Measuring the Jeans Scale of the IGM with Close Quasar Pairs

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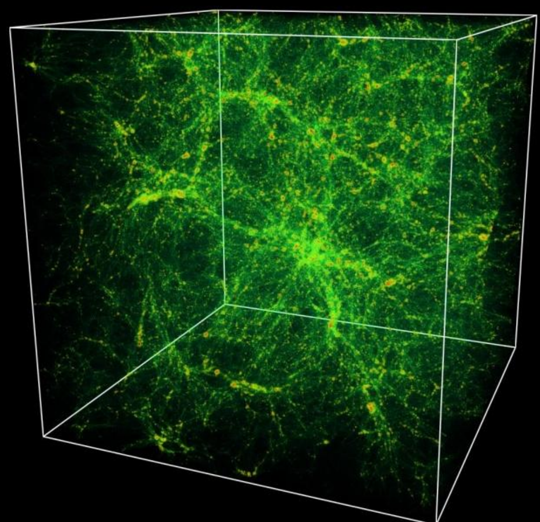
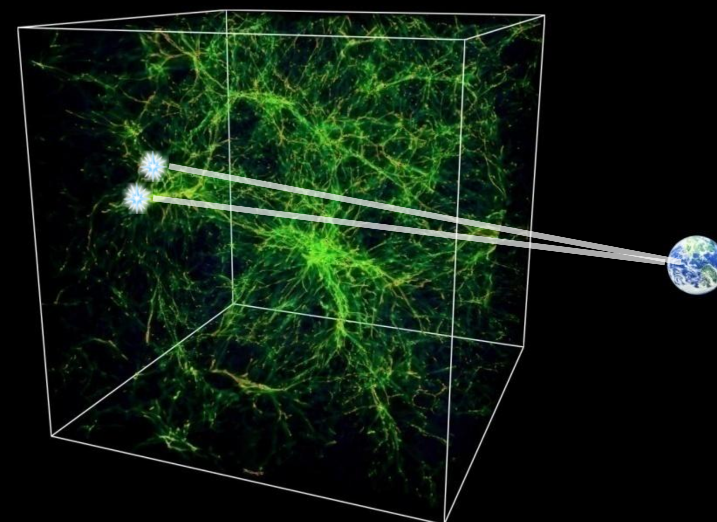
Baryons in the IGM and the Lyman-α Forest

Dark Matter

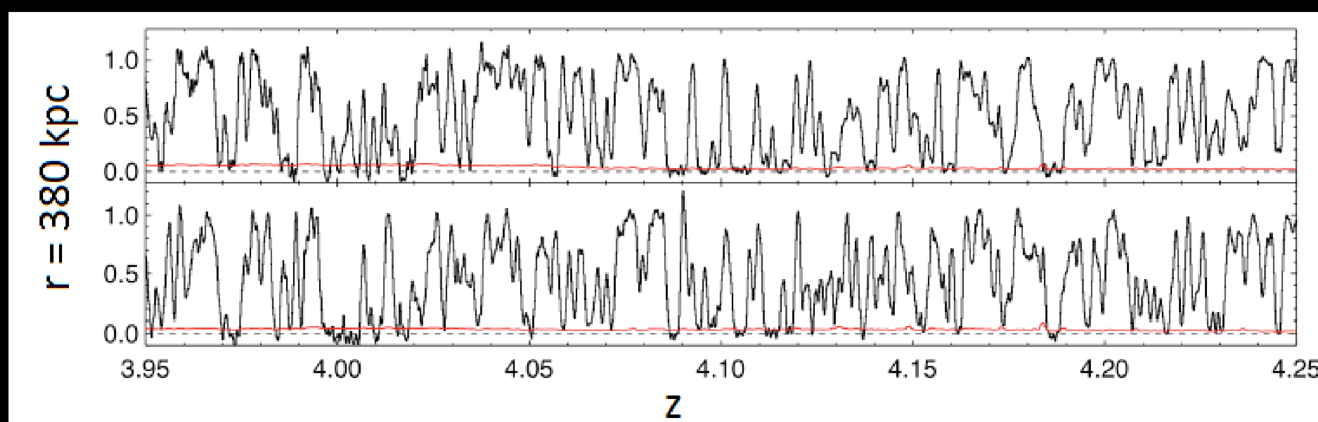


Baryons



Credit: R. Cen

Observations



The Jeans Scale as a Thermal Record

$$\lambda_J = \frac{c_s}{1+z}\sqrt{\frac{\pi}{G\rho}} \approx 1.1 \text{ Mpc} \left(\frac{T}{10^4 \text{K}}\right)^{1/2} \left(\frac{1+z}{1+3}\right)^{-1/2}$$

T increases with reionization events → Jeans scale increases

- Small-scale-structure growth and Galaxy formation suppressed

  Filtering mass:

$$M_F = \frac{4}{3}\pi\bar{\rho}\lambda_J^3$$

- **Clumpiness of the IGM** decreased by truncating power spectrum

$$C = 1 + \sigma^2_{\rm IGM} \equiv 1 + \int d\ln k \, \frac{k^3 P_{\rm IGM}(k)}{2\pi^2}$$

- The Jeans filtering scale depends on the *whole* **thermal history** (Gnedin & Hui, 1998), because the sound-crossing time λ_J/c_s is comparable to the Hubble time

$$\lambda_J^2(t) = \int_0^t f(T(t'))dt'$$

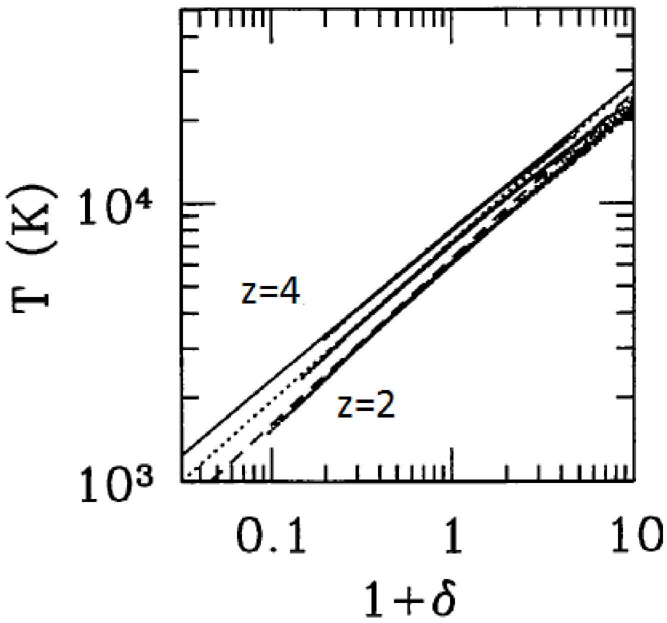
- It is a source of uncertainty in IGM studies

The Thermal State of the IGM

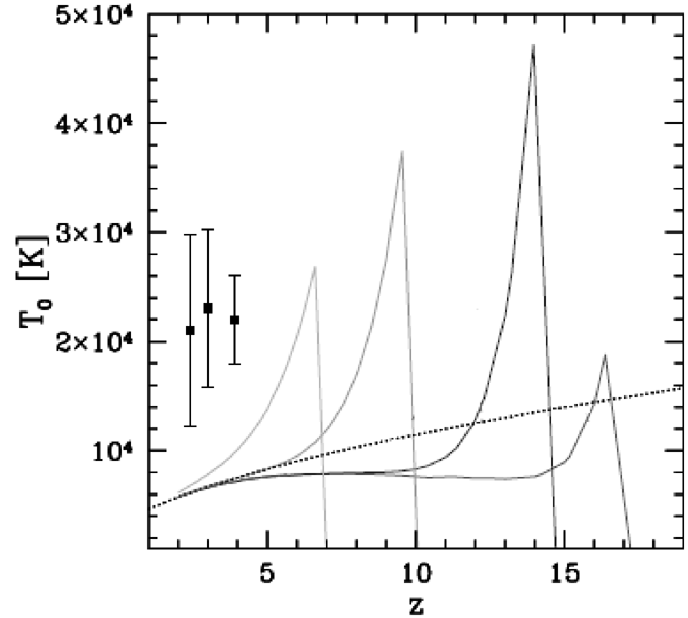
At photoionization equilibrium :

