

PRE-HEATING IN PROTO-CLUSTERS WITH LYMAN ALPHA FOREST TOMOGRAPHY

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Naoki Yoshida (IPMU), Renyue Cen (Princeton) & Metin Ata (IPMU)

OUTLINE

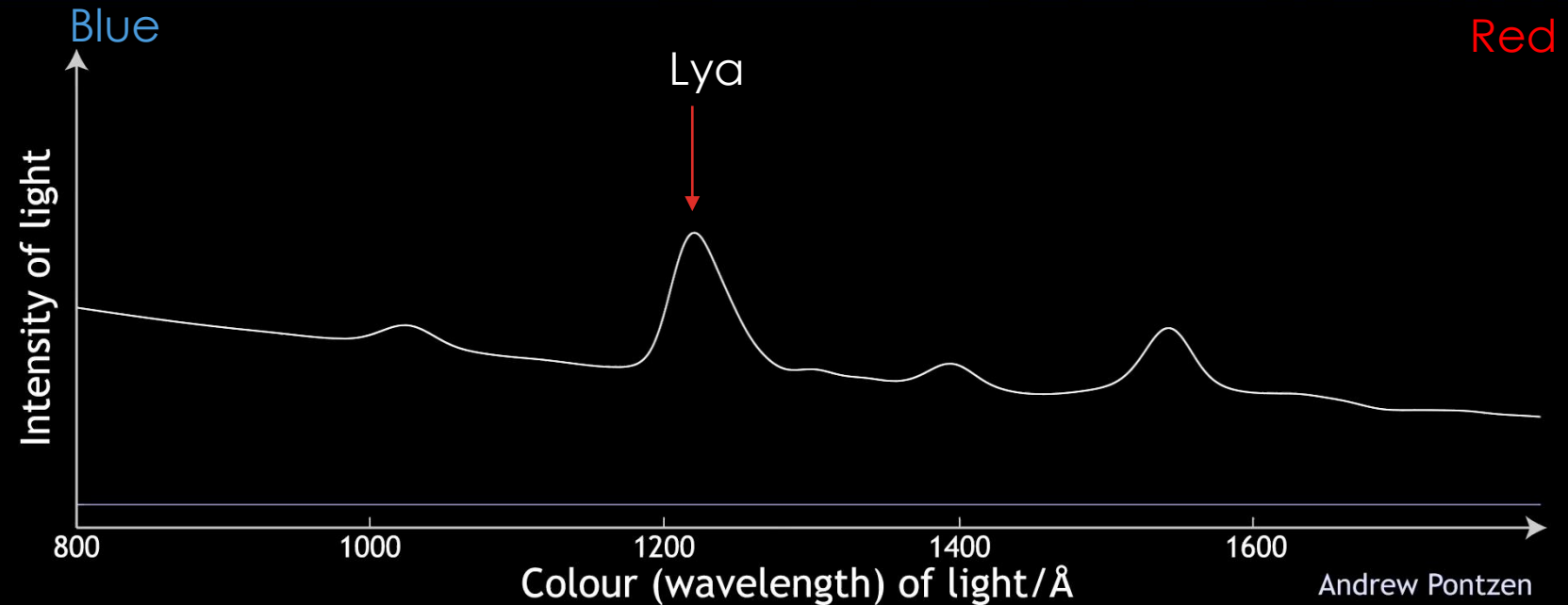
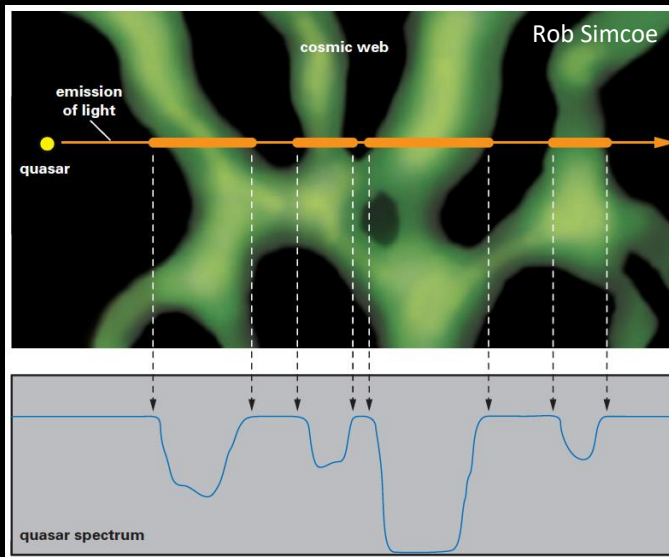
- Lyman Alpha Forest Tomography
- CLAMATO Survey
- Cluster pre-heating
- Proto-cluster Simulations & Results
- Conclusions

THE LYMAN ALPHA FOREST

- Observe: $F = F_0 e^{-\tau_\alpha}$
- Absorption depends on underlying density field and astrophysics

$$\tau_\alpha \propto n_{HI} \propto x_{HI}(\Gamma_{UVB}, T_0, \gamma) \times (1 + \delta)^\beta$$

- Can also use Lyman break galaxies as background source (Lee+2014)



Andrew Pontzen

LYMAN ALPHA FOREST TOMOGRAPHY

<https://www.youtube.com/watch?v=TVHIGDxYIQk>

- Dense distribution of sightlines allows for reconstruction of 3D absorption field (Pichon+2001, Caucci+2008)



