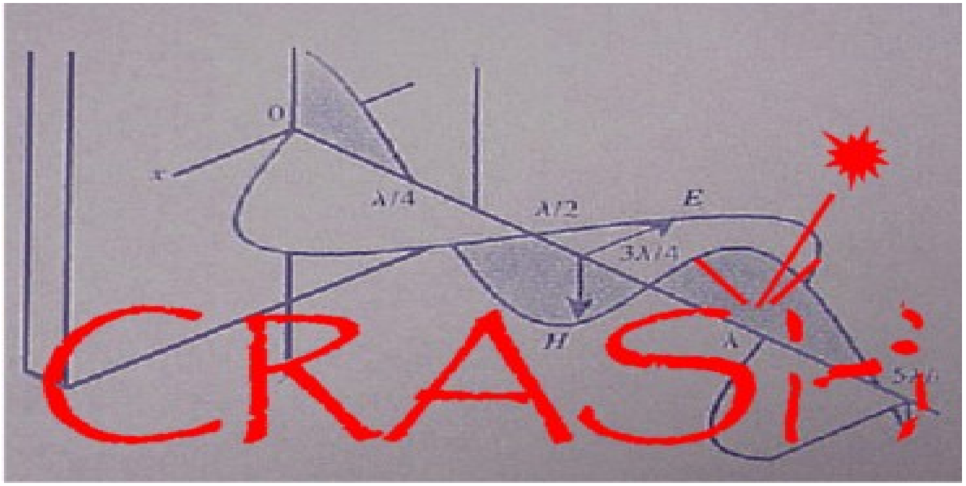

Cosmic UV background fluctuations at z~3 as traced by metal ions: radiative transfer effects

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- Helium reionisation
- UV background at z~3
- CRASH3: RT simulation through metals
- UV Fluctuations traced by η, T, τ_{SiIV}/τ_{CIV}

Intergalactic Interactions, Higgs Centre, Edinburgh - 24-28.06.2013

He reionisation

- **EPOCH**: HeII dominate at **z > 3** (Reimers 05); an extended reionisation is possible (Bolton 10; Becker 11).
  He fully ionised around **z ~2.8** (Kriss 01; Syphers 11, 11a).

- **HeII OPACITY**: highly **inhomogeneous** (Smette 02; Muzahid 11).

  $$\eta = N_{HeII}/N_{HI}$$

  oscillates in [20-200] over [2-10]h^{-1} Mpc scales (Fardal 98, Shull 99, Fechner 07)

  → Significant <u>spatial fluctuations in the radiation field</u> at the photo-ionisation edges of HI and HeII?

- **IGM T**: Statistical detections of a **jump in T around z ~3** (Hui & Gnedin 1997; Ricotti et al. 2000; Schaye et al. 2000; Bernardi et al. 2003), but **not confirmed** by independent analyses (McDonald & Miralda-Escudé 2001)

He reionisation: Lyα Forest

- η: in a photo-ionised IGM is linked to the spectral shape of the ionising background (Miralda-Escude' 93).

$$\eta \propto \frac{\Gamma_{\mathrm{HI}}}{\Gamma_{\mathrm{HeII}}},$$

Where $\Gamma_{\mathrm{HI}}, \Gamma_{\mathrm{HeII}}$ are photo-ionisation rates of HI and HeII.
→ **Spatially fluctuating spectral shape?**

- T: equation of state of photo-ionised medium follows (Hui&Gnedin 97; Valageas et al. 02):

$$T = T_0 \Delta^{\gamma - 1},$$

where T_0 is temperature at mean density and Δ is the gas overdensity (Δ <4), γ ~1.5 → 1.0. → **Fluctuations in γ ?**

UV Background modelling at z~3

- **UVB uncertain at z~3:** F. Haardt and P. Madau assume spatially uniform UVB and model it with 1D code (**CUBA**).
- For photons E > 1Ryd (13.6 eV) the **HM assumption can fail** **at z~3**:

1) POINT SOURCE VARIABILITY (Furlanetto 2008,2009, Dixon 2009):

- **QSOs are rare in space + clustering**
- **Finite lifetime**
- **Spectral index variability**.

→ HeII reionization is completed by QSOs at z~3 ?

2) RADIATIVE TRANSFER EFFECTS: could affect small and large scales

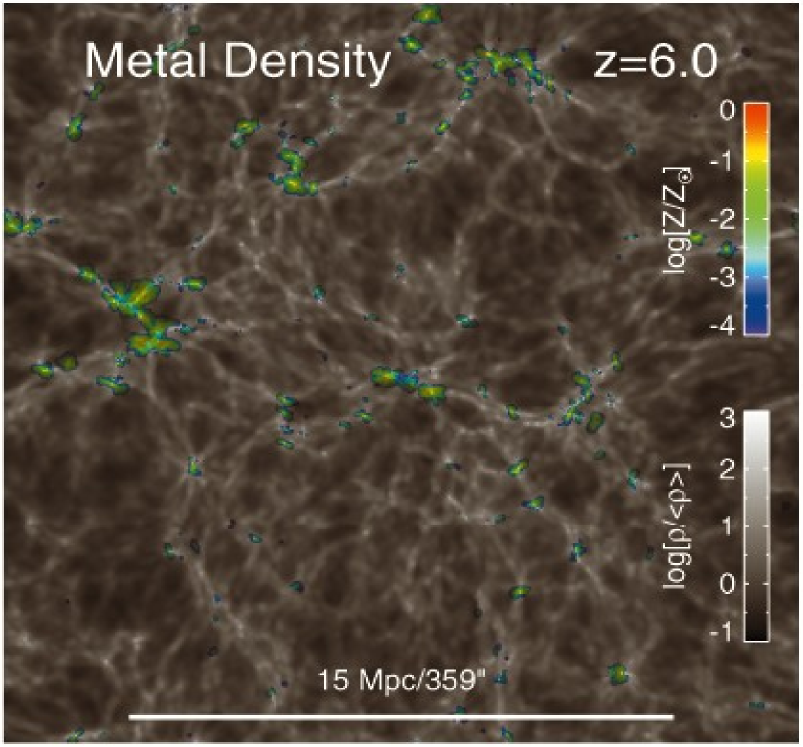
- Small scale (~10h^{-1} Mpc) RT effects **(Maselli&Ferrara 05)**
- Large scale: filtering / Collisionally ionized gas.

