From Lyα Forest to Lyα Emitters: Probing Cosmological Reionization

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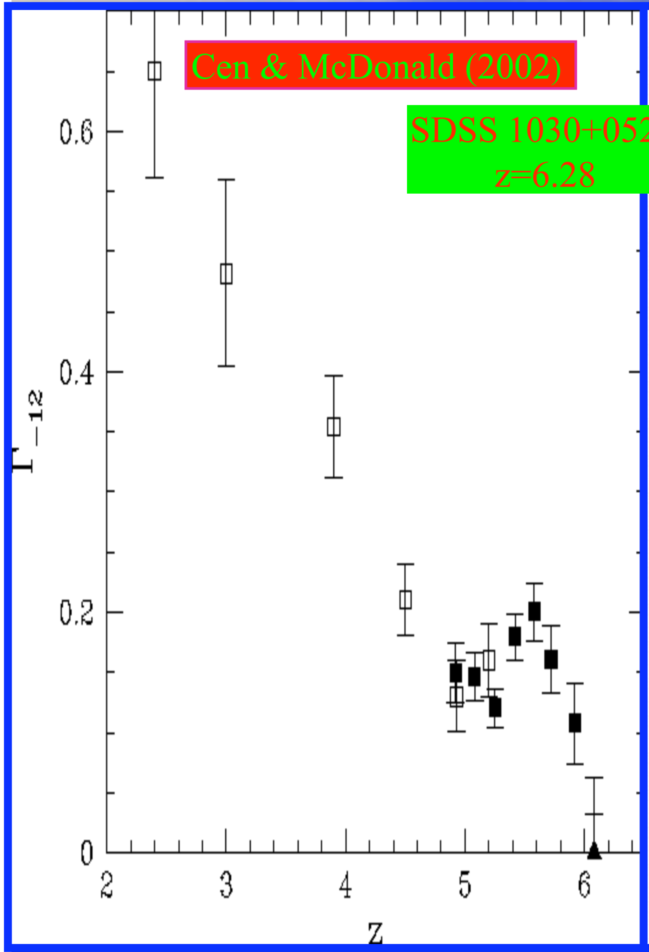
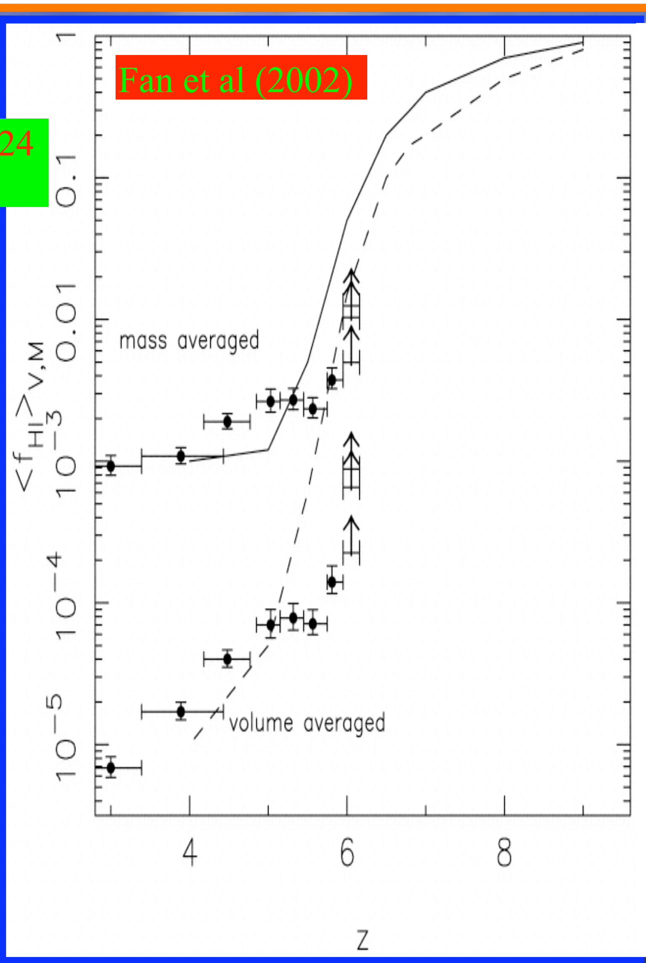
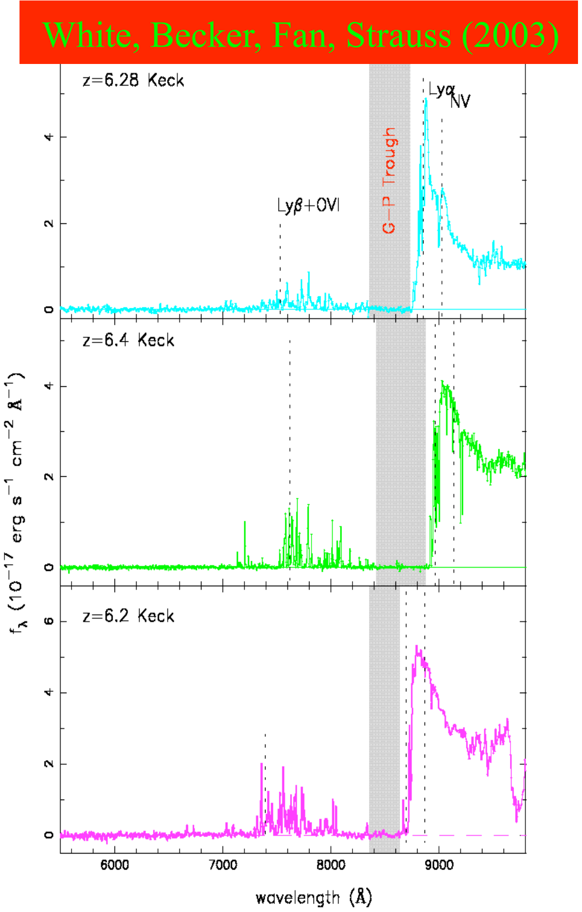
- Complex and Uncertain Reionization History
- Radiative Transfer (of Ionizing Photons) Hydrodynamic Simulations
- Probe #1: Lyα Forest at $z=4-5$
- Probe #2: Lyα Emitters at $z=5.7$ and beyond with Detailed Treatment of Transfer of Lyα photons
- Conclusions

1: SDSS: neutral fraction changes from 10^{-4} to $>10^{-2}$ from z=5.8 to 6.3


Cen & McDonald (2002)

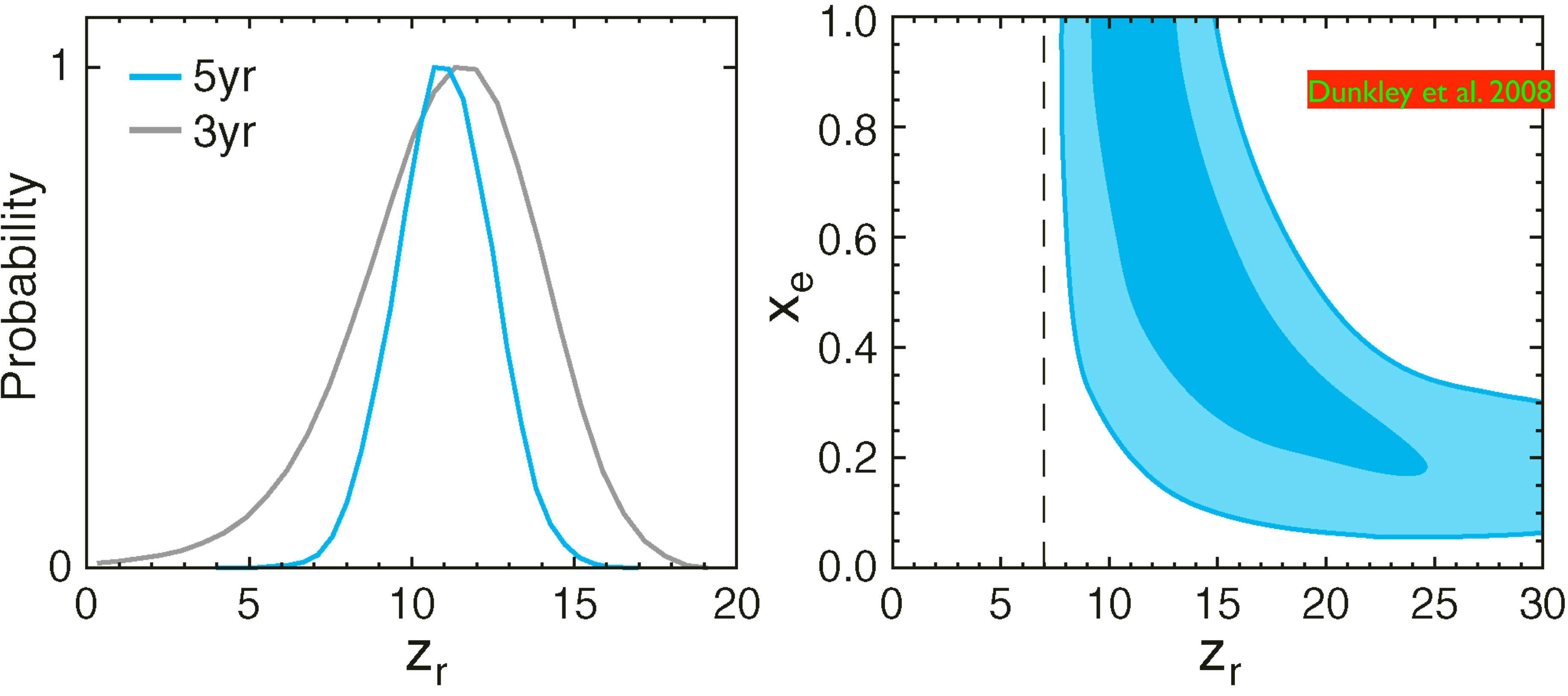
SDSS 1030+0524 z=6.28


Fan et al (2002)


White, Becker, Fan, Strauss (2003)

Naïve implication: $\tau_e=0.03-0.04$

2:WMAP5: τ_e=0.087 +- 0.017



What does it mean?

