Cosmic chemical evolution Workshop,
St. Michael's, June 4th 2010

WHIM emission as a tracer of star formation and feedback

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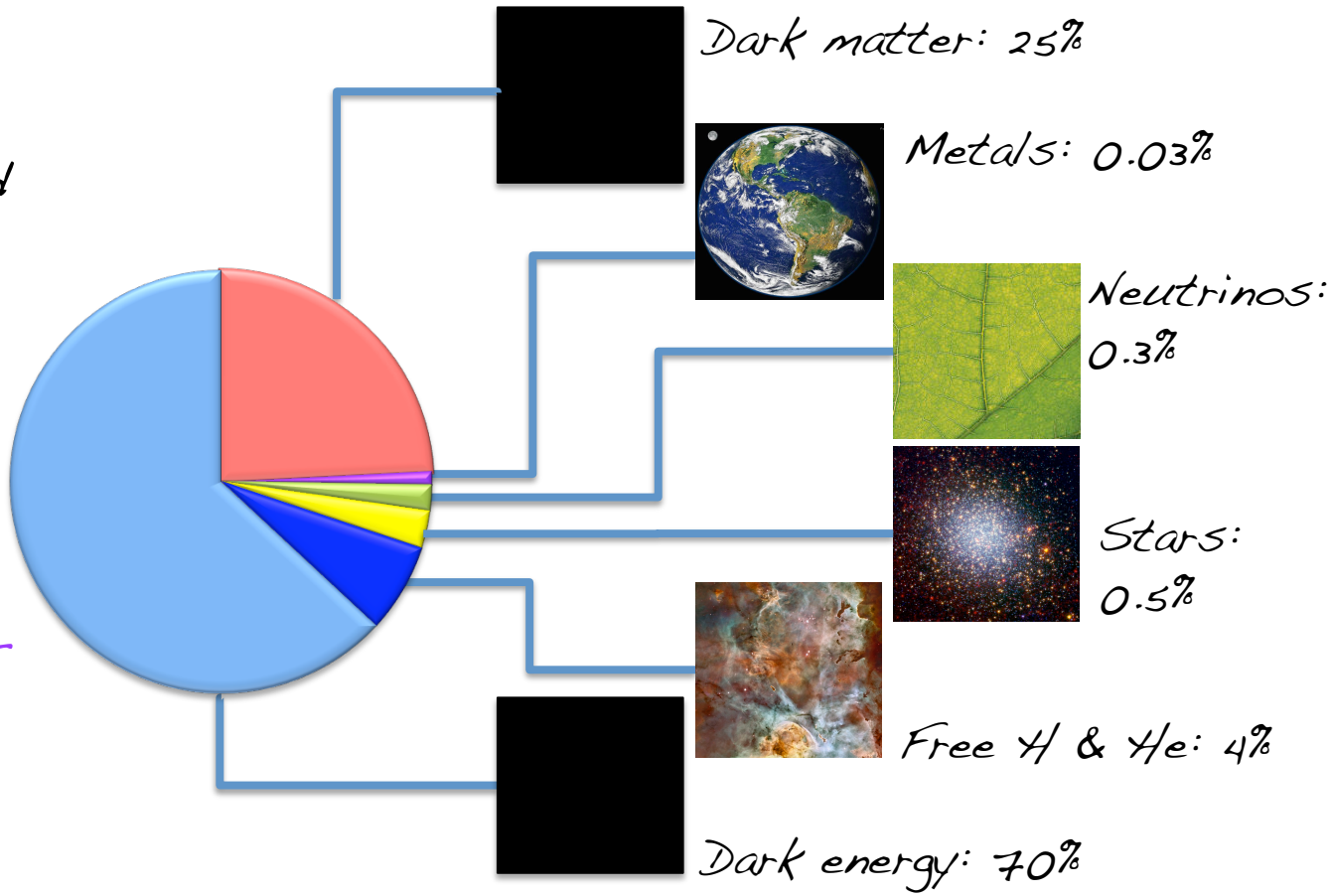
& the OWLS Team

Bertone et al 2010a,b
arXiv:0910.5723
arXiv:1002.3393

Intergalactic medium: Why do we care?

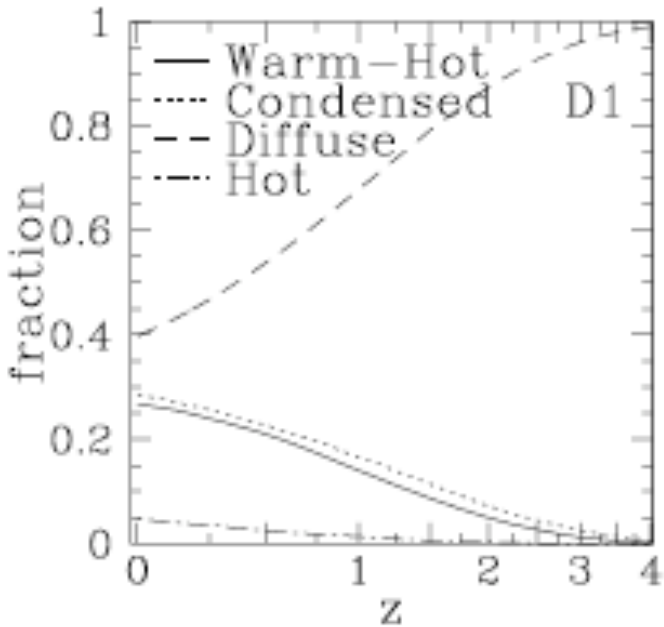
- unbiased info on matter power spectrum on largest scales
- reservoir of fuel for star and galaxy formation
- IGM metallicity constrains the cosmic SF history
- interplay IGM-feedback puts constraints on galaxy formation models

> 90% of baryonic mass is in diffuse gas
(Persic & Salucci 1992, Fukugita et al 1998, Cen & Ostriker 1999)



