Insights into intracluster medium physics via the Sunyaev-Zel’dovich Effect

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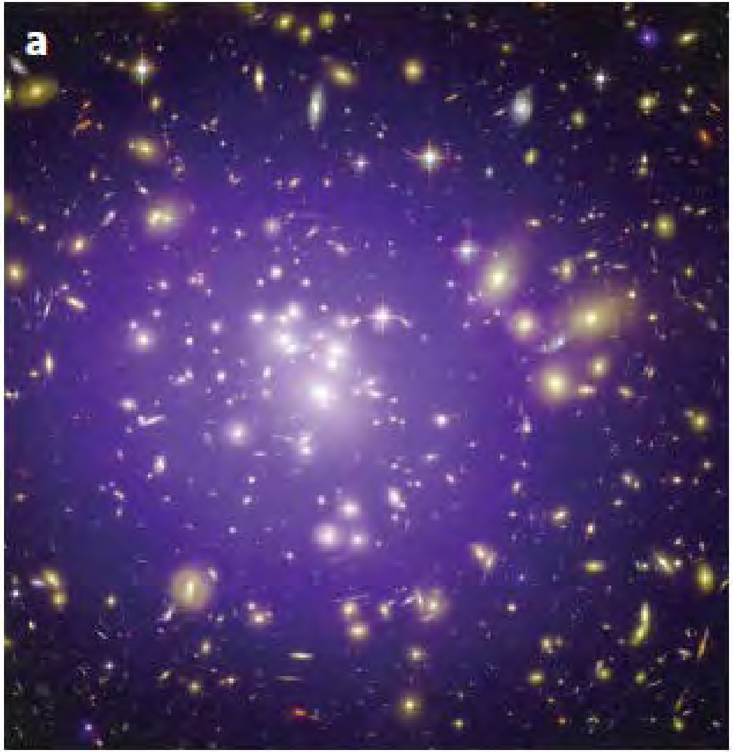
on behalf of the MUSTANG-2 team

Outline

1. Introduction to galaxy clusters, SZ
2. Profile analyses
    a. X-ray & SZ fits
3. Beyond (standard) profiles
    a. Probes of turbulence
    b. Substructure, heating, CR acceleration (gastrophysics)

Galaxy Clusters

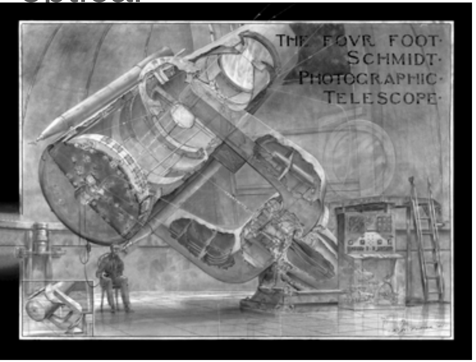
- 80-90% Dark Matter
- 9-18% ICM Gas
  - $n_e \sim 10^{-3}$ to 10^{-1} [cm^{-3}]
  - $k_B T_e \sim 5$ keV ($T_e \sim 6 \times 10^7$ K)
- 1-2% Galaxies
- $10^{14} - 10^{15}\ M_\odot$
- $R_{500} \sim 1$ Mpc
  - $R_{500} \sim 2'$ to $6'$ at $z \gtrsim 0.2$



A (very) brief history

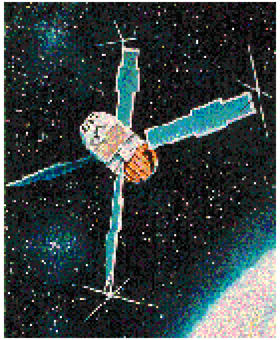
1950s

First cluster catalogs, optical



(Palomar/Caltech/Caltech Archives)

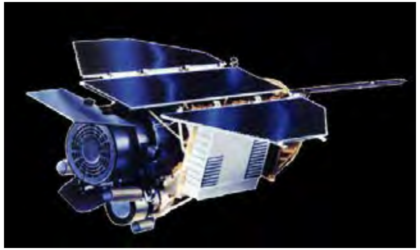
(NASA)



First X-ray satellite

1970s

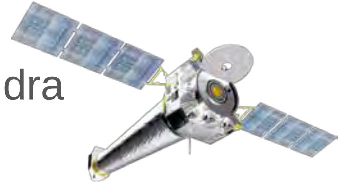
ROSAT launched



(NASA)

1990

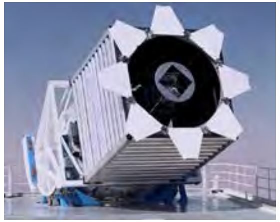
Chandra (1999)



(NASA)

XMM (1999)

(ESA)



(SDSS)

SDSS (2000)

1999

2000

2009

WISE

(Caltech)

ero

(MPE)

eRosita

2019

A (very) brief history

Penzias & Wilson
discover CMB

1965

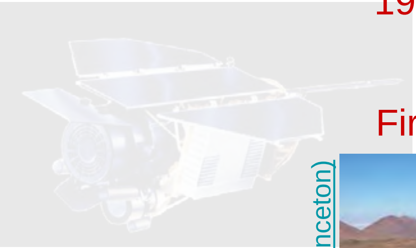
1972

SZ effect proposed

(Caltech)

One of the first
credible detections
of the SZ effect

1991



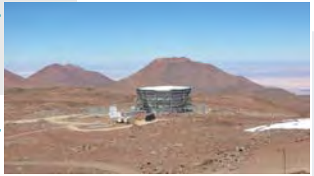
(NASA)

