The Size and Origin of Metal Enriched Regions in the Circum-Galactic Medium

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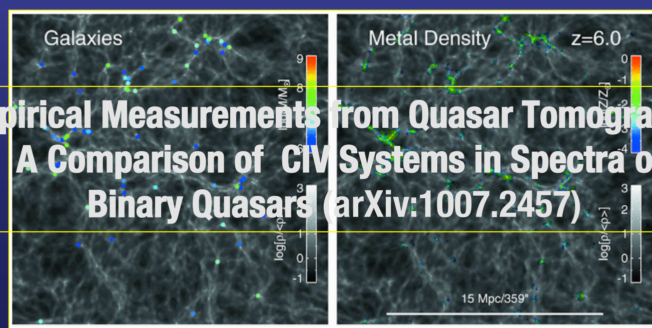
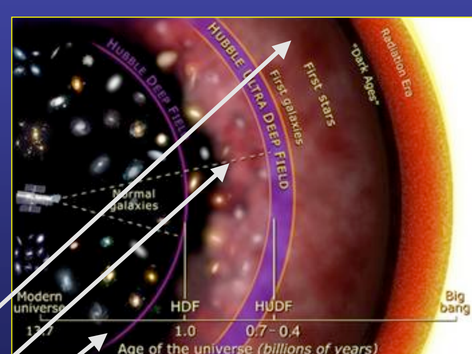


Empirical Measurements from Quasar Tomography: A Comparison of CIV Systems in Spectra of Binary Quasars (arXiv:1007.2457)

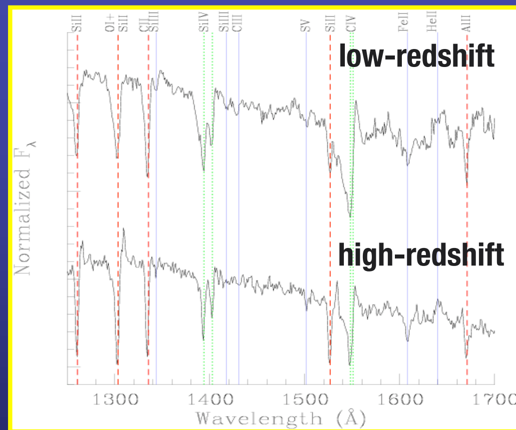
Presence of Elements Heavier than Helium in the IGM Requires Dispersal of Material Synthesized by Stars



When were metals dispersed?

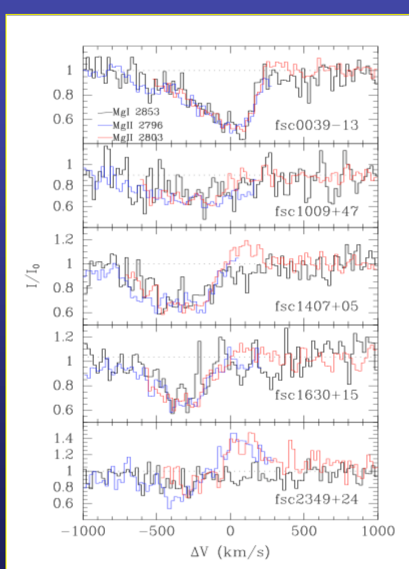
1. Pop III Stars (z > 6)
2. Early Galaxies (4 < z < 6)
3. Peak Cosmic SFR (z~1.5-3)

Mechanism: Galactic Winds Transport Metals



- Starburst galaxies at all epochs present winds.
- Measure Doppler shifts v ~ 200 km/s (up to ~800 km/s).
- Wind signature nearly identical at high and low redshift.

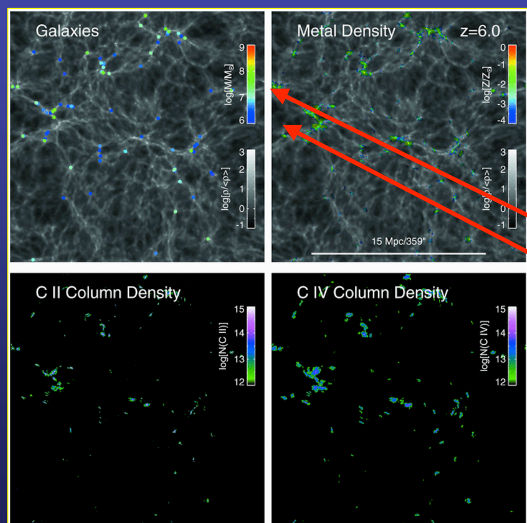
Galaxy Spectra: Where is the Outflowing Gas?