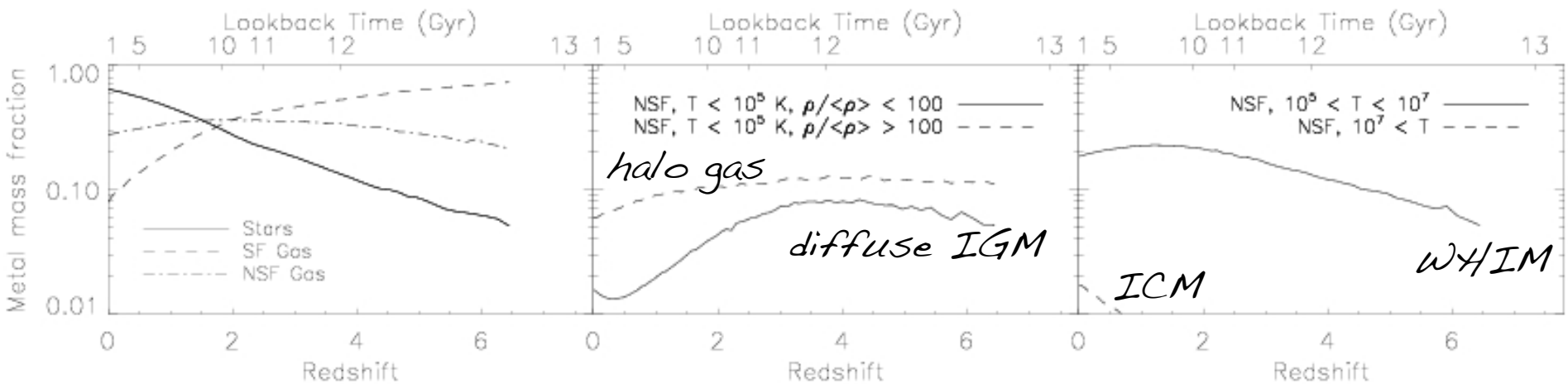
Mass and metal fractions evolution

IGM mass - Davè et al. 2001



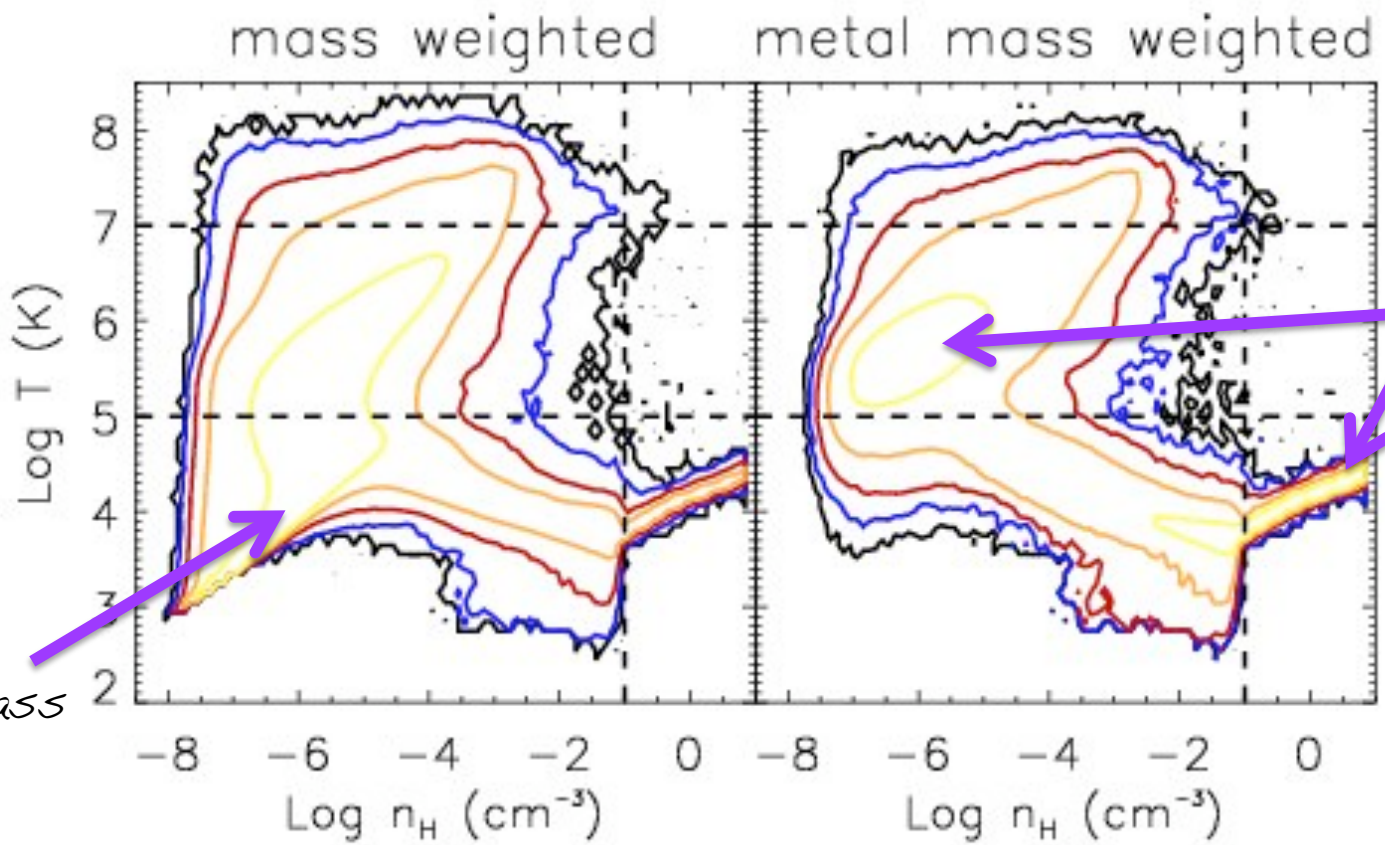
- Average IGM temperature increases with time
- Most metals locked in stars at z=0
- Average metal temperature increases with time

Metal mass - Wiersma et al 2009



IGM mass and metals

The bulk of the metal mass does not trace the bulk of the IGM mass



most mass

z=0.25

Bertone et al. 2010a (see also Wiersma et al 2009,2010)

Outline

- Introduction:
  - ✓ OWLS simulations
- Results:
  - ✓ X-ray & UV emission at z<1
  - ✓ what gas does emission trace?
  - ✓ dependence on physics

OWLS

OverWhelmingly Large Simulations

The OWLS Team:

- Joop Schaye (PI, Leiden)
- Claudio Dalla Vecchia (MPE)
- Craig Booth (Leiden)
- Rob Wiersma (MPA)
- Marcel Haas (Leiden)
- Freeke Van De Voort (Leiden)
- Tom Theuns (Durham)
- Serena Bertone (UCSC)
- Ian Mc Carthy (Cambridge)
- Alan Duffy (Perth)
- ...

OWLS

- many runs (>50) with varying physical prescriptions/numerics (Schaye et al 2010)
- cosmological hydrodynamical simulations: Gadget 3
- run on LOFAR IBM Bluegene/L
- two main sets: L=25 Mpc/h and L=100 Mpc/h boxes
- largest runs: 2×512^3 particles
- evolution from z>100 to z=2 or z=0
- WMAP3 cosmology

New physics in OWLS

- New cooling module (Wiersma, Schaye & Smith 2009):
  - ✓ cooling rates calculated element-by-element
  - ✓ photo-ionisation by evolving UV background included
- New star formation (Schaye & Dalla Vecchia 2008):
  - ✓ Kennicutt-Schmidt SF law implemented without free parameters
- Added chemodynamics (Wiersma et al. 2009):
  - ✓ 11 elements followed explicitly (H, He, C, N, O, Ne, Si, Mg, S, Ca, Fe)
  - ✓ Chabrier IMF
  - ✓ SN Ia & AGB feedback
- New wind model (Dalla Vecchia & Schaye 2008):
  - ✓ winds local to the SF event
  - ✓ hydrodynamically coupled

Physics variations in OWLS

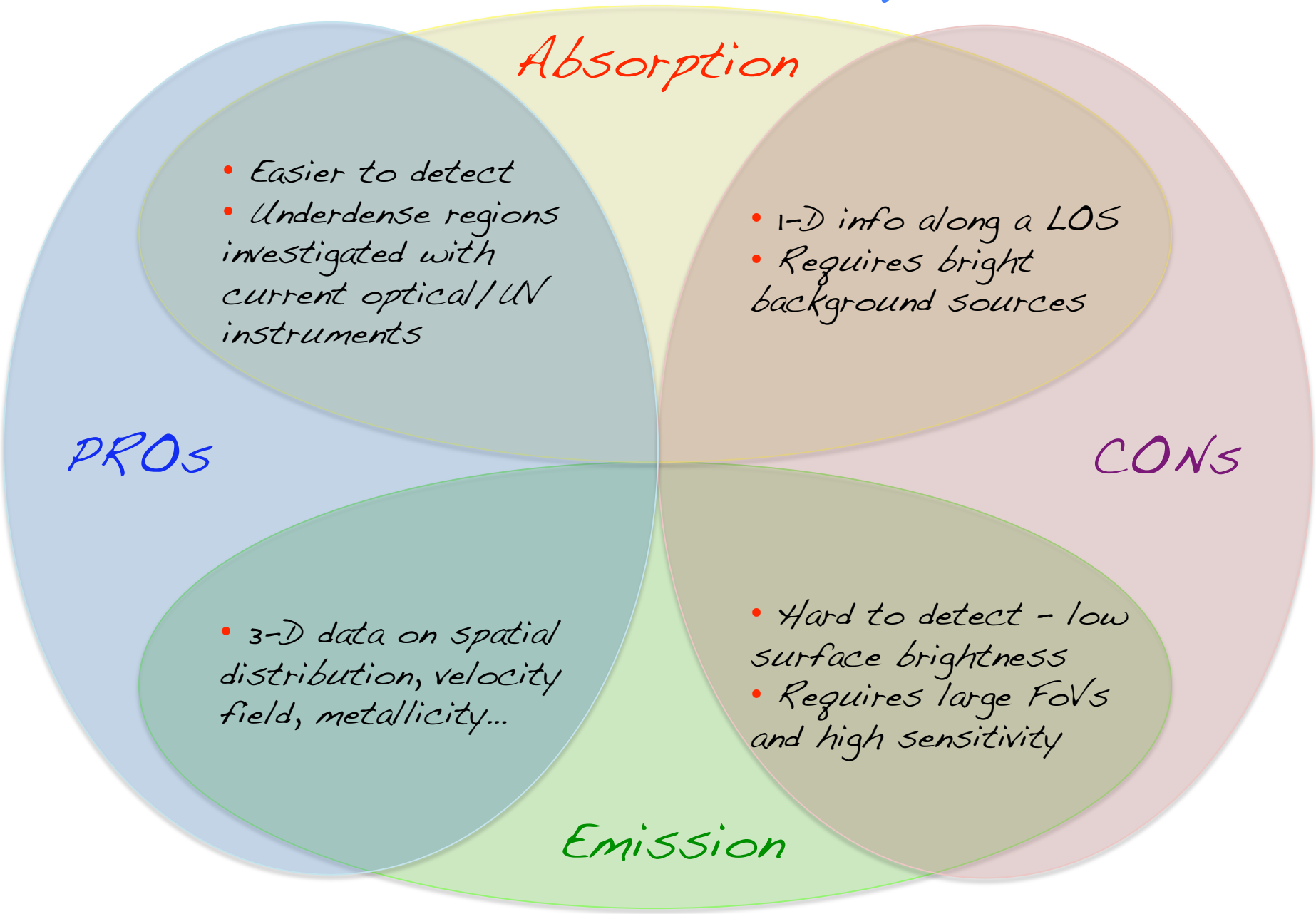
- Cosmology: WMAP1 vs WMAP3 vs WMAP5
- Reionisation & Helium reionisation
- Gas cooling: primordial abundances vs metal dependent
- Star formation:
  - ✓ top heavy IMF in bursts
  - ✓ isothermal & adiabatic EoS
  - ✓ Schmidt law normalisation
  - ✓ Metallicity-dependent SF thresholds
- Feedback:
  - ✓ no feedback
  - ✓ feedback intensity: mass loading, initial velocity...
  - ✓ feedback implementation
  - ✓ AGN feedback
- Chemodynamics:
  - ✓ Chabrier vs Salpeter IMF
  - ✓ SN Ia enrichment
  - ✓ AGB mass transfer