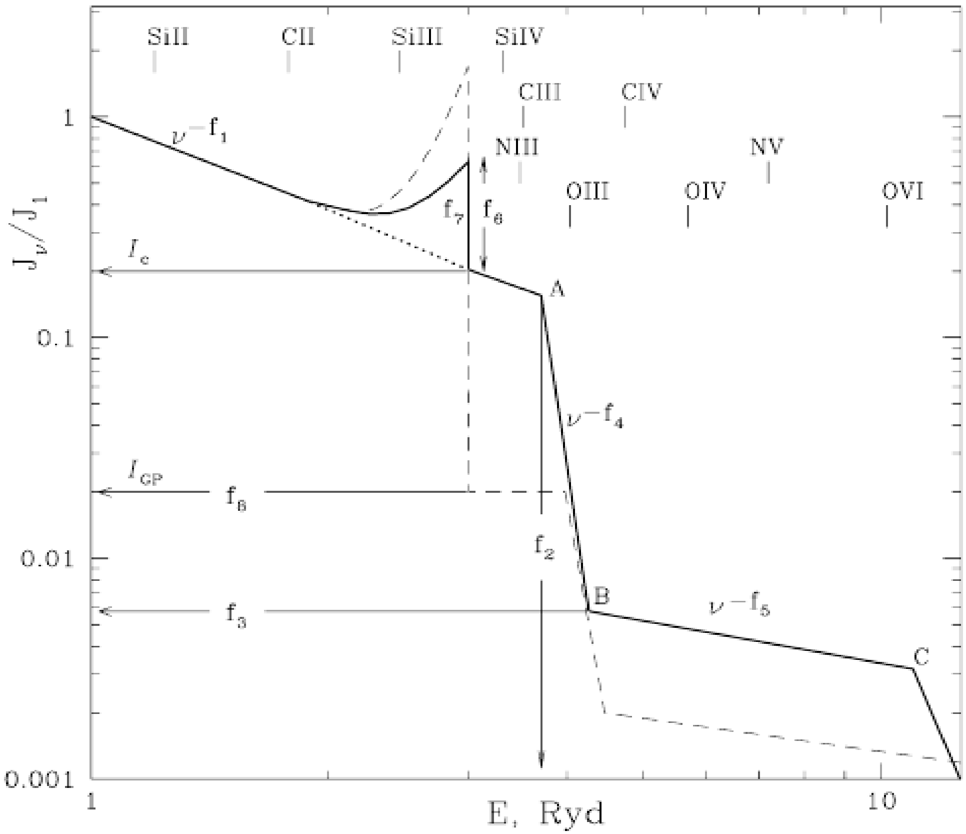
SPATIAL FLUCTUATIONS OF THE UVB INTENSITY AND SPECTRAL SHAPE ARE TRACED by H, He..

→ **CAN WE USE METAL IONS ??**

UV Spectral Shape Modelling

- A **plethora of potentials** near E=4Ryd (54.4 eV).
- Metals ions can provide additional points across the HeII absorption to fix the slope.





Oppenheimer, et al.,2009:

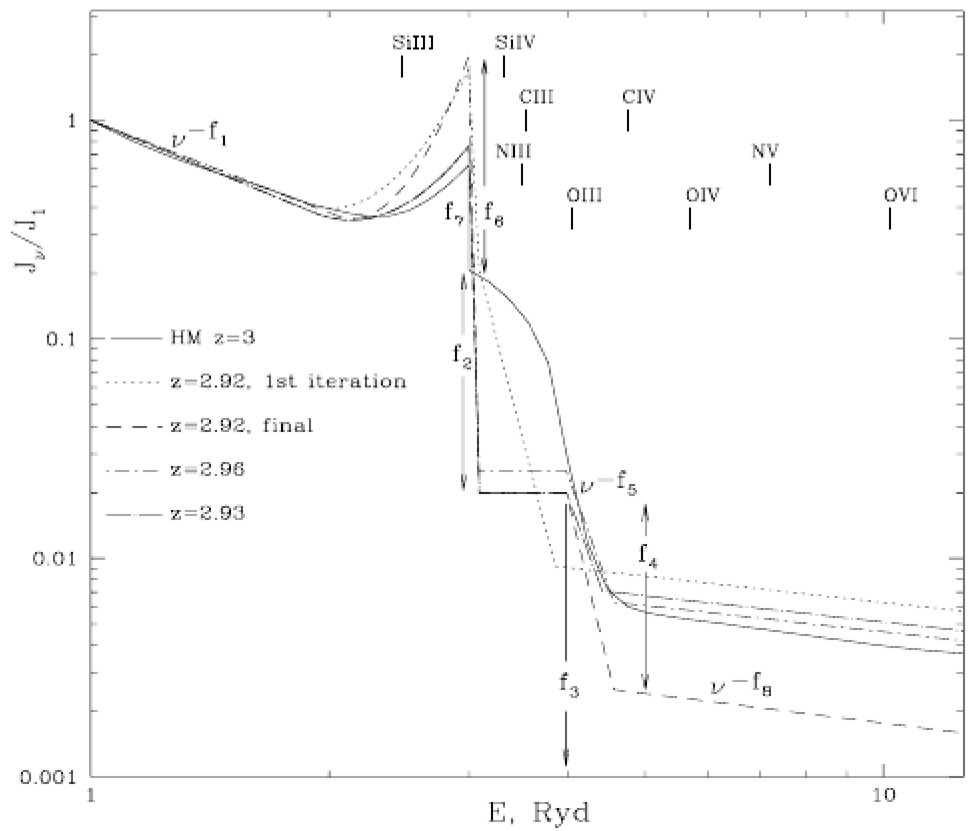
Metal ionization fractions calculated with **CLOUDY** (Ferland et al.) as function of density and temperature.

