Clustering Distortions from Lyman-alpha Radiative Transfer

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Motivation

- Ly-α: Prominent emission line for high-z galaxies

Opportunity:

- Low redshifts ($2<z<3.5$): Cosmology with HETDEX
- High redshifts: Complementary reionization probe

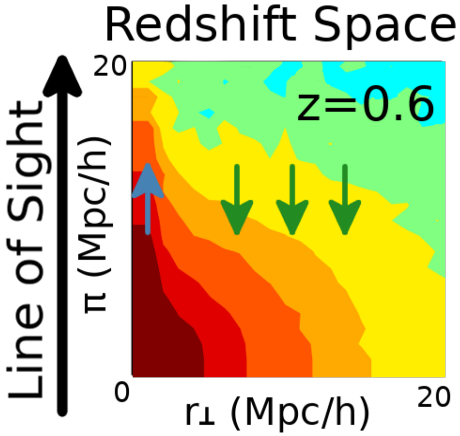
Theoretical Challenge:

- Resonant line with high optical depths

→Complex radiative transfer → Numerical simulations

RT Distortion #1: arXiv:1710.06171 (C. Behrens, **CB** et al.)
RT Distortion #2: in prep (**CB**, S. Saito et al.)

Reminder: Redshift Space Distortions



(Reid et al., 2012)

$$\vec{s} = \vec{r} + \frac{\vec{v} \cdot \hat{\pi}}{aH(z)}\hat{\pi}$$

Kaiser effect: **Squashing** due to **coherent** motion on large scales

Fingers-of-God effect: **Elongation** due to **random** motion on small scales

Radiative Transfer Distortions

Classic Redshift Space Distortions

Kaiser effect

Squashing due to **coherent** *motion* on large scales

Fingers-of-God effect

Elongation due to **random** *motion* on small scales

Radiative Transfer Distortions

RT Distortion #1

Elongation due to coherent *attenuation* on large scales

RT Distortion #2

Elongation due to random *spectrum* on small scales

Numerical Simulations

RT Distortion #1

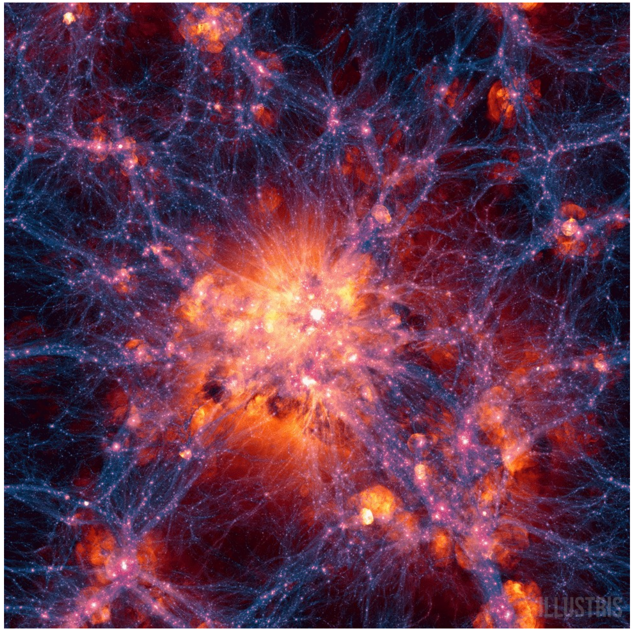
Elongation due to due coherent *attenuation* on large scales

RT Distortion #2

Elongation due to random *spectrum* on small scales

Numerical Simulations – Illustris

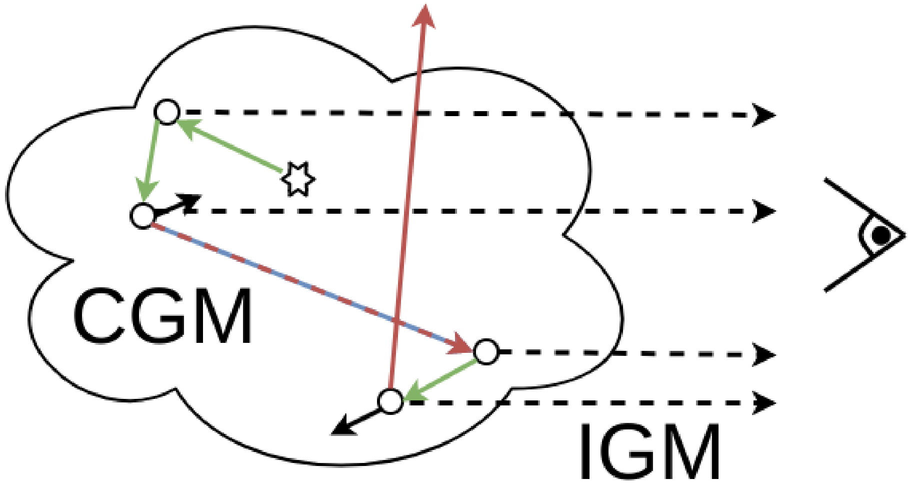
- Set of cosmological simulations run with AREPO for DM+BM physics.
- Public snapshots/halo catalogs
- Voronoi → Octree for RT simulation



Illustris Simulation

$$\mathrm{L{=}75\ Mpc/h\ /\ \Delta_{res} \approx 1\ ckpc\ /\ m_{BM/DM} = (12.6/62.6)\cdot 10^5 M_\odot}$$