Schaye et al 2010

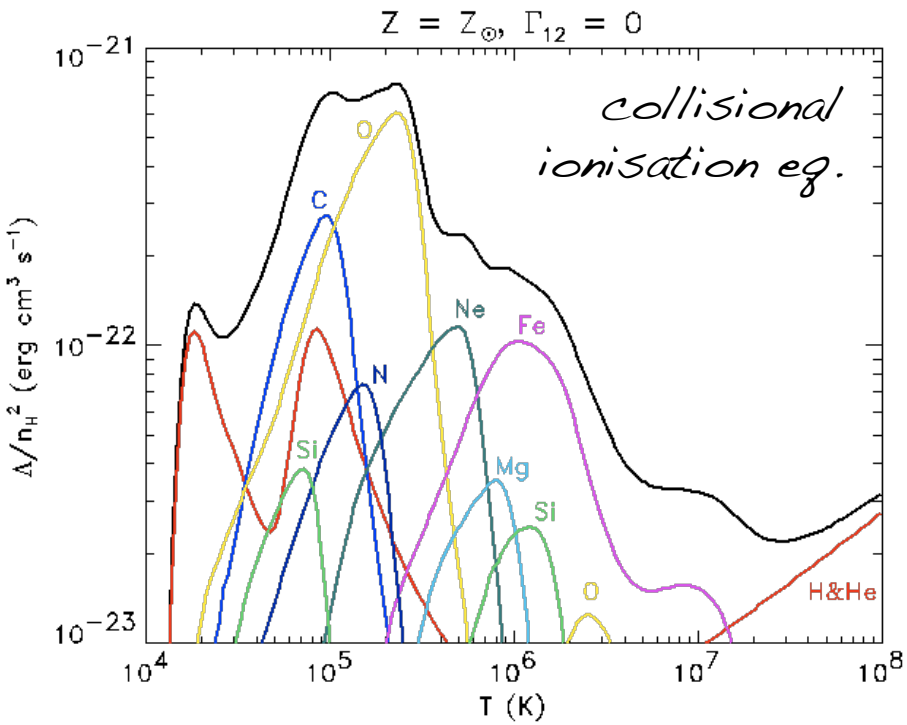
Emission at $z<1$

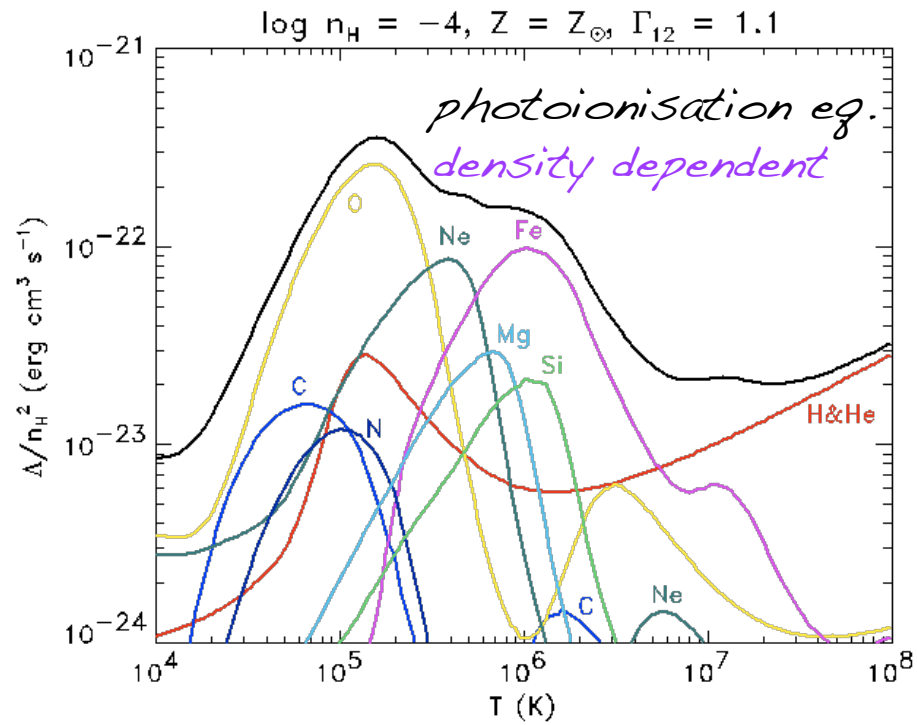
Soft X-rays & UV lines

Emission vs. Absorption



Gas cooling rates



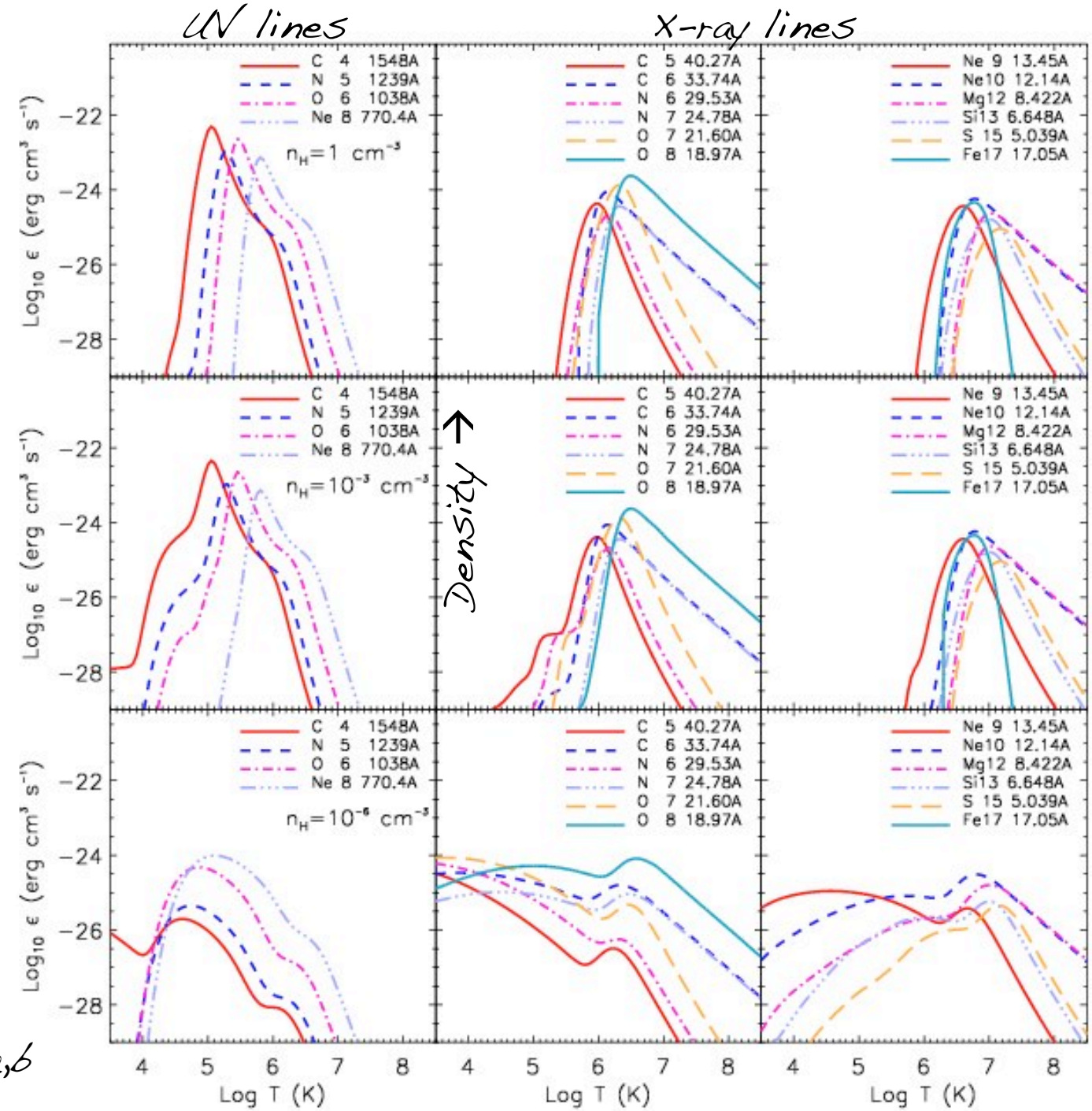


Wiersma, Schaye & Smith 2009

- Photo-ionisation by X-ray/UV BK (Haardt & Madau 2001) + collisional ionisation equilibrium
- Cooling rates calculated element by element for 11 species: takes into account changes in the relative abundances

