Understanding and mitigating the cosmological impact of radiative transfer on the clustering of Lyman-α emitters

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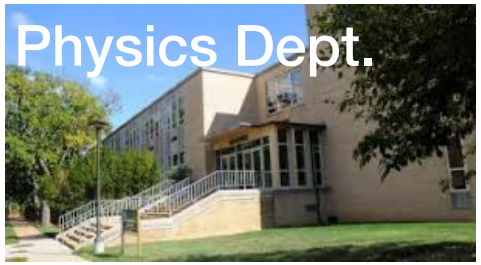
Special Seminar@Kavli IPMU, JAPAN

MISSOURI S&T

New Astrophysics Group at Missouri S&T

In ***Rolla***, Missouri (100 mile from **St. Louis**)



Marco Cavaglia

- Gravitational Wave
- LIGO

Shun Saito (me)

- cosmology, LSS
- **HETDEX**, **PFS**

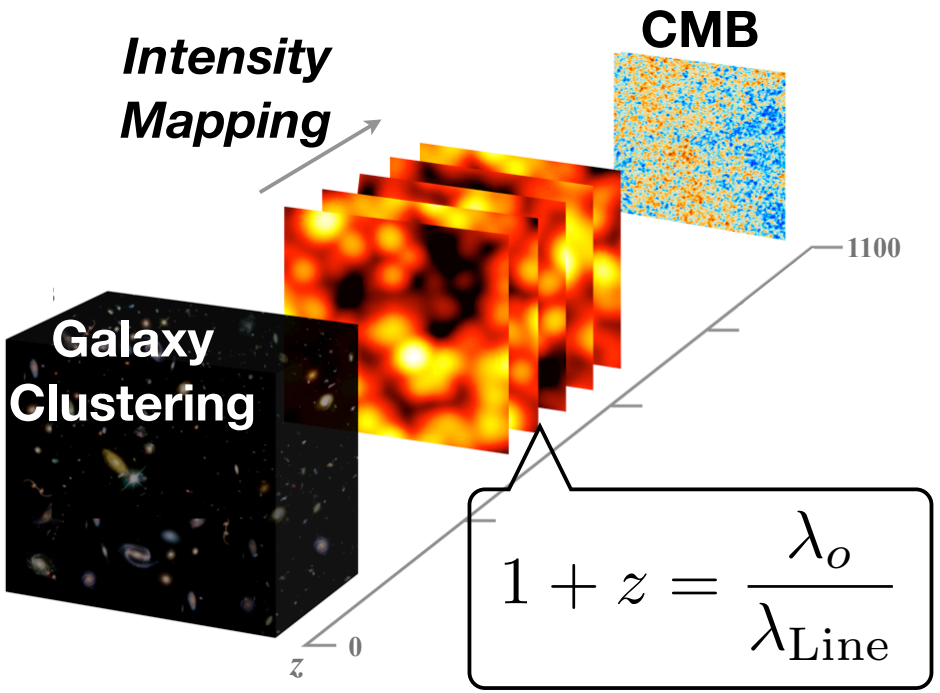
Missouri S&T joins dark energy experiment to solve accelerating cosmos mystery

Posted by Delia Croessmann

On September 26, 2019

- "***Institute for Multi-messenger Astrophysics & Cosmology*** (***iMAC***)"
- Keep your eyes on future faculty hiring (+5 in principle…)

Introduction



Kovetz+, Astro2020

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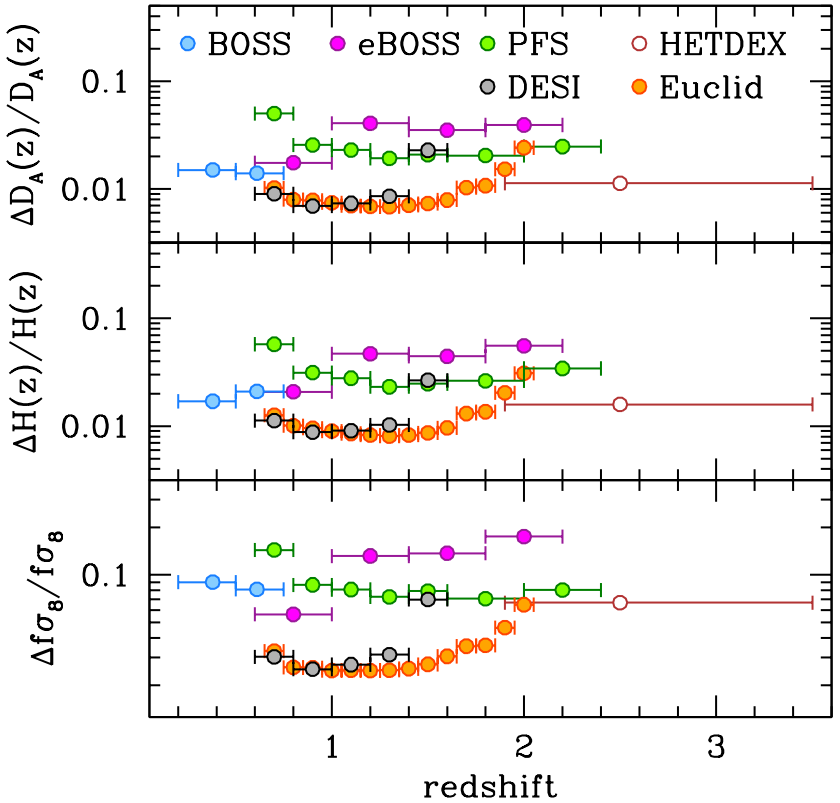
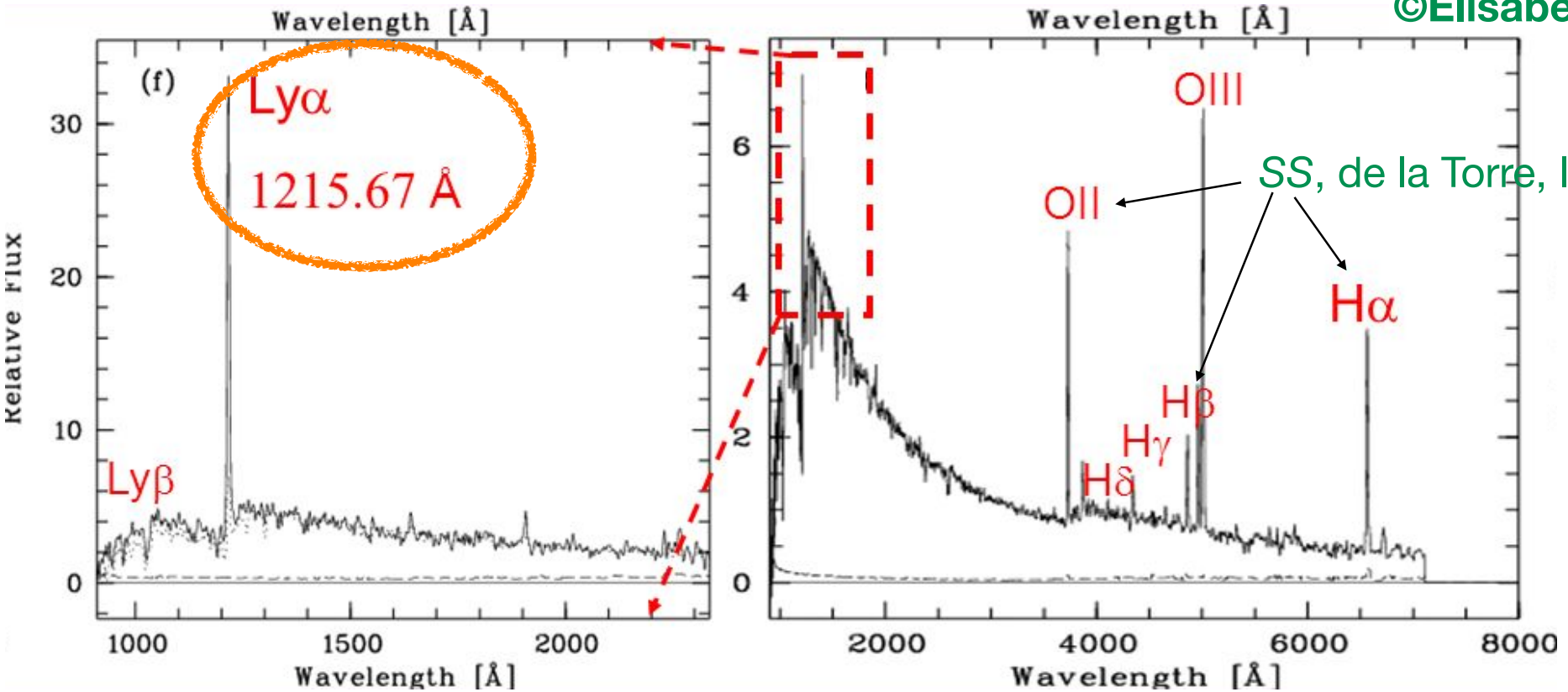


- Mapping out LSS through the 3D distribution of galaxies.
- **Galaxy Clustering** at low redshift & **Intensity Mapping** at high redshift.

Emission Line from young star-forming galaxies

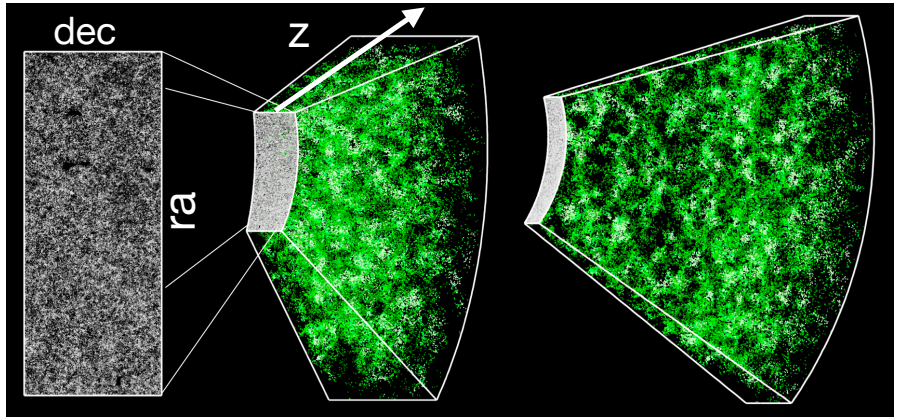
©Elisabeth Stanway



SS, de la Torre, Ilbert+(2019)

- Lyman-α Emission Line is so prominent to probe the LSS at high z.
- Planned LAE Surveys: **HETDEX** (1.9<z<3.5; 2019-), **SPHEREx** (z>5; 2023-)

Large-Scale Galaxy Clustering



- 3-dimensional galaxy map (ra, dec, **z(redshift)**)
  → distance-redshift relation
  → **x** = (X, Y, Z)

