Title: Halo gas thermodynamics from the cosmic microwave background: implications for large-scale structure and galaxy formation

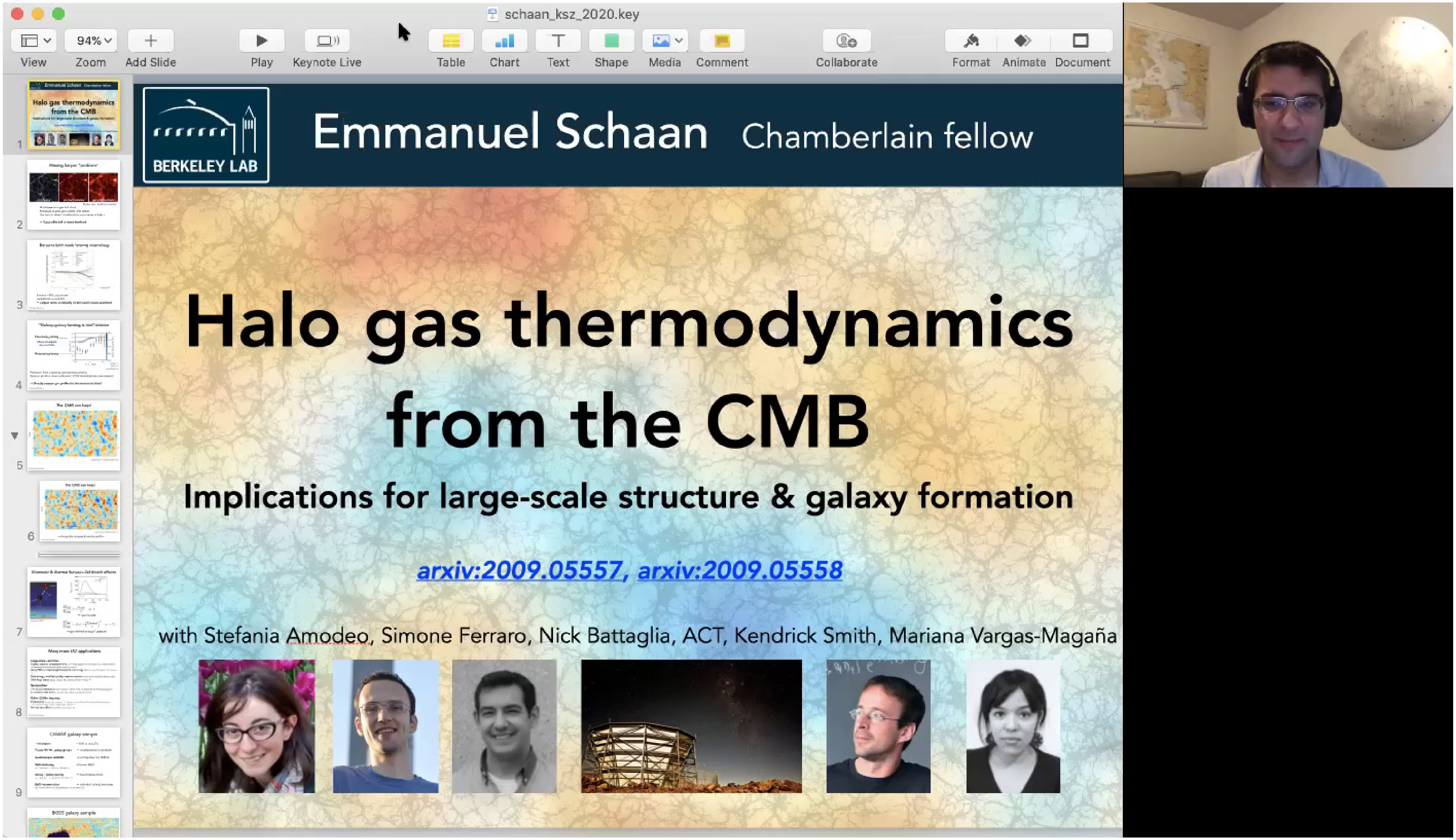
Speakers: Emmanuel Schaan

Series: Cosmology & Gravitation

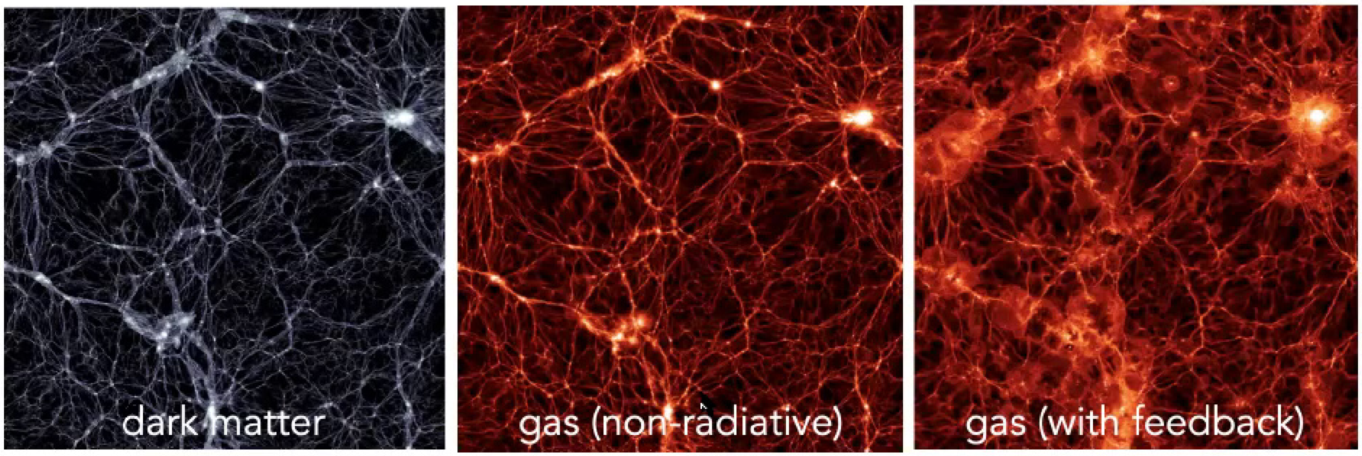
Date: September 22, 2020 - 11:00 AM

URL: http://pirsa.org/20090019

Abstract: Understanding galaxy formation is an outstanding problem in Astrophysics. The feedback processes that drive it, exploding stars and accretion onto supermassive black holes, are poorly understood. This results in an order unity uncertainty in the distribution of the gas inside halos, the ``missing baryon problem''. Because baryons are 15% of the total mass in the universe, this baryonic uncertainty is the largest theoretical systematics for percent precision weak lensing surveys like DES, HSC, Rubin Observatory, Roman Observatory and Euclid.
By measuring the kinematic and thermal Sunyaev-Zel'dovich effects (kSZ and tSZ), high resolution and high sensitivity CMB experiments can solve these issues by measuring the gas thermodynamics in galaxy groups and clusters, at high redshift and out to the outskirts of the halo. I will present joint tSZ, kSZ and dust measurement of BOSS (CMASS) galaxy groups, for which clustering and lensing data is also available. Using data from the Atacama Cosmology Telescope (ACT), we produced the highest significance kSZ measurement to date. This measurement shows with high statistical confidence that the gas is more spread out than the dark matter. It informs the modeling of the CMASS galaxy-galaxy lensing data, and shows that the small-scale ``lensing is low'' tension is not entirely caused by baryonic effects. Finally, comparing the observed kSZ and tSZ to hydrodynamical simulations reveals insight about the modalities of feedback.


schaan_ksz_2020.key
View
Zoom
Add Slide
Play
Keynote Live
Table
Chart
Text
Shape
Media
Comment
Collaborate
Format
Animate
Document
BERKELEY LAB
Emmanuel Schaan
Chamberlain fellow
Halo gas thermodynamics from the CMB
Implications for large-scale structure & galaxy formation
arxiv:2009.05557, arxiv:2009.05558
with Stefania Amodeo, Simone Ferraro, Nick Battaglia, ACT, Kendrick Smith, Mariana Vargas-Magaña

Missing baryon "problem"

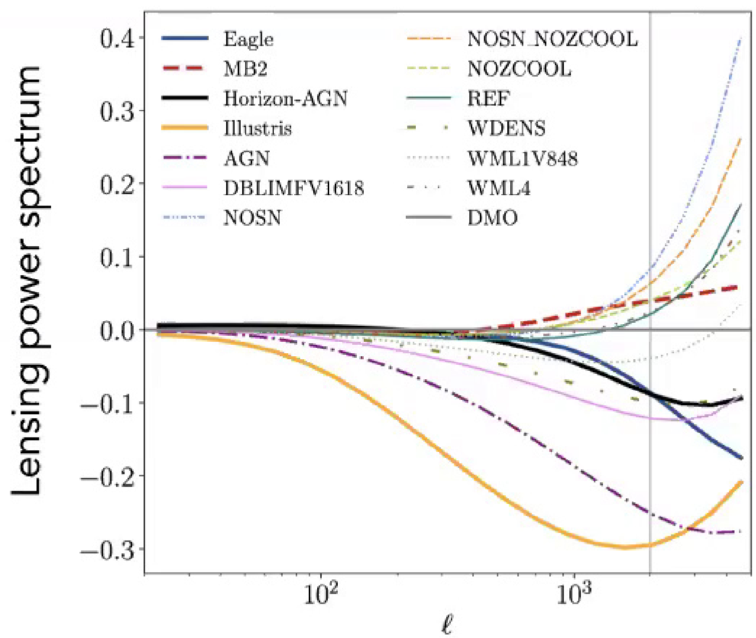


Haider+16, Illustris simulation

Most baryons in gas (not stars)
Feedback pushes gas outside virial radius
Too faint to detect outside of low mass halos, at high z

