First Measurement of the Small Scale Structure of the Intergalactic Medium

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UCB
Feb 16, 2016

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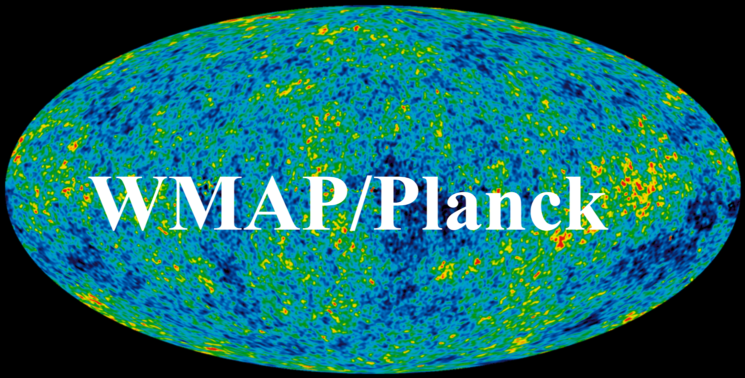
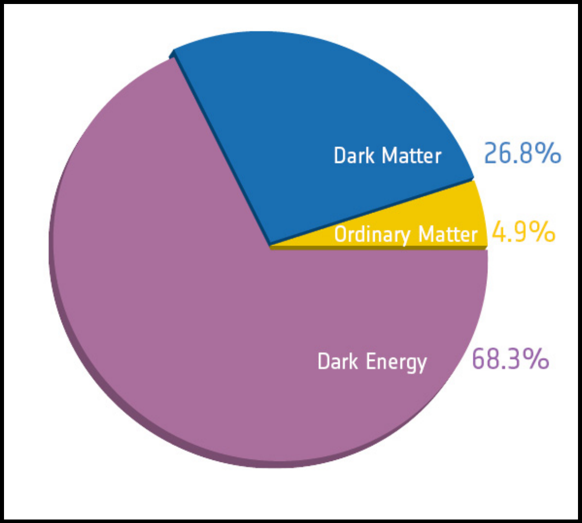
Outline

- Introduction to the intergalactic medium (IGM) and cosmic reionization
- Pressure smoothing scale of the IGM:
    - Pressure smoothing physics
    - How quasar pairs can measure it
    - Results of first measurement

The Bedrock of Cosmic Structure



CMB gives energy contents and initial conditions



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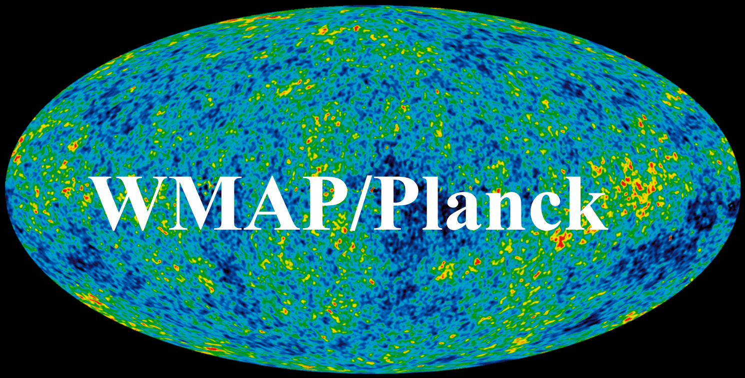
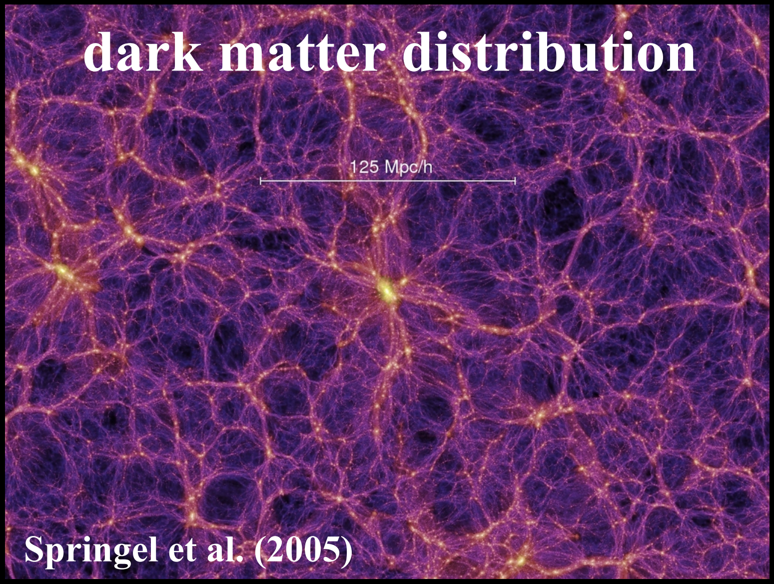


ab initio theory



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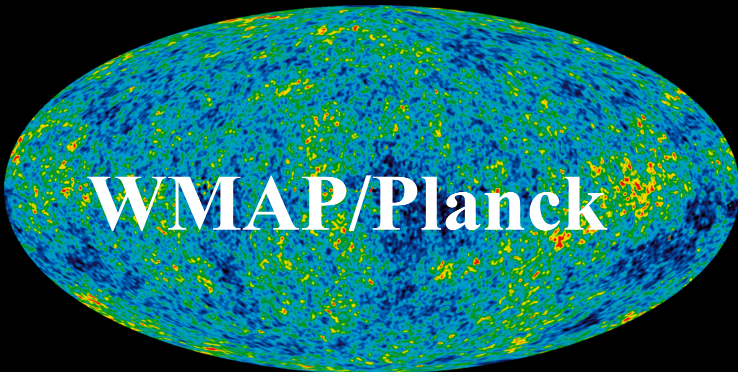
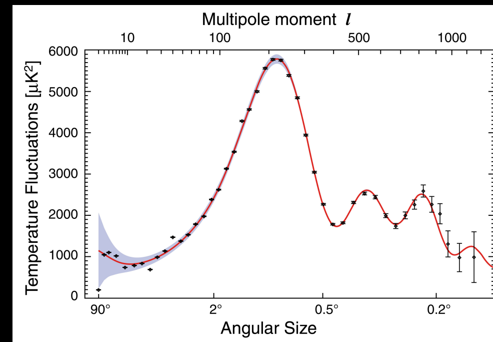
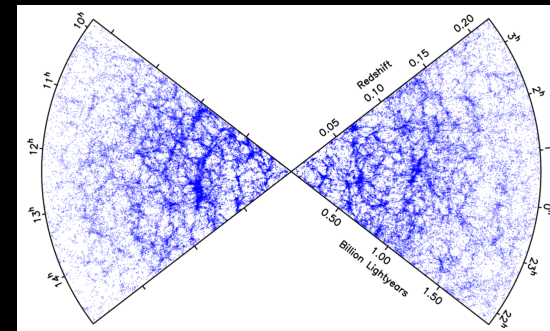


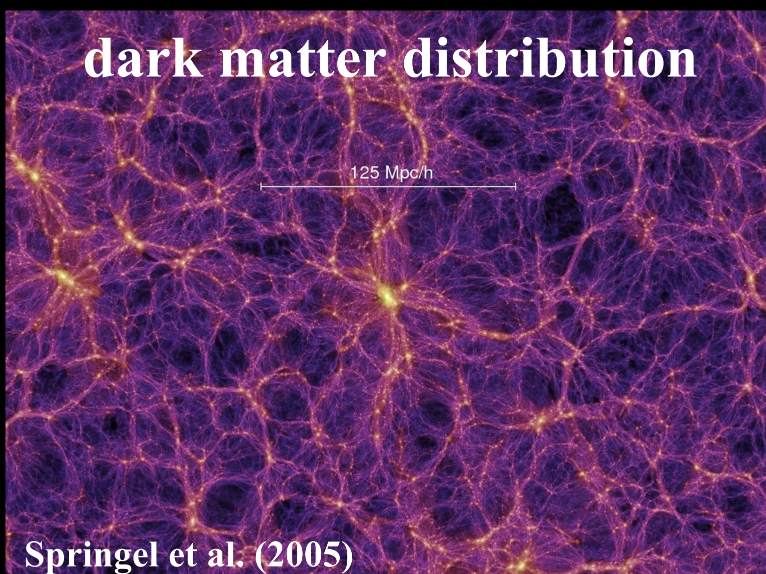


CMB



Galaxy Clustering

ab initio theory



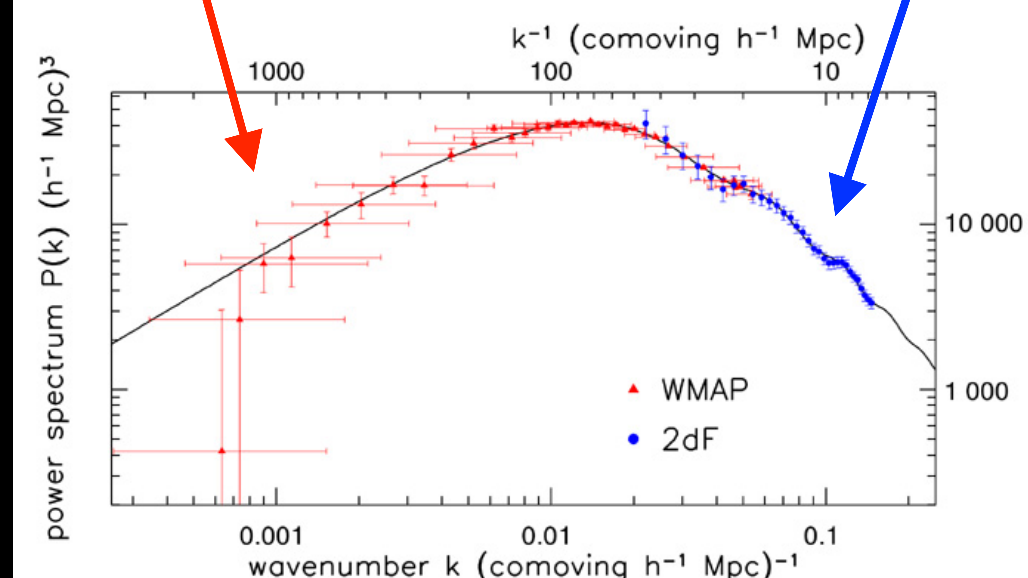
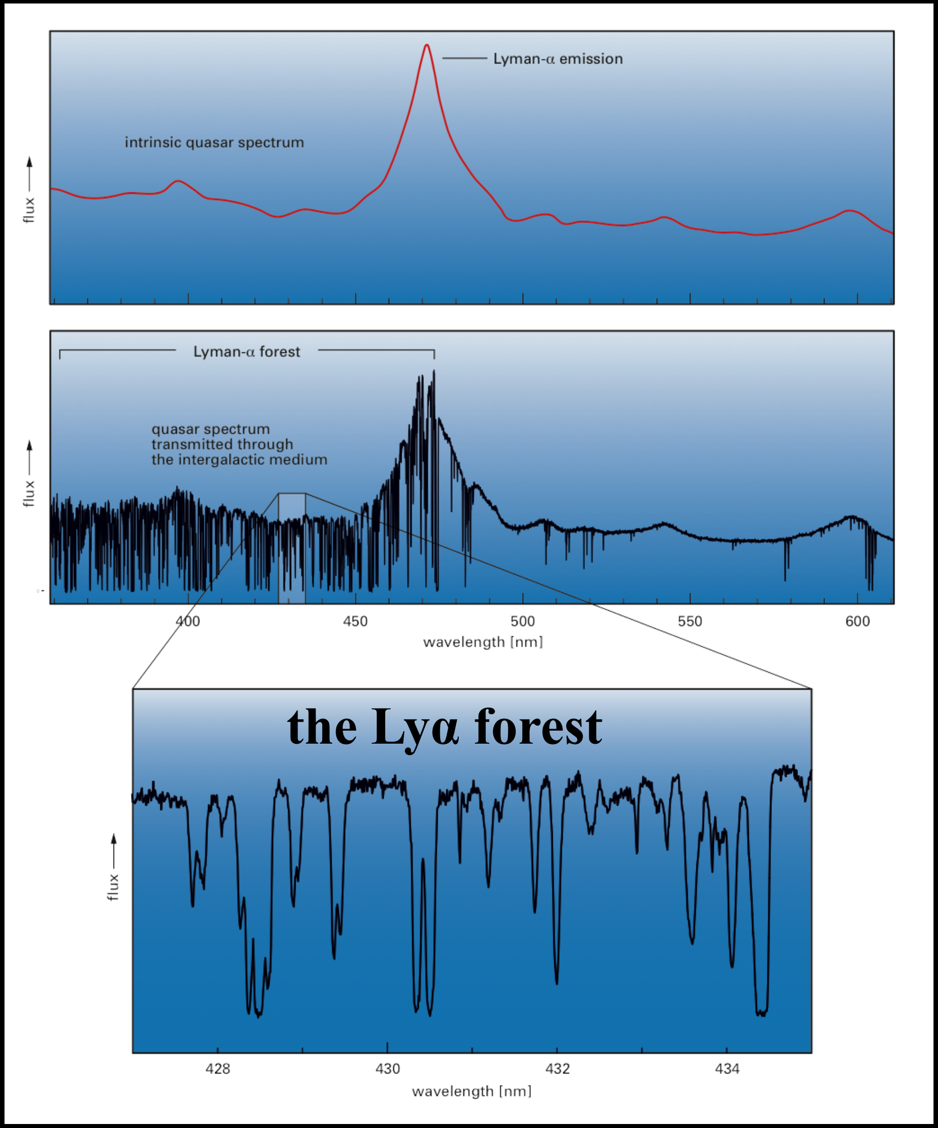
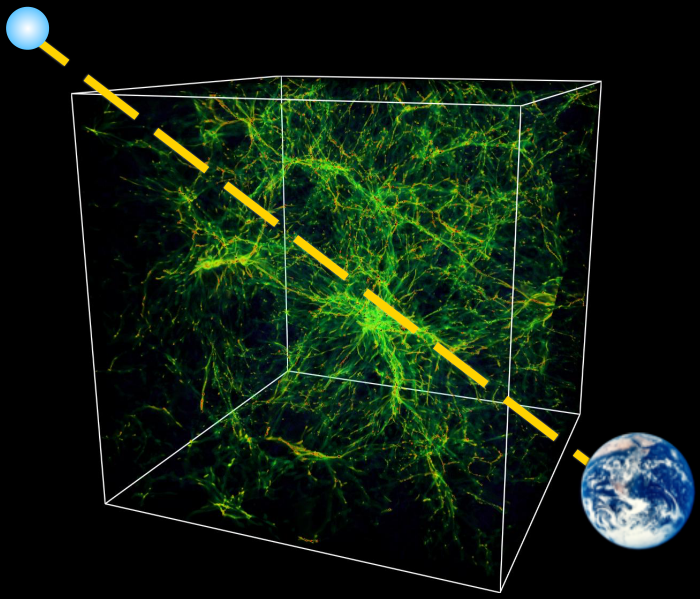


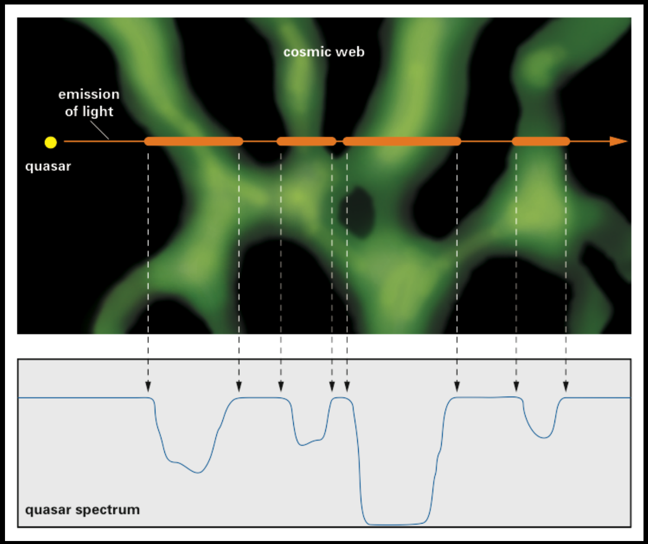
Fig 8.17 (A. Sanchez) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

What about the baryons?

Baryons in the Intergalactic Medium (IGM)







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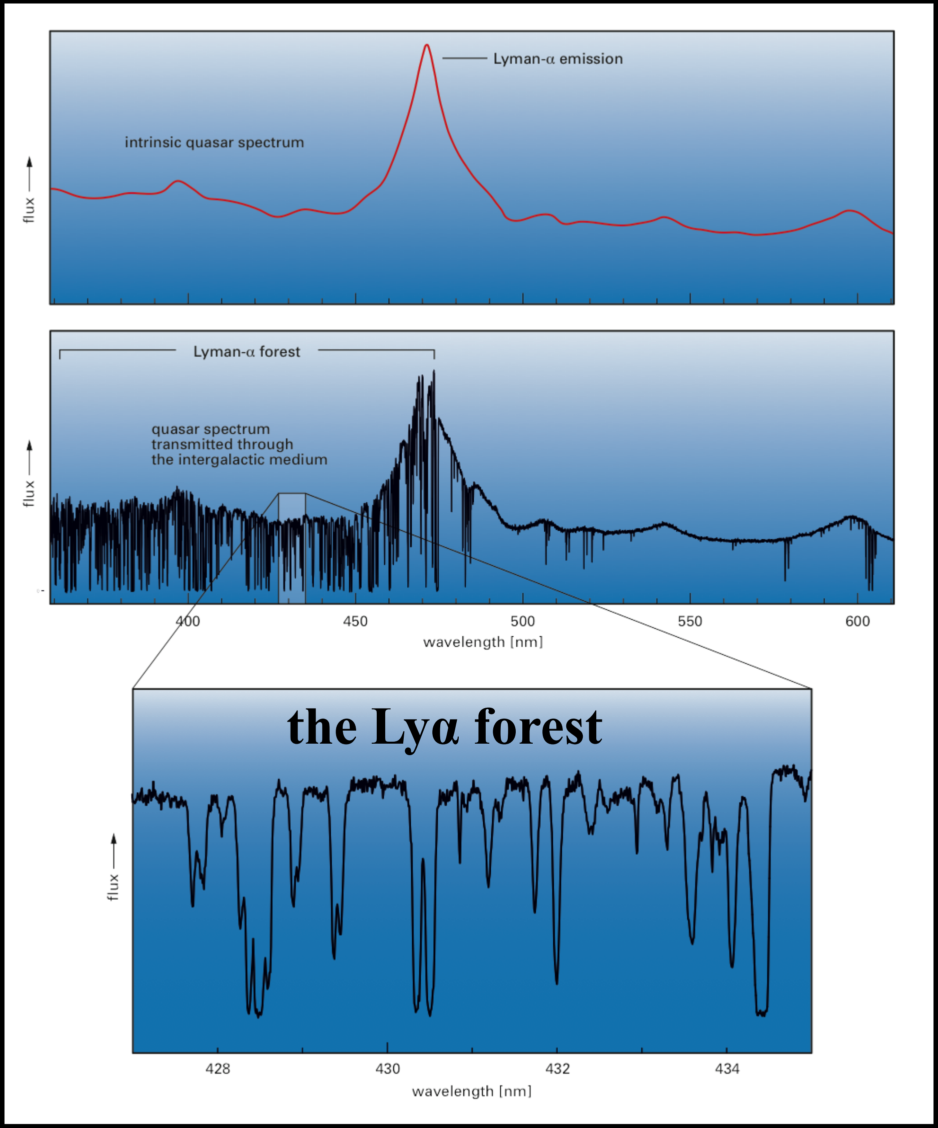
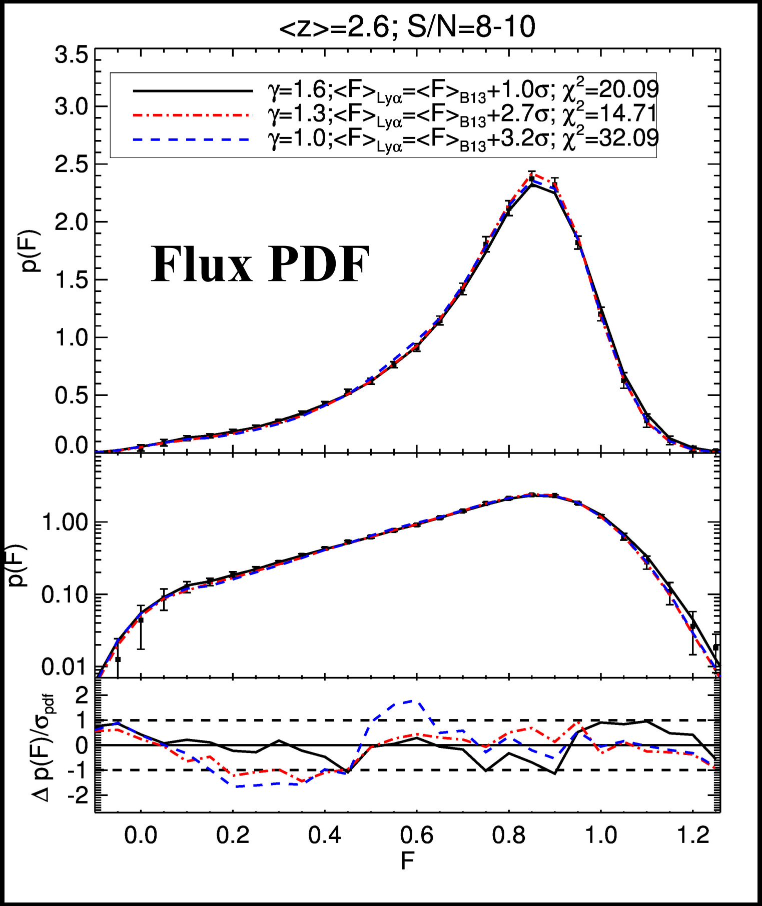


