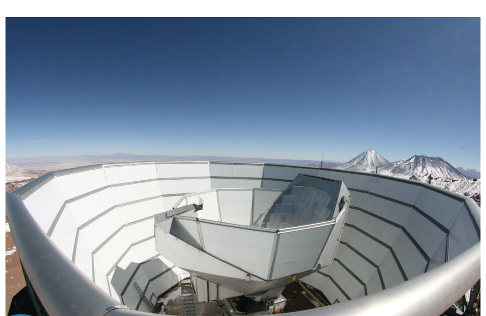
Astrophysics and Cosmology with the Sunyaev Zeldovich Effects

Boris Bolliet

DAMTP
Cambridge University



ACT cluster cosmology co-Leader
SO SZ working group co-Leader

SIMONS OBSERVATORY

ASPEN CENTER FOR PHYSICS

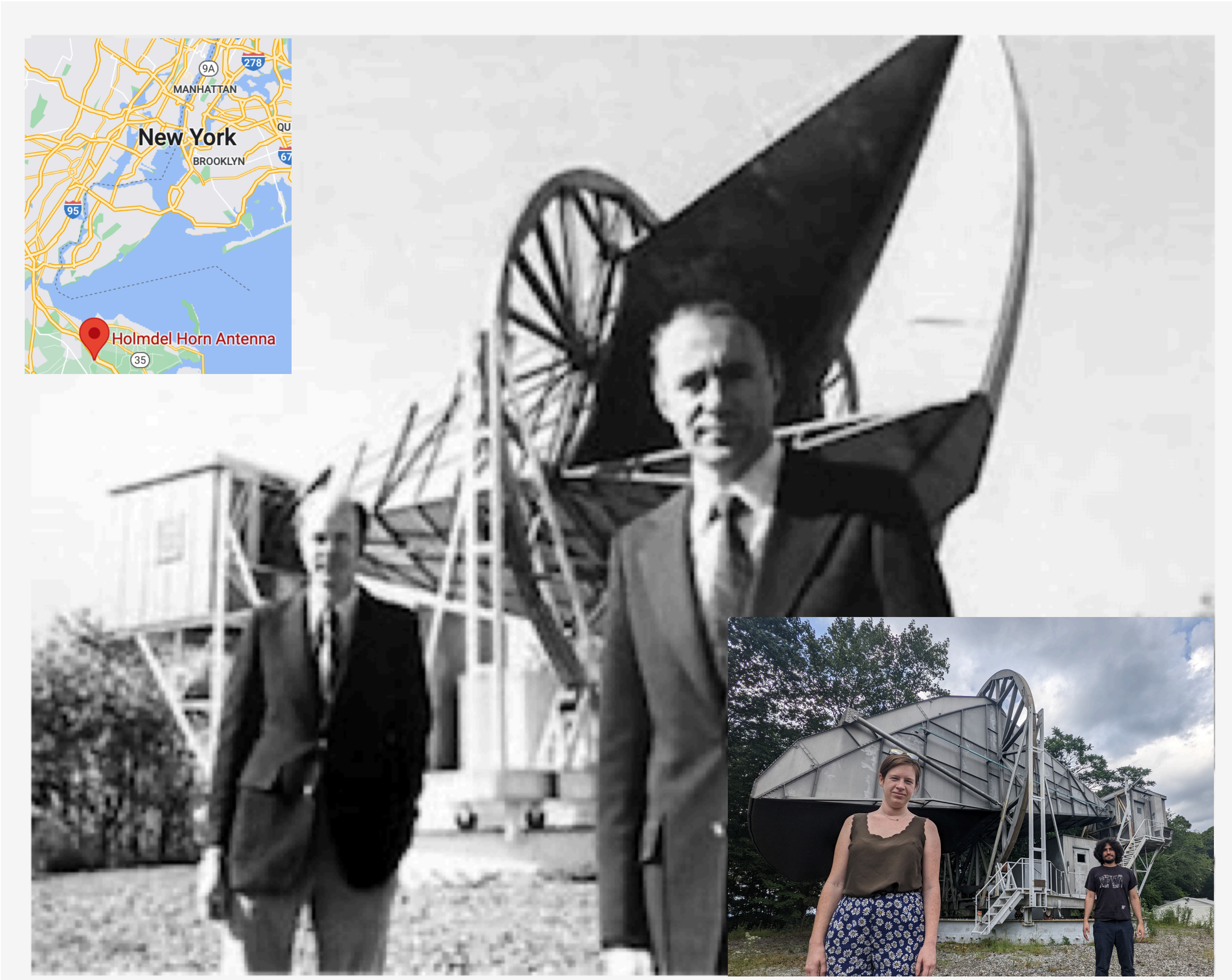
2023 SUMMER PROGRAM

May 28 to September 17, 2023

Groups and Clusters of Galaxies at the Crossroad between Astrophysics and Cosmology Aug 27 to Sept 17

Organizers:
Boris Bolliet, Cambridge University
Stefano Borgani, University of Trieste
Stefano Ettori, European Southern Observatory
***Elena Pierpaoli,** University of Southern California

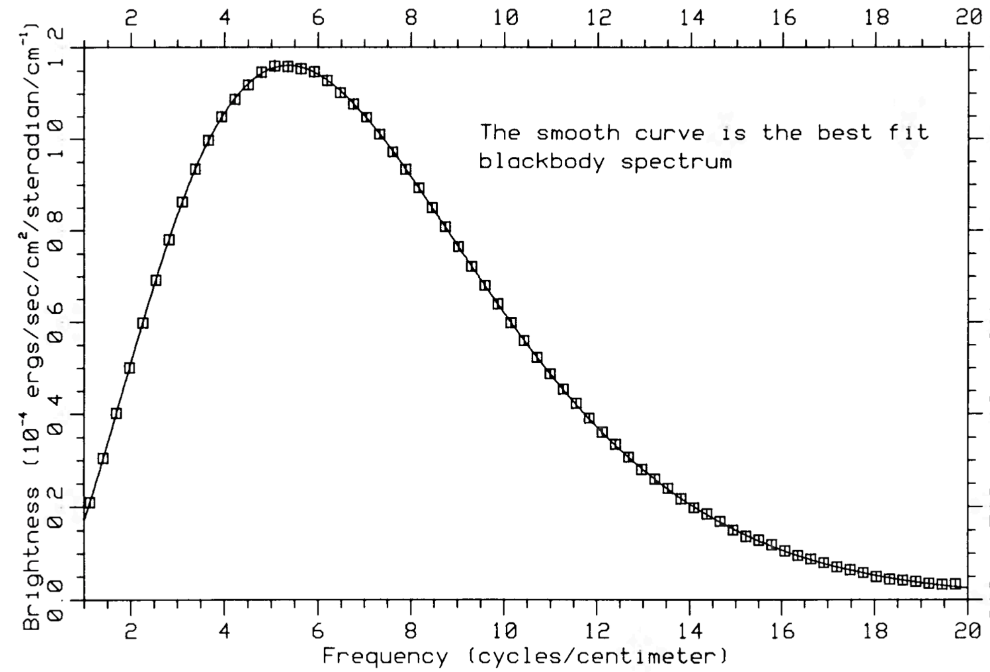
APPLICATION DEADLINE — JANUARY 31, 2023



Accidental discovery of CMB in 1964 by
Penzias and Wilson (Nobel 1978)

Young universe in **thermal equilibrium**

Radiation has a **black body** spectrum
and is isotropic



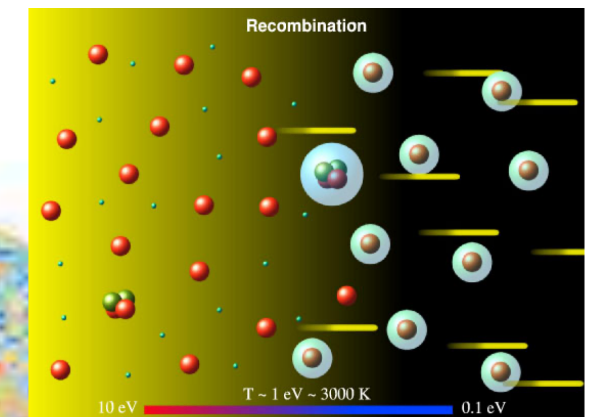
Measurement with COBE/FIRAS data
Mather et al 1990 (Nobel 2006)

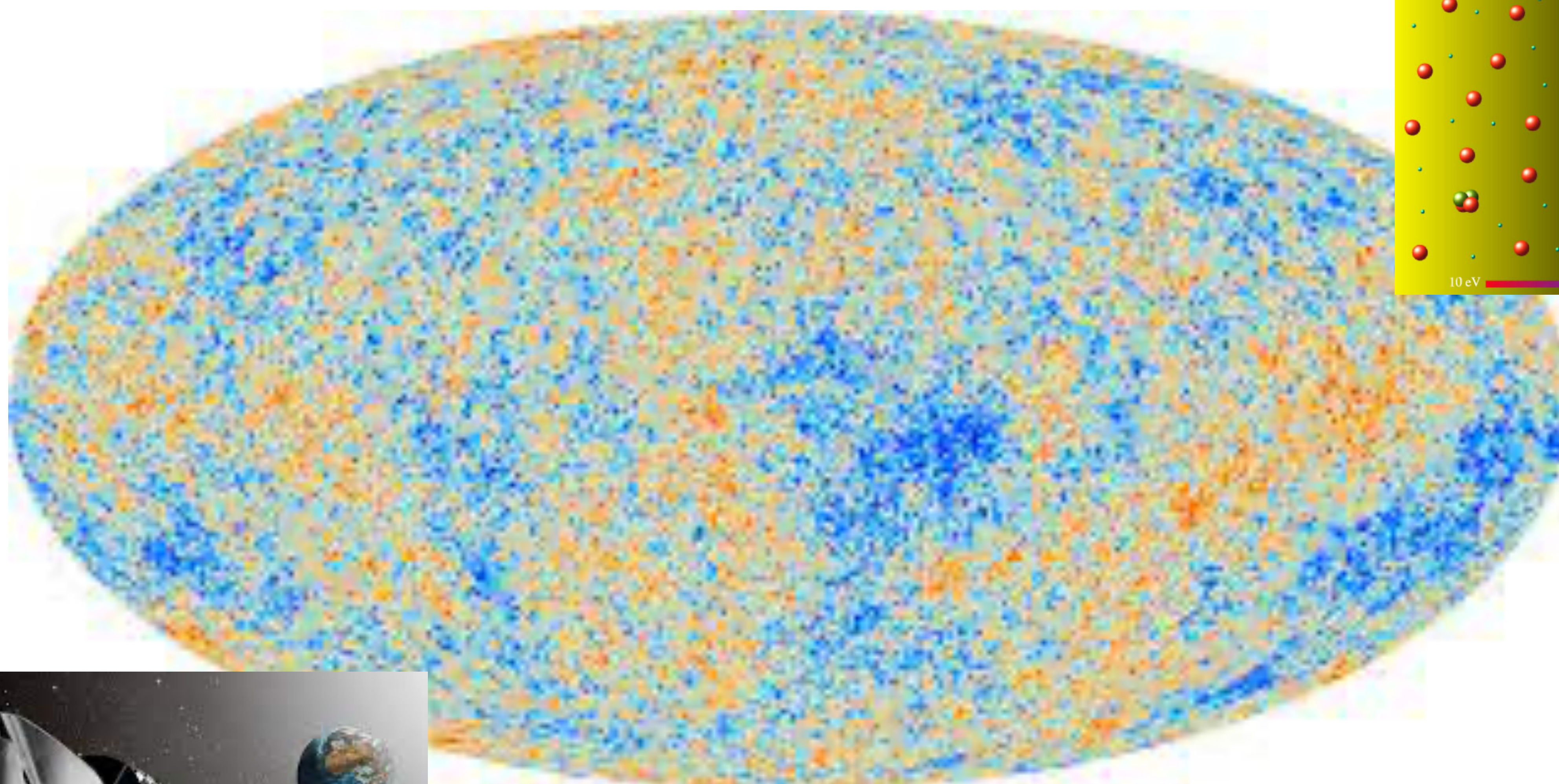
- Ultimate confirmation of the **expanding universe** (Friedmann 1922, Lemaître 1927) and the **Big Bang** model
- Clearly **detectable** (a lucky fact!)
- Opens the door to **precision cosmology**

- Isotropic radiation ($\Delta T/T \sim 10^{-5}$)
- $\bar{T} = 2.7\text{K}$
- "Emitted" at redshift $z = 1100$ when the universe was 380 000 years old

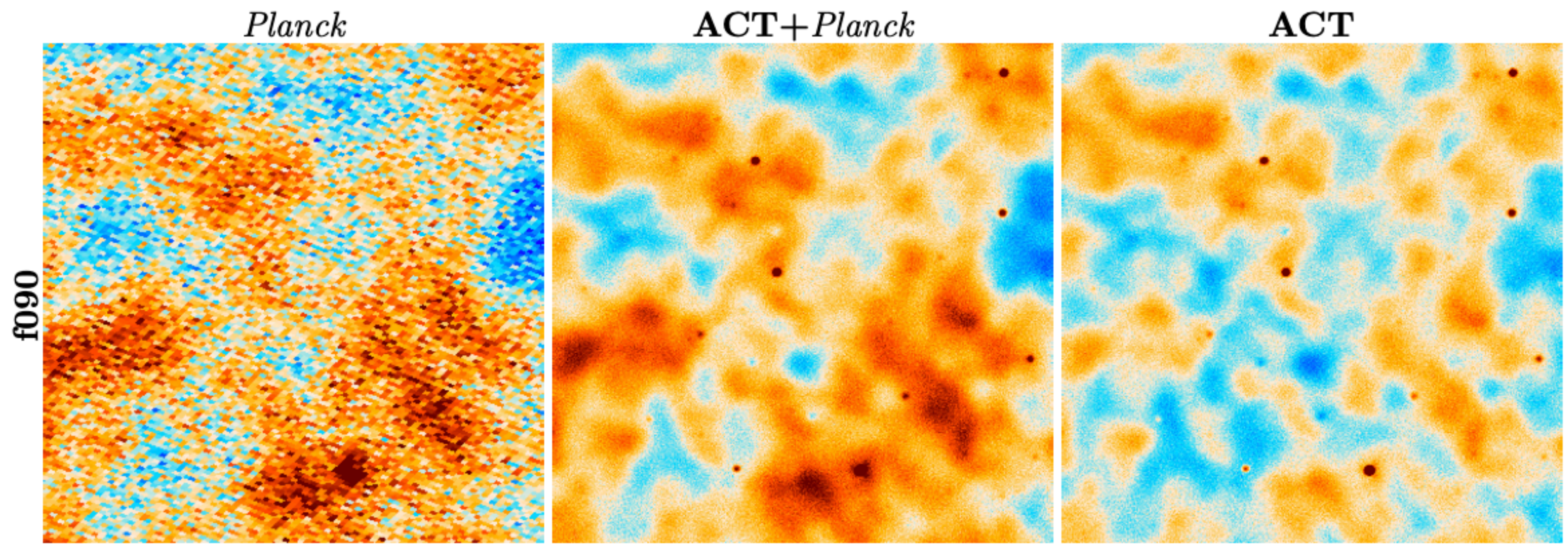
When CMB is produced universe becomes **neutral**

Hydrogen + Helium Recombination





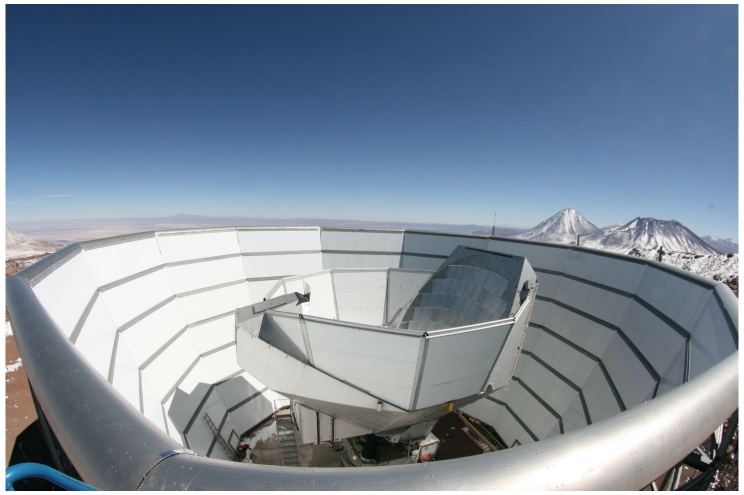
CMB seen from space by **Planck** space telescope



CMB anisotropy at 90 GHz with Planck and ACT

Naess et al 2020

High sensitivity
high resolution
large area CMB sky maps

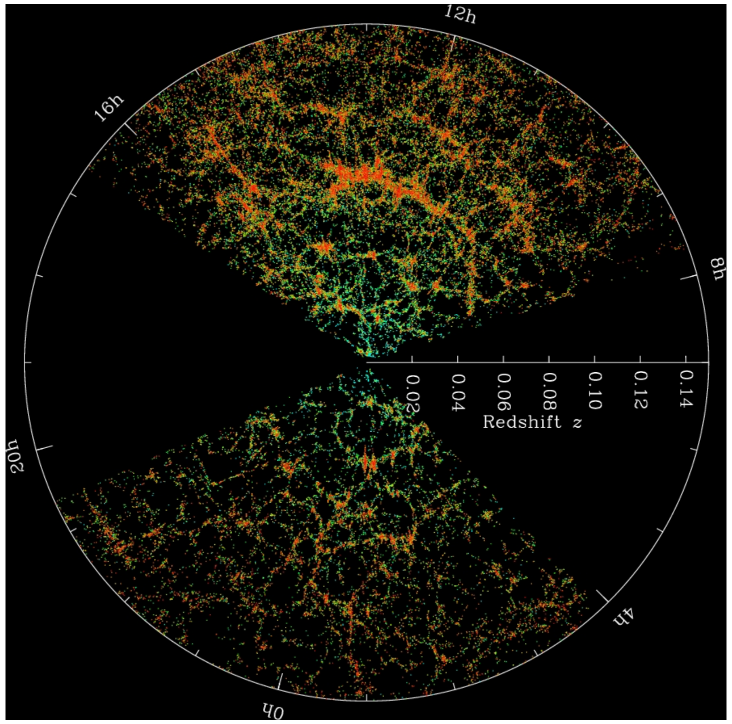


ACT (also SPT, Planck from sky)

Revealing the **large scale structure** of the universe and its **history**

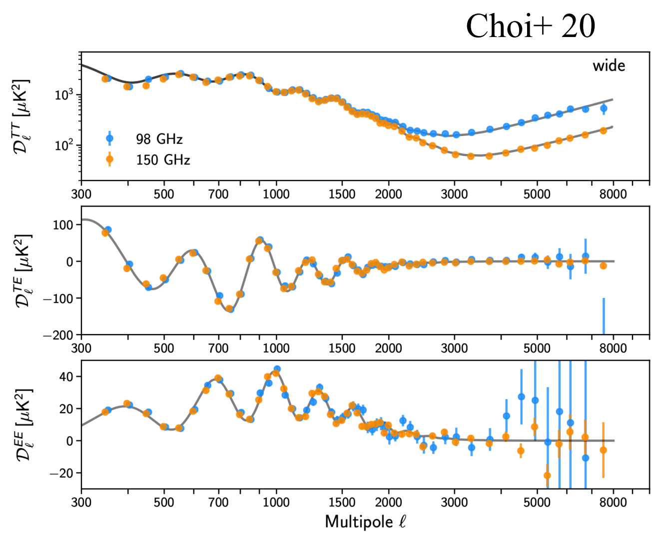
Rubin (also DES, unWISE, SDSS, DESI,…)

Galaxy surveys
with 100's of millions objects

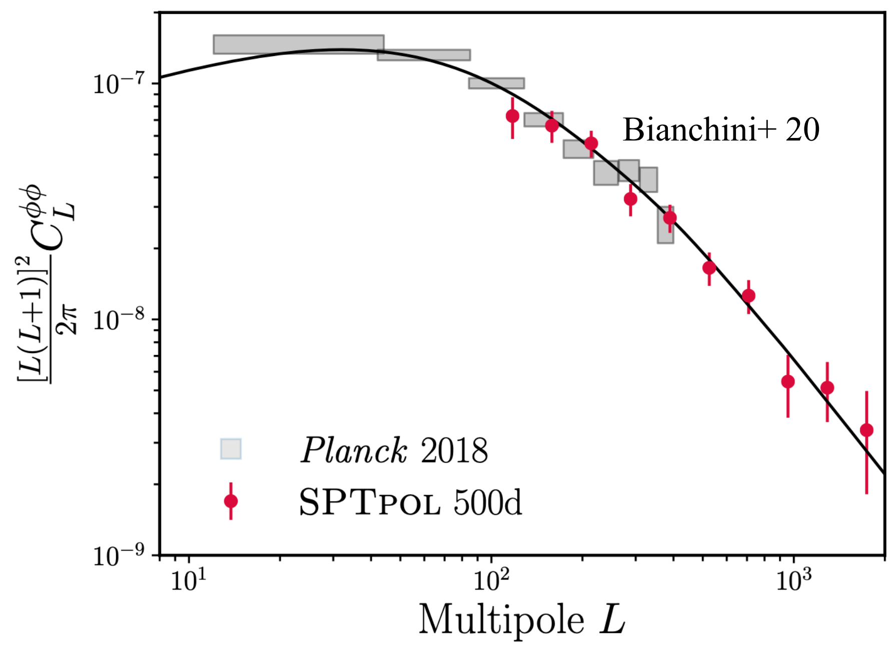


See https://www.legacysurvey.org/viewer/

- Currently relies on a few observables

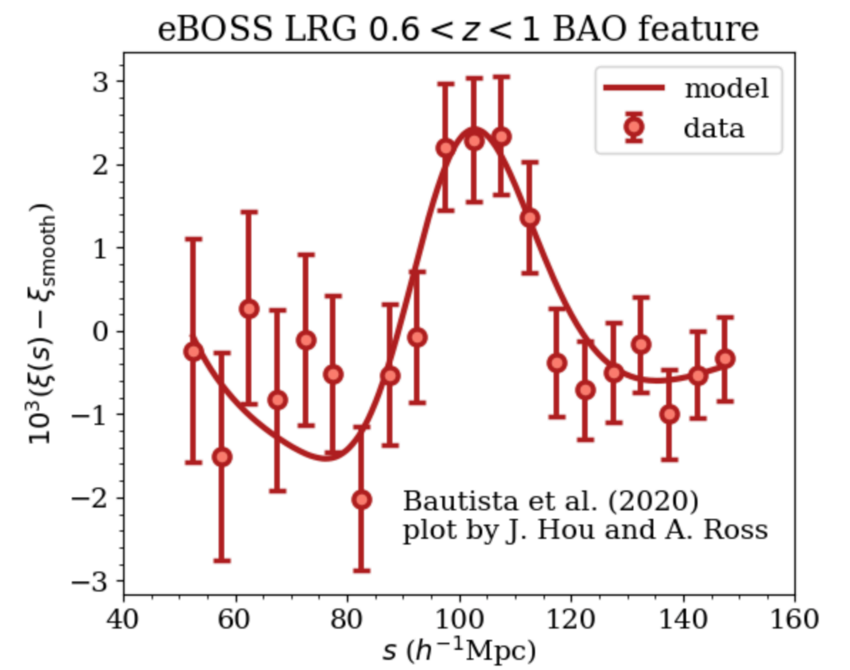


CMB Power Spectra
Temperature & Polarization

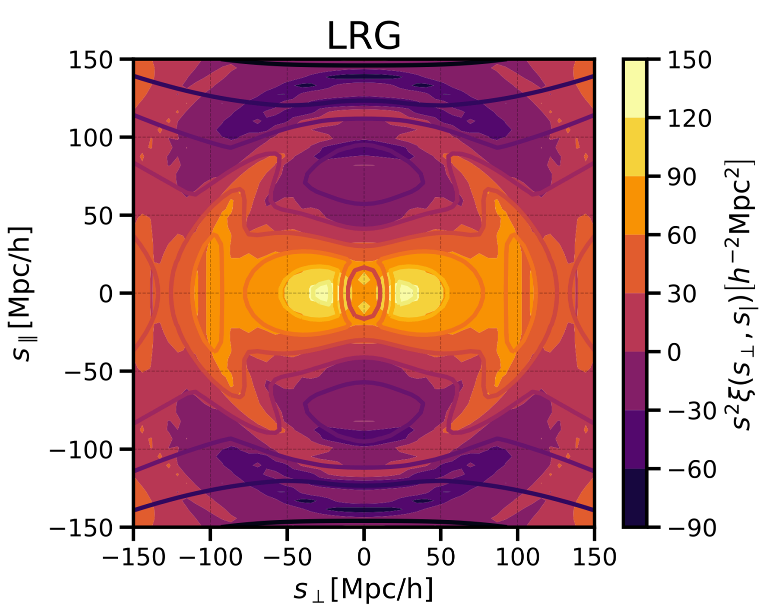


Lensing potential power spectrum

New ACT measurement coming!