CLAMATO-SURVEY

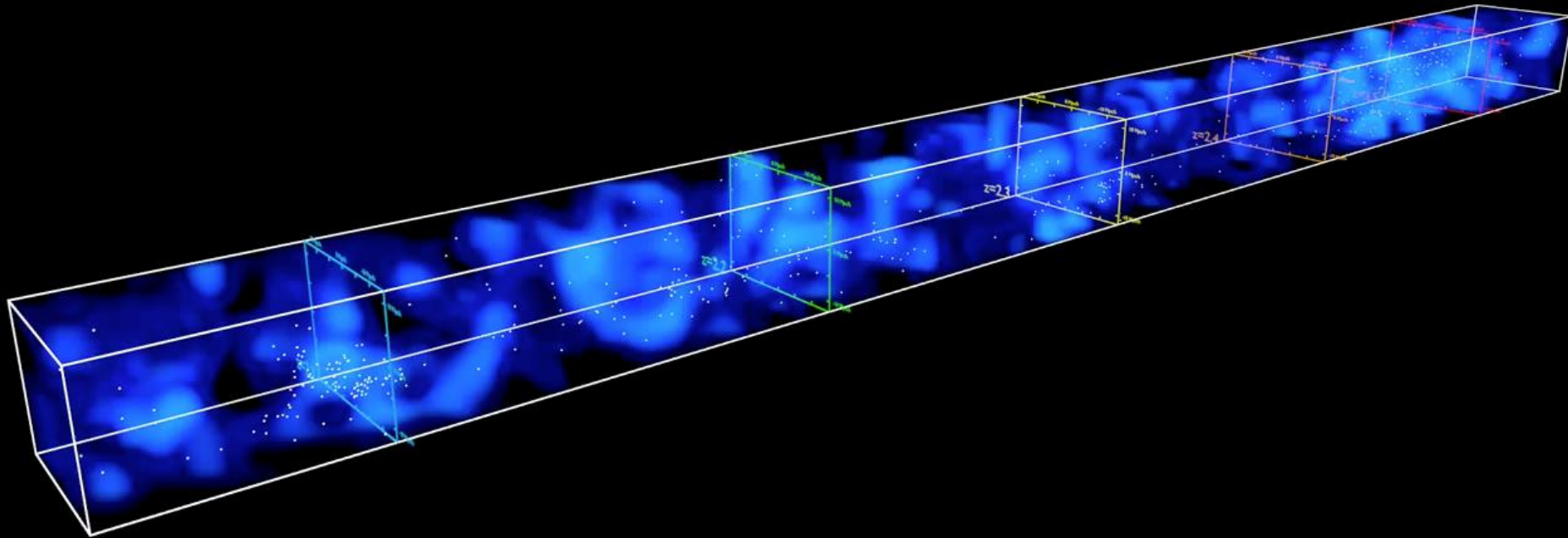
- COSMOS Lyman-Alpha Mapping And Tomography Observations
 - Survey with LRIS on Keck of the COSMOS field
 - 2-4h integrations with $g < 24.8$
- First systematic use of galaxies
- Mean transverse separation of 2.4 Mpc/h
- Ly α forest redshift range: $2.05 < z < 2.55$
 - 21 Mpc/h x 27 Mpc/h x 340 Mpc/h
- Data release public: Lee+2018
- DM density reconstruction:
Cosmic BIRTH (Kitaura+2019, Ata+2020)



Khee-Gan Lee, IPMU

CLAMATO-SURVEY

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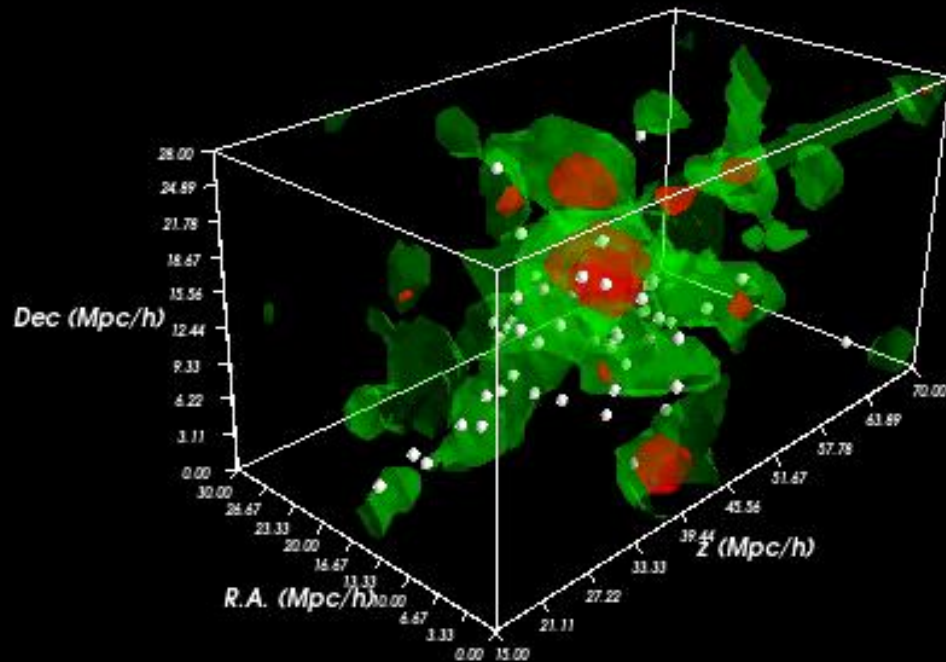
- 3D map generated by Wiener Filtering the sightlines