Lyα Forest Probability Distribution Function (PDF) from SDSS-III/ BOSS

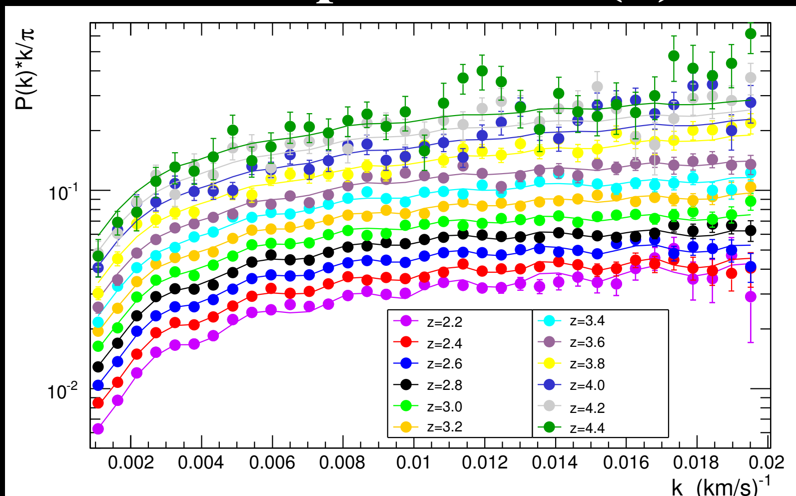


Lee, Hennawi+ 2015

Gravity + hydro of low overdensity ~ 2-5 gas easy to simulate

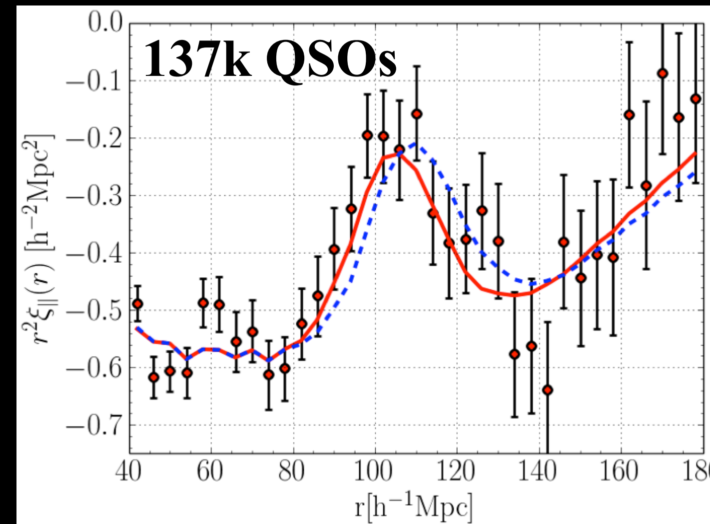
Precision Cosmology with the Lyα Forest

Power Spectrum P(k)

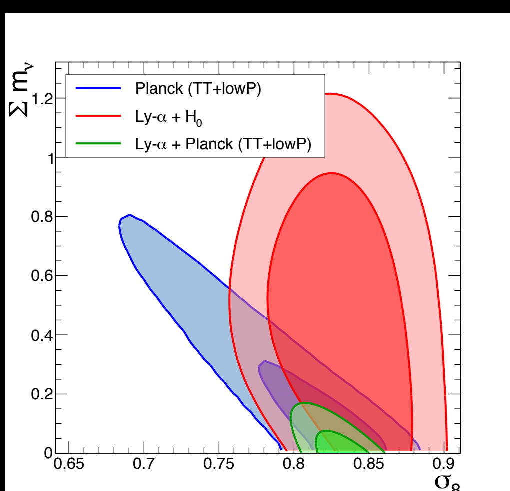


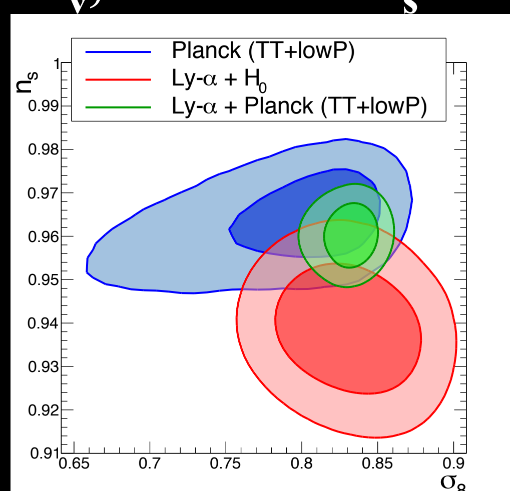
Palanque-Delabrouielle+ 2015

Baryon Acoustic Oscillation

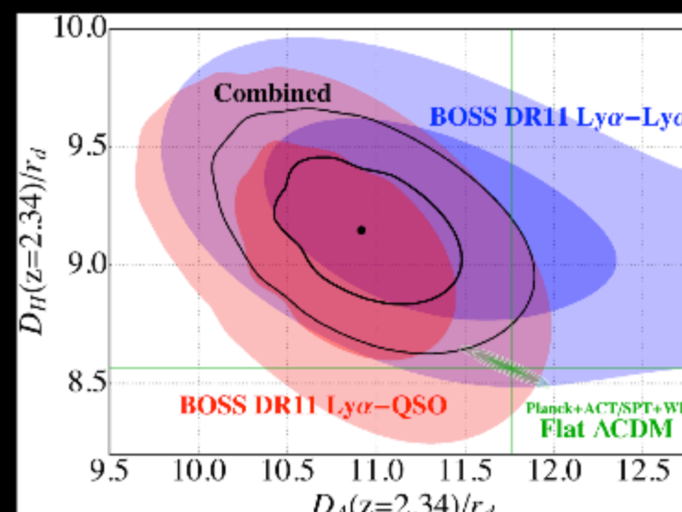


neutrino masses m_ν, inflation n_s





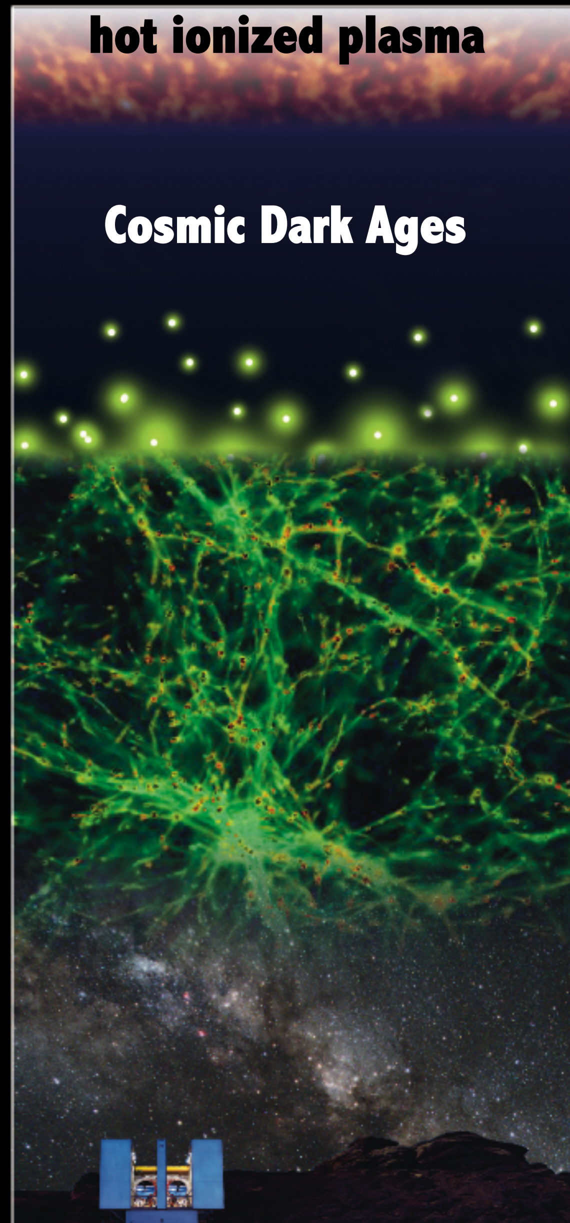
amplitude of fluctuations σ_8



De Lubac+ 2015

Cosmic Reionization

Time Since Big Bang years	redshift
400,000	$z = 1089$
2×10^8	$z = 20$
6×10^8	$z = 9$
2×10^9	$z = 3$
14×10^9	$z = 0$



Big Bang

Recombination
First neutral atoms

Galaxies/QSOs form, emit ionizing photons, reionization begins

Reionization complete
IGM higly ionized, neutral fraction ~ 10^{-5}

Helium II reionizaiton
Helium doubly ionized
$He^{+} \rightarrow He^{++}$
by hard QSO radiation

Today: Cosmologists figure it all out!

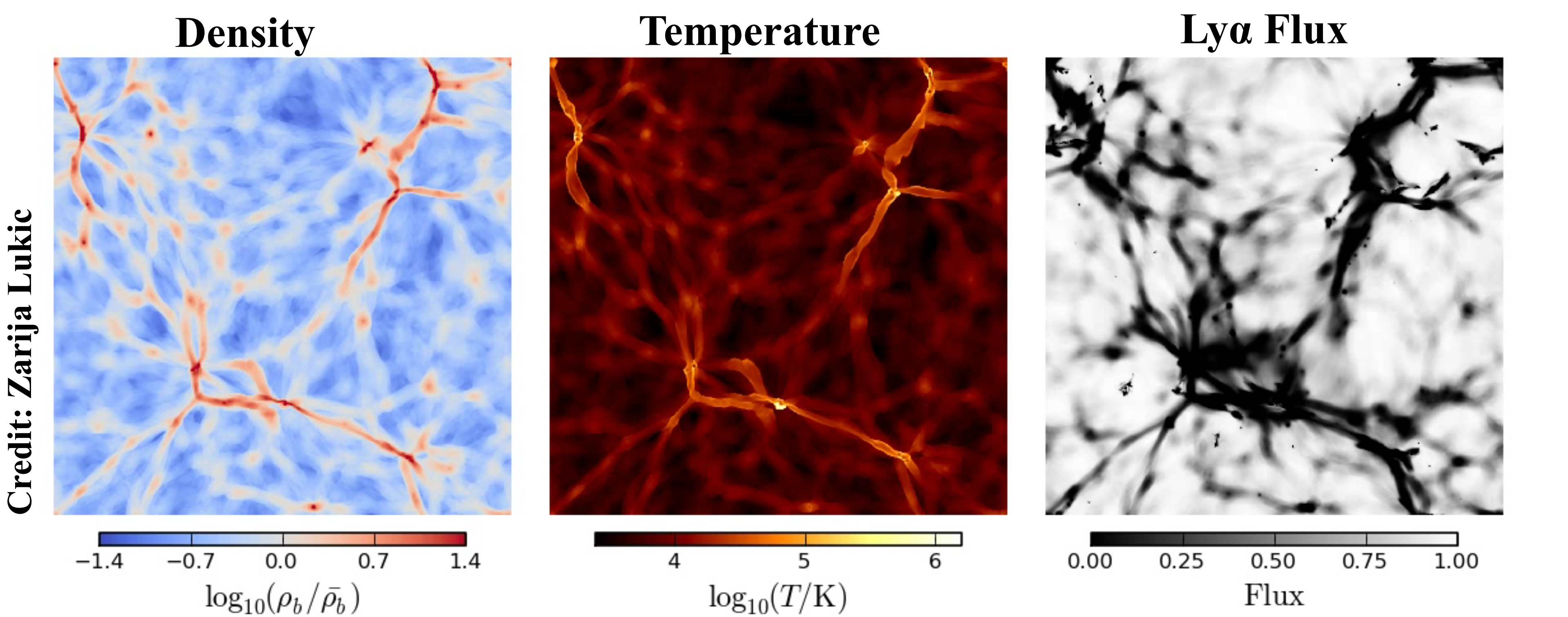
What we Can’t Simulate (*Well*): Reionization

Credit: Marcelo Alvarez & Tom Abel

- **Number density of sources?**
- **What fraction of ionizing photons escape?**
- **Galaxies? Faint AGN?**
- **How much heat injection**
- **Opacity?**

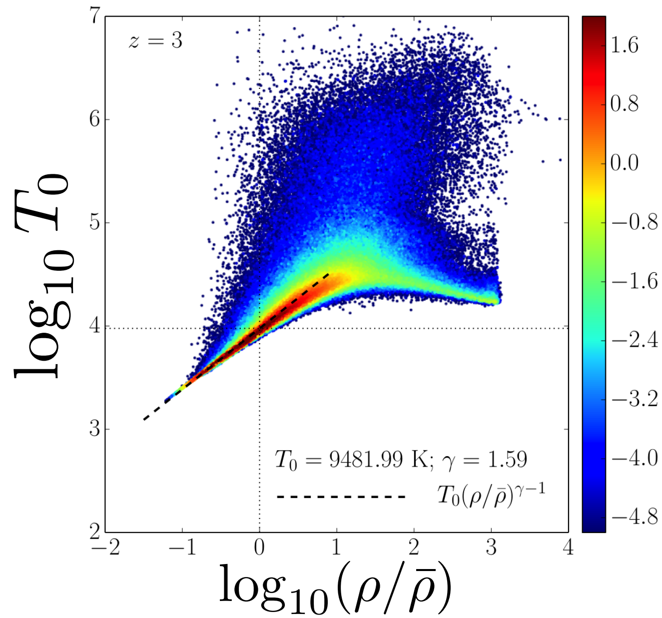
- **Radiative transfer sims of reionization, expensive, uncertain, and not very mature**
- **Need empirical constraints from the cosmic microwave background (CMB) and intergalactic medium (IGM)**

What We Can Simulate: The Lyα Forest

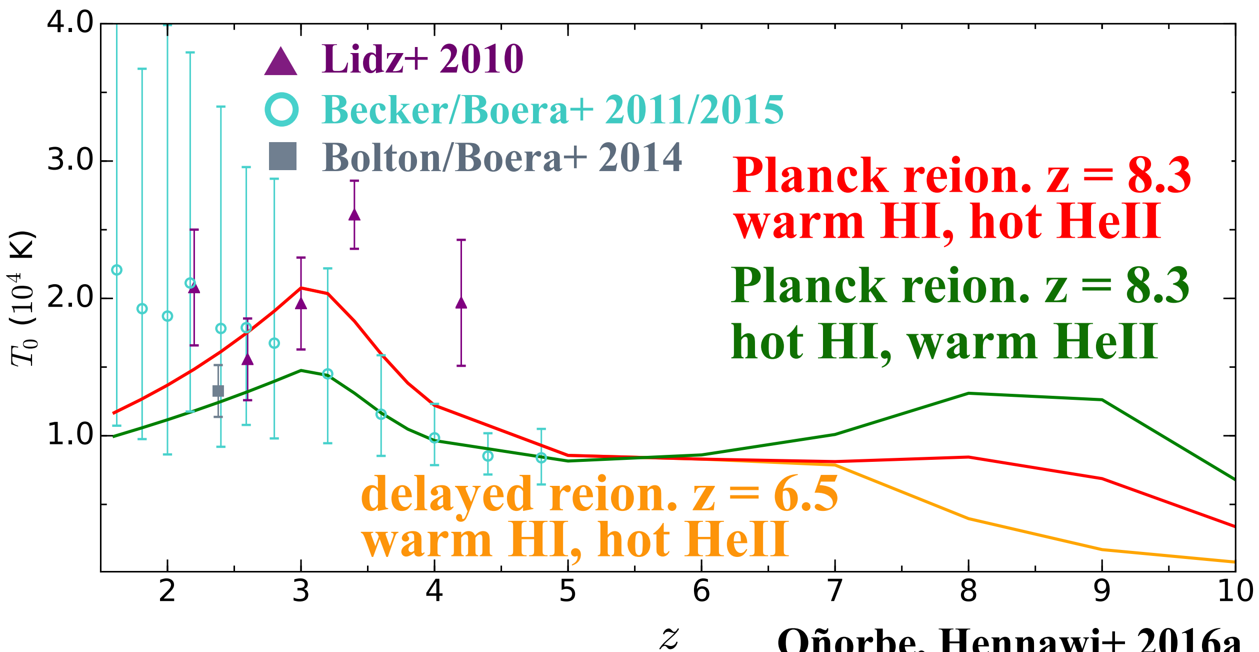


- **Low density hydro + gravity, CMB gives initial conditions**
- **"Nyx" massively parallel grid hydro code. A 40 Mpc/h 2048^3 cost $10^{5\text{-}6}$ cpu-hrs** (Almgren+ 2013; Lukic+ 2015)
- **Reionization redshift z_{re} and heat injection ΔT treated as phenomenological parameters** (Oñorbe, Hennawi+ 2016a)

The Thermal History of the Universe



Kulkarni, Hennawi+ 2015

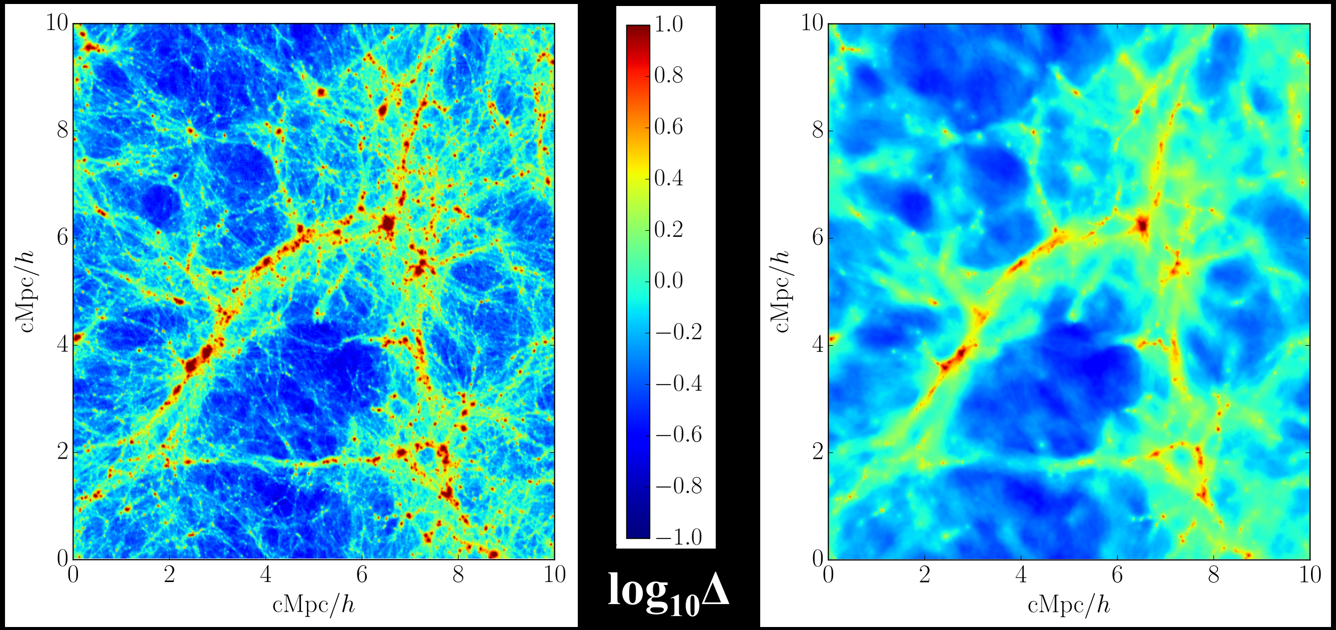


Oñorbe, Hennawi+ 2016a

- Balance of photo-heating and expansion cooling gives T-ρ relation $T(\rho) = T_0(\rho/\bar{\rho})^{\gamma-1}$
- Reionization events inject heat into the IGM. Observations of ***aftermath*** can constrain how this occurred
- Temperature T_0 sensitive to HeII reionization, but has 'forgotten' about HI reionization by z < 5

The Pressure Smoothing Scale of the IGM

Collisonless dark matter ➡



⬅ **Baryons**

Kulkarni, Hennawi+ 2015

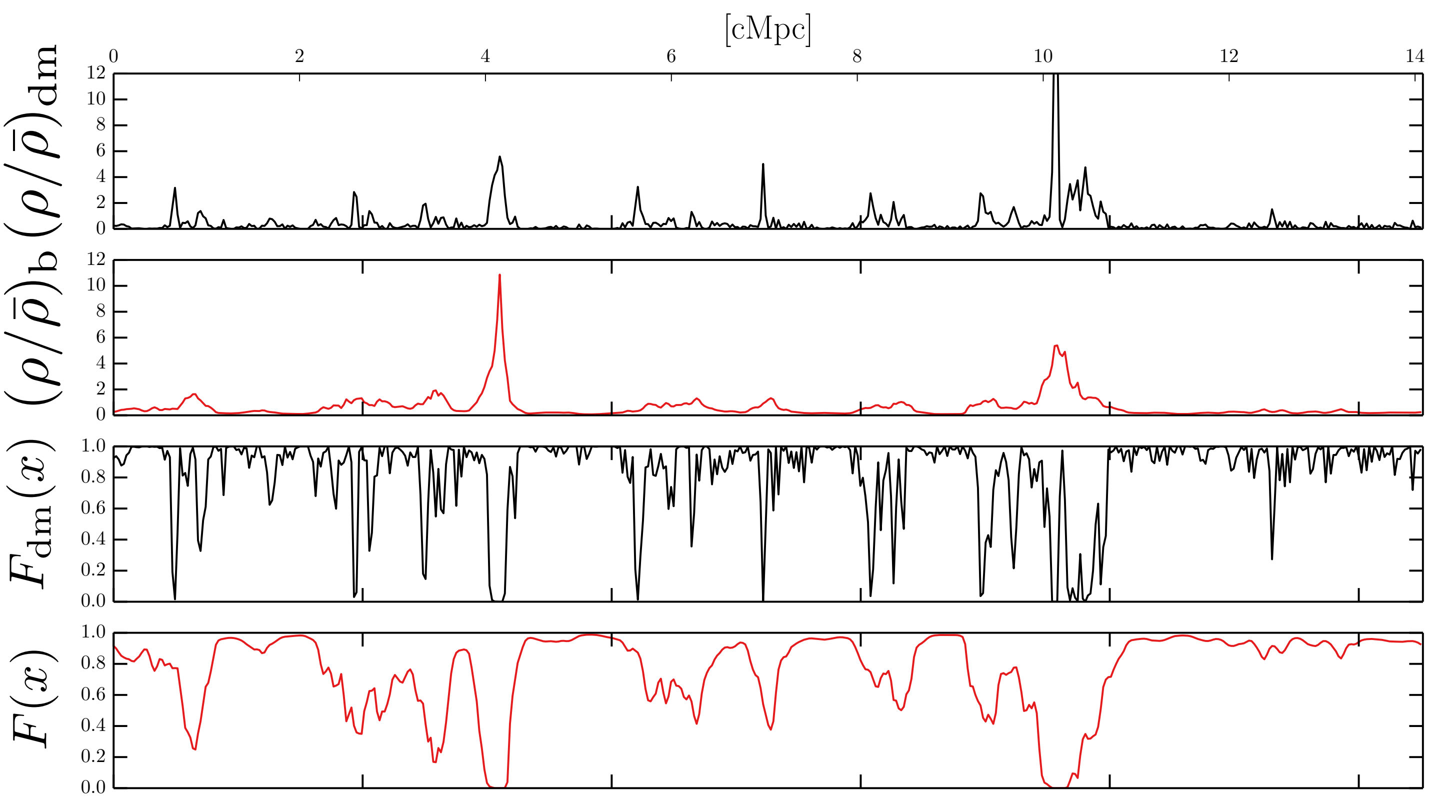
- **Gas traces large-scale distribution of dark matter, but small-scale fluctuations suppressed by pressure**

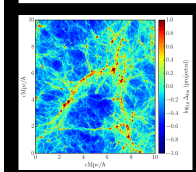
$$\lambda_{\mathrm{Jeans}} \equiv c_{\mathrm{s}}\sqrt{\frac{\pi}{G\rho}} \sim 200\,\mathrm{ckpc}\,;\ \theta_{\mathrm{Jeans}} = 6'' \,\mathrm{at}\, z = 3$$

- **In IGM sound-crossing time $\lambda_{\mathrm{Jeans}}/c_s \sim t_H$ Hubble time ➡ filtering scale depends on entire *thermal history***

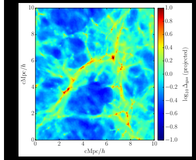
$$\lambda_{\mathrm{P}}(z) = \int_z^{\infty} f[T(z')]dz'$$