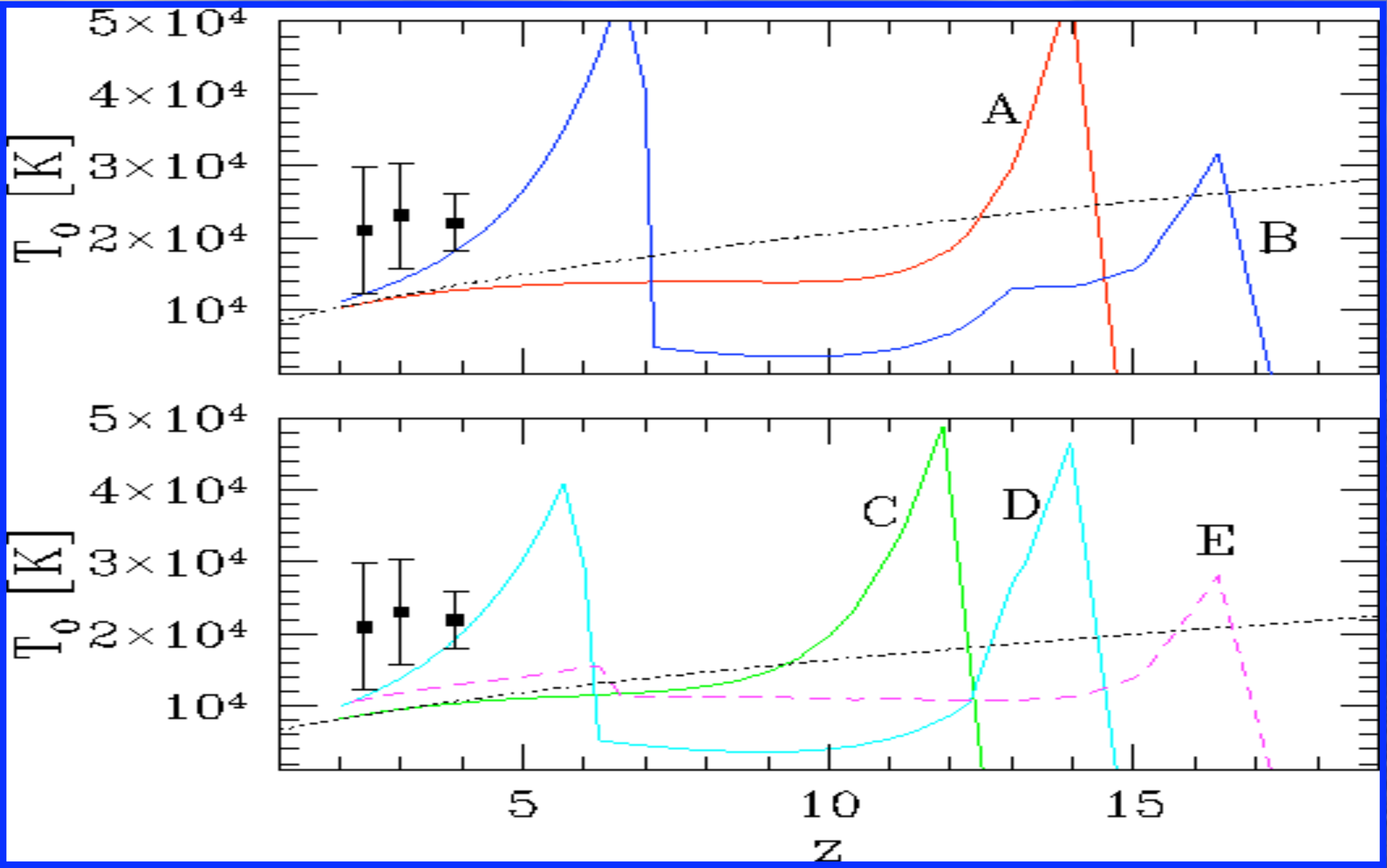
Z_{ri}~8-15 (2σ)

(assuming $x=n_{HI}/n_{Htot}=0$)

Sudden reionization at z = 6 is ruled out at 3.5σ, suggesting that reionization was prolonged.

3: Lyα forest: z_{ri} < 9-10

Hui & Haiman 2003; Theuns et al 2002



Likely Scenarios of Reionization

THE ASTROPHYSICAL JOURNAL, 659:890–907, 2007 April 20

THE EXTENDED STAR FORMATION HISTORY OF THE FIRST GENERATION OF STARS AND THE REIONIZATION OF COSMIC HYDROGEN

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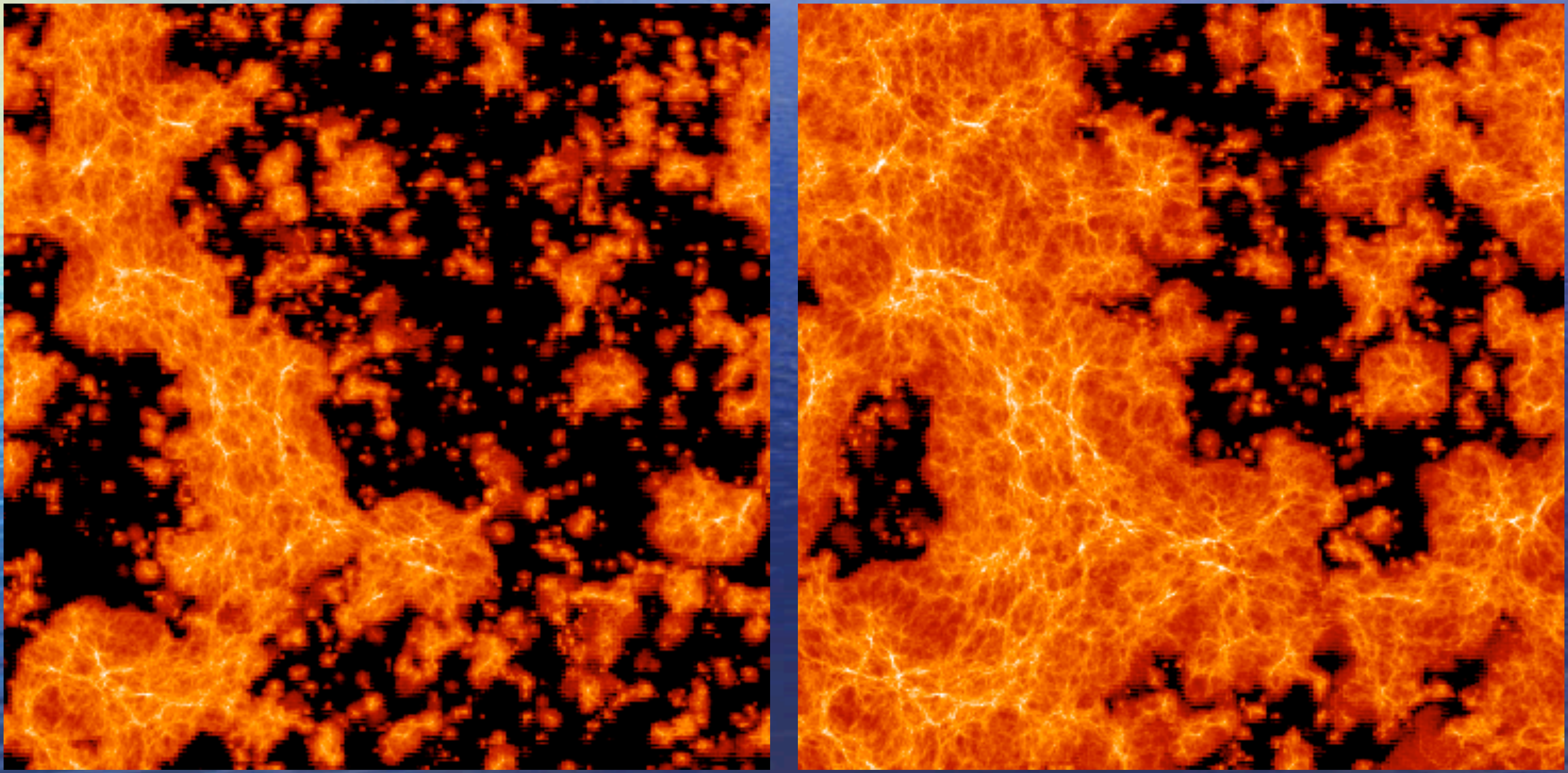
ABSTRACT

Population III star formation (SF) is thought to be quenched when the metallicity of the star-forming gas has reached a critical level. At high redshift, when the general intergalactic medium (IGM) was enriched with metals, the fraction of primordial gas that had already collapsed in minihalos was significantly larger than the fraction of primordial gas that had already been involved in Population III SF. We argue that this reservoir of minihalo gas remained largely in a metal-free state until these minihalos merged into large systems and formed stars. As a result, the era of Population III SF was significantly prolonged, leading to a total integrated Population III SF an order of magnitude larger than expected for an abrupt transition redshift. We find that the contribution of Population III SF to the reionization of hydrogen could have been significant until $z \sim 10$ and may have extended to redshifts as low as $z \sim 6$. Our modeling allows for *gradual* enrichment of the IGM, feedback from photoionization, and screening of reionization by minihalos. Nevertheless, the extended epoch of Population III SF may result in complex reionization histories. The relative contribution of Population III stars to reionization can be quantified and will be tested by three-year *WMAP* results, showing (1) if Population III stars do not contribute to reionization, $\tau_{\rm es} \leq 0.05$–0.06 and a rapid reionization at $z \sim 6$ are expected, with the mean neutral fraction quickly exceeding 50% at $z \sim 8$; (2) if the product of star formation efficiency and escape fraction for Population III stars is significantly larger than that for Population II stars, then a maximum $\tau_{\rm es} = 0.21$ is achievable; and (3) where the product of star formation efficiency and escape fraction for Population III stars is comparable to that for Population II stars, $\tau_{\rm es} = 0.09$–0.12, with reionization histories characterized by an extended ionization plateau from $z = 7$–12, where the mean neutral fraction stays in a narrow range of 0.1–0.3.

Subject headings: cosmology: theory — early universe — intergalactic medium

Online material: color figures

Large-scale Radiative Transfer Hydrodynamic Simulations of Cosmological Reionization



Collaborator: Hy Trac (CfA)

Simulation Details

Dark matter

- Particle-multi-mesh (PMM) N-body code particle mass: 3 x 10^6 Msun/h
- Spatial resoluton: 1kpc
- FoF halo catalogs at all redshifts

Radiative transfer

- Adaptive ray merging - O(N) scaling (Trac & Cen 2007)
- Calculate ionization and recombination with self-shielding

done concurrently

Baryons

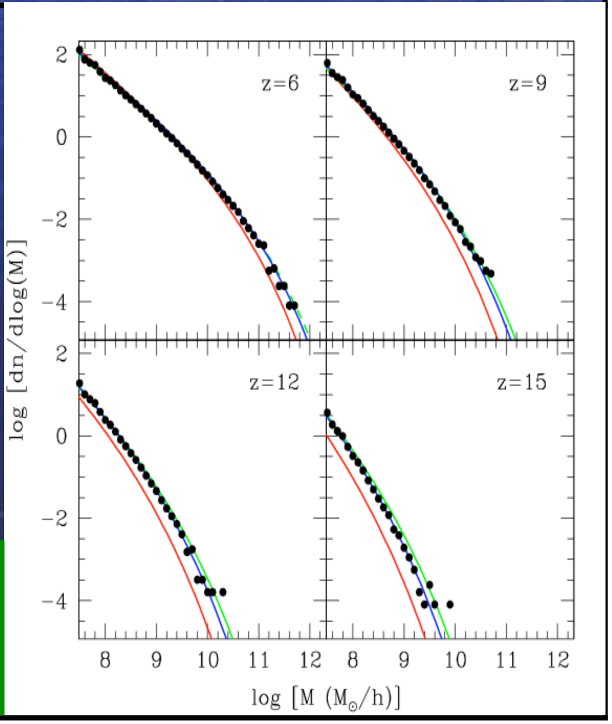
- Shock capturing TVD hydrodynamics
- Resolve Jeans mass of photoionized intergalactic medium
- Follow metal enrichment of the IGM

Star formation

- Star formation rate follows the Schmidt-Kennicutt relation
- Include Pop II and Pop III stars

Model	**L (Mpc/h)**	**Nparticles**	**z_{RI}**
Sim1	**100**	**24 billion**	**Z=6**
Sim2	**100**	**24 billion**	**Z=9**