Numerical Simulations – Radiative Transfer

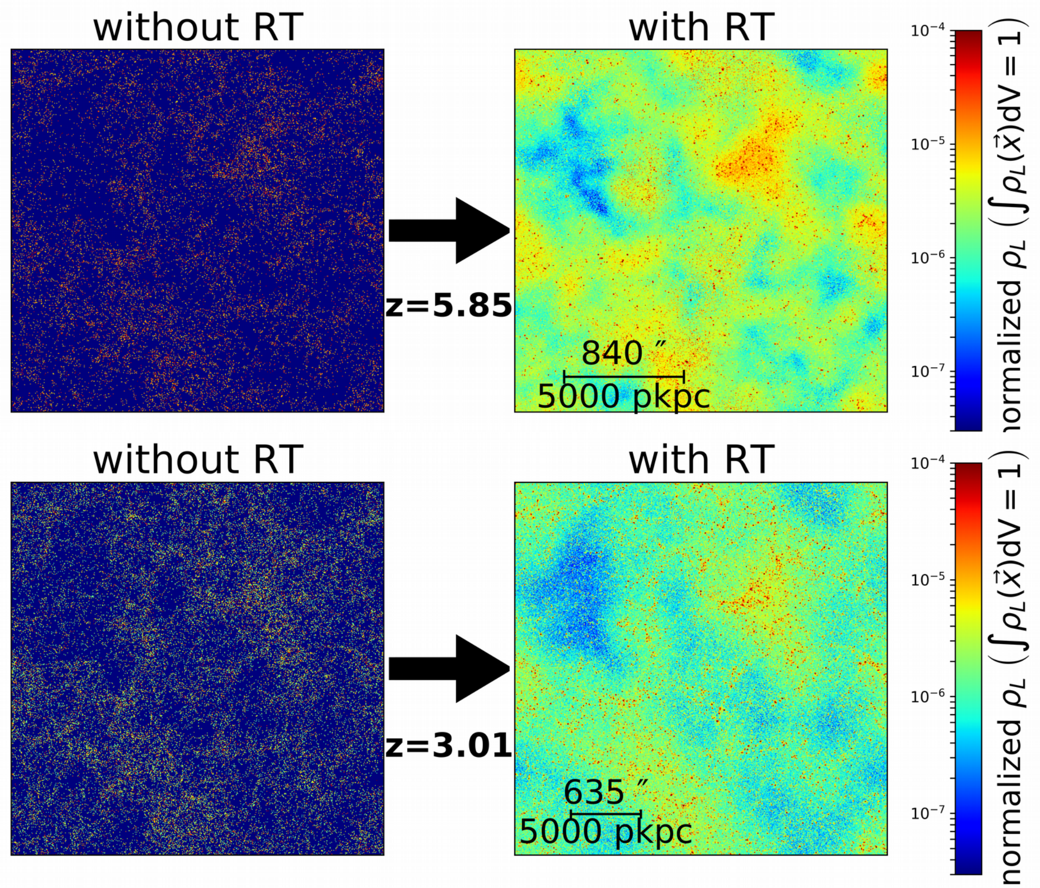


- Monte Carlo Approach
- Spawn weighted photons according to local *luminosity* and *spectrum*
- At scatterings, compute attenuated luminosity reaching observer.

Numerical Simulations – Emitter Assumptions

- Assign to luminosity and spectrum to (sub)halos:
  - All emission in sub(halo) center
  - $\mathrm{L} = \frac{\mathrm{SFR}}{\mathrm{M}_\odot/\mathrm{yr}} \cdot 10^{42}\ \mathrm{erg/s}$
  - Gaussian with $\sigma_{\mathrm{int}} \propto T_{\mathrm{vir}}^{1/2}$
  - Cut out ISM, no dust, no escape fraction…

Numerical Simulations – Visual Results



Numerical Simulations

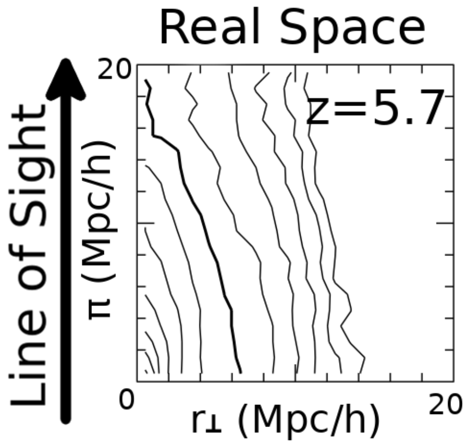
RT Distortion #1

Elongation due to due coherent *attenuation* on large scales

RT Distortion #2

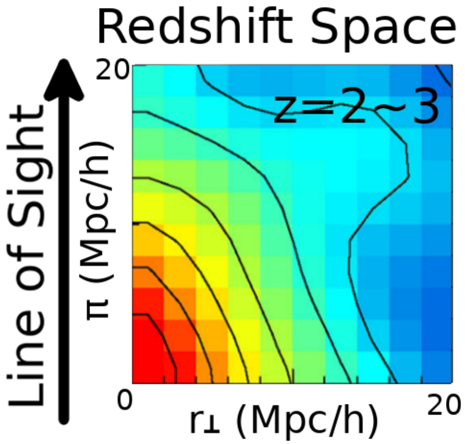
Elongation due to random *spectrum* on small scales

RT Distortion #1 – Introduction



Theory

- (Zheng et al., 2011) find anisotropic clustering due to a *Selection Effect*

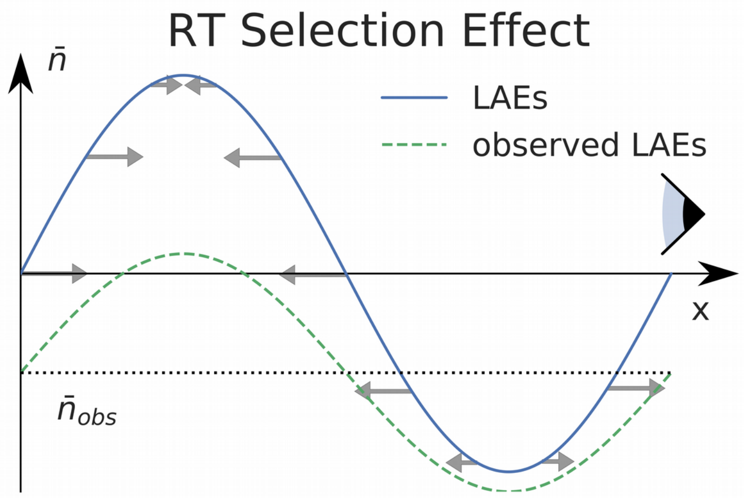


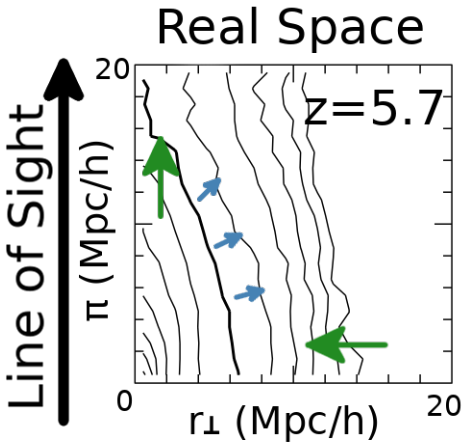
Observation

- (Croft et al., 2016) observe similar clustering effect
- Problem for Lyα surveys, such as HETDEX?

