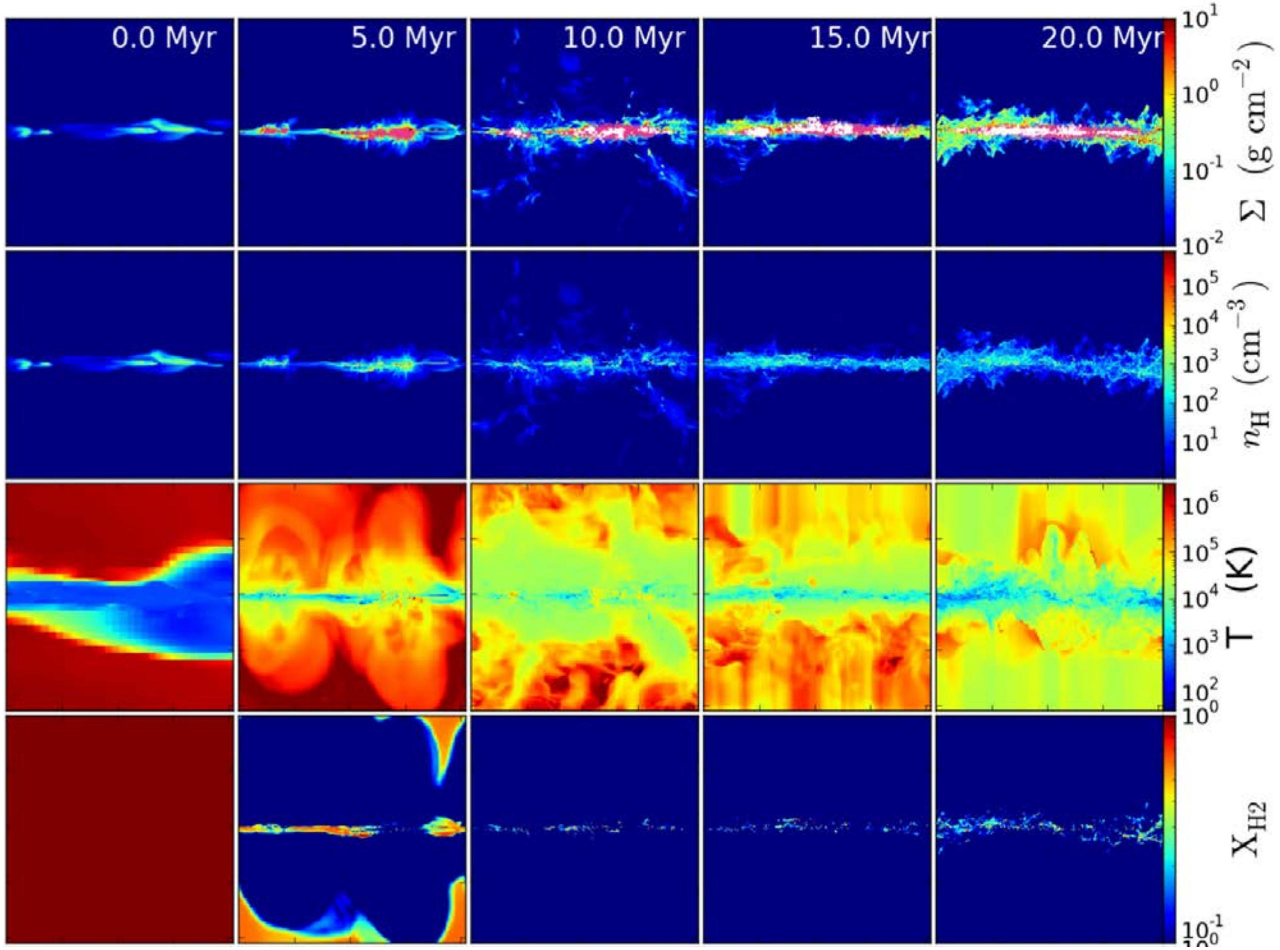
TIGRESS – multiphase ISM simualtions



- ATHENA with sinks, magnetic fields, SN, shear!, no winds, no chemistry
- Convergence for resolution scales < 8pc

Kim & Ostriker arXiv:1612.03918

Multi-phase ISM with RAMSES



- RAMSES with sinks, magnetic fields, SN, chemistry, radiation transfer, no stellar winds
- Ionisation feedback reduces star formation efficiency

Butler et al. 2017

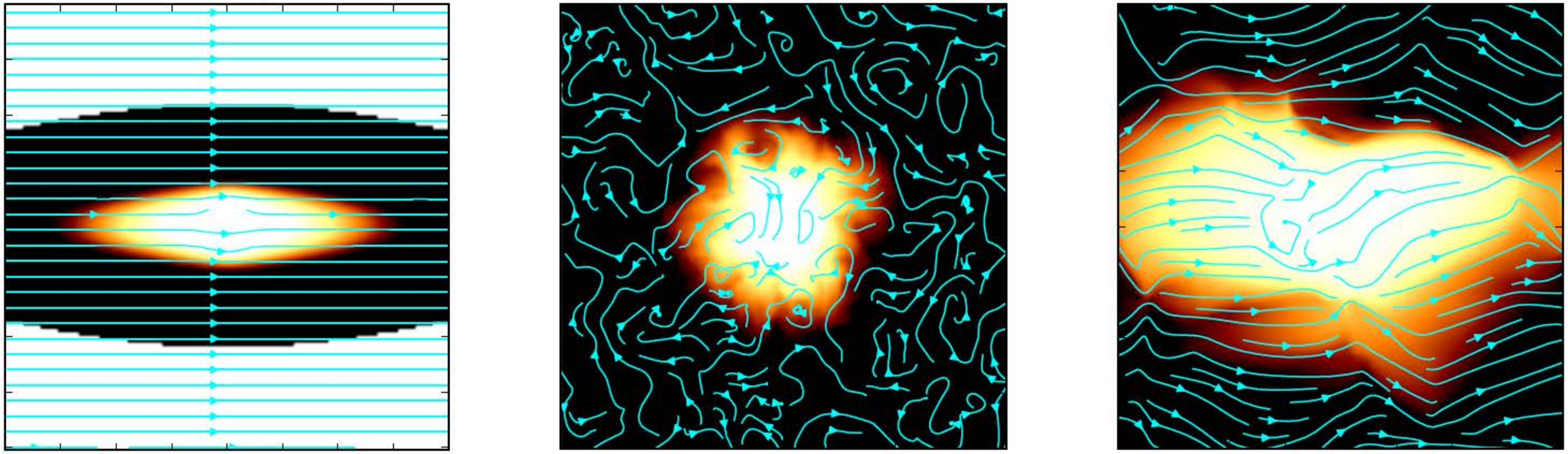
Magnetic fields and cosmic rays?

