PROBING HEATING WITH THE LYMAN ALPHA FOREST

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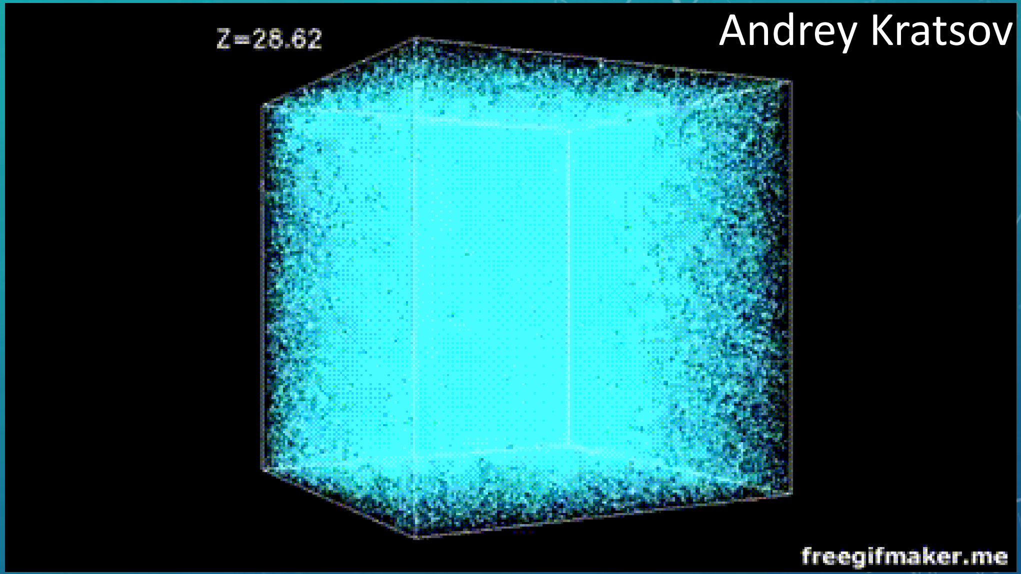
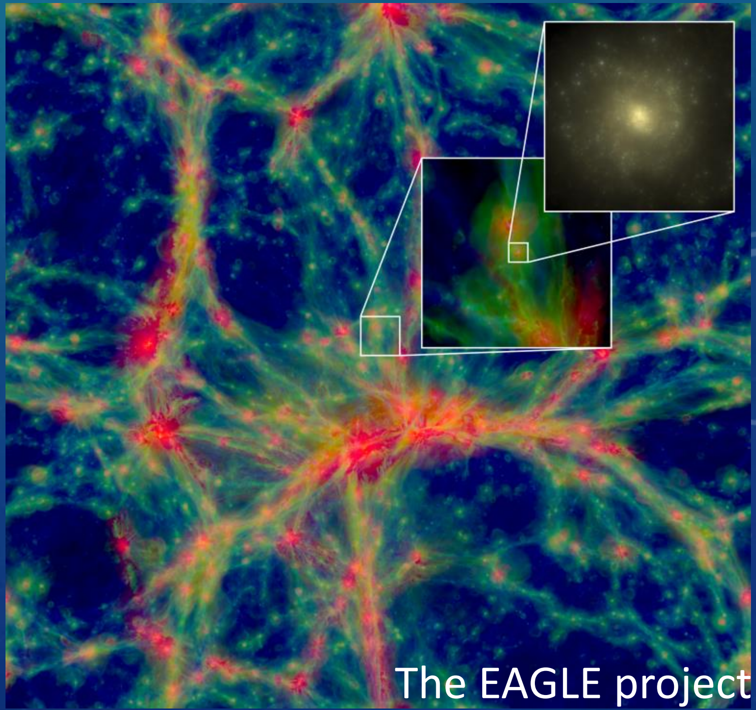
OUTLINE

- Introduction: Intergalactic medium & Lyman alpha forest
- Probing feedback
- Cluster preheating
- Conclusion

THE INTERGALACTIC MEDIUM

- Gas in between galaxies: mostly H + He
- Distribution largely follows DM field $\delta_{DM} \equiv \rho_{DM}/\ \rho_{DM,c} - 1$
    - But smoothed due to baryon pressure
- Mostly neutral at high z $\gtrsim$ 7-8
- Mostly ionized now, after reionization: $x_{HI} \lesssim 10^{-5\text{-}6}$



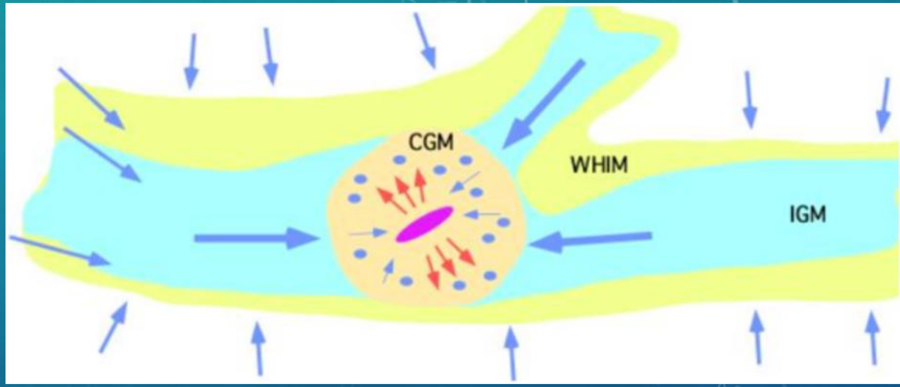


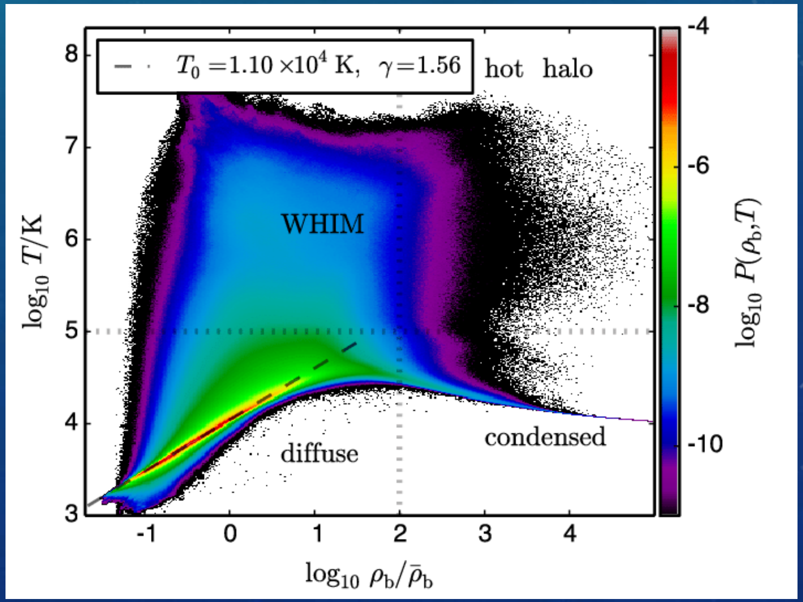
THE INTERGALACTIC MEDIUM

- WHIM (T_K=10^5- 10^7 K)
  - Shock-heated gas
  - Oxygen lines
    - X-ray
  - Thermal Sunyaev Zeldovich effect — e.g., de Graaff+2017
  - Likely contains most missing baryons

- Cold IGM (T_K=10^2- 10^5 K)
  - Sensitive to feedback/heating from AGN & galaxies
  - Lyα absorption — e.g., Pichon+2001, Lee+2014
  - Emission line intensity mapping
    - UV -> space — e.g, Silva, RK+2016
  - Integrated line intensity along filament
    - 21 cm -> radio — Takeuchi+2014, Kooistra+2017, Kooistra+2019

