Probing feedback via the distribution of gas around high redshift galaxies.

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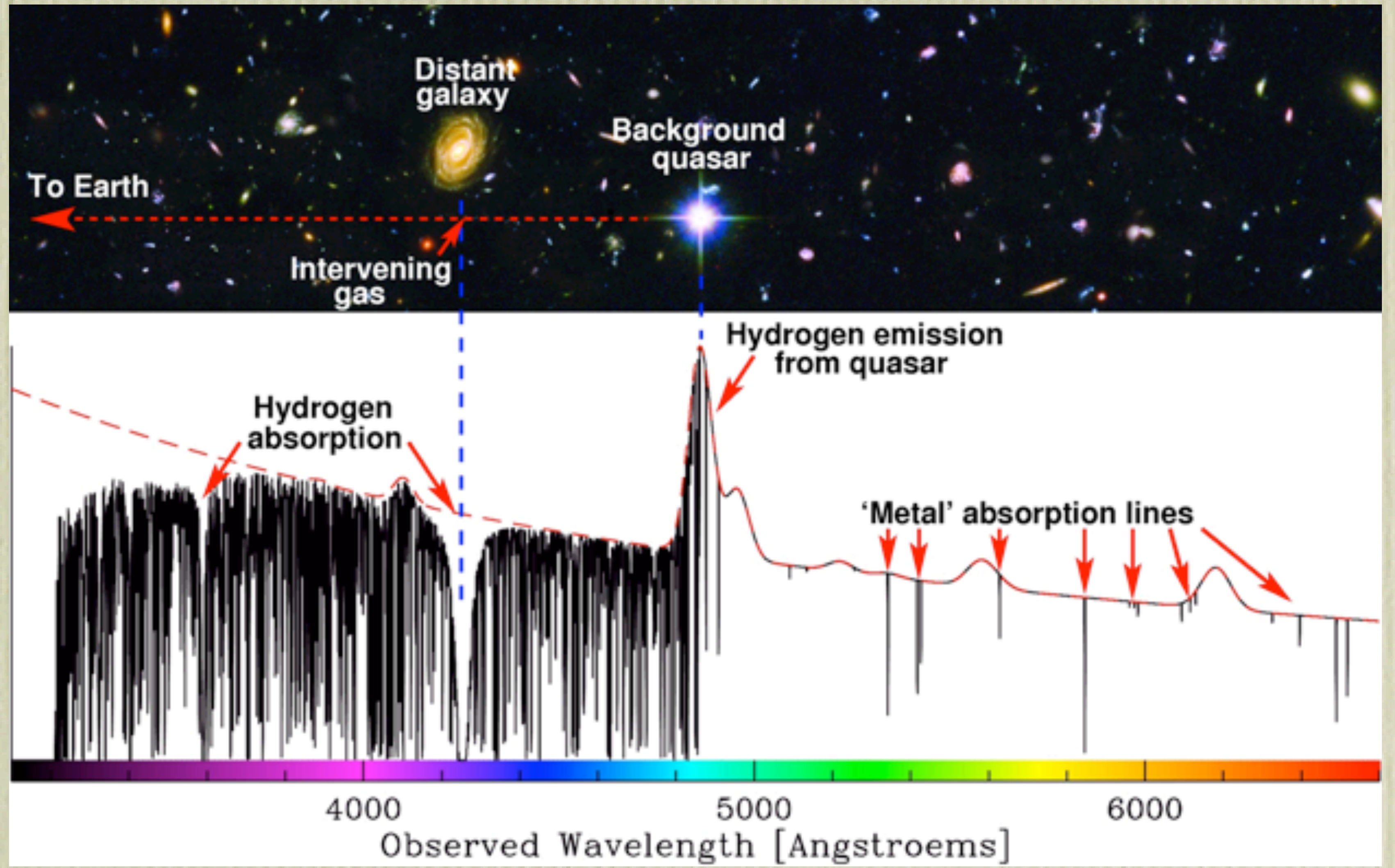
Introduction

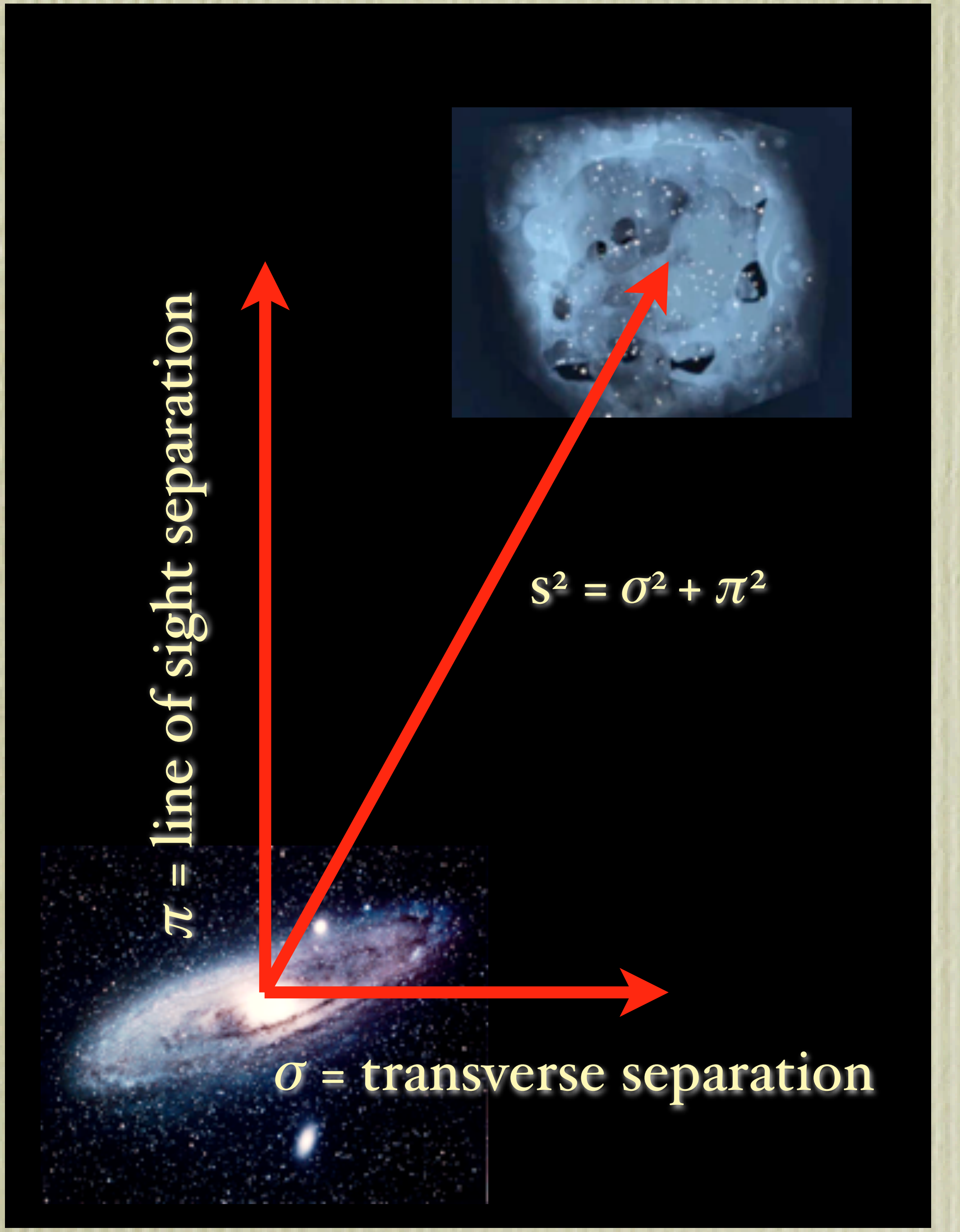
- Probe the relationship between galaxies and the IGM at $z \sim 3$ using the VLT LBG Redshift Survey.
  - ⋆ Mostly presenting work from:
    - ➡ Bielby et al. (2013)
    - ➡ Tummuangpak et al. (2013)
    - ➡ Bielby et al. (In Prep.)

