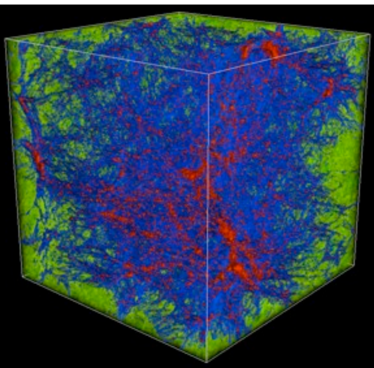

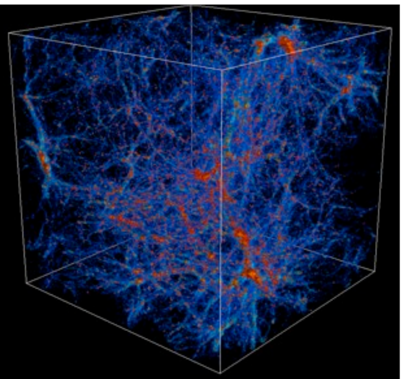

Constraining Feedback Models through Cosmological Chemical Enrichment

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UNLV

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Tae Song Lee, Robert Thompson (Grad)
Jason Jaacks, Alex Jacobson, Saju Varghese, Tony Brillhart (UG)
Yuu Niino (Kyoto), Hidenobu Yajima (Penn State)

Questions

- Do we really need feedback on large scales? -- observational evidence
- What is the energy source? -- SNe or AGN
- How can we study chemical enrichment on cosmological scales? -- simulations
- What's the next step?

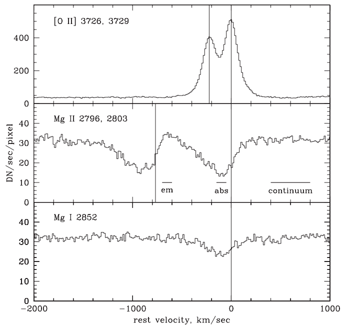
Observational Evidence for Galactic Wind

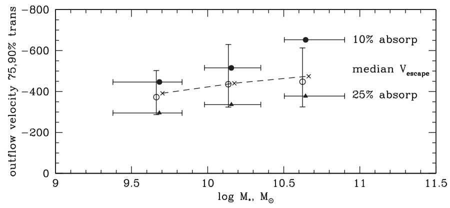
z~0

X-ray + Opt + IR

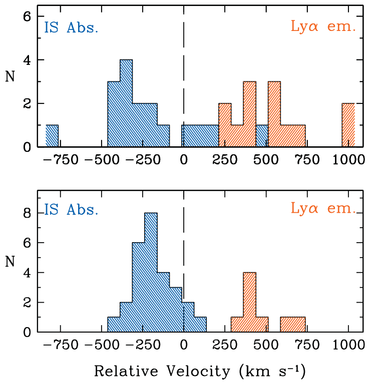
cf. Chen+ '10: DR7 SDSS gals
stacking analysis
Na I, Na D abs. lines
120-160 km/s outflows

z~1: DEEP2, ubiquitous outflow





Weiner+ '09



z~3: LBG

Steidel+ '04
common outflow vel
200-300 km/s

z~2

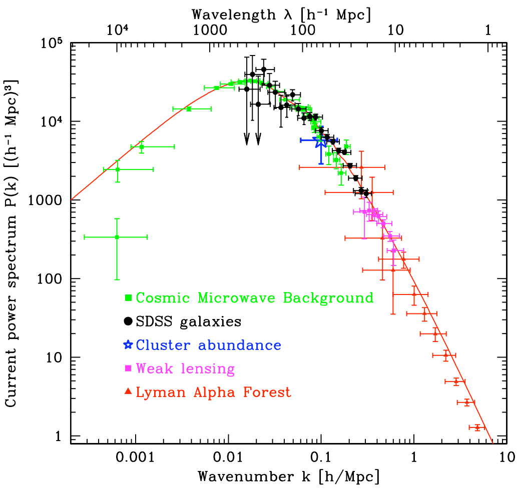
Metals also observed in ICM, groups, Lya forest, ...

Concordance ΛCDM model

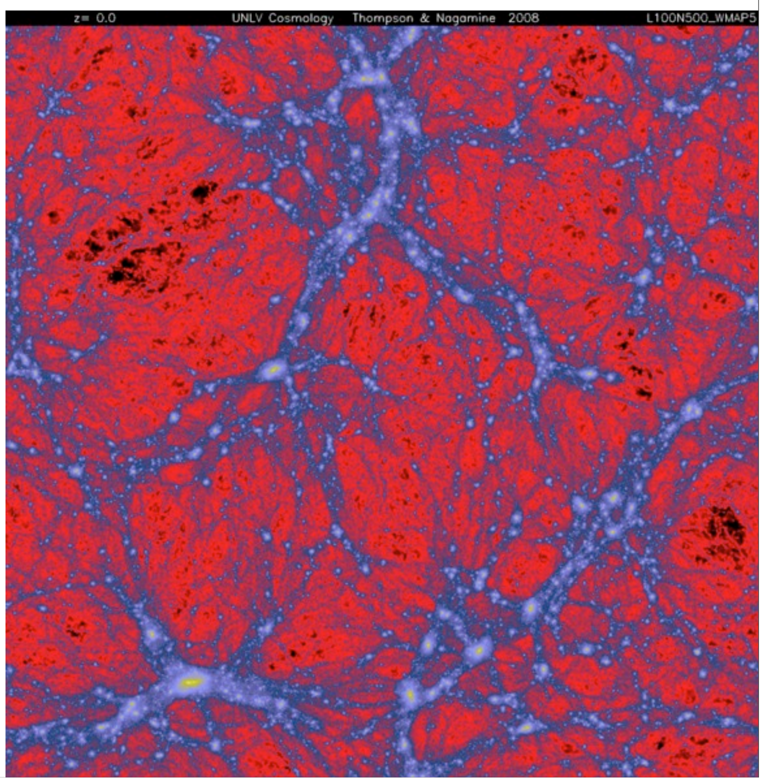
WMAP5, 7 $(\Omega_M, \Omega_\Lambda, \Omega_b, h, \sigma_8, n_s) \approx (0.26, 0.74, 0.04, 0.7, 0.8, 0.96)$