Cosmic rays are highly relativistic particles (protons) accelerated in supernova remnants – energy density in the ISM is comparable to magnetic and kinetic

Cosmic ray transport is described by a diffusion process

Diffusion mainly along magnetic fields with $K = 10^{28}$ cm^2/s

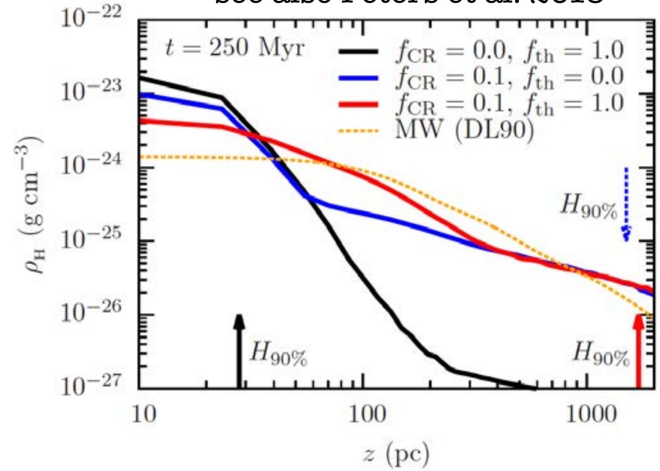
Diffusion perpendicular to magnetic fields is reduced by a factor 10



Girichidis et al. 2016

Magnetic fields and cosmic rays?

see also Peters et al. 2015

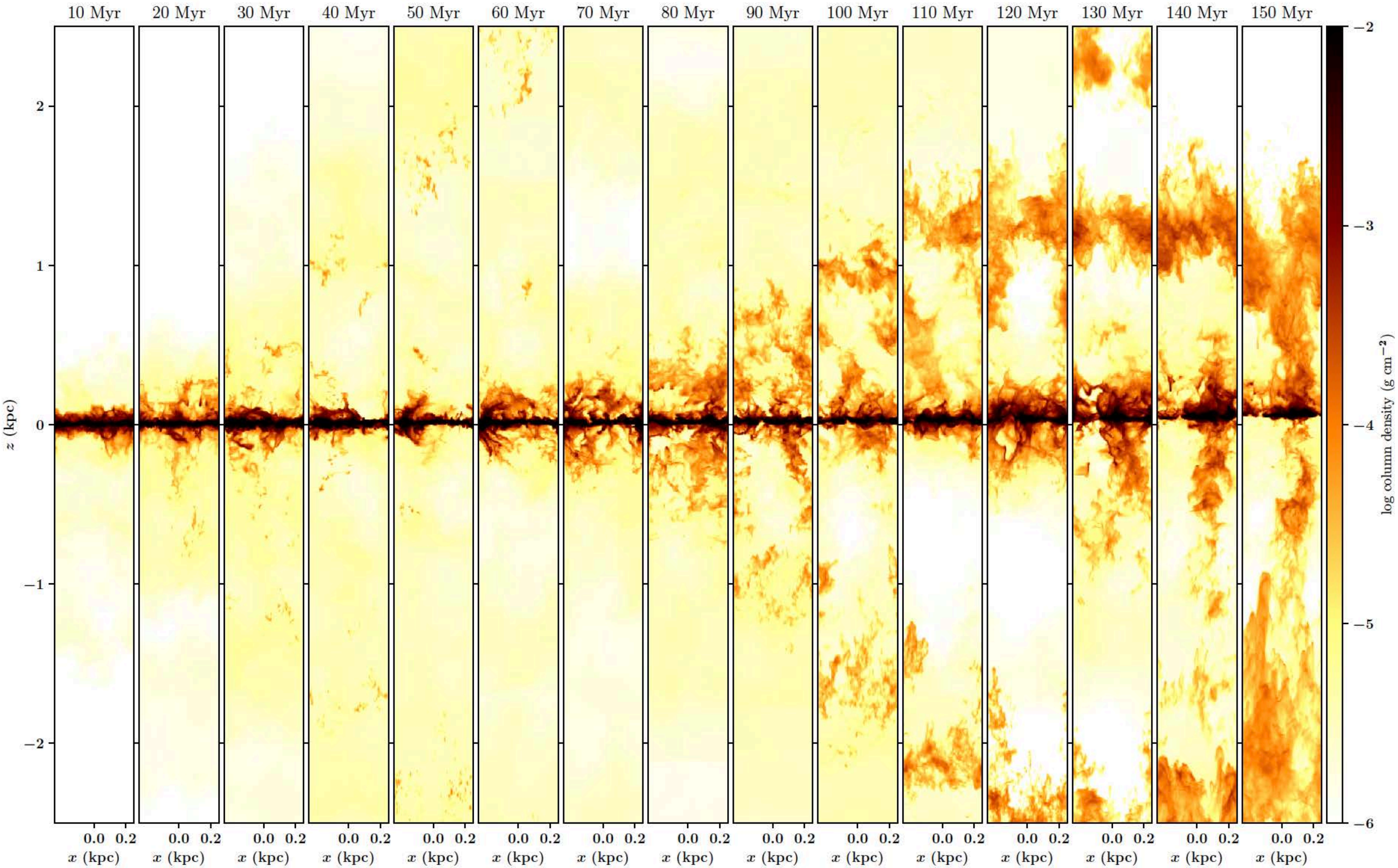


implementation for cosmic rays (Girichidis et al. 2016)

- 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)