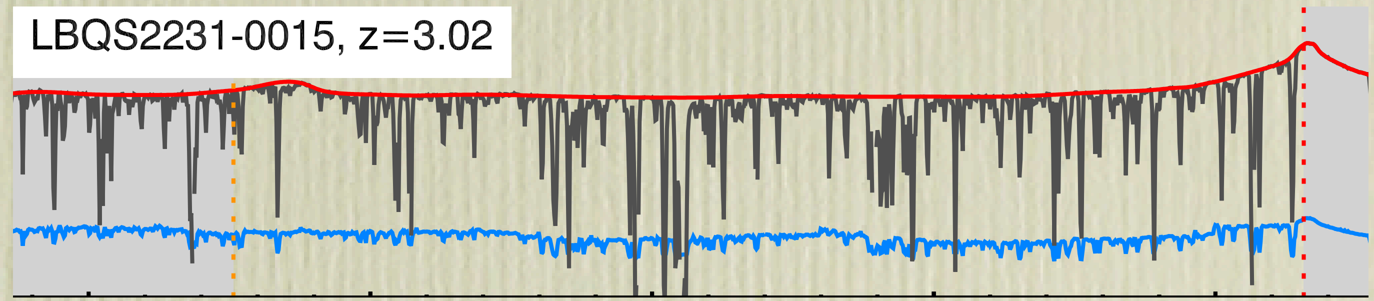
The galaxy-Lyα cross correlation



- Map the galaxy population in the foreground of distant QSOs and then trace the absorption in the Lyα forest as a function of separation from galaxy positions.

Co-ordinate/parameter definitions

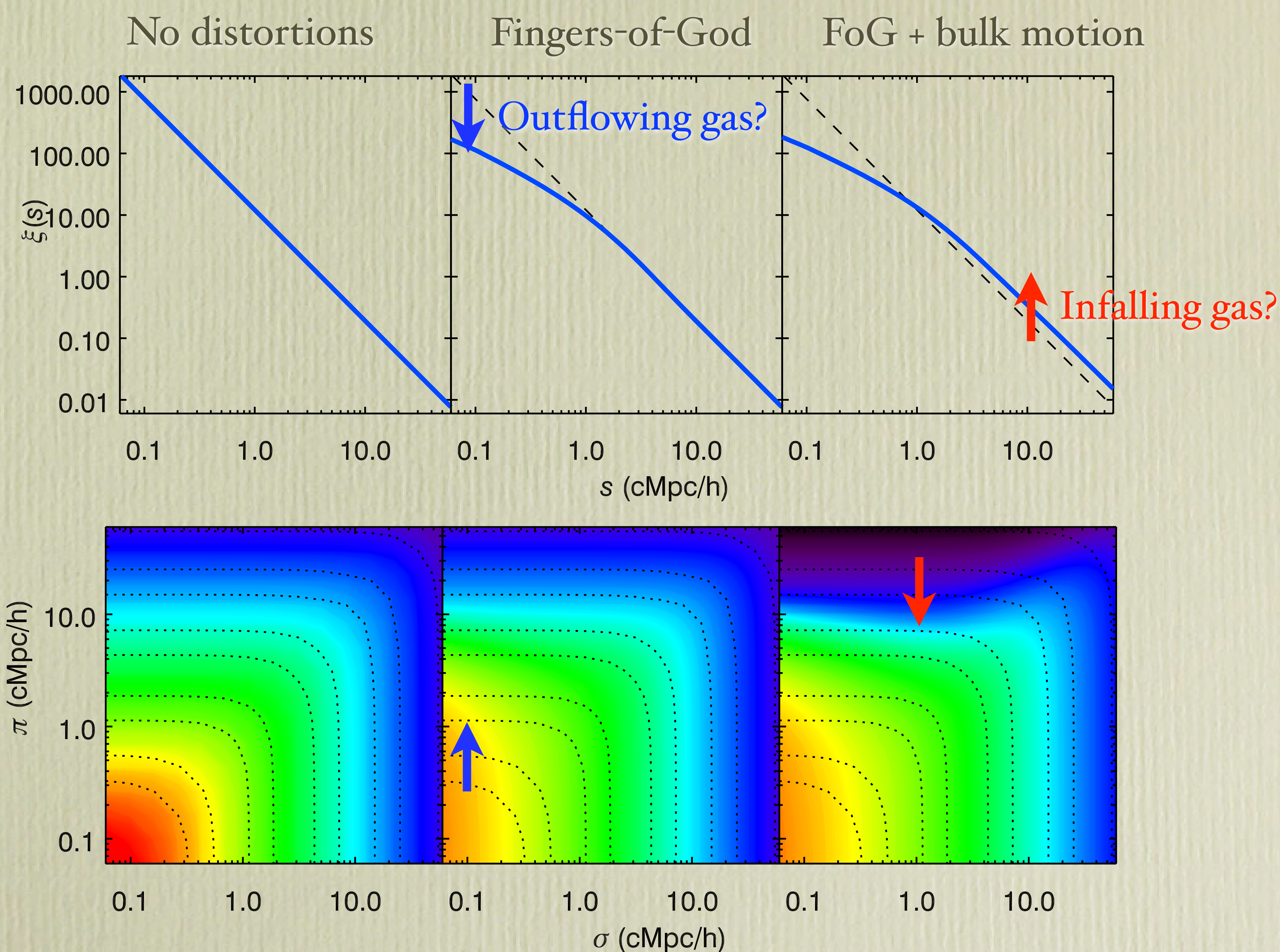




T = flux/continuum

- We calculate mean T as a function of position from galaxy positions.
- This is then a function of the gas distribution and the gas/galaxy dynamics, which we aim to characterise.

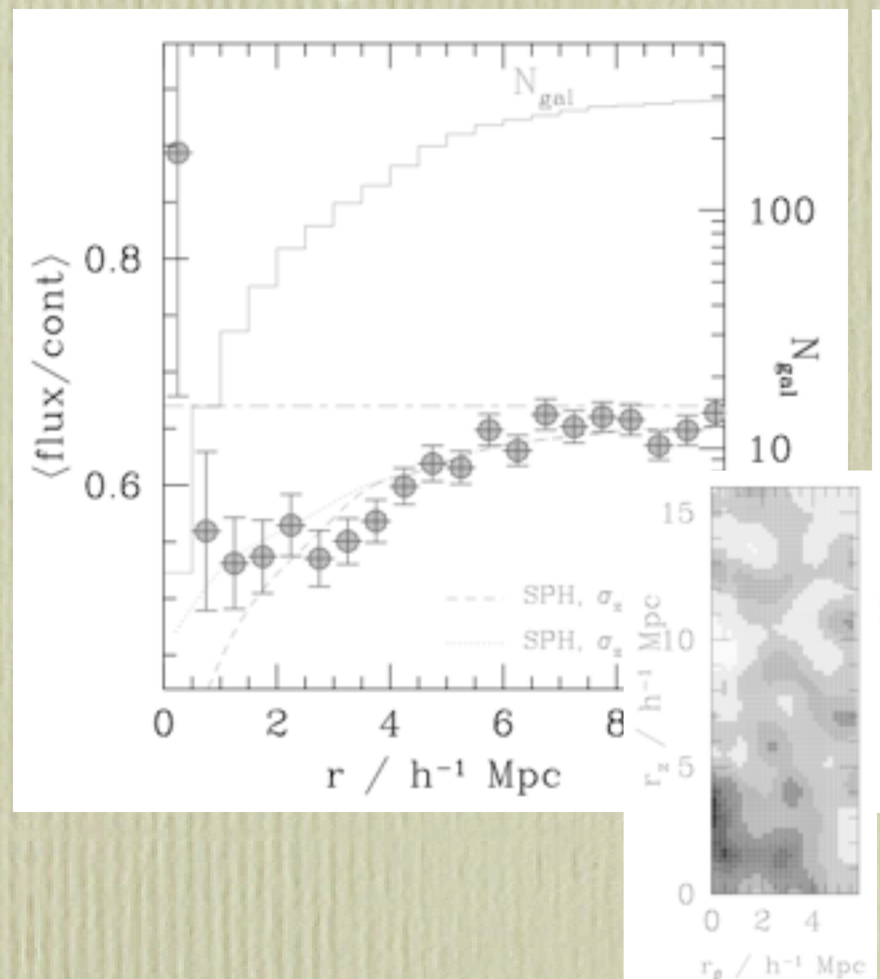
Redshift space distortions (RSD)