(Komatsu '09, '10)

- Successful on large-scales
- Then, interpret galaxy observations in the context of ΛCDM model



Tegmark et al. (2004)



WMAP cosmology

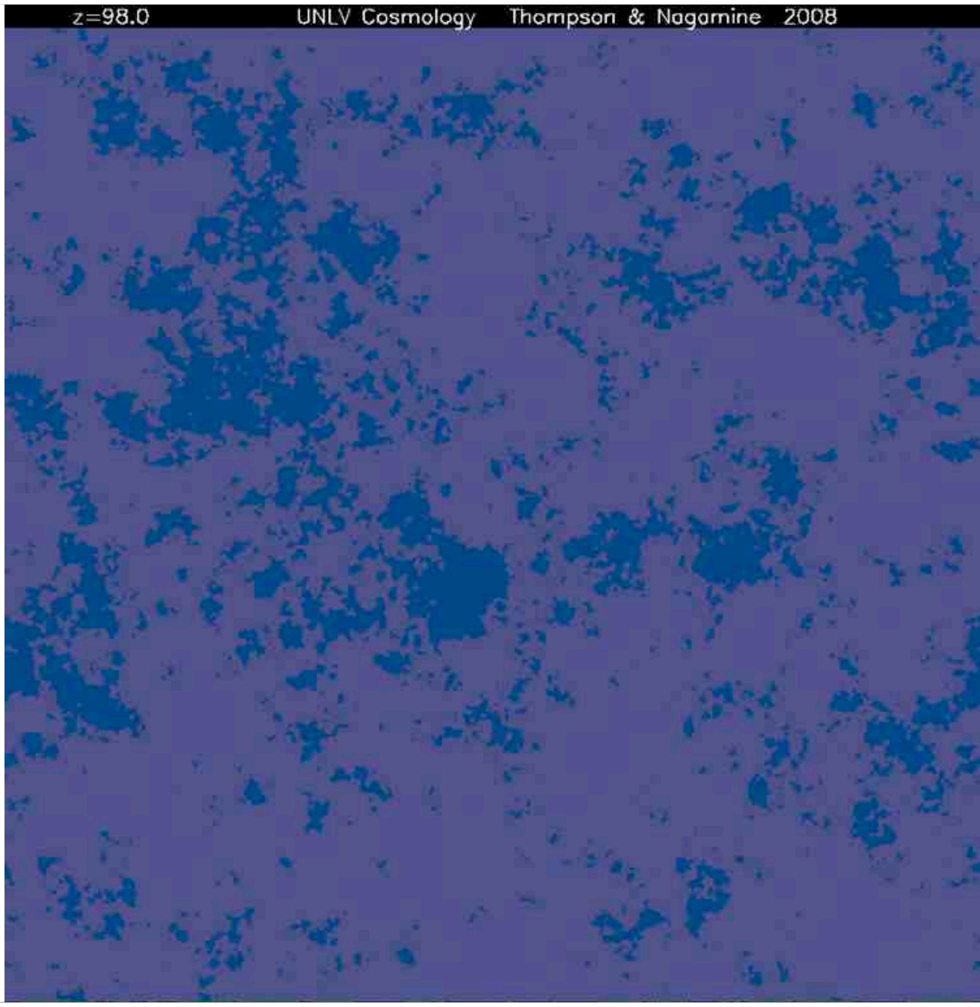
(Komatsu '09, '10)

Dark matter only sim

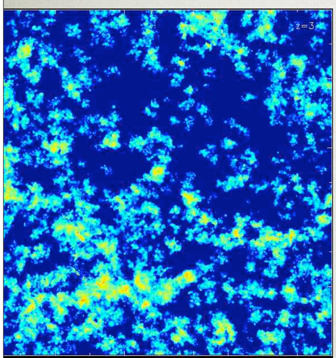
Box size 100 Mpc/h

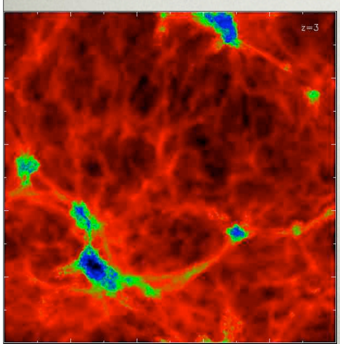
500^3 ptcls

available on my website



ΛCDM Cosmological Hydrodynamic Simulations





- GADGET-3 SPH code (Springel '05+α) modified with metal cooling, new SF and galactic outflow models w/ variable velocity, etc.

  radiative cooling/heating, star formation, SN & galactic wind feedback

- LBG/LAE@z=3-6, massive gal, EROs, DLAs, ...

