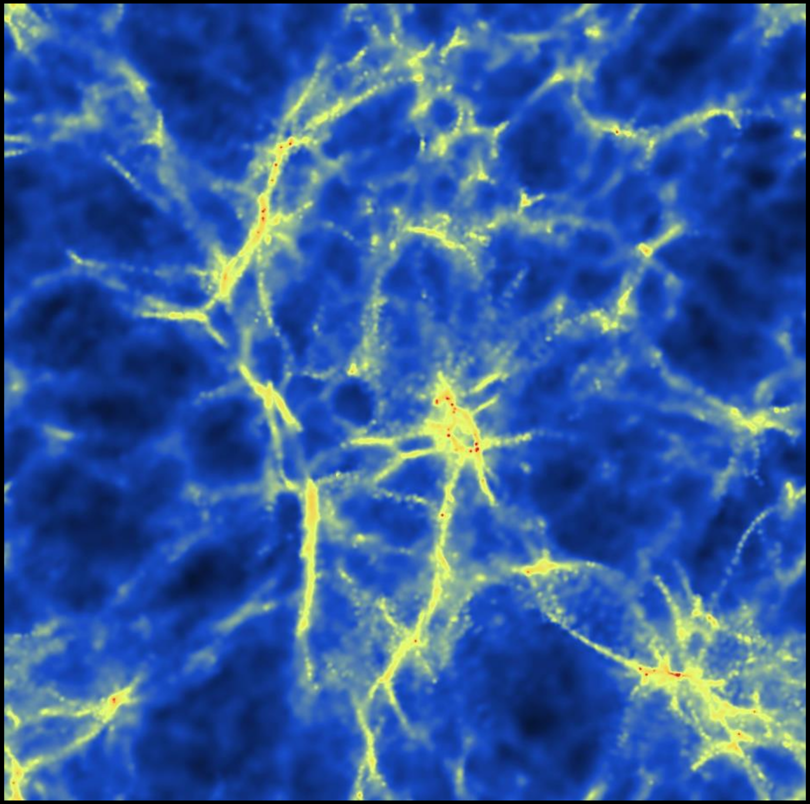
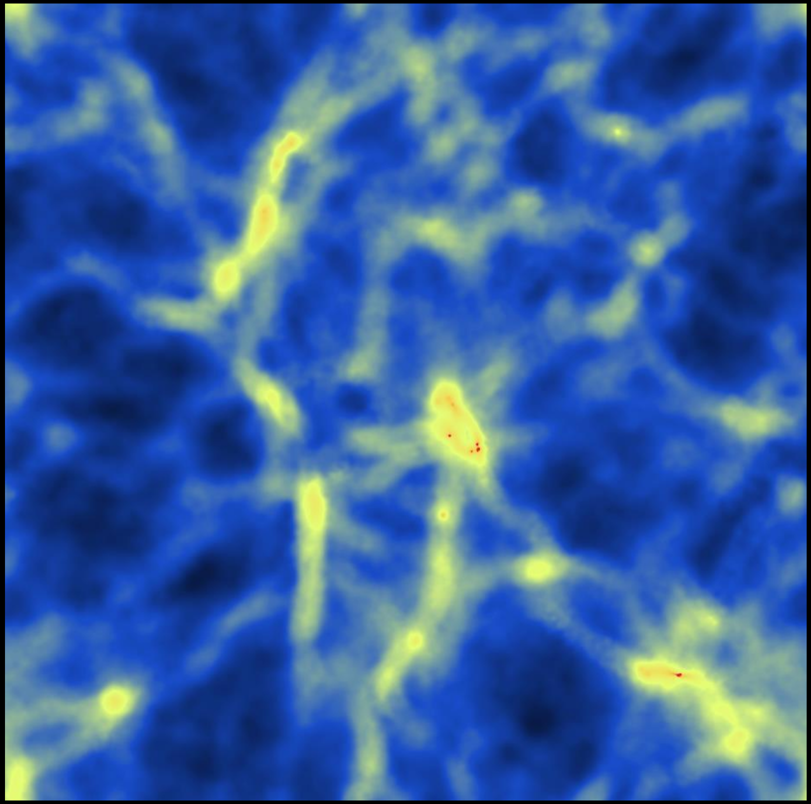
Radiation-hydrodynamical Simulations of the Epoch of Reionisation





Joop Schaye (Yope Shay)

Leiden University

Simulations of reionisation

- Reionisation is by definition a radiative transfer problem
- Radiative feedback:
  - Negative: floor on T_{vir} of galaxy halo
  - Negative: dissociation of molecules
  - Positive: Pressure smoothing reduces recombination rate
- Reionisation is thus a radiation-hydrodynamics problem

Simulations of reionisation

- Mass of objects quenched by
  - photo-heating: ~10^8 $M_\odot$ → 25 cMpc box for 1000^3 particles and 100 particles per halo
  - Photo-dissociation: ~10^5 $M_\odot$ → 3 cMpc box for 1000^3 particles and 100 particles per halo
- To begin to resolve the cold ISM phase, we need particle mass << 10^3 $M_\odot$ → 1 cMpc box for 1000^3 particles
- Consequences:
  - ➢ Cannot do radiation-hydrodynamics for simulation volumes appropriate for 21cm experiments
  - ➢ Cannot predict efficiency of stellar feedback
    - → Need to calibrate (to observed luminosity function)
  - ➢ Cannot predict escape fraction
    - → Need to calibrate (to reionisation history)

Simulations of reionisation

Cannot predict from first principles

- Galaxy mass and SFR functions
- Escape fractions
- Reionisation history

Simulations of reionisation

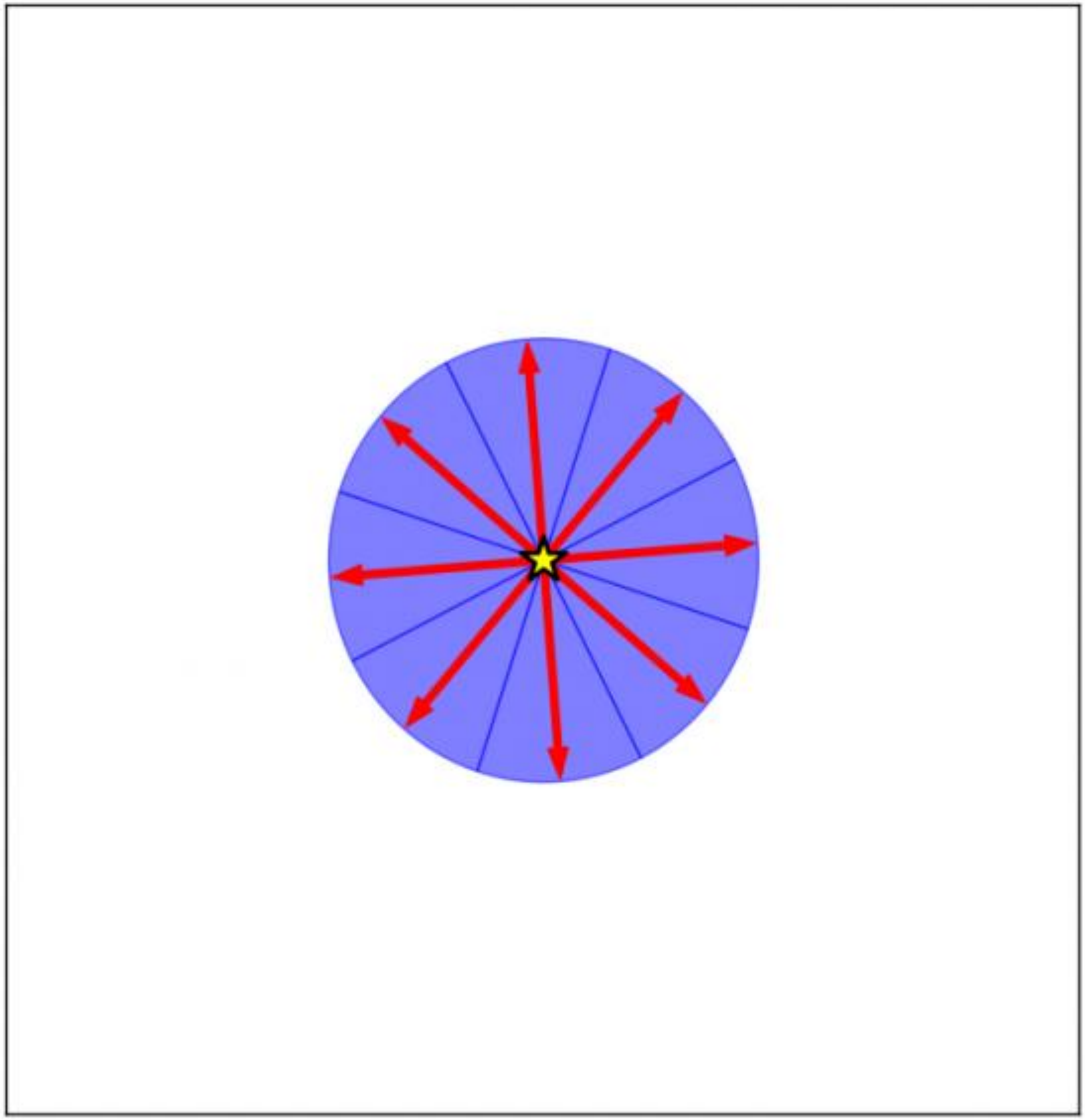
- Most reionisation simulations:
  - Post-process dark matter simulations
  - Use a radiative transfer method that is not spatially adaptive → extremely poor resolution, e.g. 500^3 in 100 cMpc box gives cell size of 200 ckpc
  - Group sources
  - Use radiative transfer with an accuracy that is limited and that cannot be controlled
- Most radiative transfer simulations are similar to semi-numerical methods, which have therefore not yet been tested

TRAPHIC

(Pawlik & JS ’08, ‘11, Pawlik+ ‘13)

- TRansport of Photons In Cones
- Uses the unstructured grid defined by SPH particles → Spatially adaptive
- Computational cost independent of the number of sources
- Photons travel at the speed of light
- Radiation-hydrodynamics
- Multifrequency
- Accurate radiative transfer, full control over the resolution
- MPI parallel, implemented in Gadget
- Optional features:
  - X-ray secondary ionizations (Jeon+ ‘13)
  - Recombination radiation (Raicevic+ ‘13)
  - UV background (Rahmati+ ‘13)

TRAPHIC: Emission



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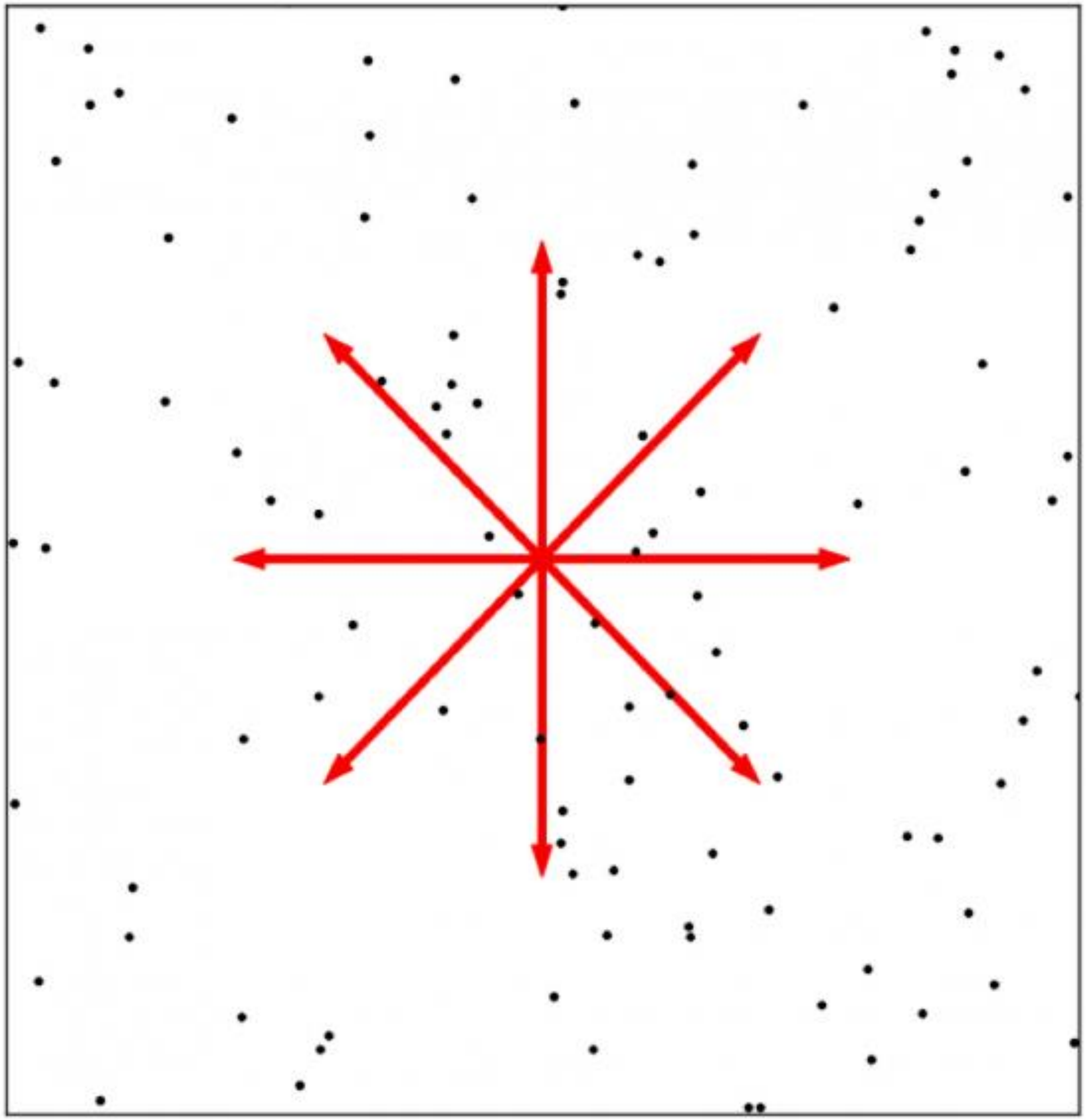