MARTIN & BOUCHE 2009 ApJ:

- The absorption troughs in galaxy spectra remain optically thick out to the highest detected velocities.
- Their shape is determined by the gas covering fraction.
- The separation of absorbing clumps evidently increases with increasing velocity. This $C_f(v)$ behavior occurs quite naturally for an accelerating flow in spherical geometry.
- Gas at large radii will be nearly impossible to detect. The trough will be too shallow. <u>The detected outflows must be near the galaxy.</u>
- *Require background light source to measure how far winds travel. Bright quasars provide higher sensitivity than background galaxies.*

Size Can Be Measured Using the Statistics of Intervening Metal Absorption-Lines



Oppenheimer & Dave 2009

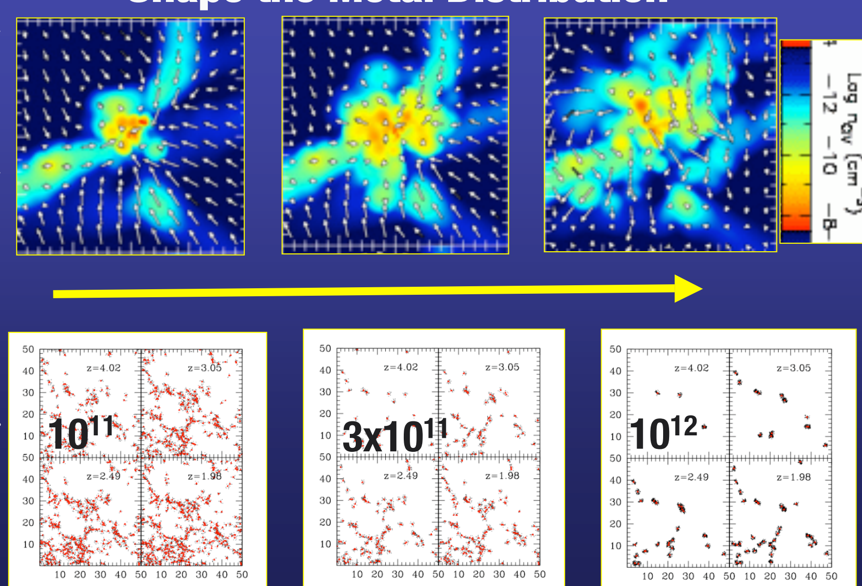
MARTIN et al. 2010 ApJ:

- CIV systems trace metals
- Distribution of CIV systems in redshift space mixes size and Doppler velocity.
- Distribution of CIV systems transverse to our sightline measures size of enriched region.

Feedback Strength and Galaxy Bias (M_h, z) both Shape the Metal Distribution

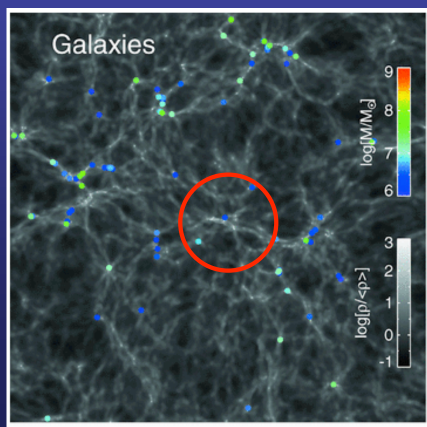
Kawata & Rauch 2007
1.6 cMpc (400 kpc)

