Measuring the IGM thermal state with wavelets

Antonella Garzilli

SISSA

ma per seguir virtute e canoscenza

In collaboration with:
Samuel Leach, Matteo Viel and James Bolton

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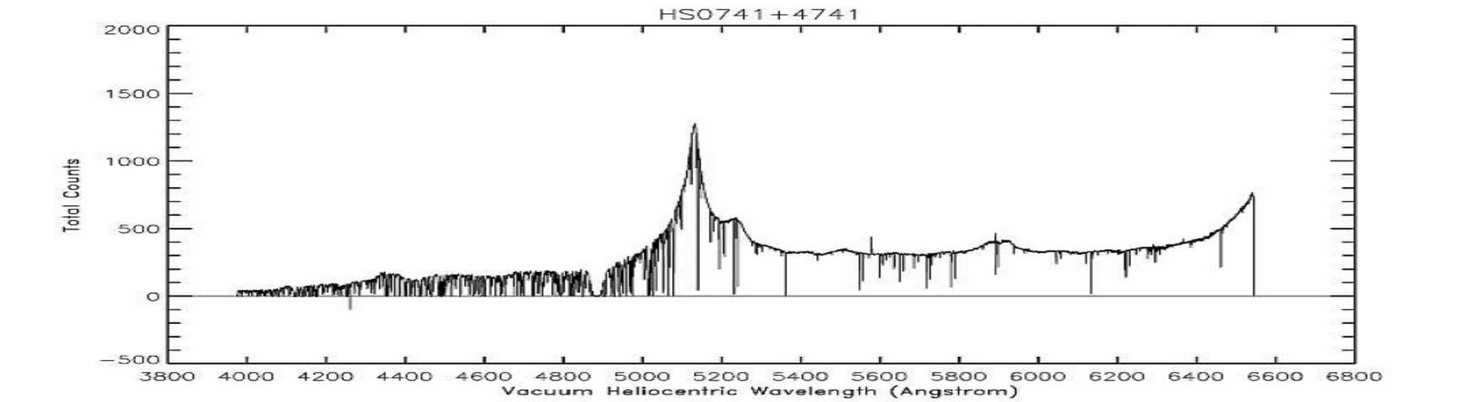
HS0741+4741
Total Counts
2000
1500
1000
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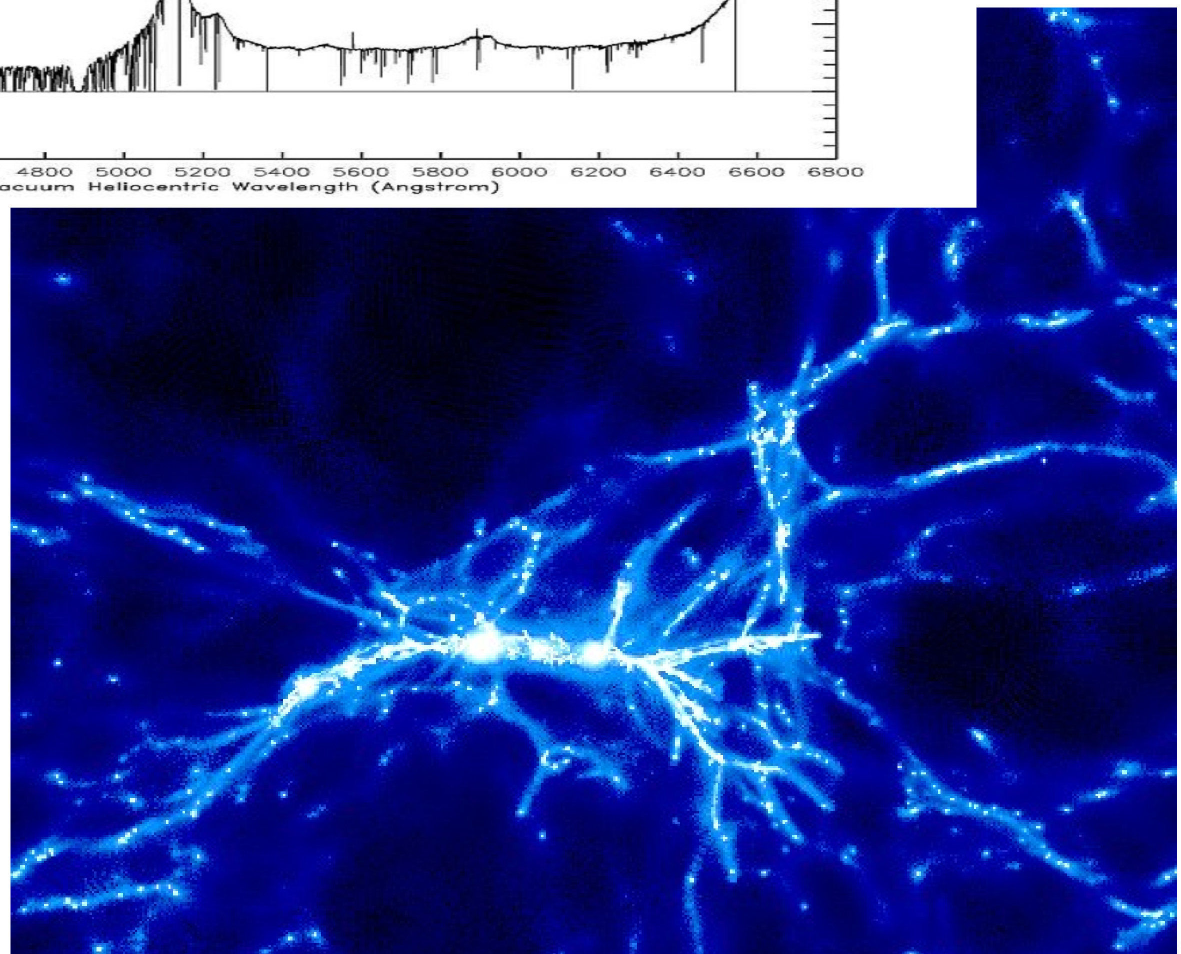
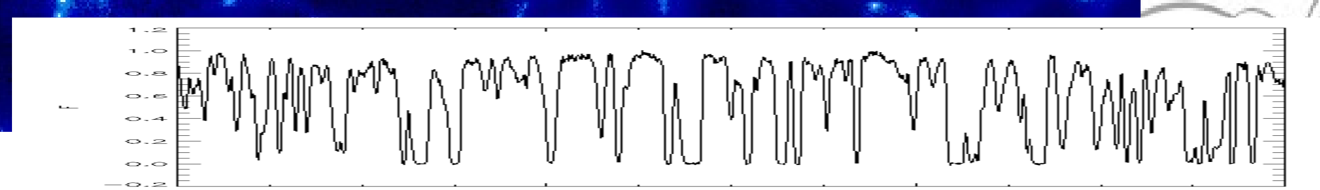
3800 4000 4200 4400 4600 4800 5000 5200 5400 5600 5800 6000 6200 6400 6600 6800
Vacuum Heliocentric Wavelength (Angstrom)

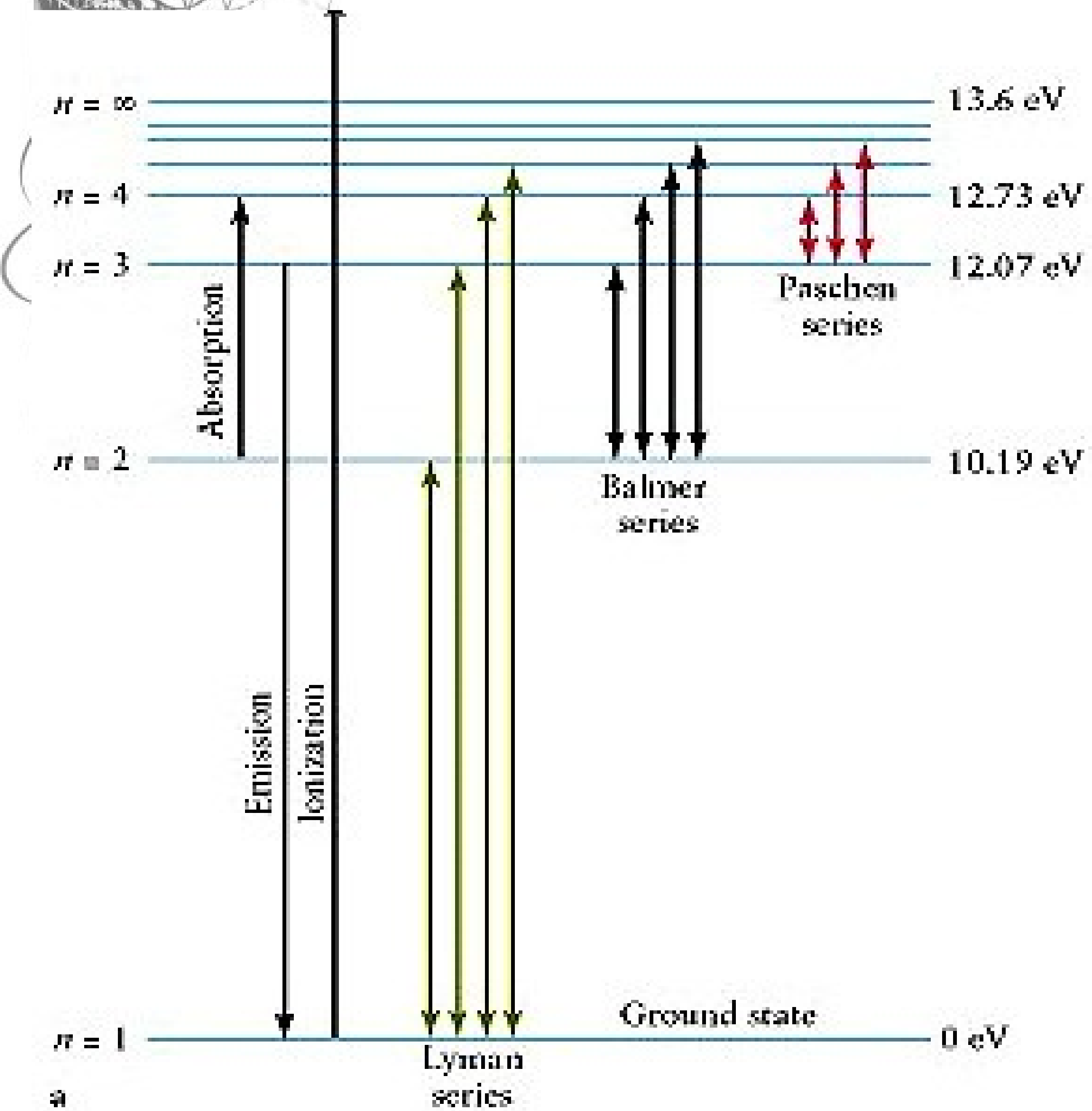



f
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
2000
4000
6000
v[km/s]

Outline

- ***Physics of IGM***
- Previous measurements of thermal state at z~2--3
- What are wavelets?
- How we applied wavelets
- Results
- Comparison with recent work
- Future work

Lyman alpha series



$$\frac{1}{\lambda} = R\left(\frac{1}{1^2} - \frac{1}{n^2}\right)$$

For Lyman α $n = 2$

$$Ly_\alpha \simeq 1215\ \text{Å}$$

Temperature & IGM structure

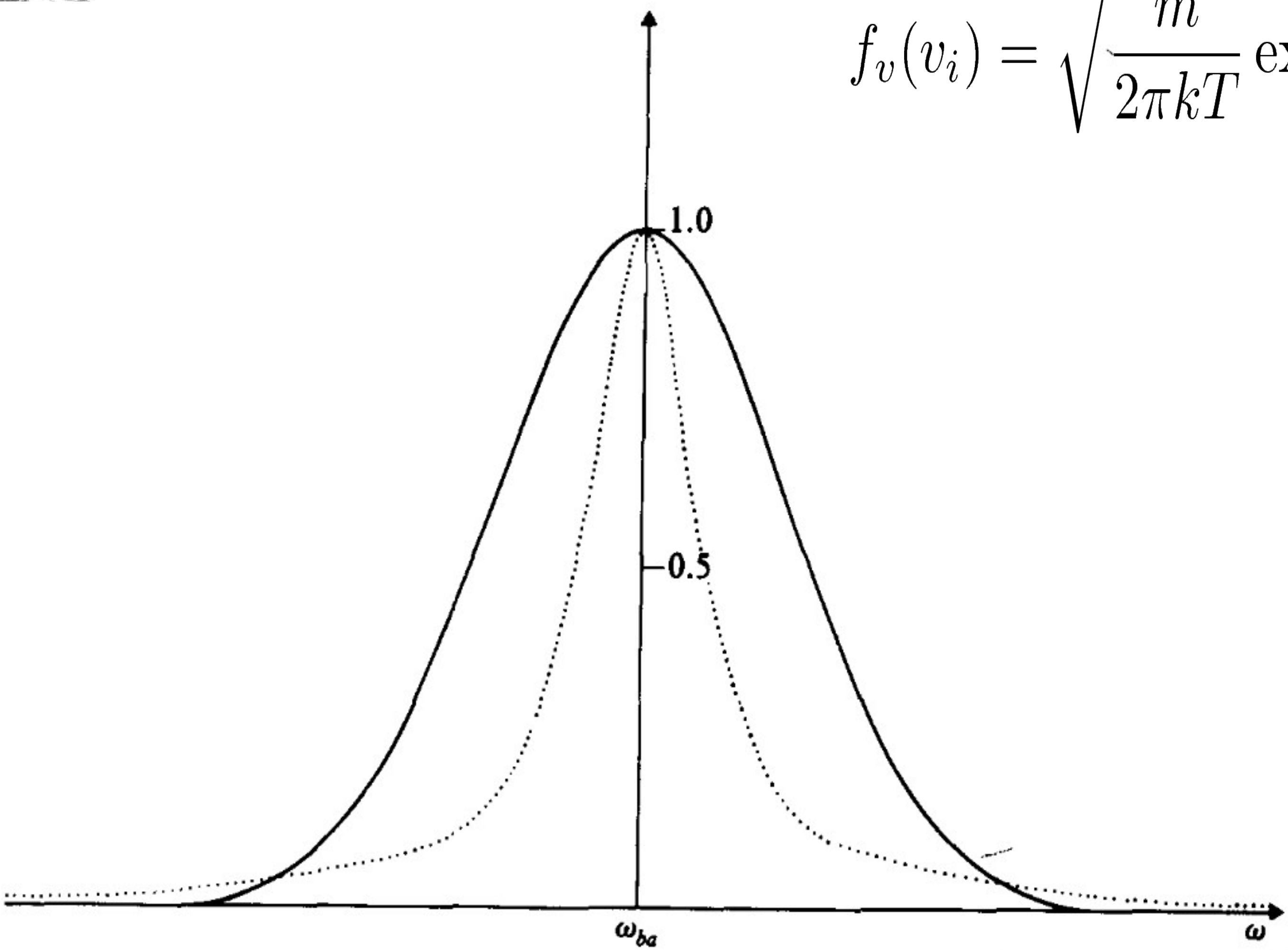
- Thermal broadening:
  smoothing absorption along the line of sight through the thermal motion of the gas

- Jeans smoothing:
  smoothing the physical distribution of the gas in three dimensions through pressure support

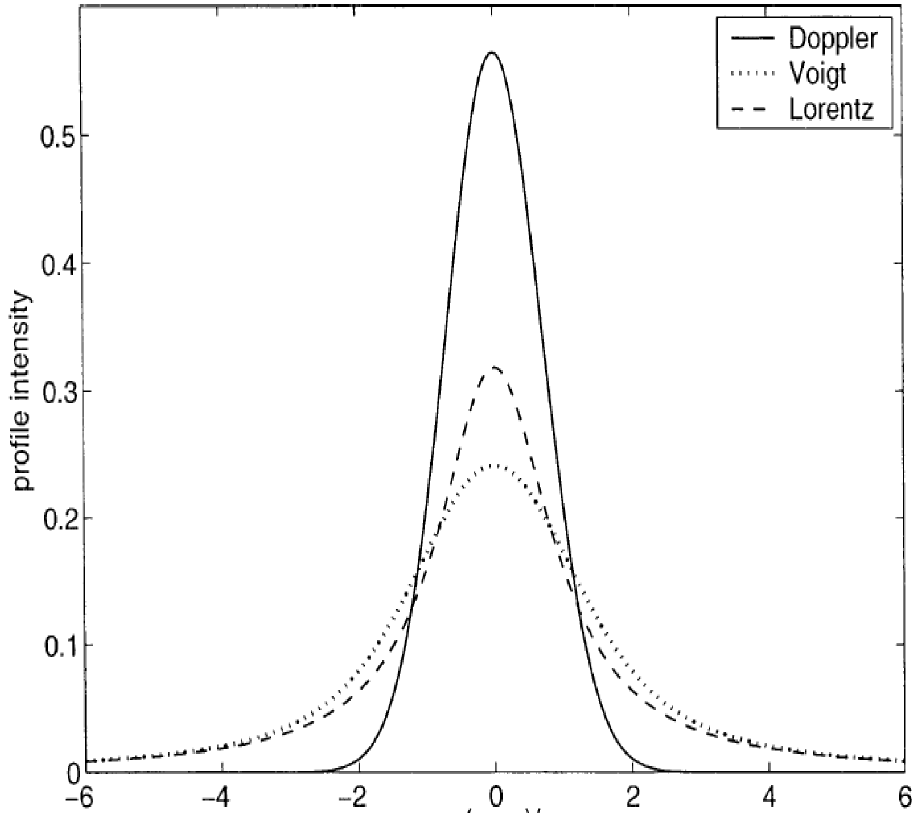
Natural profile and doppler broadening

$$\sigma_\nu = \left(\frac{\pi e^2}{m_e c}\right)\left[\frac{1}{4\pi\epsilon_0}\right] f_{lu} \frac{(\Gamma_{ul}/4\pi^2)}{(\nu - \nu_{lu})^2 + (\Gamma_{ul}/4\pi)^2}$$