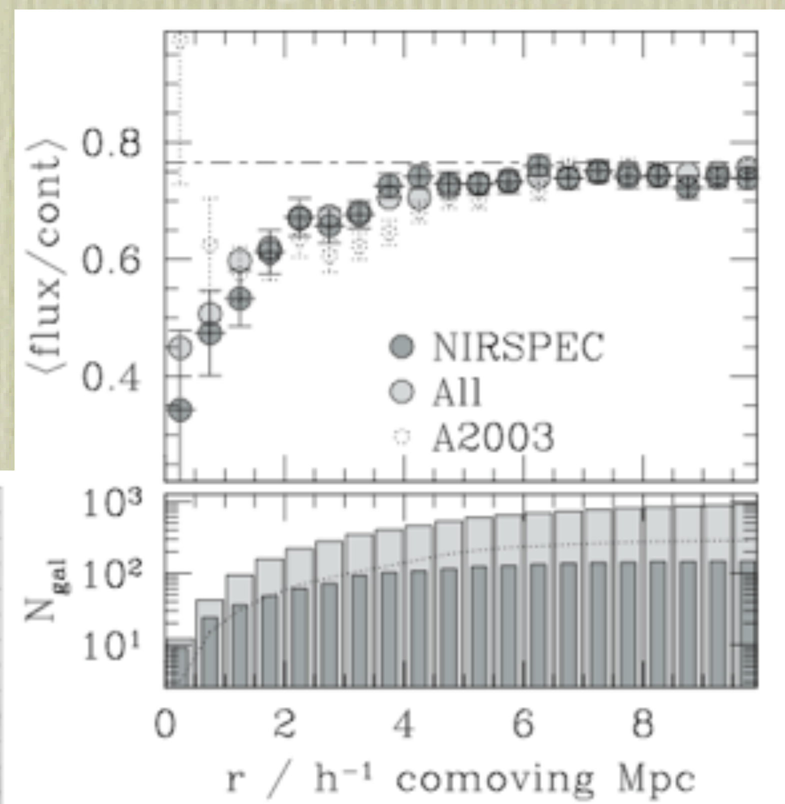
Can these dynamics be connected to the supply of material for star-formation at high redshift?

Background

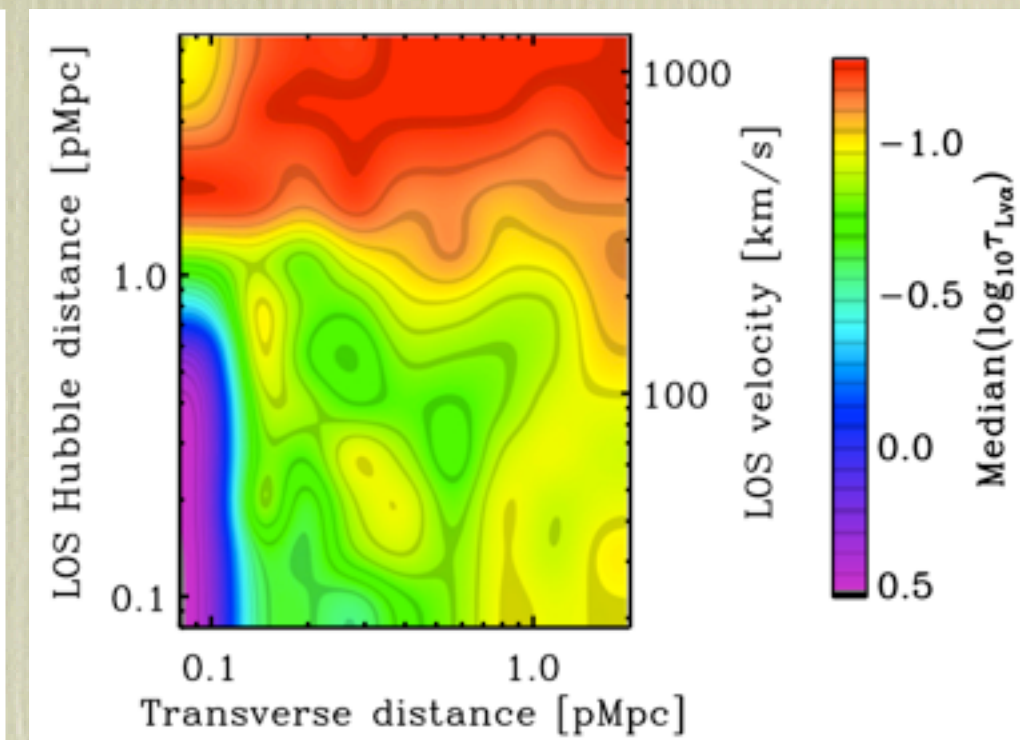
Adelberger et al. (2003)



Adelberger et al. (2005)



Rakic et al. (2012)

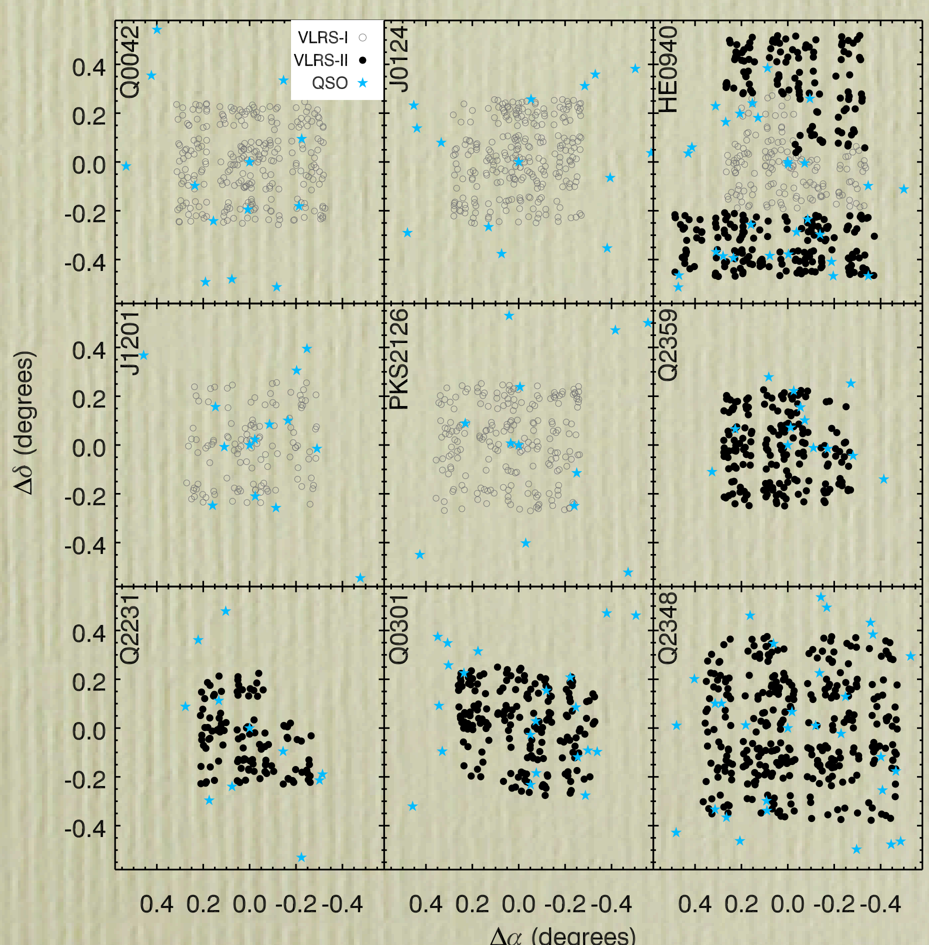


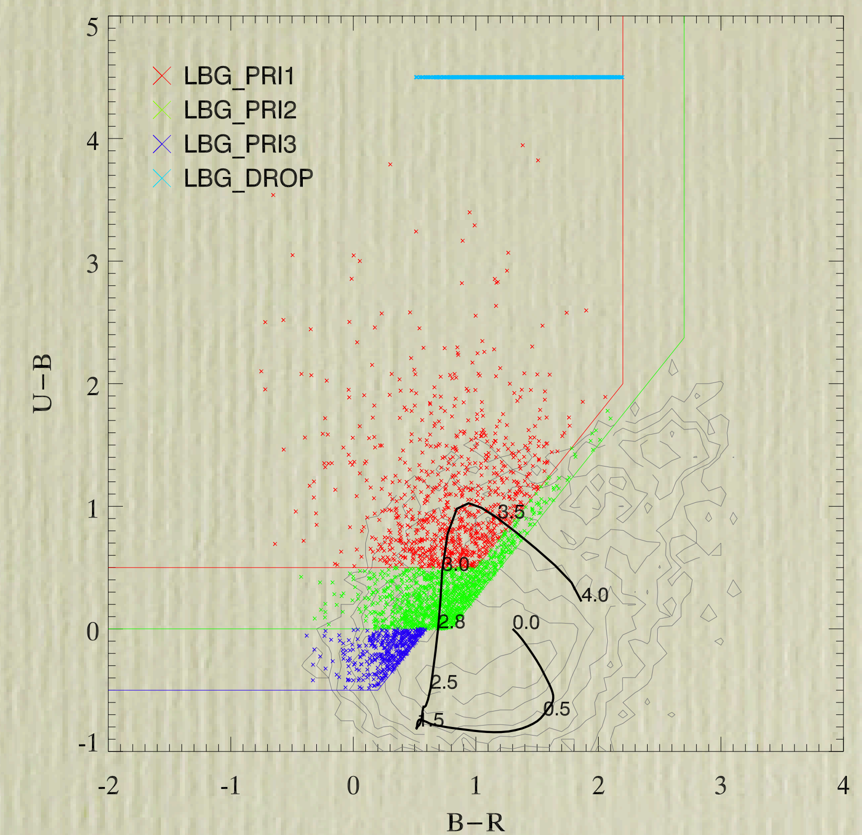
- High-redshift (i.e. z ~ 2 - 3) - dominated by the Chuck Steidel group (lots of Keck time)
  - ★ Adelberger et al. (2003, 2005)
  - ★ Crighton et al. (2011)
  - ★ Rakic et al. (2012), Rudie et al. (2012)
  - ★ Rakic et al. (2013)
- Very, very hard to do, although almost Executive Class access to Keck helps a lot!