<https://www.youtube.com/watch?v=QGtXi7P4u4g>
Created by Thomas Müller, MPA

PROTO-CLUSTERS IN CLAMATO-SURVEY

COSMOS $z=2.095$ Protocluster

Horowitz+in prep

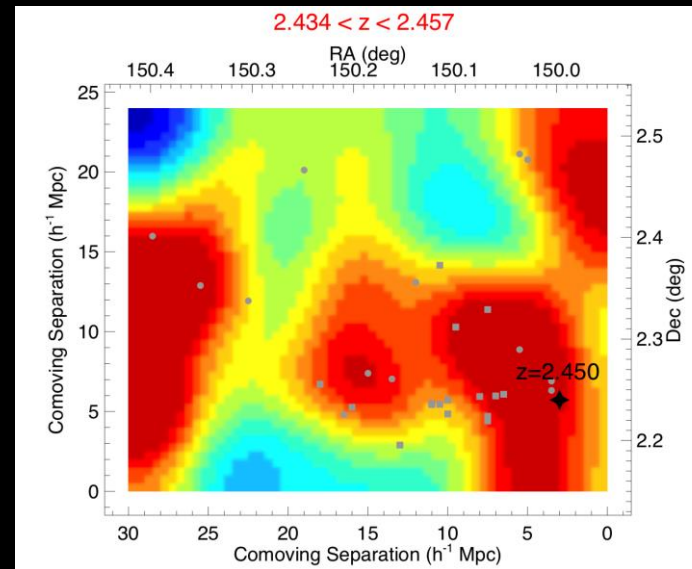


Nodes

Filaments

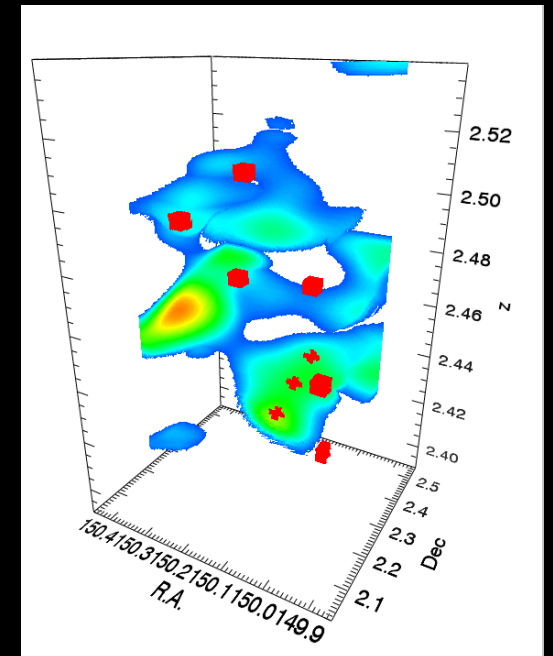
$z = 2.095$, zFOURGE
Spitler+2012

Courtesy of Khee-Gan Lee



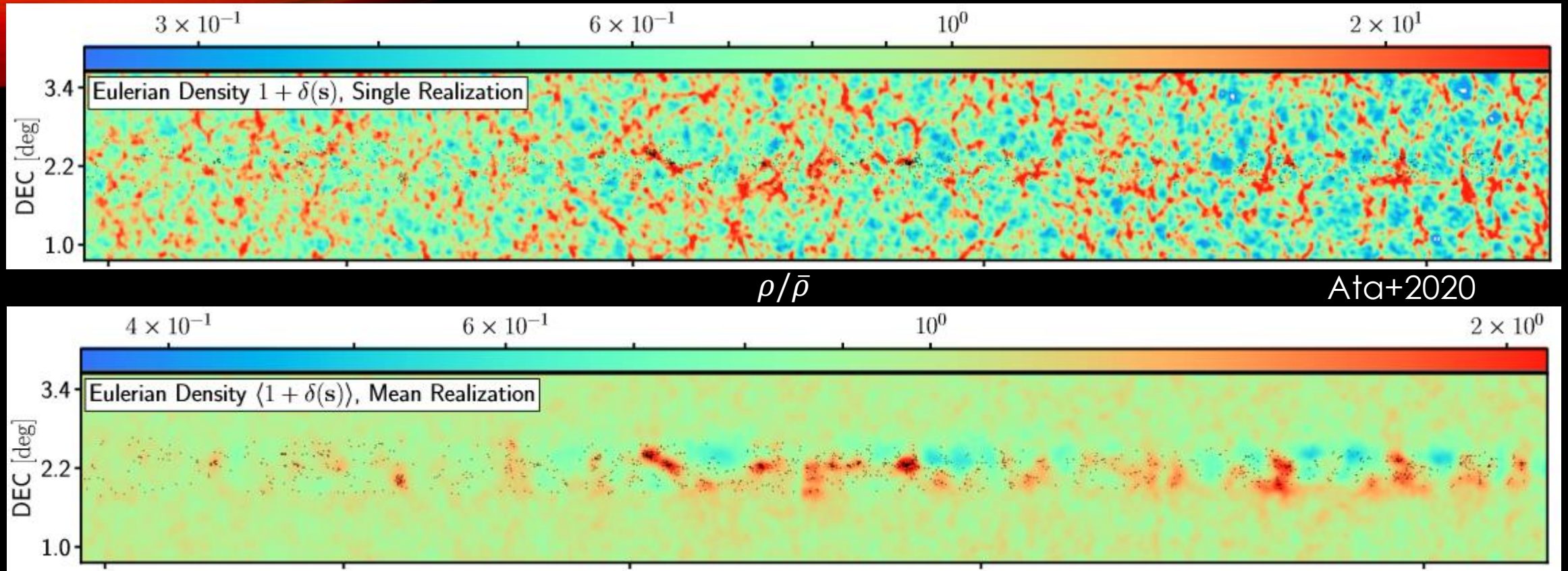
Hyperion ($z = 2.45$)

Cucciati+2018



And more...

DM-DENSITY COSMOS FIELD ⁸



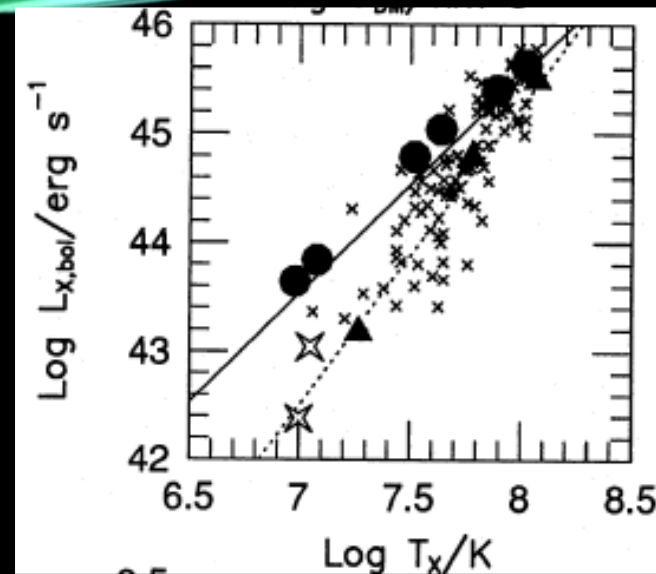
- COSMIC BIRTH (Kitaura+2019, Ata+2020): Bayesian inference of initial density field from spectroscopic galaxy survey data on a lightcone
- Use data from multiple surveys and taking into account the radial and angular selection functions
- Single realizations can be used to estimate variance



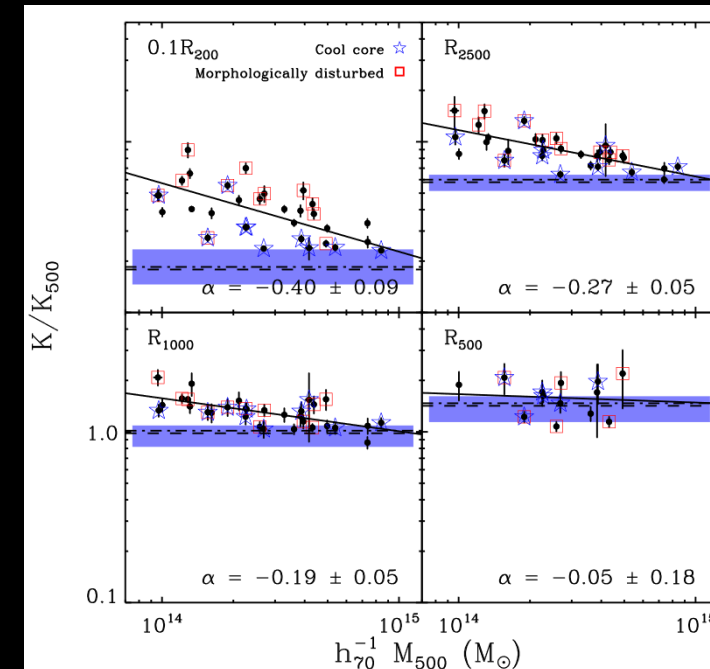
Metin Ata, IPMU

CLUSTER PREHEATING

- Without feedback, gas in clusters should mostly be heated through gravitational contraction: self-similarity
- L_X - T relation too steep to be explained by self-similarity (slope = 2)
- Excess entropy K at small/intermediate radii in clusters
- Extra heating injected into proto-clusters at high z :
 - Feedback from stars
 - AGN



Navarro, Frenk & White 1995



Pratt+2010

- simulated clusters
- \blacktriangle preheated sims
- \times , \diamond observations