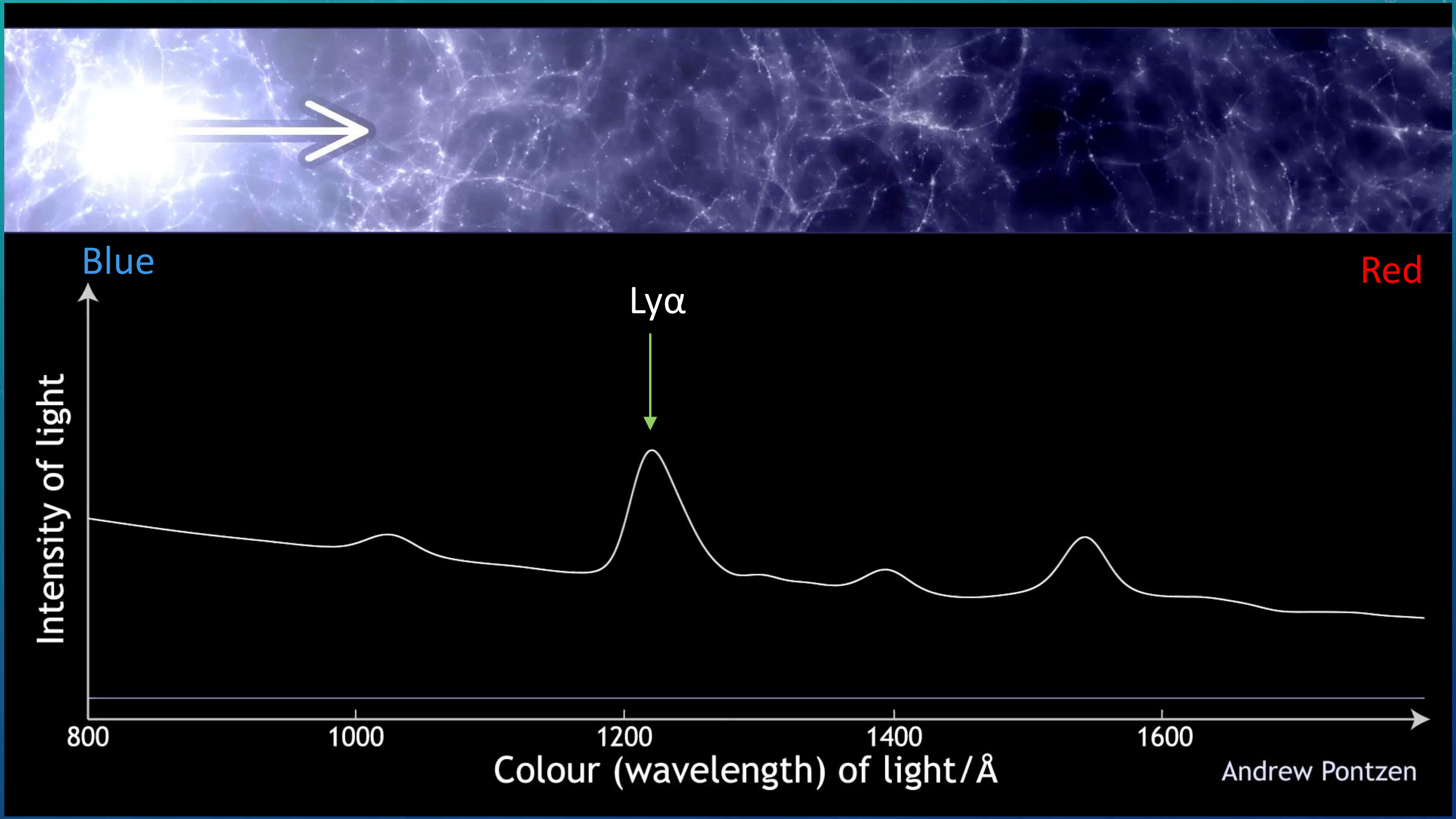
Martin+2009





Lukić+2015

THE LYMAN ALPHA FOREST

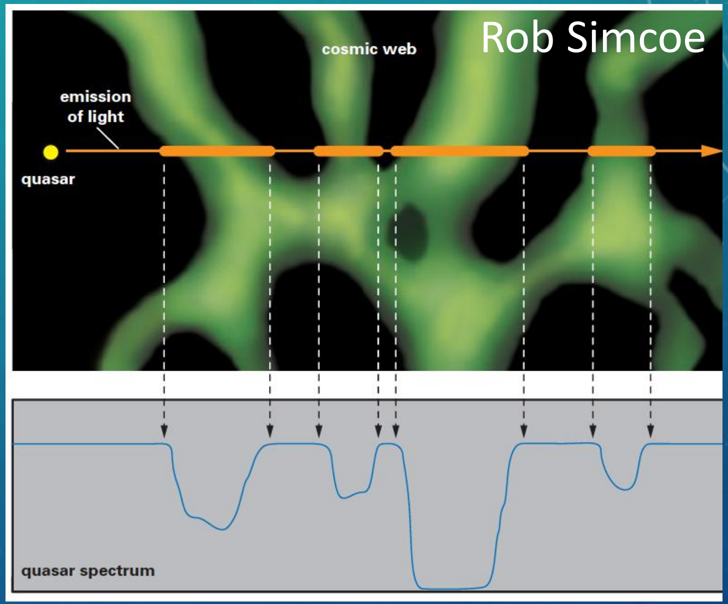


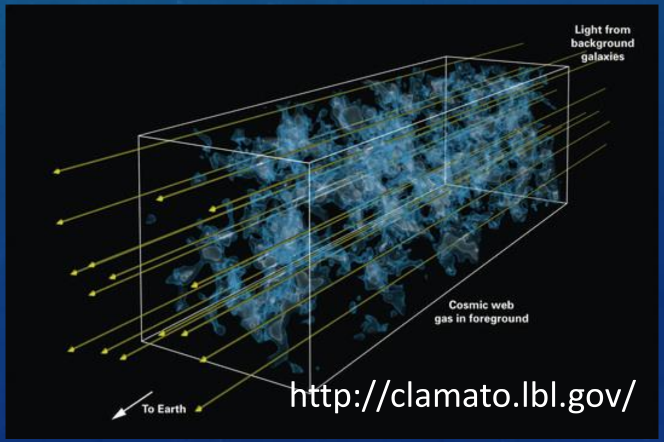
LYMAN-ALPHA FOREST

- Absorption depends on underlying density field and astrophysics

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

- Observed quantity is: $F = F_0 e^{-\tau_\alpha}$
- Can also use Lyman break galaxies as background source (Lee+2014)
- Dense distribution of sightlines allows for reconstruction of 3D absorption field (Pichon+2001, Caucci+2008)
- Fluctuating Gunn-Peterson Approximation (FGPA):
  - Temperature follows power-law: $T = T_0(1+ \delta_{DM})^{\gamma-1}$
  - Then $\tau_{FGPA} \propto (1+ \delta_{DM})^{2-0.7(\gamma-1)}$