Small-Scale Structure in the Lyα Forest





dark matter



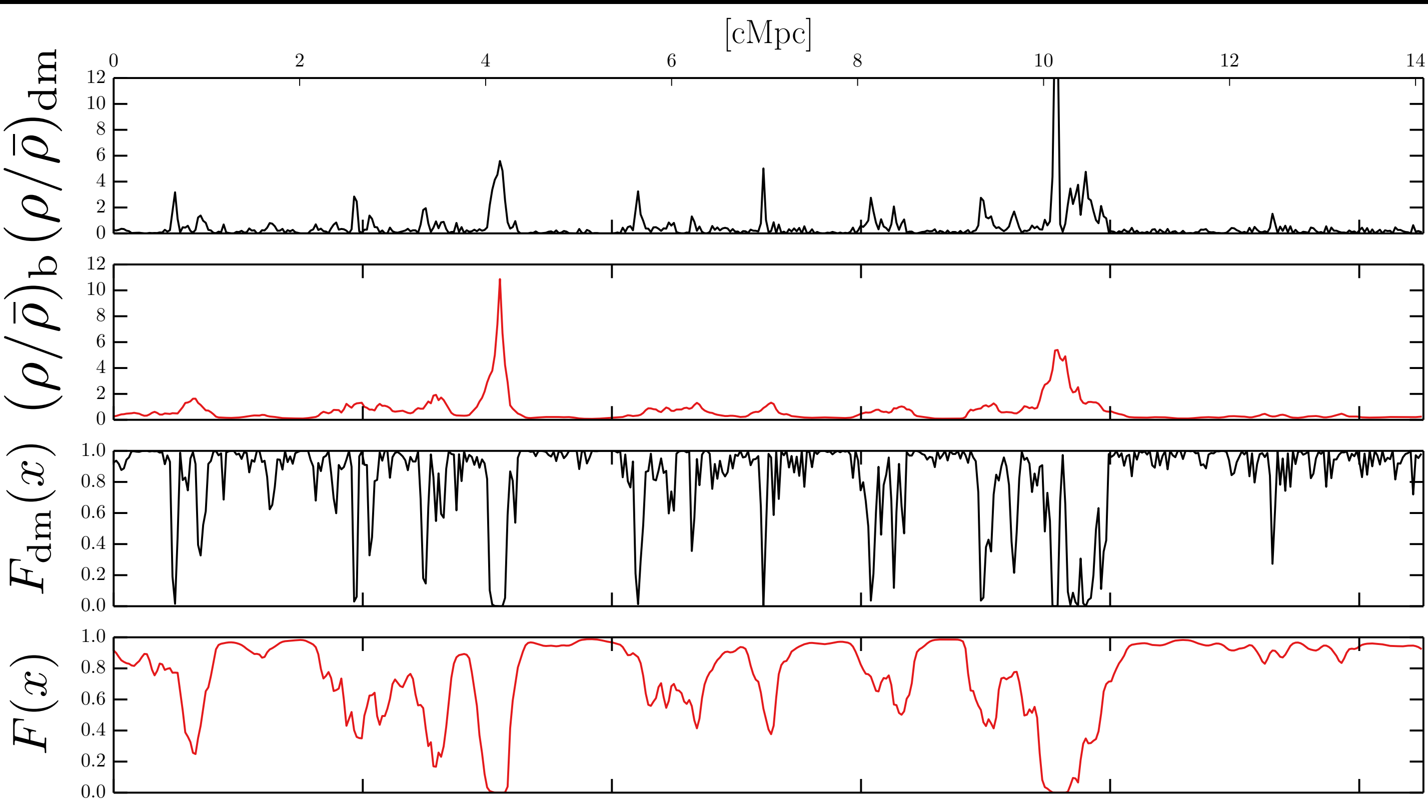
baryons

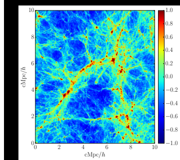
Lyα flux if gas traces DM perfectly, no redshift-space effects

Lyα flux, no redshift-space effects

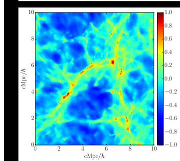
$$F = e^{-\tau};\ \tau(x) \propto (\rho/\bar{\rho})^{2-0.7(\gamma-1)};\ T = T_0(\rho/\bar{\rho})^{\gamma-1}$$

Small-Scale Structure in the Lyα Forest





dark matter



baryons

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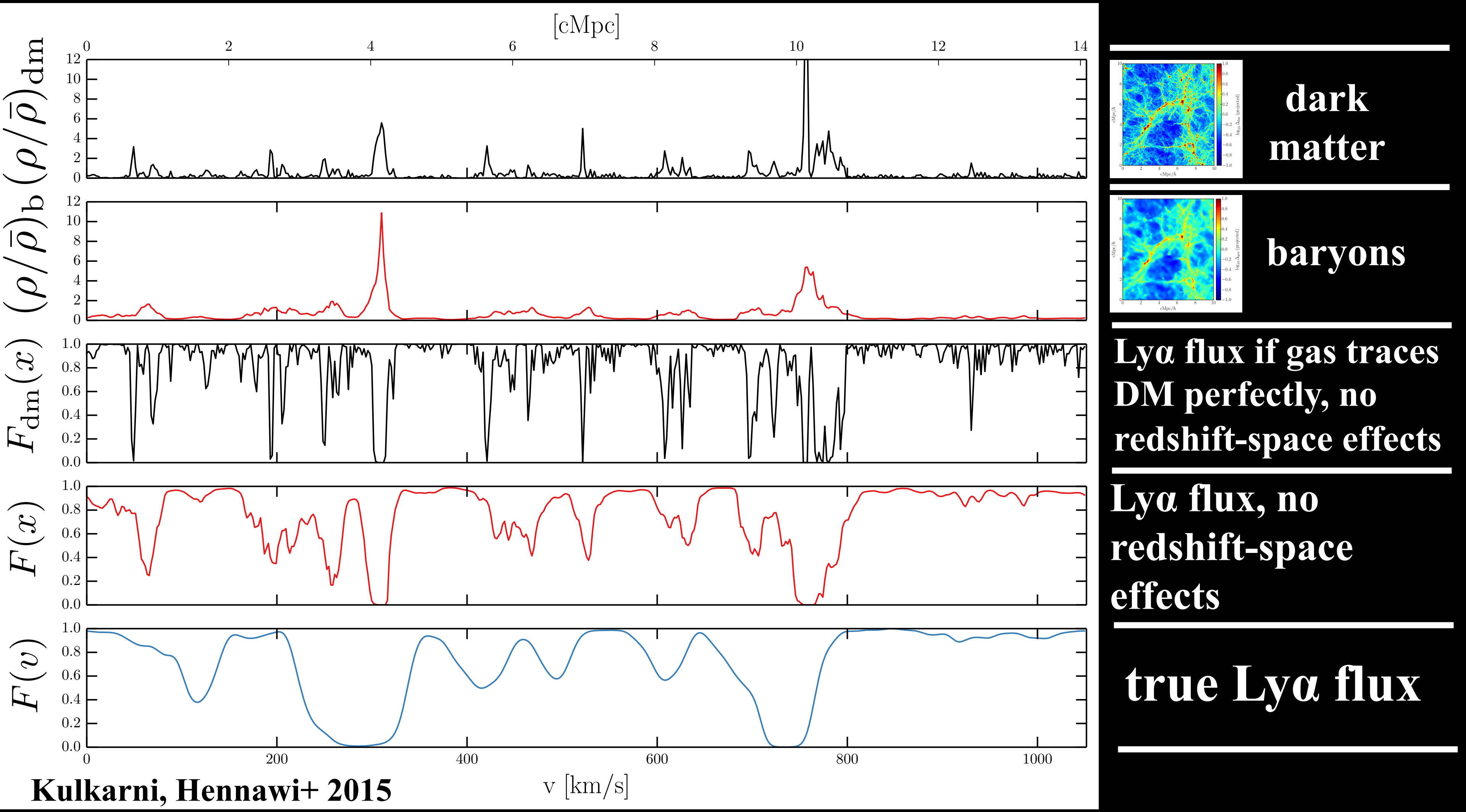
$$F = e^{-\tau};\ \ \tau(x) \propto (\rho/\bar{\rho})^{2-0.7(\gamma-1)};\ \ T = T_0(\rho/\bar{\rho})^{\gamma-1}$$

Doppler parameter

$$b = \sqrt{\frac{2k_{\rm B}T}{\mu m_{\rm p}}} = 24\,{\rm km\,s^{-1}}\left(\frac{T}{2{\times}10^4\,{\rm K}}\right)^{1/2} \Rightarrow 300\,{\rm kpc} \gtrsim \lambda_{\rm P}$$

Small-Scale Structure in the Lyα Forest



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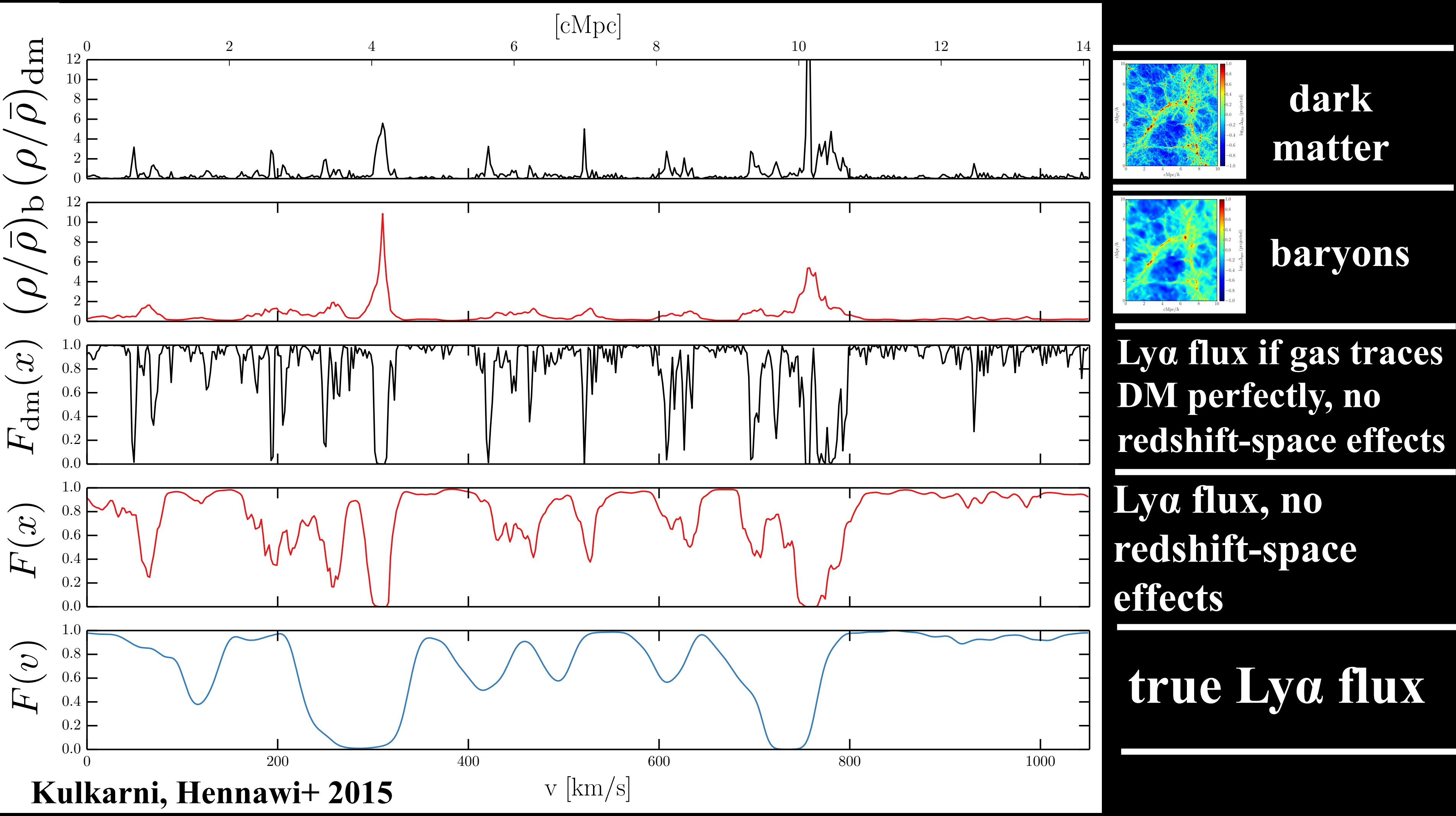
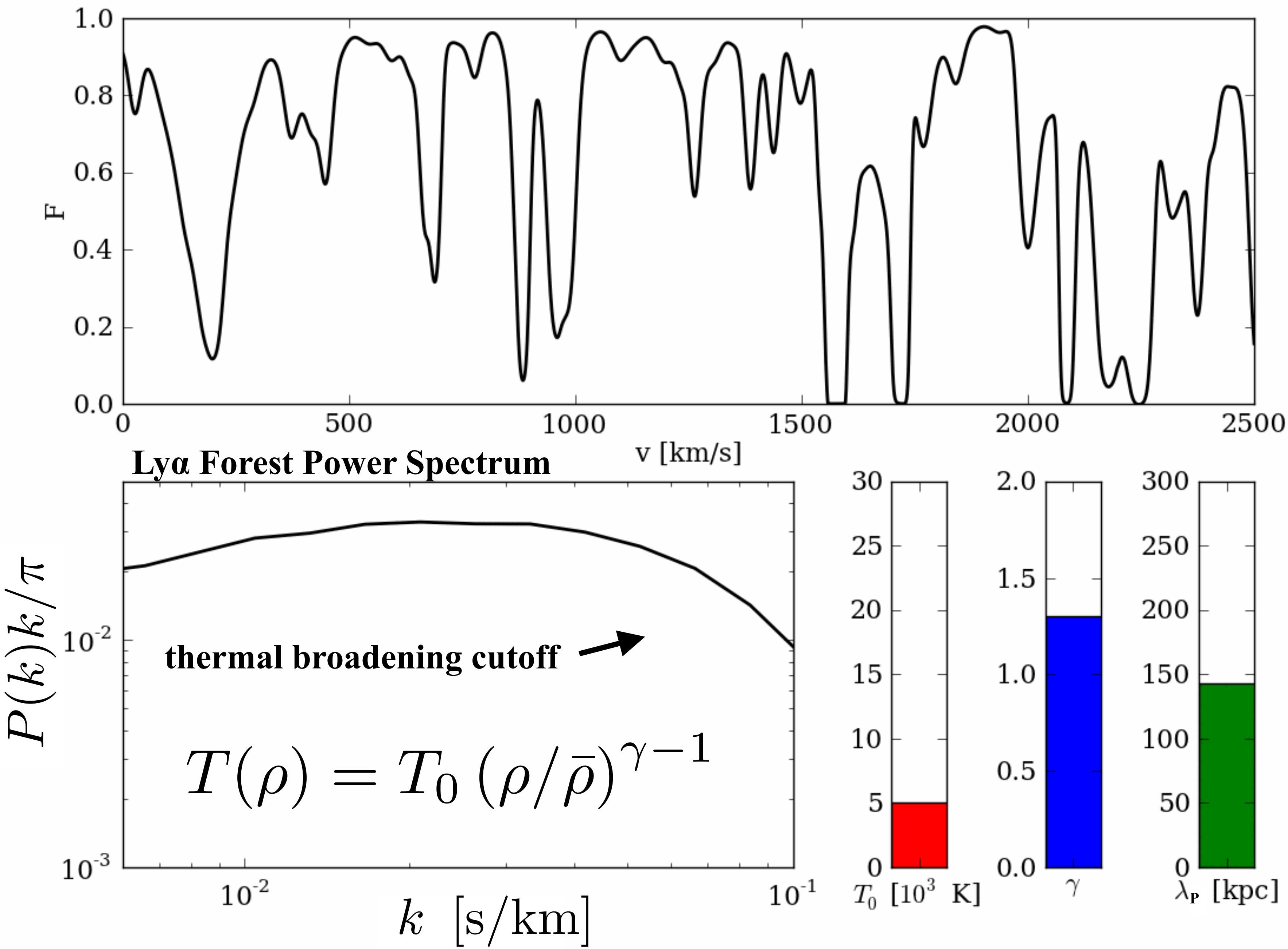
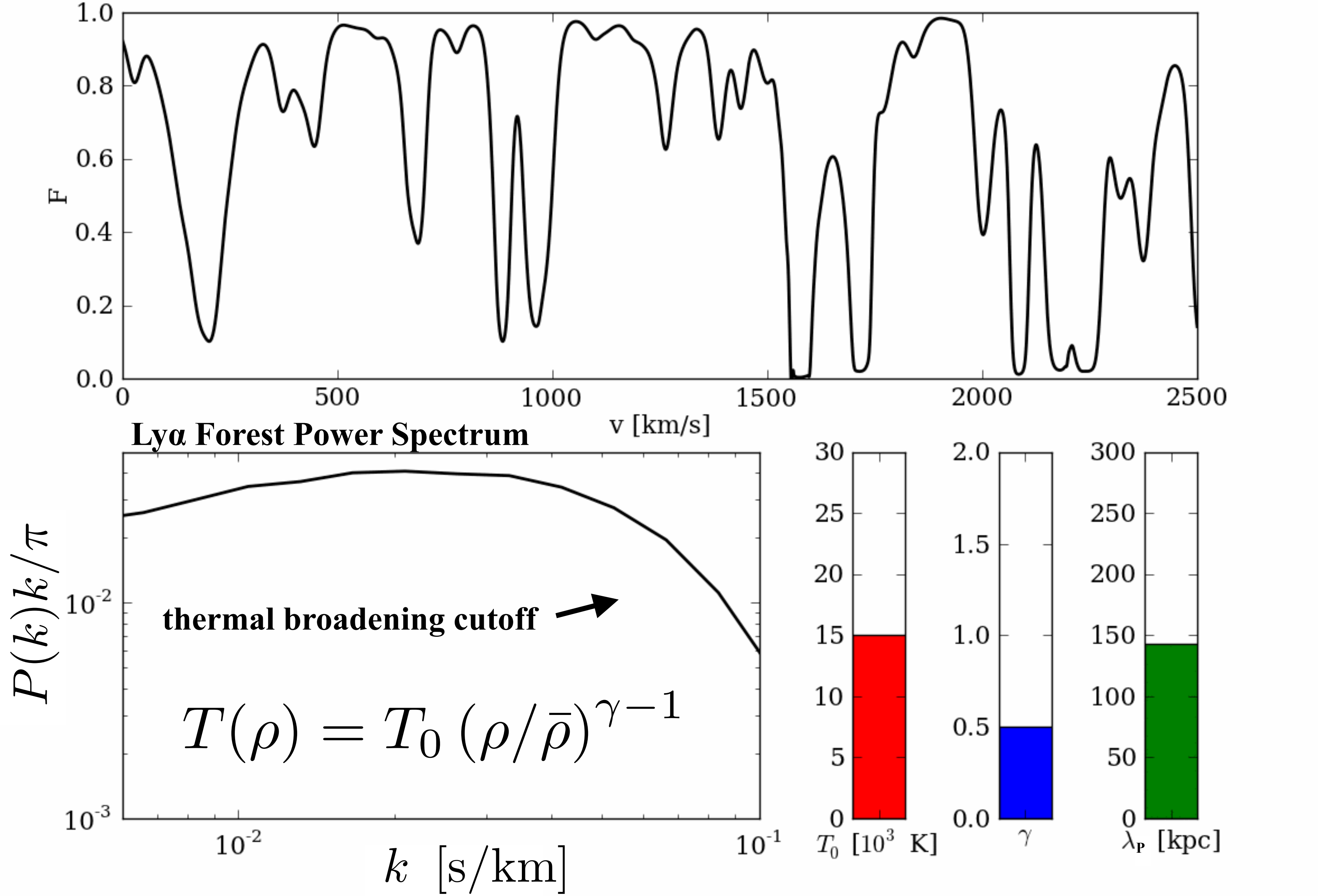
Small-Scale Structure in the Lyα Forest



Thermal Doppler broadening (and peculiar velocities) erase small-scale structure of IGM along the line-of-sight



F
v [km/s]
Lyα Forest Power Spectrum
$P(k)k/\pi$
thermal broadening cutoff
$T(\rho) = T_0\,(\rho/\bar{\rho})^{\gamma-1}$
k [s/km]
T_0 [10^3 K]
γ
λ_P [kpc]


