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Statistics of thermal gas pressure as a probe of cosmology and galaxy formation models

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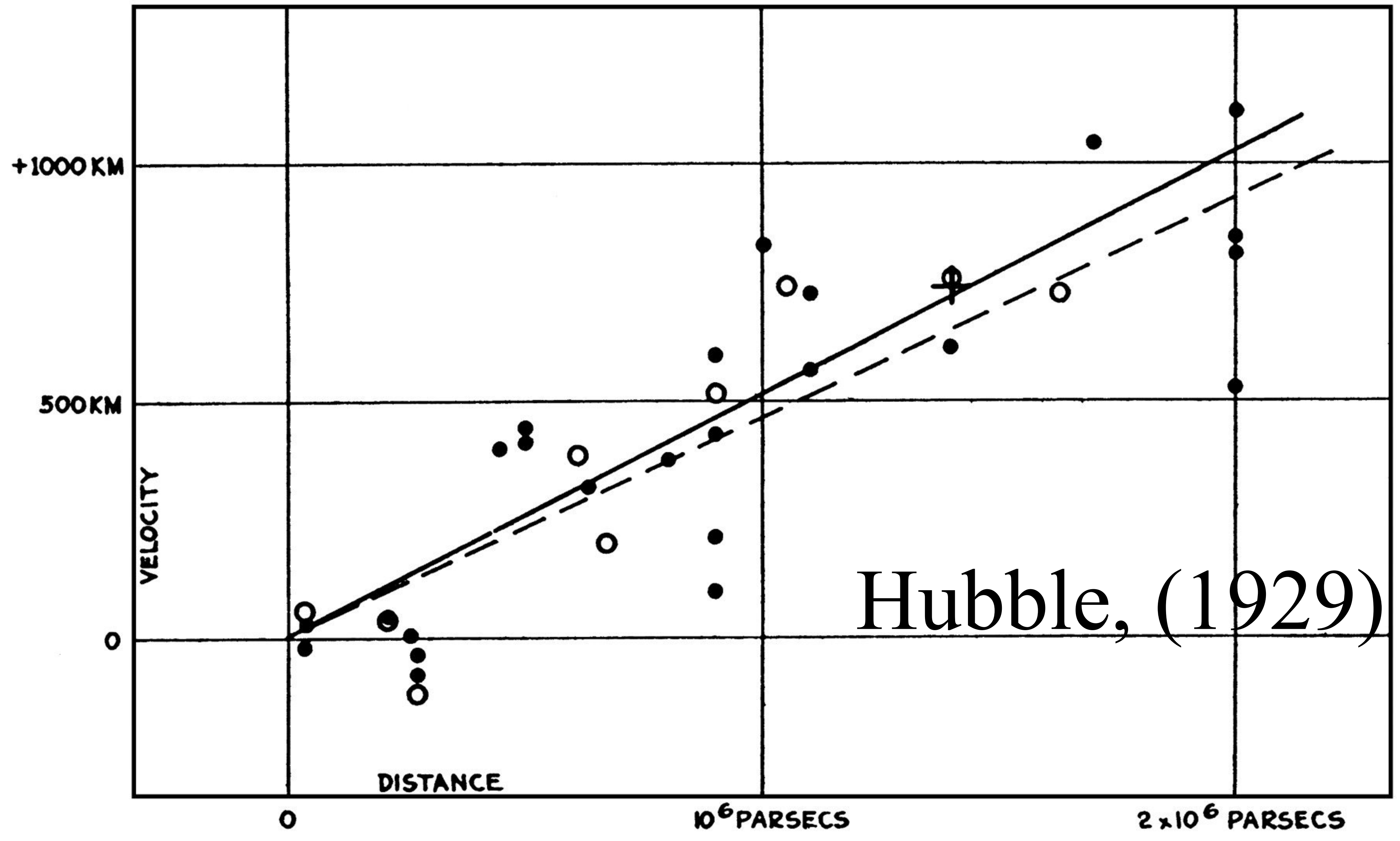
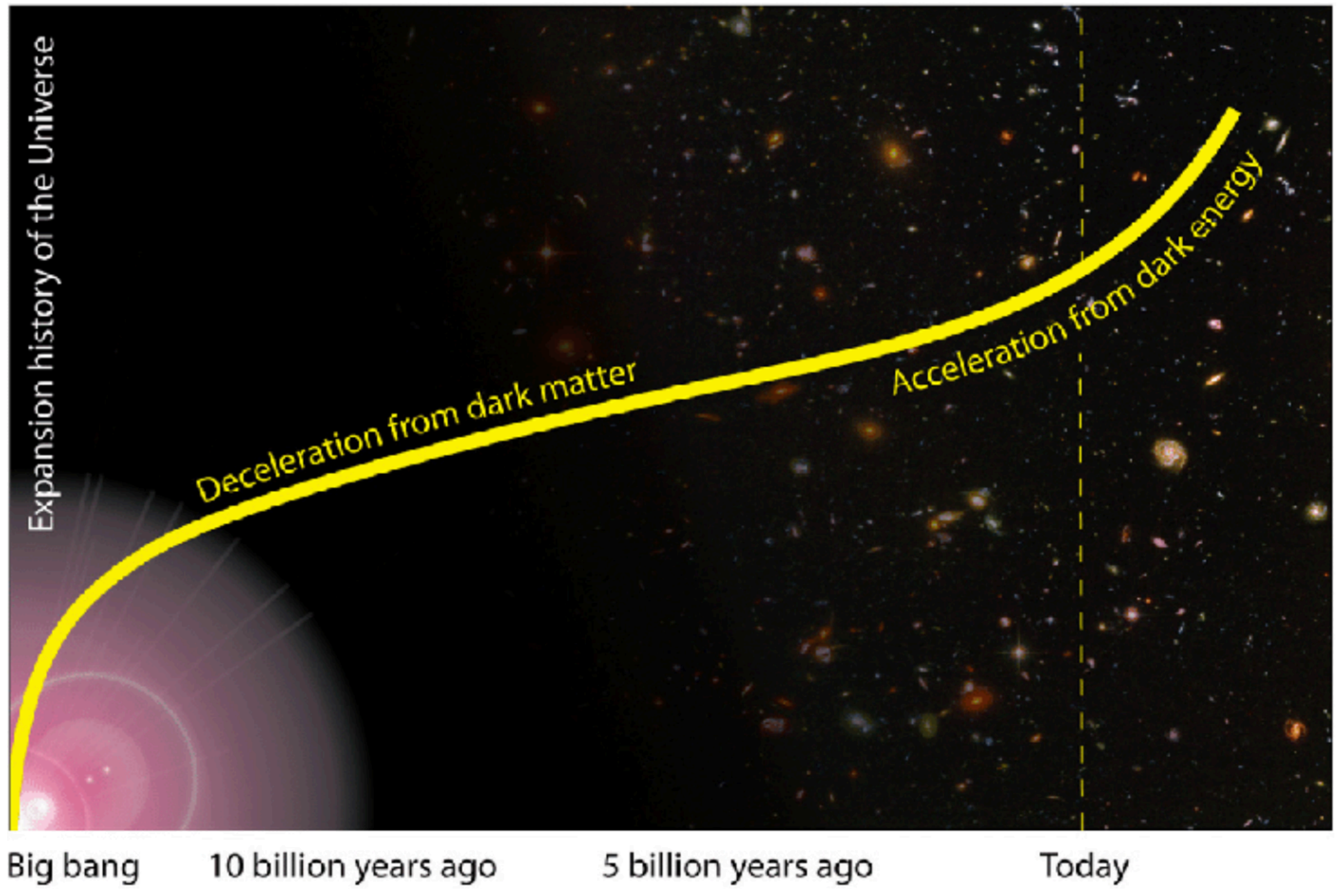
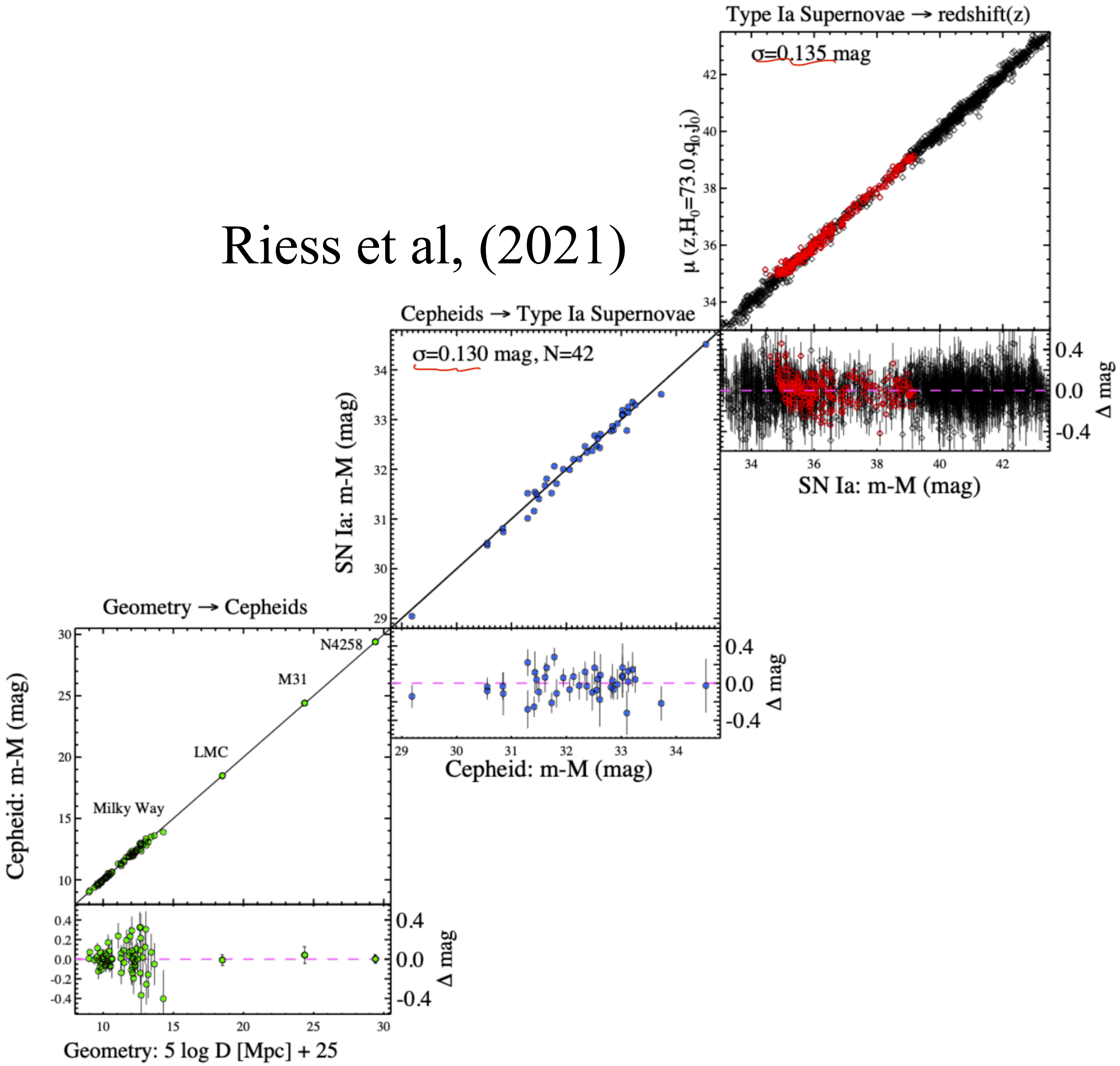
2nd Shanghai Assembly on Cosmology and Structure Formation