RT Distortion #1 – Explanation

- Attenuation correlates with:
  - Density (isotropic)
  - Velocity gradient (anisotropic)

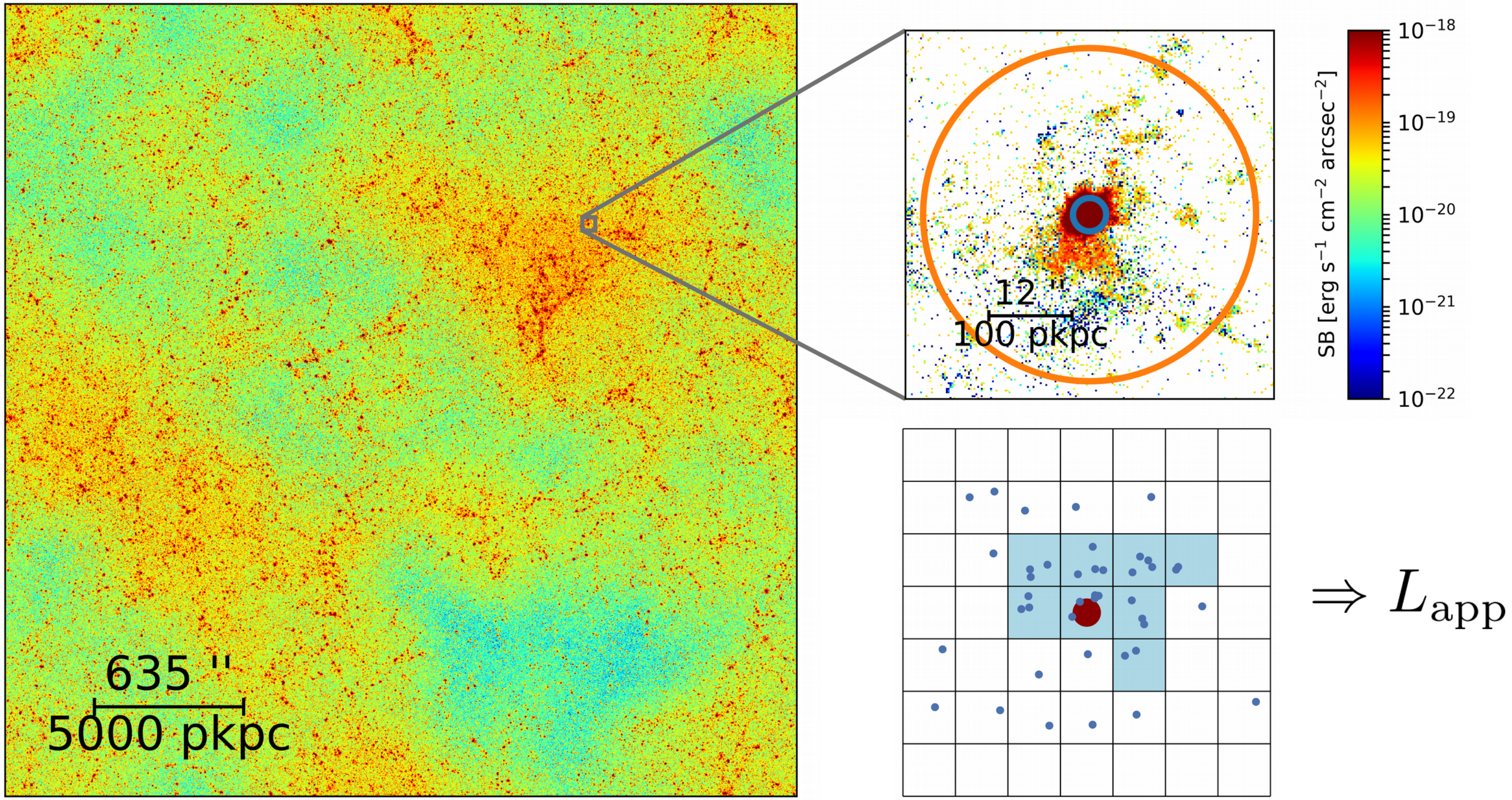




(Zheng et al., 2011)

- Resulting clustering signal:
  - Bias ↘
  - Clustering ↘ along line of sight
  - ↗ perpendicular