Scannapieco+2006
71 cMpc



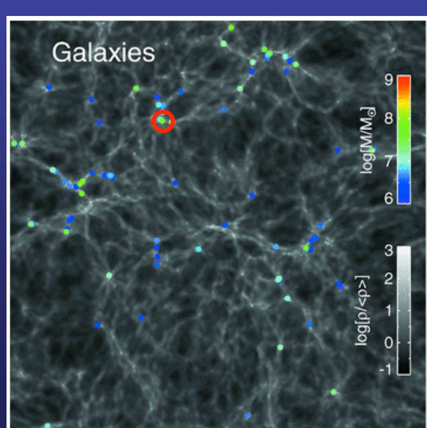
Correlation Functions 101a

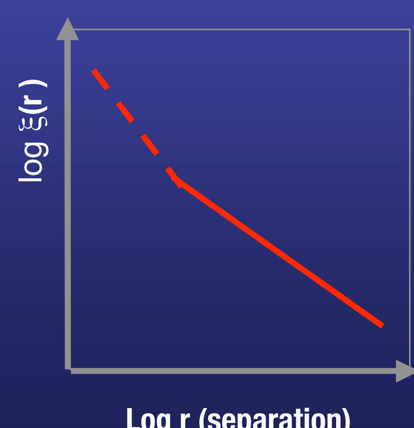
- Joint probability of finding a galaxy in dV_1 and dV_2 is
  $P_{1,2} = P(1)\ P(2|1) = n^2_{avg}\,(1+\xi)dV_1dV_2$.
- $1+\xi(r) = DD(r) / RR(r)$
- $\xi(r)$ for galaxy - galaxy correlation fitted by a power law



Correlation Functions 101b

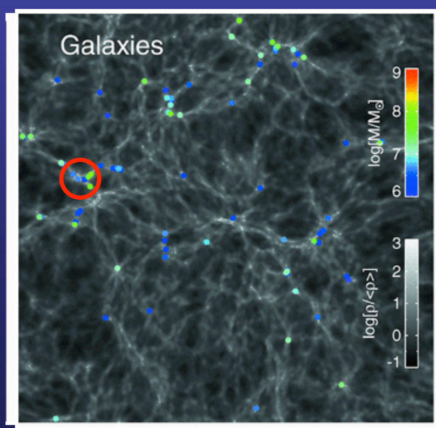
- Galaxy-galaxy correlation amplitude steepens within a halo.

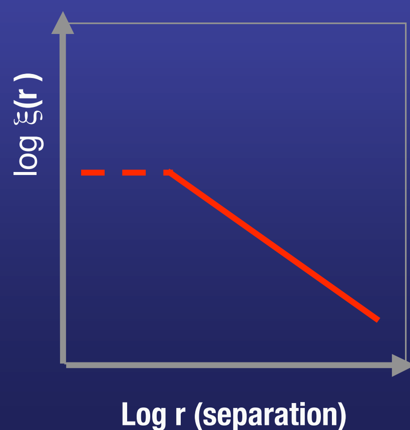




Correlation Functions 101c

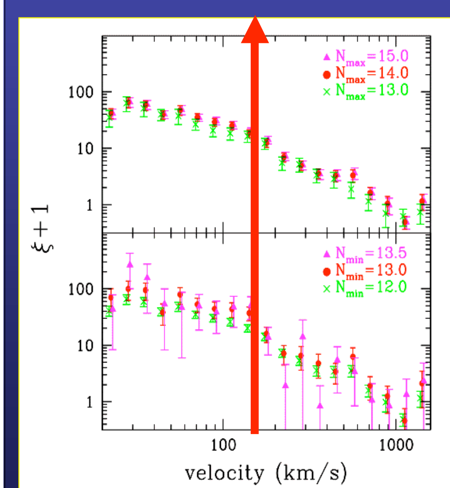
- Galactic winds smooth out the distribution of metals.
- Absorber -- absorber correlation function should flatten on small scales (< size of enriched region)