Planck launched

2007

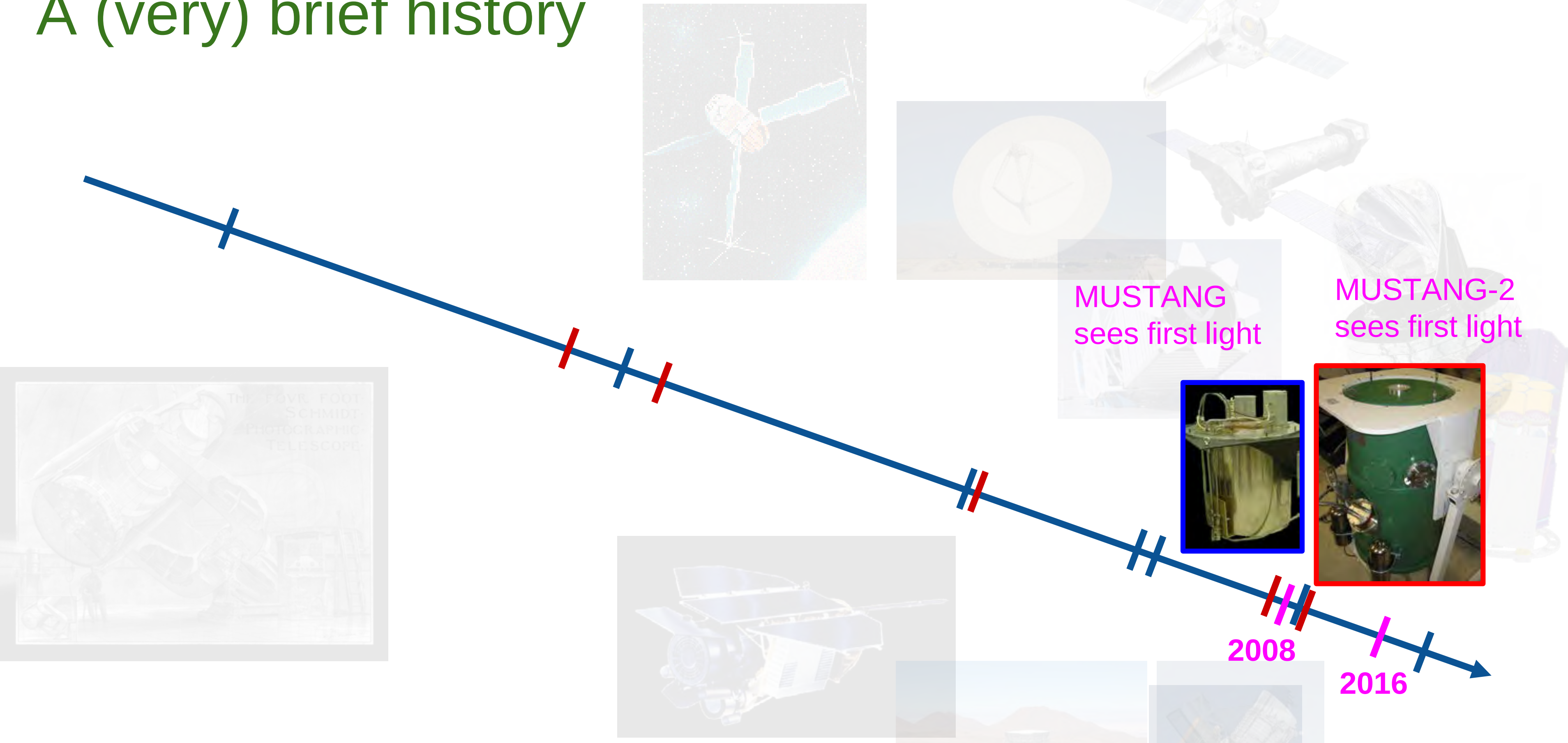
First light of ACT, SPT

(Princeton)



(UChicago)

A (very) brief history



The Sunyaev-Zel'dovich effect

The Sunyaev-Zel'dovich (SZ) effect is the inverse Compton scattering of CMB photons by free electrons in the ICM.

The SZE can be broken down into:

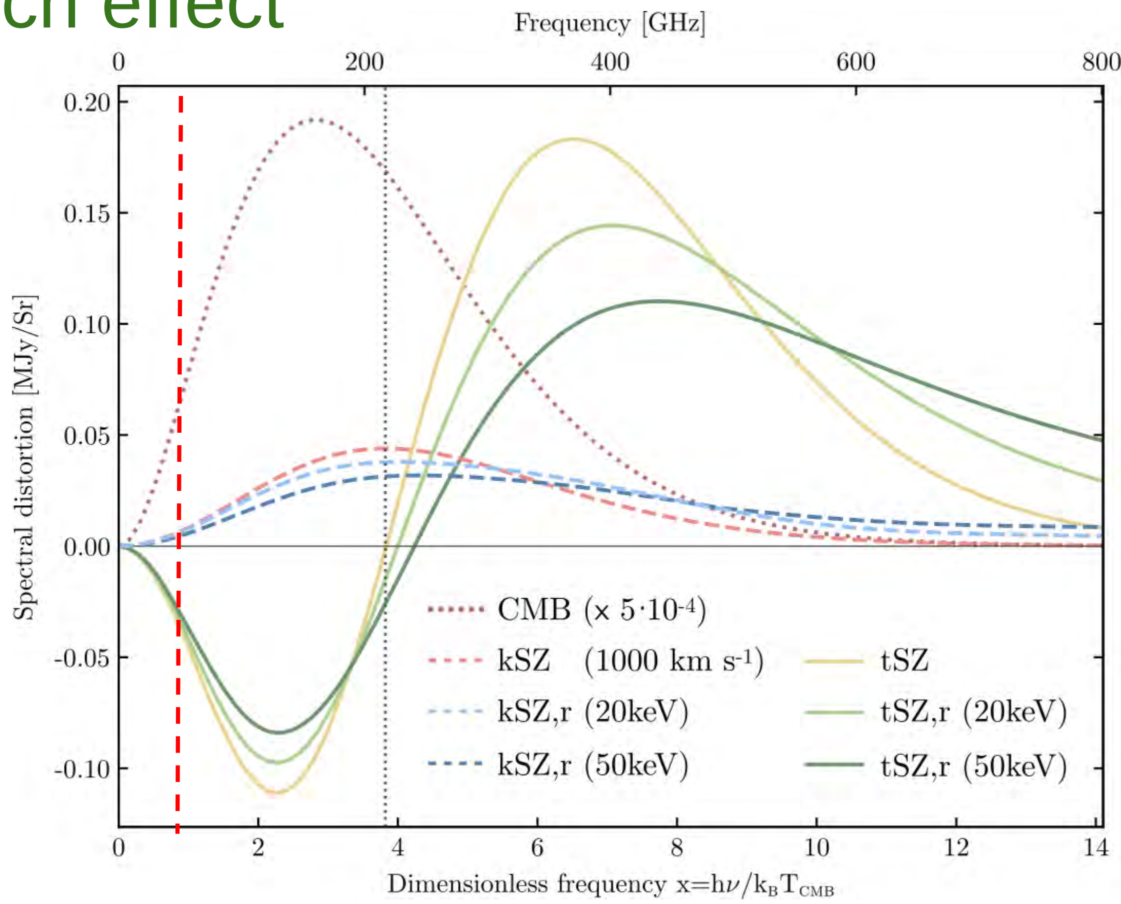
1. **thermal SZ (tSZ)**

$$y = \frac{\sigma_T}{m_e c^2} \int n_e k_B T_e d\ell$$

1. **kinematic SZ (kSZ)**

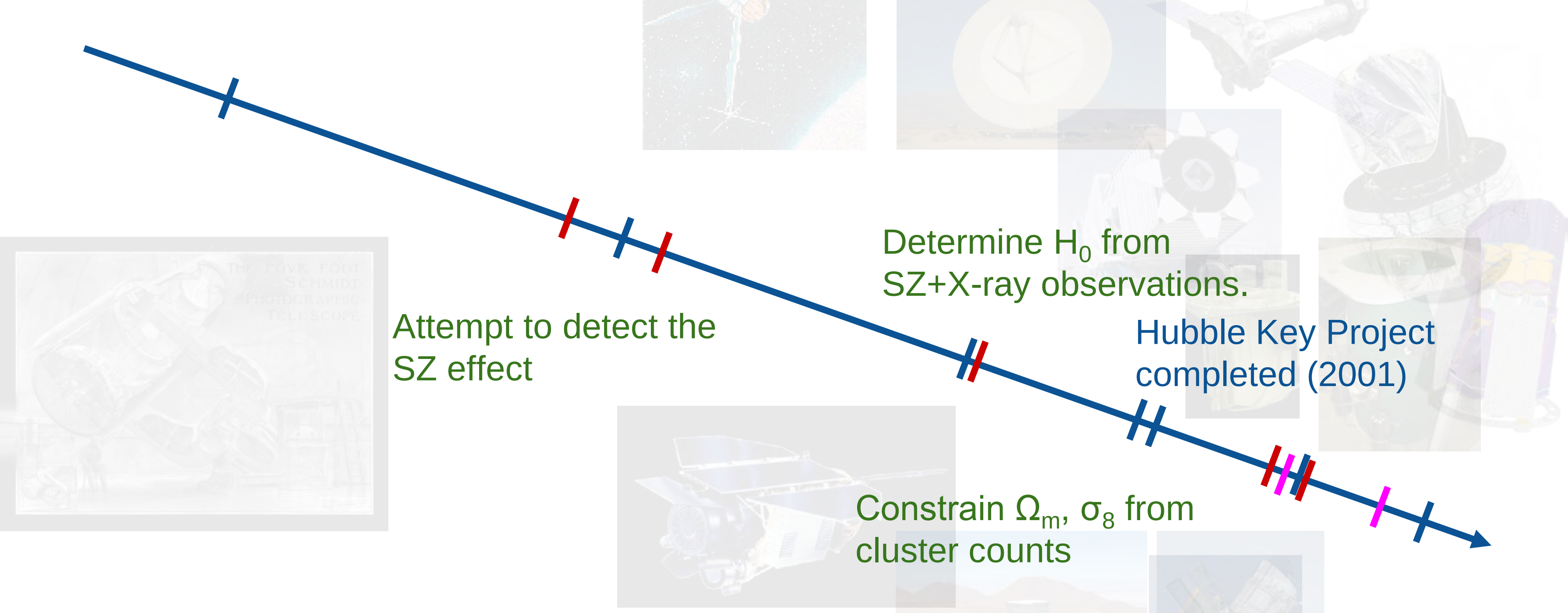
$$\frac{\Delta T_{SZE}}{T_{CMB}} = -\tau_e \left(\frac{v_{pec}}{c} \right)$$

X-ray emissivity: $\epsilon \propto n_e^2$



A (very) brief history

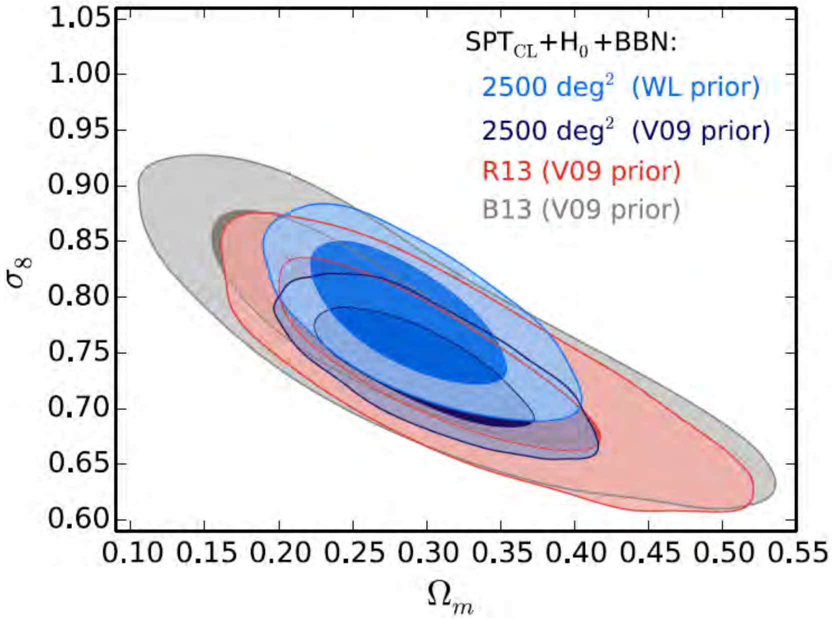
Motivation for SZ studies



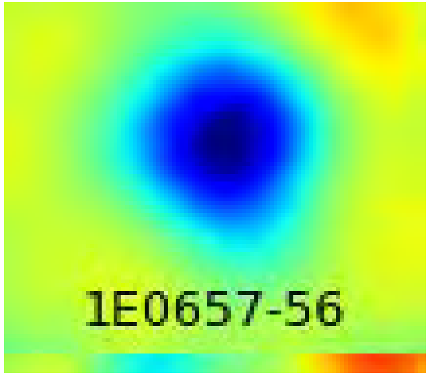
Cosmology from cluster masses

Cosmological parameters can be constrained by N(m,z)