Halo Mass Functions



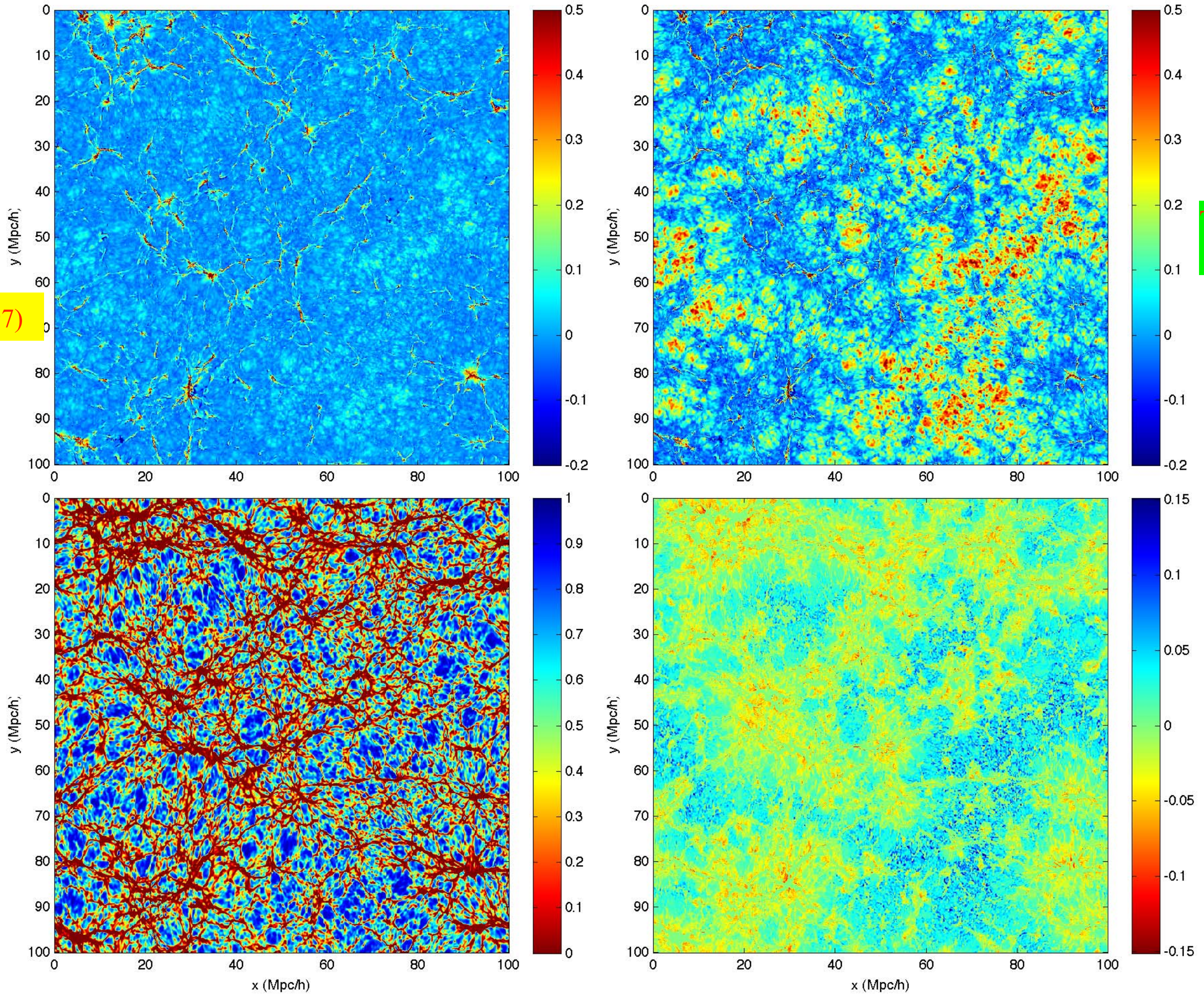
Press & Schecter (1976)
Sheth & Tormen (1999)
Warren et al (2006)

In agreement with e.g.:
- Reed et al (2007)
- Lukic et al (2007)
- Cohn & White (2007)

A Signature of Inhomogeneous Reionization

Cen, Mcdonald, Trac & Loeb (2009)

State of IGM @z=4



T/T(Eos)
$z_{RI}=9$

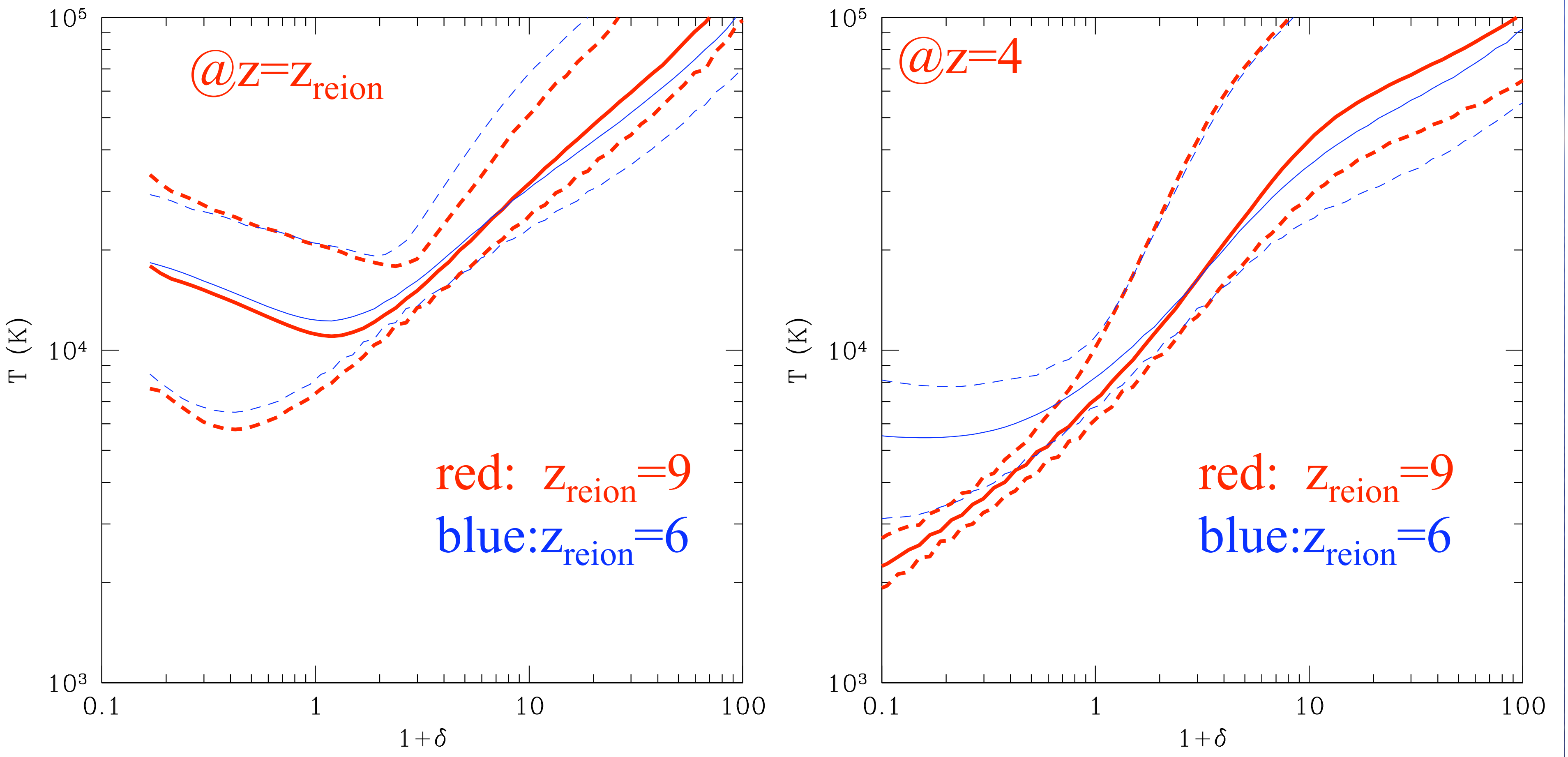
Hui & Gnedin (1997)

T/T(Eos)
$z_{RI}=6$

$\exp(-\tau)$
$z_{RI}=9$

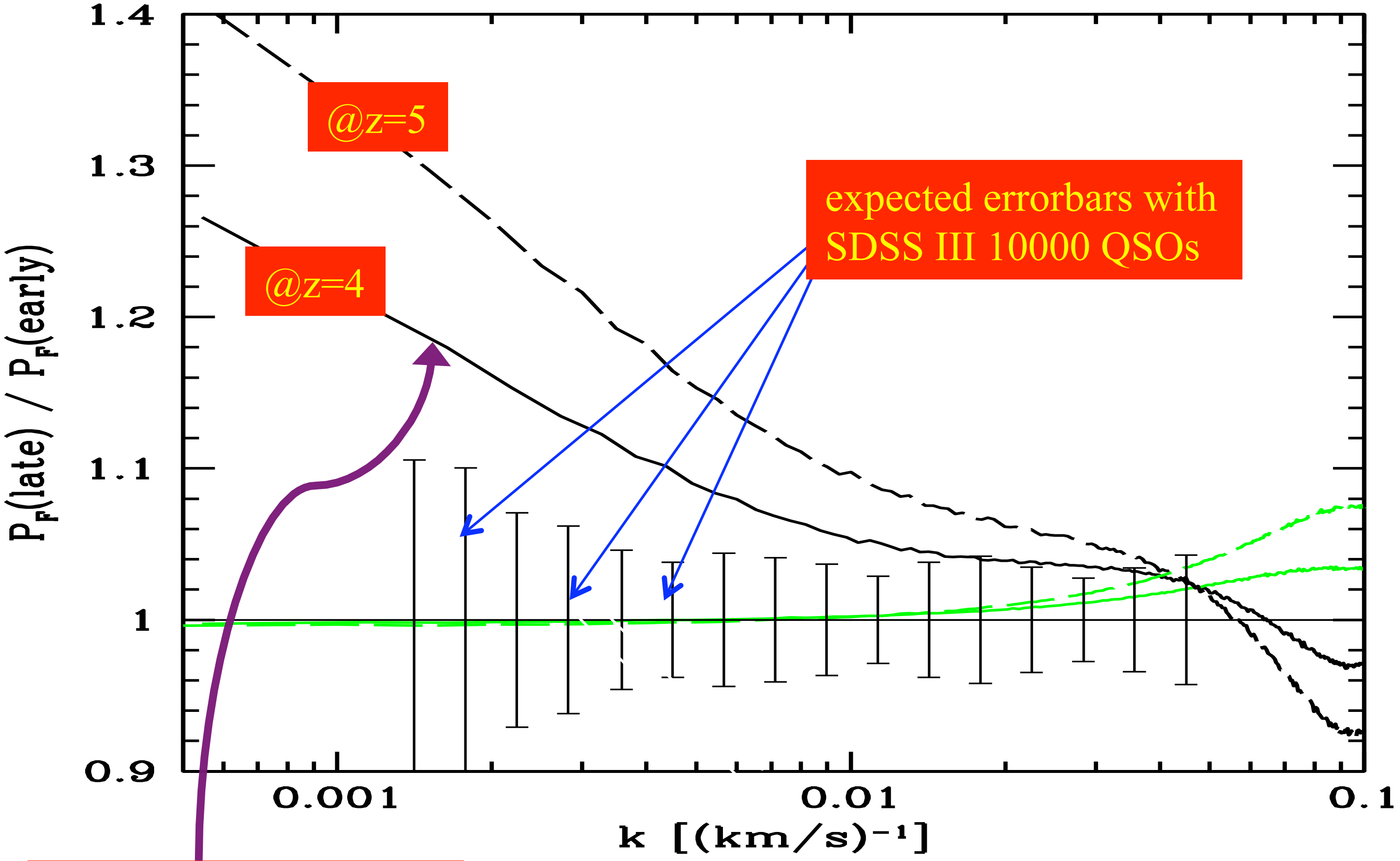
$\exp(-\tau_{late})-\exp(-\tau_{early})$

Temperature-density relation complicated



Trac, Cen & Loeb (2008)