  (KN+ 04ab, 05ab, 07, 08a,b)

- Choi & KN '09a,b, '10

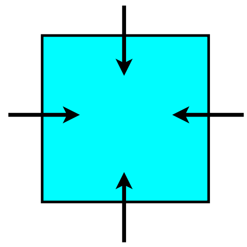
Series	Box-size	N_p	m_{DM}	m_{gas}	ϵ	z_{end}
N144L10	10.0	2×144^3	2.01×10^7	4.09×10^6	2.78	2.75
N216L10	10.0	2×216^3	5.95×10^6	1.21×10^6	1.85	2.75
N400L10	10.0	2×400^3	9.37×10^5	1.91×10^5	1.00	2.75
N400L34	33.75	2×400^3	3.60×10^7	7.33×10^6	3.38	1.00
N400L100	100.	2×400^3	9.37×10^8	1.91×10^8	10.	0.0
N600L100	100.	2×600^3	2.78×10^8	5.65×10^7	6.67	0.0
	$[h^{-1}\mathrm{Mpc}]$		$[h^{-1}M_\odot]$		$[h^{-1}\mathrm{kpc}]$	

Star Formation Model

Katz '92; Cen & Ostriker '92

- 4 criteria for a cell (or a gas parcel) to be star-forming:

1.	$\delta > \delta_{\rm th}$	(overdense)
2.	$\nabla \cdot \vec{v} < 0$	(contracting)
3.	$t_{\rm cool} < t_{\rm dyn}$	(cooling fast)
4.	$m_{\rm gas} > m_{\rm Jeans}$	(Jeans unstable)



then,

$$\dot{\rho}_\star = c_\star \frac{\rho_g}{t_\star} \qquad (c_\star \sim 0.01 - 0.1)$$

Krumholz & Tan '07

if $\quad t_\star = t_{\rm dyn} \propto \frac{1}{\sqrt{G\rho}} \longrightarrow \dot{\rho}_\star \propto \rho_g^{1.5}$

(≈ K-S law)

(n_{th} ~ 0.1 - 1 cm^{-3} suffices.)

For each star ptcl:

$(m_\star, t_{form}, Z)$

Population Synthesis Model
Chabrier IMF (~Kroupa)
[0, 100] Msun
6 metallicity
various filters
E(B-V)=0 ~ 1.0

Sub-grid/ptcl Multiphase ISM model

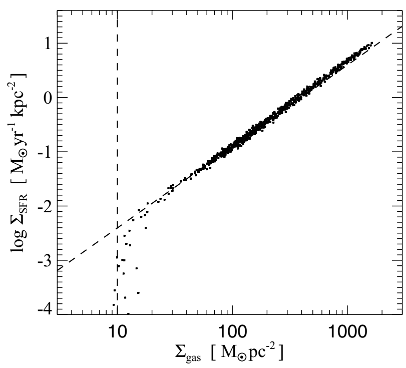
Yepes+ '97; Springel & Hernquist '03

SFR:

$$\dot{\rho}_\star = (1-\beta)\,\frac{\rho_c}{t_\star}$$

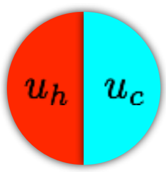
cold gas

recycling mass frac.



$$t_\star = t_\star^0 \left(\frac{\rho_g}{\rho_{\rm th}}\right)^{-0.5} \qquad t_\star^0 = 2.1\,{\rm Gyr}$$

subparticle multiphase ISM model



$$\rho_h \frac{du_h}{dt} = \beta \frac{\rho_c}{t_\star}(u_{sn} + u_c - u_h) - A\beta\frac{\rho_c}{t_\star}(u_h - u_c) - f\Lambda_{net}$$

$$u_c = {\rm const.}$$

Galactic Wind Feedback

mass-loss rate

$$\dot{M}_W = \eta \dot{M}_\star$$

wind energy

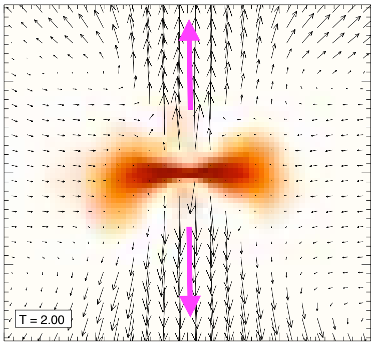
$$\frac{1}{2}\dot{M}_W v_W^2 = \chi \epsilon_{\rm SN} \dot{M}_\star$$

constant wind velocity

$$v_{\rm w} = \sqrt{\frac{2\beta\chi u_{\rm SN}}{\eta(1-\beta)}}.$$

$$v_{\rm w} = 200 - 500\ {\rm km/s}$$

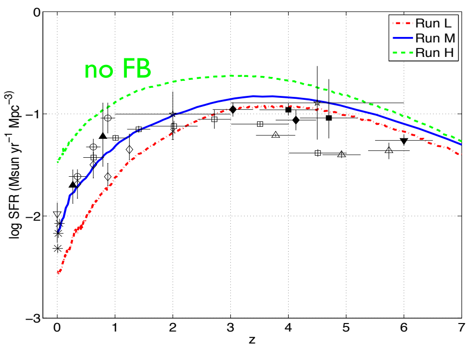
X-ray + Opt + IR



Springel & Hernquist (2003)