- fluctuation in number count $\delta_{\rm g}(\mathbf{x}) = \dfrac{n_{\rm g}(\mathbf{x}) - \bar{n}_{\rm g}}{\bar{n}_{\rm g}}$

- **Two-point statistics**

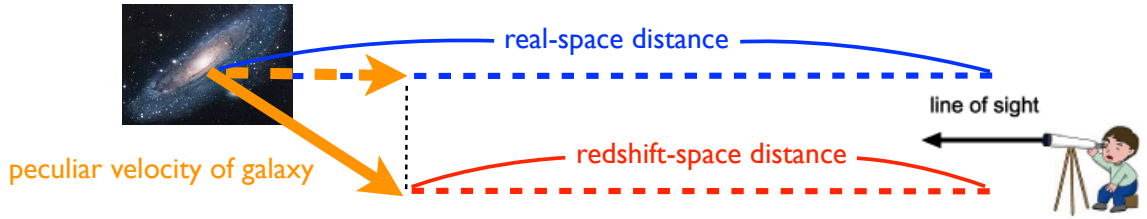
  Power Spectrum in Fourier Space $\langle \delta_{\rm g}(\mathbf{k}) \delta_{\rm g}(\mathbf{k}') \rangle = (2\pi)^3 \delta_D(\mathbf{k}+\mathbf{k}') P_{\rm g}(\mathbf{k})$

  Correlation Function in Configuration Space

  $$\langle (1+\delta_{\rm g}(\mathbf{x}))(1+\delta_{\rm g}(\mathbf{x}+\mathbf{r})) \rangle = 1 + \xi(\mathbf{r})$$

Redshift Space Distortion

- (Any kind of) peculiar velocity of galaxies contaminate to their redshifts

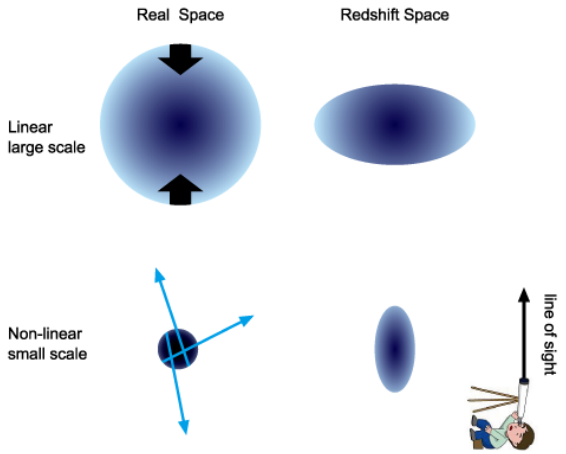


$$\vec{s} = \vec{r} + \frac{\vec{v}\cdot\hat{z}}{aH(z)}\hat{z}$$

redshift space: $\vec{s}$ = real space: $\vec{r}$ + $\frac{\vec{v}\cdot\hat{z}}{aH(z)}\hat{z}$ line of sight direction

- **Anisotropic** clustering: ***the Redshift-Space Distortion***

For a review, see my lecture note at MPA.



Large-Scale (Kaiser squashing)

clustering becomes **larger** along l.o.s

Kaiser (1987)

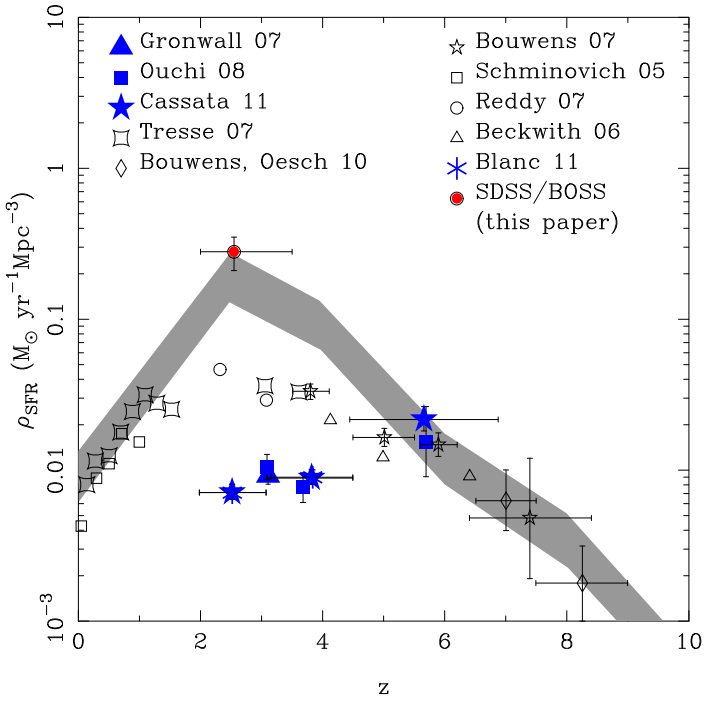
small-scale (Finger-of-God)

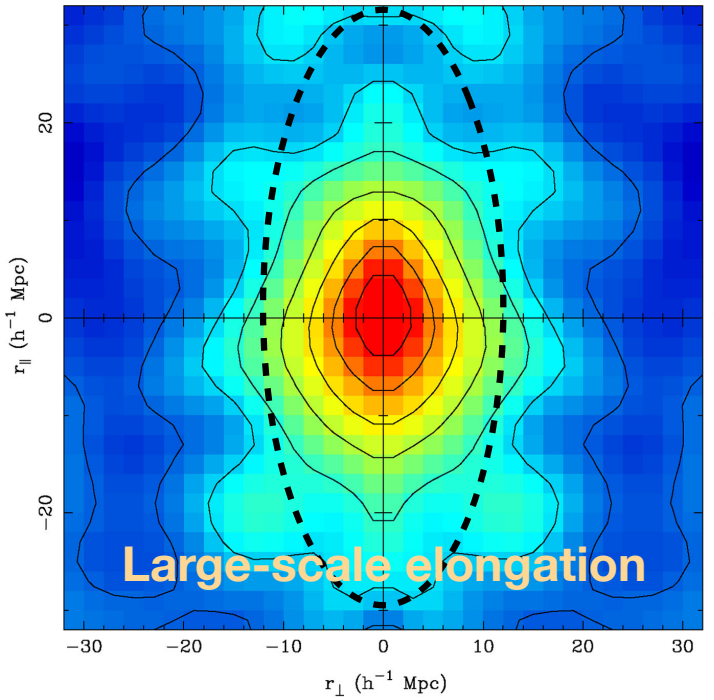
clustering becomes **smaller** along l.o.s

Jackson (1972)

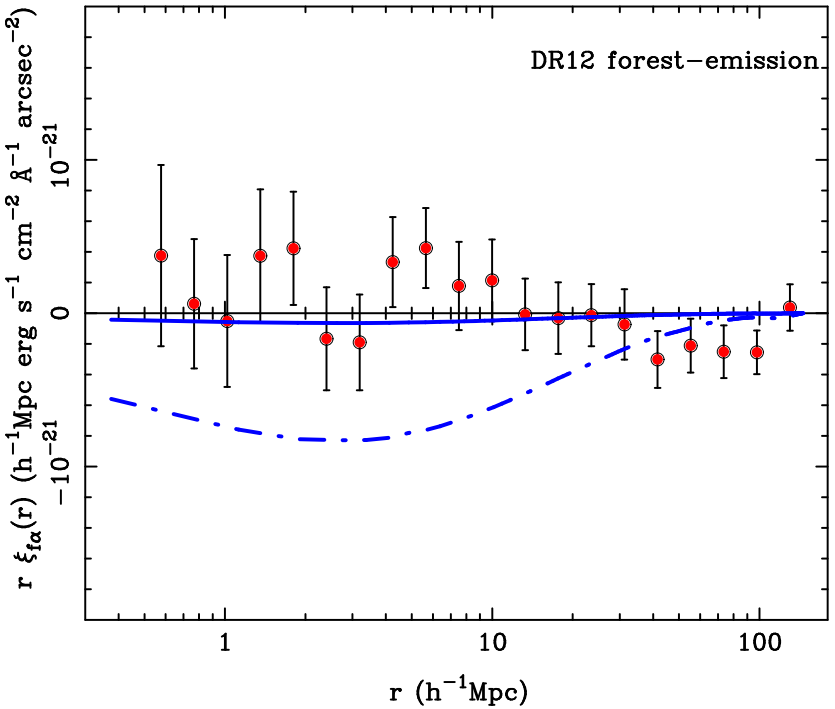
No detection of LyA IM yet!

1) QSO-LyAIM detection at **z~2** in Croft+ (2016)





2) ***No*** LyAF-LyAIM detection in Croft+ (2018)



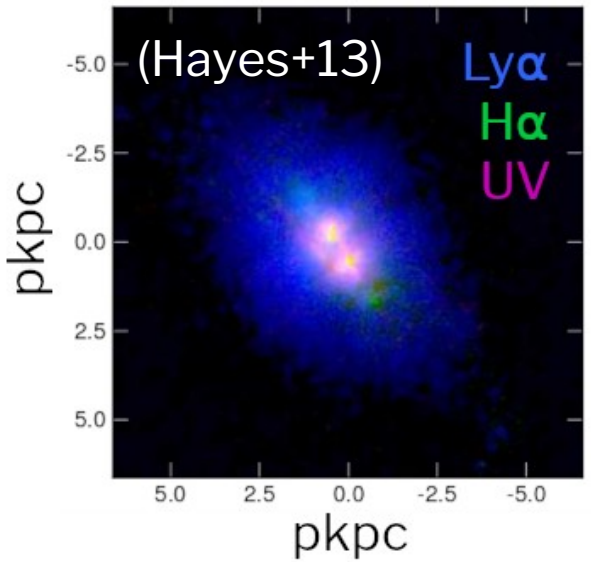
- Croft+(2016) claimed that the FoG is consistent with the RT effect in Zheng+(2011).

Why Radiative Transfer matters?