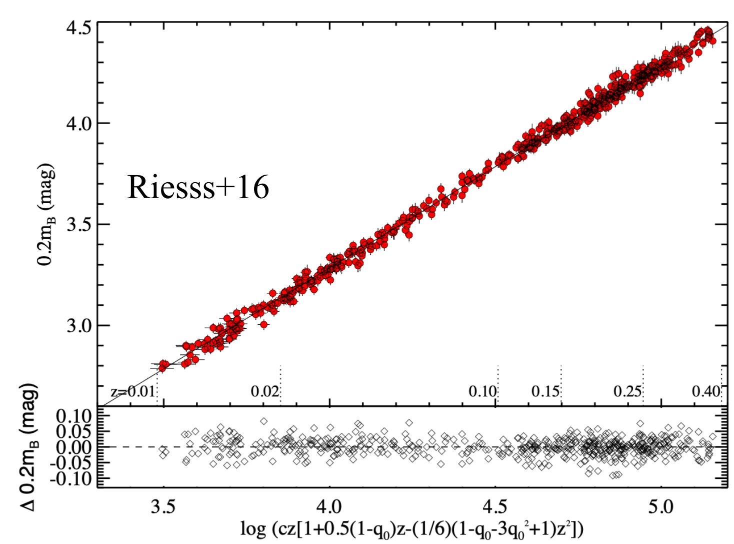


BAO

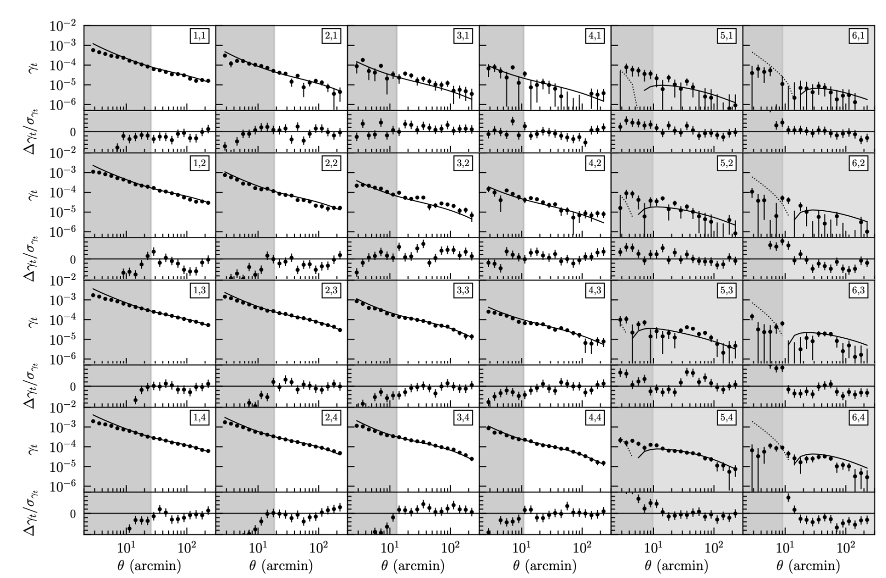


Bautista et al. (2020)
(plot by Jiamin Hou, MPE)

RSD



SNIa



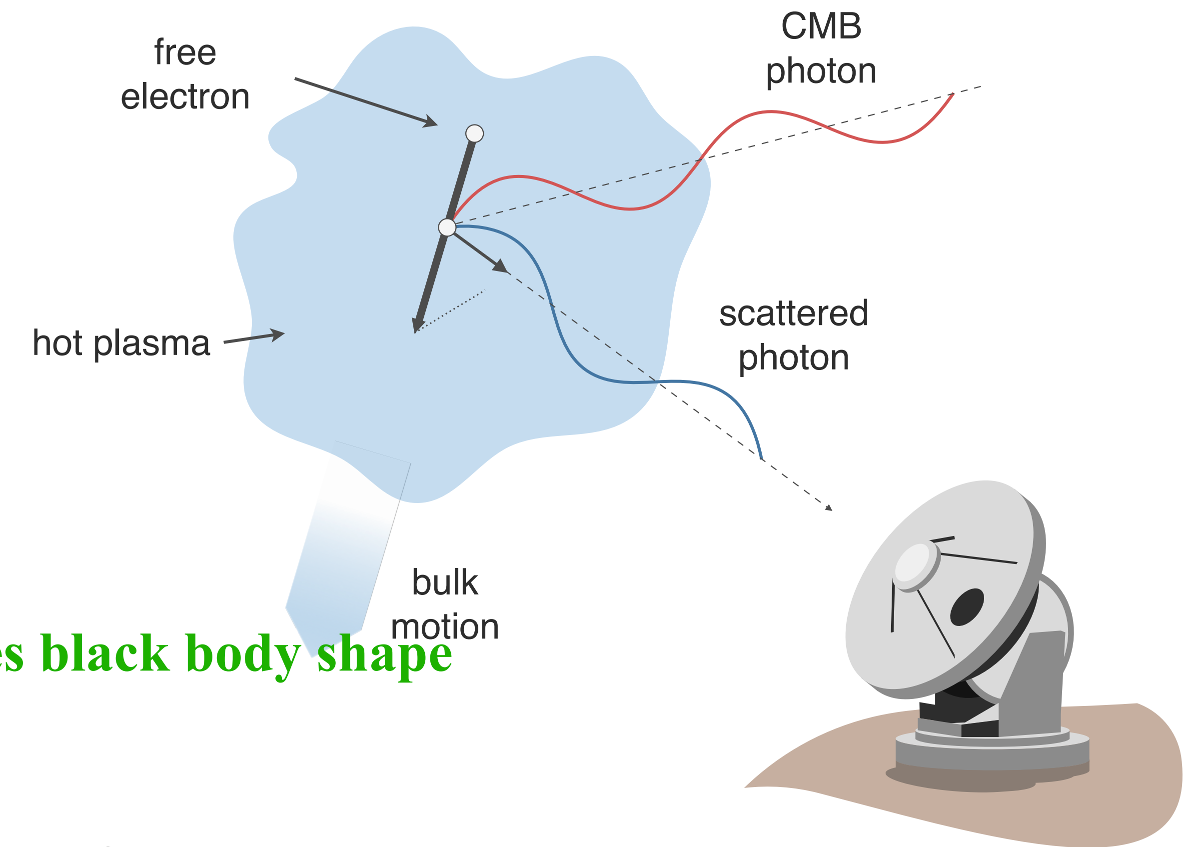
Galaxy lensing and clustering

- Only few years back, most of these probes weren't part of precision cosmology
- **SZ** (about to be) part of it…. **WHAT** is SZ? **WHY** is it important? And **HOW**?

WHAT?

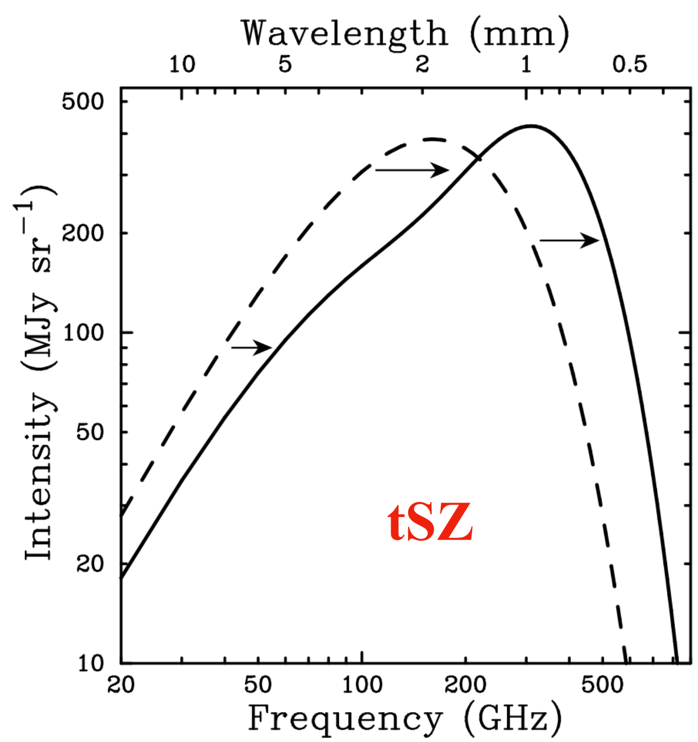
- SZ = **Compton scattering** between **CMB** and **electrons**

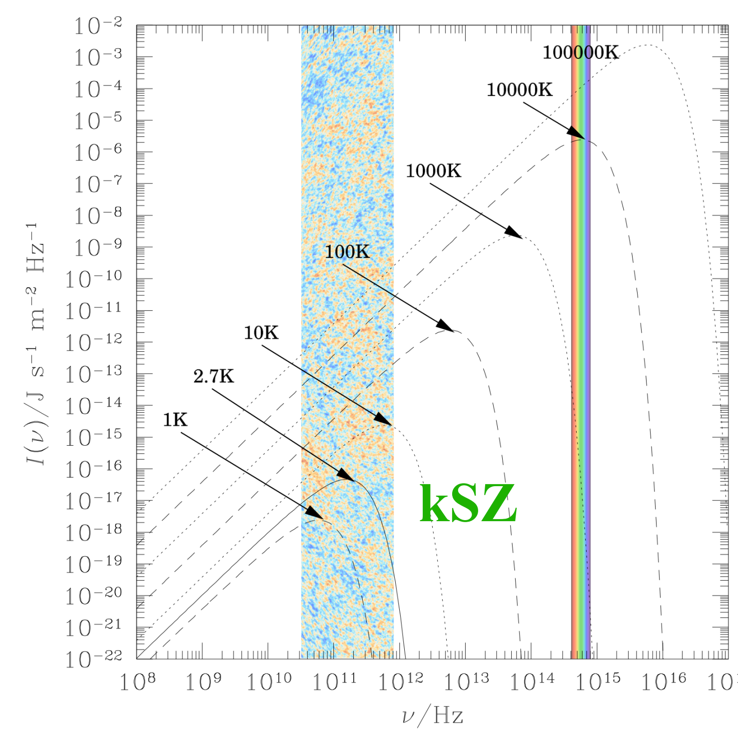
- Electrons are in the ionized plasma around galaxies
  ICM: **intra cluster medium**
  CGM: circum galactic medium



- **THERMAL "tSZ"** is **frequency dependent**

- **KINETIC "kSZ"** is Doppler boost of CMB spectrum, **preserves black body shape**





- **tSZ** effect direct probe of **gas pressure**

- **kSZ** effect direct probe of **gas momentum**
  (i.e., **velocity** and **density**)

- … some maths to understand this

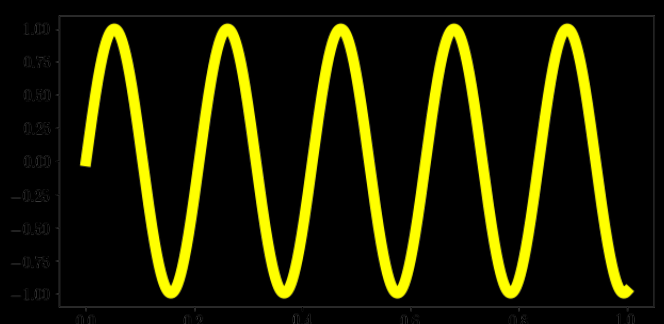
- Both tSZ and kSZ are **redshift independent**, using CMB as a backlight

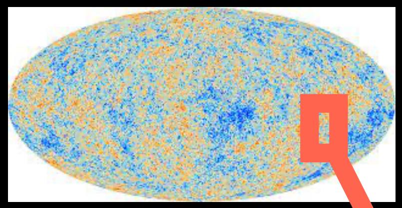
Sunyaev & Zeldovich
~1970

Inverse Compton Scattering

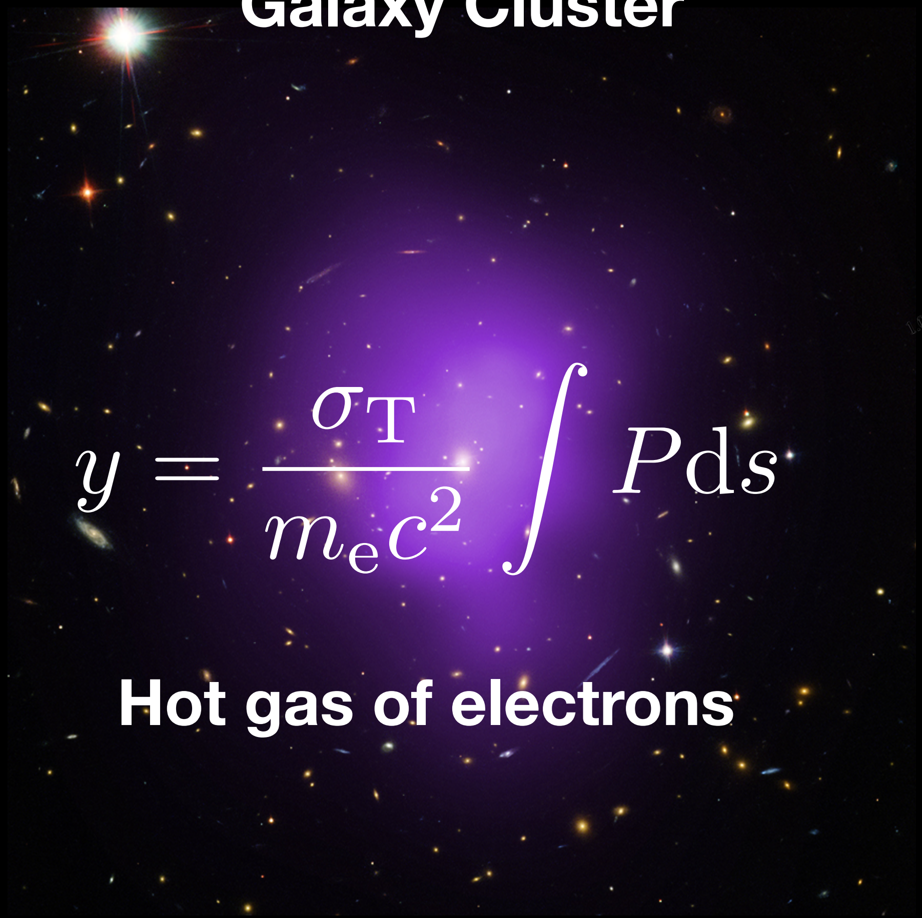
Electron gives energy to photon

CMB
photon



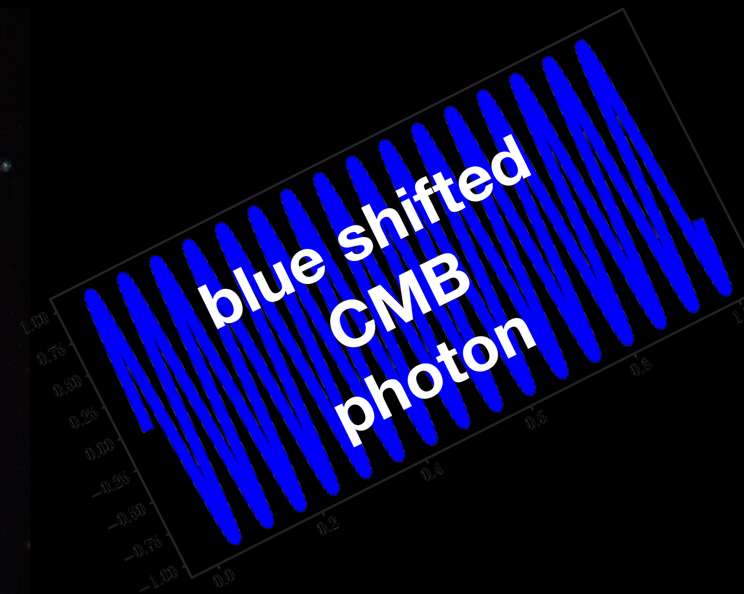


Galaxy Cluster

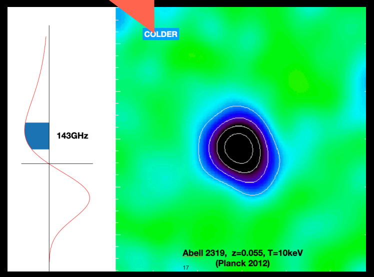


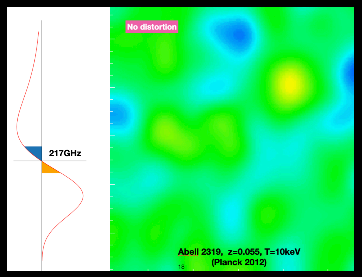
$$y = \frac{\sigma_{\rm T}}{m_{\rm e}c^2}\int P {\rm d}s$$

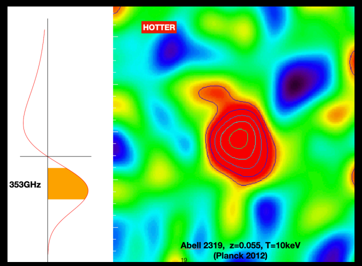
Hot gas of electrons



THERMAL SUNYAEV ZELDOVICH EFFECT

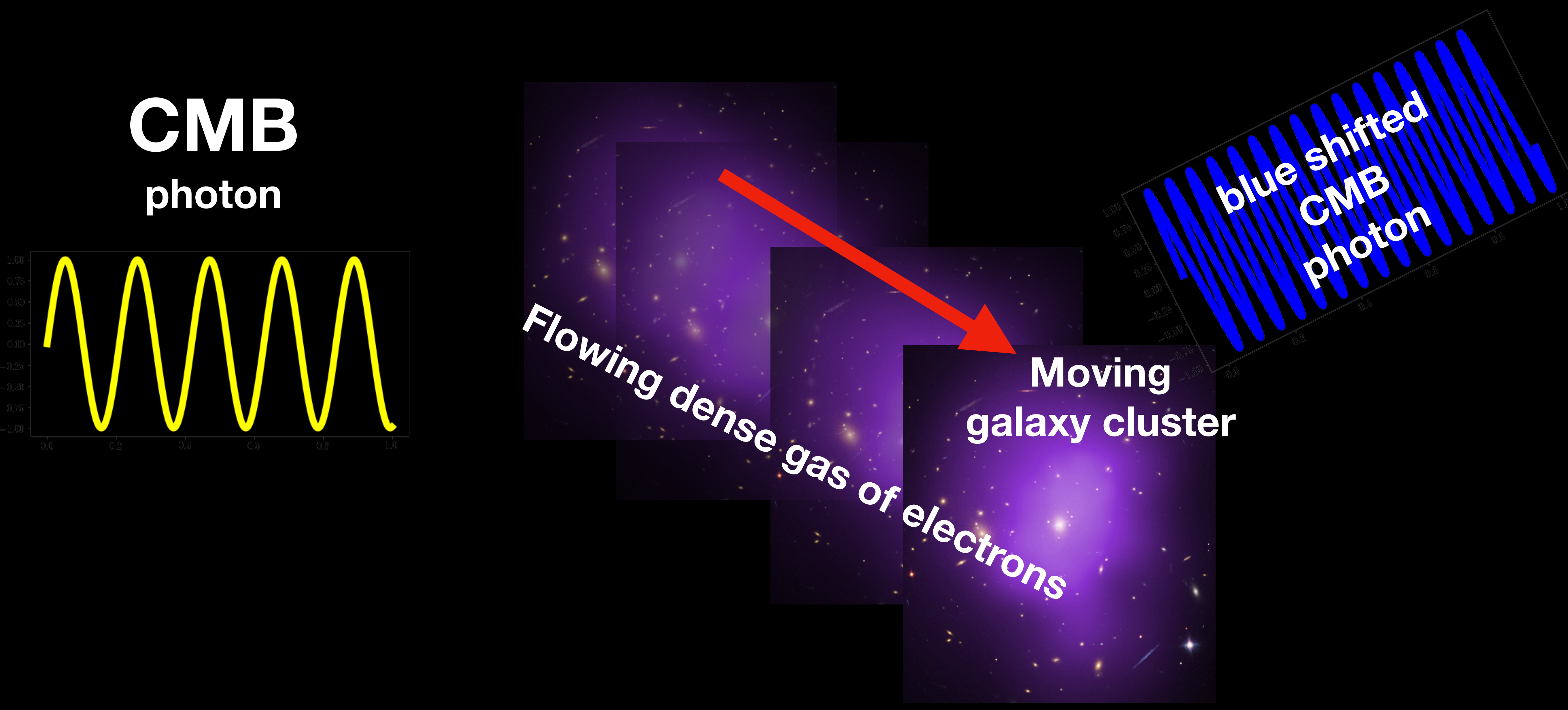






Doppler shift of photons due to electrons bulk motion

$$\Theta_{\mathrm{kSZ}} \sim \int \sigma_{\mathrm{T}} n_e \mathbf{v} \cdot \mathbf{n} \, \mathrm{d}l$$