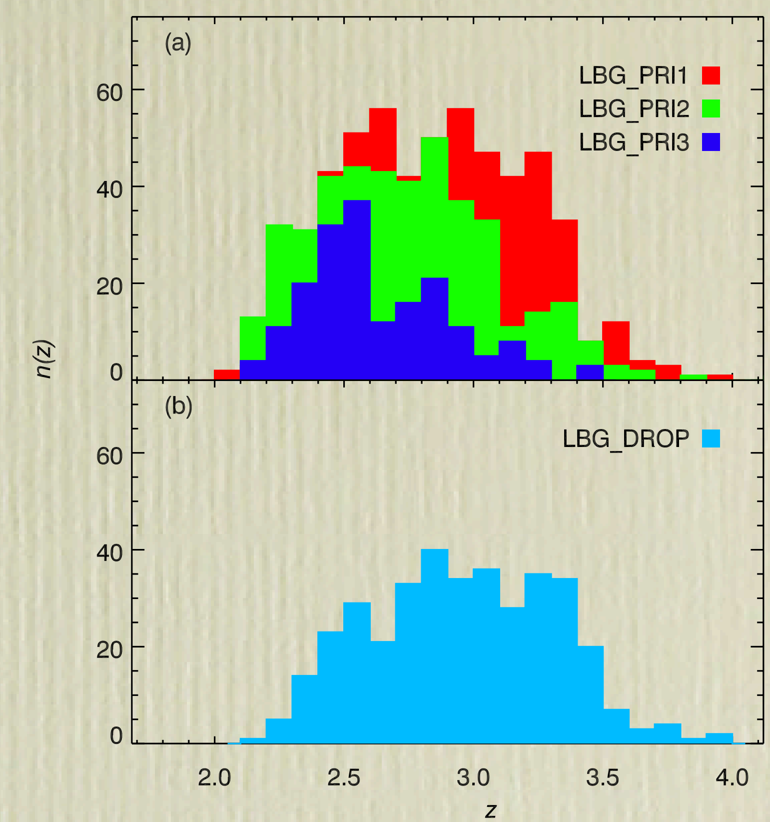
The VLRS

Bielby et al. 2013

- Lyman Break Galaxies at z ~ 2-3.5
  - ★ Selected using *UBR* colour selection comparable to Steidel et al. *UGR* selection.

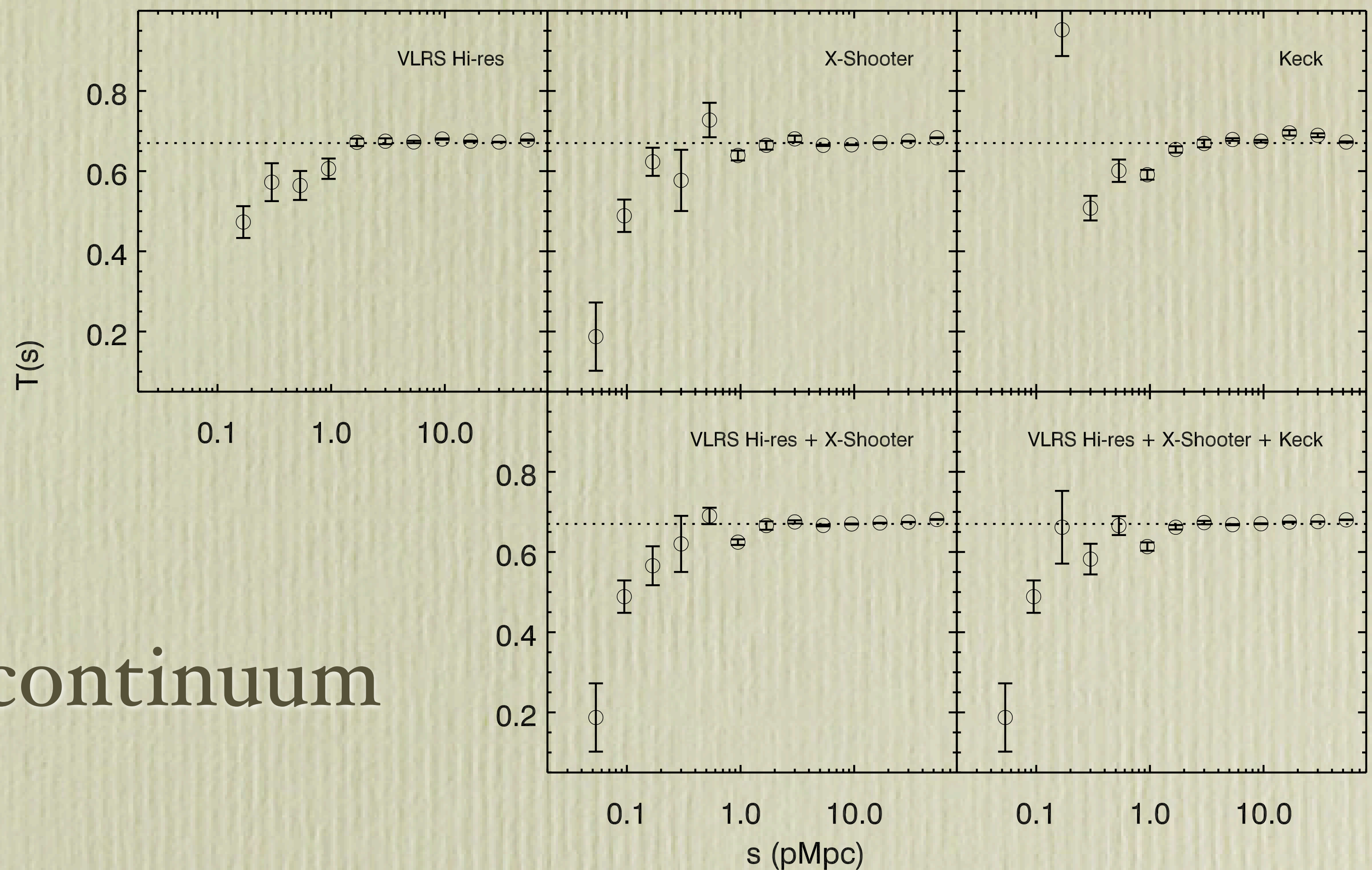






- Spectroscopically observed using:
  - ★ ~ 2,000 galaxies with VLT VIMOS, low-resolution, i.e. σ_v ~ 300km/s.
  - ★ 11 galaxies at small separations with FORS, medium-resolution, i.e. σ_v ~ 200km/s.