- Large amounts of hydrogen everywhere*
- Huge cross-section
- Falls into ground-state (quickly)

➔ Scatterings (even if largely ionized)

➔ Region of emission ≠ observed flux origin

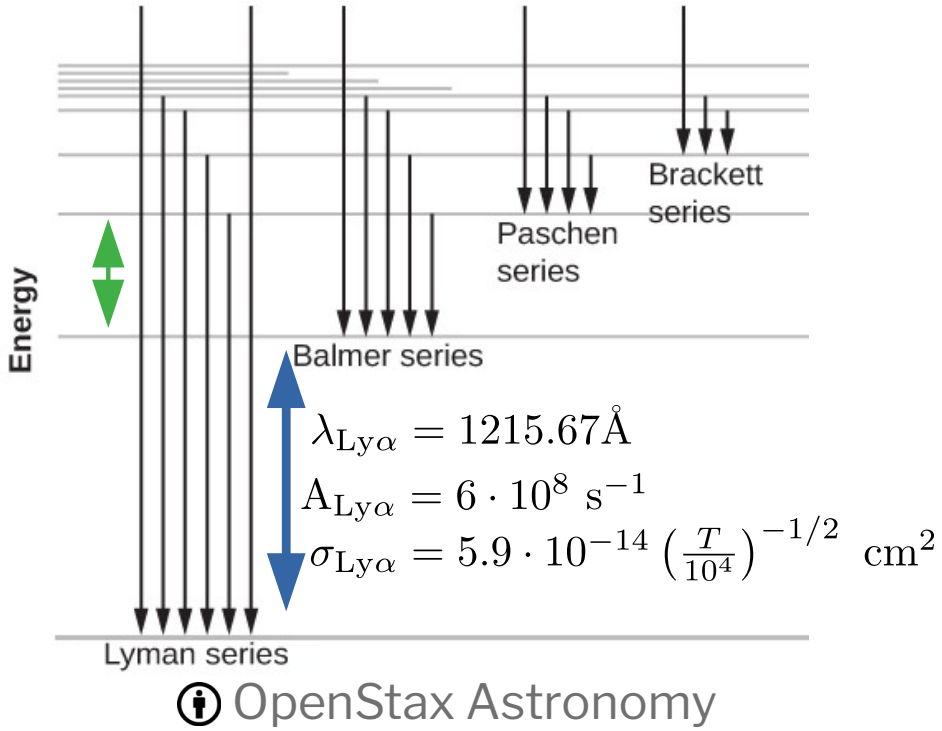


$$\frac{\mathrm{Ly}\alpha}{\mathrm{H}\alpha} \gtrapprox 10$$

➔ Scatterings

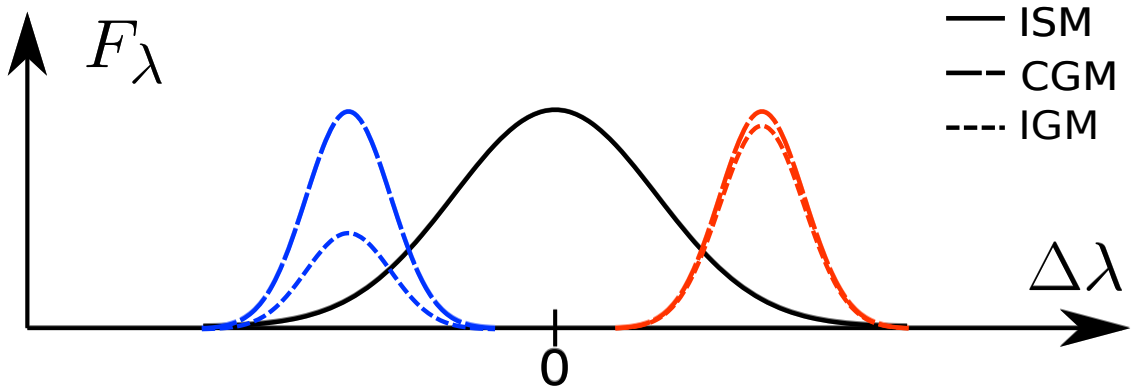
😵 Need RT

😁 Probe CGM



Why Radiative Transfer matters?

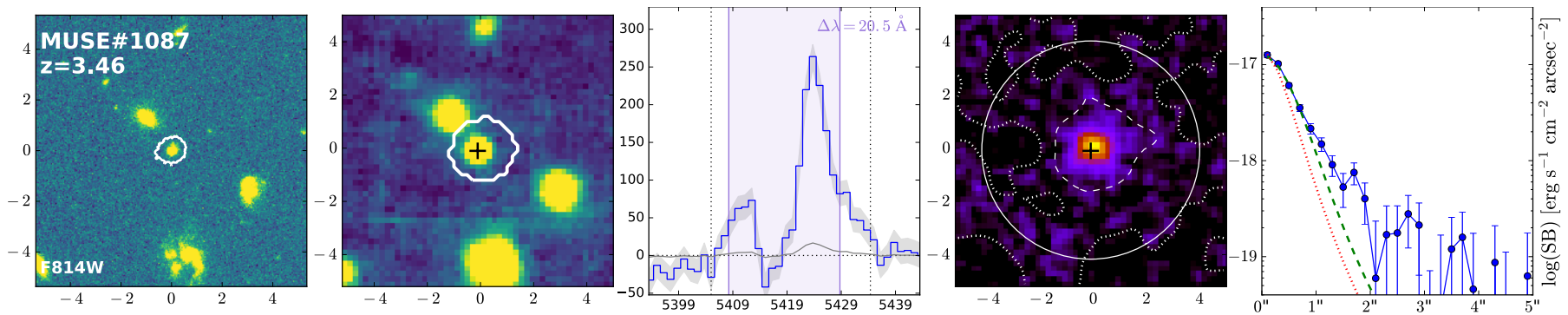
Warning: Depiction dangerously oversimplified!



Multi Scale Physics!

$$\Delta v_{\rm p} = |x_{\rm p}| v_{\rm th} \approx 160 \left(\frac{N_{\rm HI}}{10^{20}\ {\rm cm}^{-2}} \right)^{1/3} \left(\frac{T}{10^4\ {\rm K}} \right)^{1/6}\ {\rm km\ s}^{-1}$$

MUSE, Leclercq+(2017)



Impact of LyA RT on the large-scale clustering

Q1) Is the **IGM** coupling introduced by Zheng+(2011) important at z~2?

Behrens, Byrohl, *SS*, Niemeyer (2018)

Q2) Can we really ignore the impact of the LyA RT at **ISM/CGM** scales?

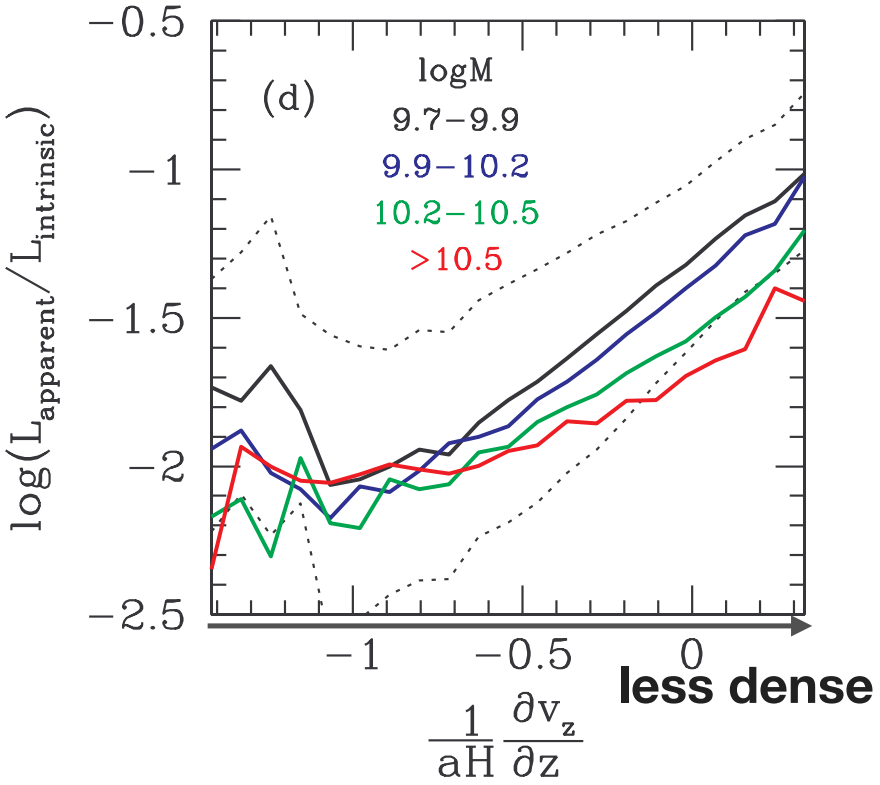
Byrohl, *SS*, Behrens (2019)

Q3) Can we mitigate such impact?

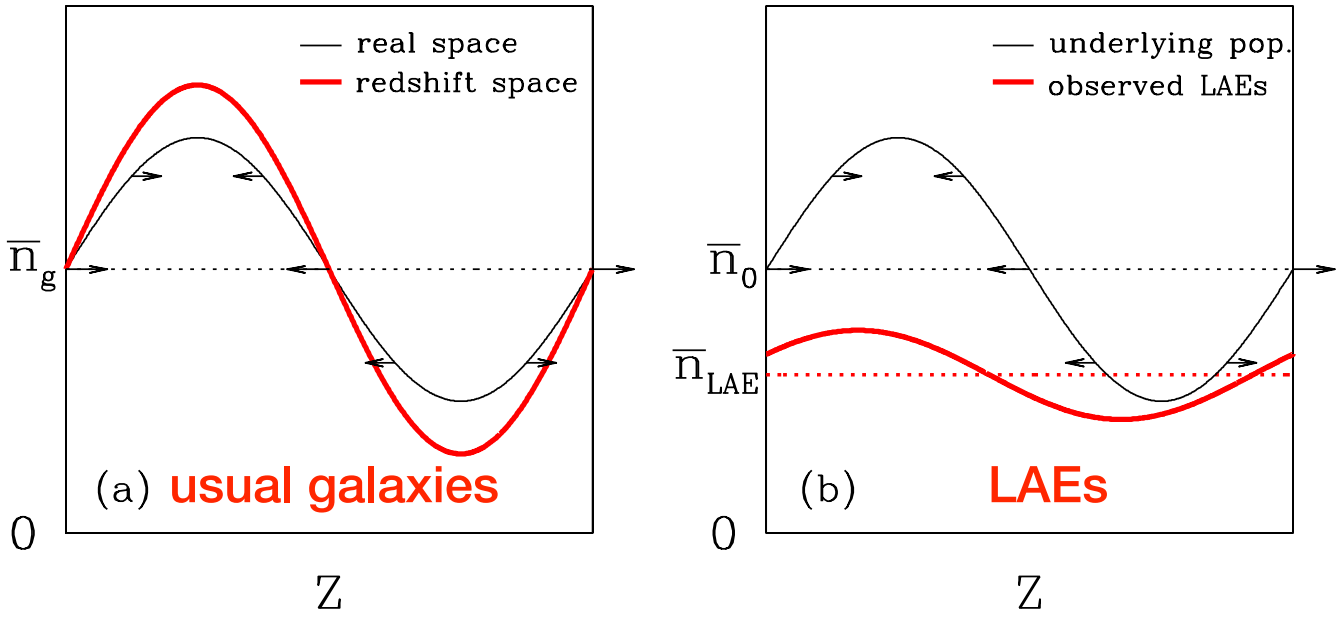
Gurung-Lopez, *SS*+, in prep.