Reionization Probe#1: Lyα forest @z=4-5

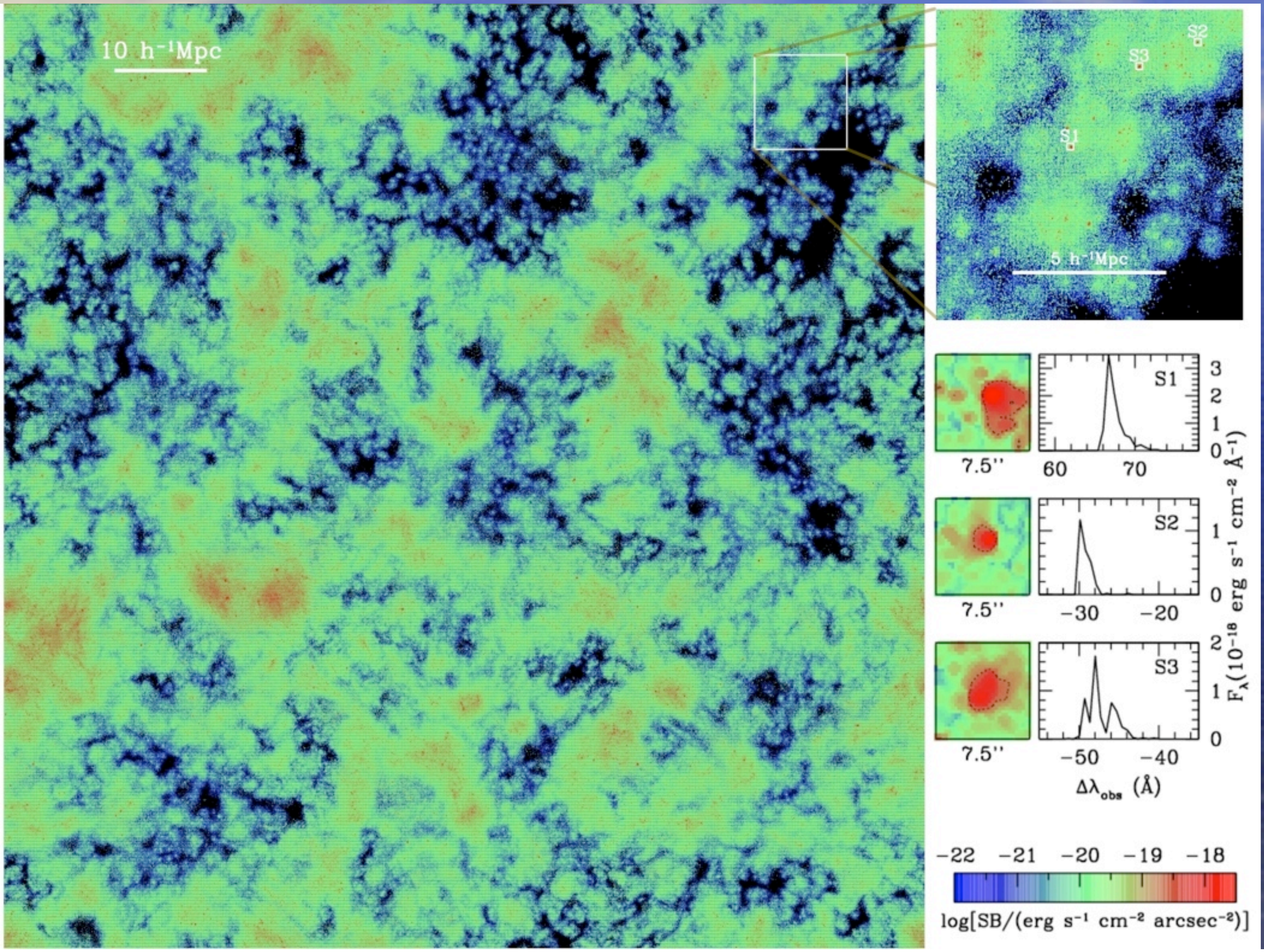


expected errorbars with SDSS III 10000 QSOs

with SDSS III data @z=4, 7σ significance

Cen, McDonald, Trac, Loeb (2009)

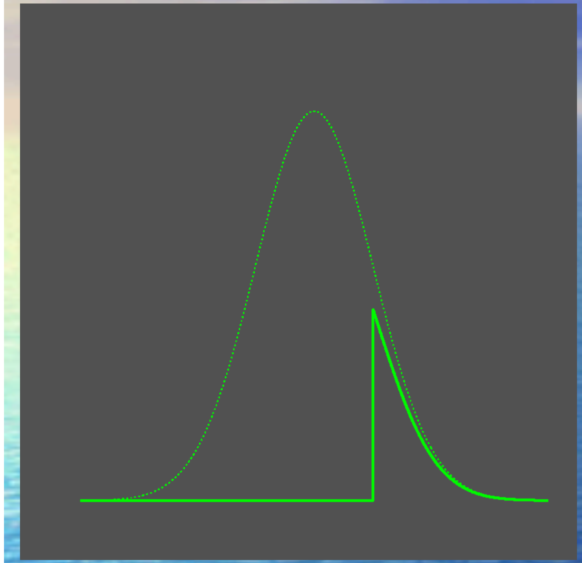
Reionization Probe#2: Lyα Emitters @z>=5.7 --- detailed transfer calculations



Collaborators:
Zheng Zheng (IAS)
Hy Trac (CfA)
Jordi Miralda-Escude (Barcelona)

Methods to Transfer Lyα Photons

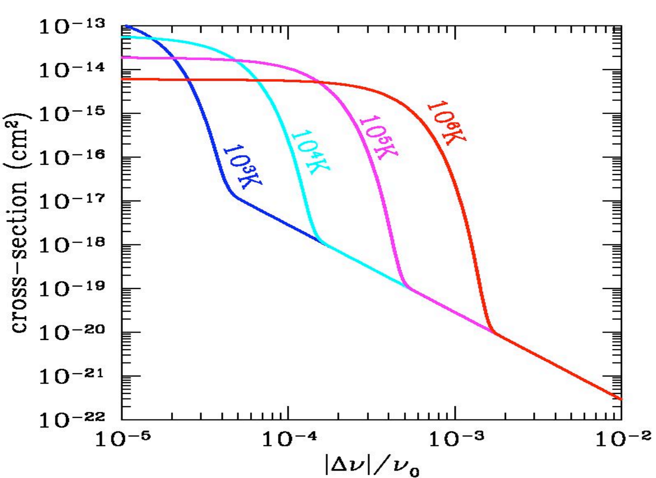
simple & fast



$\exp(-\tau_\nu)$

e.g., Dijkstra, Lidz, & Wyithe 2007, McQuinn et al. 2007, Iliev et al. 2008

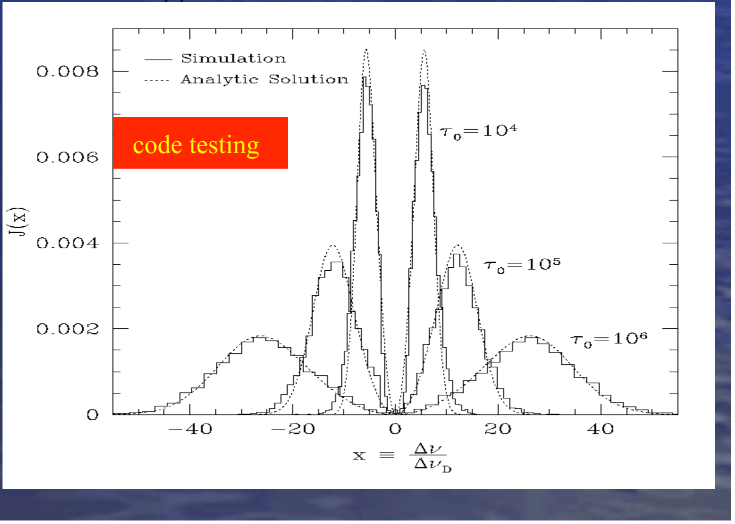
Monte-Carlo Lya transfer: slow and costly, but accurate

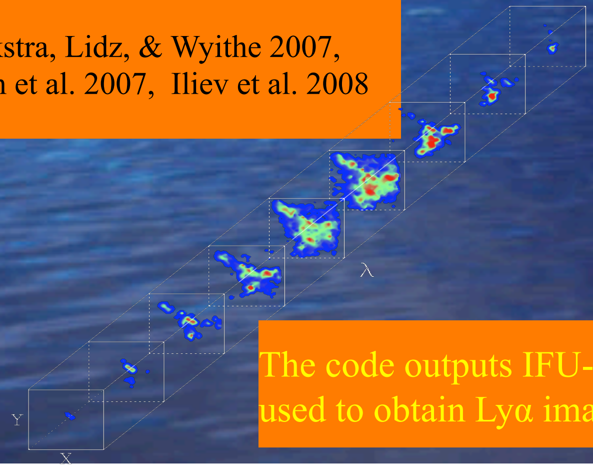


Line center $5.9 \times 10^{-14}(T/10^4 K)^{-1/2}\mathrm{cm}^2$

Line wing $2.8 \times 10^{-26}(|\Delta\nu|/\nu_0)^{-2}\mathrm{cm}^2$

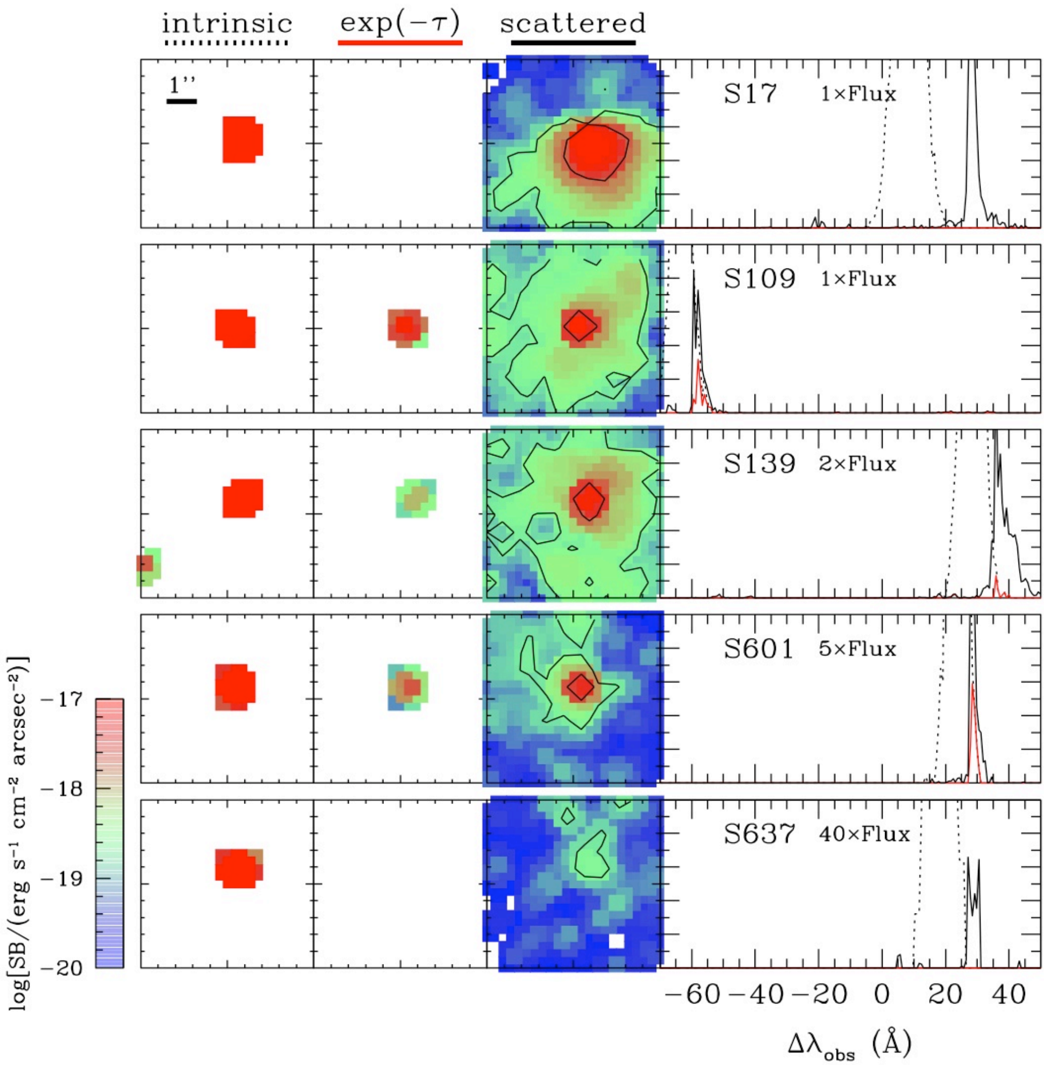
Monte Carlo Code for Lyα Radiative Transfer: Zheng-Miralda-Escude (2002) code can be applied to systems with arbitrary geometry and arbitrary distributions of gas density, temperature, emissivity, and velocity.