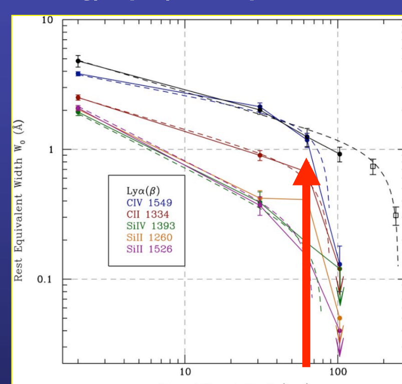




Previous Size Estimates Disagree

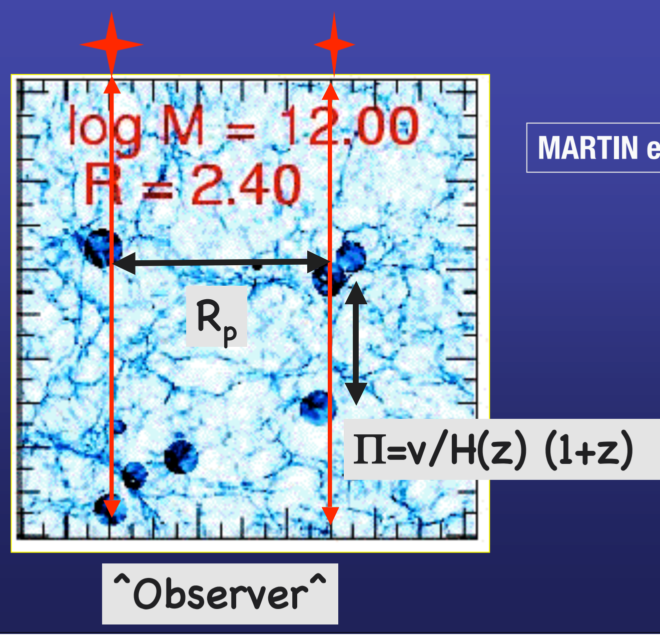
- Line-of-Sight CIV Correlation Function. Break at 150 km/s corresponds to a Hubble distance of 500 kpc, or 2.0 h_{70}^{-1} (comoving) Mpc (Scannapieco + 2006; Rauch + 1996)





- Probing the halos of foreground galaxies with background galaxies gives b=60-100 kpc (Steidel et al. 2010).