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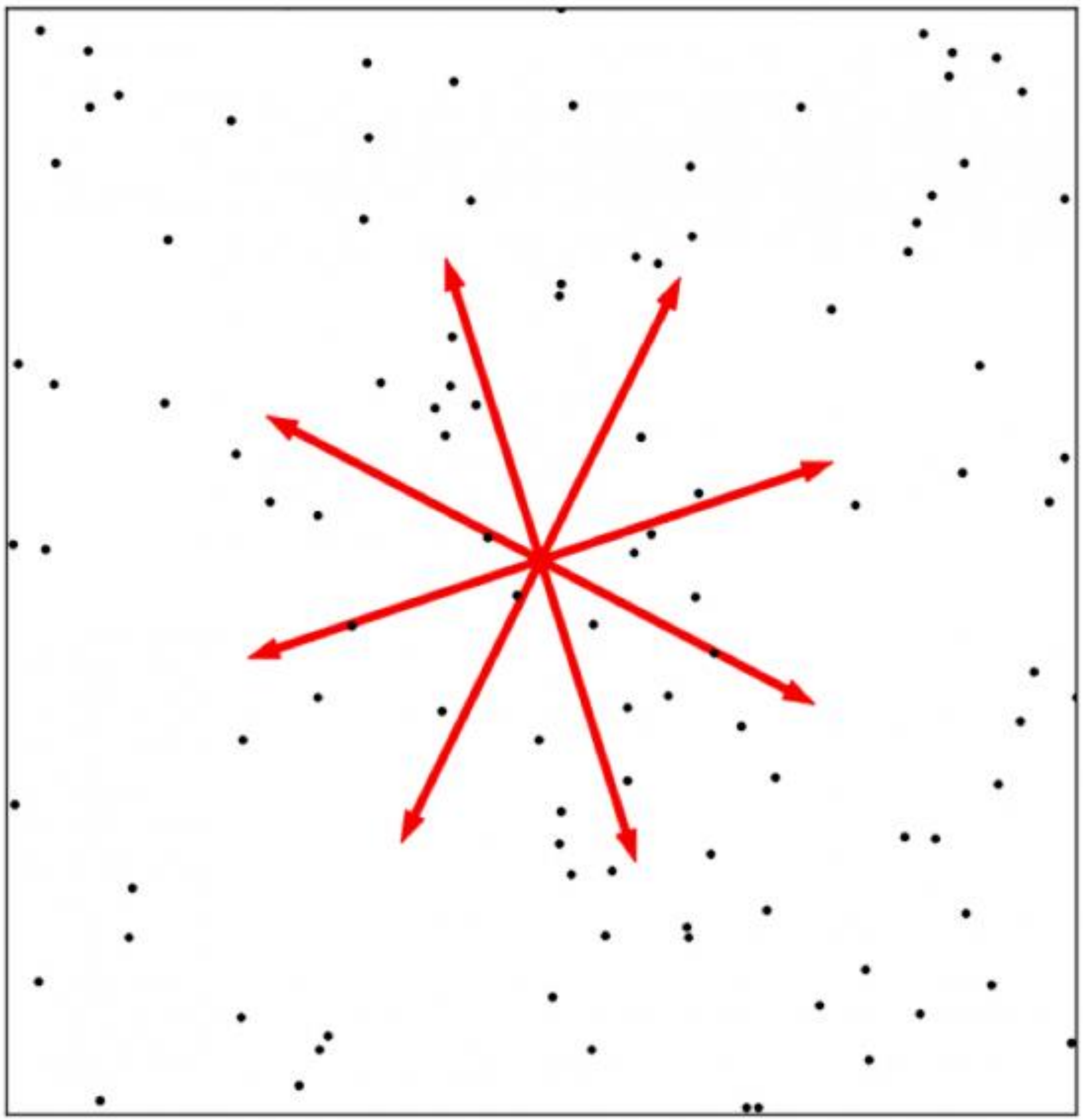
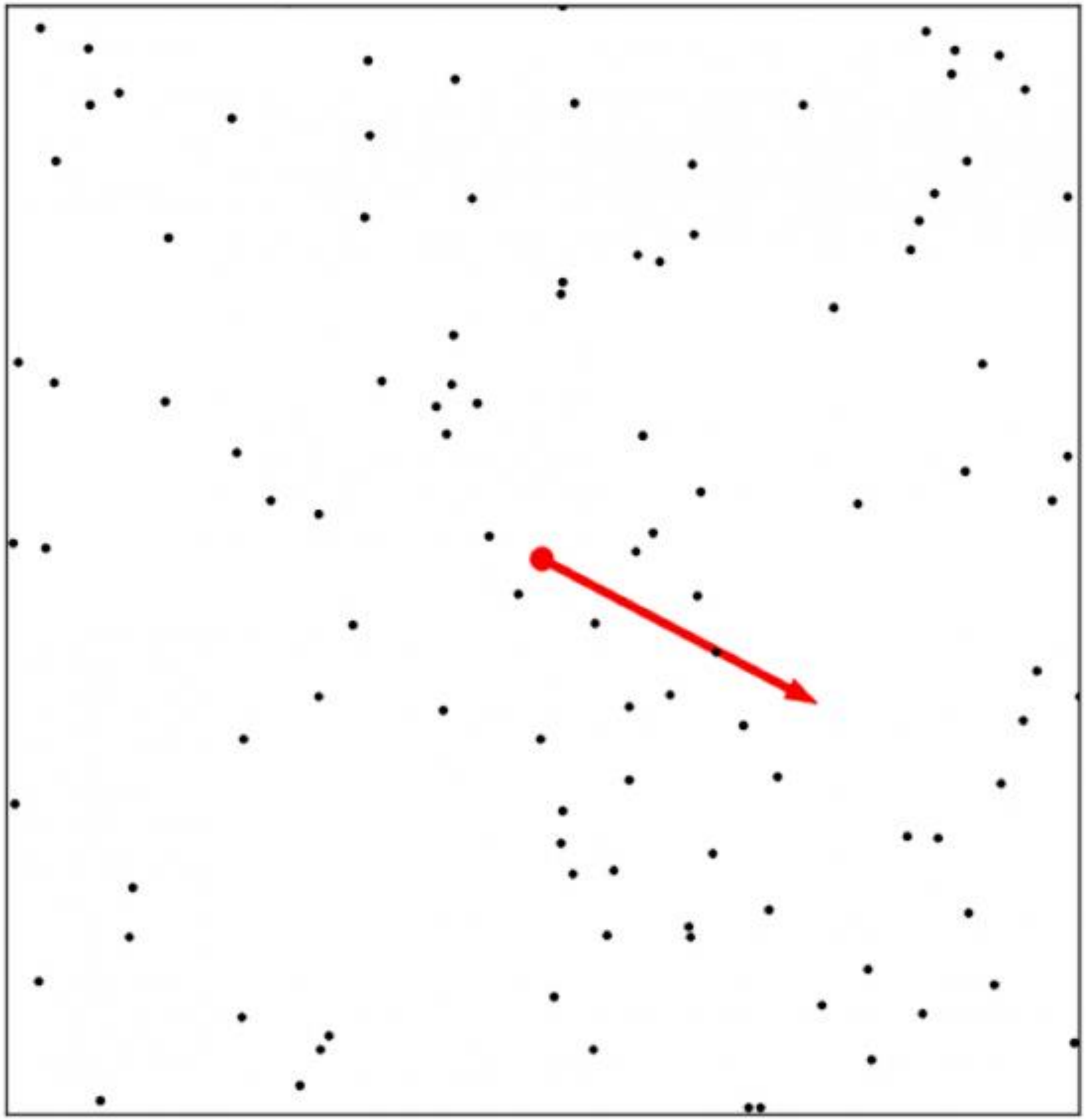


TRAPHIC: Transport



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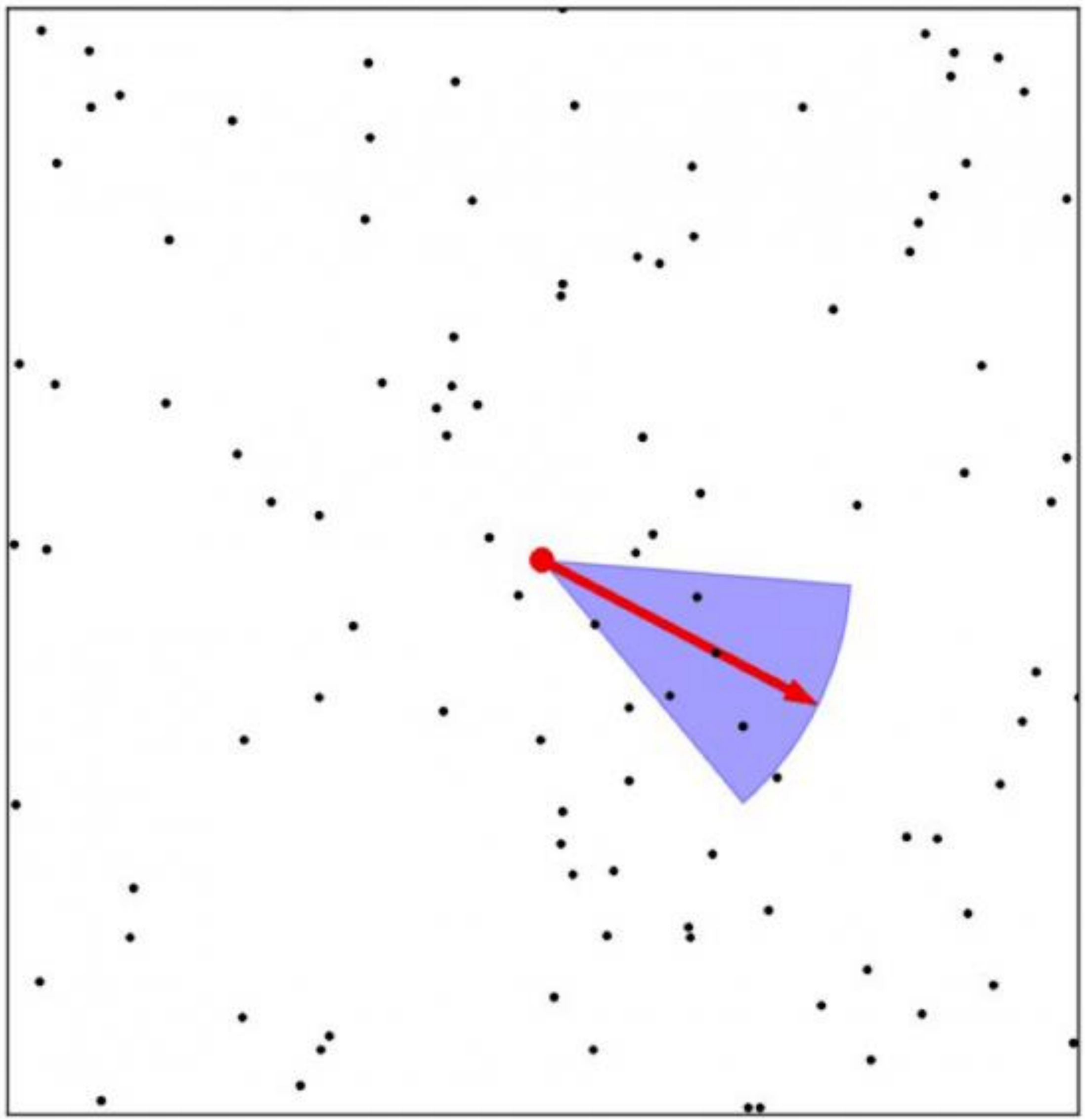