Gas emissivity

- Same assumptions as cooling rates
- UV emissivities higher than X-ray ones



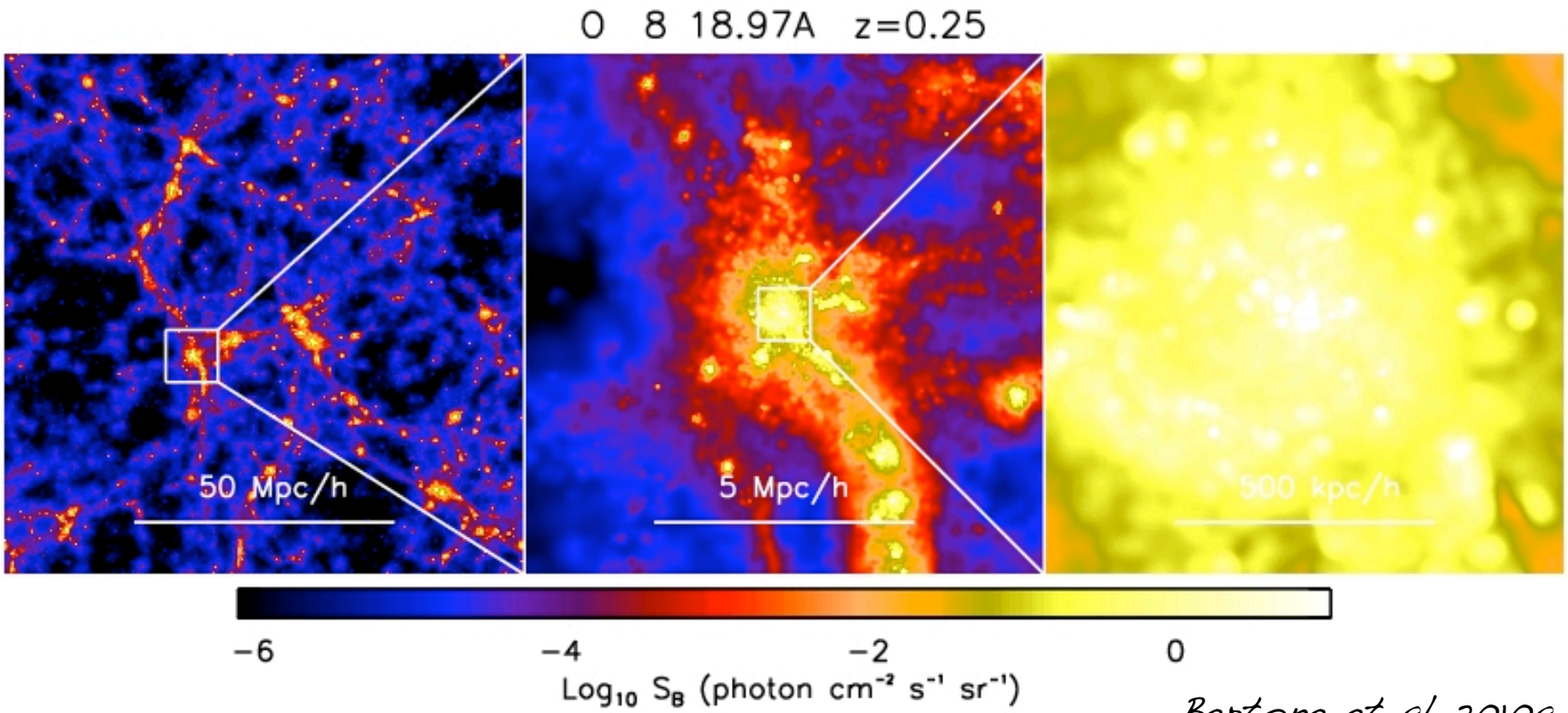
z=0.25

Bertone et al 2010a,b

Emission at low redshift: X-rays

100 Mpc/h boxes
20 Mpc/h thick slices
15" angular resolution

12 X-ray + 6 UV lines



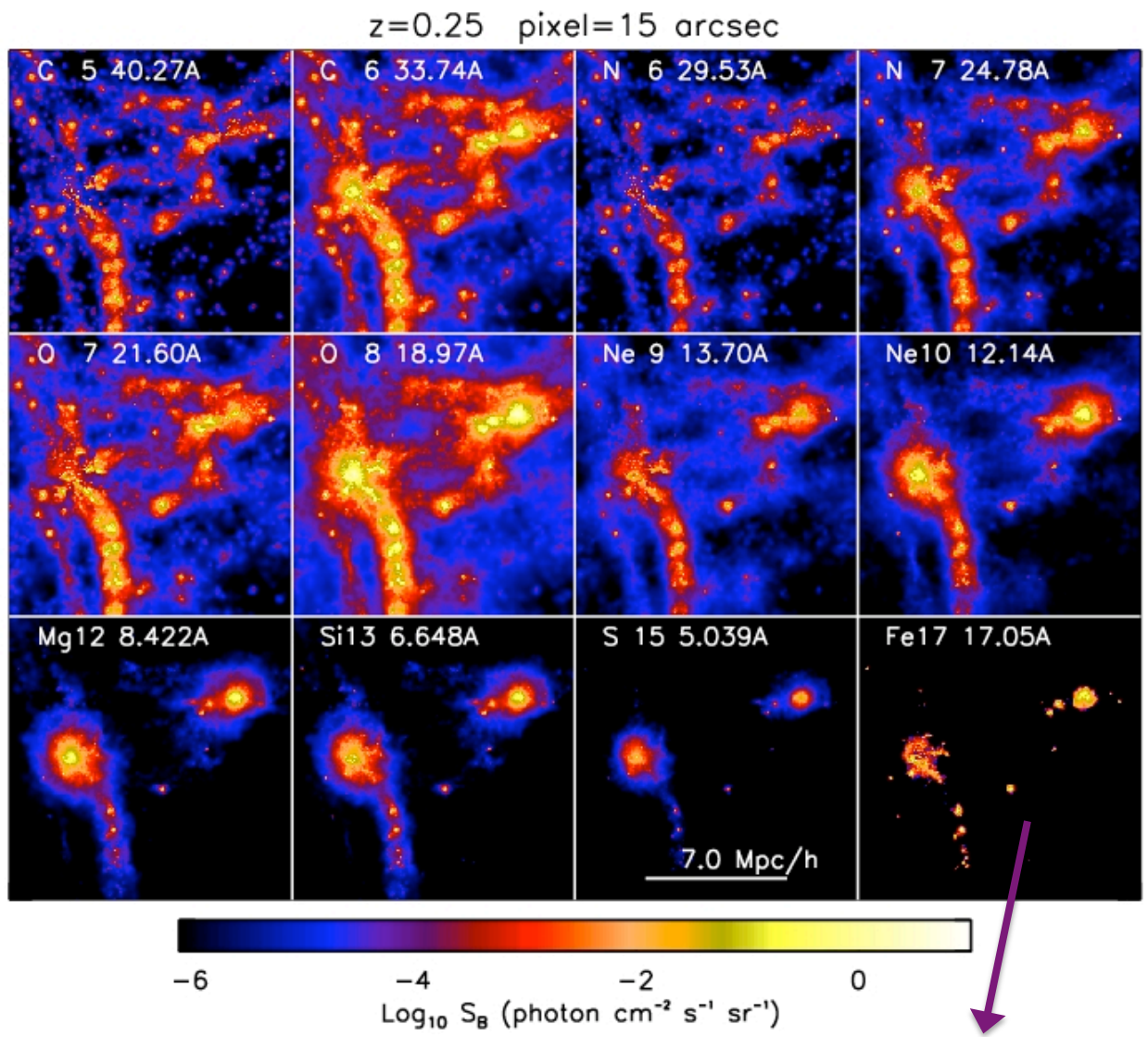
Bertone et al 2010a

X-ray lines

- O VIII strongest line

- lines from lower ionisation states and whose emissivity peaks at lower temperatures trace moderately dense IGM: C V, C VI, N VII, O VII, O VIII and Ne IX

- lines from higher ionisation states trace denser, hotter gas: C VI, O VIII, Ne X, Mg XII, Si XIII, S XV and Fe XVII