PROTO-CLUSTER SIMULATIONS ¹⁰

- Goal: effect of preheating on Ly α absorption of proto-clusters
- Zoom-in simulations of proto-cluster regions in $(300 \text{ Mpc}/h)^3$ volume simulation box with AREPO
- Turn off all feedback, no starformation, no metal cooling
- Inject energy into proto-cluster at $z = 3$:
 - Inject energy into particles with $\delta_g > 5$ to raise entropy above entropy floor (Borgani+2001)
 - Different entropy floors: $K_{\text{fl}} = 0, 30, 50$ and 100 keV cm^2

$$\delta = \rho / \bar{\rho} - 1$$

$$K = T n_e^{-2/3}$$

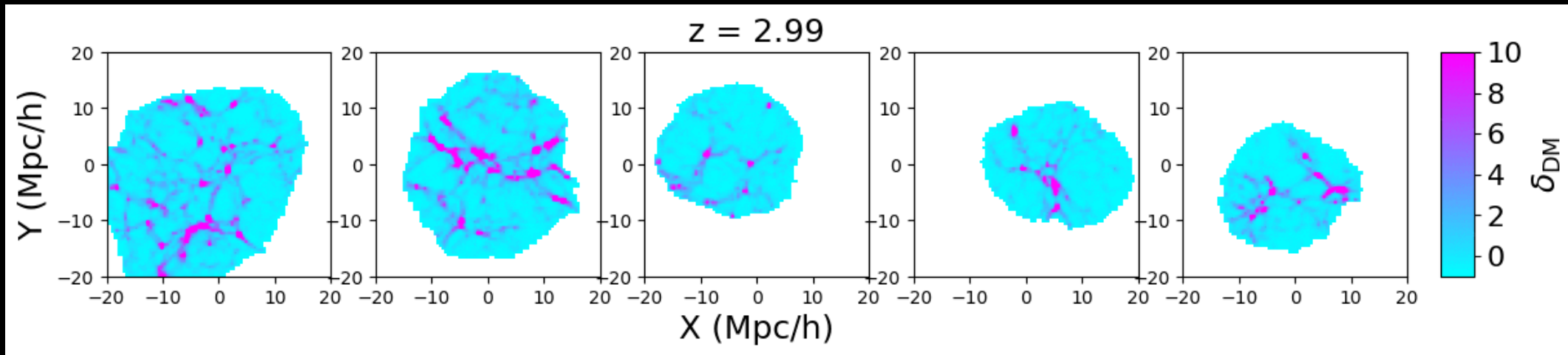
$$M_{\text{halo}}^{z=0} = 2.0 \cdot 10^{15}$$

$$1.4 \cdot 10^{15}$$

$$7.5 \cdot 10^{14}$$

$$5.9 \cdot 10^{14}$$

$$5.6 \cdot 10^{14} M_{\odot}$$



Shigeki Inoue
Tsukuba University

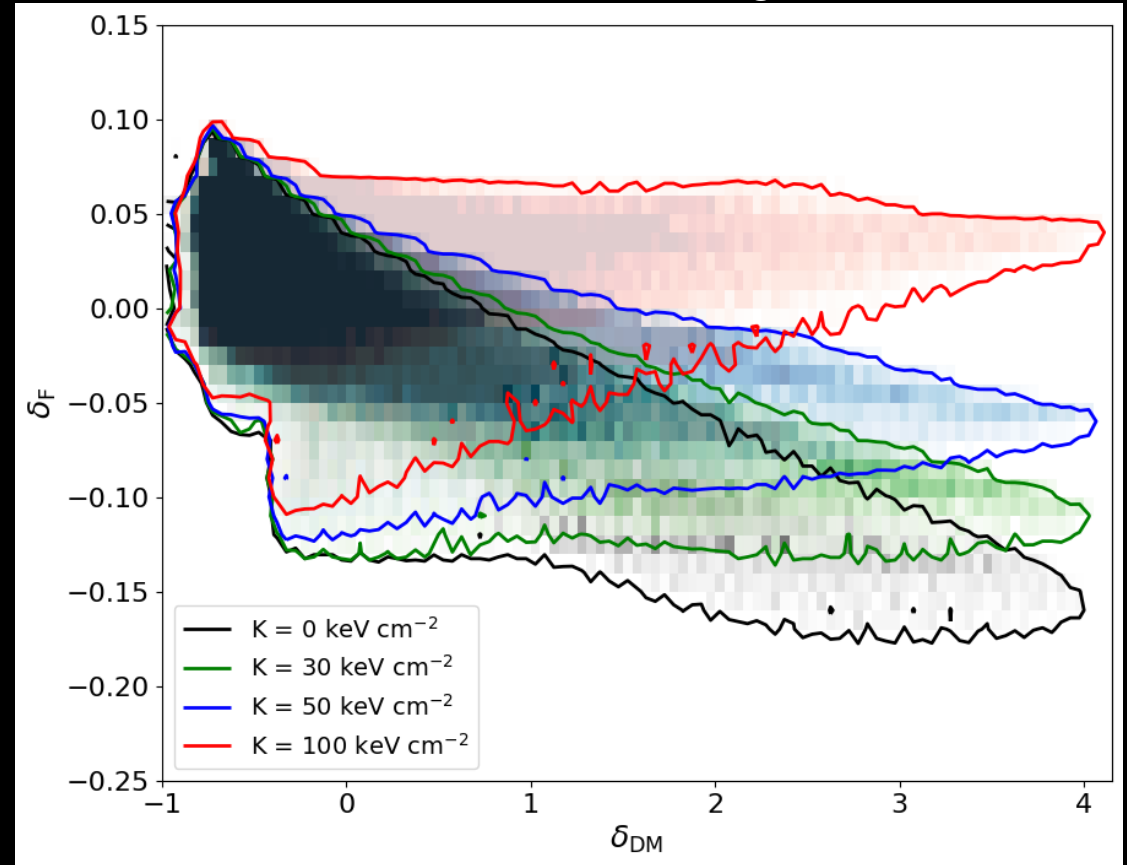
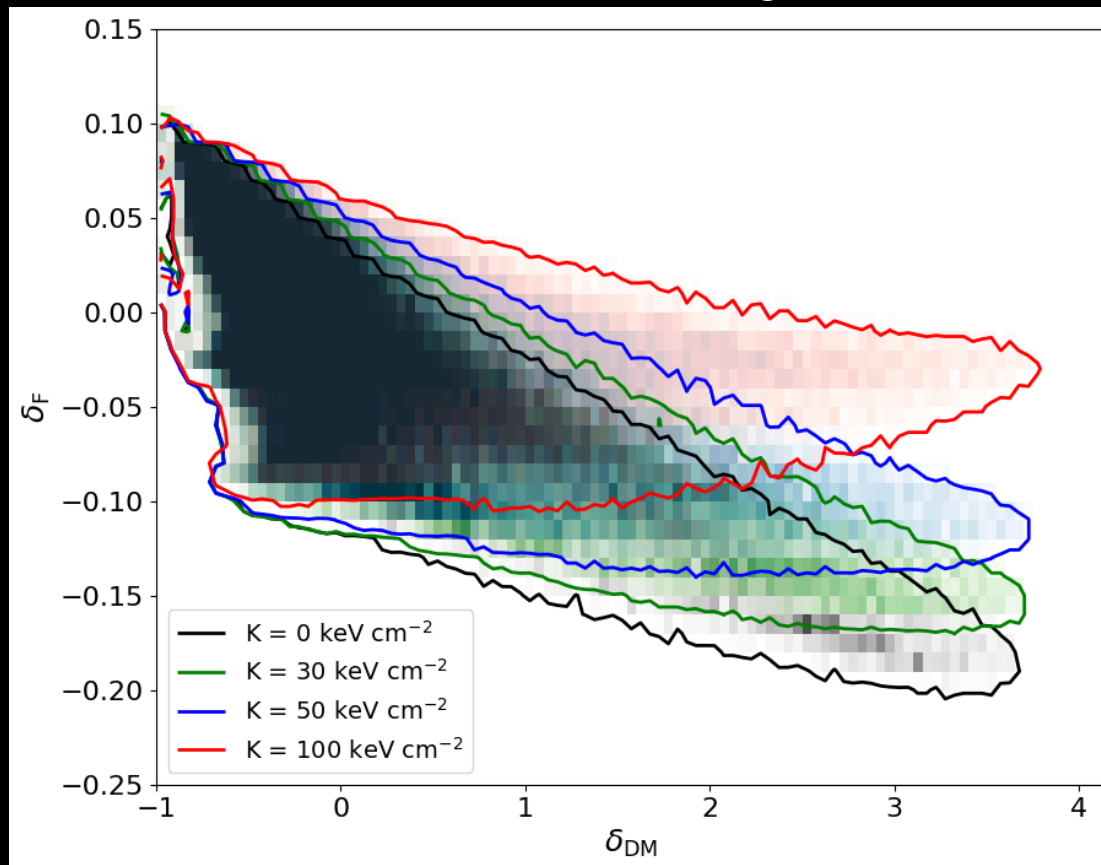
PROTO-CLUSTER SIMULATIONS ¹¹

