Argelander-
Institut
für
Astronomie

IMPRS astronomy & astrophysics
Bonn and Cologne

Constraining the gas mass fraction of galaxy clusters from the Sunyaev-Zel'dovich power spectrum

Miriam E. Ramos Ceja

Dr. K. Basu and Dr. F. Pacaud

Prof. Dr. Frank Bertoldi

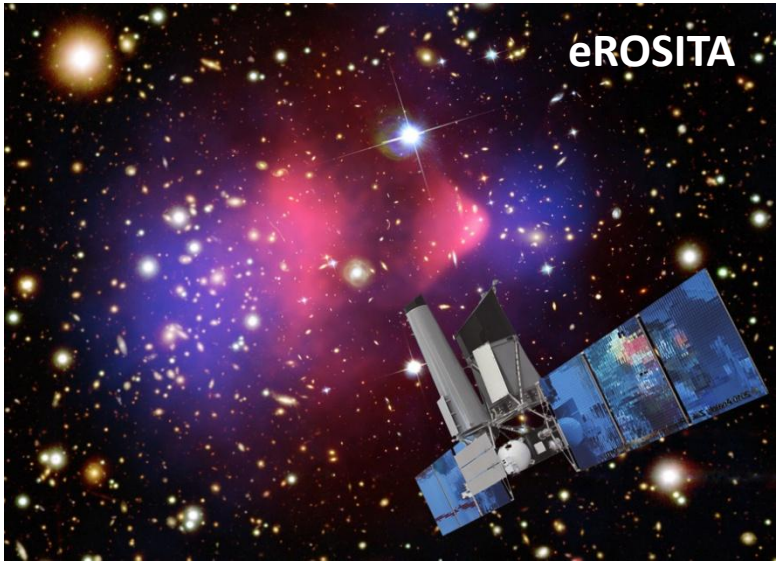
December 05 2012

PhD Project

Study the intra-cluster gas of galaxy clusters.

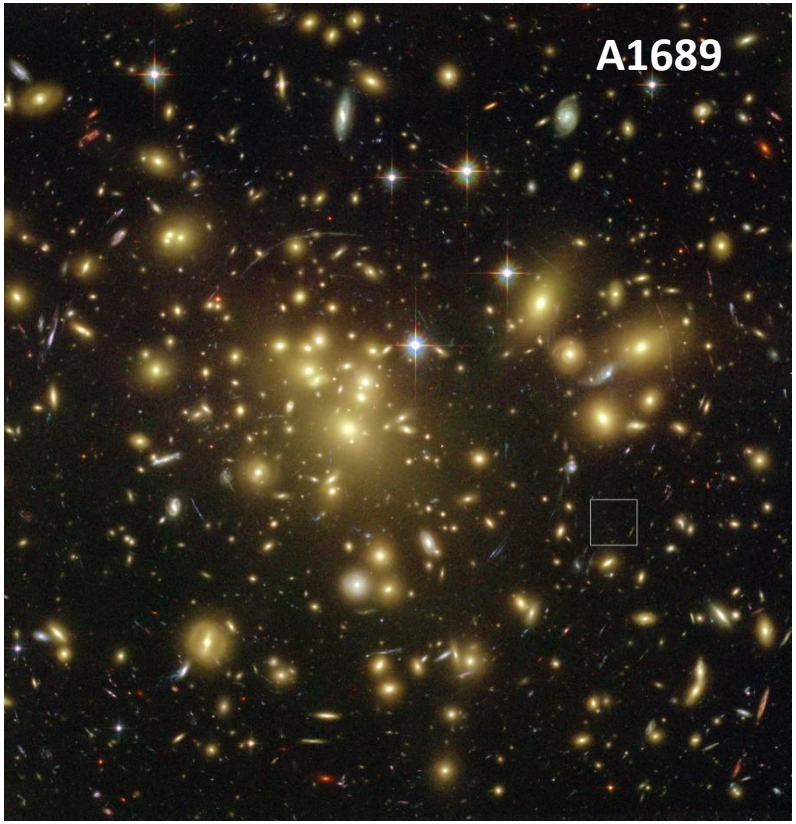
Two parts:

- Development of source detection algorithms for eROSITA.
  - Launch in 2014.
- Study the gas mass fraction of galaxy clusters from the thermal Sunyaev-Zel'dovich power spectrum.



Galaxy Clusters

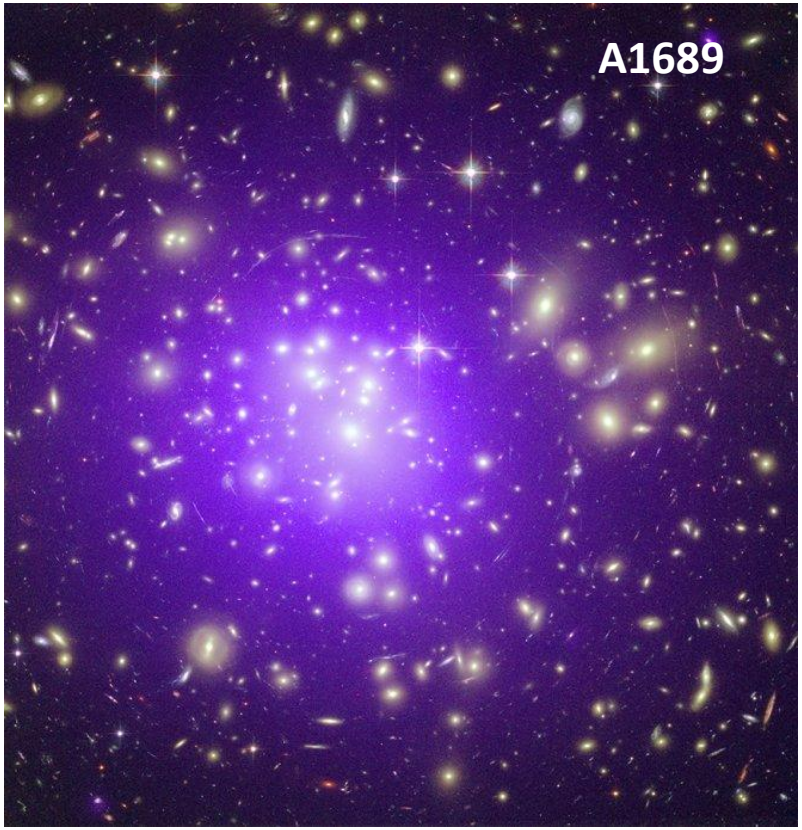
- Galaxy clusters are the most massive, gravitational bound entities of the Universe.
- Components:
  - Dark matter (~ 80%)
  - Hot intra-cluster gas (~ 16%)
  - Galaxies (~ 4%)
- How to study galaxy clusters?
  - Optical
  - Lensing
  - X-ray
  - Sunyaev-Zel'dovich effect