① Cosmic expansion history



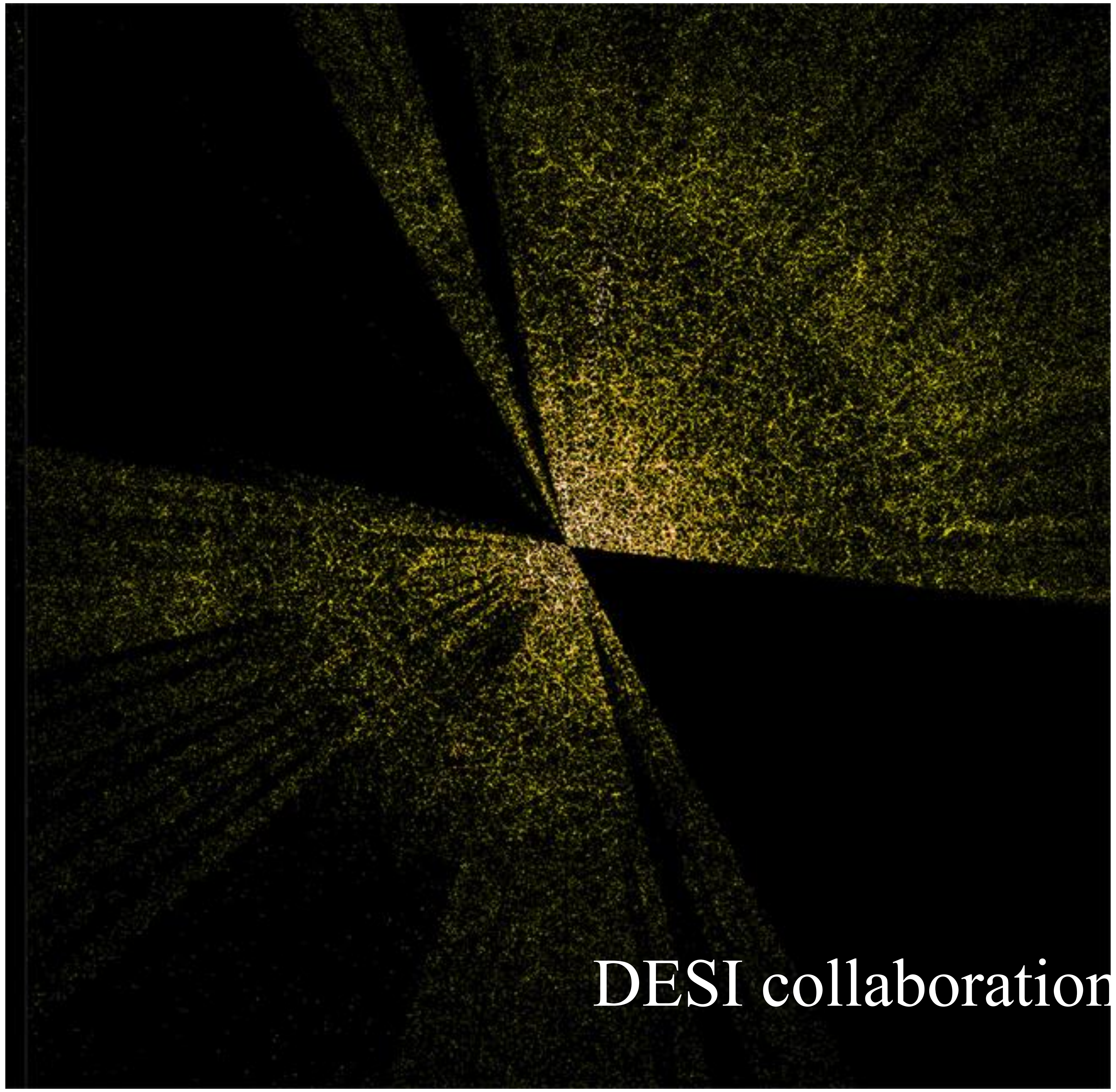
Hubble, (1929)

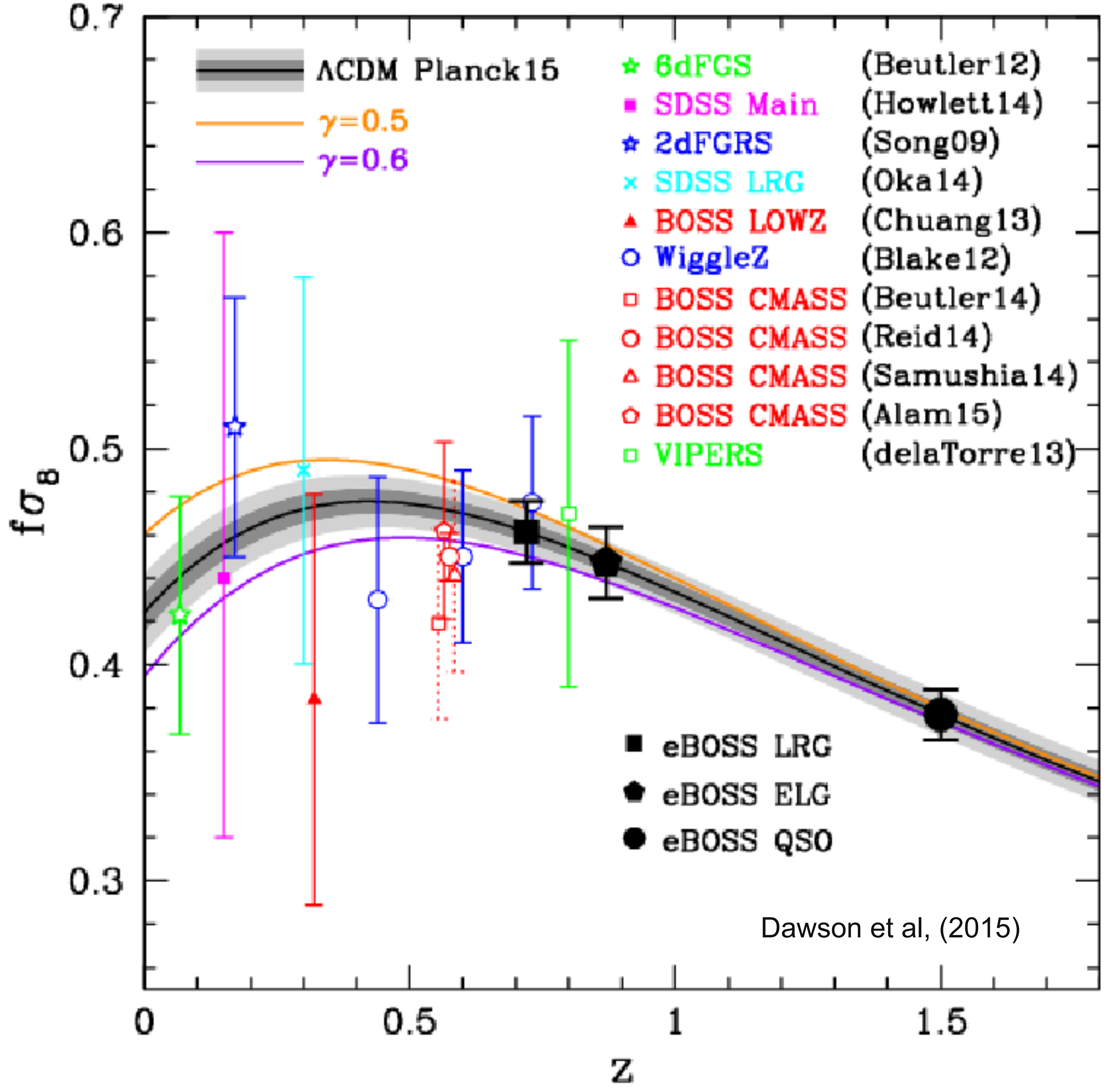




Riess et al, (2021)

② Structure growth history



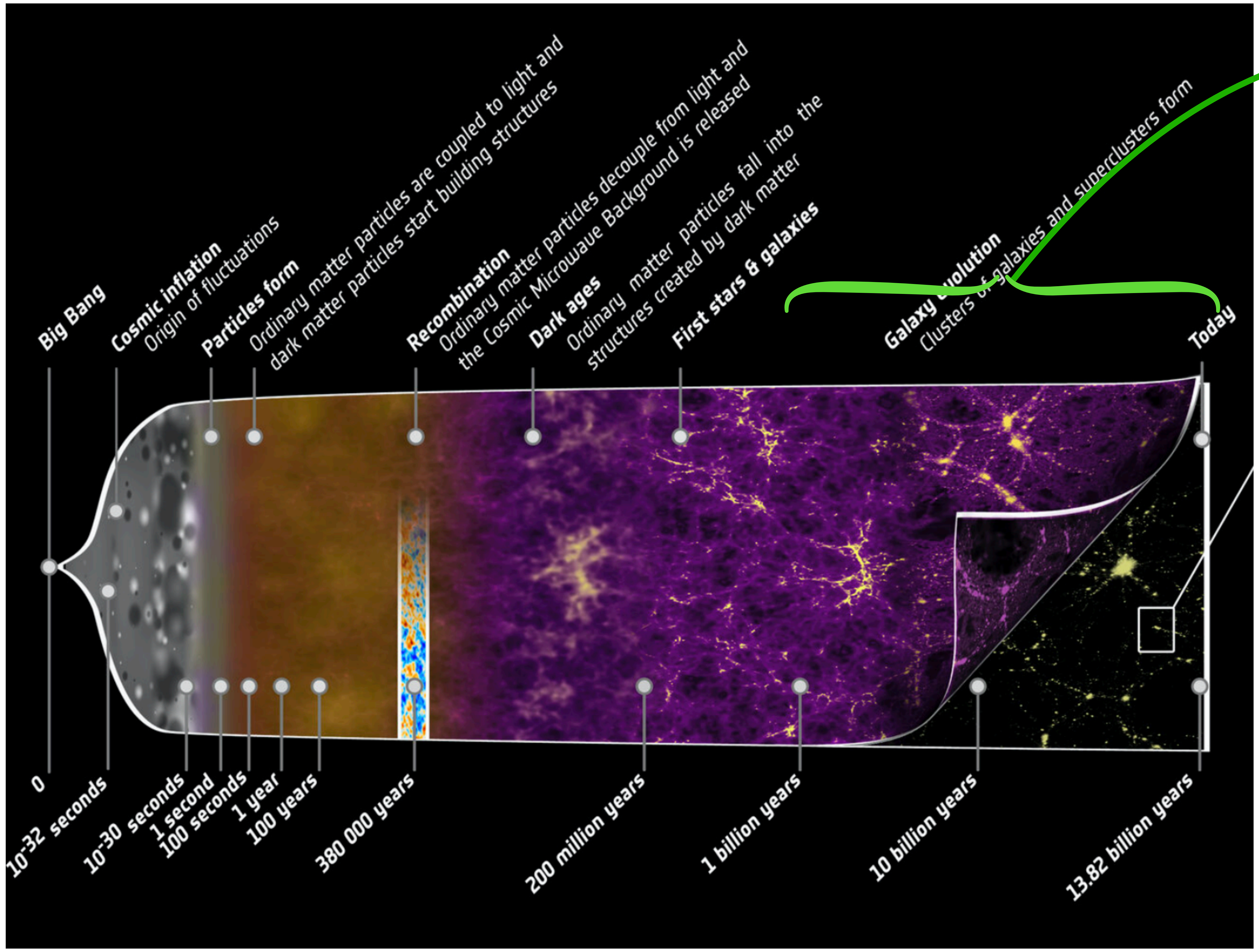


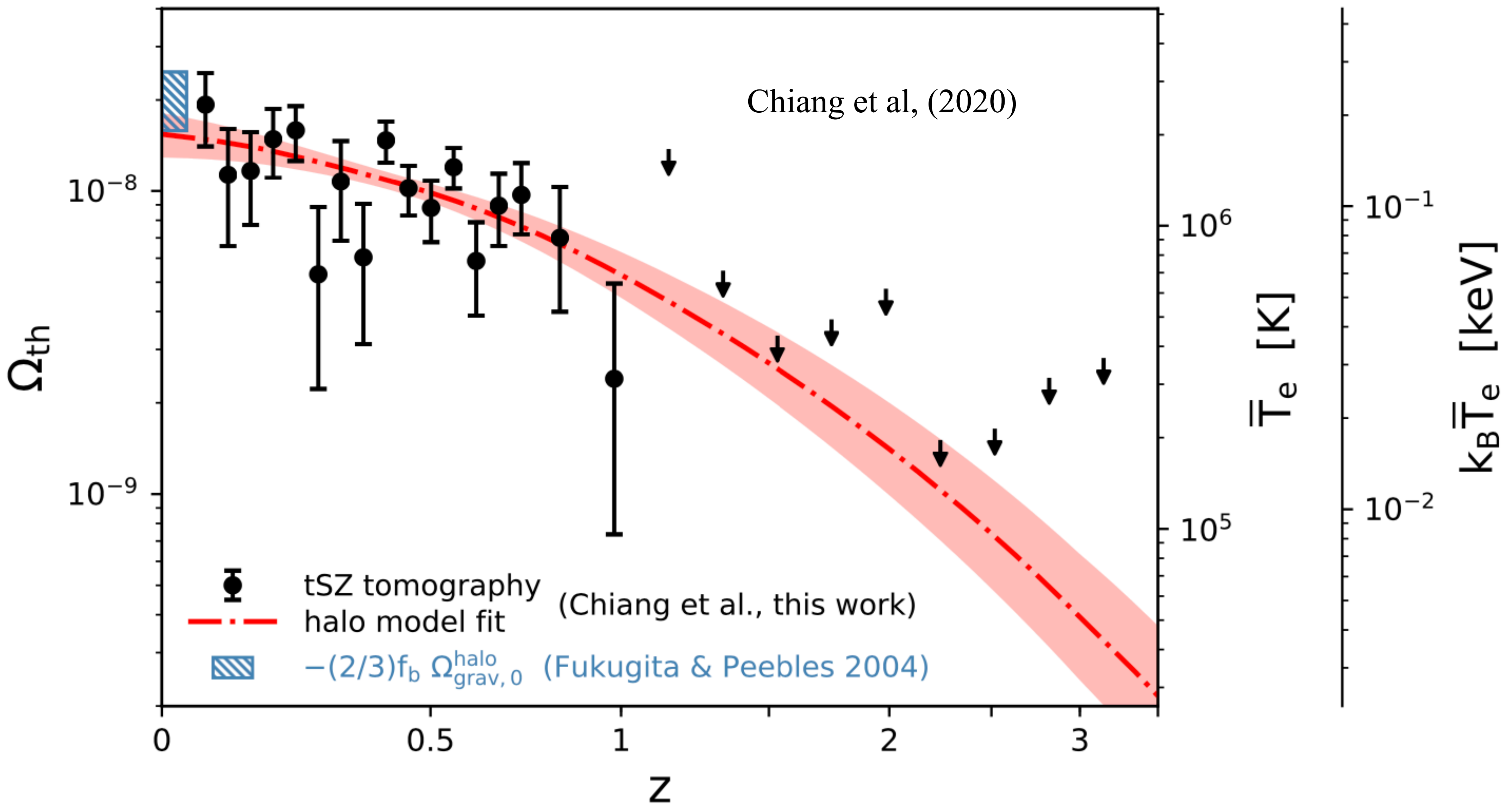
③ New Observable: Thermal history of the Universe