Effects on Galaxies & IGM

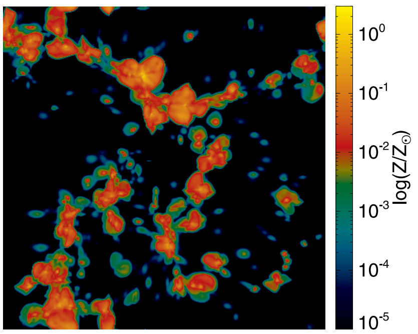
cosmic SFR

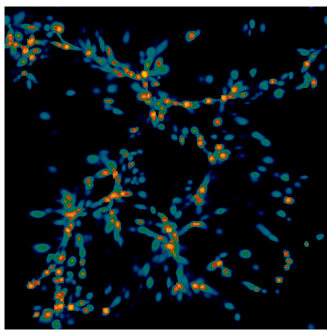


Cen & Chisari (2010)

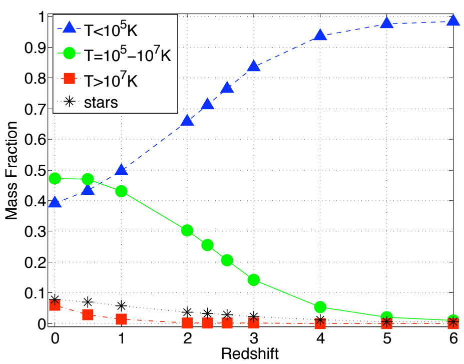
with feeback

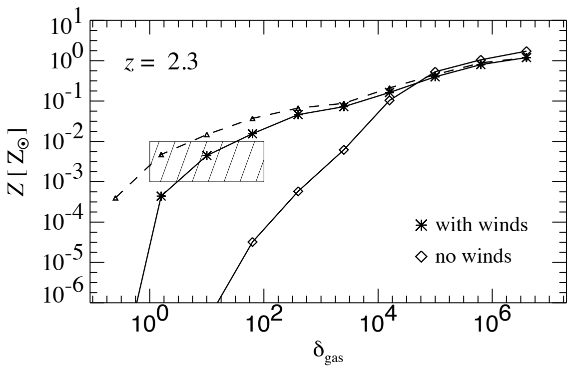
no feeback





Cen, KN, Ostriker (2005)





Springel & Hernquist (2003)

Energy vs. Momentum driven wind

$$\dot{M}_W = \eta \dot{M}_\star, \qquad \eta: \text{ mass-loading factor}$$

Energy-driven: $\frac{1}{2}\dot{M}_W V_W^2 \sim \dot{E}_{\rm SN} \sim SFR$

$$\eta = \left(\frac{\sigma_0}{\sigma_{\rm gal}}\right)^2$$

$V_W \sim V_{\rm esc} \sim \sigma_{\rm gal}$

$\sigma_0 \approx 300 \text{ km s}^{-1}$

Momentum-driven: $\dot{M}_W V_W \sim \dot{P}_{\rm rad} \sim SFR$

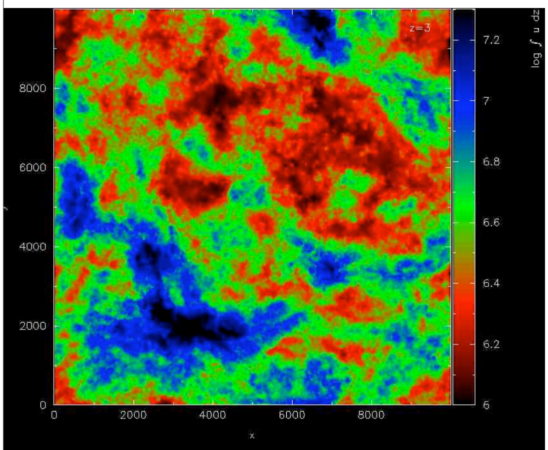
$$\eta = \frac{\sigma_0}{\sigma_{\rm gal}}$$

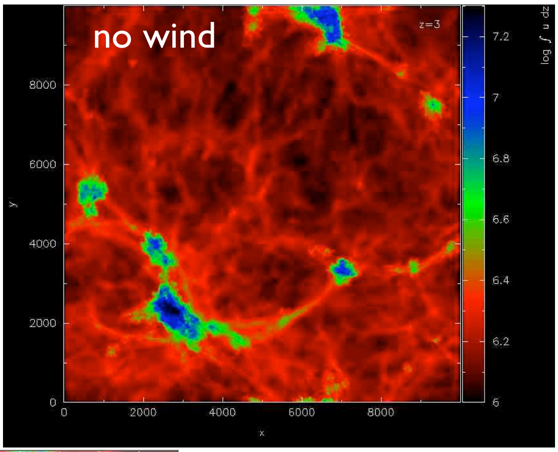
Radiation pressure from massive stars and SNe is applied to the dust particles, which entrains the wind

Higher mass-loading factor for lower mass galaxies!