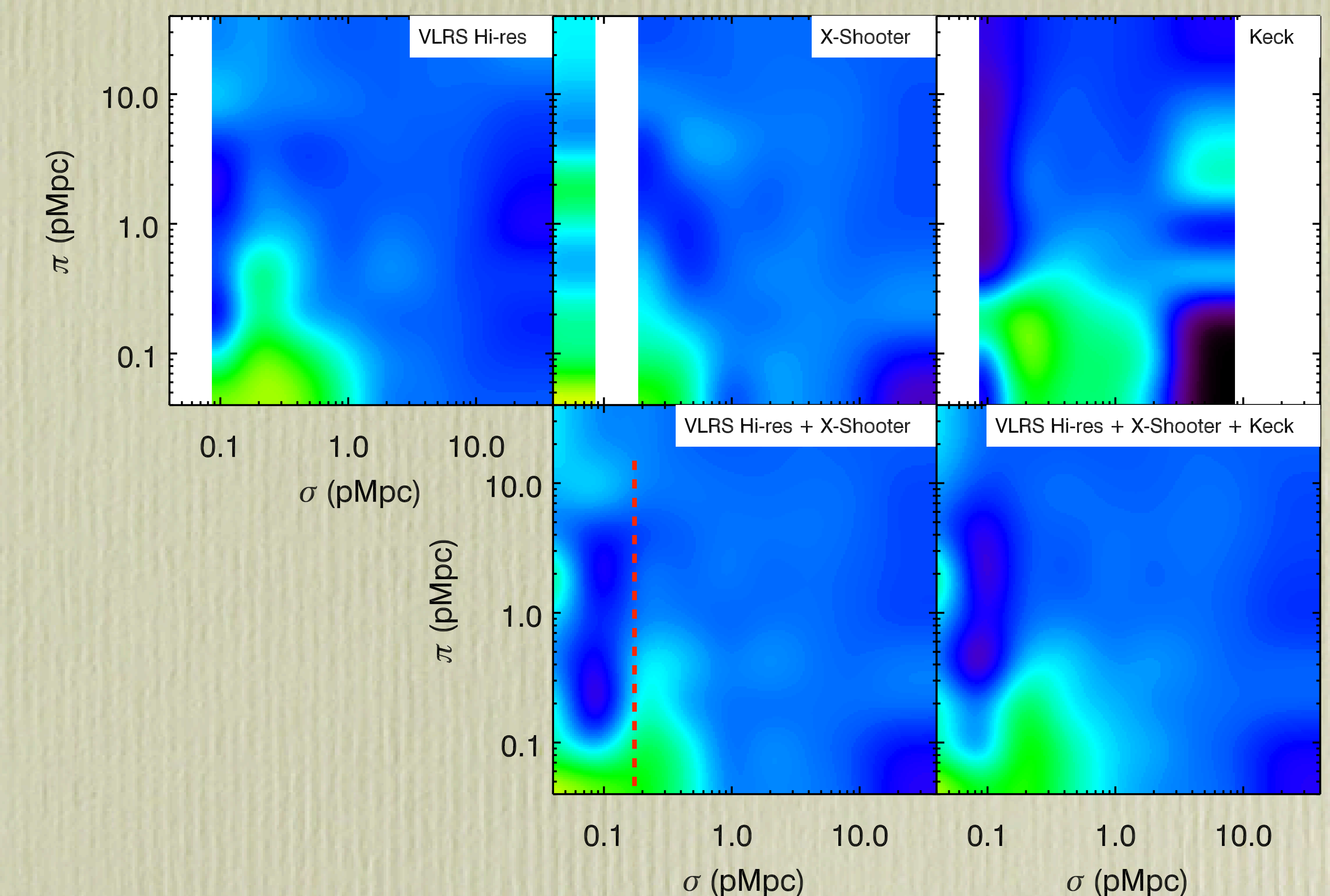
Observed galaxy-Lya cross-correlation



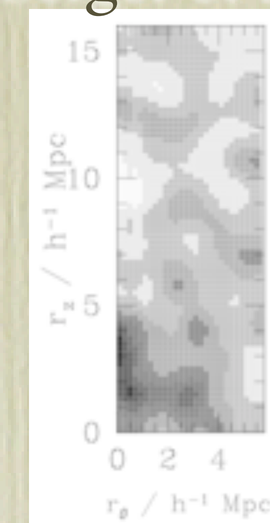
T = flux/continuum

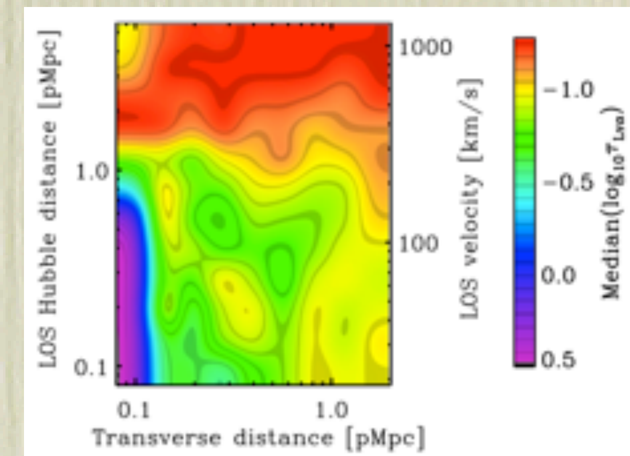
- Redshift-space cross correlation function.
  - ⋆ Consistent with global average at s > 1.5-2 pMpc/h
  - ⋆ Decline in transmissivity in the range 0.05 < s < 1.5 pMpc/h
    - ➡ Except for the Adelberger et al (2003) peak, which we observe in the Keck data at ~ 0.2 Mpc/h

Observed galaxy-Lya cross-correlation



Adelberger et al. 2003



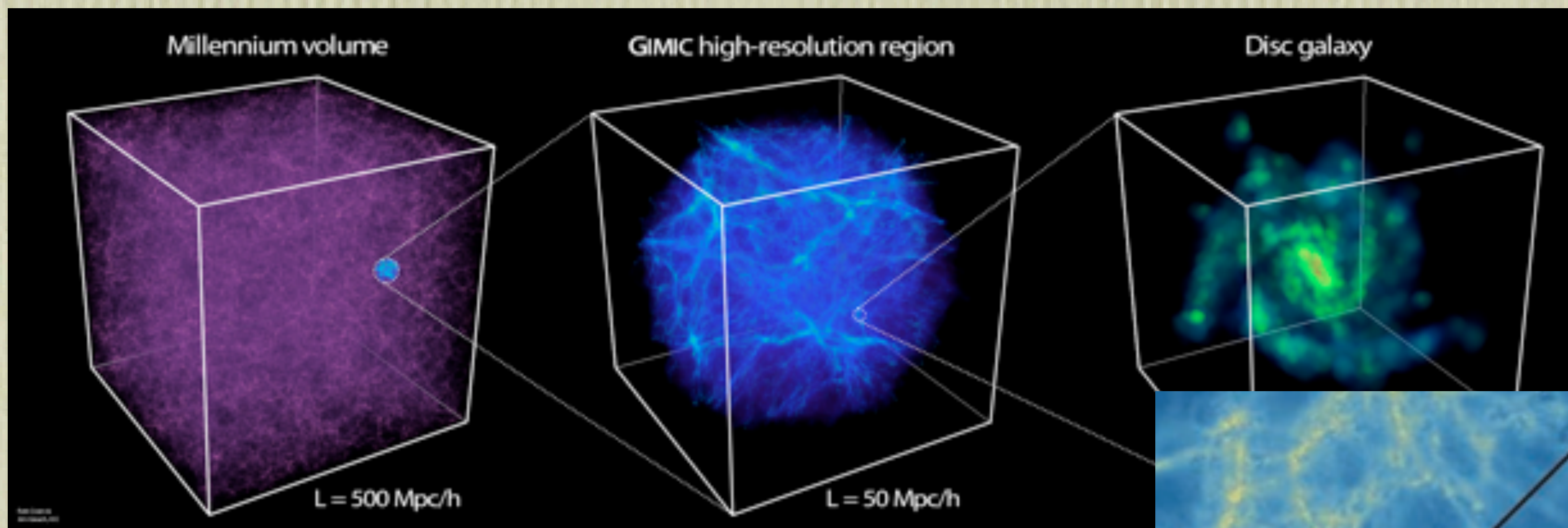


Rakic et al. 2012

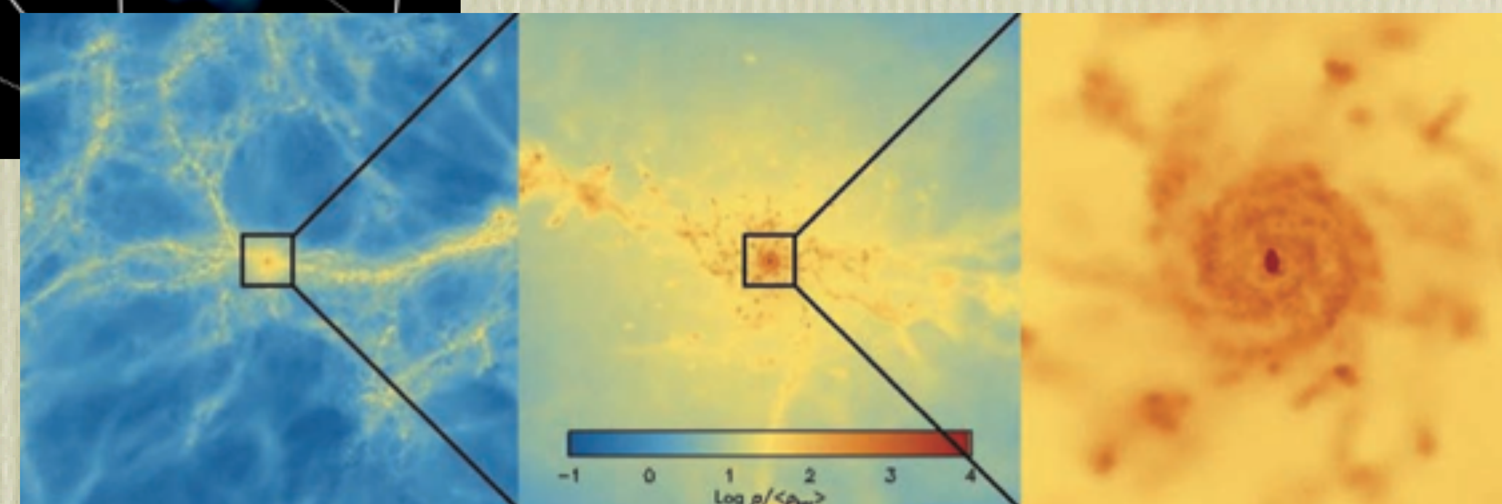
- 2-dimensional cross-correlation for the three samples and their combinations.
  - ★ Small scale 'hole' observed in the Keck sample, which was identified by Adelberger et al. (2003).
  - ★ VLRS high-resolution and X-Shooter samples show continuous decrease in *T* to small separations.