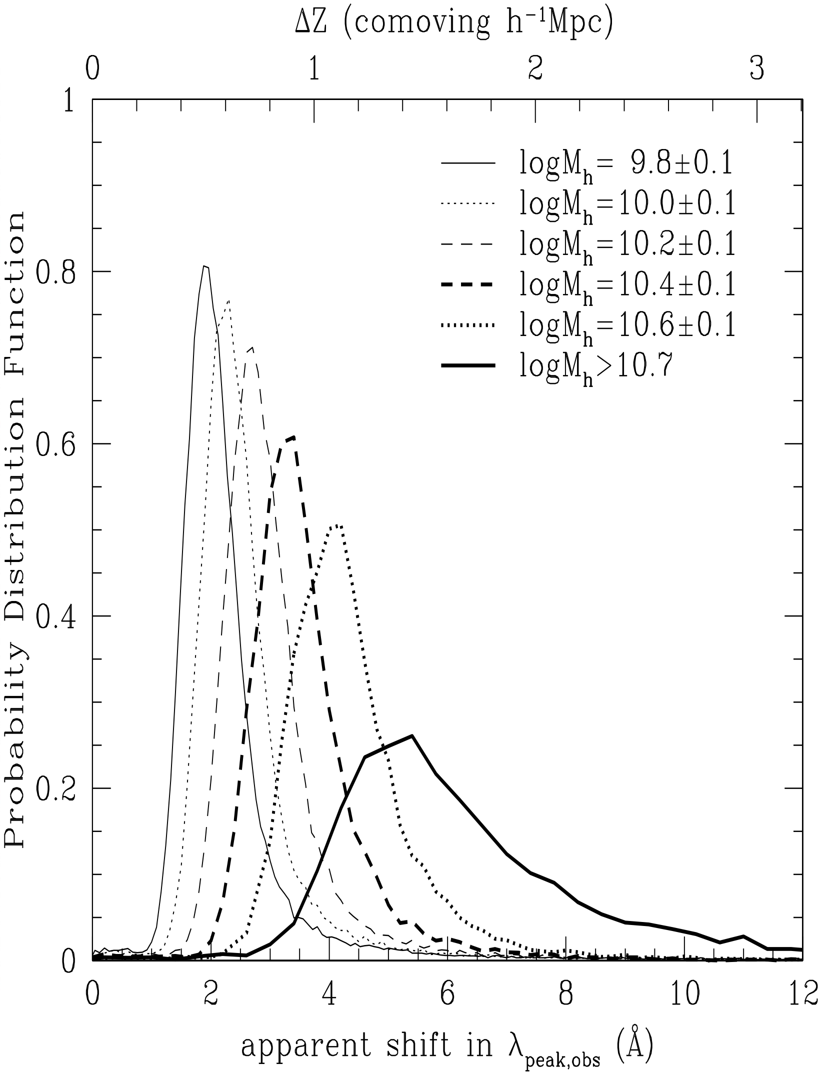




The code outputs IFU-like data cube, which can be used to obtain Lyα image and 2D spectra.

Some examples with Lyα transfer

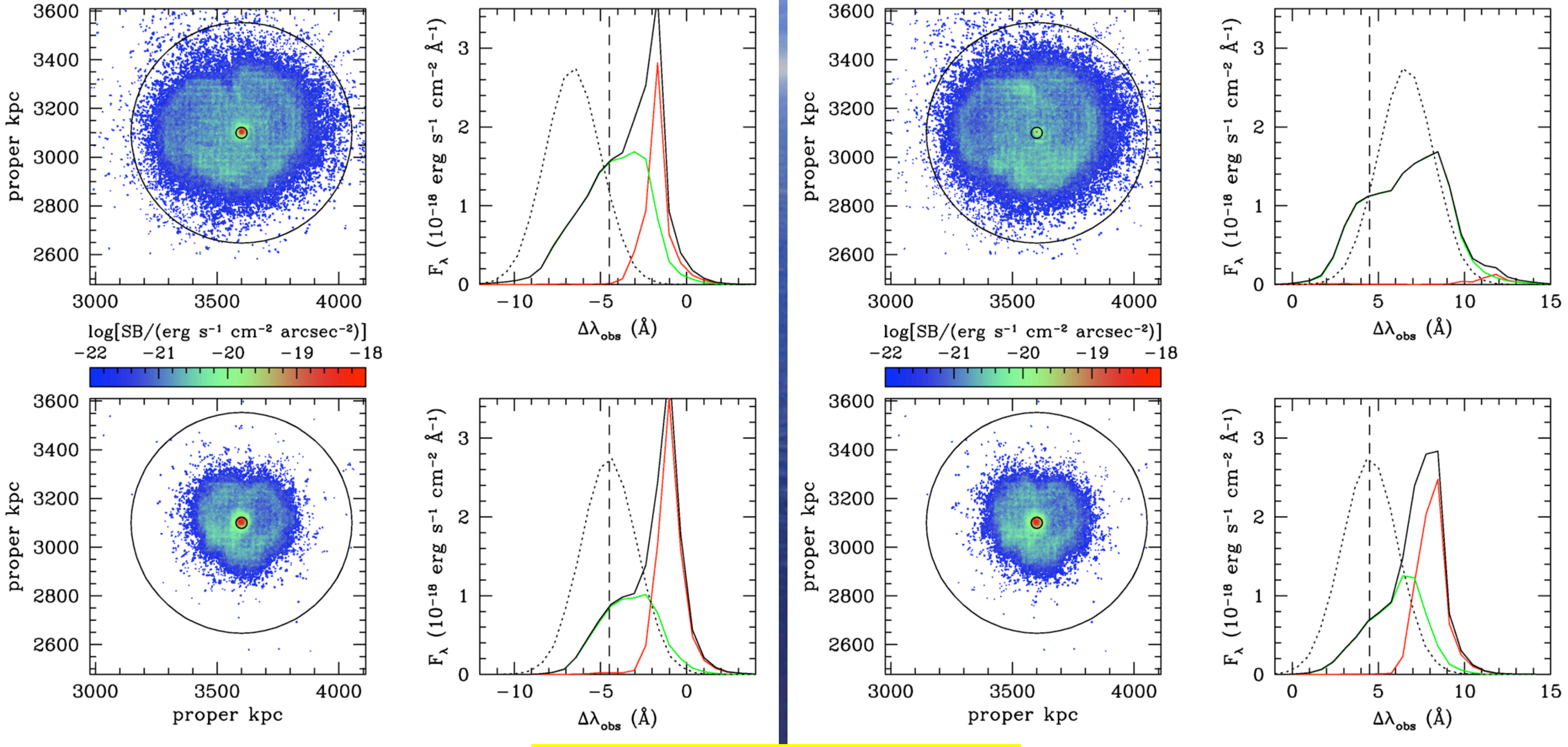




Zheng, Cen, Trac & Miralda-Escude (2009)