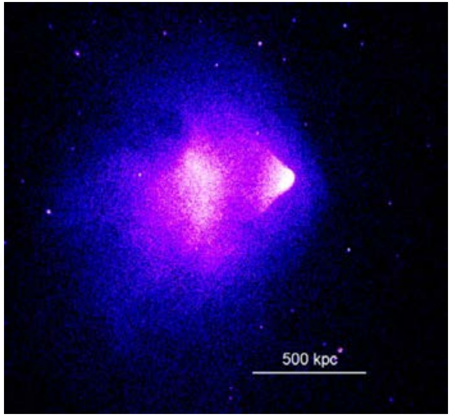
- Mass estimates are the primary limitation towards tighter cosmological constraints
- ACT, SPT have ~1’ resolution.
- MUSTANG-2 has 10” resolution



De Haan+ 2016



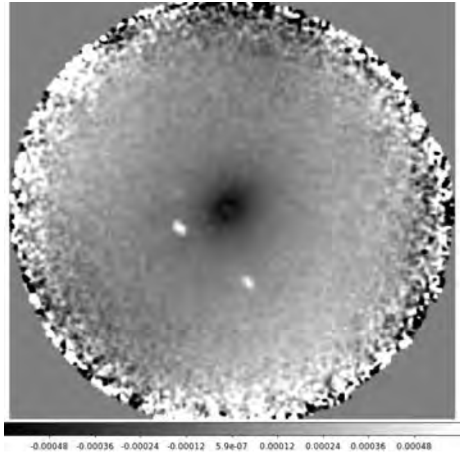
Marriage+ 2011

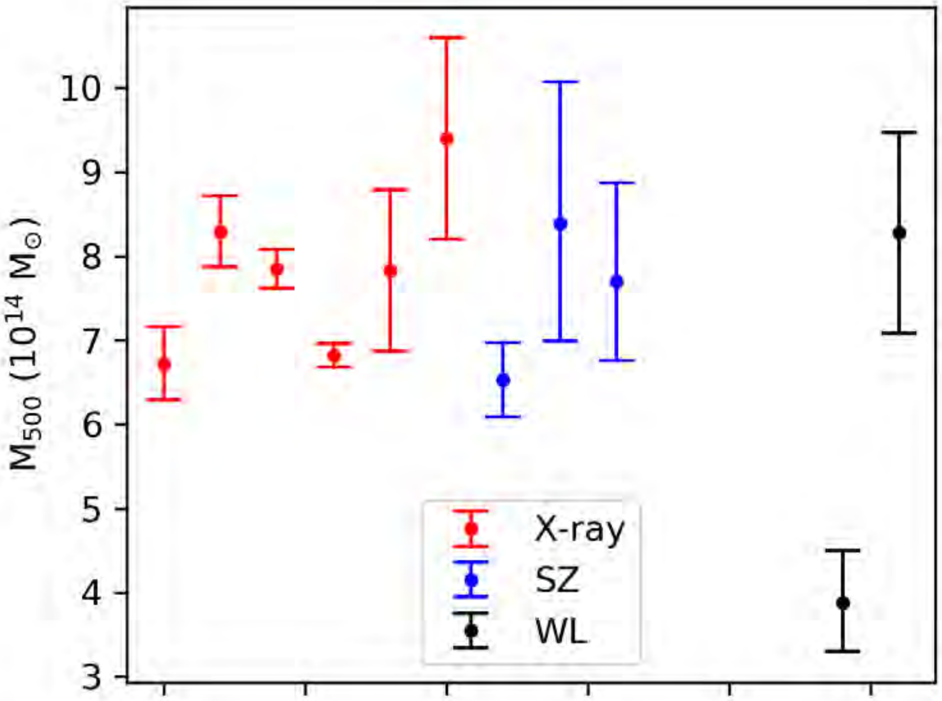


Credit: M. Markevitch

Example mass constraints of Zwicky 3146