$$T(\rho) = T_0 \left(\frac{\rho}{\rho_0}\right)^{\gamma-1}$$

Hui and Gnedin, 1997



Reionization at
z = 10



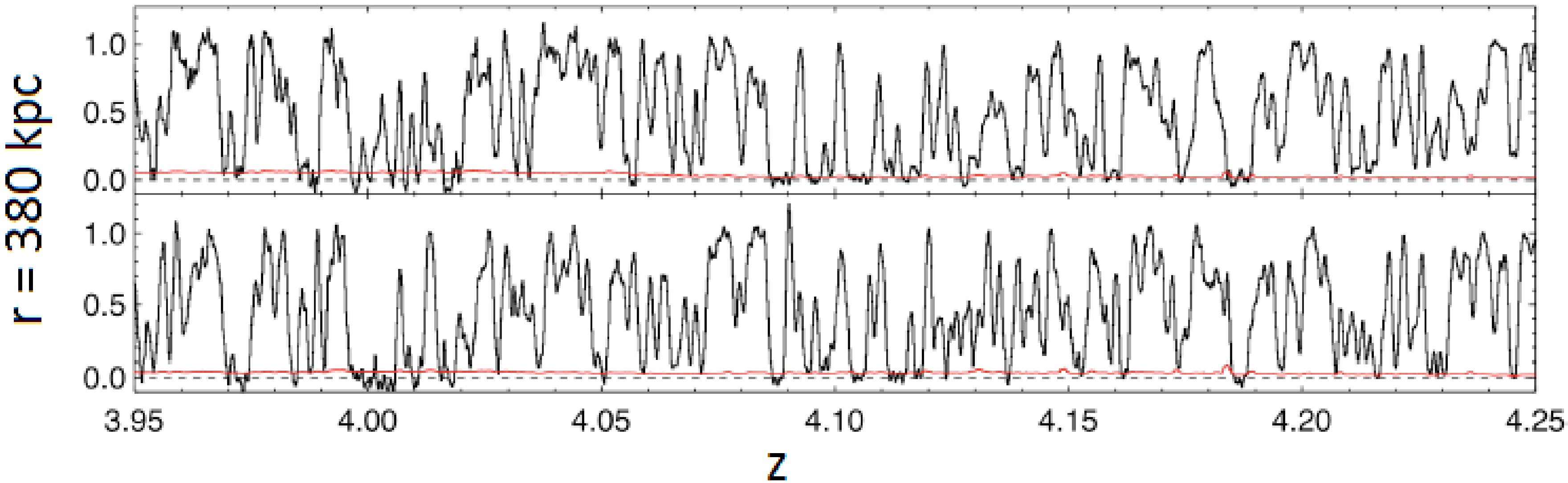
Hui and Haiman 2003 , measurements from Zaldarriaga et al. 2001

The temperature of the IGM provides little information of early reionization events

Probing the IGM with Quasar Pairs

We have a sample of ~ 300 pairs at 1.6 < z < 4.3

(Hennawi et al. 2004,2006,2009)



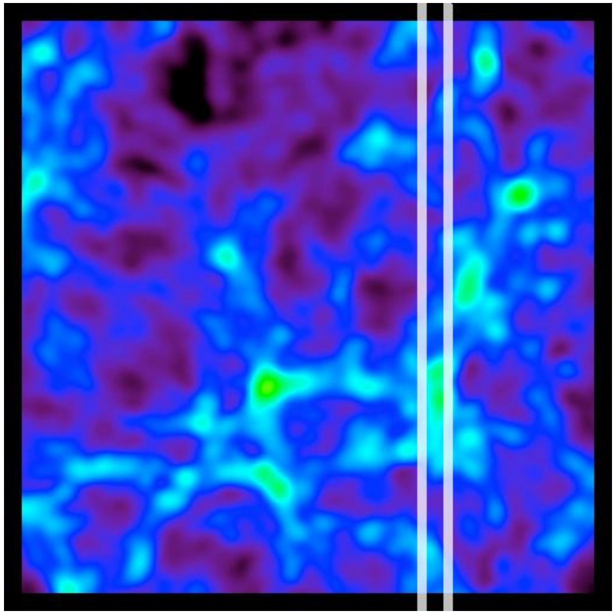
- Close separation (380 comoving kpc)
- High degree of coherence

→ We are observing the Jeans scale at z=4

The effect of temperature on the Lyman-α forest is highly uncertain:

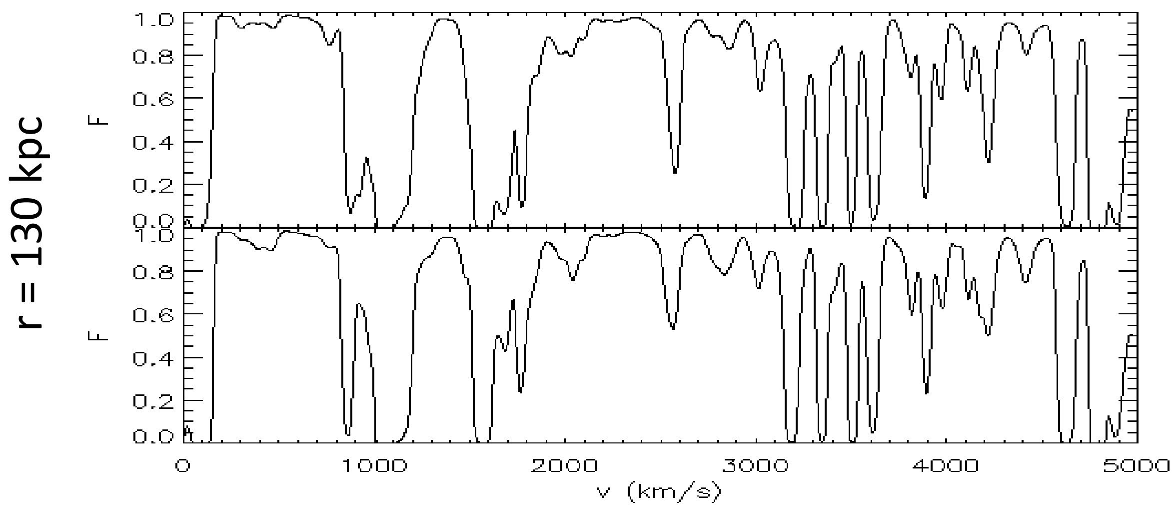
Resolving the Jeans scale in real space can give independent constraints

Methodology: Simulations and Parameter Study



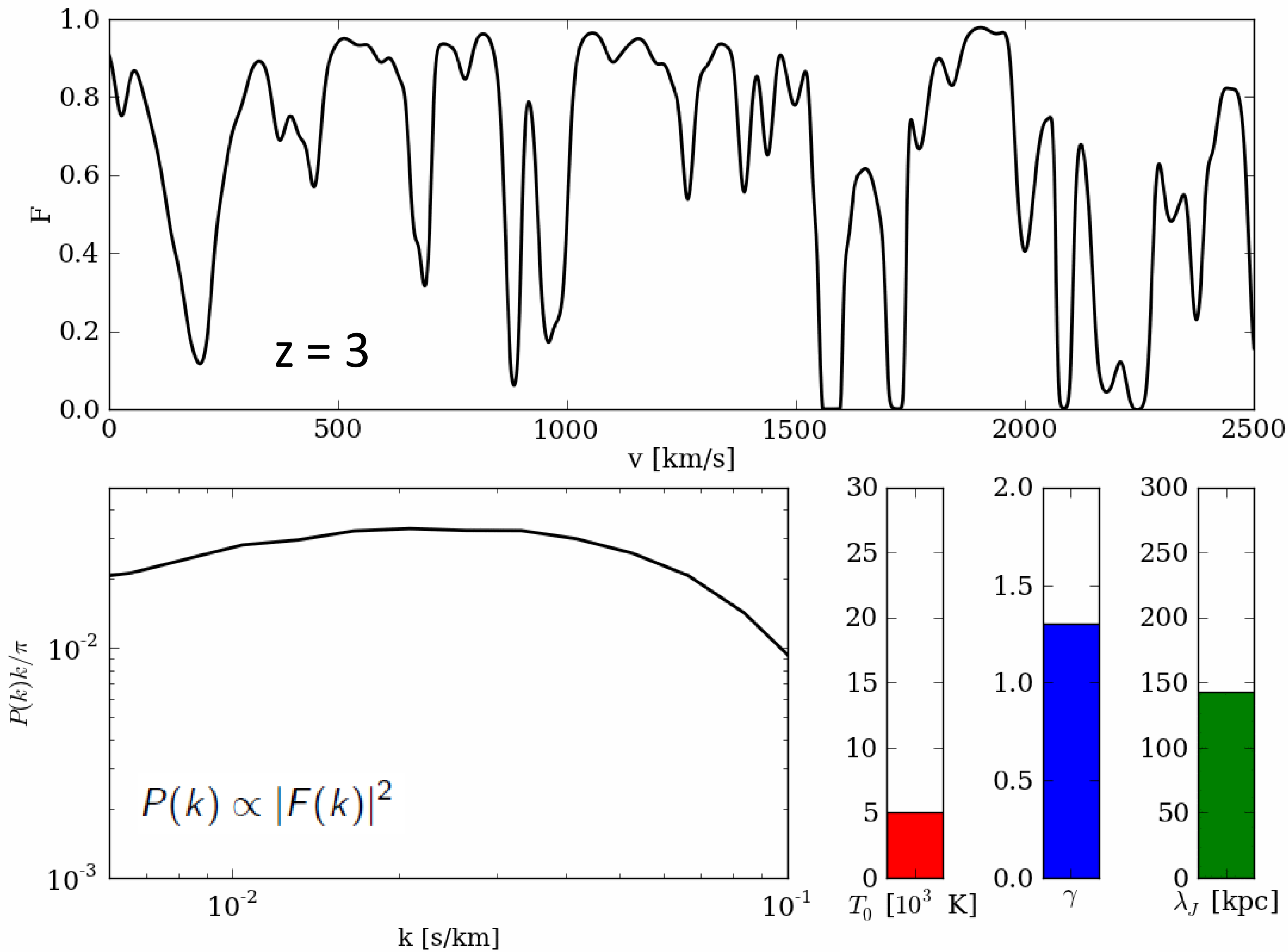
1. Dark matter only simulation, snapshot at z=3
   (Box=50 Mpc/h, n=1500^3)
2. Mimic pressure support by a smoothing density with a kernel of radius λ_J
3. Definition of the equation of state