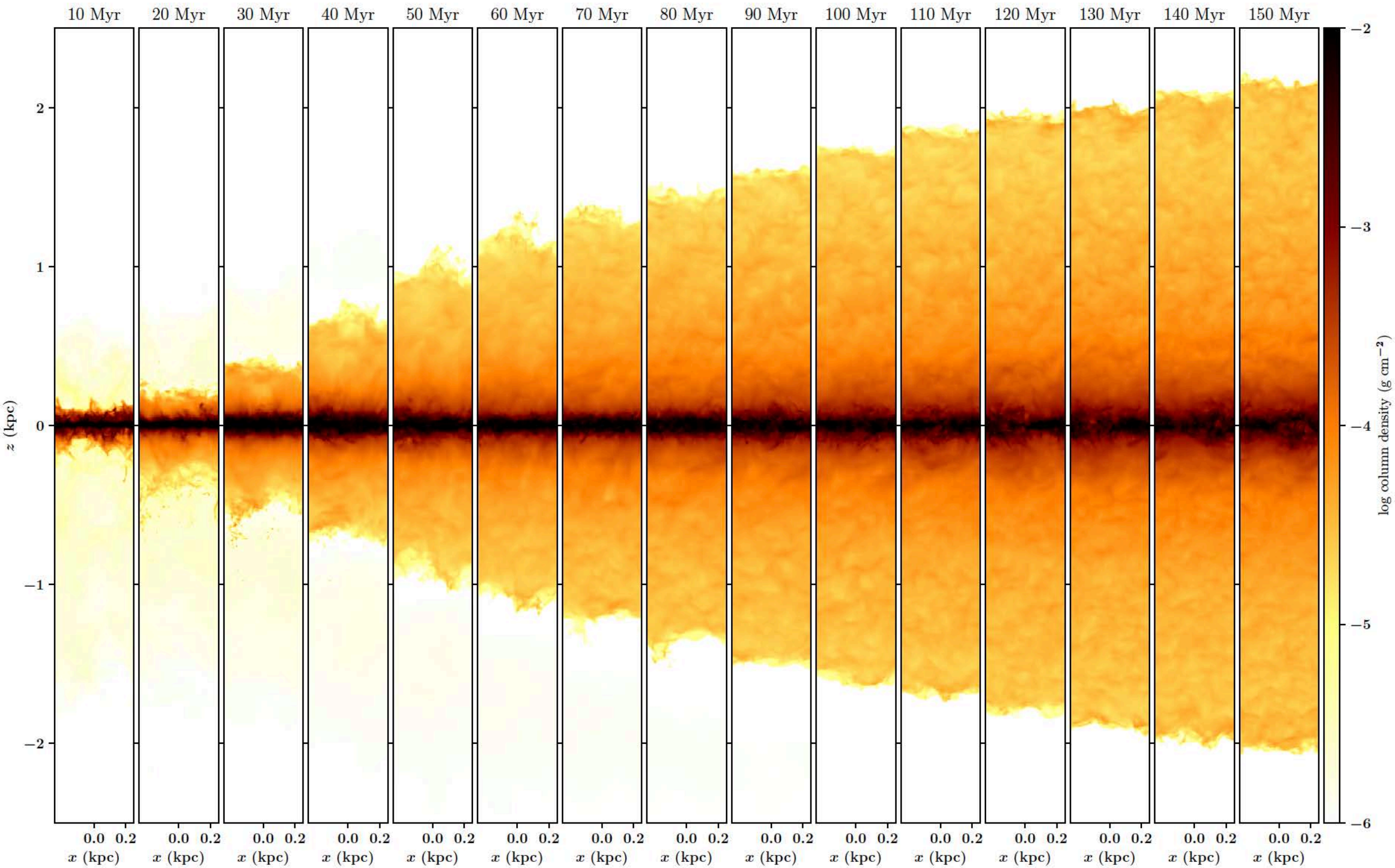
galaxy scales see: Yang et al. 2012, Hanasz et al. 2013, Booth et al. 2013, Salem & Bryan et al. 2014, Ruszkowski et al. 2016

Magnetic fields and cosmic rays?



Girichidis et al. 2018

Magnetic fields and cosmic rays?



Girichidis et al. 2018

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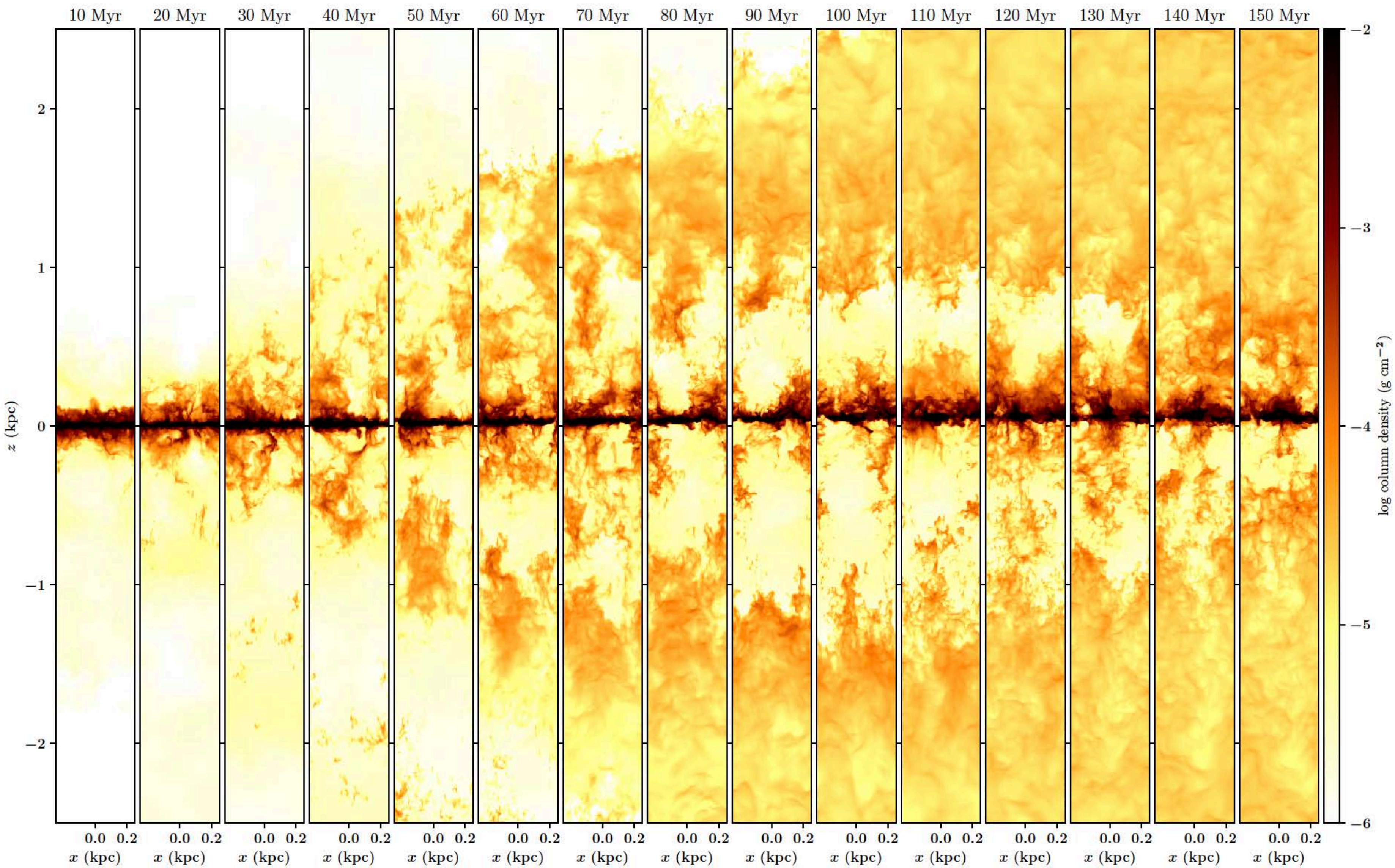
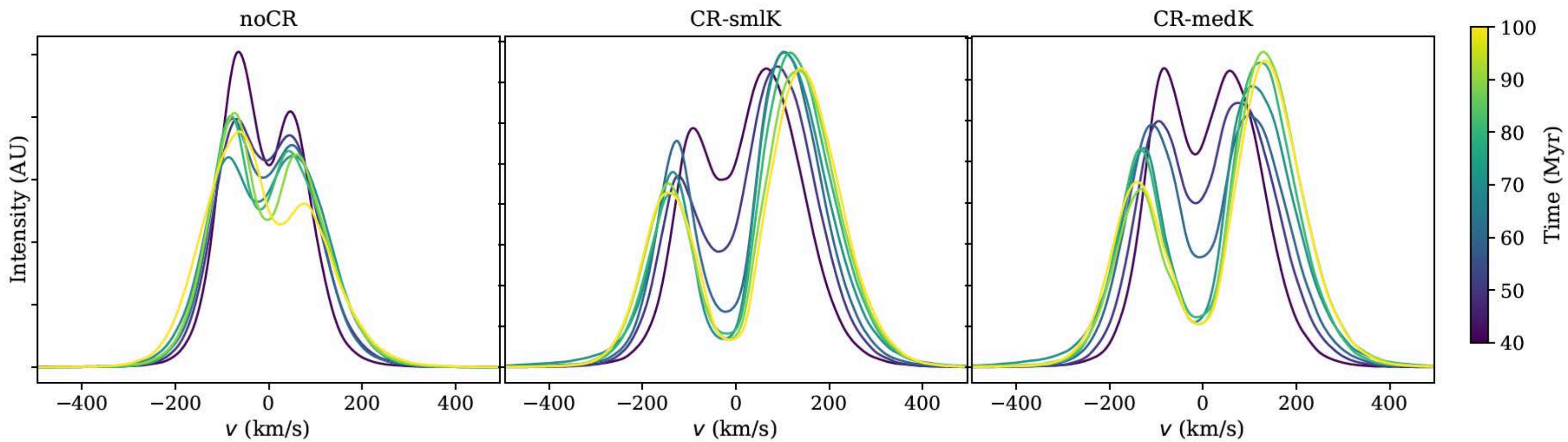
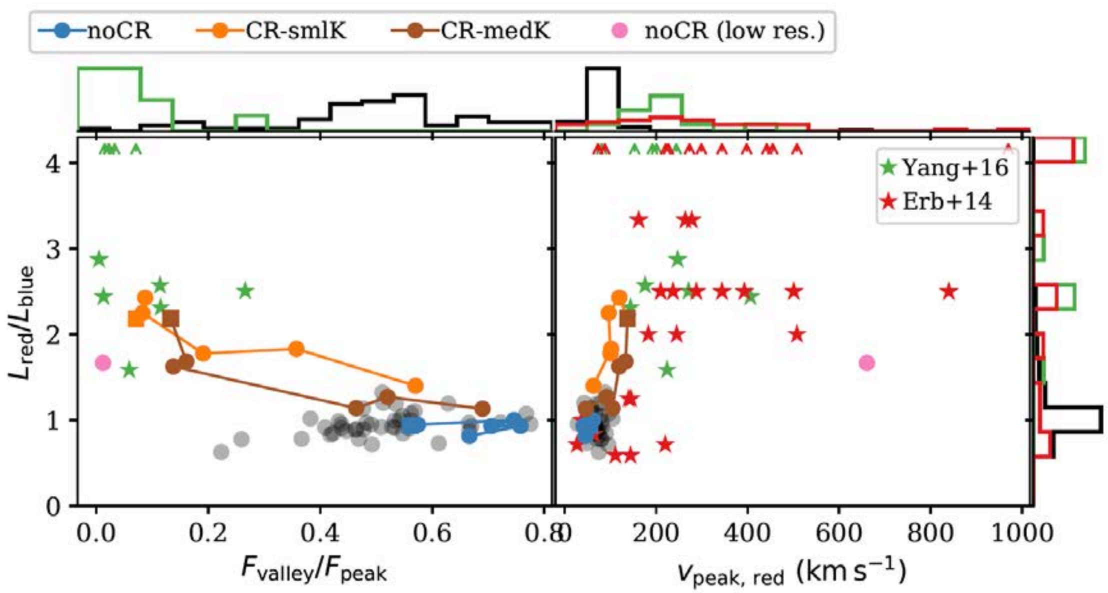