F
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k [s/km]
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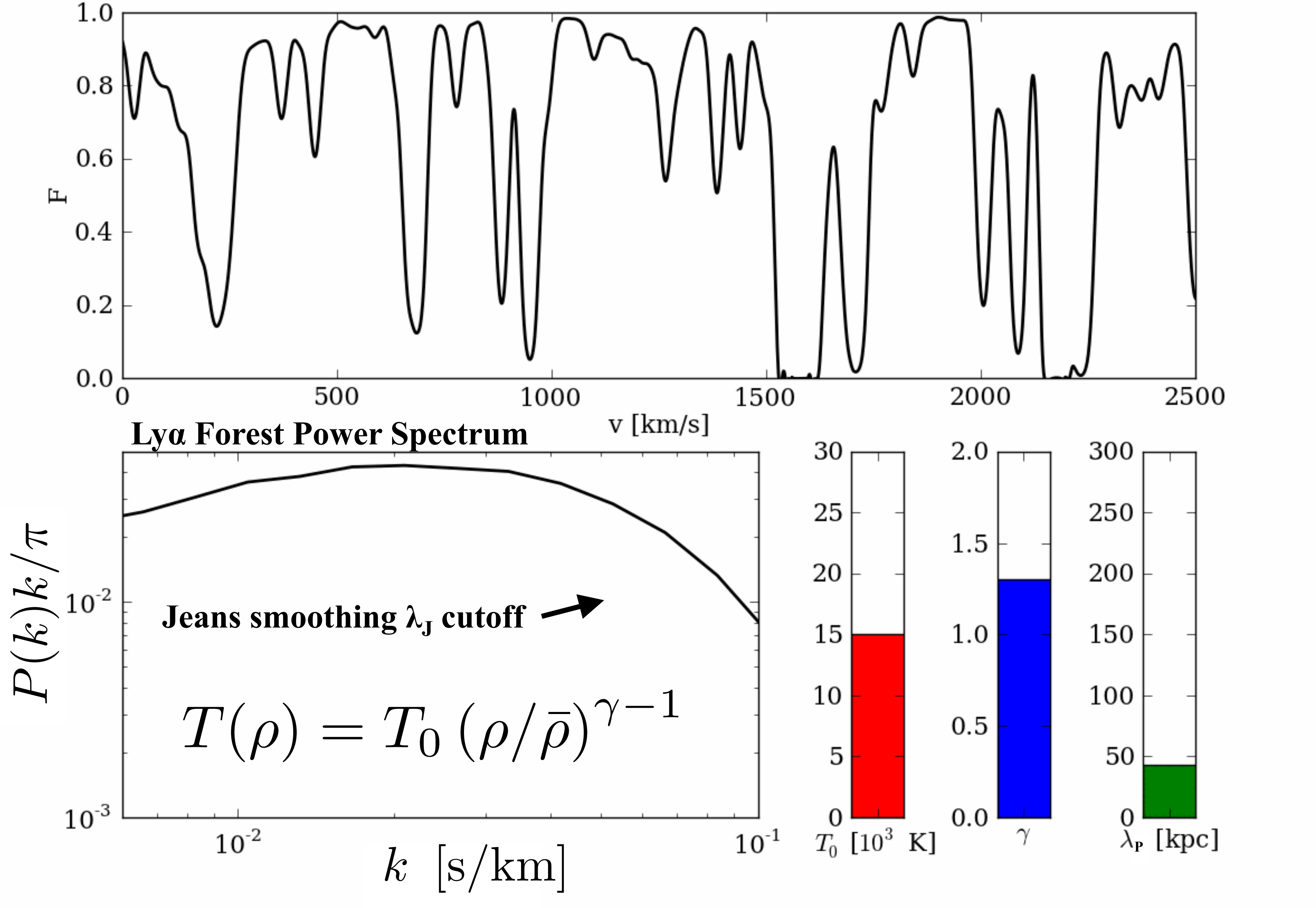
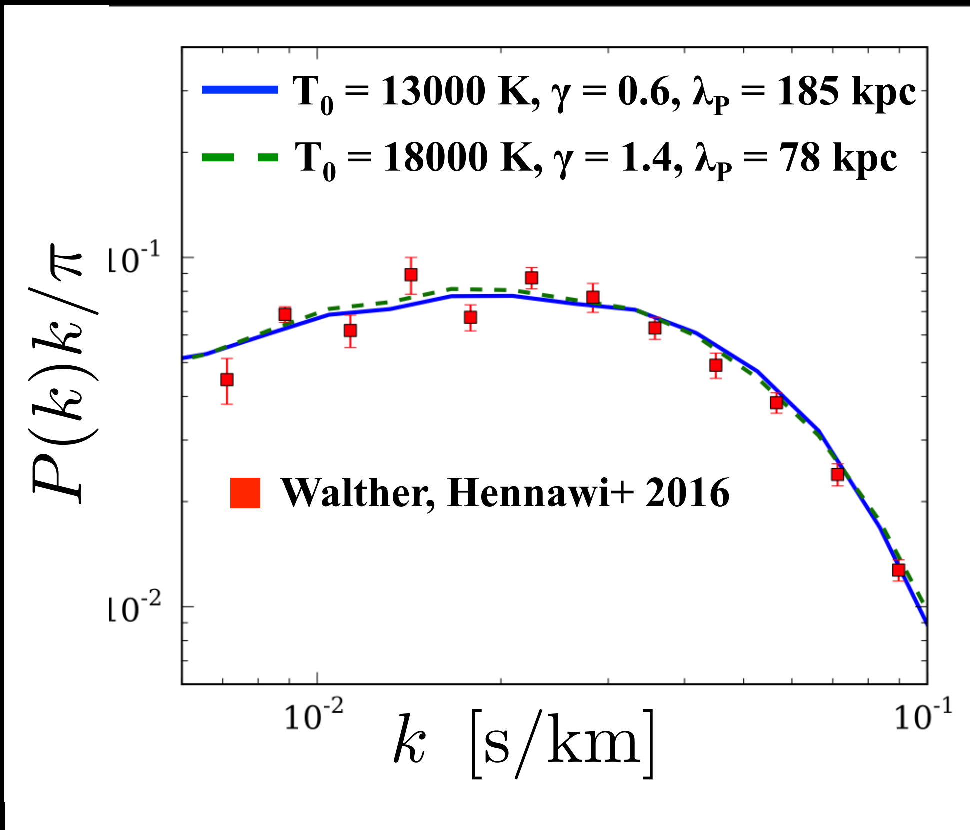
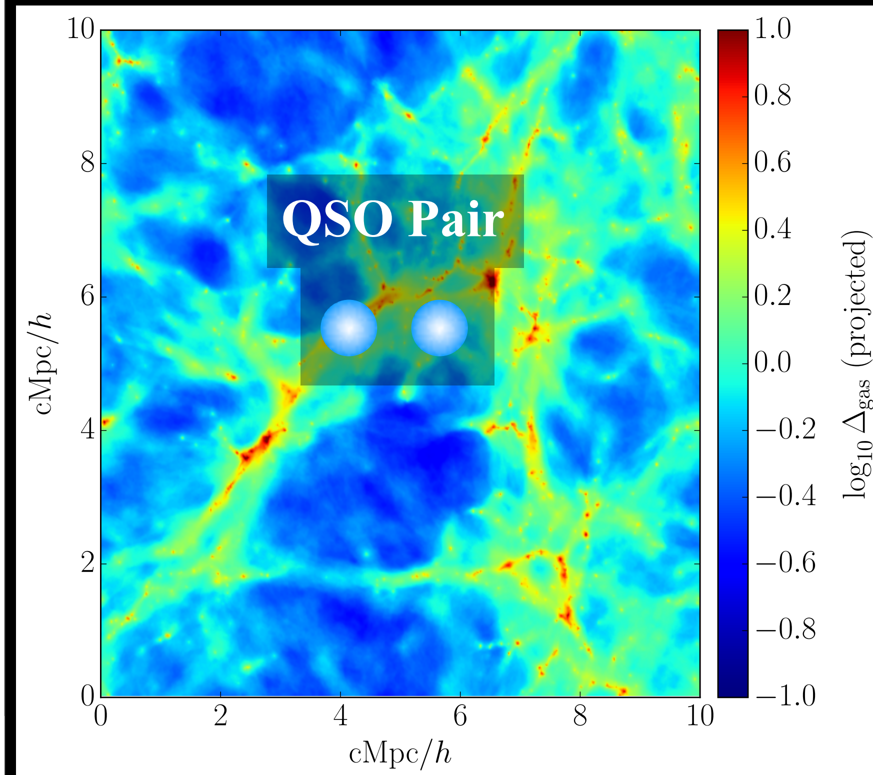

1.0
0.8
0.6
0.4
0.2
0.0
F
0
500
1000
1500
2000
2500
v [km/s]
Lyα Forest Power Spectrum
$P(k)k/\pi$
10^{-2}
10^{-3}
Jeans smoothing λ_J cutoff
$T(\rho) = T_0\,(\rho/\bar{\rho})^{\gamma-1}$
k [s/km]
10^{-1}
30
25
20
15
10
5
0
T_0 [10^3 K]
2.0
1.5
1.0
0.5
0.0
γ
300
250
200
150
100
50
0
λ_P [kpc]

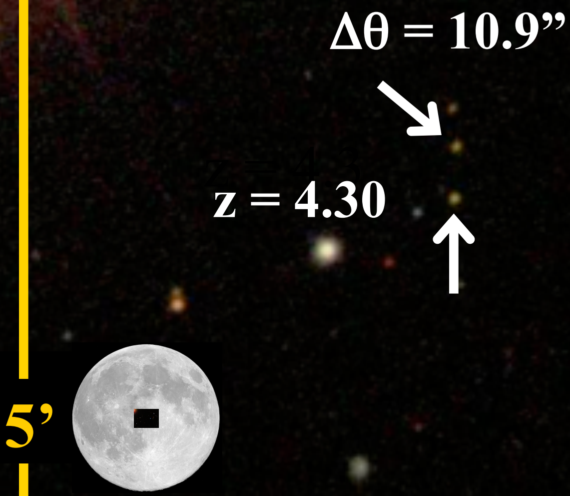
Resolving the 3D Small-Scale Structure of the IGM



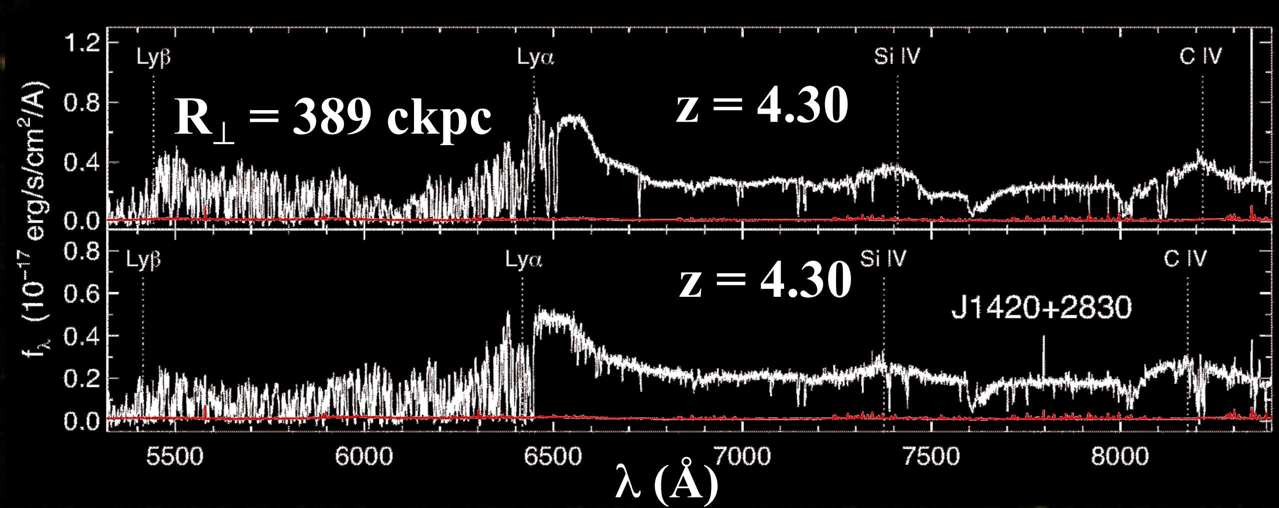


- **Problem:** Line-of-sight (1D) Lyα forest is strongly degenerate between thermal params $\{T_0, \gamma\}$ and 3D small-scale structure
- **Solution:** Measure 3D small-scale structure in transverse direction using close QSO pairs

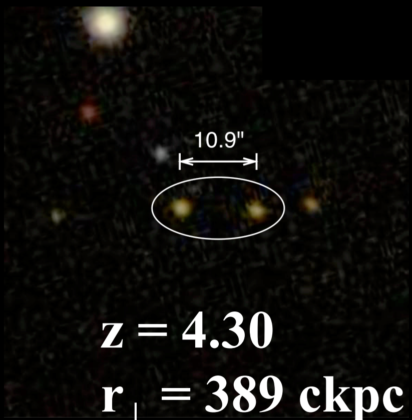
Finding Quasar Pairs

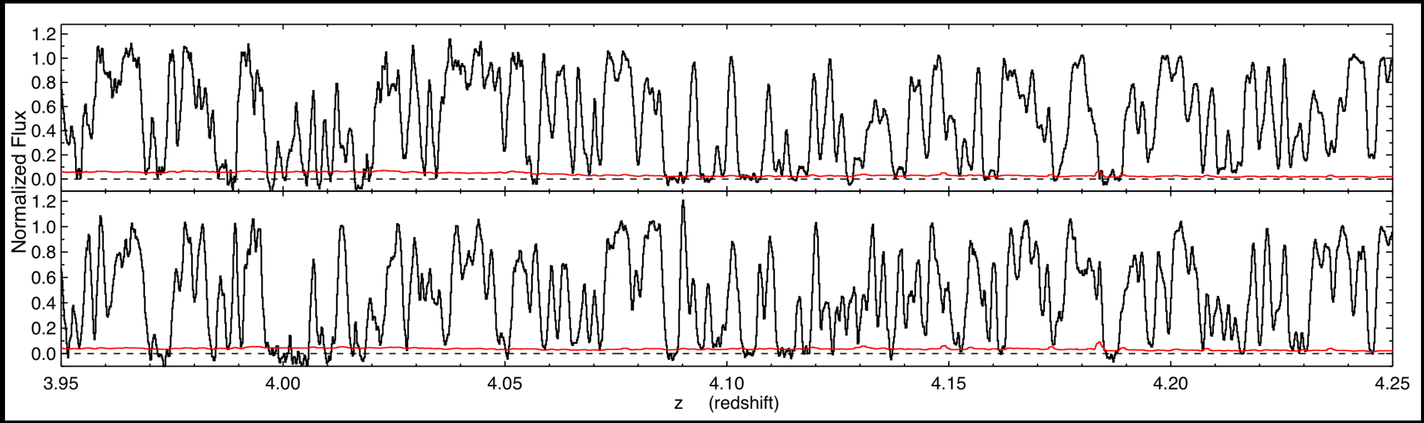


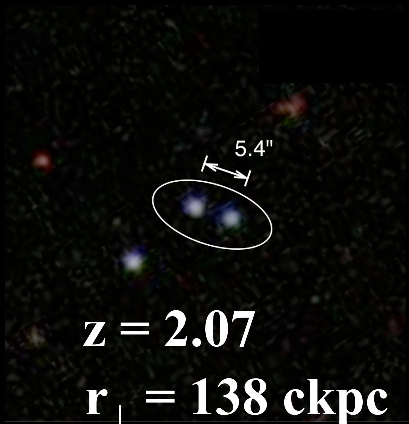
- SDSS: 10^6 × this image, ~ 10^9 objects
- ~ 100 times more stars than QSOs: (QSO pairs)/(star pairs) ~ 10^{-4}
- XD-QSO machine learning algorithm segregates QSOs from stars in 13-D (Bovy, Hennawi+ 2011; Bovy, Myers, Hennawi+ 2012)
- Pair confirmation has 25% success rate

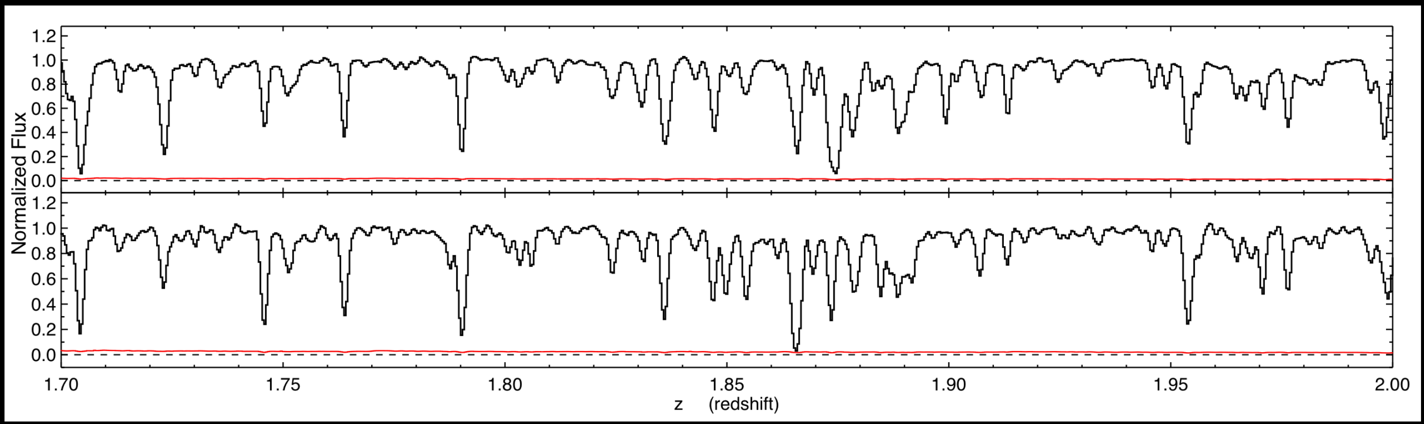


Correlated Absorption in Quasar Pair Spectra



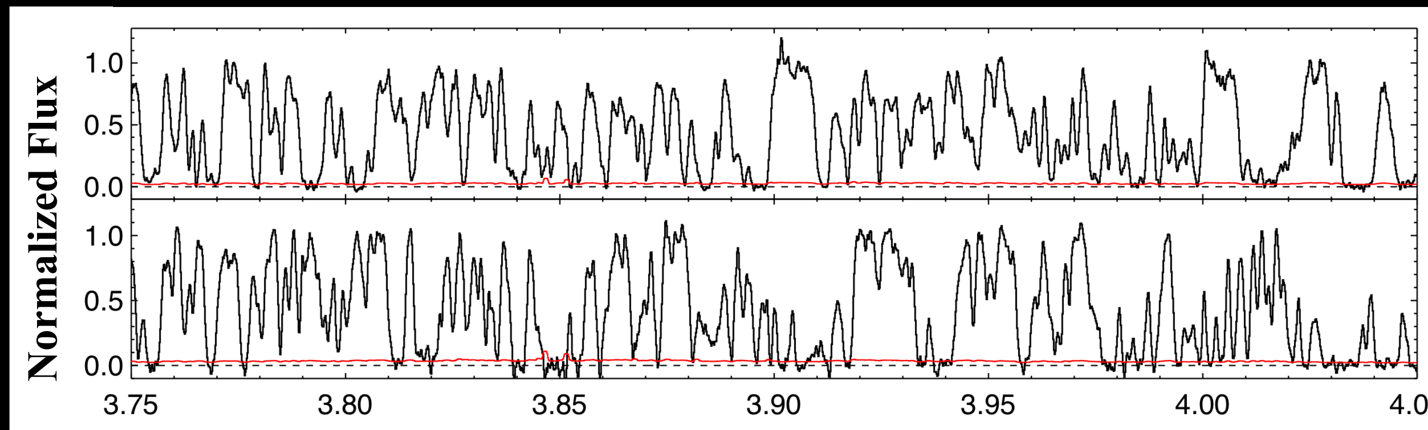


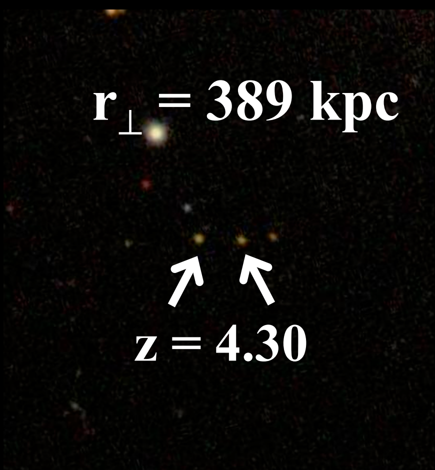


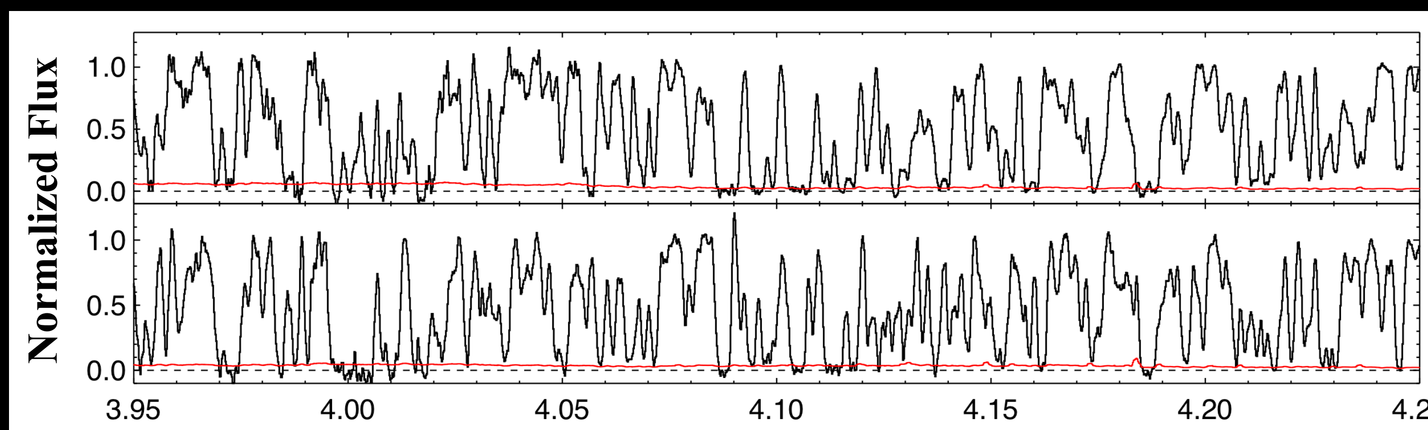


- To date ~ 300 pairs uncovered with $r_\perp$ < 700 ckpc
- High quality spectra (R > 2000, S/N > 10) from 8m class telescopes for the ~ 50 closest objects

Resolving the Pressure Smoothing Scale

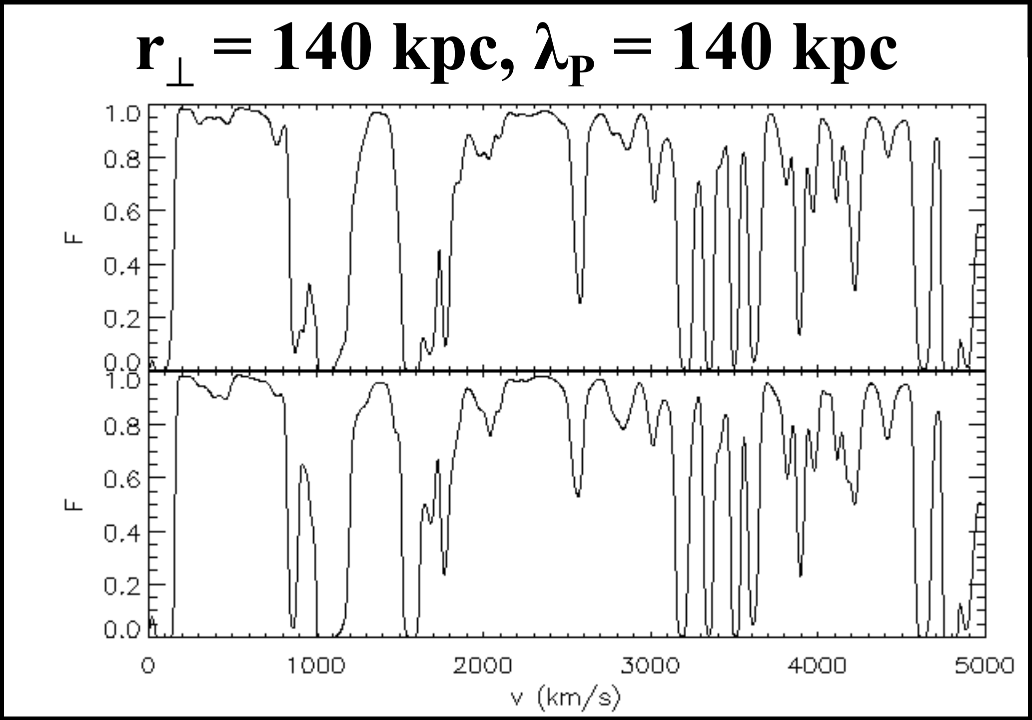






Increased coherence at small separation ➡ we are resolving the pressure smoothing scale λ_P. How do we quantify this?