→ **Gas profiles tell us about feedback**

Baryons limit weak lensing cosmology



Huang+18

Baryons ~15% total matter

Localization is uncertain

→ **Largest (30%) uncertainty on the matter power spectrum!**

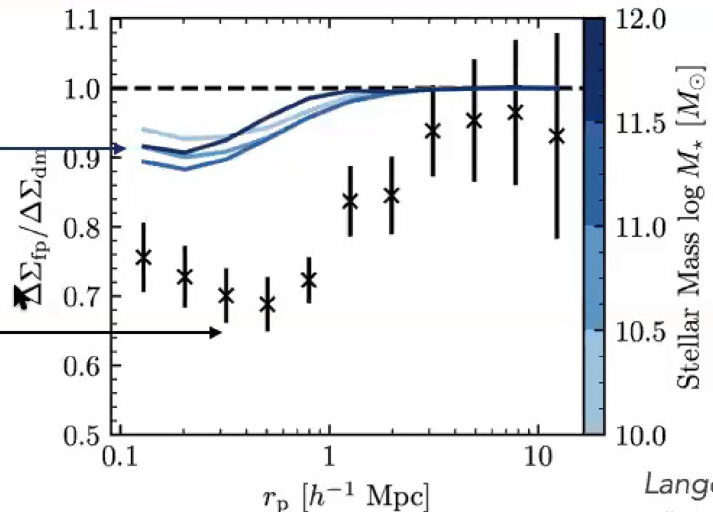
Emmanuel Schaan

"Galaxy-galaxy lensing is low" tension

Expected g-g lensing →

Effect of baryons (Illustris TNG) →

Measured g-g lensing →



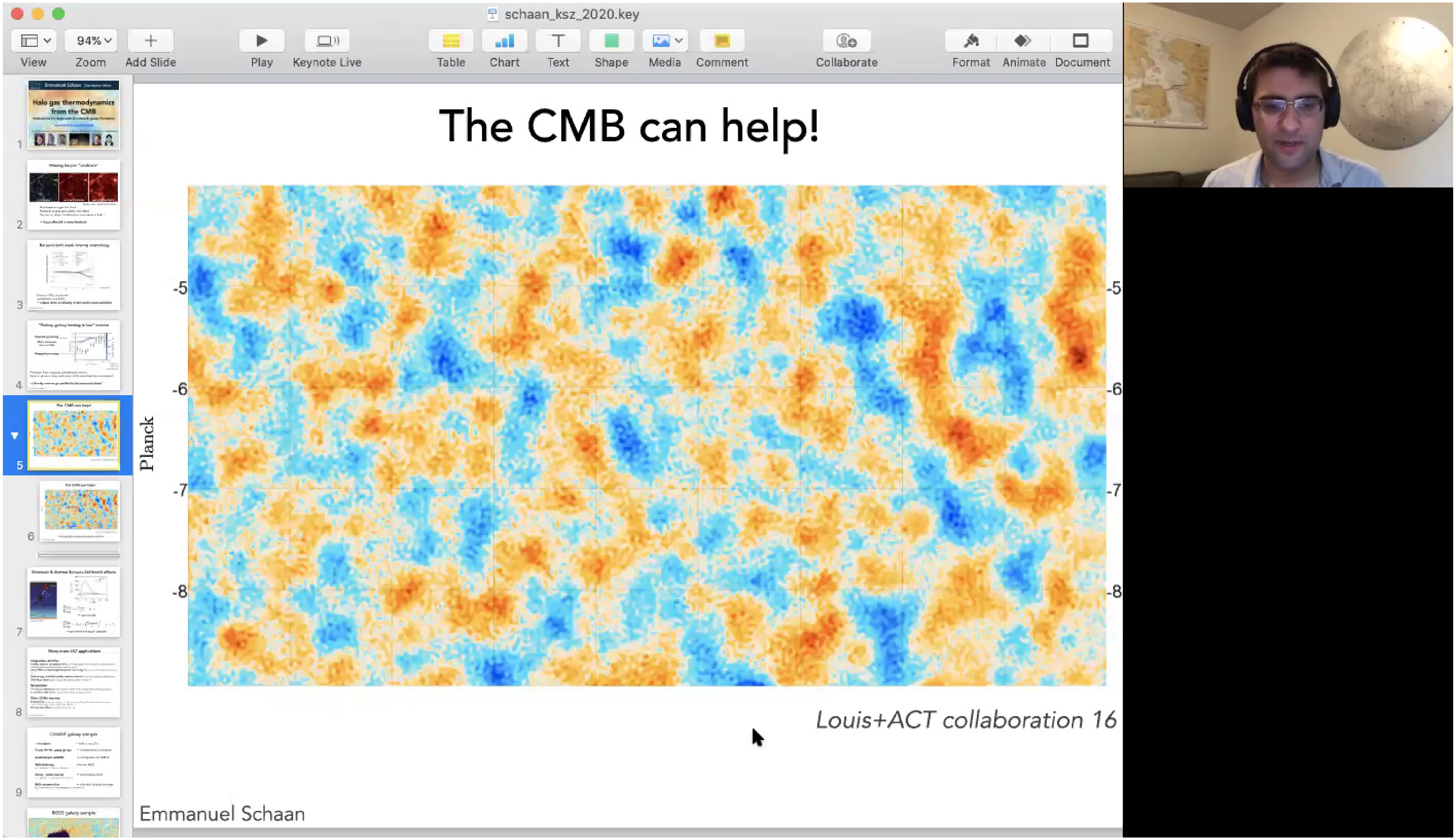
Lange+19
Saito+16
Leauthaud+16

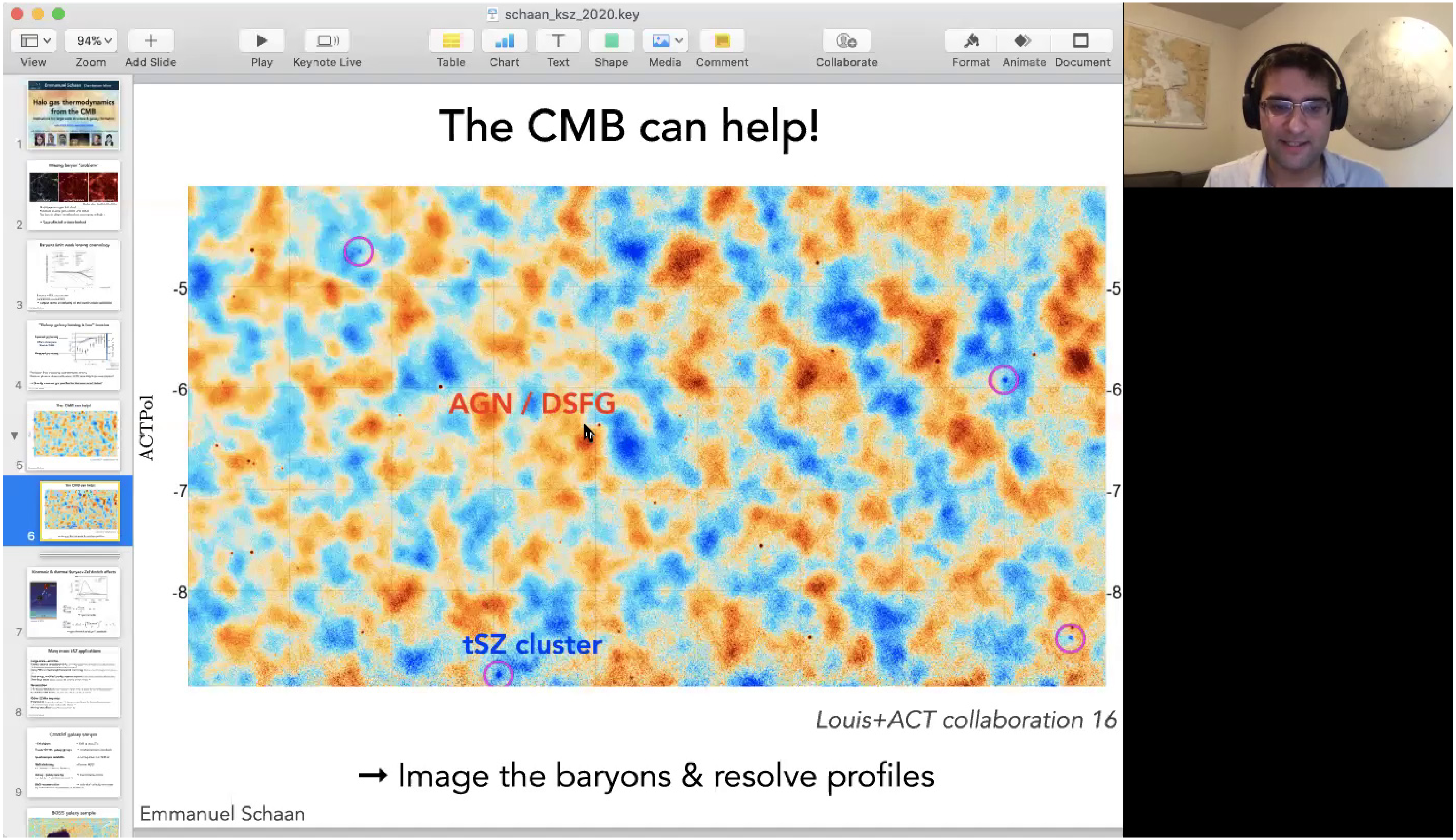
Prediction from clustering overestimates lensing

Baryons, photo-z, shear calibration, HOD, assembly bias, new physics?