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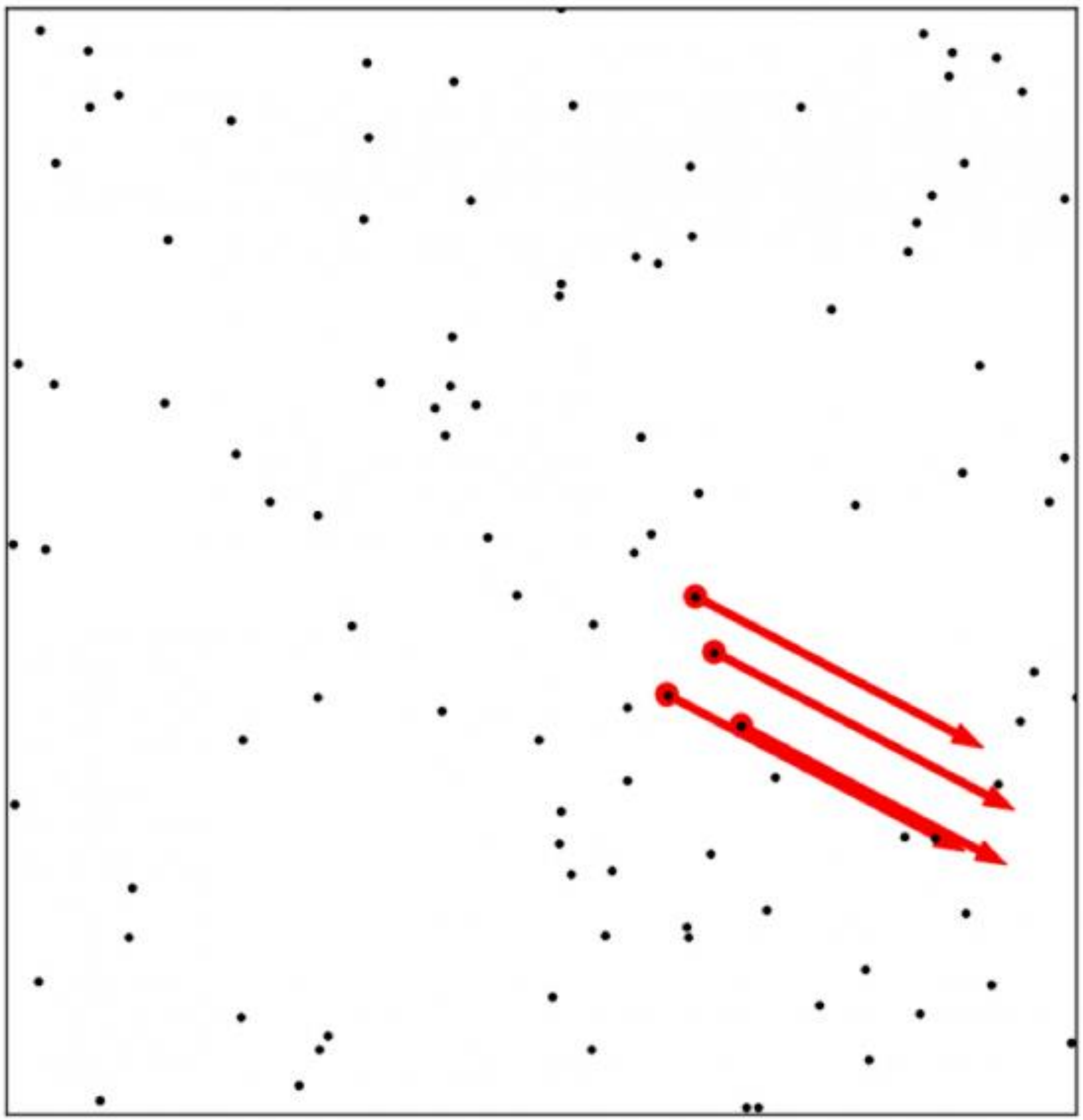
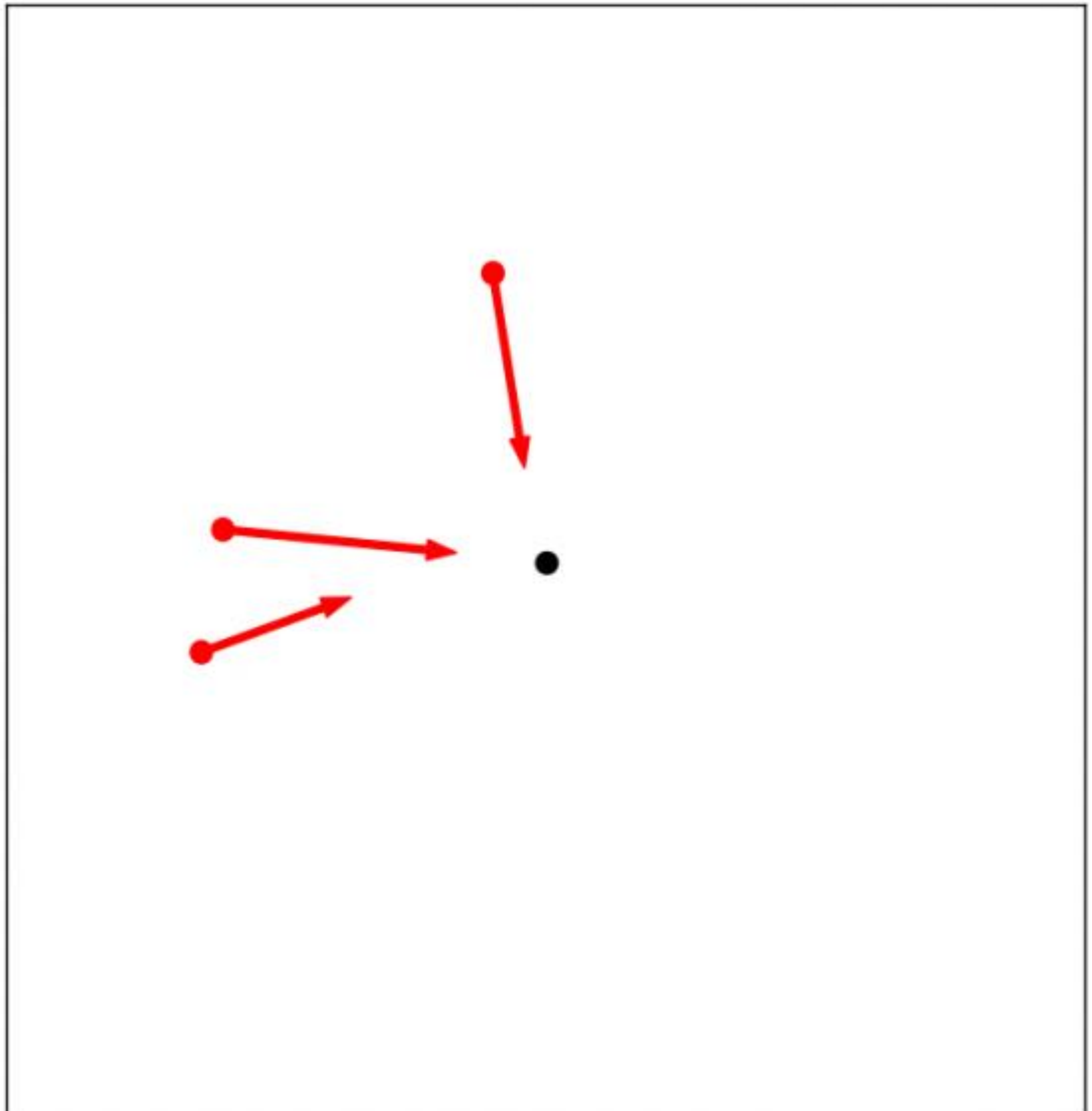


TRAPHIC: Merging



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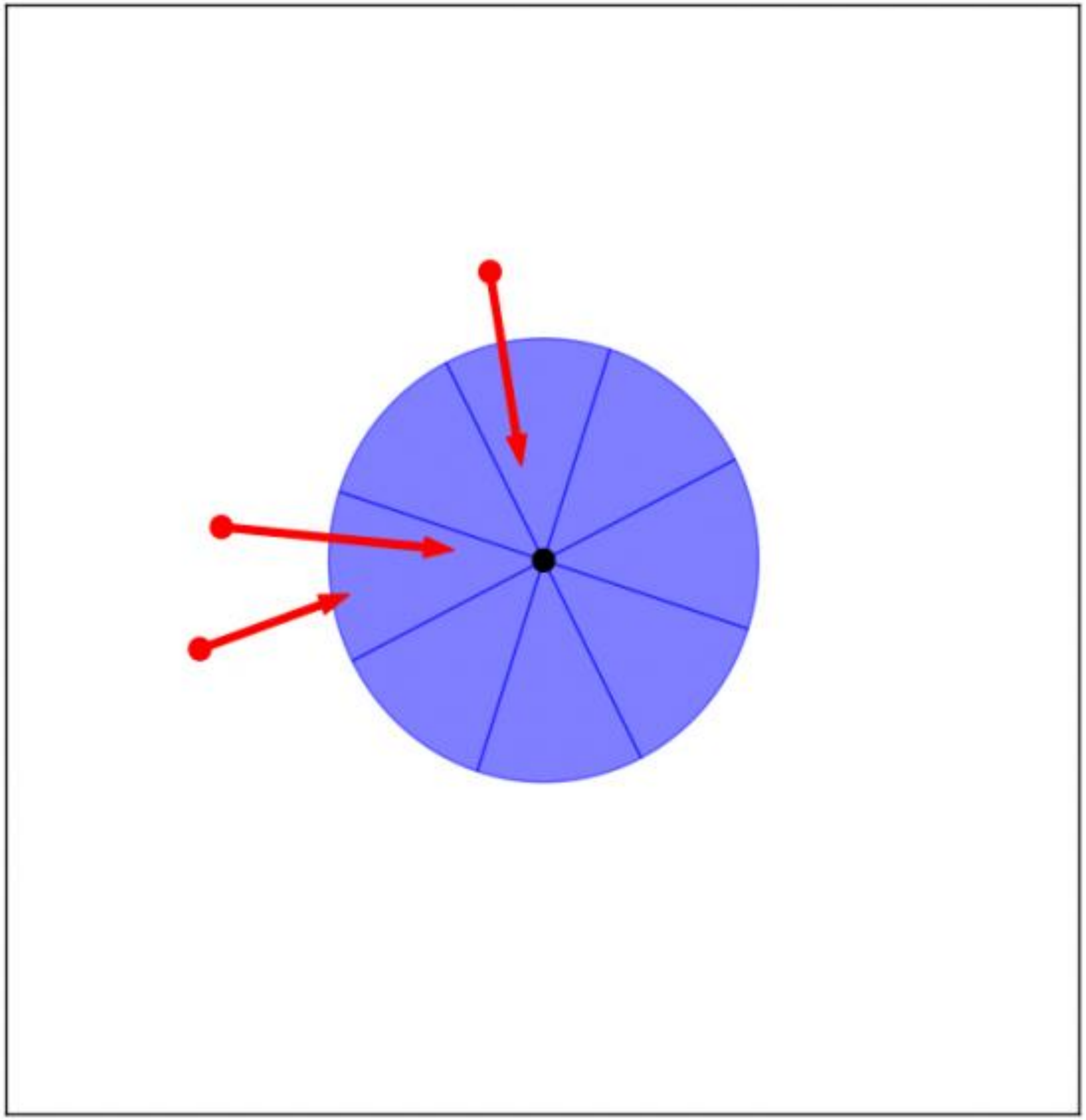

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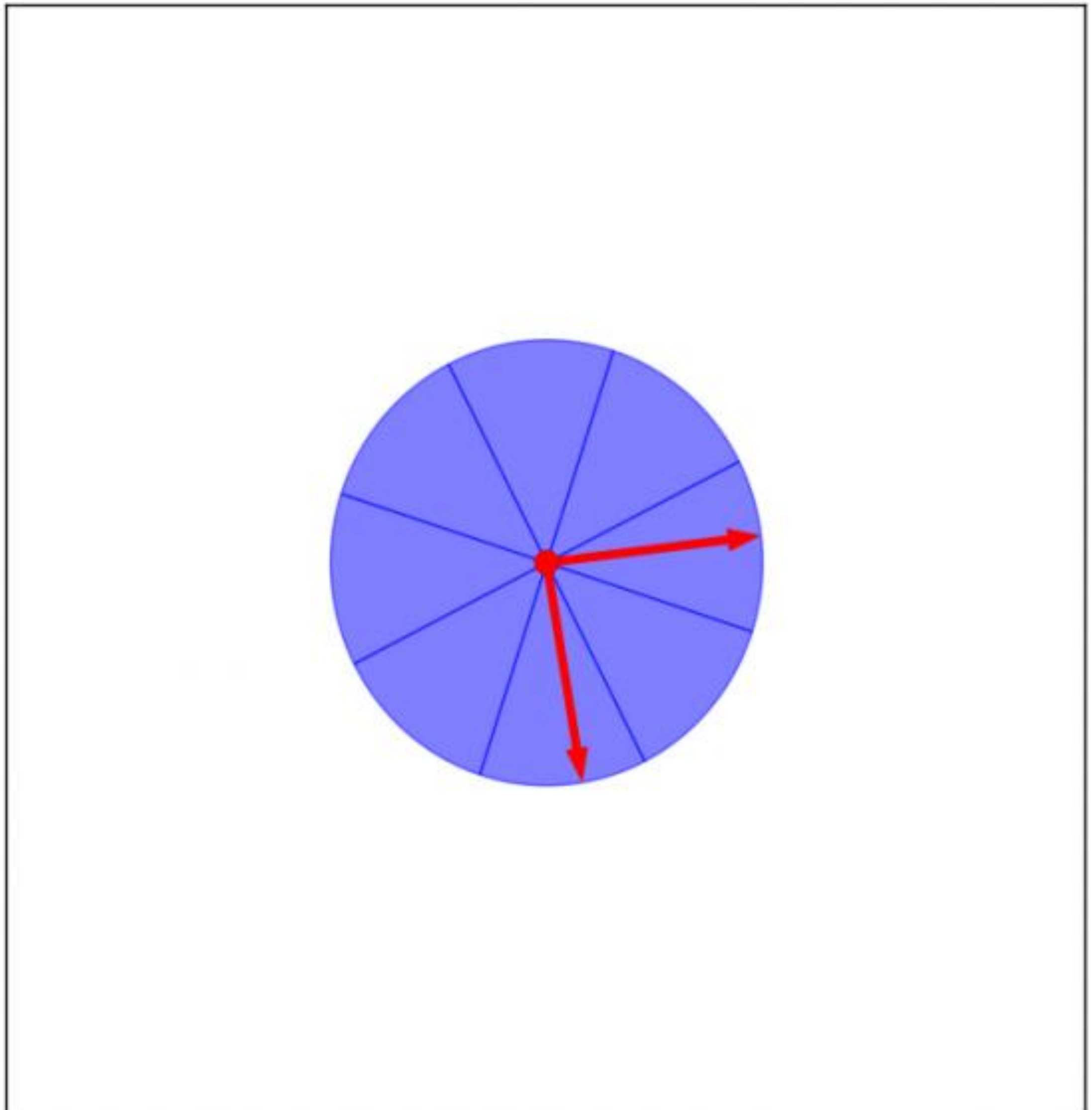