Isolating 3D Information: Phase Differences



$$\tilde{F}(k) = \rho(k)e^{i\theta(k)}$$

$$\pi(k, r_\perp) \equiv \langle \tilde{F}_1 \tilde{F}_2^* \rangle$$
$$= \langle \rho_1 \rho_2 \cos\theta_{12} \rangle$$

$$P(k) \equiv \langle \tilde{F}\tilde{F}^* \rangle \sim \langle \rho_1 \rho_2 \rangle$$

Moduli depend primarily on 1D power P(k), and bring in degeneracies $\{T_0, \gamma\}$

Rorai, Hennawi+ 2013

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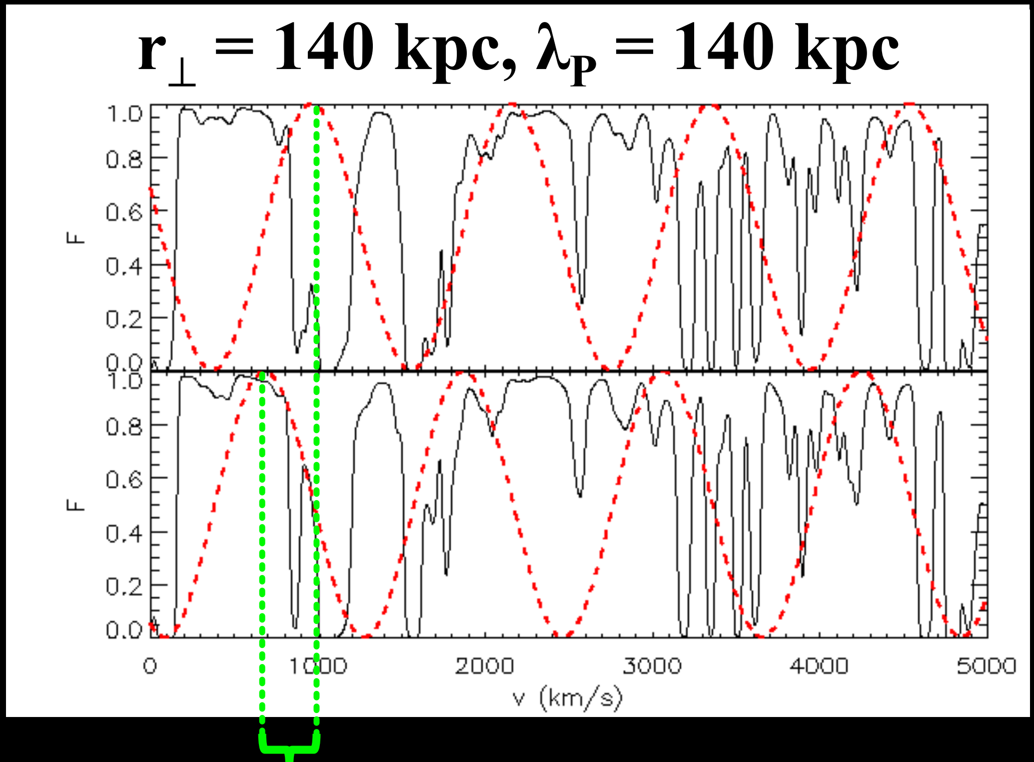

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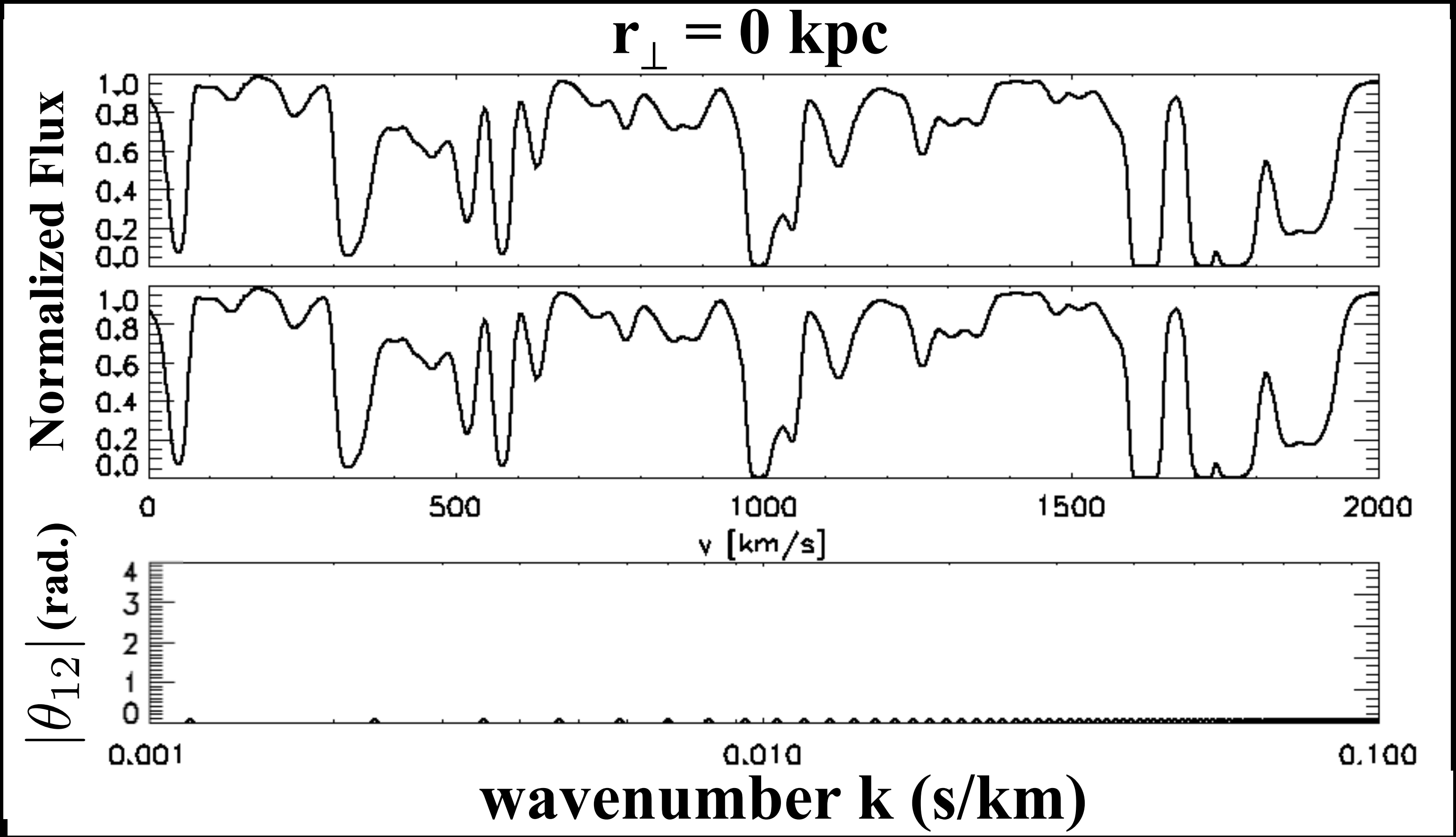
Moduli depend primarily on 1D power P(k), and bring in degeneracies $\{T_0, \gamma\}$

$$\theta_{12}(k) \equiv \theta_1(k) - \theta_2(k) = \arccos\left(\frac{\mathrm{Re}[\tilde{F}_1^*(k)\tilde{F}_2(k)]}{\sqrt{|\tilde{F}_1(k)|^2 |\tilde{F}_2(k)|^2}} \right)$$

Phase differences of homologous Fourier modes in close pairs which resolve $r_\perp \sim \lambda_P$ encode the new information about the 3D structure of IGM

Rorai, Hennawi+ 2013

Phase Coherence as Signature of Pressure Smoothing



simulated quasar pair

λ_P = 140 kpc

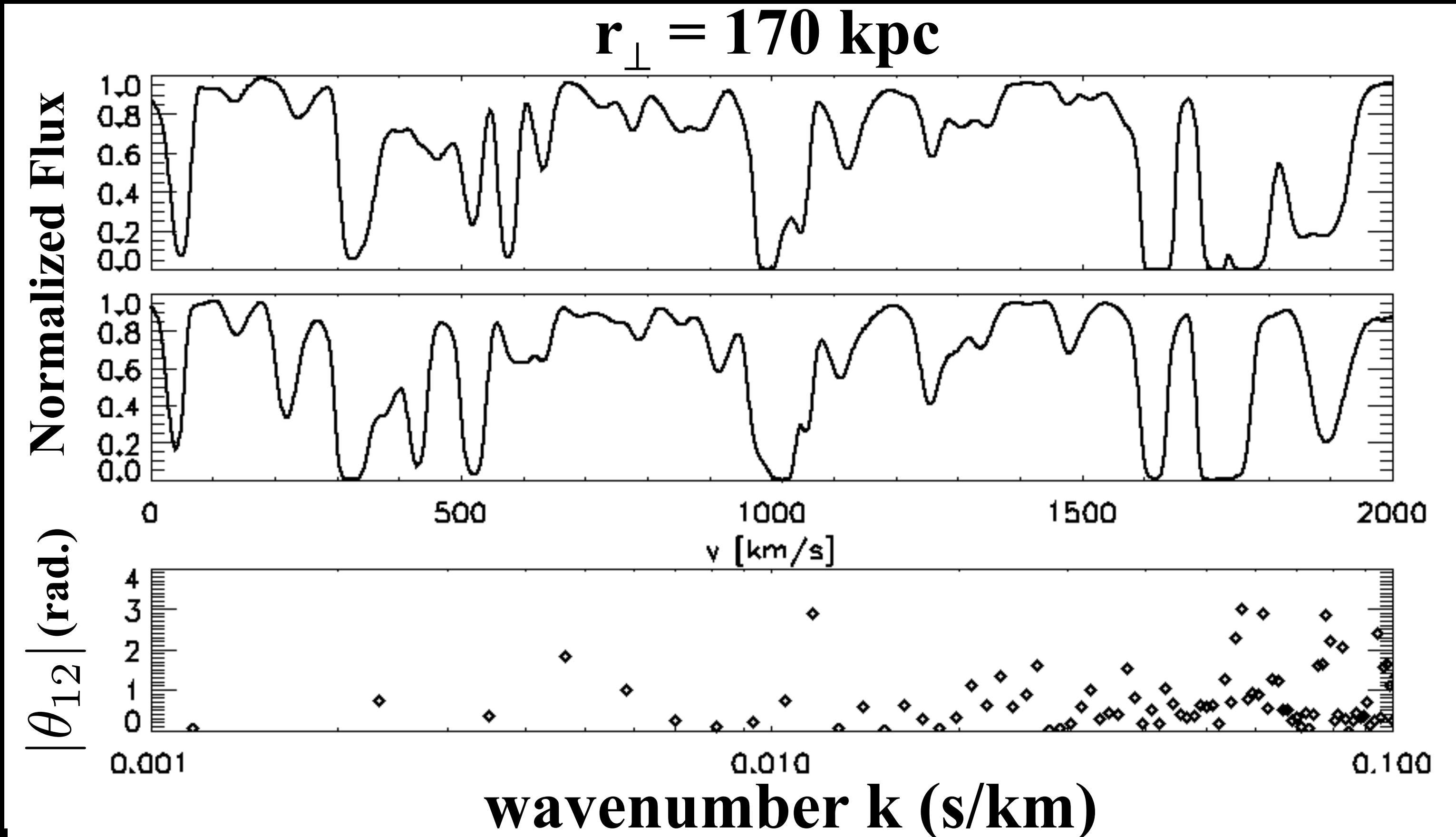
phase difference "spectrum"

- Fourier transform each spectrum
- Compute $|\theta_{12}|$ for each mode k

Smaller phase diff. ➡ more coherence

➡ larger λ_P

Phase Coherence as Signature of Pressure Smoothing



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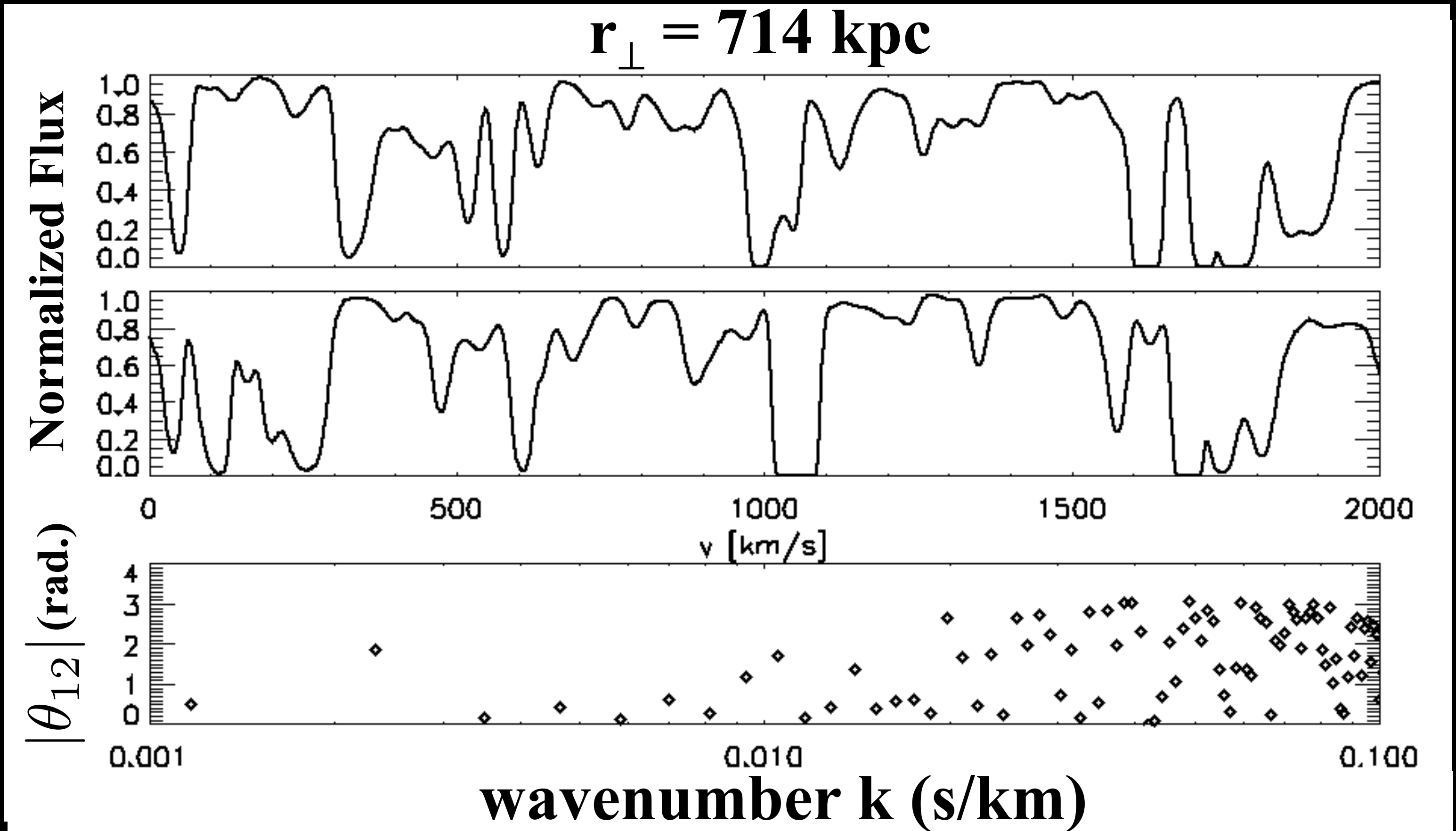

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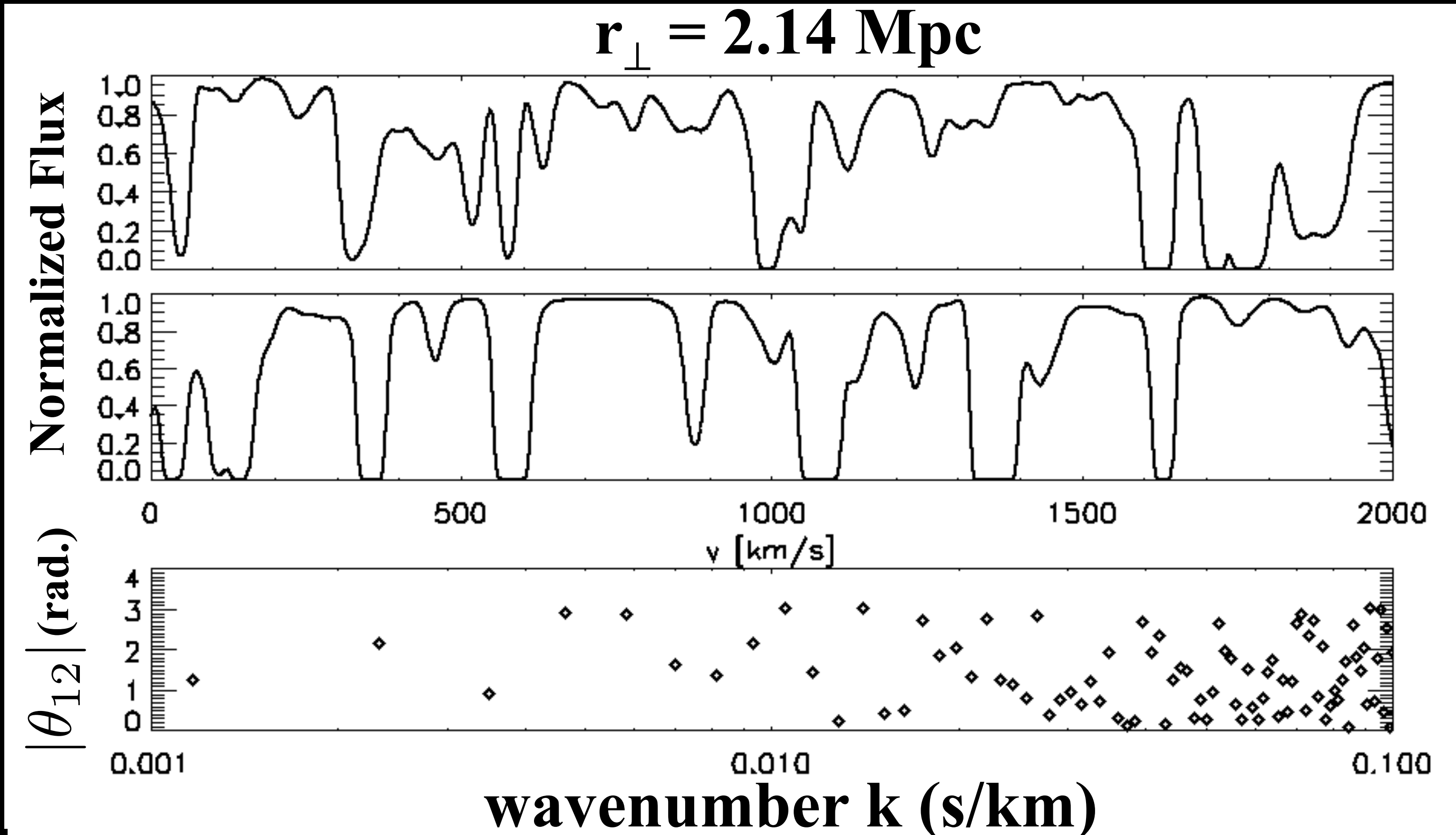
Smaller phase diff. ➡ more coherence

➡ larger λ_P

Phase Coherence as Signature of Pressure Smoothing



simulated quasar pair

$\lambda_P = 140$ kpc

phase difference "spectrum"

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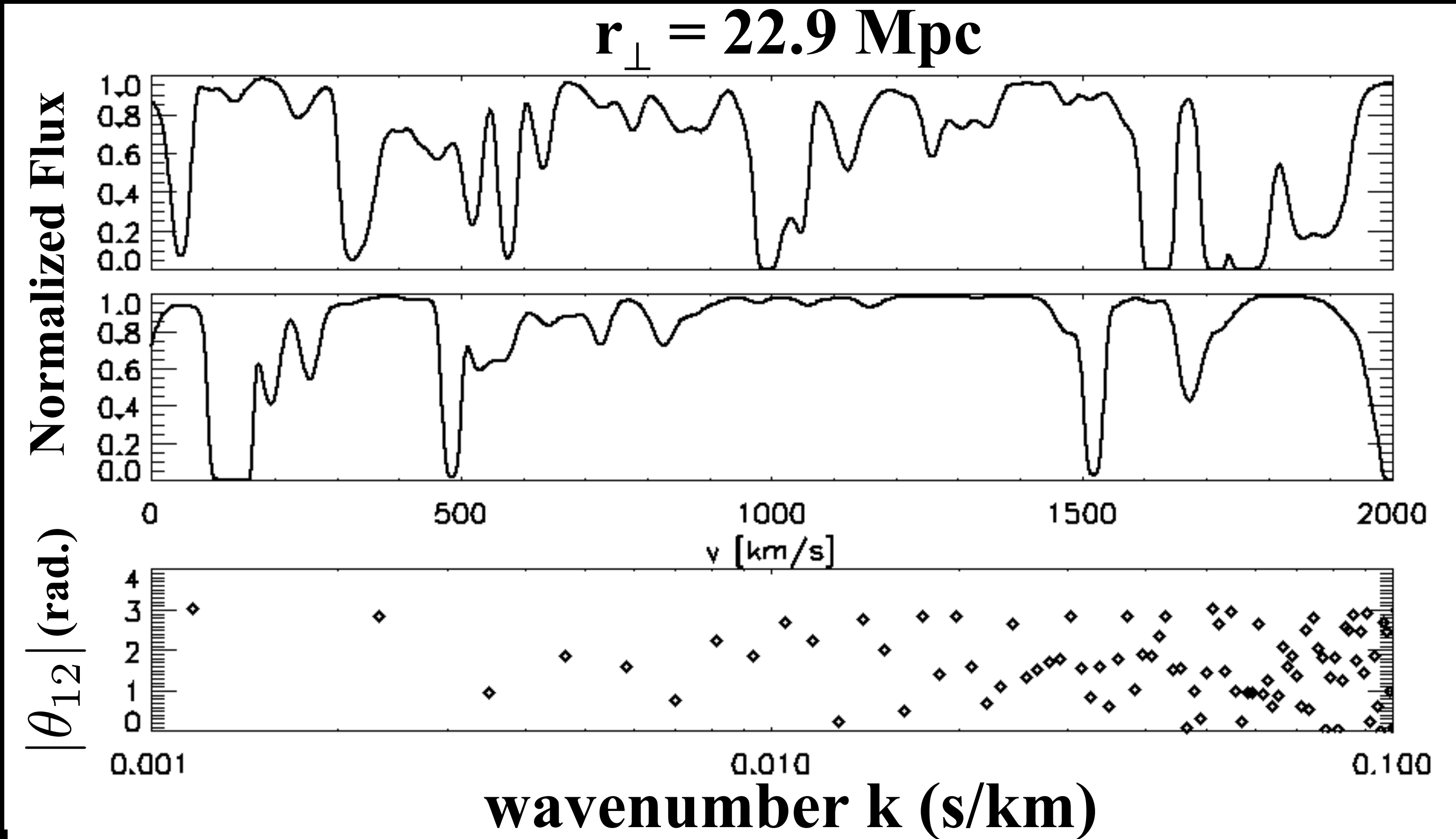