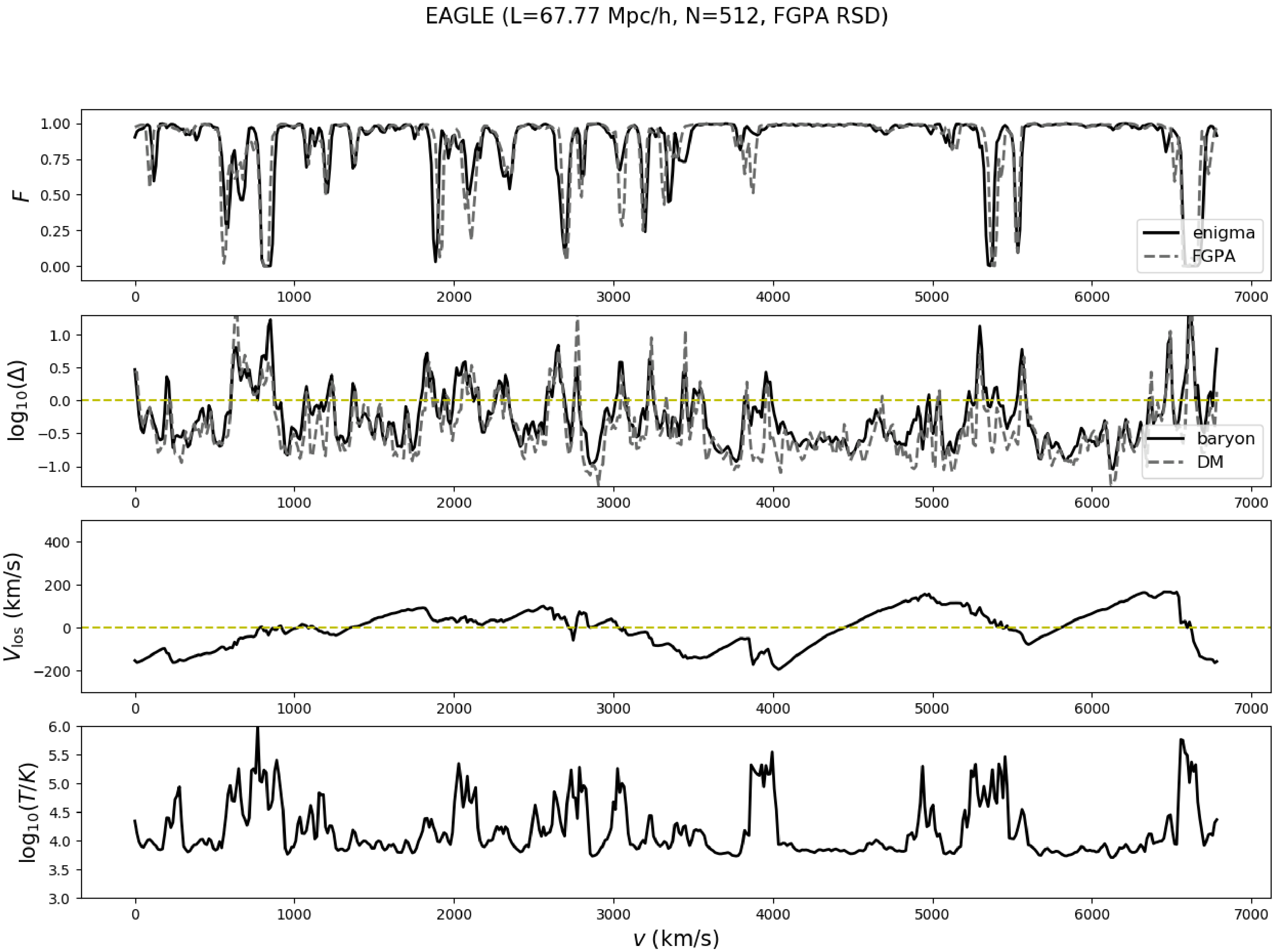




LYMAN ALPHA FOREST

- Extract Lyα skewers from simulations

$\Delta = \rho/\rho_c$

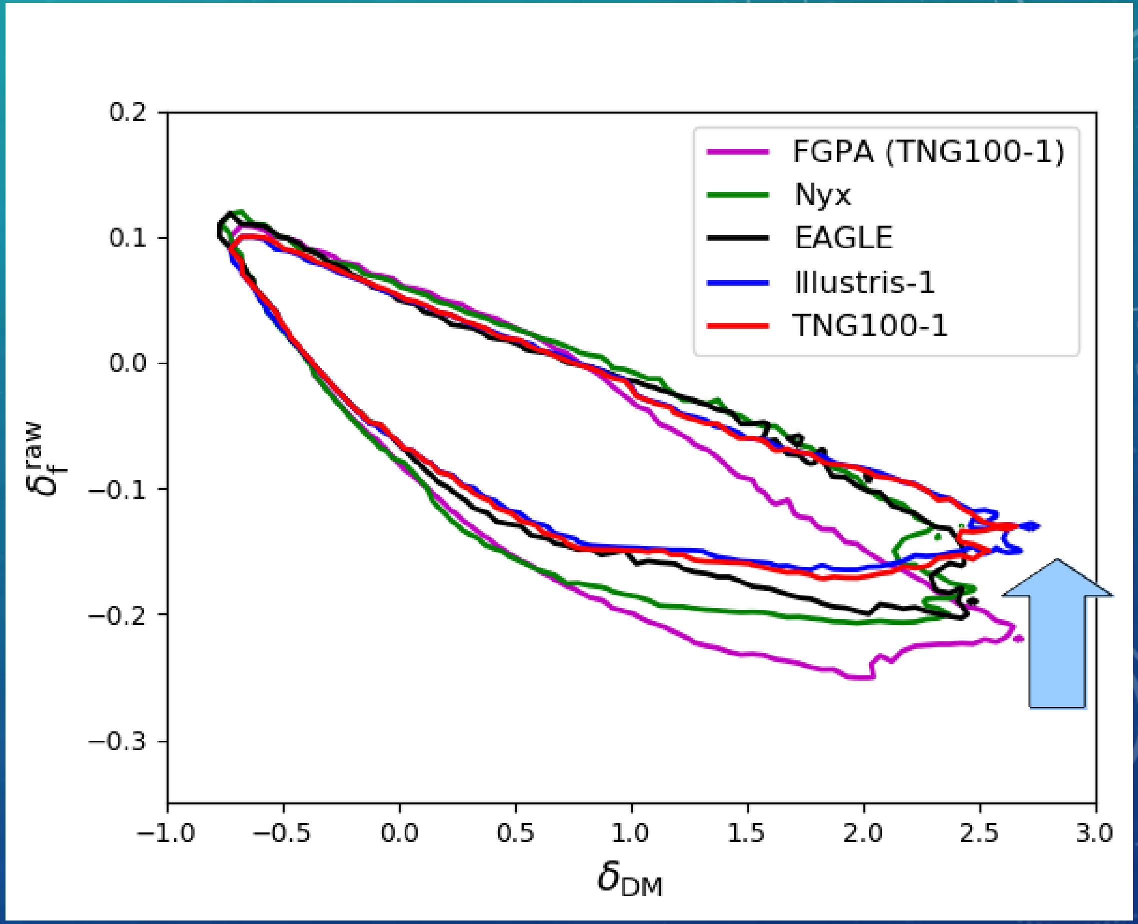


PROBING HEATING

Smoothed to 3 Mpc/h

$$\delta_F \equiv {}^{F}/_{\bar{F}} - 1$$

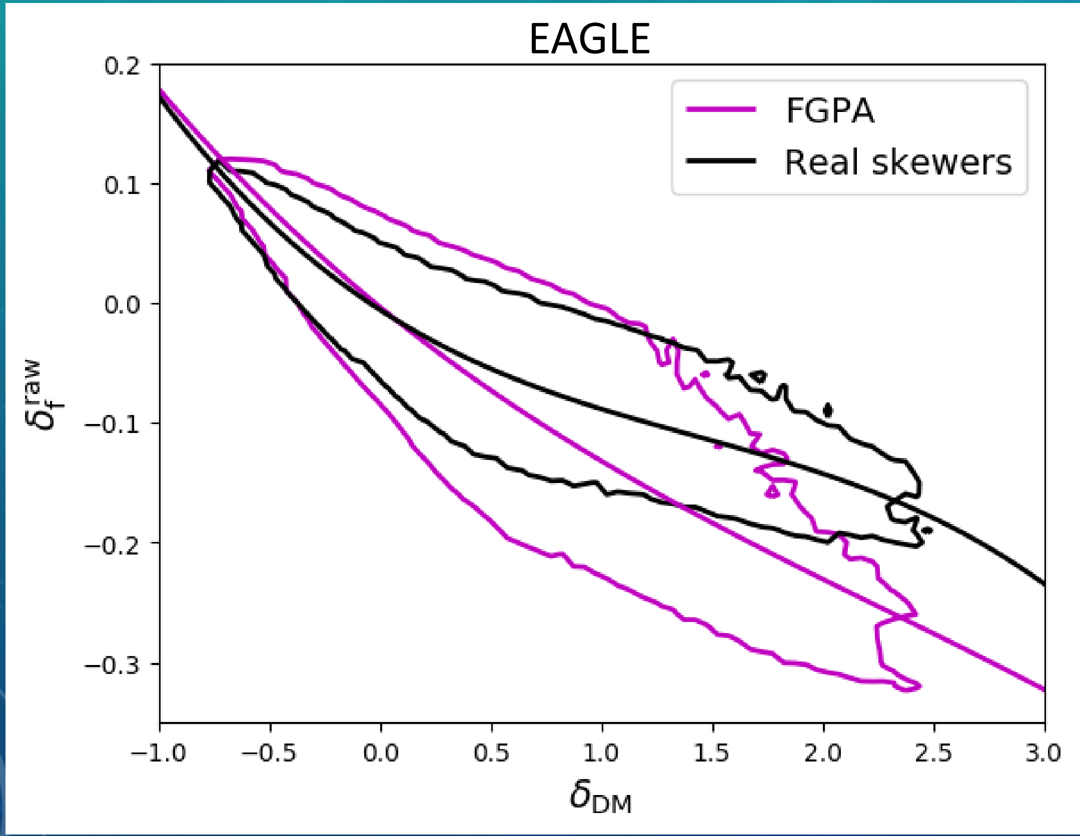
- What effect does heating have on Lyα forest?
- Simulations:
  - Nyx $(100\ \text{Mpc/h})^3$, no feedback
  - EAGLE: $(67.77\ \text{Mpc/h})^3$ including AGN feedback
  - Illustris and IllustrisTNG: same $(75\ \text{Mpc/h})^3$, different AGN/stellar feedback models
    - Illustris AGN feedback too strong
- Extract skewers on N = 800^2, 512^2, 600^2 grid along z-direction
- Extra feedback/heating moves contours upwards in Lyα transmission