KINETIC SUNYAEV ZELDOVICH EFFECT

- Boltzmann equation in CMB frame with Compton scattering

Photon occupation number

$$\frac{\partial n(\omega)}{\partial t} = -2\int \frac{d^3p}{(2\pi)^3} d^3p' d^3k' \, W \, \{n(\omega)[1+n(\omega')]f(E) - n(\omega')[1+n(\omega)]f(E')\} \, ,$$

Relativistic Maxwellian electron distribution

$$f_C(E_C) = \left[e^{\{(E_C-m)-(\mu_C-m)\}/k_BT_e} + 1\right]^{-1} \approx e^{-\{(E_C-m)-(\mu_C-m)\}/k_BT_e} ,$$

$$E_C = \gamma\left(E - \vec{\beta}\cdot\vec{p}\right)$$

- Expand in powers of $\Delta x \equiv \frac{\omega' - \omega}{k_B T_e}$
- Expand in powers of β

kSZ — **Velocity/Density**

tSZ — **Temperature/Pressure**

Thermal-kinetic SZ effect

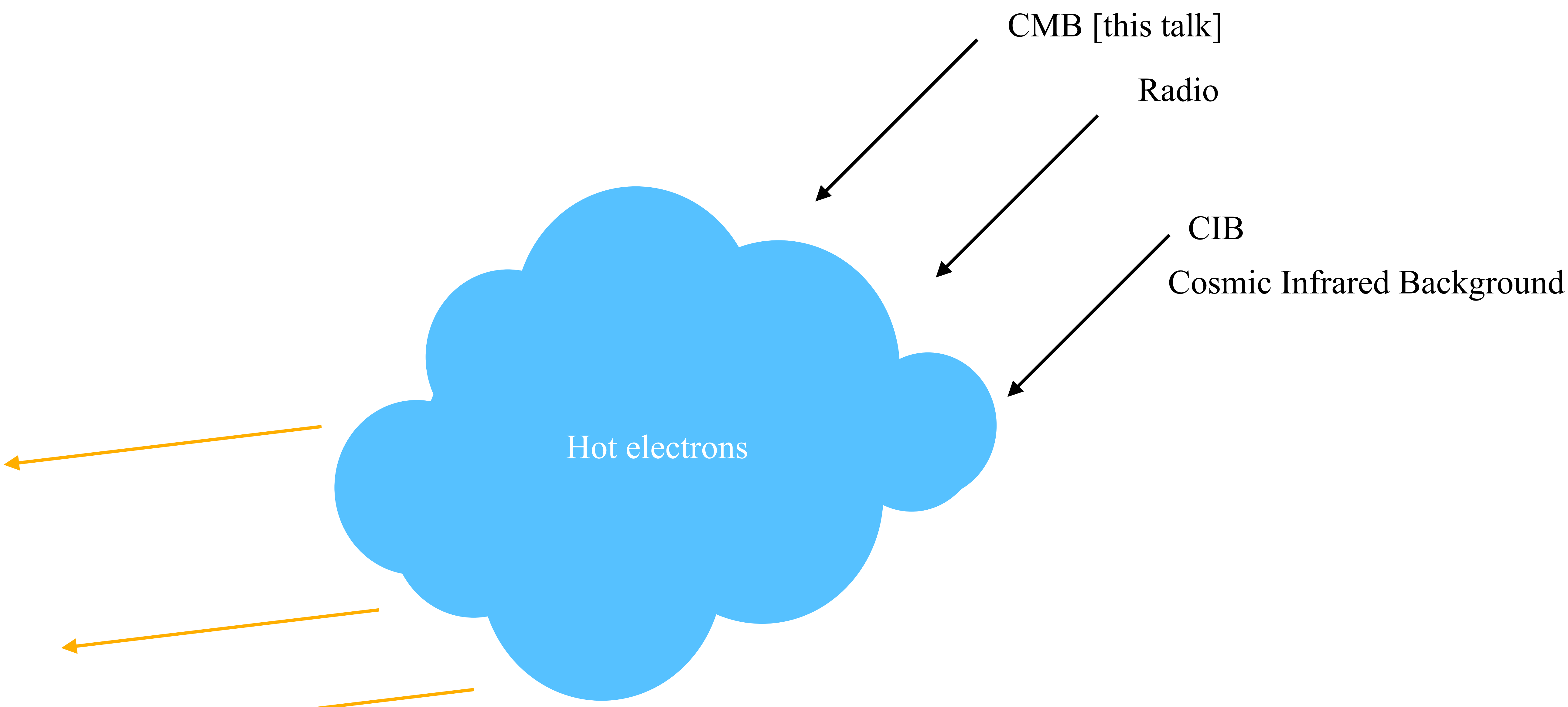
$$= \boldsymbol{v}\cdot\hat{\boldsymbol{n}}\,\mathcal{G} + \theta_e\,\mathcal{Y} + \boldsymbol{v}\cdot\hat{\boldsymbol{n}}\,\theta_e\left(\frac{2}{5}\mathcal{G} - \mathcal{Y}^{(2)} + \frac{7}{5}\mathcal{Y}^{(3)}\right)$$
$$+\ \theta_e^2\left(-\frac{3}{10}\mathcal{Y}^{(2)} - \frac{21}{10}\mathcal{Y}^{(3)} + \frac{7}{10}\mathcal{Y}^{(4)}\right) + \boldsymbol{v}\cdot\hat{\boldsymbol{n}}\,\theta_e^2\left(\frac{1}{5}\mathcal{G} - \frac{7}{10}\mathcal{Y}^{(3)} - \frac{33}{10}\mathcal{Y}^{(4)} + \frac{11}{10}\mathcal{Y}^{(5)}\right) + \mathcal{O}(v^2, \theta_e^3)$$

See Coulton et al 2020

Relativistic (thermal) SZ effect

Relativistic thermal-kinetic SZ effect

Hot electrons Inverse-Compton scatter photons irrespective of their nature

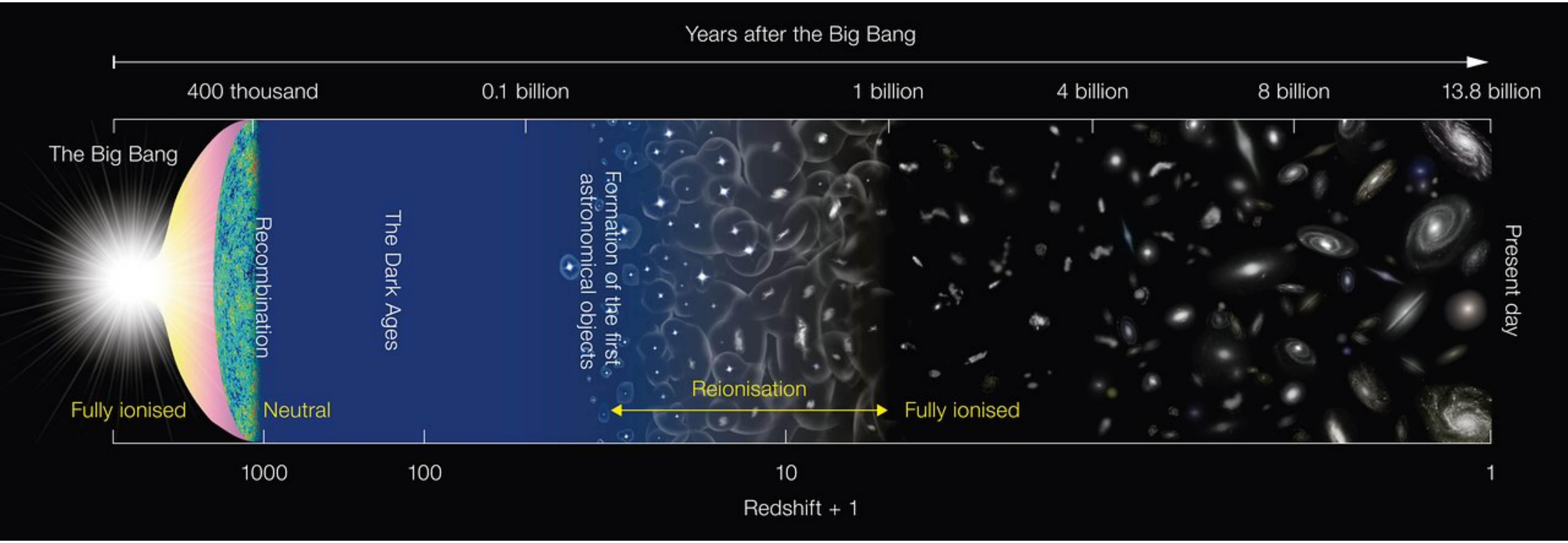


A certainly well-known fact…. which had not been studied in details until a year ago

Radio SZ: Holder & Chluba 2021

CIB SZ: Sabyr, Hill, Bolliet 2022

Kinetic SZ

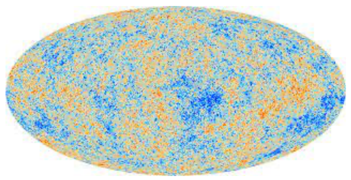


Thermal SZ

WHY?

$$\Omega_\Lambda \approx 0.7 \qquad \Omega_\mathrm{m} \approx 0.3$$

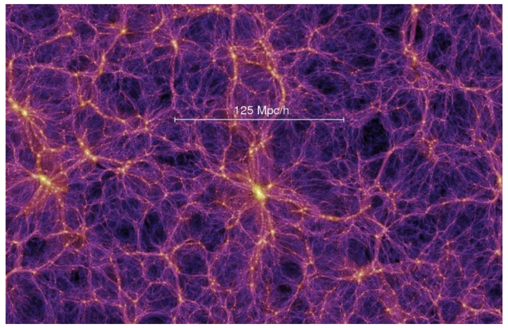
- Most of the universe is dark: dark energy (70%) dark matter (25% or 85% around galaxies)
- the **S8 tension** (matter clustering $P(k)$ at **2-3σ**) and Hubble tension (Age of the universe 4σ)



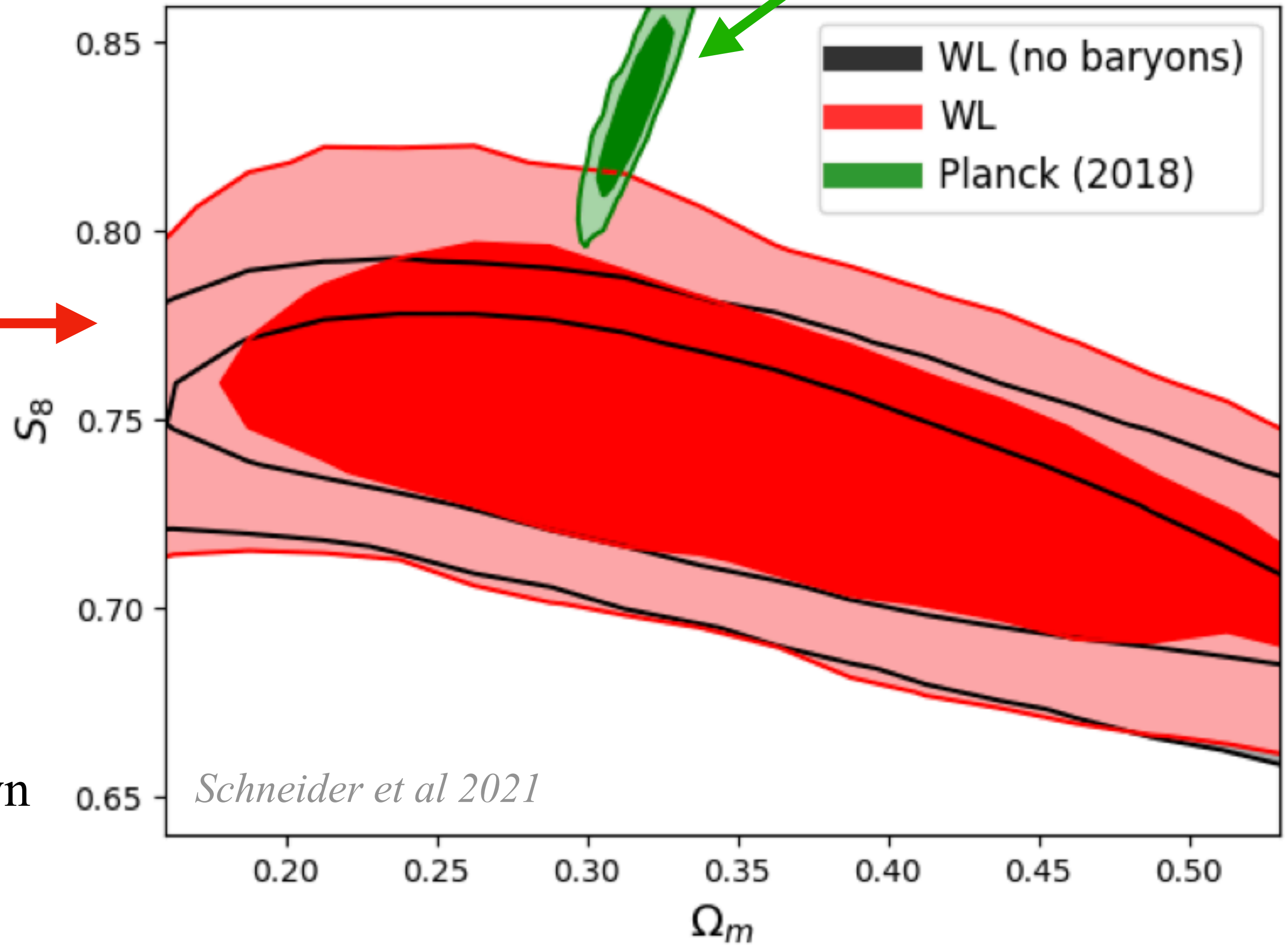
CMB
$z = 1100$

$$S_8 = \sigma_8 \Omega_\mathrm{m}^{0.5}$$

IllustrisTNG



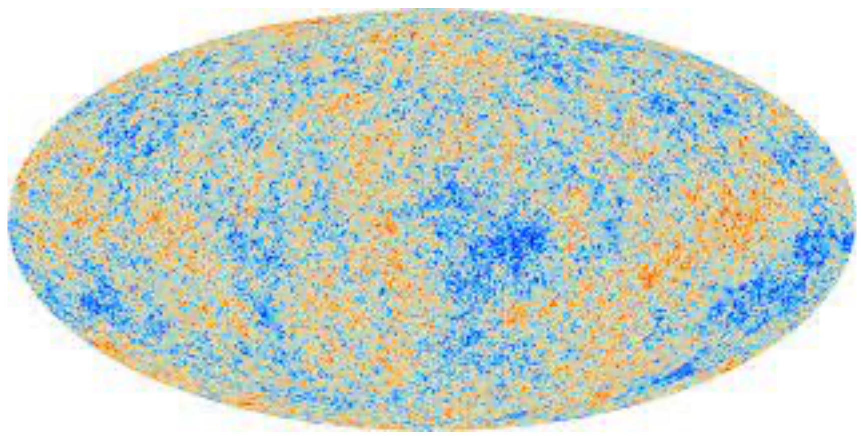
Low redshift probes
Weak Lensing
Clustering
and SZ
$z \approx 0 - 3$

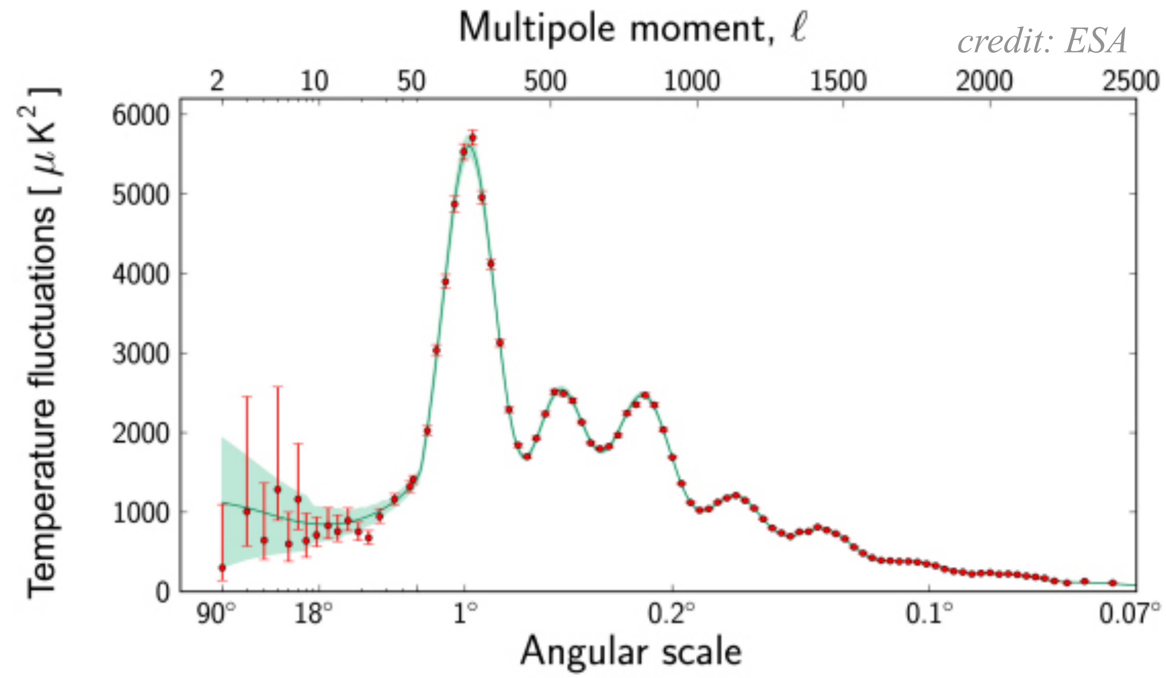


- Inflation/Big Bang
- **Galaxy formation and evolution** largely unknown
- **Baryonic effects** in precision cosmology

SZ can provide unique **insight** into these key **questions**

Analog to CMB power spectra

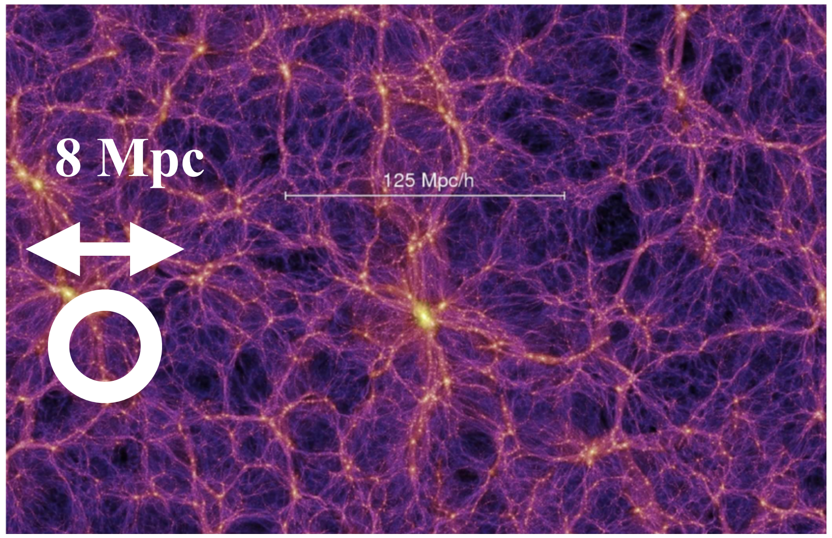


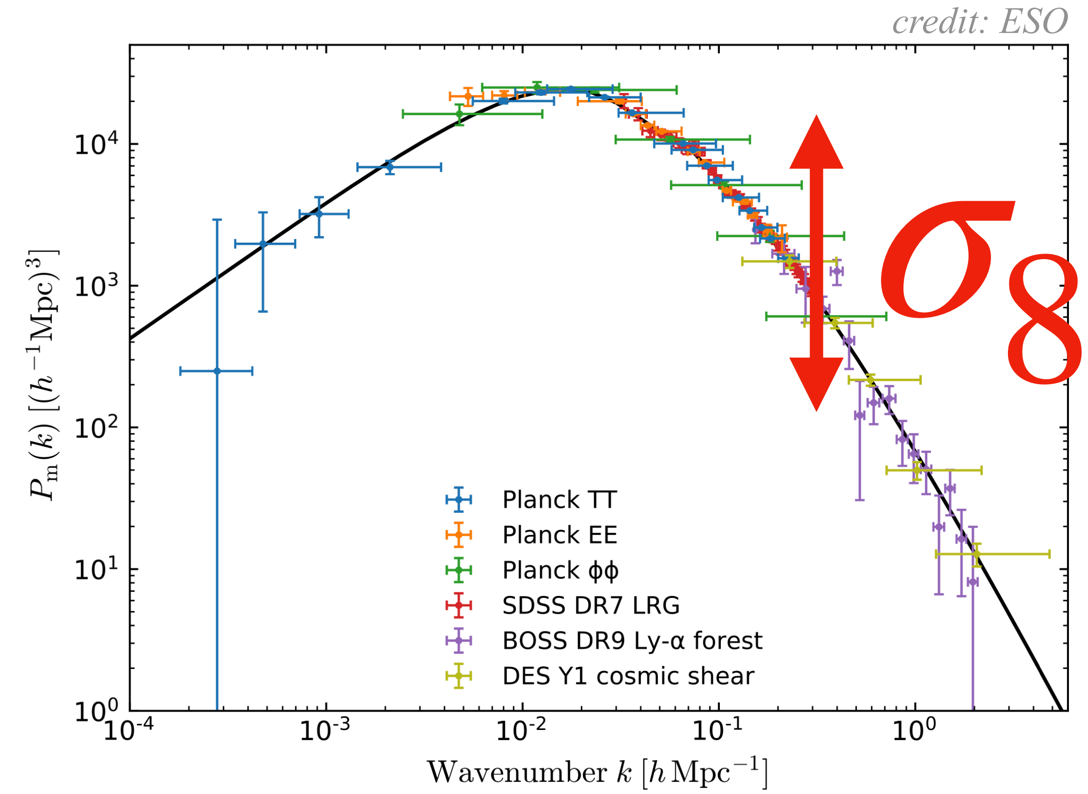


Matter power spectrum

$$\xi(r) = \langle \delta(\mathbf{x})\delta(\mathbf{x}')\rangle = \frac{1}{V}\int d^3\mathbf{x}\,\delta(\mathbf{x})\delta(\mathbf{x}-\mathbf{r}).$$

$$\xi(r) = \int \frac{d^3k}{(2\pi)^3} P(k)\, e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')}$$





$$(\sigma_8)^2 = \frac{1}{2\pi^2}\int \mathrm{d}\log k\, W^2(kR)\, k^3 P(k)$$

$$0.1\, h/\mathrm{Mpc} \lesssim k \lesssim 1\, h/\mathrm{Mpc}$$

- S8 tension means **tension between ΛCDM (model) and data (observations)**

see 2203.06142

- Is it really a tension?