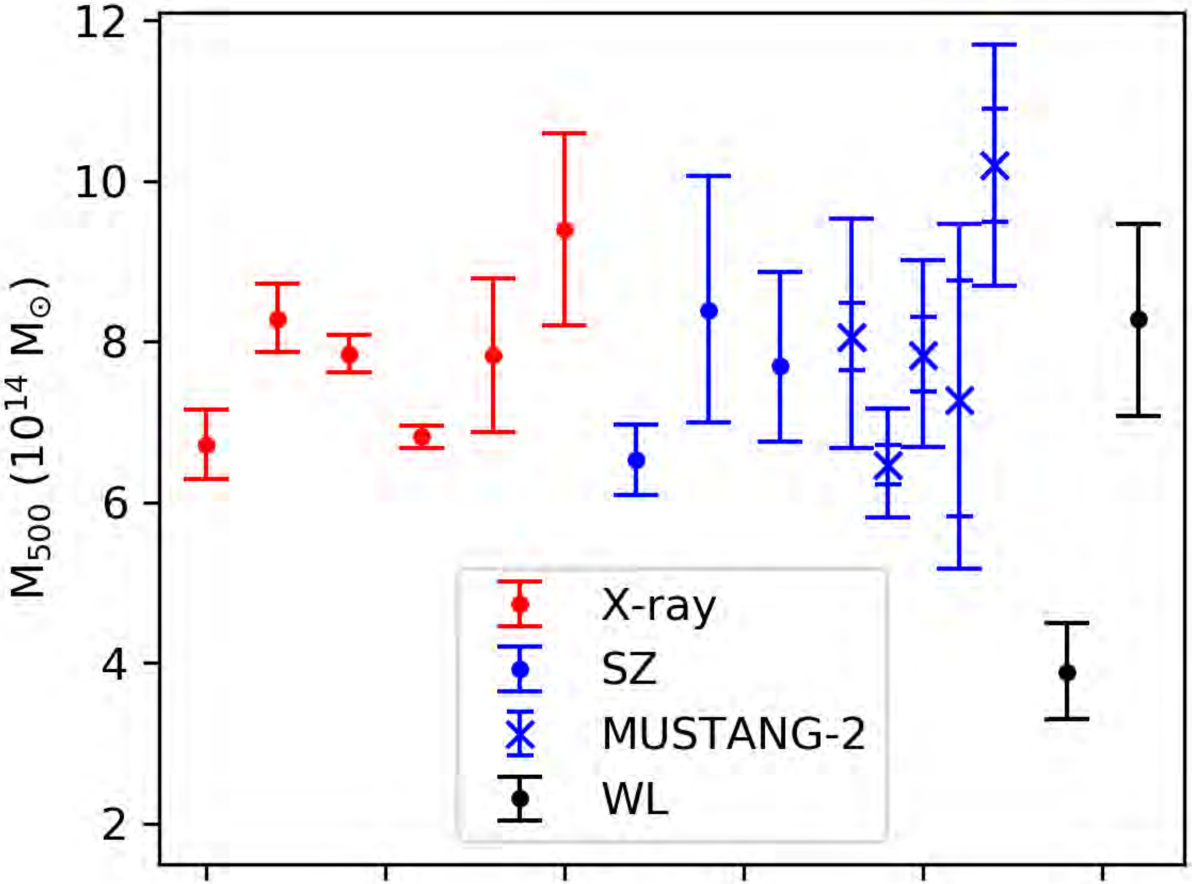
- We can estimate a mass from the pressure profile
  - via Y-M relations
  - via HSE (in tandem w/ X-ray data)
  - via the Virial Theorem (assume NFW matter profile and uniform f_{gas})
- And compare to the literature





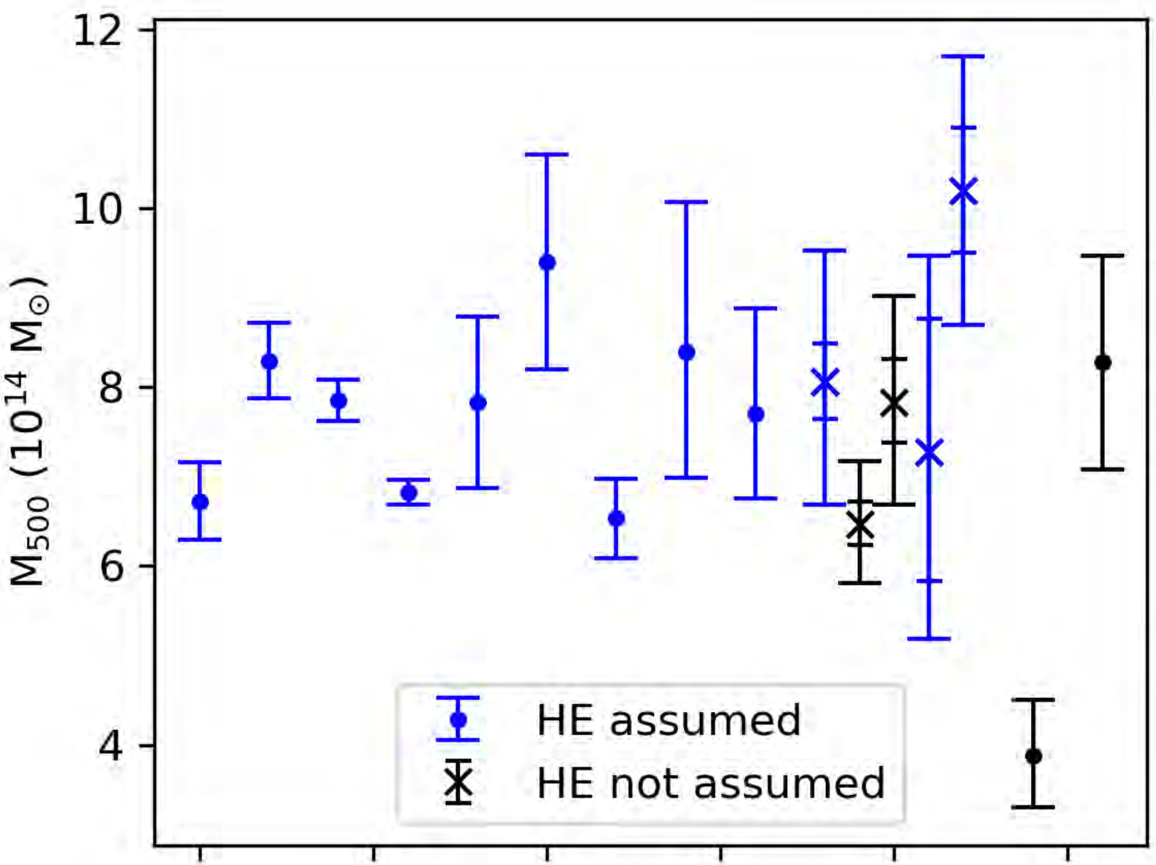
Mass estimates

- Our mass estimates are generally in agreement with the literature.