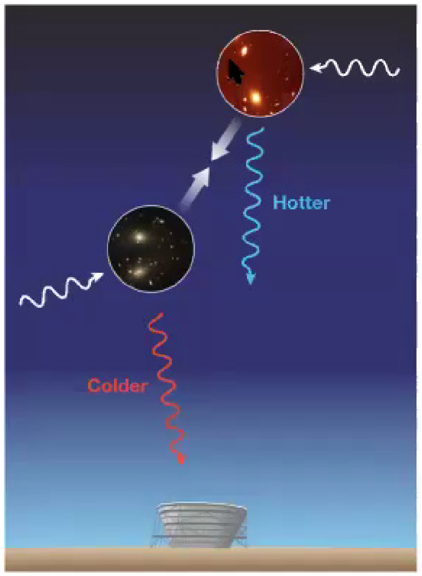
→ **Directly measure gas profiles for the same exact halos?**

Emmanuel Schaan

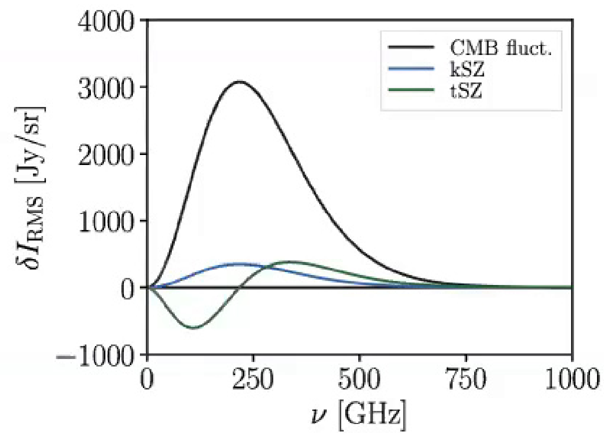

schaan_ksz_2020.key
View
Zoom
Add Slide
Play
Keynote Live
Table
Chart
Text
Shape
Media
Comment
Collaborate
Format
Animate
Document
The CMB can help!
Planck
-5
-6
-7
-8
Louis+ACT collaboration 16
Emmanuel Schaan


schaan_ksz_2020.key
The CMB can help!
ACTPol
AGN / DSFG
tSZ cluster
-5
-6
-7
-8
Louis+ACT collaboration 16
→ Image the baryons & resolve profiles
Emmanuel Schaan

Kinematic & thermal Sunyaev-Zel'dovich effects



Hand et al 2012



$$\frac{\delta T_{\rm kSZ}}{T_{\rm CMB}} = \tau \frac{v_{\rm bulk}}{c} \quad \propto \ \tau$$

→ gas density

$$\frac{\delta T_{\rm tSZ}}{T_{\rm CMB}} = f(\nu)\ \tau \left(\frac{v_{\rm thermal}}{c}\right)^2 \quad \propto \ \tau\ T_e$$

→ gas thermal energy / pressure

Many more kSZ applications

Large-scale velocities

Cosmic variance cancellation & f_{NL} *Smith Madhavacheril Munchmeyer Ferraro Utkarsh Johnson 18, Munchmeyer Madhavacheril Ferraro Johnson Smith 19*

Using FRBs to disentangle baryons & cosmology *Madhavacheril Battaglia Smith Sievers 19*

Dark energy, modified gravity, neutrino masses *Mueller deBernardis Bean Niemack 14a,b*

Ultra-large scales *Cayuso Johnson 20, Contreras Johnson Mertens 19*

Reionization

2 & 4-point estimators *Smith Ferraro 17, Ferraro Smith 18, Alvarez Ferraro Hill Hlozek Ikape 20*

Correlation with 21cm *Li Zhu Pen 18, La Plante Lidz Aguirre Kohn 20*

Other SZ-like imprints

Polarized SZ *Terrana Harris Johnson 17, Cayuso Johnson Mertens 18, Deutsch Dimastrogiovanni Johnson Munchmeyer Terrana 18, McCarthy Johnson 19*

Moving lens effect *Hotinli Meyers Johnson 20*

Emmanuel Schaan

CMASS galaxy sample

~1M objects → SNR α M x √N

Traces 10^{13} $M_\odot$ galaxy groups → most sensitive to feedback

Spectroscopic redshifts → not required, but SNR x2

BAO/clustering → known HOD

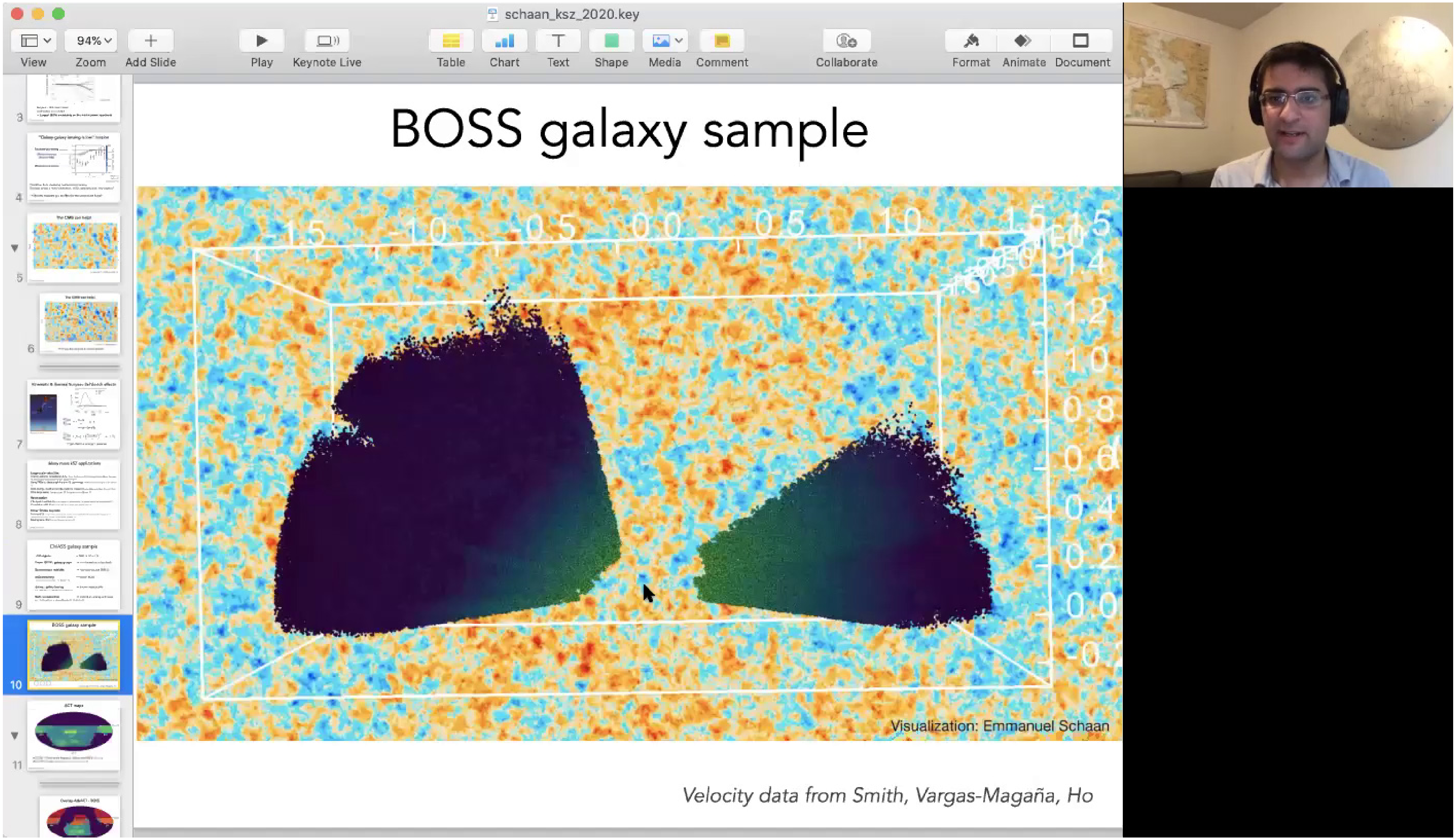
e.g., Anderson+14, Alam+16, Beutler+16

Galaxy - galaxy lensing → known mass profile

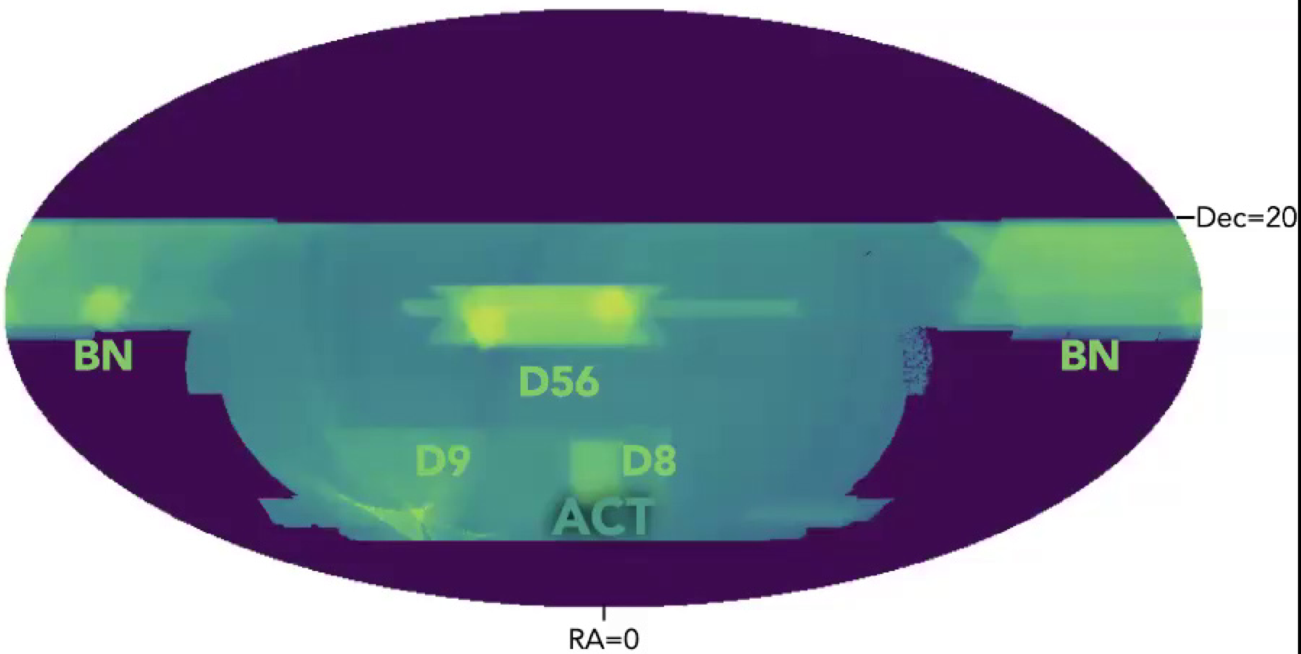
e.g., Miyatake+13, Leauthaud+16, Lange+19