IGM coupling in Zheng+(2011)

- The RT effect in **IGM** sensitive to ***velocity gradient*** **BUT at z~5.7**

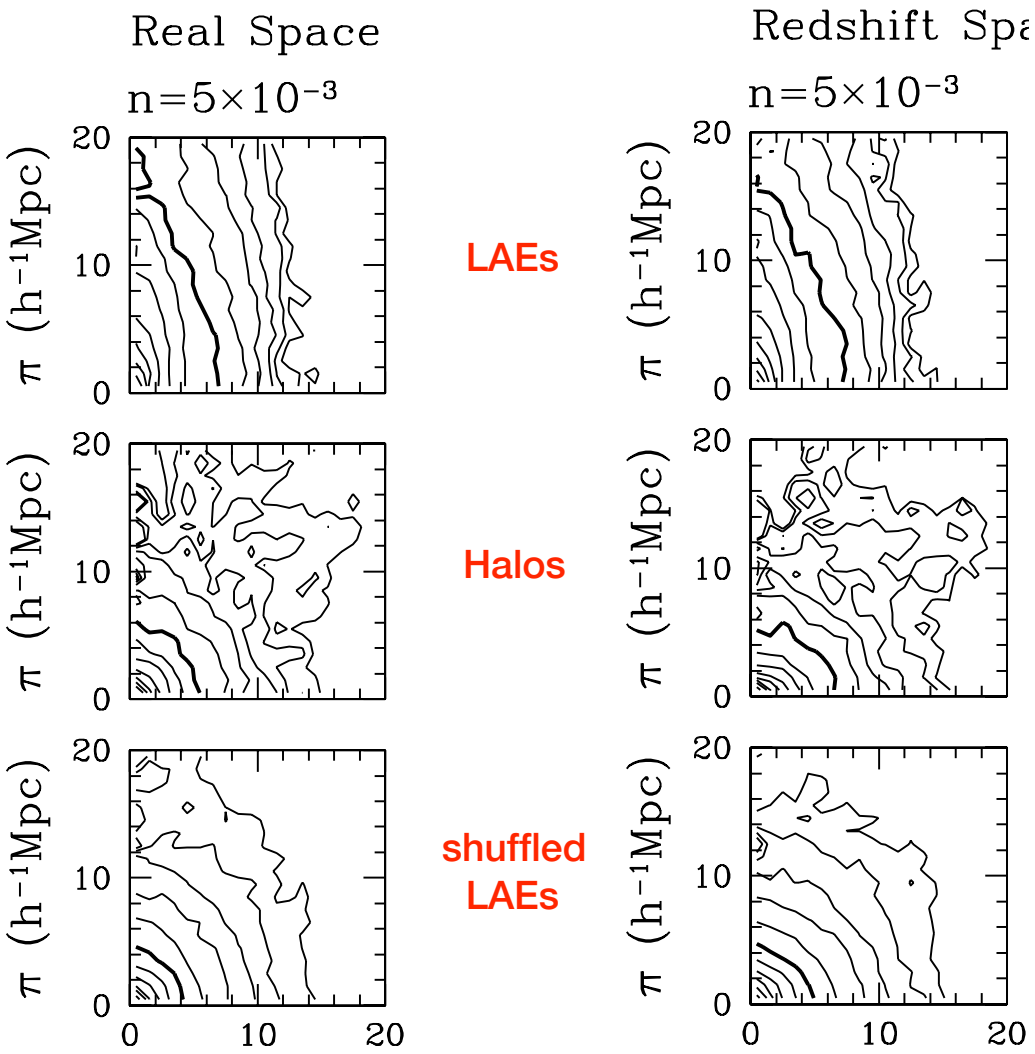


$$\delta \propto -\frac{\partial v_x}{\partial x} - \frac{\partial v_y}{\partial y} - \frac{\partial v_z}{\partial z}$$



- The RT effect in ***IGM coupling*** result in
  an elongation (negative Kaiser) at large scales
  even in ***real*** space.

IGM coupling in Zheng+(2011)

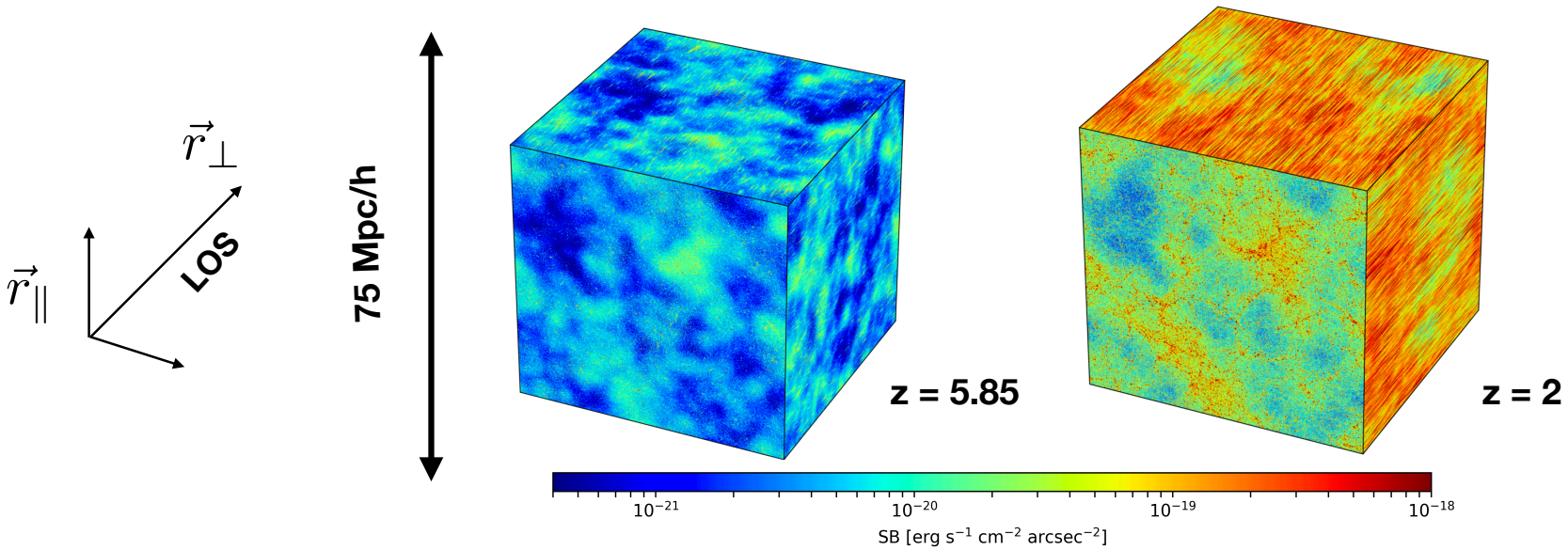


Our LyA Radiative Transfer Simulation

Behrens, Byrohl, ***SS***, Niemeyer (2018)

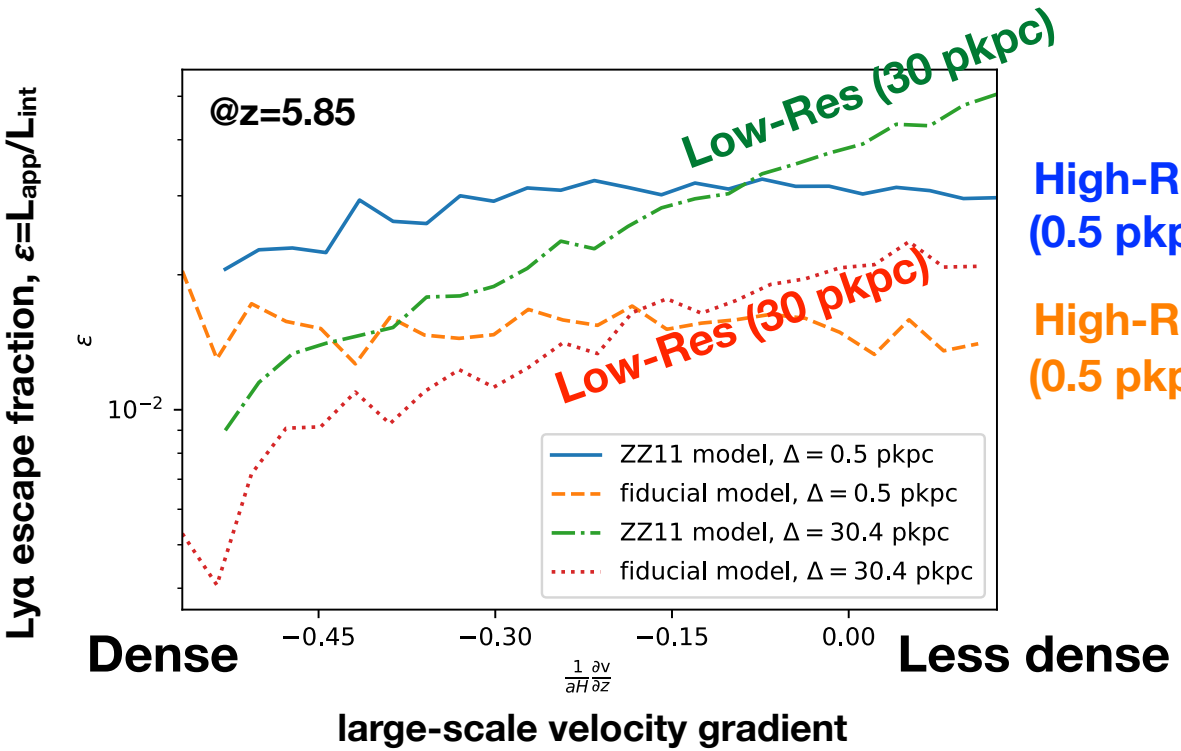
➤ **Towards a better understanding of LyA**