RT Distortion #1 – Results: Mock Observations

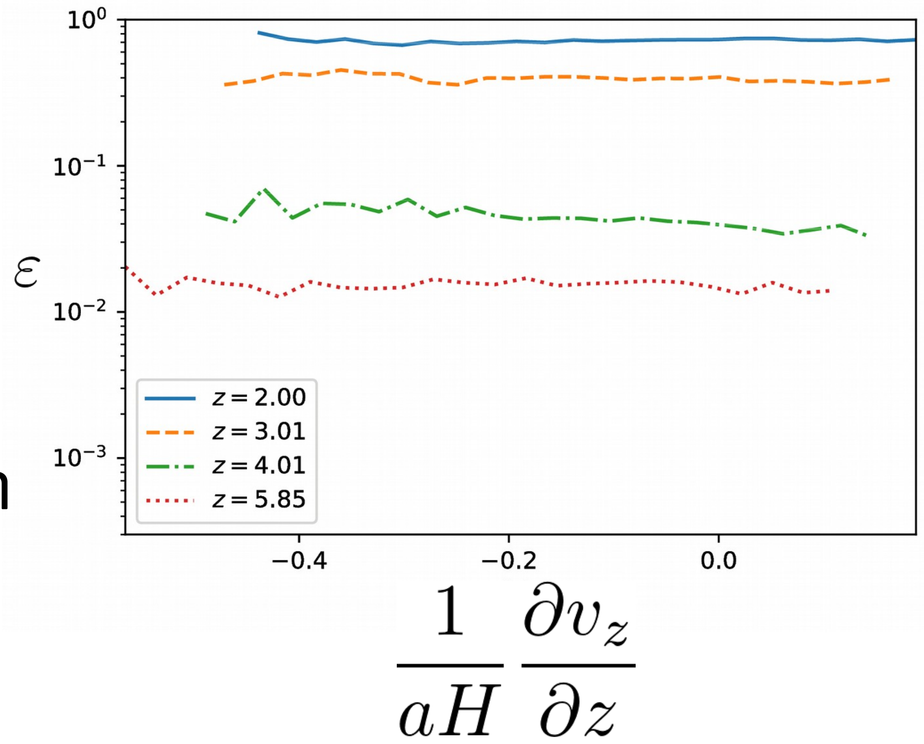


RT Distortion #1 – Results: LSS correlations

- Define the observed fraction as

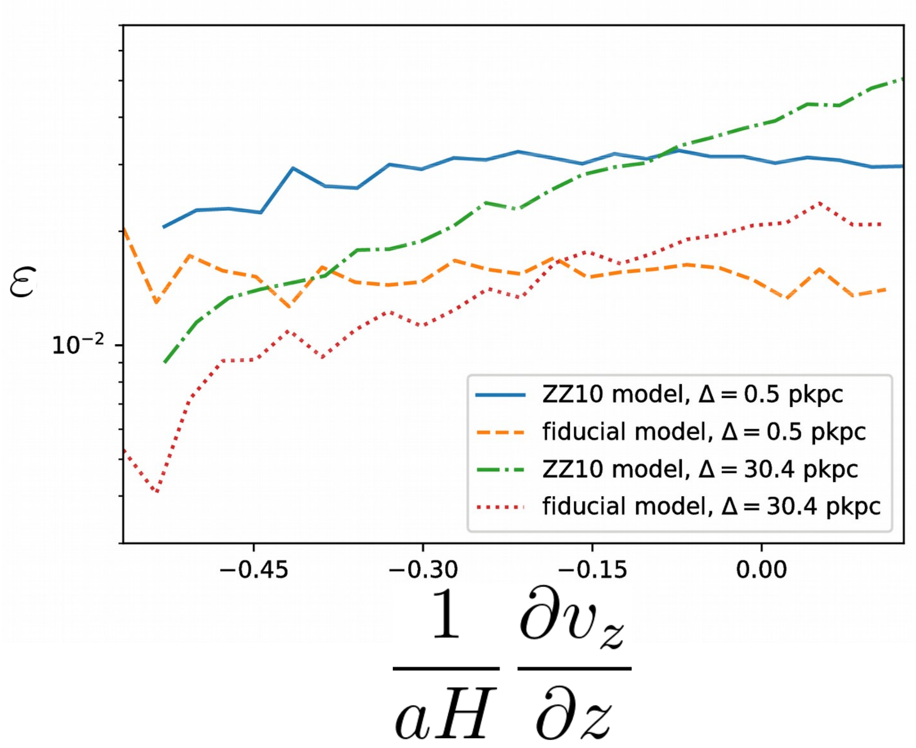
$$\varepsilon = L_{\rm app}/L_{\rm int}$$