$$T(\rho) = T_0 \left(\frac{\rho}{\rho_0}\right)^{\gamma-1}$$



We calculate 500 different thermal models, defined by T_0, γ and λ_J

Sensitivity of the LOS Power Spectrum to 1D smoothing



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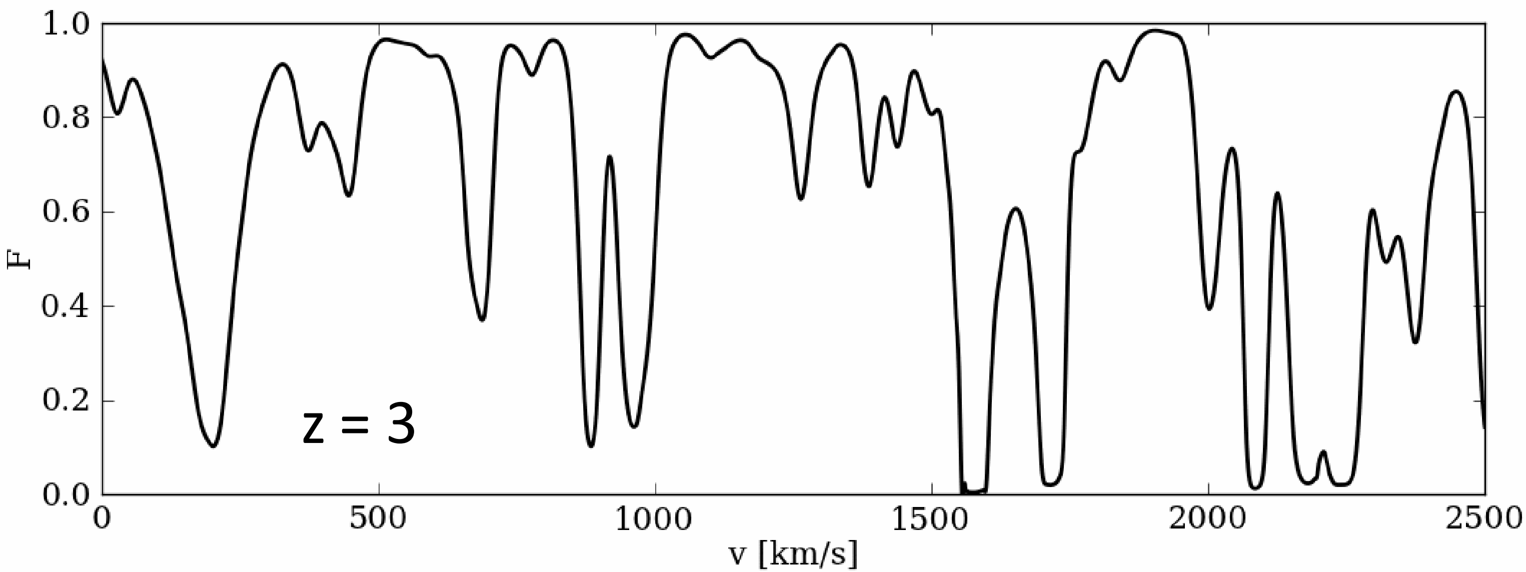
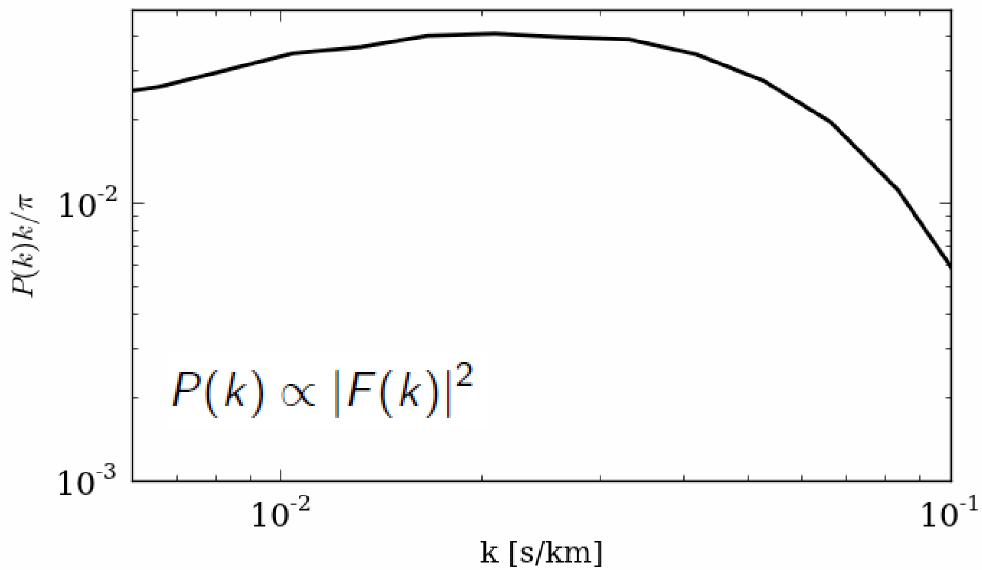
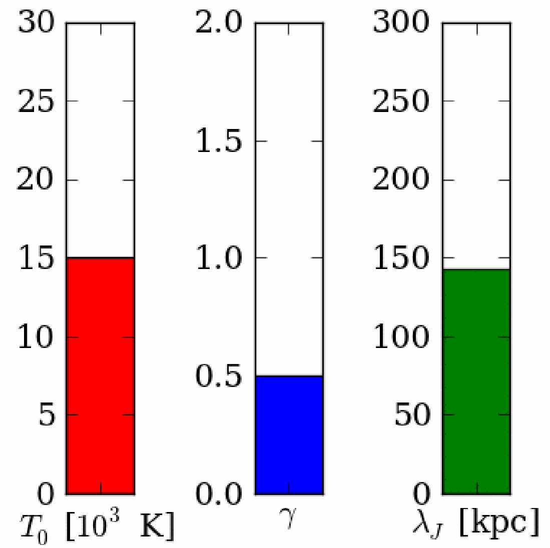
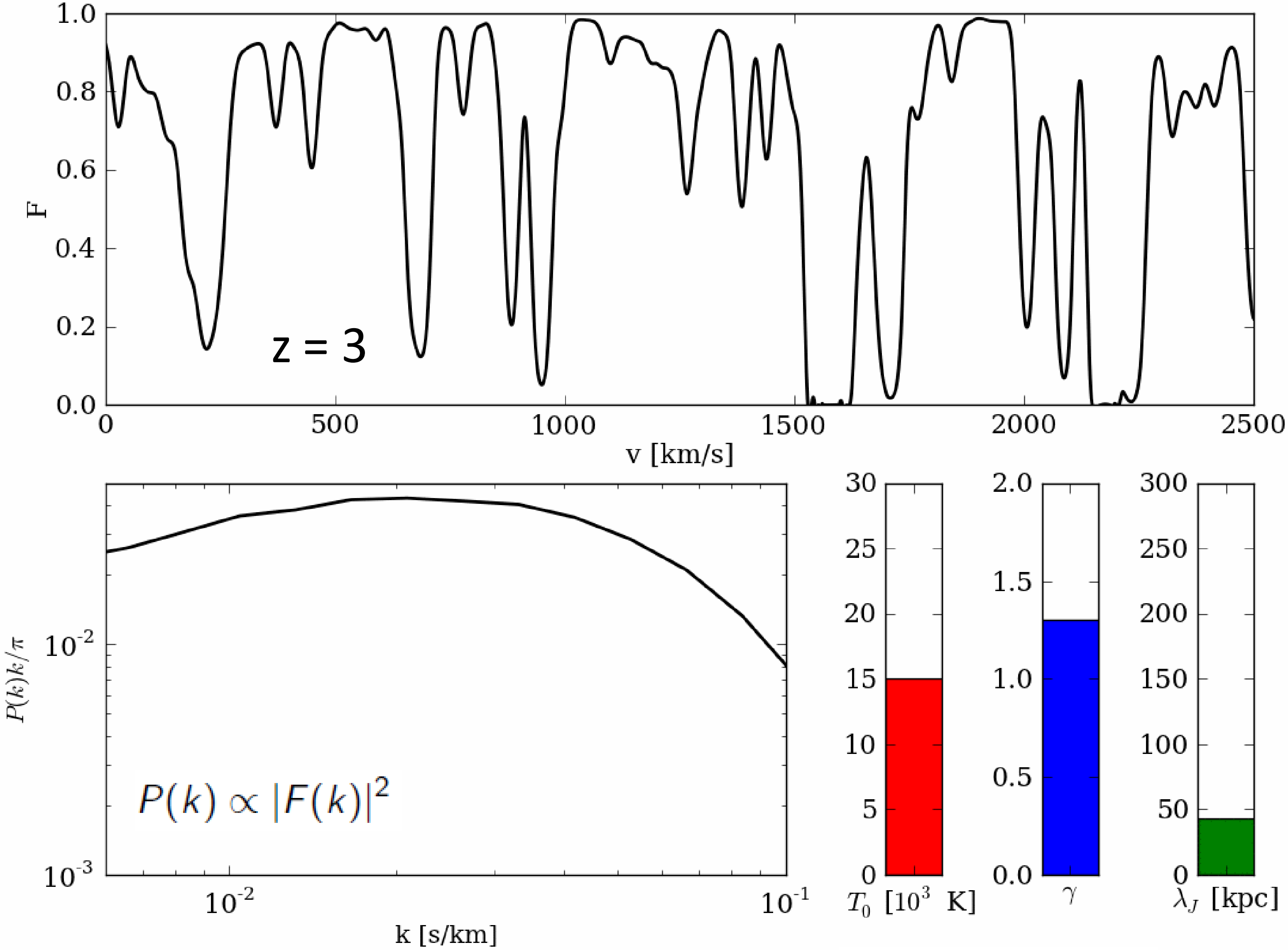