BAO reconstruction → individual velocity estimates

e.g., Padmanabhan+12, Vargas-Magaña+15, Gil-Marin+15


schaan_ksz_2020.key
BOSS galaxy sample
Visualization: Emmanuel Schaan
Velocity data from Smith, Vargas-Magaña, Ho

ACT maps

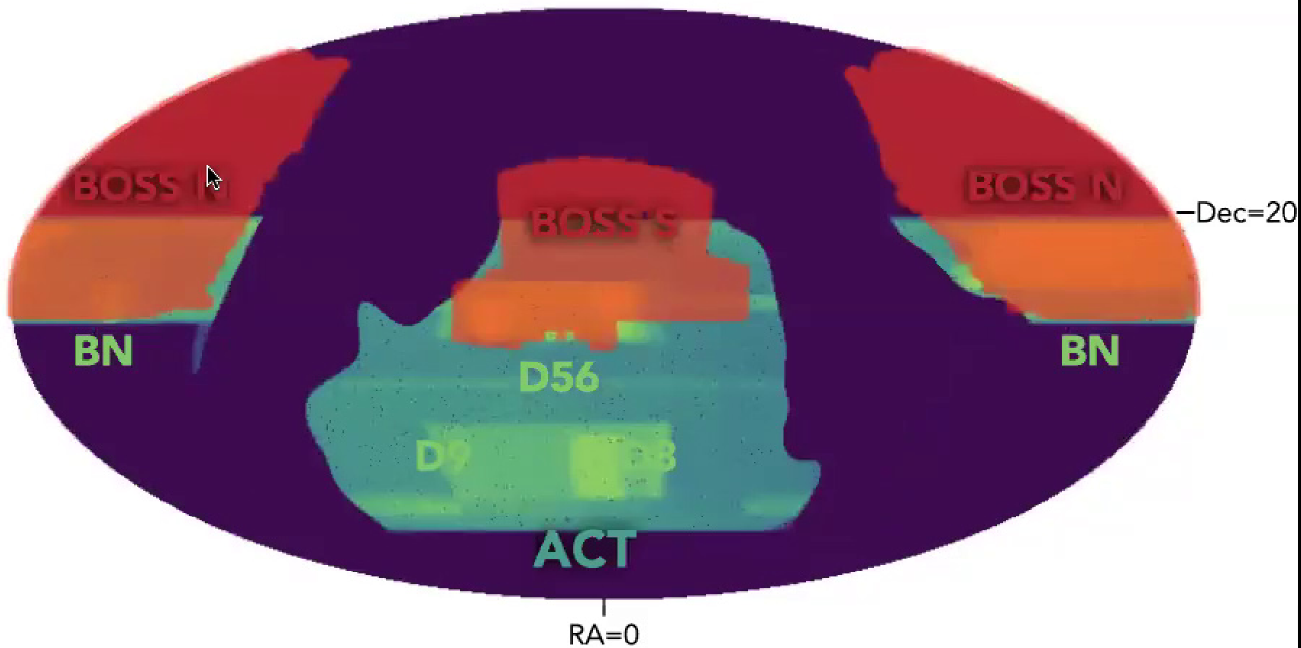


ACT DR5 + Planck single frequency 150GHz and 98GHz *Naess+20*

ACT DR4 ILC maps *Madhavacheril+20, Choi+20, Aiola+20*

Emmanuel Schaan

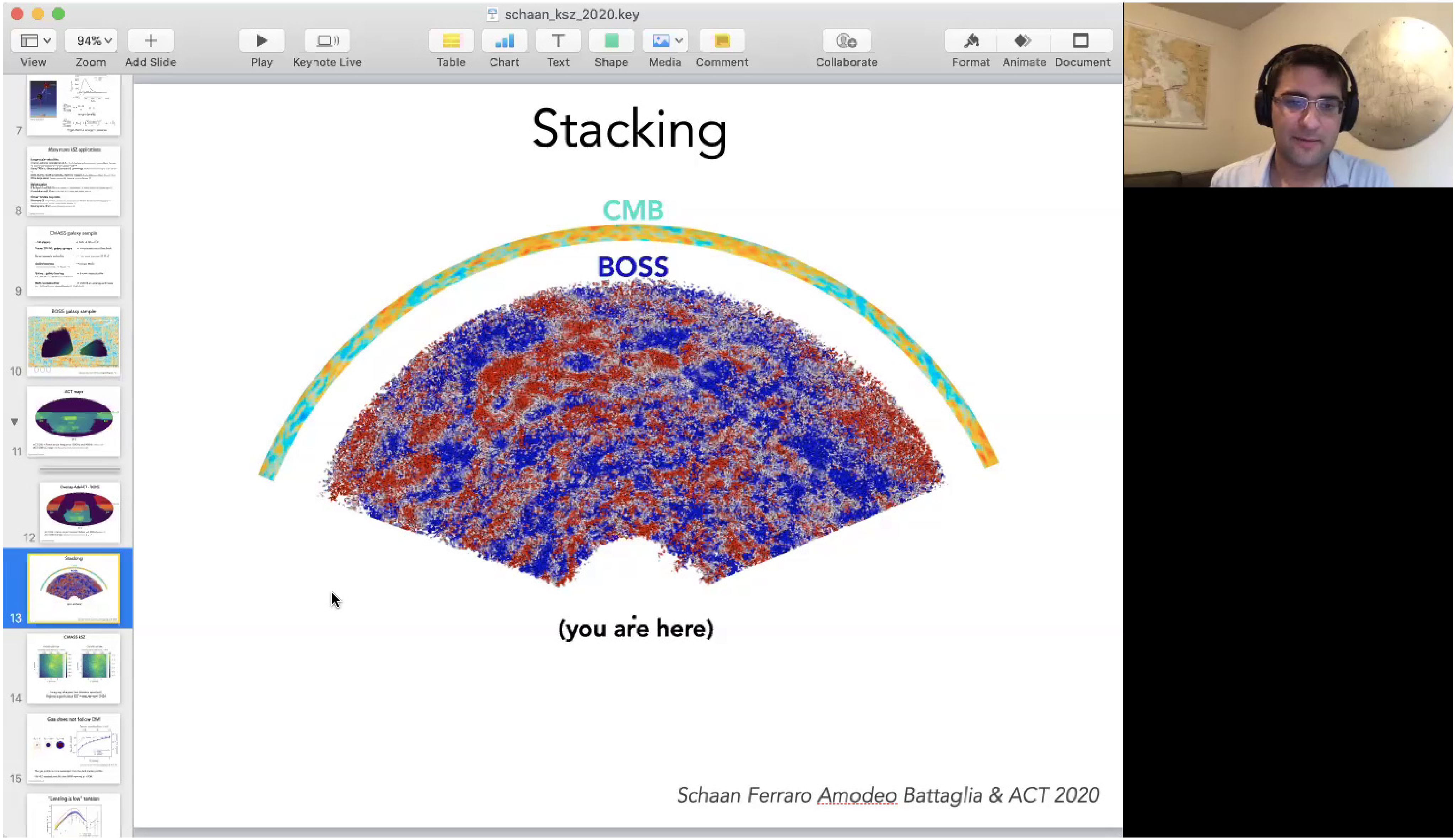
Overlap AdvACT - BOSS

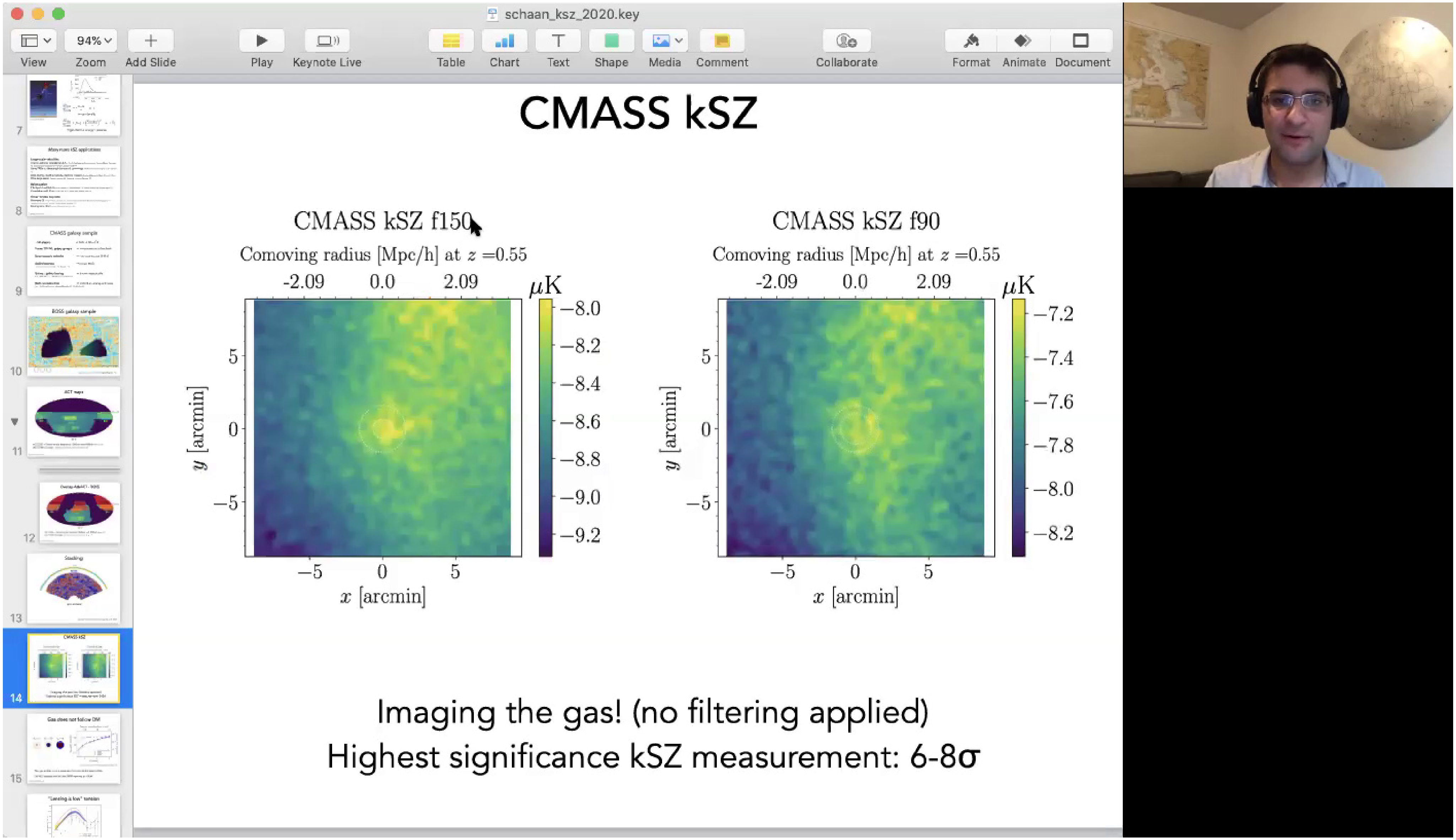


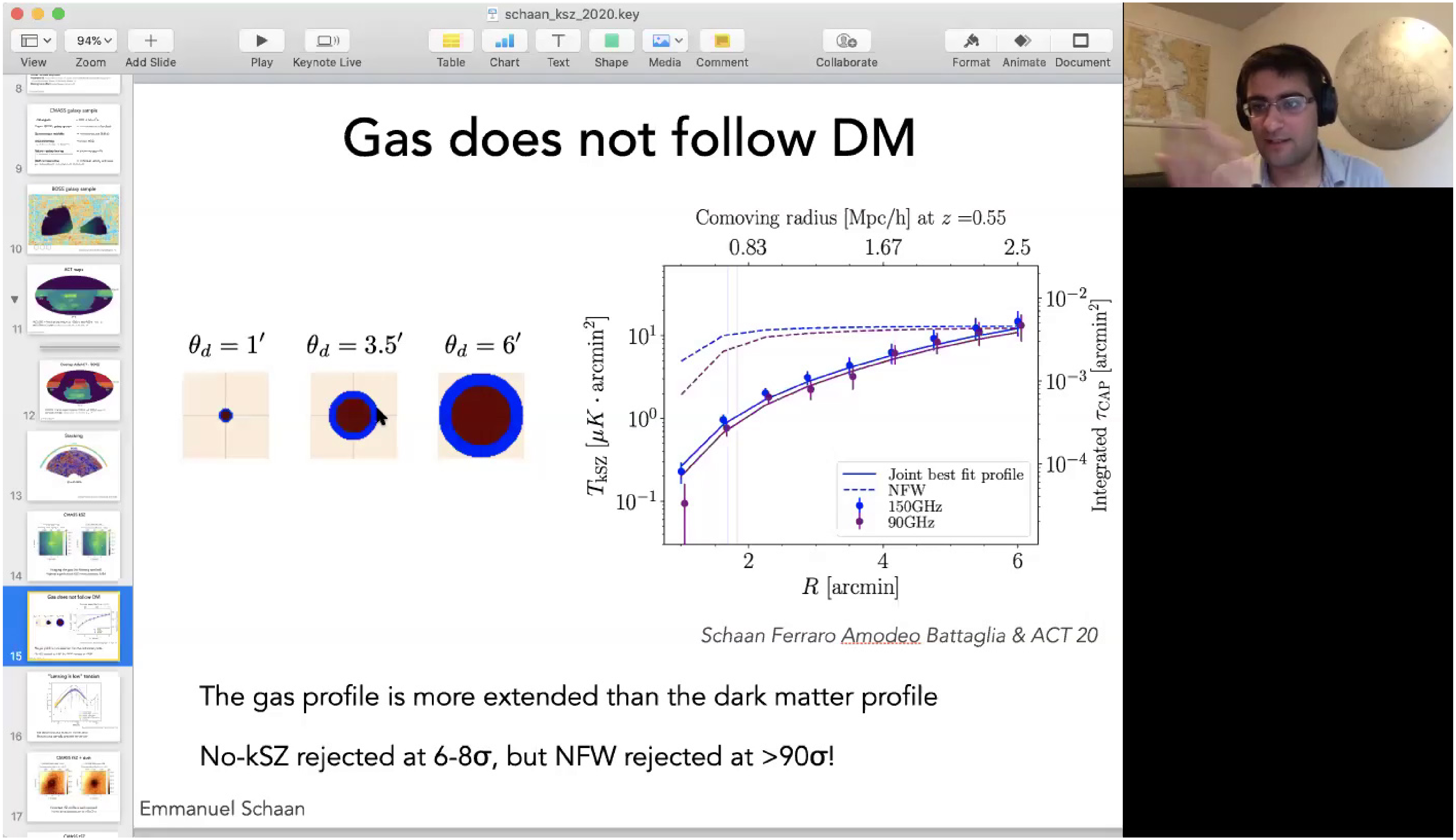
ACT DR5 + Planck single frequency 150GHz and 98GHz *Naess+20*

ACT DR4 ILC maps *Madhavacheril+20, Choi+20, Aiola+20*

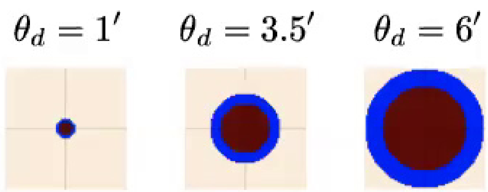
Emmanuel Schaan

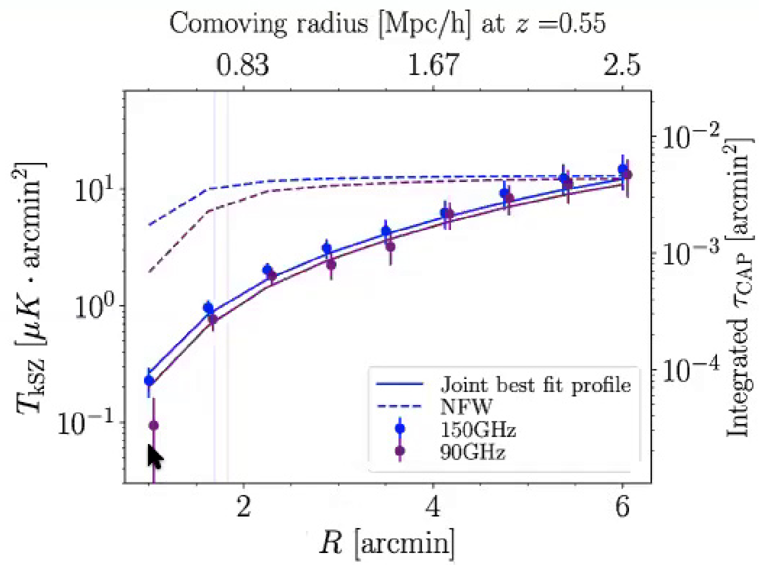

schaan_ksz_2020.key
Stacking
CMB
BOSS
(you are here)
Schaan Ferraro Amodeo Battaglia & ACT 2020


schaan_ksz_2020.key
CMASS kSZ
CMASS kSZ f150
Comoving radius [Mpc/h] at z =0.55
-2.09 0.0 2.09
μK
y [arcmin]
x [arcmin]
CMASS kSZ f90
Comoving radius [Mpc/h] at z =0.55
-2.09 0.0 2.09
μK
y [arcmin]
x [arcmin]
Imaging the gas! (no filtering applied)
Highest significance kSZ measurement: 6-8σ


schaan_ksz_2020.key
Gas does not follow DM
$\theta_d = 1'$
$\theta_d = 3.5'$
$\theta_d = 6'$
Comoving radius [Mpc/h] at z =0.55
0.83
1.67
2.5
$T_{\rm kSZ}$ [$\mu K \cdot$ arcmin^2]
Integrated $\tau_{\rm CAP}$ [arcmin^2]
R [arcmin]
Joint best fit profile
NFW
150GHz
90GHz
Schaan Ferraro Amodeo Battaglia & ACT 20
The gas profile is more extended than the dark matter profile
No-kSZ rejected at 6-8σ, but NFW rejected at >90σ!
Emmanuel Schaan

