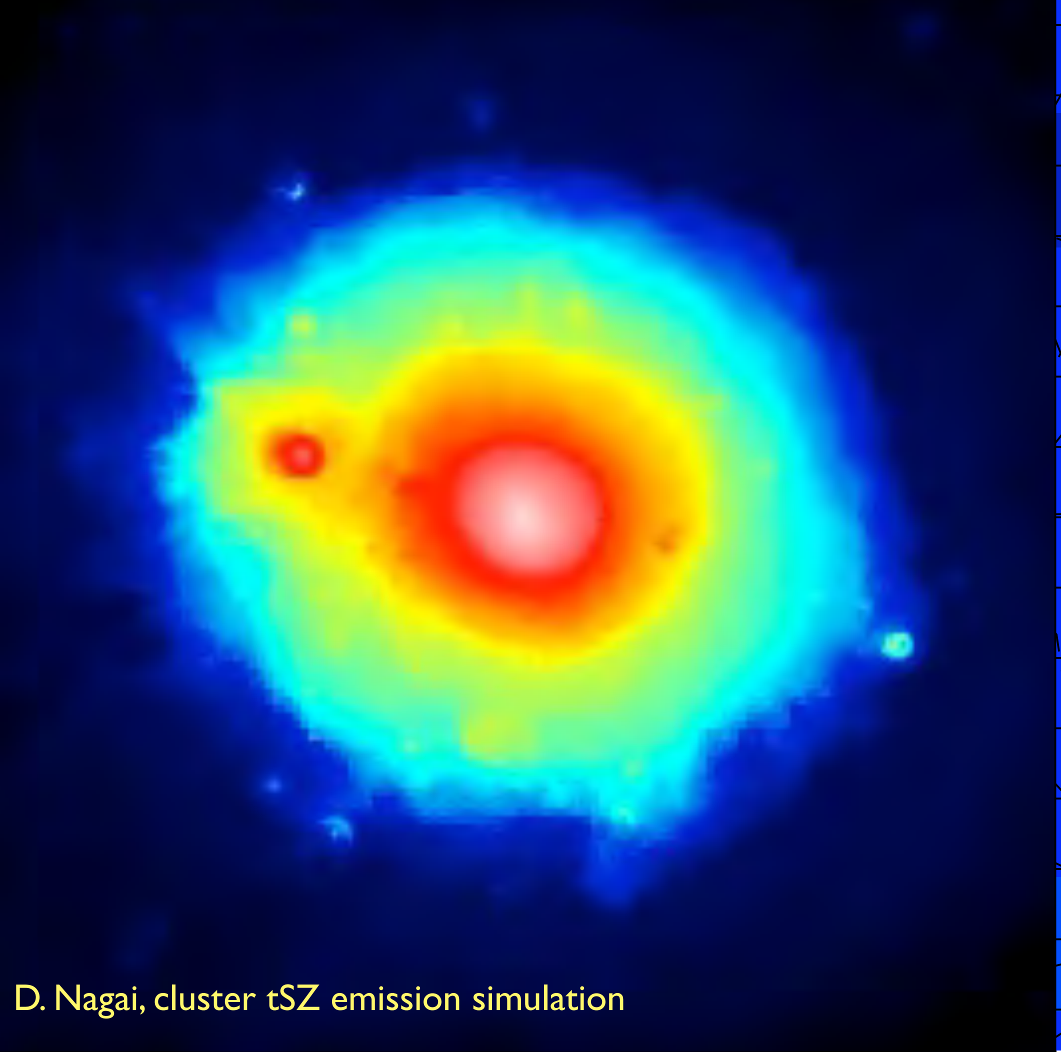
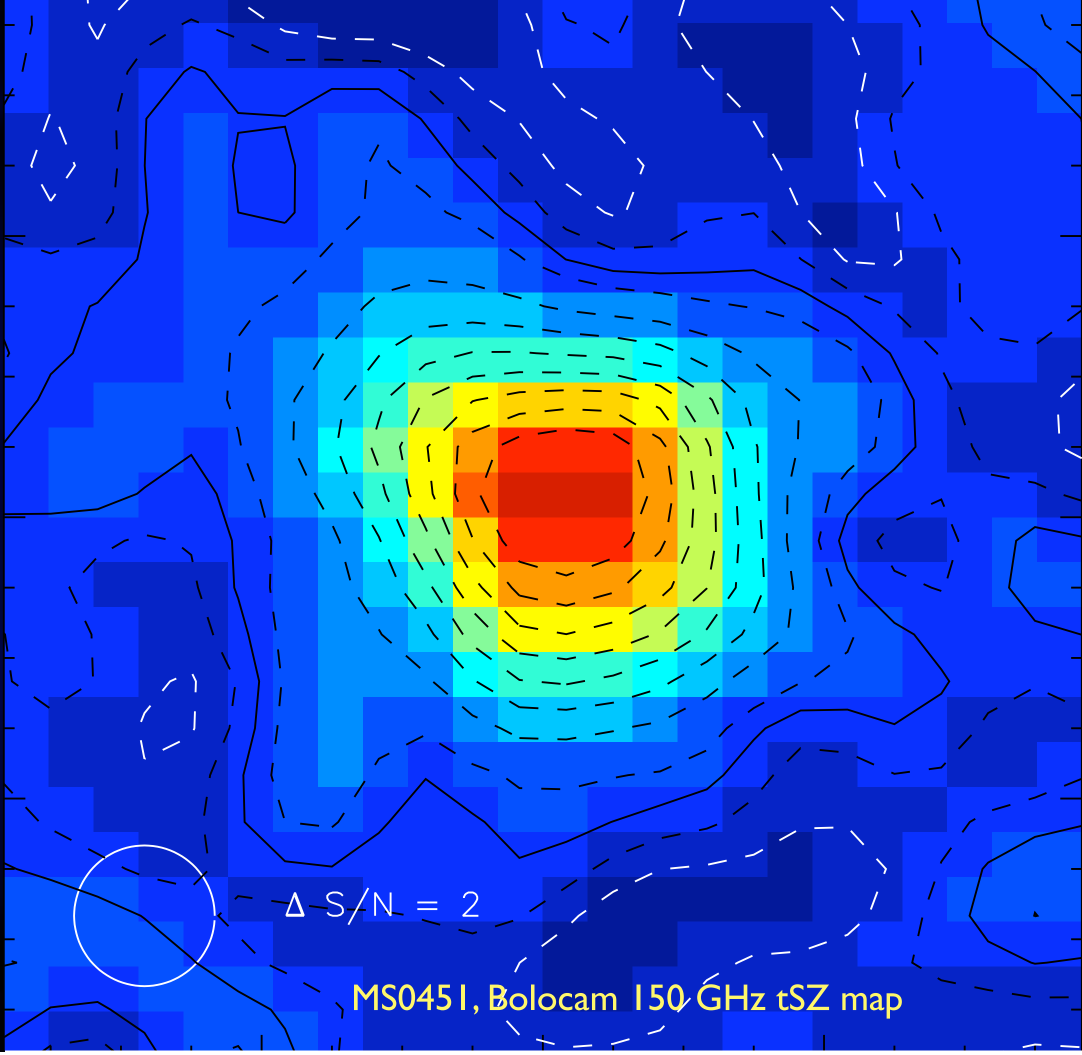
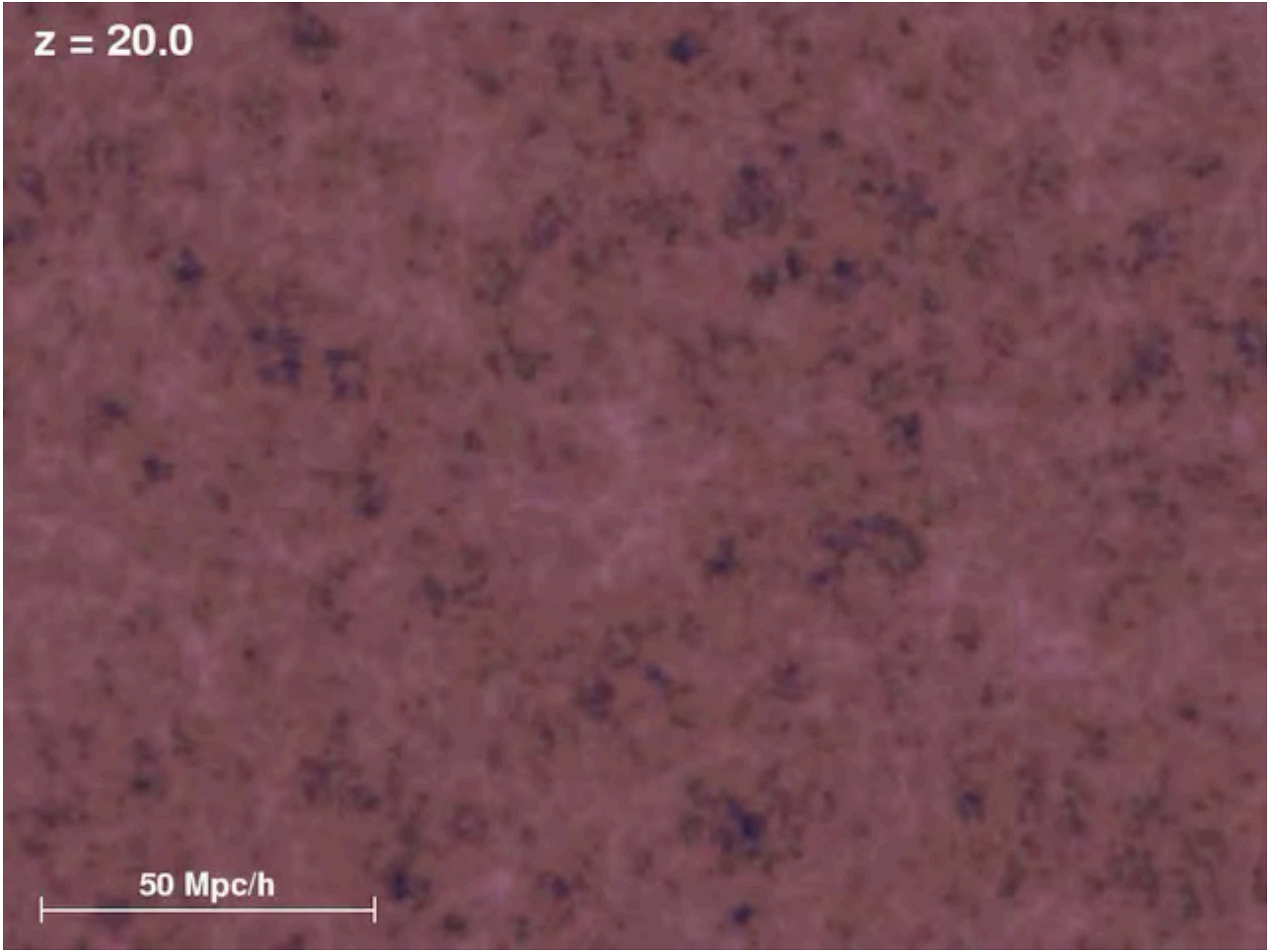


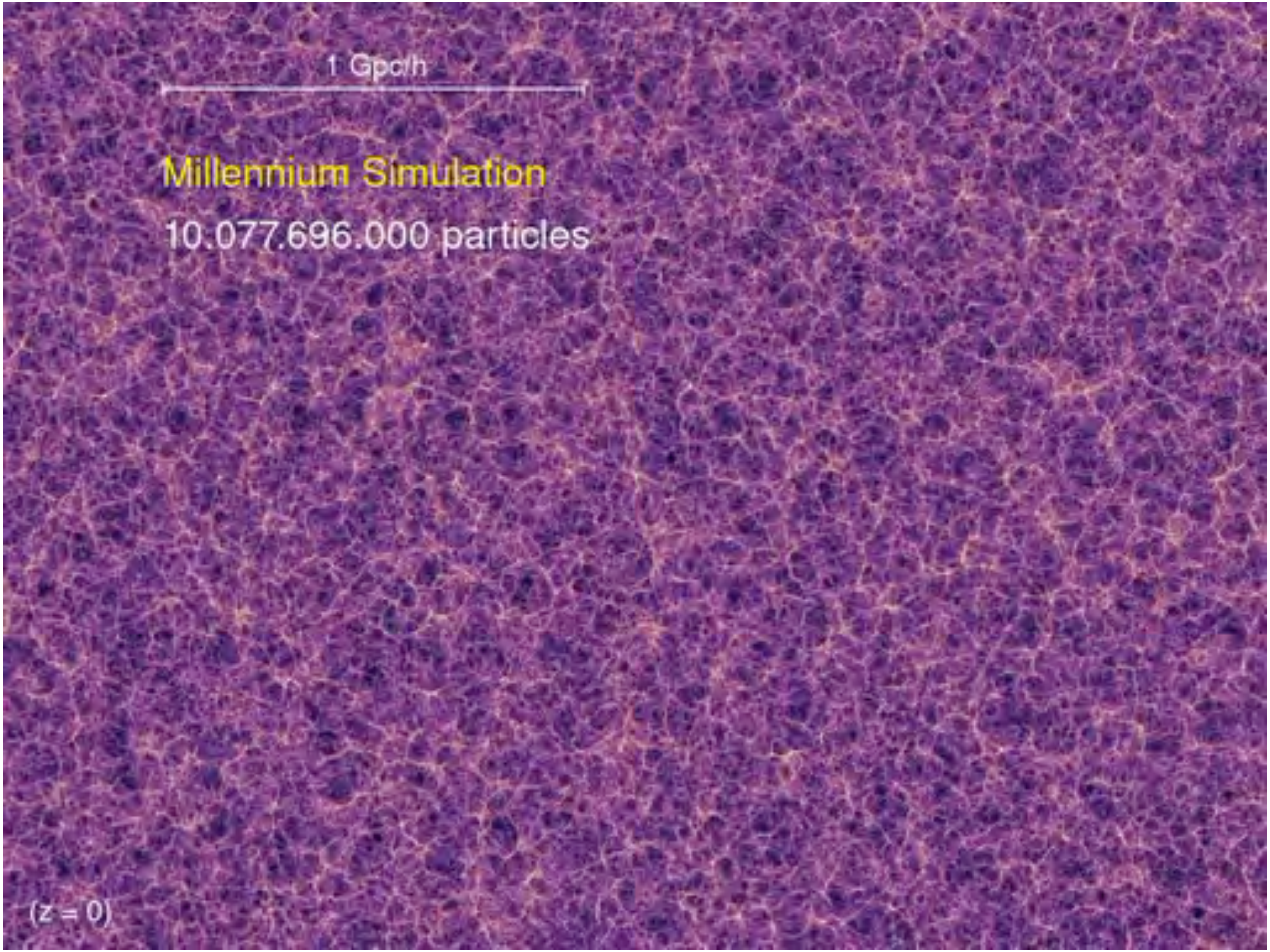


Exploring the Hot, Diffuse and Time-Domain Universe in the Millimeter/Submillimeter

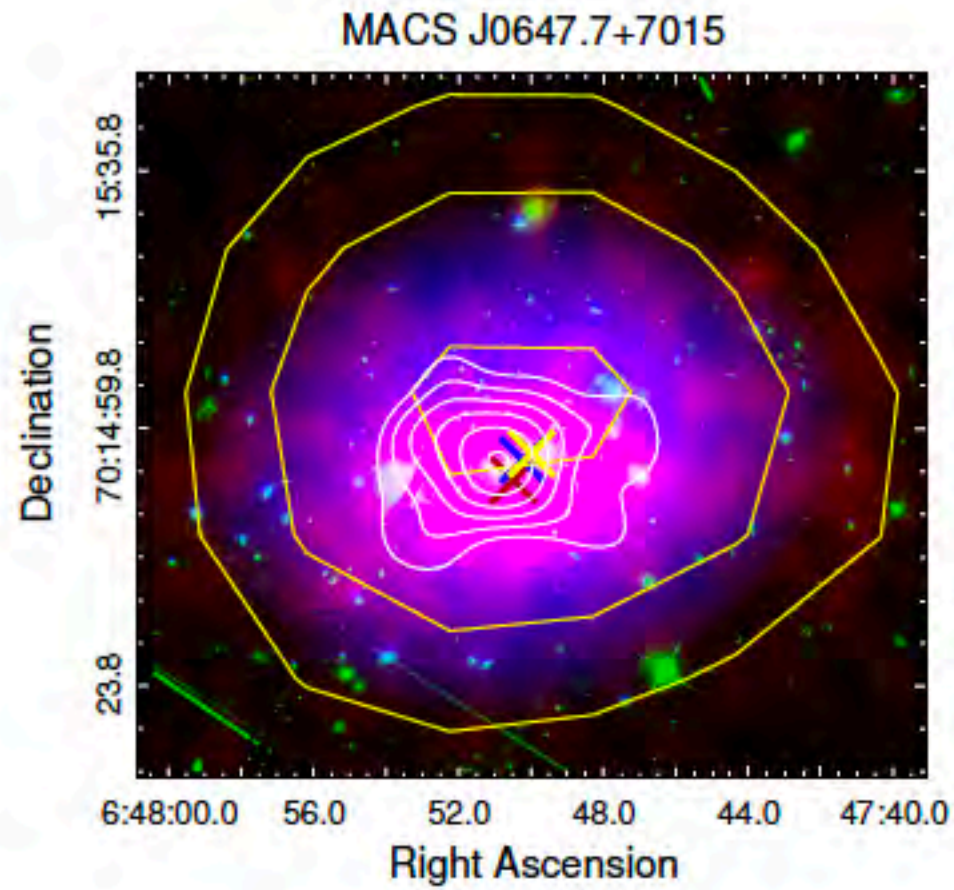
Sunil Golwala/Jack Sayers Ay111 Nov 21, 2025



http://www.mpa-garching.mpg.de/galform/data_vis/index.shtml


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

Galaxy Cluster Primer



Young et al 2014

- Most massive collapsed objects, formed at $z < 2$
- Characteristics:
  - R ~ 1-3 Mpc (10^{25} cm), collapsed from ~10 Mpc region (1 Mpc = [9, 5, 3, 2]' at z = [0.1, 0.2, 0.5, 1])
  - M ~ 10^{14} $M_\odot$ to few x 10^{15} $M_\odot$, mostly dark matter, follows generalized Navarro, Frenk, White (NFW) profile
  - Hot baryonic plasma ~ 15-20% of mass
    - T ~ 10^8 K = few keV
    - L_X = 10^{43}-10^{45} erg/sec
    - density = 0.001- 0.1/cm^3
    - sound crossing time ~ 0.5 Gyr << age → close to hydrostatic equilibrium
    - gas somewhere between isothermal ($P \propto \rho$) and adiabatic ($P \propto \rho^{5/3}$)
    - thermal conduction substantial but not perfect
    - metallicity ~ 1/3-1/2 solar
  - 10s to 100s of galaxies, ~2-3% of mass
  - magnetic field ~ 1 μG
- Observable in O/IR via detection of member galaxies
- Lensing of background galaxies in O/IR maps dark matter

green: HST image
blue: lensing mass
red: Chandra X-ray
white, yellow: SZ
Crosses: centroids for X-ray, SZ, and BCG

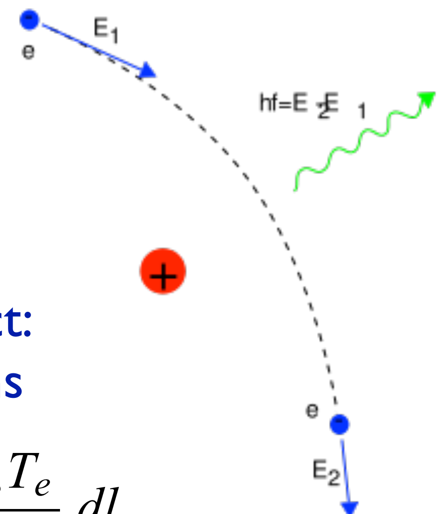
Galaxy Cluster Primer

Intracluster medium “emission” mechanisms:

X-ray emission from thermal bremsstrahlung

$$S_X = \frac{1}{4\pi(1+z)^4}\int n_e^2 \Lambda_{ee}\, dl$$

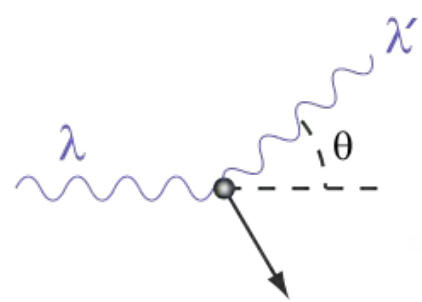
Λ_{ee} = cooling function $\propto T_e^{1/2}$



Thermal Sunyaev-Zeldovich (tSZ) effect:
Compton scattering of CMB photons

$$\Delta T_{\rm CMB} = f_{(x,T_e)} T_{\rm CMB} \int \sigma_T n_e \frac{k_B T_e}{m_e c^2}\, dl$$

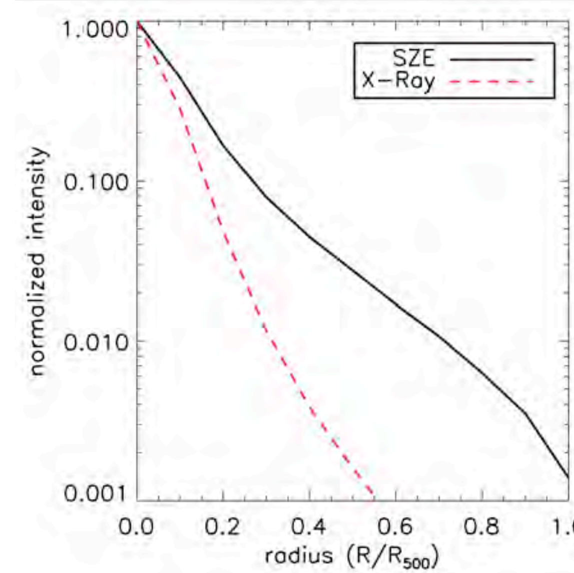
σ_T = Thomson cross-section



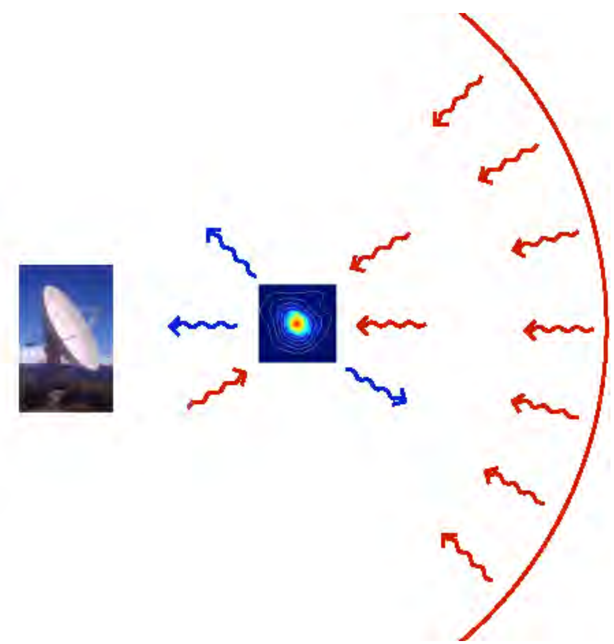
Relativistic SZ (rSZ) effect:

dependence of f on Te

Kinetic SZ (kSZ) effect:
Compton scattering due to Doppler shift
(line-of-sight peculiar velocity)



Note the different dependences on n_e and T_e!