- Finding no correlation with LSS → no clustering distortion

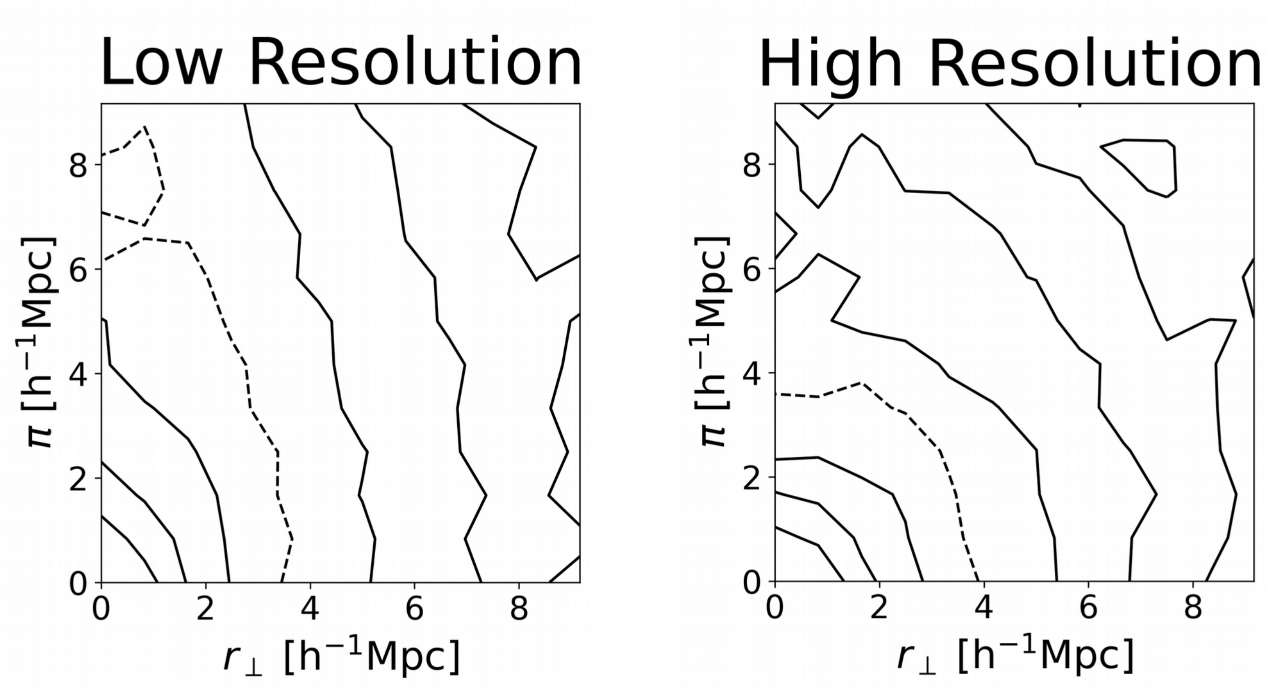


RT Distortion #1 – Results: LSS correlations

- Try to reproduce ZZ10/11:
  - Lower resolution
  - Adjust emitter model



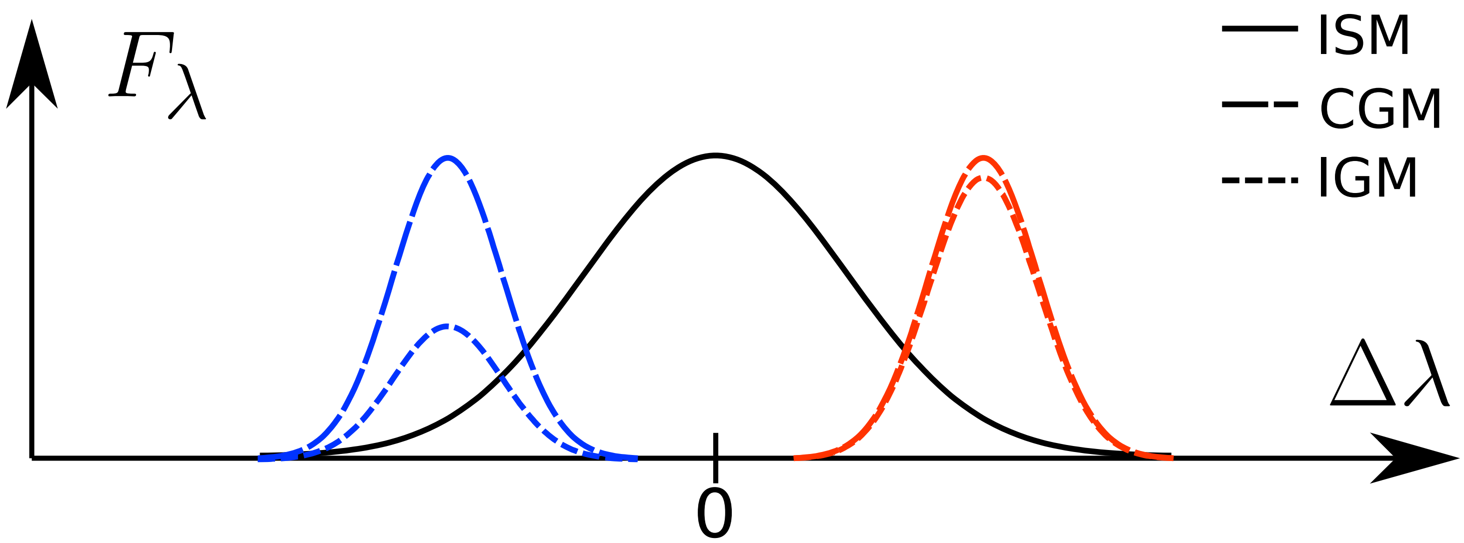
RT Distortion #1 – Results: Clustering Signal



- z = 5.9
- Resolution independent at lower redshifts

- Reproduce prior findings, but numerical effect, nevertheless physical implications.

RT Distortion #1 – Further Explanation

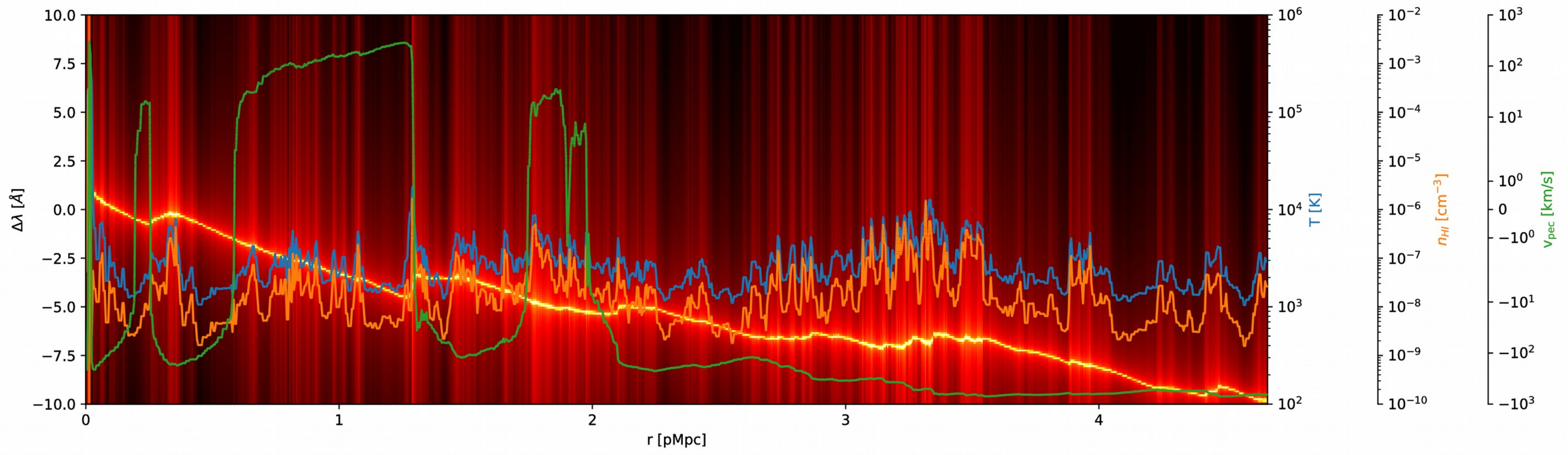


- Attenuated flux frequency dependend

  → Resolving the CGM scale matters

  … and need good modeling of ISM

RT Distortion #1 – Further Explanation



RT Distortion #1 – Summary

- Anisotropic RT distortion due to velocity gradient's impact on attenuation on large scales.
- For given setup, effect shown to be numerical.
- Does not exist for 'low'-z → good for HETDEX, etc.
- Existence at 'high'-z depends on small-scale spectral modeling.