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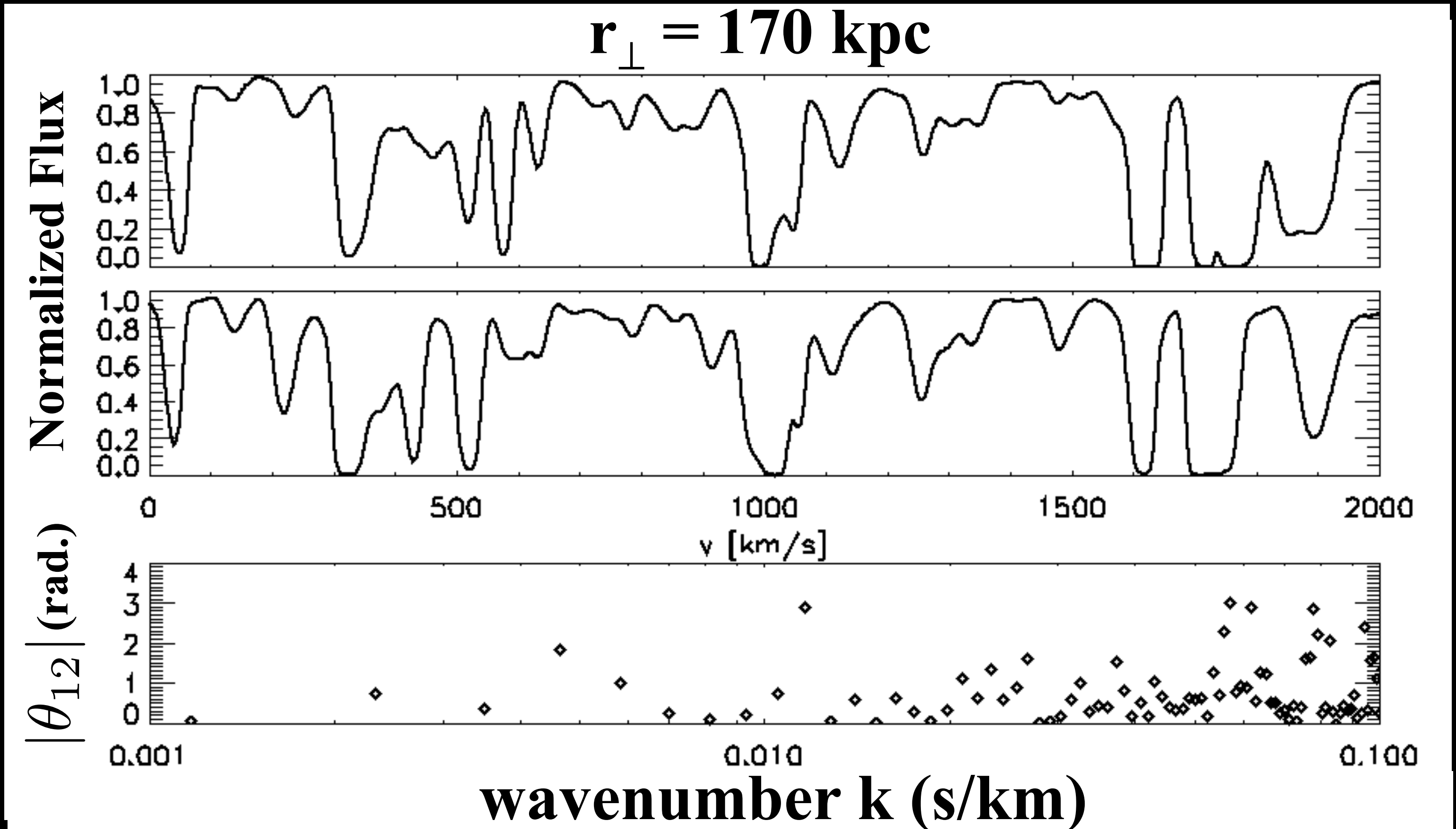

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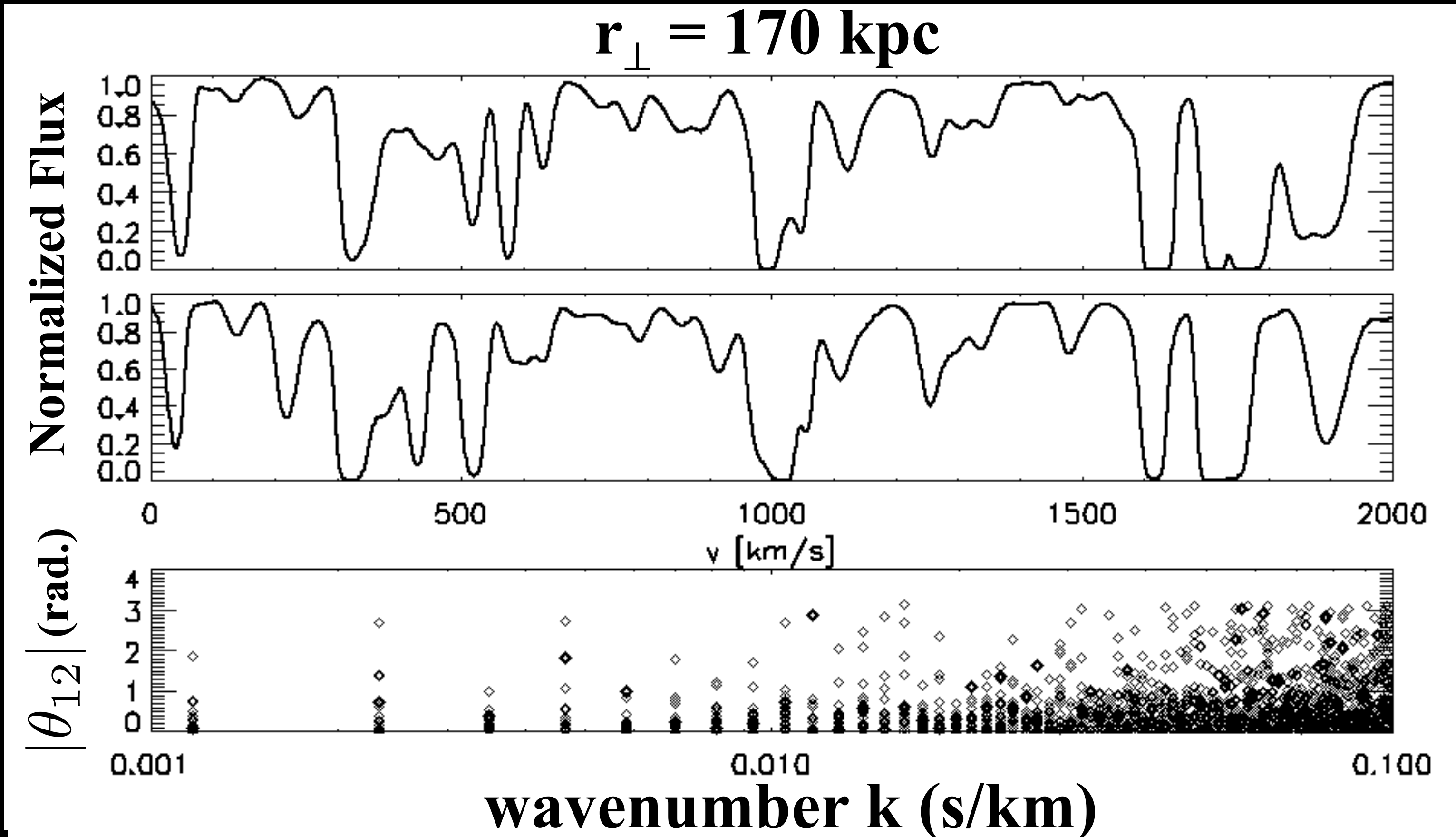

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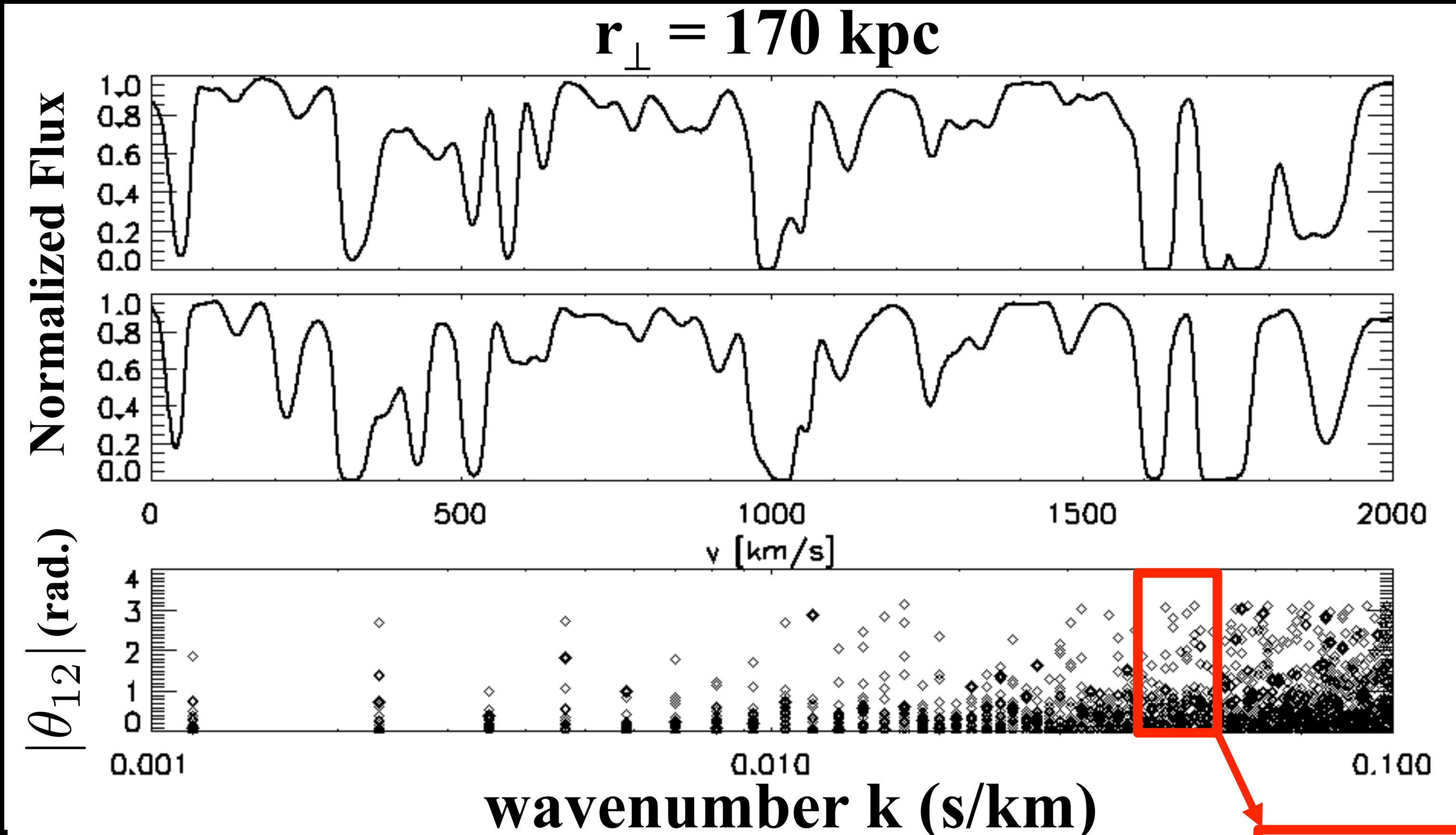

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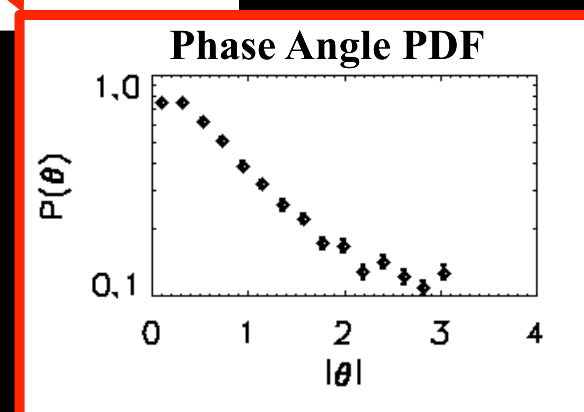

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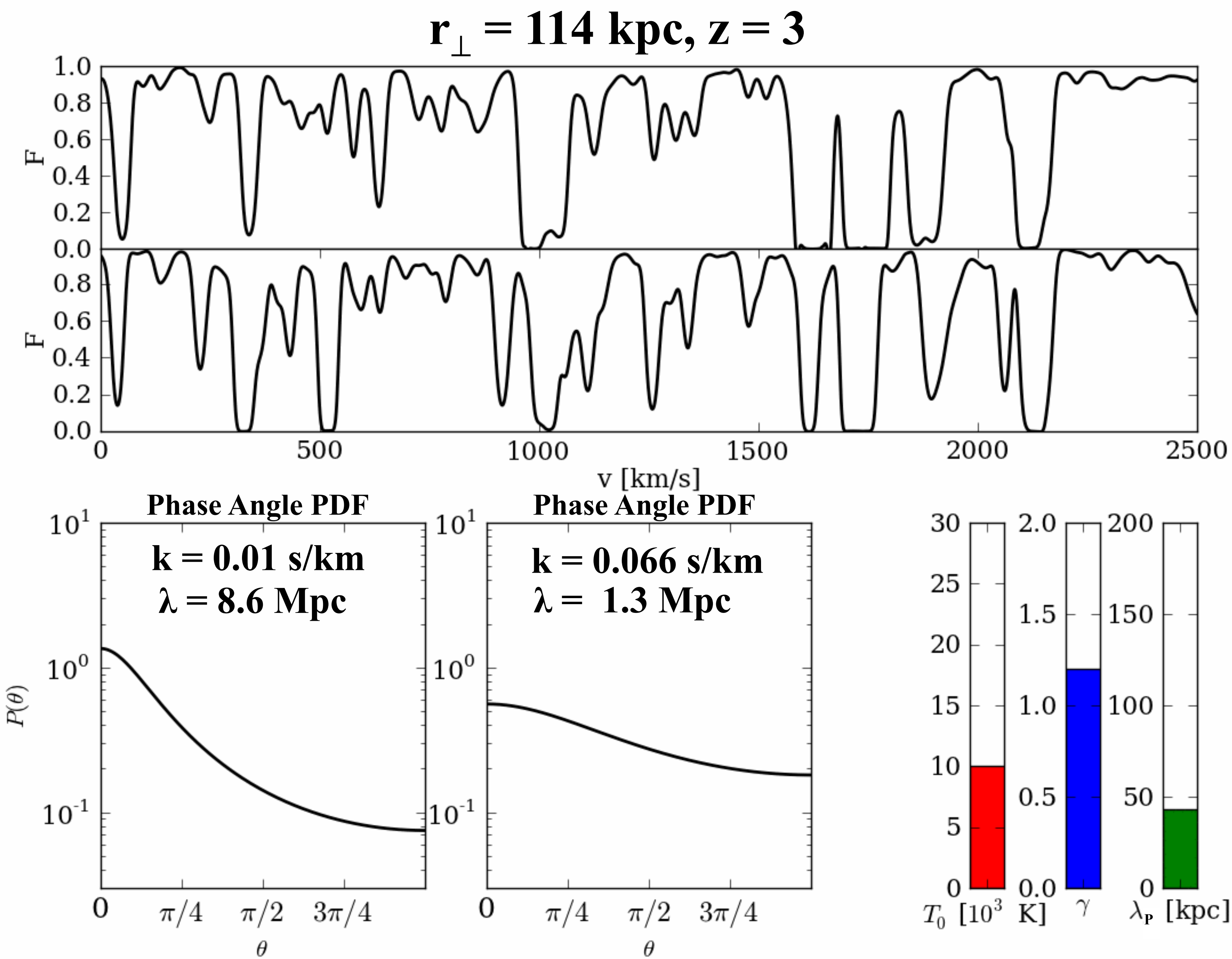
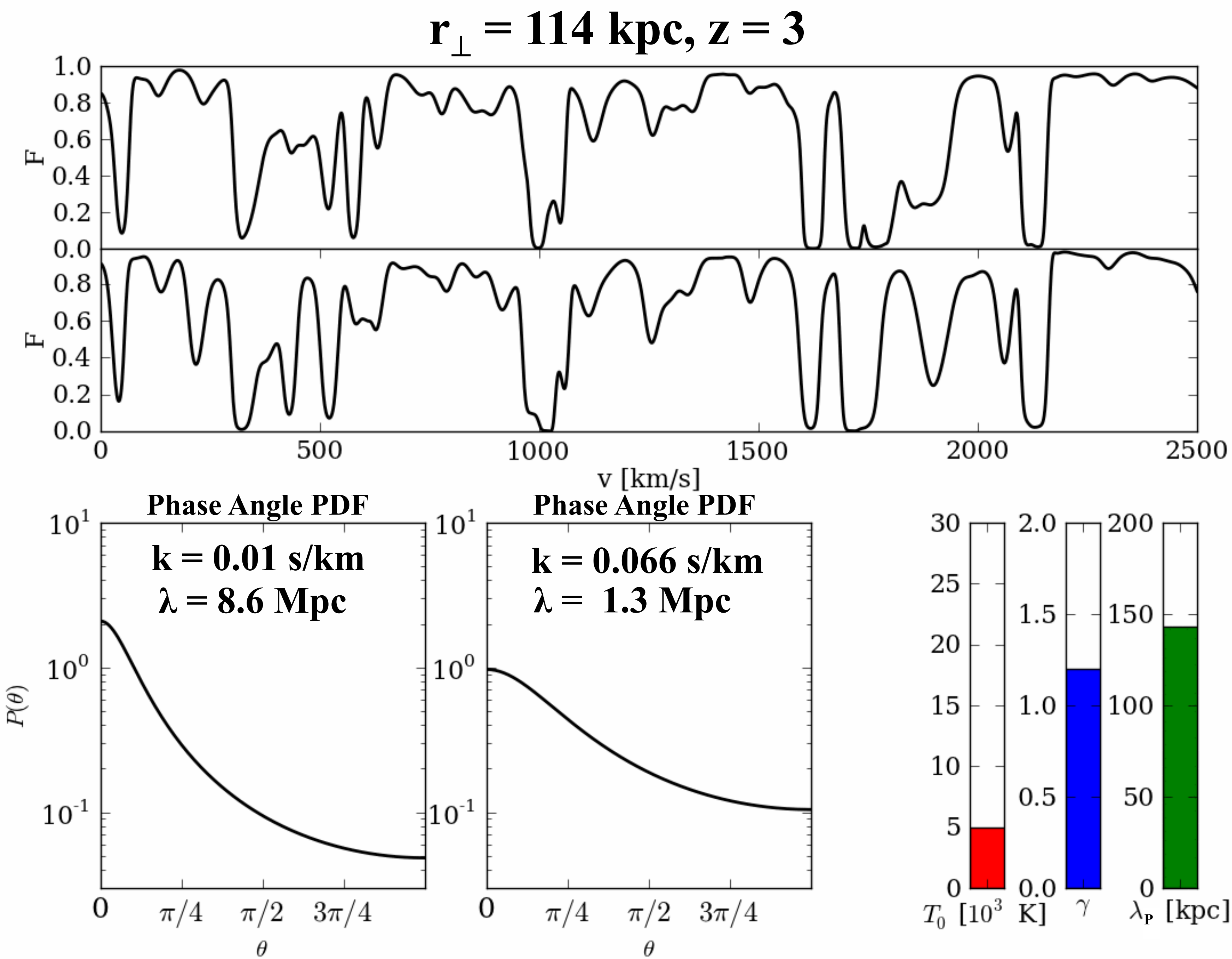


r⊥ = 114 kpc, z = 3
F
v [km/s]
Phase Angle PDF
k = 0.01 s/km
λ = 8.6 Mpc
Phase Angle PDF
k = 0.066 s/km
λ = 1.3 Mpc
P(θ)
θ
T0 [10^3 K]
γ
λP [kpc]