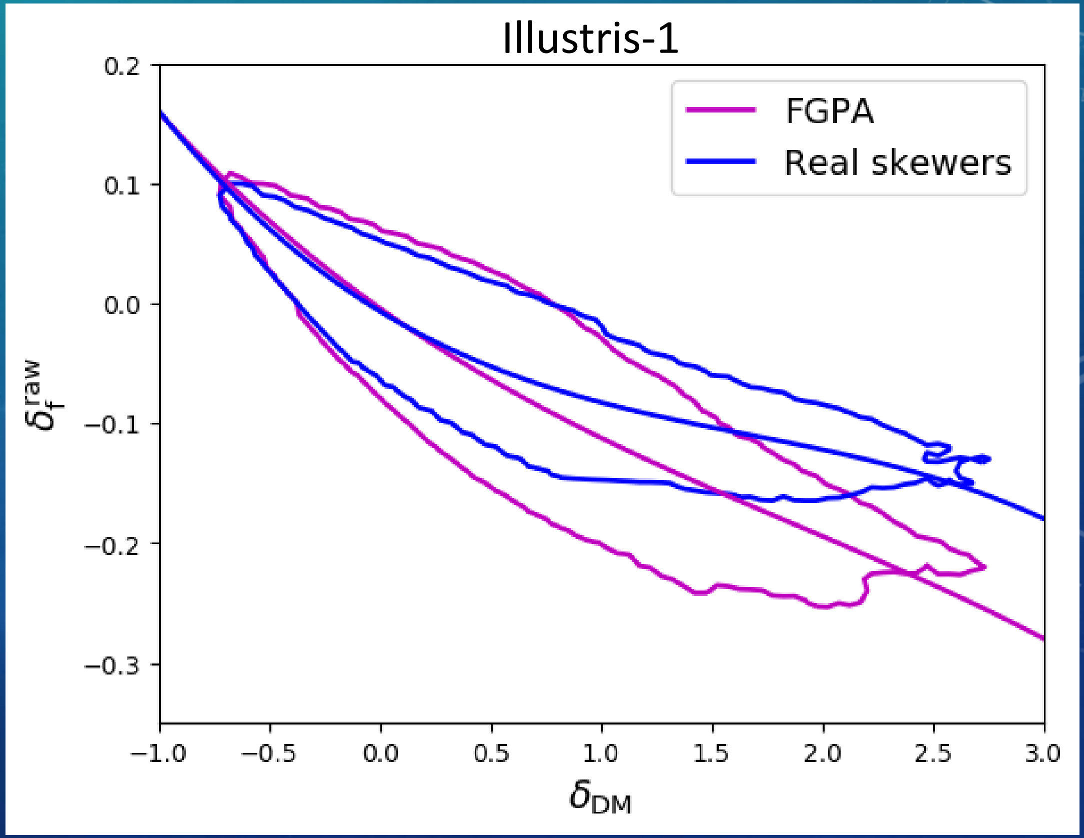


$$\delta_{DM} \equiv {}^{\rho_{DM}}/_{\rho_{DM,c}} - 1$$

PROBING HEATING

- FGPA vs true flux
  - Comparison between FGPA and real flux can be used to constrain feedback models in observations
  - Observationally need estimate for DM density field

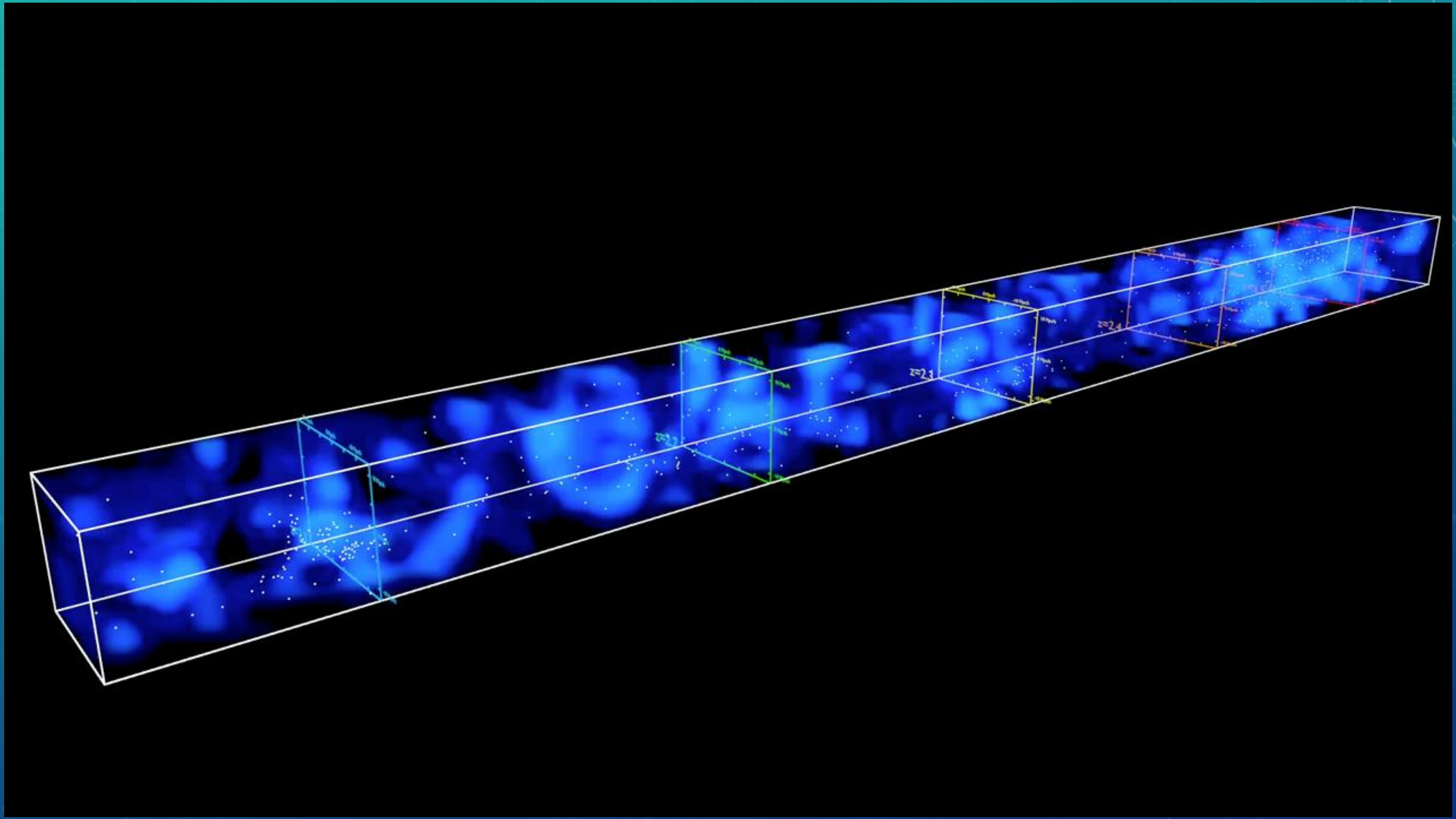




CLAMATO-SURVEY

- 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
- Lyα forest redshift range: $2.05 < z < 2.55$
  - 21 Mpc/h x 27 Mpc/h x 340 Mpc/h
- Data release public: Lee+2018