NOT SELF-CONSISTENT WITH THE RT: tables pre-assume the spectral shape !

Spectral Shape Modelling $\zeta_{obs}:\tau_{CIV}/\tau_{SiIV}$

MAYBE OBSERVATIONS CAN HELP...

- Songaila (1998): YES. Abrupt change of τ_{SiIV}/τ_{CIV} around z ~ 3 → sudden hardening of the UVB.
- Agafonova (2005-2007): YES. UVB Spectral shape shows a sharp reduction in flux in the energy range 3 Ryd < E < 4 Ryd → sudden hardening of the UVB. Metal ions can be used.
- Kim et al. (2002): NO. Do not see any abrupt change in $N_{SiIV}/N_{C\,IV}$ at 1.6 < z < 3.6. → Local sources dominated metals. Not a good tracer.
- Boksenberg (2003): NO
- Aguirre (2004): NO



Conclusions dependent on Photoionisation models. RT neglected

Simulation: small scale fluctuations induced by RT

HYDRO SETUP:

- Hydro Snapshot at z~3 (Gadget3): **metal enrichment and spreading** accounted for (Maio 2010). Scale: 10/h Mpc.
- 11 metals (Tornatore 2007). We consider **only C, O, Si** .. other metals can be added.
- **HM96 UVB model**.

RT SETUP:

- CRASH in post-processing.
- **Photo-ionised metals**. Collisionally ionised regions accounted for separately.
- **Spatially homogeneous HM96 UVB**.
- C,O,Si ions evaluated **including cooling by metal lines**.

IC:

- In absence of a full reionisation setting the initial ionisation, it **starts from neutral gas at T~100K**.
- Follows the RT as in Maselli and Ferrara 2005.

AIM:

- **Amplitude of spatial fluctuations** in :

$$\eta = \eta(\Delta)$$

$$T = T(\Delta)$$

$$\zeta = \zeta(\Delta)$$

induced by the RT due to the cosmic web at z~3.

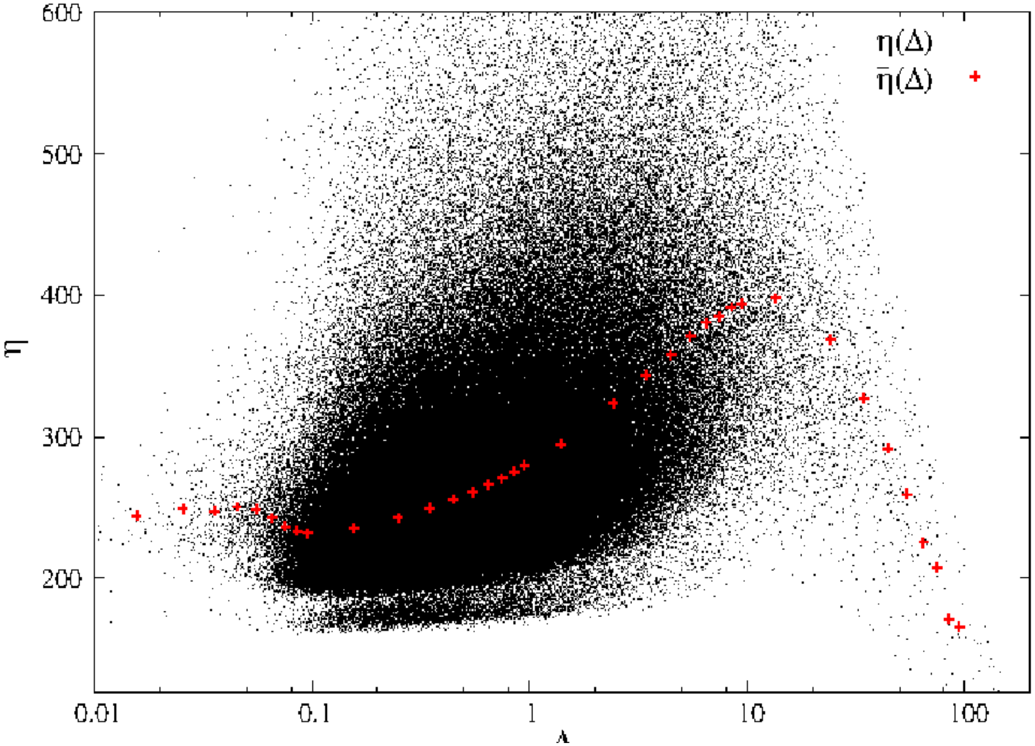
- Theoretically confirms that the metal line ratios can be used as tool