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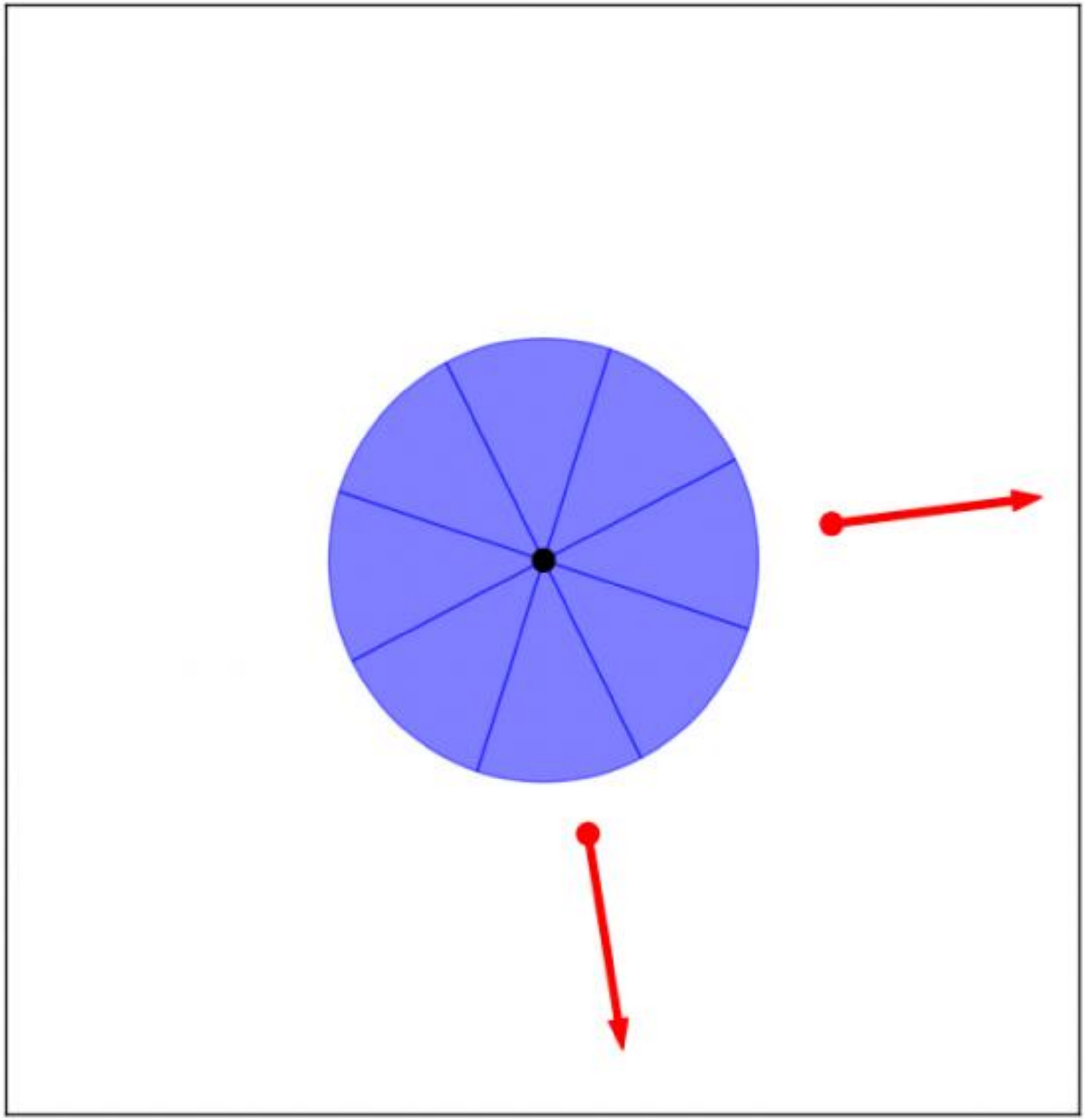
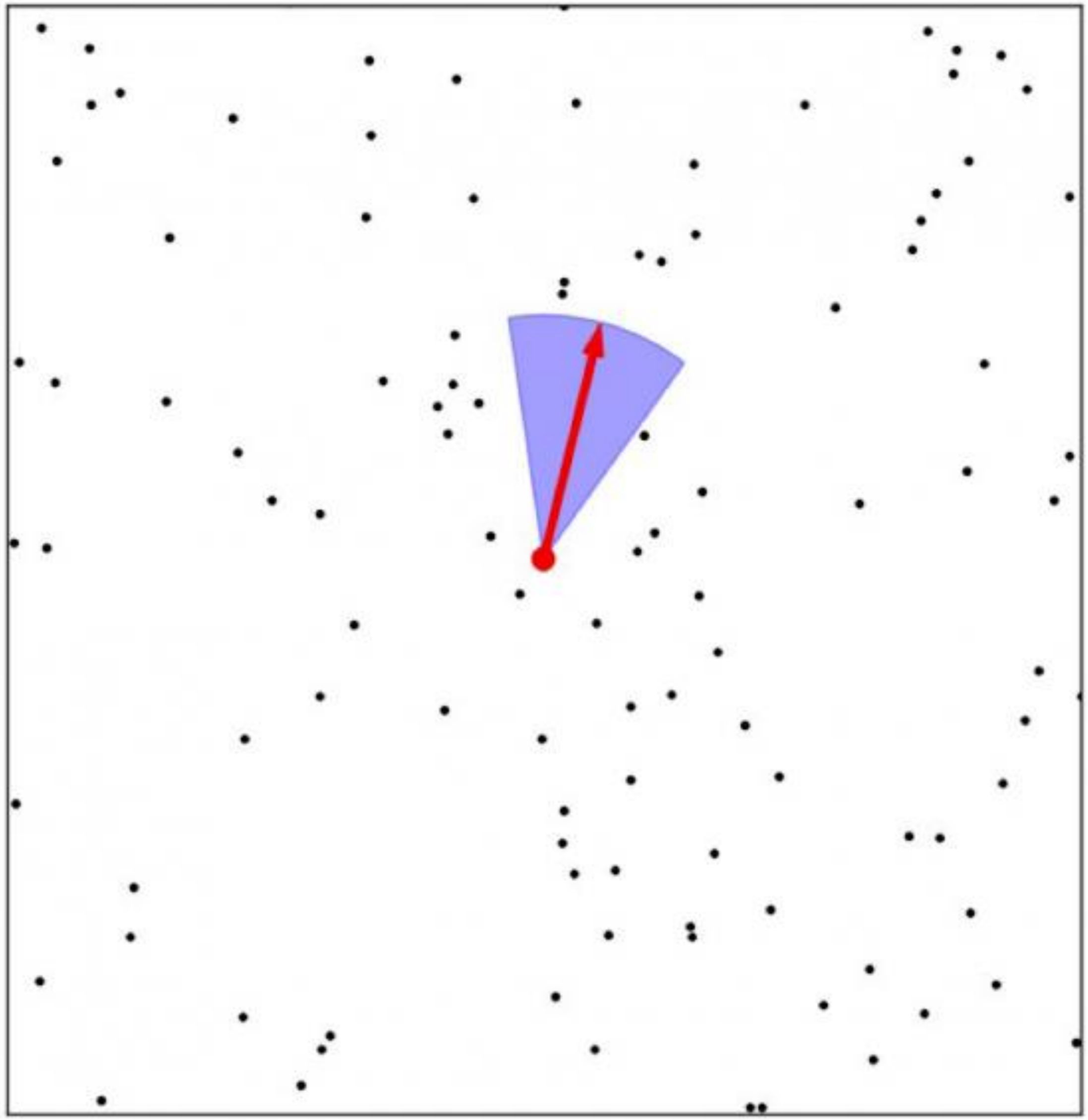


TRAPHIC: Virtual particles (VIPs)



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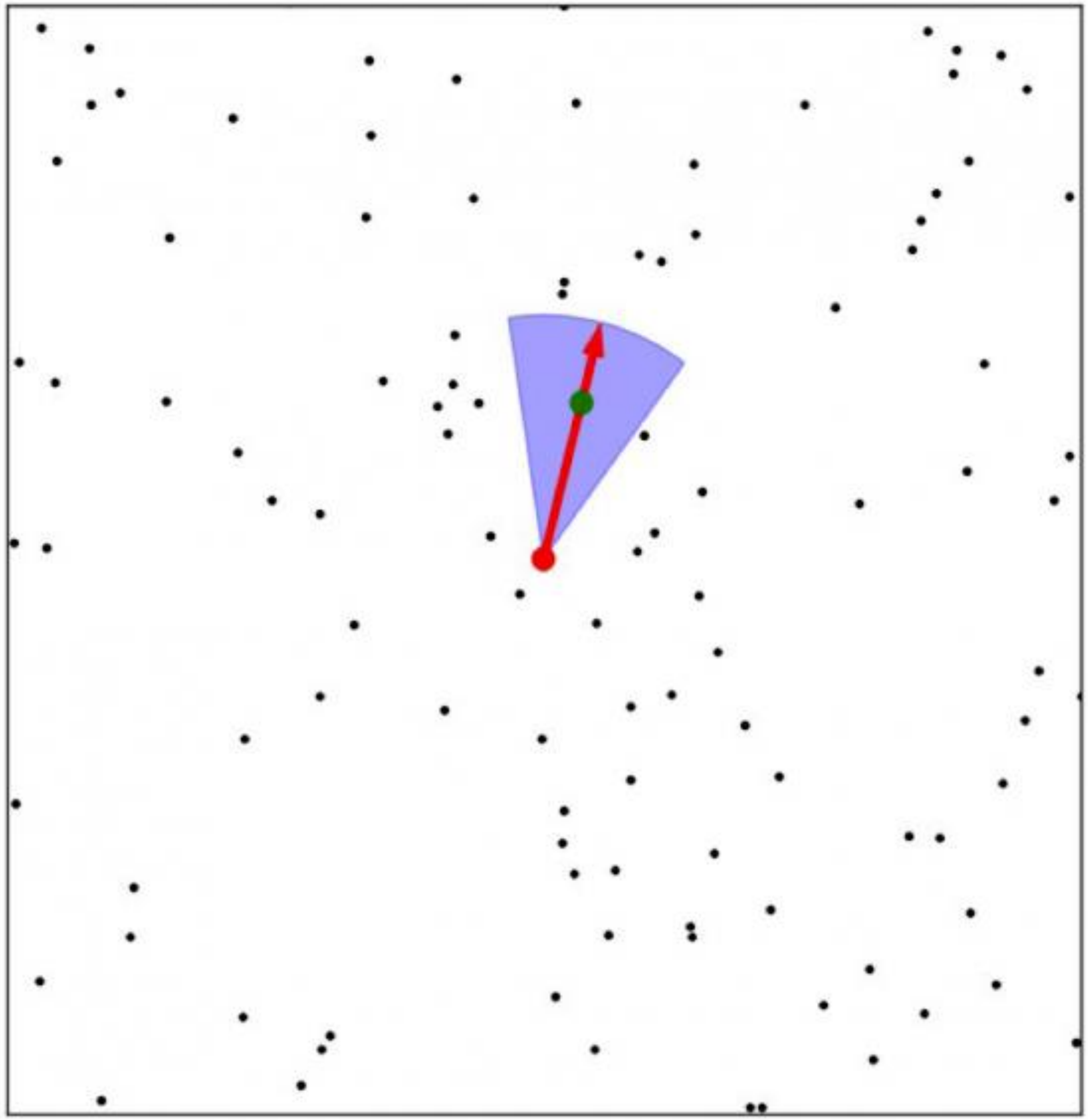