- $\delta_F \equiv F/\bar{F} - 1$, where \bar{F} is observed mean flux (Becker+2013)
- Extract random spectra, normalize fluxes with random zoom-in regions
- Heat injection causes distribution for proto-clusters to tilt

δ_{DM} and δ_F
smoothed to
3 Mpc/h

$$M_{halo}^{z=0} = 5.9 \cdot 10^{14} M_{\odot}$$

$$M_{halo}^{z=0} = 7.5 \cdot 10^{14} M_{\odot}$$

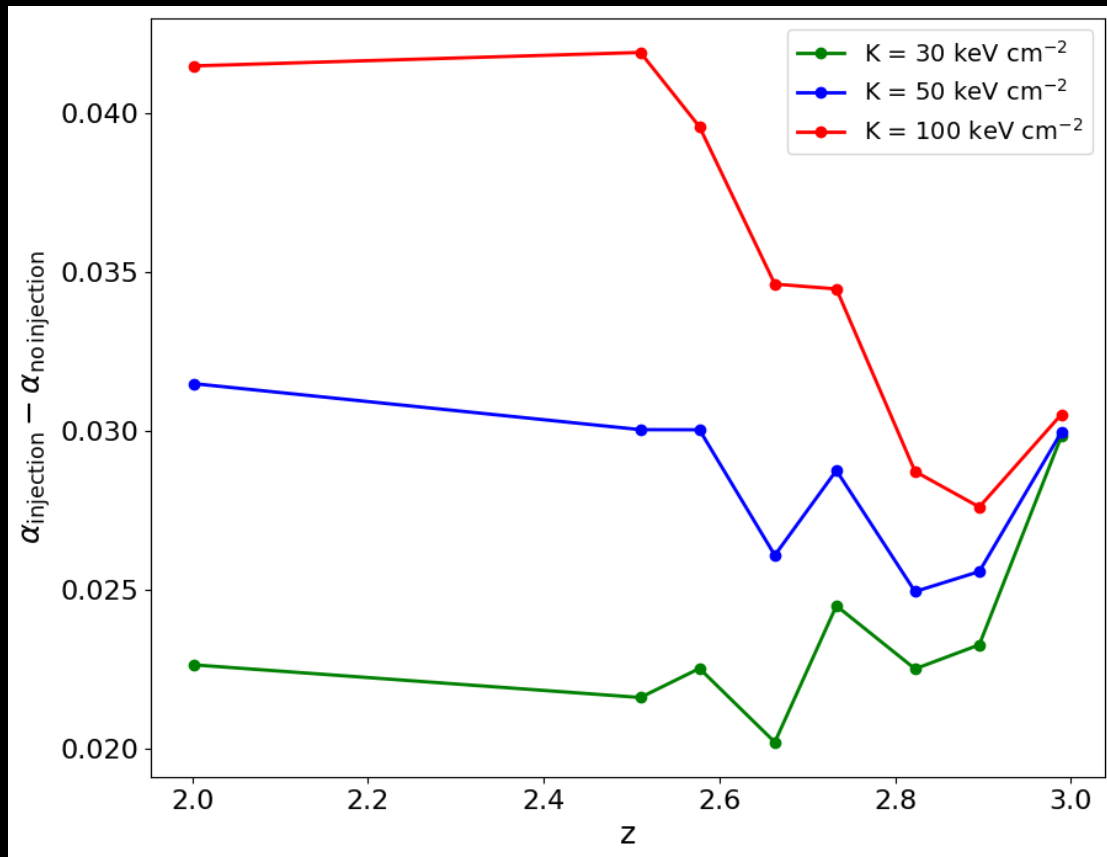


PROTO-CLUSTER SIMULATIONS

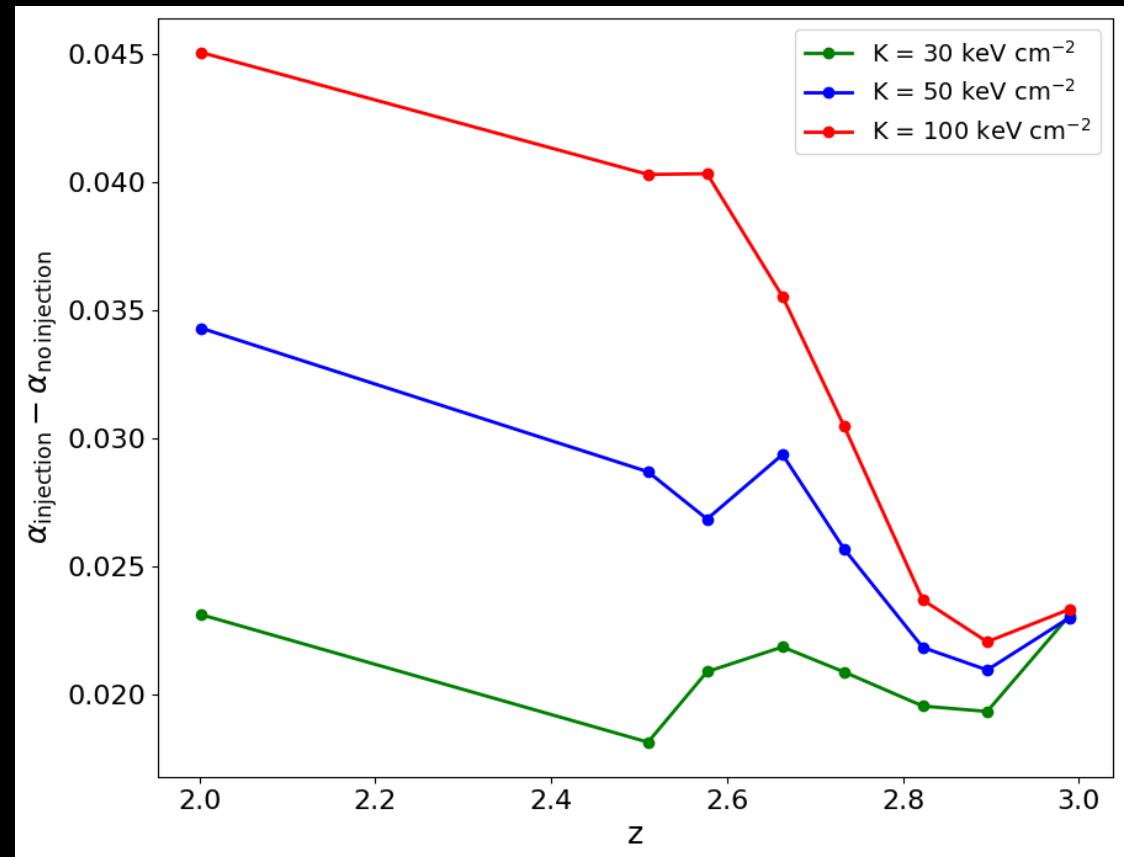
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- Slope α evaluated at $1 \geq \delta_{\text{DM}} \leq 3$