$$f_v(v_i) = \sqrt{\frac{m}{2\pi kT}} \exp\left[-\frac{mv_i^2}{2kT}\right]$$



Voigt profile



$$b = \sqrt{\frac{2k_bT}{m}}$$

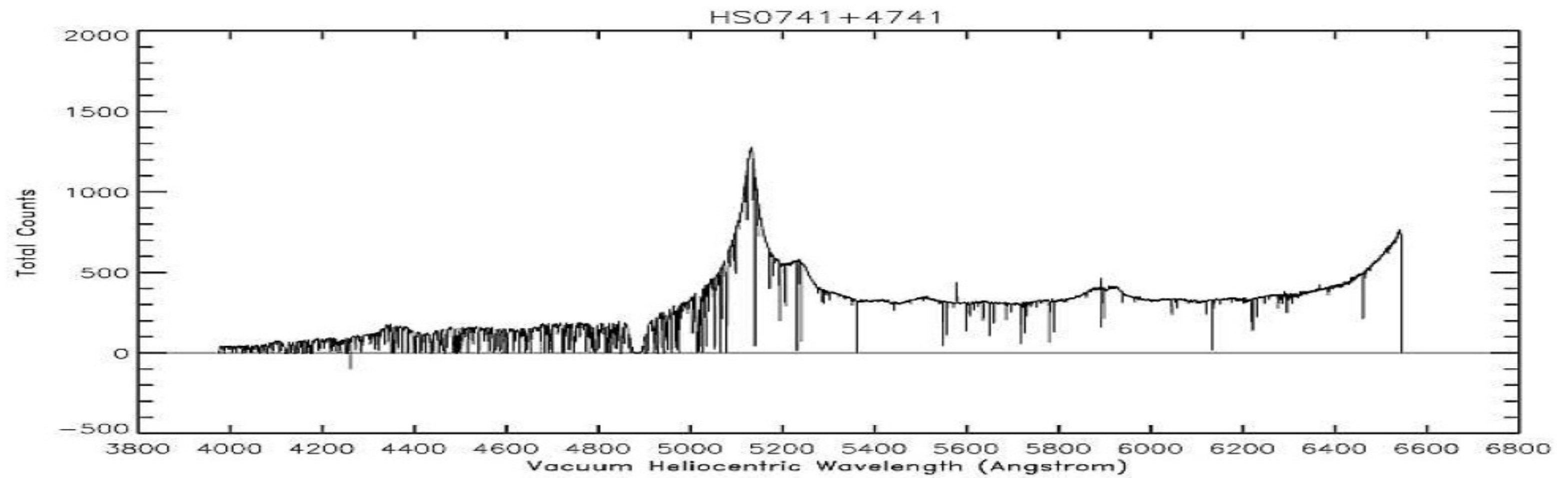
$$a = \frac{\Gamma_{ul}}{4\pi\Delta\nu_D}, \quad \Delta\nu_D = \nu_{lu}\frac{b}{c}$$

$$x = \frac{\nu - \nu_{lu}}{\Delta\nu_D}$$

$$\sigma_\nu = \left(\frac{\pi e^2}{m_e c}\right)\left[\frac{1}{4\pi\epsilon_0}\right] f_{lu}\phi(a,\nu)$$

$$\phi(a,\nu) \approx H(a,x) = \frac{a}{\pi}\int dy \frac{e^{-y^2}}{(x-y)^2 + a^2}$$

Gunn-Peterson effect



$$\lambda_{lu} < \lambda < \lambda_{lu} \frac{a(t)}{a(t_0)}$$

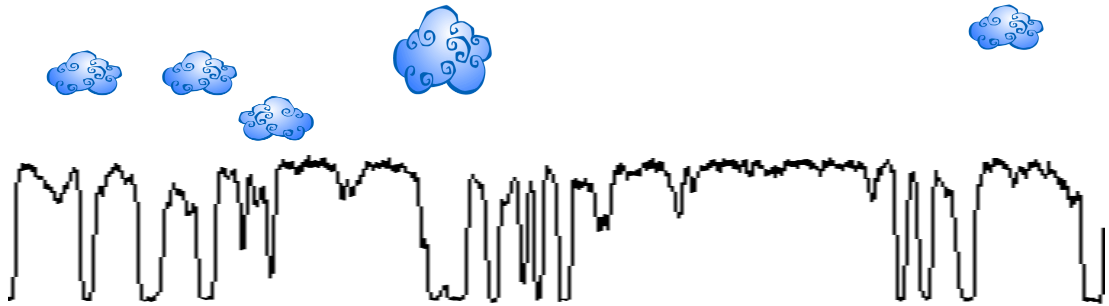
t_0 emission time

$$\tau_\nu = \int_{s_0}^{s} ds' n(s', t') \sigma_{\nu'} =$$

$$= 1.2 \cdot 10^4 \frac{(1+z)^3}{[\Omega_m (1+z)^3 + \Omega_K (1+z)^2 + \Omega_v]^{1/2}} \left(\frac{f_{lu} \lambda}{506.0 \mathring{A}} \right) \left(\frac{\langle n \rangle}{\langle n_H \rangle} \right)$$

For an homogeneous medium

Discrete absorption features



$$\tau_\nu = \sum_i \tau_\nu(i)$$

$$\tau_\nu(i) = \int_{s_i - \Delta s/2}^{s_i + \Delta s/2} ds' n(s', ti)\sigma_{\nu'} \qquad \nu' = \nu \frac{a(t)}{a(t_i)}$$

$$\tau_\nu = \pi^{1/2} \tau_0 \langle \phi(a, x) \rangle$$

$$\tau_0 = \frac{\pi^{1/2} e^2}{m_e c} \left[\frac{1}{4\pi\epsilon_0} \right] \frac{N}{b} \lambda_{lu} f_{lu}$$

Optical depth line centre

Espressing absorption features like discrete spatial structure is an approximation

IGM is an evolving spatial continuum

Discrete absorption features

TABLE I Summary of absorption line system properties

	Line parameters		Physical characteristics			
Absorber class	$N_{\rm HI}$ ($\rm cm^{-2}$)	b^a ($\rm km\,s^{-1}$)	n^b ($\rm m^{-3}$)	T^b (K)	Size (kpc)	$[M/H]^c$
Lyα forest	$\lesssim 10^{17}$	15–60	0.01 – 1000	5000 – 50000	15–1000(?)	-3.5 – -2
LLS	$10^{17} - 10^{19}$	~ 15	$\sim 10^3 - 10^4$	~ 30000	–	-3 – -2
Super LLS	$10^{19} - 2\times 10^{20}$	~ 15	$\sim 10^4$	~ 10000	–	-1 – +0.6
DLA	$> 2\times 10^{20}$	~ 15	$\sim 10^7; \sim 10^4$	$\sim 100; \sim 10000$	$\sim 10 - 20$(?)	-1.5 – -0.8

[a]Approximate ranges. Not well determined for most Lyman Limit Systems and super Lyman Limit Systems.

[b]Values not well constrained by direct observations.

[c]Approximate metallicity range, expressed as a logarithmic fraction of solar: $[M/H] = \log_{10}(M/H) - \log_{10}(M/H)_\odot$.

Meiksin, 2009

Ionization – Ultra Violet Background (UVB)

Steady state ionization equilibrium equations

$$
\begin{aligned}
1 - Y_{HI} &= Y_{HI} I_{HI} \\
Y_{HeII} &= Y_{HeI} I_{HeI} \\
1 - Y_{HeI} - Y_{HeII} &= Y_{HeII} I_{HeII}
\end{aligned}
$$

where

$$I_{HI} = \frac{\Gamma_{HI}}{n_e \alpha_{HI}(T)}$$

α_{HI} Recombination rate of hydrogen

$$\Gamma_{HI} = \int_{\nu_L}^{\infty} d\nu 4\pi \frac{J(\nu)}{h\nu} \sigma_{HI}(\nu)$$

Haardt et Madau, 1996

Equation of state for the IGM

The true equation of state of the gas is
the ideal equation of state

The “equation of state” of the IGM is determined by equilibrium between:

- Photoheating of hydrogen and helium
- Cooling due to the adiabatic expansion of the Universe
- Recombination cooling

$$\frac{dT}{dt} = -2HT + \frac{2T}{3(1+\delta)}\frac{d\delta}{dt} - \frac{T}{\sum_i \tilde{X}_i}\frac{d\sum_i \tilde{X}_i}{dt} + \frac{2}{3k_B n_b}\frac{dQ}{dt}$$

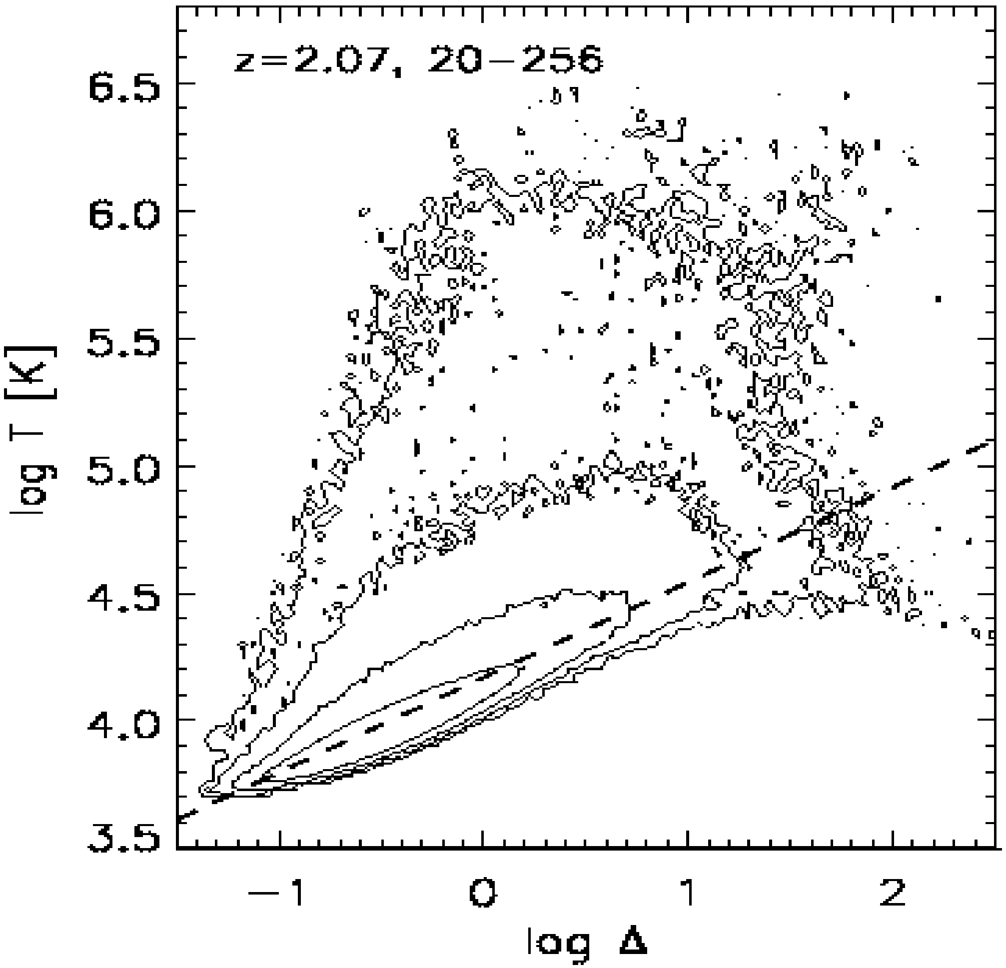
Expansion of Universe

Change in number of species

Effect of surrounding radiation field

Hui et Gnedin, 1997

Equation of state for the IGM



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

$$T_0 \approx 10^4 K$$

$$\gamma \lesssim 1.62$$

$$\Delta = \frac{\rho}{\langle \rho \rangle} < 10$$

Bolton et al, 2008

Hui et Gnedin, 1997

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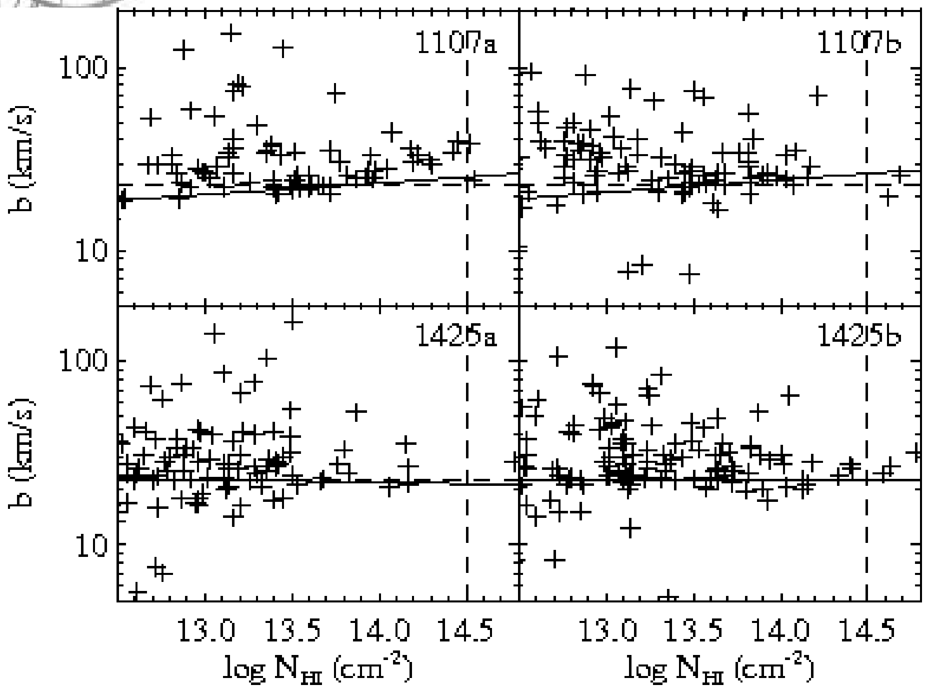
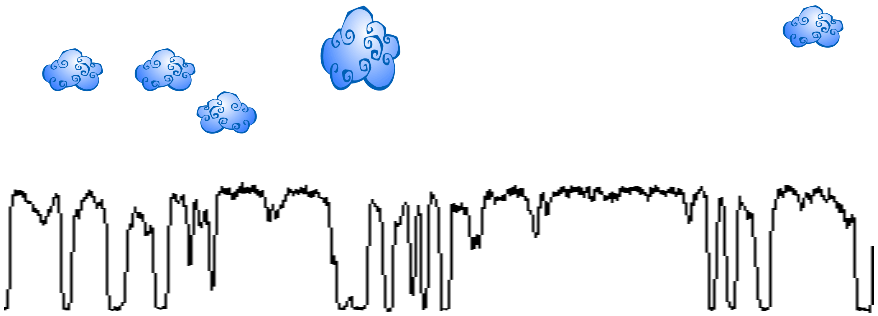
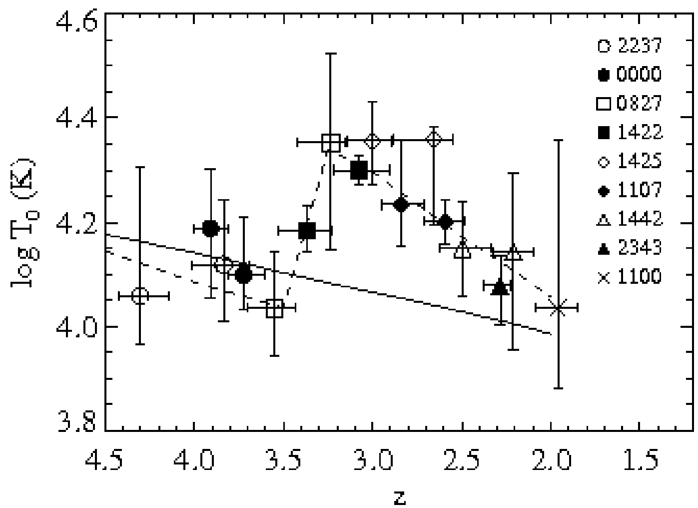
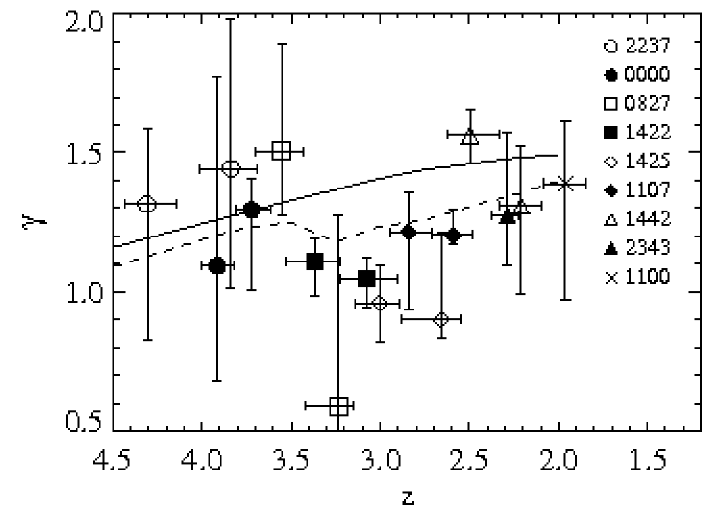
Thermal state of IGM -- Schaye et al (2000)