Transverse (Angular) Correlation of CIV Systems

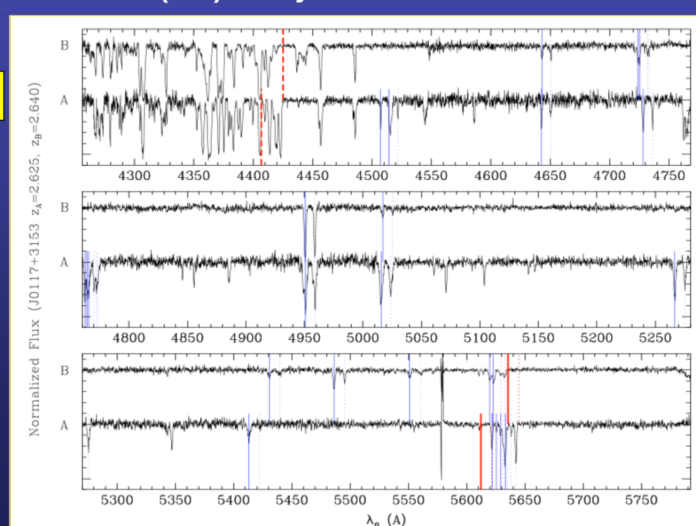


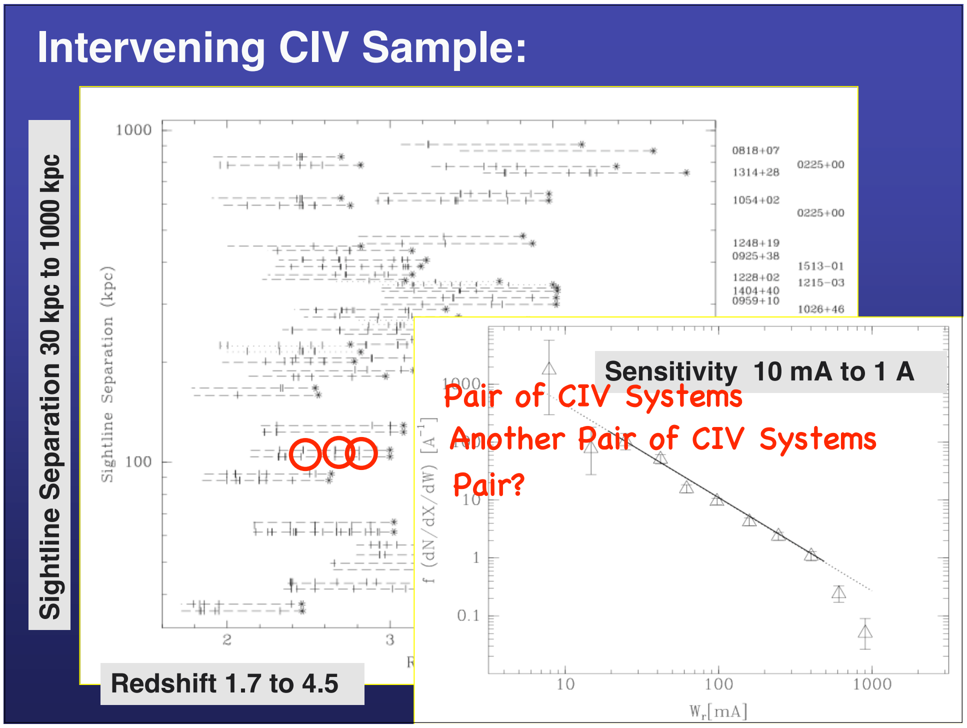
MARTIN et al. 2010 ApJ

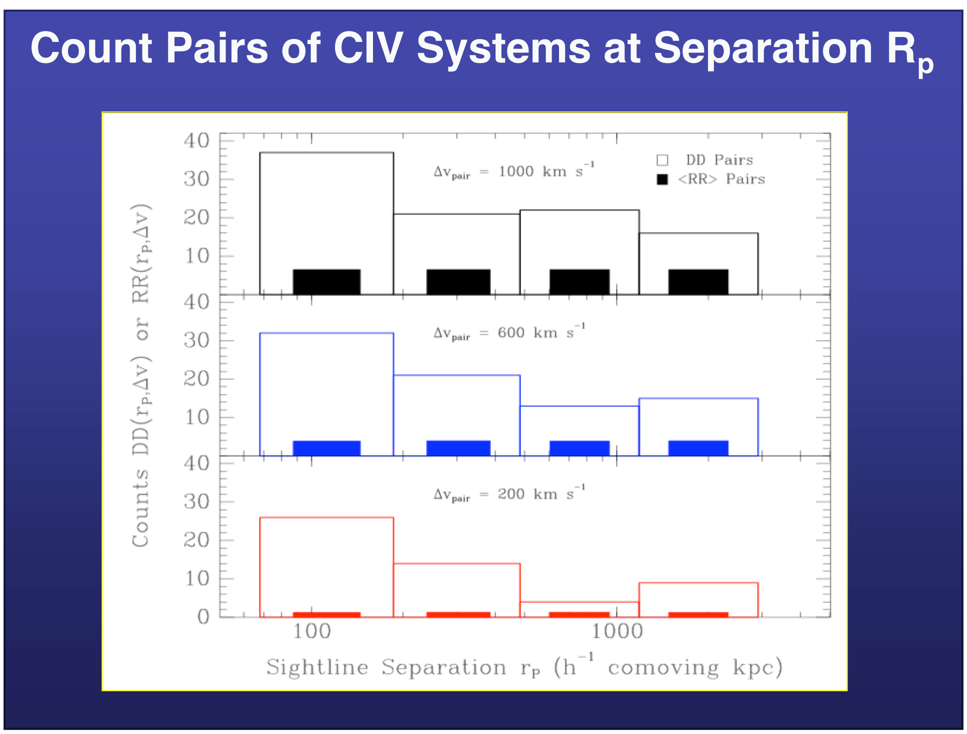
Echellete Spectroscopy with Keck/ESI

- Binary Quasars at $1.7 < z < 4.5$ (Hennawi)
- 55 Sightlines with 450 (316) CIV systems