$$T(\rho) = T_0 \left(\frac{\rho}{\rho_0} \right)^{\gamma - 1}$$

Sensitivity of the LOS Power Spectrum to 3D smoothing

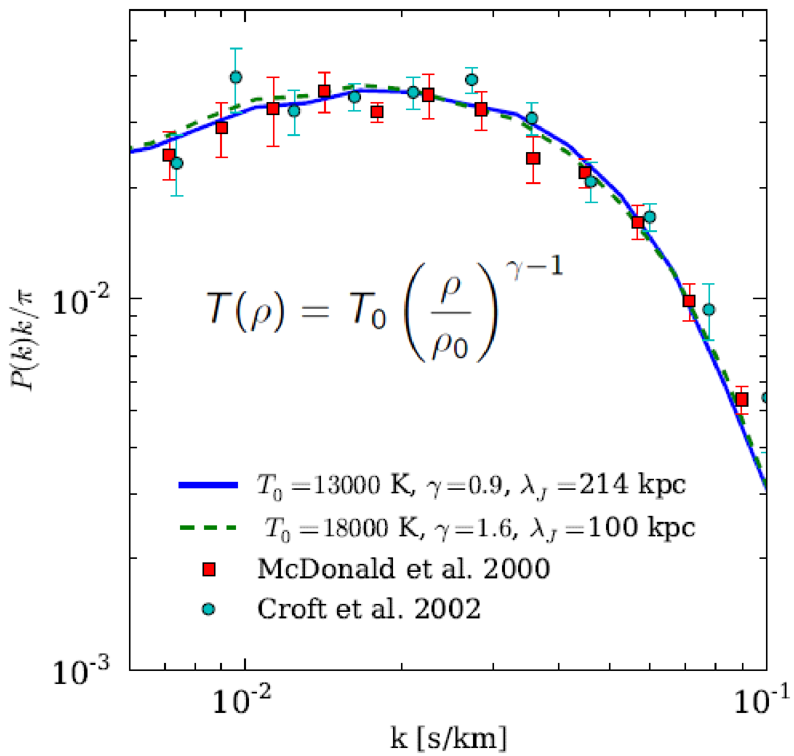


$$T(\rho) = T_0 \left(\frac{\rho}{\rho_0} \right)^{\gamma-1}$$

1D Degeneracies Broken by Pairs

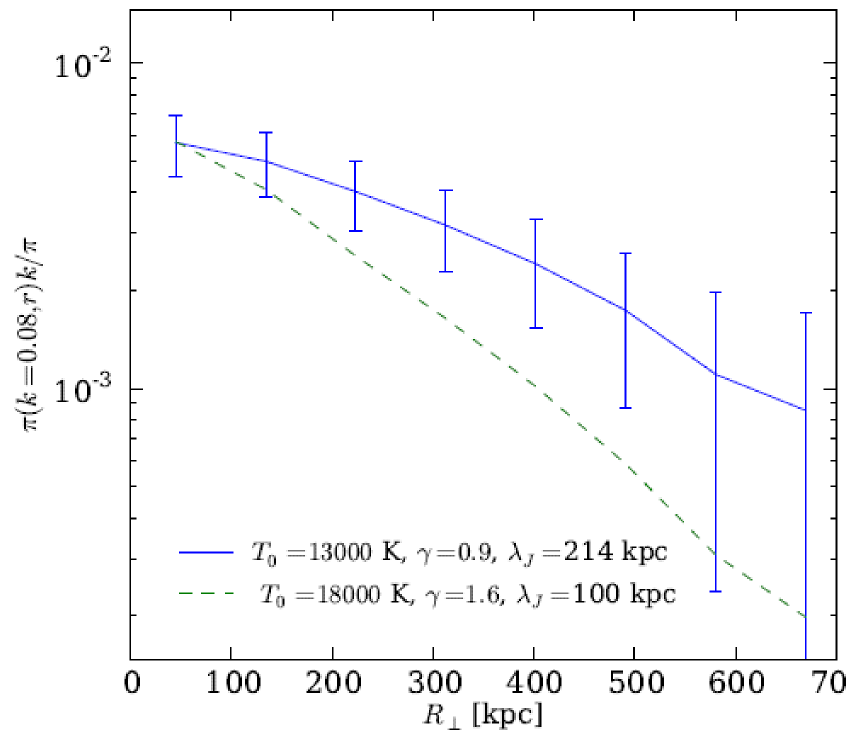
Different thermal models compatible with the measured line-of-sight power