NASA/STScI

Galaxy Clusters

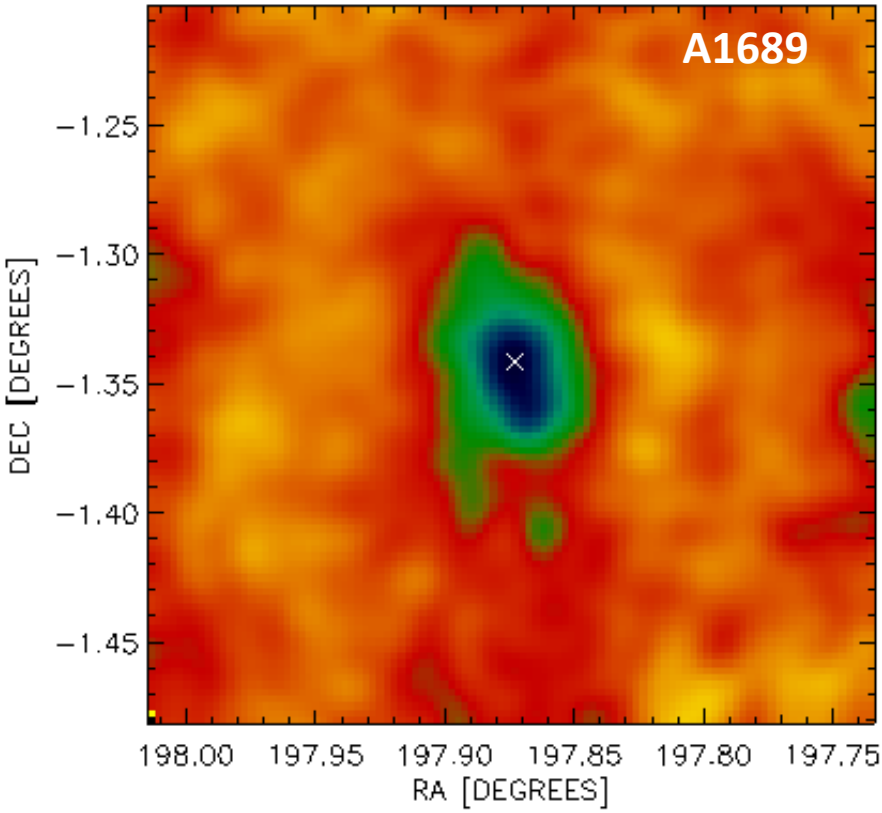
- Galaxy clusters are the most massive, gravitational bound entities of the Universe.
- Components:
  - Dark matter (~ 80%)
  - Hot intra-cluster gas (~ 16%)
  - Galaxies (~ 4%)
- How to study galaxy clusters?
  - Optical
  - Lensing
  - X-ray
  - Sunyaev-Zel'dovich effect



Optical: NASA/STScI
X-ray: NASA/CXC/MIT/E.-H Peng.

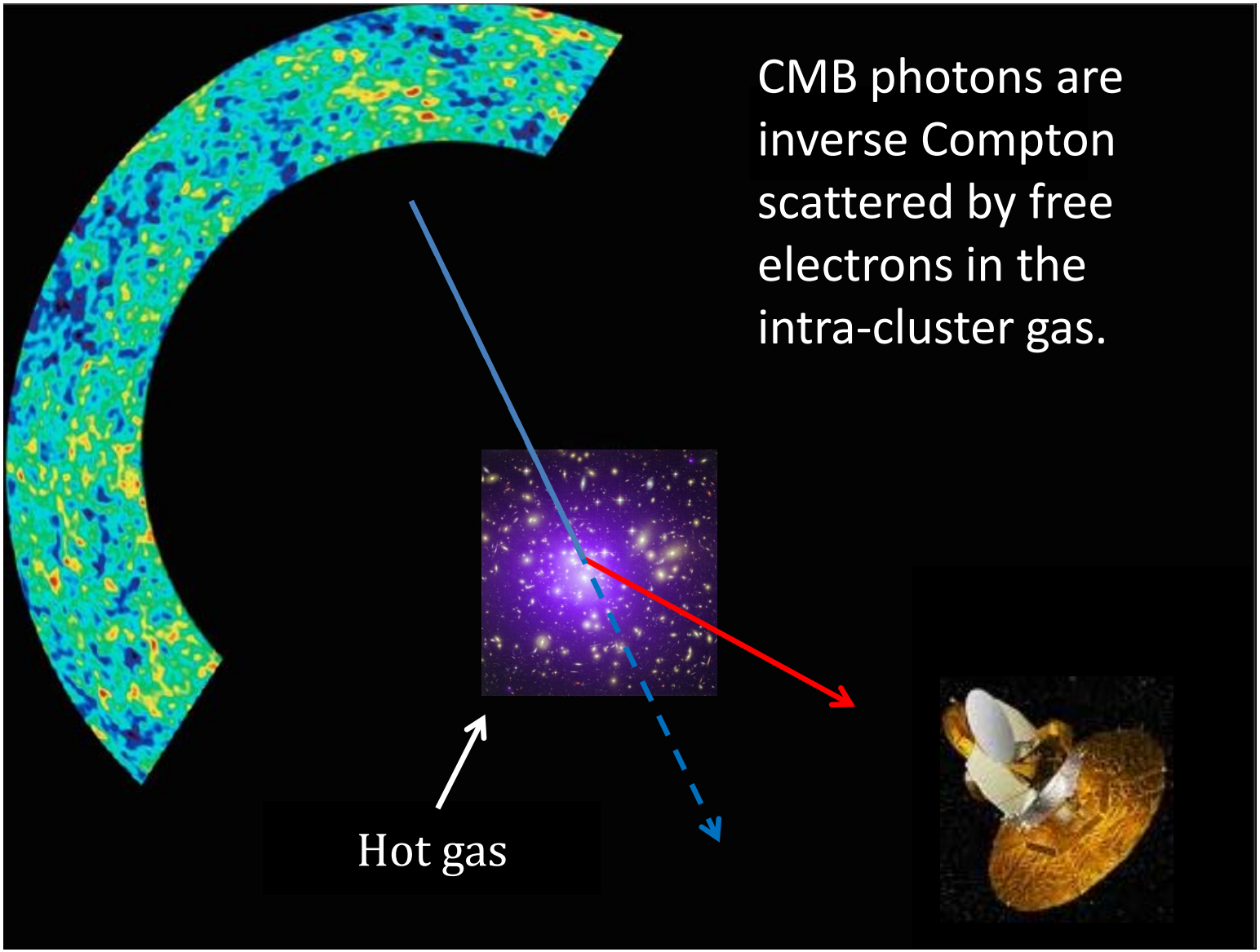
Galaxy Clusters

- Galaxy clusters are the most massive, gravitational bound entities of the Universe.
- Components:
  - Dark matter (~ 80%)
  - Hot intra-cluster gas (~ 16%)
  - Galaxies (~ 4%)
- How to study galaxy clusters?
  - Optical
  - Lensing
  - X-ray
  - Sunyaev-Zel'dovich effect