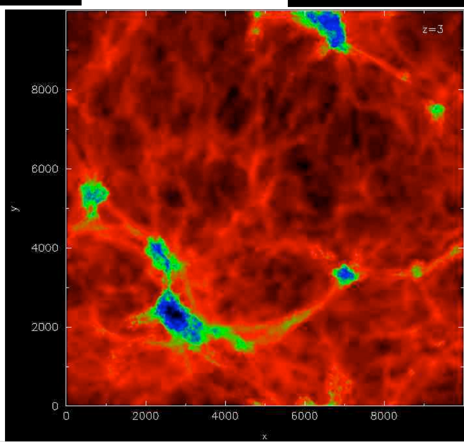
SN feedback & Wind model

constant speed (SH03)





Multicomponent variable velocity (MVV) wind model (based on momentum-driven wind)

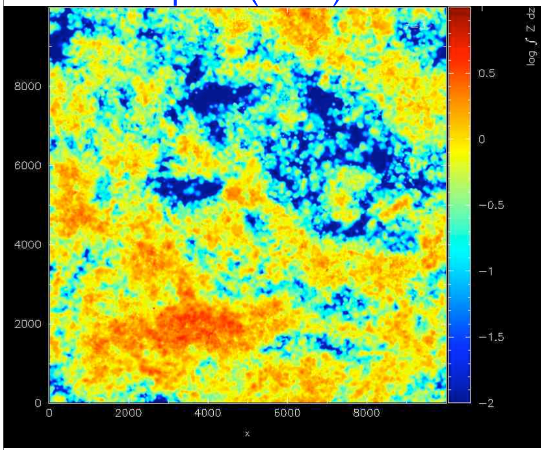


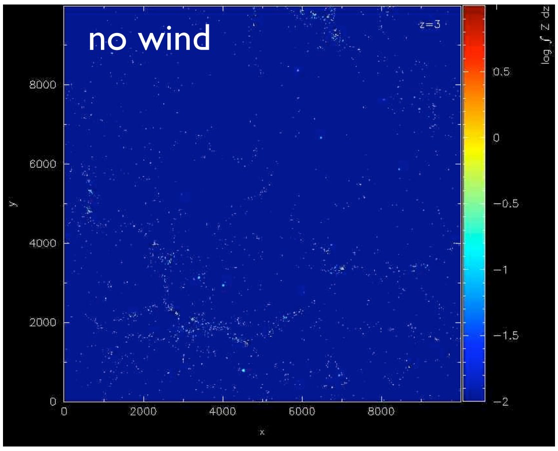
Projected internal energy distribution

Choi & KN '10

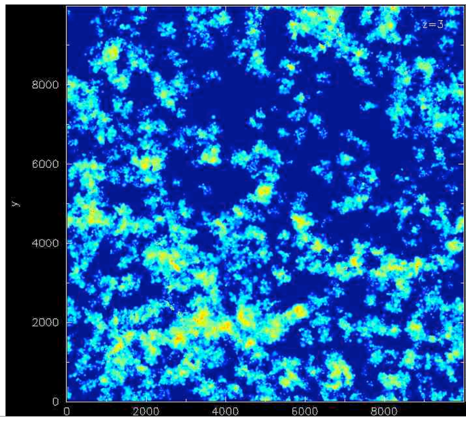
SN feedback & IGM Enrichment

constant speed (SH03)





Multicomponent variable velocity (MVV) wind model (based on momentum-driven wind)