Numerical Simulations

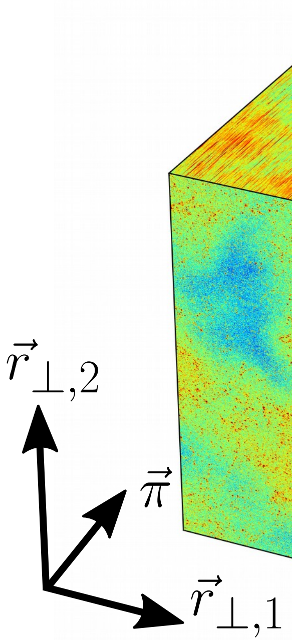
RT Distortion #1

Elongation due to due coherent *attenuation* on large scales

RT Distortion #2

Elongation due to random *spectrum* on small scales

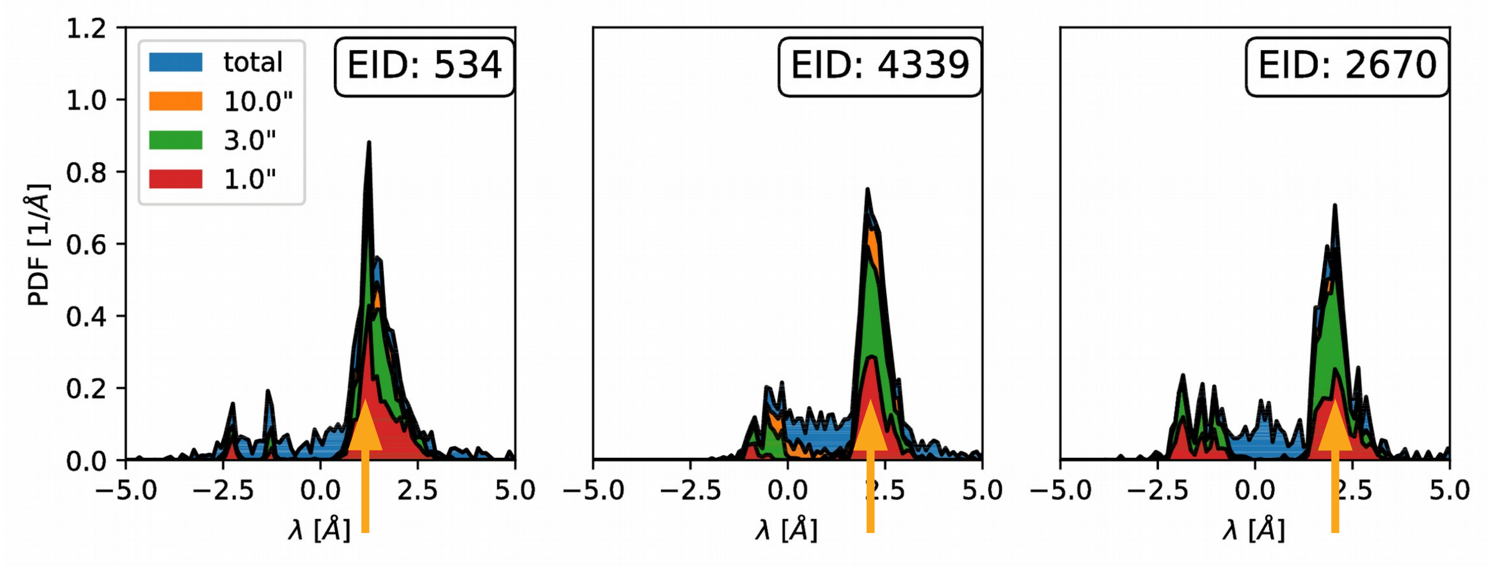
RT Distortion #2 – Introduction



- Until now only concerned with flux, not spectra.
- Intensity maps show a significant smearing along line of sight due frequency diffusion.