Self-Similar, Universal Cluster Model

Assume gravity dominates, not baryonic physics

- A spherical overdensity breaks away from expansion, collapses, and virializes; density at virialization is cosmology-dependent $\Delta_v \approx 180$. Defines virial radius ("edge of cluster"), total mass M_{tot}

$$\frac{4}{3}\pi\rho_c(z)\Delta_v(z)r_{\rm vir}^3 = M_{\rm tot}$$

$\rho_c(z)$ = critical density at redshift z
$\propto \; E^2(z) = \Omega_{M0}(1+z)^3 + \Omega_\Lambda + \Omega_{k0}(1+z)^2$

- Assume isothermality of gas (virialization to logical extreme) in non-singular isothermal sphere with gas temperature related to galaxy velocities

$$n_e(\boldsymbol{r}) = n_{e_0}\left(1+\frac{r^2}{r_c^2}\right)^{-3\beta/2} \qquad \beta = \frac{\mu m_p \sigma^2}{kT_e}$$

σ = 1D galaxy velocity dispersion
T_e = gas (electron) temperature
β = 1 for ideal gas in equipartition, no gravity

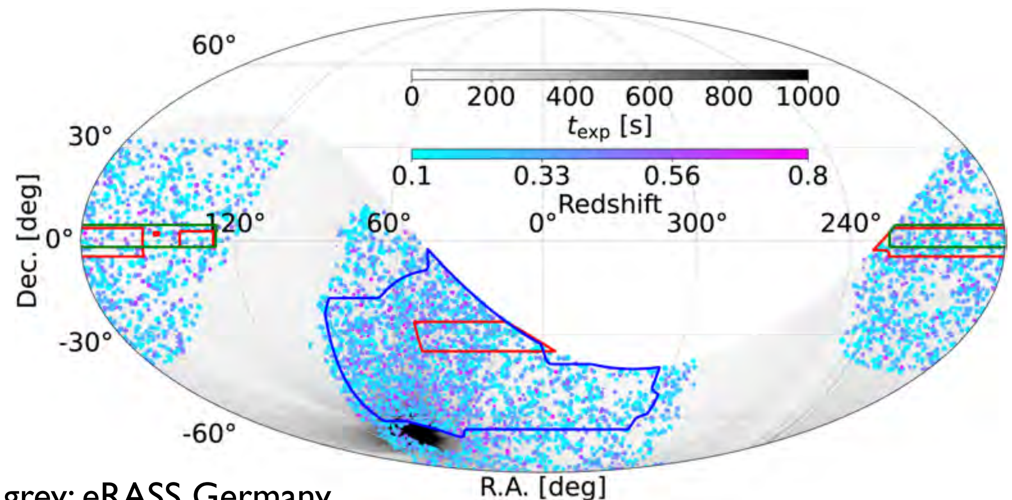
- Require hydrostatic equilibrium (gas pressure provides support against gravity): relates total mass sourcing gravity to gas temperature and density profile

$$M(r) = \frac{3\beta kT_e}{G\mu m_p}\frac{r^3}{r_c^2+r^2}$$

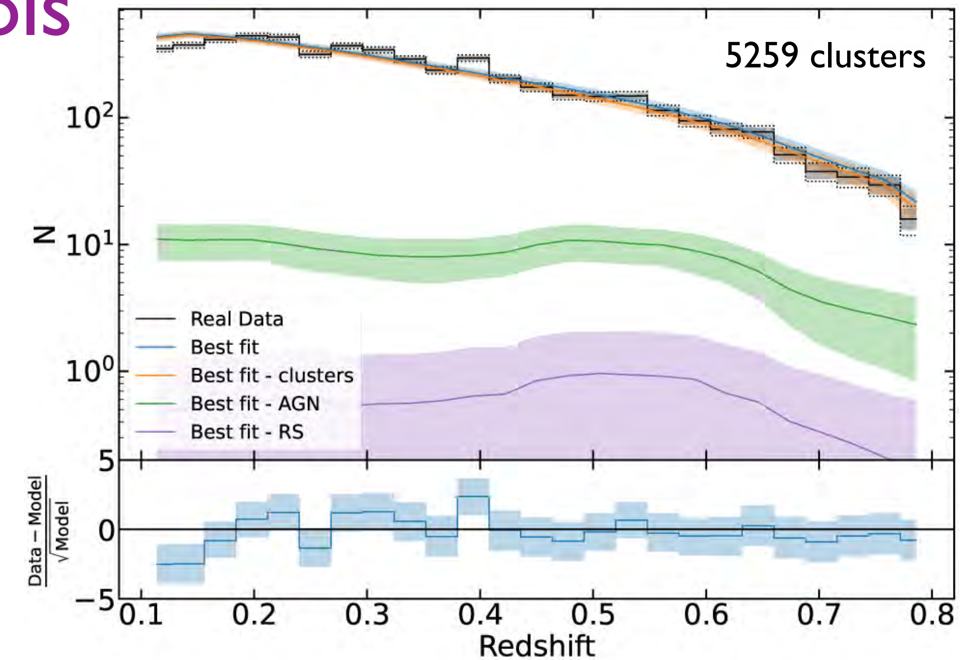
Clusters as Cosmological Tools

- Scaling relations and universal pressure profile suggest clusters are "well-behaved" and close to self-similar expectations
- What can we do with them?
  - Geometrical tests
    - Angular diameter distance as function of z:
      - assume X-ray and SZ derived from same spherical plasma; different dependences on D_A (n_e vs. n_e^2) enable reconstruction of D_A (e.g., Wan et al 2021)
      - assume $f_{\rm gas}$ is independent of z and use differing dependences of estimates for $M_{\rm gas}$ and $M_{\rm tot}$ on D_A to estimate D_A (e.g., Mantz et al 2022)
  - Growth function + volume element tests: indirect measurements of cosmo params $\Omega_{\rm m}$, Ω_Λ, equation of state parameter w
    - $dN(>M)/dz$ as function of z: abundance of clusters above a mass threshold as function of z measures combination of growth function and volume element, present day value measures normalization of density fluct. PS, σ_8
    - dN/dM as function of z: variation in mass function with z measures growth function, present day value measures normalization of density fluct. PS, σ_8
    - SZ secondary anisotropy spectrum: ensemble of clusters over cosmic time
    - All need connection between M and an observable: scaling relations v. important
    - M-independent prospect: peculiar velocity field via kinetic SZ effect

Clusters as Cosmological Tools

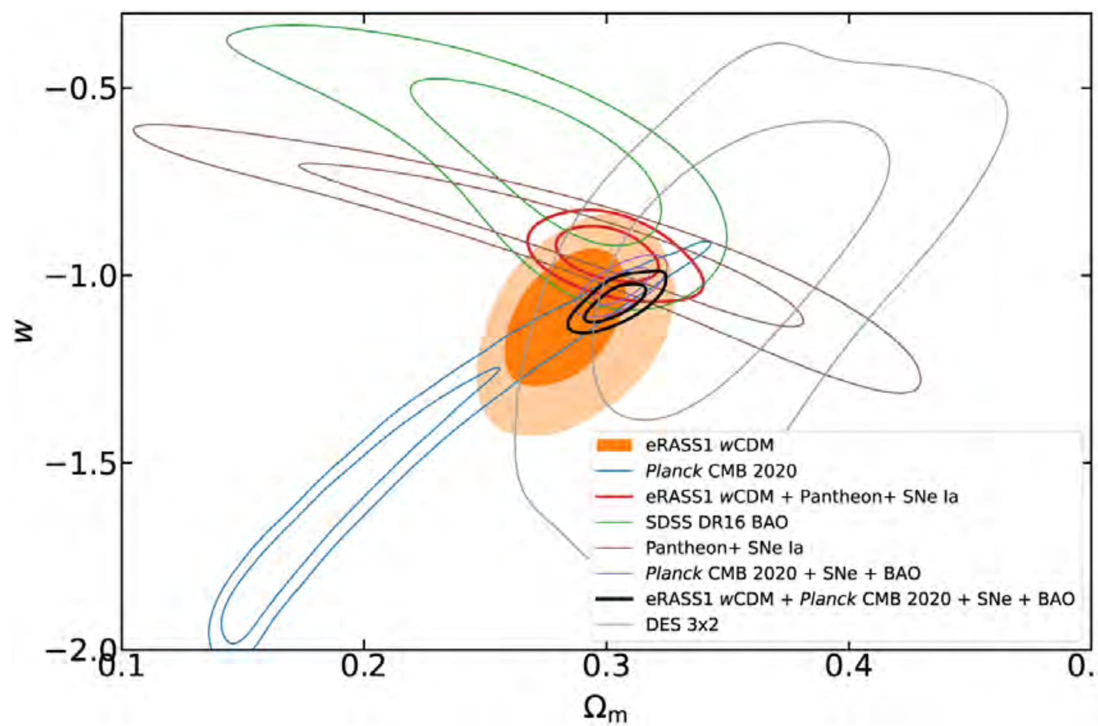


grey: eRASS Germany
dots: optically confirmed; outlines: lensing overlap



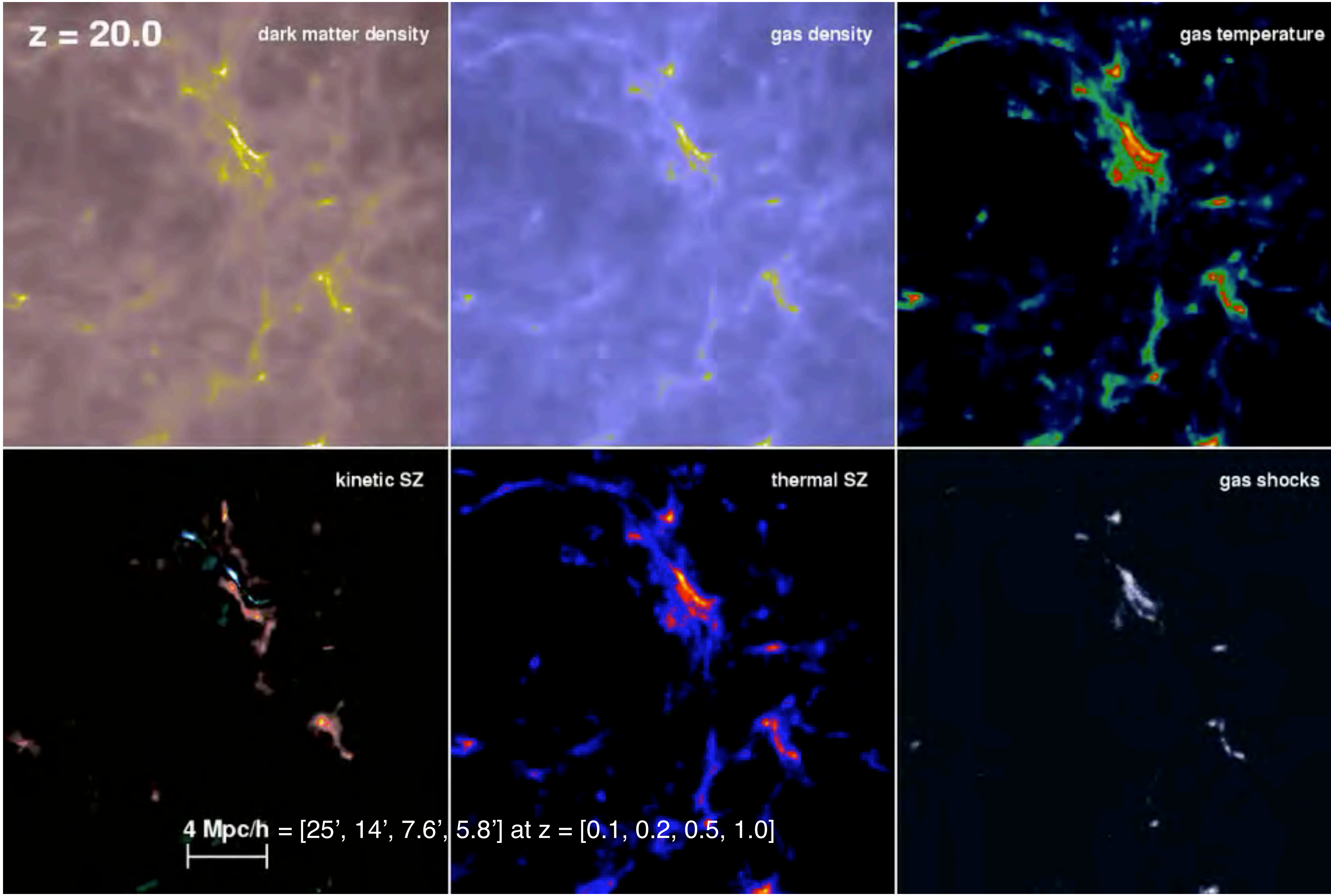
$dN(>M)/dz$ from eROSITA

- First all-sky X-ray survey since ROSAT RASS in 1990s
  - (but sky split between Germany and Russia…)
- Mass calibrated using lensing
  - Scatter contributes to uncertainty
- Consistent with other cosmo probes, helps to tighten constraints



Ghirardini et al 2024

It’s really more complicated than that...



Questions, Questions, Questions

Underlying structure

Does the dark matter profile match simulations? Is it reflective of the redshift of formation? How does it evolve with time? How do scaling relation parameters depend on formation history and current morphology? How much dark matter substructure is preserved?

Composition

What is the baryon fraction as a function of radius and redshift? How are the baryons divided among stars, cold gas, and hot gas? What is the metallicity as a function of radius and redshift? Is there segregation of different elements? How did cluster magnetic fields come into existence and evolve?

Formation and Virialization

How is the kinetic energy of infalling gas thermalized? What are the bulk motions in the ICM? What do they tell us about the cluster assembly history? How much does the ICM deviate from hydrostatic equilibrium? What is the size and cause of temperature gradients in the ICM?

Energy Input and Loss Mechanisms

What is the role of radiative cooling? What is the form and effect of feedback from galaxies (AGN, winds, cosmic rays)? What is the cosmic ray content of the ICM? What impact does it have on the thermodynamics?

Physics of the ICM Plasma

What is the microscopic plasma physics of the ICM: thermal conductivity, viscosity, electron-ion equilibration time? What is the level of turbulence in the ICM? How is it created? Is the ICM stable against convective instability? What is the magnetohydrodynamics of the ICM, and how does it affect the plasma's properties?

What are the systematic limits on our ability to constrain cosmology with clusters?

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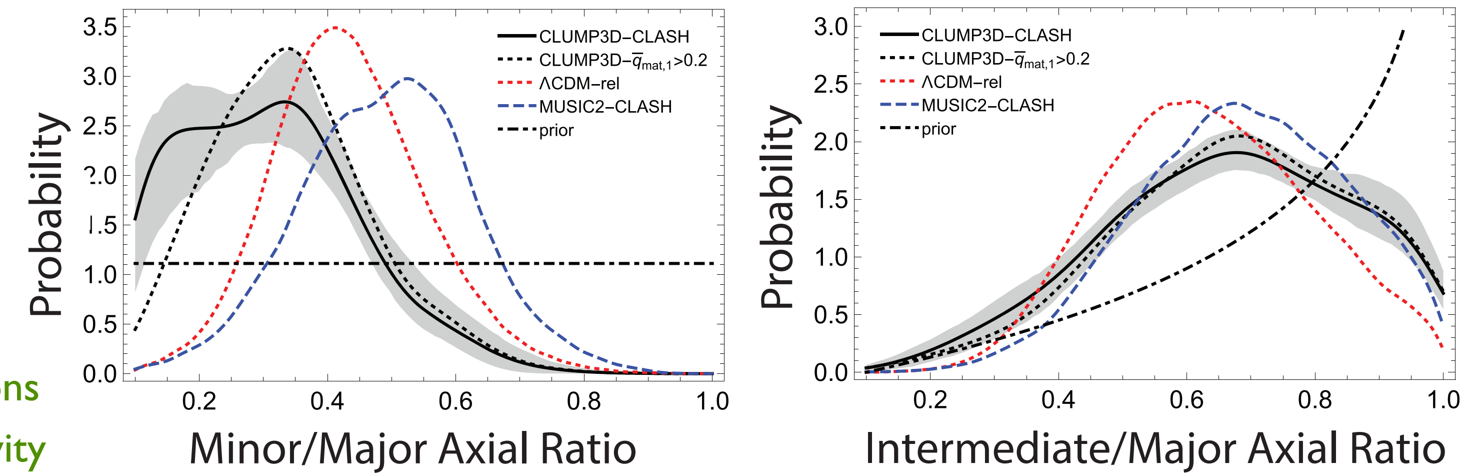
What is the distribution of galaxy cluster shapes?