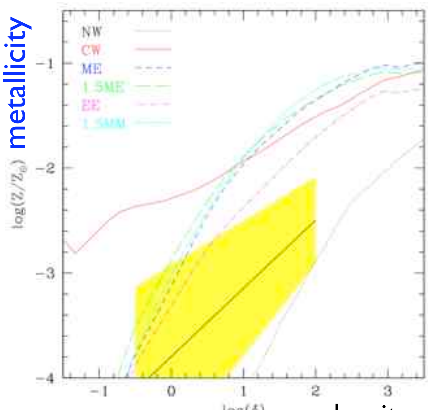


Projected metallicity distribution

Choi & KN '10

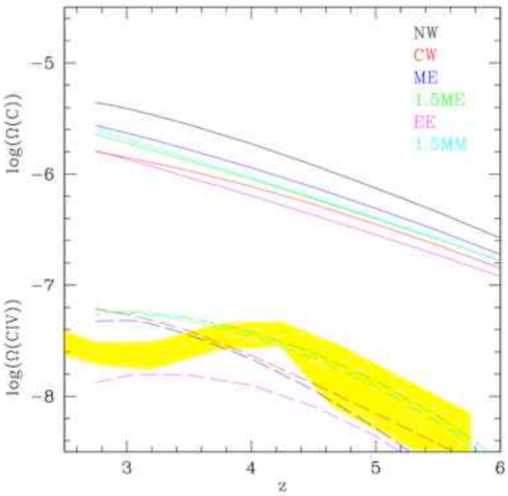
IGM metal enrichment & Temp

metallicity

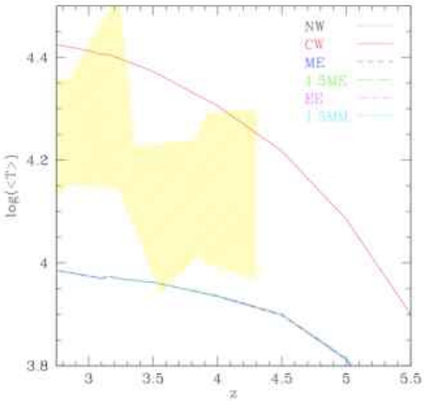


overdensity

C & Civ mass



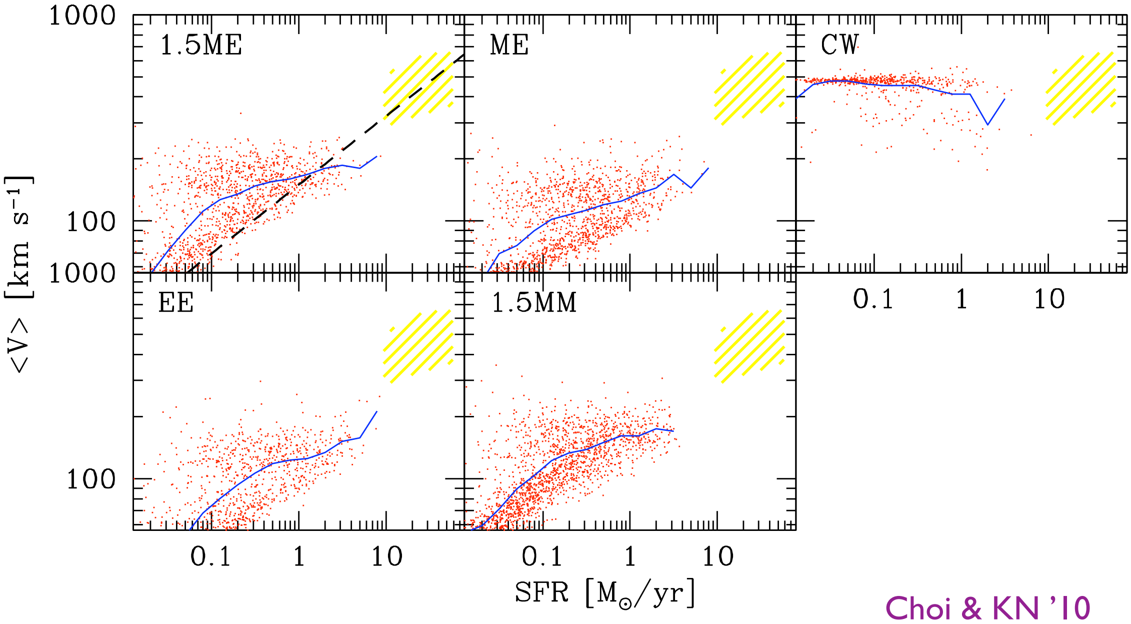
redshift



IGM temperature

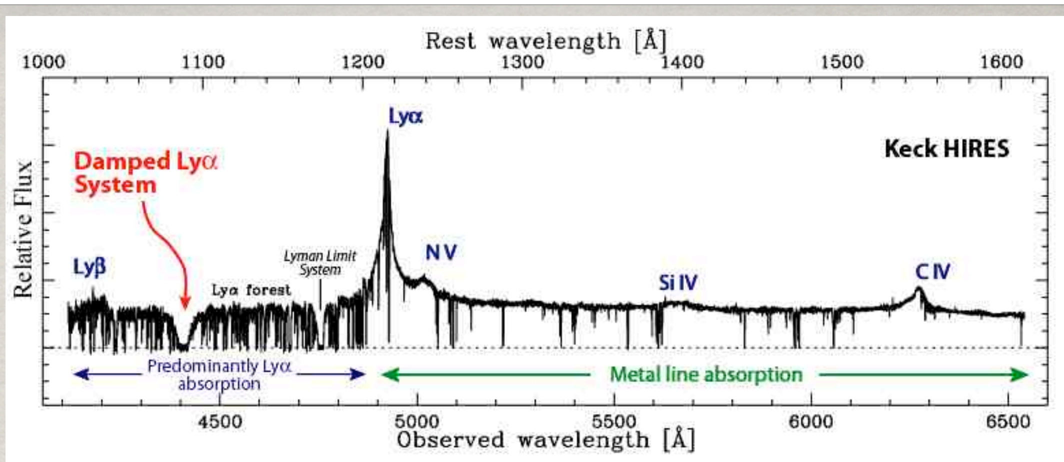
Choi & KN '10

Outflow Velocities



Choi & KN '10

What are DLAs?



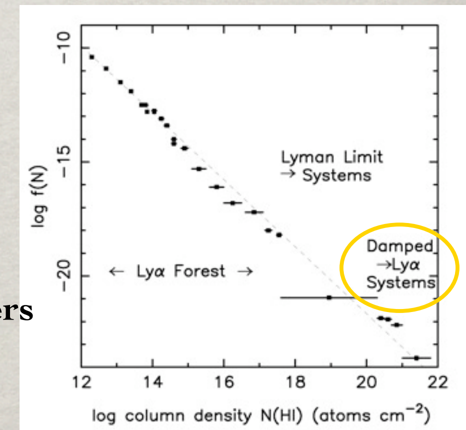
$N_{\rm HI} > 2 \times 10^{20}\ {\rm cm}^{-2}$