Girichidis et al. 2018

Observable impact of cosmic rays?

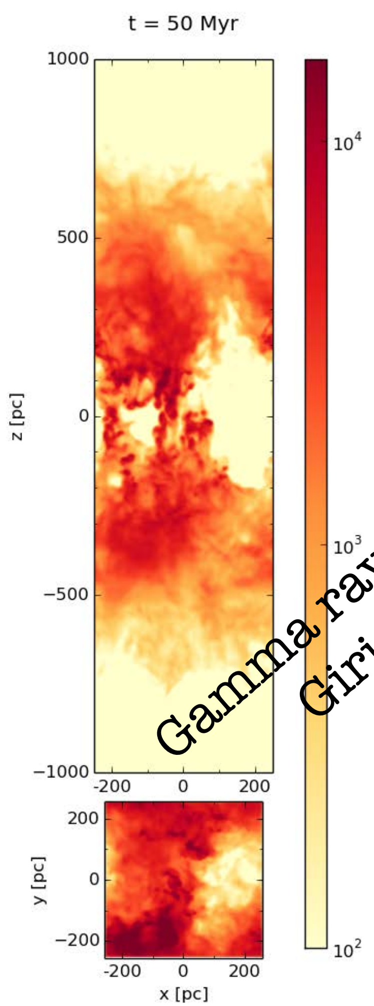


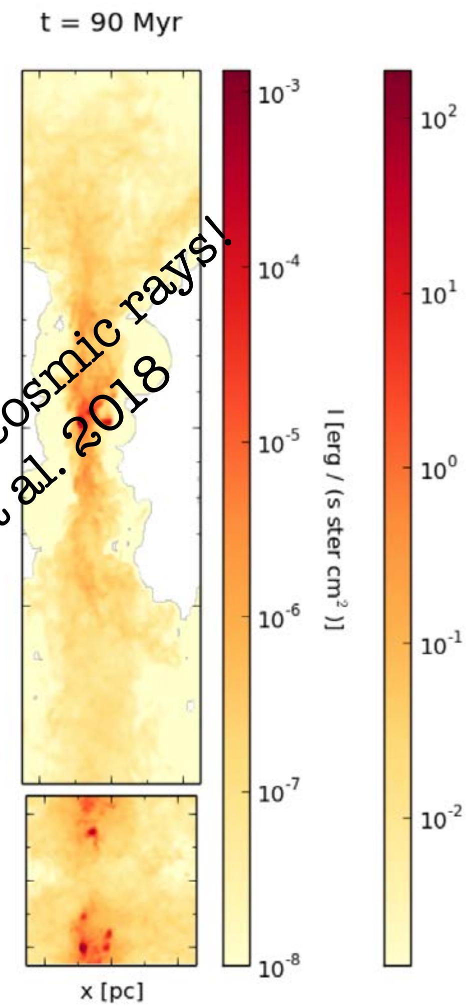


Grönke et al. 2018, in prep.