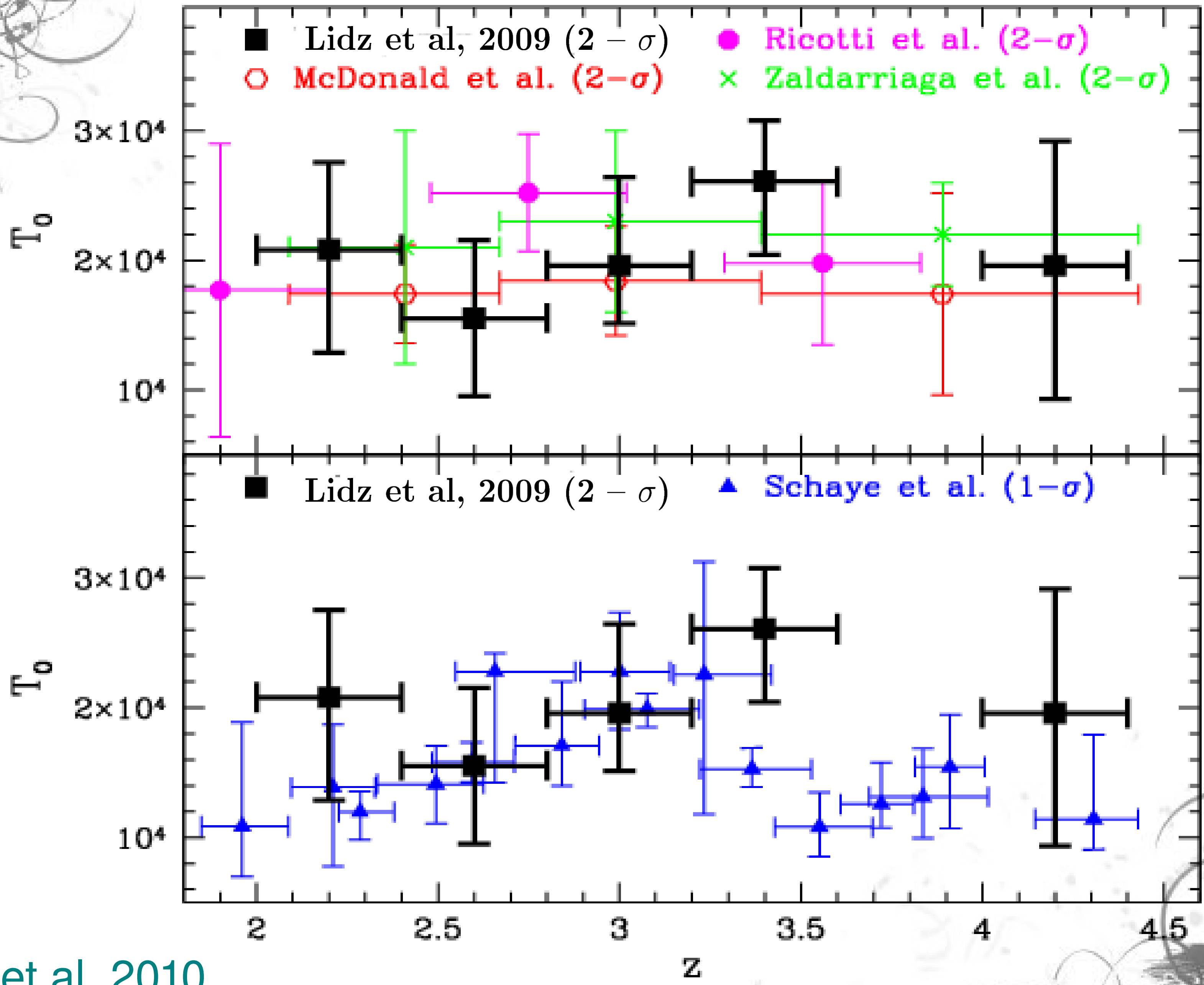






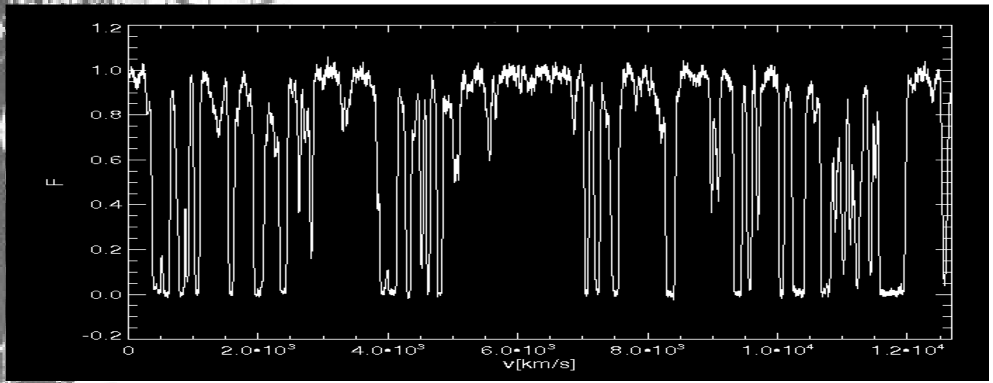


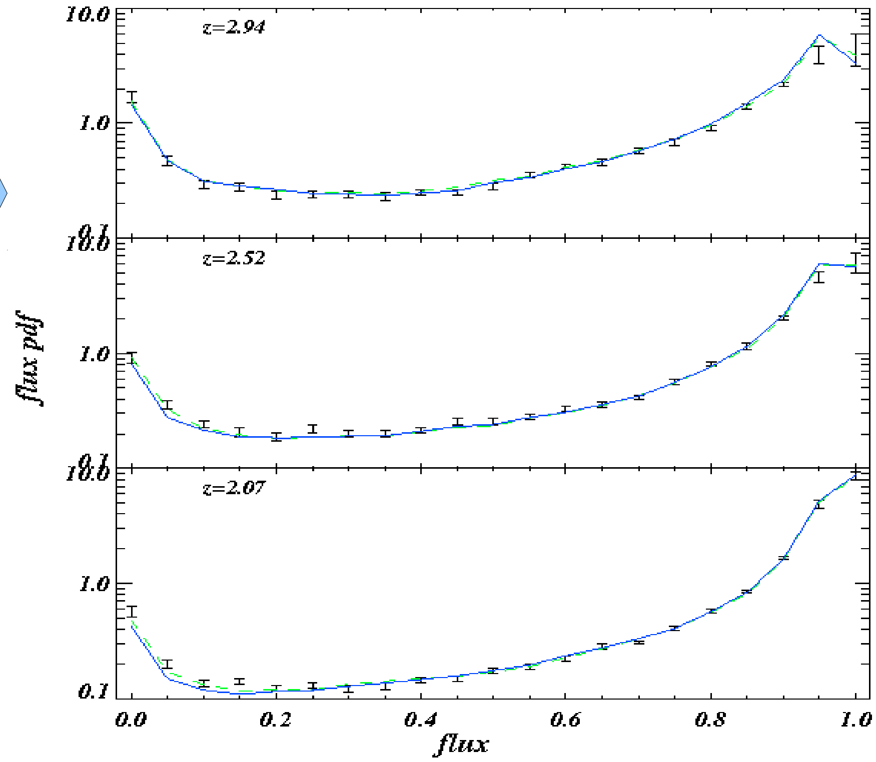
Thermal state of IGM



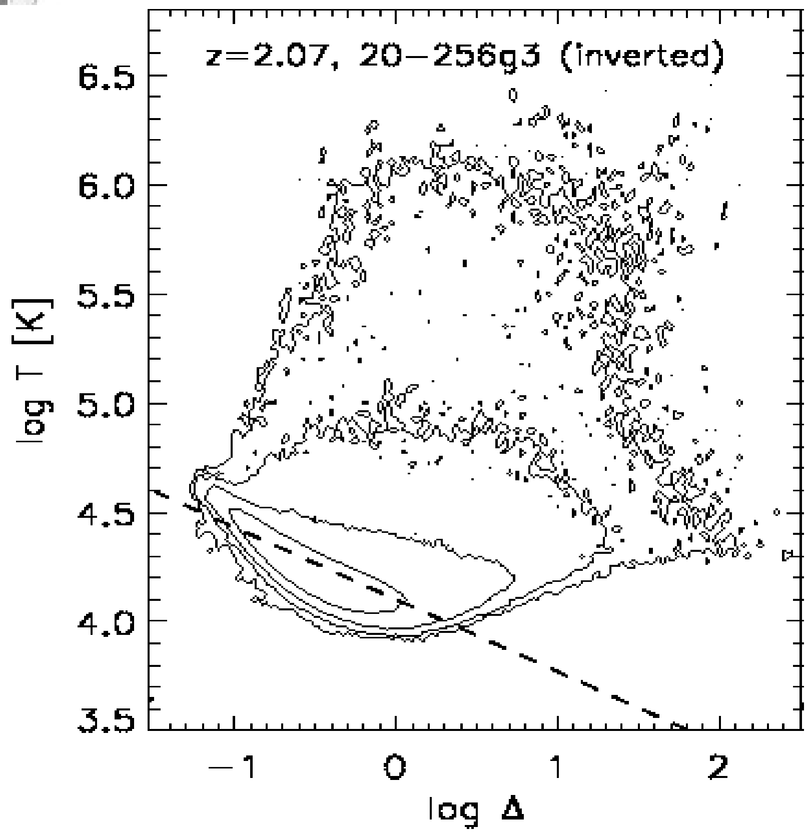
Lidz et al, 2010

Thermal state of IGM – Flux PDF





Viel et al, 2009

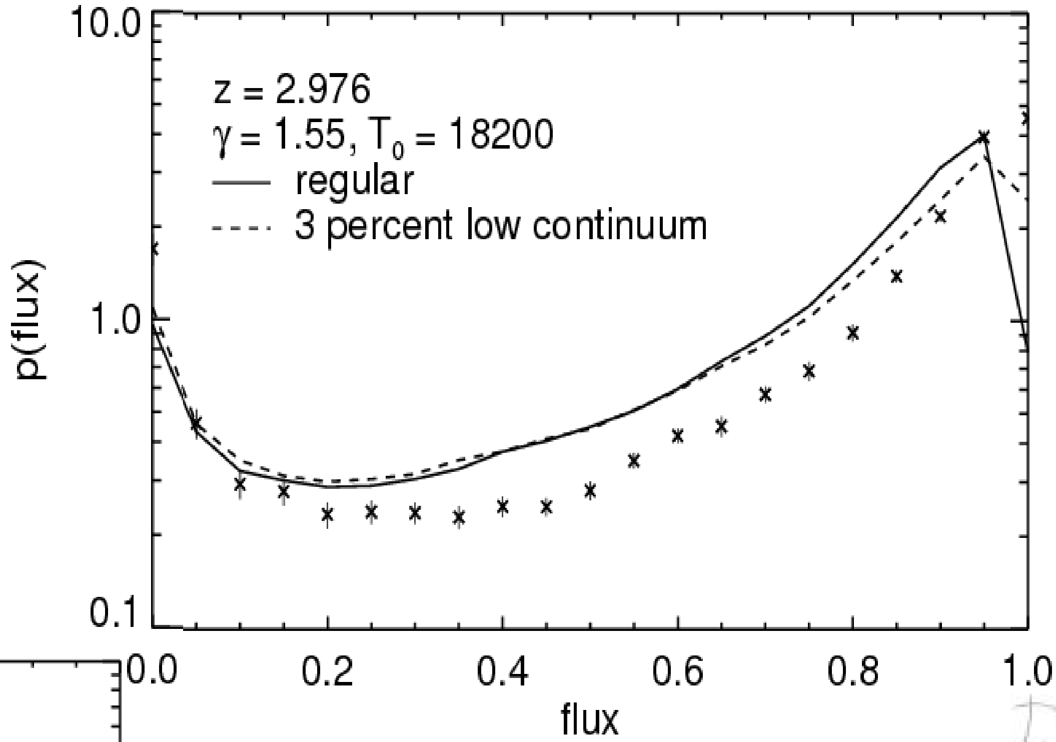


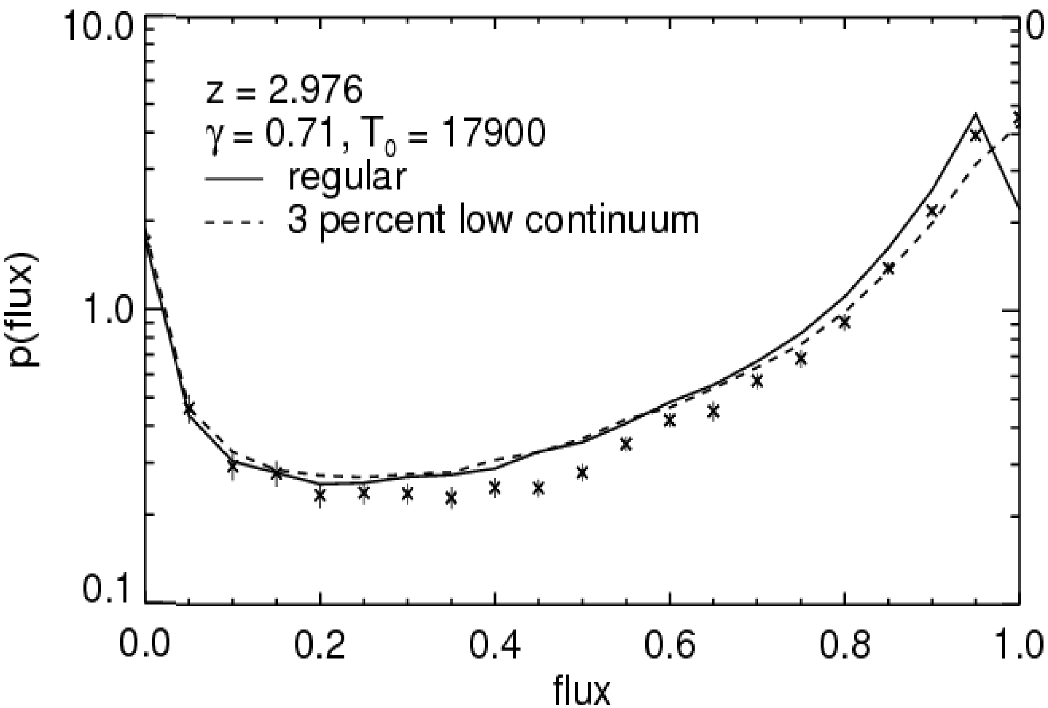
Bolton et al, 2008

Inverted equation of state

Furlanetto & Oh, 2008

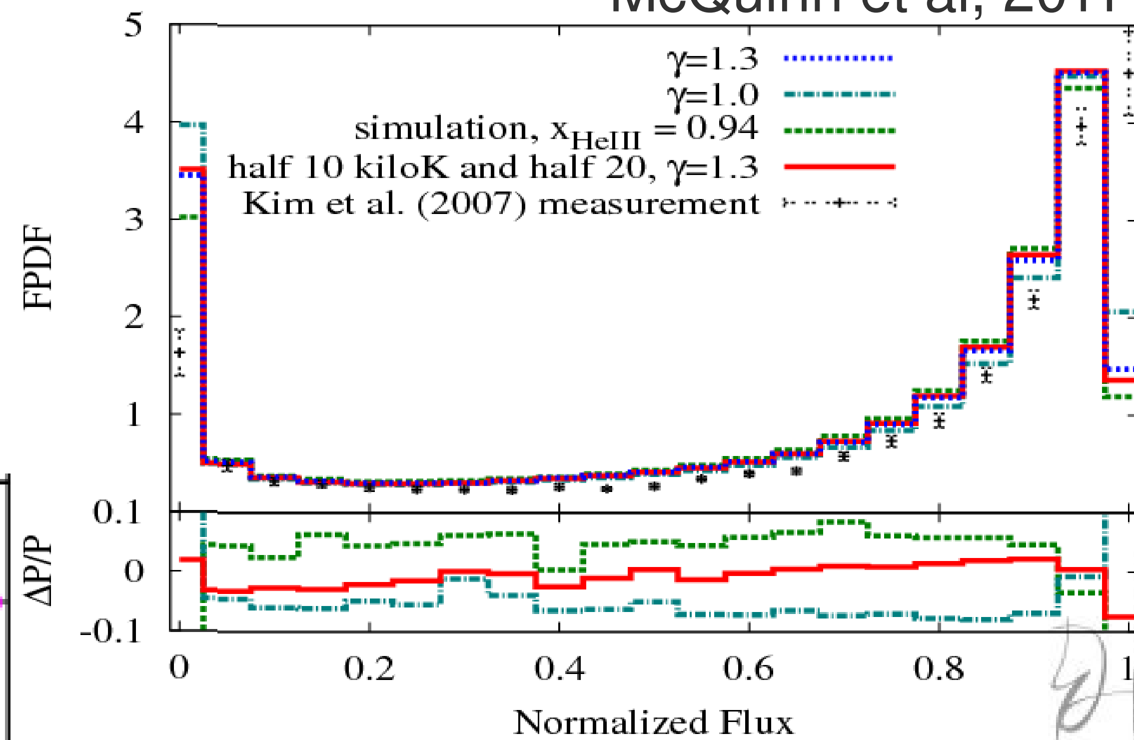
Thermal state of IGM – Flux PDF



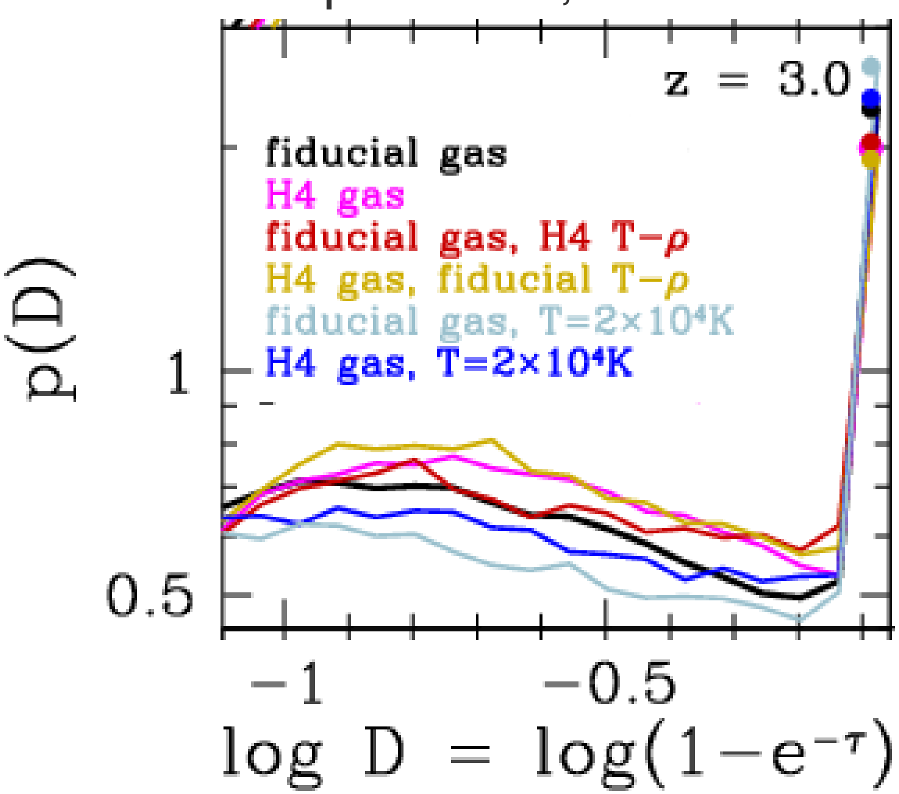


Thermal state of IGM – Flux PDF

McQuinn et al, 2011

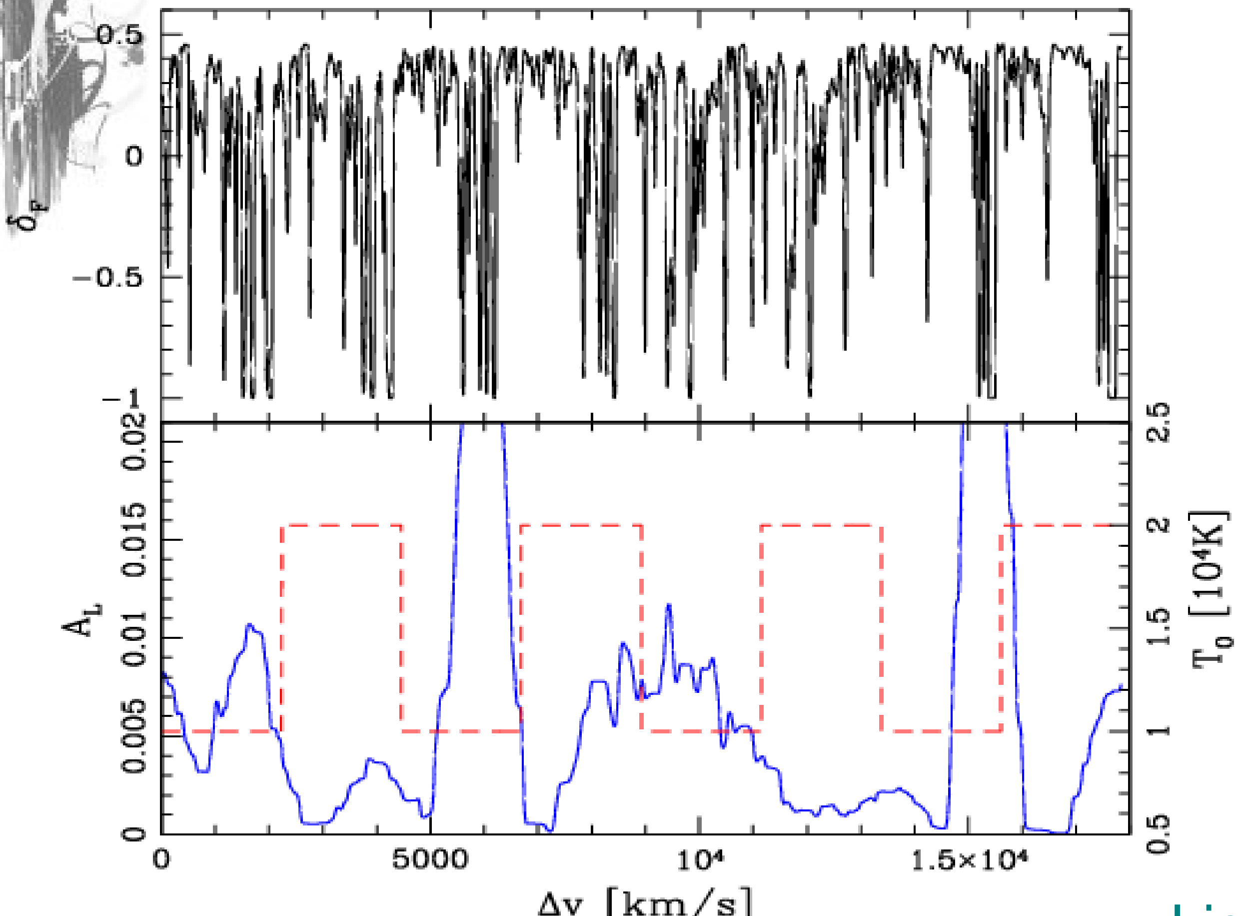