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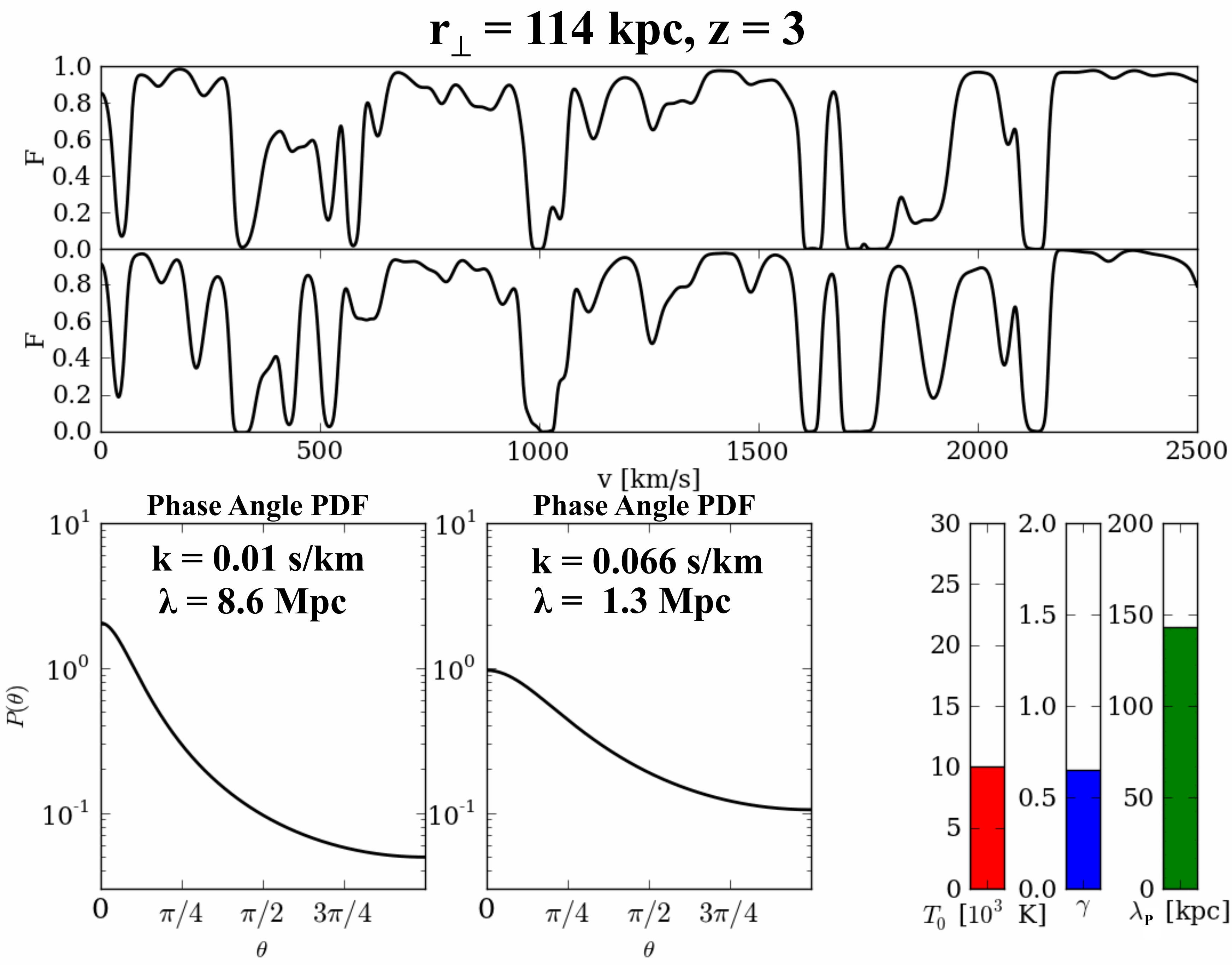
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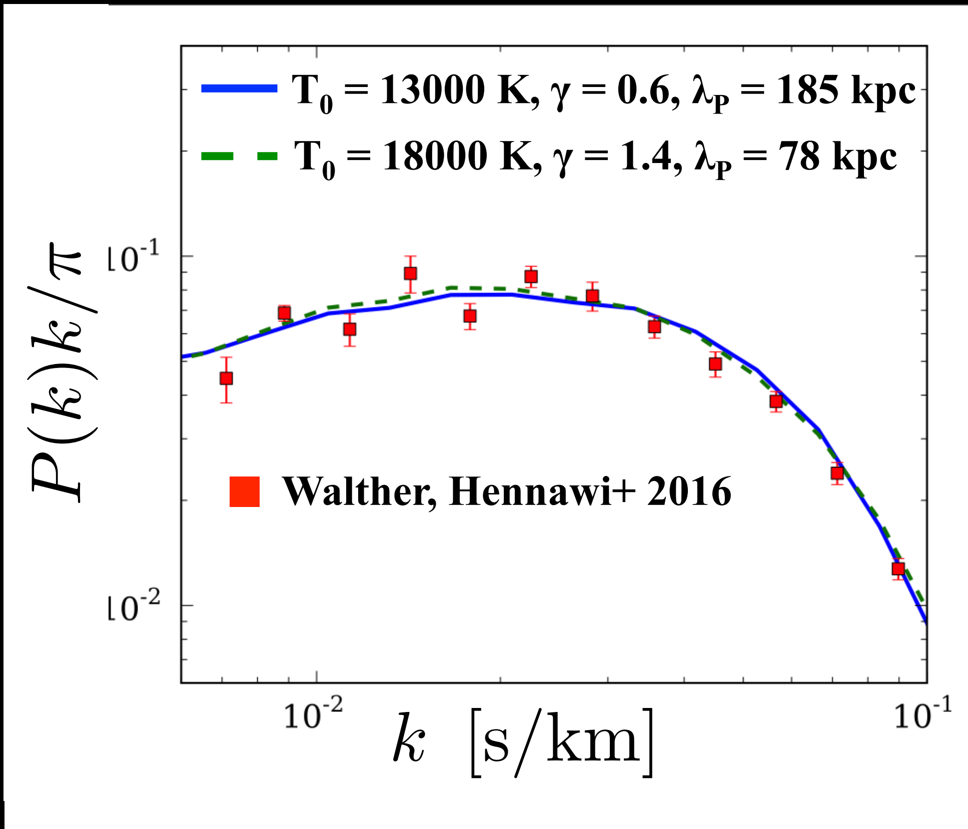
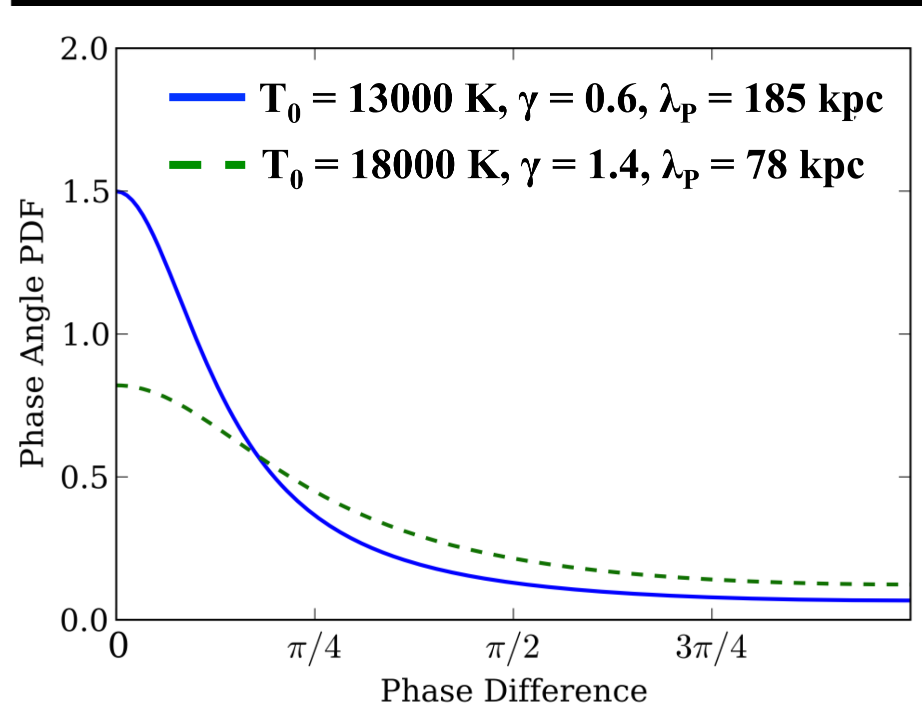
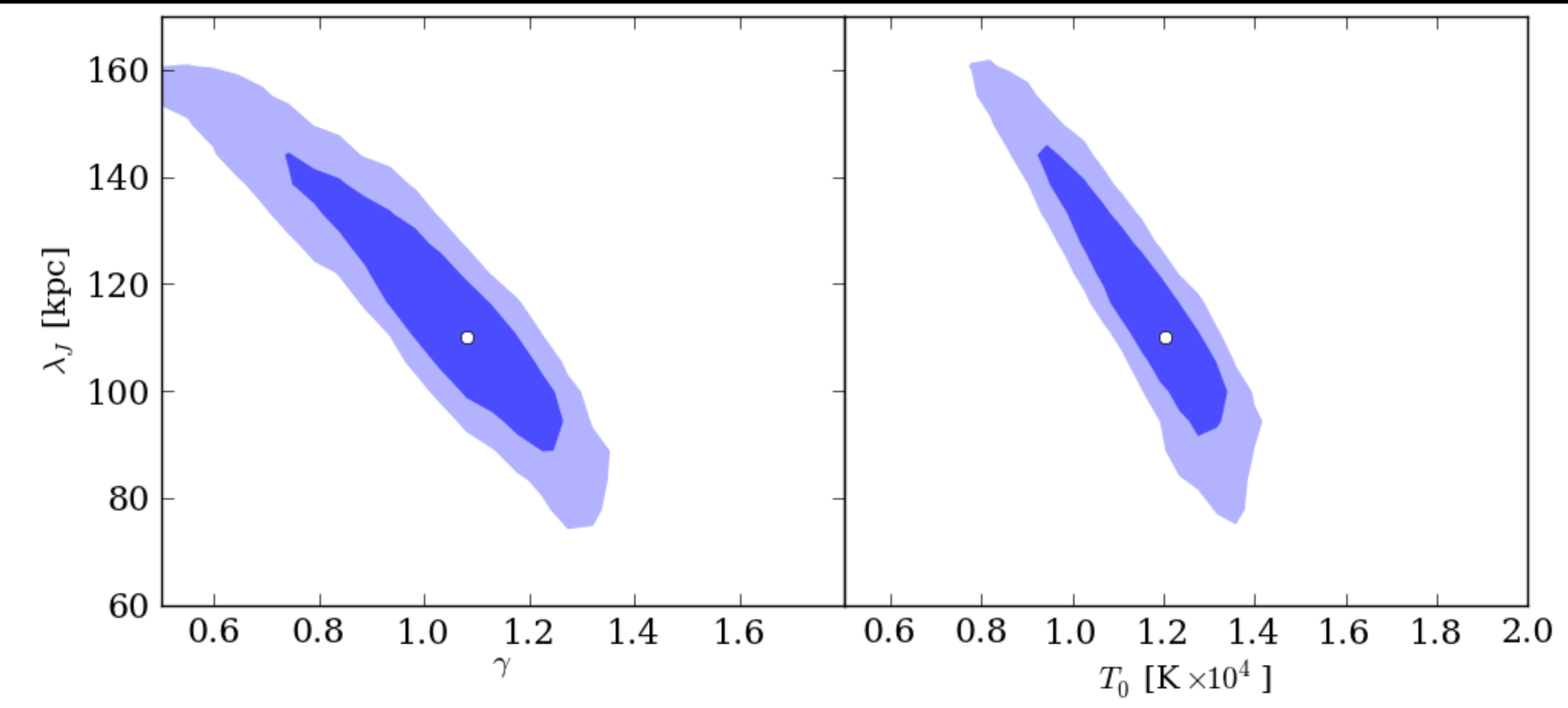
Resolving the 3D Small-Scale Structure of the IGM



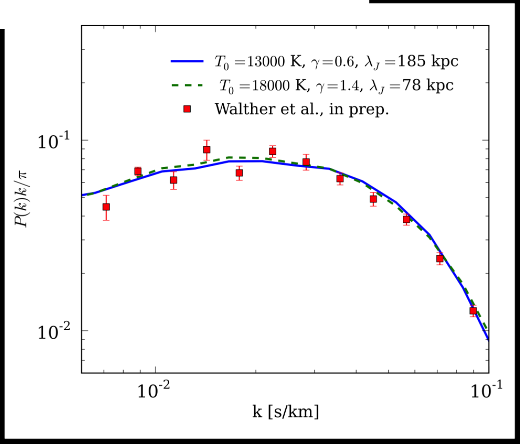


- **Problem:** Line-of-sight (1D) Lyα forest is strongly degenerate between thermal params $\{T_0,\gamma\}$ and 3D small-scale structure
- **Solution:** QSO pairs + phase angle PDF breaks degeneracy, enabling precision measurement of pressure scale λ_P

Simulated Jeans Scale Precision Constraints



Lyα forest power spectrum (1D) strongly degenerate between thermal parameters $\{T_0, \gamma\}$, $T(\rho) = T_0 \, (\rho/\bar{\rho})^{\gamma-1}$, and pressure smoothing scale λ_P



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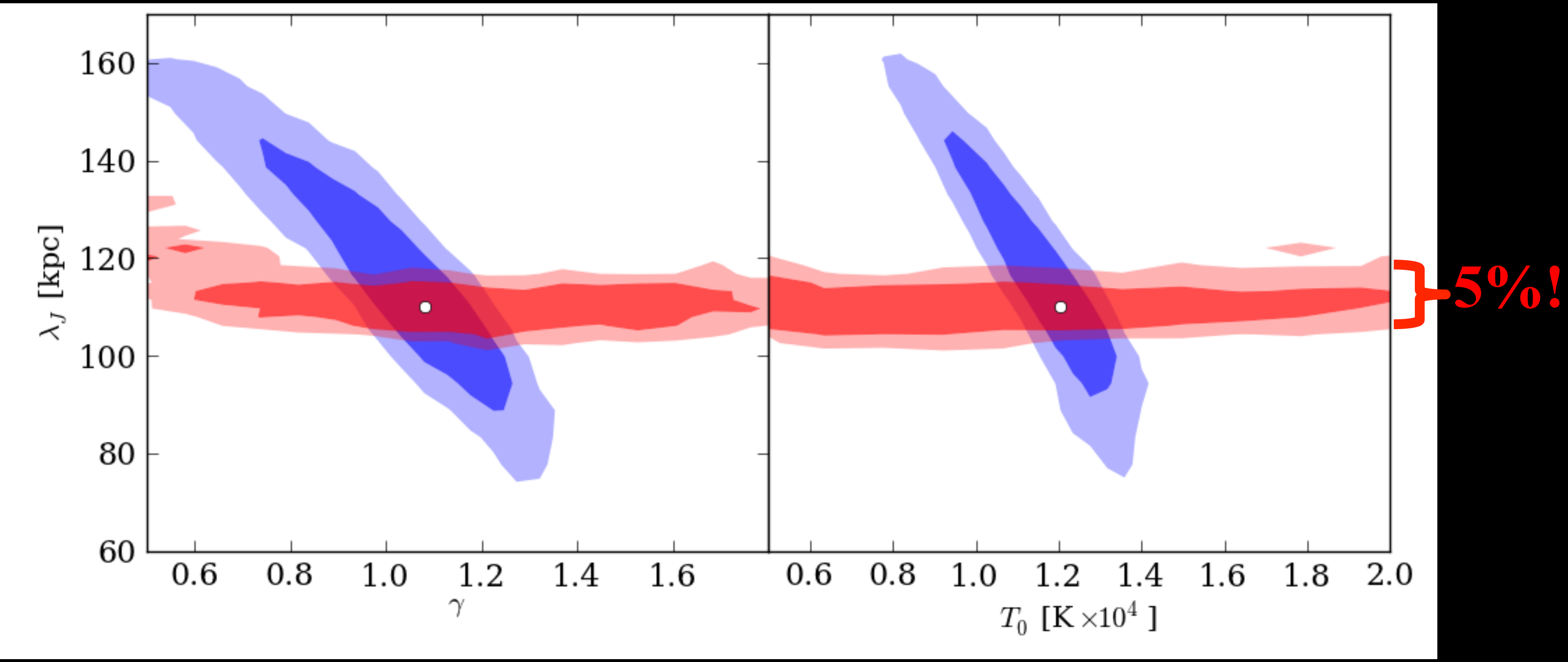
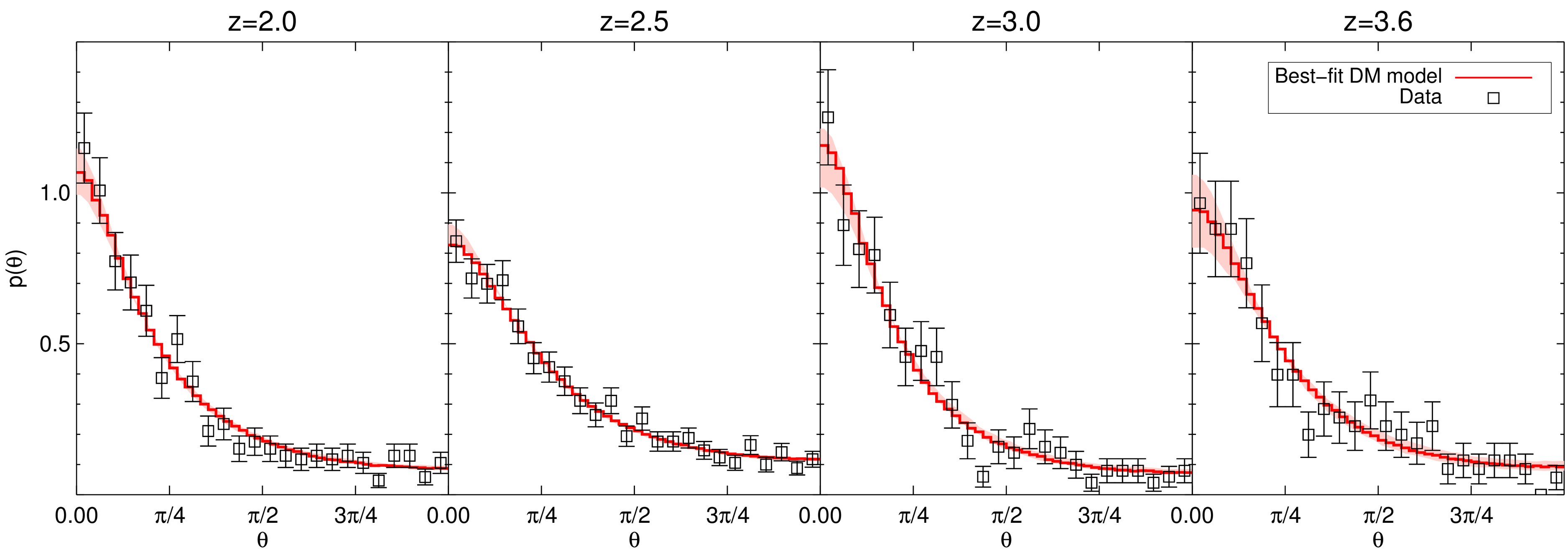


Rorai, Hennawi+ 2013

Realistic sample of just 20 QSO pairs can constrain the pressure smoothing scale λ_P to 5% precision

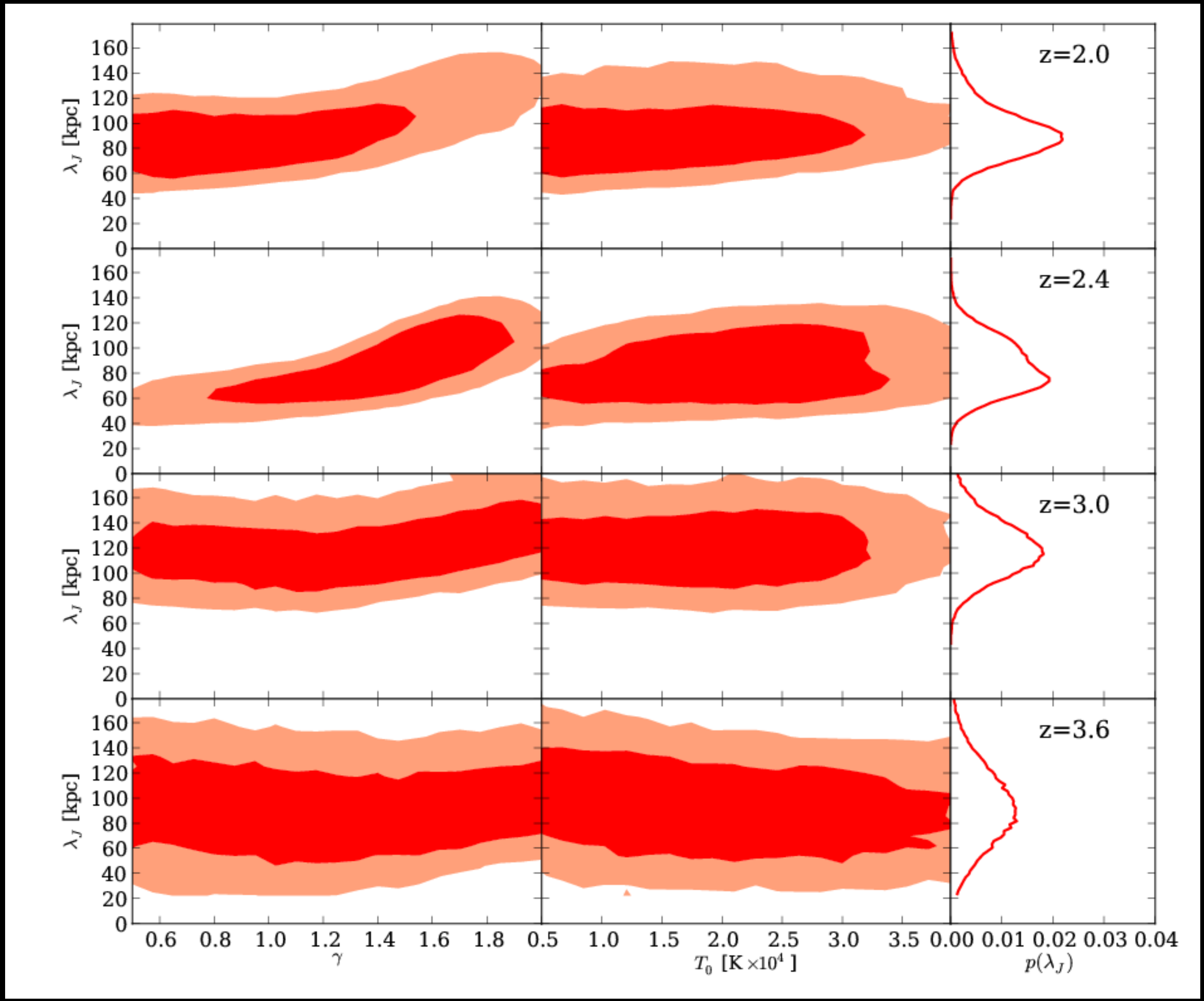
First Measurement of Pressure Smoothing Scale Using Quasar Pairs



Rorai, Hennawi+ 2016

Measurement of phase angle PDF from a sample of 25 quasar pair spectra $1.7 < z_{Ly\alpha} < 3.9$

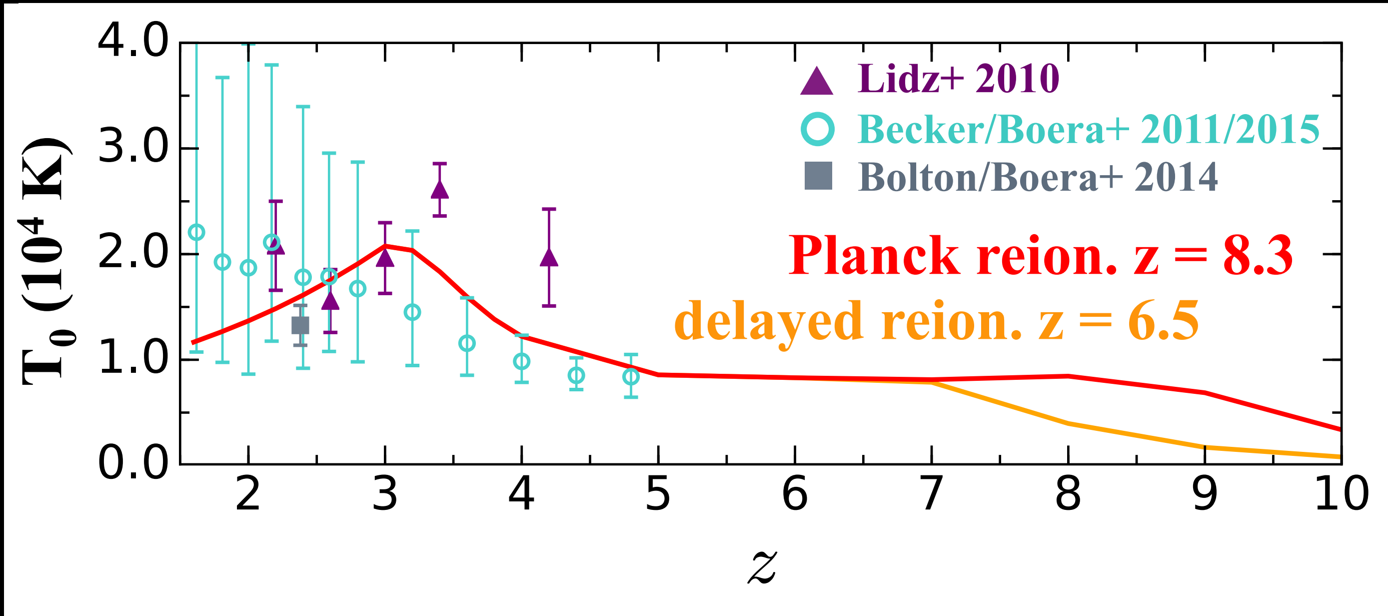
First Measurement of Pressure Smoothing Scale Using Quasar Pairs



Rorai, Hennawi+ 2016

Measured in four redshift bins with 30-50% errors.