Fluctuations in η

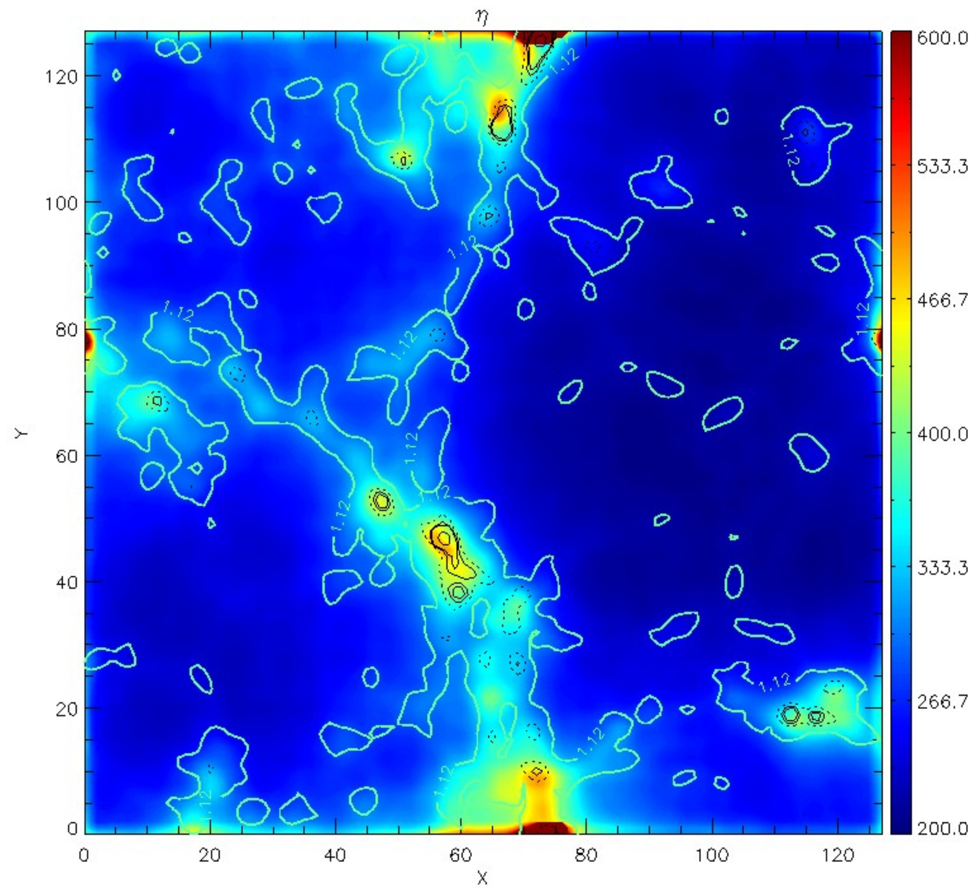
- We use the approximation in Fardall 98..

$$\eta \sim \frac{\alpha_{\mathrm{HeII}}(T)}{\alpha_{\mathrm{HI}}(T)} \frac{n_{\mathrm{HeIII}}}{n_{\mathrm{HII}}} \frac{\Gamma_{\mathrm{HI}}}{\Gamma_{\mathrm{HeII}}},$$

- Evident **spatial correlation η(Δ)**



Scatter plot of η(Δ) at t~5.5 10^6 yrs. The average value of η(Δ) in red crosses.

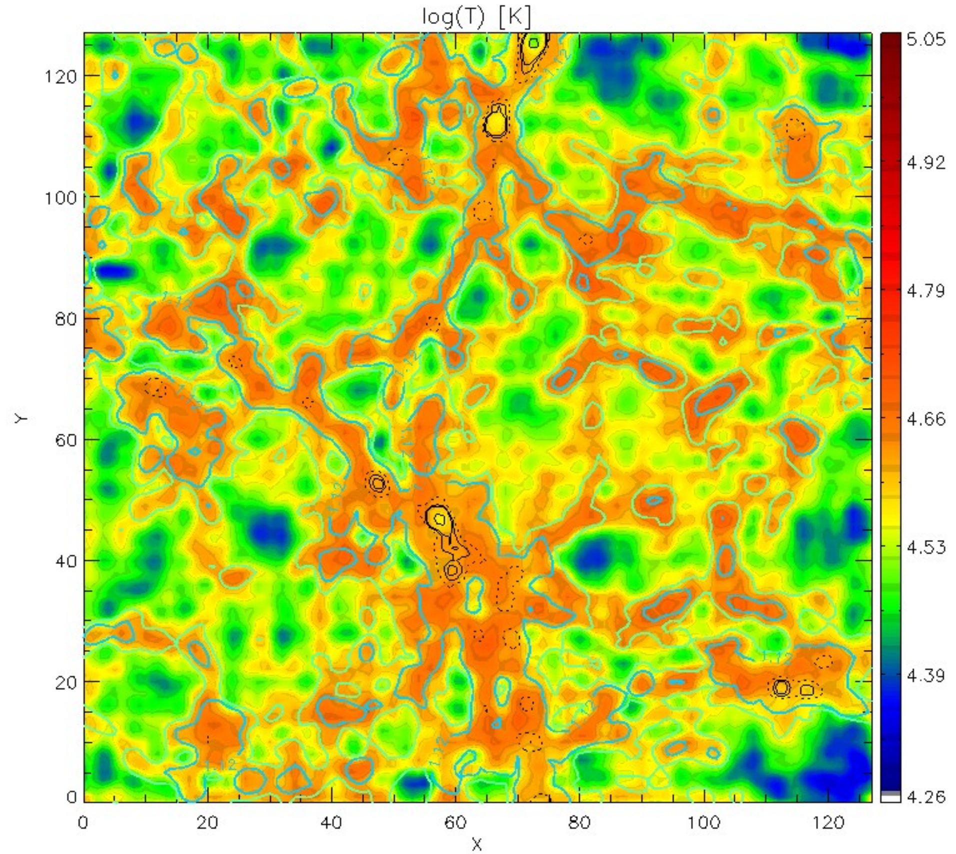


Slice cut at t~5.5 10^6 yrs. Δ ~1 white solid line, Δ ~5 black dashed, Δ~10 black solid