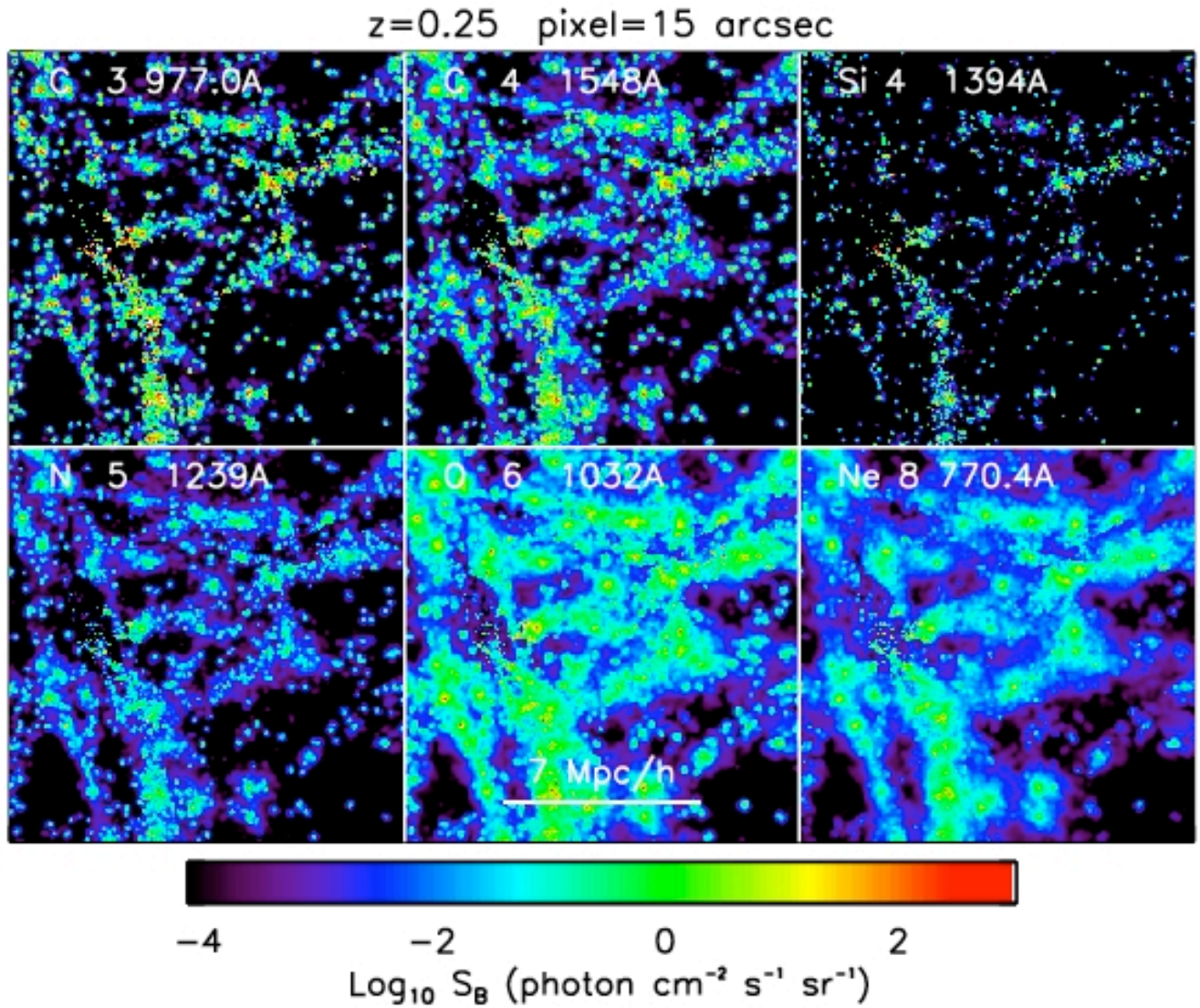
- Fe XVII emission has different spatial distribution than other elements: later enrichment by SN Ia

Bertone et al 2010a

UV lines

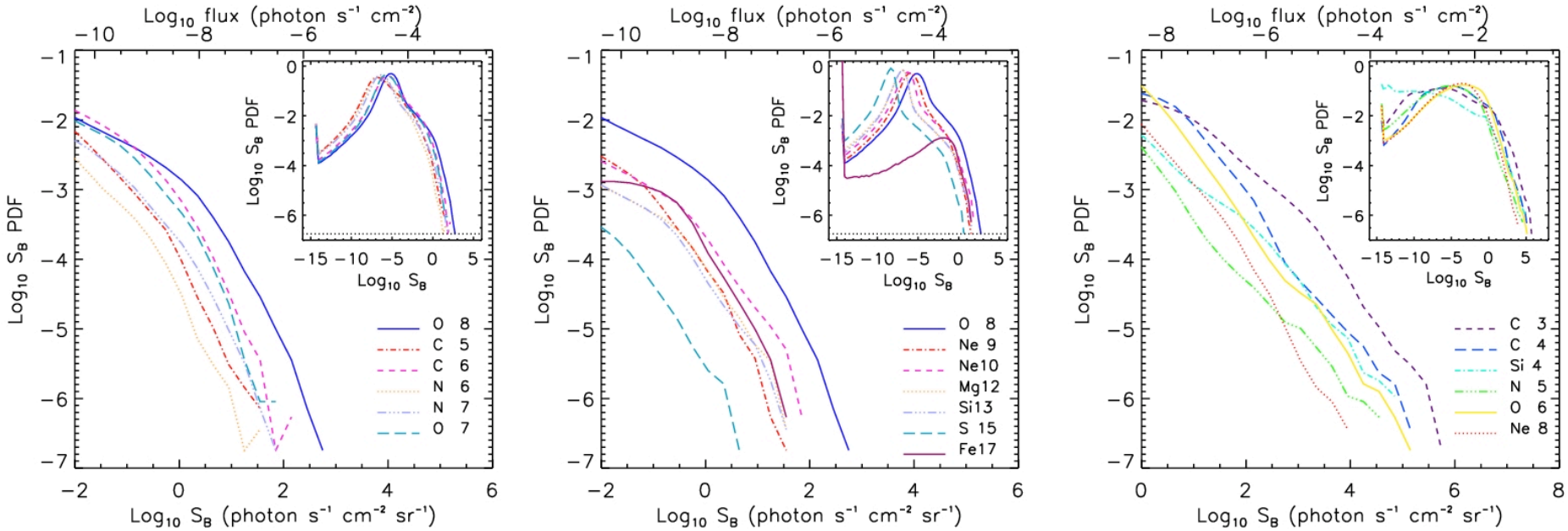
- C III and C IV strongest lines: trace gas in proximity of galaxies
- O VI and NeVIII trace more diffuse gas than C IV - different spatial distribution
- no emission from the hottest gas in groups

Bertone et al 2010b



UV emission is a good tracer of galaxies and of mildly dense IGM, but not of IGM in very dense environments

Surface brightness PDFs



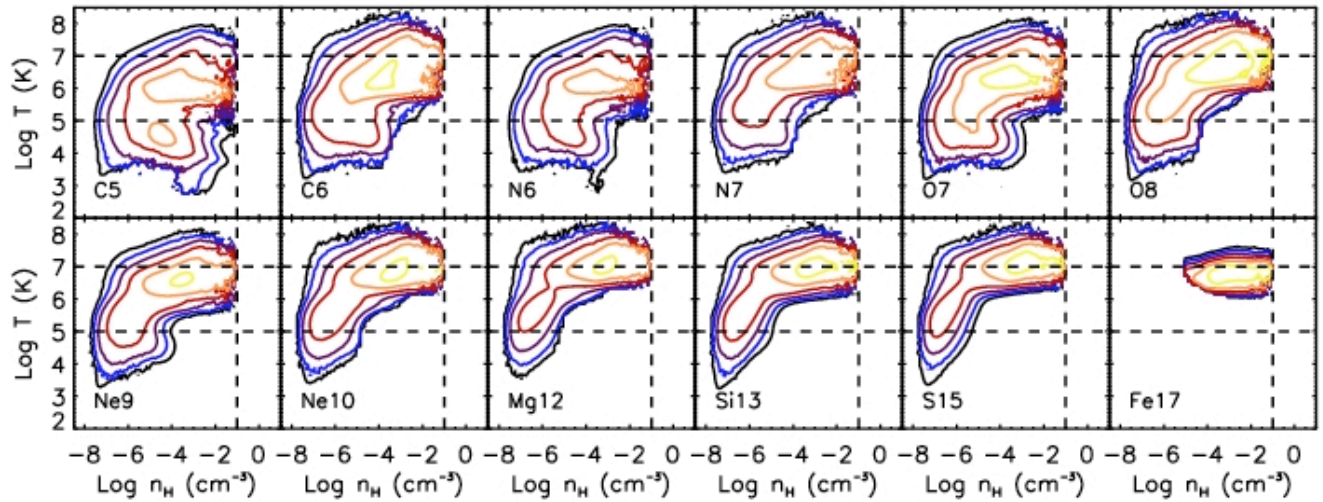
- C IV and O VI lines detectable by FIREBALL (Tuttle et al 2008)
- Detection of X-ray lines requires new instruments: WFI on the International X-ray Observatory (IXO) and Xenia

Bertone et al 2010a,b

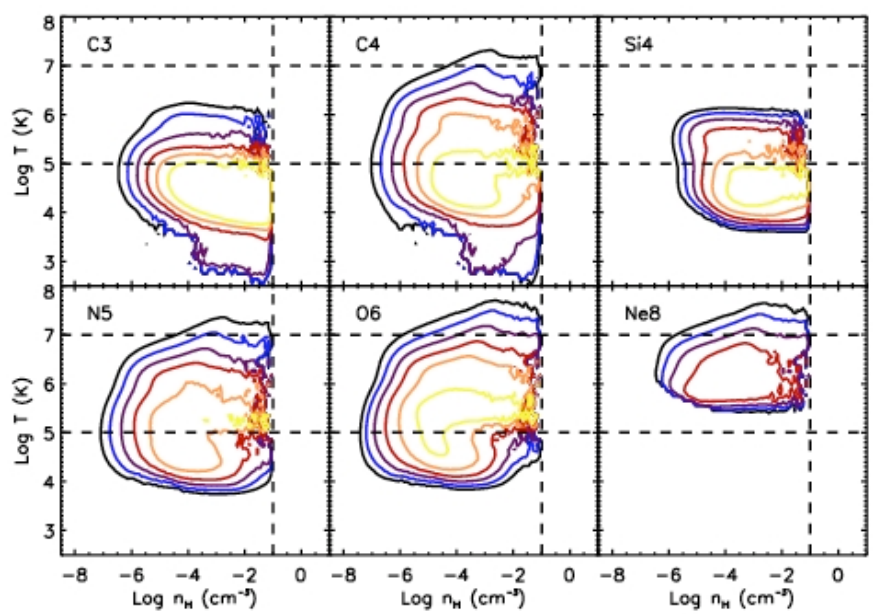
What gas produces the emission?