(after recombination)

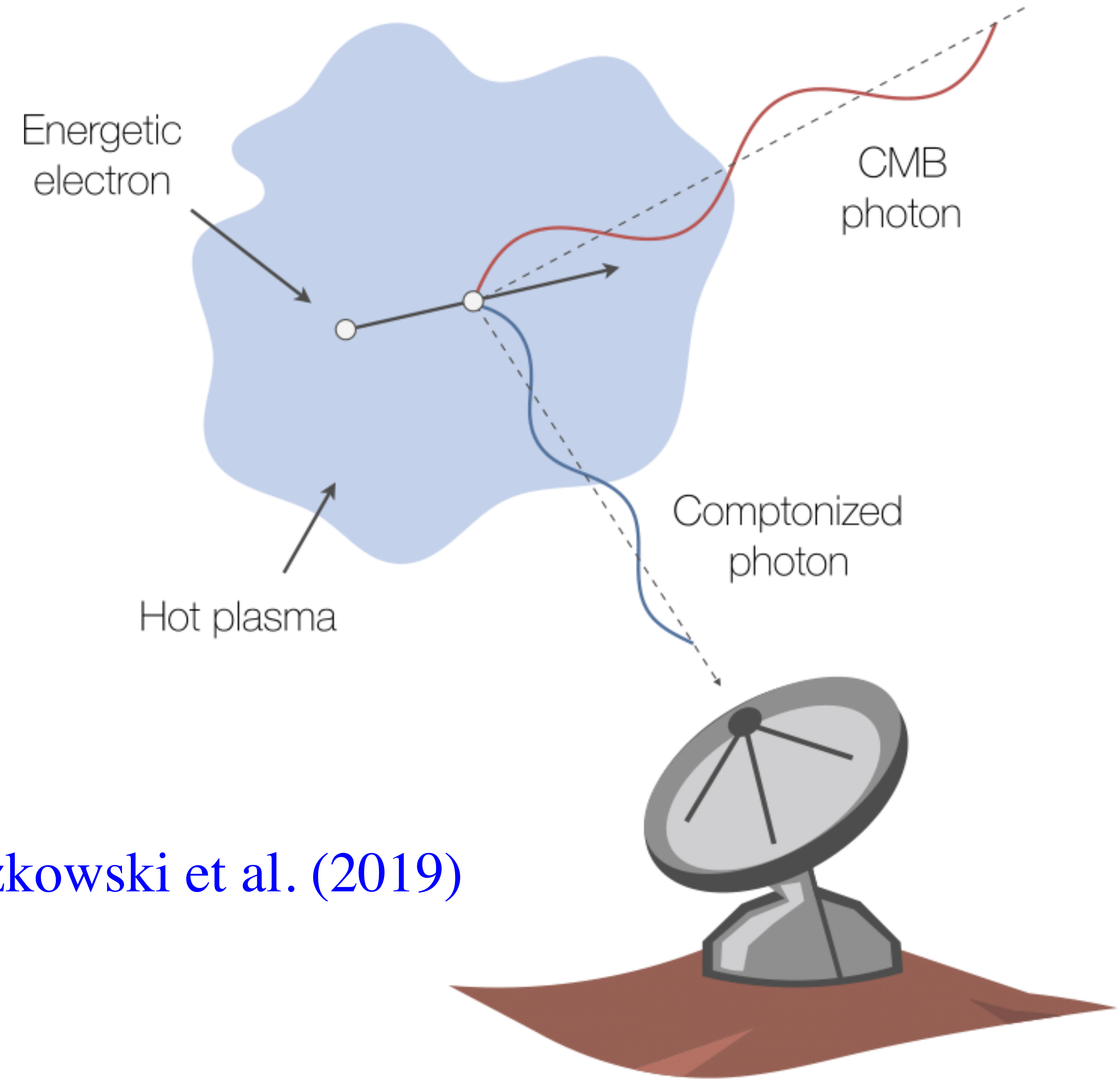
The mean temperature of gas as a function of redshift

Goal Can we use this new tool to test cosmology and galaxy formation model?





How can we take the temperature of our Universe? Thermal Sunyaev-Zeldovich (tSZ) effect!

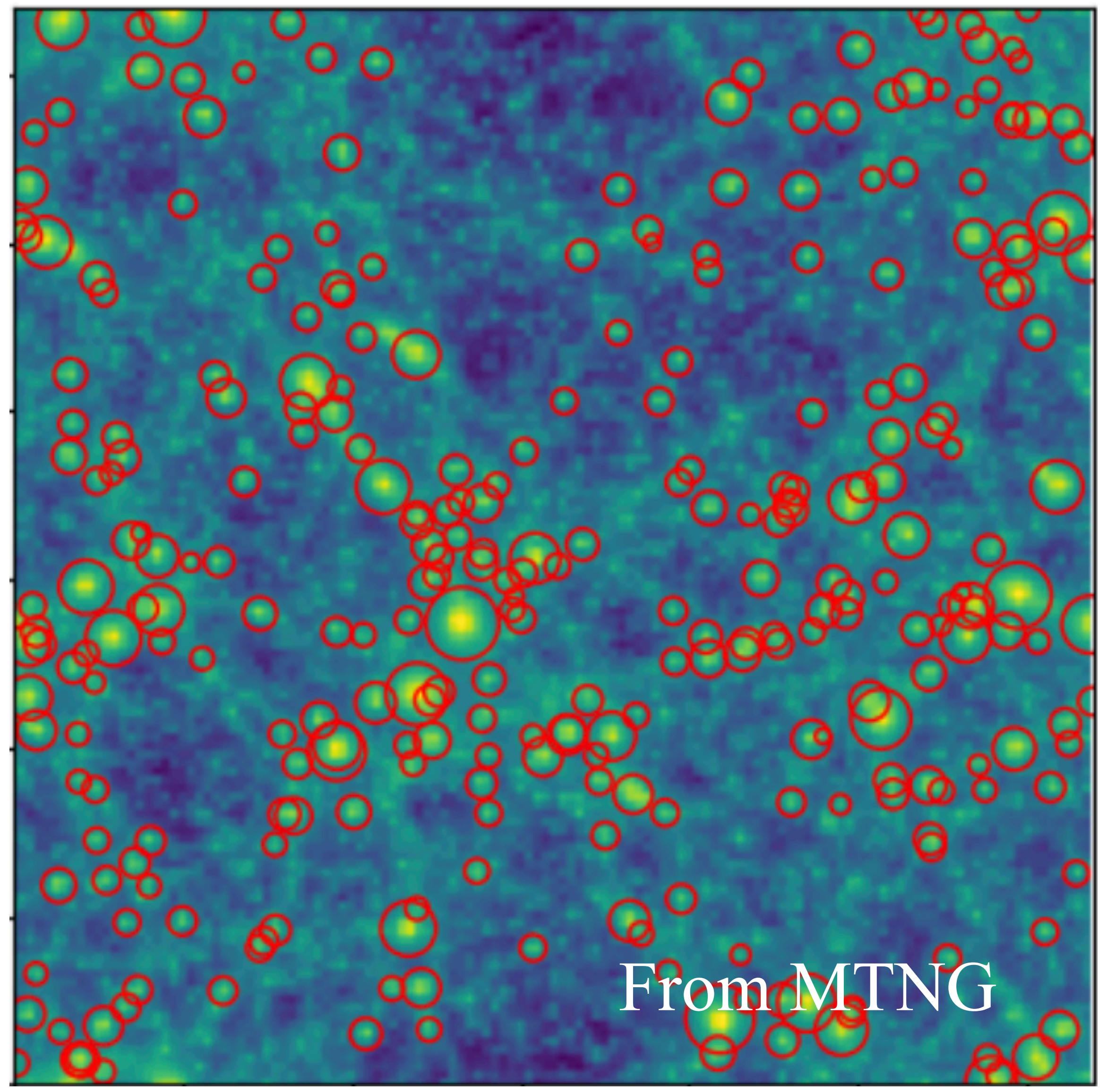


Mroczkowski et al. (2019)

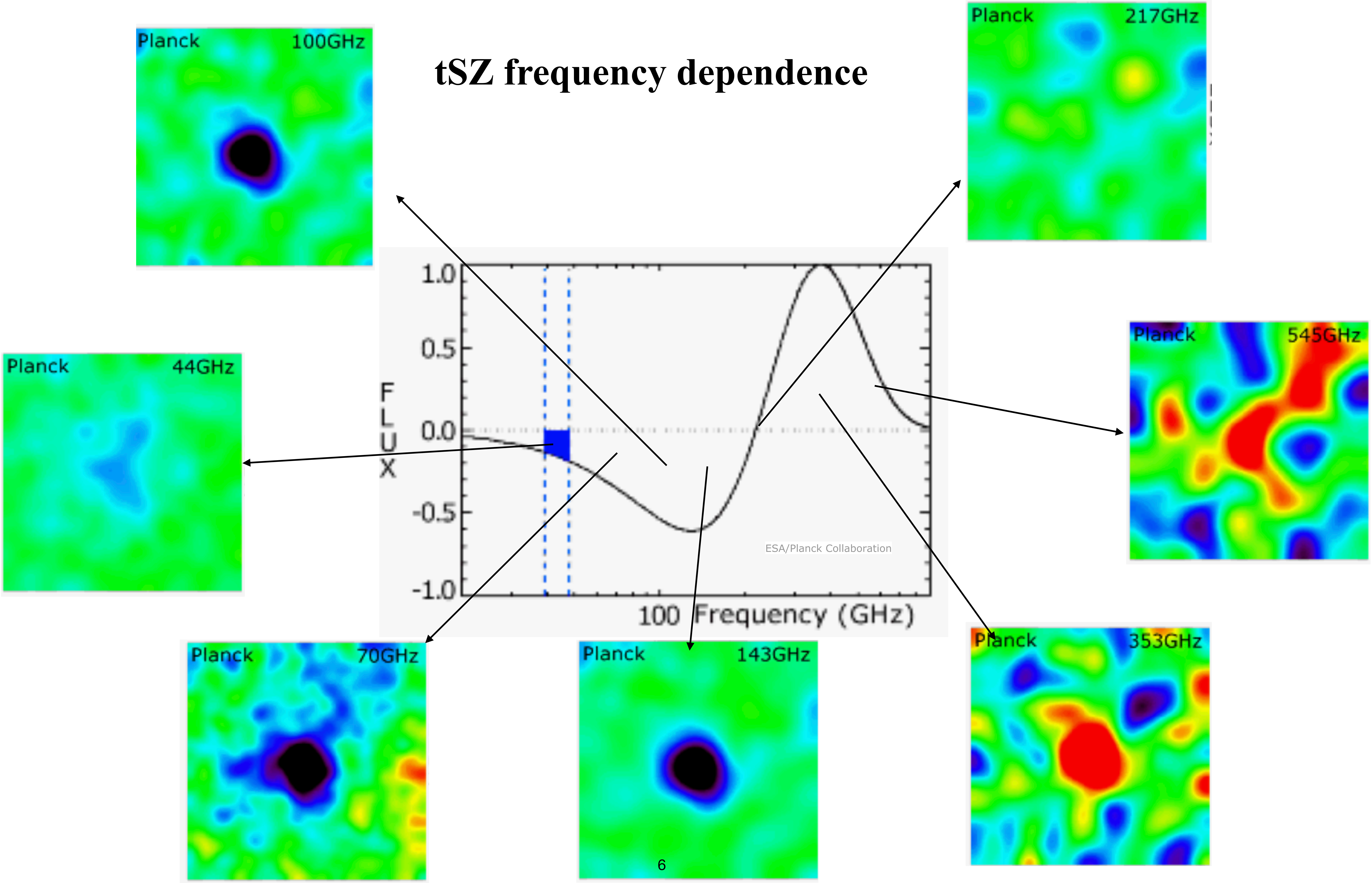
$$P_e = n_e k_B T_e$$

$$y(\hat{n}) = \frac{\sigma_T}{m_e c^2} \int \frac{d\chi}{1+z} P_e(\chi, \hat{\theta})$$