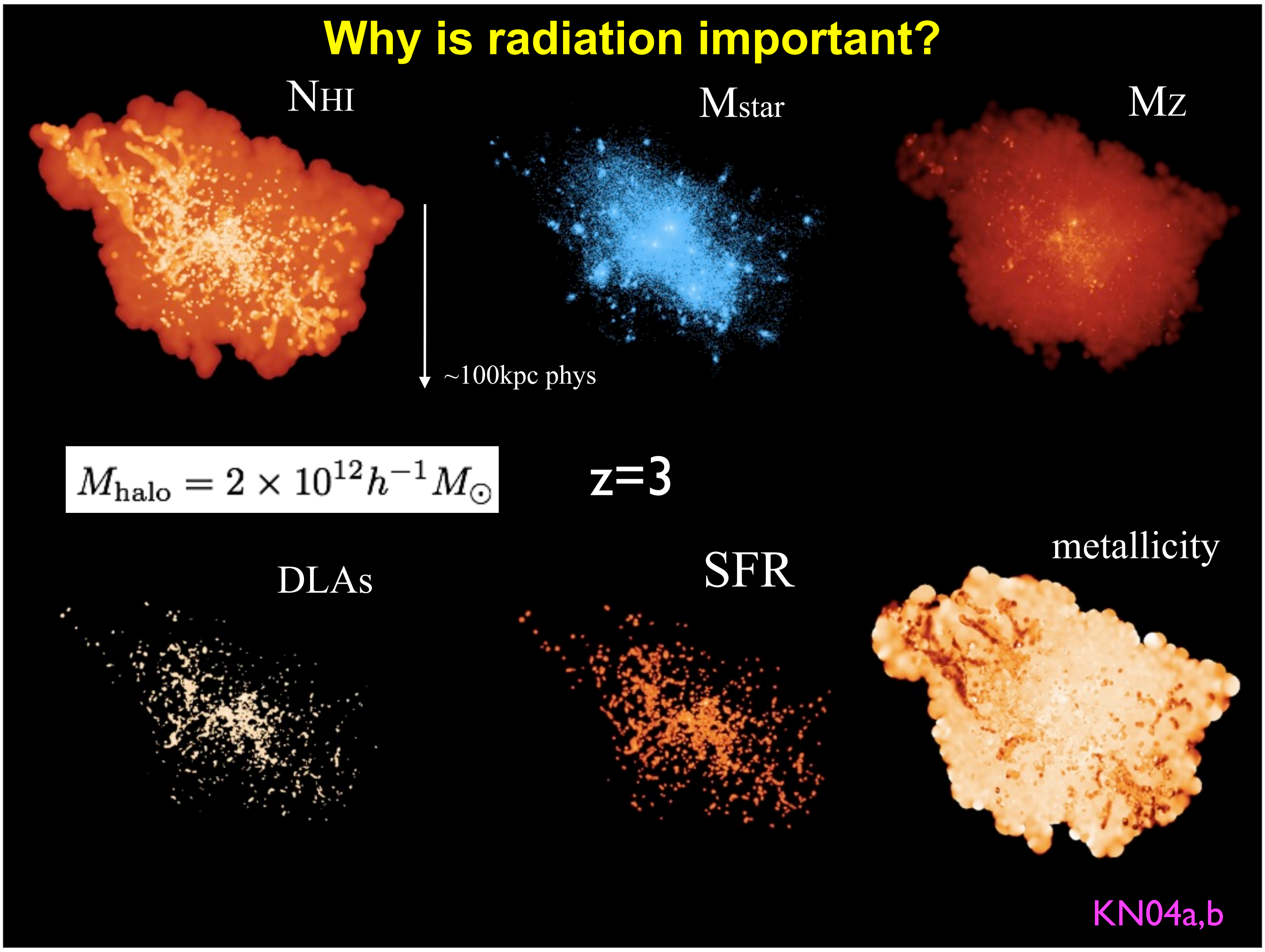
(Wolfe+ '86)

Direct probe of HI gas in high-z universe

DLAs are heavy-weight champions of HI absorbers

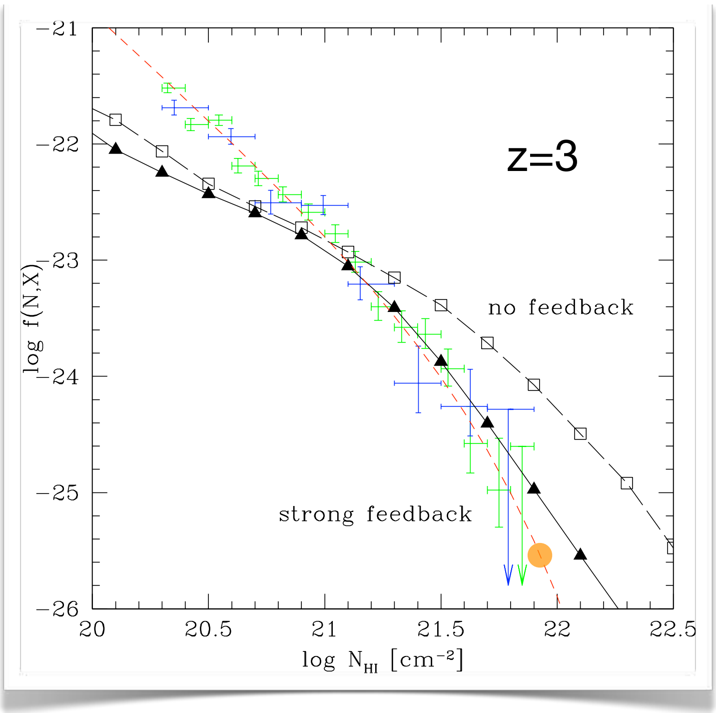
Would like to understand these systems in the context of CDM model