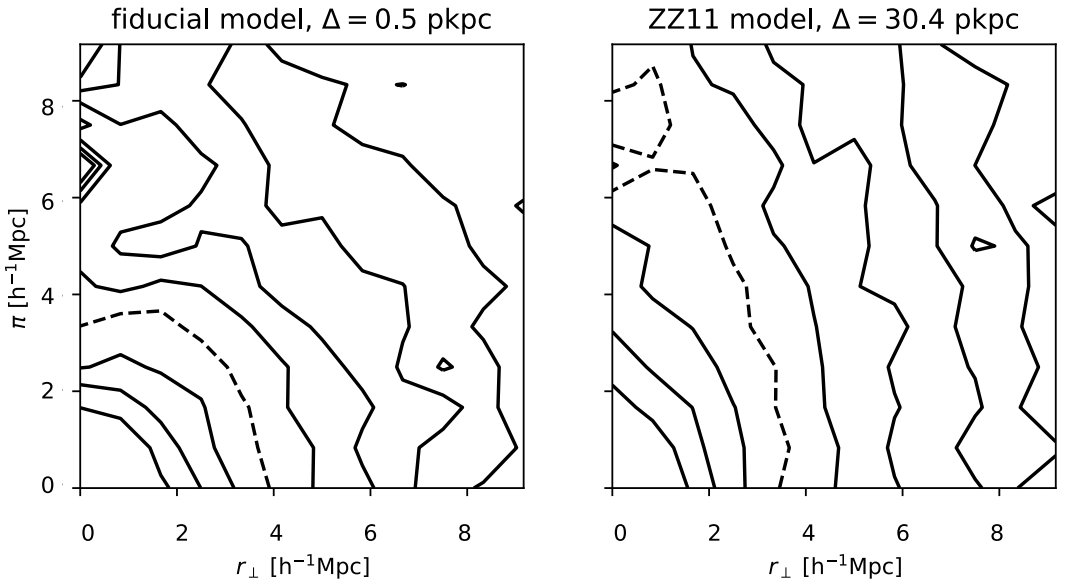
- run LyA RT on the ***Illustris*** simulation Vogelsberger+(2014)
- assumptions (focus on *the large-scale clustering*):
  - initial gaussian profile with virial velocity & $L_{int} = \frac{\mathrm{SFR}}{\mathrm{M}_\odot/\mathrm{yr}} \times 10^{42}\mathrm{erg/s}$
  - Physical but **Unrealistic**: Inconsistent LyA LFs. Dust not included etc…



RT resolution is important

Behrens, Byrohl, ***SS***, Niemeyer (2018)

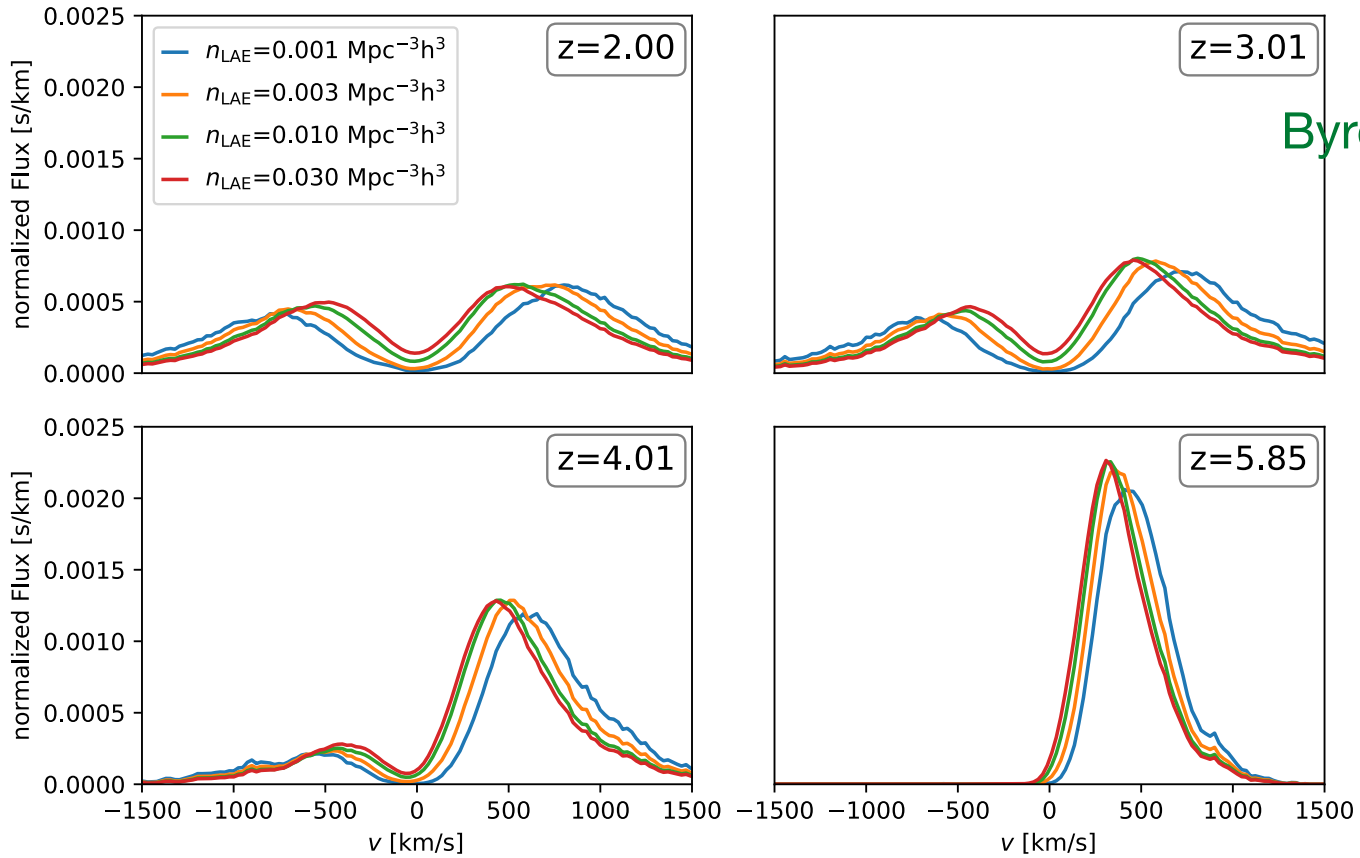




- Zheng+(2011) overestimated the IGM coupling due to the poor resolution.
- The impact becomes less significant at lower z as expected.

What about Redshift Space?

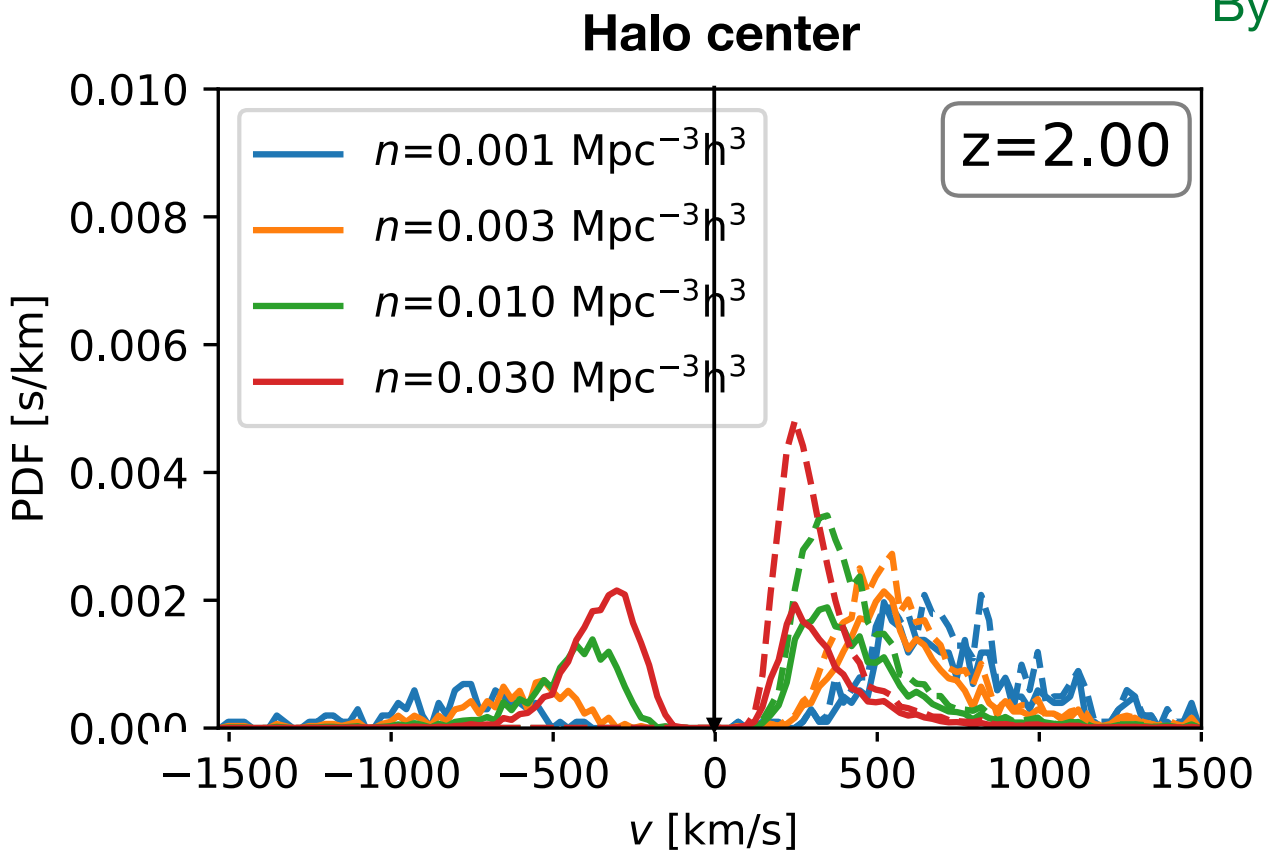
- Zheng+(2011) underestimated the RT effect at **ISM/CGM** scales.
- LAE's radial position is identified as **a peak of its spectrum**.



Byrohl, *SS*, Behrens (2019)

What about Redshift Space?

Byrohl, *SS*, Behrens (2019)



redshift space $\vec{s} = \vec{r} + \frac{\vec{v}\cdot\hat{z}}{aH(z)}\hat{z}$ line of sight direction

real space

- The peak position deviates from the halo center
  → can induce an additional velocity in RSD.