Emission traces moderately dense gas, not the bulk of the IGM mass and metals.

emission-weighted particle distributions



- the peak temperature of the emission increases with atomic number and ionisation state
- X-ray emission traces gas with $T > 10^6$K
- O VI and Ne VIII trace diffuse gas
- C III, C IV and Si IV trace the CGM



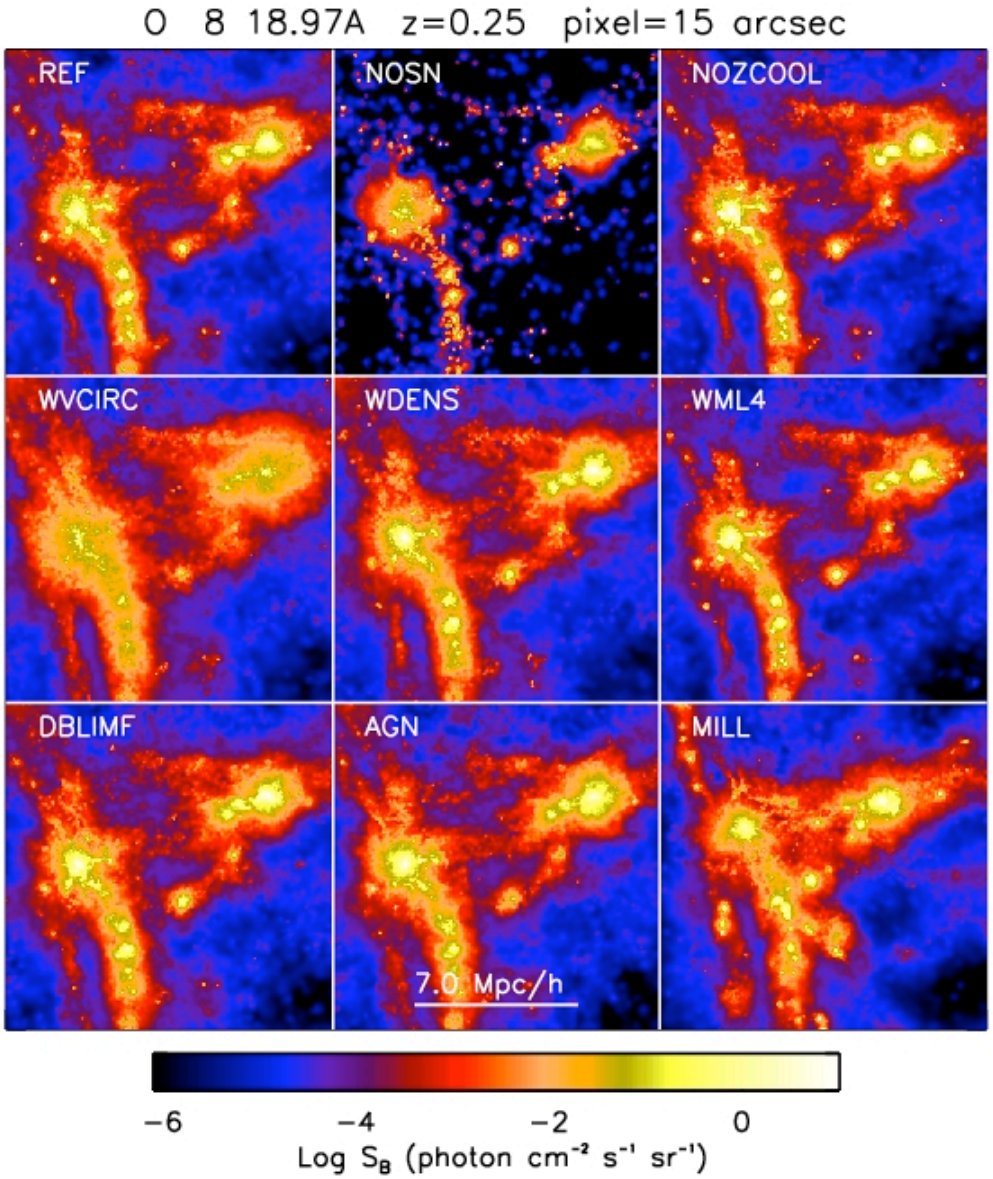
Bertone et al 2010a,b

Impact of physics

What happens when changing the physical model?

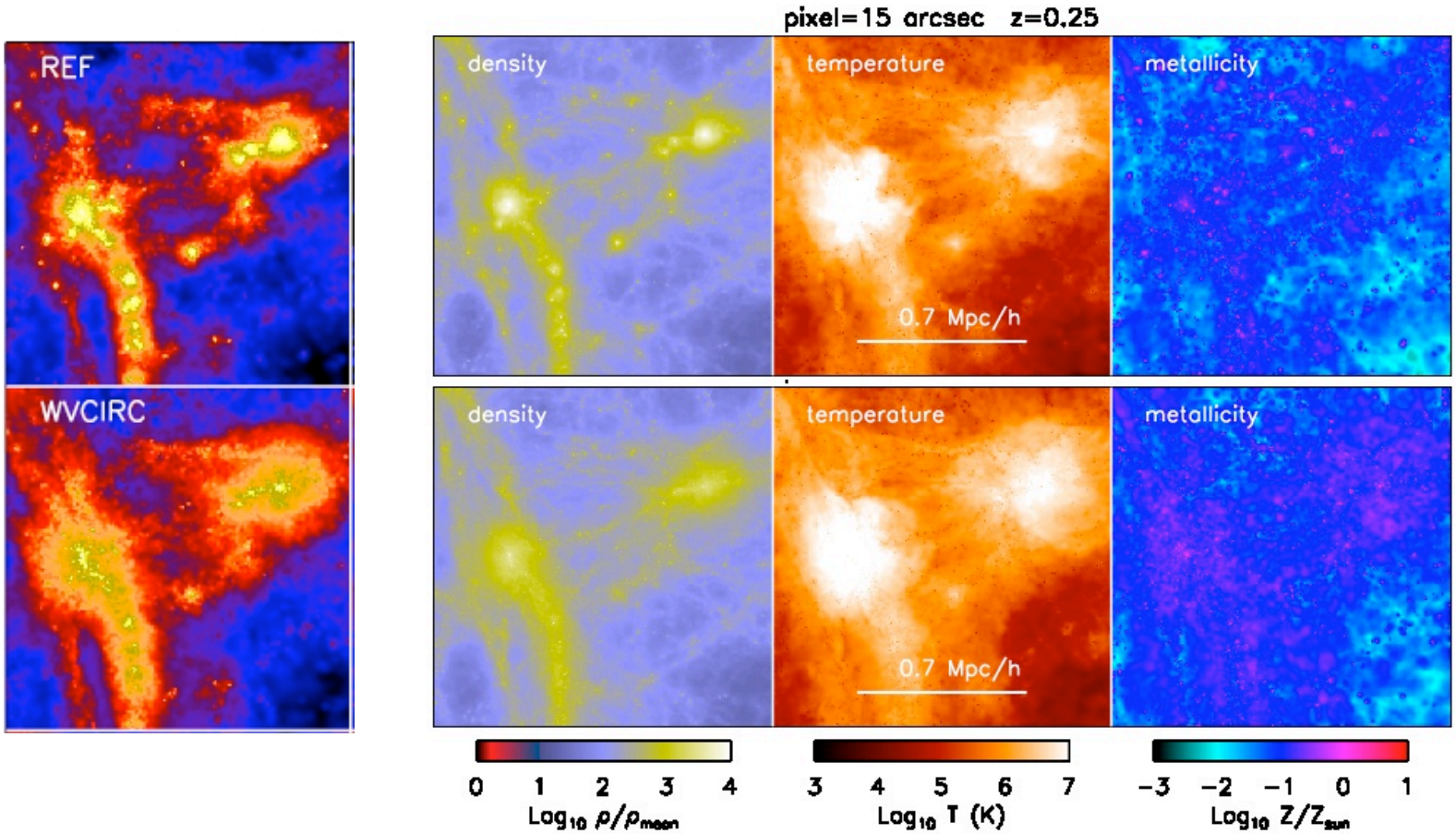
Impact of physics: X-rays

- *no feedback*: no metal transport → localised emission
- *primordial cooling rates*: longer cooling times → stronger emission at high density (≈100 times)
- *momentum-driven winds*: metals more spread in IGM → weaker emission (≈100 times)
- *AGN feedback*: weaker emission in dense regions