Gas does not follow DM





Schaan Ferraro Amodeo Battaglia & ACT 20

The gas profile is more extended than the dark matter profile

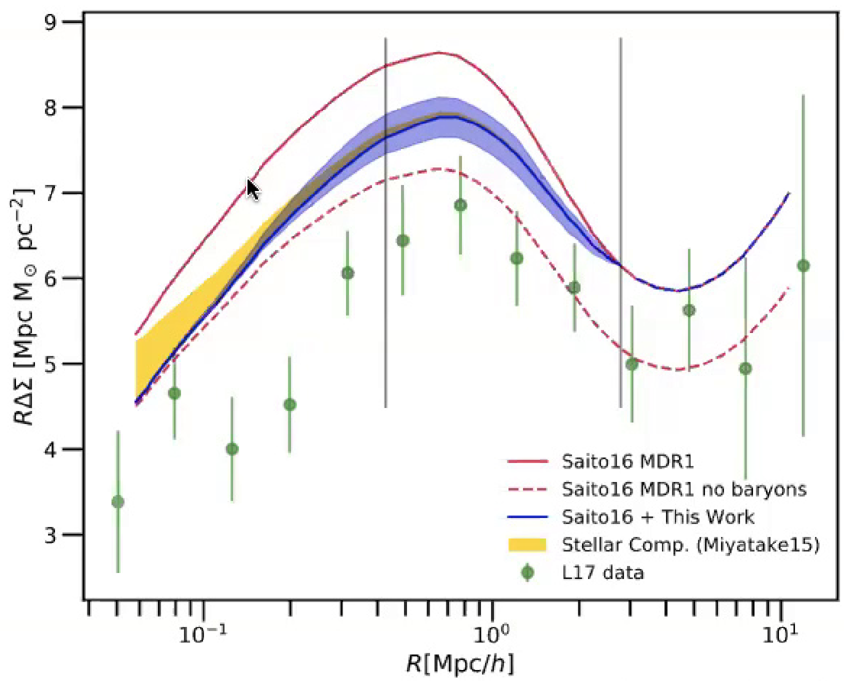
No-kSZ rejected at 6-8σ, but NFW rejected at >90σ!

Emmanuel Schaan

schaan_ksz_2020.key

View Zoom Add Slide Play Keynote Live Table Chart Text Shape Media Comment Collaborate Format Animate Document

"Lensing is low" tension

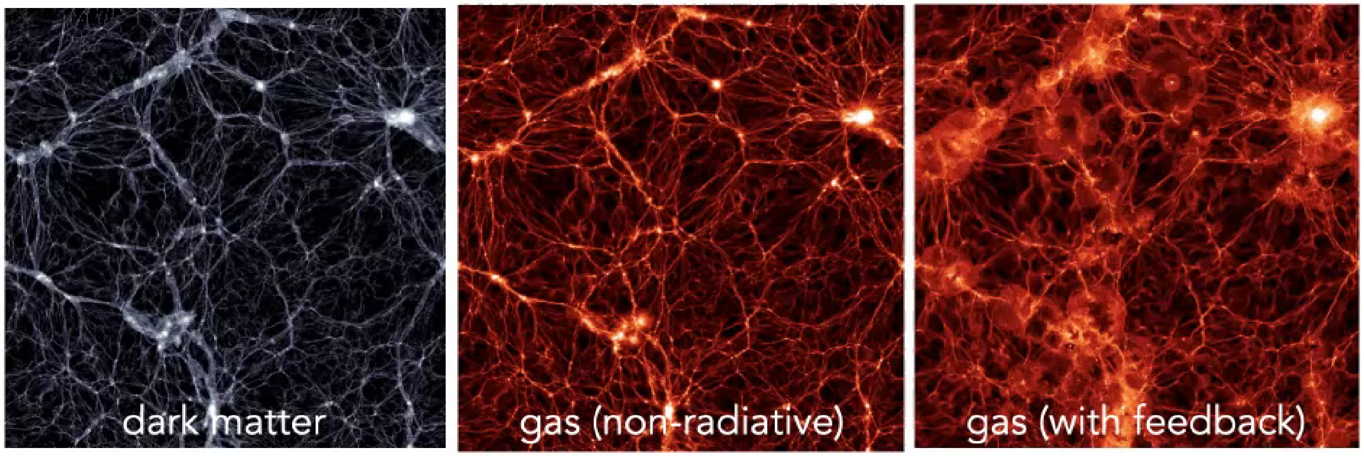


Amodeo Battaglia Schaan Ferraro & ACT 20

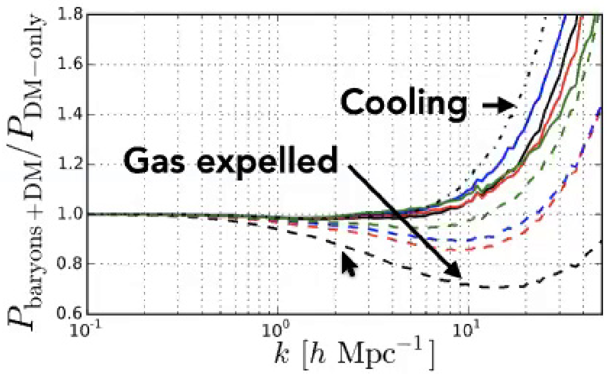
kSZ determines the baryonic contribution!

Baryons only partially alleviate the tension

Gas in clusters: galaxy formation & LSS



Haider+16, Illustris simulation

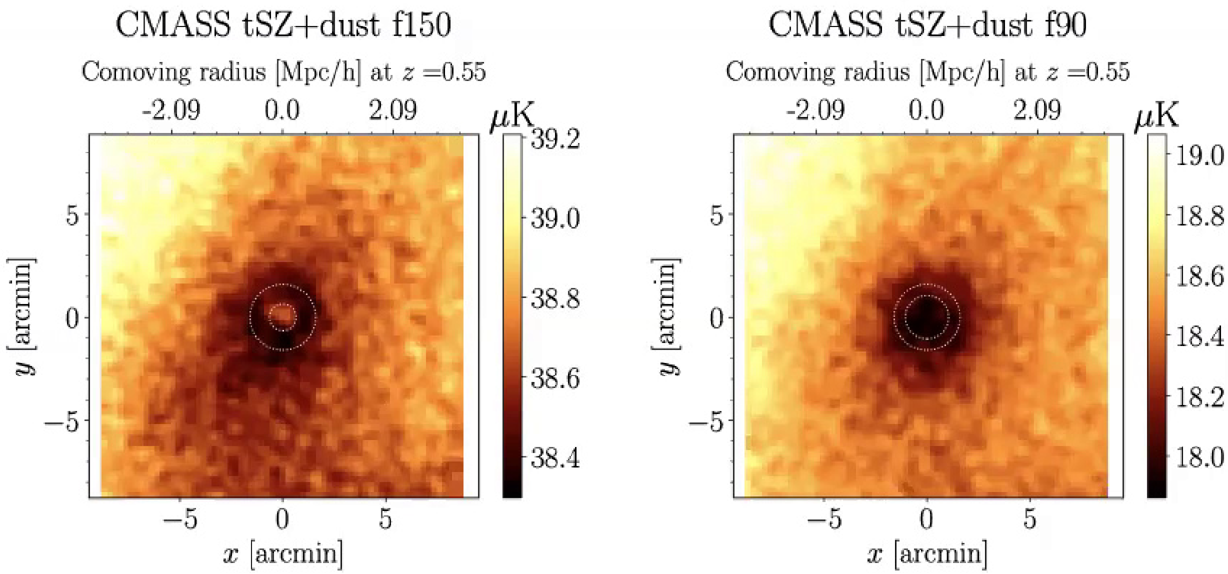


Foreman Becker Wechsler 16

→ Measuring gas profile constrains feedback mechanisms

Feedback is the largest source of uncertainty on the small-scale matter power spectrum

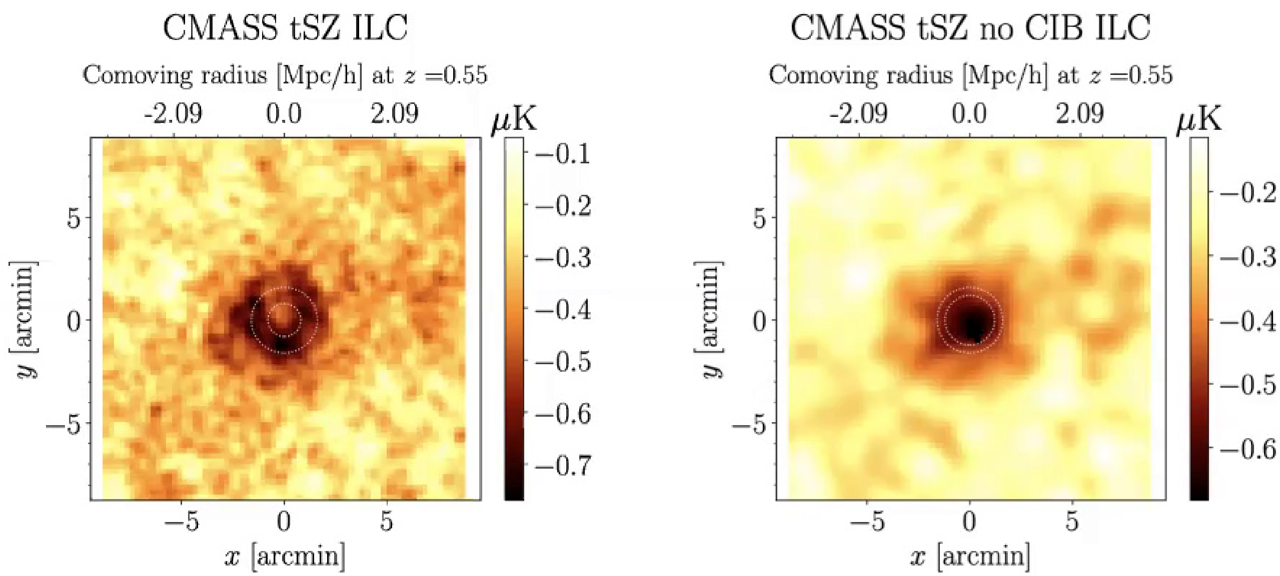
CMASS tSZ + dust



Extended tSZ profile is well resolved!