Modeling Nonlinear RSD

Byrohl, SS, Behrens (2019)

➤ **Redshift-space density field (exact under plain-parallel approx.)**

$$\delta_g^s(\vec{k}) = \int d^3x \left\{\delta_g(\vec{x}) - f\partial_z u_z(\vec{x})\right\} e^{i\vec{k}\cdot\vec{x} + ifk_z u_z(\vec{x})}$$

➤ **Redshift-space power spectrum** Scoccimarro (2004), Taruya, Nishimichi, SS (2010)

$$\mathcal{A}(\vec{x}) \equiv \delta_g(\vec{x}) + f\partial_z u_z(\vec{x})$$

$$\begin{aligned} P_g^s(\vec{k}) \quad = \quad & \int d^3r\, e^{i\vec{k}\cdot\vec{r}} \exp\left\{\left\langle e^{-ifk_z\Delta u_z}\right\rangle_c\right\} \\ & \times \left\{\left\langle e^{-ifk_z\Delta u_z}\mathcal{A}(\vec{x})\mathcal{A}(\vec{x}')\right\rangle_c \right. \\ & \left. + \left\langle e^{-ifk_z\Delta u_z}\mathcal{A}(\vec{x})\right\rangle_c \left\langle e^{-ifk_z\Delta u_z}\mathcal{A}(\vec{x}')\right\rangle_c \right\} \end{aligned}$$

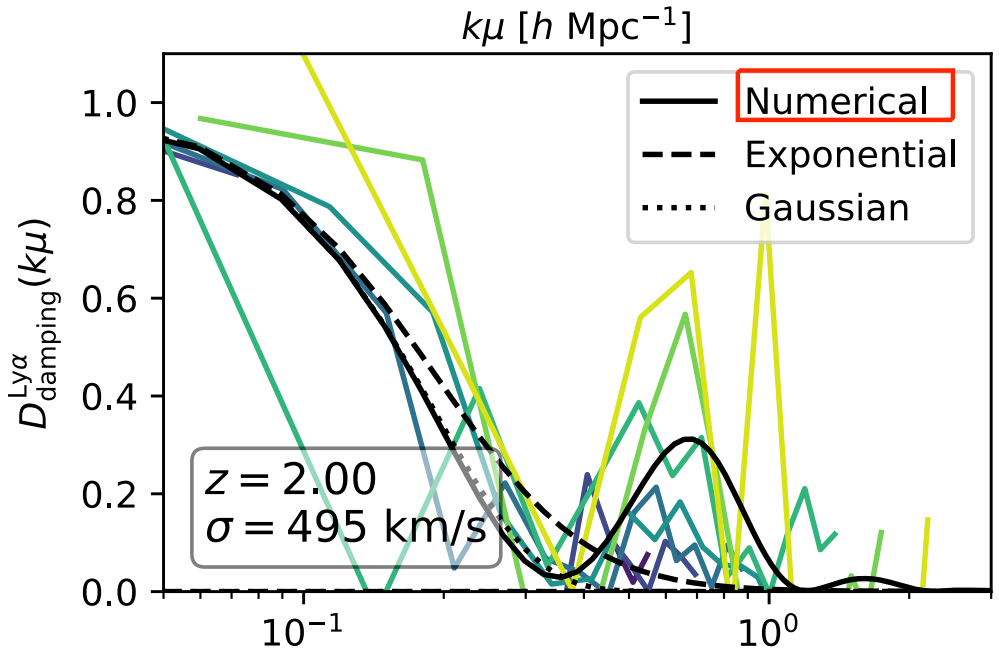
➤ **Overall factor depends on 1pt cumulant.** Zheng & Song (2016), Vlah+(2018)

$$D_{\rm FoG}(k,\mu) = \left|\left\langle e^{ifk\mu u_z}\right\rangle\right|^2 = \left|\int du_z\, P(u_z) e^{ifk\mu u_z}\right|^2$$

Velocity PDF

Diffusion induces an additional FoG

Byrohl, SS, Behrens (2019)

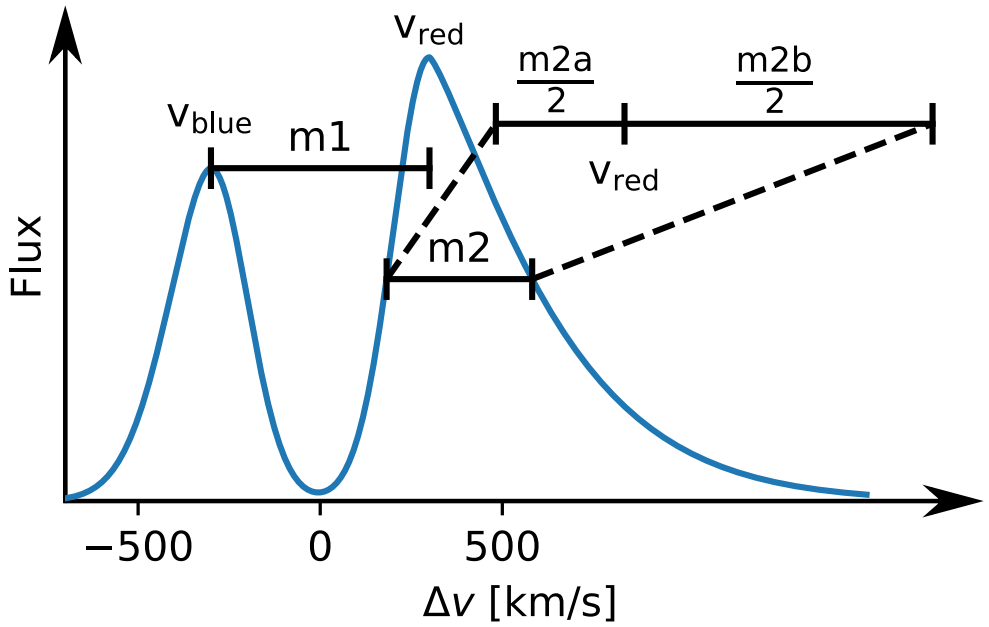


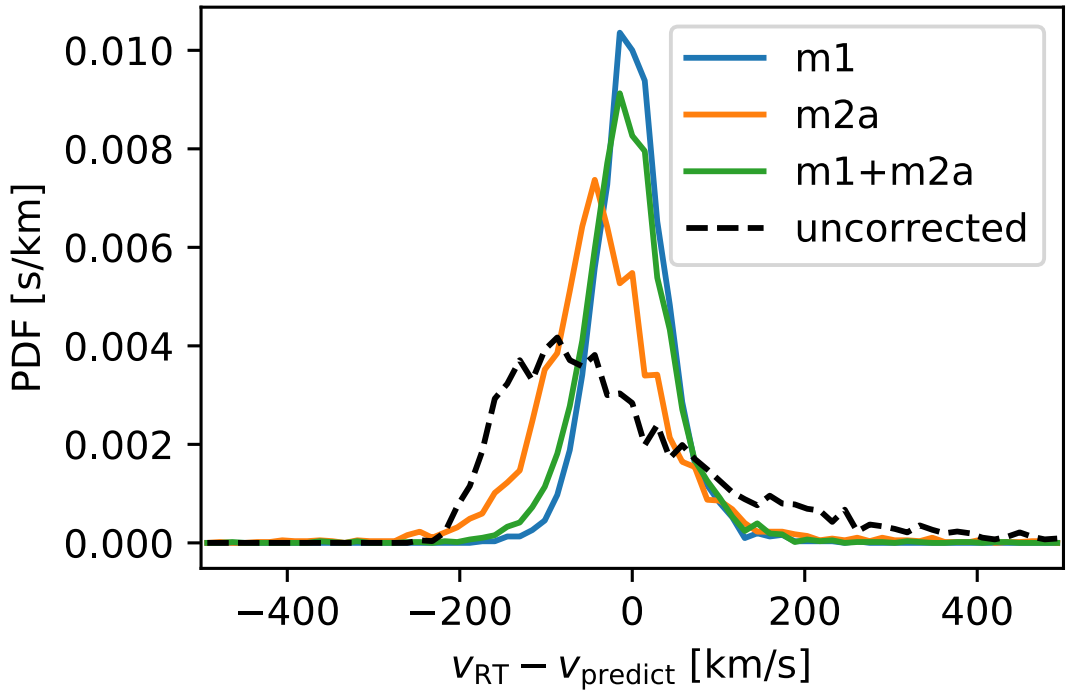
- **Find a new *Finger-of-God* damping due to RT (diffusion).**
  - double peak leads to the oscillation in the damping.
  - Caveats:
    1) Neutral hydrogen in Illustris galaxies seems overestimated. Outflow is likely smeared out.
    2) Our simulation is NOT realistic w.r.t. observations.

Can we mitigate the impact of the diffusion FoG?

Byrohl, *SS*, Behrens (2019)

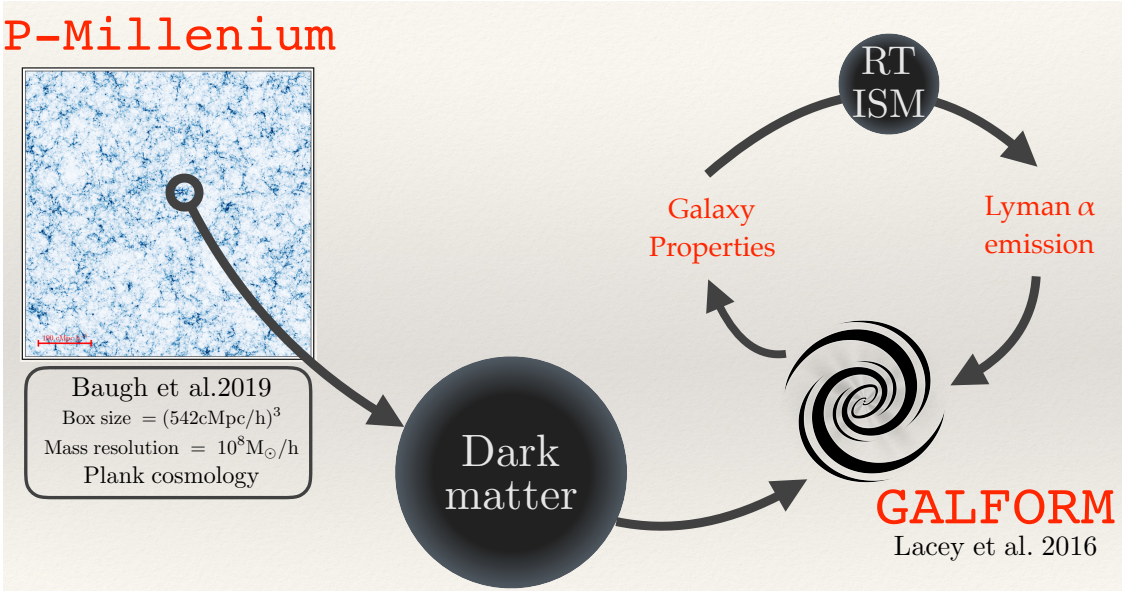
➤ **Spectral information can potentially help us identify the original position.** Verhamme+(2018)