⟵ less spherical

Sereno et al 2018



Motivation

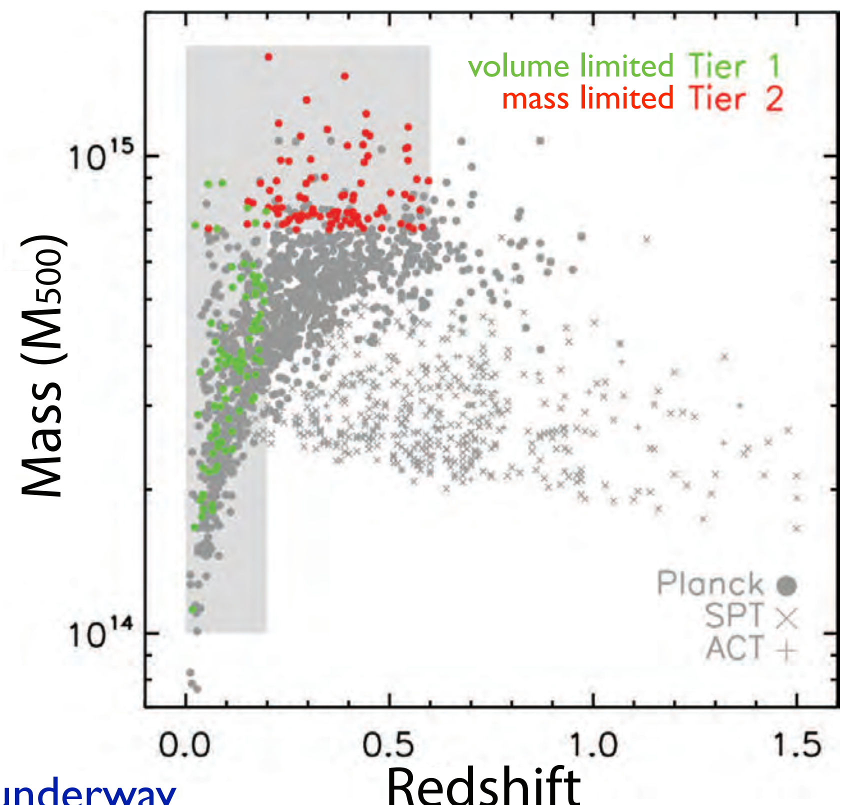
- Shapes depend on how/when galaxy clusters form;
- $\Longrightarrow$ sensitive to
  - underlying cosmology
  - dark matter self-interactions
  - detailed properties of gravity
  - non-gravitational physical processes in the ICM
- Clusters ~ triaxial ellipses
- SZ brightness $\sim n_e T_e \, \Delta l$, X-ray brightness $\sim n_e^2 \, \Delta l$
  - $\Longrightarrow$ constrain LOS cluster length $\Delta l \sim (SZ)^2/(XR \times T_e^2)$

CLASH triaxial shape analysis w/SZ + XR

- more robust concentration-mass relation than lensing alone
- suggests recently formed halos less spherical

XMM-Heritage Triaxial Shape program

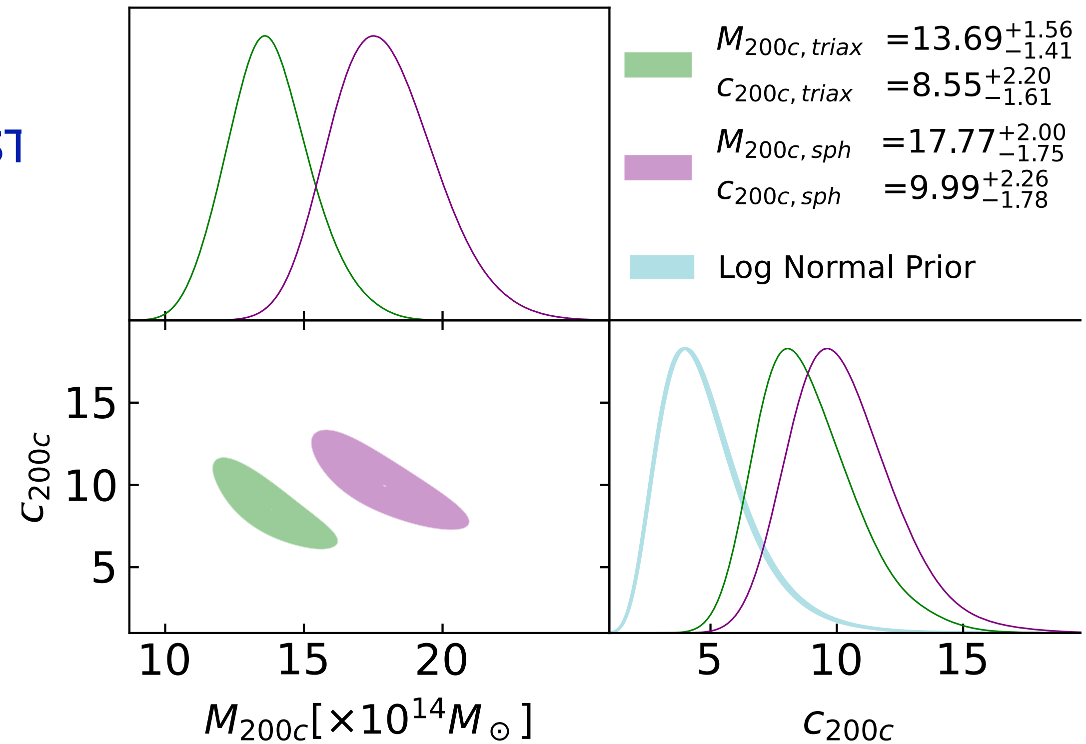
- 3 Msec for 118 SZ-selected clusters SZ WG, obs done
- weak lensing via Caltech Subaru exchange time
- x5 more clusters than CLASH $\Longrightarrow$ definitive analysis
- demo projects completed, multi-year analysis of full sample underway



CHEX-MATE Results To Date

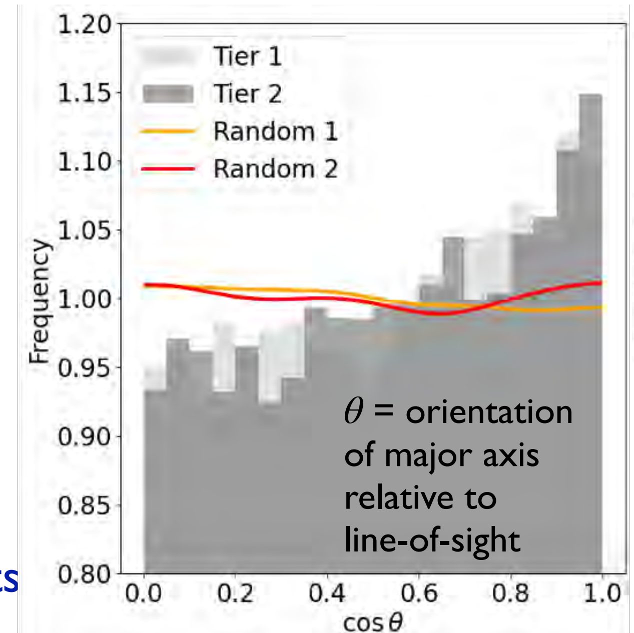
Triaxial Modeling of A1689

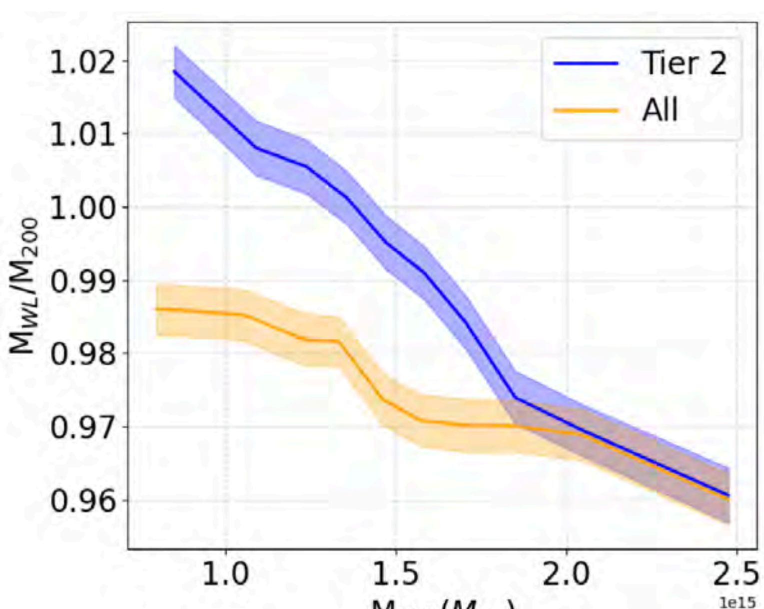
- Ph Y4 grad A. Gavidia, former pd J. Kim (→ Asst Prof, KAIST
- Mass estimate difference ≫ statistical uncertainties: triaxial modeling needed for 10%-level mass estimates
- Concentration affected at ~ statistical uncertainty: potential significant bias in a large sample



CHEX-MATE systematics

- Ay Y3 grad H. Saxena
- Triaxiality important!
- Selection function depends on orientation angle; also elongation
- Weak lensing mass estimates biased by up to 2%
  - Up to 5% for Tier 1
- Critical for %-level constraints





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Two papers published, third has been reviewed!

A&A, 686, A97 (2024)
https://doi.org/10.1051/0004-6361/202347399

Astronomy & Astrophysics

CHEX-MATE: CLUster Multi-Probes in Three Dimensions (CLUMP-3D)

I. Gas analysis method using X-ray and Sunyaev–Zel'dovich effect data

Junhan Kim[1,2], Jack Sayers[1], Mauro Sereno[3,4], Iacopo Bartalucci[5], Loris Chappuis[6], Sabrina De Grandi[7], Federico De Luca[8,9], Marco De Petris[10], Megan E. Donahue[11], Dominique Eckert[6], Stefano Ettori[3,4], Massimo Gaspari[24,12], Fabio Gastaldello[5], Raphael Gavazzi[13,14], Adriana Gavidia[1], Simona Ghizzardi[5], Asif Iqbal[15], Scott T. Kay[16], Lorenzo Lovisari[5,17], Ben J. Maughan[18], Pasquale Mazzotta[8,9], Nobuhiro Okabe[19,20,21], Etienne Pointecouteau[22], Gabriel W. Pratt[15], Mariachiara Rossetti[5], and Keiichi Umetsu[23]

Astronomy & Astrophysics manuscript no. main
July 16, 2025

CHEX-MATE: Cluster Multi-Probes in Three Dimensions (CLUMP-3D)

II. Combined Gas and Dark Matter Analysis from X-ray, SZE, and WL

A. Gavidia[1], J. Kim[2], J. Sayers[1], M. Sereno[3,4], L. Chappuis[5,6], D. Eckert[6], K. Umetsu[7], H. Bourdin[8,9], F. De Luca[8,9], S. Ettori[3,4], M. Gaspari[10], R. Gavazzi[11,12], S. Kay[13], L. Lovisari[14,15], P. Mazzotta[8,9], G. W. Pratt[5], E. Rasia[16,17], and M. Rossetti[14]

A&A, 700, A128 (2025)
https://doi.org/10.1051/0004-6361/202555719

Astronomy & Astrophysics

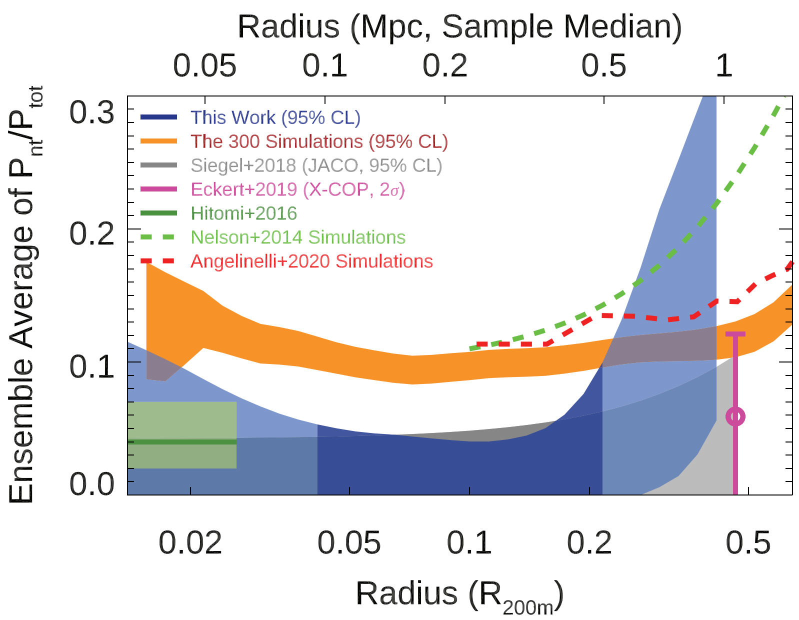
CHEX-MATE: The impact of triaxiality and orientation on Planck SZ cluster selection and weak lensing mass measurements

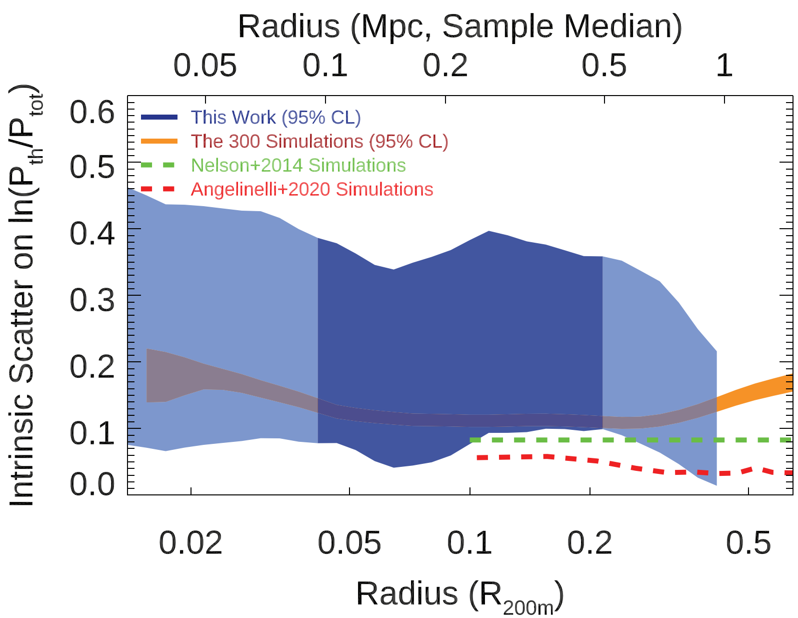
H. Saxena[1,*], J. Sayers[1], A. Gavidia[1], J.-B. Melin[2], E. T. Lau[3], J. Kim[4], L. Chappuis[2,17], D. Eckert[17], S. Ettori[6,7], M. Gaspari[12], F. Gastaldello[8], C. Giocoli[6,7], S. Kay[18], L. Lovisari[8,9], B. Maughan[19], F. Oppizzi[11], M. De Petris[13], G. W. Pratt[5], E. Pointecouteau[10], E. Rasia[14,15,16], M. Rossetti[8], and M. Sereno[6,7]

Analysis beginning to calibrate Euclid,
which requires 1% accuracy in WL masses!

Non-Thermal Pressure → tSZ Deficit

CLASH (16 clusters, *ad hoc* selection)





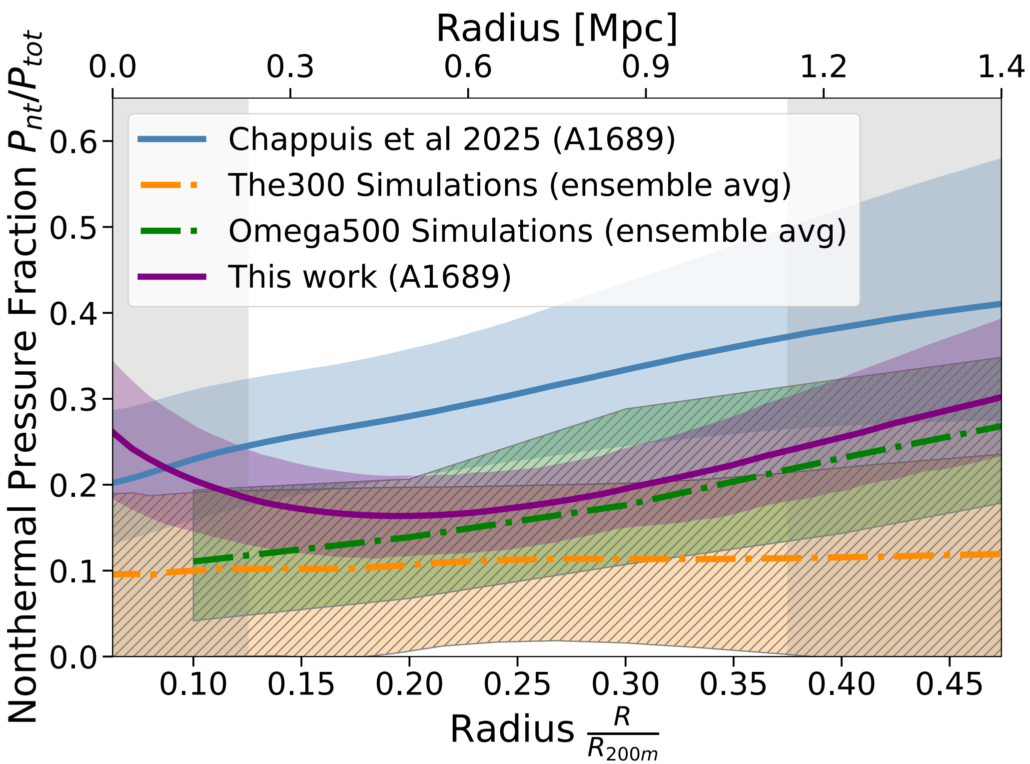
Sayers et al 2021

Prior results

- Weak-lensing + X-ray + Bolocam tSZ for CLASH
- Consistency with simulations observed at large radius
- Non-thermal pressure at small radius lower than sims
- ⟹ There is thermalization not accounted for by sims
- CHEX-MATE will test this with more statistical precision and cleaner selection function

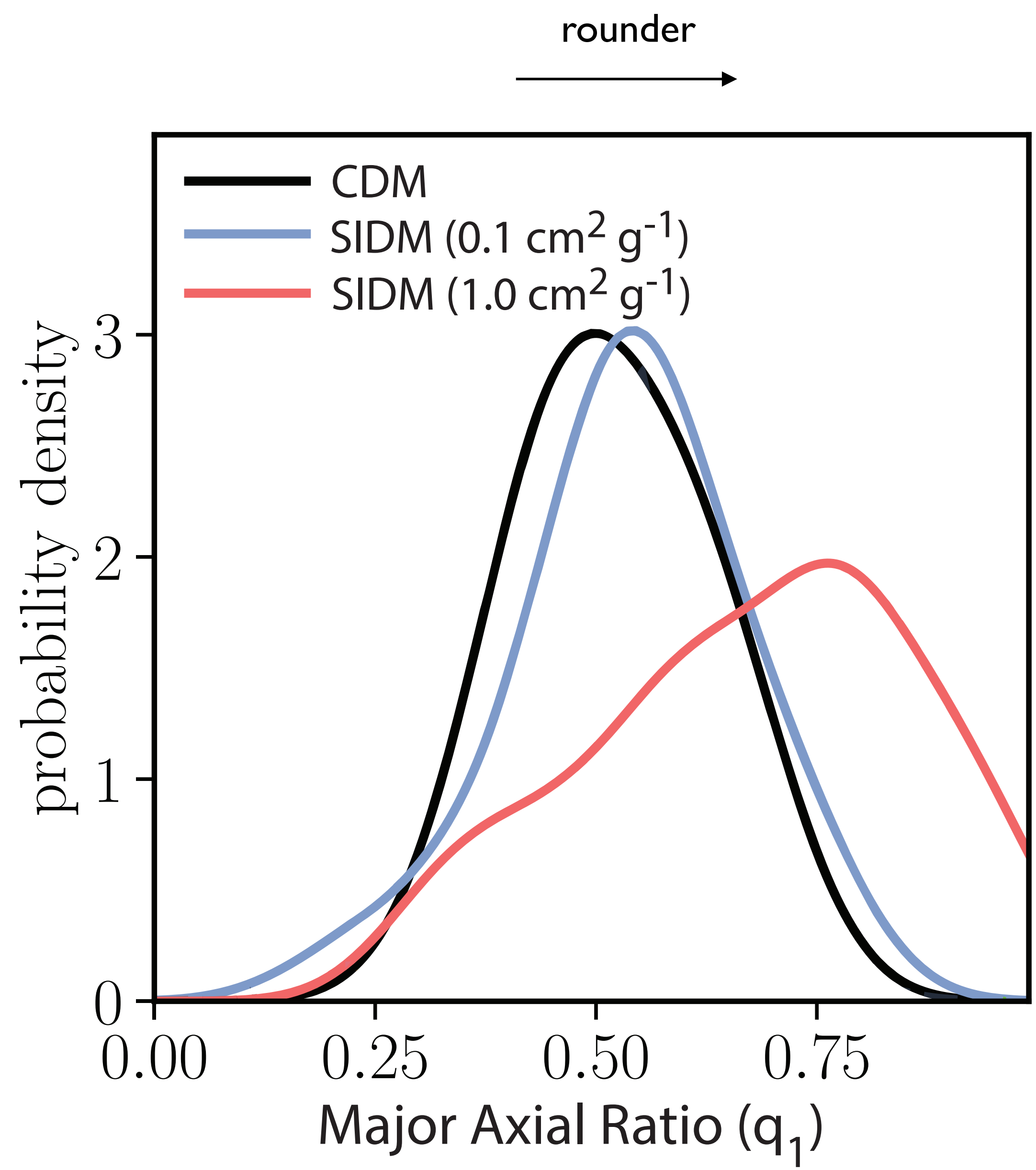
Initial CHEX-MATE results

- Abell 1689 consistent with being relaxed, low P_{nt}



Bonus: Contraints on Self-Interacting DM

- Halo axial ratios tests whether DM is self-interacting (SIDM)
  - SIDM causes rounding of halos
  - Could address "core-cusp" problem in dwarf galaxies
    - Density profiles flatter than expected for non-SIDM
    - Baryonic systematic limit ability to directly measure
  - Bullet Cluster geometries constraining but rare
    - $\lesssim$ 1 cm²/g from Bullet
    - Triaxiality tests provide more statistical power
- CHEX-MATE will improve constraint to $\pm$0.15 cm²/g



ICM Velocity Structure in Mergers

Question:

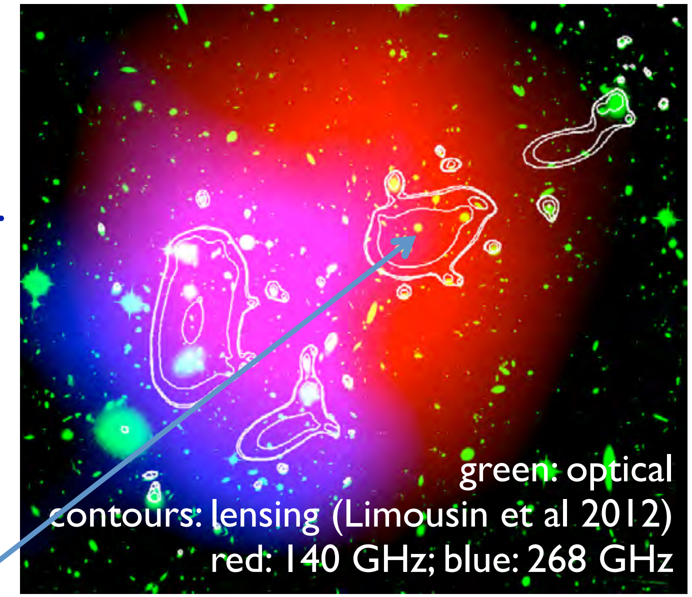
What are the dynamics and associated physics processes in cluster mergers?