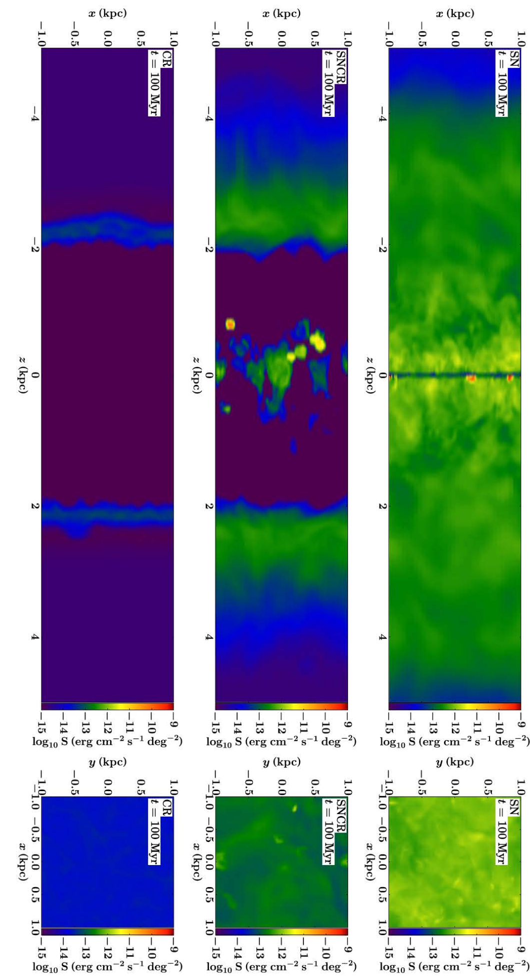
- Cosmic rays generate a diffuse atomic layer making outflows more smooth (Girichidis et al. 2018, sub.)
- Less Ly$_\alpha$ flux at line center, more asymmetric line profiles – higher red peak
- Better agreement with observations

Comparison to observations at different wavelengths





Gamma rays from cosmic rays!
Girichidis et al. 2018



HI emission

[CII] emission

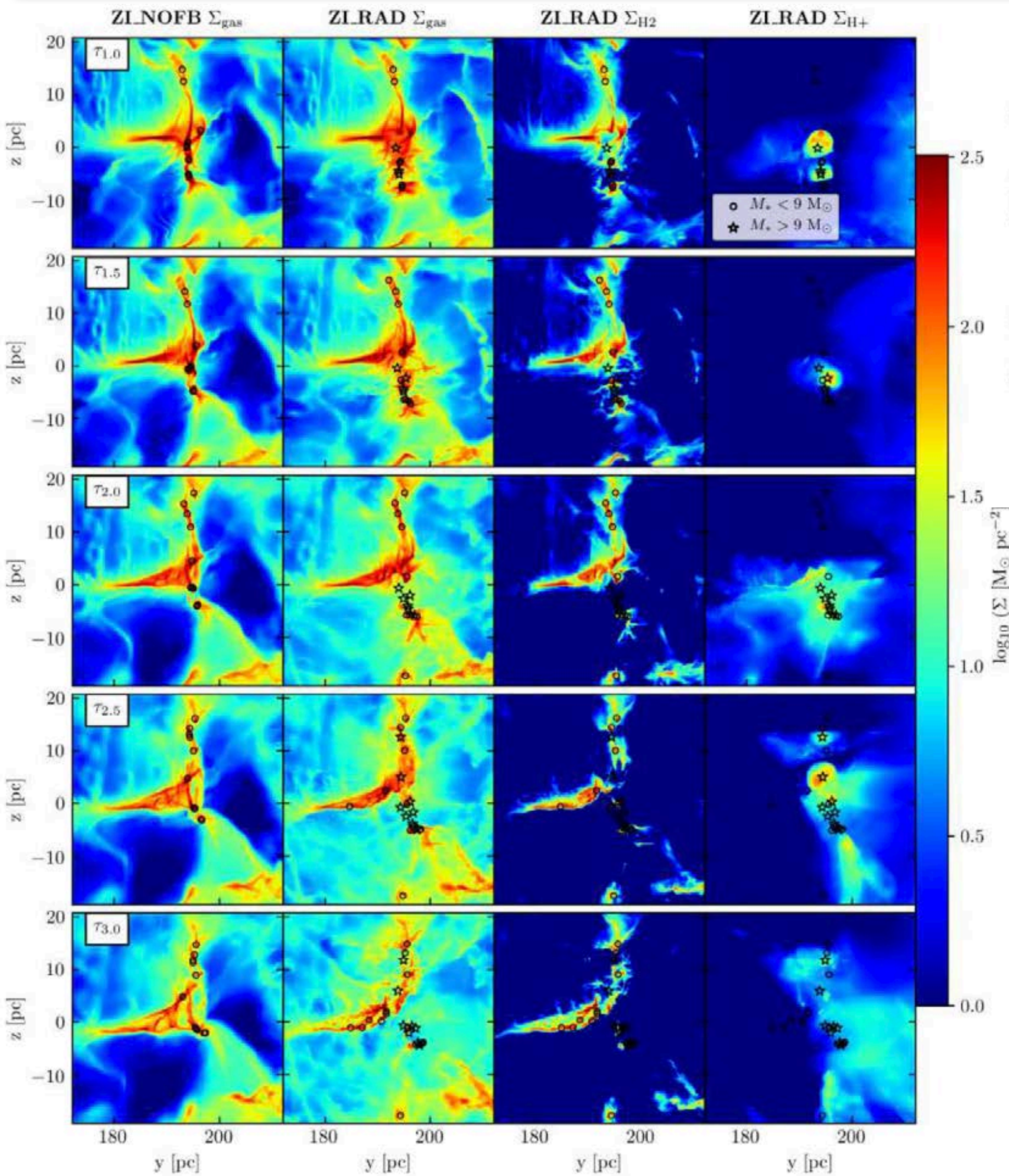
X-ray emission

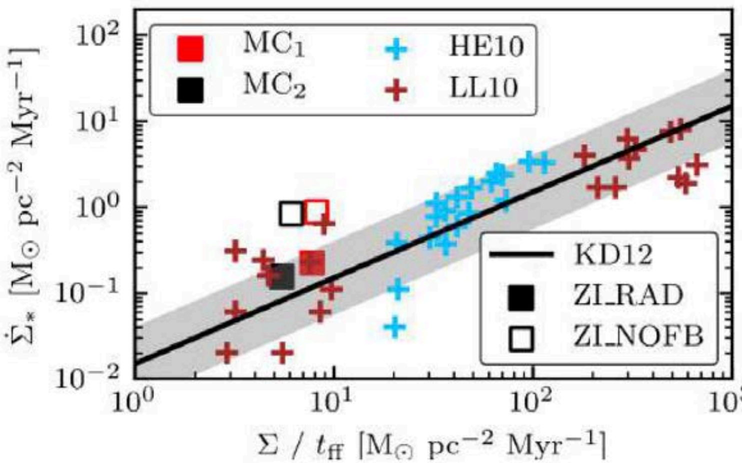
Franneck et al., in prep.