Point-like dust emission at 150 GHz

CMASS tSZ

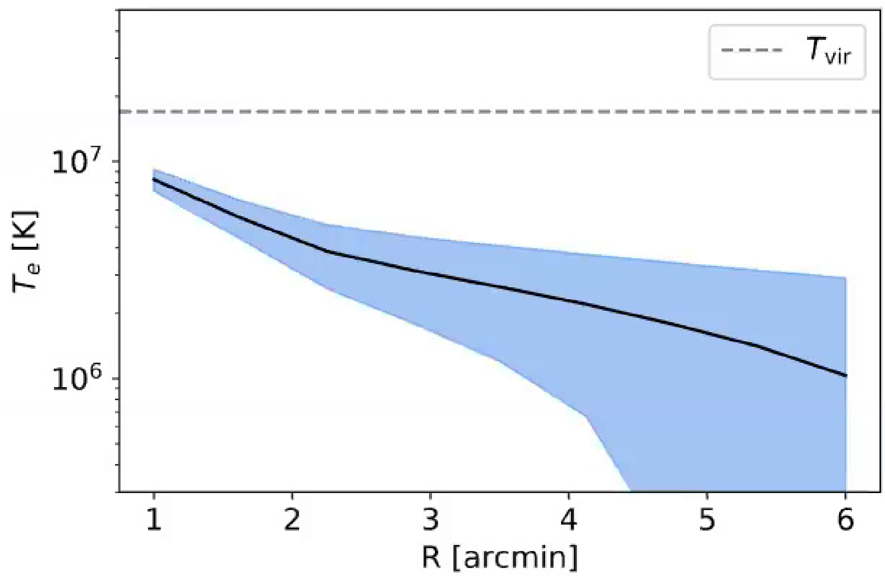


The ILC with CIB deprojection is effective at nulling the dust emission.

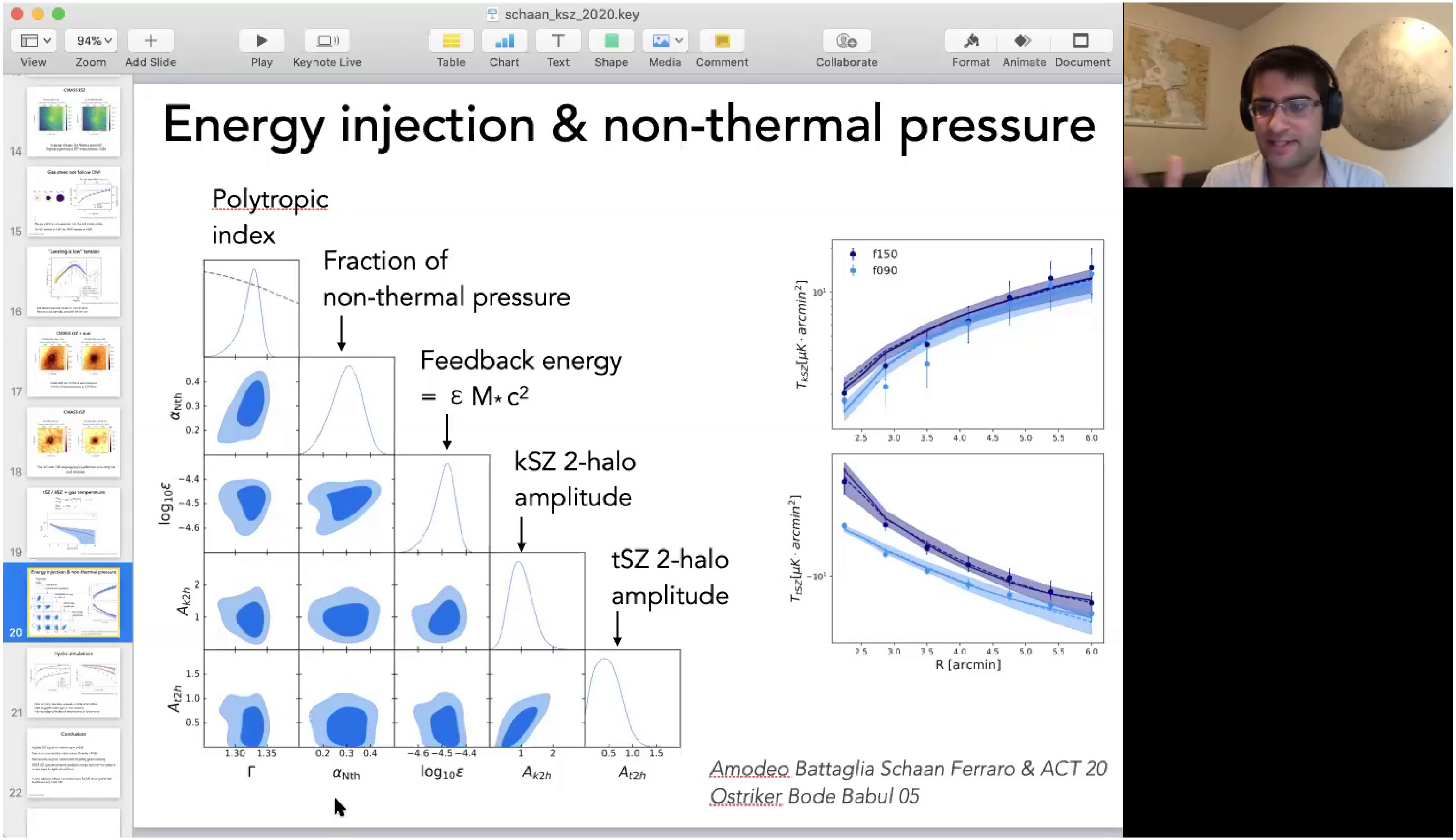
tSZ / kSZ = gas temperature

$$\frac{\delta T_{\rm tSZ}}{T_{\rm CMB}} = f(\nu)\,\tau \left(\frac{v_{\rm thermal}}{c}\right)^2 \quad \propto \tau\, T_e$$

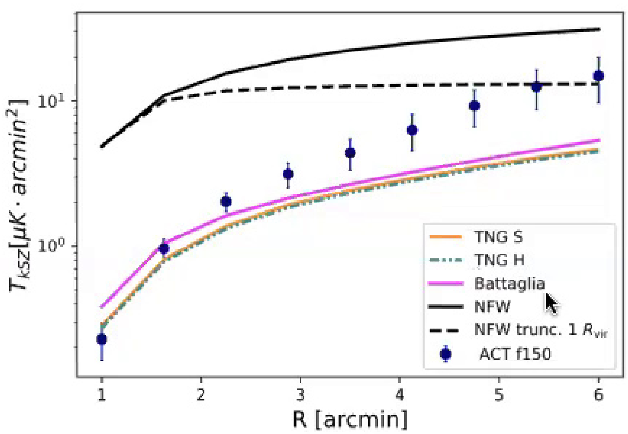
$$\frac{\delta T_{\rm kSZ}}{T_{\rm CMB}} = \tau \frac{v_{\rm bulk}}{c} \quad \propto \tau$$

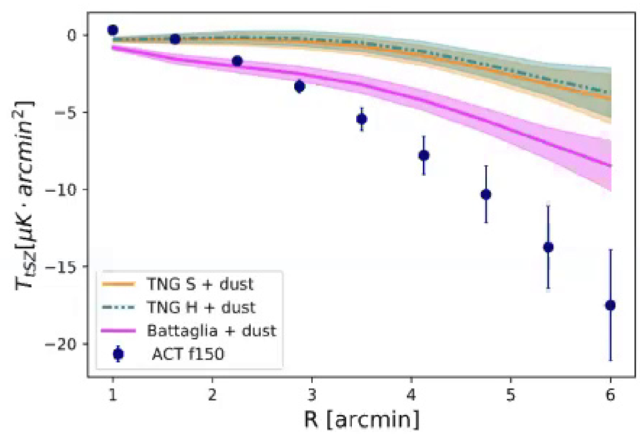


Amodeo Battaglia Schaan Ferraro & ACT 20


schaan_ksz_2020.key
Energy injection & non-thermal pressure
Polytropic index
Fraction of non-thermal pressure
Feedback energy = ε M* c²
kSZ 2-halo amplitude
tSZ 2-halo amplitude
f150
f090
R [arcmin]
Amodeo Battaglia Schaan Ferraro & ACT 20
Ostriker Bode Babul 05

Hydro simulations





Amodeo Battaglia Schaan Ferraro & ACT 20

New territory: low halo masses, outside virial radius
Data suggests hotter gas in the outskirts
Informs subgrid feedback prescriptions in hydro sims

Conclusions

Highest kSZ signal-to-noise to date (6-8σ)