- Slope tilt evolves with redshift, biggest difference at $z \sim 2$

$$M_{\text{halo}}^{z=0} = 5.9 \cdot 10^{14} M_{\odot}$$



$$M_{\text{halo}}^{z=0} = 7.5 \cdot 10^{14} M_{\odot}$$



PROTO-CLUSTER SIMULATIONS ¹³

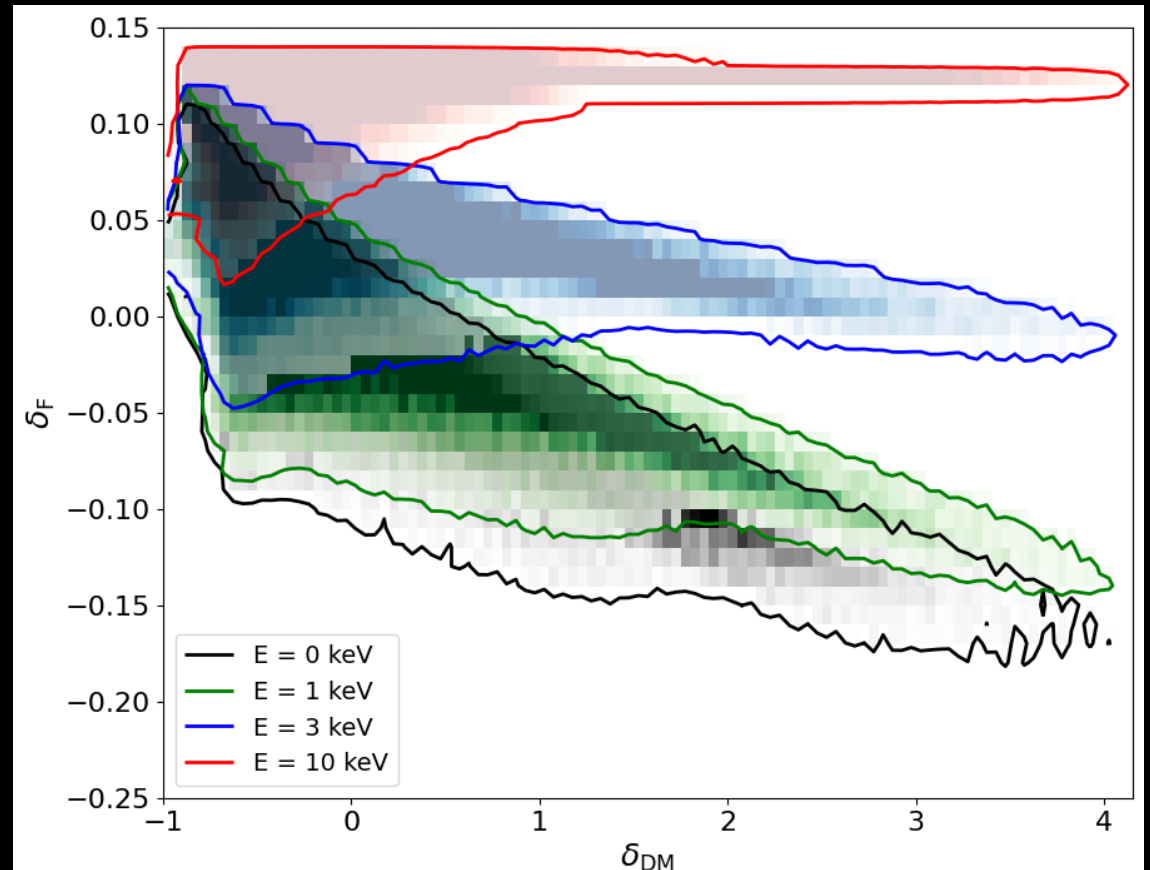
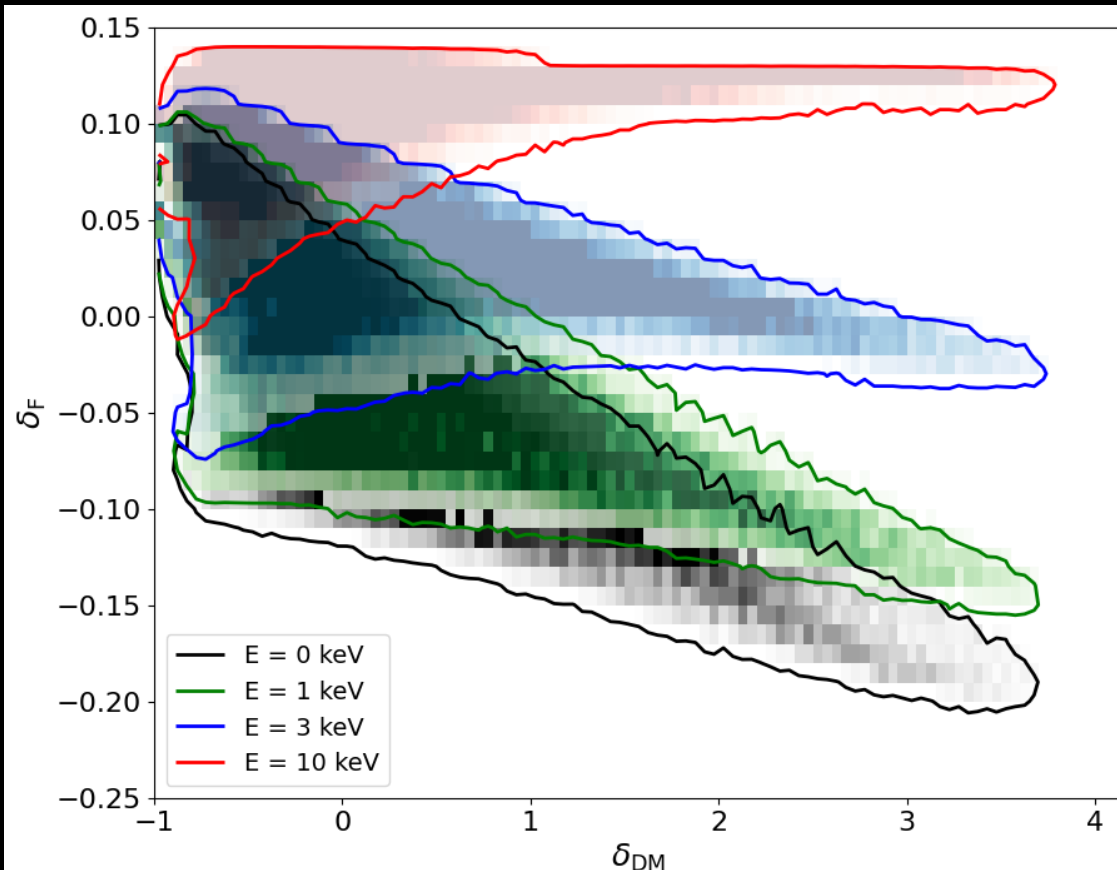
- Higher resolution simulations: $2 \times 10^8 M_\odot/h$ DM resolution
- Different energy injection scheme:
 - Inject energy into every particle (Renyue Cen, Princeton)