Bertone et al 2010a

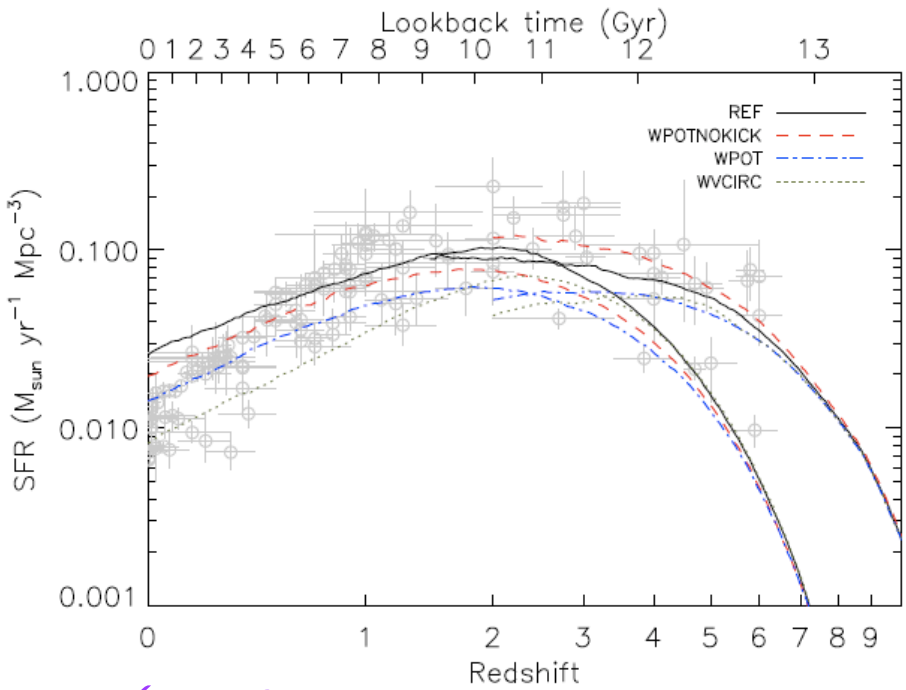
Temperature, density and metallicity

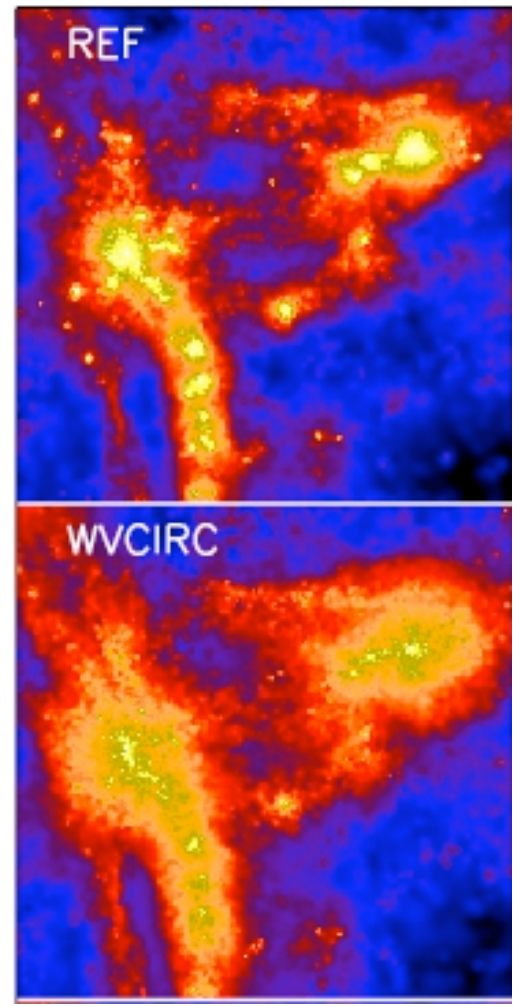


The spatial distribution of the emission reflects those of the gas temperature, density and metallicity

Pressure vs. momentum-driven winds

Differences in emission reflect relative differences in star formation history and metal enrichment

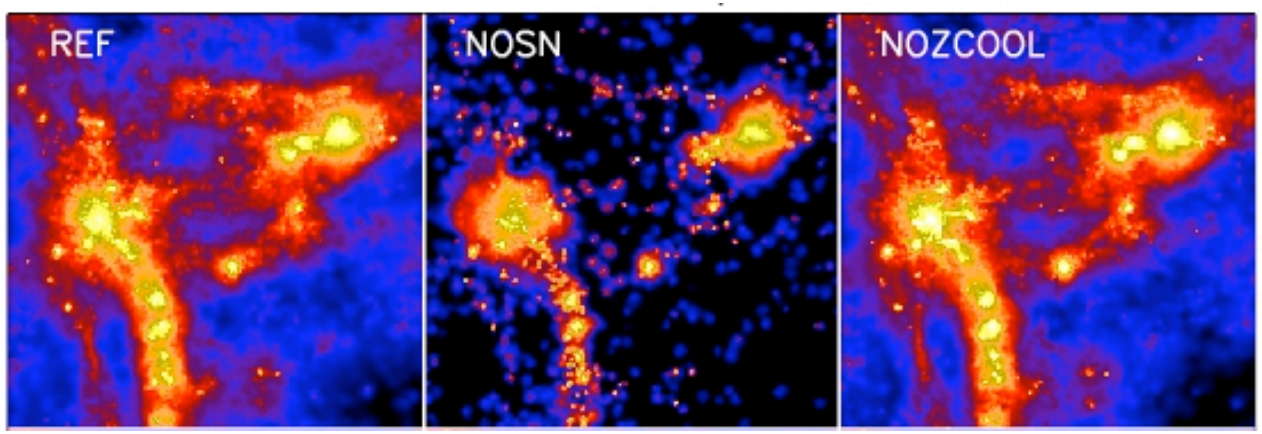


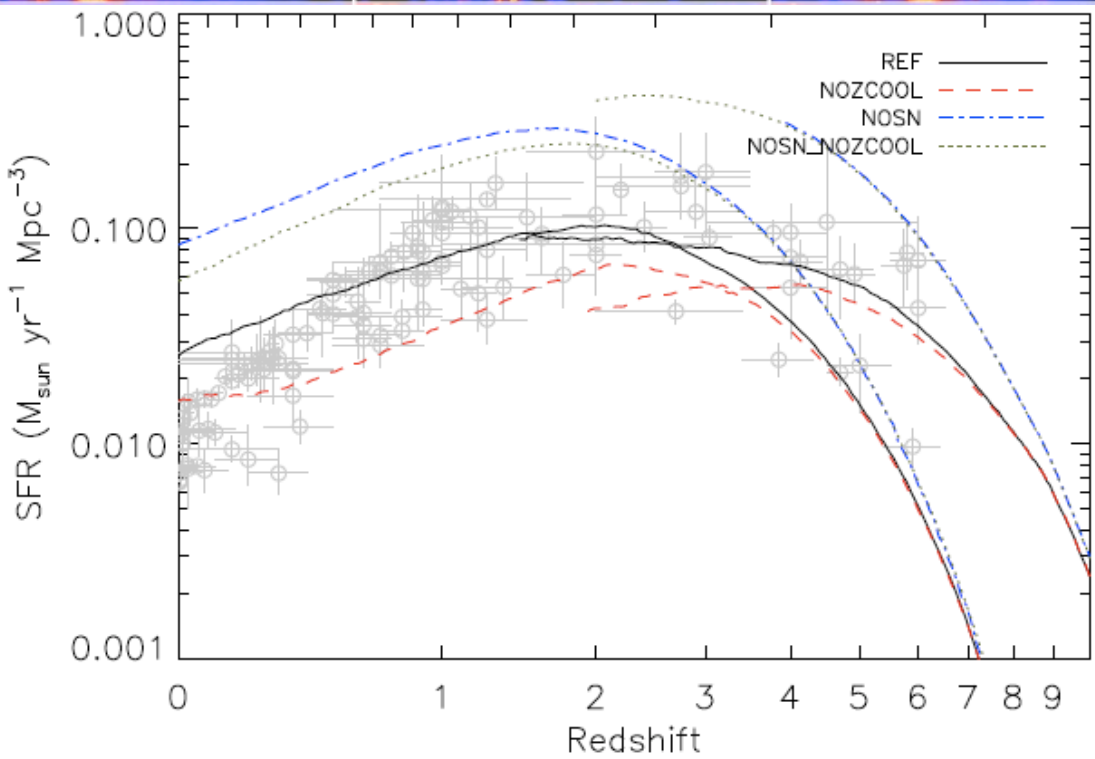


- WVCIRC:
  - Fewer stars
  - Stronger feedback in large haloes
  - More widespread metal enrichment