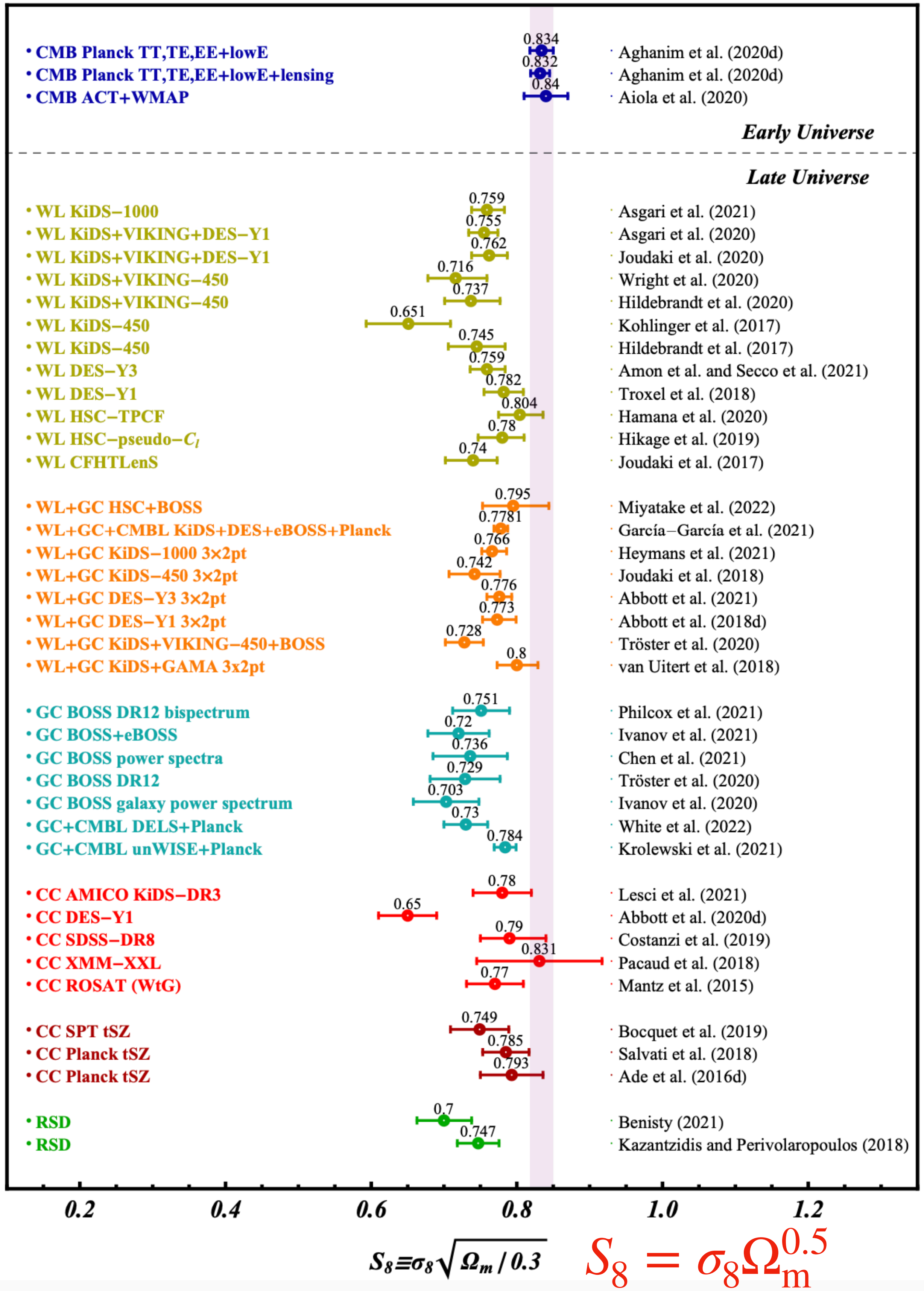
  2-3σ is not that much… but…

Tension is seen in many **different datasets** using **different probes**, that are **independent**

- Is the **model** wrong?

SZ
Tight constraints on cosmology.
Test of ΛCDM.

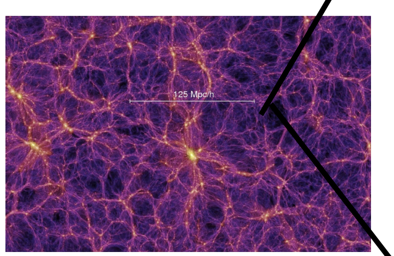
See Bolliet, Comis, Komatsu, Macias-Perez 2018
Bolliet et al 2019

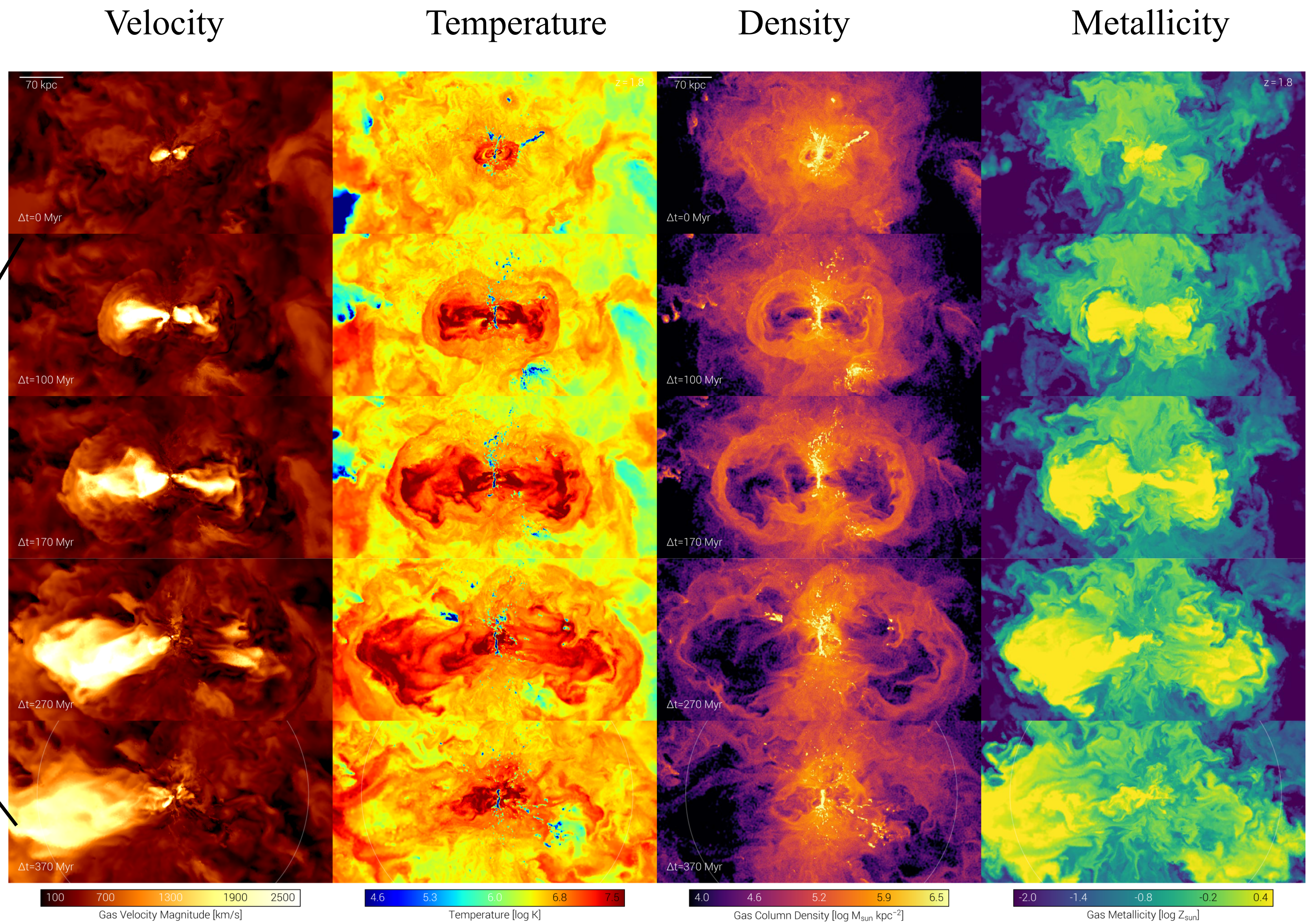


$S_8 = \sigma_8 \Omega_{\mathrm{m}}^{0.5}$

Is the **data** wrong? Systematics (instrumental and **modeling**)

Feedback from supermassive black hole in Illustris TNG

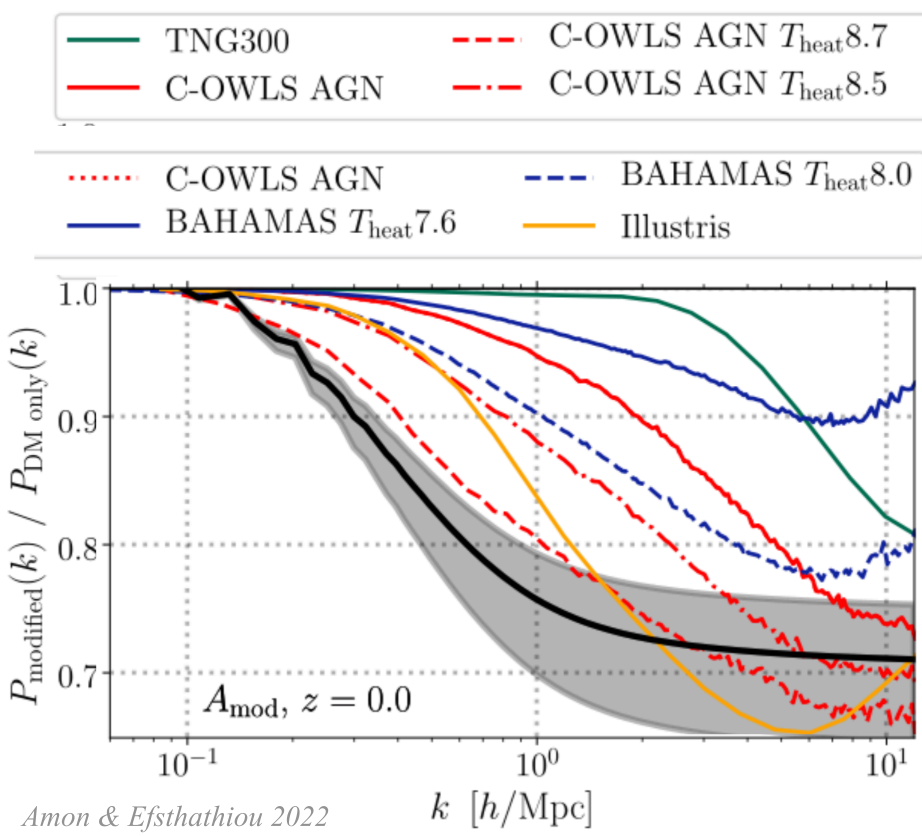




Baryonic feedback (Black holes, AGN, SN) processes convert **gravitational energy into heat**, altering the distribution of matter around galaxies, **extending to the virial radius and beyond**

Poorly understood due to current **scarcity of observational data**….

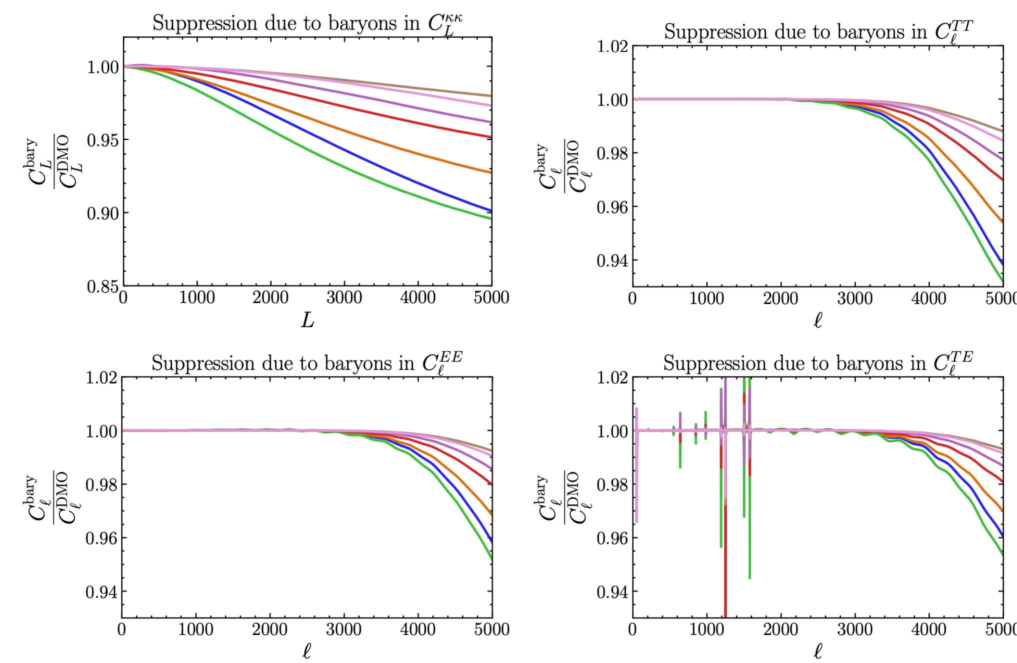
Altered matter distribution from **baryonic effects** translates into **suppression of small-scale** matter power spectrum compared to a “dark matter only” prediction.



Amon & Efsthathiou 2022

Small-scale Matter **P(k)** is the **central brick** for observables associated with **weak lensing and clustering**

Example: **Lensed CMB** power spectra



McCarthy et al 2021

- **Biased** cosmological constraints (σ_8, neutrino mass,…), e.g., systematics that **need to be quantified**.
- Effect on **higher-oder statistics** ?

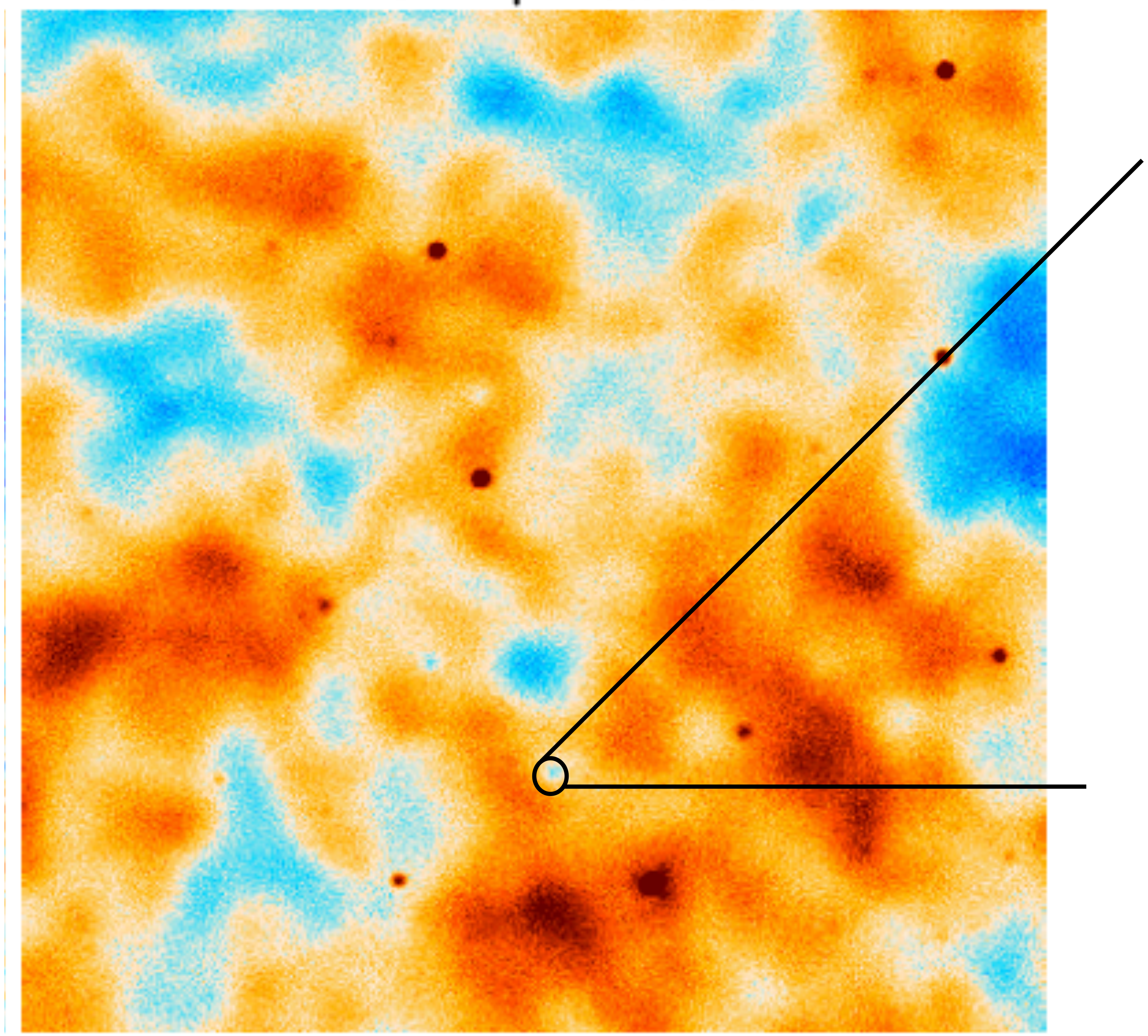
See Foreman et al, Barreira et al 2019

NASA Decadal Survey

Of all the observational diagnostics at our disposal, the **SZ effect most directly constrains** the **energy content of gas** in galactic halos produced by the combined effects of gravitational collapse and stellar and black hole **feedback**.