CLAMATO-SURVEY

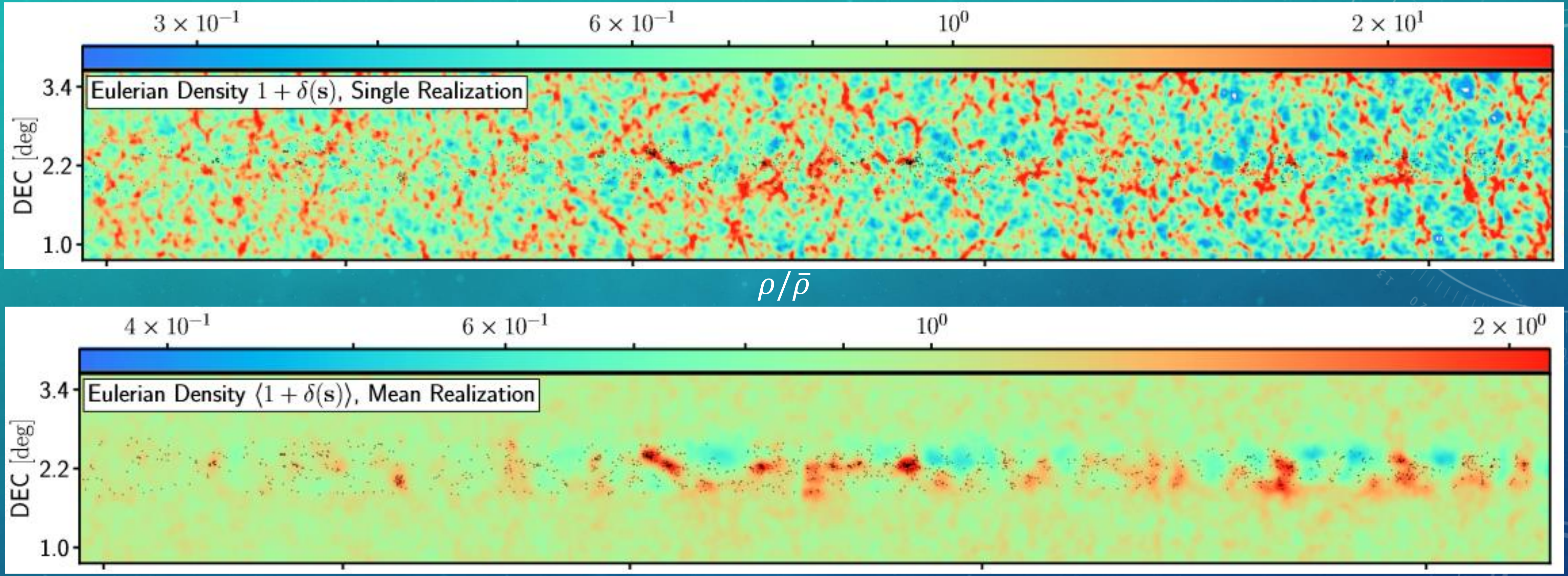


- 3D map generated by Wiener Filtering the sightlines

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

DM-DENSITY COSMOS FIELD

Ata+2020

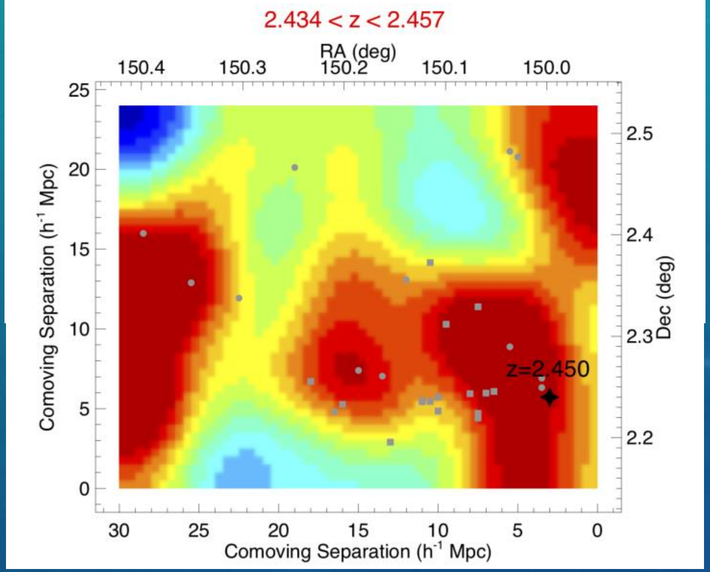


- COSMIC BIRTH (Kitaura+2019,Ata+2020):
  Bayesian inference of initial density field from spectroscopic galaxy survey data
- Use data from multiple surveys and taking into account the radial and angular selection functions
- Single realizations can be used to estimate variance

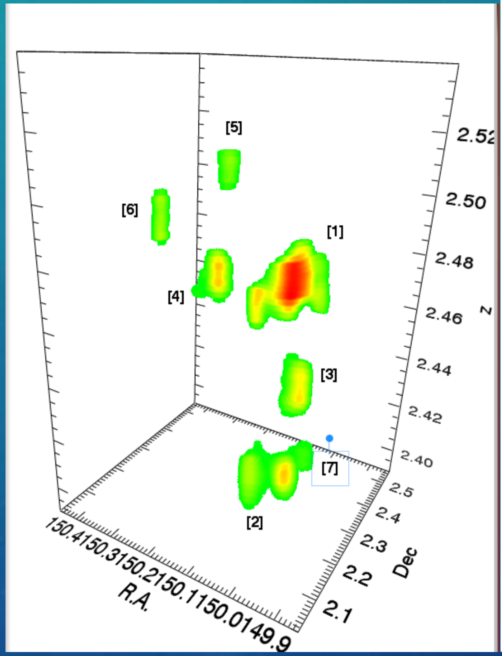
COSMOS FIELD PROTO-CLUSTERS

- Lyα absorption field recovers known overdensities seen in galaxy distributions (e.g., Lee + 2018)
- Use CLAMATO survey to study proto-clusters

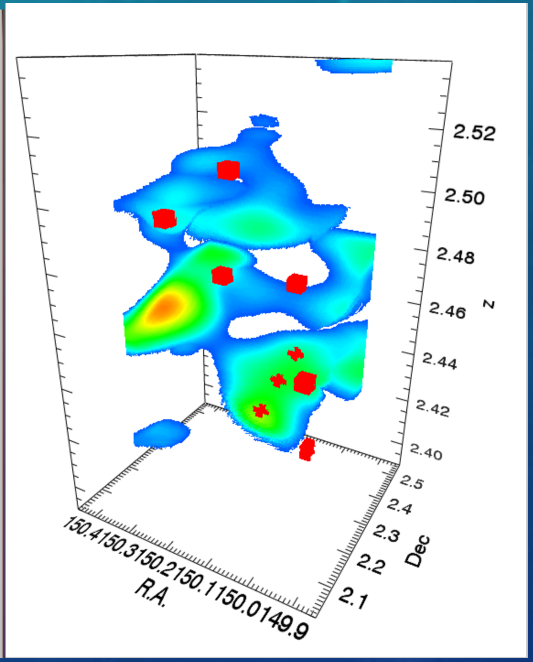
Courtesy of Khee-Gan Lee



"Hyperion" overdensity at z ~ 2.5



VUDS galaxy density

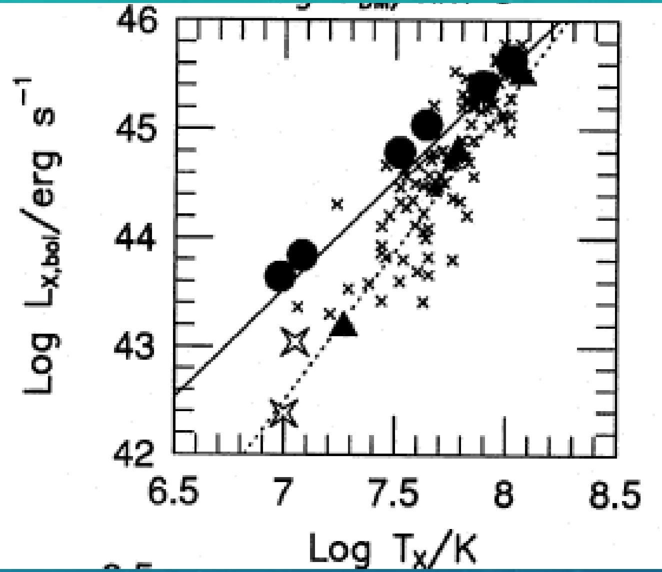


CLAMATO Lyα absorption

Cucciati+2018

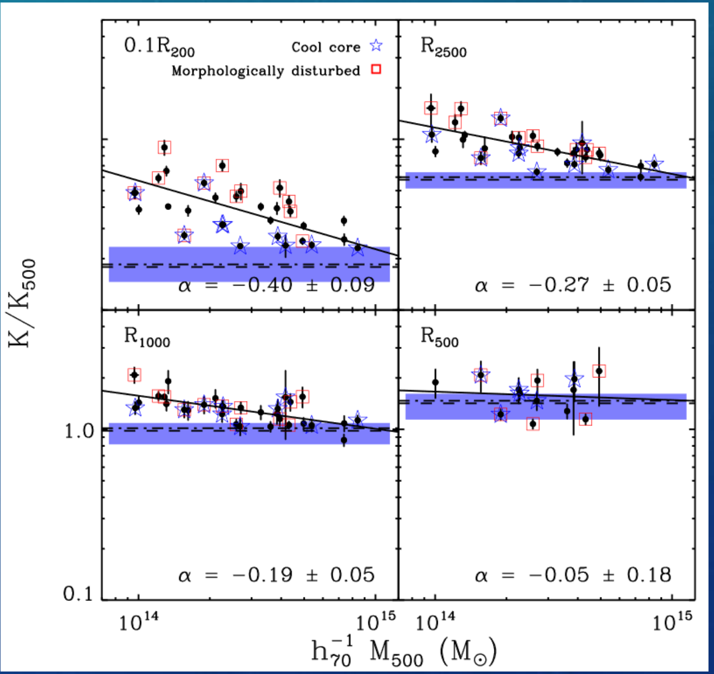
CLUSTER PREHEATING

- Galaxy clusters form from large overdensities
- 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 into proto-clusters at high z :
  - Feedback from stars
  - AGN