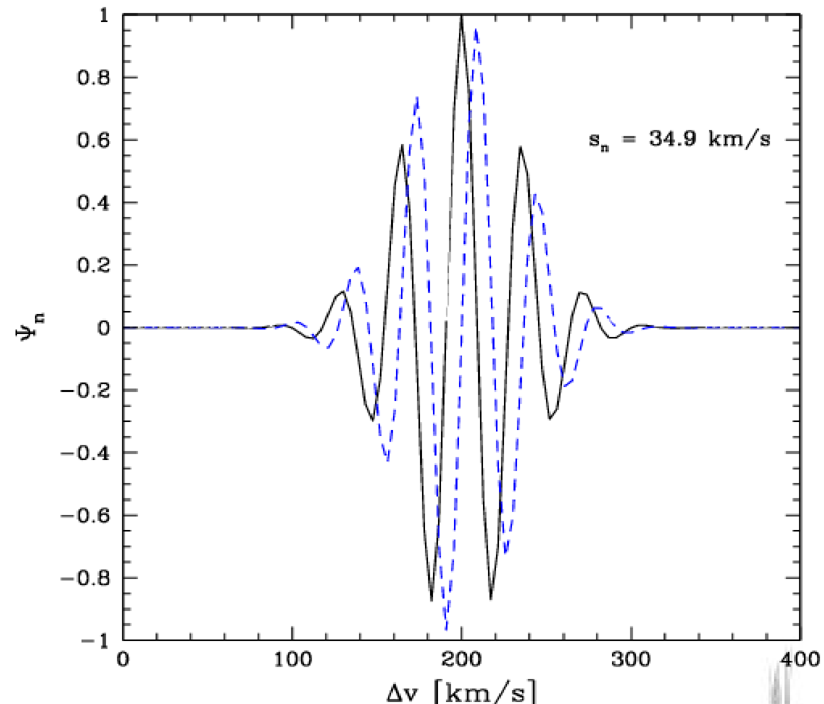
Peeples et al, 2010



z=3

Thermal state of IGM – Wavelet filtering

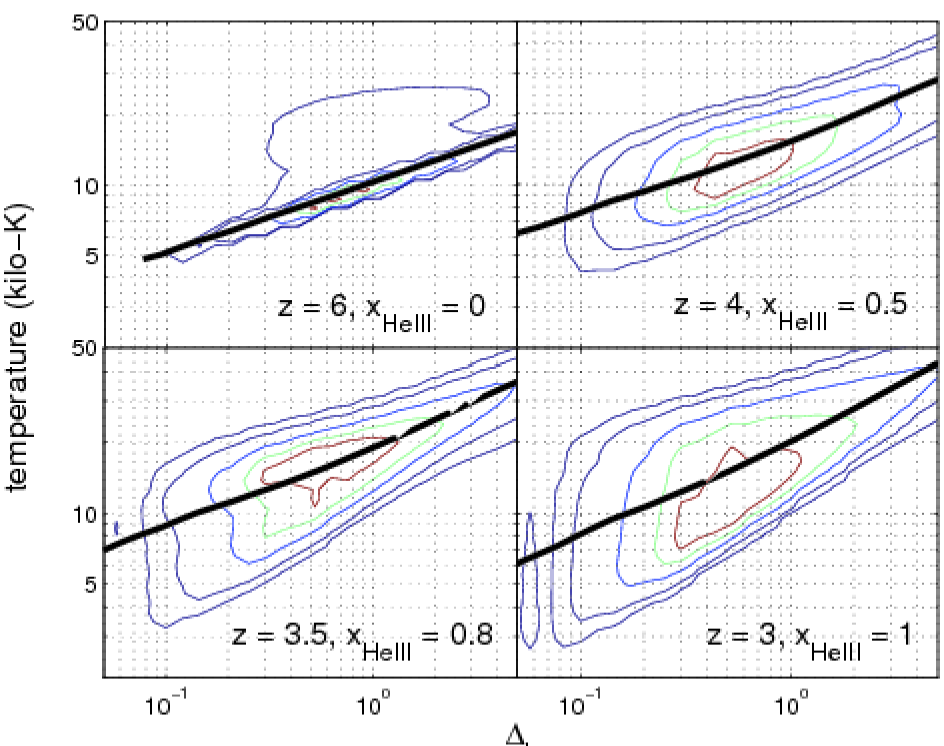


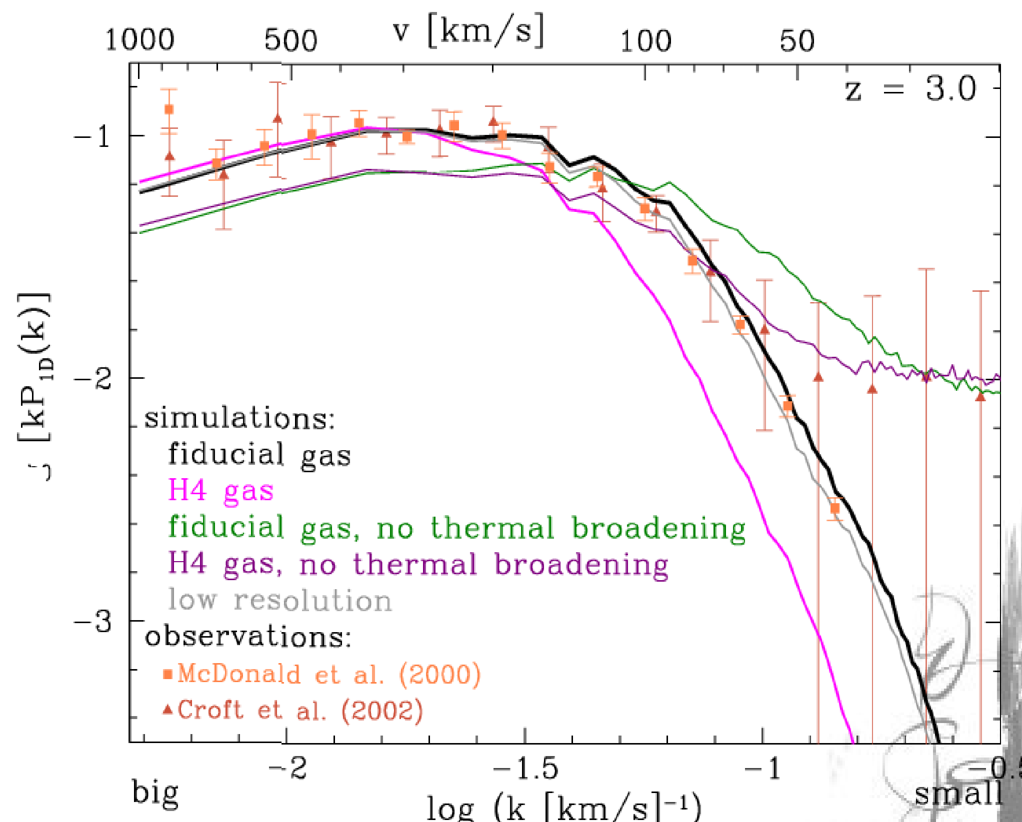


Lidz et al, 2010

Thermal state of IGM – Wavelet filtering

McQuinn et al , 2009





Peeples et al, 2010

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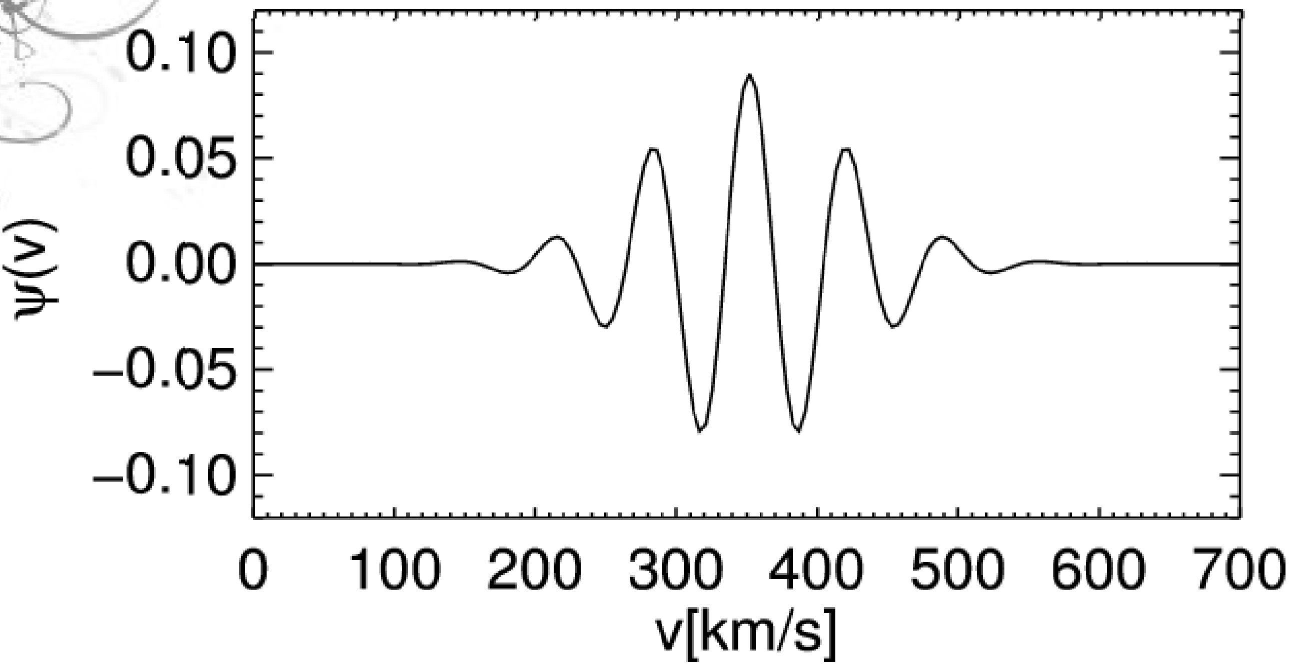
Wavelets

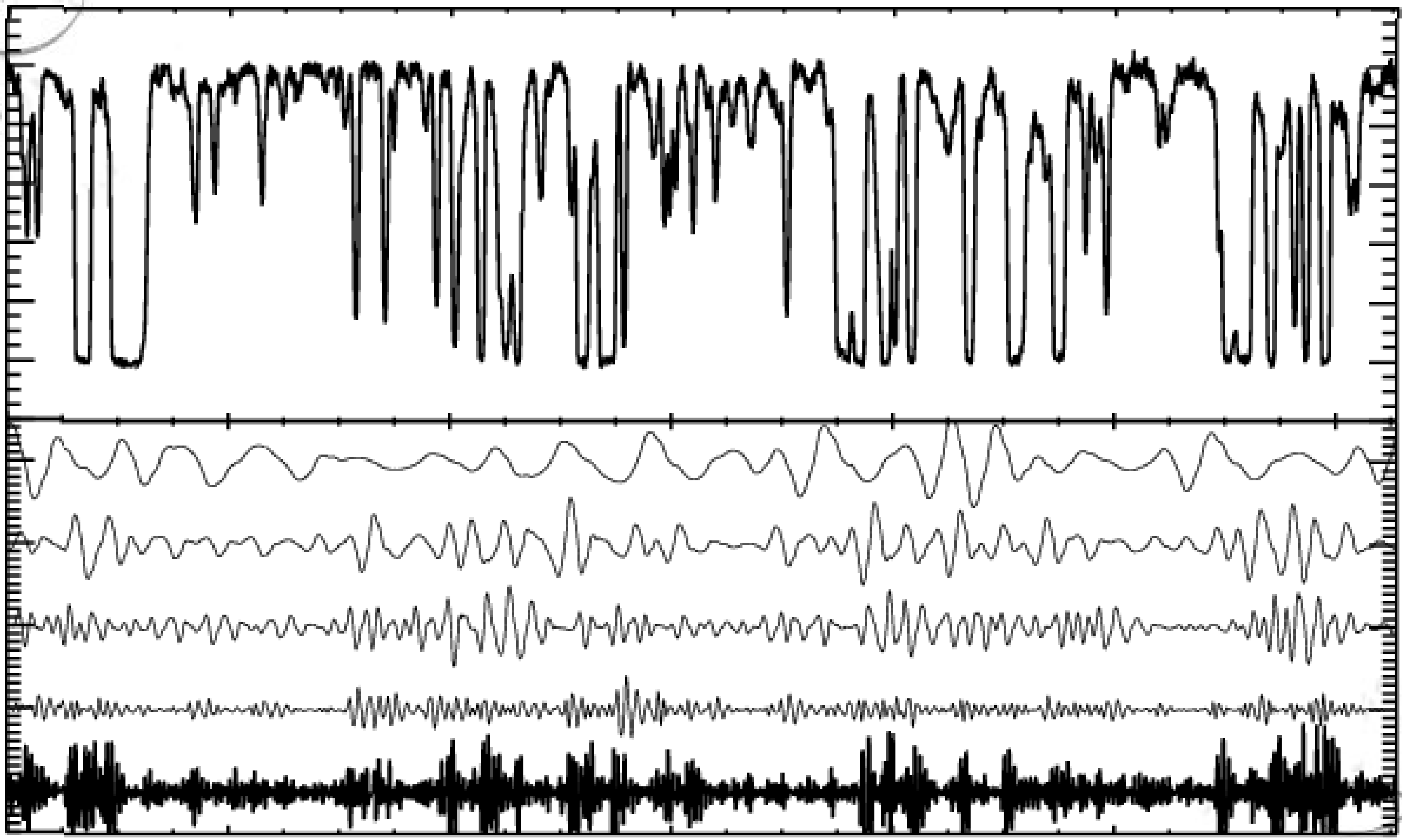


$$\psi_k(v) = \mathcal{A} \exp(-ikv/2\pi) \exp(-v^2/2s^2)$$

$$s = \frac{2\pi}{k}$$

Theuns et Zaroubi (2002)
Zaldarriaga (2002)

Wavelets



v (km/s)