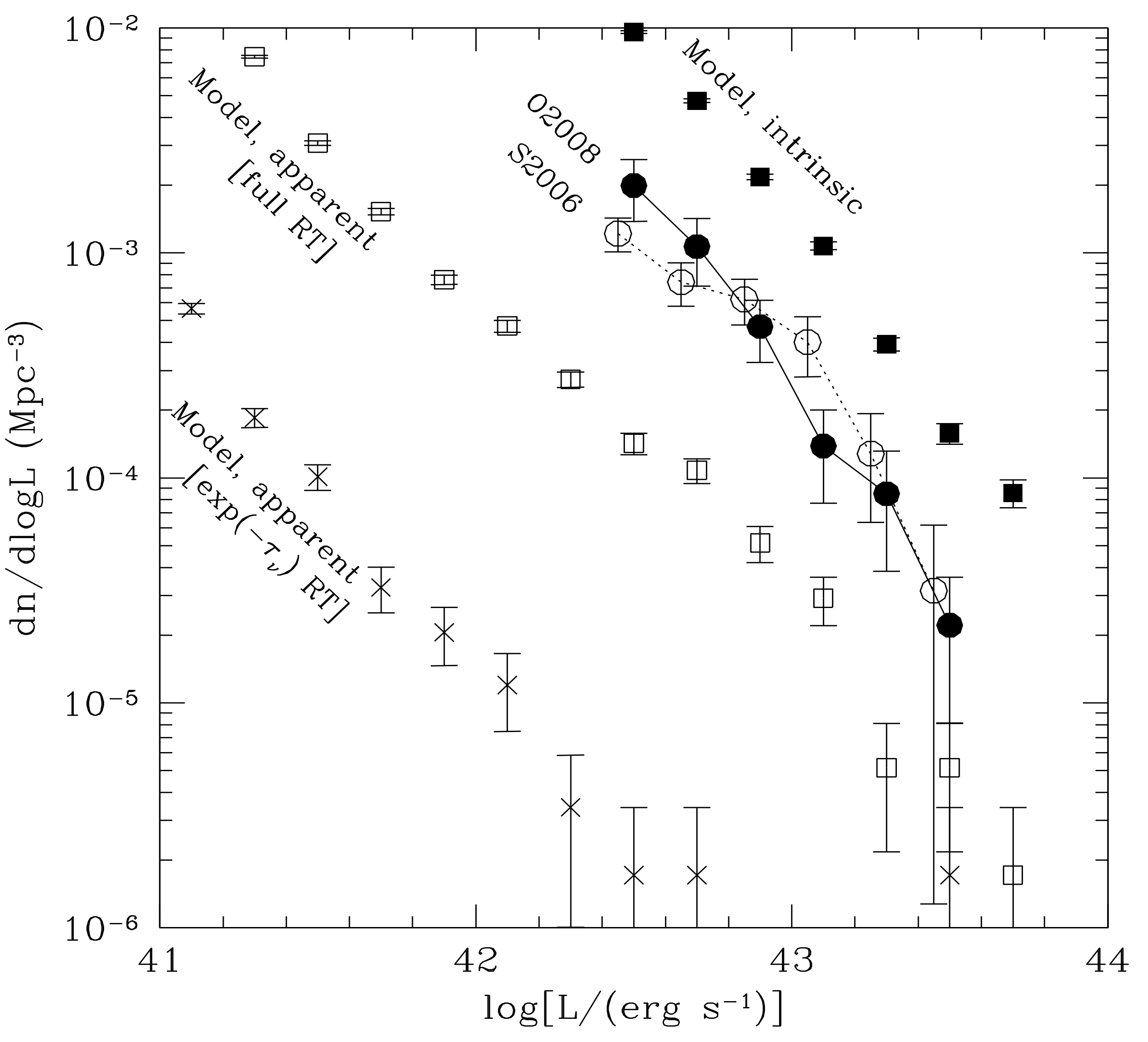
Importance of Peculiar Velocity

with peculiar velocity



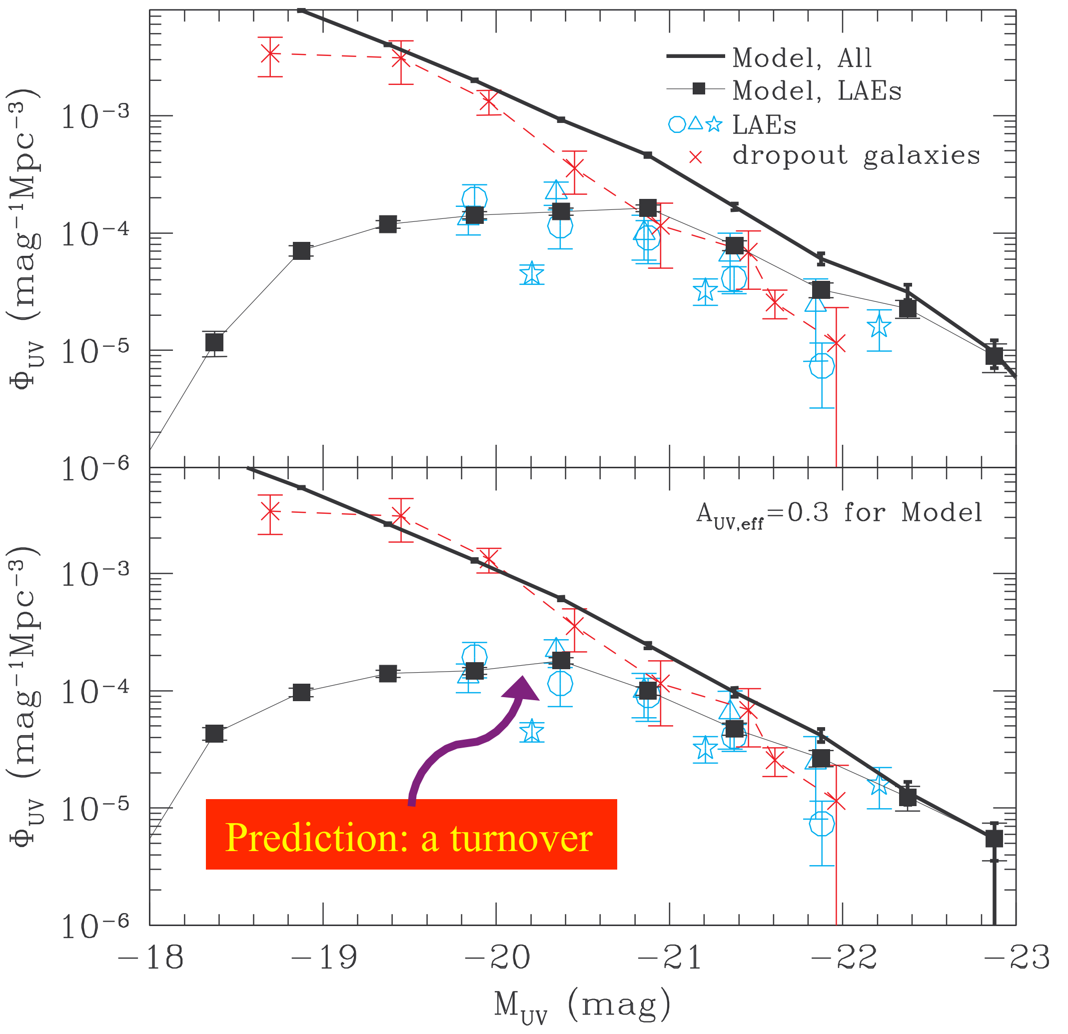
without peculiar velocity

Lyα LF from Lyα transfer computations



Zheng, Cen, Trac, Miralda-Escude (2009)

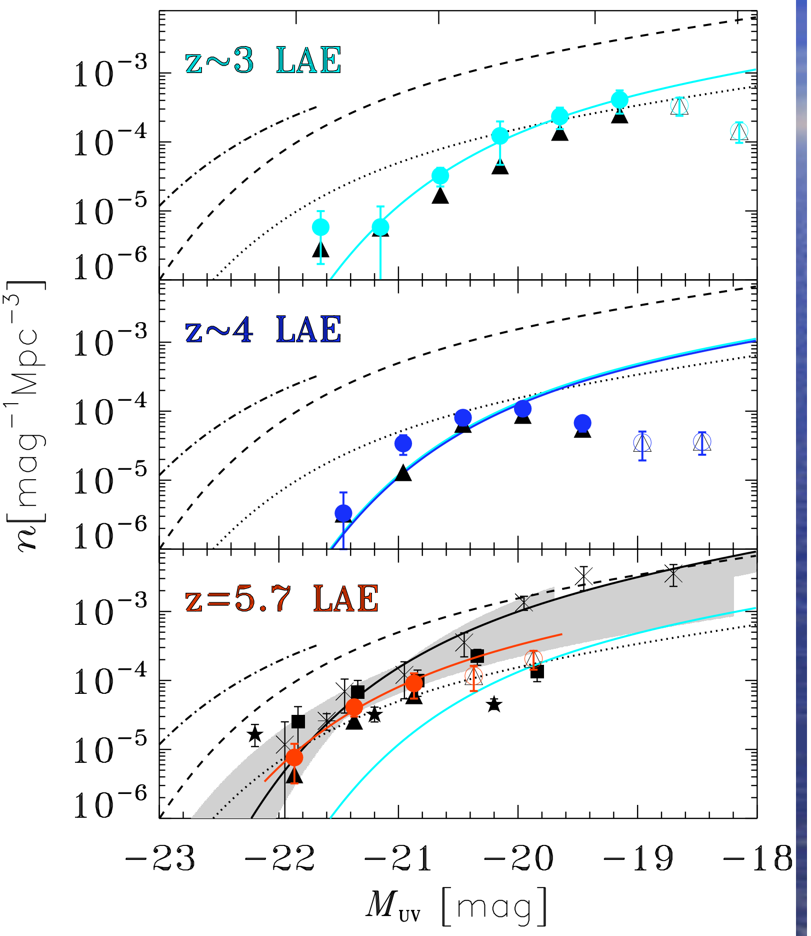
UV LF from Lyα transfer computations



Prediction: a turnover

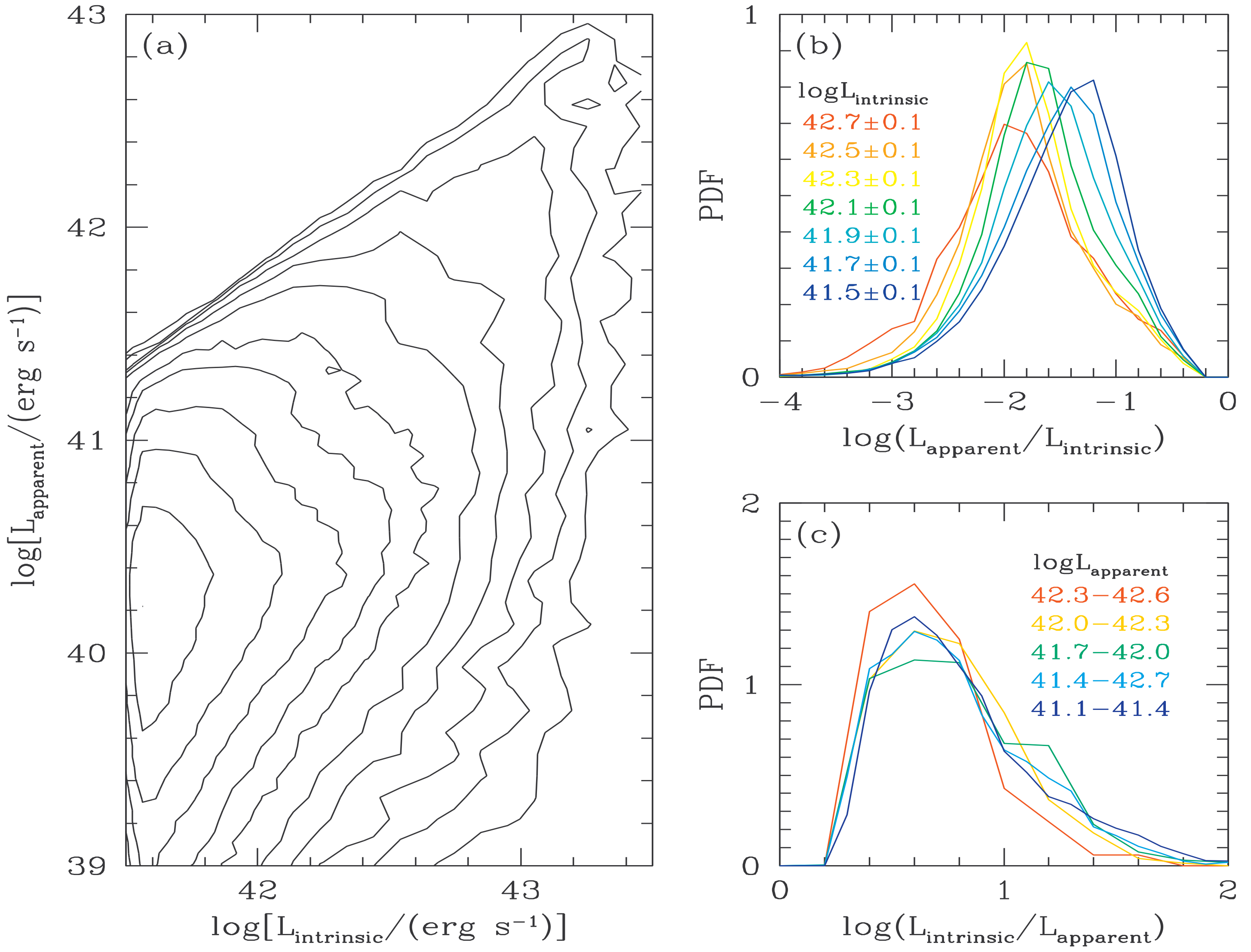
Zheng, Cen, Trac, Miralda-Escude (2009)