- simulated clusters
- ▲ preheated sims
- x, ✧ observations

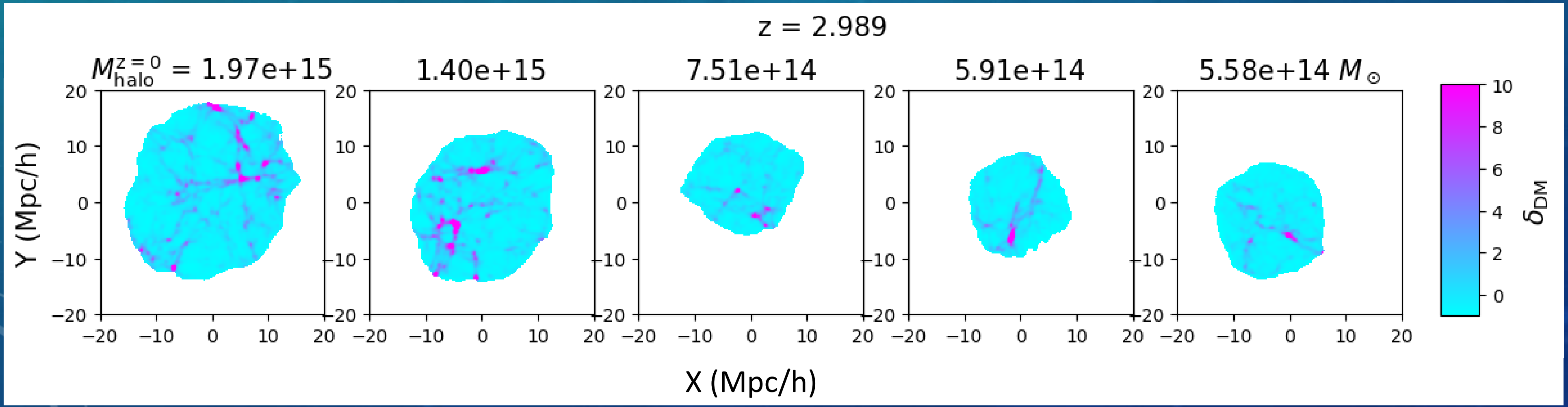
Navarro, Frenk & White 1995



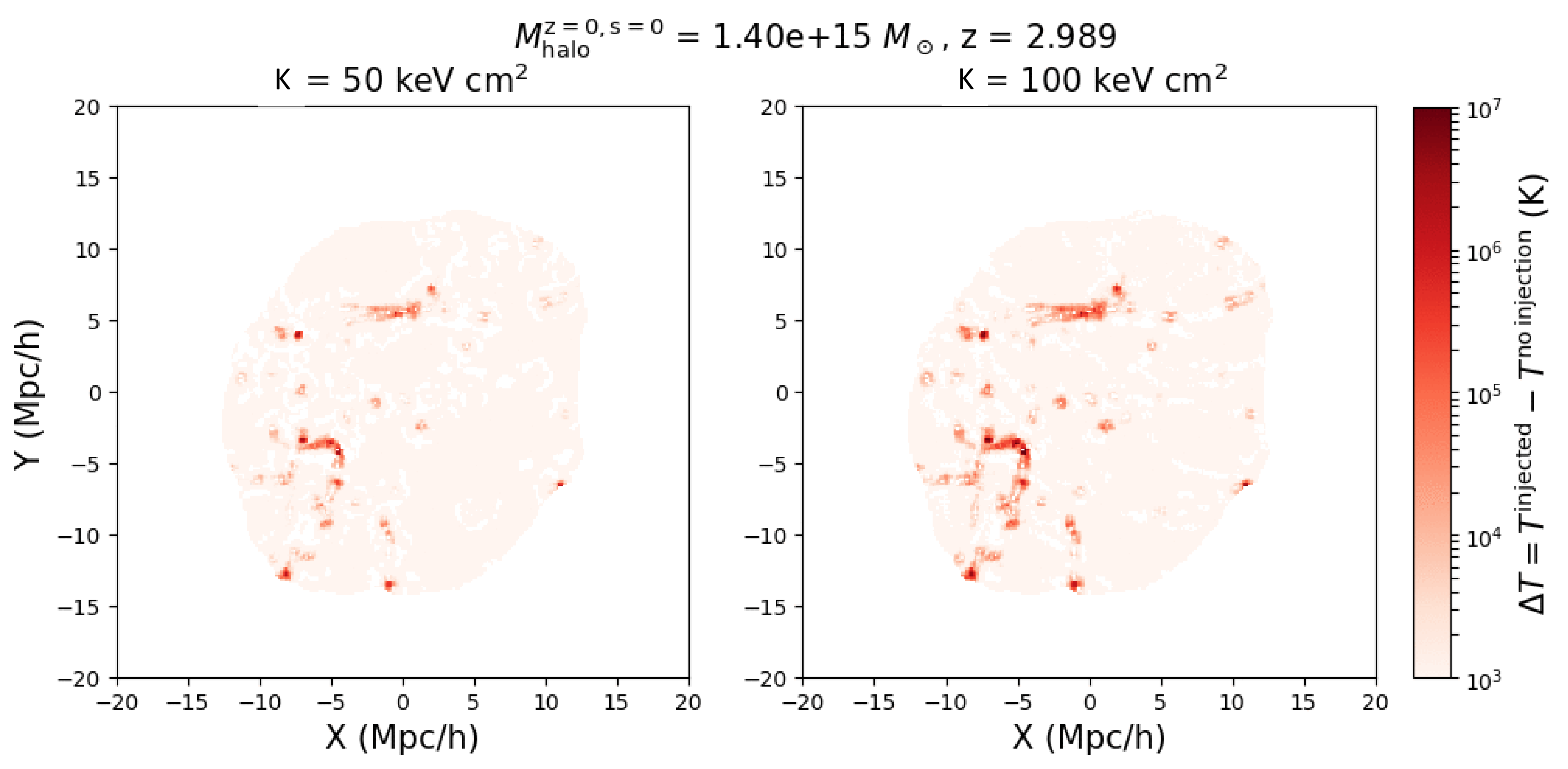
Pratt+2010

PROTO-CLUSTER SIMULATIONS

- Goal: effect of preheating on Lyα absorption of proto-clusters
- Zoom-in simulations of proto-cluster regions in (300 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 δ_g>5 to raise entropy above entropy floor (Borgani+2001)
  - Different entropy floors: K_{fl} = 0, 30, 50 and 100 keV cm^2 $K = T\, n_e^{-2/3}$



PROTO-CLUSTER SIMULATIONS



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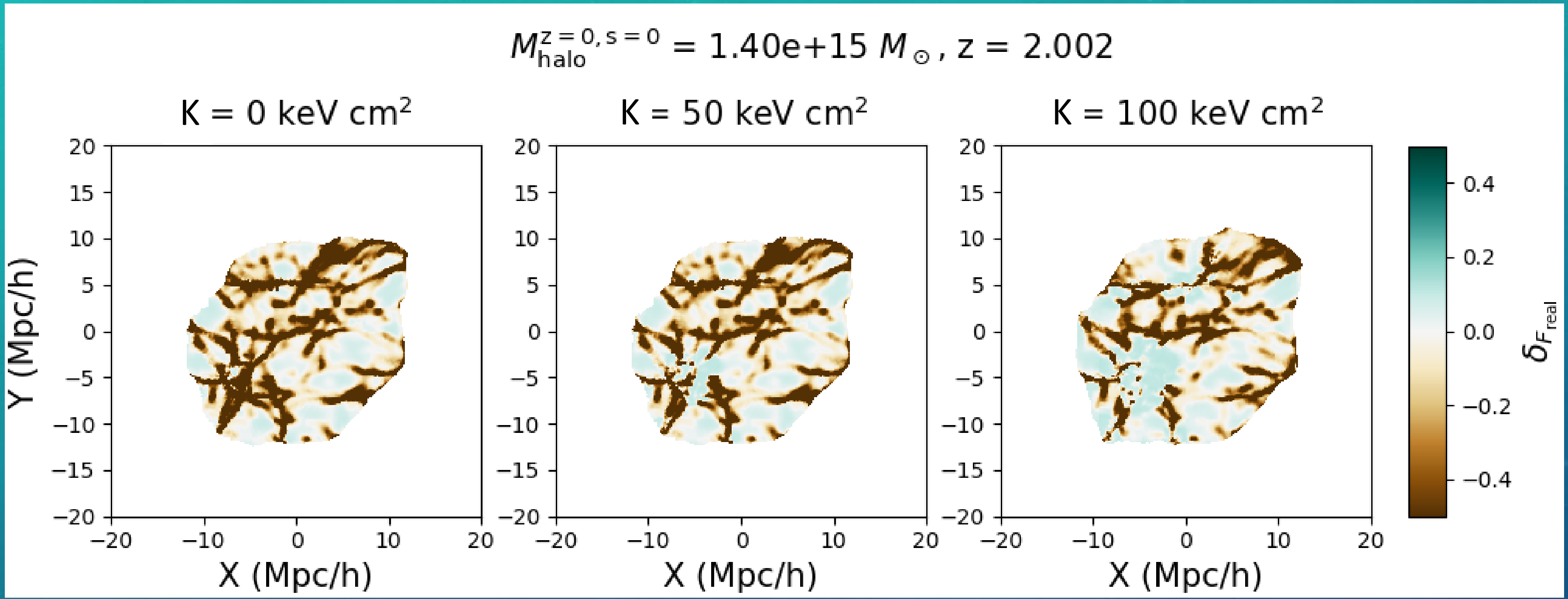