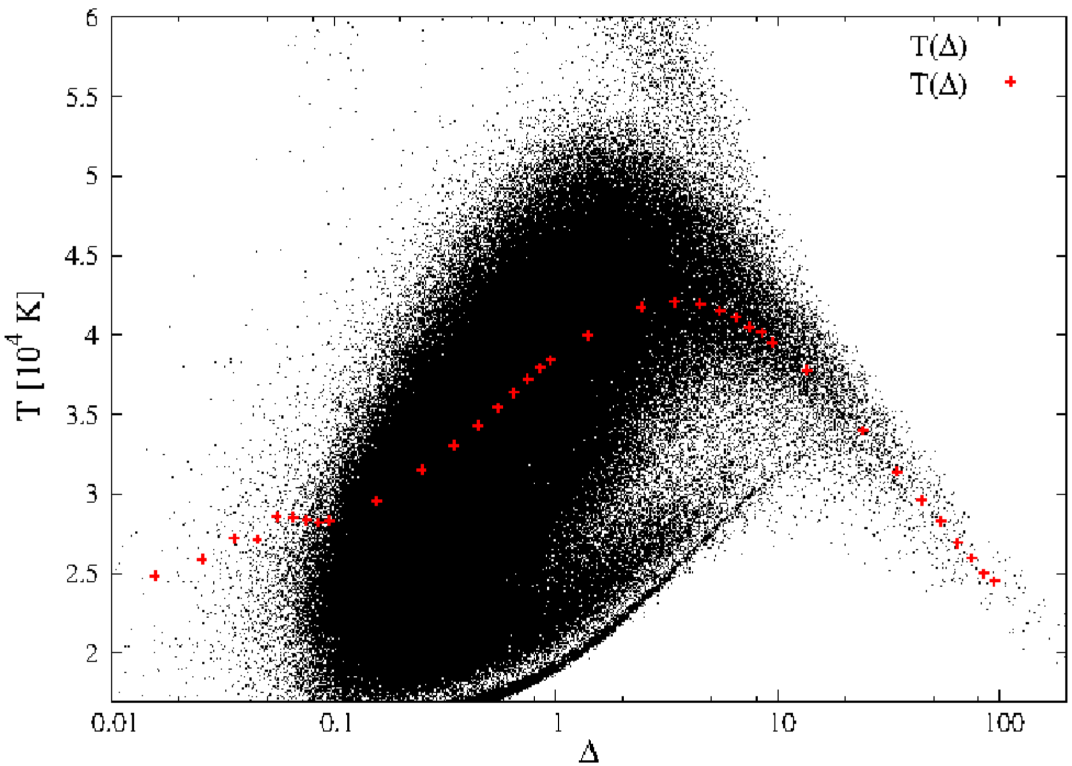
- <η> ~ 277 at z~3
- 210 < η < 285 in 80% cells volume, δρ/<ρ> ~ 10-20% fluctuations.
- δρ/<ρ> up to 60% in 20% volume.

Fluctuations in T

- Calculated self-consistently with H,He, metal cooling.
- Evident **spatial correlation T(Δ)**
- Metal cooling efficient in **few percent of volume** (Z >0.5ZSol) introduces scatter**.**



Slice cut at t~5.5 10^6 yrs. Δ ~0.5 cyan solid line, Δ ~1 white solid line, Δ ~5 black dashed, Δ~10 black solid



Scatter plot of T(Δ) at t~5.5 10^6 yrs. The average value of T(Δ) in red crosses.

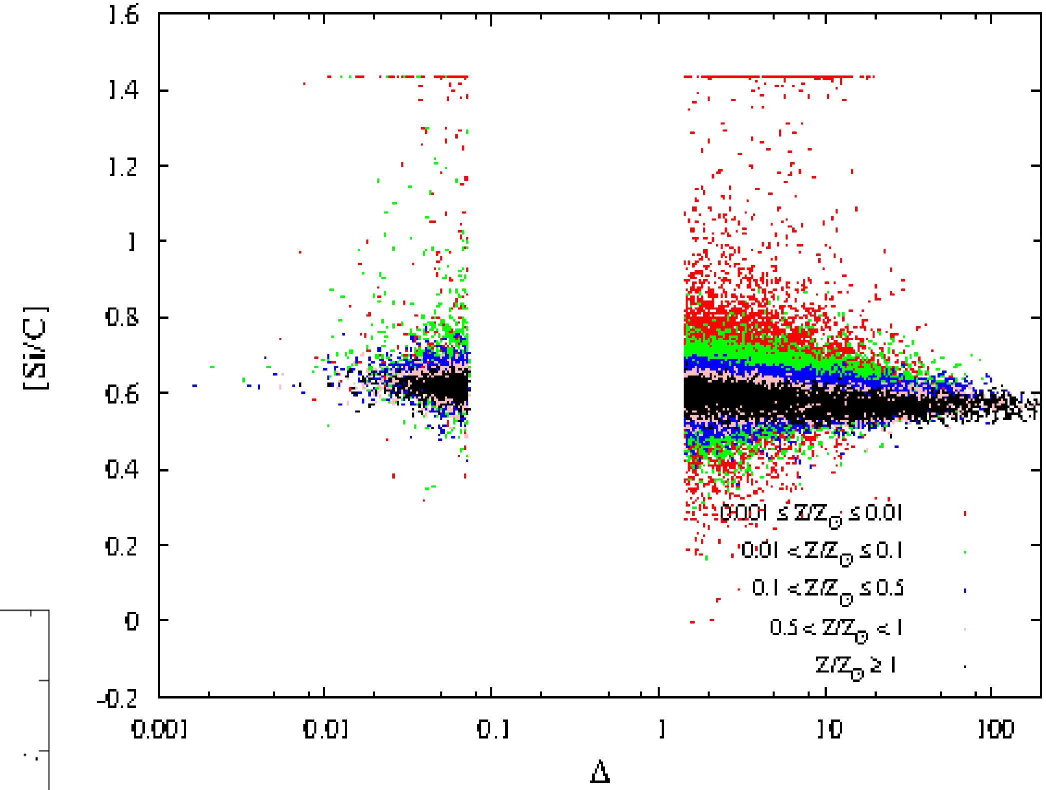
- <T> 3.2 10^4 [K] at z~3
- **δT/<T> ~ 10% in Δ < 1.**
- **δT/<T> up to 40% in Δ > 1.**