The simulations

Crain et al. 2009



Schaye et al. 2010

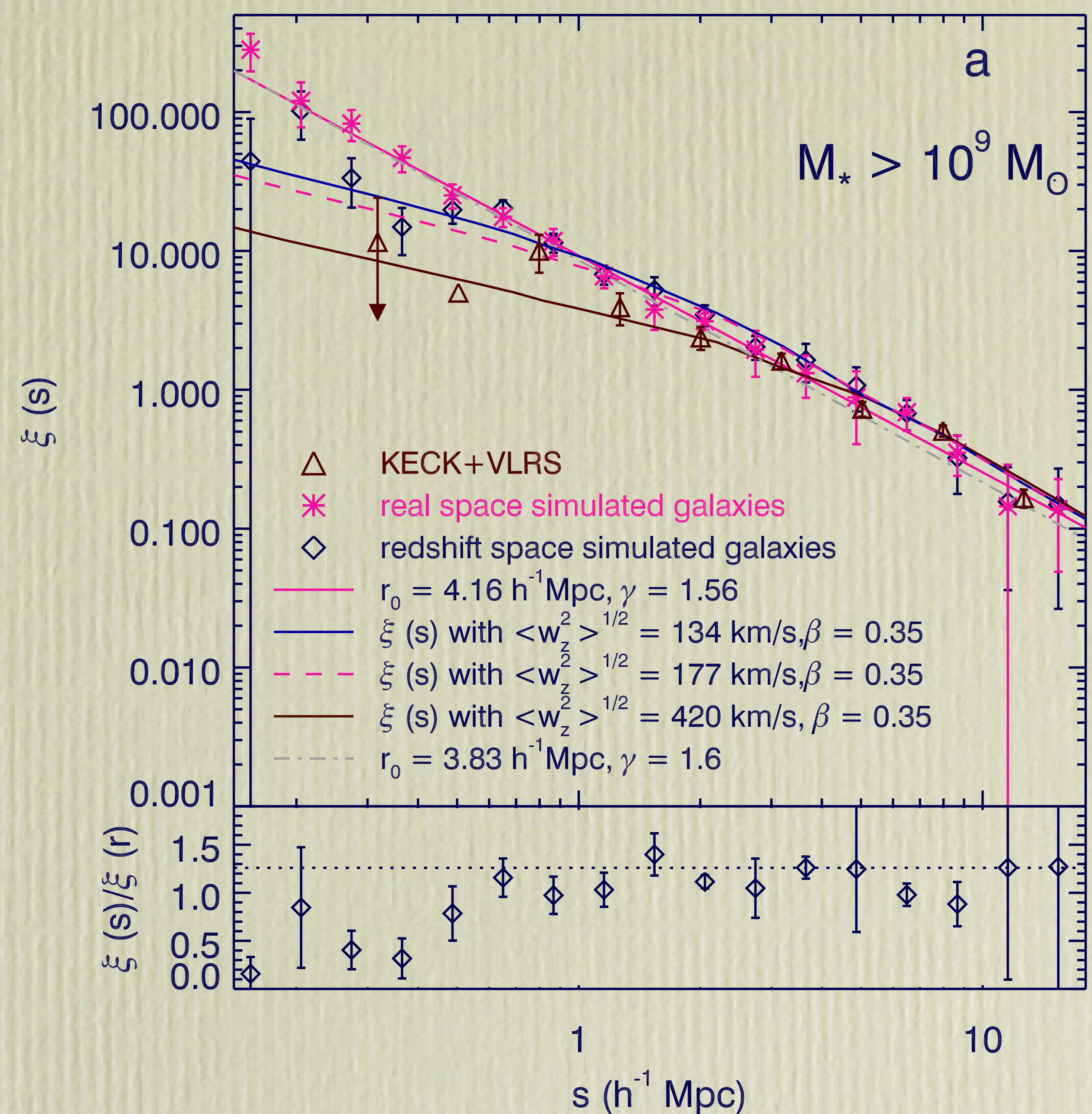


- 25 cMpc/h radius sphere in 0σ density region/REF L025N512: High resolution, 25 cMpc/h cube.
- SNe feedback:
  - ⋆ Kinetic wind model of Dalla Vecchia & Schaye (2008).
  - ⋆ Initial wind velocity, v_w = 600 km/s.
  - ⋆ Mass-loading parameter $\beta = 4/\eta = 2$. (ratio of mass of gas that receives an impulsive kick to the mass of stars formed).
  - ⋆ Energetically feasible, requiring approximately 80 percent of the total energy available from Type II SNe.
- GIMIC: Millenium Simulation cosmology: $\{\Omega_m, \Omega_b, \Omega_\Lambda, \sigma_8, n_s, h\} = \{0.25, 0.045, 0.75, 0.9, 1, 0.73\}$
- OWLS: WMAP 3-year cosmology: $\{\Omega_m, \Omega_b, \Omega_\Lambda, \sigma_8, n_s, h\} = \{0.238, 0.0418, 0.762, 0.74, 0.951, 0.73\}$