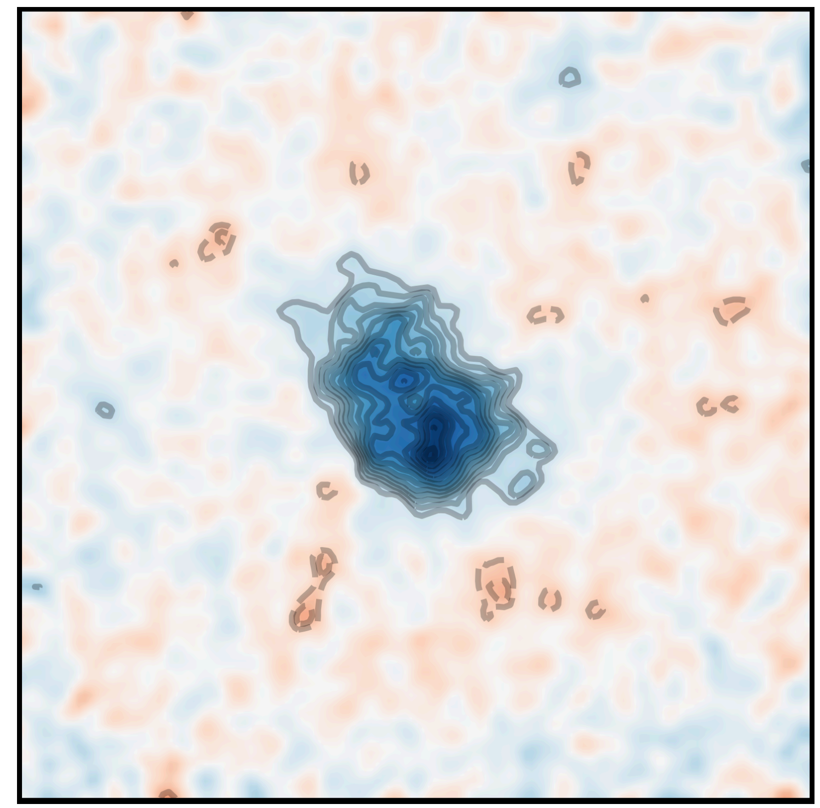
- High-resolution data

ACT+*Planck*



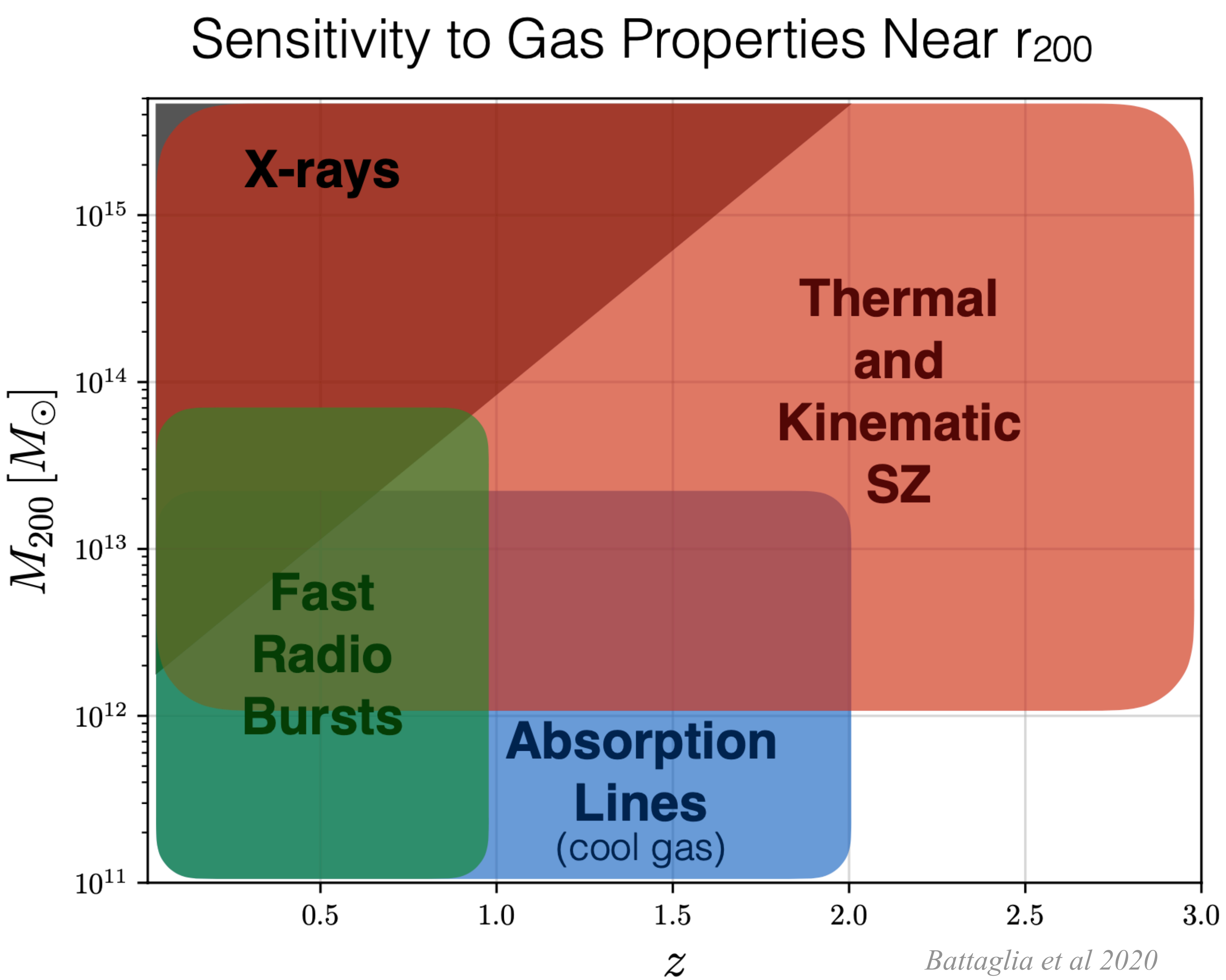
Naess et al 2020

NIKA2

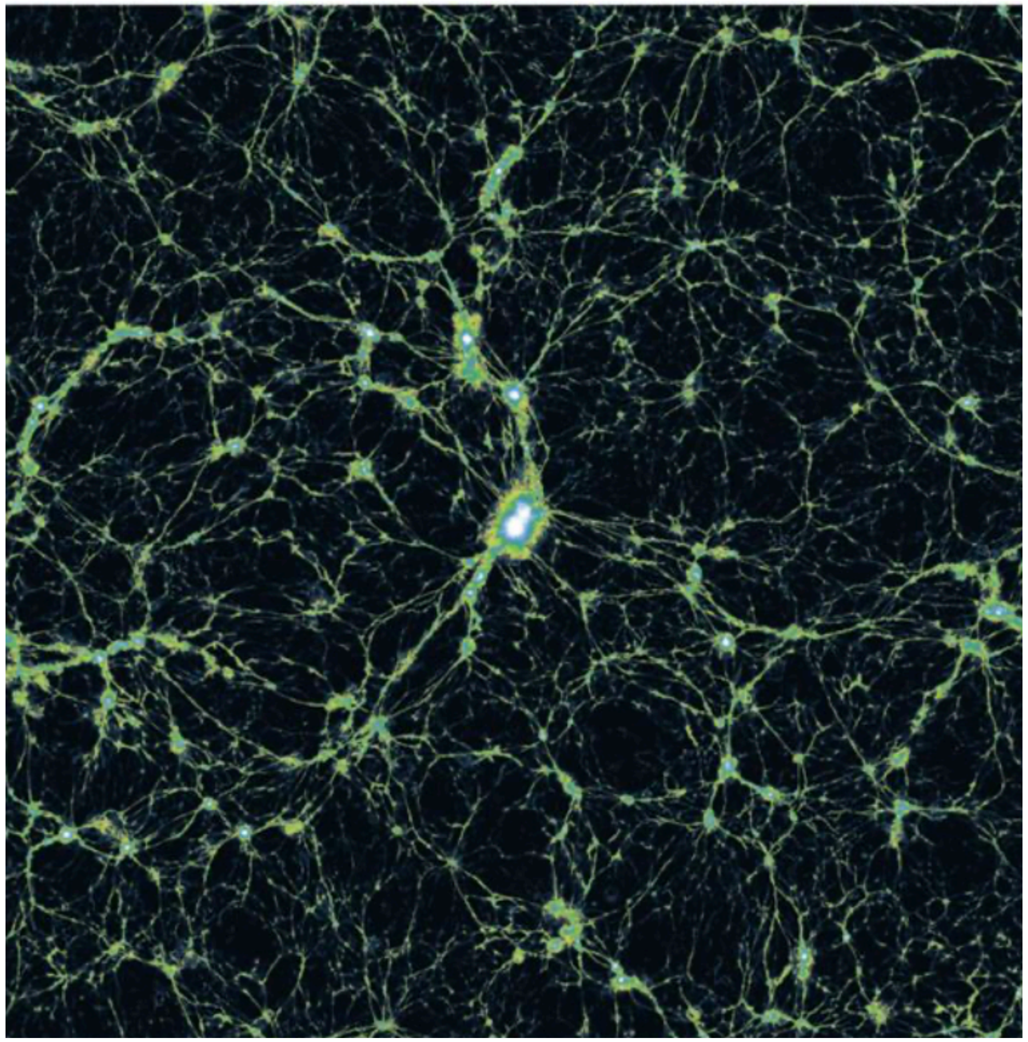


Artis et al 2022

- And… compared to other probes, **SZ** reaches **high redshift** and **low-mass halos**



Battaglia et al 2020



Illustris TNG

Able to **map the ionized gas** at the boundaries of galaxies

HOW?

1. Where do the SZ **cosmological constraints** come from?

tSZ cluster counts
tSZ power spectrum
tSZ cross-correlations

kSZ tomography

2. How do we measure **baryons** with SZ?

tSZ power spectrum
tSZ cross-correlations

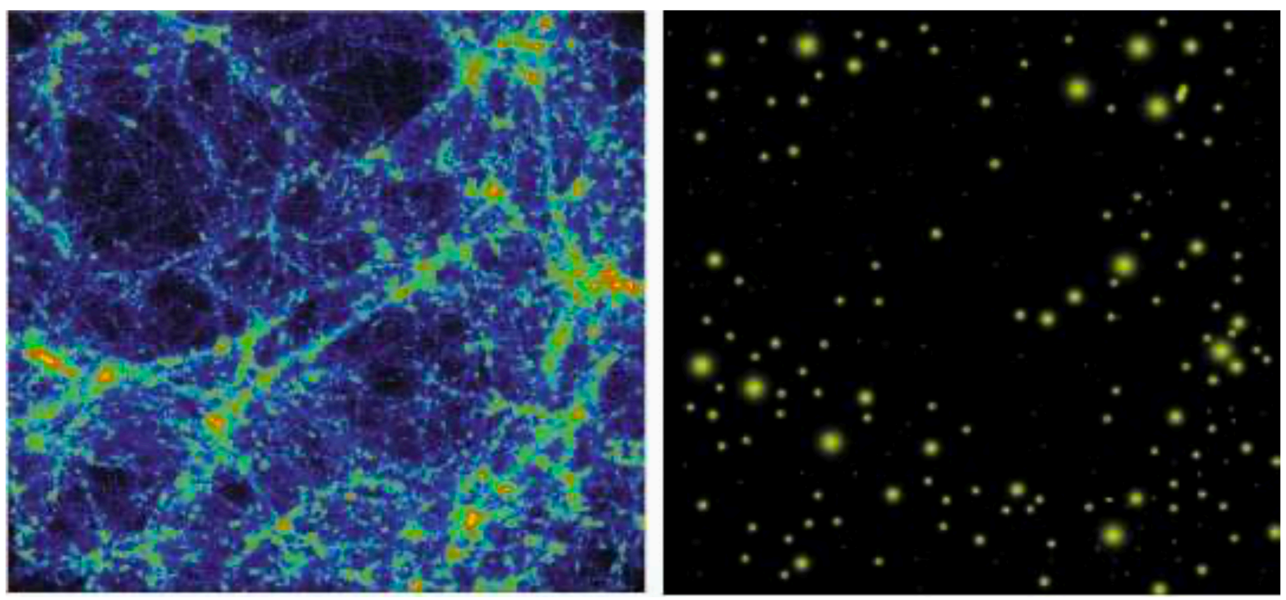
tSZ and kSZ stacking analyses
kSZ cross-correlations

- Number of clusters, **abundance** of clusters of a given mass at a given time, can be **predicted in ΛCDM** (and extensions)

- Steep function of **cosmological parameters** σ_8 and Ω_m (and others)

$$N_\mathrm{theory} \propto \sigma_8^{9.8}\Omega_\mathrm{m}^{2.9}$$

Total number of clusters



Cooray & Sheth 2002

Wikipedia

- **Given number of clusters, infer cosmological parameters** with maximum likelihood method (Poisson):

$$\ln \mathscr{L} = N_\mathrm{data} \ln N_\mathrm{theory} - N_\mathrm{theory} - \ln(N_\mathrm{data}!)$$

- Can do this in **bins of redshift** and ~~masses~~ **signal-to-noise** $\xi = Y(M,z)/\sigma_Y$

$$\bar{N}_{ij} = \frac{\mathrm{d}N}{\mathrm{d}z\mathrm{d}\xi}\Delta z_i \Delta\xi_j \qquad \frac{\mathrm{d}N}{\mathrm{d}z\mathrm{d}\xi} = \int \mathrm{d}\Omega \int \mathrm{d}M \frac{\mathrm{d}V}{\mathrm{d}z\mathrm{d}\Omega}\frac{\mathrm{d}N}{\mathrm{d}M\mathrm{d}V}\mathcal{P}(\xi,\xi_j)$$

Detection probability

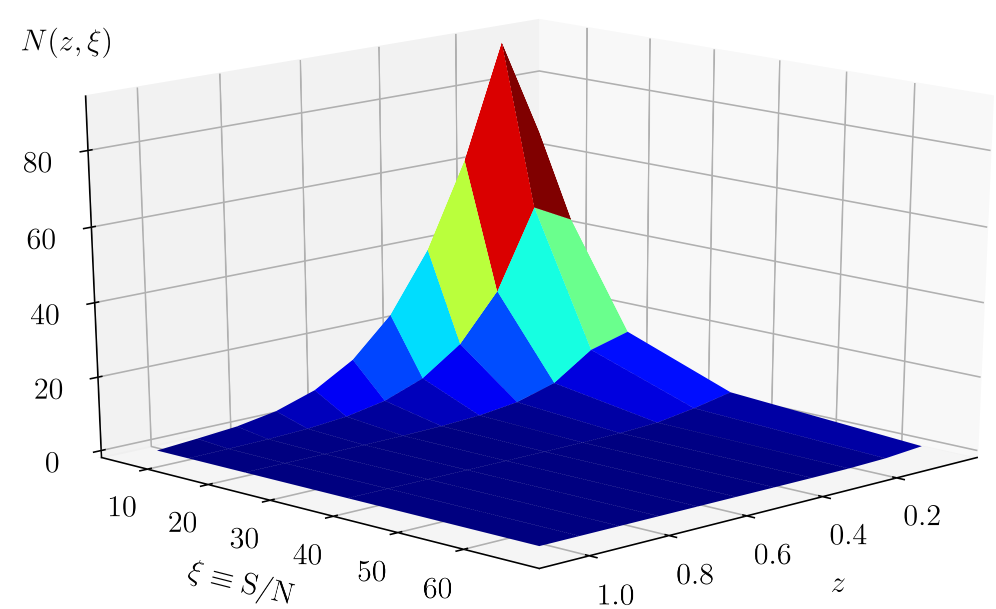
- Maximum likelihood

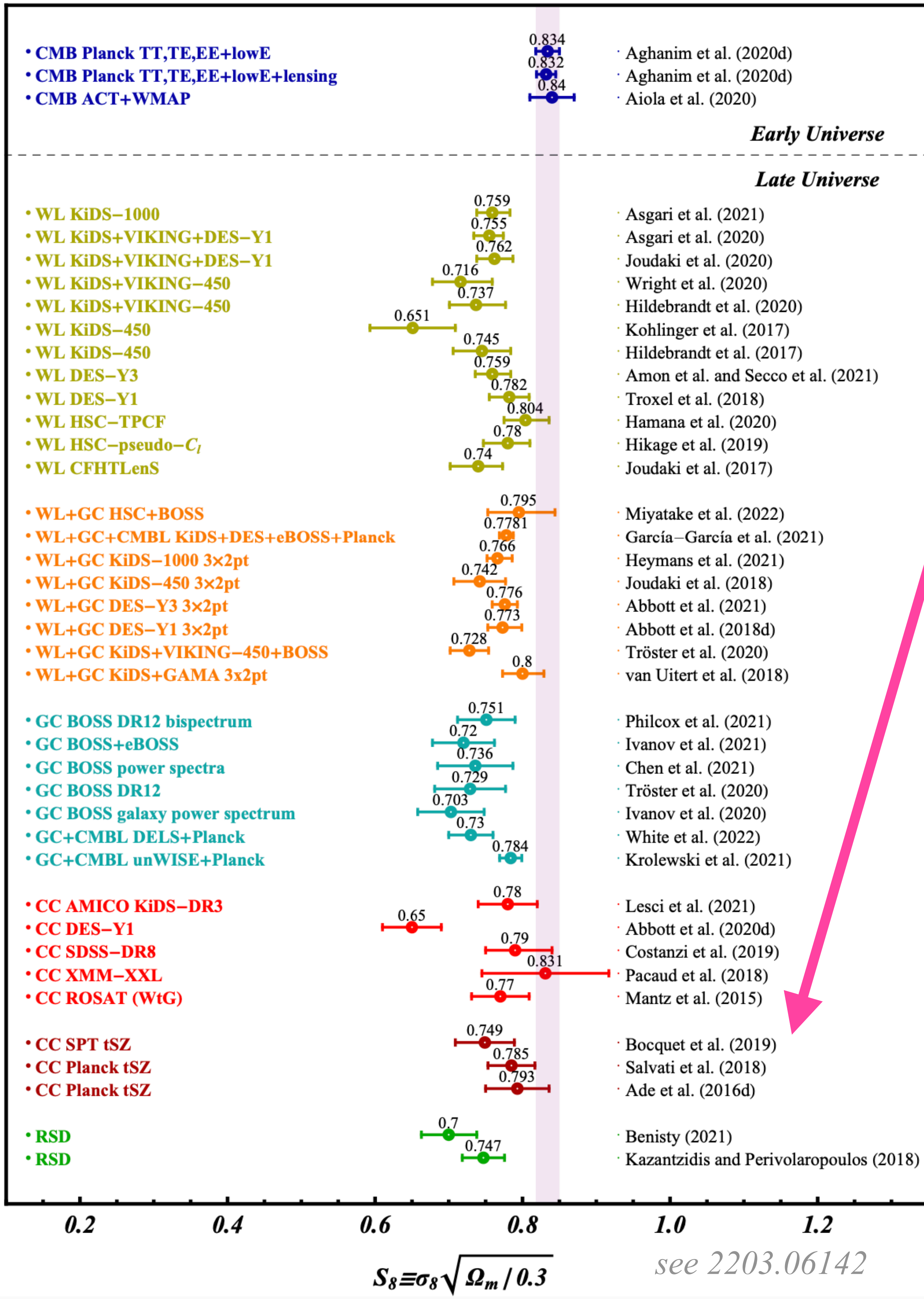
predicted

$$\ln\mathcal{L} = \sum_{ij}[N_{ij}\ln\bar{N}_{ij} - \bar{N}_{ij} - \ln(N_{ij}!)]$$

catalogue

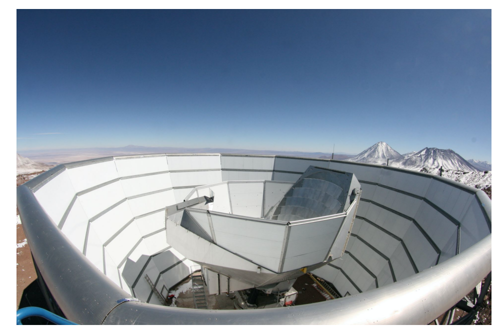
Bin index
(z_i, ξ_j)





see 2203.06142

- Simple and clean probe
- **Current constraints** from Planck and SPT are **competitive**
- co-Leading analysis with **ACT data**

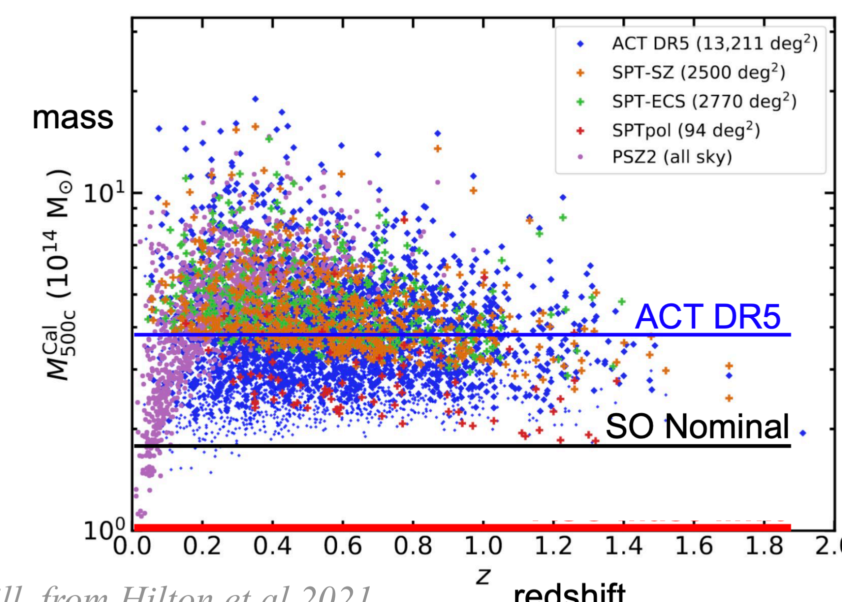


Nick Battaglia (Cornell)
Eunseong Lee (Cornell)
Matt Hilton (KwaZulu-Natal)
Andrina Nicola (Bonn)

Planck 2015: 439 with SNR>6, **ACT DR5 = 3xPlanck**
SPT 2019: 343 with SNR>5, **ACT DR5 = 7xSPT**