Motivation:

~ half of a typical cluster's mass is acquired from mergers

Merger velocities are sensitive to cosmology

Interesting merger-driven physics — shocks, sloshing cores, etc.



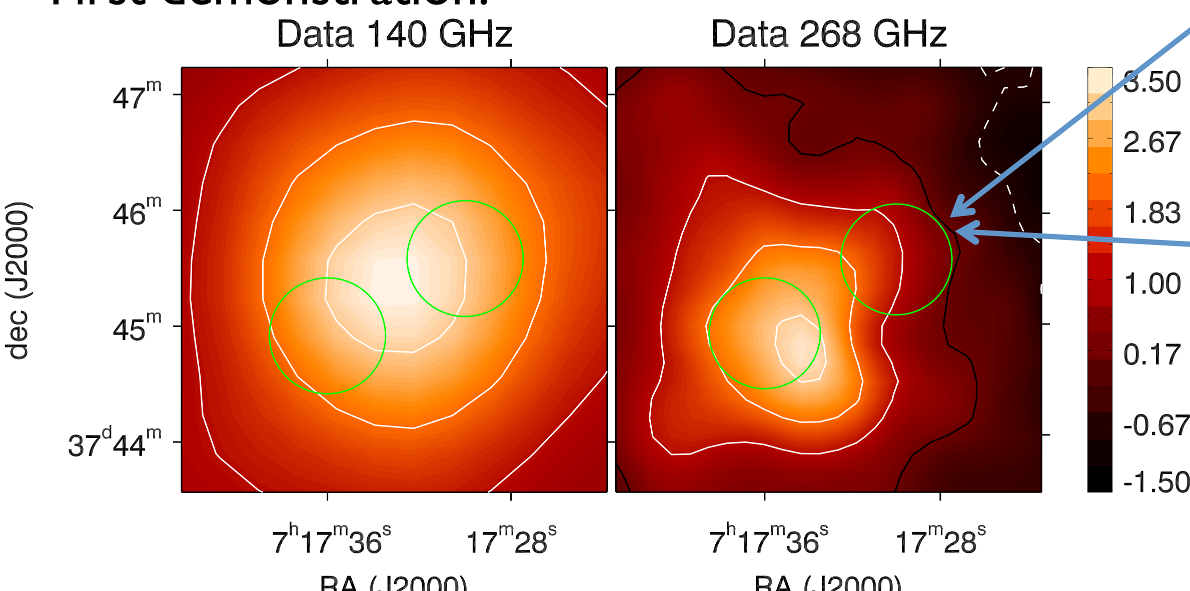
Approach

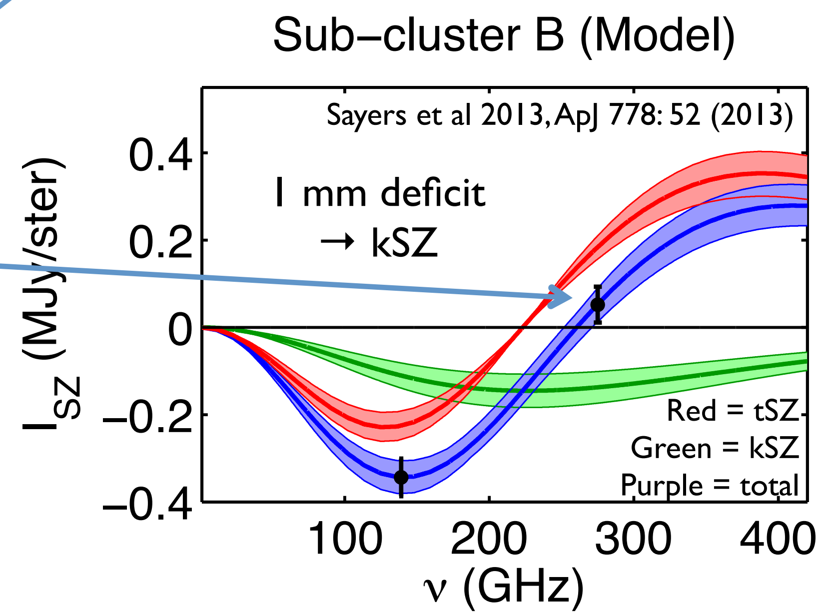
Most studies use plane-of-sky morphology (e.g., Bullet cluster)

Line-of-sight ICM velocity is now become accessible:

- X-ray spectroscopy: XRISM (now), *Athena* (future)
- Doppler shift via kinetic SZ

First demonstration:

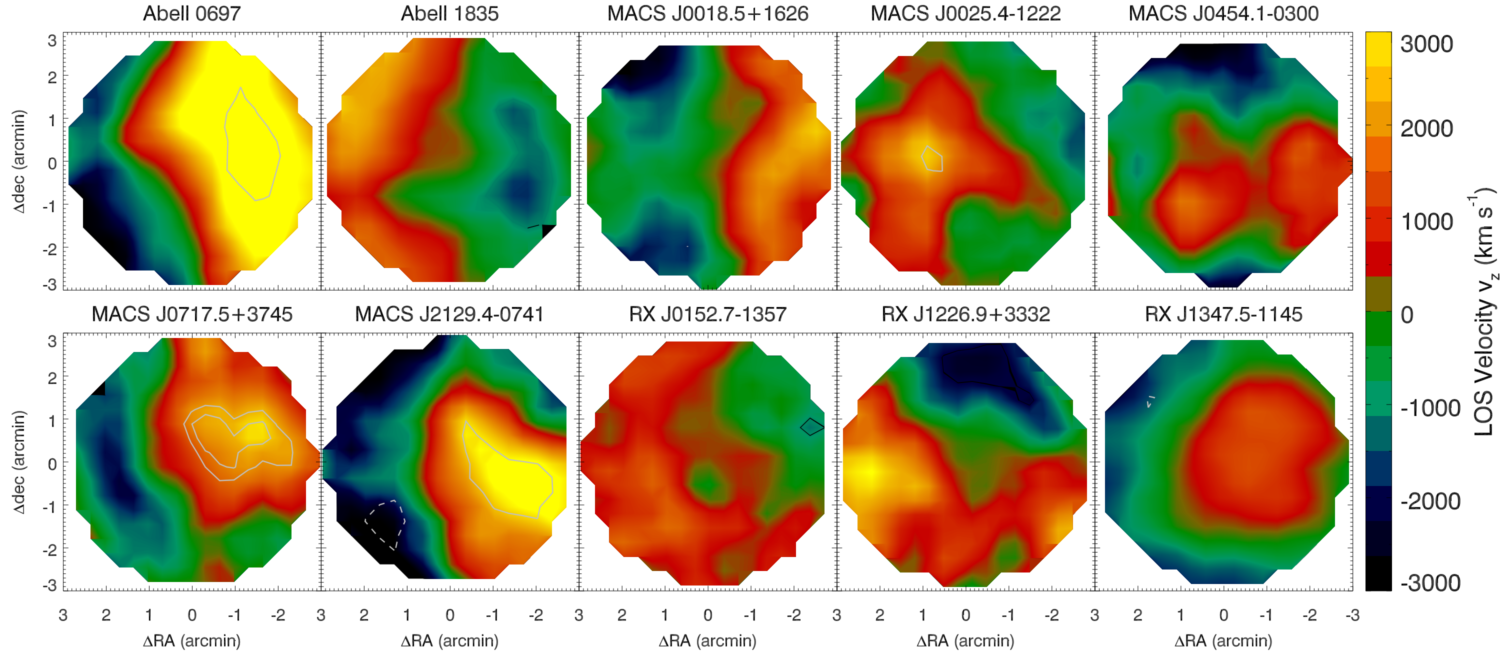




ICM Velocity Structure in Mergers

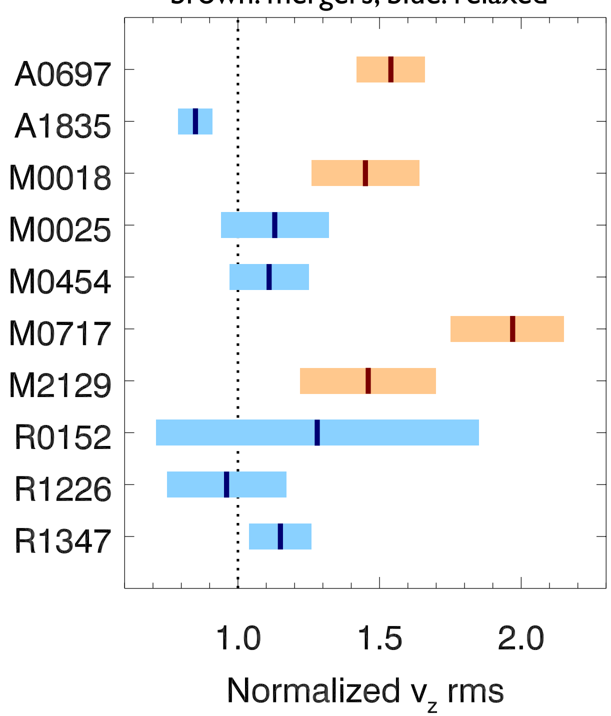
Expanded project:

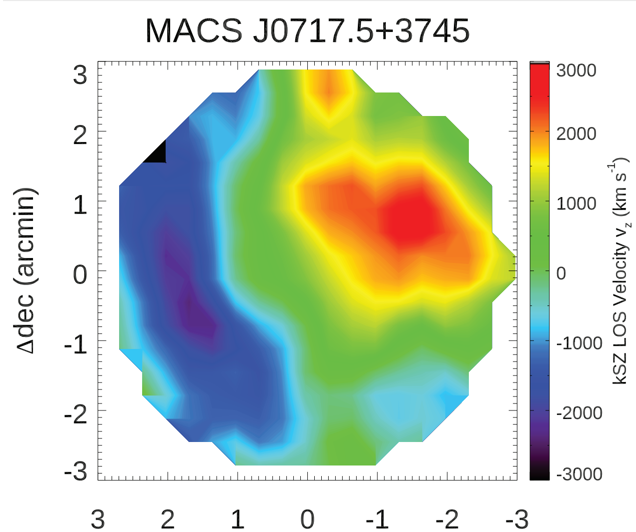
- Consistent detection of v_z rms in excess of noise for mergers, none for relaxed clusters
- Cluster member v_z via Keck spectroscopy
- LMT/Toltec better mm-wave data: time allotted



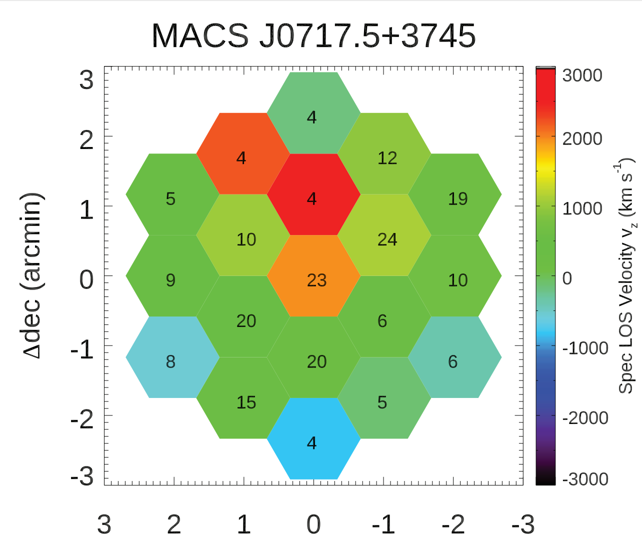
Sayers et al, ApJ 880:45 (2019)

brown: mergers; blue: relaxed



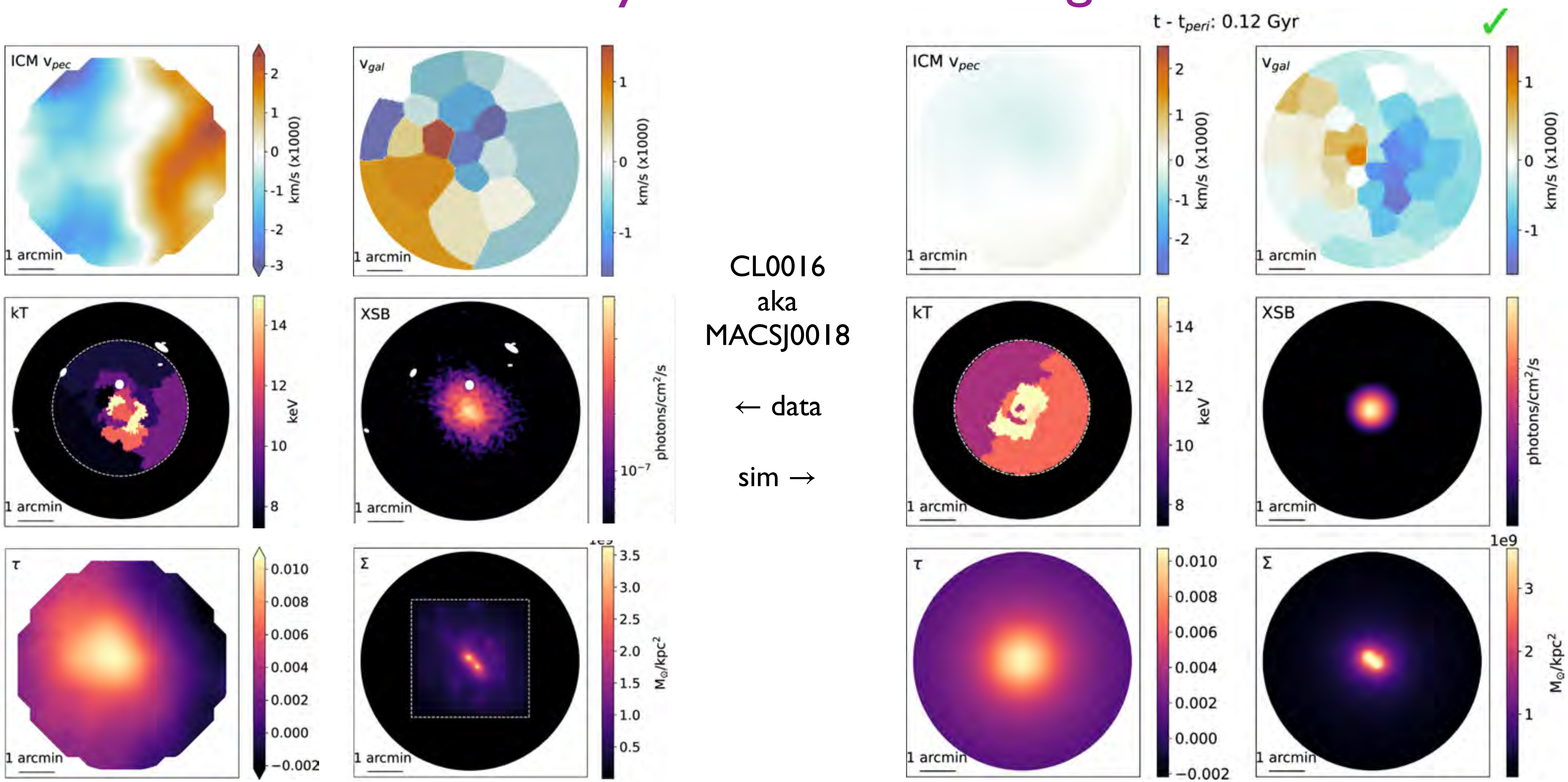


kSZ Velocity



Spec Velocity

ICM Velocity Structure in Mergers



Joint Lensing/X-Ray/kSZ/vz modeling of galaxy mergers (Emily Silich, Y5 Ay grad)

- Merger simulations provided by John ZuHone (CfA)
- X-ray and spectroscopy reductions initially by collaborators, moving in-house
- Forward-model all the data and identify best initial conditions statistically and by eye
- *Discovered DM-baryon velocity decoupling analogous to spatial decoupling in Bullet Cluster (DM tests!)*
- Now defining more rigorous statistical tests for sim-data comparisons

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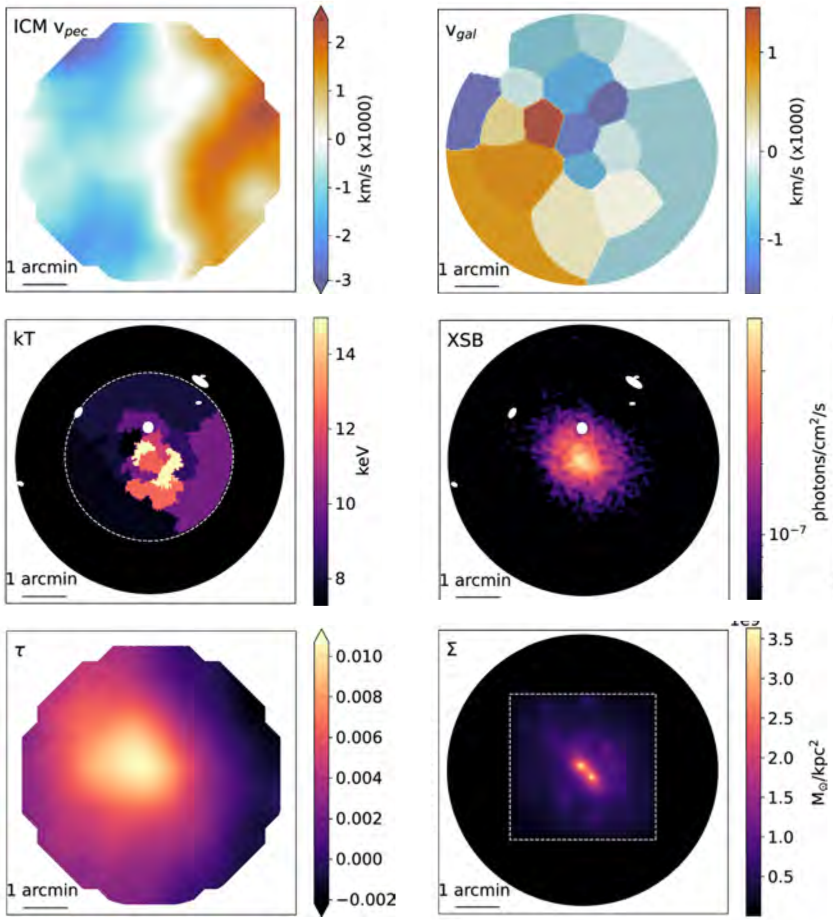
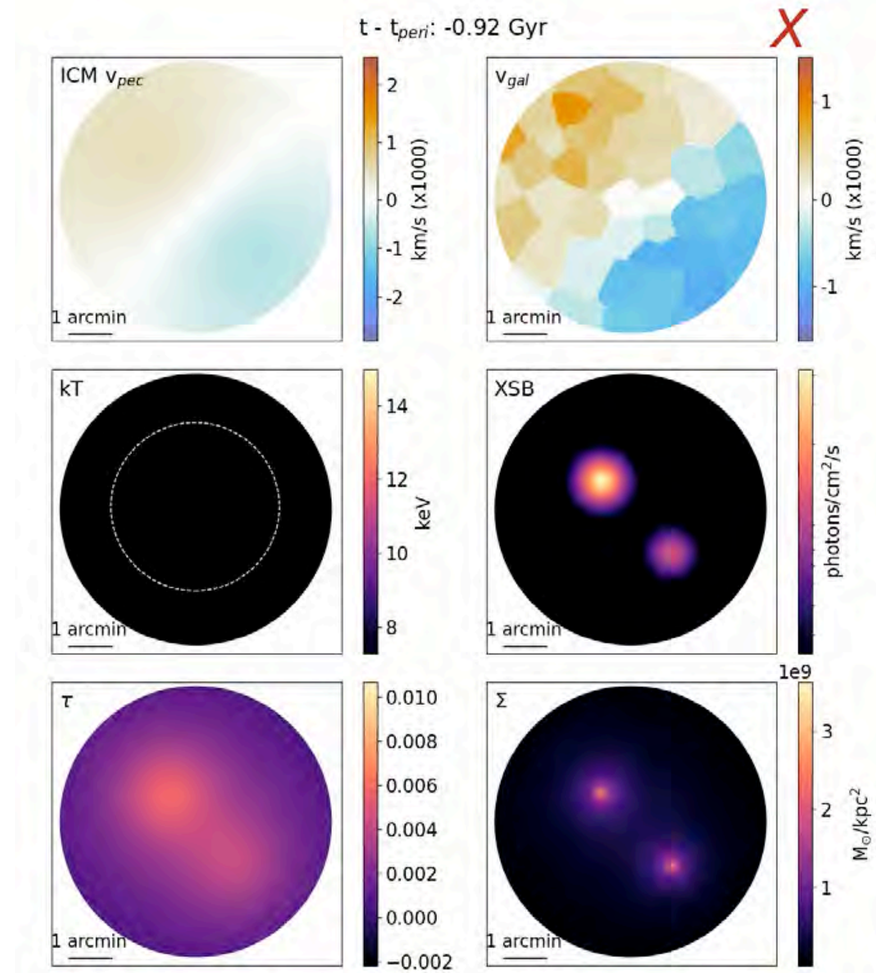