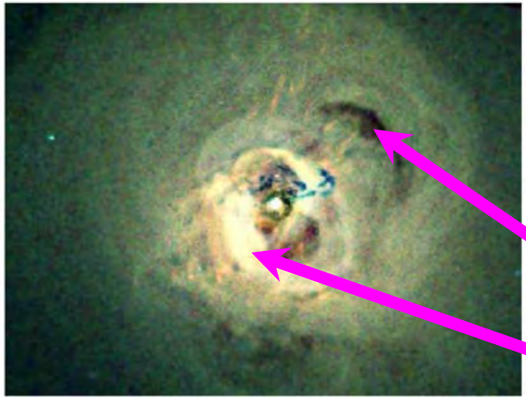
Inferred hydrostatic bias

- $b = (M_{True} - M_{HSE})/M_{True}$
- For clusters, we generally expect $0.1 \lesssim b \lesssim 0.3$
- We find b =0.07 for when using M_{HSE} and $M_{WL,Klein+19}$
- Generally, it seems that non-thermal pressure support is low in Zw3146



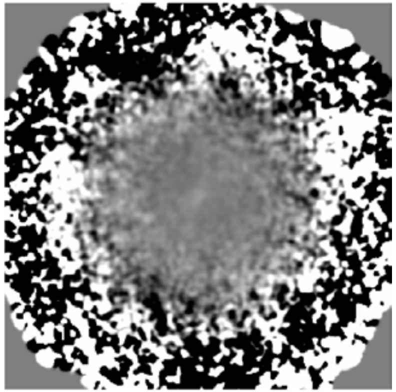
ICM Physics:

Beyond a smooth thermal distribution



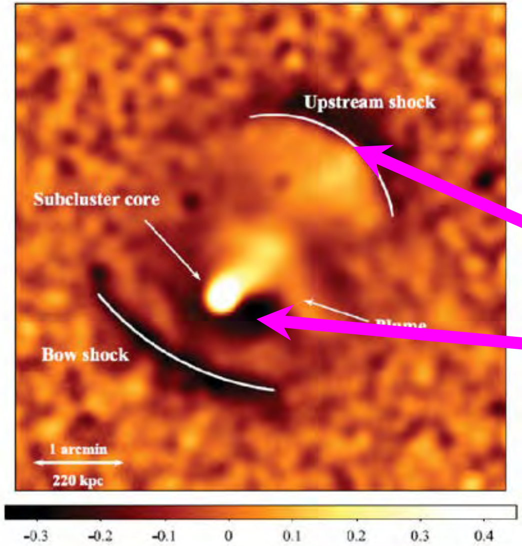
Fabian+ 2006

- X-ray cavities
- Sloshing
- Turbulence*
- Radio relics
- Radio halos
- Radio phoenixes
- Shocks
- Cold fronts

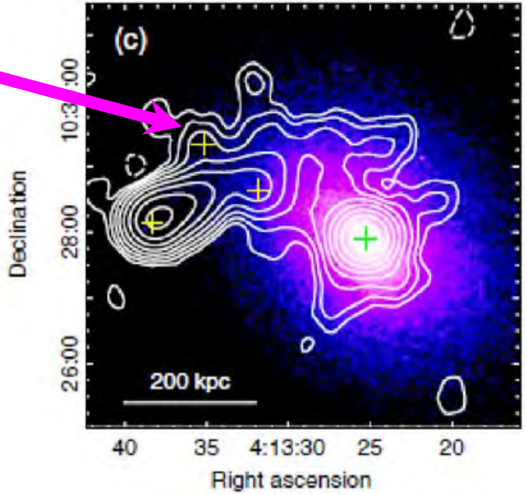


* δy/<y> of M-2 data Zw3146

Russell+ 2012

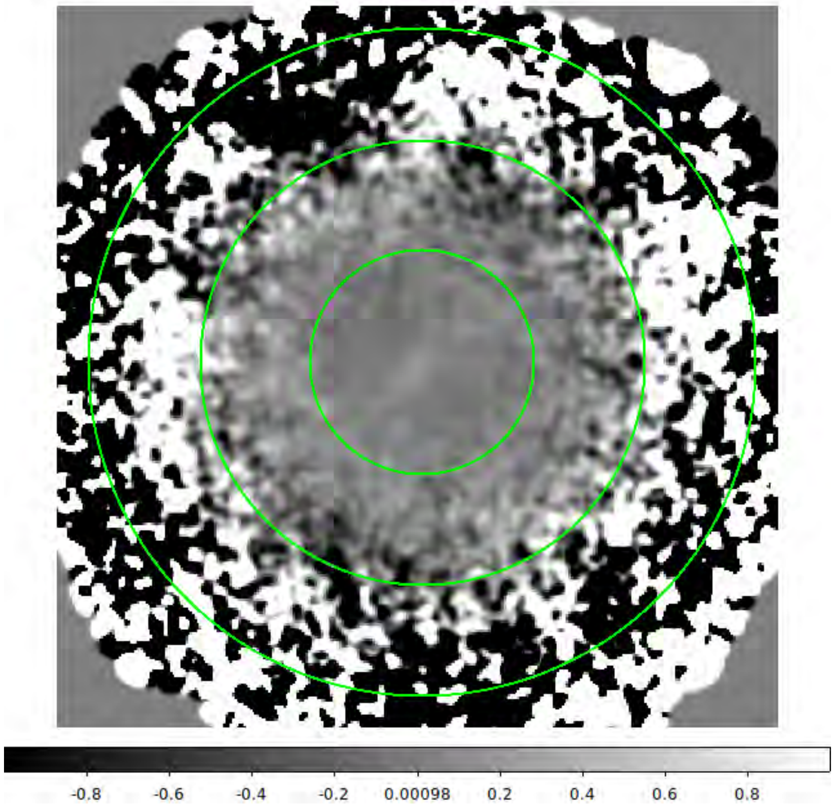


Giacintucci+ 2014



Pressure fluctuations in Zwicky 3146

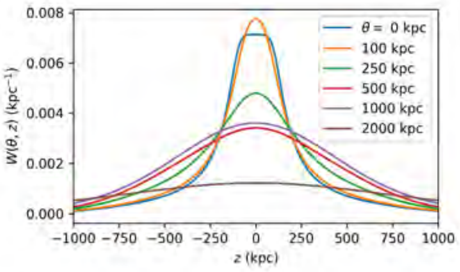
- Pressure fluctuations can be derived from δy/<y>
  - <y> = model; δy = y - <y>
- A simple quantification of pressure fluctuations (presumably from turbulence) is just to take the RMS of δy/<y>.
  - However, this captures RMS simply due to noise
  - Both noise and <y> vary with radius, making constraints more difficult at large radii.
- Divide the cluster into 3 regions
  - After subtracting the RMS due to noise, we find a residual RMS (from the cluster) of ~0.05 to ~0.07.