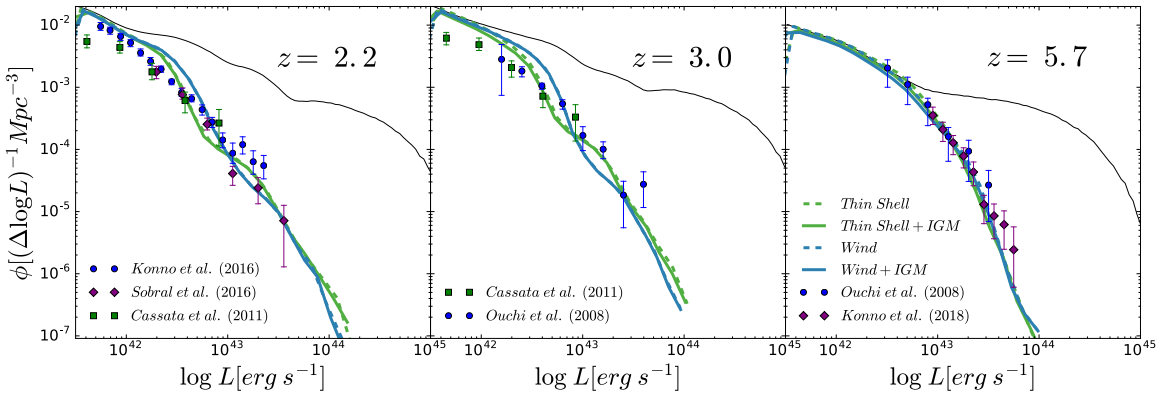


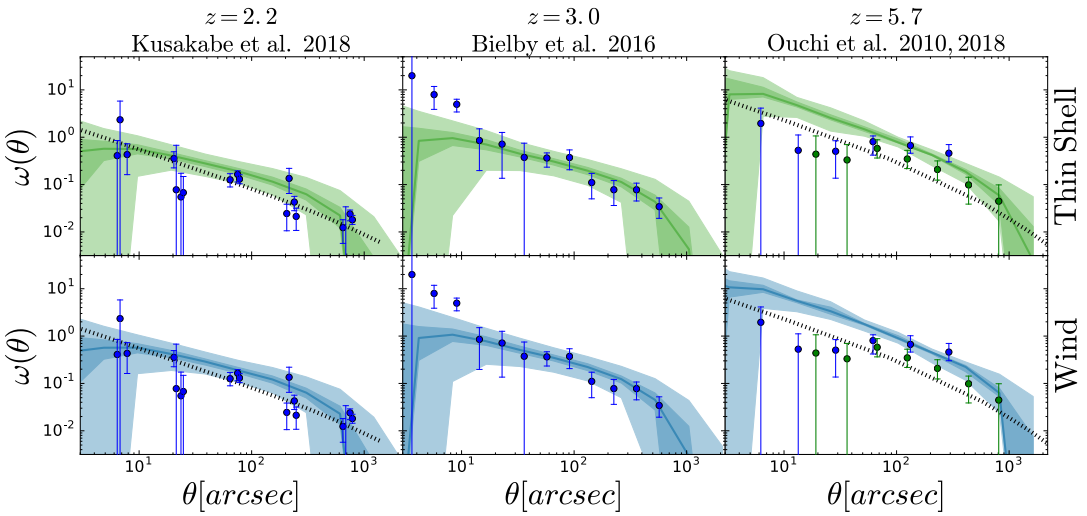


Switch to a more empirical simulation

➤ **Better statistics from a SAM simulation.** Gurung-Lopez+(2018)

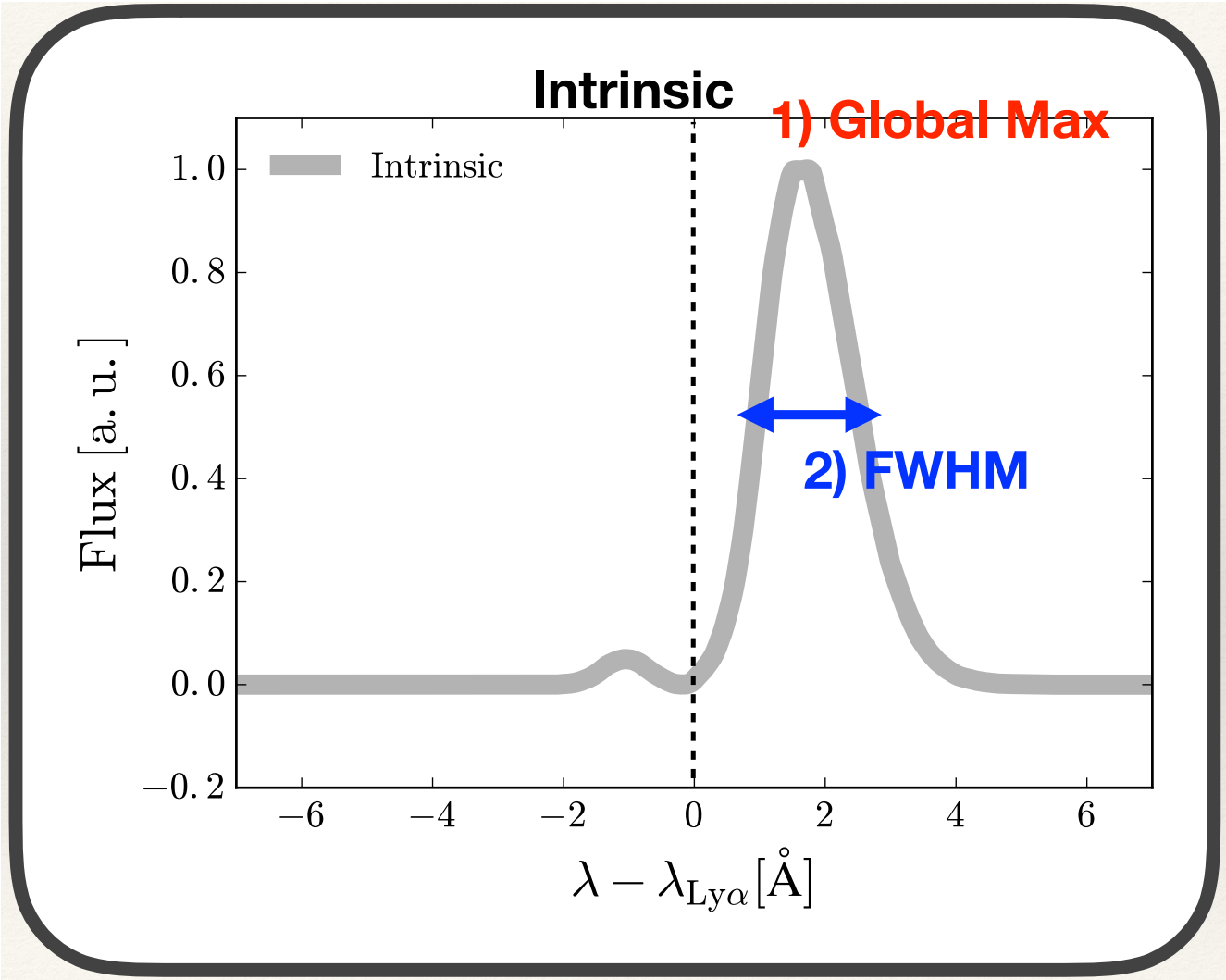






◆ Caveat: RT only on the ISM scales.