Subaru/XMM-Newton Deep Survey



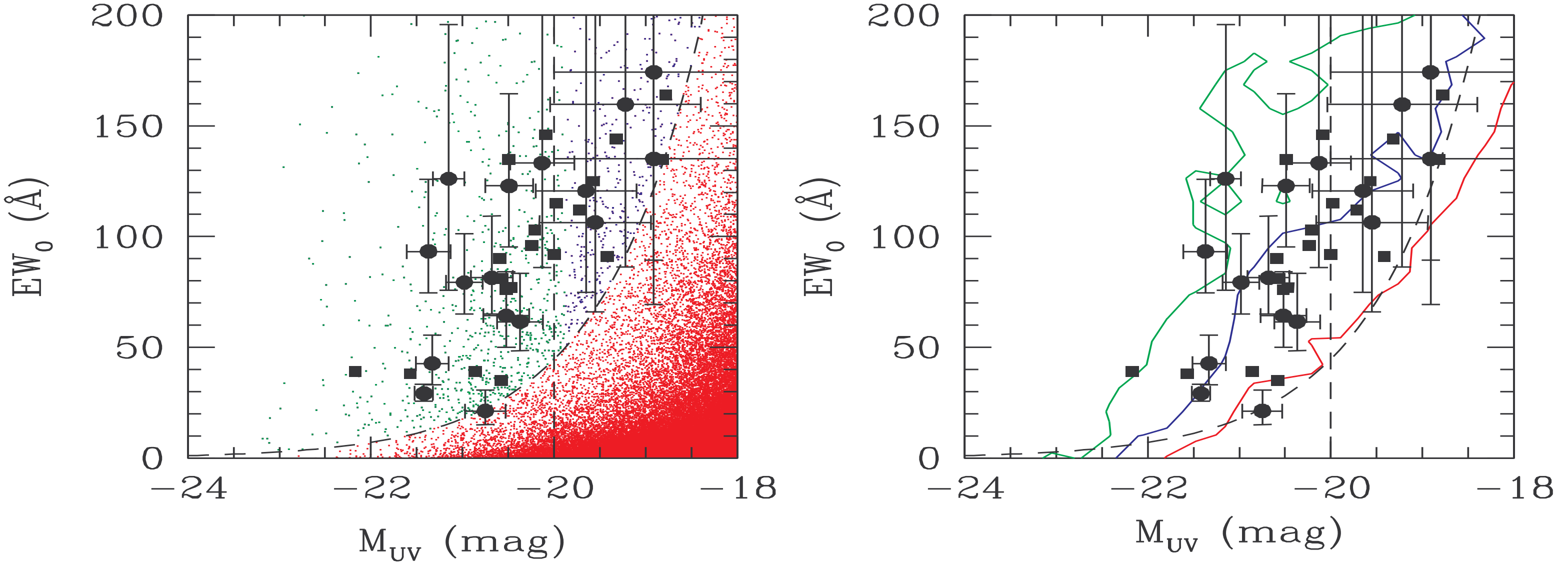
Ouchi et al. (2008)

From Intrinsic to Apparent Lyα Luminosity



Zheng, Cen, Trac, Miralda-Escude (2009)

UV LF from Lyα transfer computations

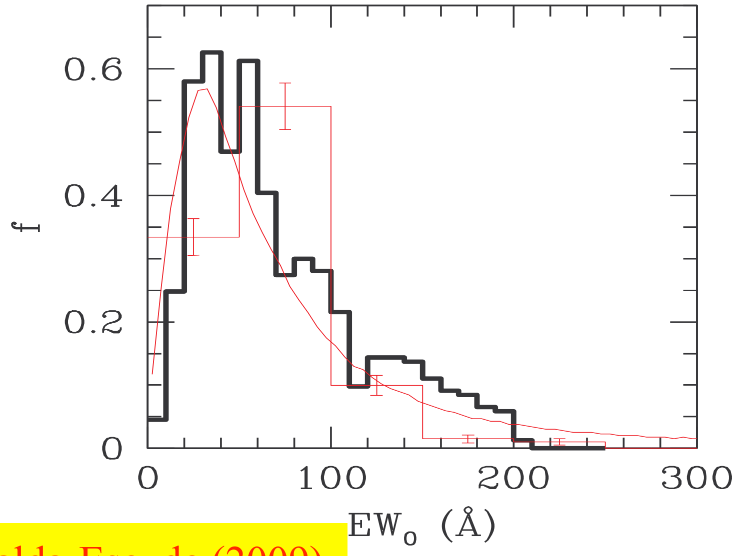


Symbols and Red curves from Subaru/XMM-Newton Deep Survey (Ouchi et al. 2008)

Dashed curve: detection limit for Lya luminosity in SXDS (z=5.7)

Vertical dashed line: 3σ detection limit for UV luminosity

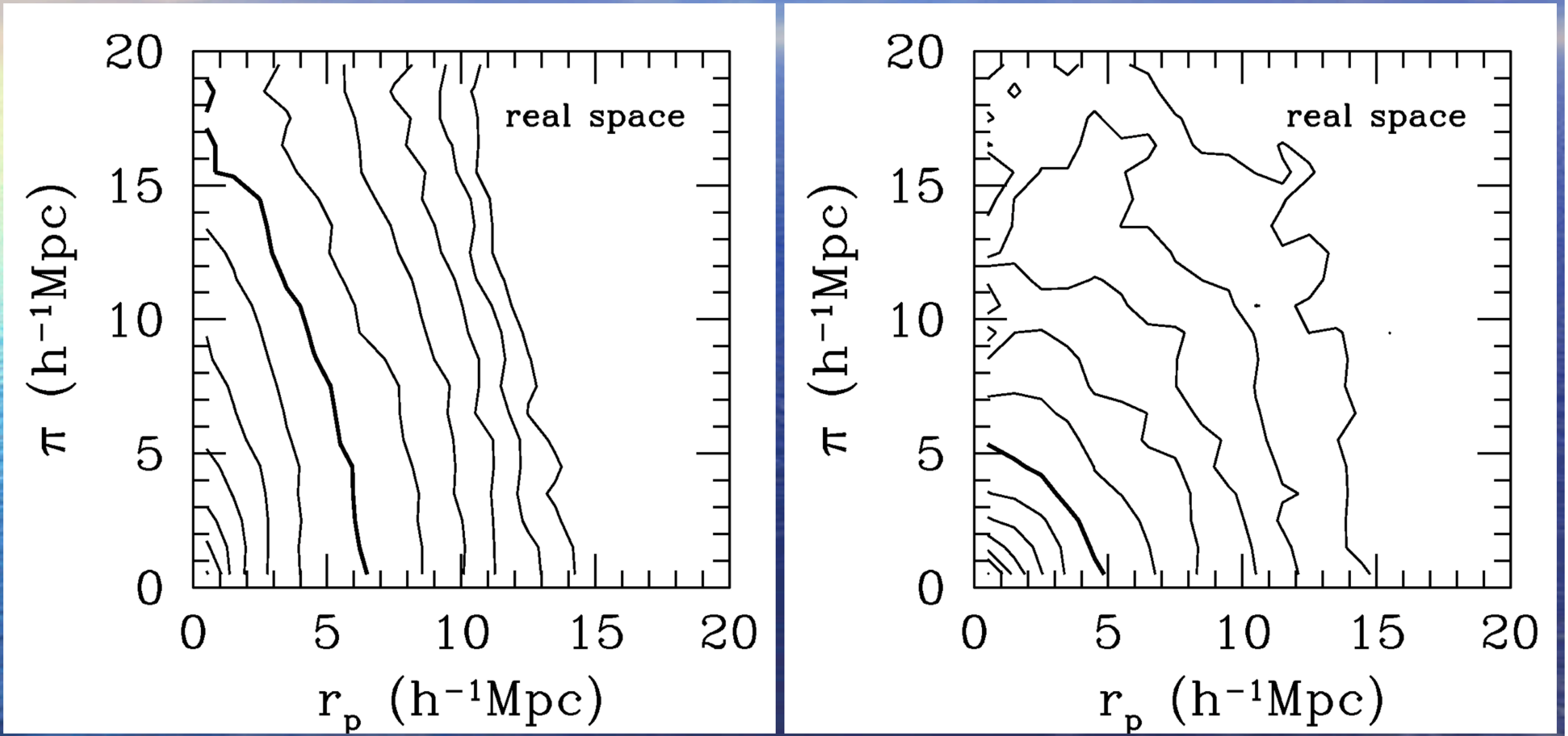
Red, blue and green curves: high to low probability density of dots



Zheng, Cen, Trac, Miralda-Escude (2009)