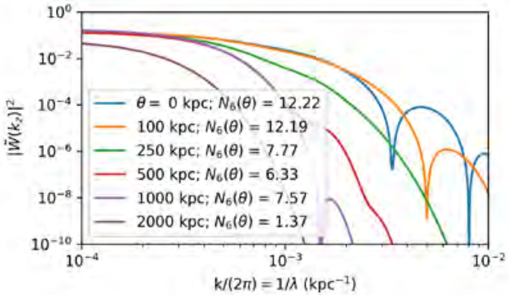


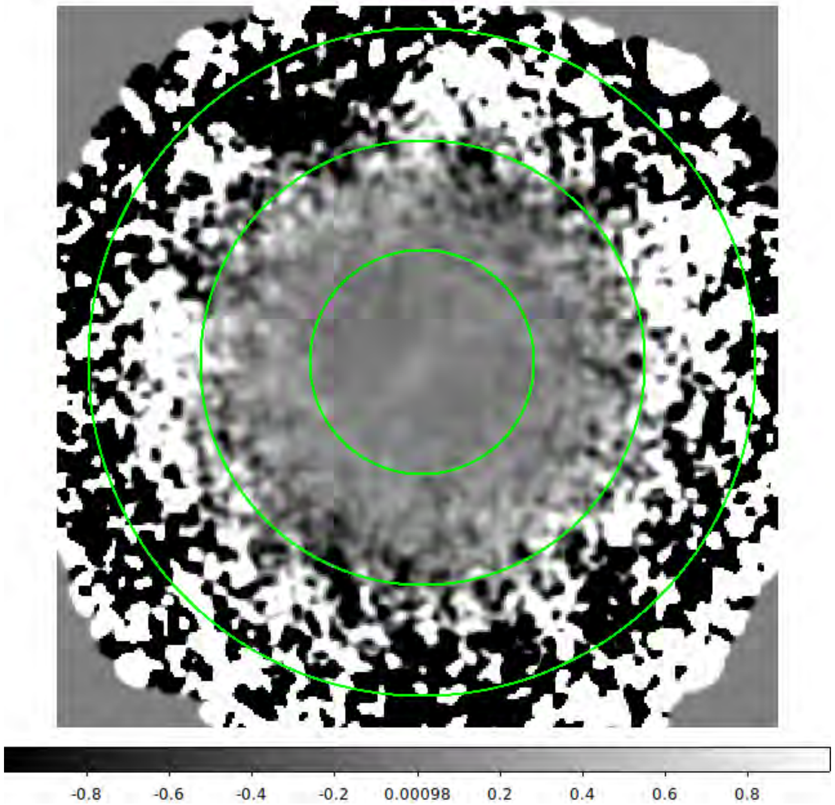
Pressure fluctuations in Zwicky 3146

- Taking power spectra of δy/<y> can reveal even more
  - The amplitude is still a measure of total turbulence
- The slope of the power spectrum (in pressure space)

$$P_y(k_\theta) \approx P_P(k_\theta) \int \frac{\mathrm{d}k_z}{2\pi} \left|\tilde{W}(k_z, \theta)\right|^2$$
$$\approx N(\theta)\, P_P(k_\theta)\,.$$





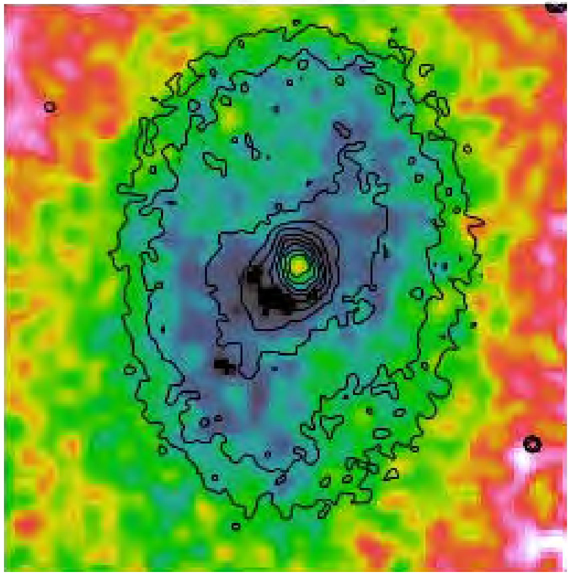


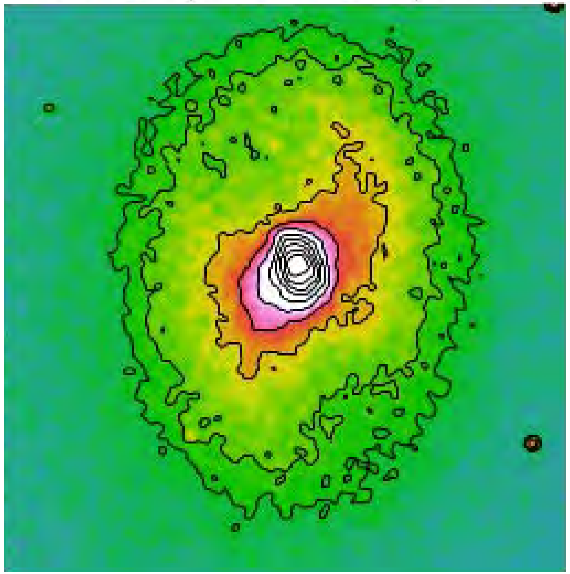
We are currently pursuing this investigation!