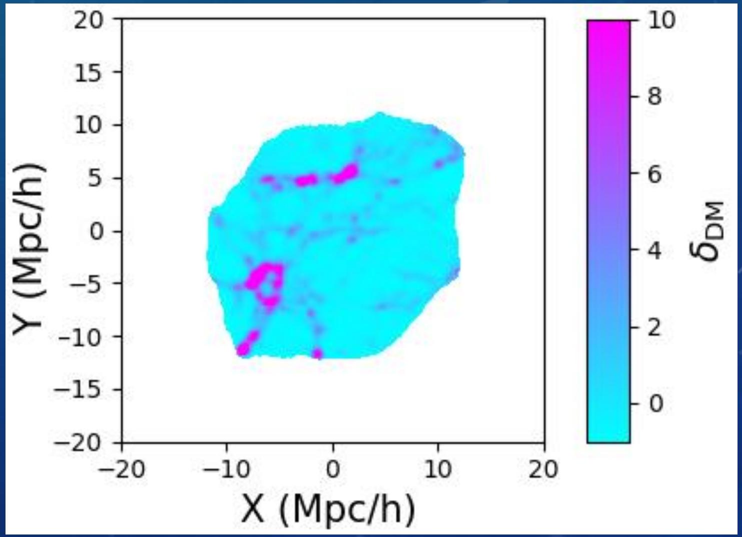
$$\delta_{F_{real}} \equiv {F_{real}}/{\bar{F}} - 1$$

Where $\bar{F}$ from Becker+2013

- Real-space Lyα flux (Kulkarni+2015)

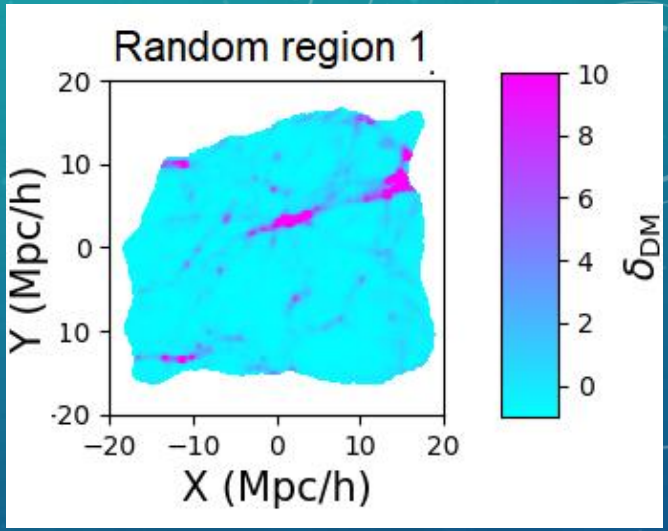
$$F_{real} = e^{-\tau_{real}}$$

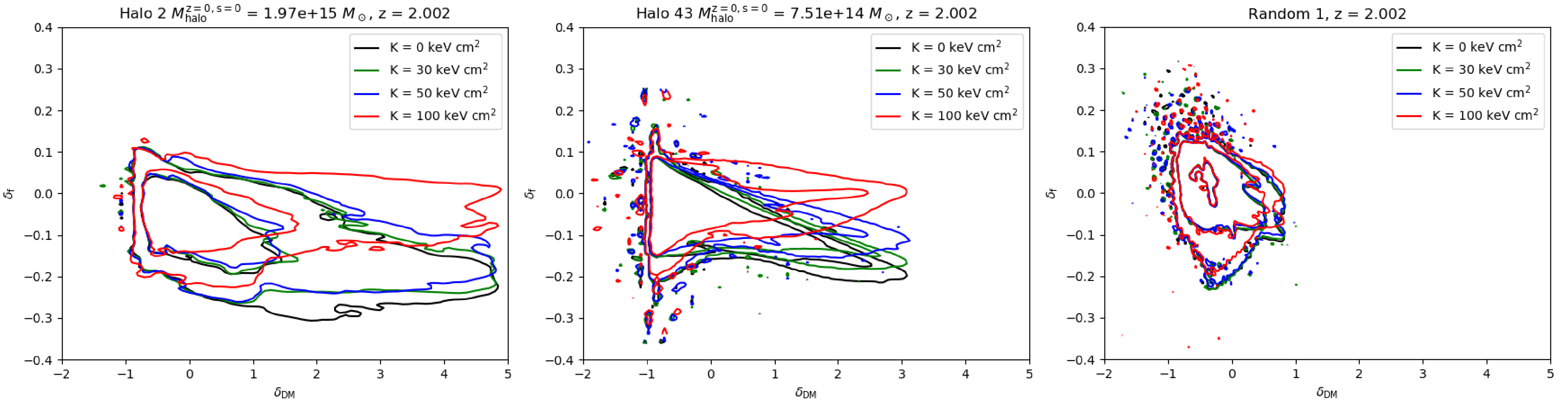
$$\tau_{real} = \frac{3\lambda_\alpha^3 A_{10}}{8\pi H(z)} n_{HI}$$



PROTO-CLUSTER SIMULATIONS

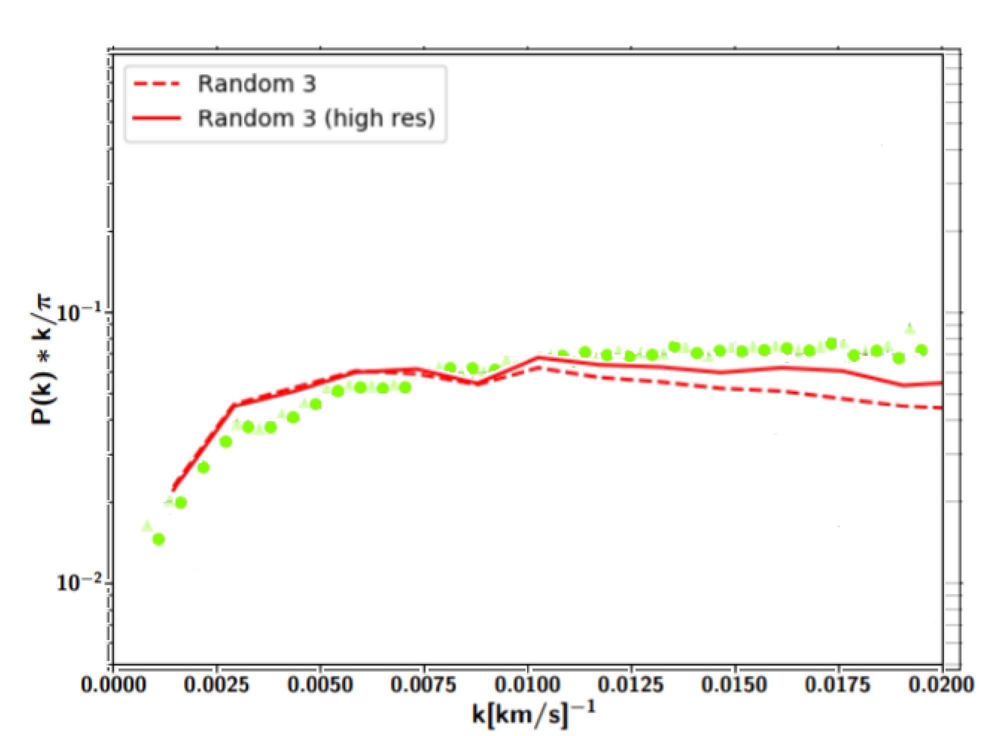
- Extract random spectra, add noise with CLAMATO specifications
- Heat injection causes distribution for proto-clusters to tilt
- Random regions for control sample