The simulations: galaxy samples

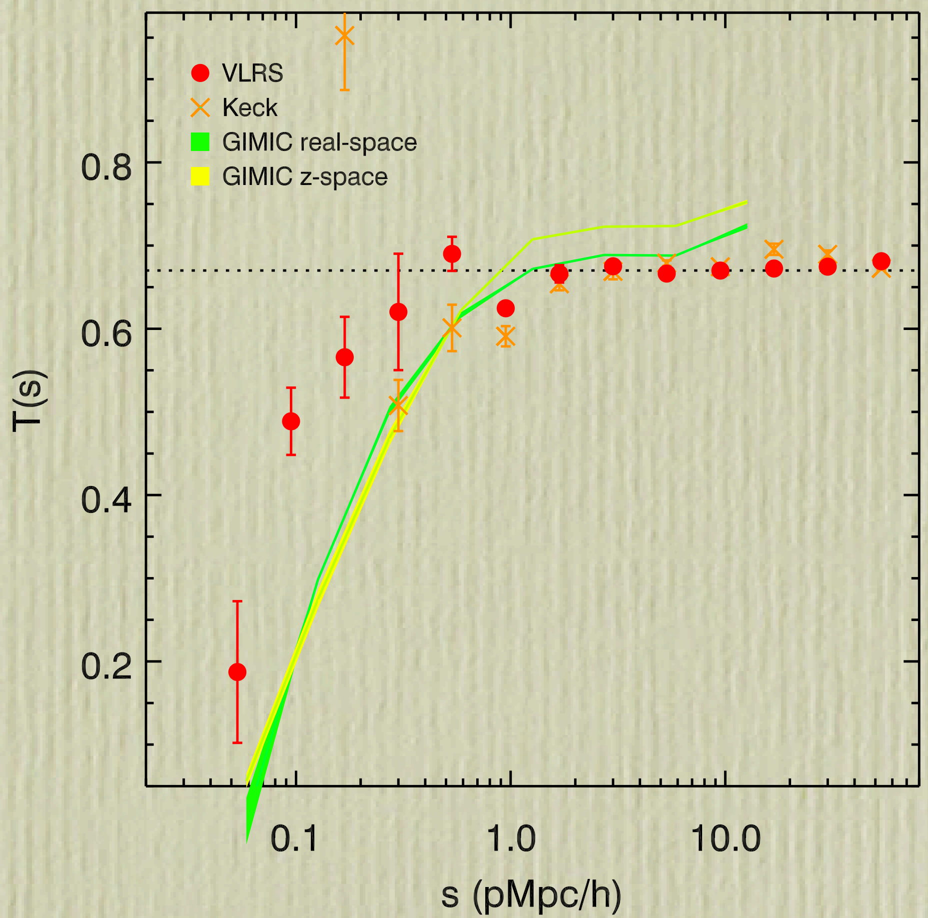
Tummuangpak et al. 2013

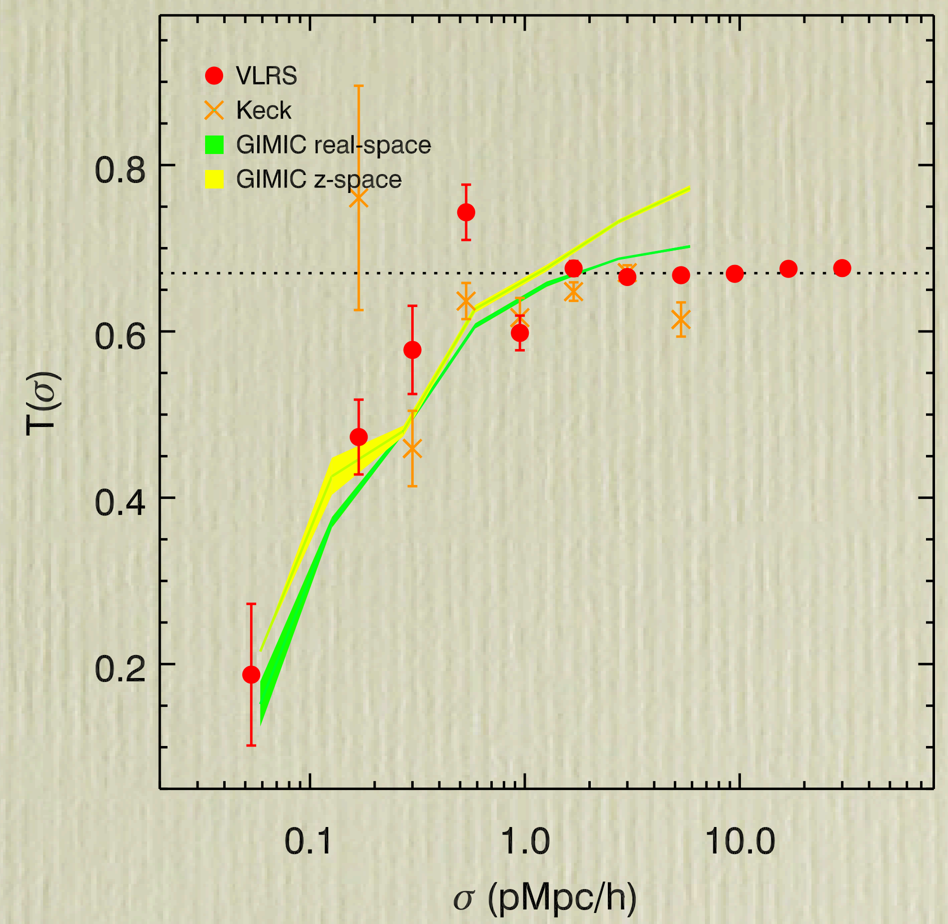
- GIMIC:
  - ★ Galaxy selection based on a stellar-mass cut.
    - ➡ Tuned to give equivalent clustering measurements to the observed LBG population - r_0~4cMpc/h - and thus comparable DM halos.
- OWLS:
  - ★ For initial analysis, take the same mass cut as in GIMIC for straight comparison.
  - ★ Given the lower σ_8 in OWLS, this will give lower mass DM halos.



Observed v GIMIC

Tummuangpak et al. 2013



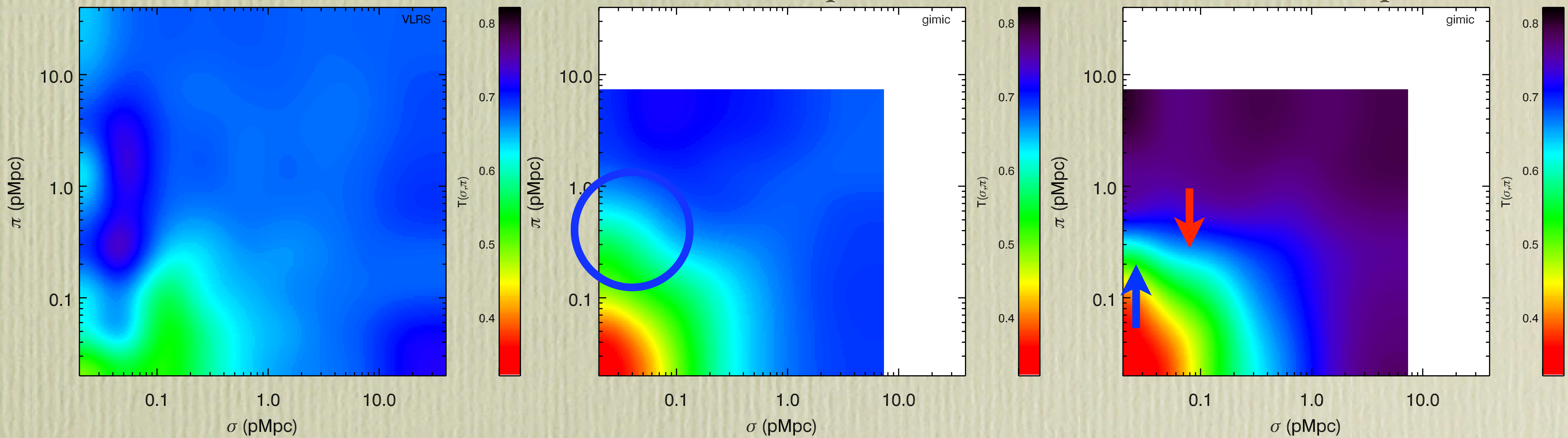


- Comparison of observations and results from GIMIC 0-sigma sphere.
  - ★ Function of redshift space distance, *s*, and projected distance, σ.
  - ★ Simulation results reproduce the observed results when measuring as a function of projected distance.

Observed v GIMIC - 2D

Tummuangpak et al. 2013

Observed | Sim real-space | Sim redshift-space



- Comparison of observations and results from GIMIC 0-sigma sphere.
- Simulations show -
  - ★ Extension in z-space seen at small scales, i.e. < 0.2 pMpc/h.
  - ★ Flattening (infall) seen at scales of ~ 0.3-0.5 pMpc/h.
- Observations less clear, but profile beyond σ ~ 0.1 pMpc/h is comparable.
  - ★ At σ < 0.1 pMpc/h velocity errors on galaxy redshifts and small numbers of galaxies come into play.