X-ray cavities

Physical scenario Physical scenario	$F_{90\ \mathrm{GHz}}$ (mJy)	$F_{150\ \mathrm{GHz}}$ (mJy)	$F_{260\ \mathrm{GHz}}$ (mJy)
No bubble	-1.1 mJy	-1.3 mJy	$+0.9$ mJy
Mag. support equal to relativistic support	-0.1 mJy	-0.15 mJy	$+0.13$ mJy
Very hot relativistic gas	-0.8 mJy	-1.0 mJy	$+0.7$ mJy
Cosmic ray electron	< -0.1 mJy	< -0.13 mJy	< -0.13 mJy
Cosmic ray proton	0.0 mJy	0.0 mJy	0.0 mJy

MUSTANG-2
16 hours on source





Chandra
124 hours on source

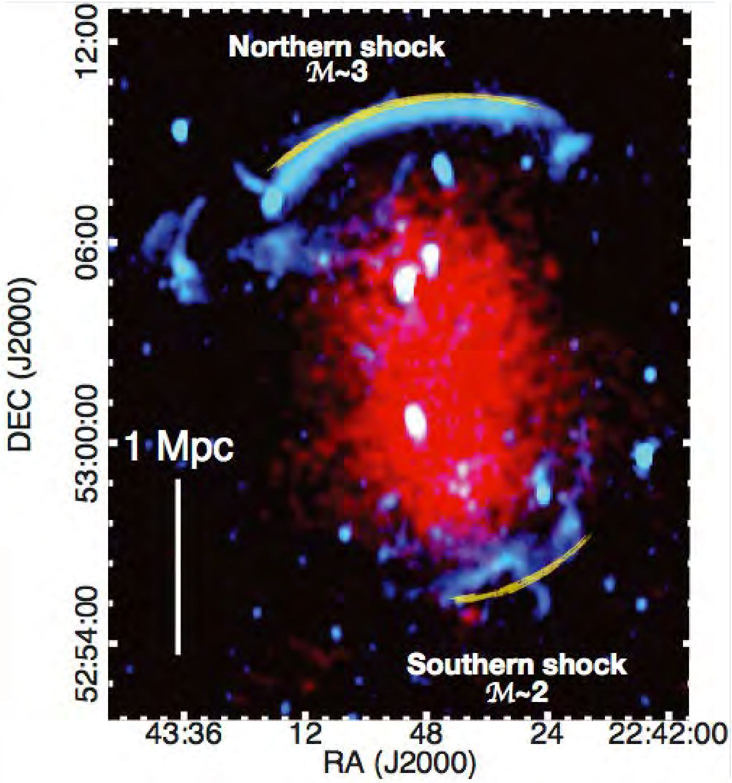
Association with radio features?

- Shocks are expected to play a role in CR acceleration - what do we actually see?
- "Sausage" cluster (CIZA J2242.8+5301) has a ~2 MPc relic
- Mach numbers calculated from radio and X-ray were ~2 sigma apart (Stroe+ 2013 compared to Akamatsu+ 2015)
  - Some values in Hoang+ 2017 bring radio and X-ray into good agreement.

$$\alpha = \frac{\mathcal{M}^2 + 1}{\mathcal{M}^2 - 1} \equiv \alpha_{inj} + \frac{1}{2}$$

$$\frac{P_{\rm down}}{P_{\rm up}} = \frac{5\mathcal{M}^2 - 1}{4}$$

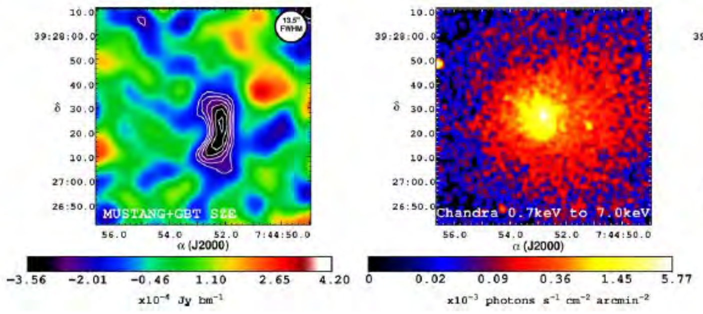
$$\frac{T_2}{T_1} = \frac{5\mathcal{M}^4 + 14\mathcal{M}^2 - 3}{16\mathcal{M}^2}$$



Akamatsu+ 2015

Shocks

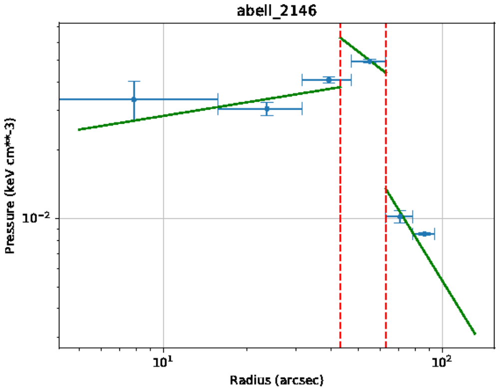
- SZ is quite uniquely (well) suited for finding shocks and constraining shock parameters (e.g. Mach number)



Korngut+ 2011

Okabe+ 2020

- <u>In tandem</u> with X-rays, SZ can constrain temperatures
- Simulated observations of Abell 2146 (using values from Russell+ 2012) show that a 16 hour on source w/ MUSTANG-2 can well recover a pressure profile towards the shock front
- Uncertainty of $T_{e,SZ/X\text{-}ray}$ ~ $T_{e,X\text{-}ray}$ (for 32 hours of MUSTANG-2 and ~420 ks of Chandra time)



Conclusions

1. High resolution increases profile resolution - critical for high redshift clusters.
    a. It also opens the door to seeing residuals when removing a bulk component, be it substructure or fluctuations
2. Power spectra analysis is a powerful, yet nascent, way to probe turbulence (without velocity dispersion)
    a. I think there is very much more to be seen in these types of investigations!
    b. This will offer a direct way to infer hydrostatic bias (and compare with what is inferred when WL measurements exist), and thus has consequences on cosmological constraints from galaxy clusters.
3. SZ observations are no longer restricted to measuring the “bulk” SZ signal.
    a. Though, when we do, we don’t need to assume a pressure profile shape.
    b. We can see substructure *and* infer physical properties of the substructure, and by extension physical mechanisms at play
4. Though some of this can be done with SZ alone, joint SZ + X-ray analyses will be very powerful.

End

- Jonathan Sievers
- Vittorio Ghirardini
- Simon Dicker
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- Esra Bulbul
- Ian Lowe
- Sara Stanchfield