100 kpc at z = 3

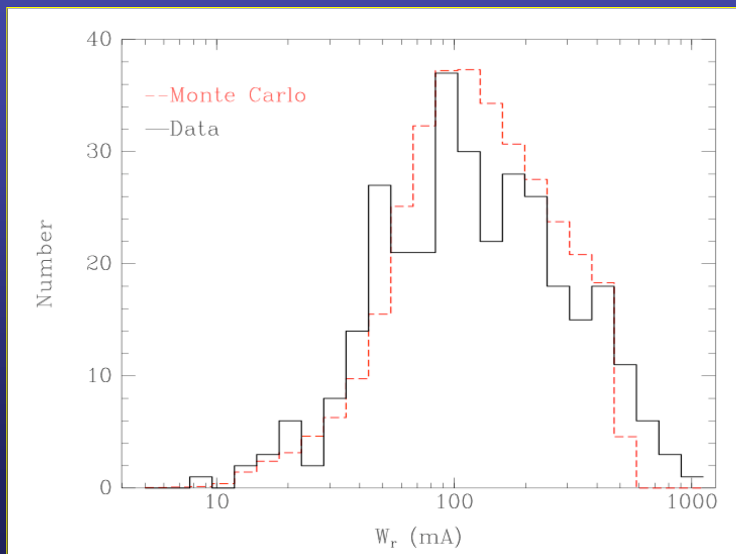



Intervening CIV Sample:
Sightline Separation 30 kpc to 1000 kpc
Sightline Separation (kpc)
1000
100
2
3
0818+07
1314+28
1054+02
1248+19
0925+38
1228+02
1404+40
0959+10
0225+00
0225+00
1513-01
1215-03
1026+46
Redshift 1.7 to 4.5
Sensitivity 10 mA to 1 A
Pair of CIV Systems
Another Pair of CIV Systems
Pair?
f (dN/dX/dW) [A^-1]
1000
10
1
0.1
10
100
1000
W_r[mA]


Count Pairs of CIV Systems at Separation R_p
Counts DD(r_p,Δv) or RR(r_p,Δv)
40
30
20
10
0
Δv_pair = 1000 km s^-1
DD Pairs
<RR> Pairs
Δv_pair = 600 km s^-1
Δv_pair = 200 km s^-1
100
1000
Sightline Separation r_p (h^-1 comoving kpc)

Normalize Counts by Chance Coincidences:

Choose Random Redshifts for CIV Systems



Fitted Correlation Functions:

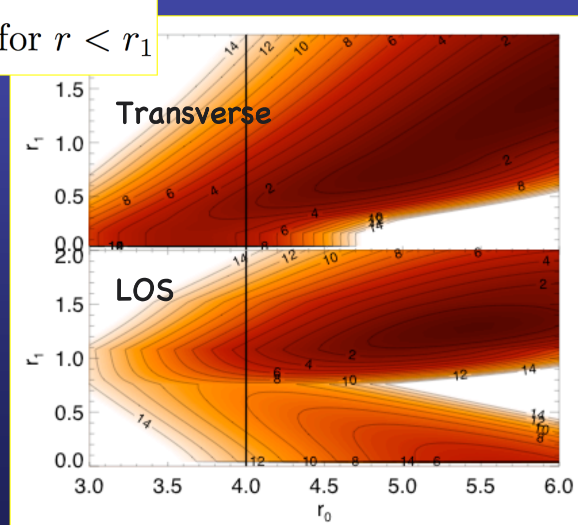
Transverse vs. Line-of-Sight

$$\xi(r) = (r_0/r)^\gamma \text{ for } r \geq r_1$$
$$(r_0/r_1)^\gamma \text{ for } r < r_1$$

- Correlation length for galaxies is 4.0 h^{-1} cMpc (Adelberger et al 2005a)

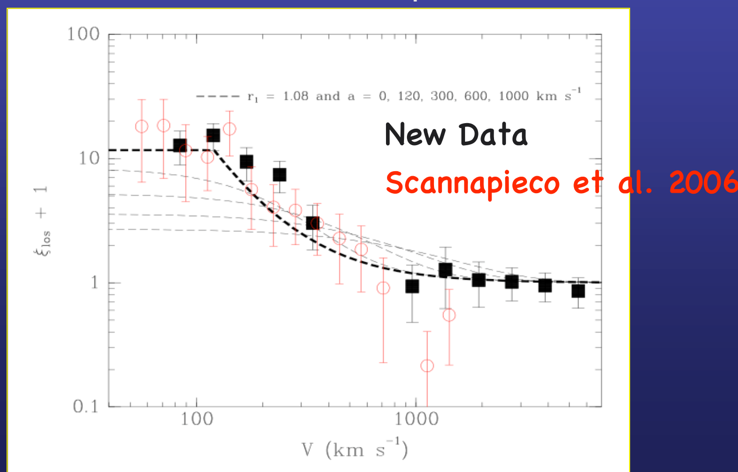
- Power law fit to CIV clustering breaks at smaller r_1 for the transverse case.

- Transverse and LOS correlations measure the same real-space distribution, so r_1 must be the same in each direction.