The Jeans scale dominates the transverse coherence



Line-of-sight power spectrum

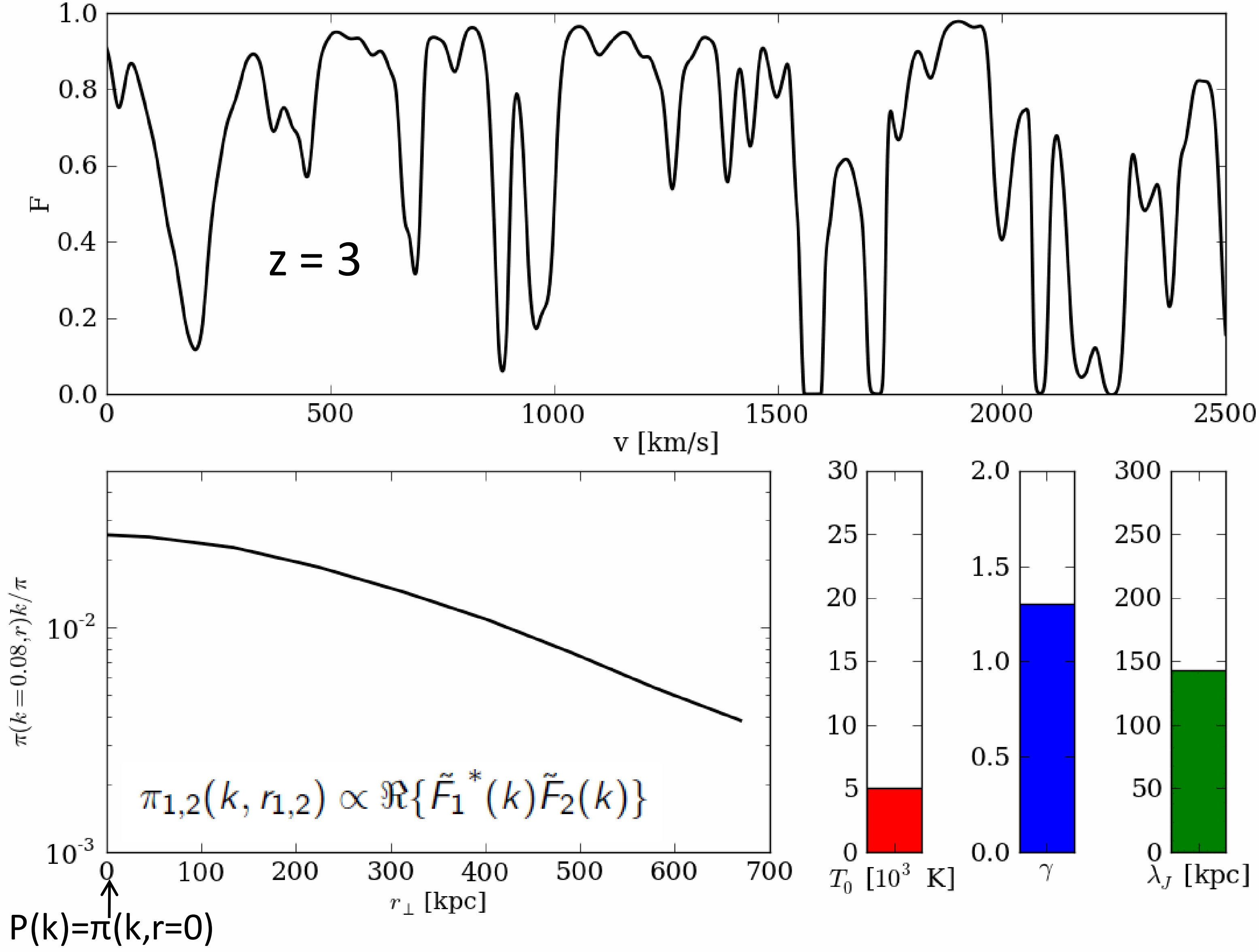
$$P(k) \propto |F(k)|^2$$



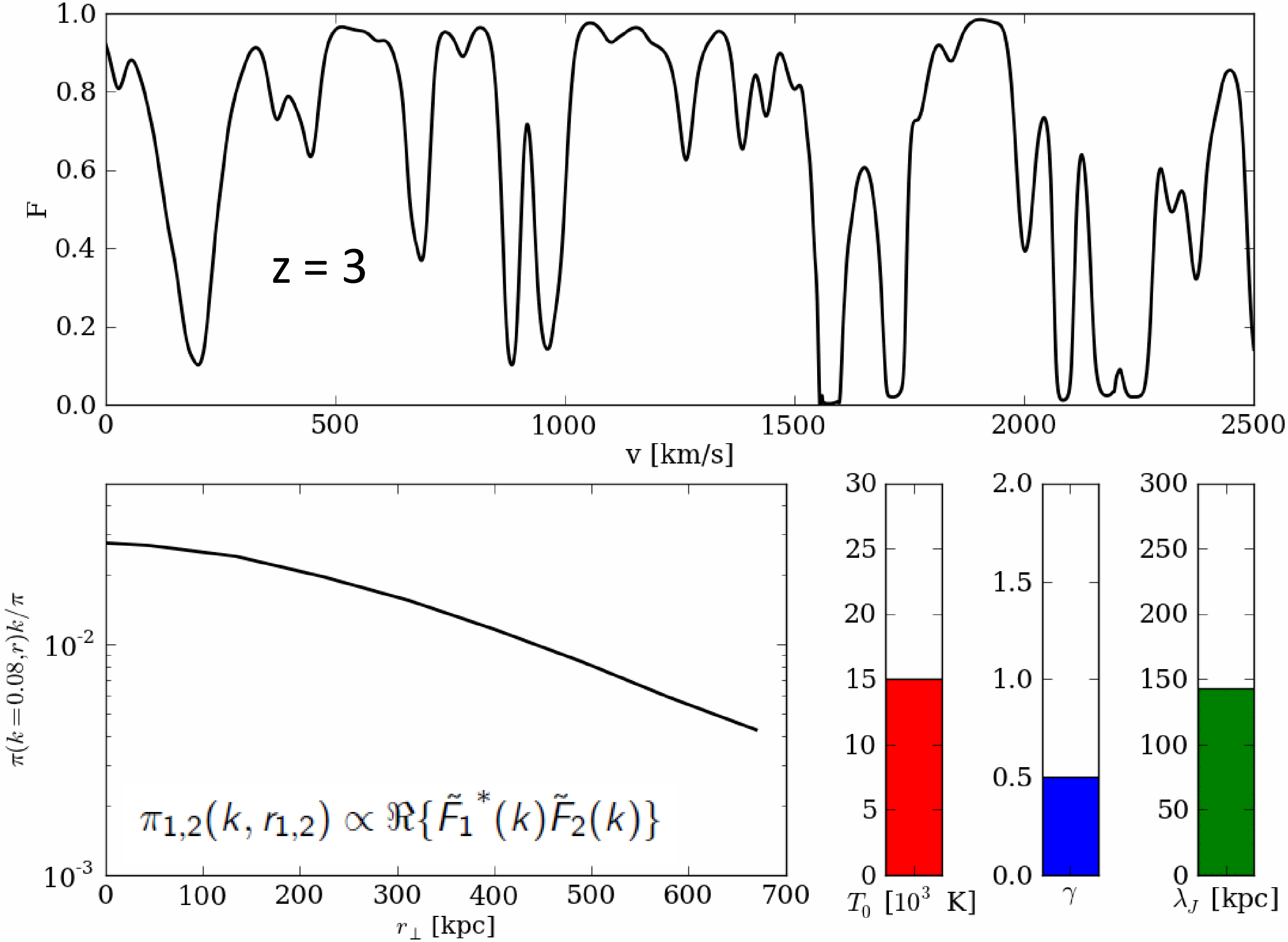
Cross power spectrum

$$\pi_{1,2}(k, r_{1,2}) \propto \Re\{\tilde{F}_1^*(k)\tilde{F}_2(k)\}$$

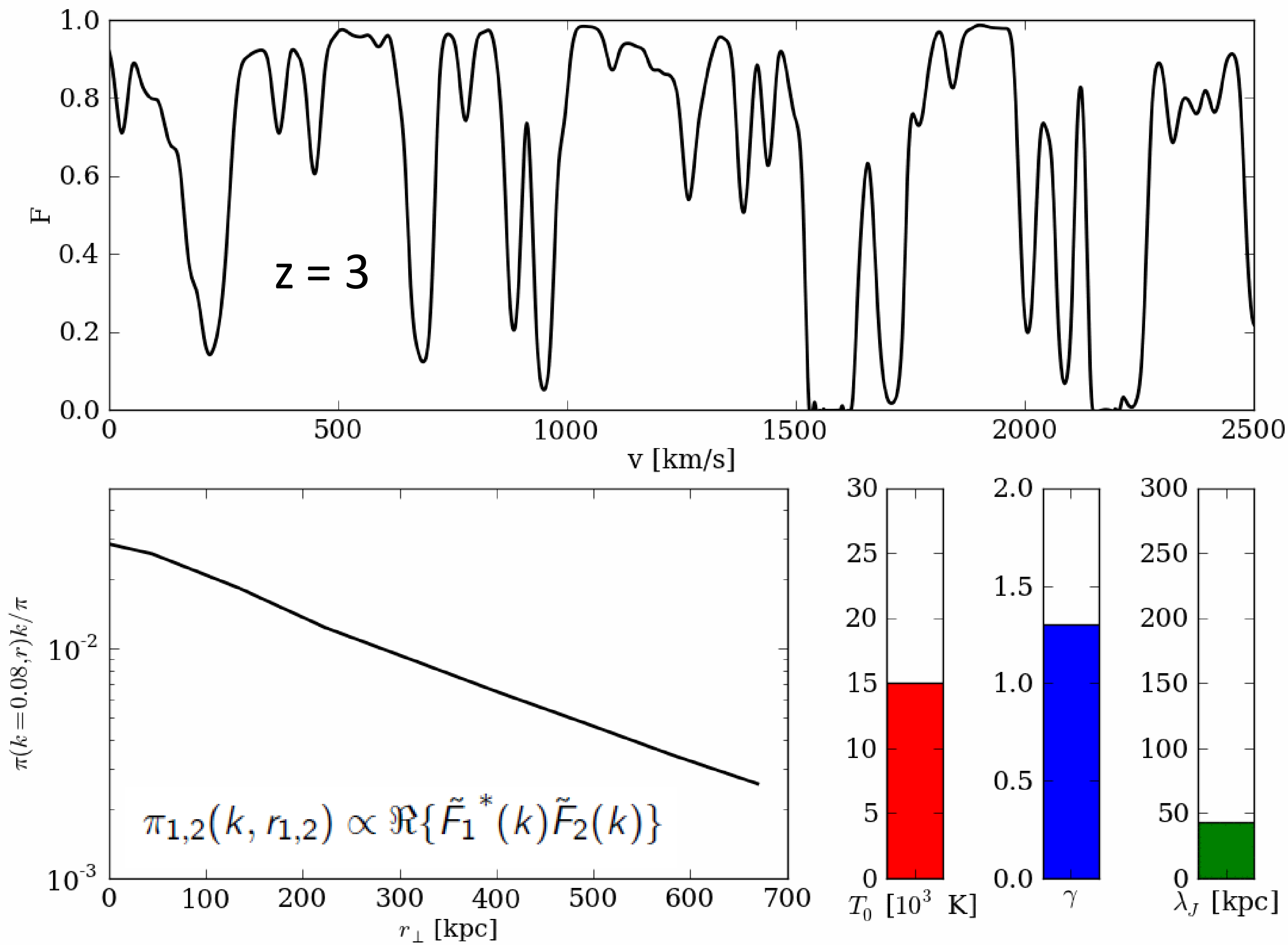
Sensitivity of the Cross Power Spectrum to 1D smoothing



Sensitivity of the Cross Power Spectrum to 1D smoothing

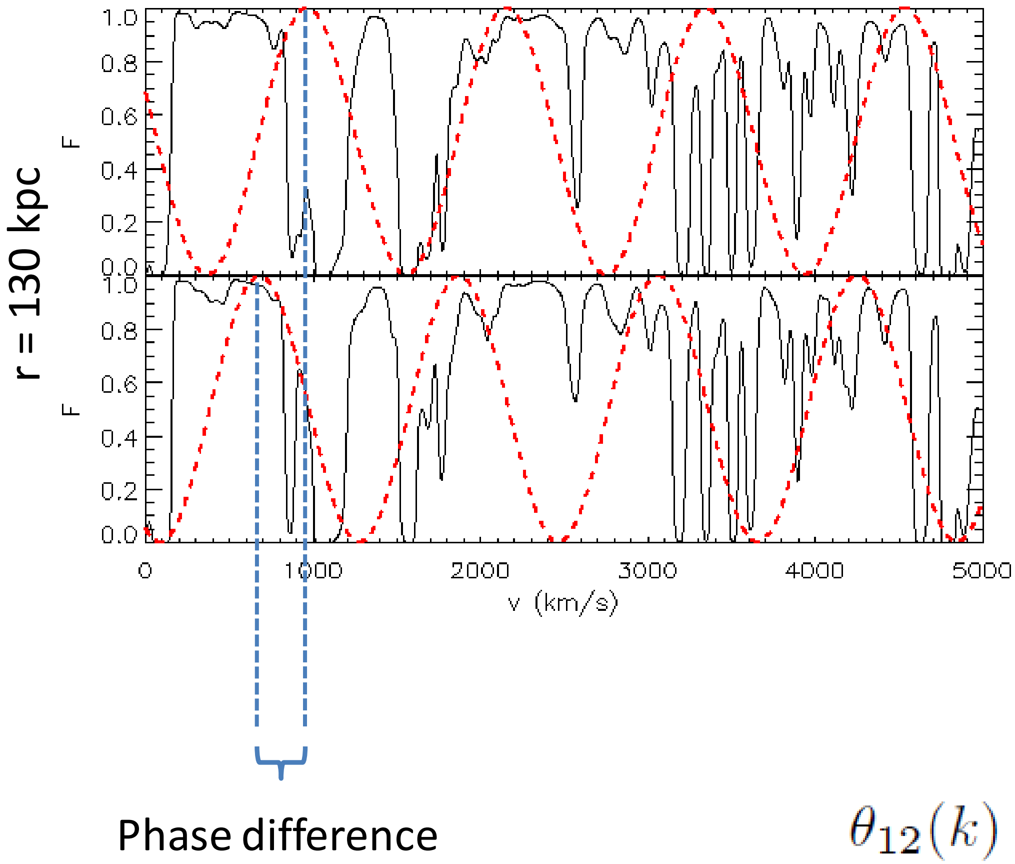


Sensitivity of the Cross Power Spectrum to 3D smoothing



Is Cross Power the Optimal Statistic?