Schaye et al 2010

No SN feedback & cooling rates



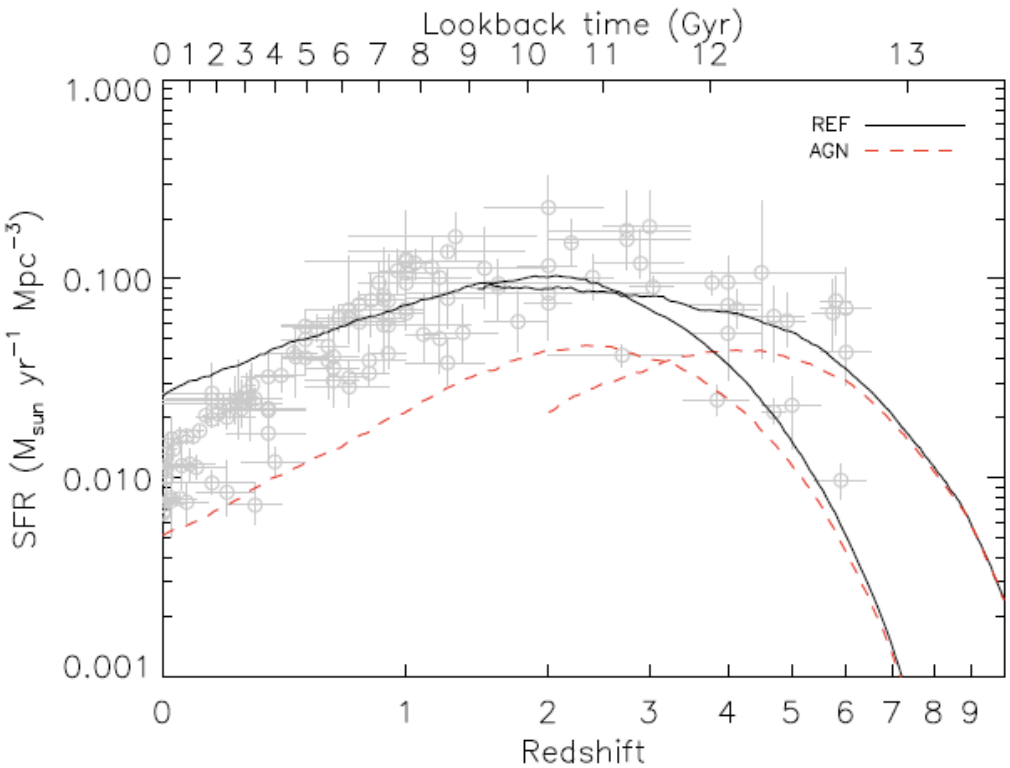


- NOSN:
  - No SN feedback.
  - More stars, no metal transport.
- NOZCOOL:
  - cooling rates for H+He only (no metals).
  - Fewer stars.

Schaye et al 2010

AGN feedback

- AGN:
  - Less gas cooling in centres of larger haloes
  - Fewer stars.



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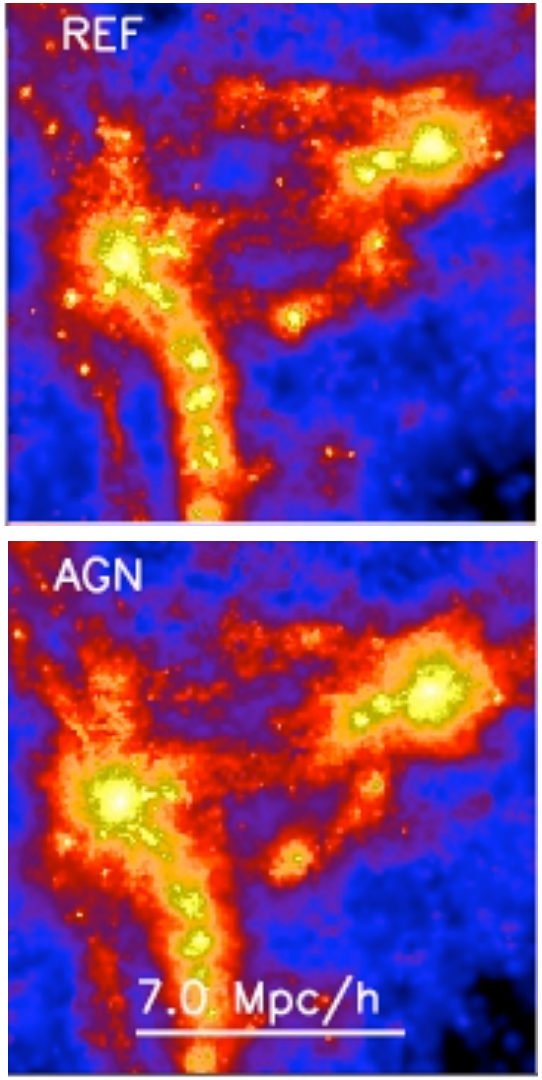
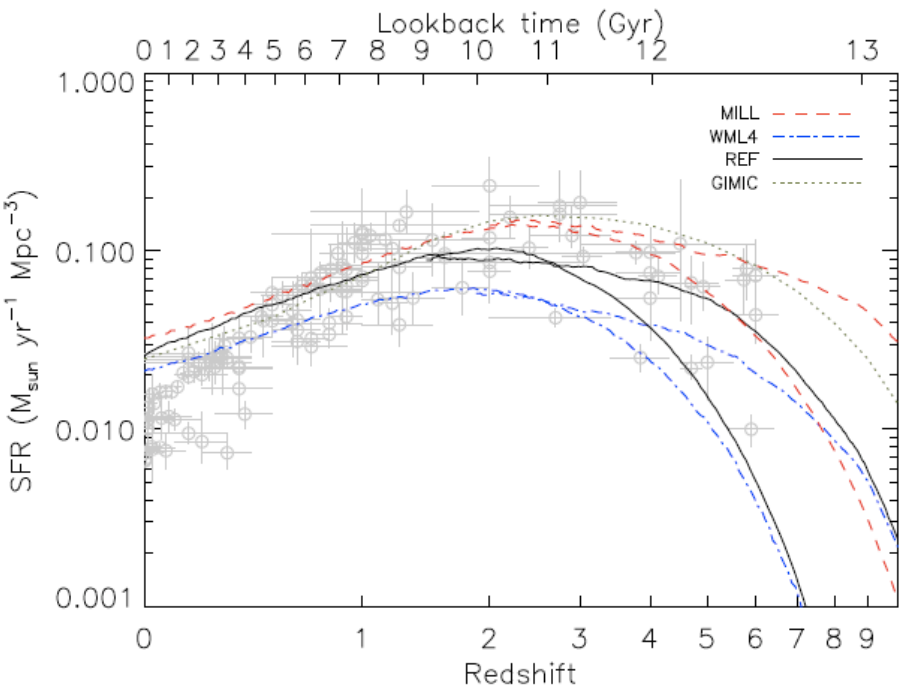


Cosmology

- MILL:
  - WMAP1 cosmology.
  - More stars, structures more evolved.
- WML4:
  - Stronger feedback (2x).
  - Fewer stars.



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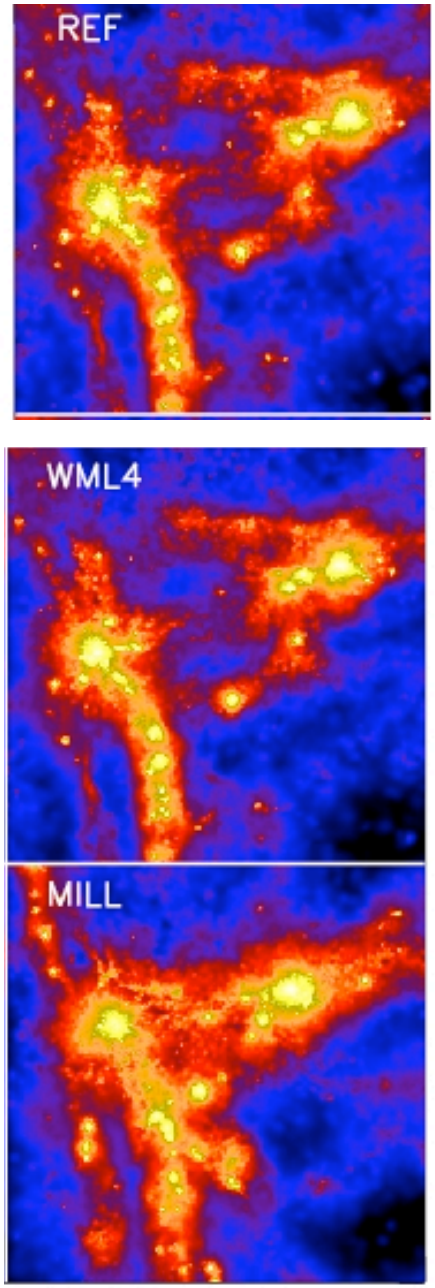

Summary

- Dense cool gas in the haloes of galaxies is traced by:
  - UV lines: C III, C IV, Si IV
- Low density WHIM gas in filaments is traced by:
  - UV lines: O VI, Ne VIII
  - X-ray lines from He-like atoms: C V, O VII, Ne IX
  - X-ray lines from H-like atoms with low atomic numbers: C VI, O VIII
- Dense hot gas in clusters and groups is traced by:
  - X-ray lines from fully ionised atoms: O VIII, Ne X..
  - X-ray lines from elements with high atomic numbers: Mg XII, Si XIII etc.
- Detection of WHIM emission by future telescopes:
  - challenging in low density regions
  - very likely in groups and cluster outskirts