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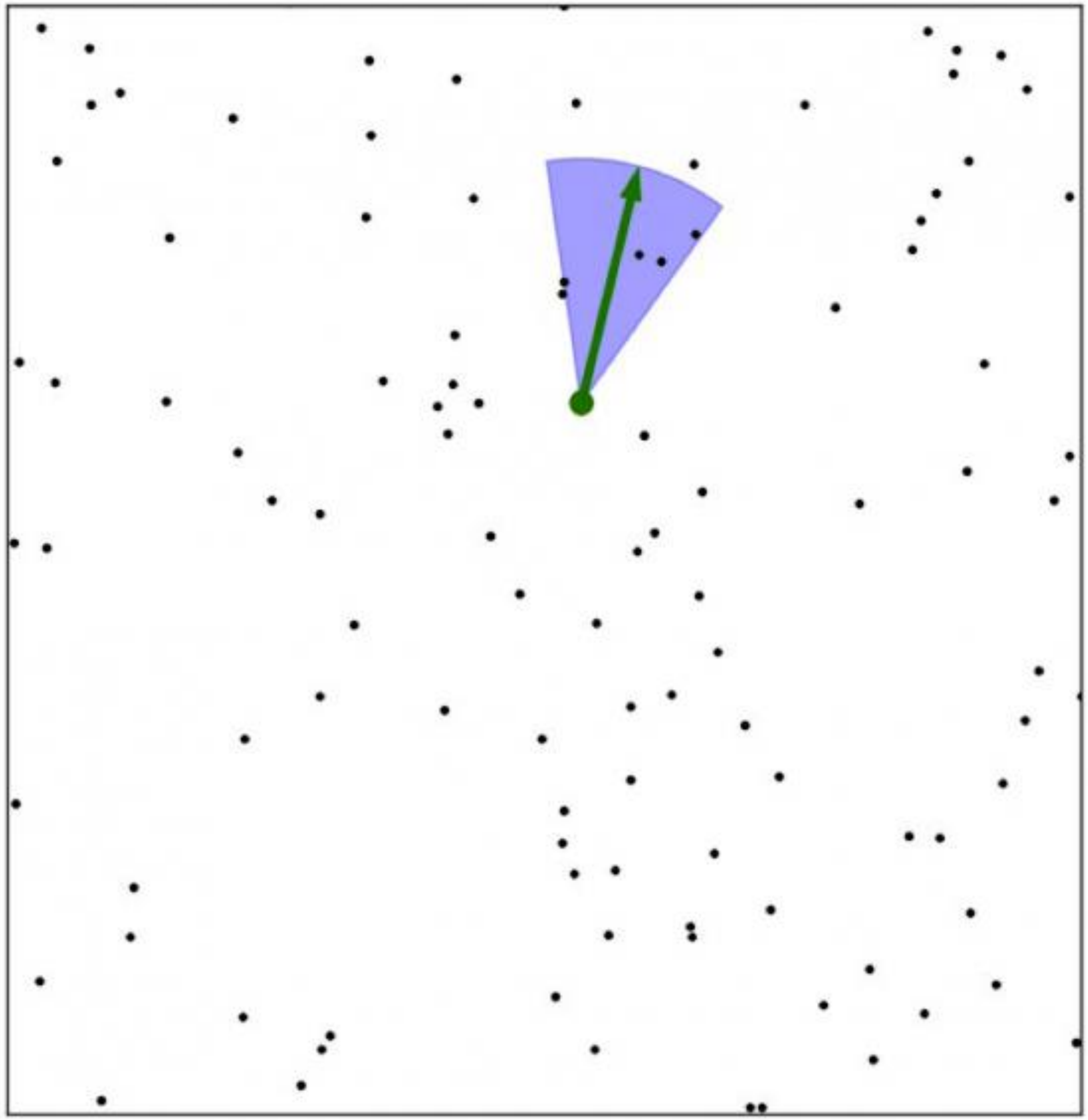


Radiation-hydrodynamical simulations of reionisation

If the multiphase ISM is unresolved, then for each resolution we need to:

- Calibrate subgrid stellar feedback to fit luminosity function
- Calibrate subgrid escape fraction (i.e. luminosities) to desired reionisation history

This is done in the Aurora project (Rahmati talk)

But let's first see what we get without calibration…

Spatially adaptive radiation-hydrodynamical simulations of galaxy formation during cosmological reionization

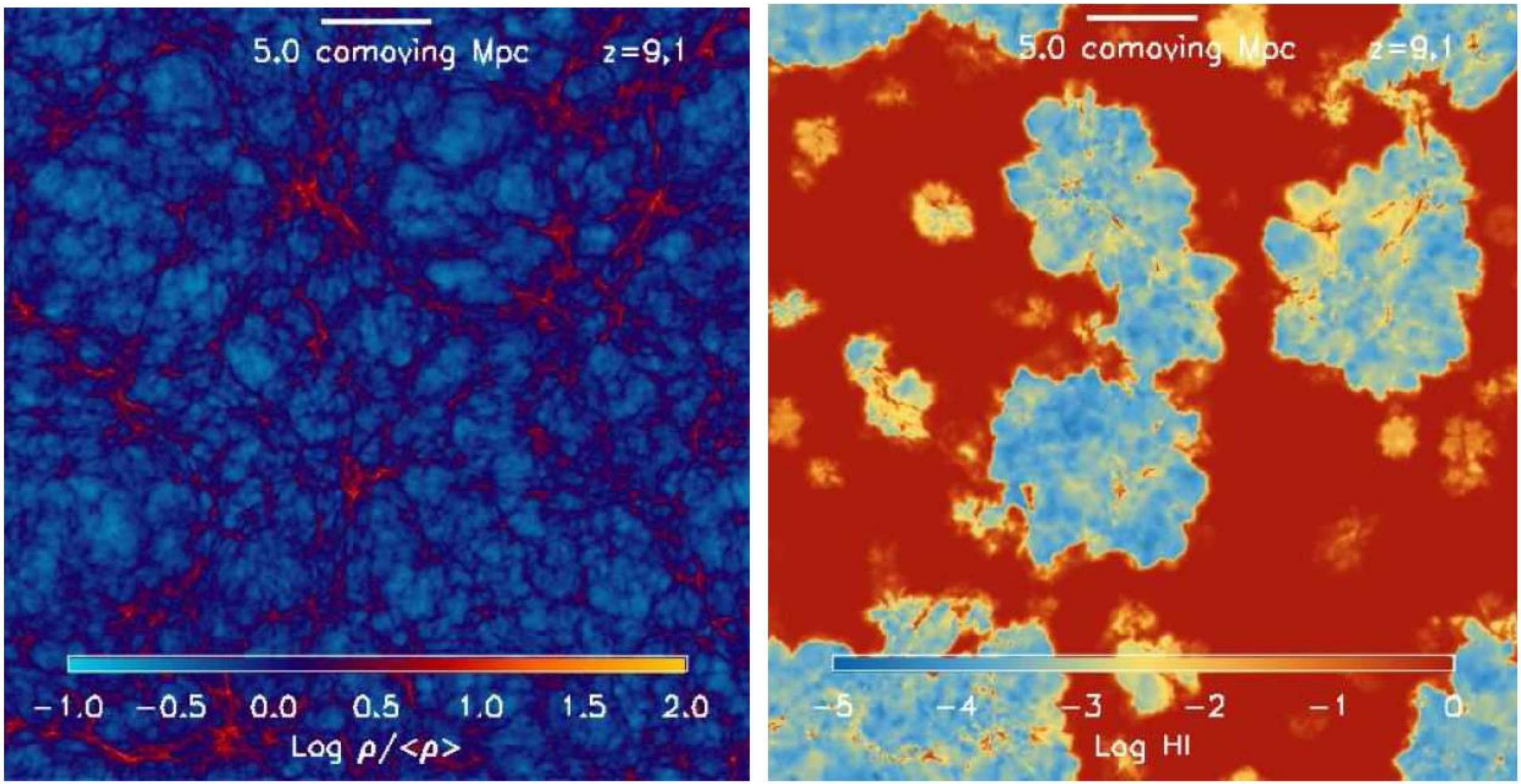
Andreas H. Pawlik[1⋆], Joop Schaye[2], Claudio Dalla Vecchia[3,4]

2015, MNRAS, 451, 1586

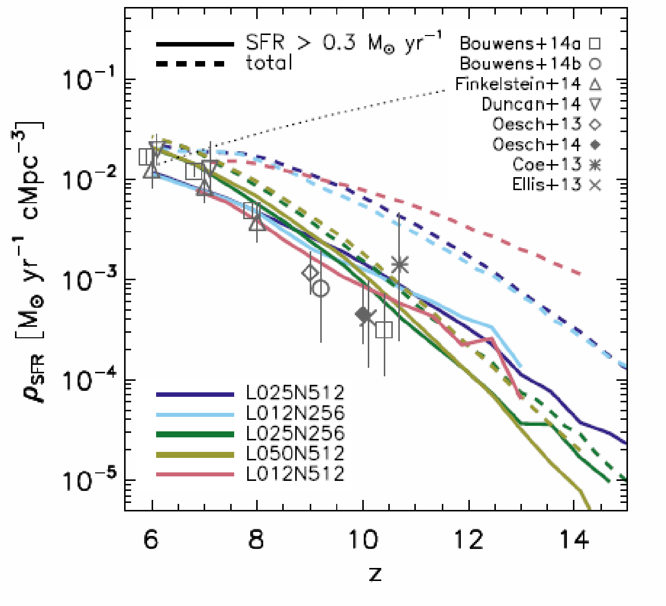
- Spatially adaptive radiation hydrodynamics with TRAPHIC
- Cosmological simulations, box size up to 50 Mpc
- Up to 2×512^3 particles, equivalent to $\sim 13{,}000^3$ uniform grid
- Supernova feedback and photoheating individually turned on and off
- Different box sizes and resolutions
- Feedback underestimated due to finite resolution

Spatially adaptive radiation-hydrodynamical simulations of galaxy formation during cosmological reionization

Andreas H. Pawlik[1*], Joop Schaye[2], Claudio Dalla Vecchia[3,4]



Global evolution: Box size and resolution



Pawlik, JS & Dalla Vecchia (2015)

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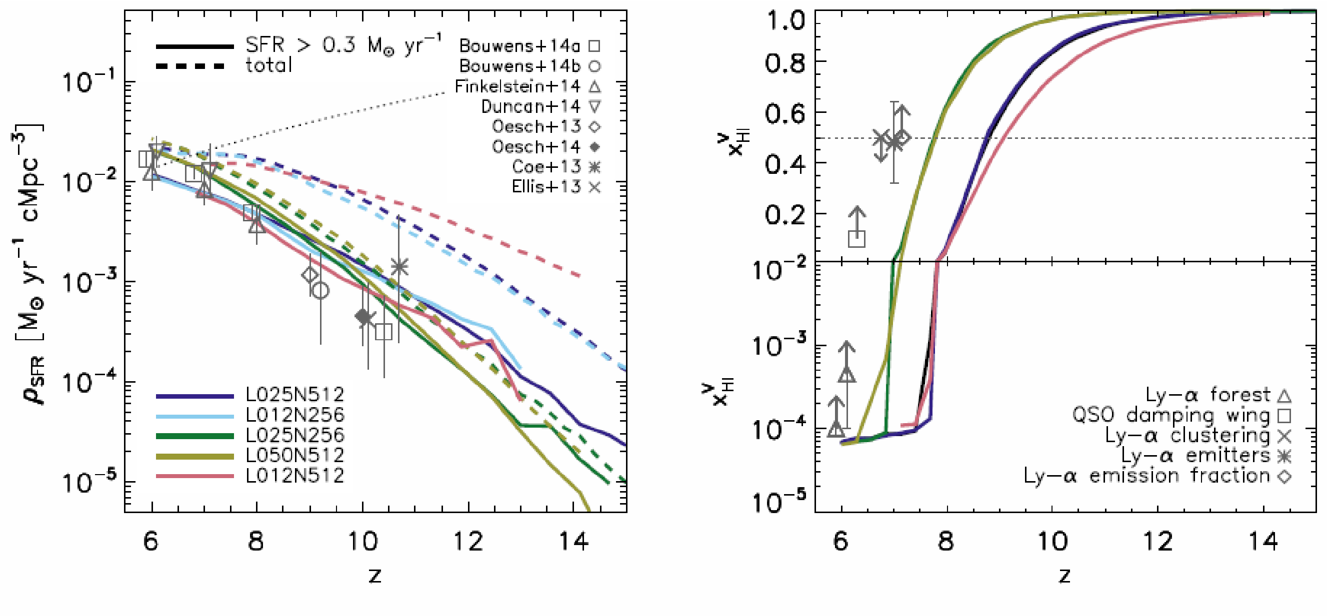

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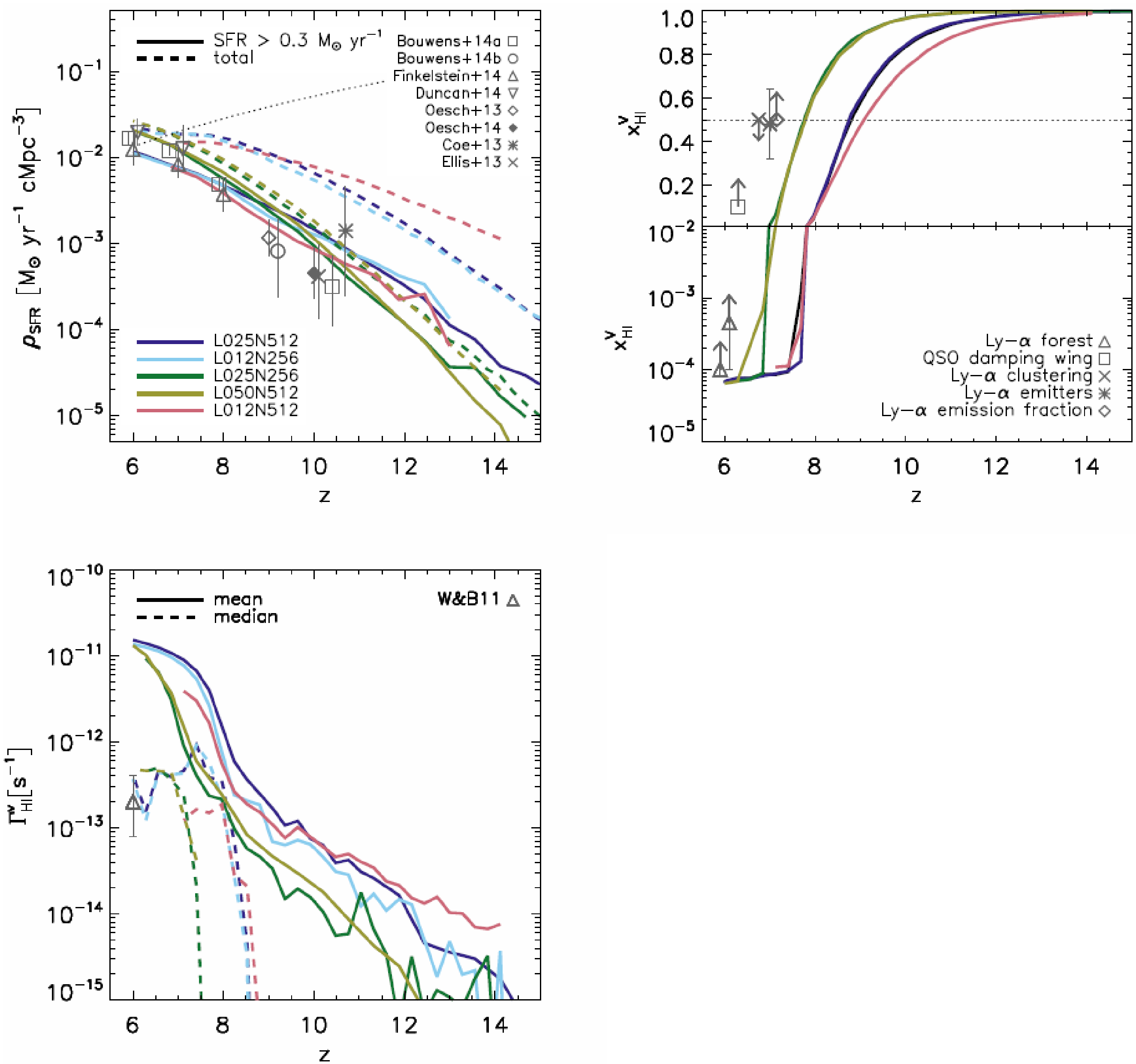