Clustering of z~5.7 LAEs

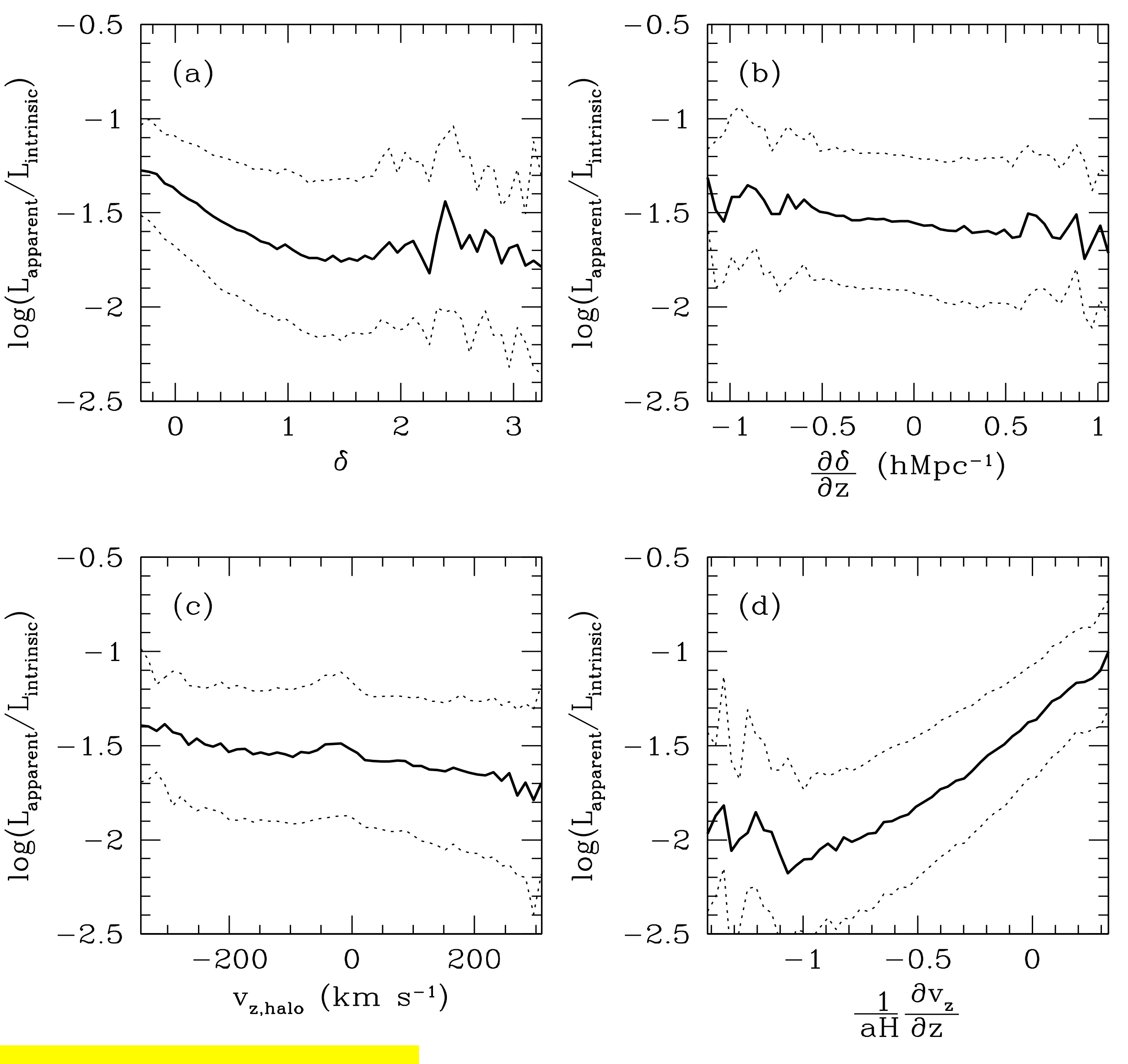
Two-point correlation function



LAEs $L_{\mathrm{apparent}} > 10^{41.1}\mathrm{erg/s}$

Halos with the same number density

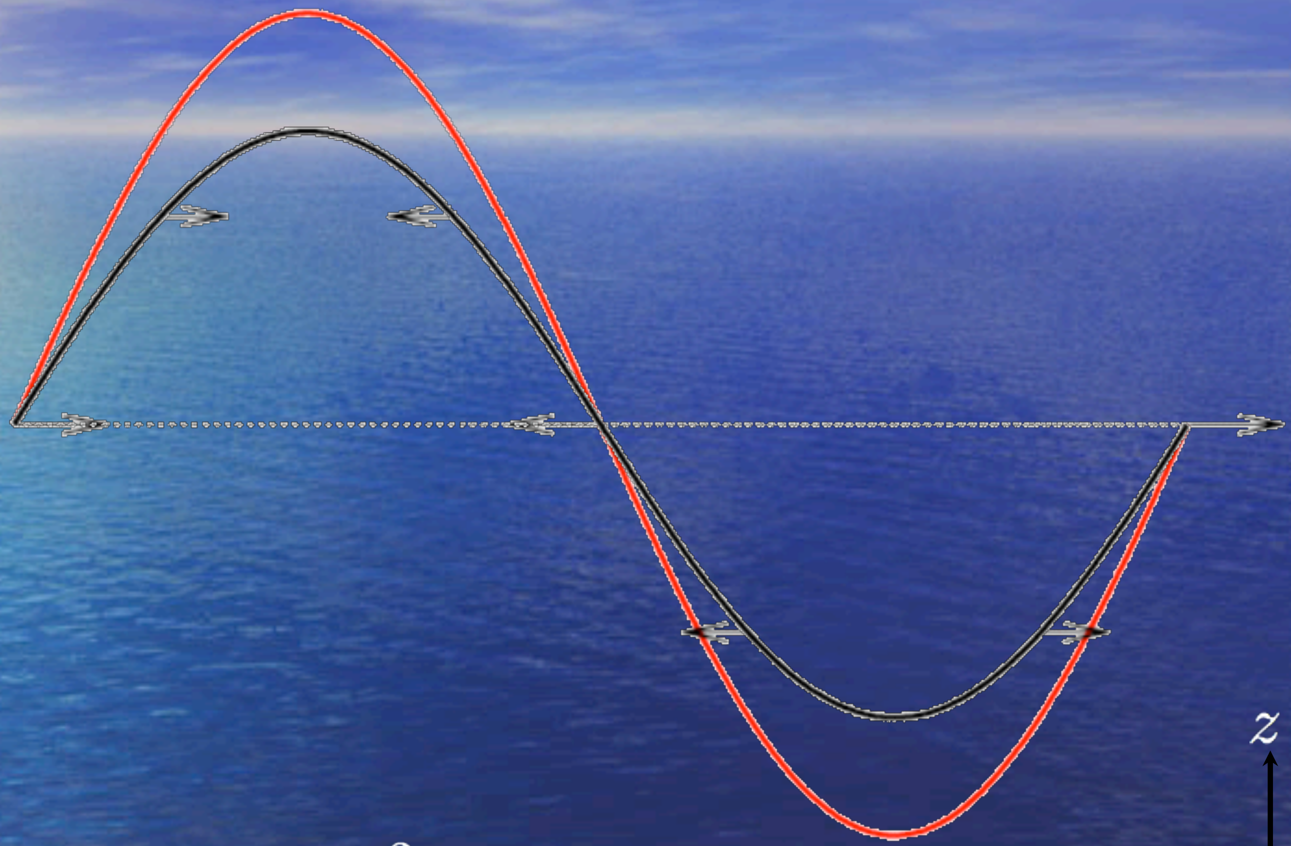
LSS modulation on Lyα transfer



Zheng, Cen, Trac, Miralda-Escude (2009)

Redshift distortion

(Kaiser 1987)

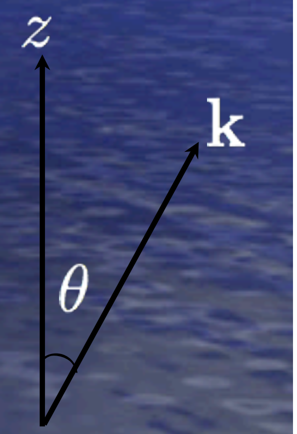


real space $$P_g(\mathbf{k}) = b^2 P_m(k)$$

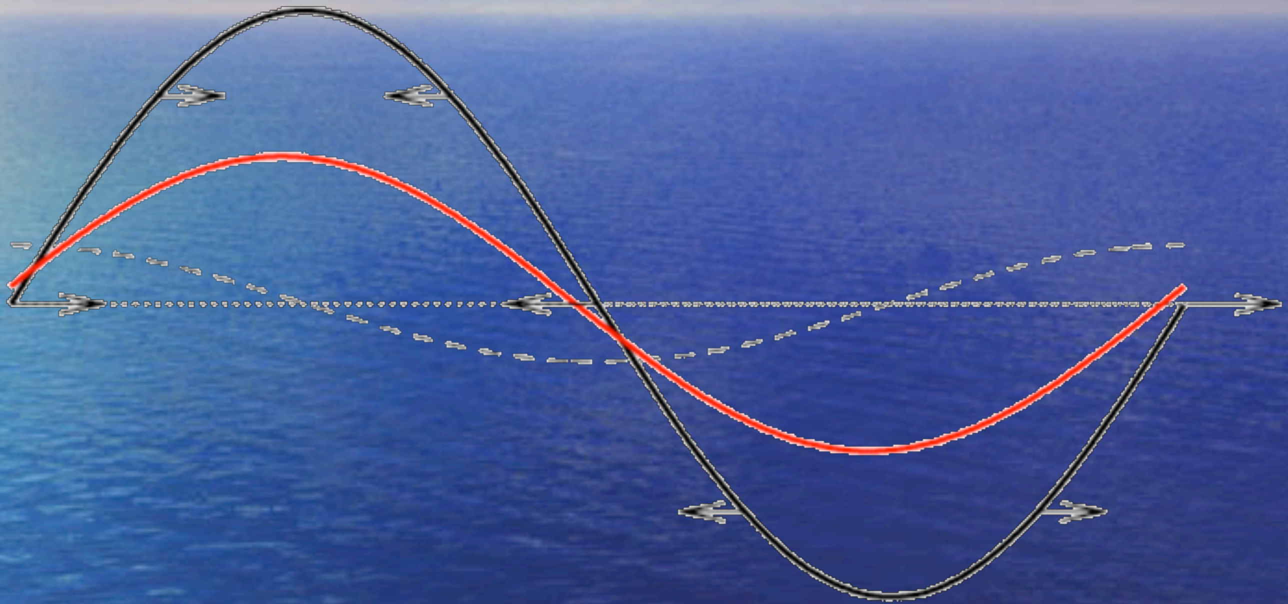
redshift space $$P_g^s(\mathbf{k}) = (1+\beta\mu^2)^2 b^2 P_m(k)$$

$$\mu = \cos\theta = \frac{k_z}{k}$$

$$\beta = \frac{1}{b}\frac{d\ln D}{d\ln a}$$



Distortion from Lyman-alpha selection



$$P_g^{ss}(\mathbf{k}) = \left\{ \left[(1-\alpha_1/b) + (1-\alpha_2)\beta\mu^2\right]^2 + \left[\alpha_3\beta/(r_{\rm H}k) + \alpha_4 r_{\rm H}k/b\right]^2\mu^2 \right\} b^2 P_m(k)$$

density

redshift distortion

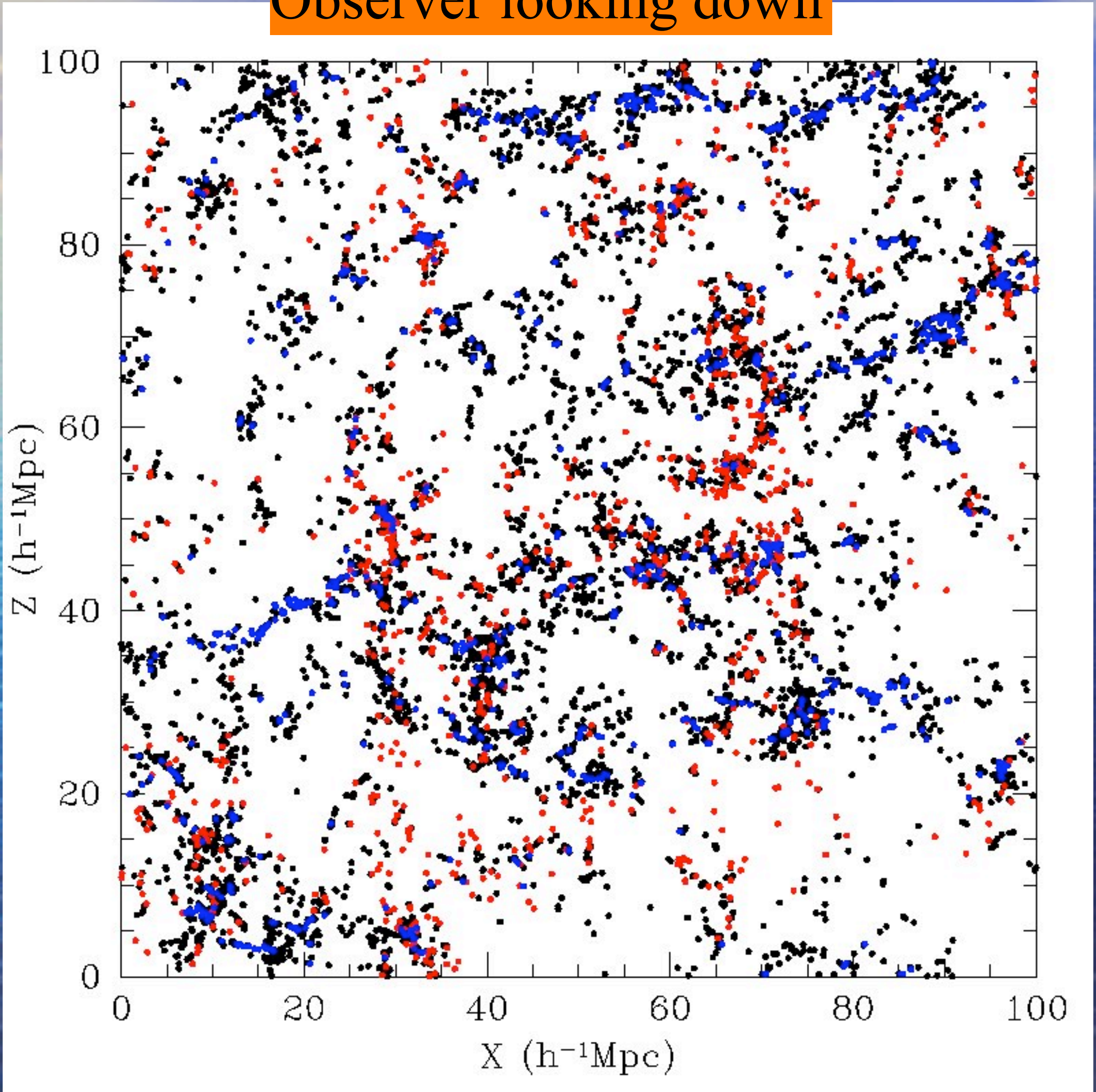
velocity gradient

velocity

density gradient

Lyα Transfer and LSS Power (e.g., BAO)

Observer looking down



HETDEX, …

weakly suppressed

strongly suppressed

Conclusions

- **Lyα forest @z=4-5 may be significantly affected by EoR hence may provide a good probe of EoR**

  (e.g., distinguishing z_{RI}=6 and 9 at ~7σ)

- **Detailed Lyα transfer calculations yield quantitatively and often qualitatively different results compared to simple models with respect to key quantities, including Lyα LF, UV LF of LAEs, EW distribution of LAEs, 2-p correlation function, …**

- **Lyα transfer calculations are likely indispensable for some key applications, including probing the sources of and ionizing state of the IGM during cosmological reionization, BAO measurements using LAEs**