Fluctuations in ζ_{obs}

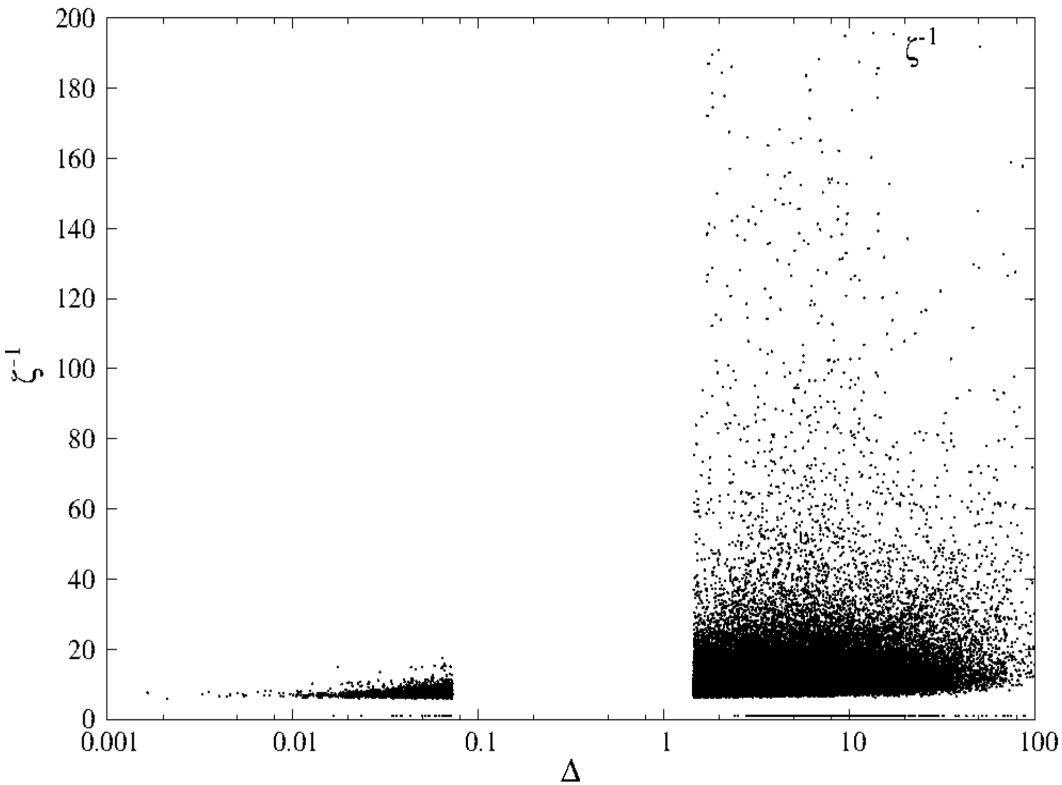
- Calculated in photo-ionisation equilibrium as:

$$\zeta_{obs} \equiv \frac{\tau_{\mathrm{SiIV}}}{\tau_{\mathrm{CIV}}} \sim \frac{\sigma_{\mathrm{SiIV}} n_{\mathrm{SiI}} x_{\mathrm{SiIV}}}{\sigma_{\mathrm{CIV}} n_{\mathrm{CI}} x_{\mathrm{CIV}}} \sim 1.7 \frac{x_{\mathrm{SiIV}}}{x_{\mathrm{CIV}}} 10^{[\mathrm{SiIV/CIV}]-0.77}$$

- Sensitive both to spectral shape and [SiIV/CIV].



Scatter plot of [Si/C]. Δ ~0.5 cyan solid line, Δ ~1 white solid line, Δ ~5 black dashed, Δ~10 black solid

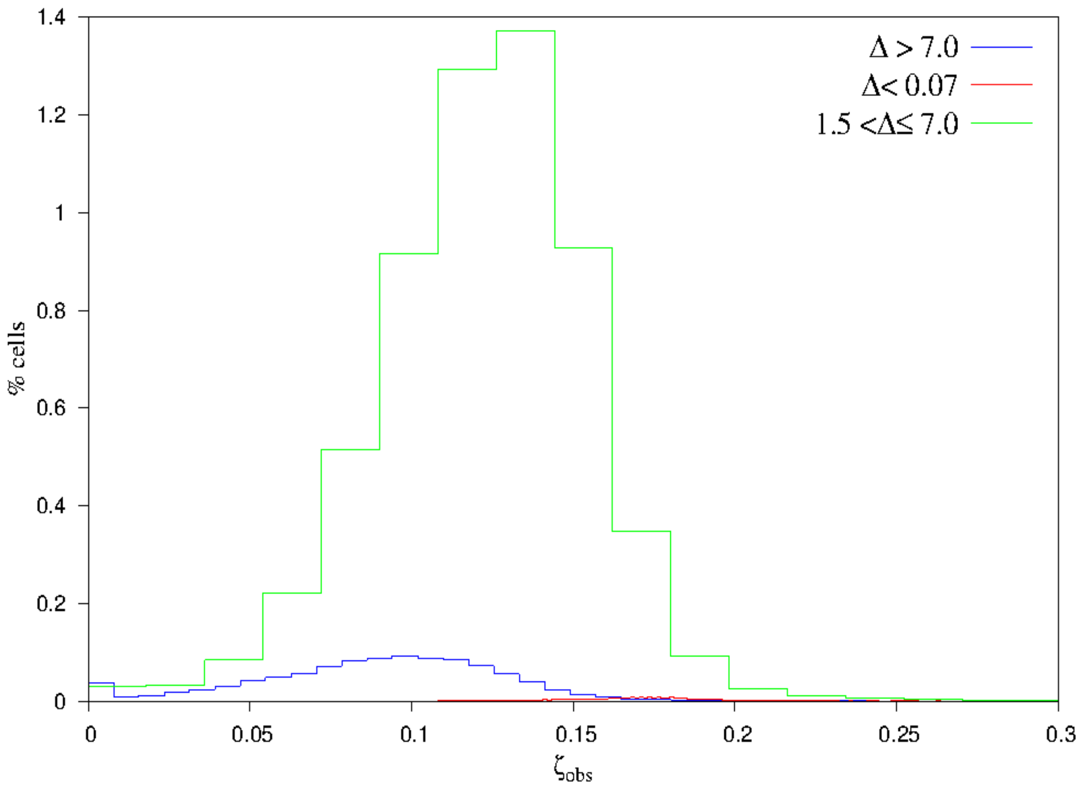


Scatter plot of $x_{CIV}/x_{SiIV}(\Delta) \sim \zeta^{-1}$ at t~5.5 10^6 yrs.