Preliminary

$$M_{halo}^{Z=0} = 5.9 \cdot 10^{14} M_\odot$$

$$M_{halo}^{Z=0} = 7.5 \cdot 10^{14} M_\odot$$

δ_{DM} and δ_F
smoothed to
3 Mpc/h



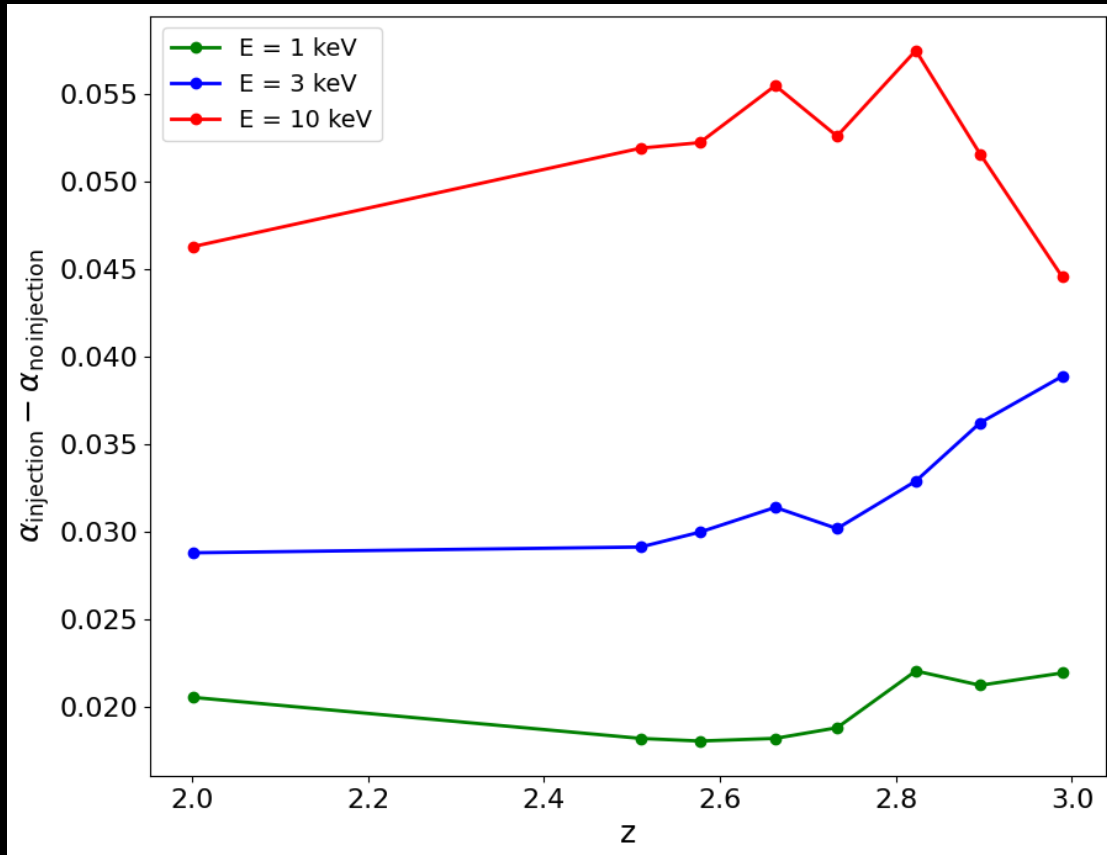
PROTO-CLUSTER SIMULATIONS ¹⁴

Preliminary

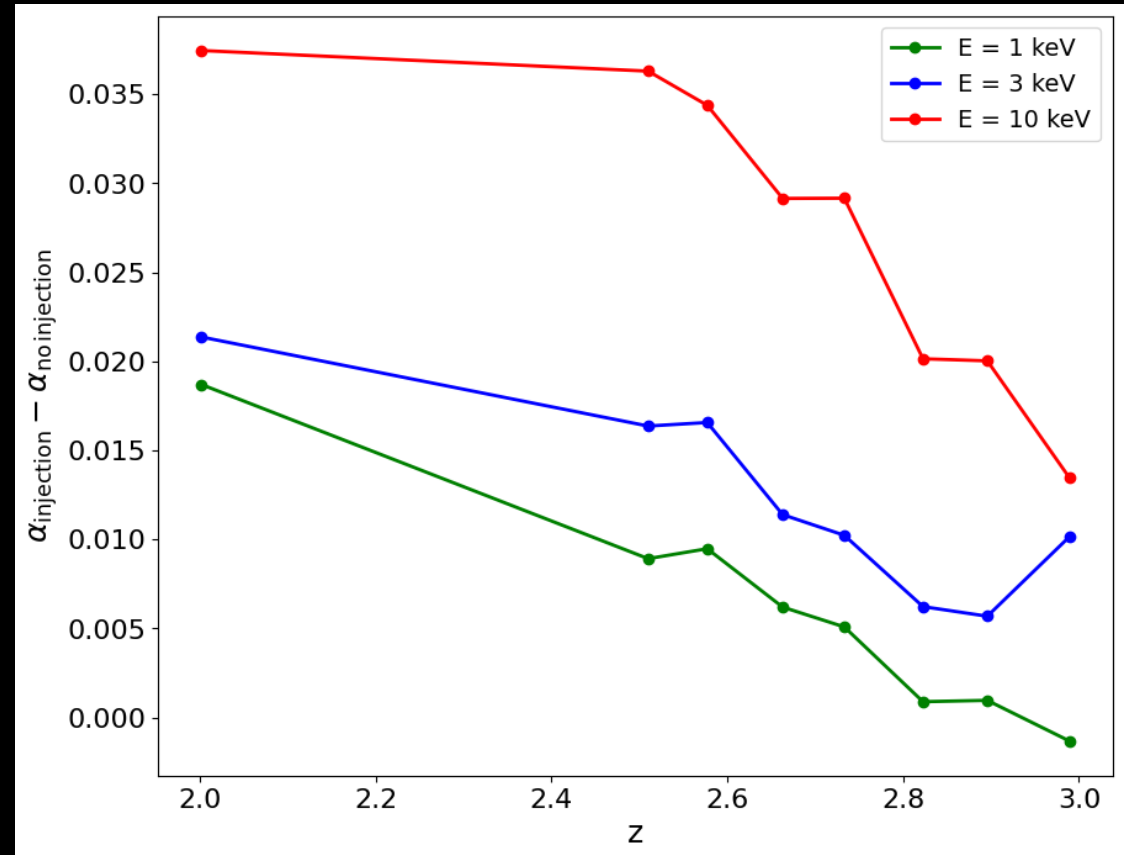
- Slope tilt evolves similarly with redshift for high-mass protocluster
- Flatter evolution for low-mass proto-cluster?

Slopes are evaluated
at $1 \geq \delta_{DM} \leq 3$

$$M_{halo}^{z=0} = 5.9 \cdot 10^{14} M_{\odot}$$



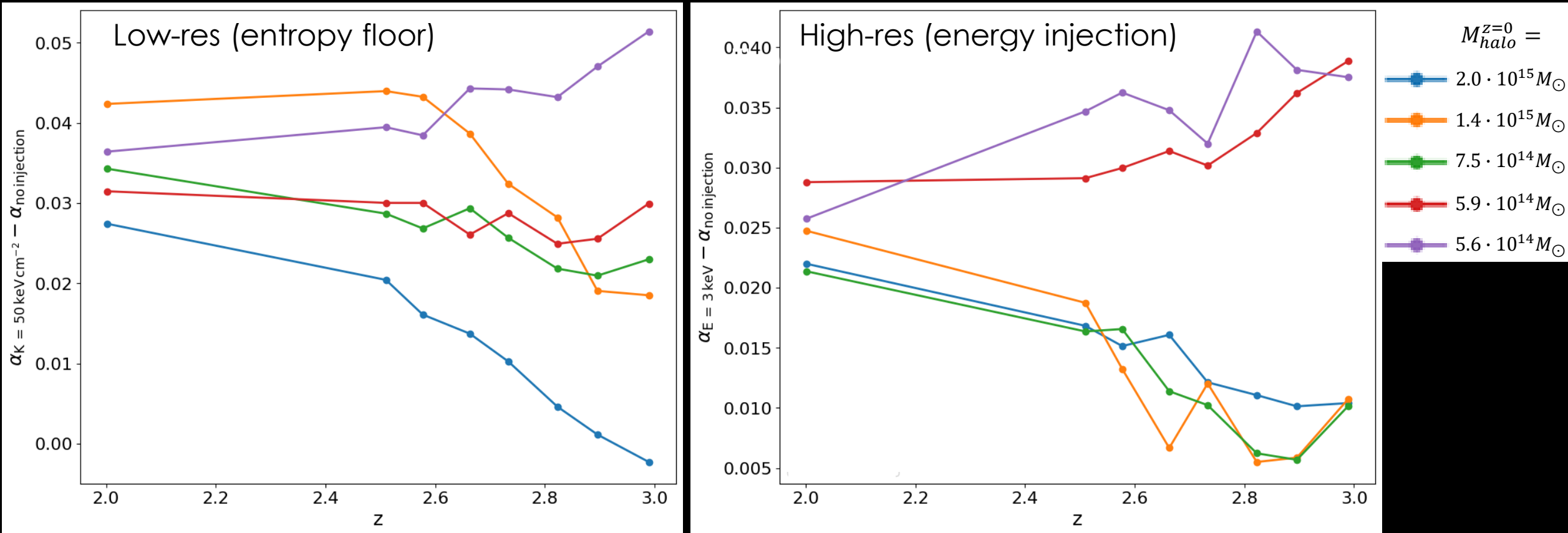
$$M_{halo}^{z=0} = 7.5 \cdot 10^{14} M_{\odot}$$



PROTO-CLUSTER SIMULATIONS¹⁵

Preliminary

- Slope α evaluated at $1 \geq \delta_{\text{DM}} \leq 3$
- Lower-resolution simulations: similar values of $z = 2$ slope difference
- For higher-resolution simulations the slope evolution appears to split between high- and low-mass populations at $z = 3$



CONCLUSIONS:

- Zoom-in simulations of proto-clusters at $z = 2-3$
- Effect of preheating on Ly α absorption in proto-clusters:
 - Heat injection at $z = 3$
 - Entropy floor
 - Energy injection
 - Tilts $\delta_{\text{DM}}-\delta_{\text{F}}$ distribution
 - Difference from no-injection evolves with redshift
- CLAMATO survey combined with DM density reconstructions allows for this study with both Ly α absorption field & DM density field
- In progress:
 - Full comparison with CLAMATO data and BIRTH DM density reconstructions to constrain feedback models & cluster preheating in COSMOS field