Cross power defined in Fourier space as: $\pi_{1,2}(k, r_{1,2}) \propto \Re\{\tilde{F_1}^*(k)\tilde{F_2}(k)\}$



In terms of moduli and phases:

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

$$\pi(k, r_{1,2}) \propto \rho_1(k)\rho_2(k) \cos\theta_{12}(k)$$

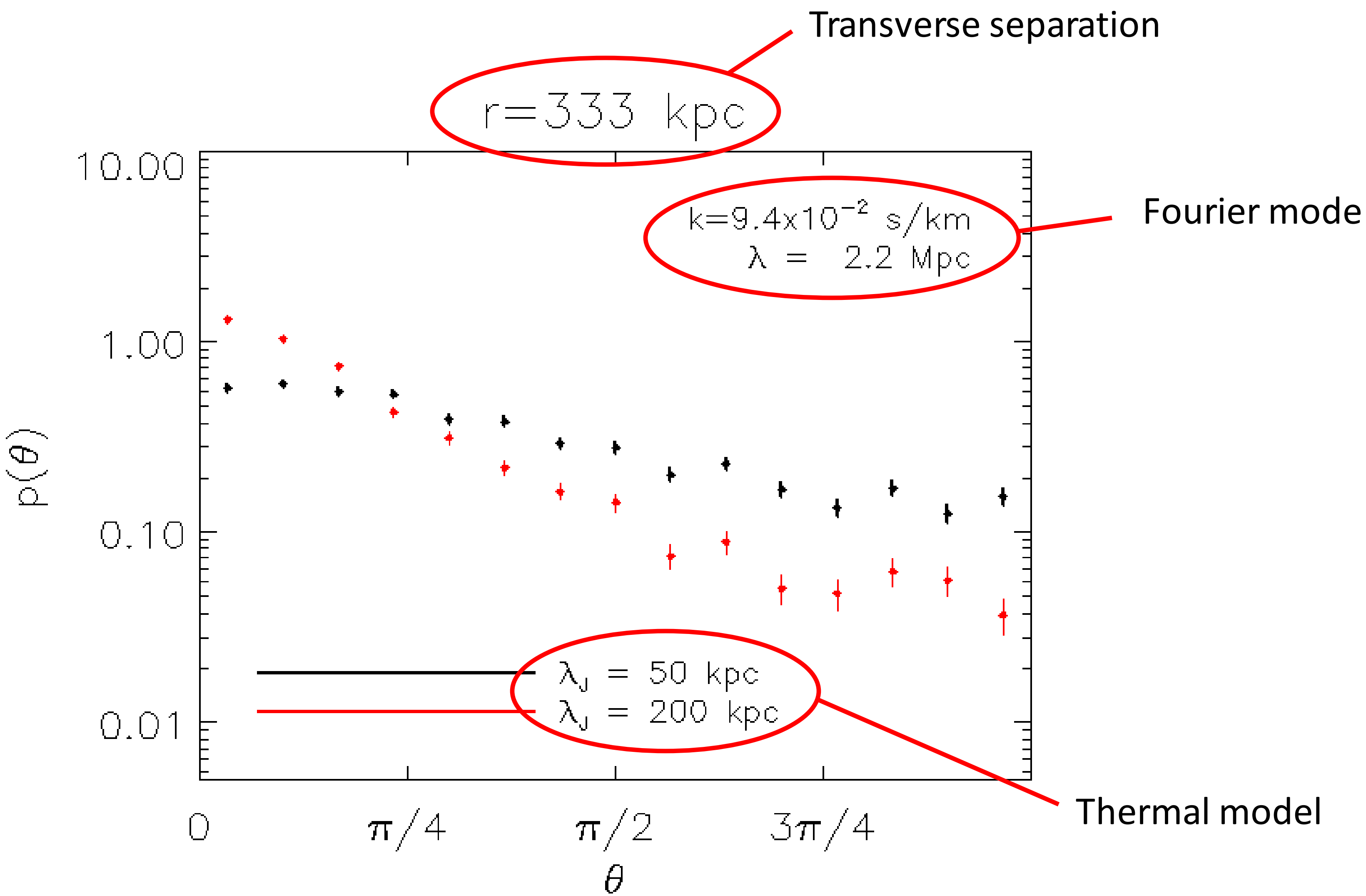
The amplitudes of the modes depend on the LOS power: $P(k) \sim \langle \rho_1 \rho_2 \rangle$

Angular part retains the new 3D information of pairs

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

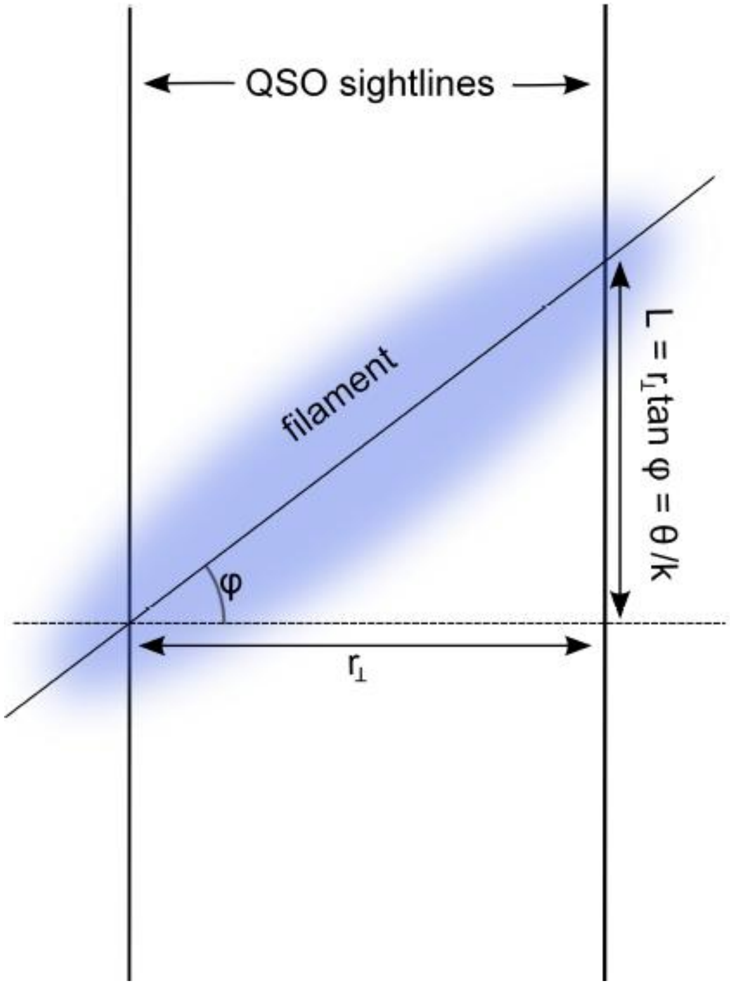
Problem: what is the best estimator for the angular component?