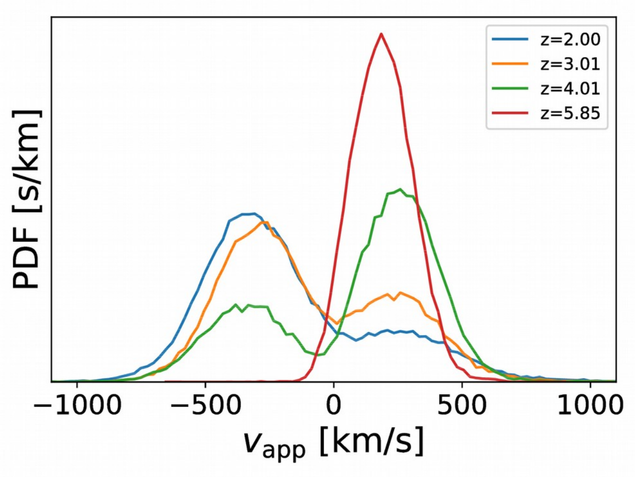
RT Distortion #2 – Introduction

- For simplicity, identify LAE’s position with its global peak



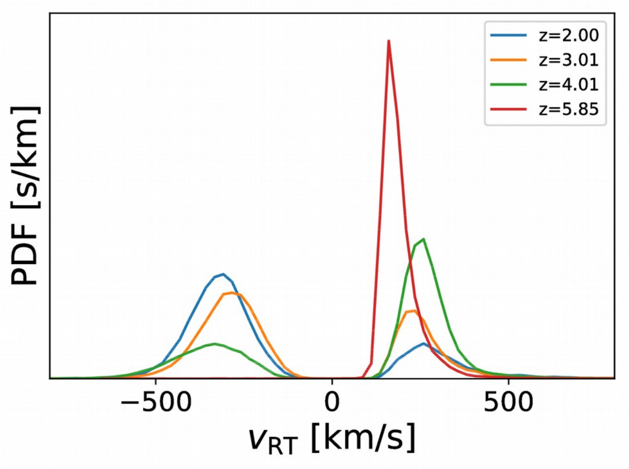
z=3.0

RT Distortion #2 – Peak Distribution



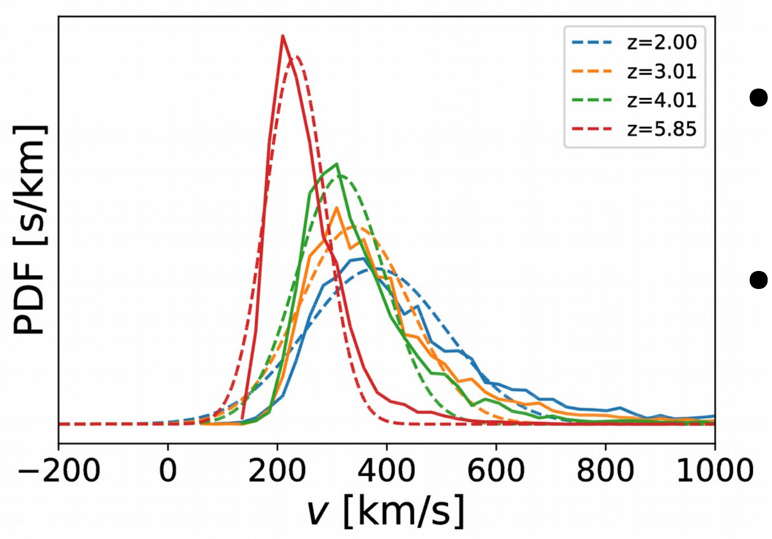
$$\vec{s} = \vec{r} + \frac{\vec{v} \cdot \hat{\pi}}{aH(z)} \hat{\pi}$$

- Velocity decomposition:
  $$v_{\mathrm{RT}} = v_{\mathrm{app}} - v_{\mathrm{pec}}$$
- Contributions are uncorrelated



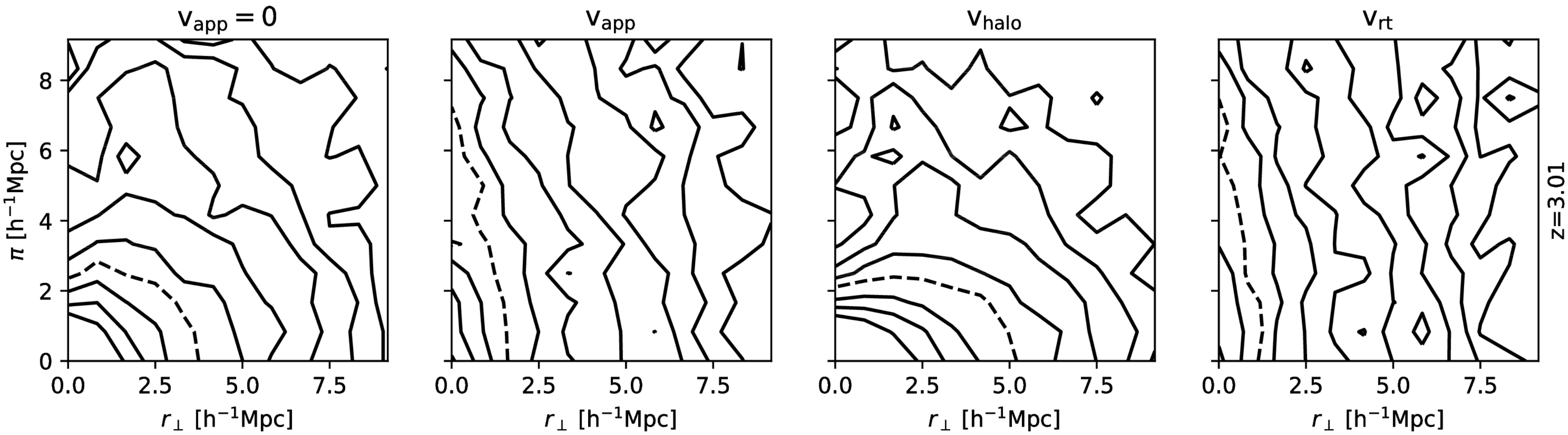
RT Distortion #2 – Peak Distribution

- Dominating blue peak at low redshifts inconsistent with observations.



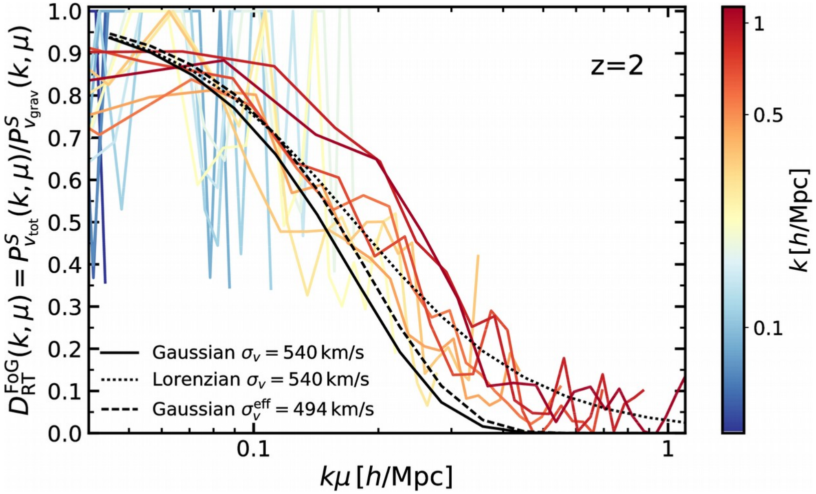
- Need to improve small-scale modeling
- Short-term hack: Use red peaks only (*Appendix*)

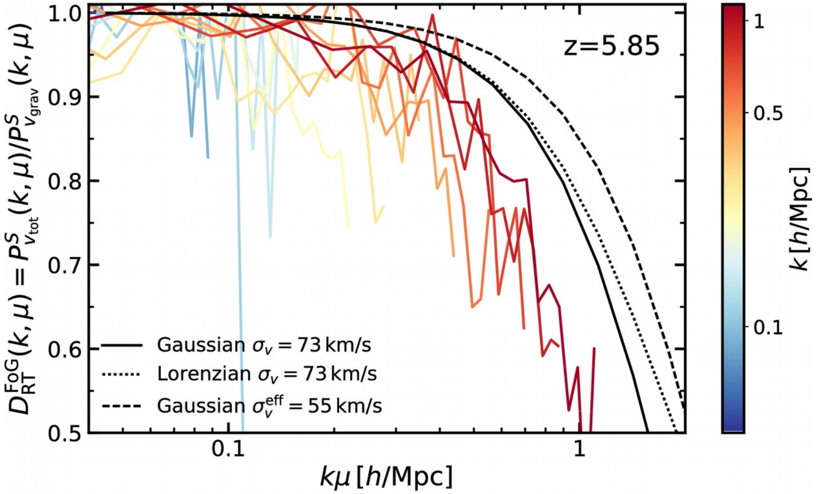
RT Distortion #2 – Clustering Signal



- Radiative transfer ‘velocity’ dominates over grav. part

RT Distortion #2 – Result: Clustering Model





- Modeling with Gaussian damping fails: $D_{\mathrm{FoG}} = \exp\left[-k^2\mu^2 f^2 \sigma^2_{v_{\mathrm{RT}}}\right]$