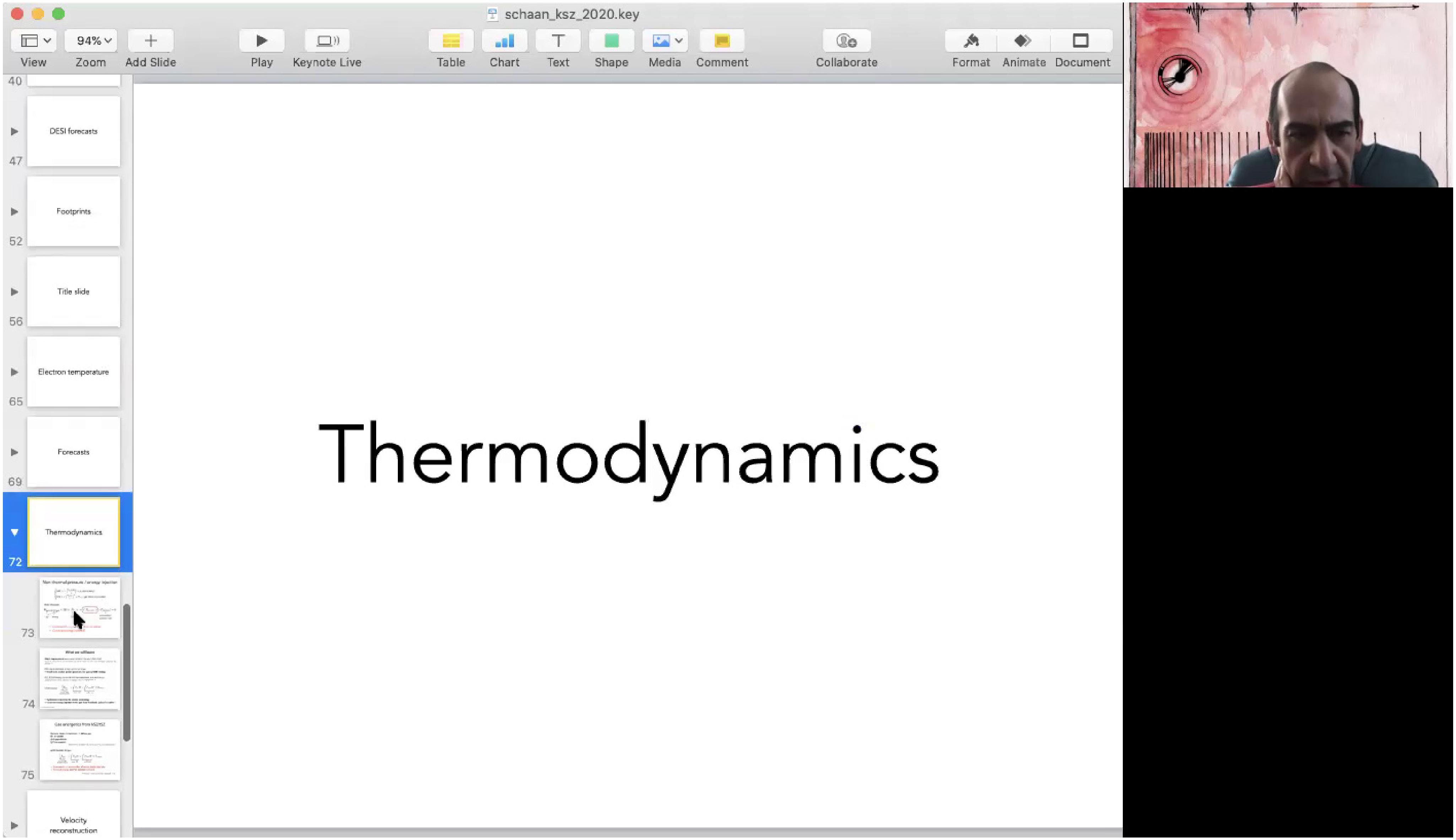
Gas more extended than dark matter (formally >90σ)

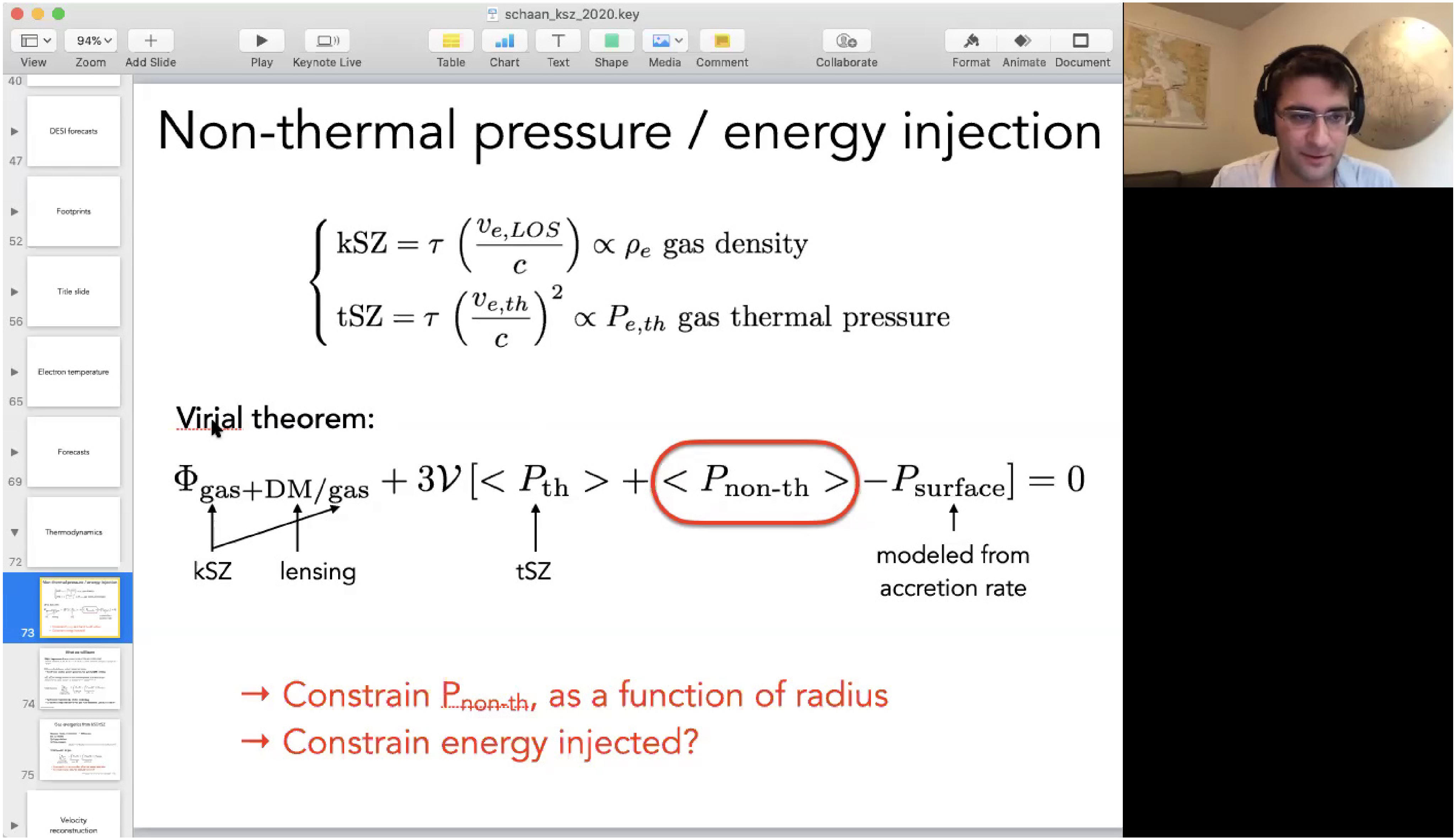
KSZ fixes the baryonic contribution to galaxy-galaxy lensing

KSZ & tSZ: gas temperature, feedback energy, non-thermal pressure
→ new input for hydro simulations

Future: baryonic effects on cosmic shear & CMB lensing with Mat Madhavacheril, Colin Hill

Emmanuel Schaan


schaan_ksz_2020.key
View
94%
Zoom
Add Slide
Play
Keynote Live
Table
Chart
Text
Shape
Media
Comment
Collaborate
Format
Animate
Document
40
DESI forecasts
47
Footprints
52
Title slide
56
Electron temperature
65
Forecasts
69
Thermodynamics
72
73
74
75
Velocity reconstruction
Thermodynamics


schaan_ksz_2020.key
View
Zoom
Add Slide
Play
Keynote Live
Table
Chart
Text
Shape
Media
Comment
Collaborate
Format
Animate
Document
DESI forecasts
Footprints
Title slide
Electron temperature
Forecasts
Thermodynamics
Velocity reconstruction
Non-thermal pressure / energy injection
$\mathrm{kSZ} = \tau \left(\frac{v_{e,LOS}}{c}\right) \propto \rho_e$ gas density
$\mathrm{tSZ} = \tau \left(\frac{v_{e,th}}{c}\right)^2 \propto P_{e,th}$ gas thermal pressure
Virial theorem:
$\Phi_{\mathrm{gas+DM/gas}} + 3\mathcal{V}\left[< P_{\mathrm{th}} > + < P_{\mathrm{non\text{-}th}} > - P_{\mathrm{surface}}\right] = 0$
kSZ
lensing
tSZ
modeled from accretion rate
→ Constrain $P_{\mathrm{non\text{-}th}}$, as a function of radius
→ Constrain energy injected?

schaan_ksz_2020.key

Ostriker Bode Babul gas model

ICM model, applied to IGM

Ostriker Bode Babul 05, Bode Ostriker Vikhlinin 09, Shaw+10

Gas initially follows dark matter —> energy E_i

Fixed fraction of gas turns into stars

Feedback injects energy $\epsilon M_\star c^2$ back into gas

Gas relaxes to a polytrope $\rho_{\rm gas}(r) = \rho_0 \theta(r)^{\frac{1}{\Gamma-1}}, P_{\rm tot}(r) = P_0 \theta(r)^{\frac{\Gamma}{\Gamma-1}}$

in equilibrium $dP_{\rm tot}/dr = -\rho_{\rm gas} d\Phi/dr$

with a non-thermal pressure $P_{\rm nth}/P_{\rm th} = \alpha_{\rm nth}(R/R_{200m})^{n_{\rm nth}}$

and total energy $E_f = E_i + \epsilon M_\star c^2 + \Delta E_p$

Emmanuel Schaan