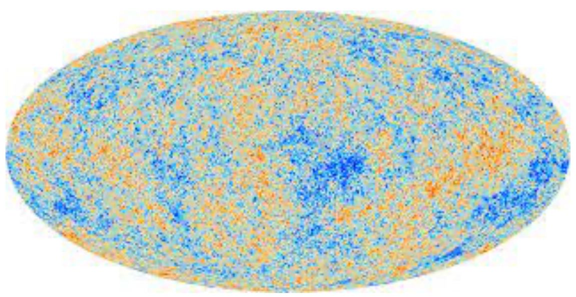
- New **SZ S8 constraints coming-up**

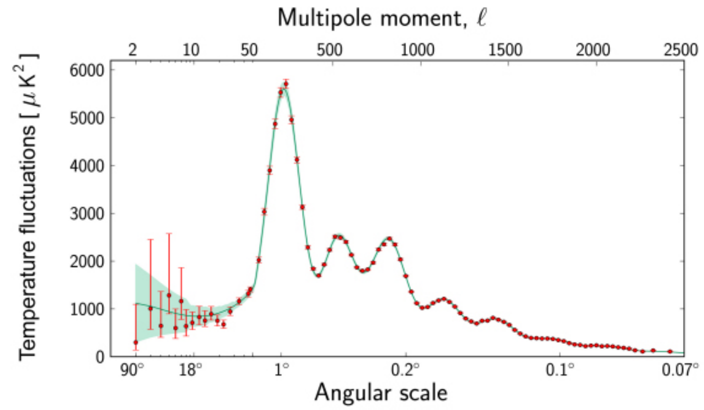
- SIMONS OBSERVATORY



Credit: Hill, from Hilton et al 2021

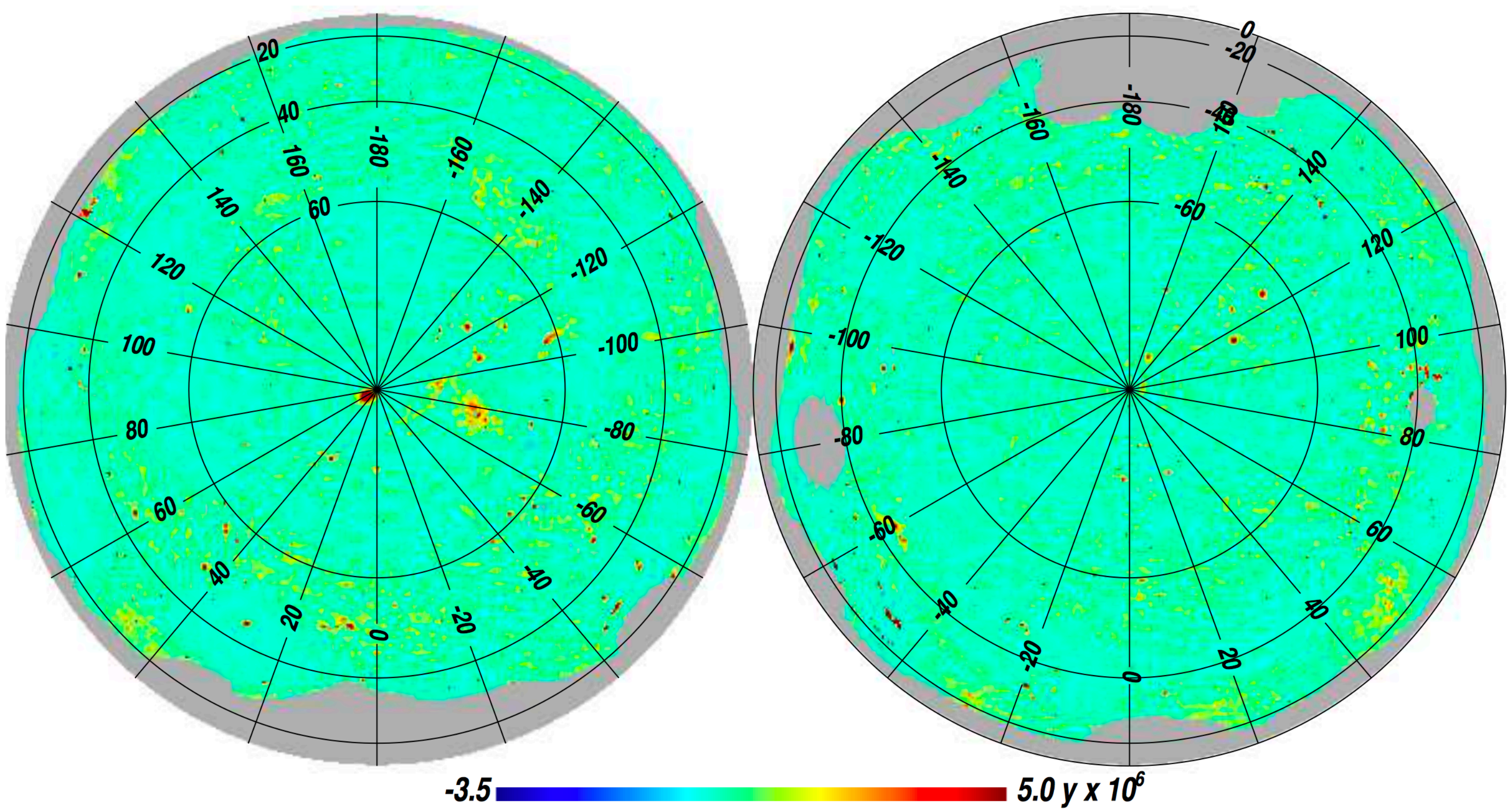
CMB power spectra





- Analog to CMB temperature anisotropy power spectrum from CMB map

Planck "y-map"

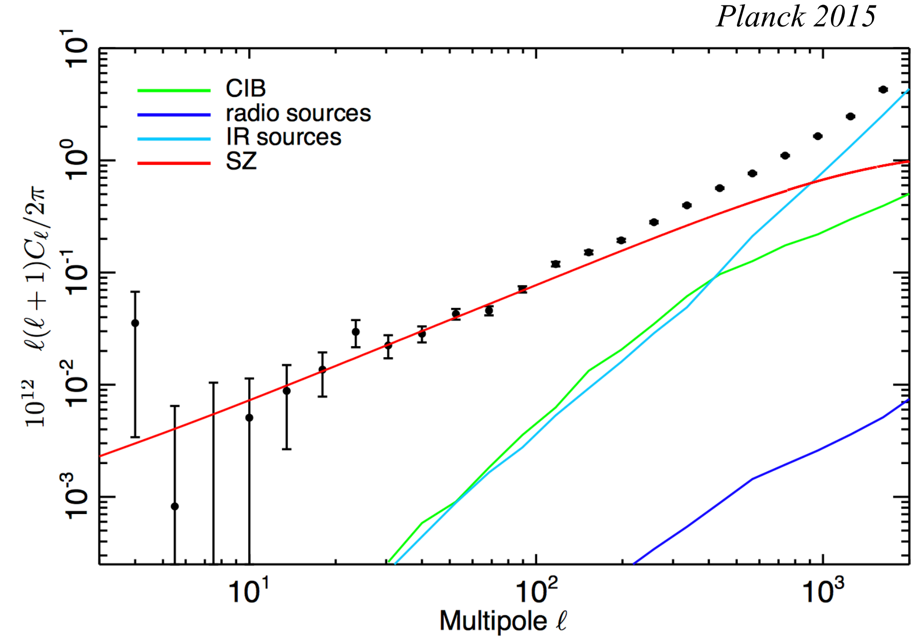


Map of the thermal Sunyaev Zeldovich effect

$$y = \frac{\sigma_{\mathrm{T}}}{m_{\mathrm{e}}c^2}\int P\mathrm{d}s$$

- Requires **component separation**

Planck 2015



- **tSZ power spectrum from *y*-map**
- ACT *y*-map in the making

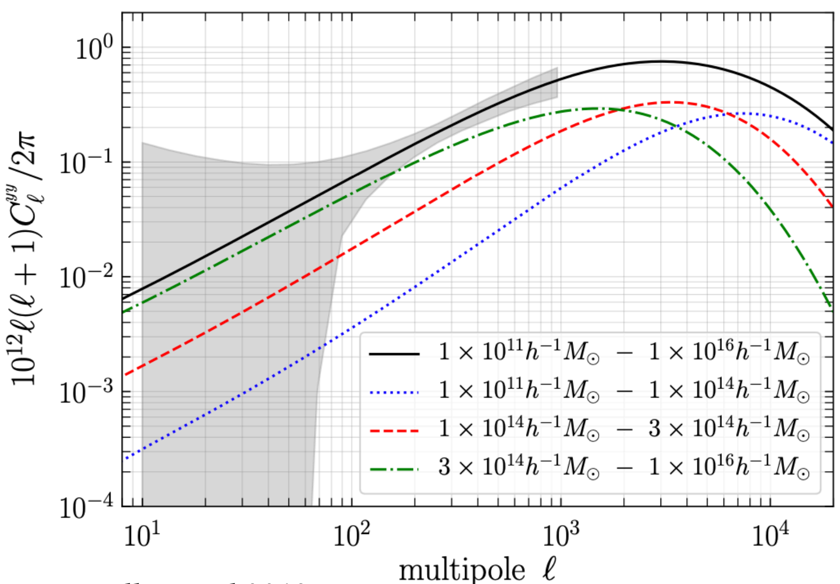
- tSZ power spectrum formula

$$C_\ell^{\mathrm{tSZ}} = \int_{z_{\min}}^{z_{\max}} \mathrm{d}z \frac{dV}{dz d\Omega} \int_{\ln M_{\min}}^{\ln M_{\max}} d\ln M \frac{dn}{d\ln M} \left|y_\ell\,(M, z)\right|^2$$

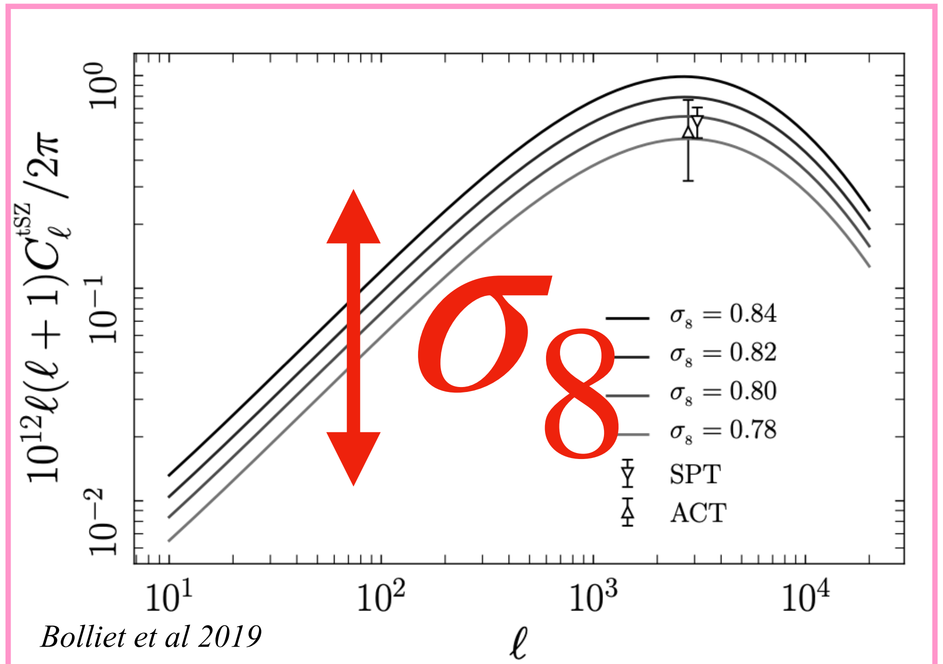
Komatsu & Kitayama 1999, Komatsu & Seljak 2002

Number of clusters

2D Fourier transform
of the **radial pressure profile**

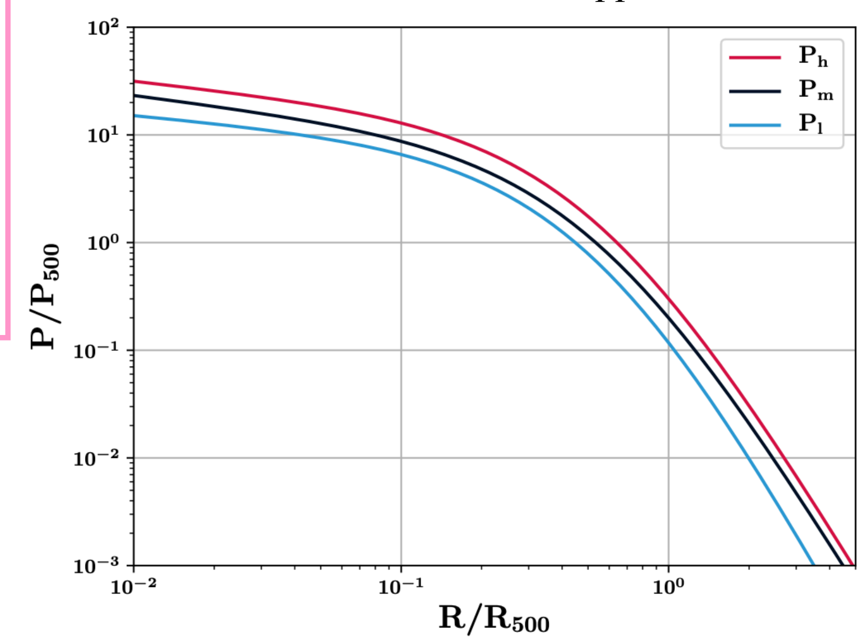


Rotti, Bolliet et al 2019



Bolliet et al 2019

Ruppin et al 2021

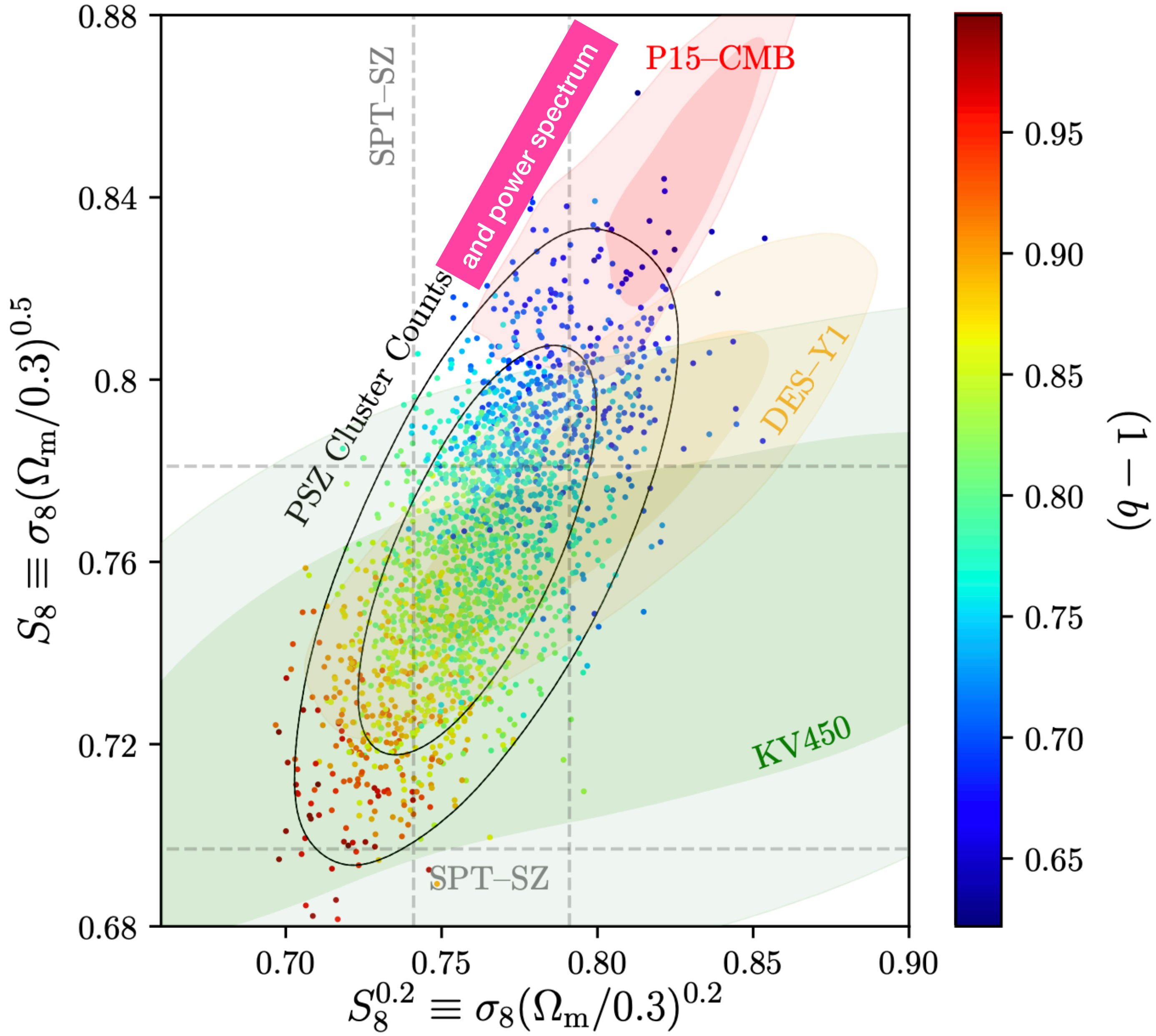


- Sensitive probe of cosmology

- Expect important input from **NIKA2** data…. And **upcoming ACT data**!

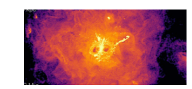
- Agreement between Planck tSZ power spectrum and cluster counts, and SPT constraints (cluster counts)
- Consistent with weak-lensing/clustering constraints (KIDS/DES/HSC)
- 2-3σ lower than CMB

Bolliet et al 1906.10359



Reconcile CMB and SZ?

1. Large feedback/Non thermal pressure… (i.e., change normalization of Mass-Observable relation)

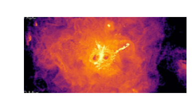


2. $\Sigma m_\nu \approx 0.3\,\mathrm{eV}$ (i.e., lower P(k) at high-k)

see Bolliet, Salvati, McCarthy, SPT

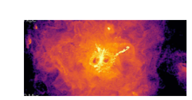
Could solve the tension with WL data simultaneously, but **solutions are extreme**

3. Systematics in X-ray temperature calibration (i.e., change normalization of Mass-Observable relation)



4. Systematics in pressure profile/HMF calibration

see Ruppin et al 2021, Artis et al 2021



KV450 from Hildebrandt et al 1812.06076 (shear)
DES Y1 from 1810.02499 (3x2pt)
SPT SZ from bocquet et al 1812.01679

SZ cosmology will be robust when astrophysics degeneracy (baryons) is solved

HOW?

1. Where do the SZ **cosmological constraints** come from?

tSZ cluster counts
tSZ power spectrum
tSZ cross-correlations

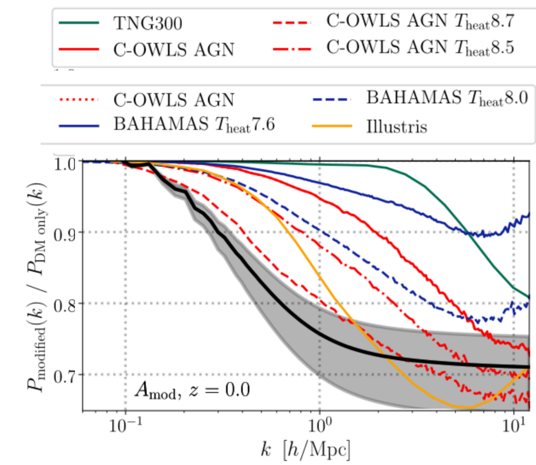
kSZ tomography

2. How do we measure **baryons** with SZ?

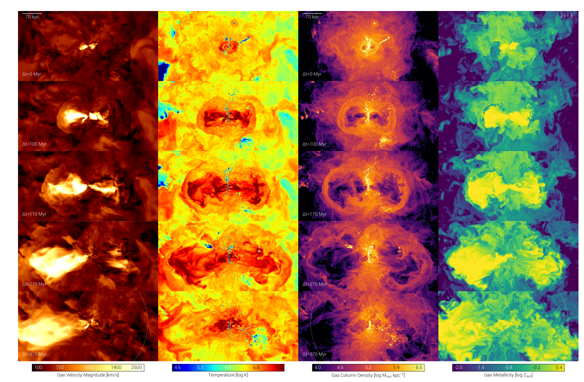
tSZ power spectrum
tSZ cross-correlations

tSZ and kSZ stacking analyses
kSZ cross-correlations

- **Crucial for precision cosmology**, to assert robustness of constraints from weak lensing and SZ



- Tight constraints on **baryonic feedback processes**
- **Thermodynamical state of ICM an CGM** gas from observations
- Inform galaxy formation and evolution research

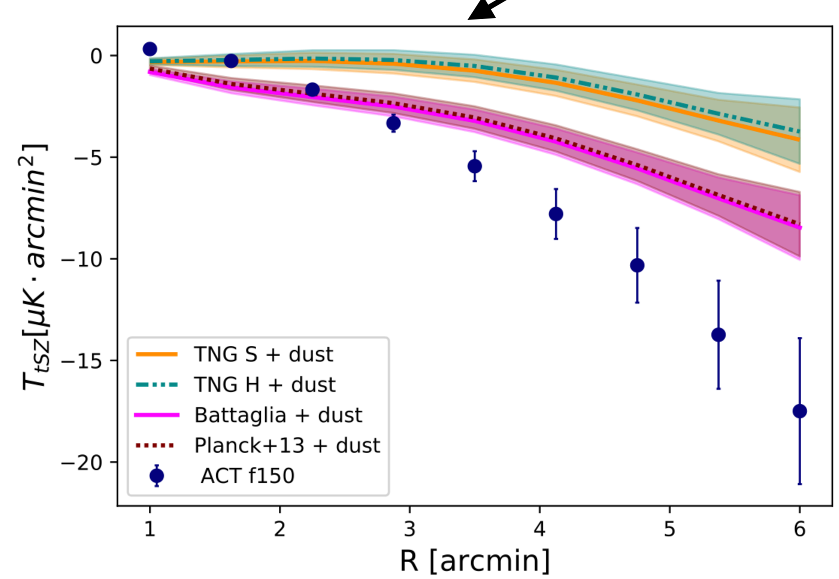


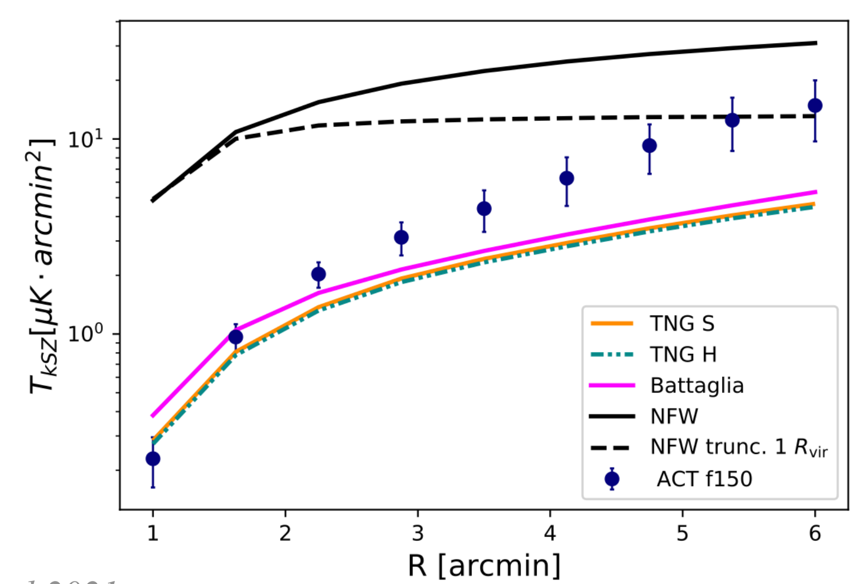
Shape of gas pressure and density is a direct probe of feedback