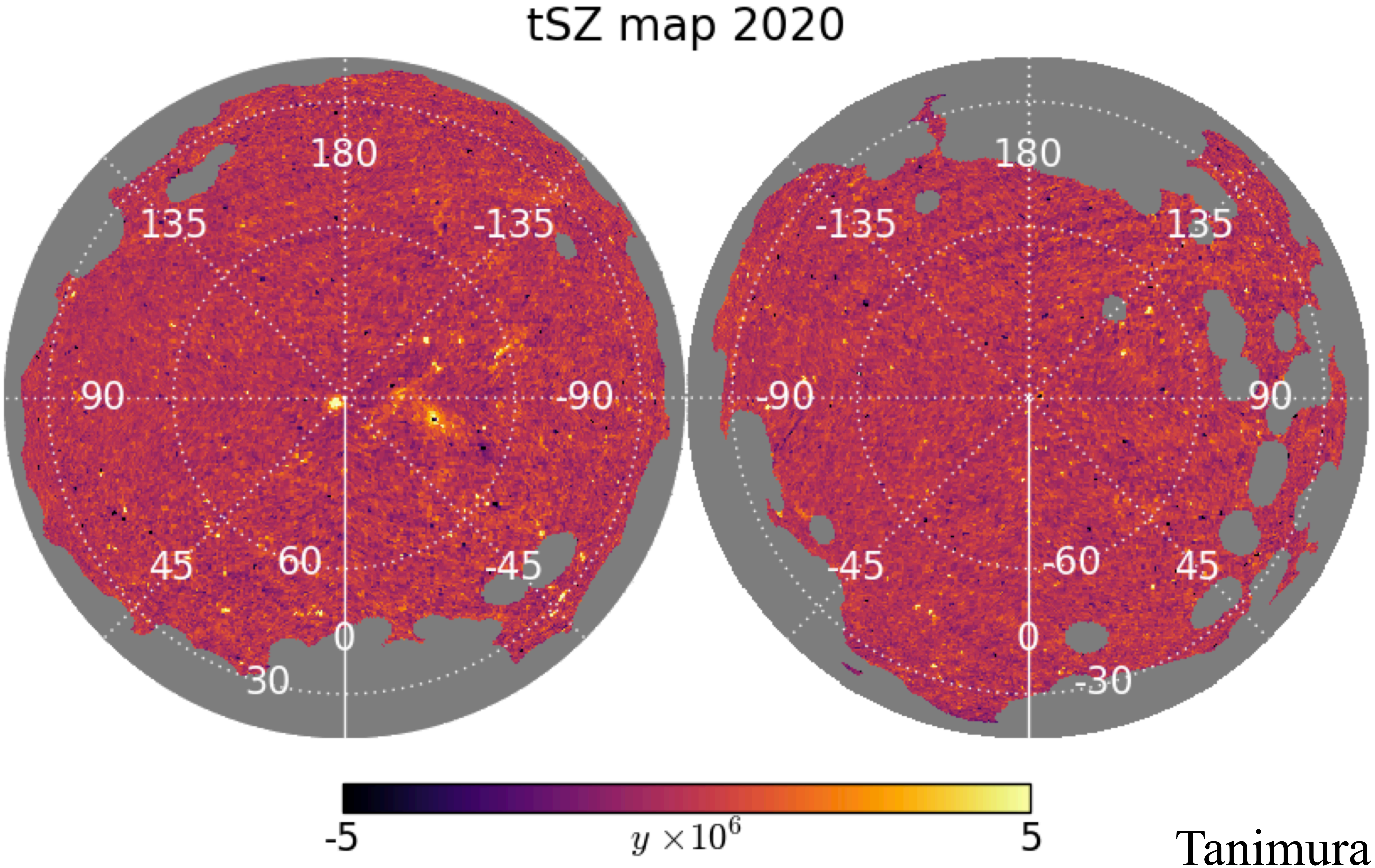
Pe distribution in the Universe



tSZ frequency dependence



The full-sky of thermal SZ effect (Compton-y map)



Tanimura et al, (2021)

BUT: No redshift information

Solution: cross-correlate with large scale tracers having redshift

The spatial distribution of the electron pressure is described by

$$P_e(\mathbf{x}, z) = \bar{P}_e(z) + \delta P_e(\mathbf{x}, z)$$

It is a biased tracer of the matter field. On the large scale, it can be described by

$$\delta P_e(\mathbf{k}, z) \simeq \bar{P}_e(z) b_y(z) \delta_{\mathrm{m}}(\mathbf{k}, z)$$

The cross power spectrum of pressure and matter is

$$\langle P_e(\mathbf{k}, z)\delta_{\mathrm{m}}(\mathbf{k}', z)\rangle = (2\pi)^3 \delta_{\mathrm{D}}^{(3)}(\mathbf{k} + \mathbf{k}') P_{P_e\mathrm{m}}(k, z)$$

$$P_{P_e\mathrm{m}}(k, z) \simeq \langle b_{\mathrm{h}} P_e\rangle(z) P_{\mathrm{mm}}(k, z)$$

$$\langle b_{\mathrm{h}} P_e\rangle(z) = b_y(z)\bar{P}_e(z)$$

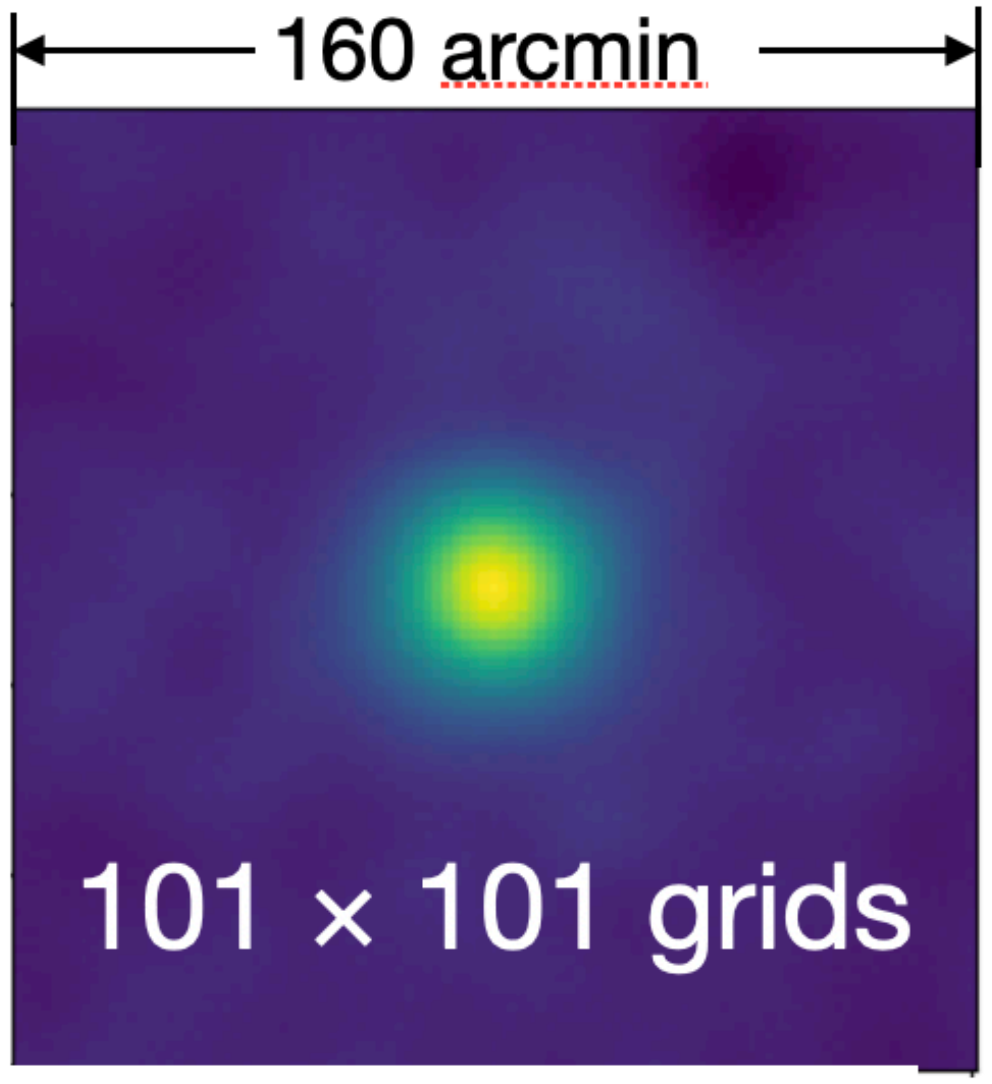
The observable we force in this work

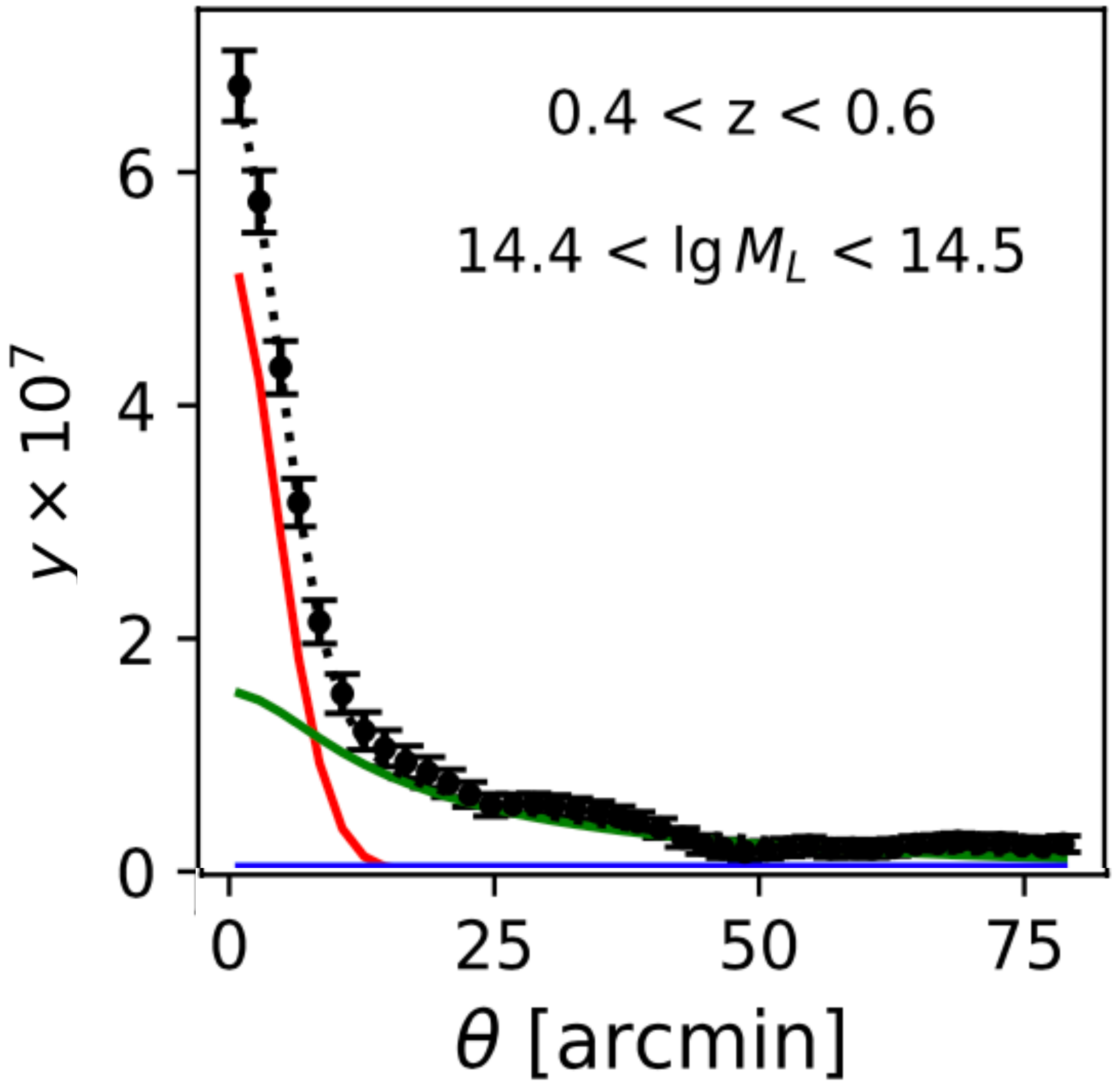
$$\boxed{\langle b_{\mathrm{h}} P_e\rangle(z)} = \lim_{k\to 0} \frac{P_{P_e\mathrm{m}}(k, z)}{P_{\mathrm{mm}}(k, z)}$$

To connect with observation, the cross power spectrum between galaxy and pressure is

$$P_{P_e\mathrm{g}}(k, z) \simeq \langle b_{\mathrm{h}} P_e\rangle(z) b_{\mathrm{g}}(z) P_{\mathrm{mm}}(k, z)$$