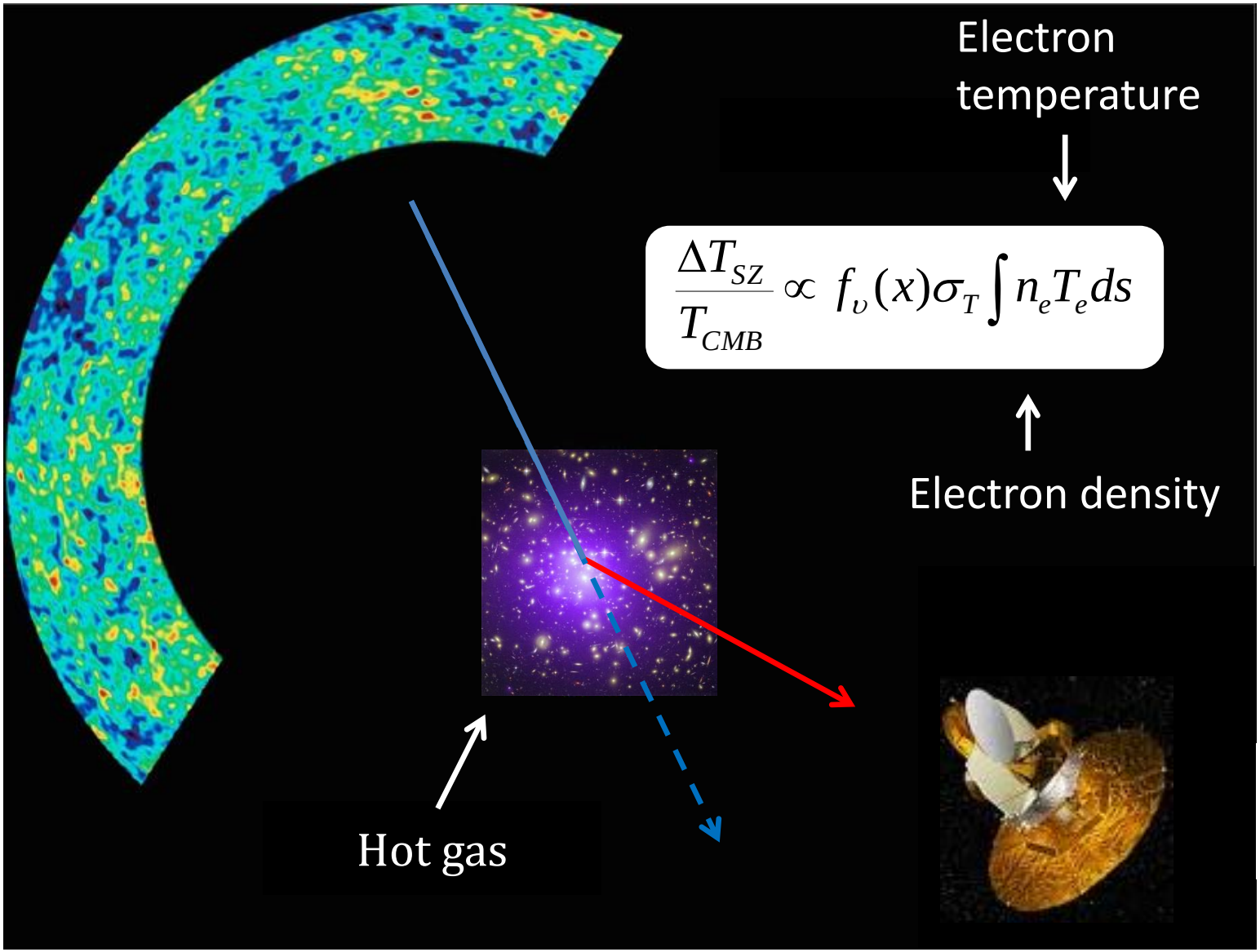


Martin Nord

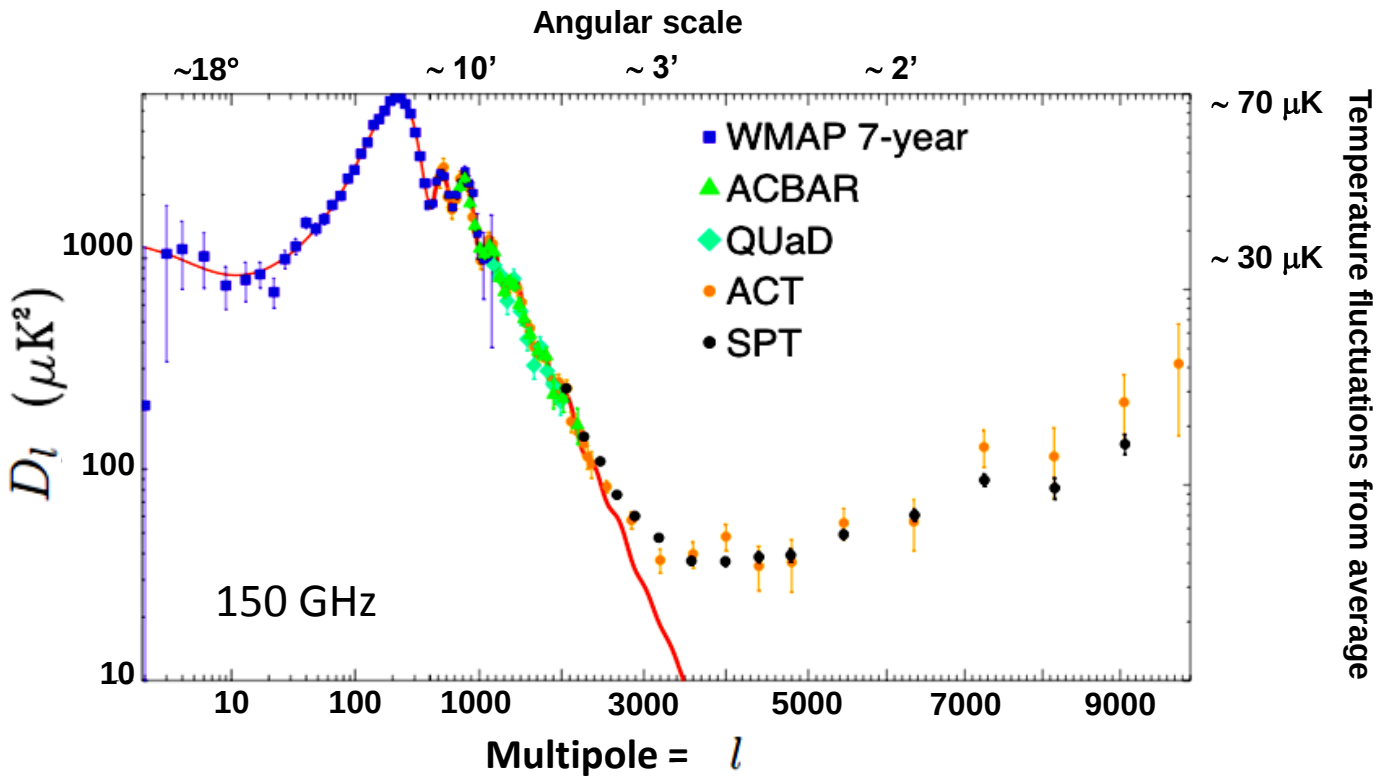
Thermal Sunyaev-Zel'dovich (tSZ) effect



Thermal Sunyaev-Zel'dovich (tSZ) effect

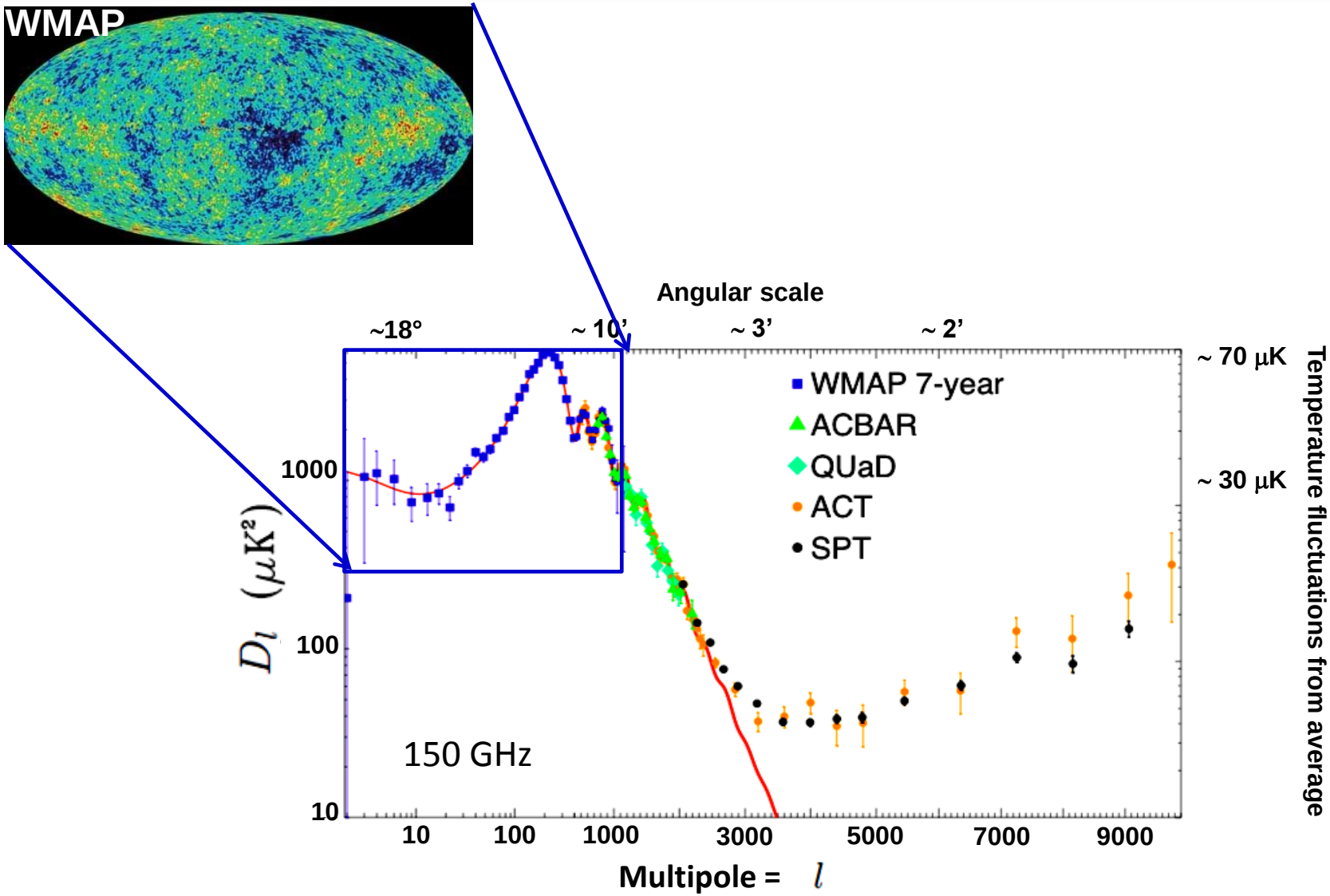


CMB power spectrum