CL0016
aka
MACSJ0018

← data

sim →



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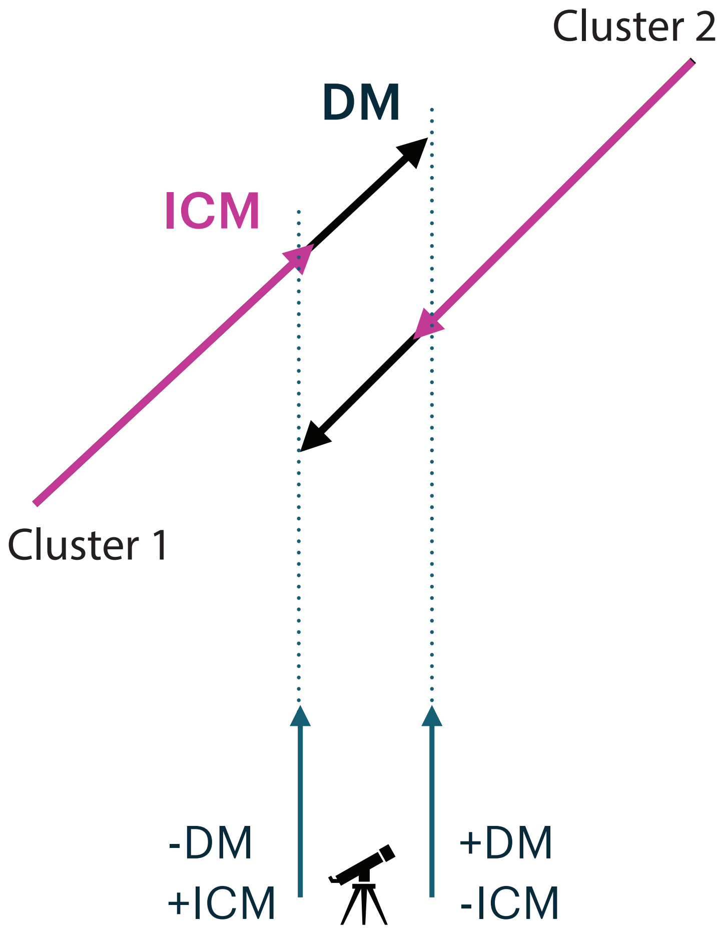
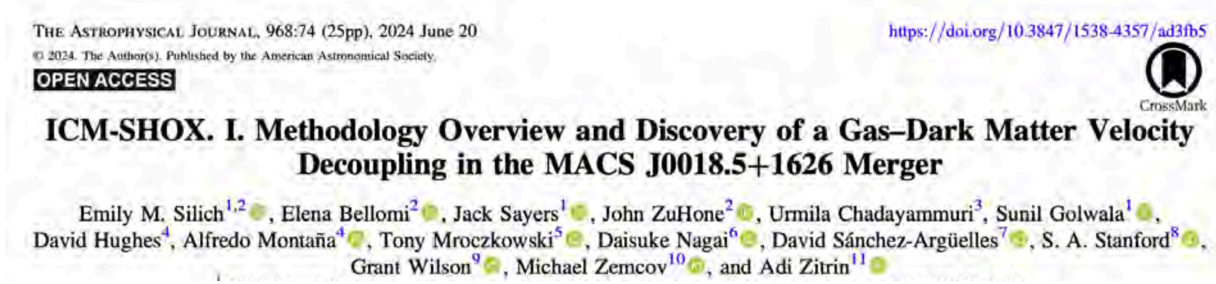




The Astrophysical Journal, 968:74 (25pp), 2024 June 20
https://doi.org/10.3847/1538-4357/ad3fb5

ICM-SHOX. I. Methodology Overview and Discovery of a Gas–Dark Matter Velocity Decoupling in the MACS J0018.5+1626 Merger

Emily M. Silich[1,2], Elena Bellomi[2], Jack Sayers[1], John ZuHone[2], Urmila Chadayammuri[3], Sunil Golwala[1], David Hughes[4], Alfredo Montaña[4], Tony Mroczkowski[5], Daisuke Nagai[6], David Sánchez-Argüelles[7], S. A. Stanford[8], Grant Wilson[9], Michael Zemcov[10], and Adi Zitrin[11]

Joint Lensing/X-Ray/kSZ/vz modeling of galaxy mergers (Emily Silich, Y5 Ay grad)

- Merger simulations provided by John ZuHone (CfA)
- X-ray and spectroscopy reductions initially by collaborators, moving in-house
- Forward-model all the data and identify best initial conditions statistically and by eye
- *Discovered DM-baryon velocity decoupling analogous to spatial decoupling in Bullet Cluster (DM tests!)*
- Now defining more rigorous statistical tests for sim-data comparisons

Probing ICM Turbulence in A3366 (Merger)

ICM turbulence provides significant non-thermal pressure support (P_{nt}). What is the physics?

- Is it Kolmogorov ($k^{-1/3}$)?
- What is injection scale?
  - Large: accretion
  - Small: galaxy feedback

ICM density fluctuations provide a probe

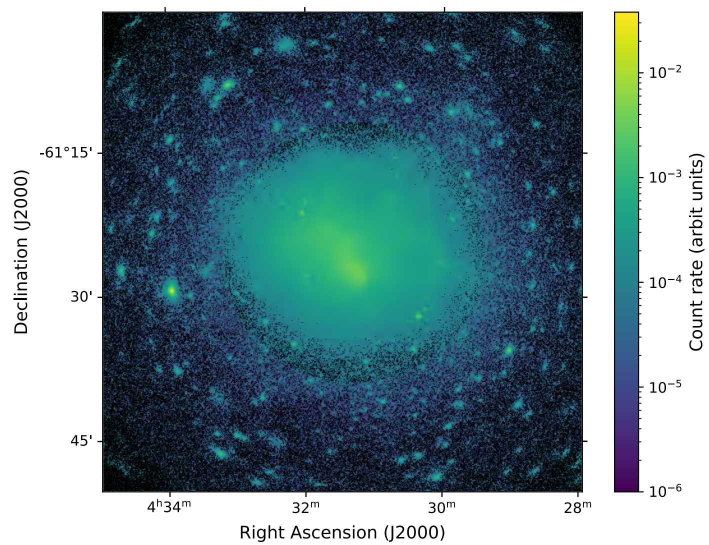
- Sims $\Longrightarrow \frac{\delta v}{v} \propto \frac{\delta p}{p} \propto \frac{\delta \rho}{\rho}$
- use density (X-ray) and pressure (SZ) fluctuations to measure velocity fluctuations

SZ probes to larger radius

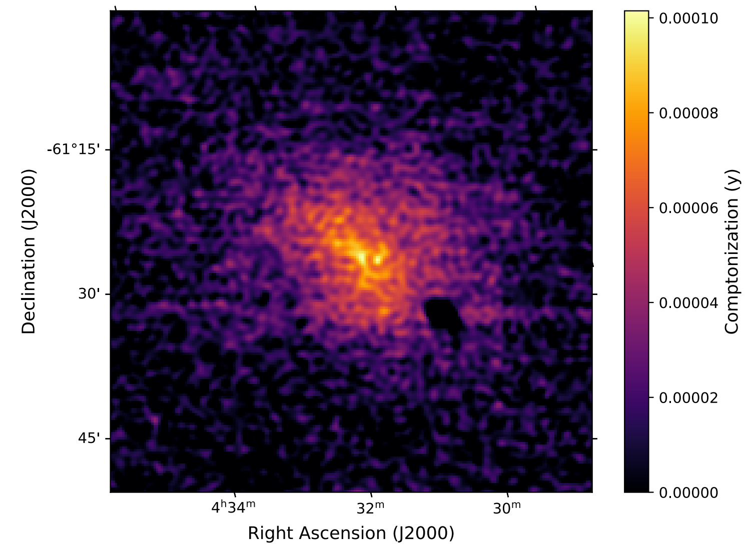
SZ/X = 1.4 ± 0.7

- > 1 consistent with expectations for mergers

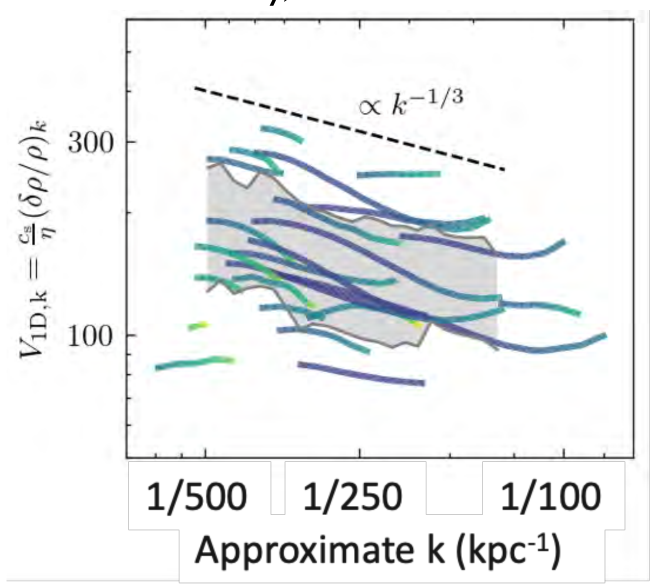
eROSITA X-ray



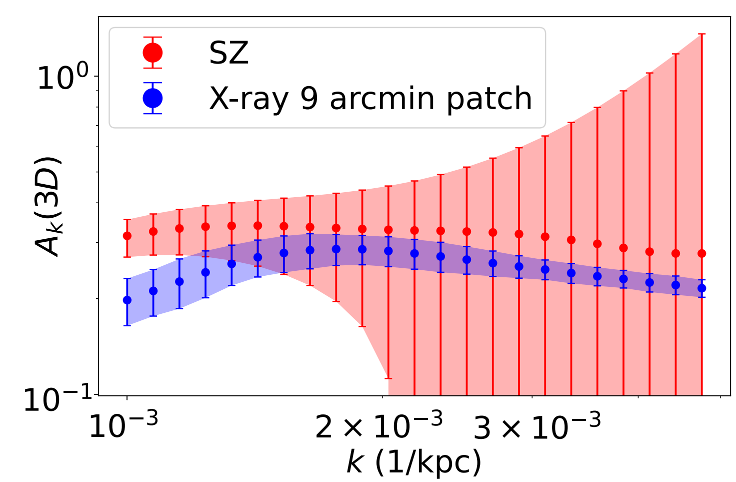
SPT SZ



X-ray, 24 relaxed clusters



A2366, SZ and X-ray



A New Explanation for the Cooling Flow Problem: Cosmic Rays

Cooling flow problem

- X-ray emission around brightest cluster galaxy at center implies high radiative cooling rate: gas should cool, collapse, and form stars
- But this star formation not seen

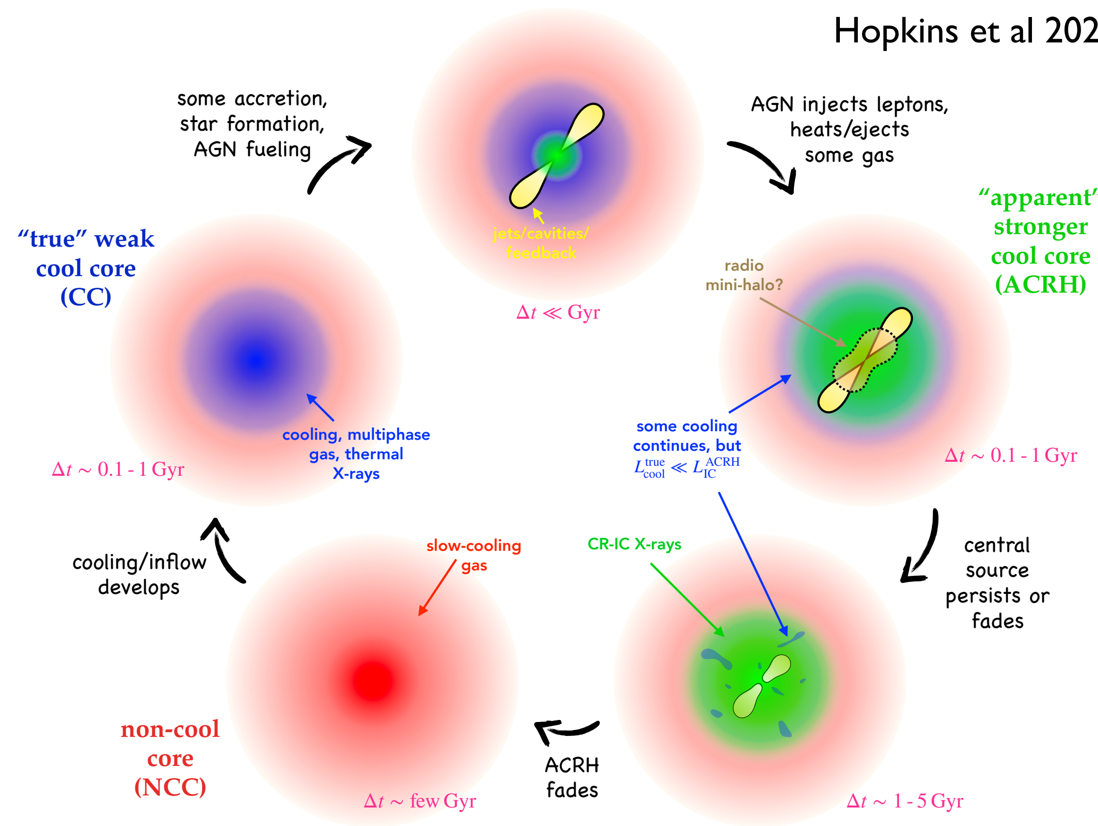
Novel proposal by Hopkins and Quataert:

- not thermal bremsstrahlung, but inverse Compton scattering of CMB off ancient 0.1-1 GeV cosmic ray electrons

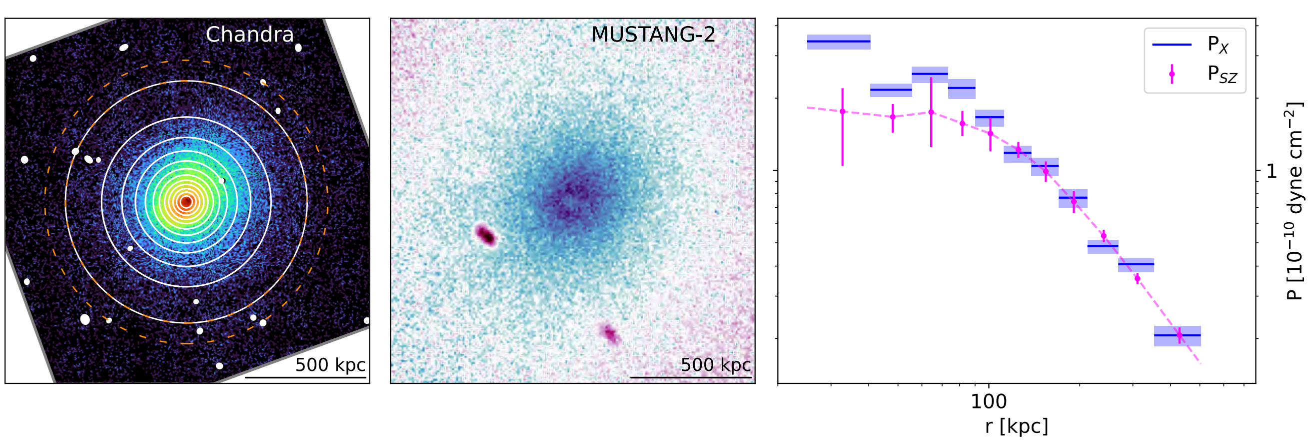
Test by comparing high-resolution SZ-inferred thermal pressure to X-ray

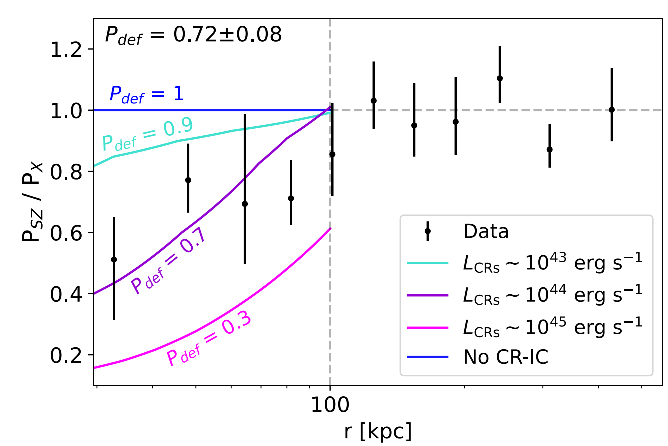
- Expect SZ pressure deficit relative to X-ray because X-ray overestimates
- ~3σ signal in first test on Zw Cl 3146

Hopkins et al 2025



Silich et al 2025





A New Solution to the Cooling Flow Problem: Cosmic Rays

Cooling flow problem

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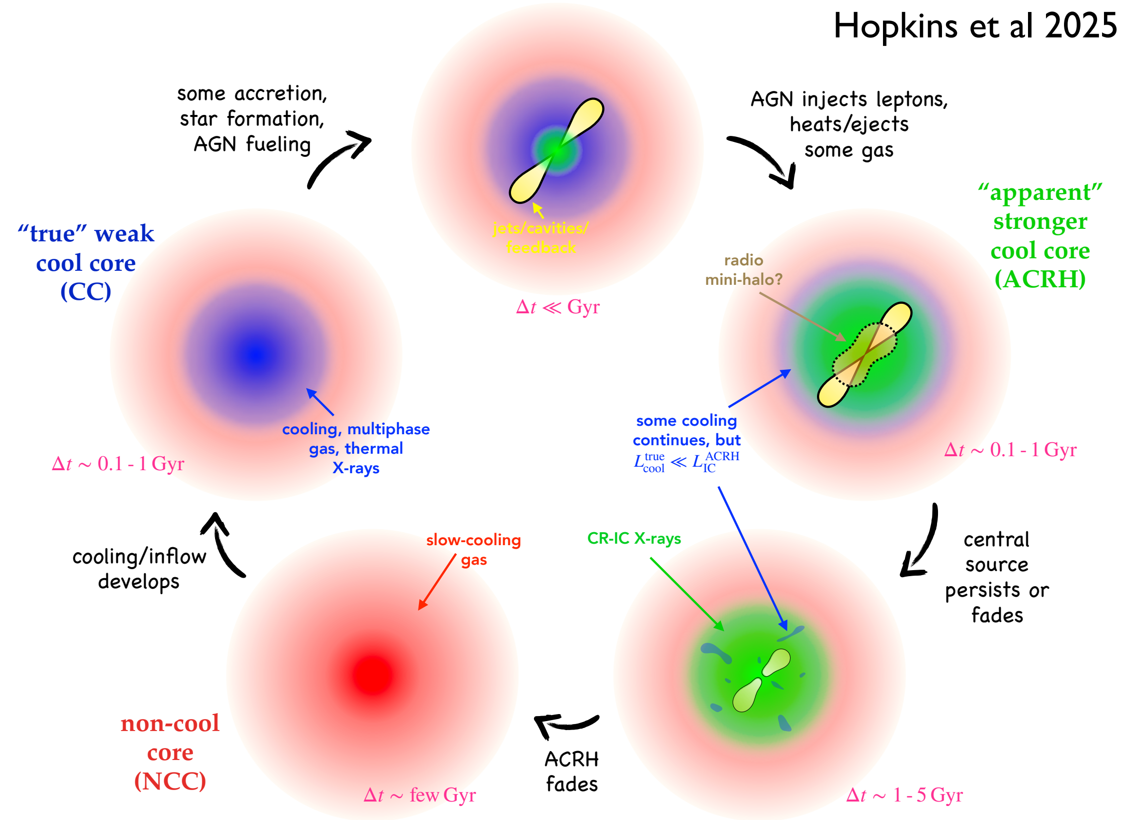
Hopkins et al 2025