Probability Distribution of Phases



We need a model for the probability distribution

Statistical Distribution of the Phases: Ansatz



• A filament produce absorption features in two close spectra

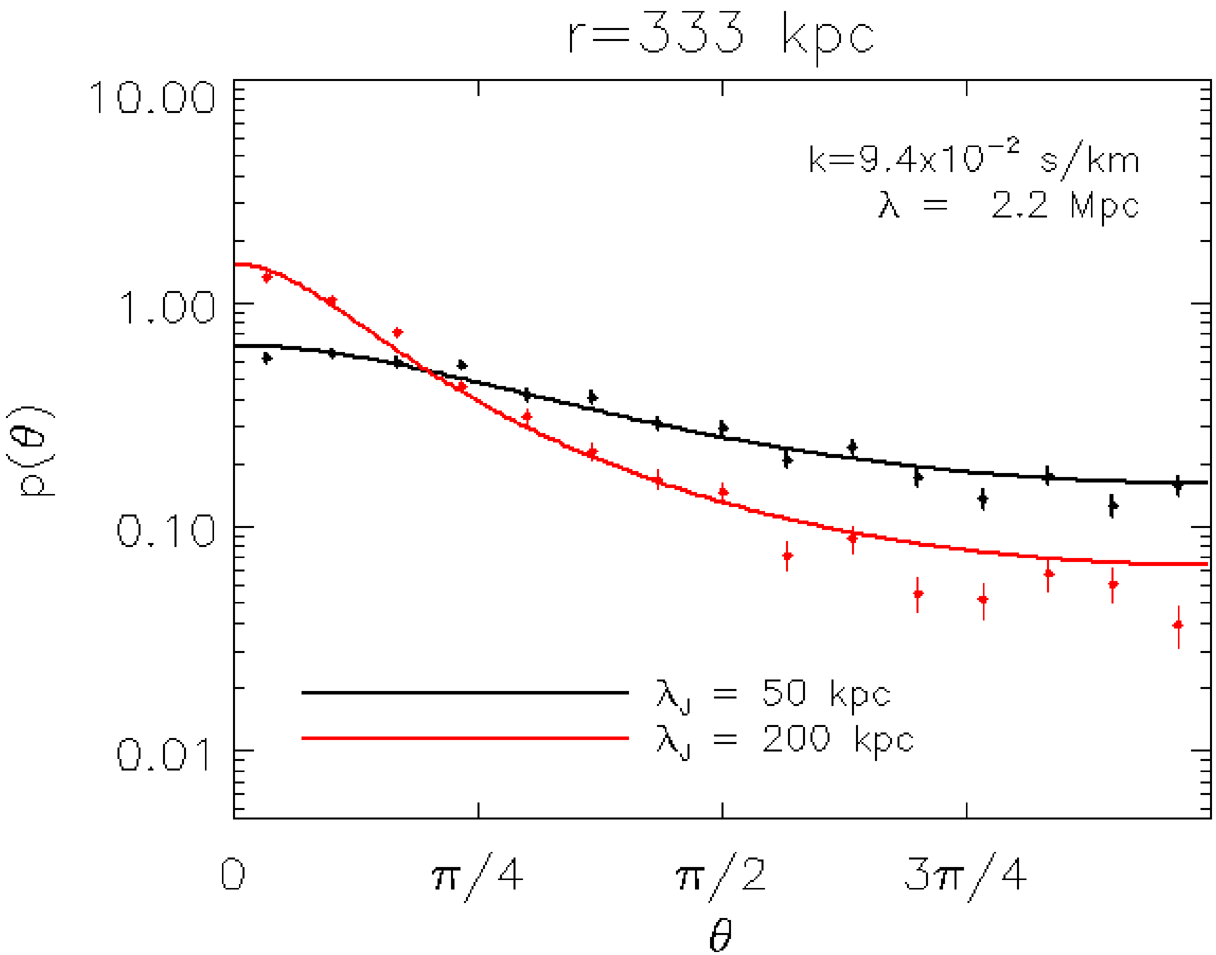
• Phase differences are driven by the orientation of these filaments

•If the orientation φ is uniformly distributed, then the phase Θ follows a *wrapped Cauchy distribution*

$$P_{WC}(\theta;\zeta) = \frac{1}{2\pi}\frac{1-\zeta^2}{1+\zeta^2-2\zeta\cos(\theta)}$$

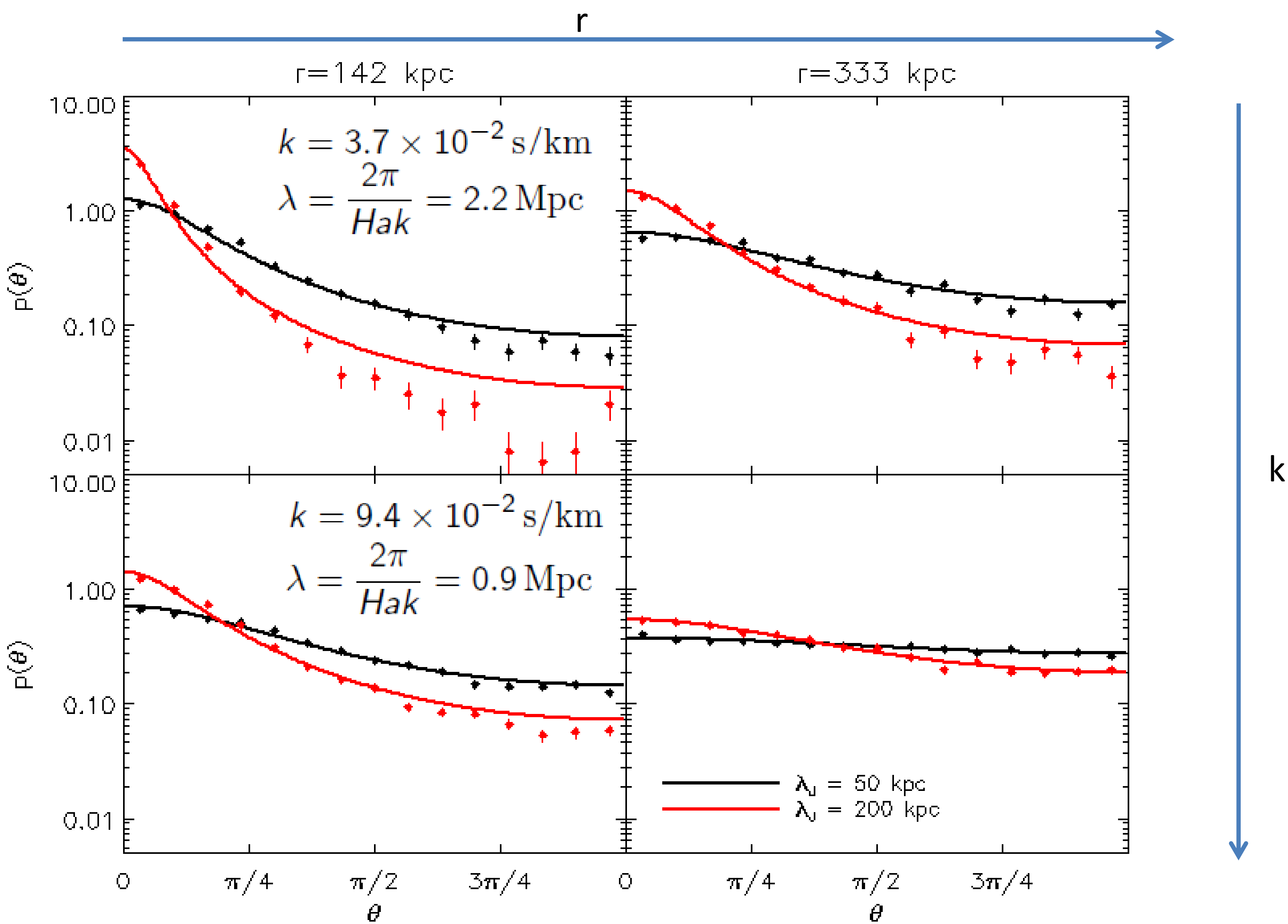
Defines a 1-parameter family of functions

Probability Distribution of Phases



Wrapped-Cauchy fits well our simulations

Dependencies of the Phase Distributions



A Bayesian Likelihood for the Phase PDF

1 - A quasar pair data set provides a set of phase differences $\{\Theta(k_i, r_j)\}$

2 - We predict the probability of measuring those phases for each of the 500 thermal models *(Likelihood function)*

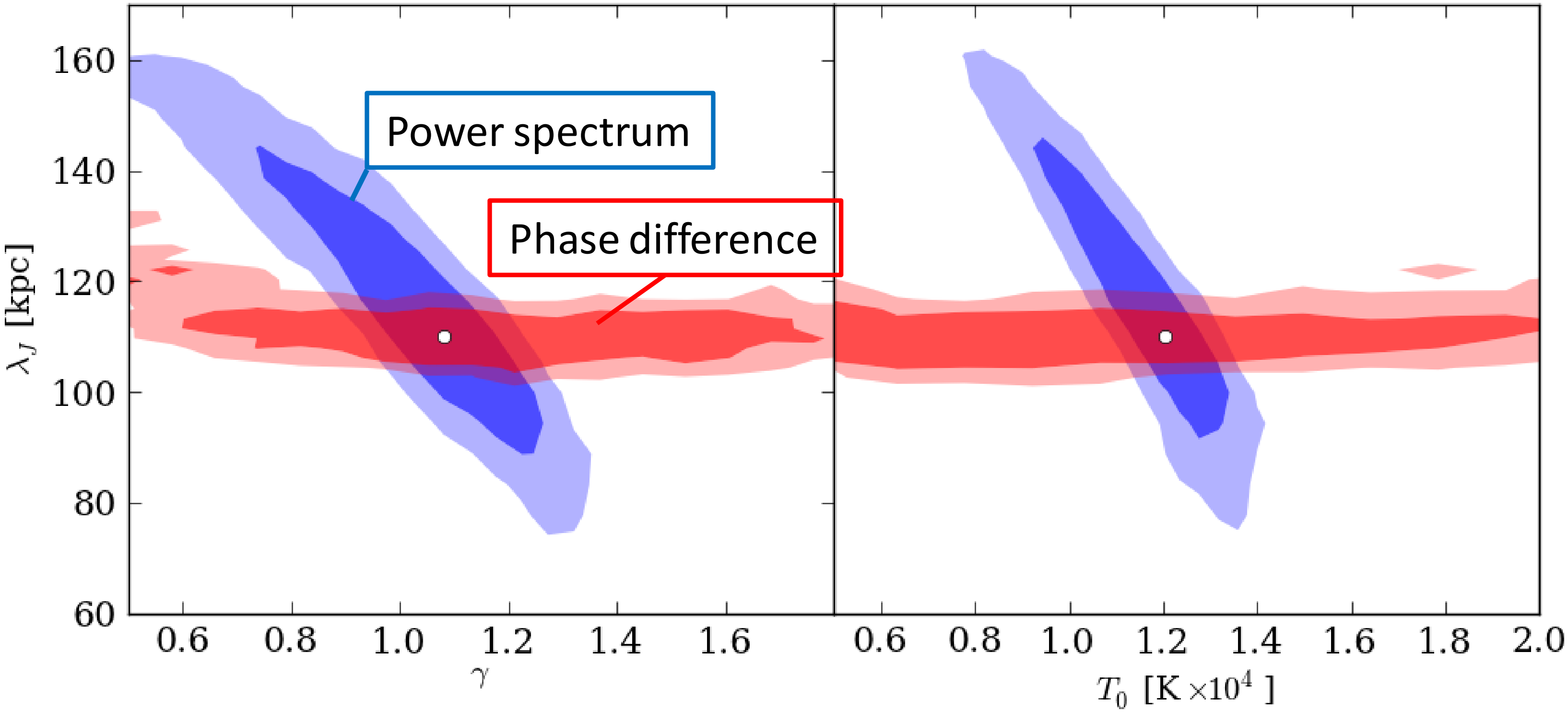
$$L(\{\theta\}|T_0, \gamma, \lambda_J) = \prod_{i,j} P(\theta(k_i, r_j)|T_0, \gamma, \lambda_J)$$