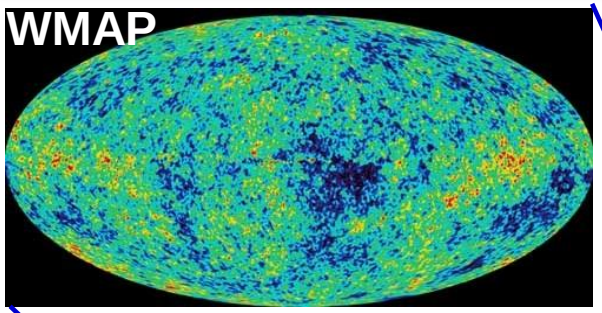
Shirokoff et al. 2011

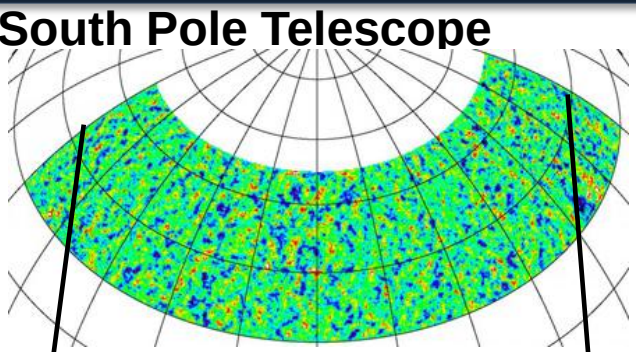
CMB power spectrum

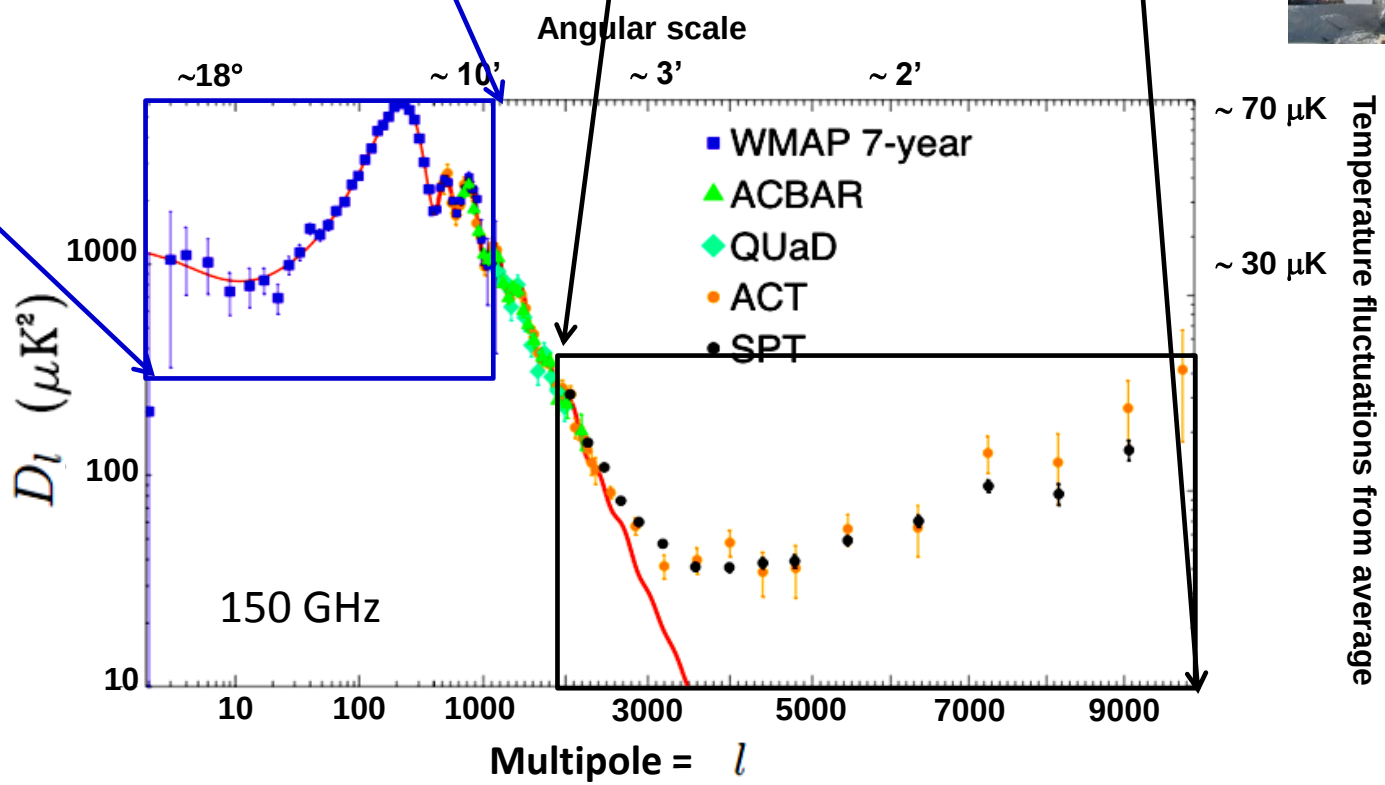


Shirokoff et al. 2011

CMB power spectrum

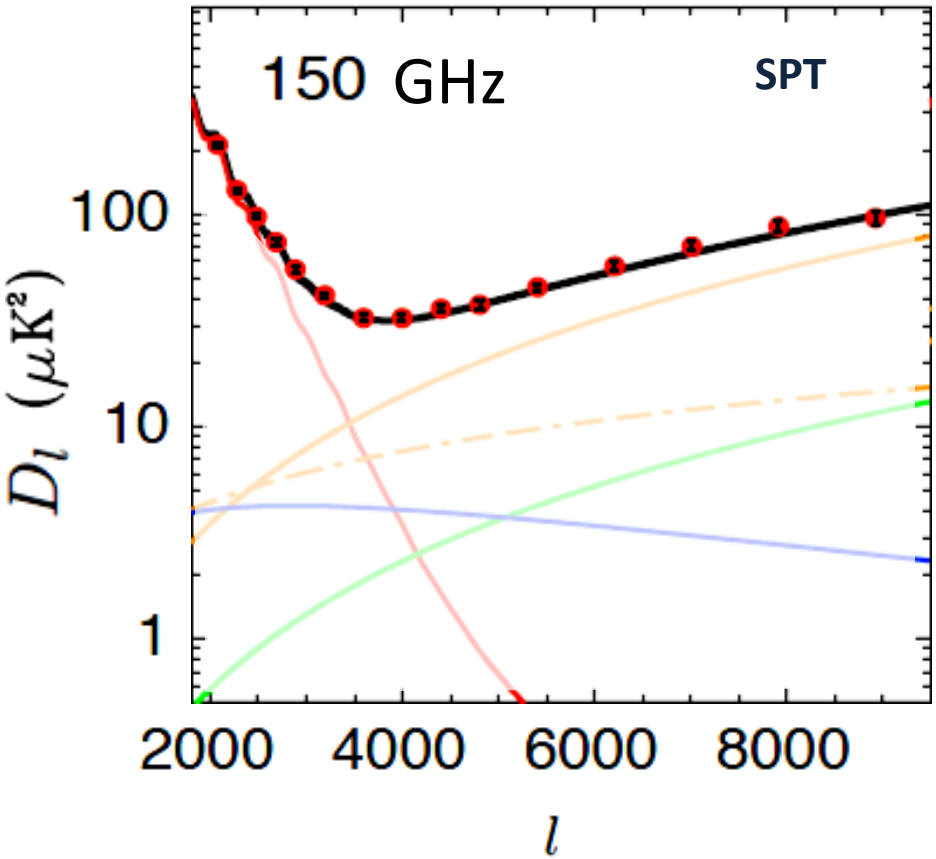