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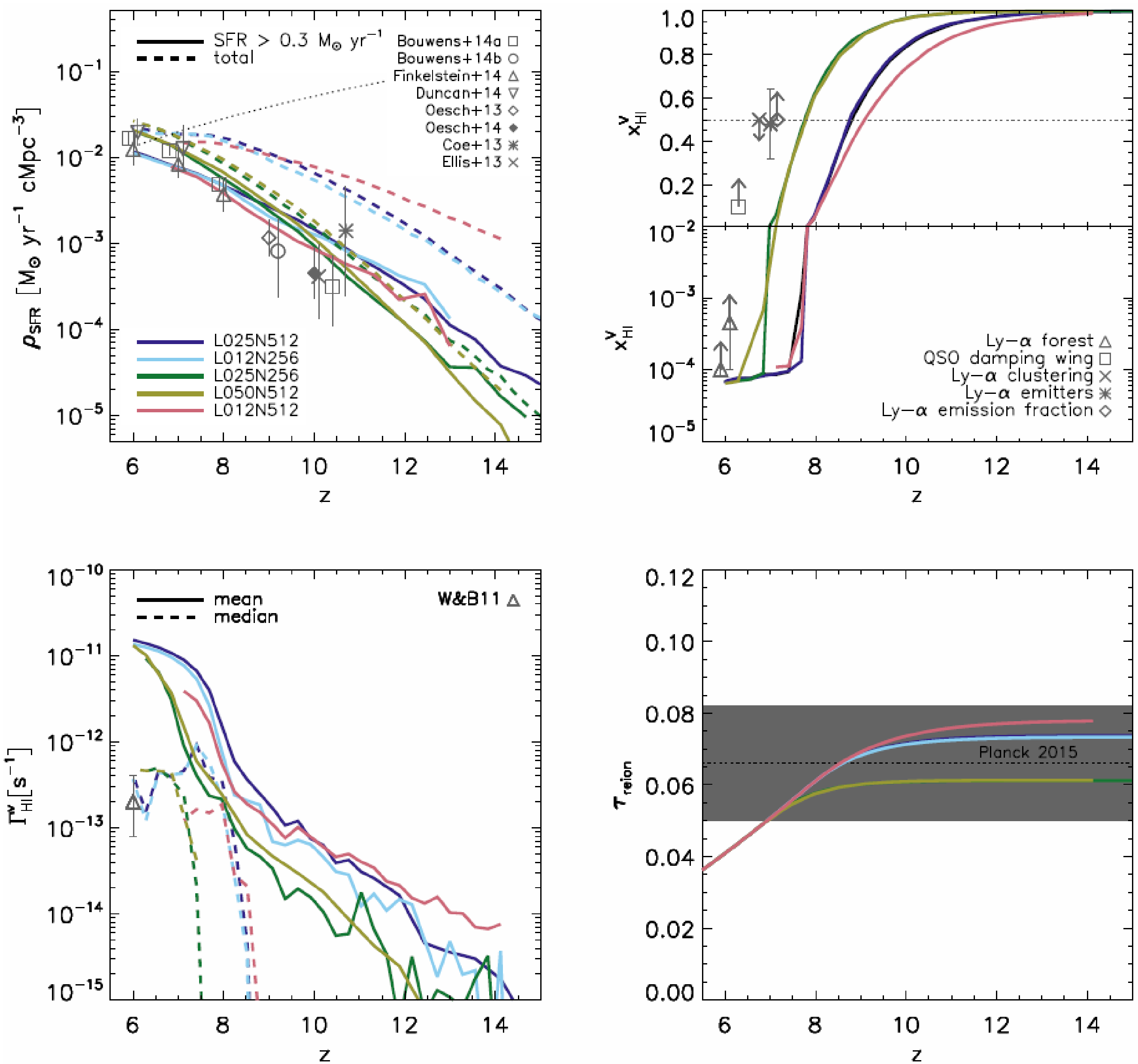
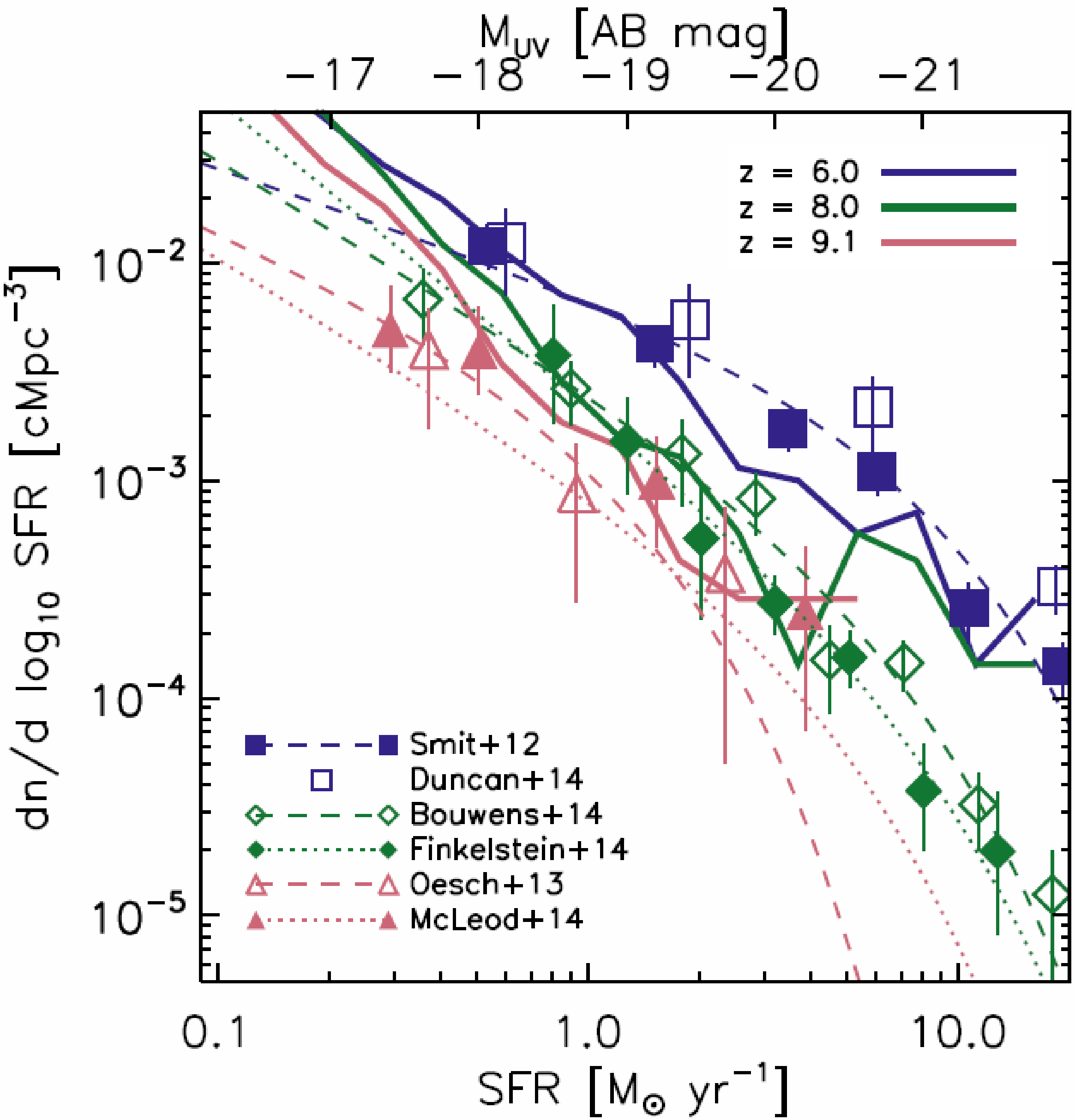


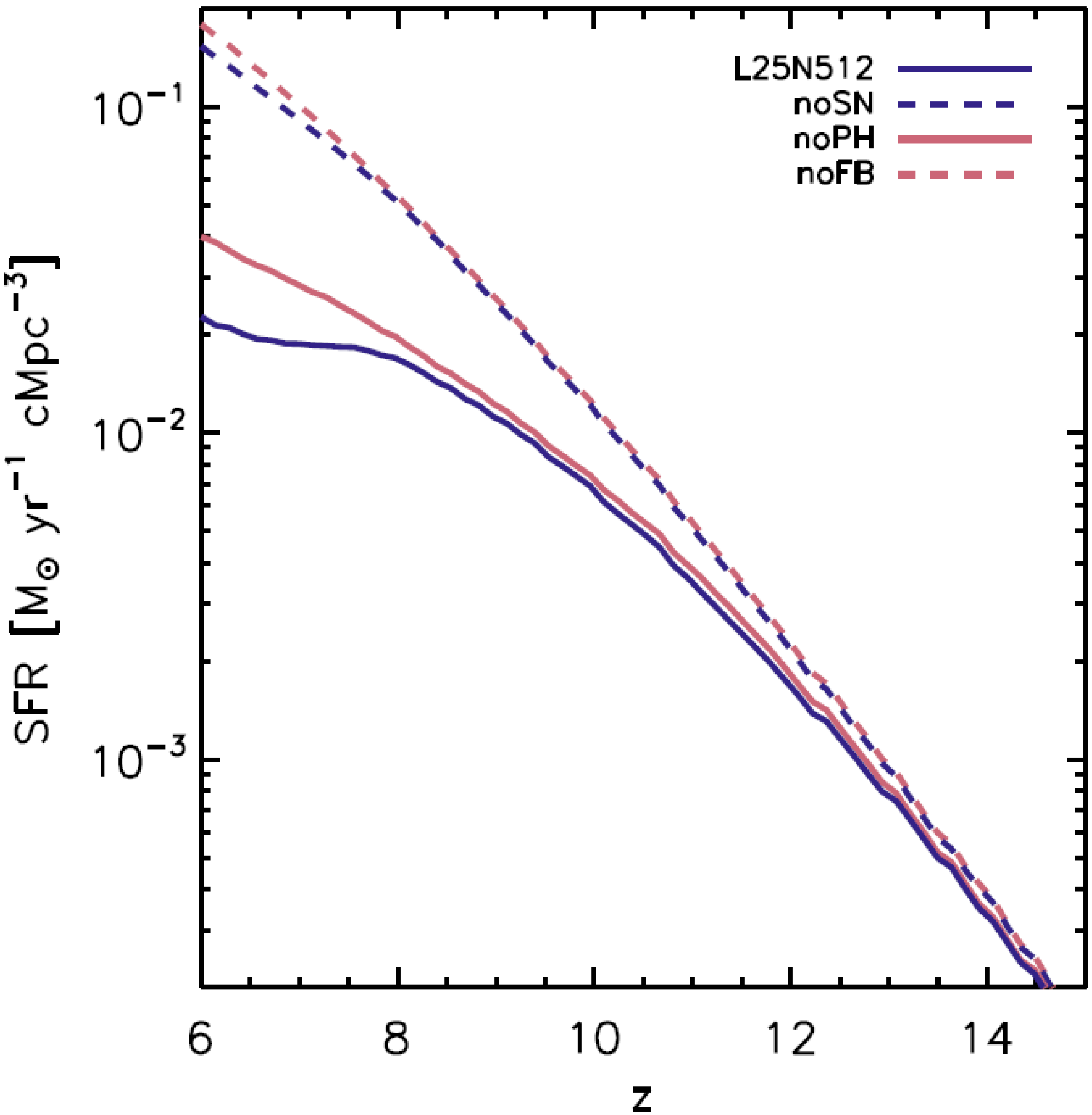
Pawlik, JS & Dalla Vecchia (2015)