- **HOW?**

tSZ power spectrum
tSZ cross-correlations

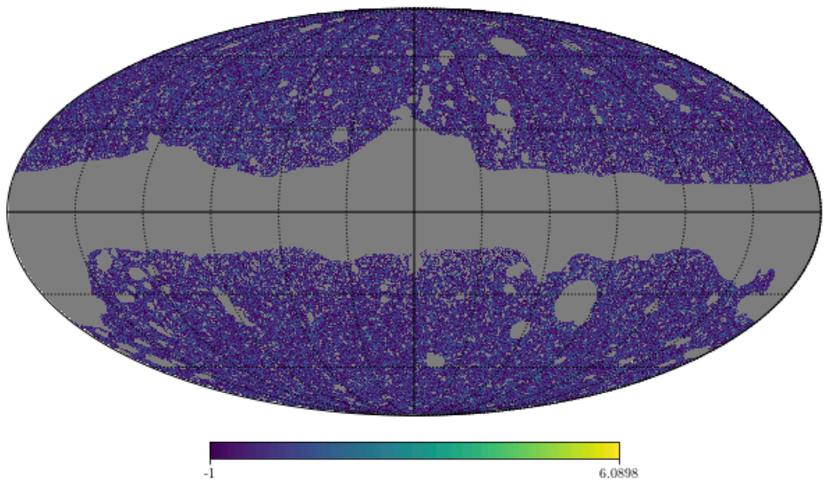
tSZ and kSZ stacking analyses →
kSZ cross-correlations

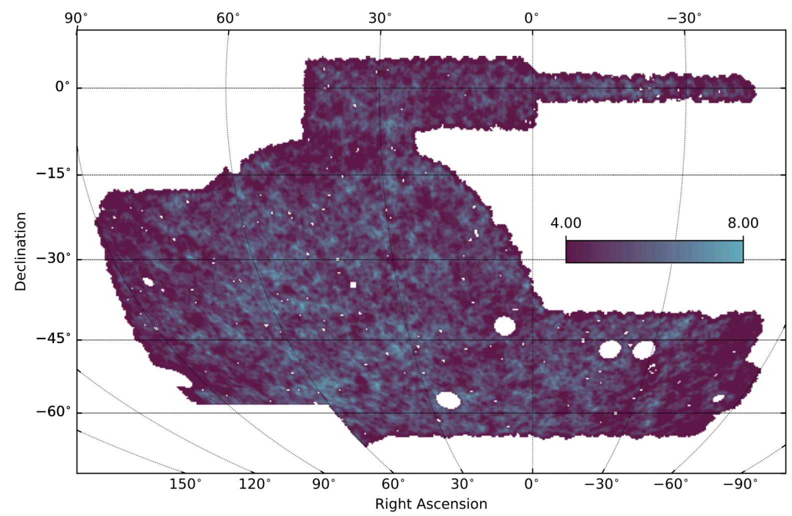


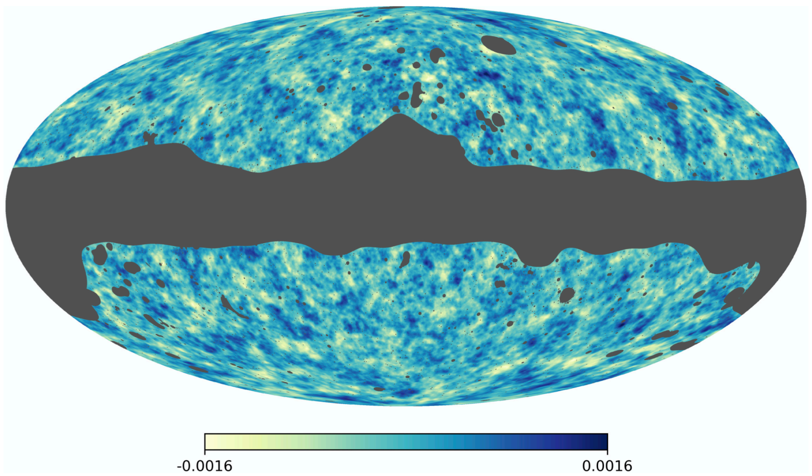


Amodeo et al 2021

- Can **probe gas in clusters/groups** relevant to each **large scale structure tracer experiment**







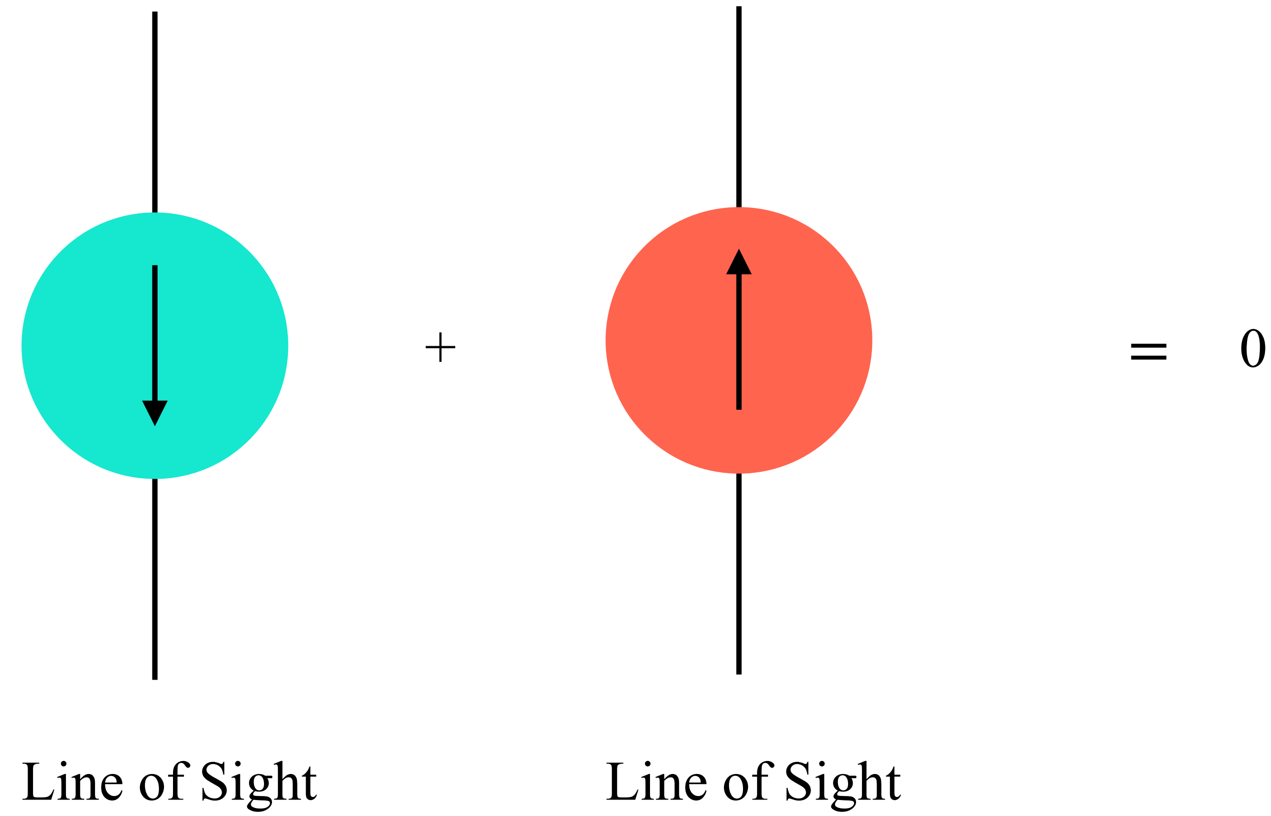
	$\delta_{\rm g}$	$\kappa_{\rm g}$	$\kappa_{\rm cmb}$
Current:	unWISE, CMASS	DES	Planck, ACT
Future:	Rubin, Euclid	Rubin, Euclid	AdvACT, SO, S4

- Possible with **photometric surveys** (other kSZ methods often require spectroscopic redshifts)

- Ingredients: **foreground cleaned CMB map**, projected **map of LSS tracers**

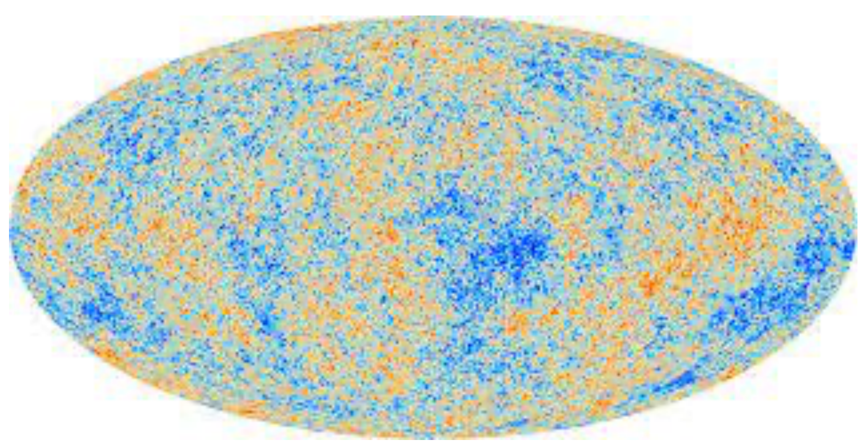
$$\frac{\delta T_{\rm kSZ}}{T_0}(\hat{\mathbf{r}}) = -\int dl\, \sigma_T\, n_e \frac{\mathbf{v}\cdot\hat{\mathbf{r}}}{c}$$

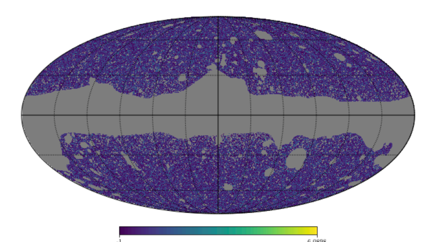
goal to measure gas density



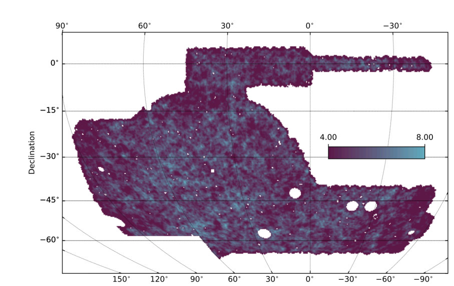
- Avoid velocity cancellation by **squaring CMB map**

- Heuristically

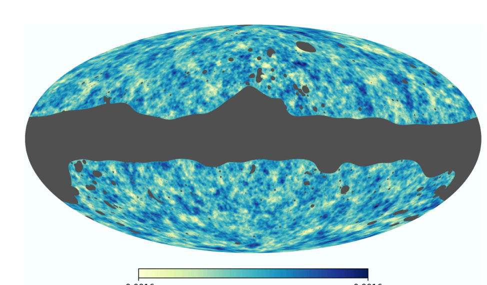
[]^2 x



or



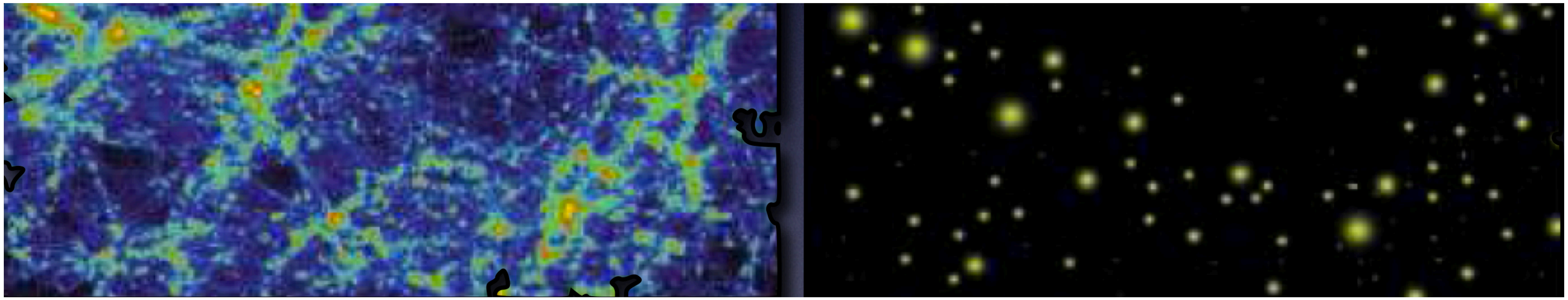
or



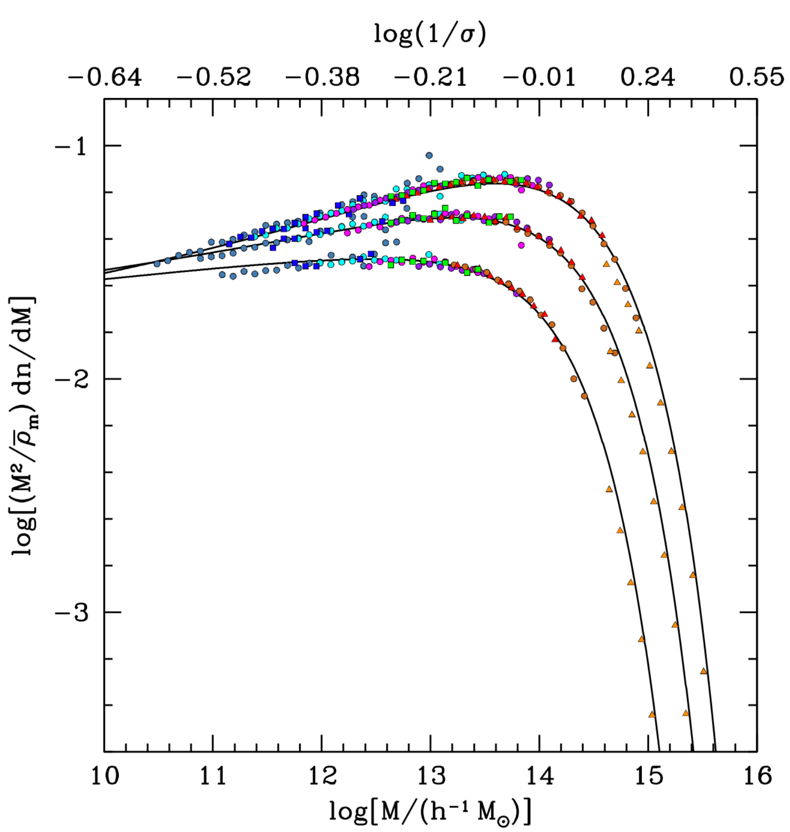
- Model?

See Bolliet, Hill, Ferraro, Kusiak, Krolewski 2022

- Develop theoretical framework to accommodate parameterized density profiles: **Halo Model**

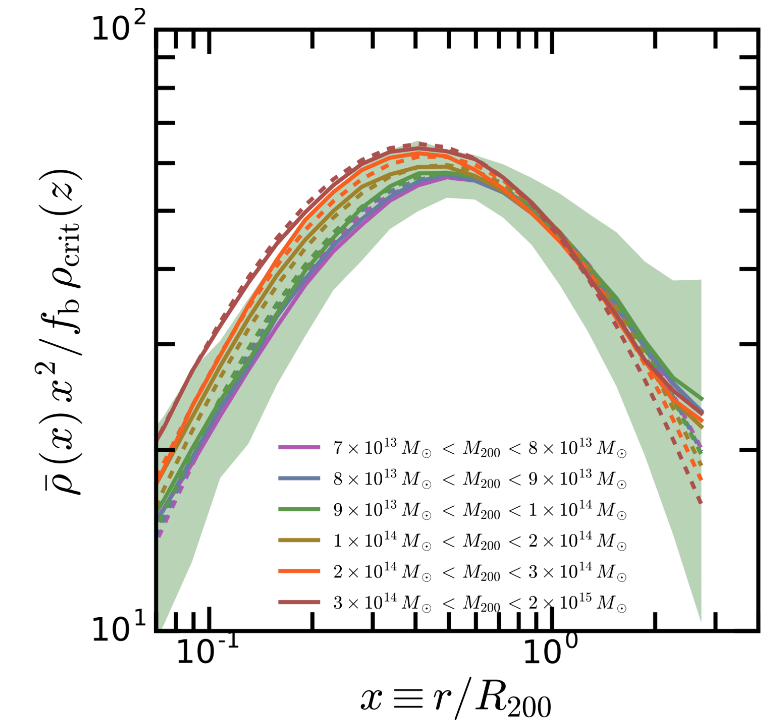


Main theory ingredients: **halo mass function** and **radial distribution of tracers within halos**



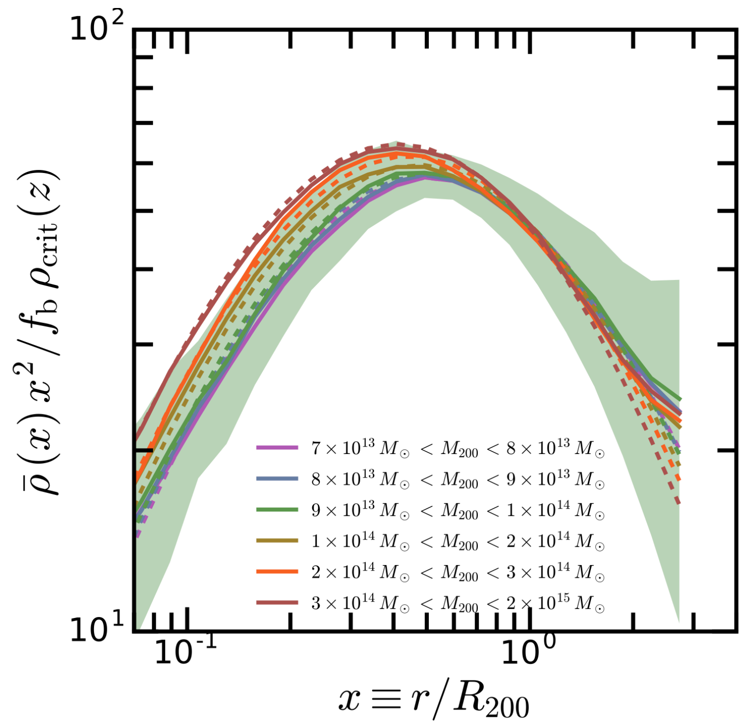
Tinker et al 2008
halo mass function

$$\bar{\rho}_{\rm fit} = \rho_0 \, (x/x_{\rm c})^{\gamma} \left[1 + (x/x_{\rm c})^{\alpha}\right]^{-\left(\frac{\beta-\gamma}{\alpha}\right)}$$



Battaglia et al 2010
density profile

$$\bar{\rho}_{\rm fit} = \rho_0 \left(x/x_{\rm c}\right)^{\gamma} \left[1 + \left(x/x_{\rm c}\right)^{\alpha}\right]^{-\left(\frac{\beta-\gamma}{\alpha}\right)}$$



Battaglia et al 2010
density profile

Density profile of the gas

We employ the **GNFW parameterization**, with slopes having a mass and redshift dependence.