Shirokoff et al. 2011

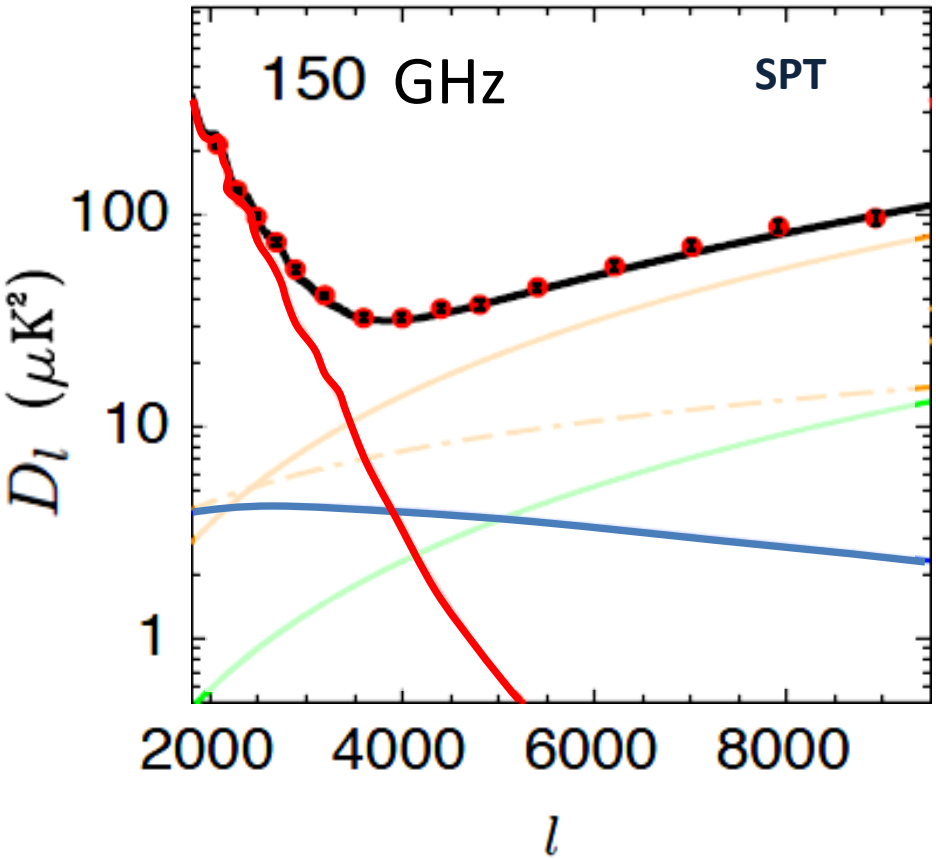
SPT measurements: microwave sky



Reichardt et al. 2012

At l > 2500 the microwave sky is composed of:

SPT measurements: microwave sky



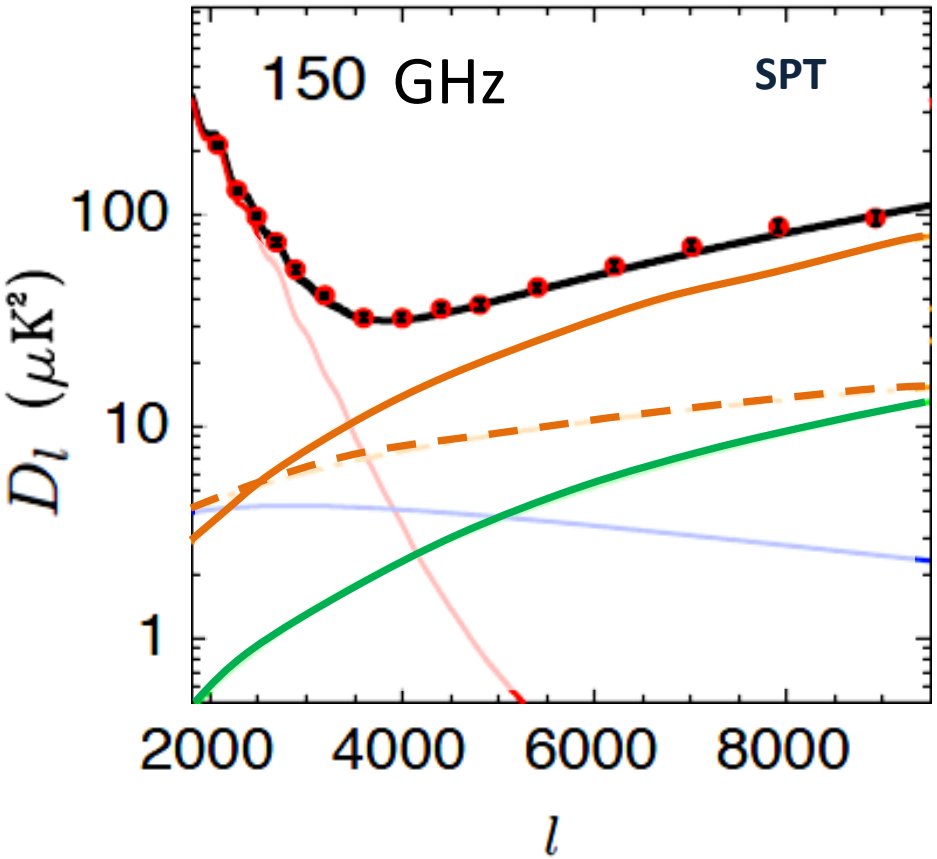
Reichardt et al. 2012

At l > 2500 the microwave sky is composed of:

1. Lensed CMB
2. Thermal SZ signal

} Secondary anisotropies

SPT measurements: microwave sky



Reichardt et al. 2012

At l > 2500 the microwave sky is composed of:

1. Lensed CMB
2. Thermal SZ signal

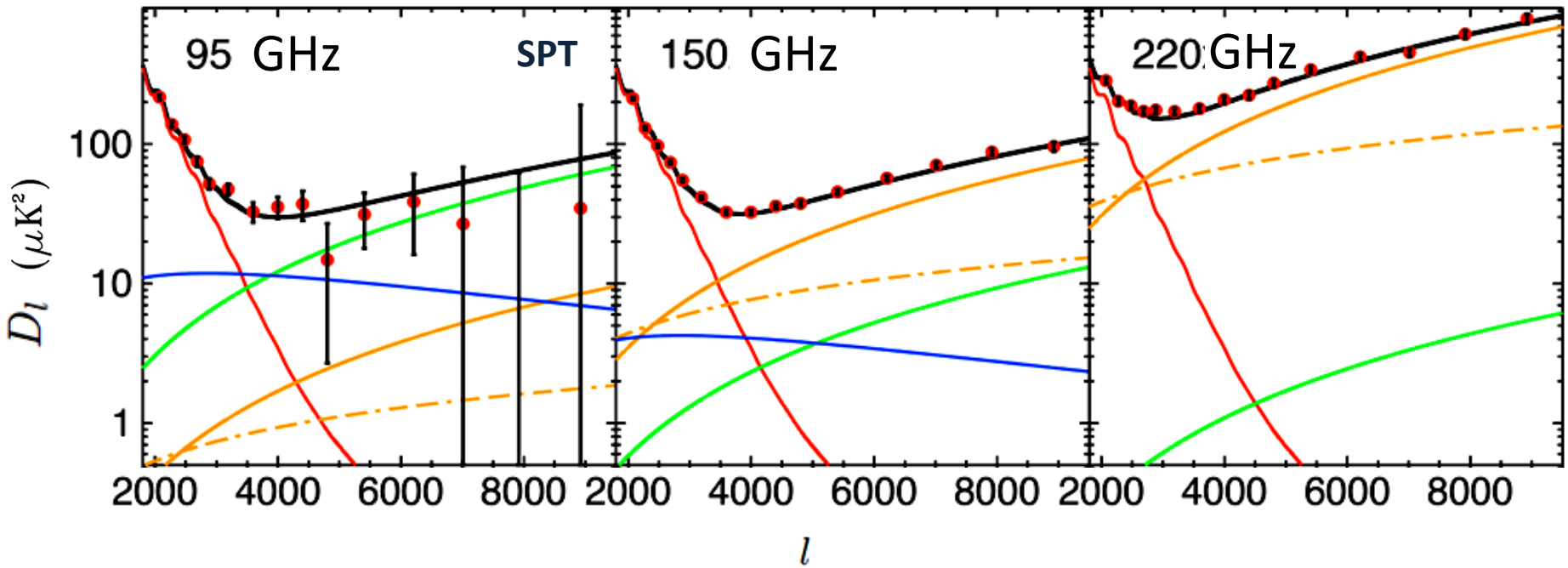
Secondary anisotropies

3. Infrared galaxies:
   a. Clustered
   b. Poisson
4. Radio galaxies

Galactic and extra-galactic emitters

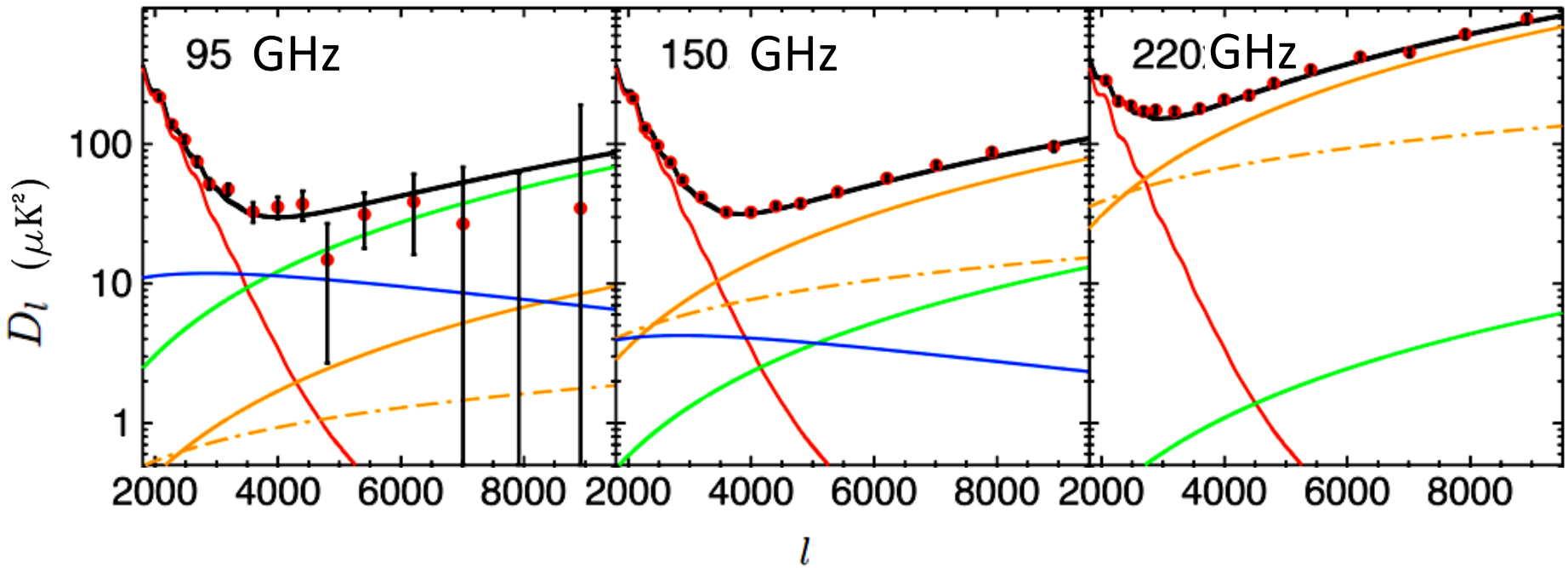
SPT measurements: microwave sky

- Multifrequency observations of the microwave sky:
  - Different contribution at different frequencies.
  - Yields important constraints on the components.



SPT measurements: microwave sky

- Multifrequency observations of the microwave sky:
  - Different contribution at different frequencies.
  - Yields important constraints on the components.



- Current tSZ constraints are significant **lower** than predicted.