Evolution of UV Luminosity Function



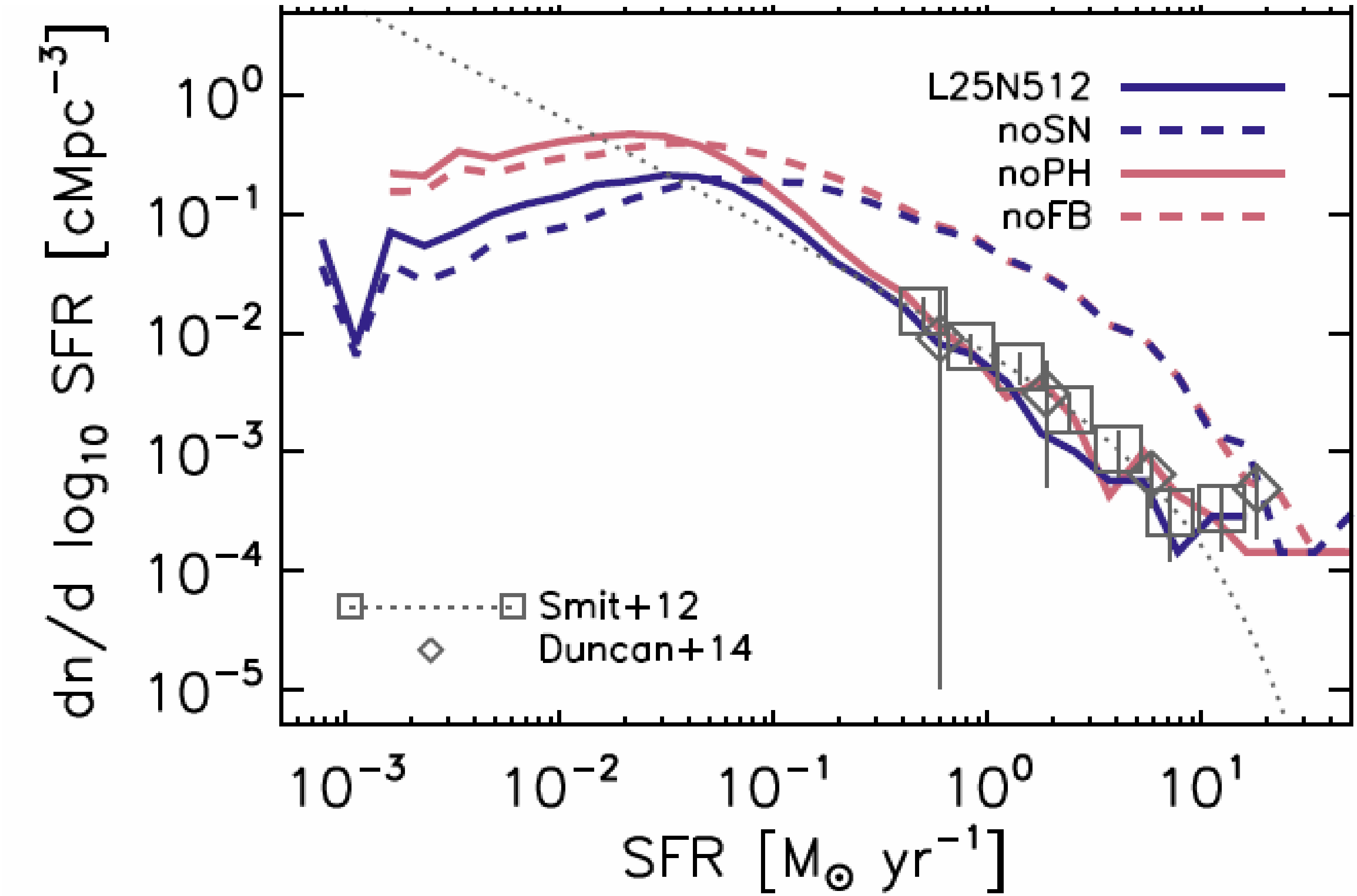
Pawlik, JS & Dalla Vecchia (2015)

Evolution of SFR density



Pawlik, JS & Dalla Vecchia (2015)

Effects of supernovae and photoheating



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Pawlik, JS & Dalla Vecchia (2015)

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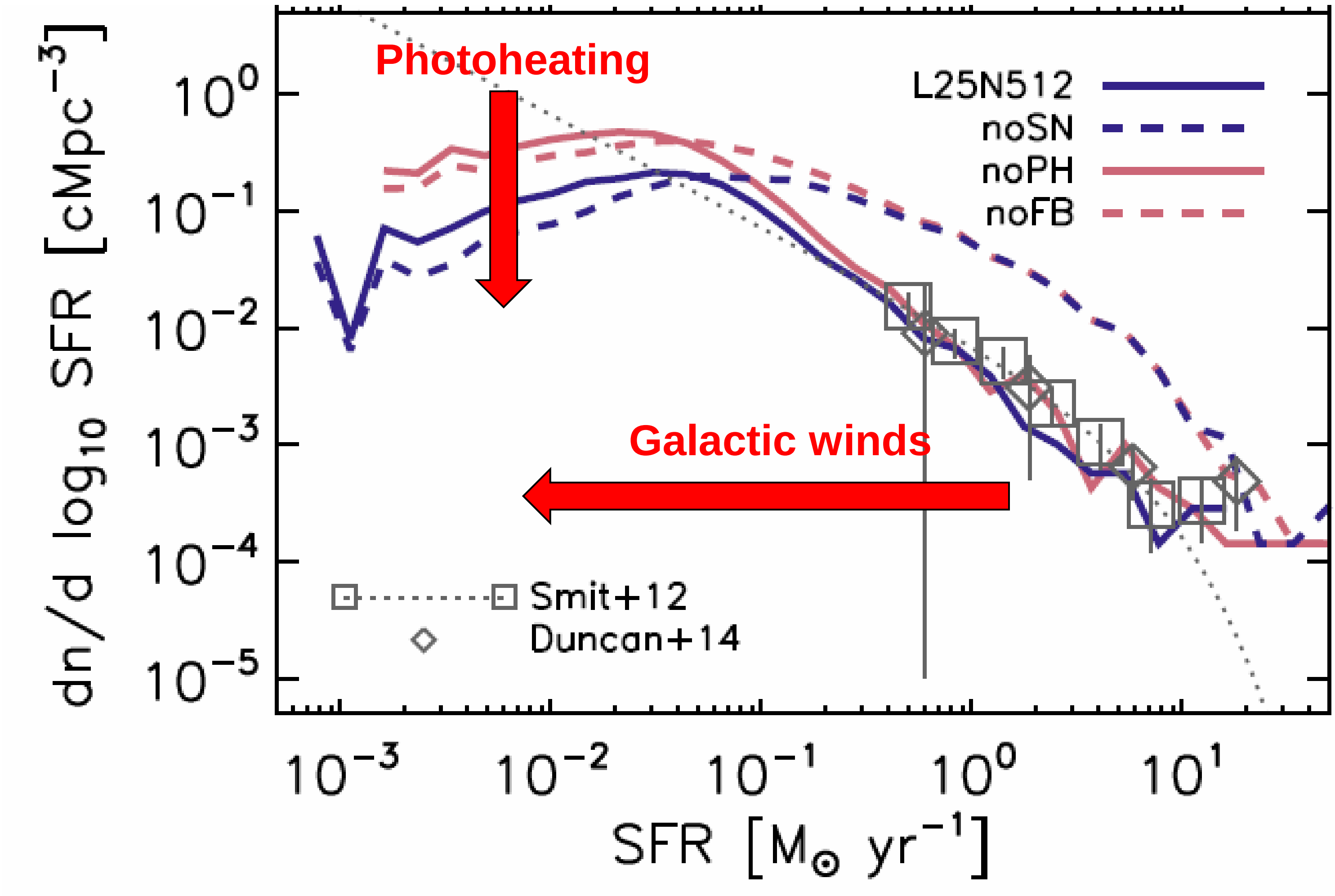

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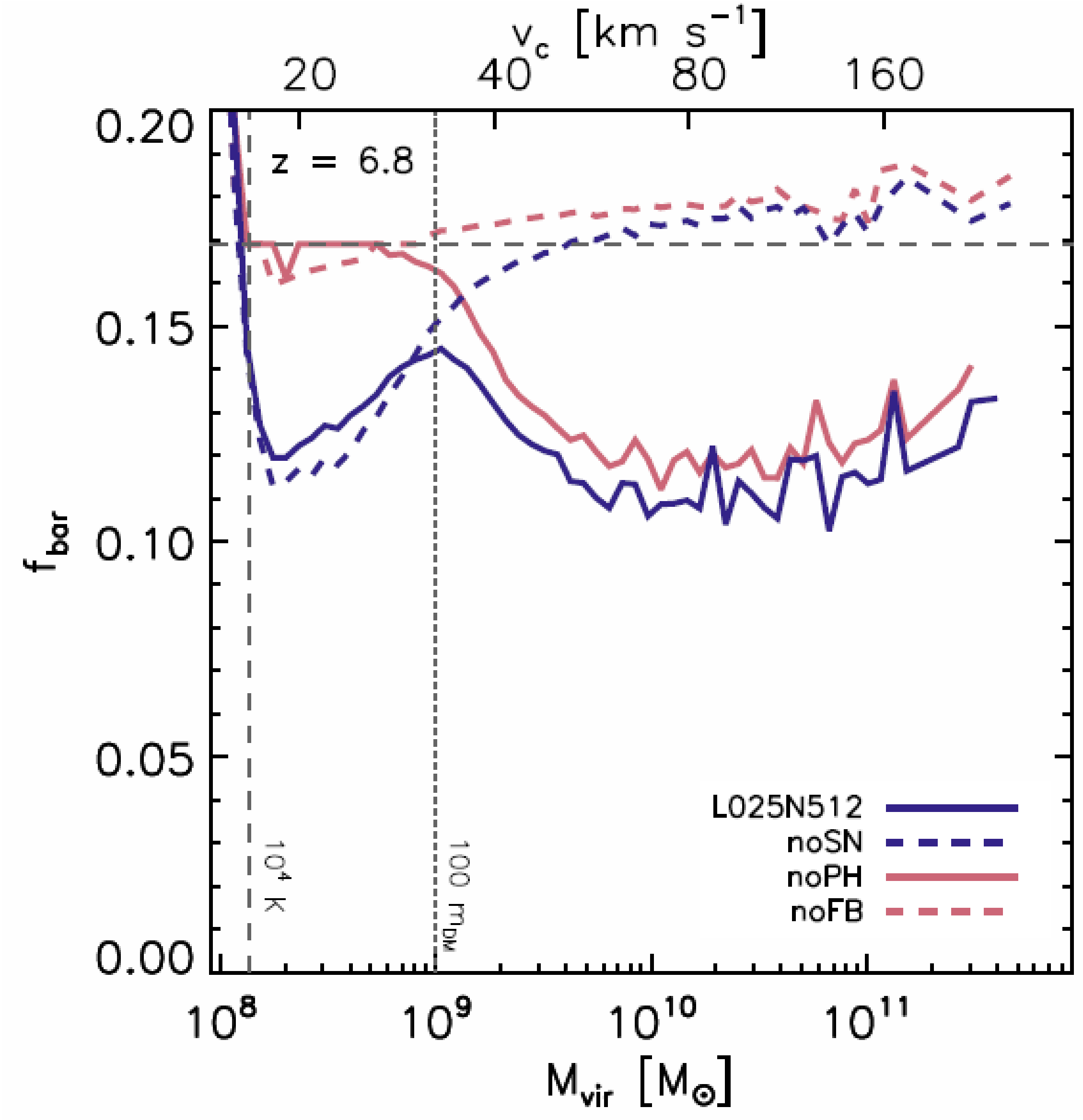
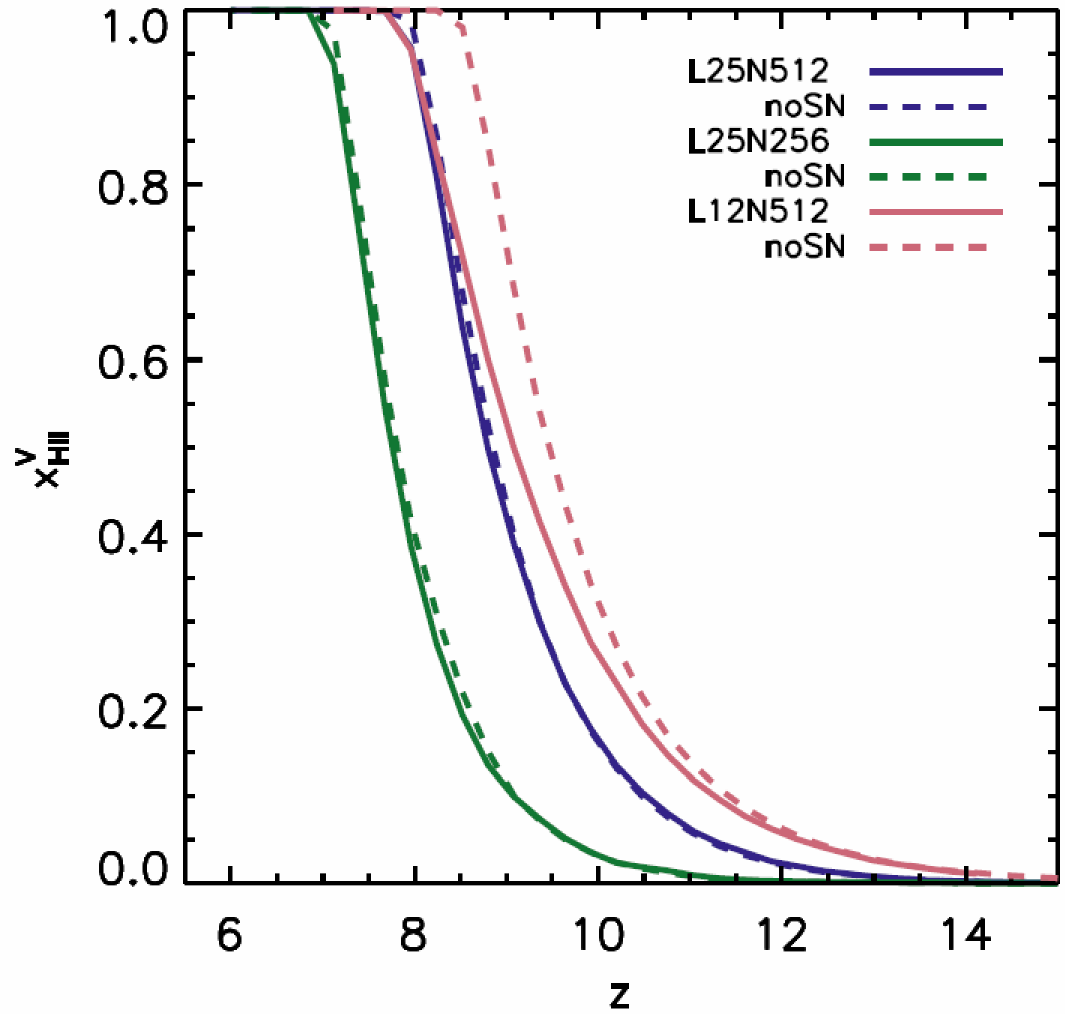