  … and so does a cumulant expansion of the PDF

  → analytic PDF for v_{RT} needed

  → can't stay agnostic concerning underlying physics

RT Distortion #2 – Summary

- Anisotropic RT distortion due to small-scale spectral variations.
- Standard deviations roughly 100-200km/s over redshift range from 2 to 6.
- However, complex damping factor to due PDF’s shape.
- Just as distortion #1 depends on the small-scale spectral modeling

Overall Summary

- Run radiative transfer simulations to construct mock observations quantifying clustering distortions.

RT Distortion #1

Elongation due to coherent *attenuation* on large scales

- Prior findings numerical artifact
- No indication of effect at 4≤z

  → Good news for HETDEX!

RT Distortion #2

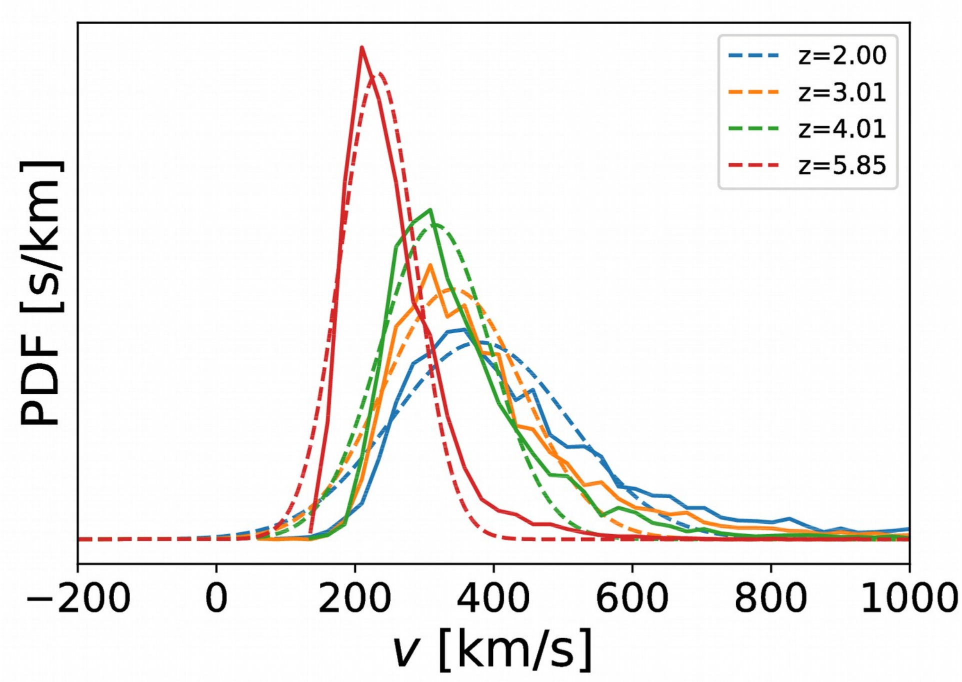
Elongation due to random *spectrum* on small scales

- Significant small-scale distortion
- Modeling tricky

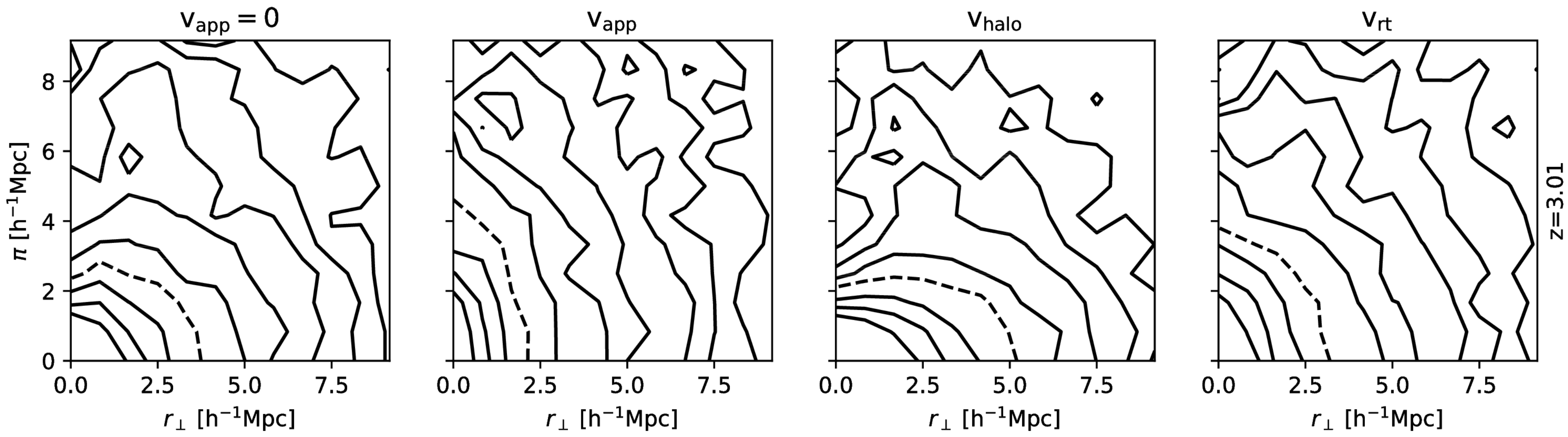
- Need to improve on spectral input.

Appendix

RT Distortion #2 – Result: Conservative Spectra



RT Distortion #2 – Result: Conservative Spectra



RT Distortion #2 – Result: Conservative Spectra