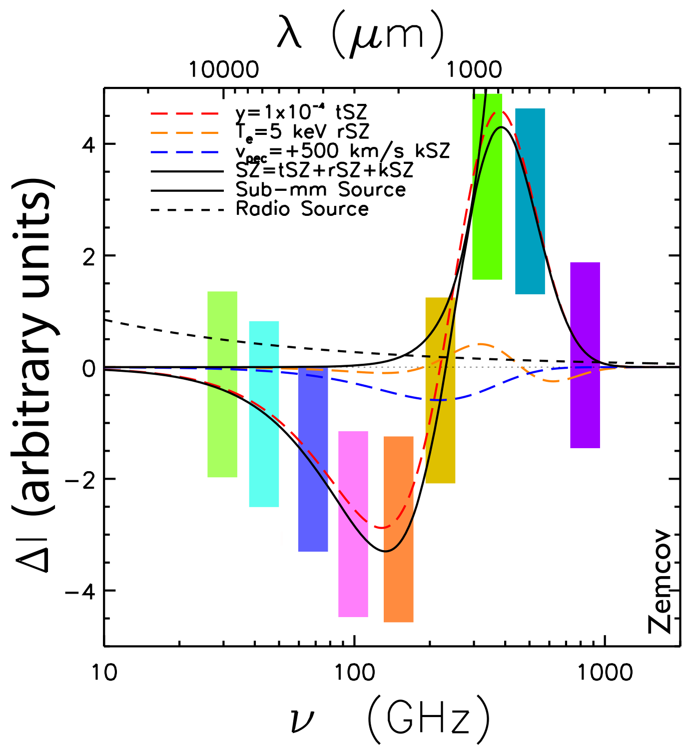


Draft version October 14, 2025
Typeset using LaTeX **twocolumn** style in AASTeX7.0.1

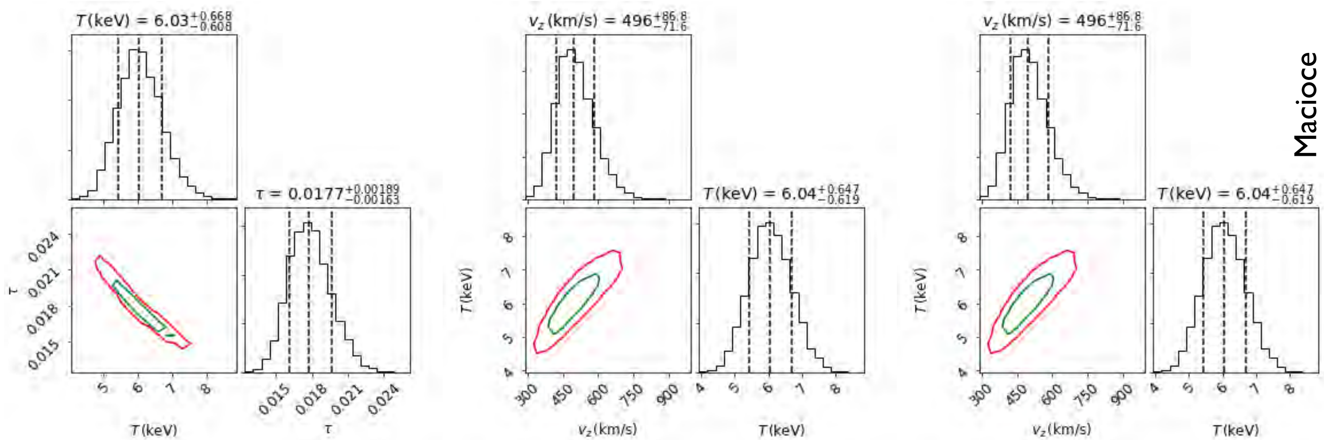
Exploring a cosmic ray inverse-Compton origin to the SZ-to-X-ray pressure deficit in the cool core cluster ZwCl 3146

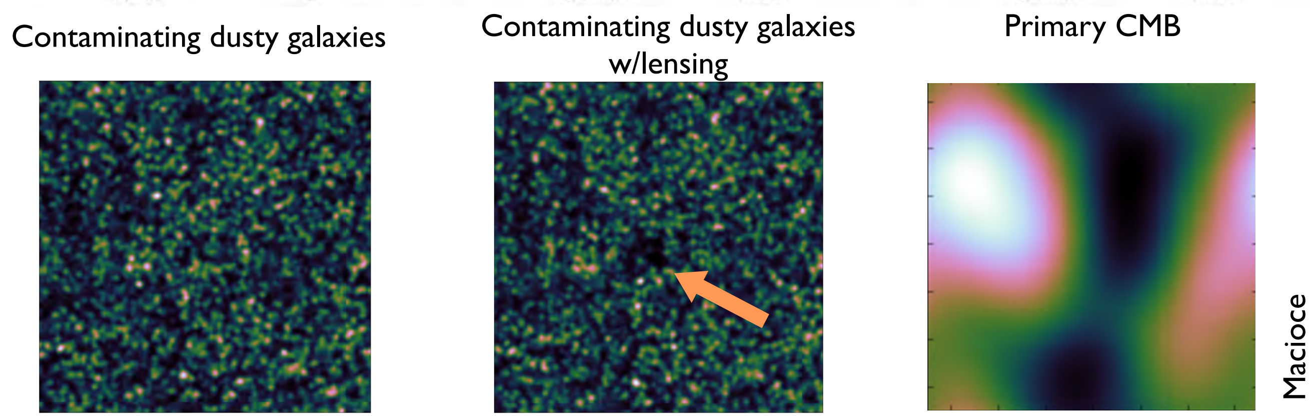
Emily M. Silich,[1] Jack Sayers,[1] Philip F. Hopkins,[1] Charles Romero,[2] Brian Mason,[3] John Orlowski-Scherer,[2] and Craig L. Sarazin[4]

Systematics Limits to kSZ Precision



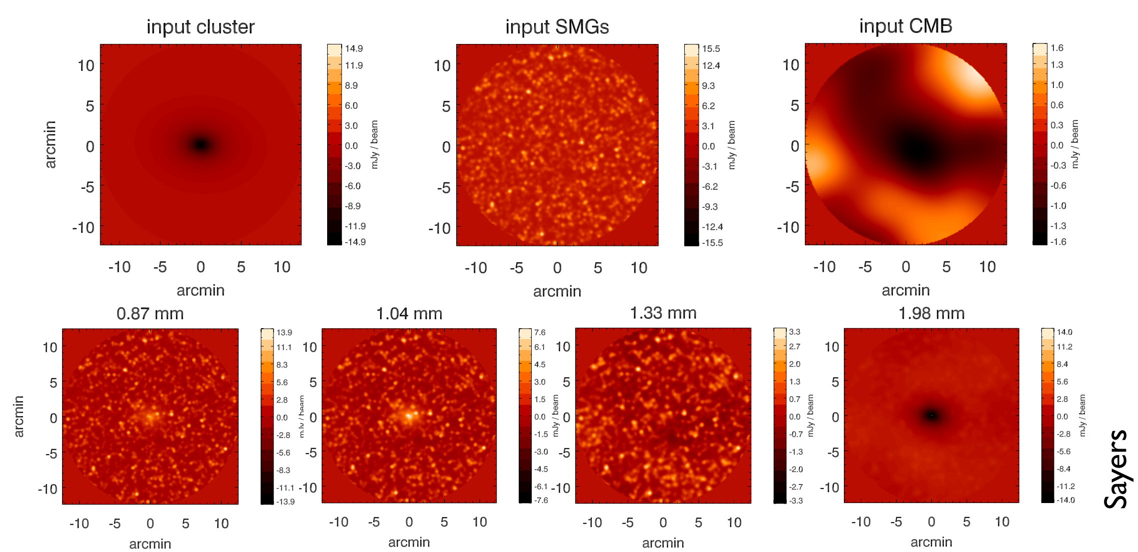
No contaminating galaxies, just tSZ + kSZ + relativistic effects, 10% prior on T_e: $\sigma_v < 100$ km/s



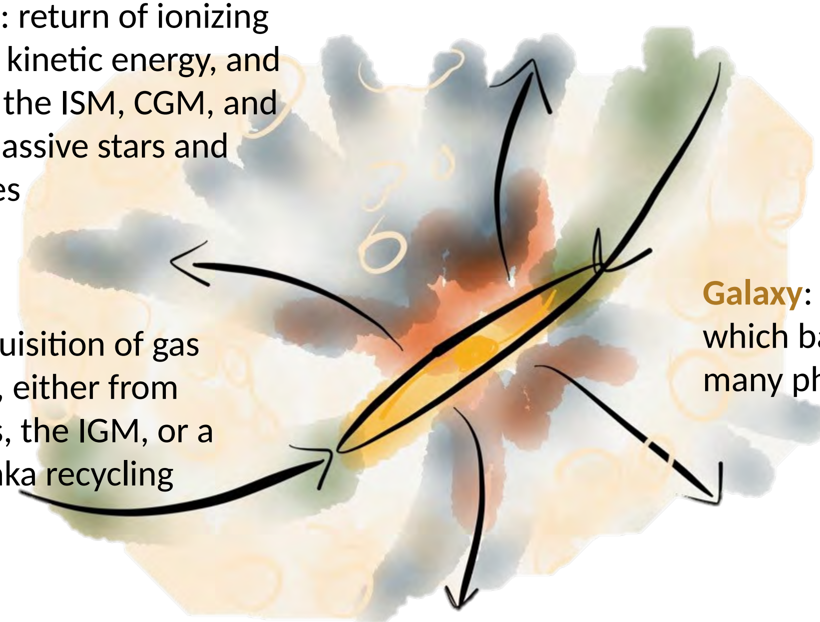


Multi-band coverage necessary for teasing apart SZ effects and contaminating galaxies, degeneracy between v_{pec} and T_e

Ongoing project to simulate ultimate limits to kSZ sensitivity for bulk (cosmological) and internal ICM velocities

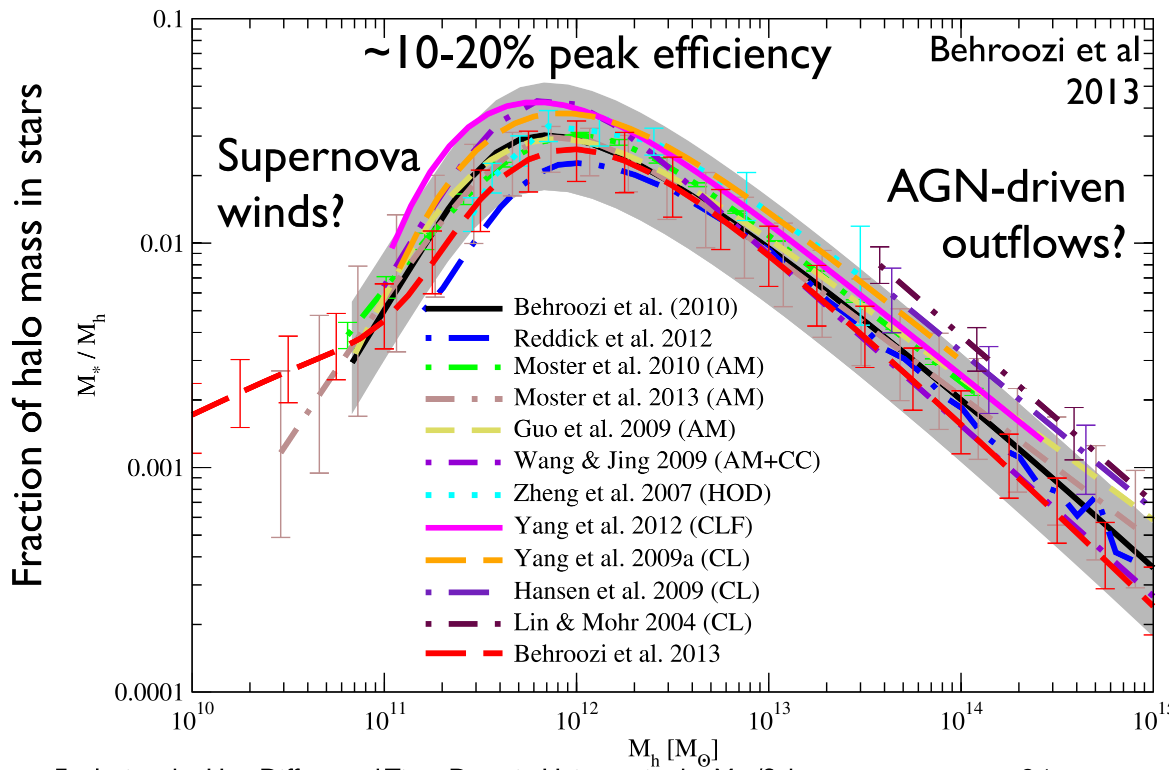


The Galaxy-CGM-IGM Connection and the Inefficiency of Star Formation in Galaxies



Star formation remarkably inefficient

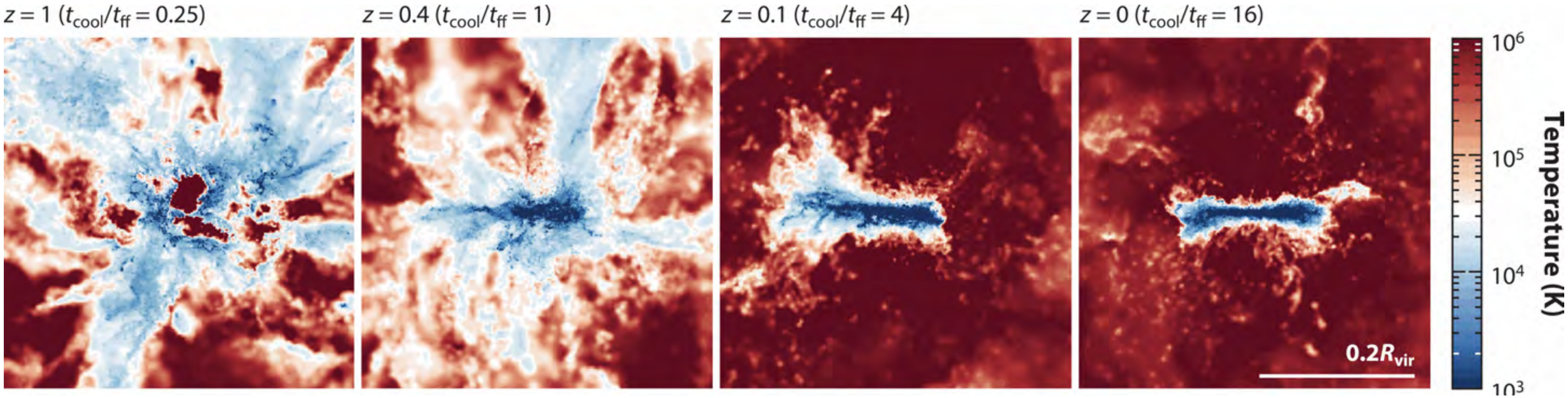
- Driving of gas out to CGM, stanching of gas inflow believed to limit SF efficiency
- CGM and IGM also reservoir for feeding SF



The galaxy-CGM-IGM connection in galaxies and galaxy clusters with SZ:

- Thermal SZ calorimetry of hot CGM measures gas that can't form stars: the inefficiency part of the equation
- Thermal SZ + X-ray + lensing indirectly measures accretion into cold degrees of freedom that provide support against *G*: also inefficiency
- Kinetic SZ directly measures cold degrees of freedom, both circulating and infalling (efficiency and inefficiency)

CGM with the SZ Effect



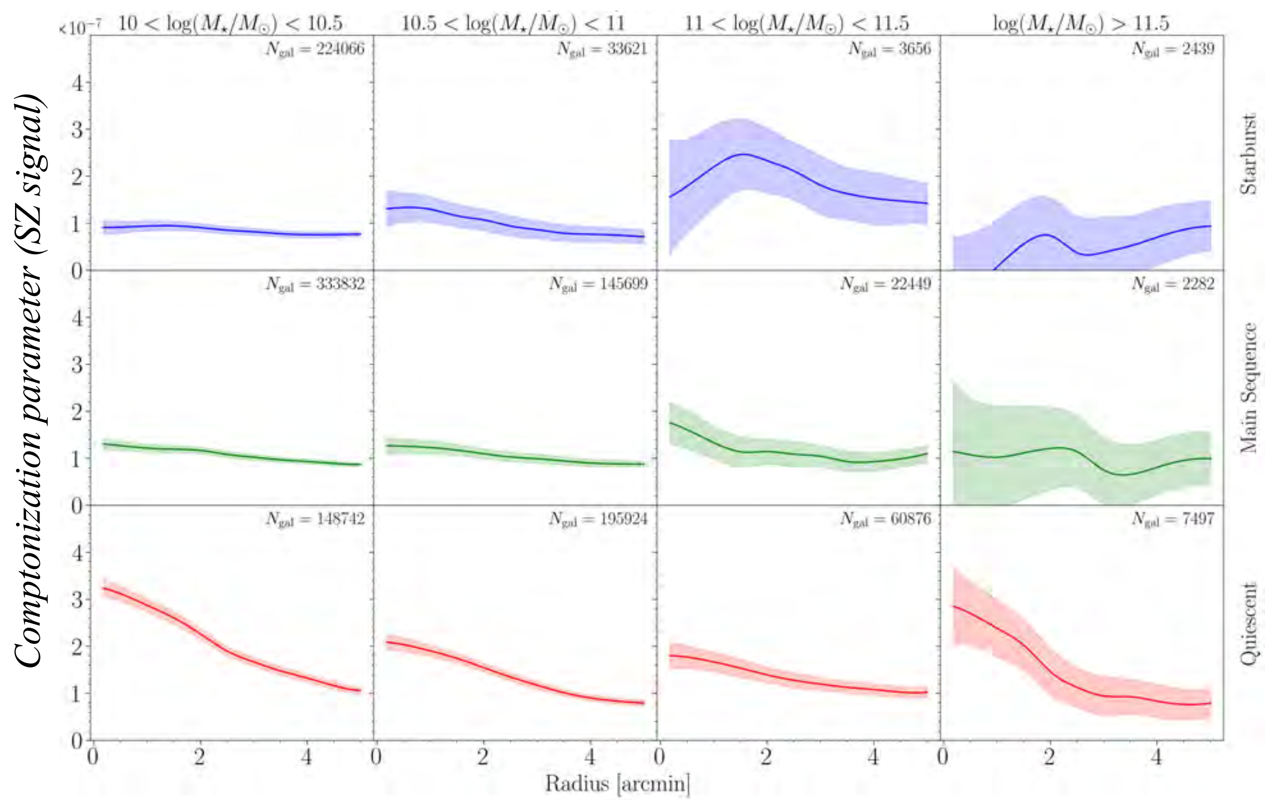
Faucher-Giguère C-A, Oh SP. 2023
Annu. Rev. Astron. Astrophys. 61:131–95

Specific questions

- How efficient is shock heating and thermalization?
- What are the residual cold motions/ material?
- How does ejected energy heat CGM and ICM, escape to IGM?