The Thermal History of the Universe

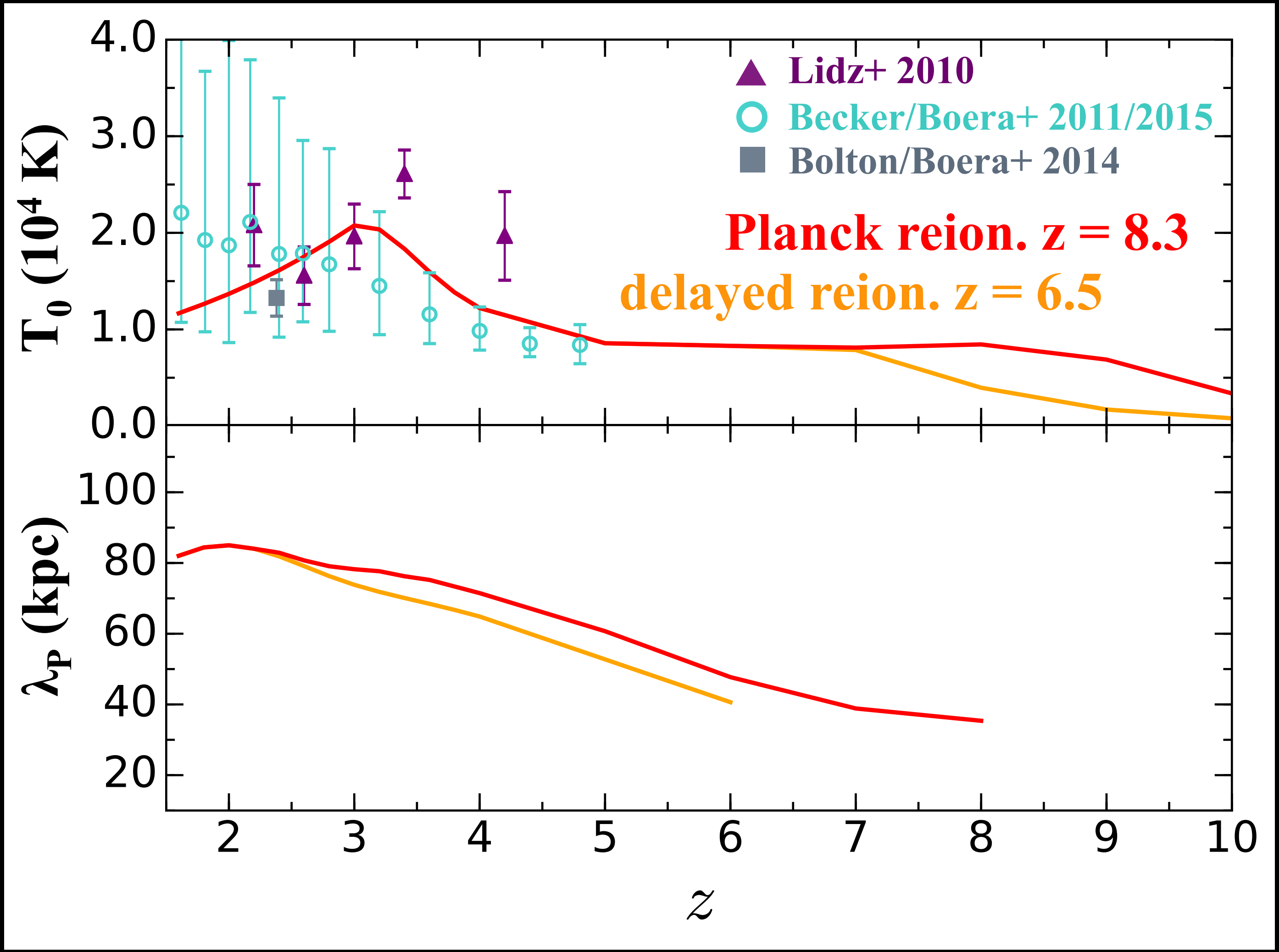


Oñorbe, Hennawi+ 2016b

temperature at mean density

Temperature evolution for two different reionization models: z = 8.3 (Planck) and z = 6.5 (delayed)

The Thermal History of the Universe



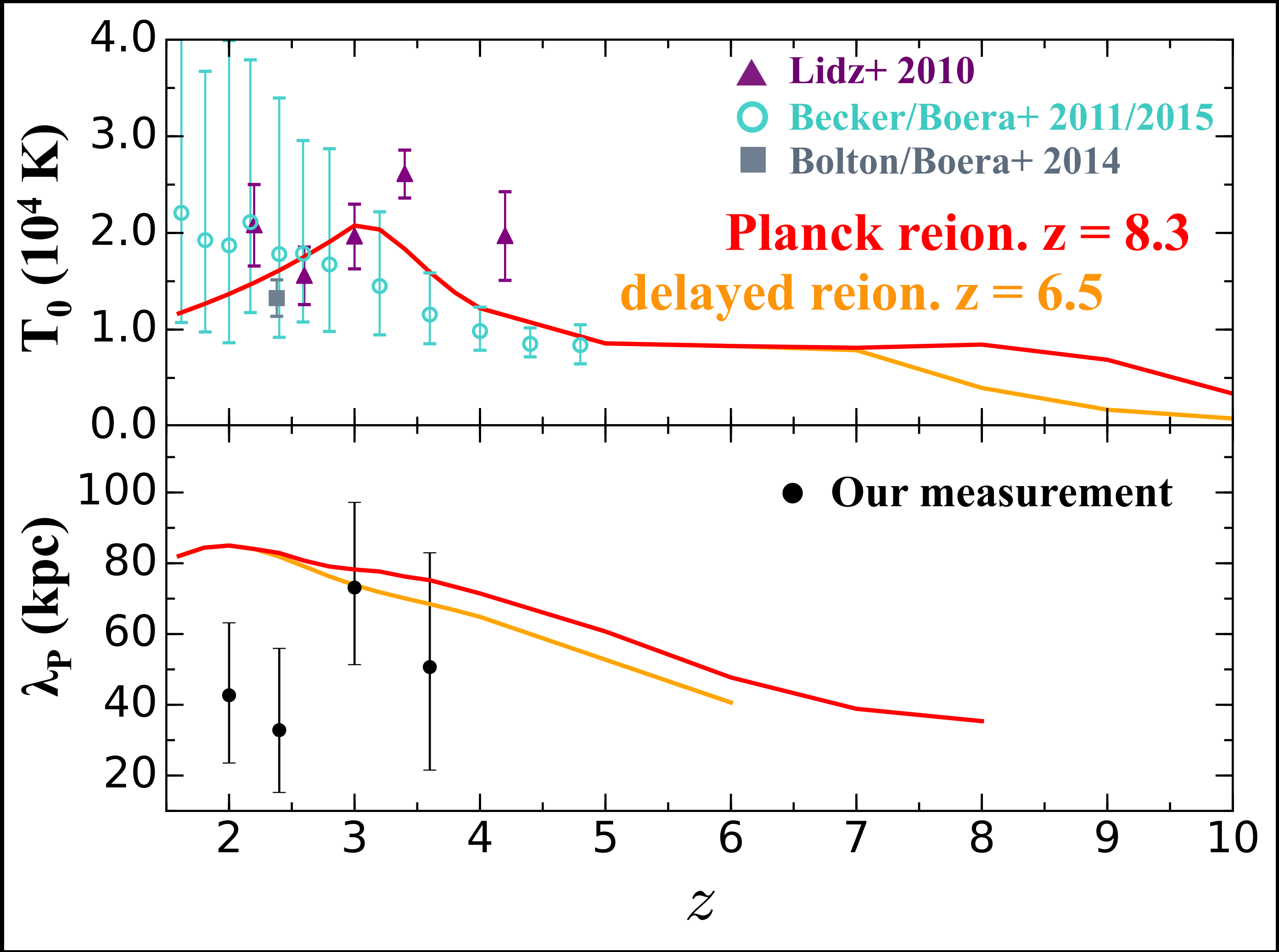
Oñorbe, Hennawi+ 2016b

temperature at mean density

pressure smoothing scale

Although temperature 'forgets' about HI reionization, filtering scale provides thermal record of early heating

The Thermal History of the Universe



Oñorbe, Hennawi+ 2016b

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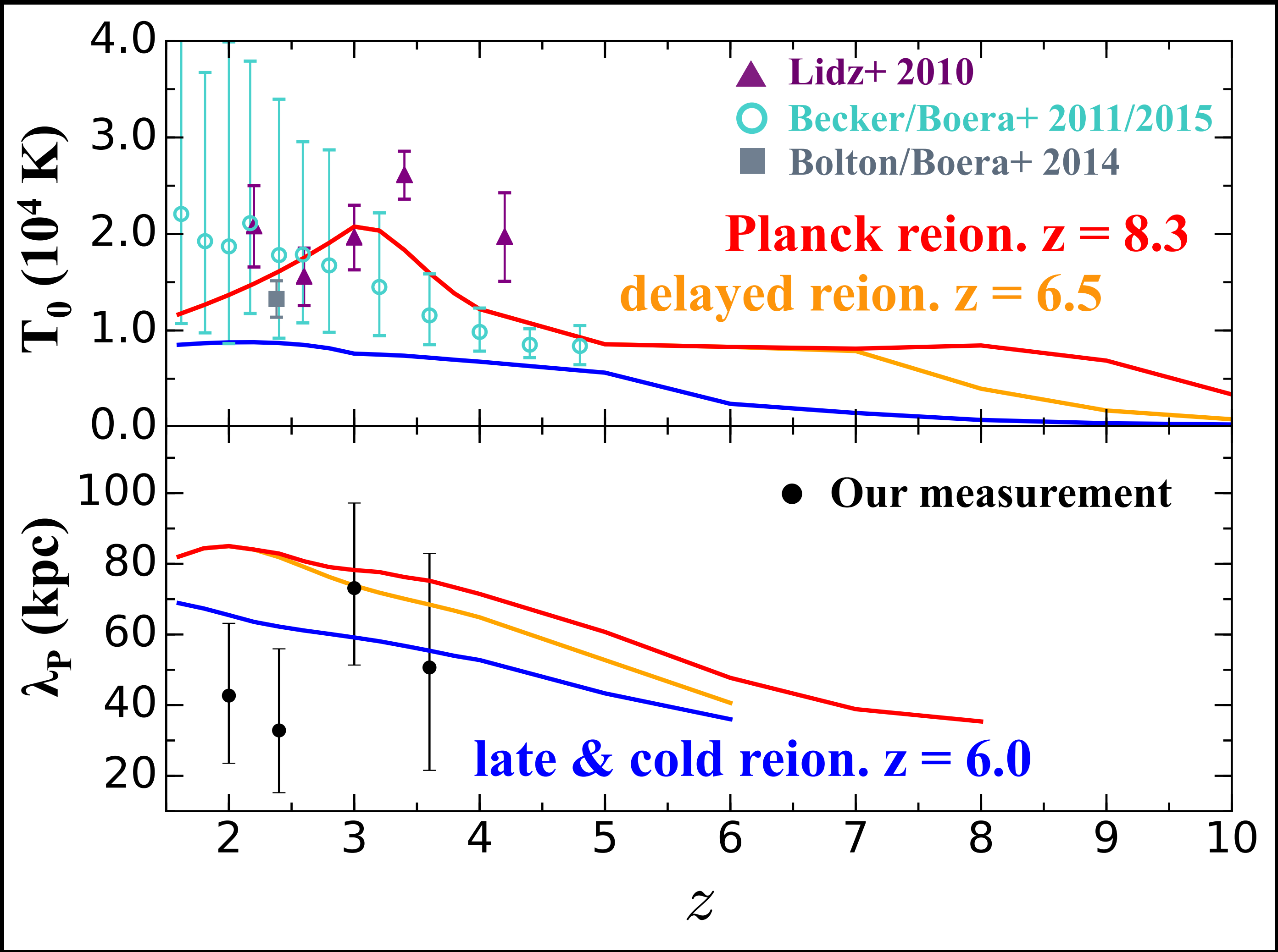
Small Scale Crisis in the IGM?



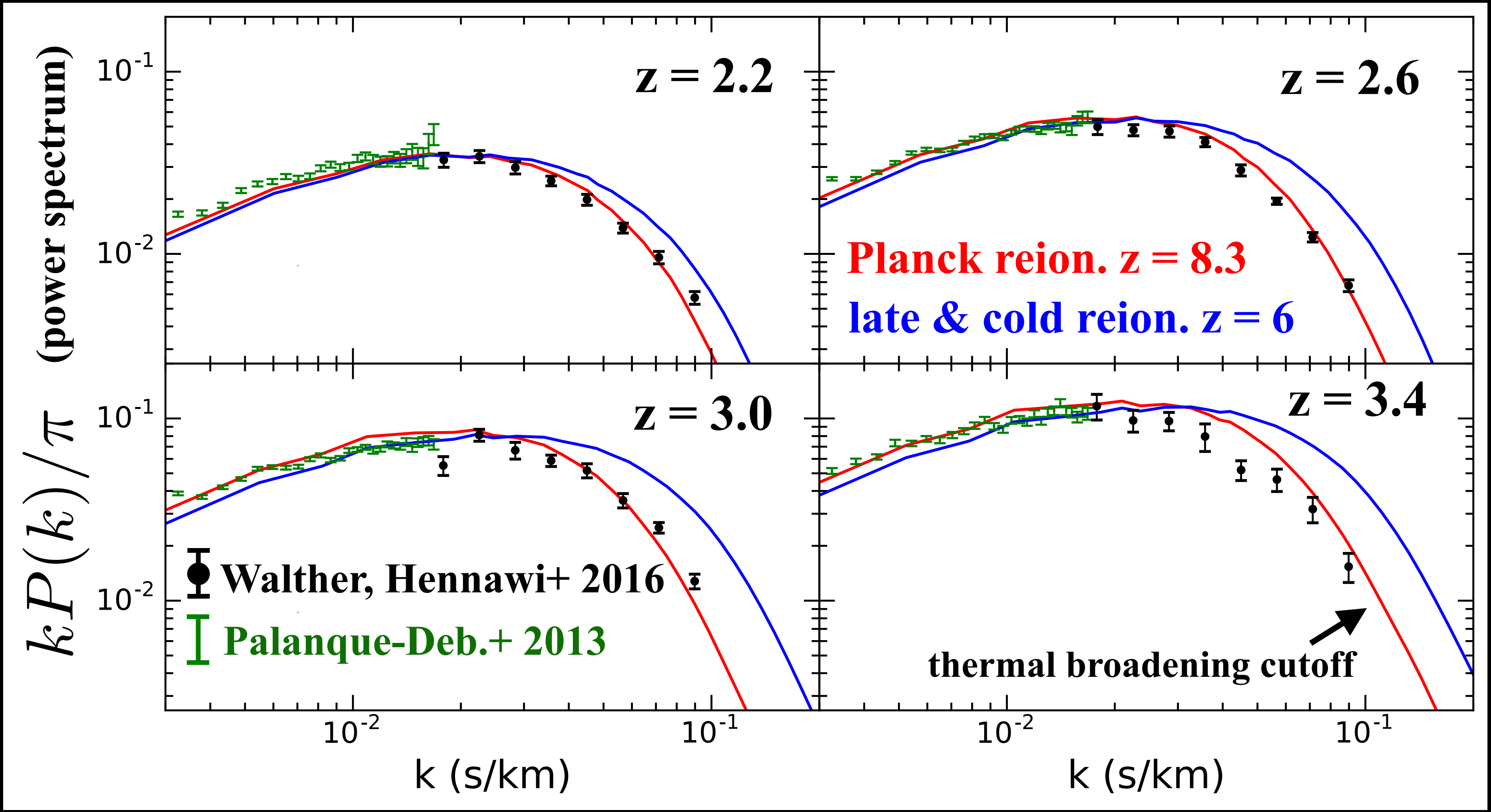
Oñorbe, Hennawi+ 2016b

temperature at mean density

pressure smoothing scale

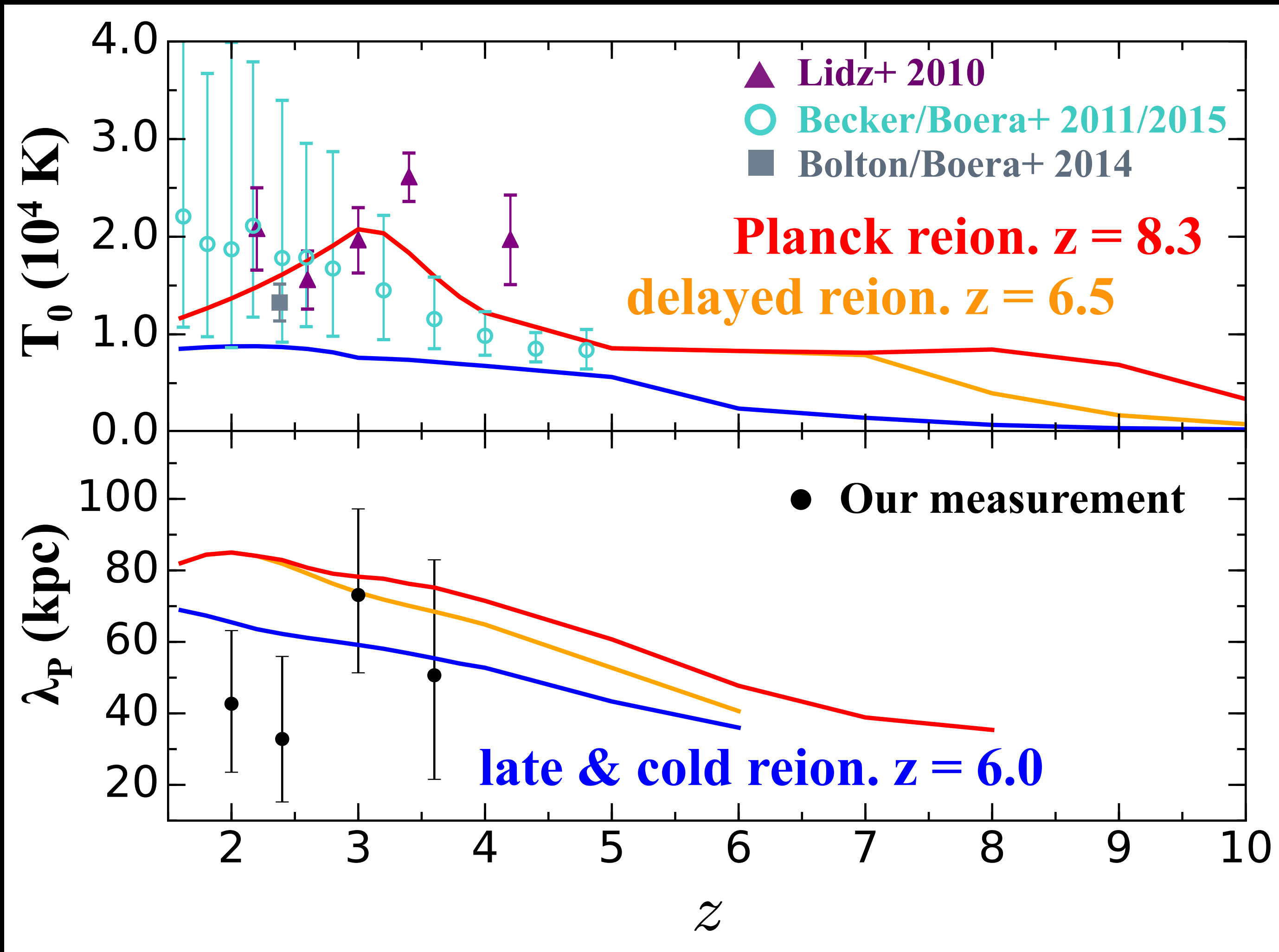
Pressure smoothing scale at z < 3 too small relative to sims. which reproduce IGM temperature T_0 measurements

Power Spectrum Confirms the Crisis



Power spectrum thermal broadening cutoff requires hot IGM
T ~ 15-20,000K. Late & cold reion. model clearly ruled out.

So What's Next?



Oñorbe, Hennawi+ 2016b

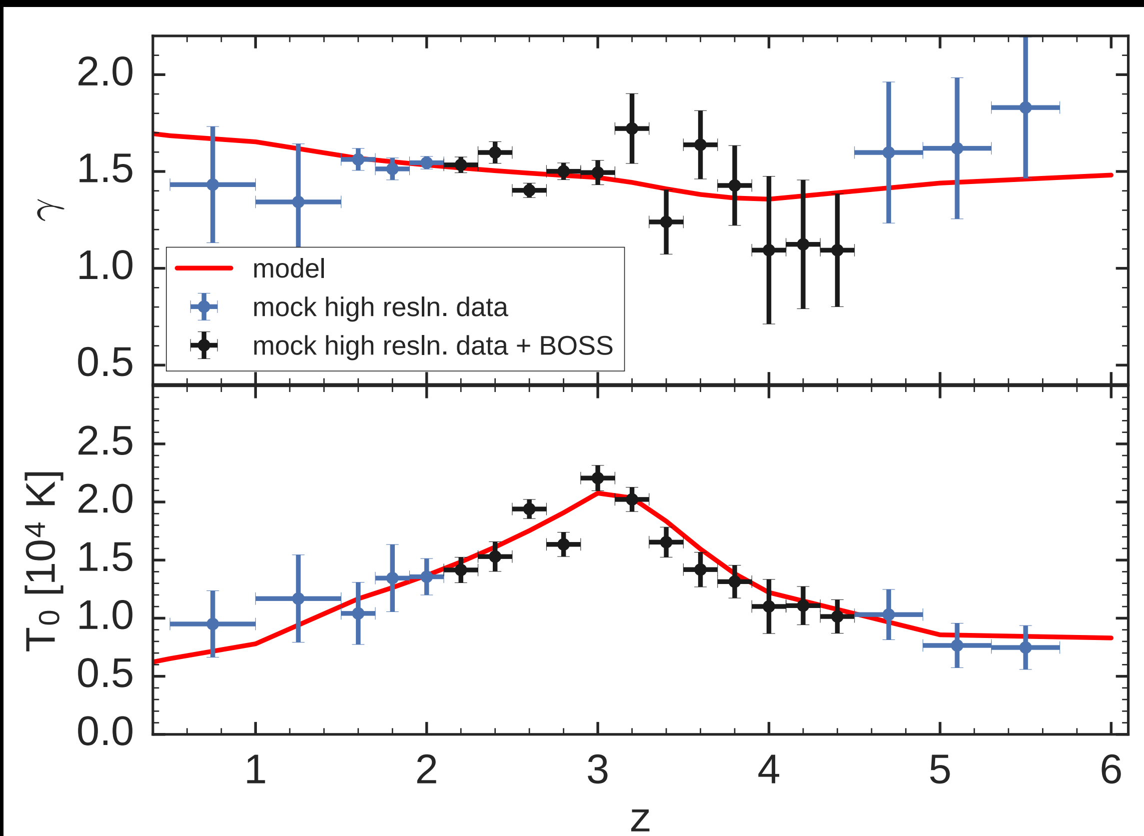
temperature at mean density

pressure smoothing scale

Let's be honest….these measurements don't look all that great

Future Prospects for IGM Thermal State

- With ~ 10 nights of telescope time, and improvements to method we can achieve ~ 10% error on λ_P
- Existing ~ 500 archival spectra (single quasars) covering $0.5 < z < 5.5$ can precisely measure power spectrum P(k)



Simulated reconstruction of IGM thermal history from P(k) given existing archival data

Walther, Hennawi+ 2016

Summary

- The IGM pressure smoothing scale λ_P provides a thermal record of early heating by cosmic reionization
- Data mining of massive sky surveys identifies hundreds of rare QSO pairs which can measure this scale
- Phase differences of homologous Fourier modes in QSO pairs encode 3D information on λ_P
- First measurement yields λ_P too small relative to sims reproducing IGM measured IGM temperatures