Peters et al. 2016

Molecular cloud formation and early star formation

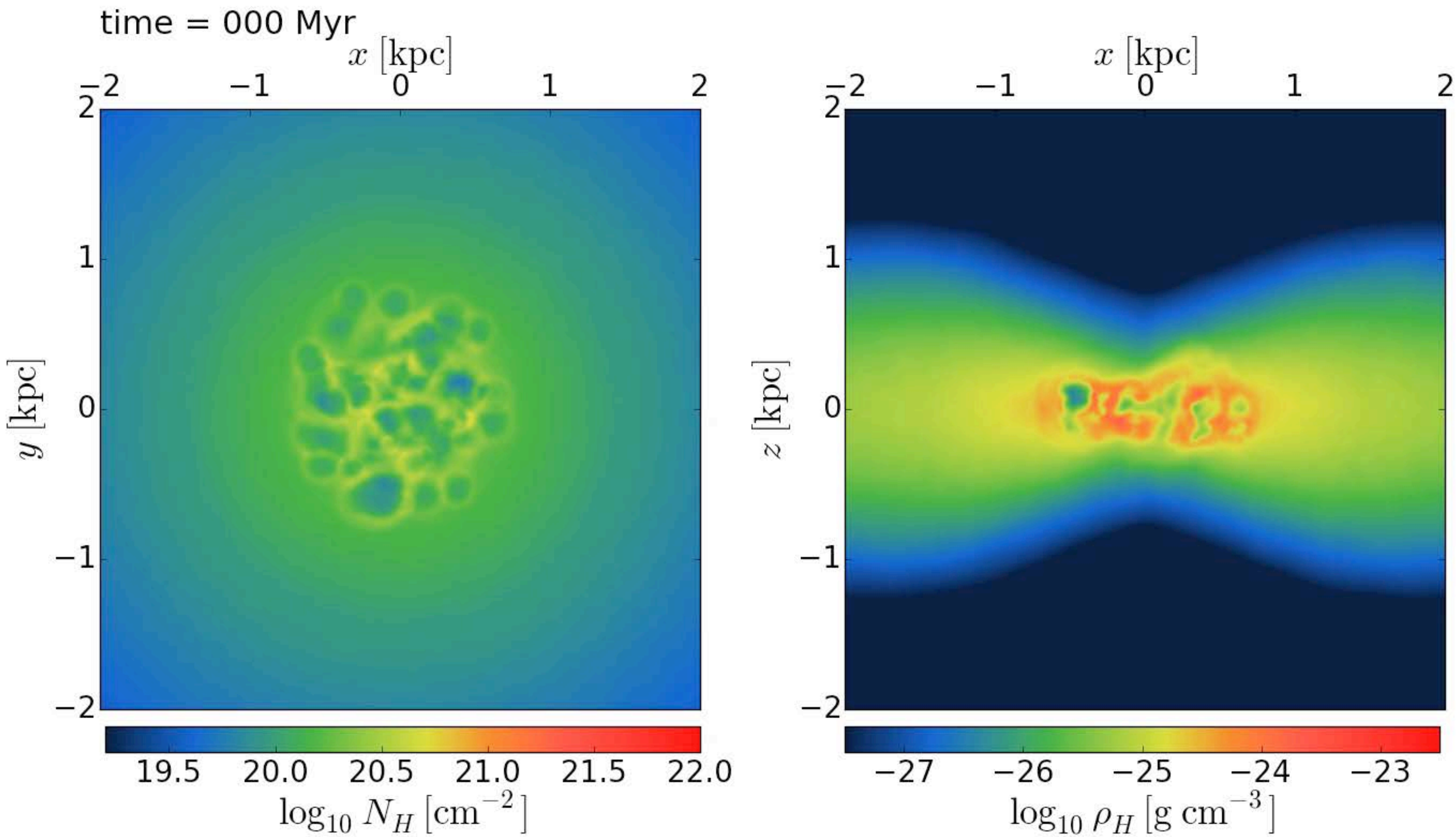
Haid et al. 2018





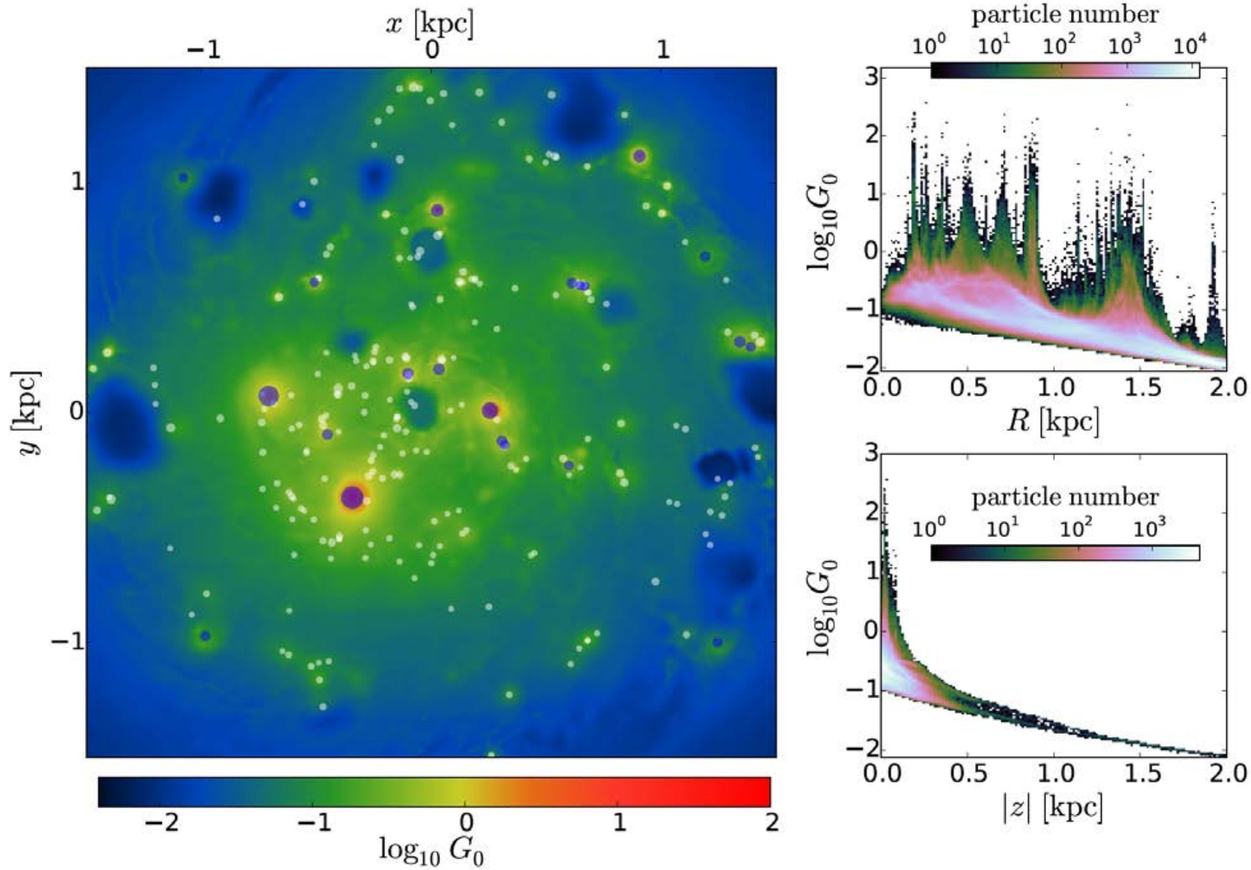
- Zoom simulations (0.1 pc) of individual low mass clouds with TreeRay (Wünsch et al. in prep) radiation transfer
- Early ionizing radiation regulates star formation efficiency
- More stellar sinks (trigger) but lower mass (suppression)