Analyses now and future:

- Stacking using ACT + galaxy surveys
  - Y. Xie, ShNU grad student
- Better statistics with Euclid/Roman/ LSST + Simons Observatory
- Lower masses with LMT + existing deep fields, LCT in the future



Summary of Observational and Forecasting Projects

Triaxial shapes and SIDM

Multi-yr full analysis using the XMM-Heritage CHEX-MATE sample (Saxena)

Non-thermal pressure

Multi-yr full analysis using the XMM-Heritage CHEX-MATE sample (Gavidia)

Merger studies

Multi-yr analysis using existing data, new data coming - Chandra/ALMA/LMT (Silich, White)

ICM turbulence fluctuations

Demonstrate case complete with paper soon, more cases, possible new X-ray data from Einstein Probe (Saxena)

Cosmic Ray Inverse Compton

Demonstrate case complete, more cases, new SZ data coming from GBT (Silich)

WHIM in Large Scale Structure Filaments

Project underway based on eROSITA and Planck data, plus new data coming from Einstein Probe (White)

Cluster Cosmology - AGN and SZ Detection

Pilot study complete with paper soon, more existing data, planned path forward w/ VLA/ATCA/ALMA (Saxena)

Cluster Cosmology - Triaxiality and Weak Lensing Mass Calibration

multi-yr collaborative project with UMich, now underway (Gavidia, Saxena)

Dust Within the Intra-Cluster Medium

multi-yr collaborative project with RIT, opportunities related to dust and relativistic SZ

kSZ forecasting

multi-yr project to incorporate instrumental/calibration effects

CGM studies

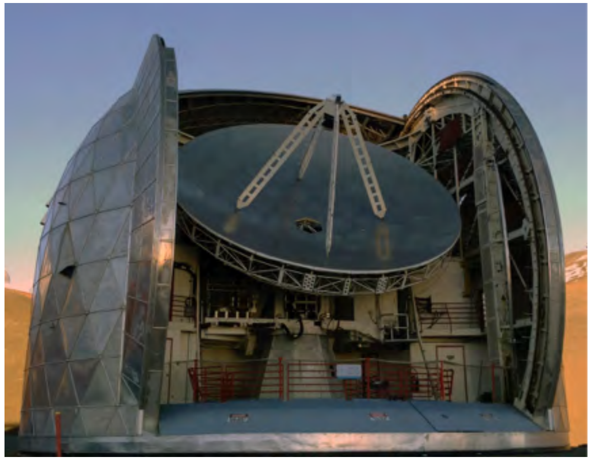
studies with existing samples underway, can be extended; new data coming soon

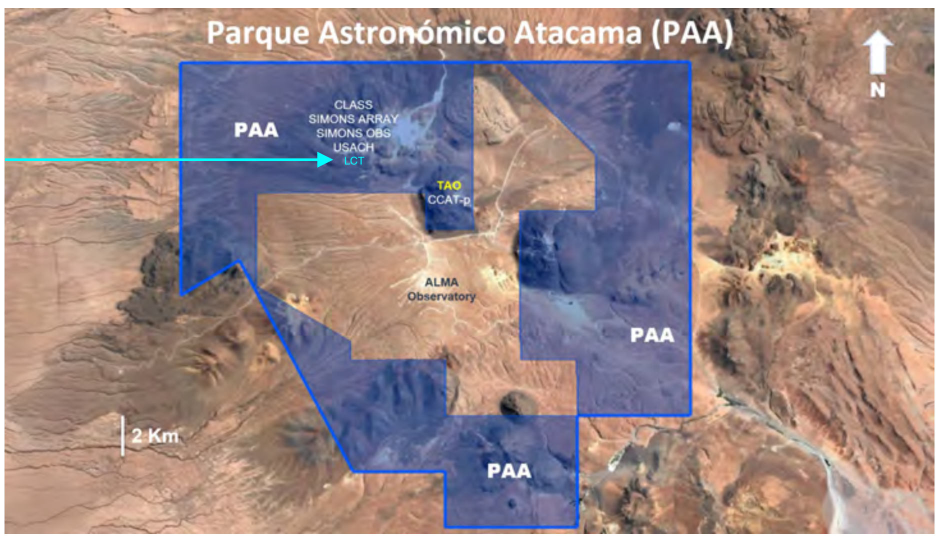
explore ALMA studies of individual galaxies or stacking using ALMA surveys

Instrumentation

- Leighton Chajnantor Telescope (LCT)
  - Move of Caltech's 10.4 m mm/submm telescope to Chile
- Ongoing developments to enable multi-band imaging of SZ and mm-wave time-domain sources on LCT
  - Multi-scale phased-array antennas to enable measurement of 6 spectral bands in a single focal plane
  - Background-limited microstrip-coupled kinetic inductance detectors (KIDs) to provide excellent sensitivity in all spectral bands
  - Microstripline and parallel-plate capacitors using 1 μm thick crystalline silicon to minimize KID two-level-system noise and antenna microstripline loss
  - Broadband, antireflection-structured, gradient-index silicon optics
- Ample opportunities for instrumentation and engineering work with a range of levels of time commitment

Leighton Chajnantor Telescope





UNIVERSIDAD DE CONCEPCION

Take advantage of new technologies and the world's highest surface accuracy submm telescope to explore new scientific frontiers and build an international partnership

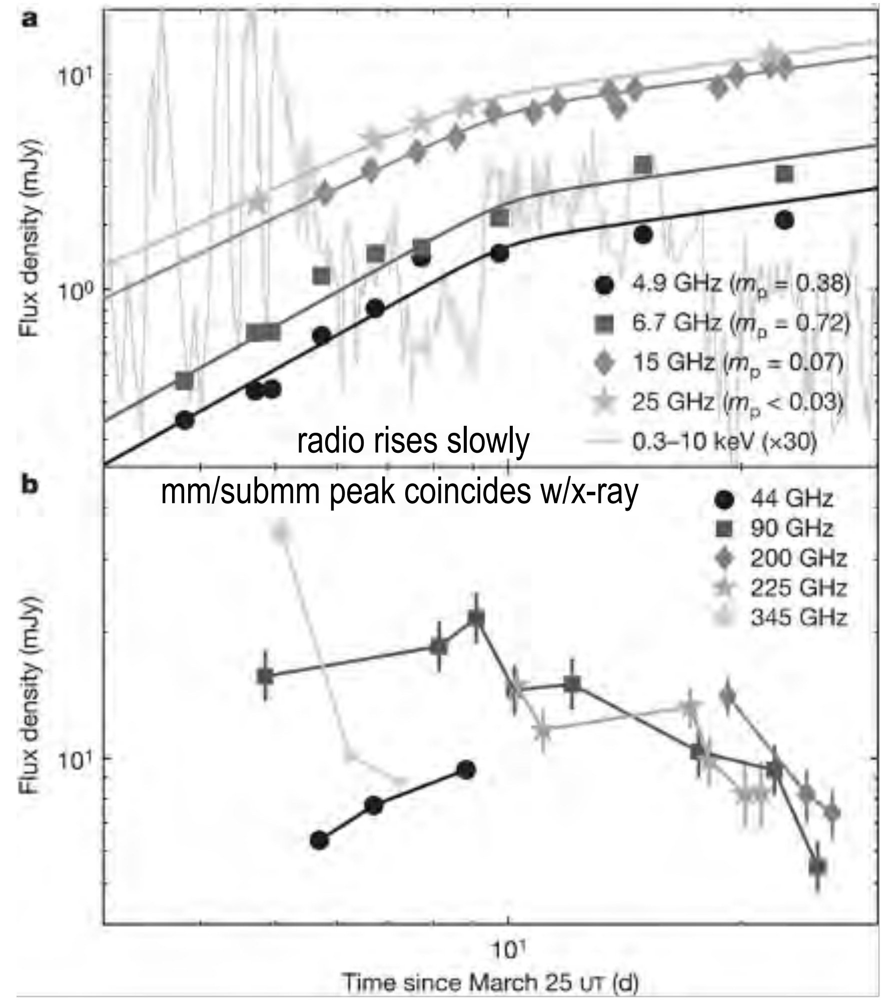
- Move 10.4-m, 11 μm rms Leighton Telescope from Hawaii to better site in Chile
- Deploy cutting-edge mm/submm instruments
  - Multiband cameras
  - "Integral field units" — 3D mappers
- Focus on new scientific goals with "whole-observatory" programs
  - Coherent time-domain astronomy program
  - 300-1000 hr projects focused on major goals
- Technology-enabled fully remote operations
- Strategic international partnership
  - Shanghai Normal University Key Lab for Astrophysics: C. Shu
  - U de Concepcion Center for Astronomical Instrumentation (CePIA): R. Reeves
  - Caltech
  - significant contributions by all partners to facility, instrumentation, and science

New Scientific Opportunities in the Sub/mm

Transient and time-domain astronomy

- Stellar death — ubiquitous synchrotron emission
  - A veritable zoo:
    - massive stars: core-collapse supernovae, low-luminosity and long-duration γ-ray bursts
    - black holes shredding stars: tidal disruption events
    - black holes and white dwarfs accreting material
  - from jets, outflows, and shocks interacting with circumstellar medium (CSM): bright in mm/submm, self-absorbed in cm
  - Reflects mass loss prior to explosion
- Stellar activity
  - Cyclotron emission in flaring stars, perhaps due to magnetic reconnection: Exoplanet habitability?
- Episodic accretion
  - Synchotron from active galactic nuclei (AGN: supermassive BH at centers of galaxies) jets: $R_{emission} \sim 1/\nu$, correlated with γ-rays and neutrinos
  - Varying thermal dust emission from young stellar objects: explains low quiescent luminosity

Tidal disruption event *Swift* J1644+57 (Zauderer et al 2011)



Tool: multiband measurements of time-varying mm/submm emission

Kinetic Inductance Detectors

Superconductors have an AC inductance due to inertia of Cooper pairs

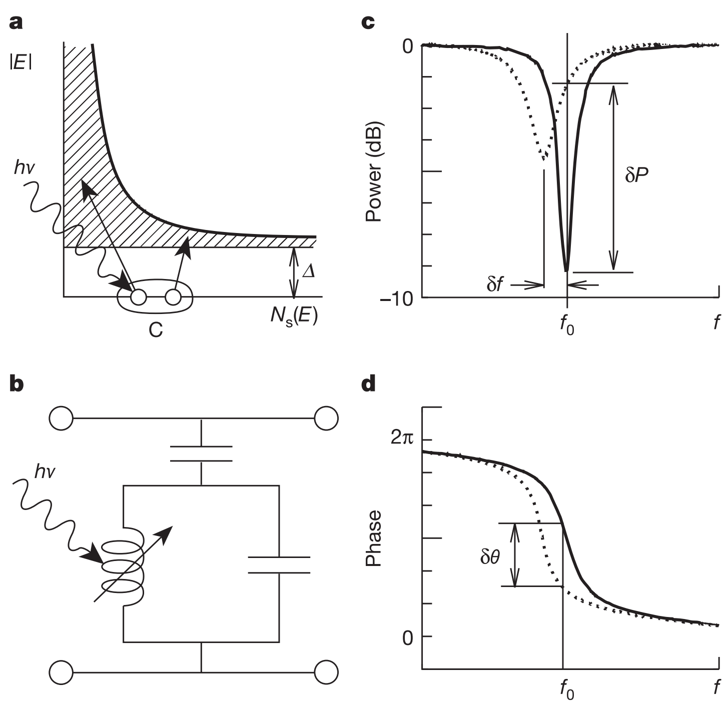
- alternately, due to magnetic energy stored in screening supercurrent

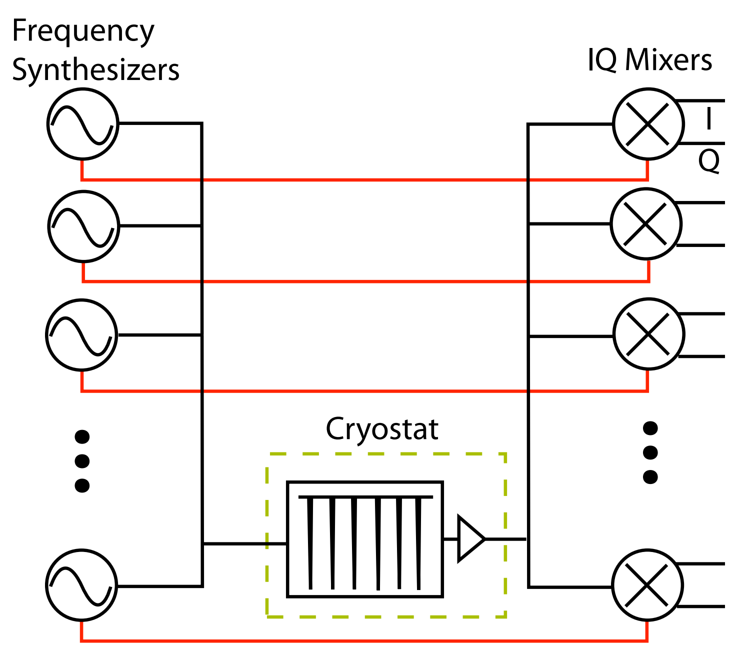
Changes when Cooper pairs are broken by energy input from light

Sense the change by monitoring a resonant circuit

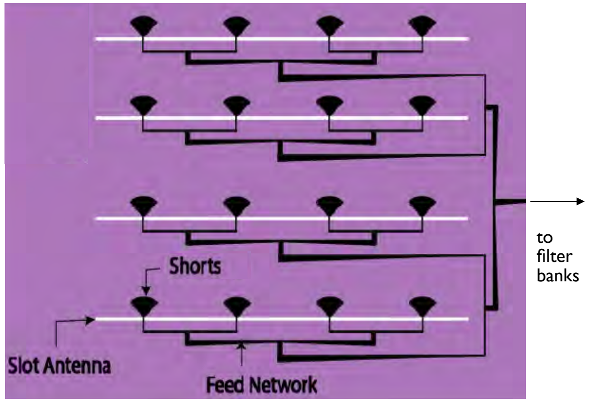
Key point: superconductors provide very high Q ($Q_i > 10^7$ achieved), so thousands of such resonators can be monitored with a single feedline

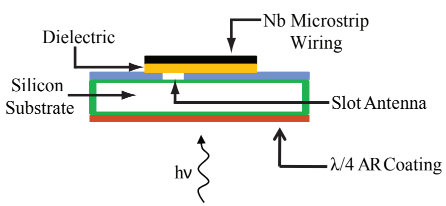
- enormous cryogenic multiplex technology relative to existing ones
- very simple cryogenic readout components





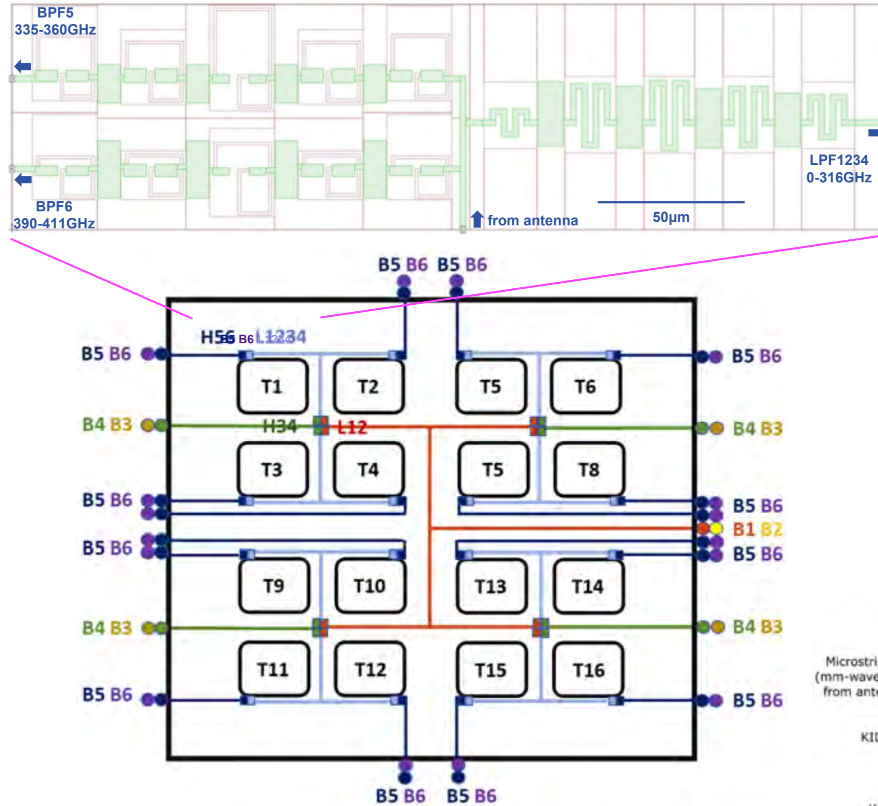
NEW-MUSIC: the Next-generation Extended Wavelength Multiband Submillimeter Inductance Camera





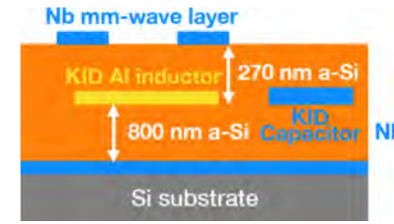
band	ν	$\Delta\nu$
B1	90 GHz	35 GHz
B2	150 GHz	40 GHz
B3	230 GHz	35 GHz
B4	290 GHz	40 GHz
B5	345 GHz	30 GHz
B6	405 GHz	25 GHz

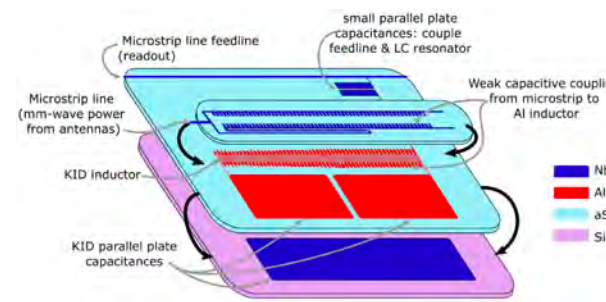
B5/B6 BPF + B1234 LPF

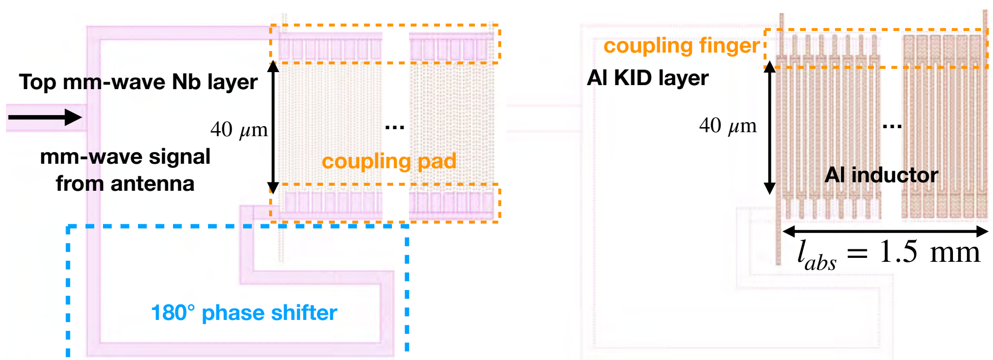


pixel scales with diffraction spot size

microstrip coupling to a-Si:H embedded KID







Millimeter-wave coupling design for Band 4-6

Large a-Si:H PPC to yield acceptable TLS noise (can reduce in size)

Golwala et al (SPIE 2012, 2024)
Ji et al (SPIE 2014)
Shu et al (LTD-19)
Martin et al (LTD-20)
Defrance et al (PRMat 2024)

Broadband Anti-Reflection-Structured Silicon Optics

Motivation

- Crystalline silicon is excellent optical material:
  - High index
  - High conductivity
  - Low loss
- But high index necessitates ARC
- Need wide bandwidth ARC for applications
  - CMB pol: 23-130 GHz, 73-415 GHz (5.7:1)
  - SZ, mm time-domain: 73-415 GHz (5.7:1)

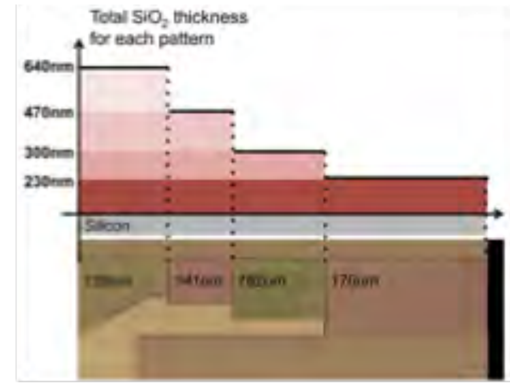
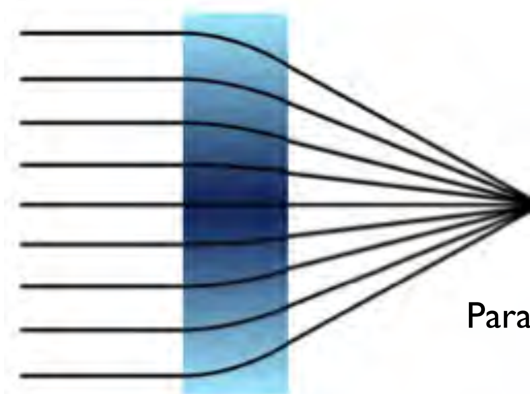
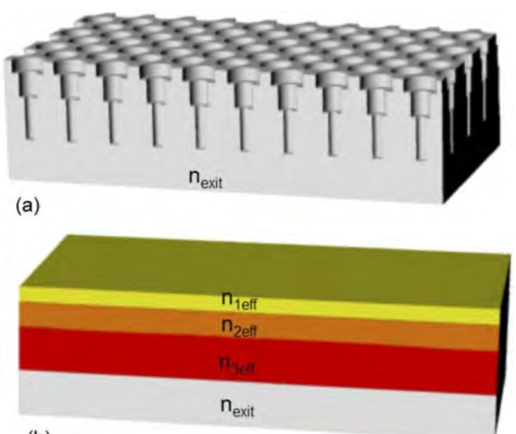


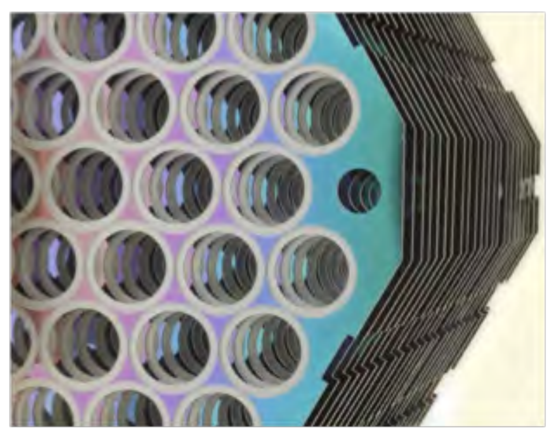
Fig. 5: Each equivalent SiO_2 thickness is calculated for every step of the pattern. Bottom diagram: Visually showing how a thicker mask is needed for shallower etches. Between etches, SiO_2 is uniformly removed over the wafer to expose each silicon etch pattern sequentially.