Measure tSZ effect by combining Planck y-map and DESI group catalog





1h-term   2h-term

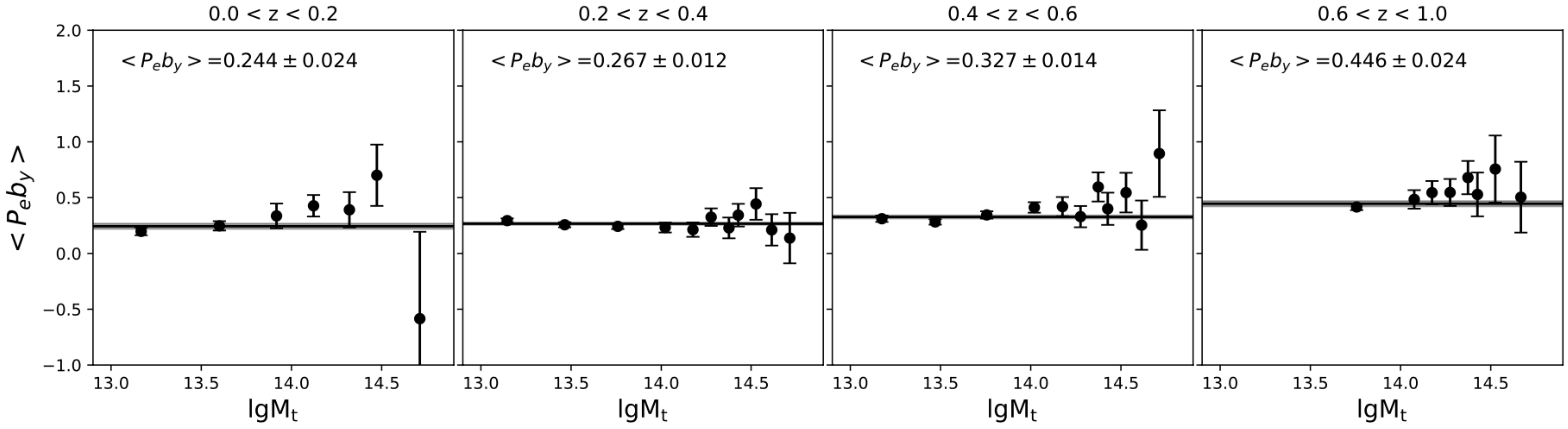
$$y^{\rm th}(\theta) = A_1 y_1(\theta) + A_2 y_2(\theta) + A_3 y_3(\theta)$$ Background term

Baryon fraction as a function of cluster mass/redshift

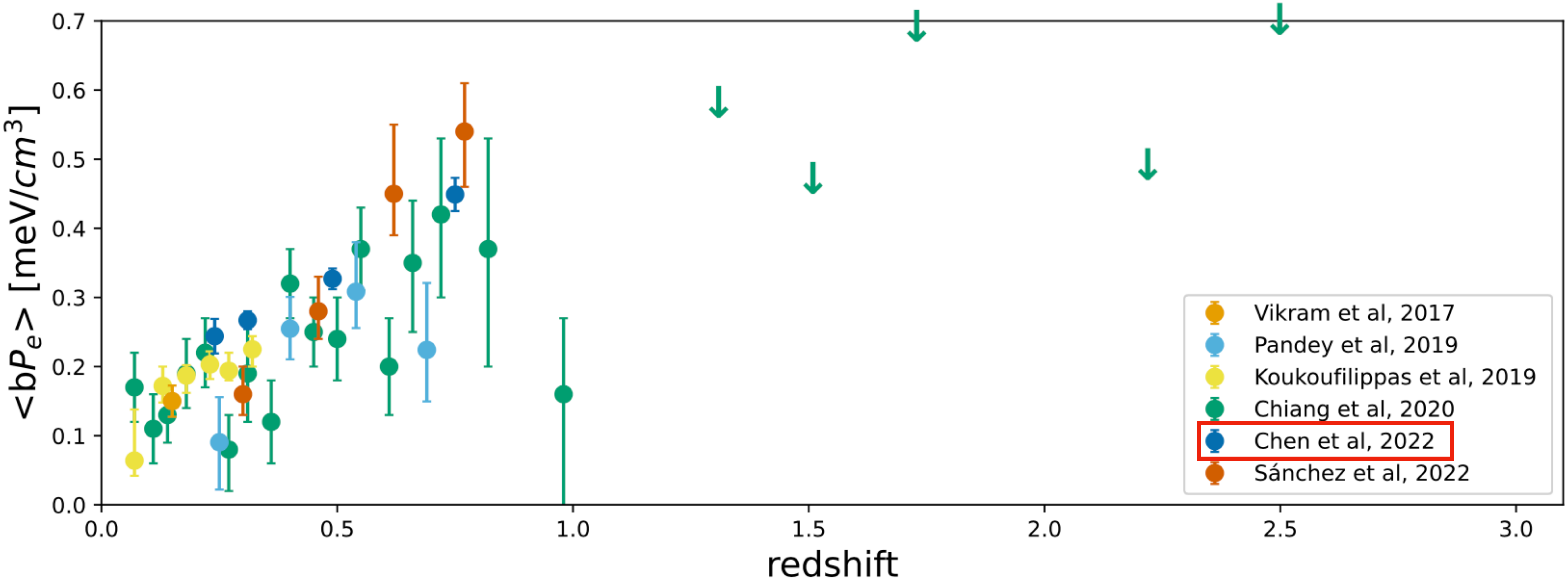
$\langle b_{\rm h} P_e \rangle$

The 2h-term measurement

(Chen et al. 2023)



Measurements of <bhPe>

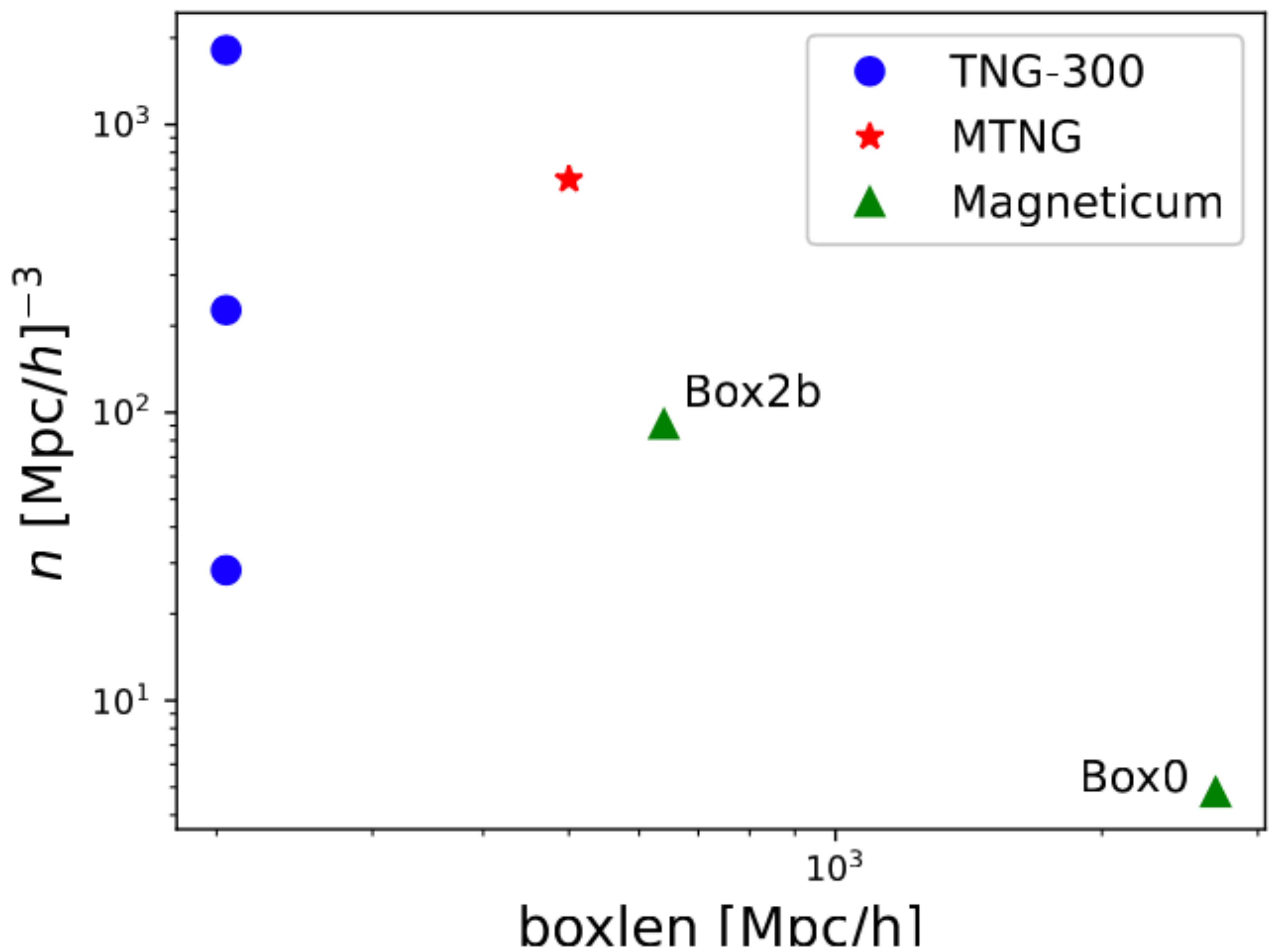


Simulations

To investigate $\langle b_h P_e \rangle$, the simulations should be

- hydrodynamic
- large enough

	MillenniumTNG/illustrisTNG				Magneticum	
	MTNG	TNG300-1	TNG300-2	TNG300-3	Box0	Box2b
code	Arepo				P-GADGET	
box size (Mpc/h)	500	205	205	205	2688	640
$N_p^{1/3}$	4320	2500	1250	625	4536	2880
Cosmology	Planck16				WMAP7	

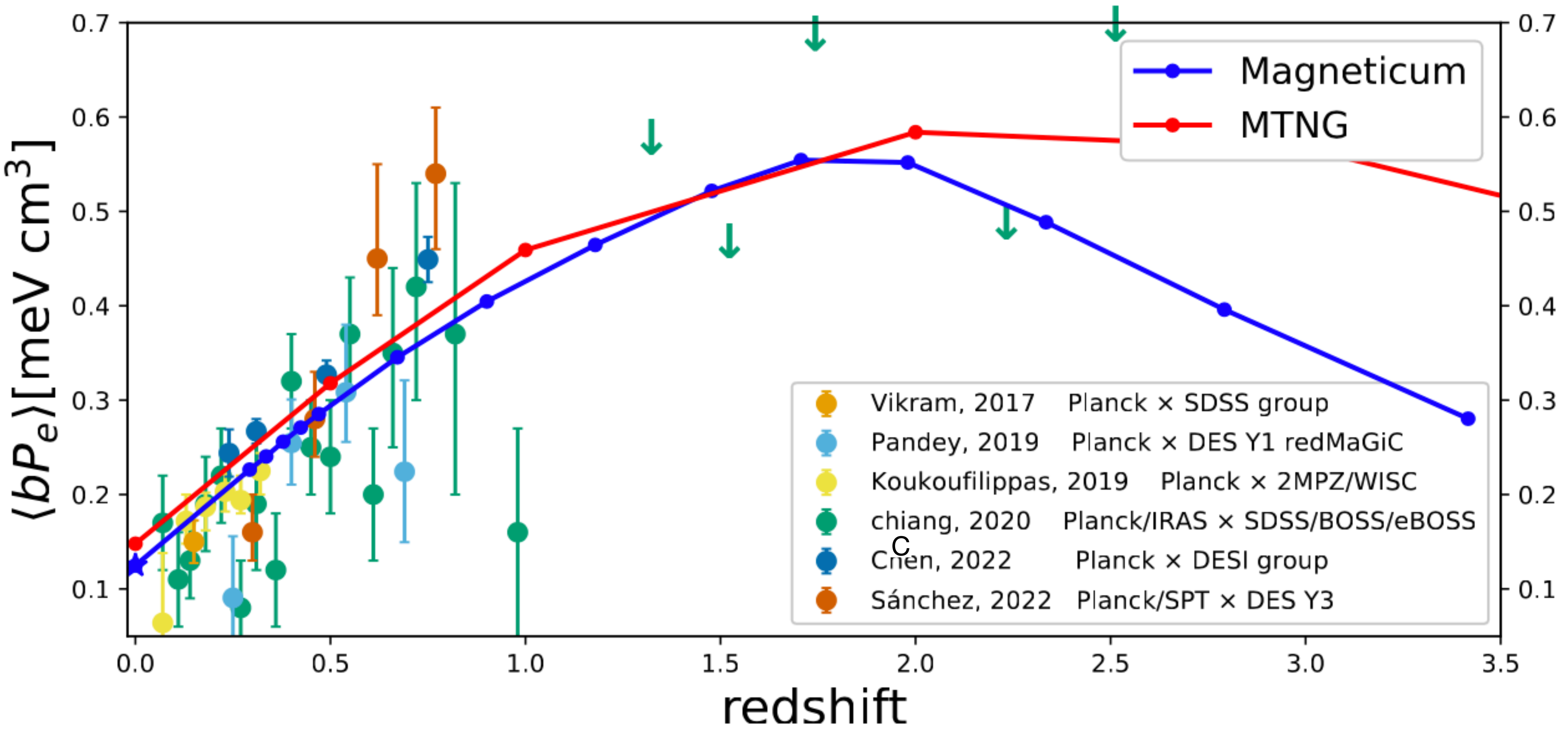


They include baryonic processes:

CMB/UV/X-ray background	chemical evolution	BH seeding
radiative cooling rate	star formation rate	BH accretion
multiphase ISM	SN feedback model	AGN 'Quasar' feedback mode
	Galactic winds	AGN 'radior' feedback mode

Many of them cannot be resolved and are described by sub-grid parameters

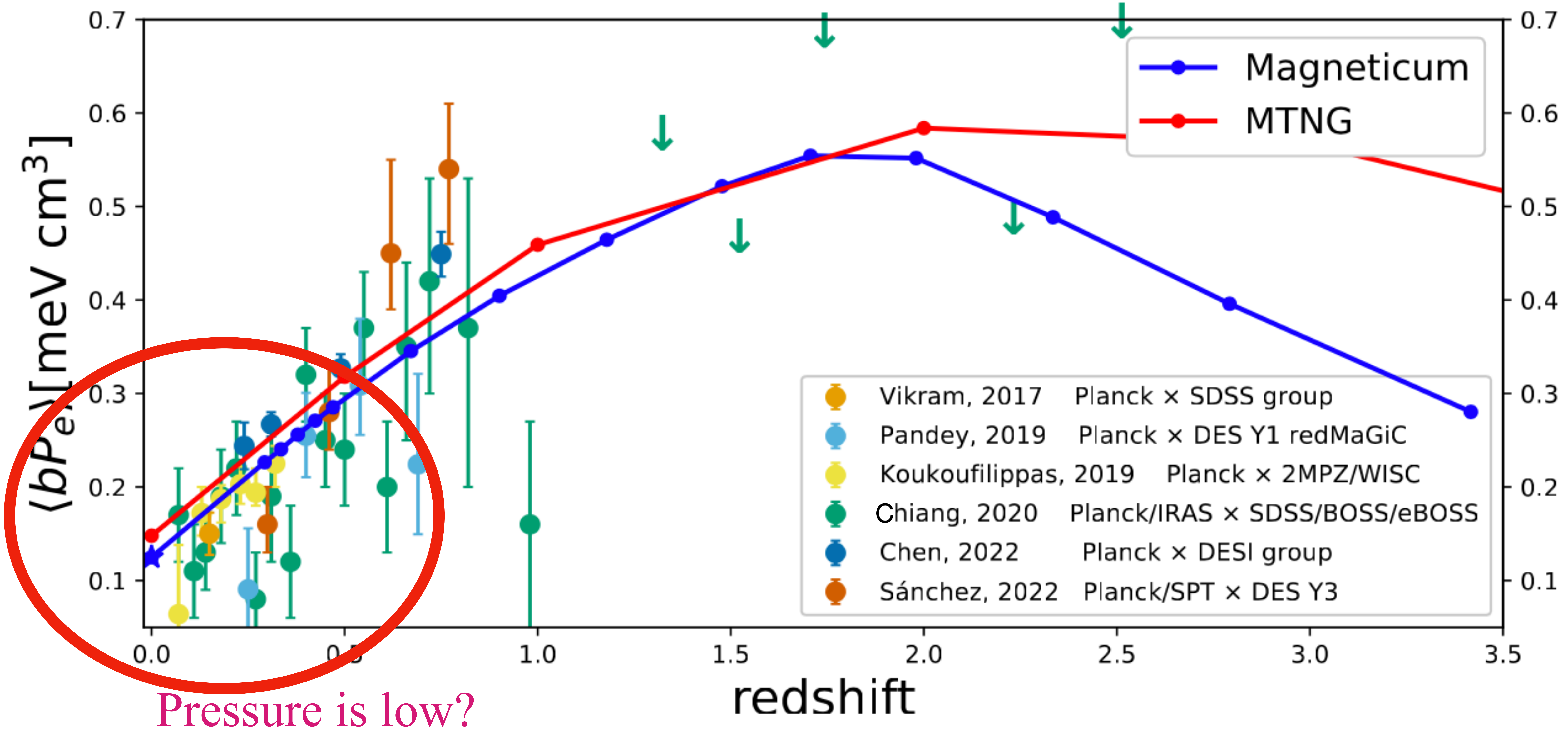
Compare $\langle b_h P_e \rangle$ in simulations with different galaxy formation models and the observations….



Low Redshift: cosmology

$$\langle b_{\rm h} P_e \rangle_{\rm obs} = A \langle b_{\rm h} P_e \rangle_{\rm MTNG}$$

$$A = 0.926 \pm 0.024 \ (z < 0.5)$$

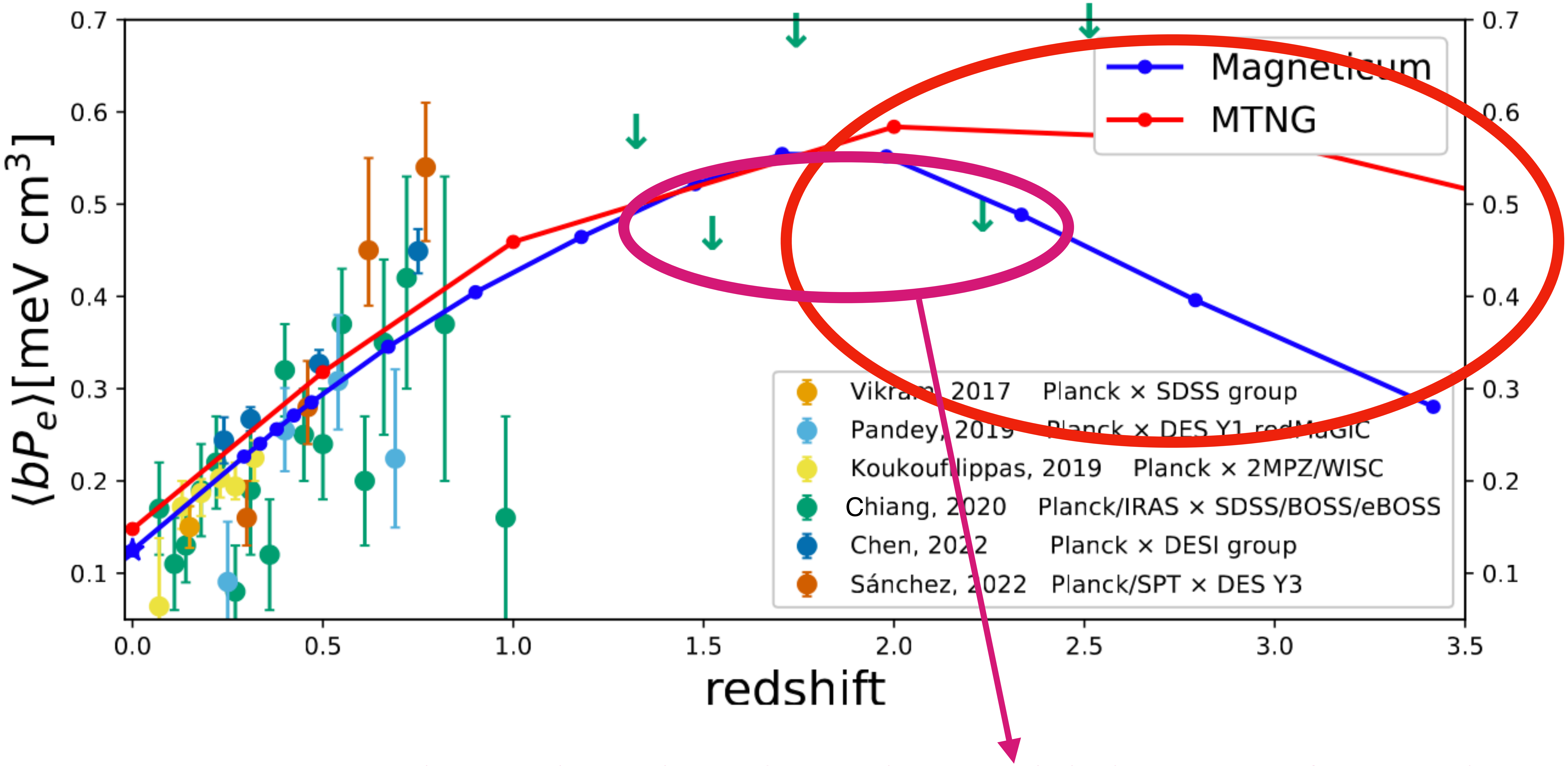


Pressure is low?

Cosmology (relation to "lensing is low" problem)? or Galaxy Formation model?

High Redshift

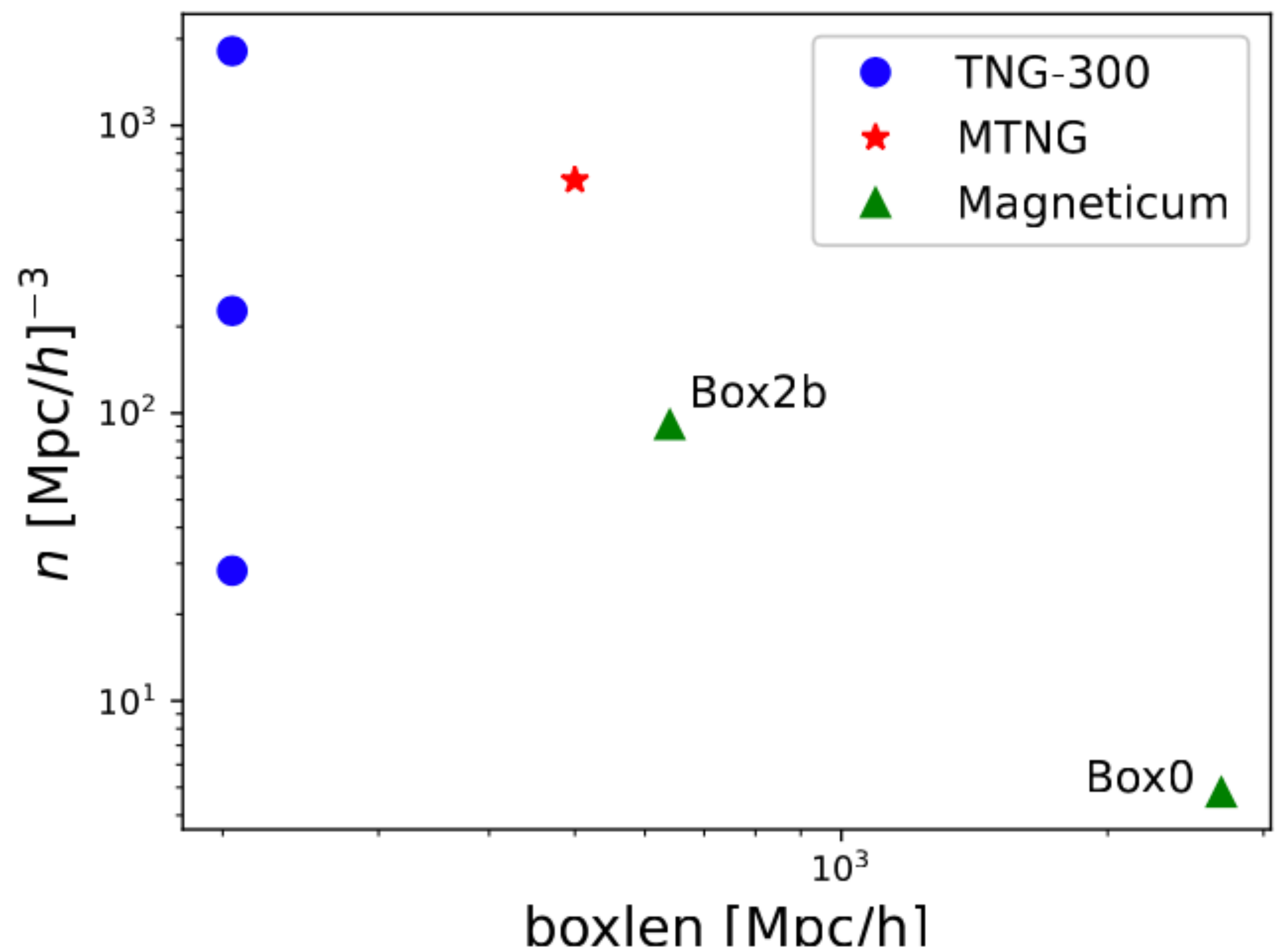
Galaxy formation model?