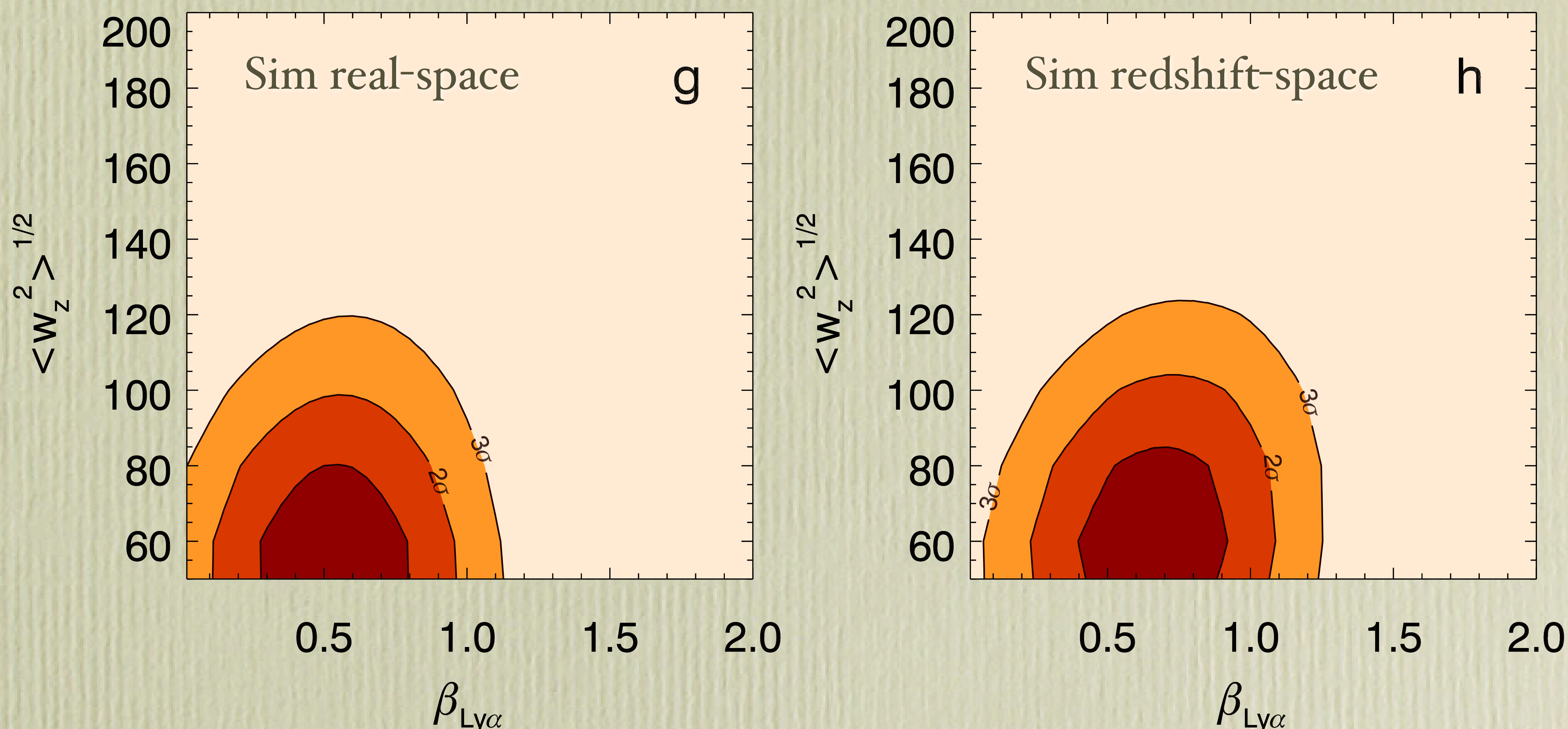
Fitting the redshift-space distortions

- Following galaxy-galaxy fitting:
  - ⋆ Use basic power-law for real-space starting point:
    - ➡ $\xi = (r/r_0)^{\gamma}$
  - ⋆ Add in Gaussian smoothing characterized by velocity dispersion, a:
    - ➡ $f = e^{\sqrt{2}|v|/a}/\sqrt{2}a$
  - ⋆ And factor in large scale bulk motions using β:
    - ➡ $\beta = \Omega^{0.6}/b$
    - ➡ $\xi_z/\xi_r = (1 + 2/3\,\beta + 1/5\,\beta^2) + (4/3\,\beta + 4/7\,\beta^2)\,P_2(\mu) + \ldots..$

See Peebles, Peacock etc.

Observed v GIMIC - 2D

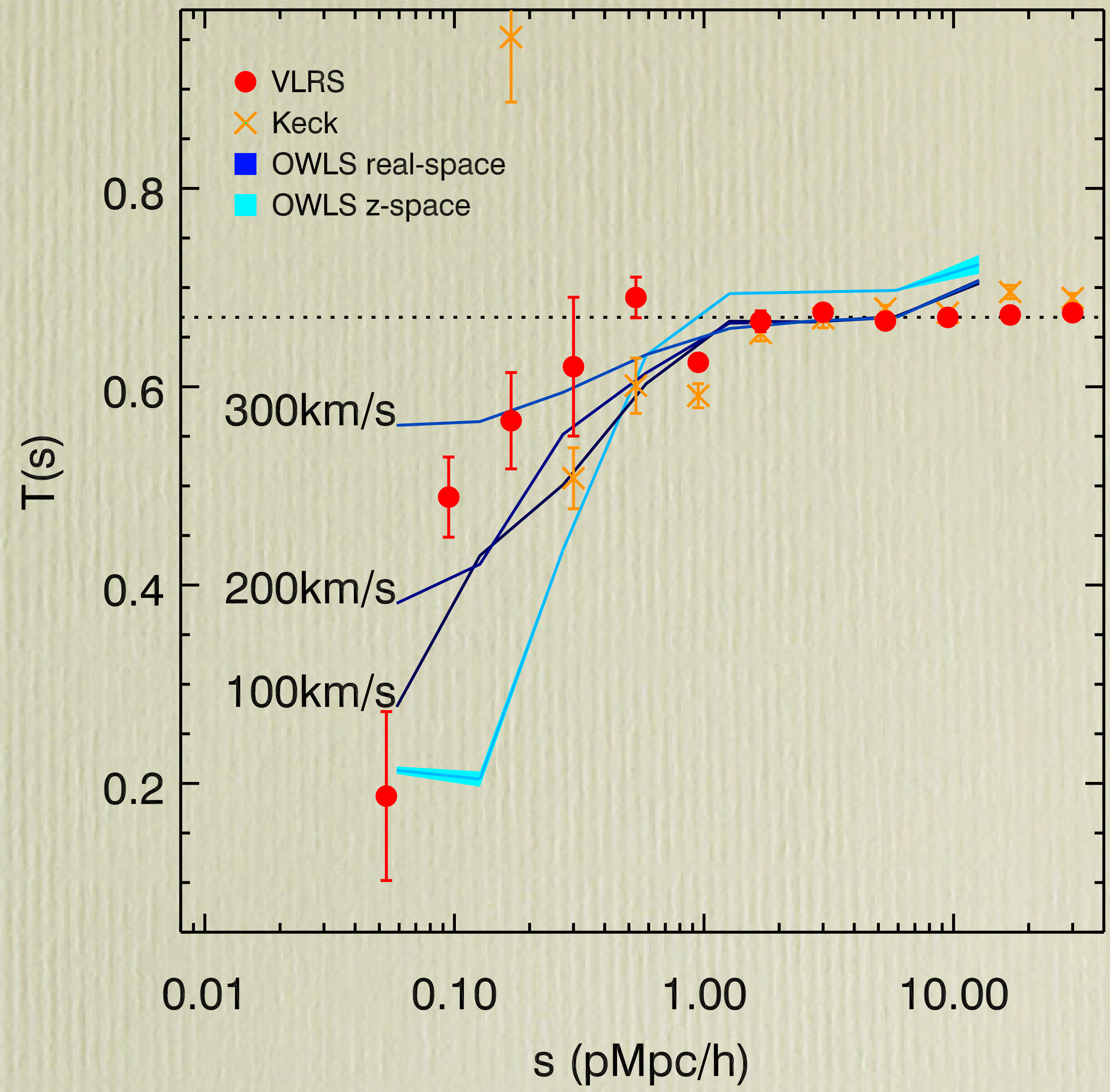
Tummuangpak et al. 2013



- But..
  - ⋆ fitting with redshift-space model doesn't work so well and doesn't show what we observe visually!
  - ⋆ Both real and redshift space fits indicate high beta and no peculiar velocities.
  - ⋆ Work in progress!

Effects of redshift uncertainties

- VLRS redshift uncertainties are $\Delta v \sim 200\text{-}300$km/s
- Apply random velocities to the galaxies in the OWLS simulations and recalculate the result.
  - ★ Use σ_v = 100, 200 & 300km/s.
- Except for smallest separation (which is based on one data-point) OWLS analysis is consistent with the data given σ_v=300 km/s.
- *VLT KMOS observations will improve the results significantly.*



Summary

- Observations:
  - ⋆ > 2,000 galaxy redshifts measured at $2<z<3.5$.
  - ⋆ 11 QSOs with high-resolution spectroscopy and 19 QSOs with mid-resolution spectroscopy from X-Shooter.
  - ⋆ Cross-correlation of galaxies and Lyα show the gas distribution to increase within ~ 1.5-2 pMpc/h.
- Ongoing/future endeavours:
  - ⋆ KMOS observations improving galaxy numbers and redshift accuracy close to sightlines.
  - ⋆ Explore parameter space for different feedback implementations in the simulations.

The VLT LBG Redshift Survey (VLRS)

- A survey of $z \sim 3$ Lyman-break galaxies around bright background quasars using VLT VIMOS.
  - ★ Using the VLT with VIMOS allows us to cover large fields allowing us to:
    - ➡ a) probe the gas-galaxy relationship out to large scales
    - ➡ b) perform wide field auto-correlation analysis of the galaxy sample.
  - ★ QSOs have either existing VLT UVES or Keck HiRES high resolution spectroscopic coverage.
  - ★ Additional spectroscopy has now been added of fainter background QSOs within three of the fields using moderate resolution observations with VLT X-Shooter.

The QSO sample

- VLT UVES
  - ★ 7 spectra, mostly field centres.
  - ★ R~40,000
- VLT X-shooter
  - ★ Spectra of 15 z ~ 3 QSOs
  - ★ R ~ 4,000-6,000 (UV/Optical)
- Keck HiRES
  - ★ 4 QSO spectra
  - ★ R~40,000
- Continuum fitting using Neil Crighton's python fitting code (see Crighton et al. 2011).