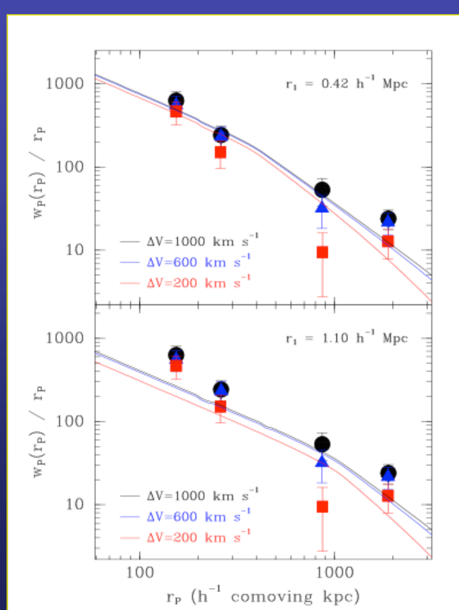


LOS CIV-CIV Correlation Function

- Metals cluster like Lyman-break galaxies on large scales. Consistent with correlation length r_0 = 4.0 h^{-1} cMpc.
- In the absence of peculiar velocities, metals appear smoother than galaxies on scales below r_1 = 1.1 h^{-1} cMpc.



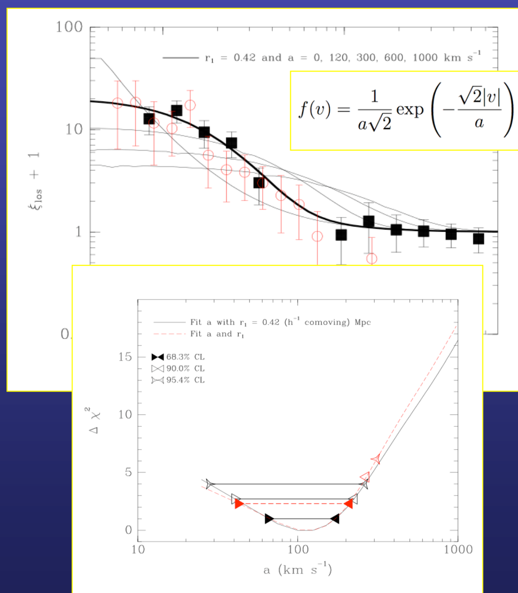
Transverse CIV-CIV Correlation Function



$$w(R) = \int \xi(r)\, d\pi$$

- Adopt correlation length from galaxy-galaxy clustering.
- Power-law flattens on scale r_1 = 0.42 h^{-1} cMpc.
- The larger scale fitted to the LOS CF, r_1=1.1 h^{-1} cMpc, is inconsistent with this measurement.
- <u>Conclude that the line-of-sight correlation function is smeared out by Doppler shifts</u>.
- *We can fit the size of these peculiar velocities.*

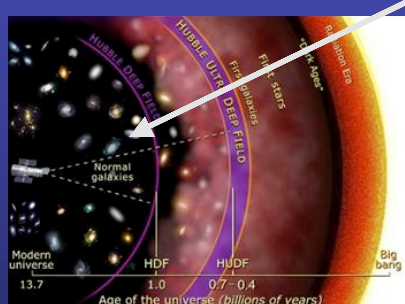
LOS CIV-CIV Correlation Function with Velocity Kicks



$$f(v) = \frac{1}{a\sqrt{2}} \exp\left(-\frac{\sqrt{2}|v|}{a}\right)$$

- Take r_1=0.42 h^{-1} cMpc.
- No room for radial kicks any larger than v_l=120 km/s along the LOS.
- Velocities v=200 km/s could results from gravitational accelerations between galaxies, virial motion, gas infall, or galactic winds.
- Velocity kicks v_l~300 or larger are highly inconsistent with the clustering of CIV systems.