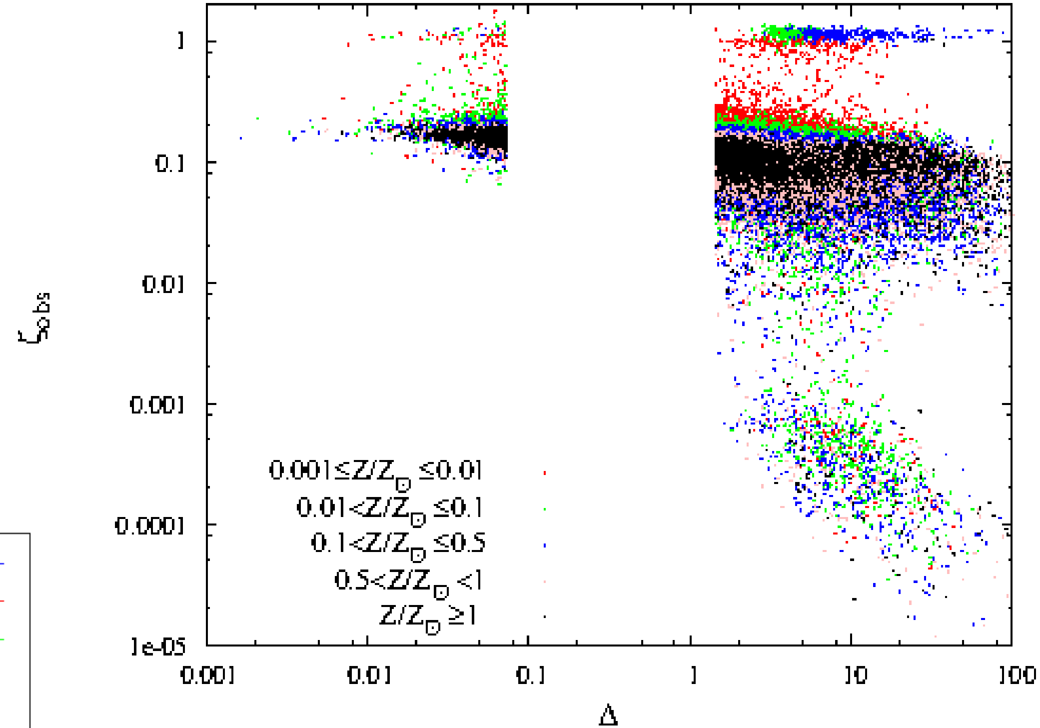
- <[Si/C]> 0.77 at z~3 (see Aguirre 04)
- **0.4 < [Si/C] < 0.8 in 0.1 < Δ < 10. It scatters with the gas metallicity Z.**
- ζ^{-1} increases with Δ: 8 → 48
- ζ^{-1} shows a scatter from 20 to 40% only around ζ^{-1} ~8.

Fluctuations in ζ_{obs}

- Clear decreasing **trend with Δ**
- **Scatter** increases from **25% up to 50%** at Δ –> 10.
- **Associated with metallicity 0.1< Z< 0.5**



Statistics of ζ_{obs} at t~5.5 10^6 yrs in different over-density systems as indicated by colours in legend.



Scatter plot of ζ_{obs} at t~5.5 10^6 yrs. Colours indicate the metallicity of the systems as in legend.

- **Under-dense regions statistically irrelevant.**
- **Fluctuations of ζ_{obs} up to 40% in less than 0.15% volume.**
- **Fluctuations ~ 15% in ~3% volume.**

Why ?

- The **shaping** is **a function of Δ. It is well traced by fluctuations of η and T.**

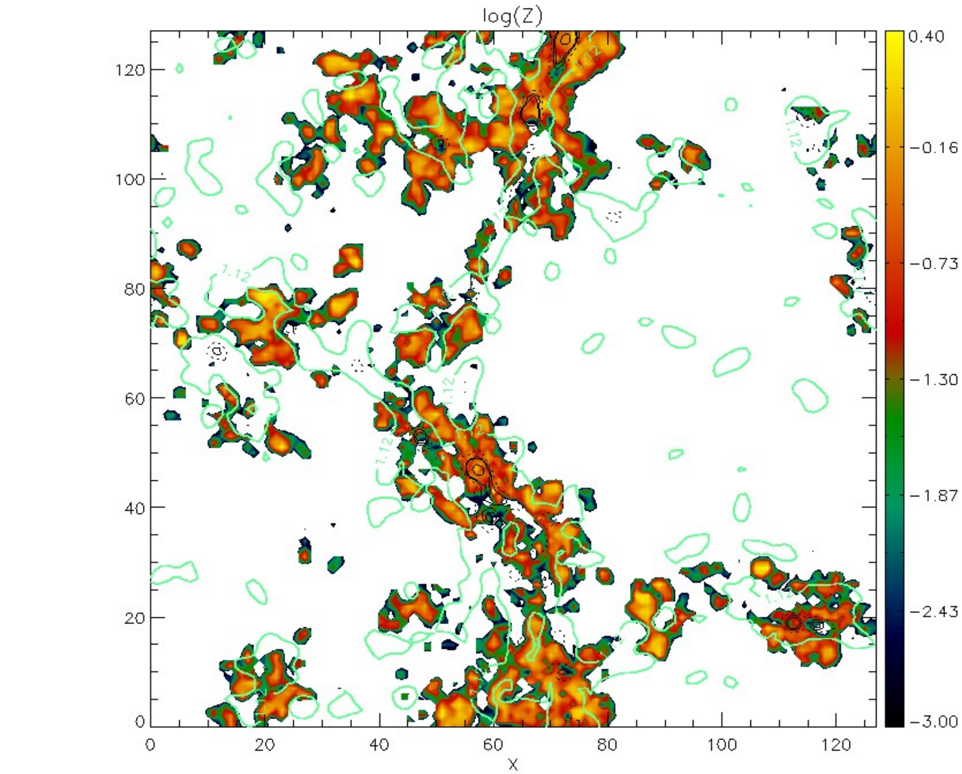
- **CRASH is sensitive to fluctuations of** ζ^{-1} deriving from the UVB shaping.