Correcting a radial position from its spectrum



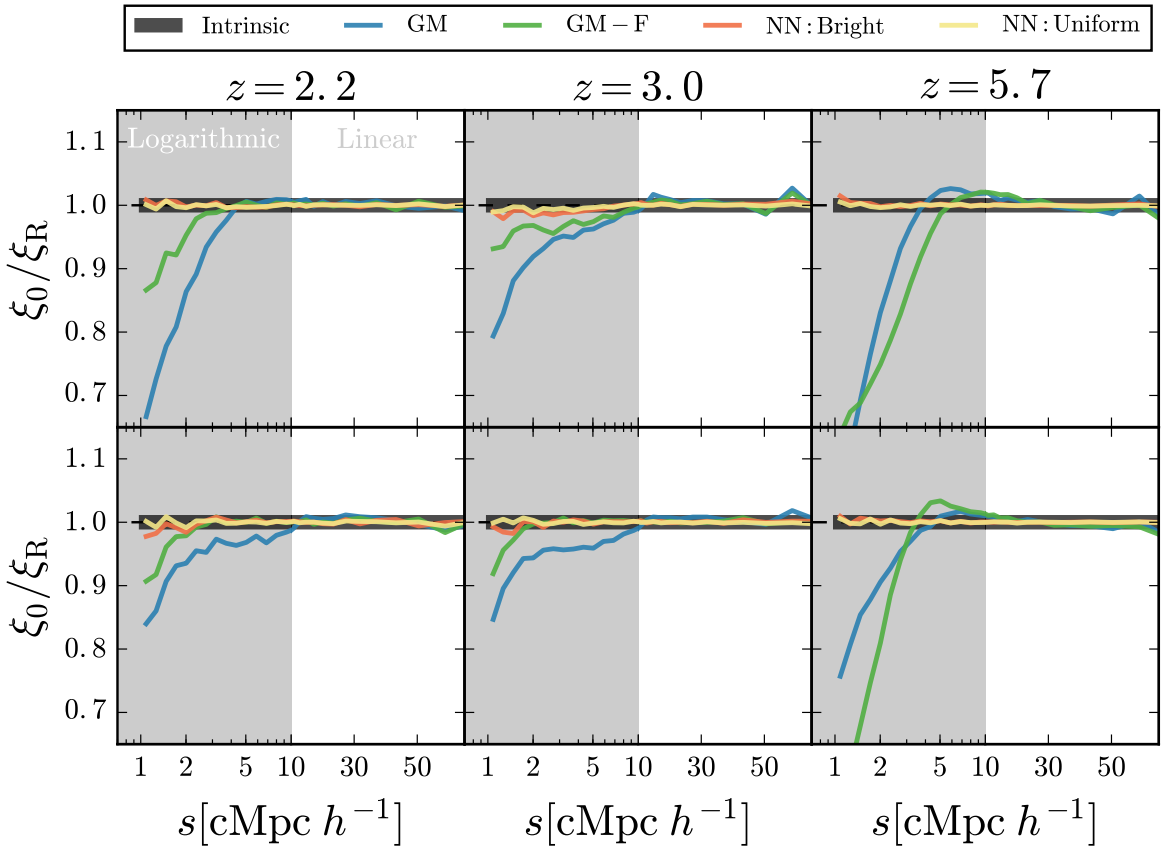
1) Global maximum

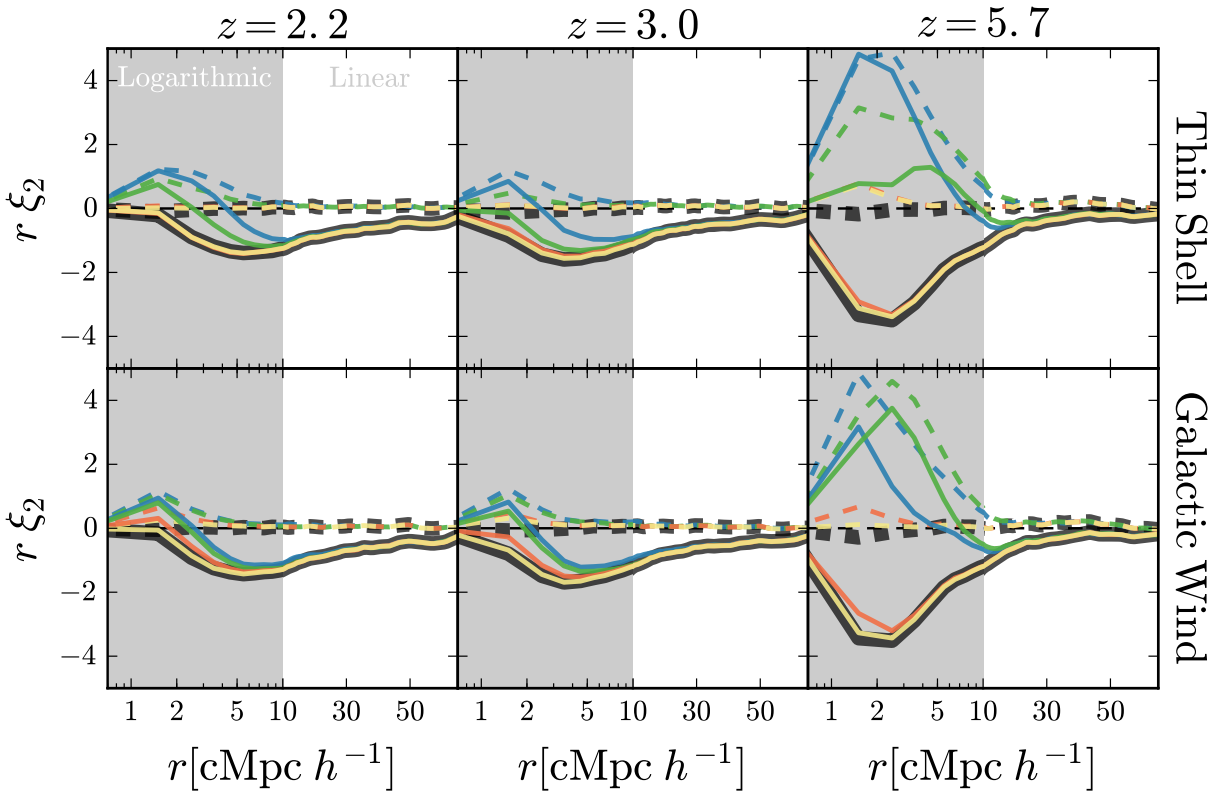
2) Verhamme et al. 2018

3) Neural network : Uniform

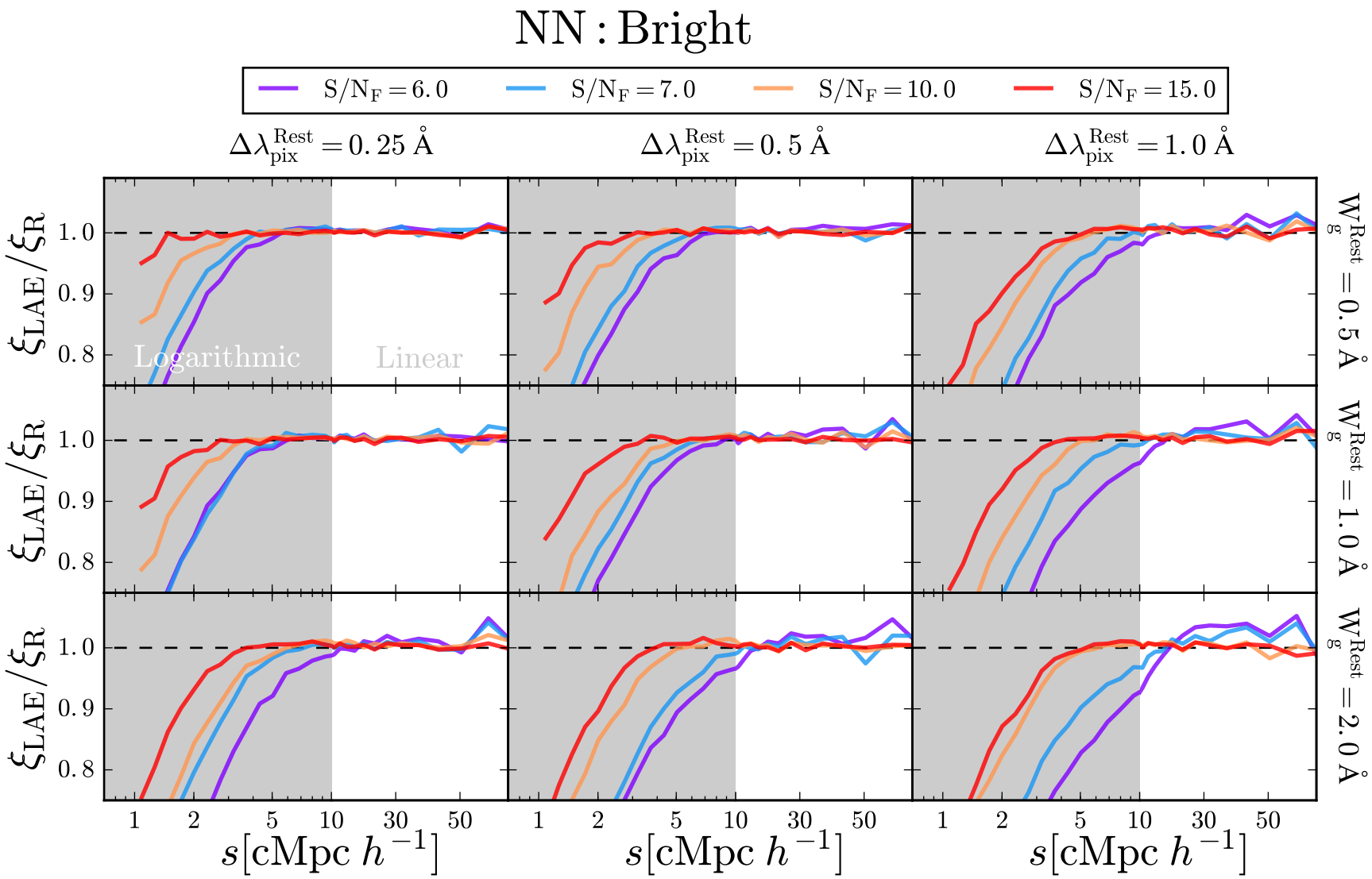
4) Neural network : Bright

Mitigating the FoG effect





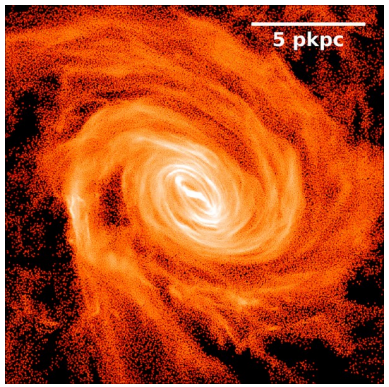
Mitigating the FoG effect in a more realistic situation

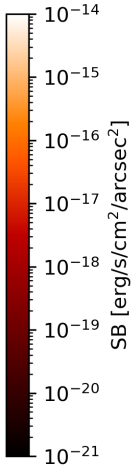


Towards simulating a more realistic LAE

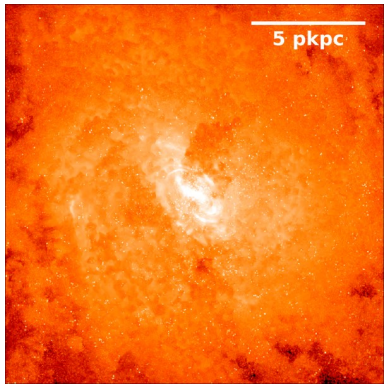
- Chris Byrohl (MPA) has developed a new RT code.

No RT

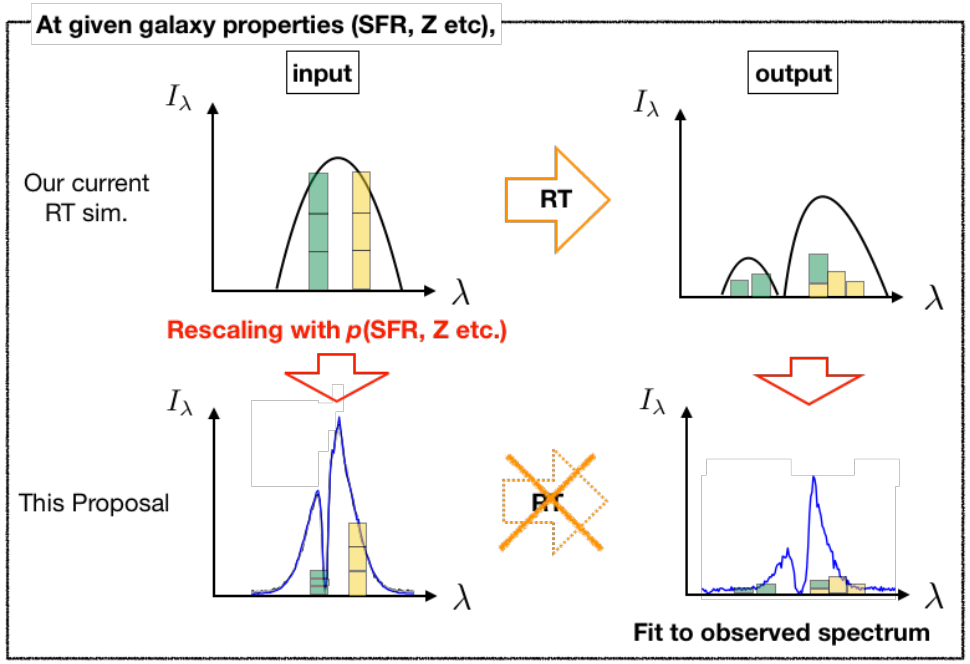




RT



- Simple empirical rescaling works?



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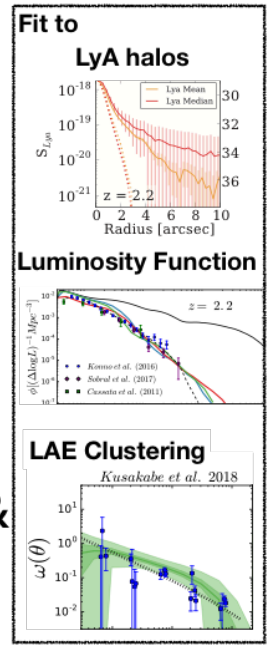

Stay tuned!

Summary

- LyA Radiative Transfer involves multi-scale physics, and its impact on the large-scale clustering cannot be ignored.

- Q1) The IGM coupling introduced by Zheng+(2011) was overestimated due to their poor RT spacial resolution. Not so important at z~2.

- Q2) Diffusion could induce an additional FoG effect.

- Q3) Could mitigate the diffusion effect from spectral information.