Column density distribution $f(N_{HI})$

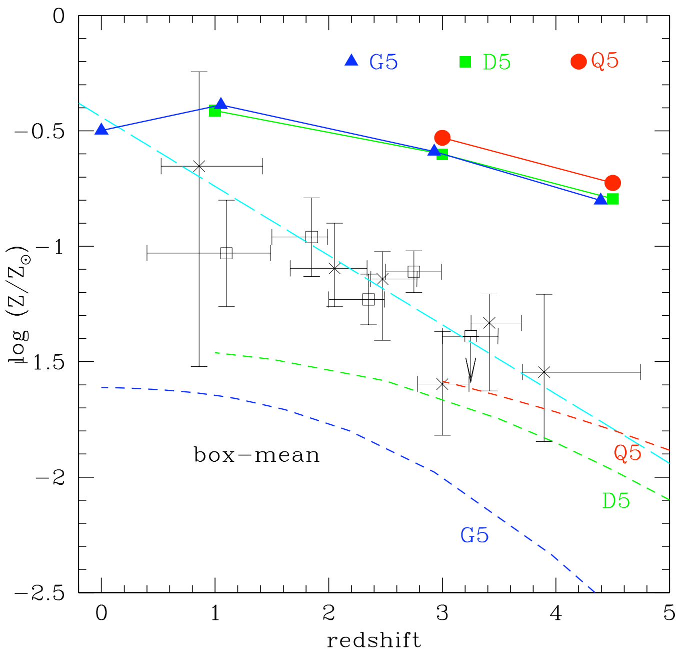
- High N_{HI}-end OK for strong feedback run.
- No feedback run overpredicts at high N_{HI}.
- Shortage of $f(N_{HI})$ at $\log N_{HI} <\sim 21$ in sim. --> problem related to the self-shielding of gas



KN+ ‘04a,b

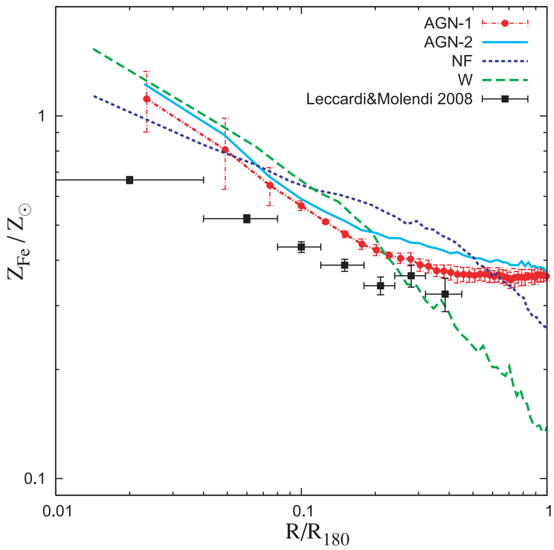
Cosmic Chemical Evolution w/ DLAs

- DLAs can probe cosmic chemical evolution in and near the galaxies
- The rate of evolution
- Data points: Pettini+ '99; Prochaska+ '03

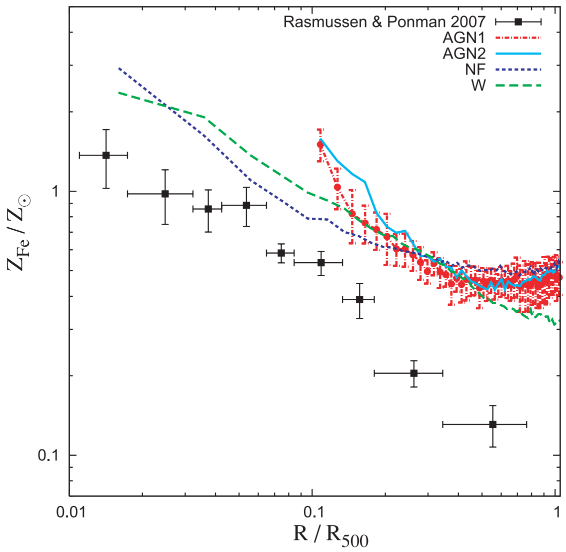


KN+ '04b

Cluster Metal Gradient



Galaxy Clusters: $T_{500} > 3$ keV



Groups: $T_{500} < 3$ keV

Fabjan+ '10, SPH simulations with AGN feedback

Summary & Future Work

- Significant evidence for chemical enrichment on cosmological scales by galactic outflows & AGNs.
- Cosmological hydro sims can be a useful tool to constrain the feedback strength and its effect on IGM & galaxies.
- New models (energy-driven vs. momentum-driven) are being explored.
- QSO absorption systems (Lya forest, DLAs, etc.) are good probes of cosmic chemical enrichment.
- Future: AGN feedback, detailed chemistry w/ diff elements, yields, etc.