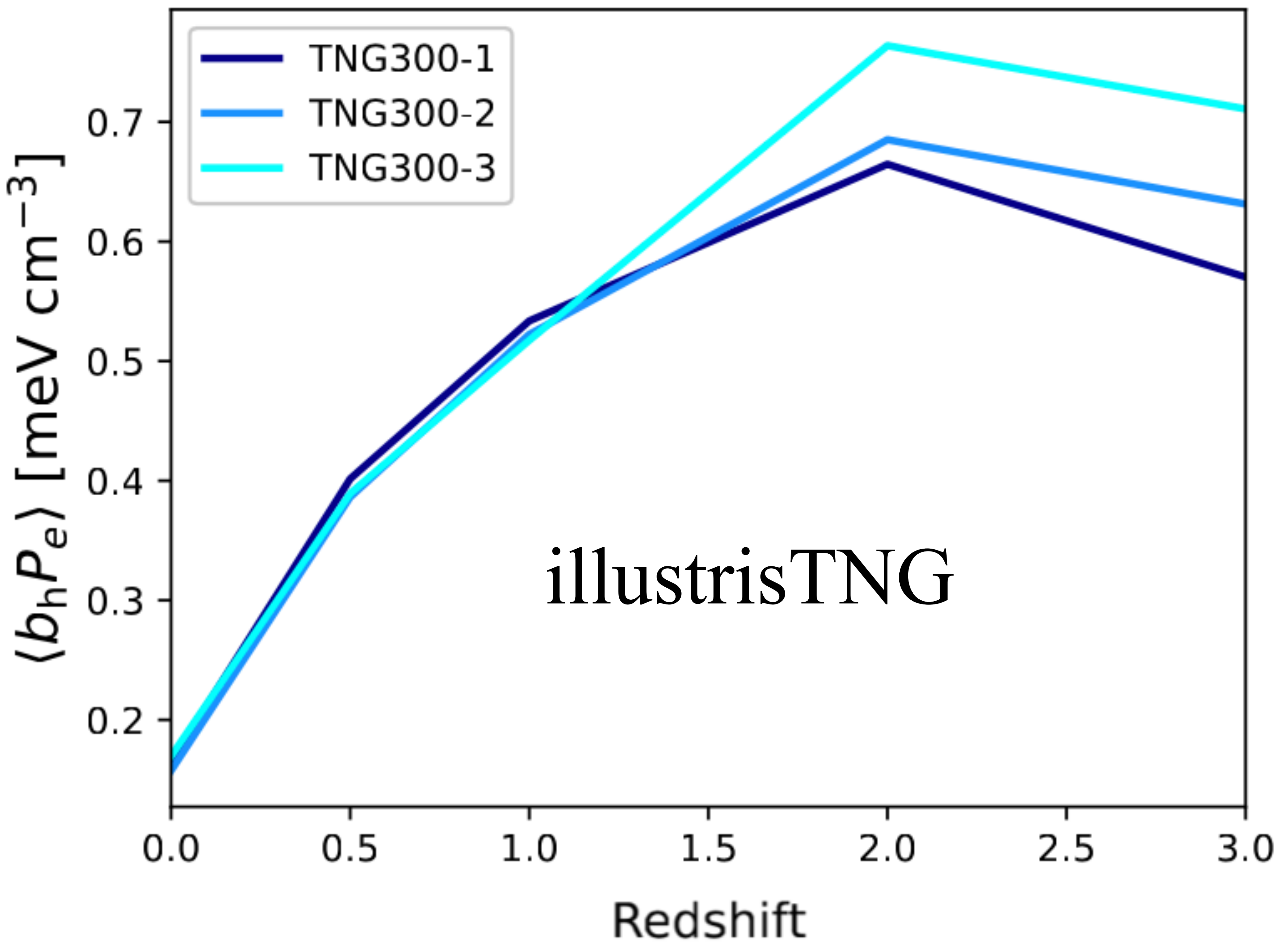


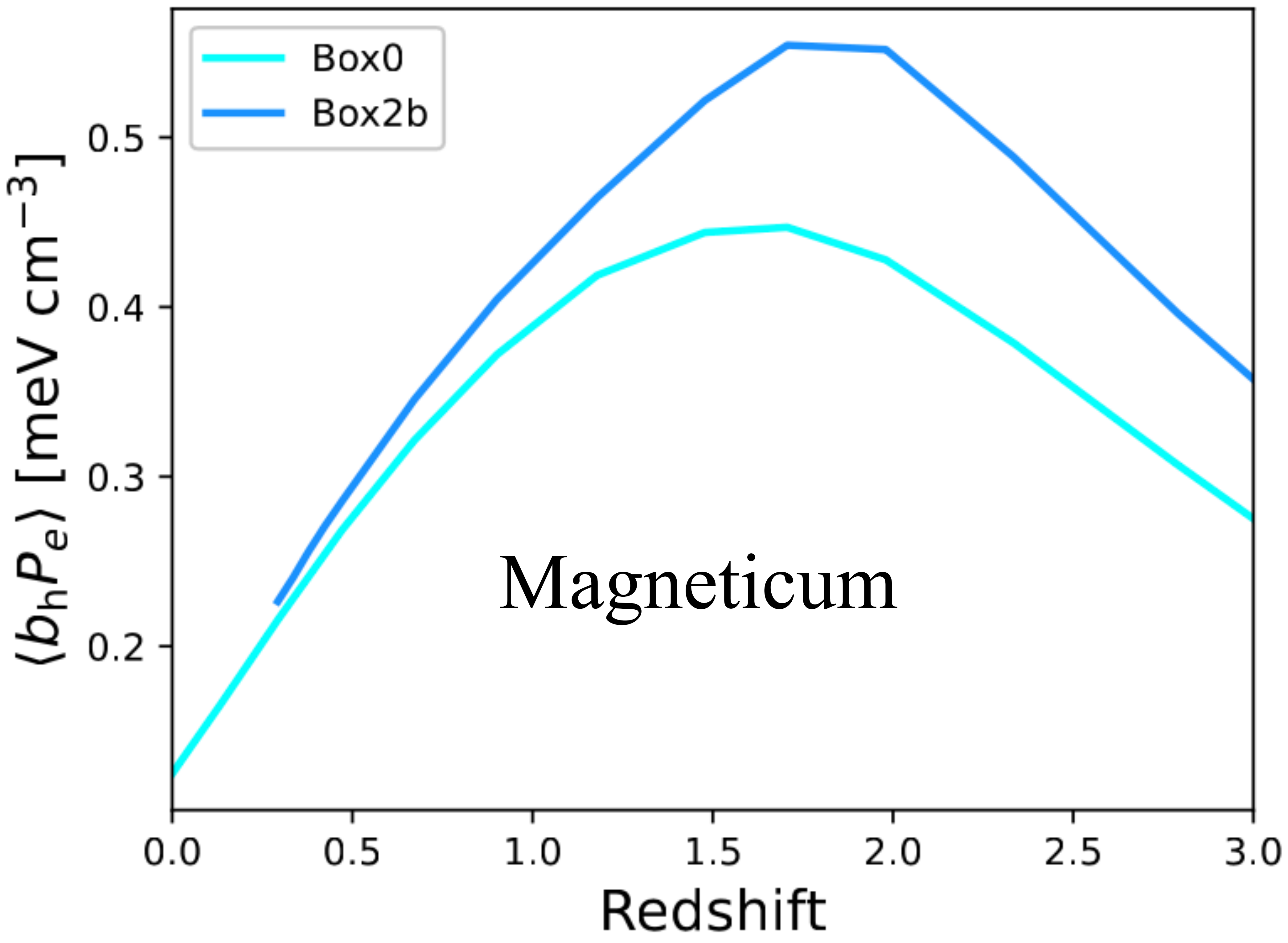
Rule out the galaxy formation models in MTNG/Magneticum?

Dependence on mass resolution

In TNG simulations, $\langle b_h P_e \rangle$ decreases with increasing mass resolution, however in Magneticum simulations the situation is different.