Individual star formation and feedback in dwarf galaxies



Hu, Naab et al. 2017

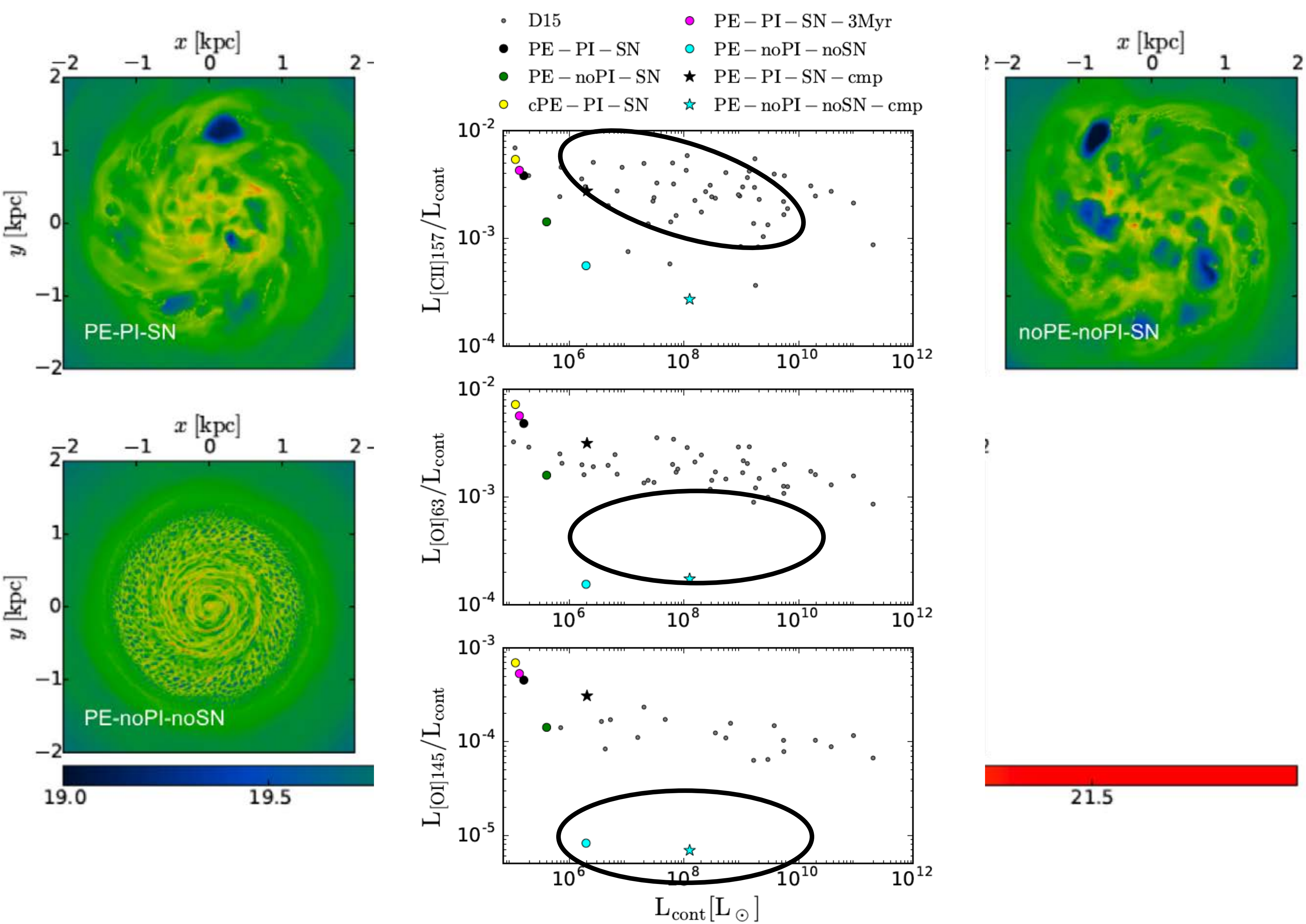
Star formation in dwarf galaxies



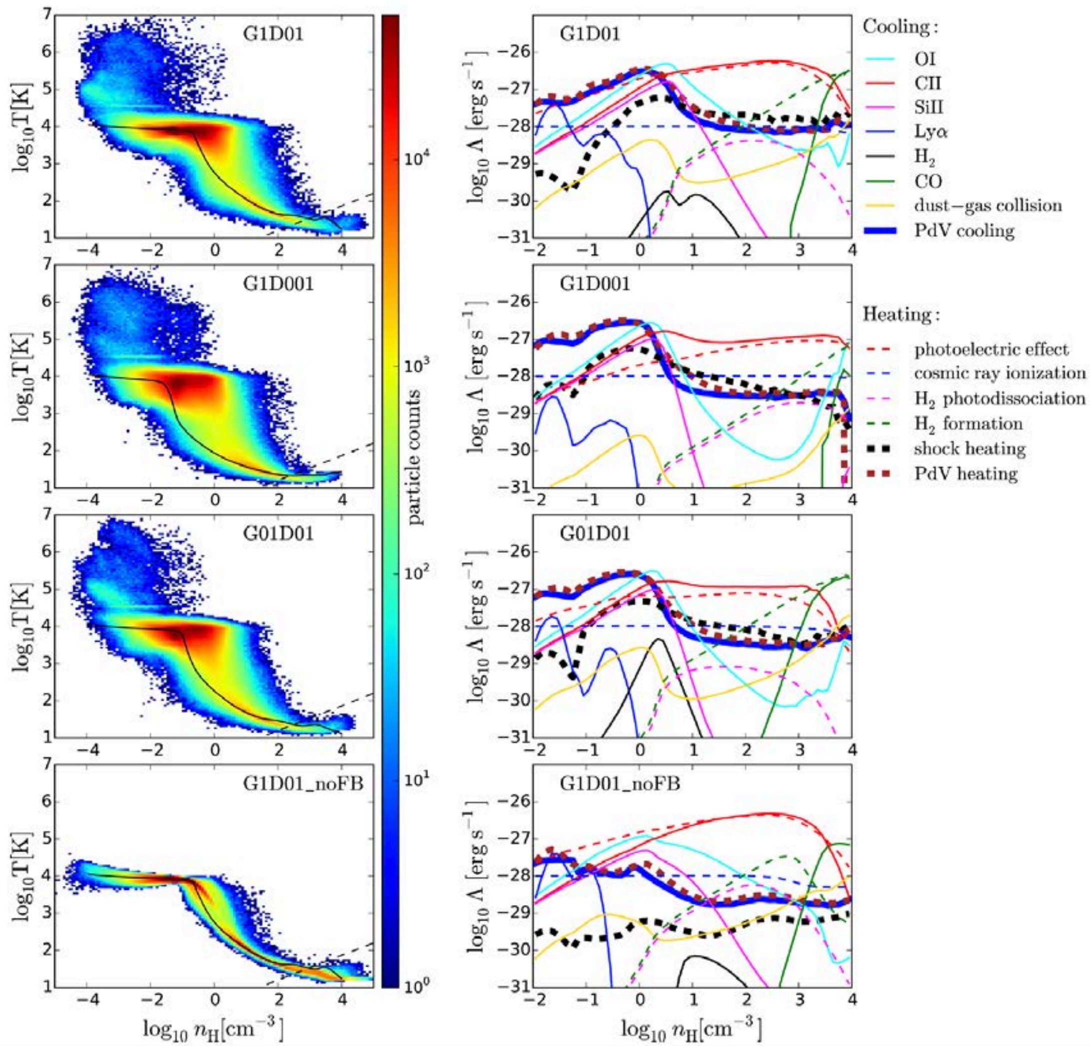
- Stars are randomly sampled from IMF – conversion of gas particles to star particles is adjusted accordingly
- Radiation field from massive stars approximated in the optically thin limit (low dust-to-gas ratios)
- Photoionization approximated (see Hopkins, Quataert & Murray 2012)

Hu et al. 2017

Physical conclusions from galaxy scale simulations?!