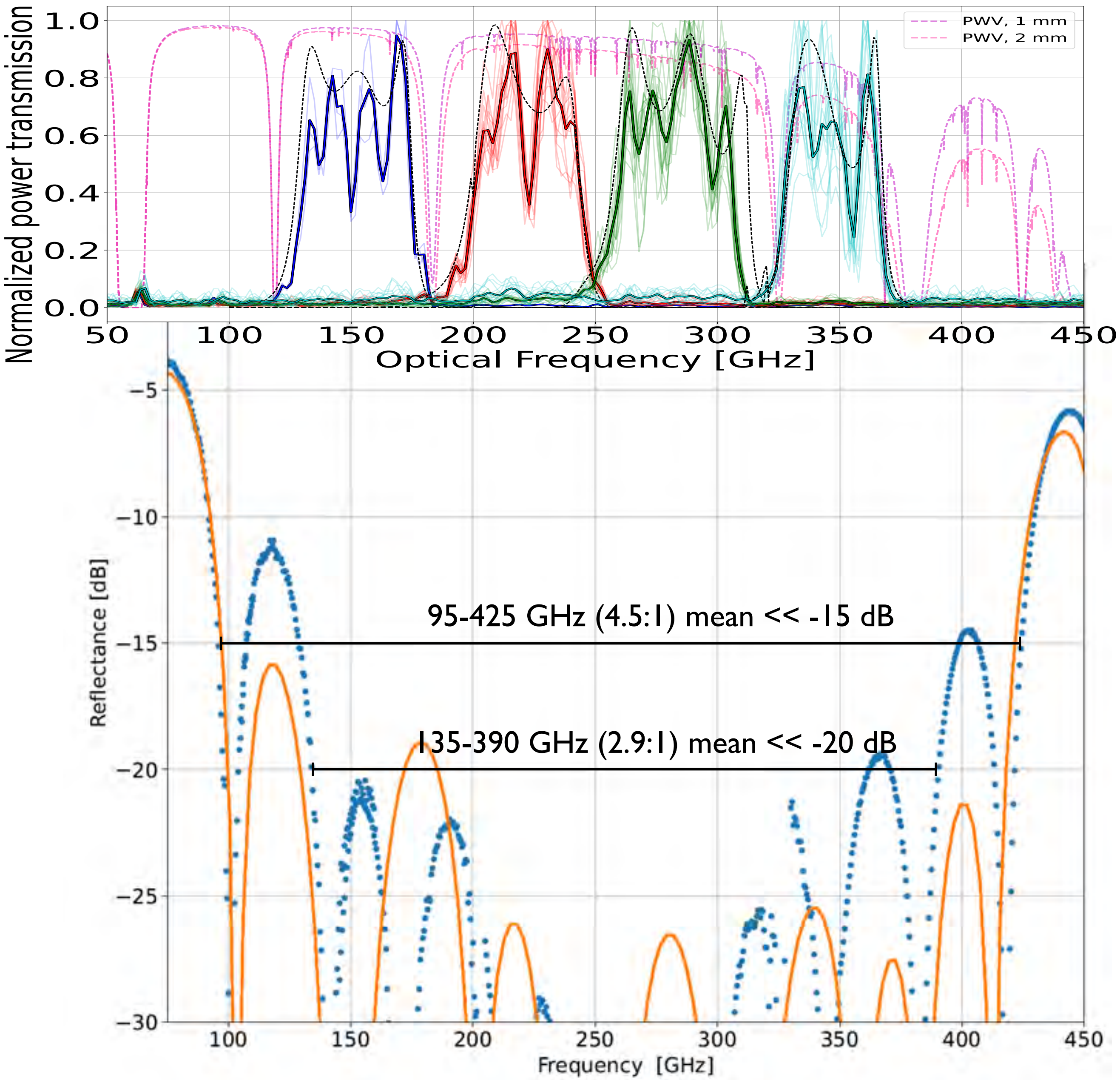
Parabolic index
variation
= parabolic lens

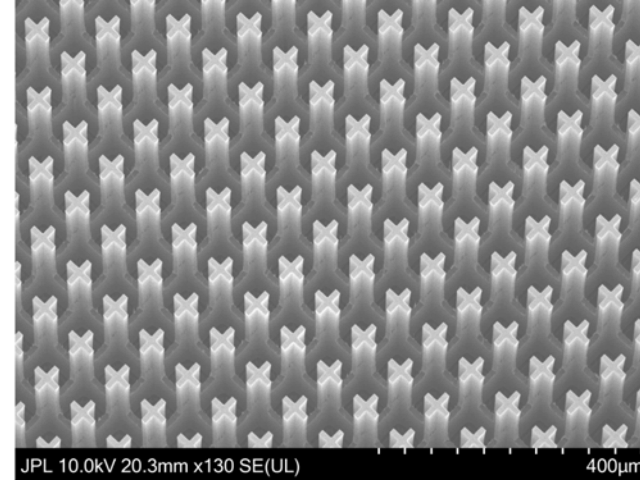
Technique

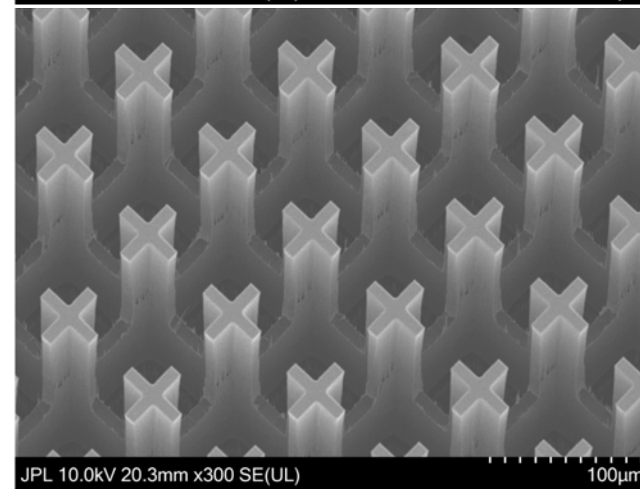


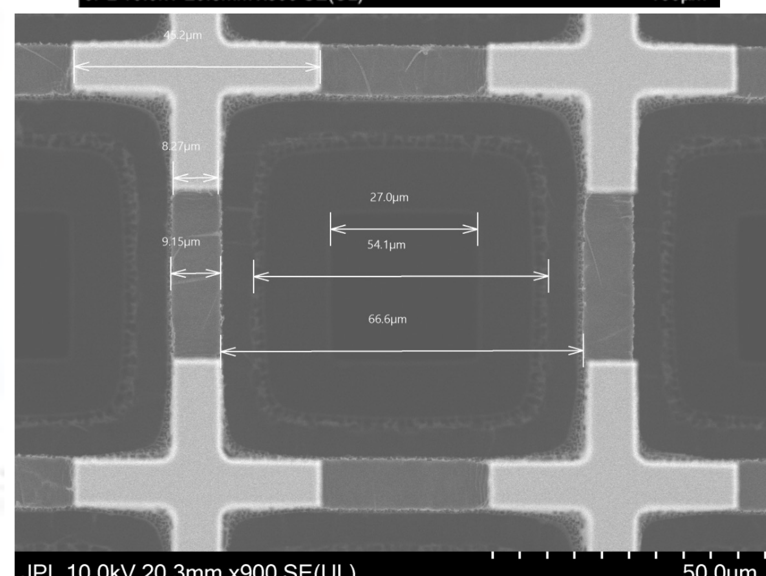


4-Layer AR Demonstration





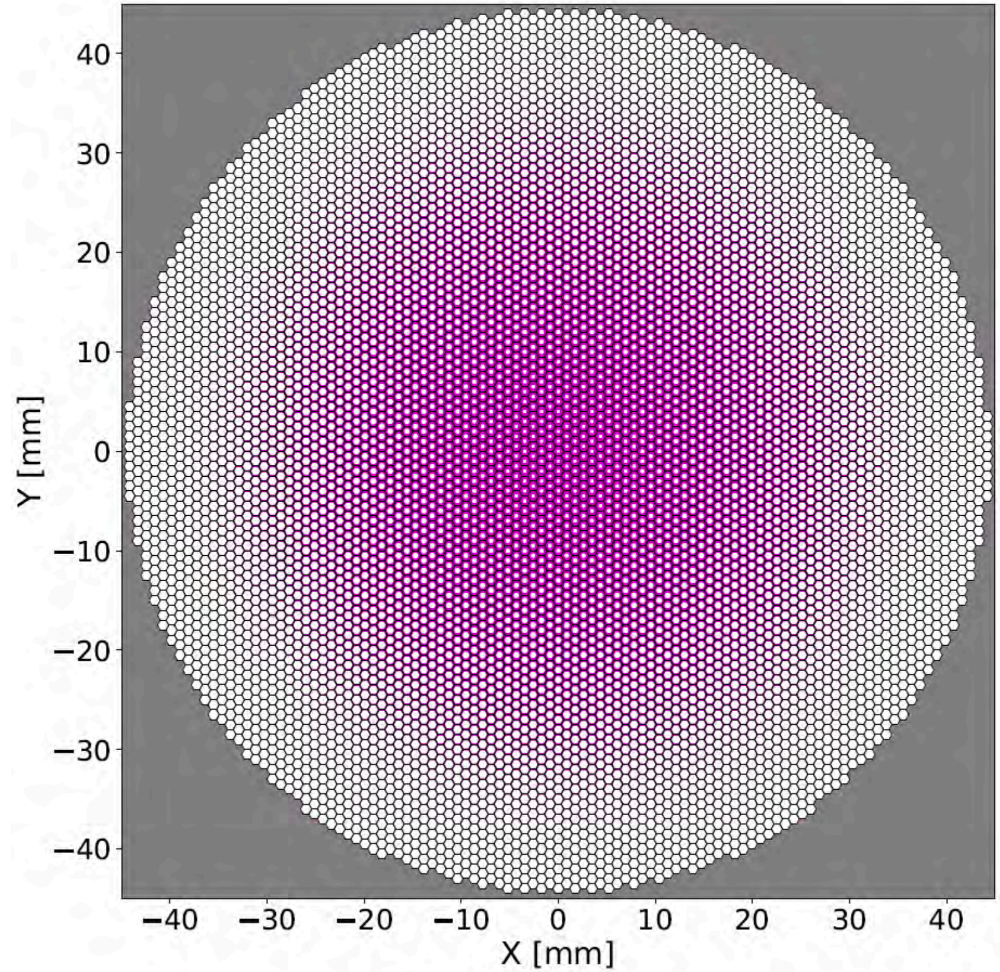


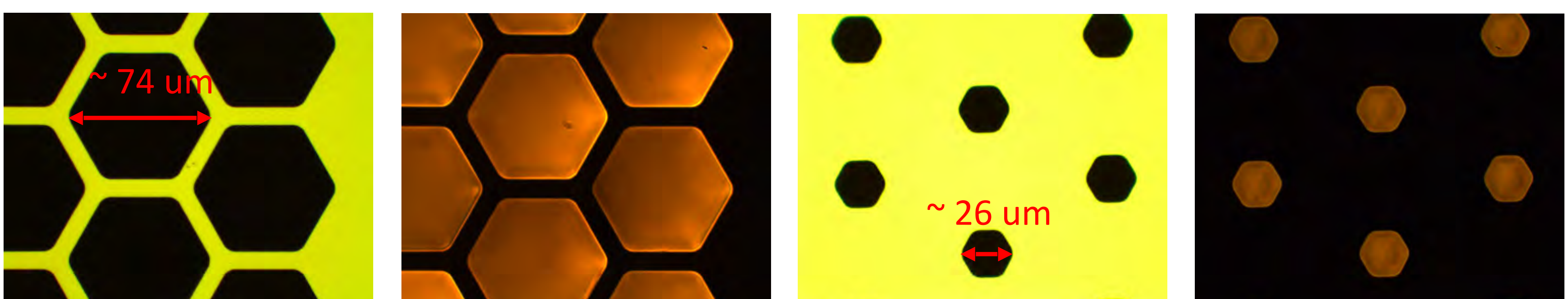


Next step: 6 layers!

Gradient Index Lenses

- Hexagonal hole pattern
- Size varying with radius to vary index
- 1 mm thickness wafers
- Clamp many together
- Fab in process
  - A couple clever tricks needed…

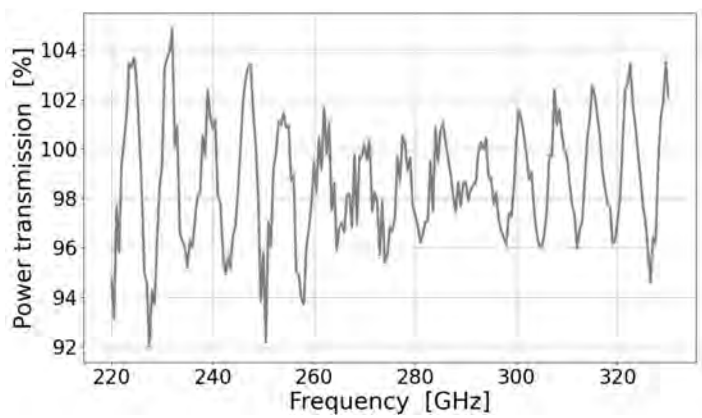




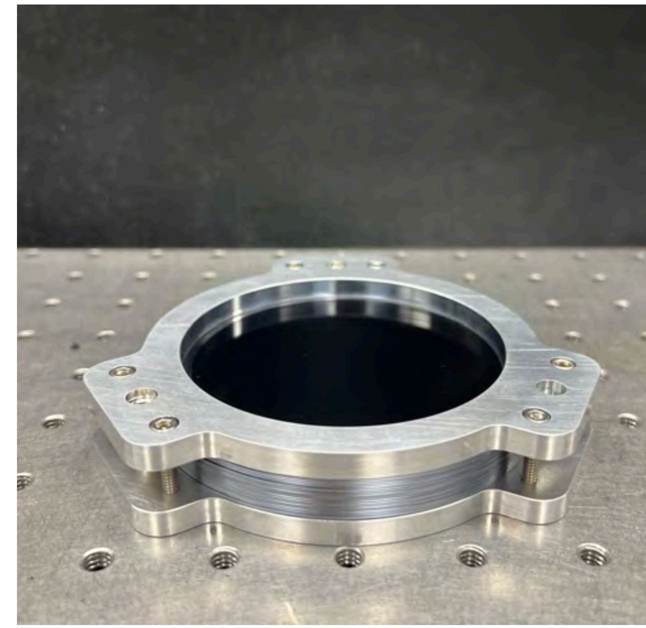
Gradient Index Lenses

Excellent performance!

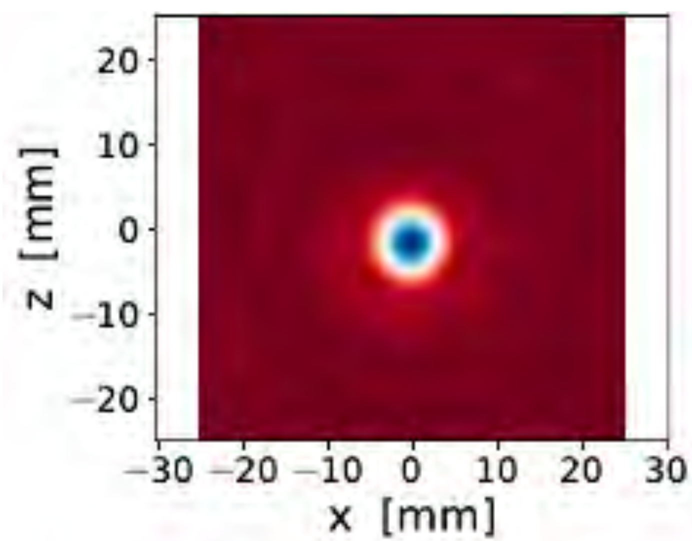
- 5-wafer version:
  - focal length: 229 mm measured, 238 mm expected
  - beam waist: 3.8-3.9 mm measured, 3.5 mm expected
- T = 1 within 5%
- 18-wafer version,
  f = 75 mm,
  waist = 1.6 mm
  showing good
  performance too,
  though stronger
  fringing to be understood



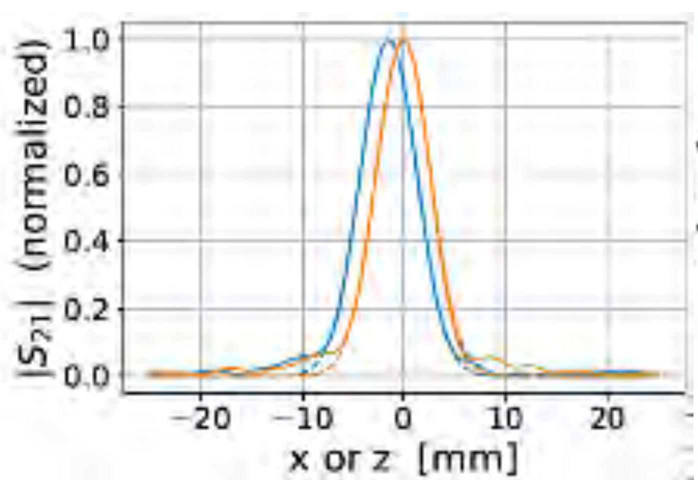
GRIN optic w/16 wafers +
3-layer AR wafers



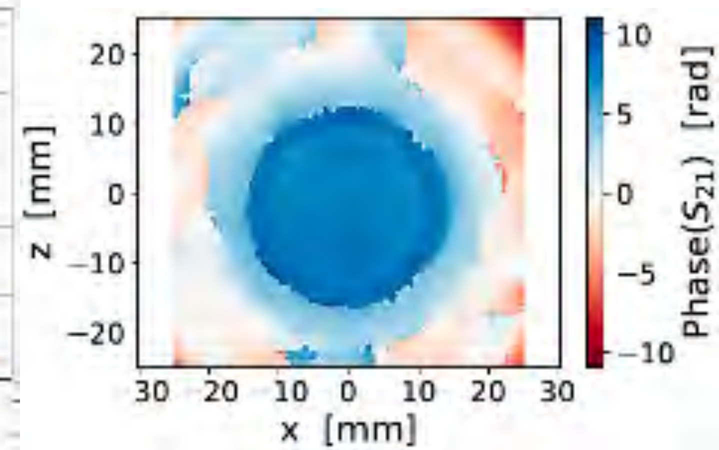
Power



E Field Magnitude



E Field Phase



Conclusion

Many exciting topics in cluster studies and instrumentation at mm/submm wavelengths:

- Analyses using in-hand and in-process data sets for various cluster science topics
- Simulations of ultimate kSZ sensitivity: can we do cosmology with cluster peculiar velocities?
- Early efforts to use SZ to study CGM
- LCT: A new facility for mm/submm time-domain astronomy, cluster and CGM SZ
- Development of detectors and optics for multiple spectral bands

Many graduate opportunities, ranging from pure instrumentation to pure analysis (though a mix is typical and preferred)