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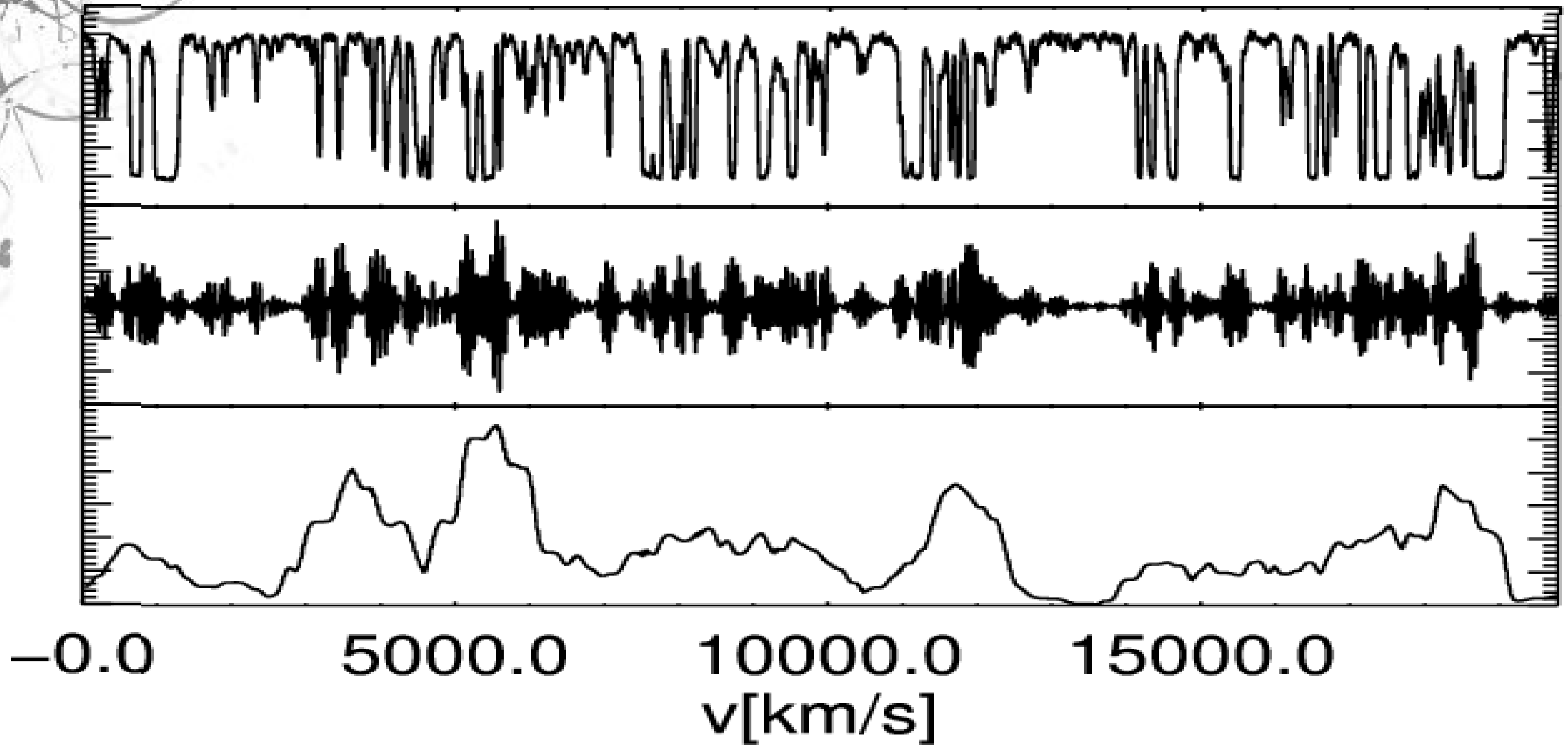
Wavelet amplitude of a spectrum

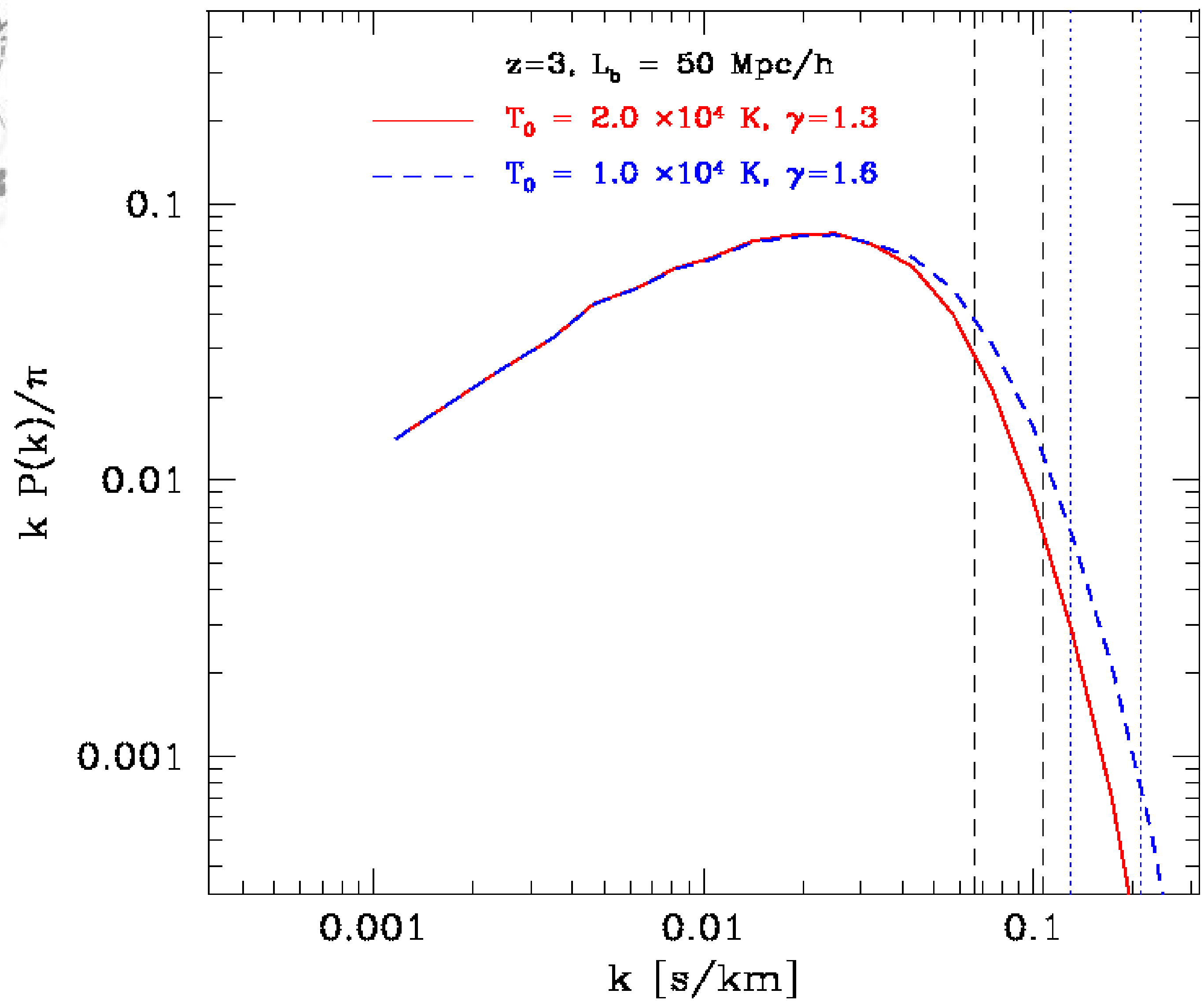


$$a(x) = \int dx' \psi(x - x') f(x')$$

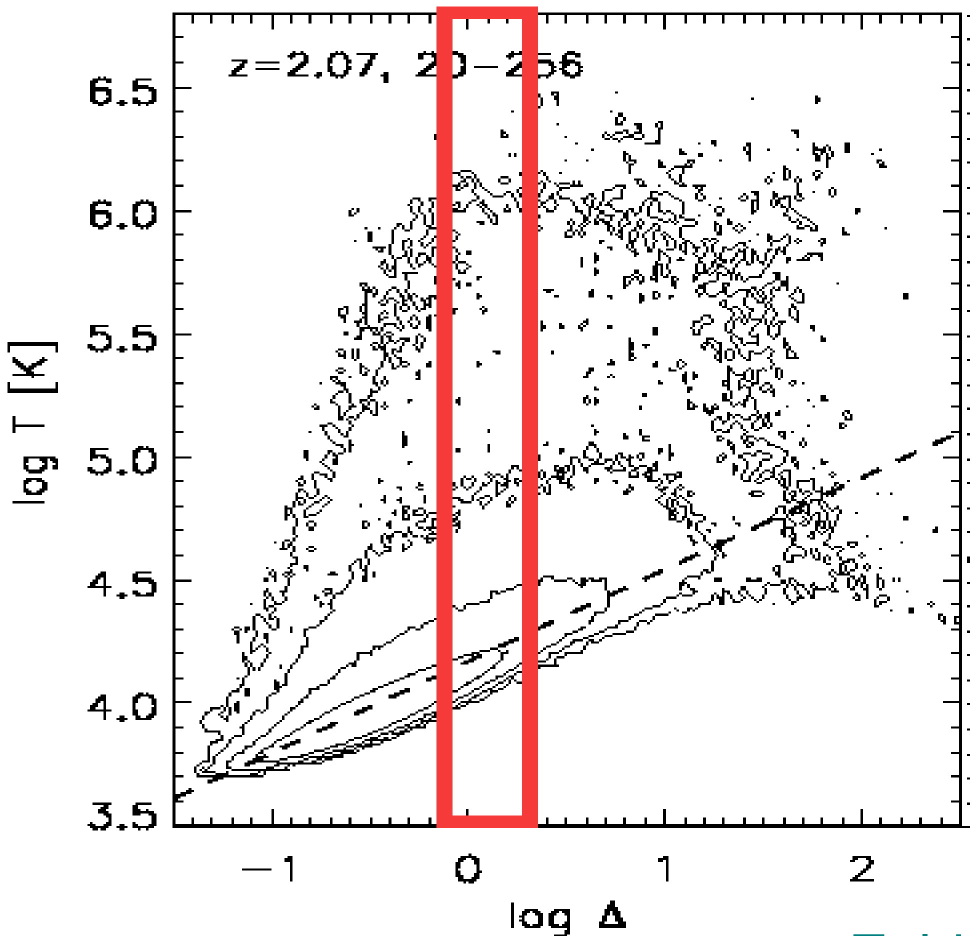
$$A_L(x') = \int_{-\infty}^{+\infty} dx' \Theta(|x - x'|, \frac{L}{2}) |a(x')|^2$$

Wavelet and power spectra

Lidz et al, 2010



Gas densities probed by wavelets



$$0.9 < \Delta < 1.8$$

for z ~ 3

Zaldarriaga et al, 2001

Linking theory with observations

Observed spectra

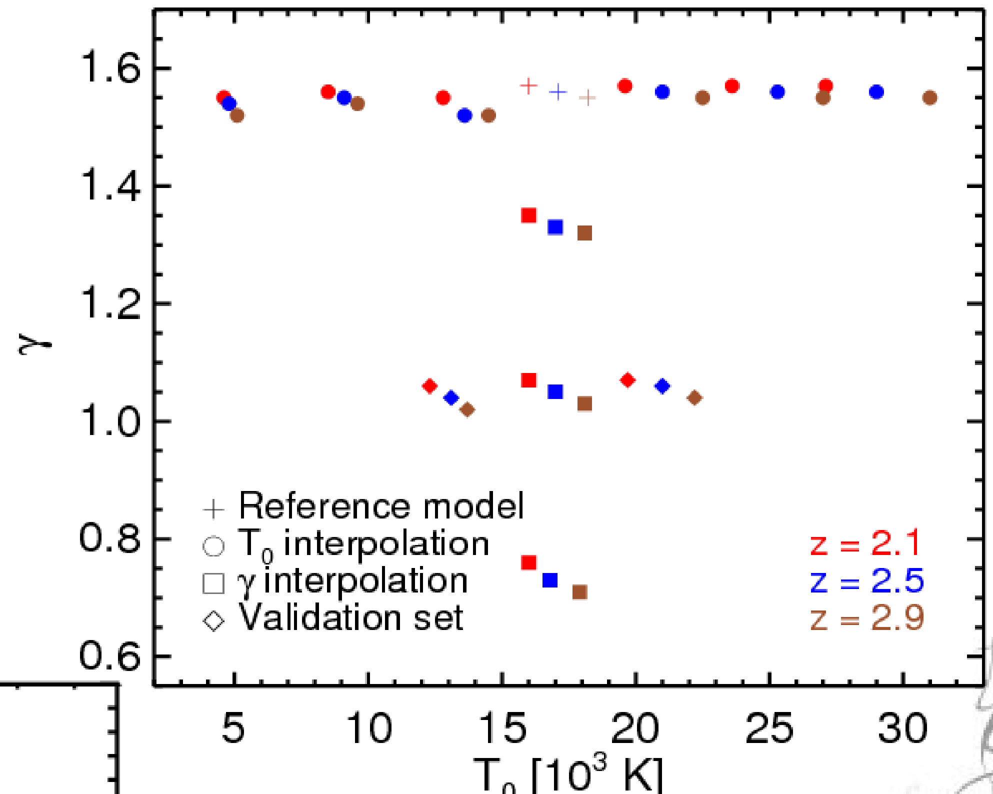
- 18 spectra from UVES of VLT (Kim et al, 2007)
- Metal cleaned
- Continuum fitted
- Normalized
- High S/ N ~ 50

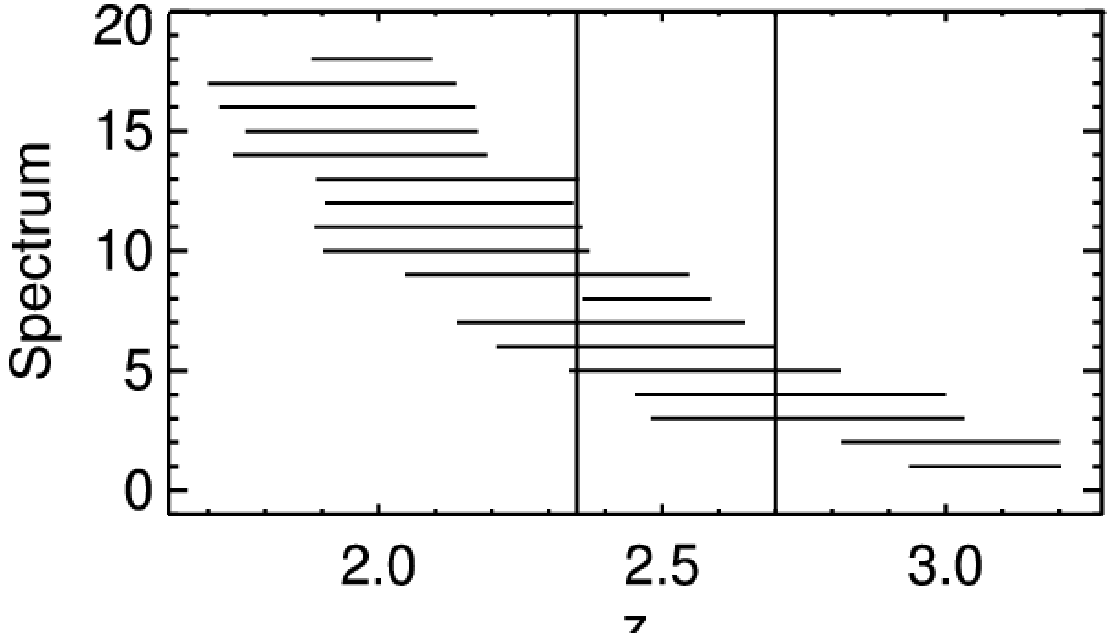
Hydrodynamical Numerical simulations

- High resolution numerical simulations(gas + DM) – Gadget 3 (Springel, 2005)
- 256-512^3 particles
- 10Mpc boxsize
- Uniform ultraviolet background (Haardt et Madau, 2001)

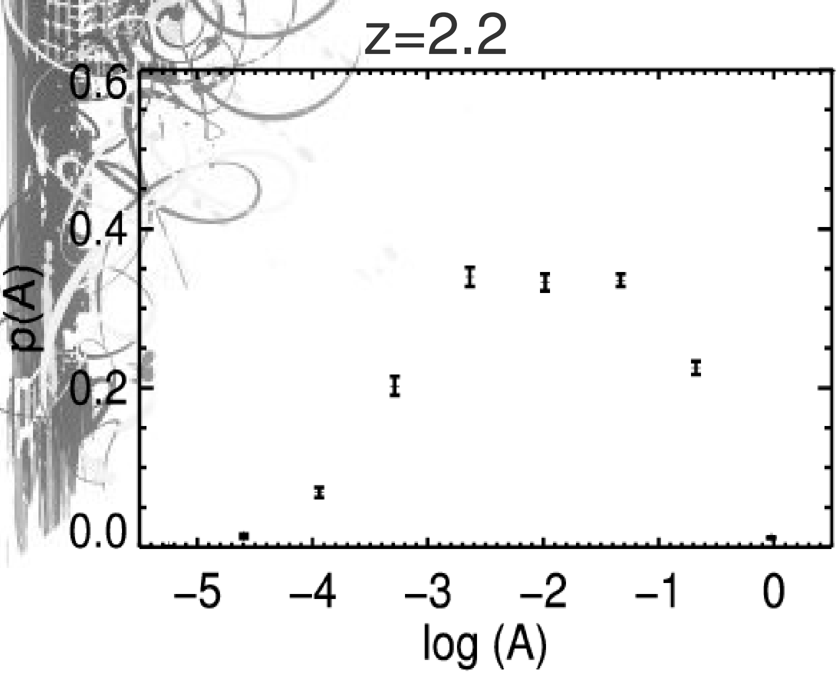
- Interpolation among cosmological and astrophysical parameters
$T_0, \gamma, \tau_{\rm eff}, H_0, \Omega_{\rm m}, n_s, \sigma_8$
- Exploration of likelihood function by Multinest (Feroz et Hobson, 2008)