Metal Dispersal by Galactic Winds

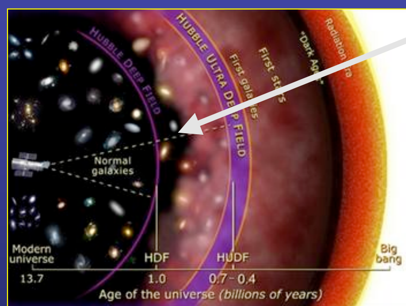


$$R \simeq 61 \text{ kpc} \left(\frac{v}{200 \text{ kms}^{-1}}\right)\left(\frac{\tau}{300 \text{ Myr}}\right)$$

DISPERSAL AT z~3

- (+) Metals biased like Lyman-break galaxies.
- (-) Enriched region is large, R~150 kpc (or 0.42 h^{-1} cMpc).
- (-) Average outflow speed over this scale is slow, less than 200 km/s.
- (-) Median stellar age is just 300 Myr. About 20% are 1 Gyr old (Shapley et al. 2001).
- *Difficult for the typical LBG to spread metals this far.*

Implications for Circum-Galactic Metal Enrichment

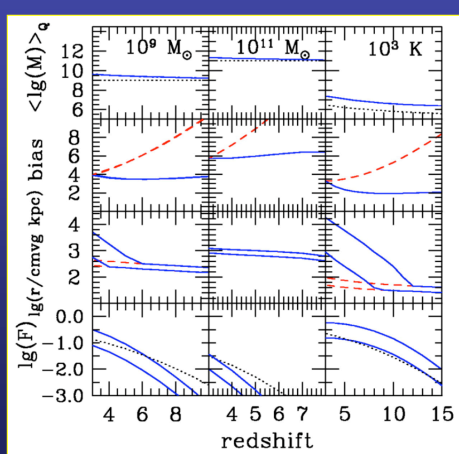


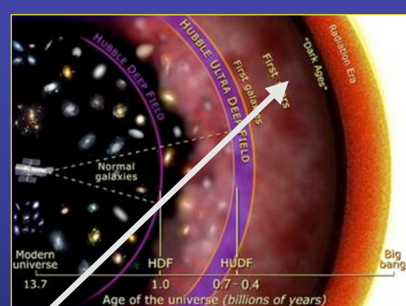
$$\frac{dN}{dz} \approx 1.4 \left(\frac{n_{gal}}{3.7 \times 10^{-3} h^3 \text{ Mpc}^{-3}} \right) \times \left(\frac{r_1}{0.42\, h^{-1} \text{ Mpc}} \right)^2 \left(\frac{450h \text{ km s}^{-1}\text{Mpc}^{-1}}{H(z)} \right)$$

DISPERSAL AT z~4-6

- **Metal sources must be biased like z=3 LBGs. Examples: (1) Redshift 6 galaxies with masses 30 times lower. (2) Redshift 4.3 galaxies with masses 5 times lower.**
- **(+) Earlier injection makes it easier to enrich a large comoving volume. The expansion of the universe helps. There's more time. And metals escape more easily from lower mass galaxies.**
- **Large number of lower mass galaxies easily accounts for redshift-path density of CIV.**
- ***Data consistent with Post-Reionization Dispersal of Metals.***

Implications for Circum-Galactic Metal Enrichment



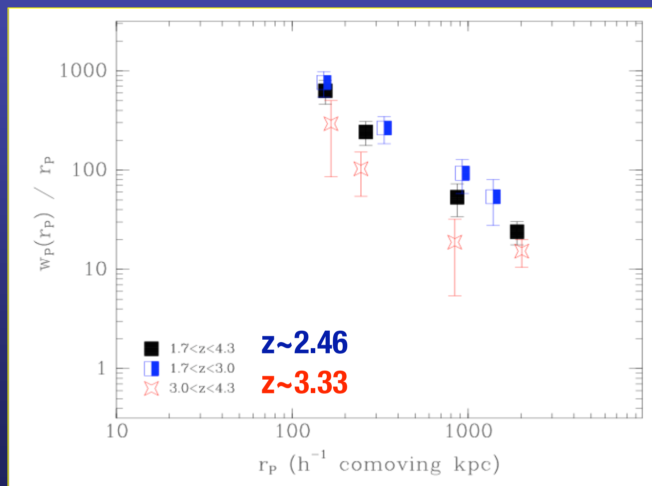


DISPERSAL AT z > 6

- **Bubbles of metals from different galaxies will overlap.**
- **Should detect rapid growth in size of enriched region at epoch of overlap.**

Measured Evolution in the Size of Metal Enriched Regions

- Amplitude increases with cosmic time
- Evolution in break r_1 not constrained by current data.
- May be possible to measure size evolution. Would constrain how much earlier metals were dispersed.



Measurements of the size of enriched regions and their relative velocities at 1.7 < z < 4.5 provide a new constraint on chemical enrichment and feedback processes.