3 - Via MCMC techniques, we do a Bayesian analysis of parameter space, estimating:

- **Degeneracies** between parameters
- **Accuracy** of a measurement

Estimated Constraints on Thermal Parameters

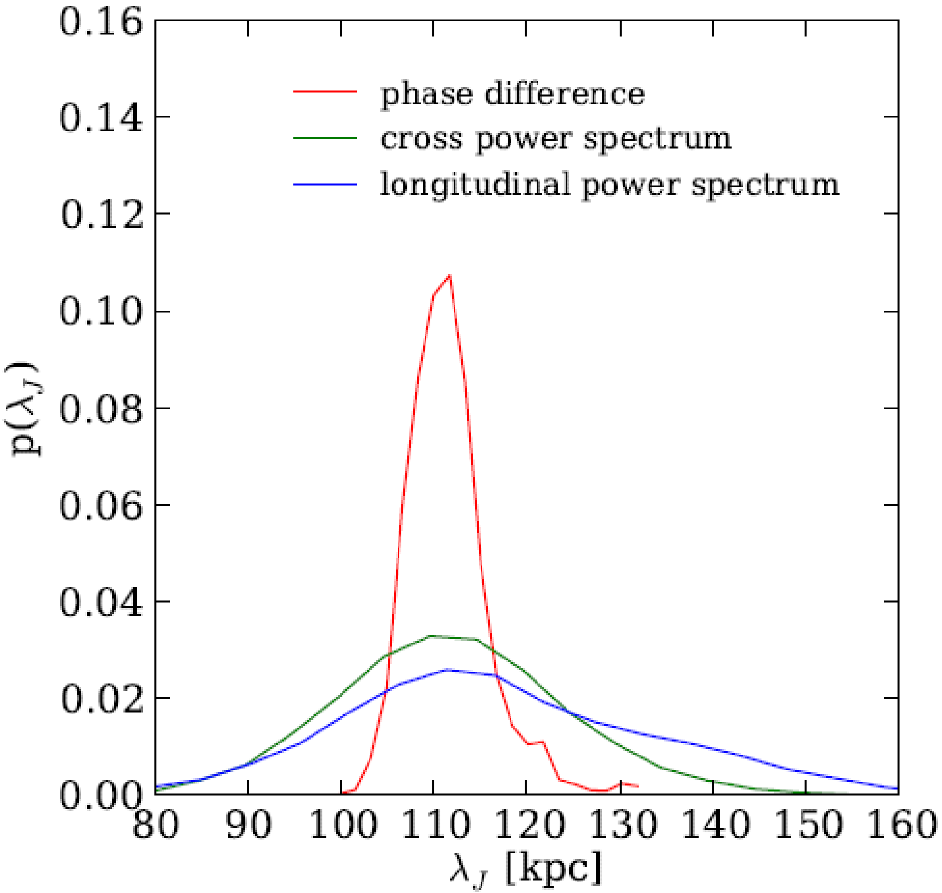
We assume a sample of 20 spectra (LOS power)
20 pairs (phase difference)



Rorai et al. 2013

Jeans scale measurements are independent on the equation of state

Accuracy of the Jeans Scale Measurement



We can achieve a precision up to 5% with only 20 pairs

Phase difference statistic is by far more efficient than LOS power and cross-power

Typical precision of IGM temperature measurements is ~ 30%

Noise decreases the precision by few %

Nice Properties of Phase Differences

- Invariant under convolution with symmetric Kernel W

$$W(k) = \int \underbrace{W(x)}_{\text{even}} \cos(kx) + i \int \underbrace{W(x)}_{\text{even}} \underbrace{\sin(kx)}_{\text{odd}} = \text{real} \longrightarrow \text{No change in phases}$$

  - Thermal Broadening has very small effect
  - Resolution does not need to be precisely modeled

- Sensitive to the Jeans scale also at low k
  - High-resolution spectra are not required if we resolve the Jeans scale in the transverse dimension

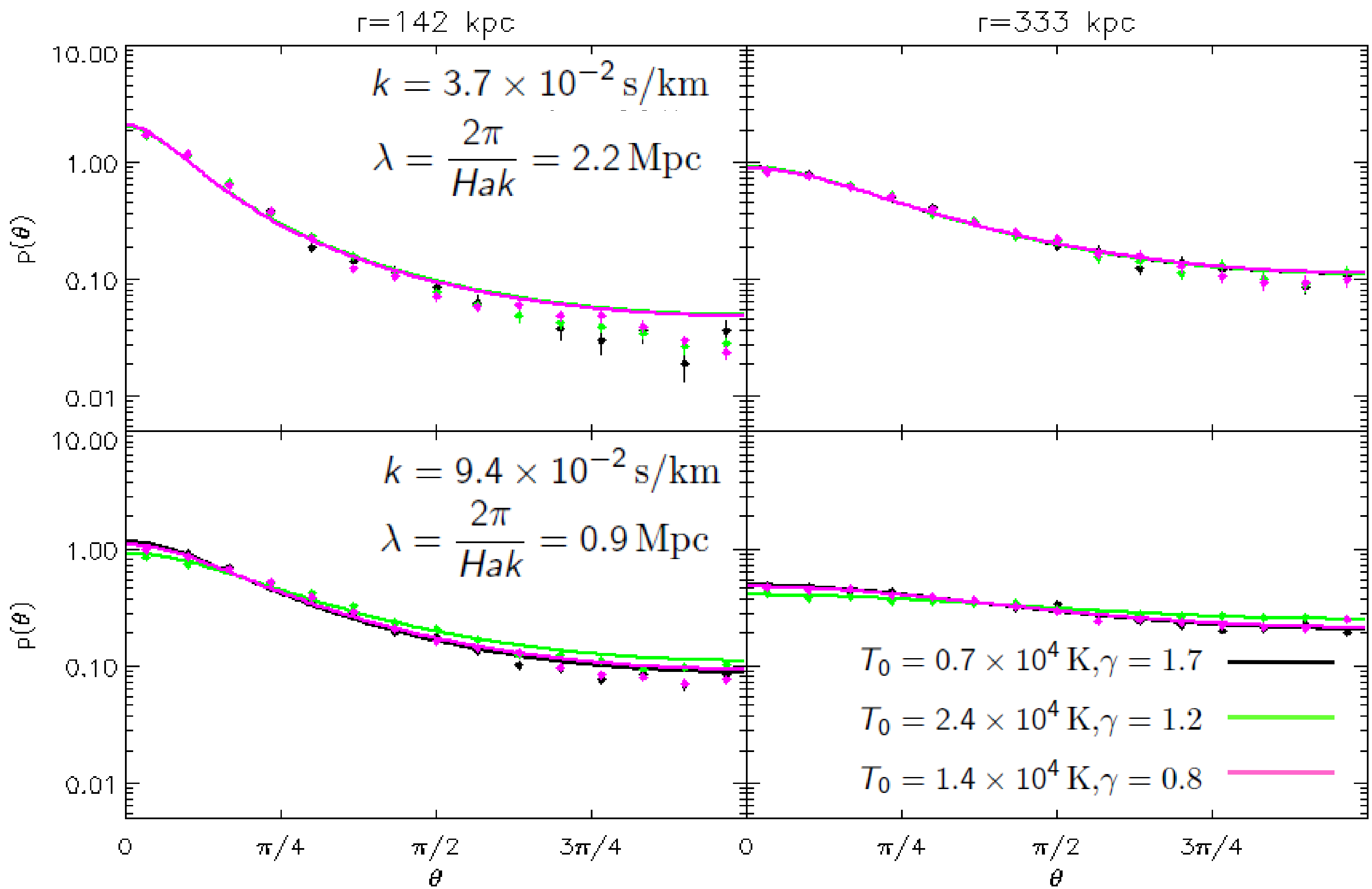
$$P(k) = \int_k^\infty 2\pi k' P_{3D}(k') dk'$$

- Invariant under rescaling of the *normalized* flux

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

  - Robustness to uncertainties in continuum fitting

Sensitivity to the Equation-of-State Parameters



Phases are almost independent of the equation of state

Summary

- The Jeans scale is a key quantity for galaxy formation, reionization and thermal history

- Close QSO pairs will provide a first accurate measurement of the Jeans scale

- The phase analysis is insensitive to the equation of state parameters T_0 and ϒ

- Combining this with others ly-α forest statistic can break degeneracies and give tight constraints on the thermal history of the IGM