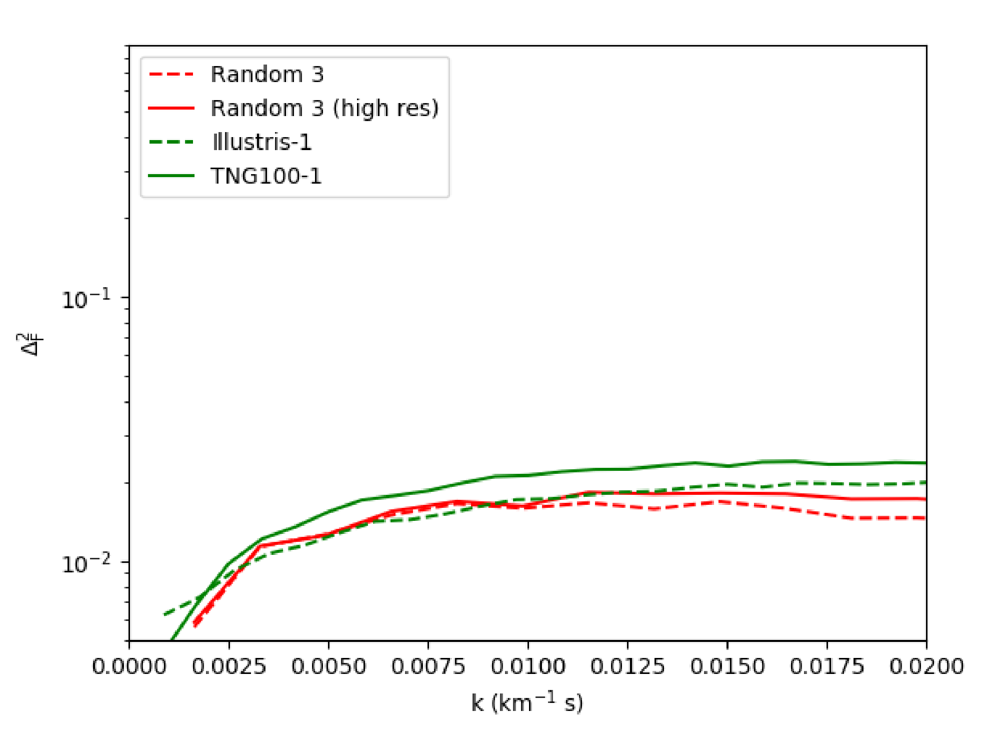


PROTO-CLUSTER SIMULATIONS

- Simulations do not have sufficient resolution to reach observed Lyα forest scales
  - Switch to higher resolution: 2×10^8 $M_\odot/h$ DM resolution
- Injection scheme fails at higher resolution: clusters explode
- New scheme: inject constant energy at z = 3 for all particles

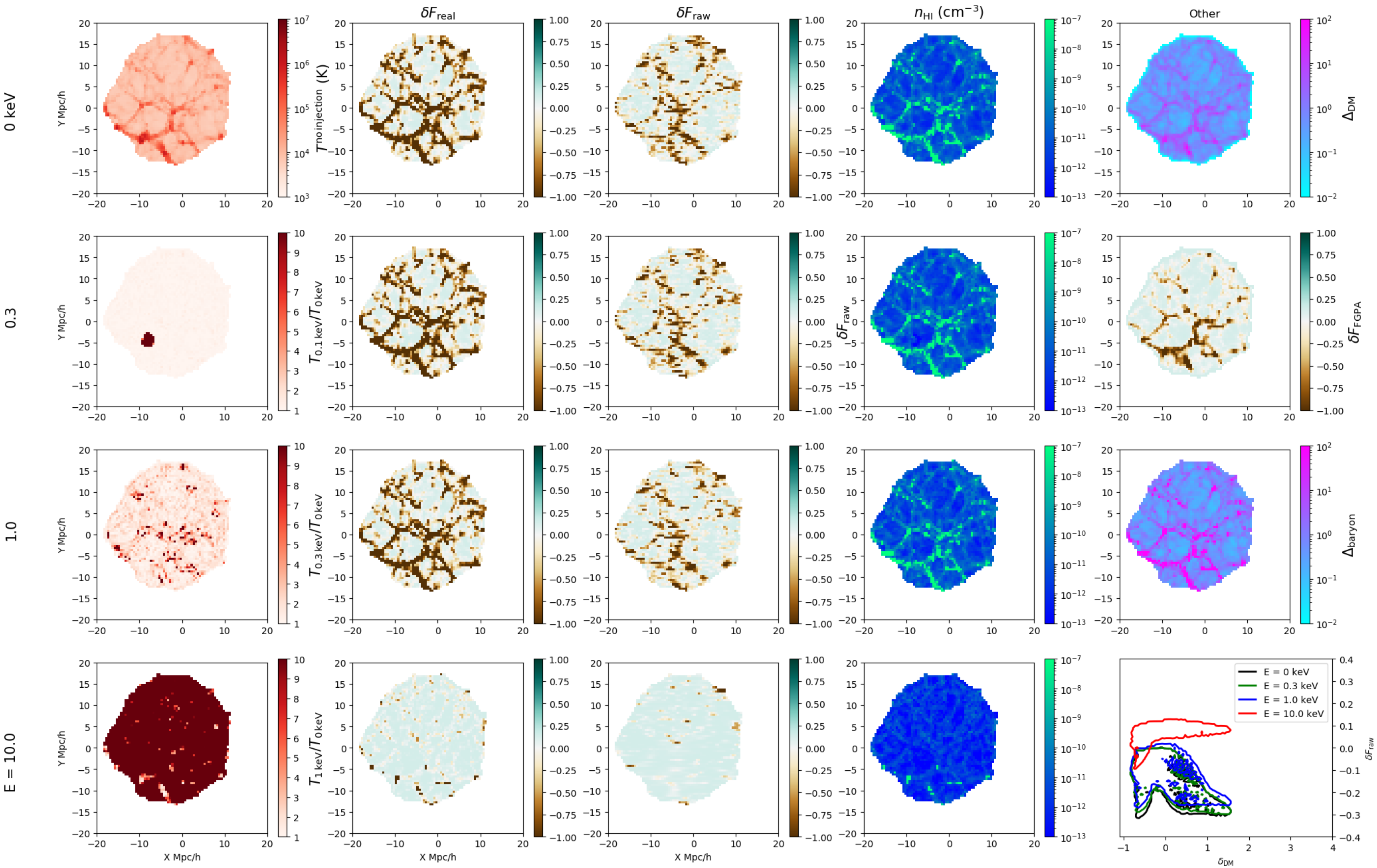


z = 3 (SDSS DR14, Chabanier+2018)



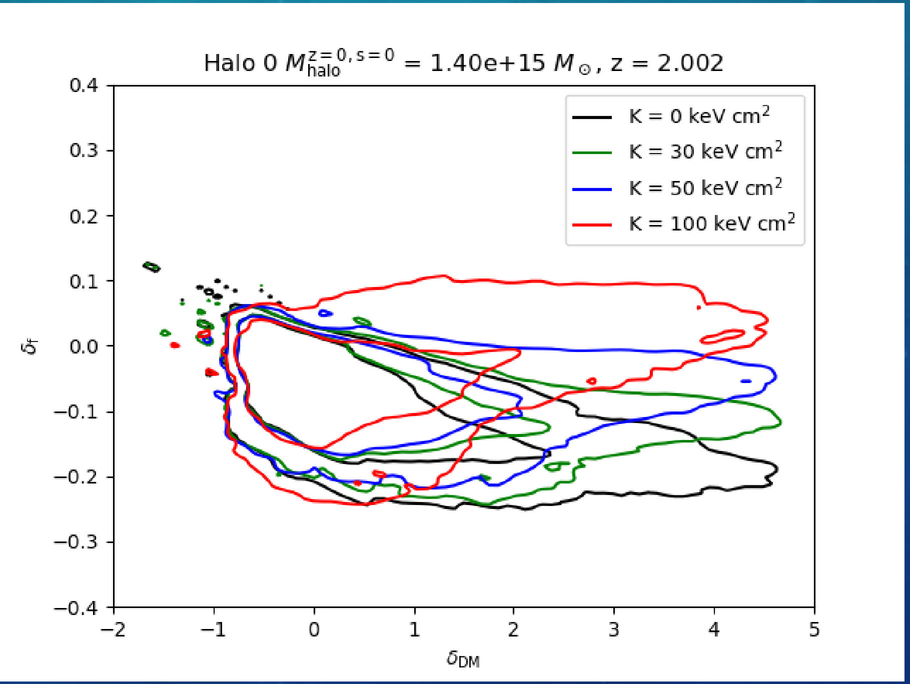
z = 2

Halo 43, $M_{\rm halo}^{z=0,\,s=0}$ = 7.51e+14 $M_\odot$, z = 2.002



NEXT STEPS

- Finish higher-resolution simulations, energy-based injection scheme
  - 1 keV, 3 keV & 10 keV per particle
- Compare to data in CLAMATO
  - Use DM density reconstruction realizations as variance



CONCLUSIONS:

- Lyman alpha forest excellent probe of heating/feedback in IGM
  - FGPA vs observed flux
- Zoom-in simulations of proto-clusters at z = 2-3
- Effect of preheating on Lyα absorption in proto-clusters:
  - Heat injection at z = 3
  - Tilts δ_{DM}-δ_F distribution at z = 2
- CLAMATO survey allows for this study with both Lyα absorption field & DM density field
- In progress:
  - Run higher resolution proto-cluster simulations with energy-based injection scheme
  - Full comparison with CLAMATO data to constrain feedback models & cluster preheating