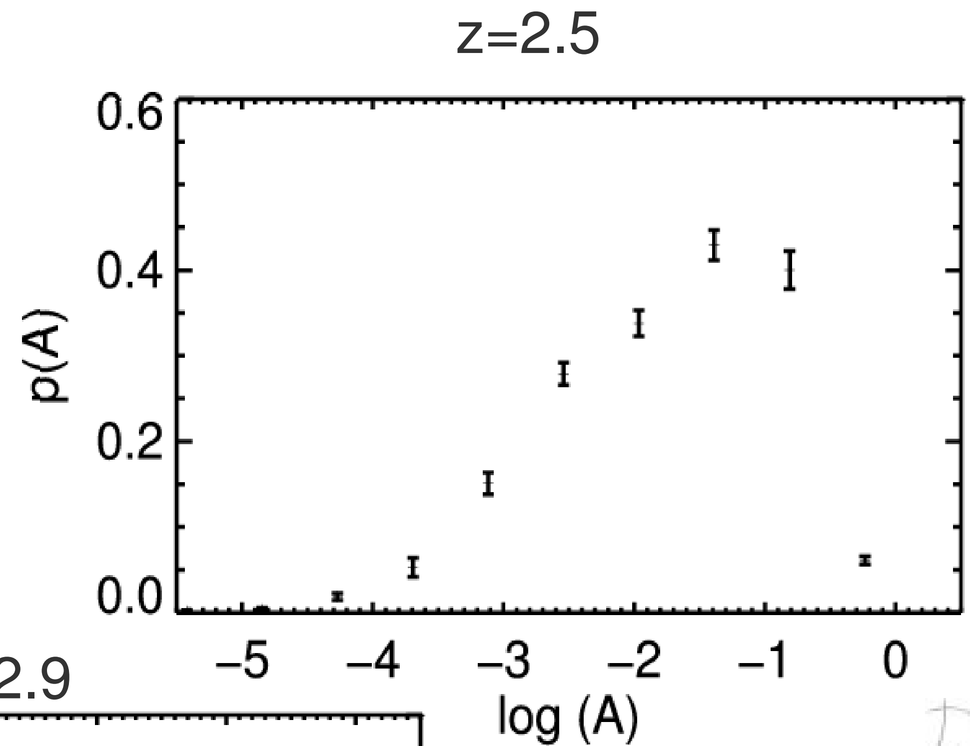
Observed & Simulated Spectra



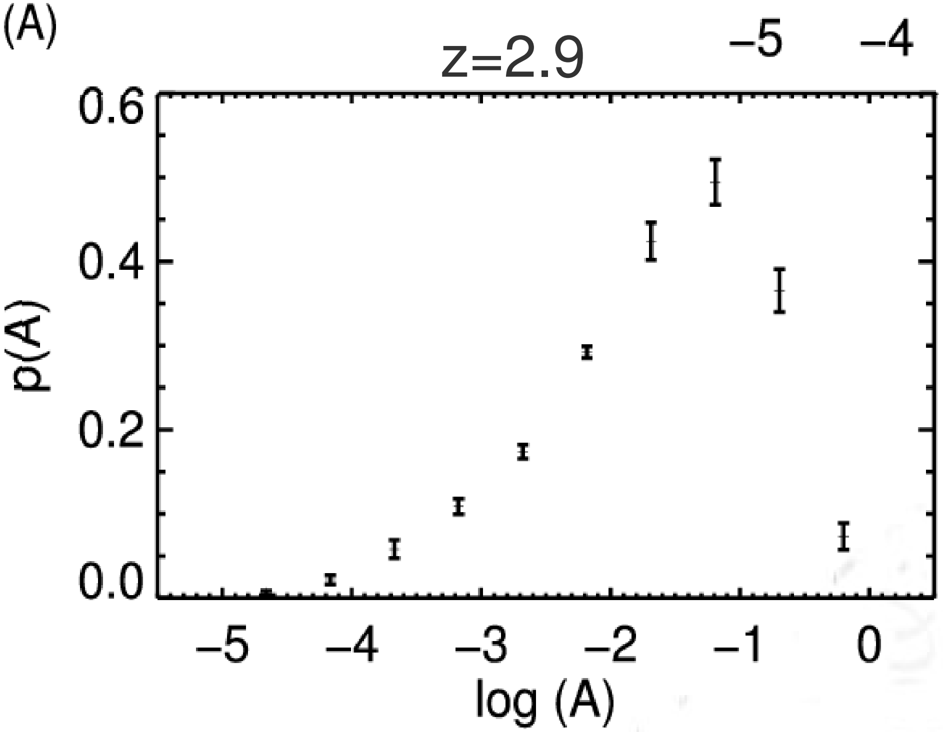


Wavelet amplitude PDF





$r = 70\mathrm{km/s}$



Interpolation scheme

Likelihood analysis

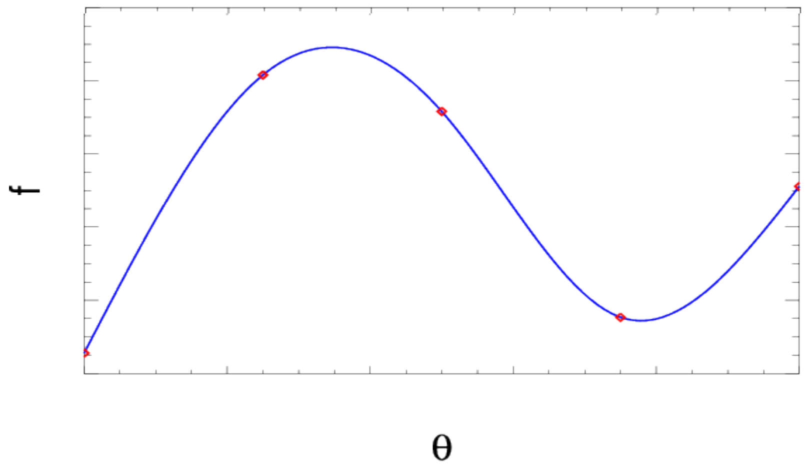
$$\ln L(\theta) \propto (p(A,\theta) - \tilde{p}(A))^T \cdot C^{-1} \cdot (p(A,\theta) - \tilde{p}(A))$$

$$\theta = \{T_0, \gamma, \tau_{\rm eff}, H_0, \Omega_{\rm m}, n_s, \sigma_8\}$$

Continuous in θ

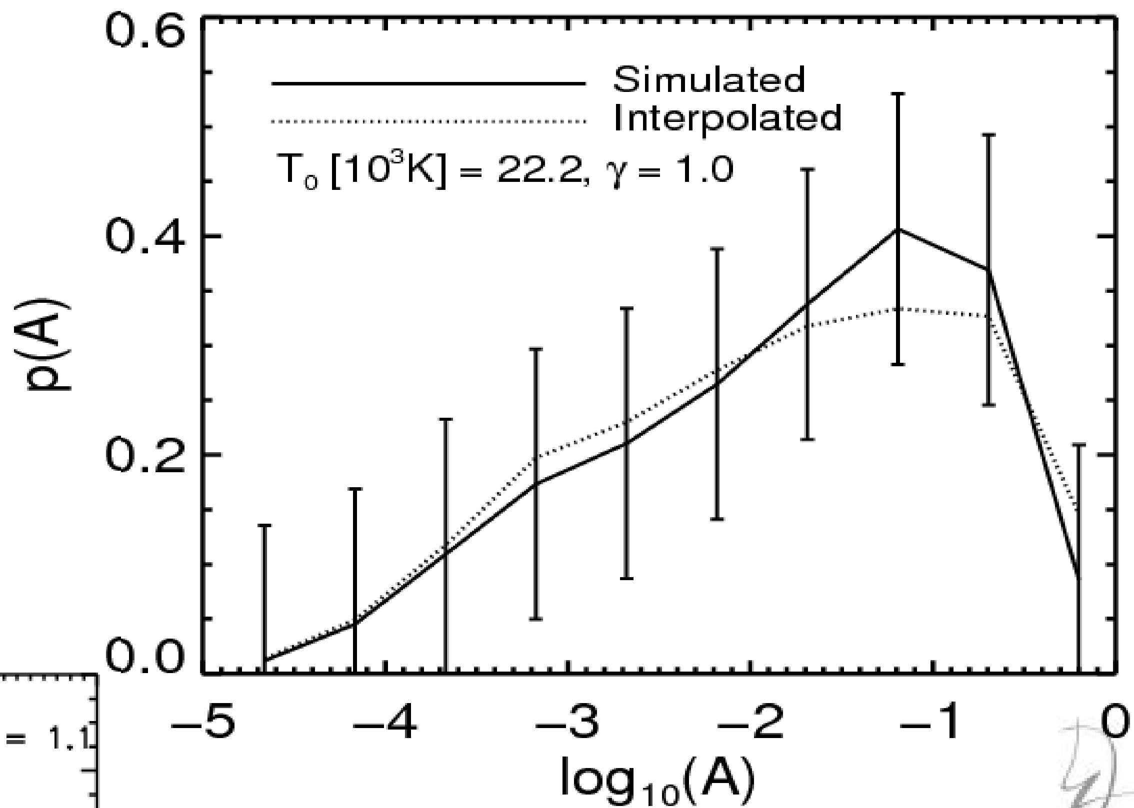
interpolation scheme "taylor expansion" as in Viel et al, 2009

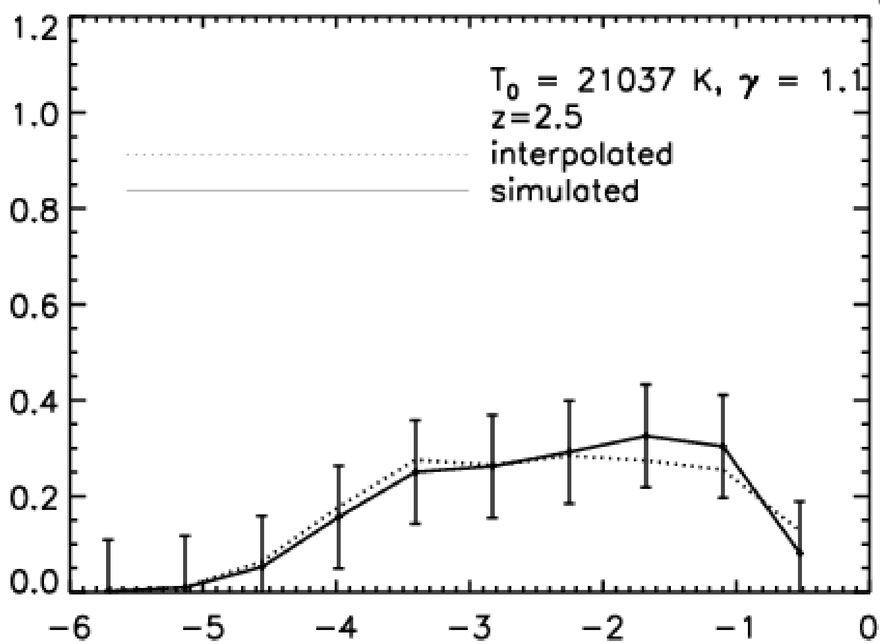
$$p(A_i,\theta) = p(A_i,\theta^*) + f_{\theta_0}(\theta_0 - \theta^*{}_0) + \ldots + f_{\theta_n}(\theta_n - \theta^*{}_n)$$