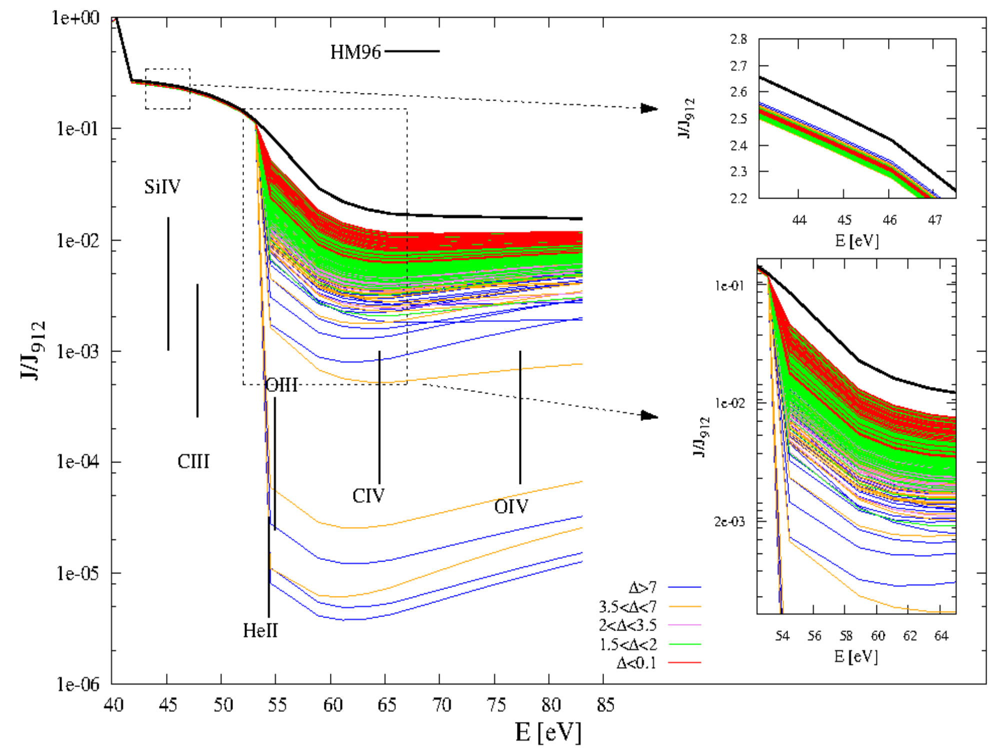
- Metal enriched domain in which **Z>0.1Zsol reduced to 7% of total**.

- **Mechanical Feedback de-correlates Z–Δ reducing the available volume in which shaping is relevant.**

- Fluctuations of ζ_{obs} up to 40% in less than 0.15% volume.

- Fluctuations ~ 15% in ~3% volume.



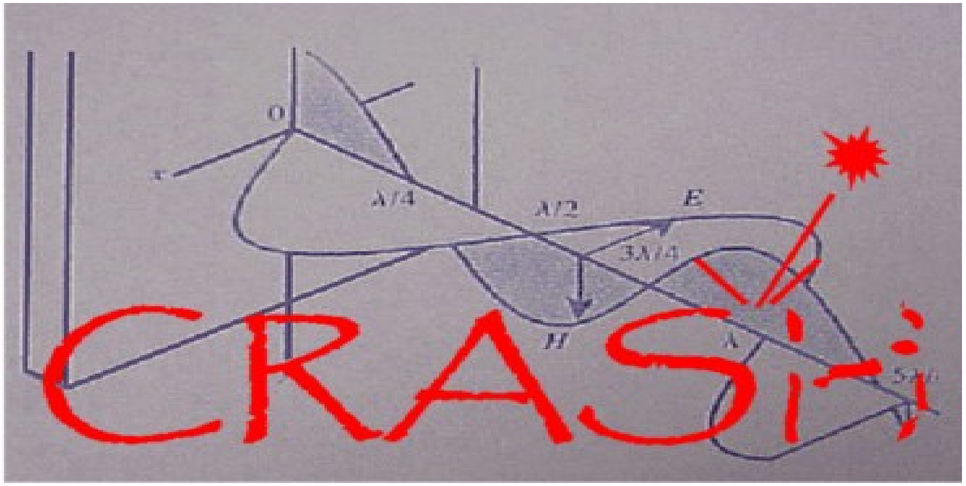


Conclusions

- RT induces **fluctuations up to 40% in η and T**.
- RT induces also **fluctuations in** metal component tracked by ζ_{obs} **but visible in few % of volume**.

but.....

- Other metal tracers to be investigated, e.g. OVI.
- Effects galaxy variability on small scales: dominate the ionisation of metals or induce fluctuations ?
- Is the **large scale** background produced by **QSOs** homogeneous? Does it fluctuate? How is this affecting the small scales?



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THANK YOU