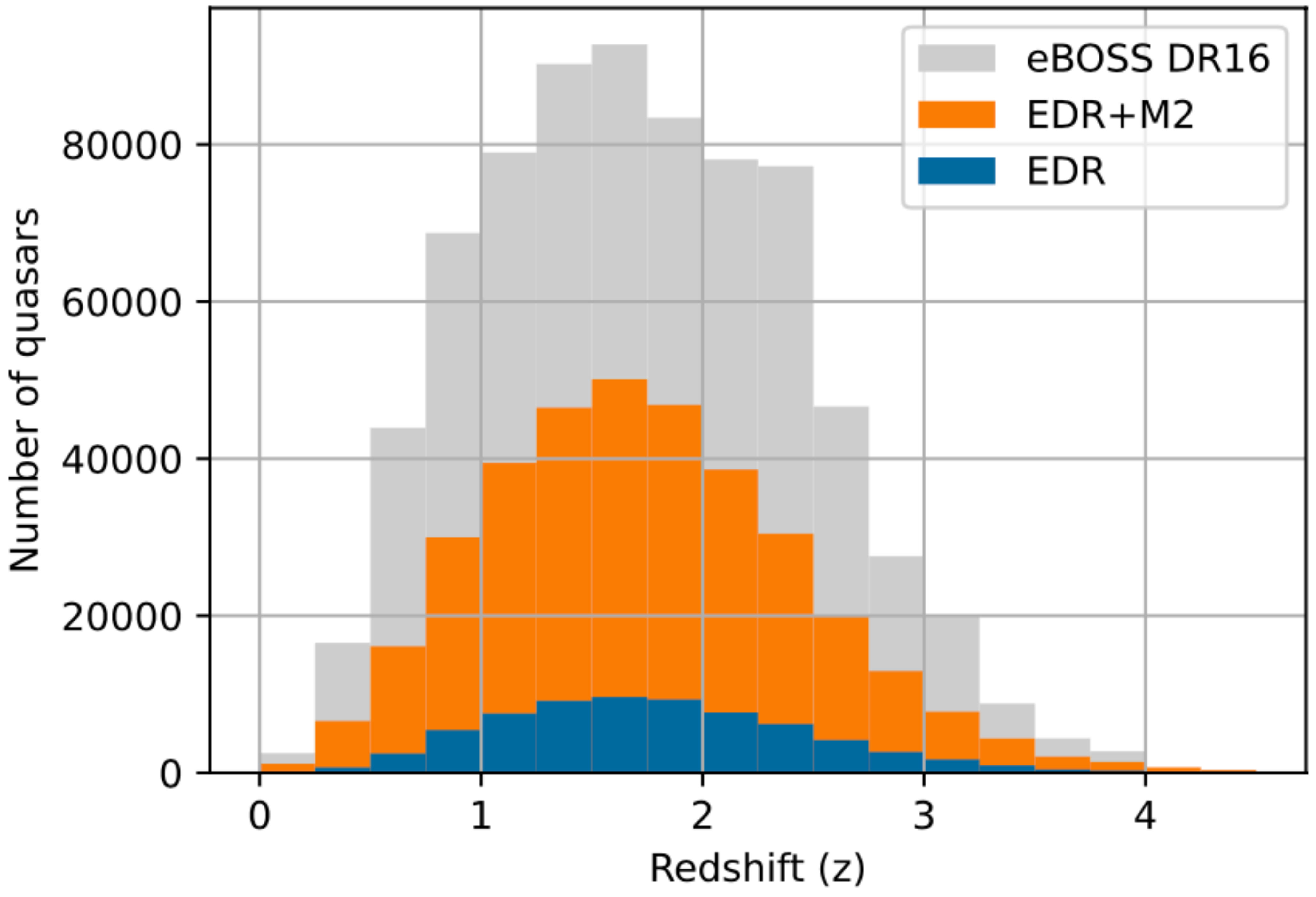


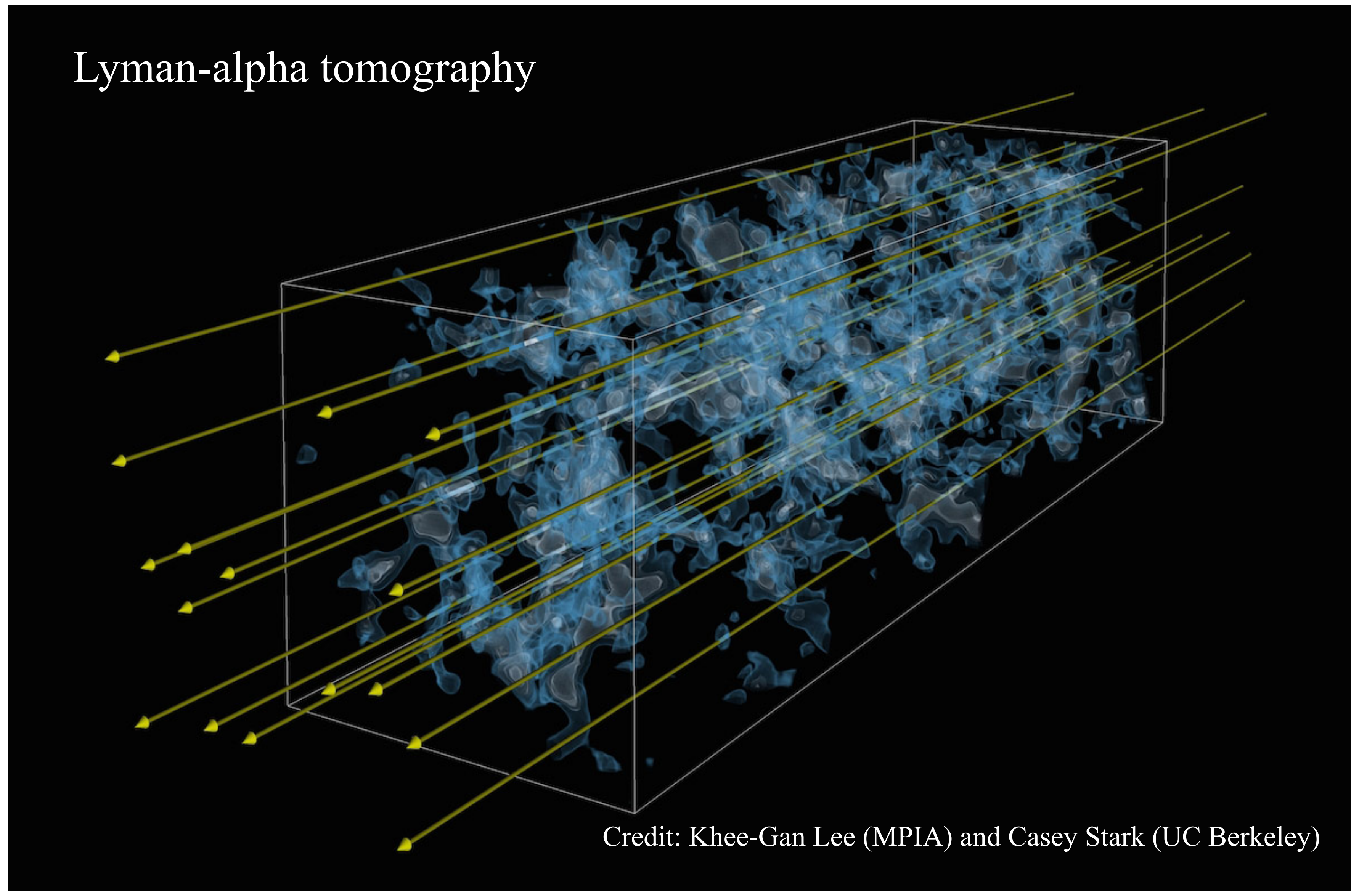


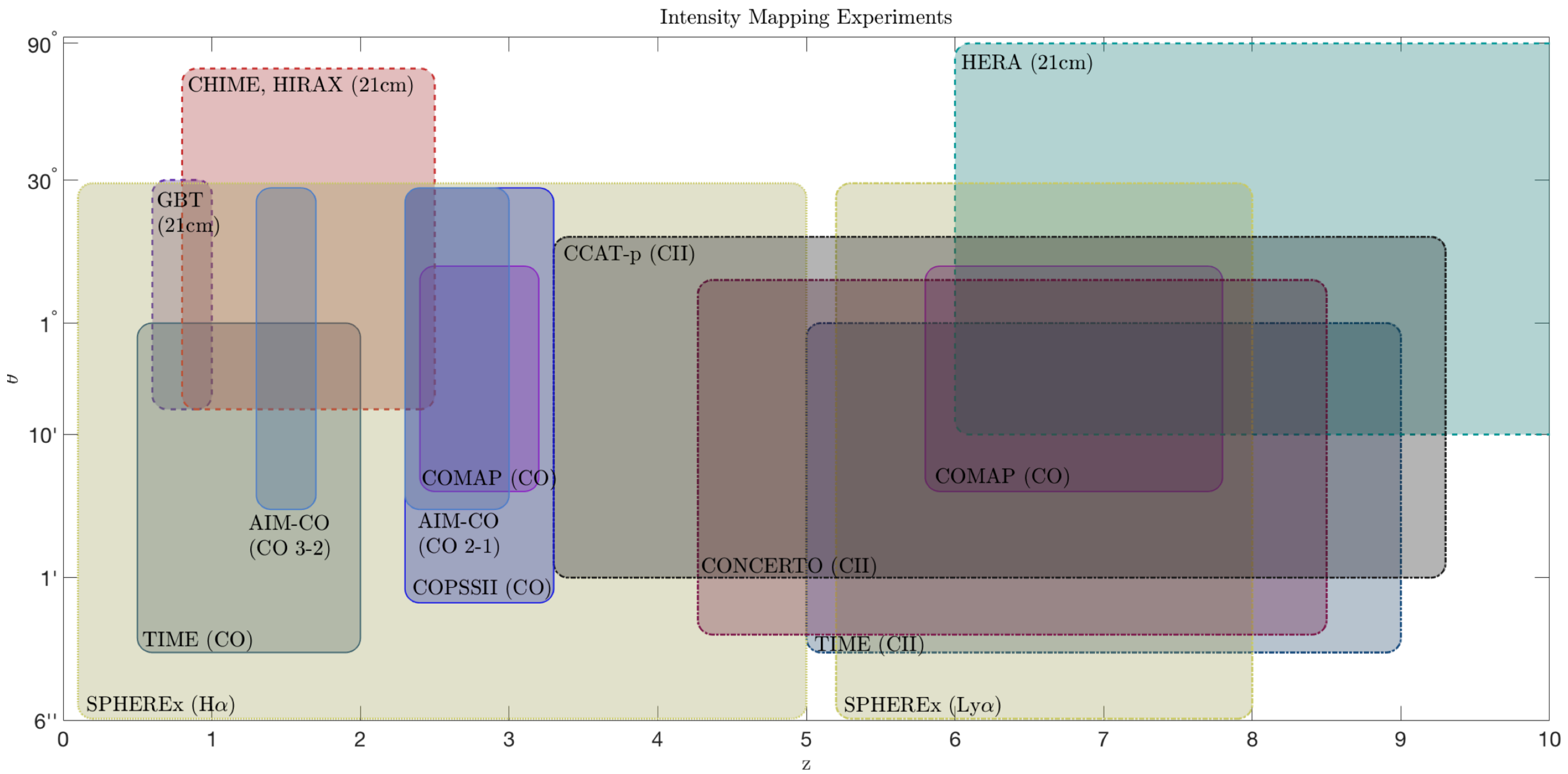
Future Measurements
Possible large-scale tracers at high redshift

For example, high redshift Quasars, lyman-α forest, intensity mapping…

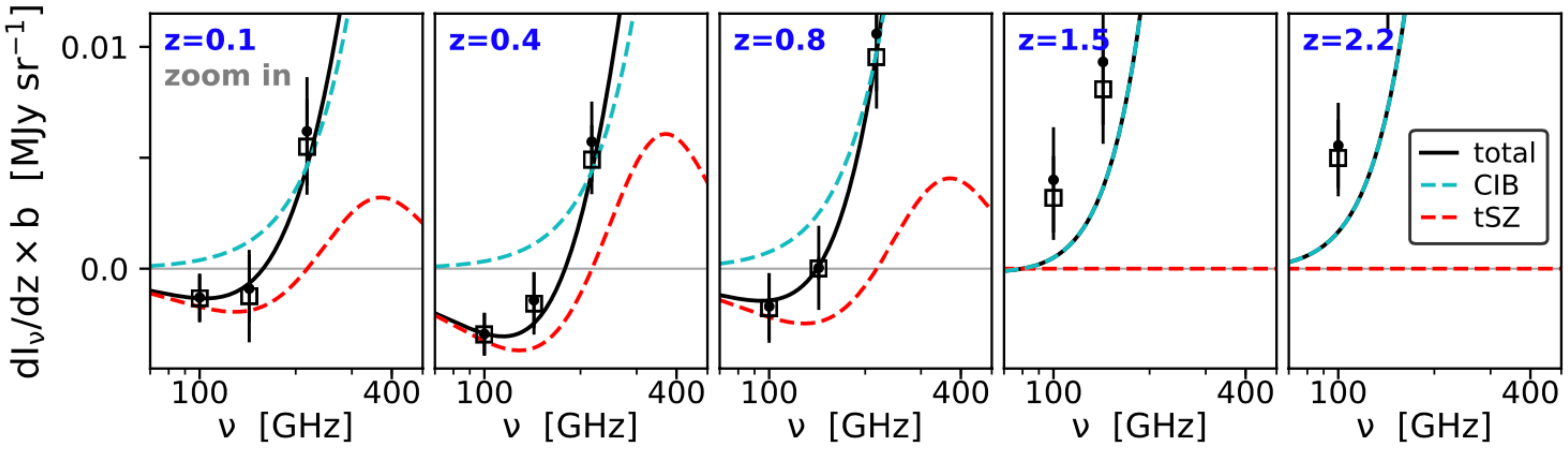
DESI two month observation



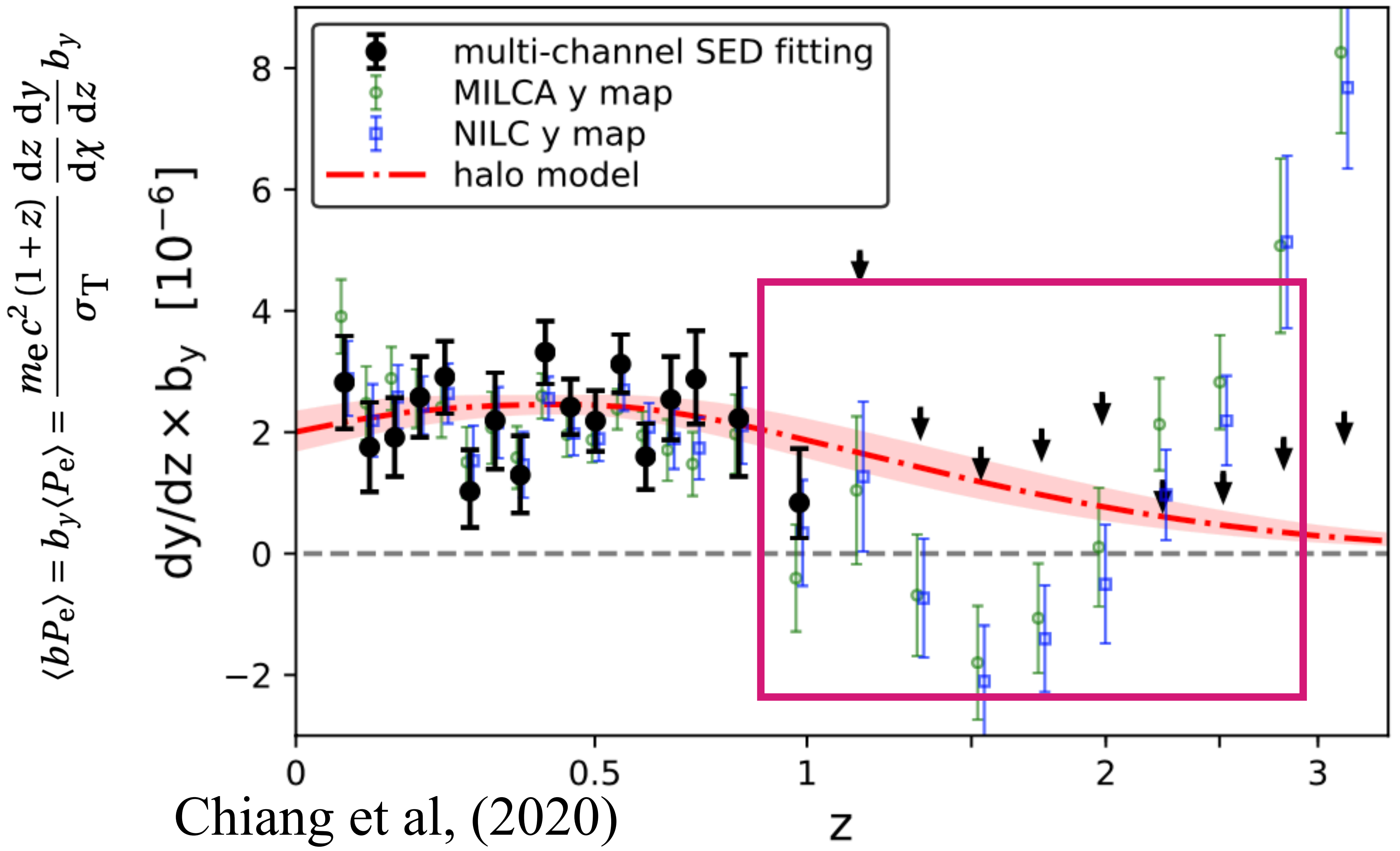




Future Measurements
CIB contamination at high redshift



Chiang et al, (2020)



Chiang et al, (2020)

- CIB contamination in Planck y-maps is significant and induce an unphysically negative result.
- Current CIB model seems underestimating the CIB intensities.(Draine & Hensley 2012)

Take-away message

- Low redshift measurements of $\langle b_h P_e \rangle$ can used to constrain cosmology model and help explain the S8 tension.

- High redshift measurement of $\langle b_h P_e \rangle$ serves as a validation tool for galaxy formation models.

- In the near future, the publication of several high redshift large-scale tracer catalogs will enable precise measurements of $\langle b_h P_e \rangle$.

- CIB contamination poses a significant systematic challenge at high redshifts during tSZ effect measurements.