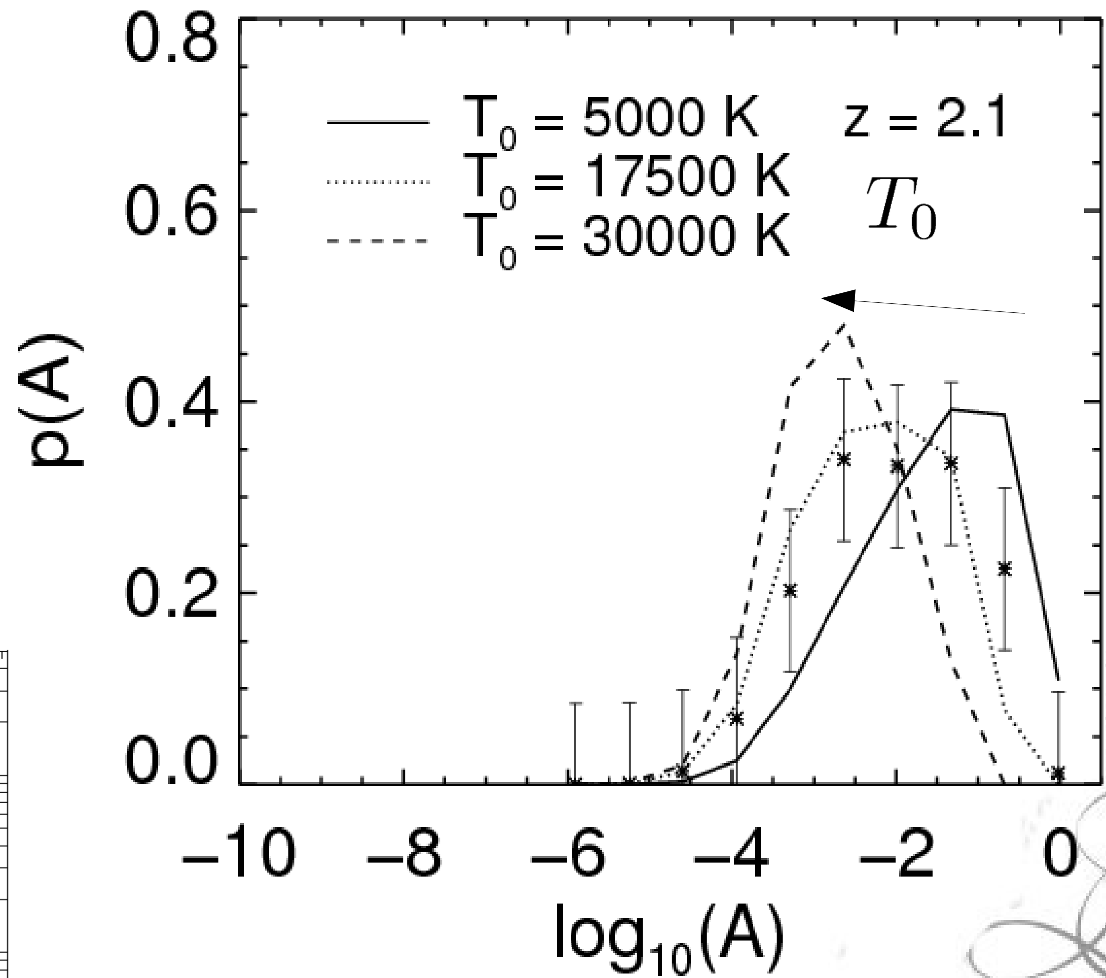
Cubic spline interpolation

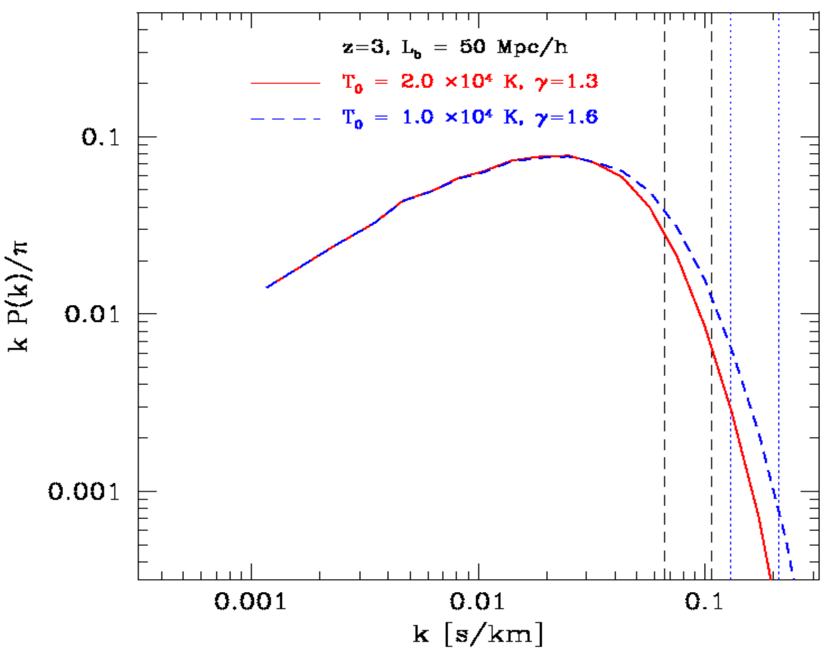
Interpolation scheme



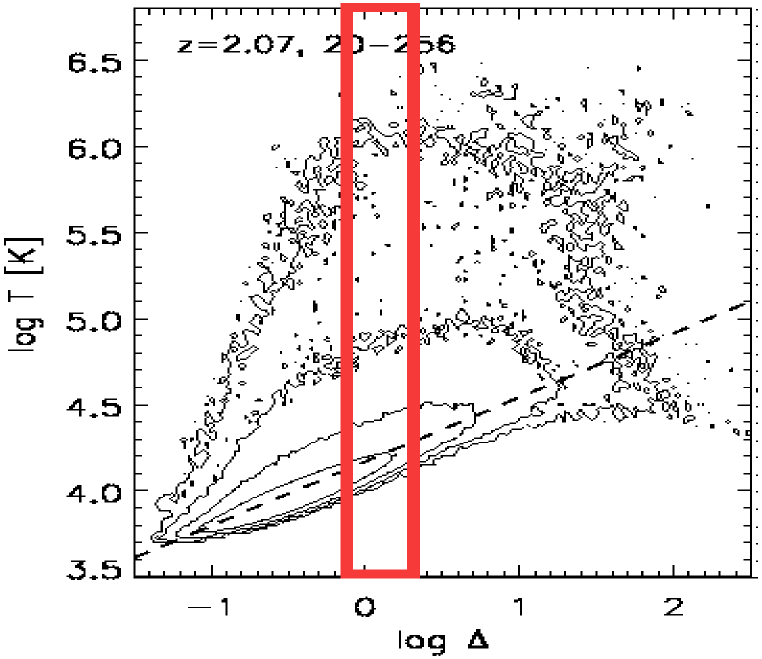


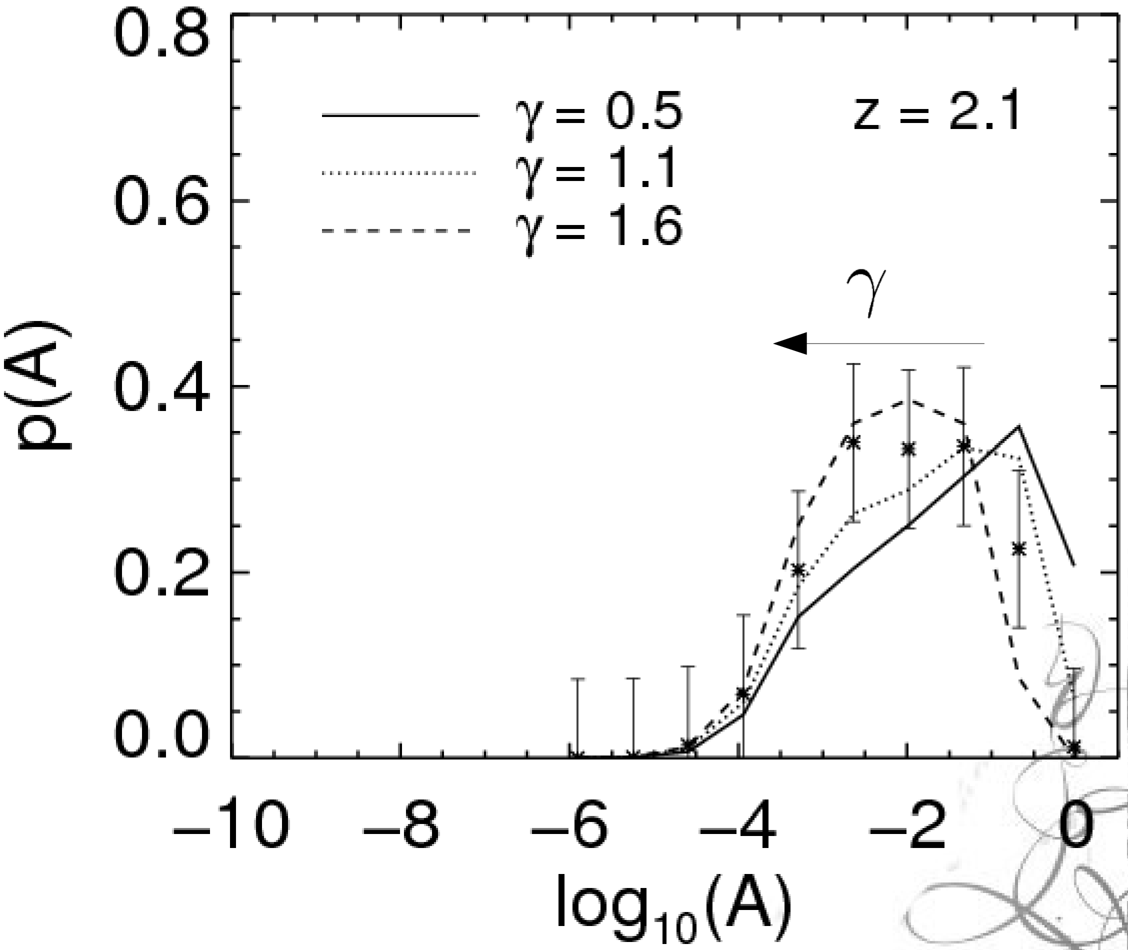
Wavelets as a thermometer



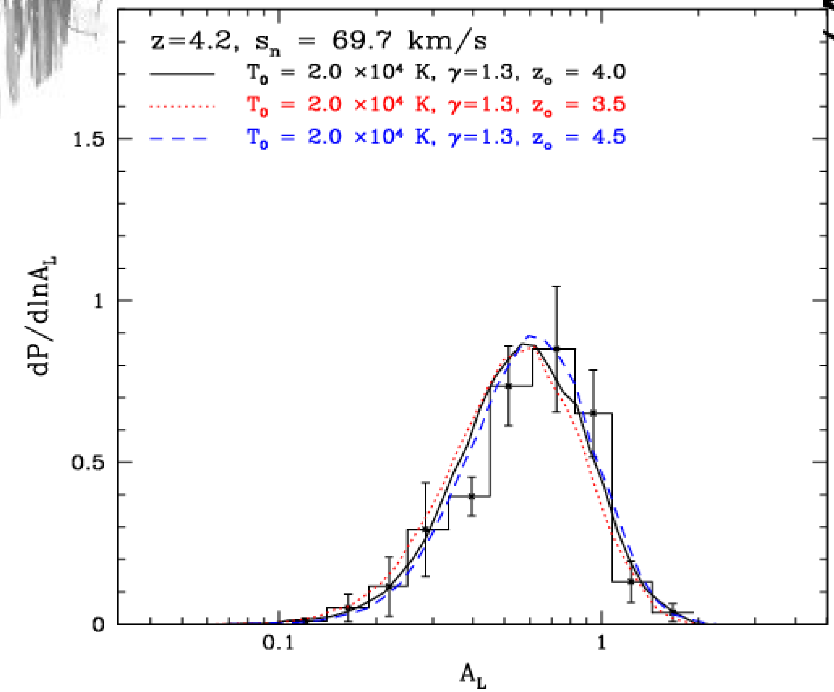


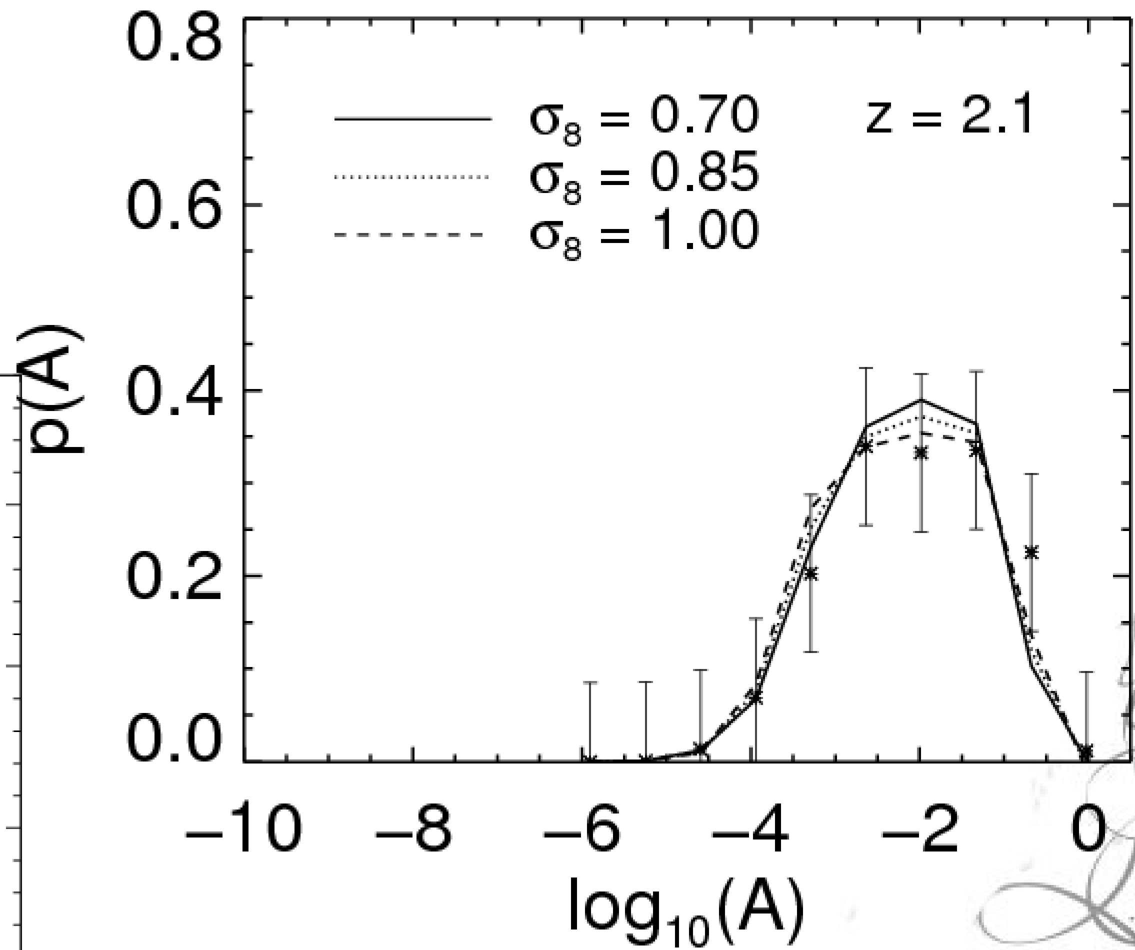
Wavelets as a thermometer





Wavelets & cosmological parameters





Lower redshift > higher density fluctuations
Higher redshift > lower density fluctuations
Lidz et al, 2010

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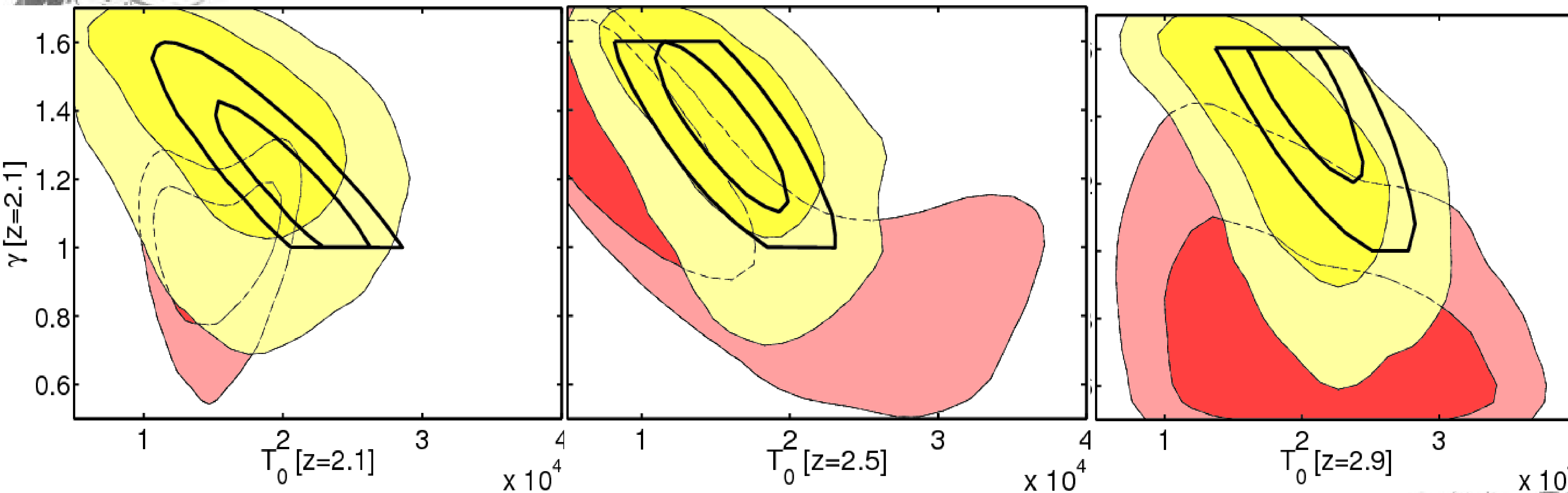
Constraints on IGM thermal state

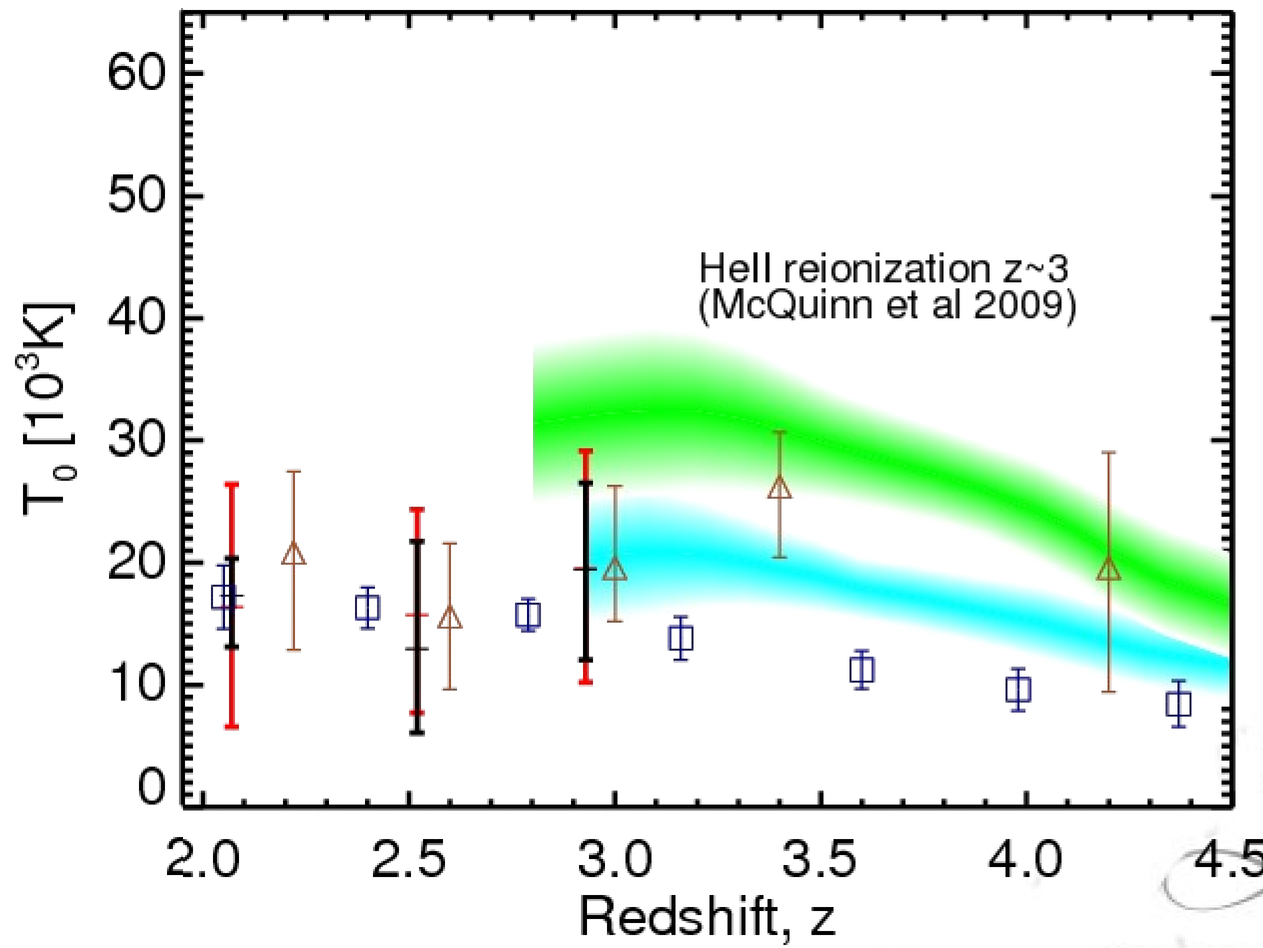


Wavelet filtering

Flux PDF (Viel et al, 2009)

Lidz et al, 2010

Results: wavelet filtering & joint analysis



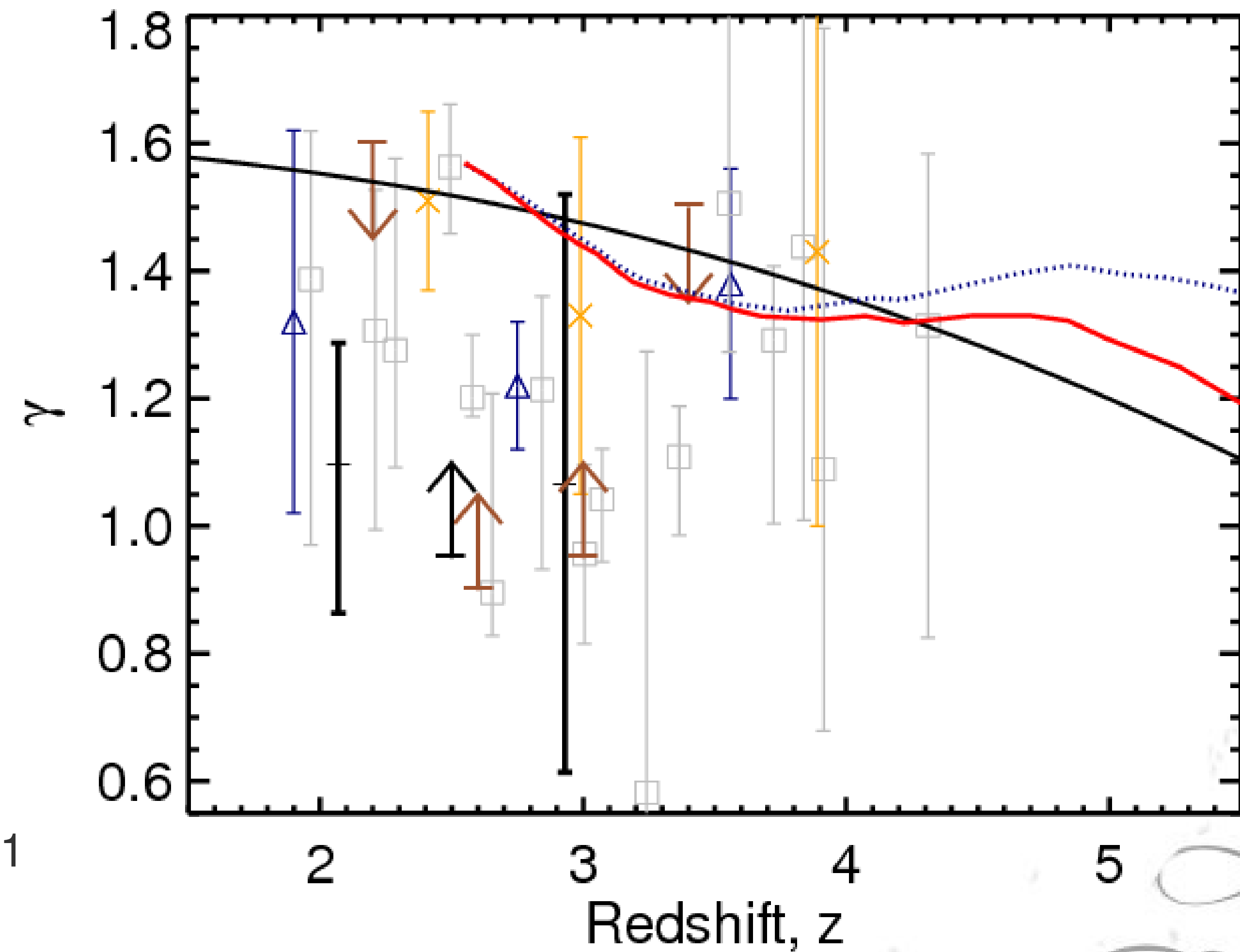
△ Lidz et al, 2010

Wavelet filtering

Wavelet + flux

□ Becker et al, 2011

Results: wavelet filtering & joint analysis



Ricotti et al, 2000

Lidz et al, 2010

McDonald et al, 2001

Wavelet + flux

Schaye et al, 2000

HeII reionization @ z=6

McQuinn et al, 2009 – L1

McQuinn et al, 2009 – L1b

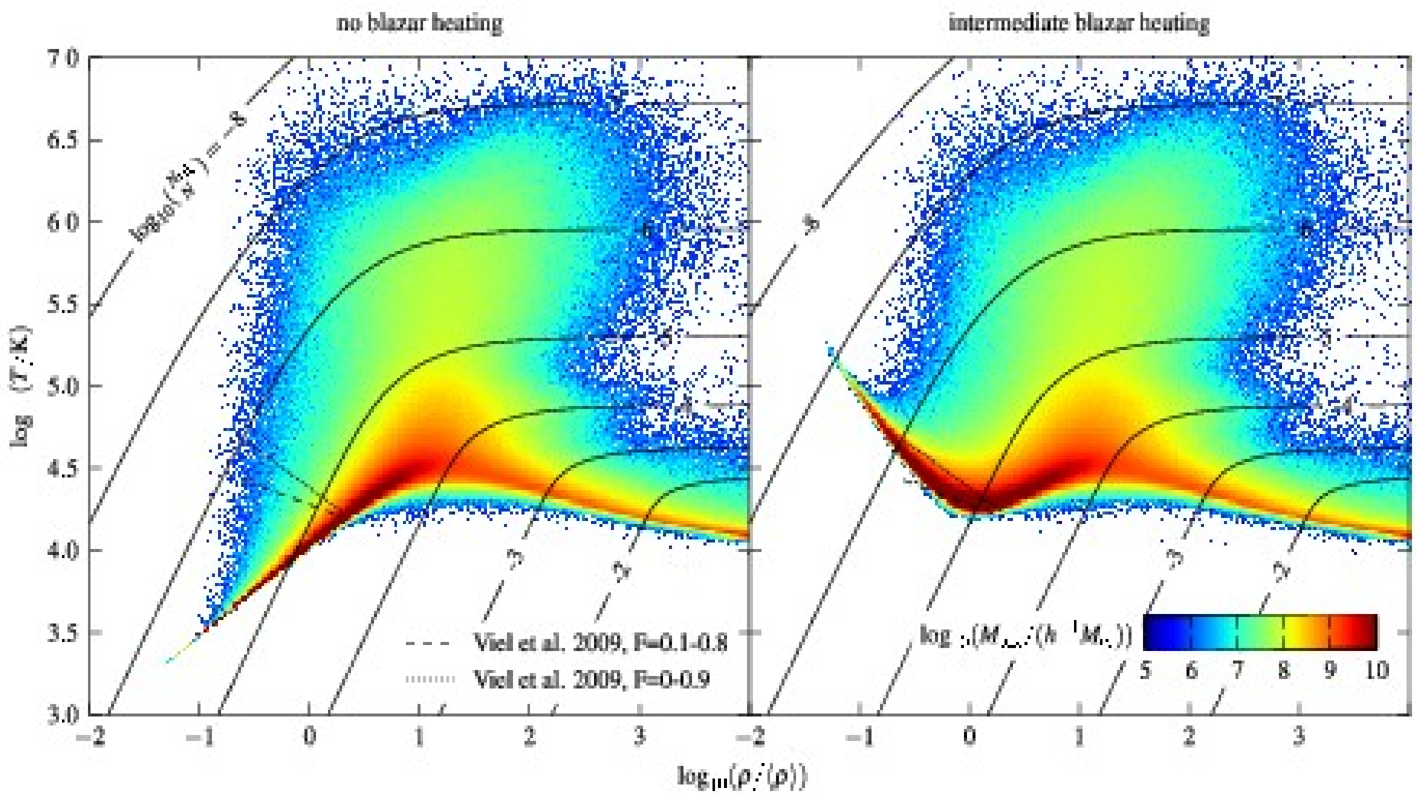
Results: wavelet filtering & joint analysis