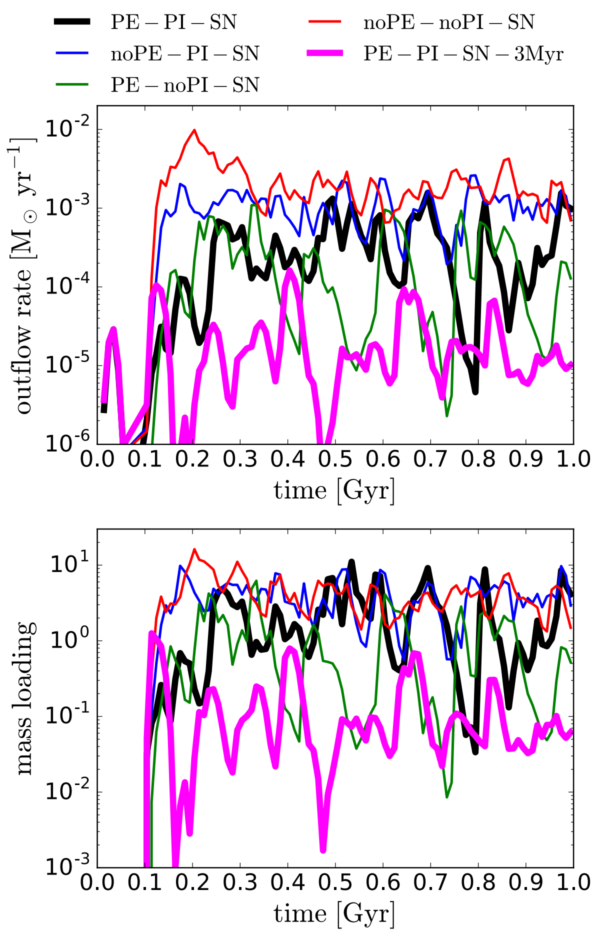
Shocks in a galactic context

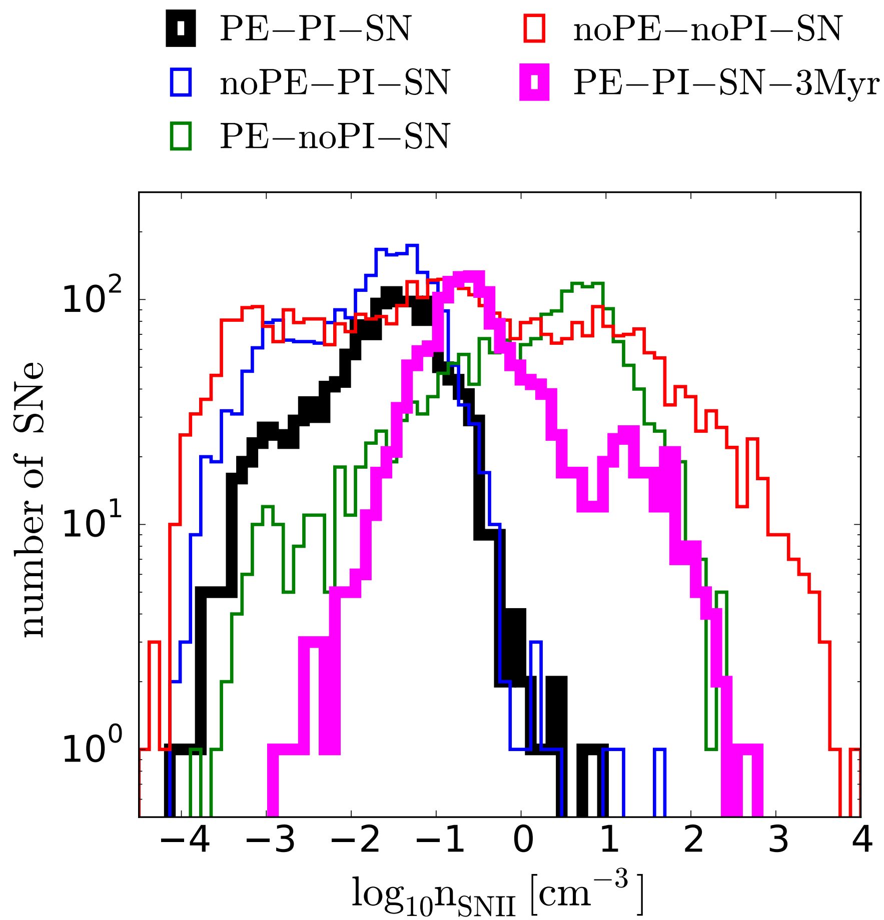


Hu et al. 2016

- Shocks contribute to heating at moderate densities
- At high densities heating is dominated by photoelectric effect, cooling by CII
- Significant uncertainties due to resolution, shock identification, numerical method etc.
- How much energy is dissipated in shocks?

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
- Beware of non-thermal components – magnetic fields, cosmic rays