*(**Dark matter** profile is **always** assumed to follow **NFW**)*

$$\rho_{\rm gas}(r) = f_{\rm b}\rho_{\rm crit}(z) u_{\rm gas}^{\rm gNFW}(r) \quad \text{with} \quad u_{\rm gas}^{\rm gNFW}(r) = C \left(\frac{r}{x_{\rm c} r_{\rm 200c}}\right)^{\gamma} \left[1 + \left(\frac{r}{x_{\rm c} r_{\rm 200c}}\right)^{\alpha}\right]^{-\frac{\beta+\gamma}{\alpha}} \tag{26}$$

where we adopt a mass definition at $\Delta = 200$, keep the inner slope parameter fixed to $\gamma = -0.2$ and use $x_c = 0.5$ as in Battaglia (2016). The functions $\{C, \alpha, \beta, \gamma\}$ are fitted to hydrodynamical simulations and written as

$$p = A_0 \left(\frac{m_{\rm 200c}}{10^{14} {\rm M}_\odot}\right)^{A_m} (1+z)^{A_z} \quad \text{for} \quad p \in \{C, \alpha, \beta, \gamma\}. \tag{27}$$

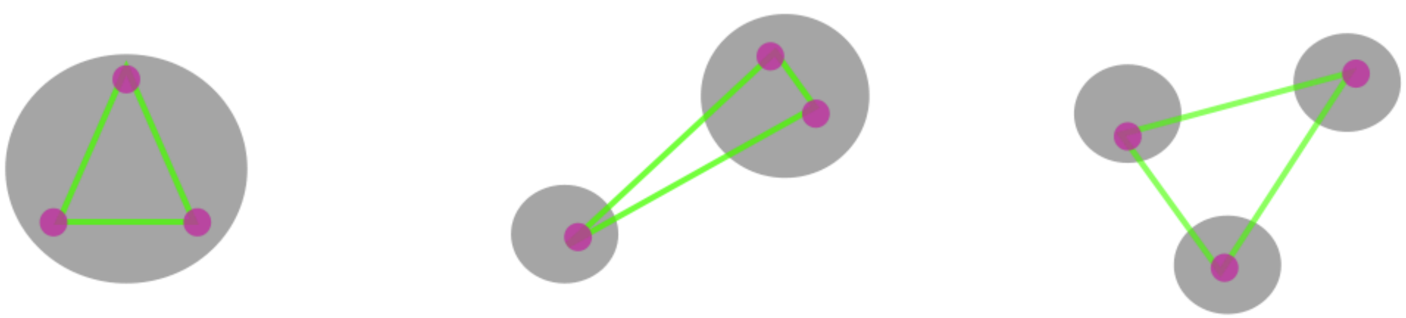
- The projected-field kSZ power spectrum is an integral/convolution of the $\mathrm{kSZ}^2 \times \mathrm{LSS}$ **bispectrum**

$$C_\ell^{\mathrm{kSZ}^2X} = \int \mathrm{d}v W^{\mathrm{kSZ}}(\chi)^2 W^X(\chi) T(\ell,\chi) \quad \text{with} \quad T(\ell,\chi) = \int \frac{\mathrm{d}^2\boldsymbol{\ell}'}{(2\pi)^2} f(\ell') f(|\boldsymbol{\ell}+\boldsymbol{\ell}'|) B_{v_g^2 X}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

Redshift kernel of kSZ and X

Wiener filter
(data analysis trick
to maximize SNR)

- Halo model **bispectrum** expression



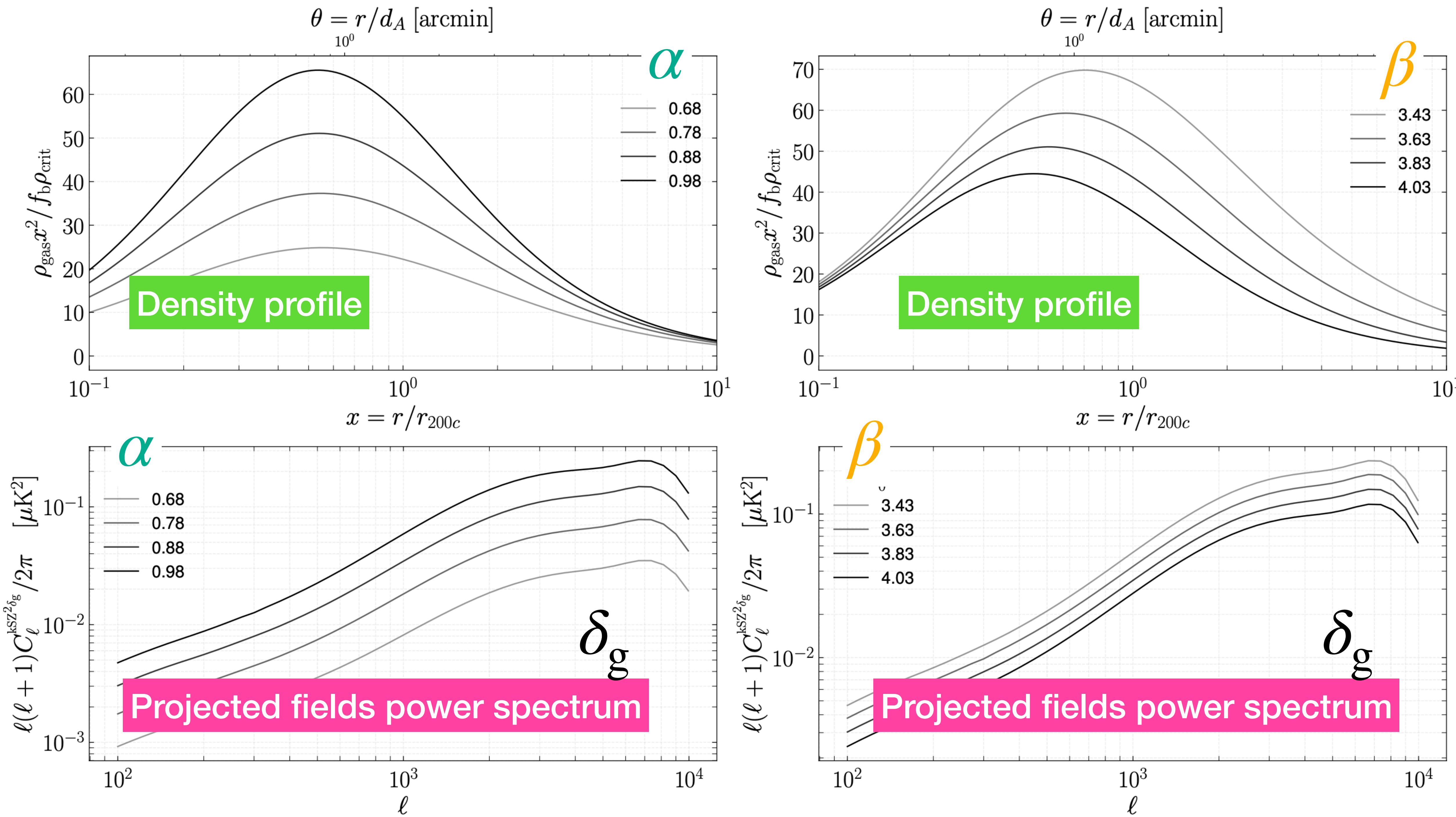
$$B^{1\mathrm{h}} = \int \mathrm{d}n_1 \hat{u}^X_{k_1}(m_1)\hat{u}^Y_{k_2}(m_1)\hat{u}^Z_{k_3}(m_1)$$

$$B^{2\mathrm{h}} = \int \mathrm{d}n_1 \hat{u}^X_{k_1}(m_1)\hat{u}^Y_{k_2}(m_1) \int \mathrm{d}n_2 \hat{u}^Z_{k_3}(m_2) P_L(k_3) + 2\mathrm{cyc}$$

$$B^{3\mathrm{h}} = 2\int \mathrm{d}n_1 b^{(1)}(m_1)\hat{u}^X_{k_1}(m_1)P_L(k_1) \int \mathrm{d}n_2 b^{(1)}(m_2)\hat{u}^Y_{k_2}(m_2)P_L(k_2) \int \mathrm{d}n_3 b^{(1)}(m_3)\hat{u}^Z_{k_3}(m_3) F_2(k_1,k_2,k_3)$$
$$+ \int \mathrm{d}n_1 b^{(1)}(m_1)\hat{u}^X_{k_1}(m_1)P_L(k_1) \int \mathrm{d}n_2 b^{(1)}(m_2)\hat{u}^Y_{k_2}(m_2)P_L(k_2) \int \mathrm{d}n_3 b^{(2)}(m_3)\hat{u}^Z_{k_3}(m_3) + 2\mathrm{cyc}$$

Separable expression+convolution: can use FFTs (thanks Mat M.!)

Changing the **slopes** of the gas **density profile**



- Goal is to measure these parameters
- Fast and accurate **numerical code**
  (used as a reference by DESC/CCL for CIB and SZ)

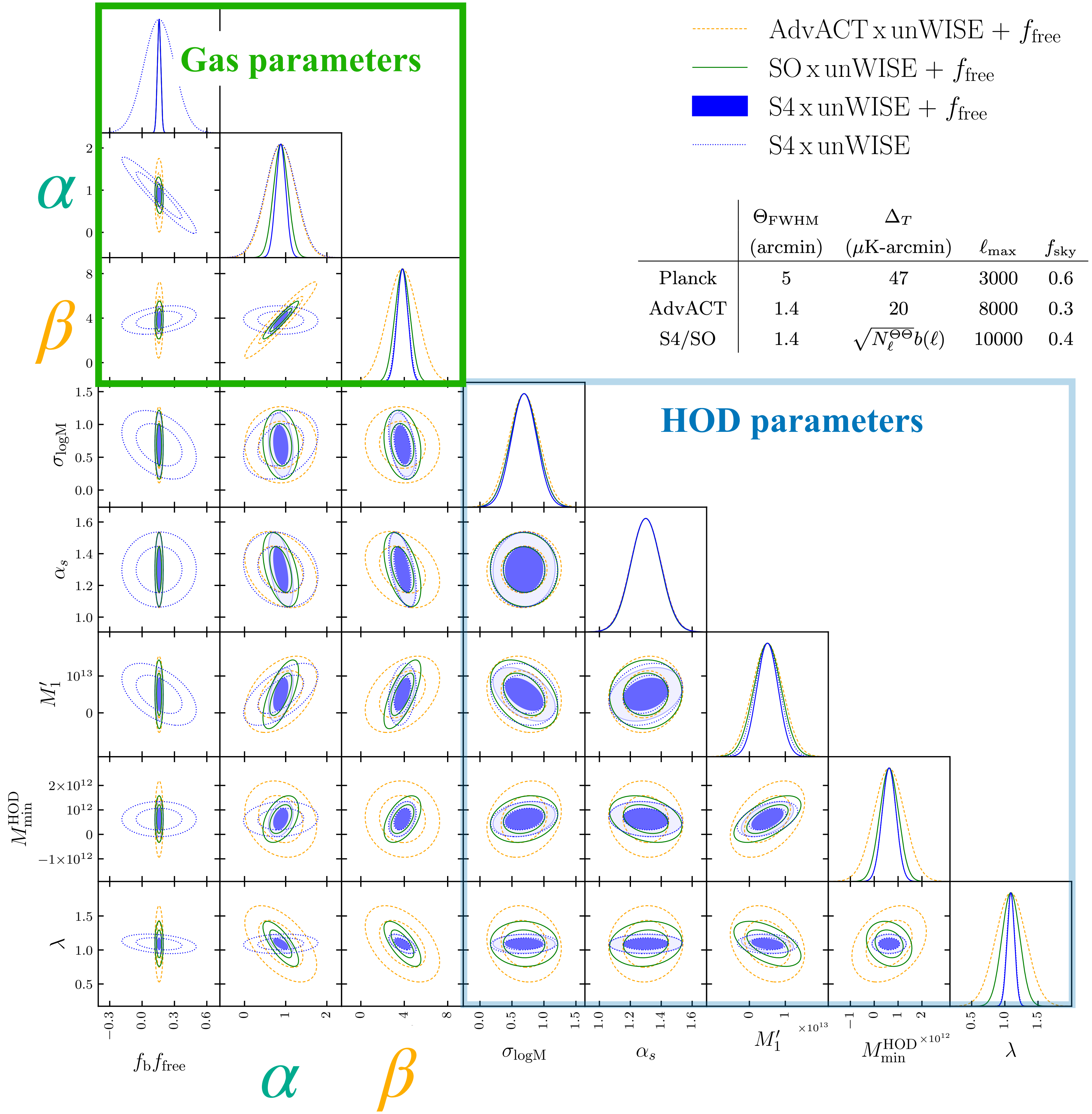
borisbolliet / class_sz Public
forked from lesgourg/class_public

- **Fisher matrix** calculations

$$C_\ell^{\mathrm{kSZ}^2\delta_g}$$

Typical halo mass

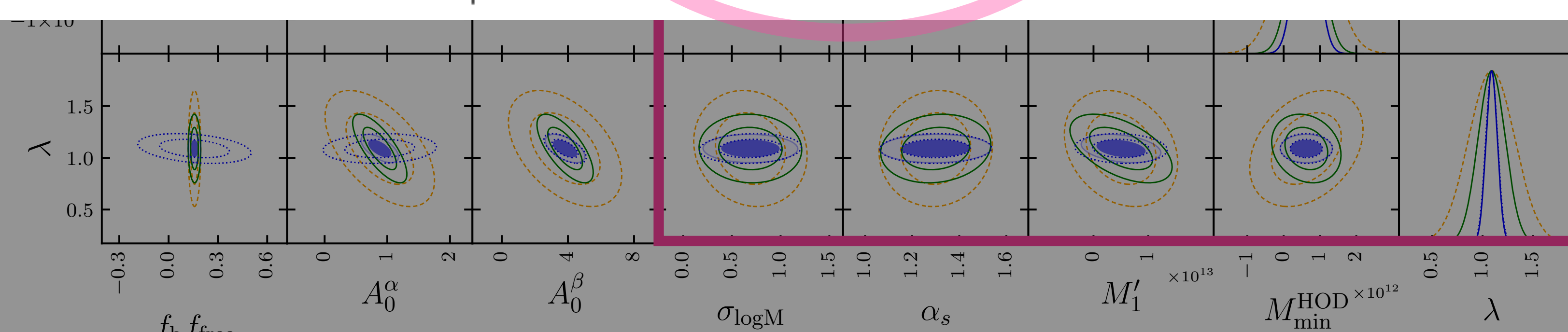
$1-5\times10^{13}\,\mathrm{M_{sun}}/h$

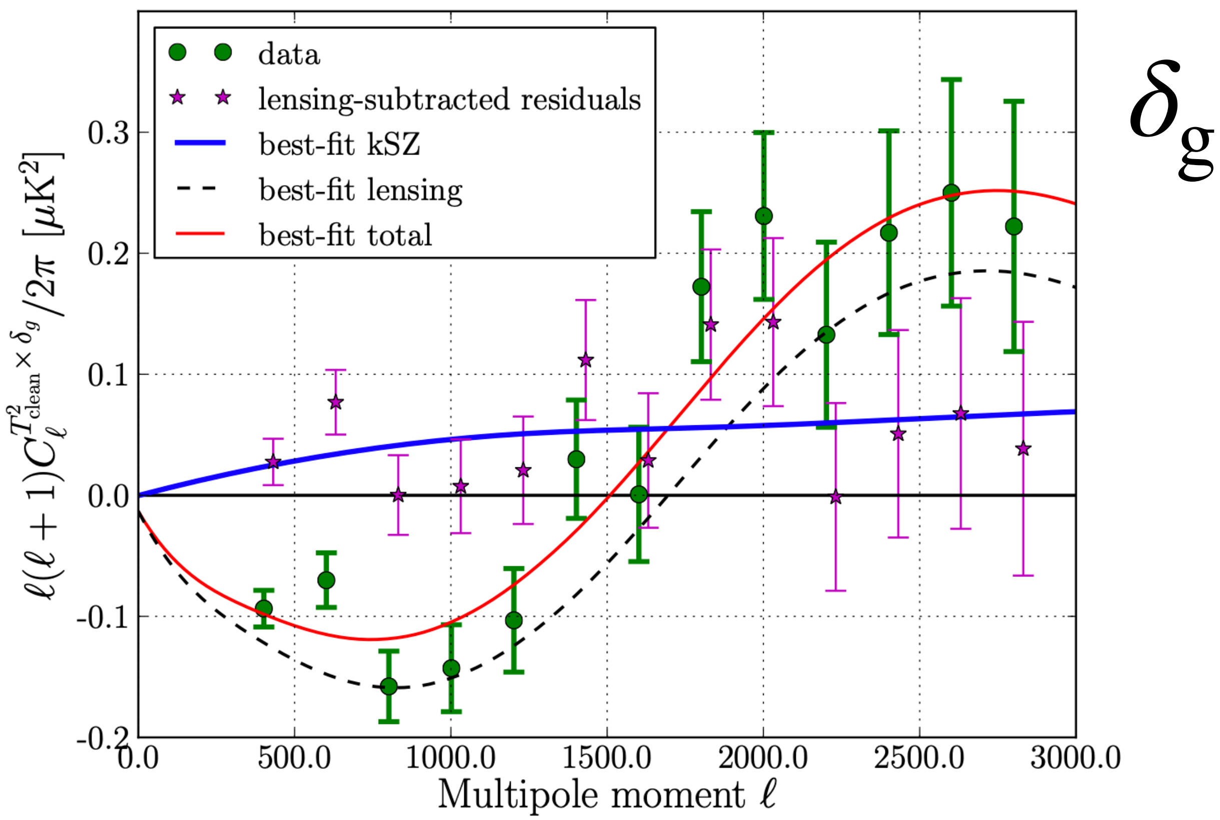


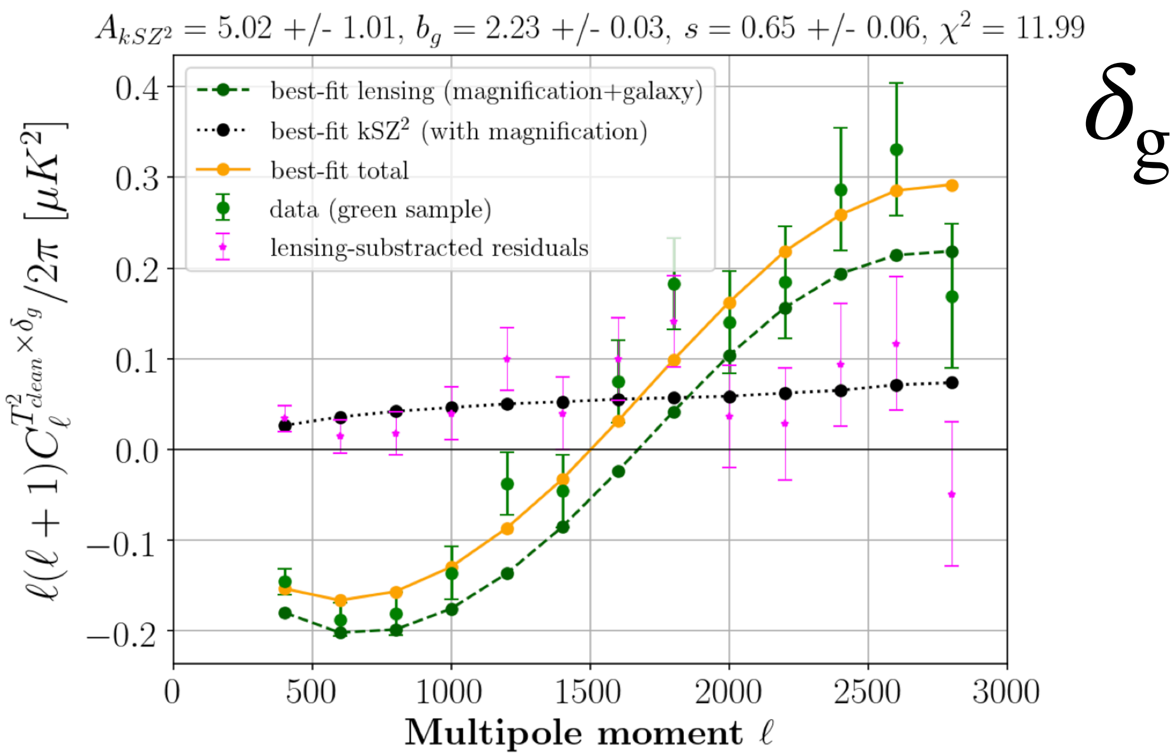
	$\Theta_{\rm FWHM}$ (arcmin)	Δ_T (μK-arcmin)	$\ell_{\max}$	$f_{\rm sky}$
Planck	5	47	3000	0.6
AdvACT	1.4	20	8000	0.3
S4/SO	1.4	$\sqrt{N_\ell^{\Theta\Theta}b(\ell)}$	10000	0.4

- Fisher matrix calculations

		$\mathrm{SNR_{tot}}$	$\left(\frac{\Delta A_0^\beta}{A_0^\beta}\right)^{-1}$	$\left(\frac{\Delta A_0^\alpha}{A_0^\alpha}\right)^{-1}$	$\left(\frac{\Delta f_{\rm free}}{f_{\rm free}}\right)^{-1}$	
δ_g	*Planck* × *unWISE*	1.7	0.18 (0.37)	0.29 (0.38)	0.19 (10)	
	AdvACT × *unWISE*	17.8	1.72 (2.87)	2.22 (2.54)	0.71 (10)	→ Data available
	SO × *unWISE*	61.9	3.70 (5.51)	2.07 (4.98)	0.78 (10)	→ Gas profile
	CMB-S4 × *unWISE*	102.9	7.32 (7.83)	2.38 (7.18)	1.12 (10)	
κ_g	AdvACT × DES	2.24	0.28 (0.79)	0.59 (0.88)	0.09 (10)	
	AdvACT × VRO/*Euclid*	5.98	0.92 (2.11)	1.72 (2.44)	0.31 (10)	→ First detection
	SO × DES	6.14	1.03 (2.75)	0.93 (2.34)	0.23 (10)	
	SO × VRO/*Euclid*	18.81	3.89 (6.84)	3.24 (8.22)	0.88 (10)	
	CMB-S4 × DES	9.71	2.19 (4.36)	1.33 (5.23)	0.40 (10)	
	CMB-S4 × VRO/*Euclid*	29.72	8.57 (13.07)	4.71 (15.08)	1.51 (10)	
$\kappa_{\rm cmb}$	SO	16.39	0.92 (2.84)	1.72 (2.72)	0.94 (10)	→ First detection
	CMB-S4	34.52	2.76 (7.01)	5.75 (7.79)	2.4 (10)	







First Detections of projected fields kSZ
$4-5\,\sigma$

Hill, Ferraro, Battaglia, Liu, Spergel 2016
Planck WISE

Kusiak, Bolliet, Ferraro, Hill, Krolewski 2021
Planck unWISE

- First detections **very recent**, only able to detect the signal… not sensitive to radial shape of the gas
- **Data already on hand** (ACT) should allow **first detections** of **kSZ-galaxy lensing cross-correlations**
- **Shape of the gas** will be measured with next generation CMB maps: SO and S4, providing **cutting-edge baryonic feedback constraints**, enabling calibration of baryonic effects in precision cosmology

WHAT?

Inverse Compton-scattering (thermal) and Doppler shift (kinetic) probes pressure and momentum of the gas around galaxies.

WHY?

SZ is a simple and powerful probe of cosmology.

We need measurements of ICM/CGM gas thermodynamical state to reduce uncertainty in precision cosmology, also to learn about galaxy formation and evolution.

With ACT, SO, S4 SZ is the way to go.

HOW?

For cosmology:
Cluster counts, tSZ power spectrum, kSZ tomography.

For baryons:
Cross-correlations. Stacking. Projected-field kSZ power spectrum.

The “how” is **fully dependent on synergies with LSS surveys**, like Rubin and Euclid.

Thanksz !