		Wavelet PDF	Flux PDF	Joint analysis
$\langle z \rangle = 2.1$	T_0 [10^3 K]	16 ± 5	15 ± 3	17 ± 2
	γ	> 0.86	0.99 ± 0.14	1.11 ± 0.11
	$\tau_{\rm eff}$	(0.14 ± 0.04)	0.133 ± 0.004	0.130 ± 0.004
$\langle z \rangle = 2.5$	T_0 [10^3 K]	16 ± 4	14 ± 9	13 ± 4
	γ	> 0.92	> 0.69	> 0.95
	$\tau_{\rm eff}$	(0.22 ± 0.05)	0.212 ± 0.011	0.200 ± 0.009
$\langle z \rangle = 2.9$	T_0 [10^3 K]	20 ± 5	21 ± 7	19 ± 4
	γ	> 0.80	< 1.24	1.1 ± 0.2
	$\tau_{\rm eff}$	(0.36 ± 0.09)	0.290 ± 0.019	0.27 ± 0.02

Outline

- Physics of IGM
- Previous measurements of thermal state at z~2--3
- What are wavelets?
- How we applied wavelets
- Results
- ***Comparison with recent work***

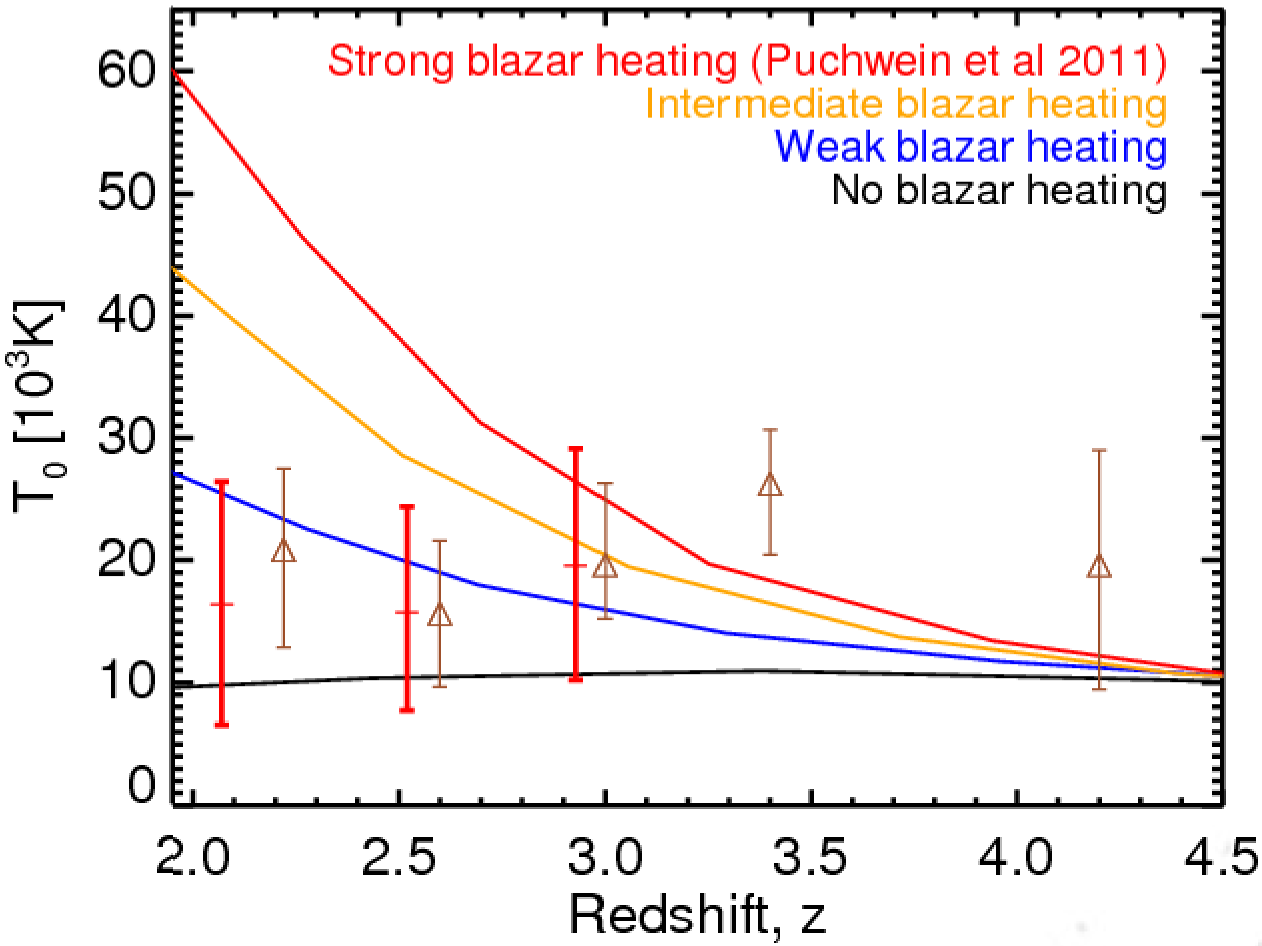
Blazar heating



- TeV emission from Blazars
- Universe at high redshift opaque to TeV emission
- IGM as a calorimeter for Blazar emission
- Changed Temperature Density plane distribution

Puchwein et al, 2012

Blazar heating



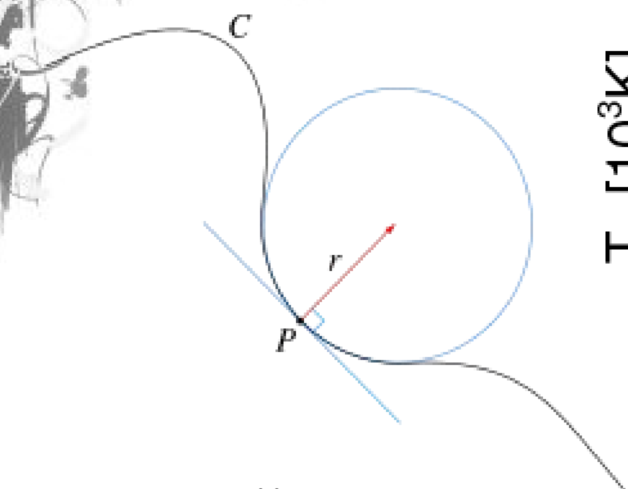
△ Lidz et al, 2010

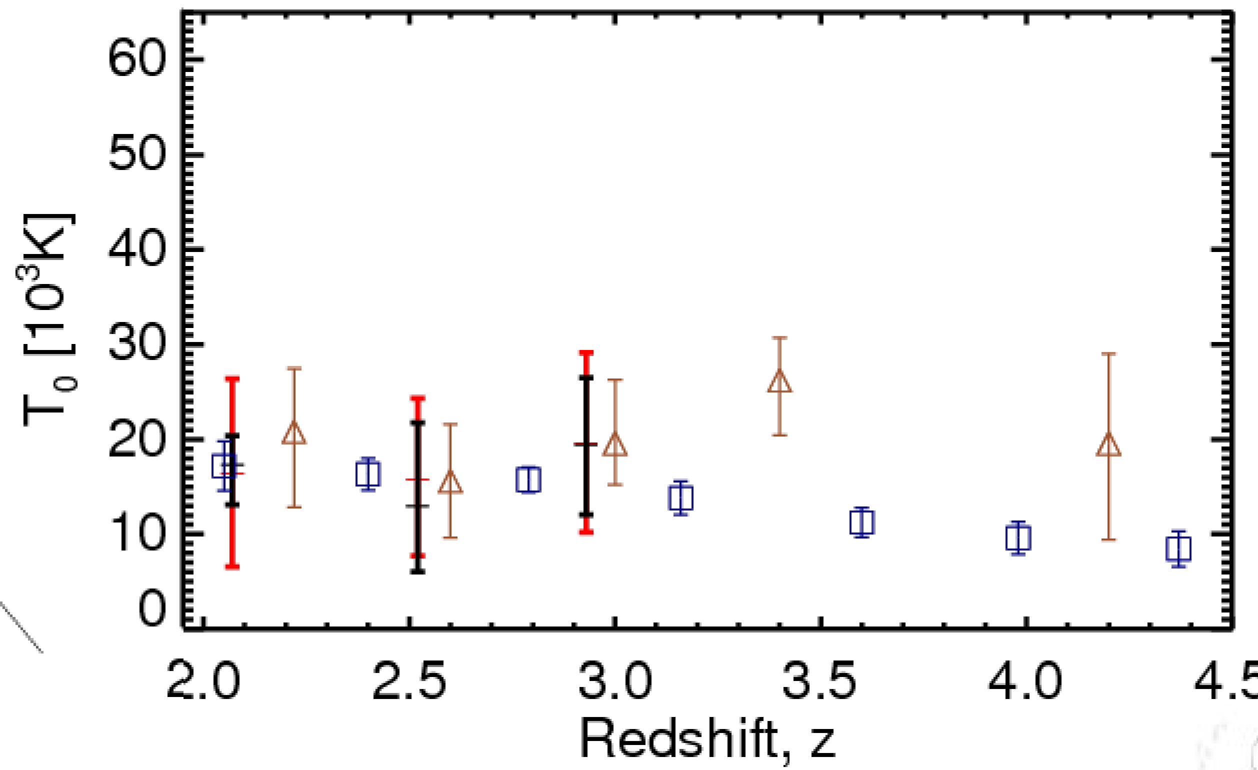
✚ Our work

Outline

- Physics of IGM
- Previous measurements of thermal state at z~2--3
- What are wavelets?
- How we applied wavelets
- Results
- Comparison with recent work
- ***Future work***

Curvature





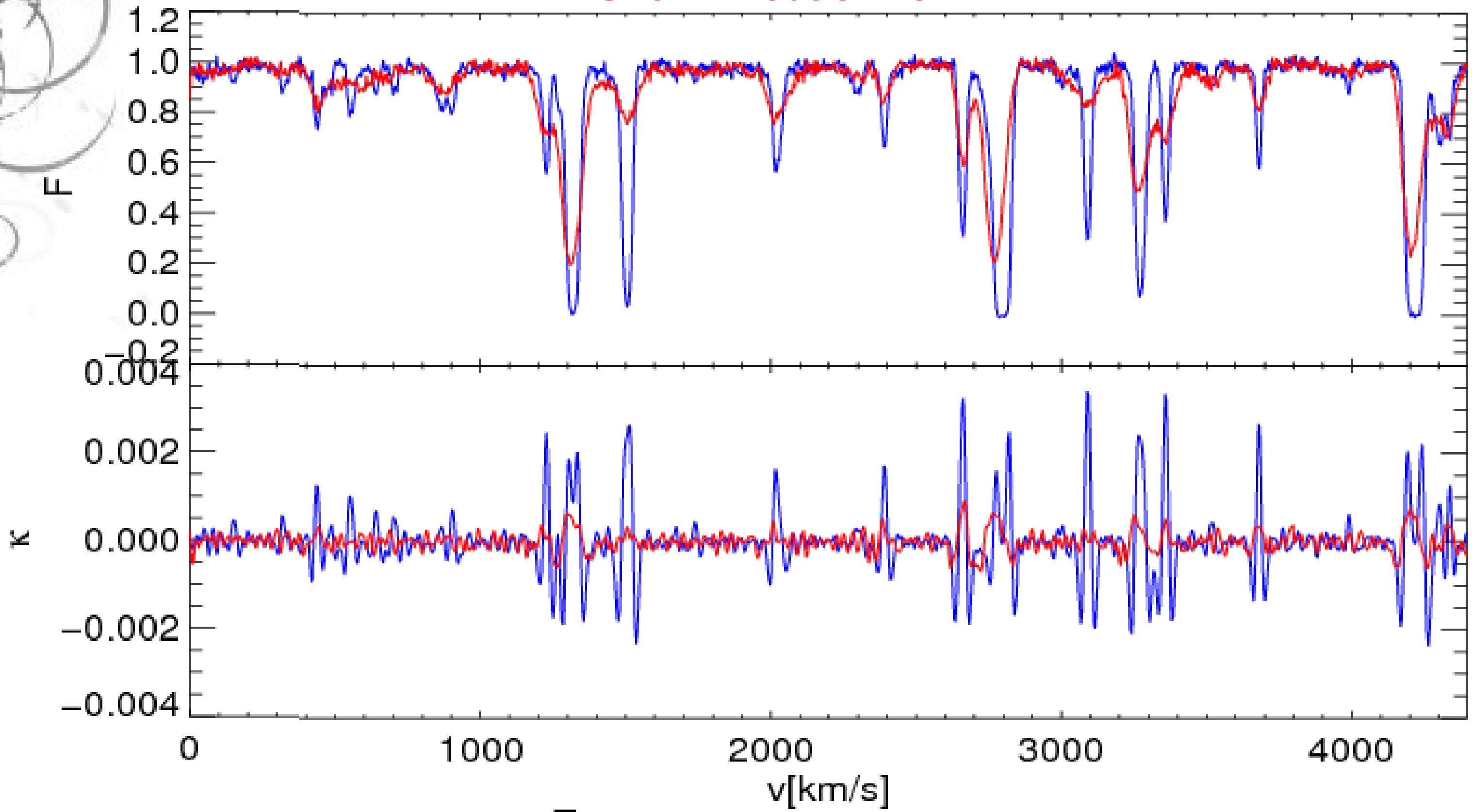
$$\frac{y''}{(1+y'^2)^{3/2}}$$

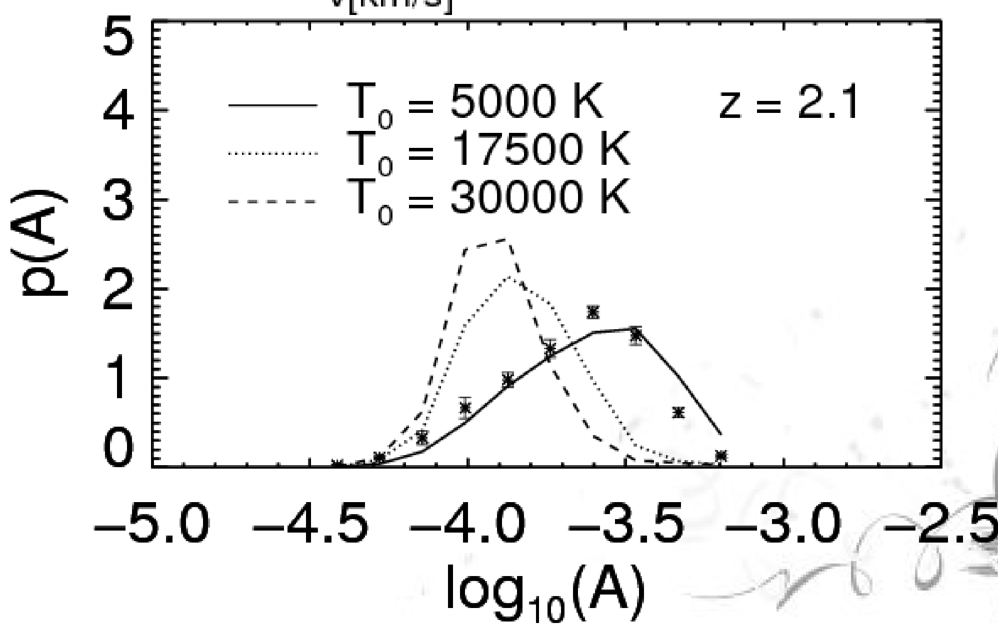
△ Lidz et al, 2010

✚ Our work

□ Becker et al, 2011

Curvature





$\gamma = 1.5$

$T_0 = 30000K$

$T_0 = 5000K$

Conclusions

- Wavelet filtering analysis of the thermal state of the IGM: agreement with results from Lidz et al, 2010
- Varied the relevant cosmological parameters, mild dependence from σ_8 in the lowest redshift bin
- Joint analysis with flux PDF
- Thermal history consistent with previous observations, compatible with additional source of heating at $z < 4$
- Result from joint analysis consistent with $\gamma \sim 1.1 - 1.3$ inverted temperature-density relation still possible $(\gamma < 1)$