Pawlik, JS & Dalla Vecchia (2015)

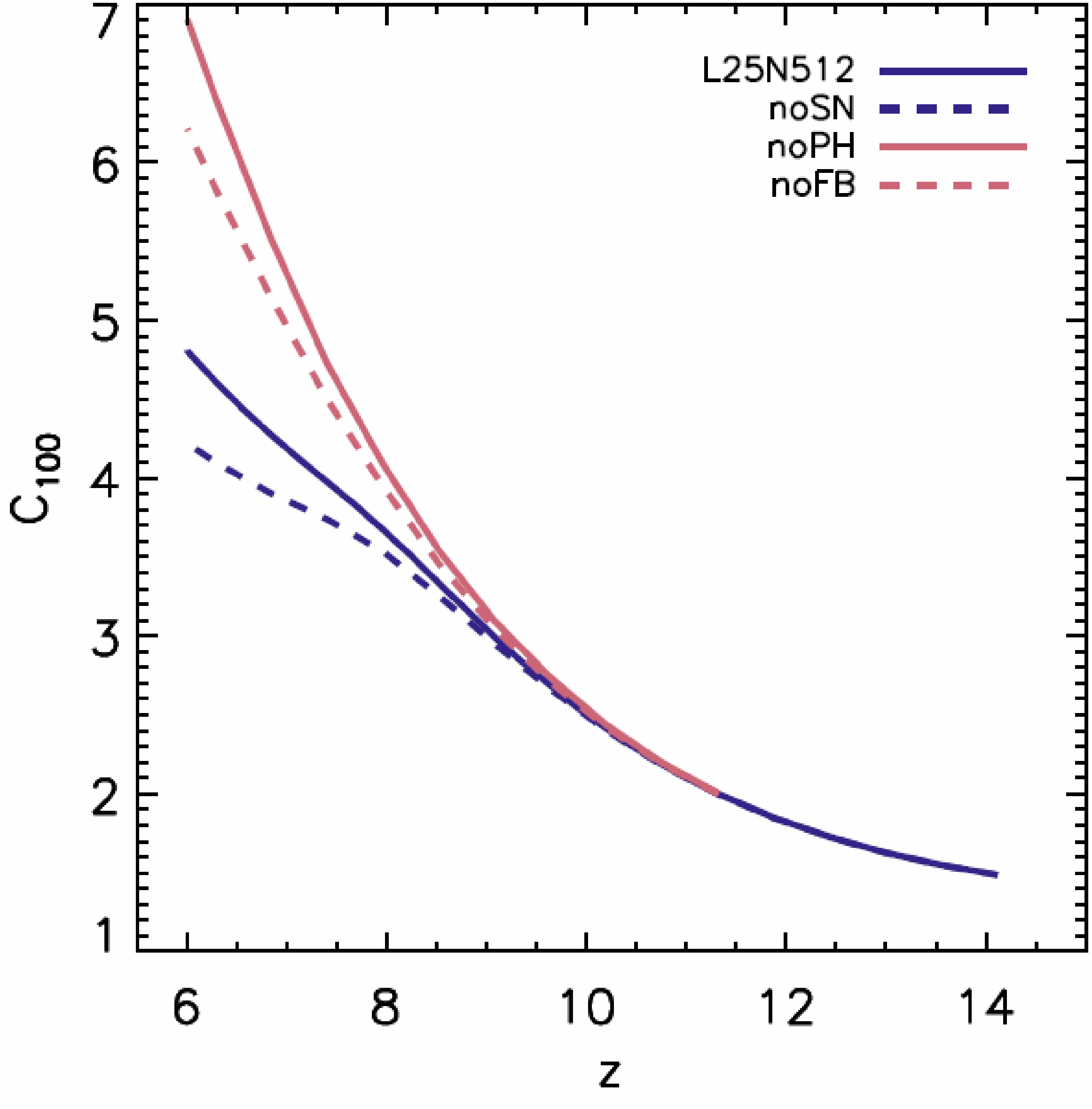
Reionisation history: Feedback and resolution



Winds reduce SFR, but increase escape fraction

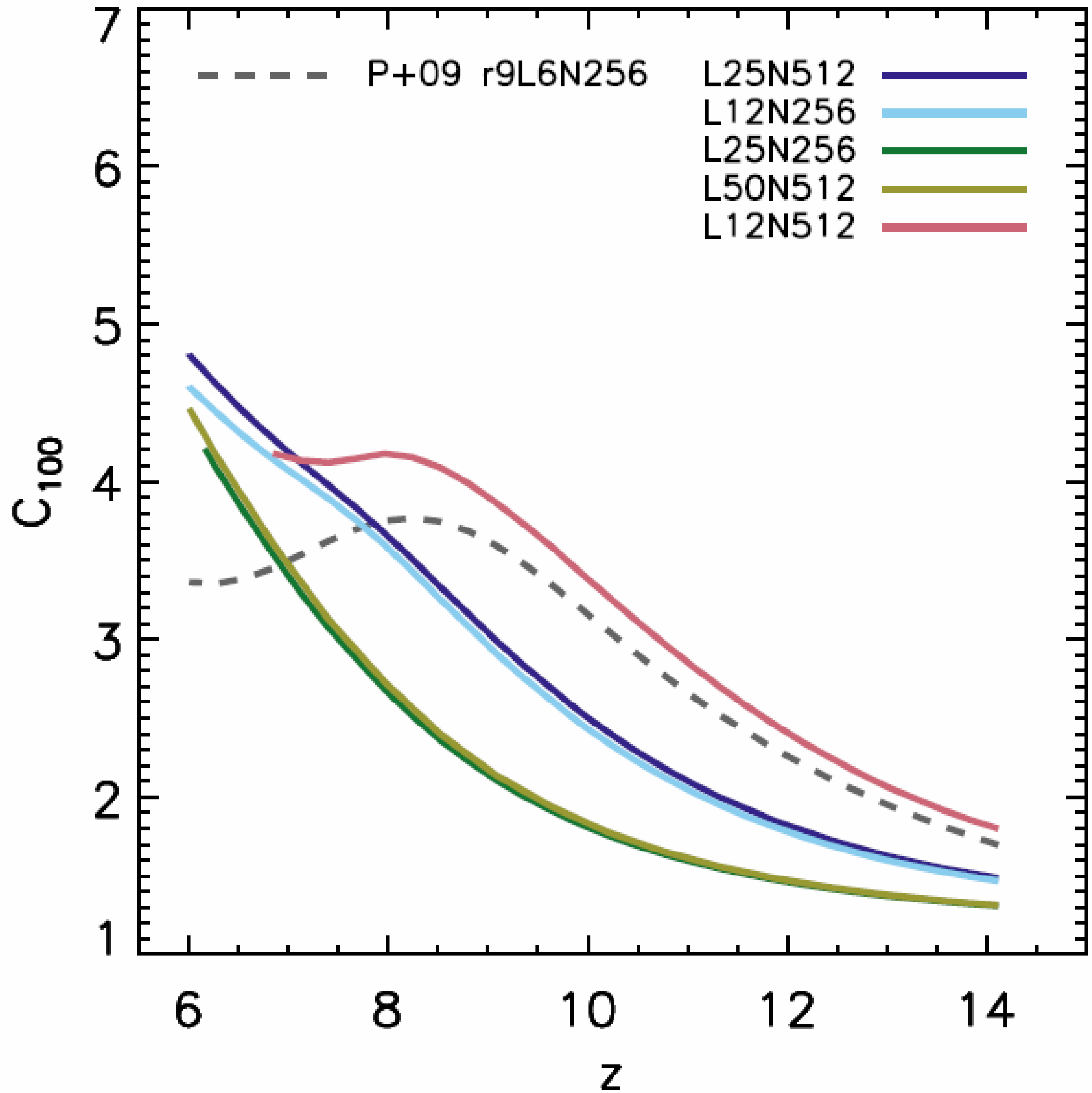
Pawlik, JS & Dalla Vecchia (2015)

Clumping factor: Effect of feedback



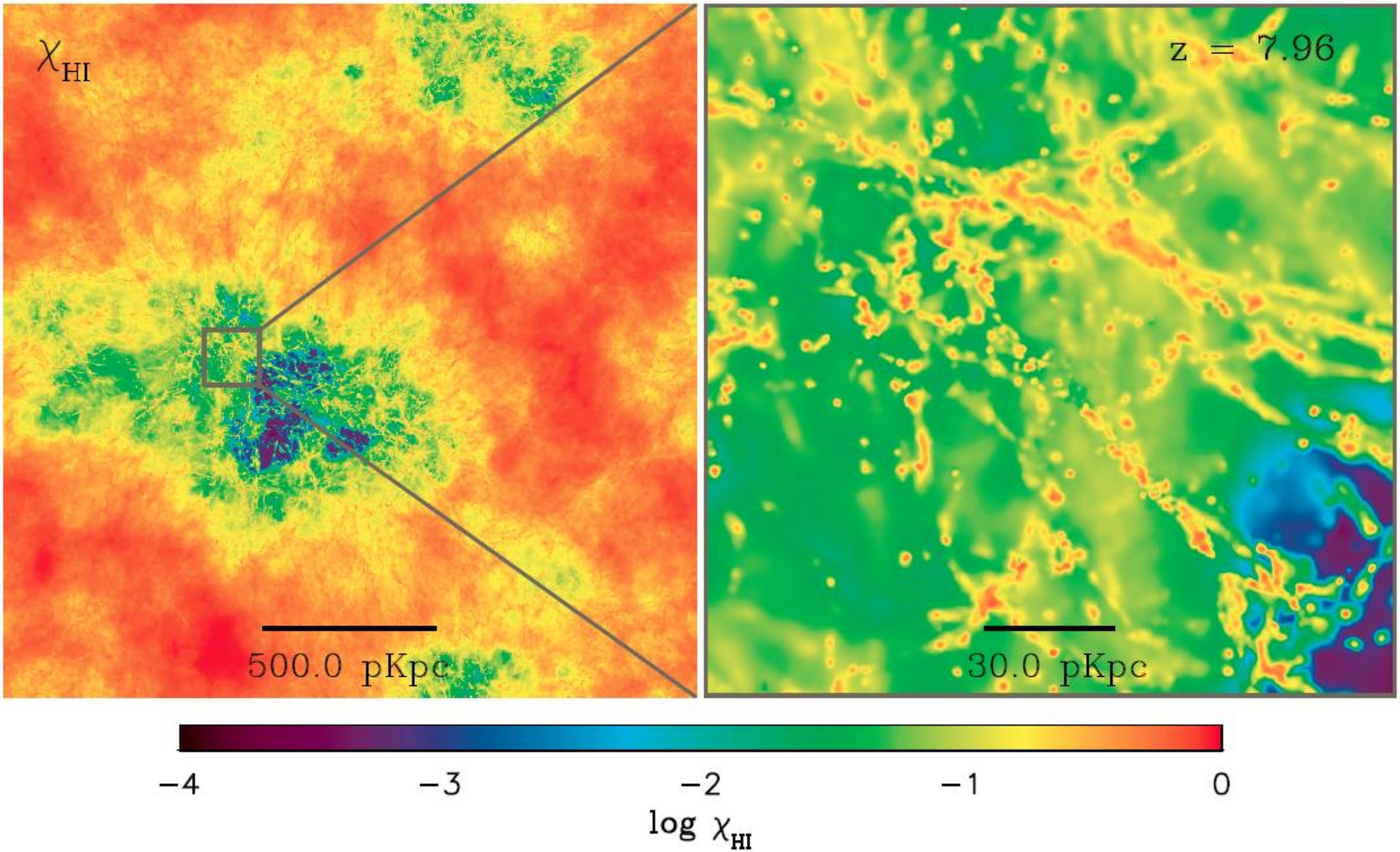
Pawlik, JS & Dalla Vecchia (2015)

Clumping factor: Box size and resolution



Pawlik, JS & Dalla Vecchia (2015)

The Aurora project



Pawlik, Rahmati, JS+ (2016)

The Aurora project

Improvements relative to Pawlik+ ‘15:

- Up to 2×1024^3 particles
- Time step limiter
- Includes helium in the (non-equil.) chemistry
- Includes metal enrichment (but not metal cooling)
- Metallicity-dependent luminosities
- Subgrid stellar feedback and escape fraction calibrated to yield the same results at different resolutions

Pawlik, Rahmati, JS+ (2016)

Conclusions

- Cosmological radiative transfer simulations cannot predict the star formation history, escape fraction, and reionization history
- Need to calibrate stellar feedback and subgrid escape fraction (for each resolution)
- Photoheating has both negative and positive effects on reionization
- Spatially adaptive simulations are starting to capture the effects of photoheating
- Galactic winds increase the escape fraction
- Clean separation as a function of mass between the effects of winds and photo-heating (but might be due to limited resolution!)
- Let us know if you are interested in TRAPHIC and/or Aurora