Predicting the tSZ Power Spectrum

The distribution of temperature fluctuations on the sky induced by a **population of clusters:**

$$D_l \propto f_\nu^2(x) \int_0^{z_{\max}} dz \frac{dV}{dz} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_l(M,z)|^2$$

Predicting the tSZ Power Spectrum

The distribution of temperature fluctuations on the sky induced by a **population of clusters:**

$$D_l \propto f_\nu^2(x) \int_0^{z_{\max}} dz \frac{dV}{dz} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_l(M,z)|^2$$

Compton y -parameter

$$y = \frac{\sigma_T}{m_e c^2} \int_{-\infty}^{\infty} P_e ds$$

Predicting the tSZ Power Spectrum

The distribution of temperature fluctuations on the sky induced by a **population of clusters:**

$$D_l \propto f_\nu^2(x) \int_0^{z_{\max}} dz \frac{dV}{dz} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_l(M,z)|^2$$

Halo mass function

Compton y -parameter

$$y = \frac{\sigma_T}{m_e c^2} \int_{-\infty}^{\infty} P_e ds$$

Predicting the tSZ Power Spectrum

The distribution of temperature fluctuations on the sky induced by a **population of clusters:**

$$D_l \propto f_\nu^2(x) \int_0^{z_{\max}} dz \frac{dV}{dz} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_l(M,z)|^2$$

Co-moving volume

Halo mass function

Compton y -parameter

$$y = \frac{\sigma_T}{m_e c^2} \int_{-\infty}^{\infty} P_e ds$$

Predicting the tSZ Power Spectrum

The distribution of temperature fluctuations on the sky induced by a **population of clusters:**

$$D_l \propto f_\nu^2(x) \int_0^{z_{\max}} dz \frac{dV}{dz} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_l(M,z)|^2$$

Spectral function

Co-moving volume

Halo mass function

Compton y -parameter

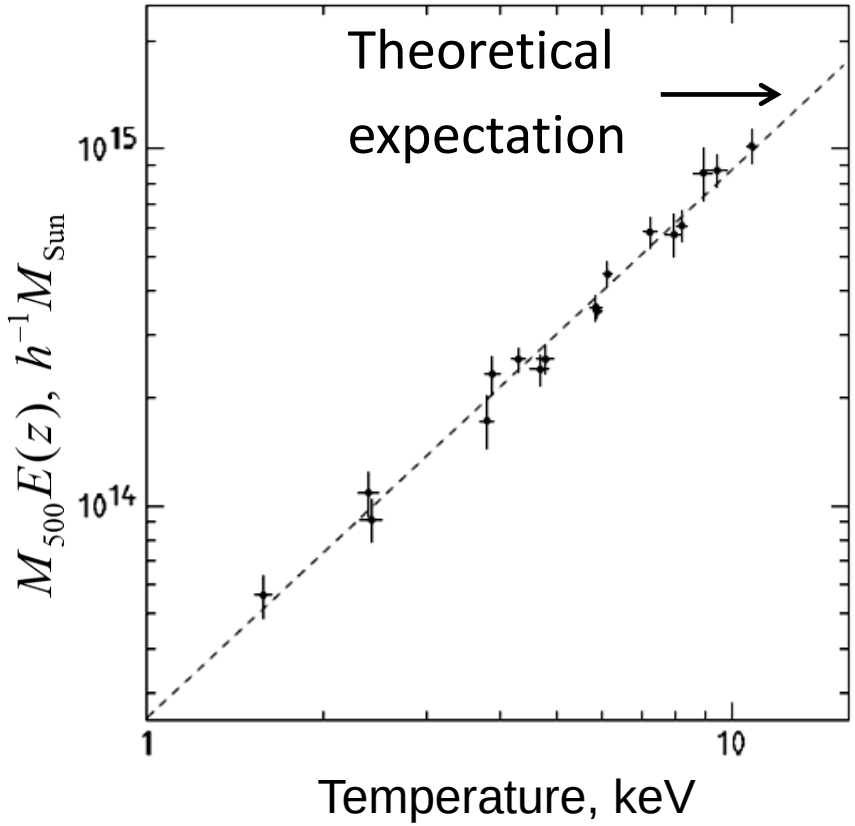
$$y = \frac{\sigma_T}{m_e c^2} \int_{-\infty}^{\infty} P_e ds$$

Self-similar model

- Physics of the ICM: only **gravity determines** the properties of the hot diffuse gas.
- Gravity has no preferred scale:
  → **Galaxy clusters of different size/mass are scaled version of each other.**
- Use the relation between observables to study galaxy clusters: **scaling relations**.

$$M_{\Delta_c} \propto T^{3/2} E^{-1}(z)$$

$$E(z) = \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$$



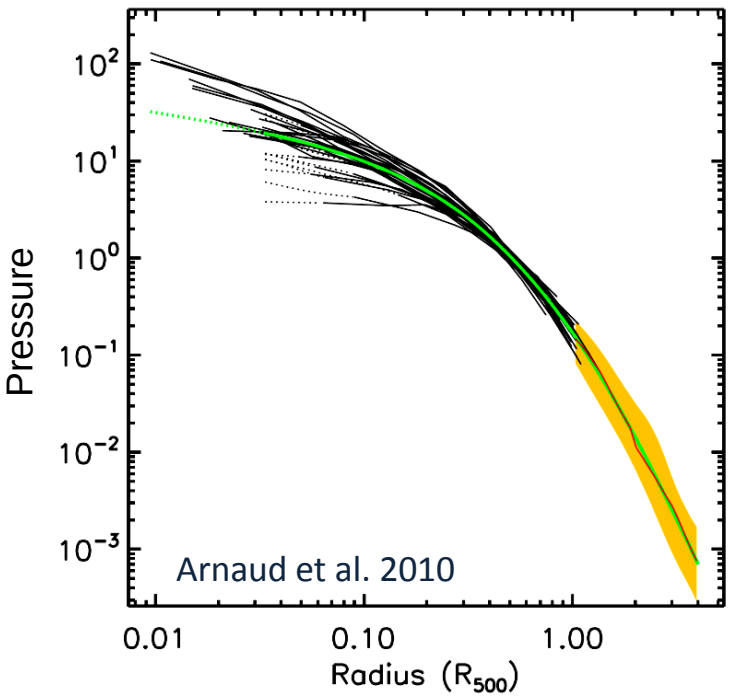
Vikhlinin et al. 2009

Observed Pressure profile

Arnaud et al. (2010): electron pressure profile,

- 33 local clusters: $z < 0.2$
- High mass clusters: $7 \times 10^{13} \lesssim M_{500}/h^{-1}\ \mathrm{M}_\odot \lesssim 6 \times 10^{14}$

$$P_{\mathrm{e}}(r) = 3.4\ h^2 \mathrm{eV\ cm}^{-3}\ E^{\frac{8}{3}}(z) \left[\frac{M_{500}}{(2 \times 10^{14}/h)\ \mathrm{M}_\odot} \right]^{\frac{2}{3}+0.12} p(r/r_{500}),$$

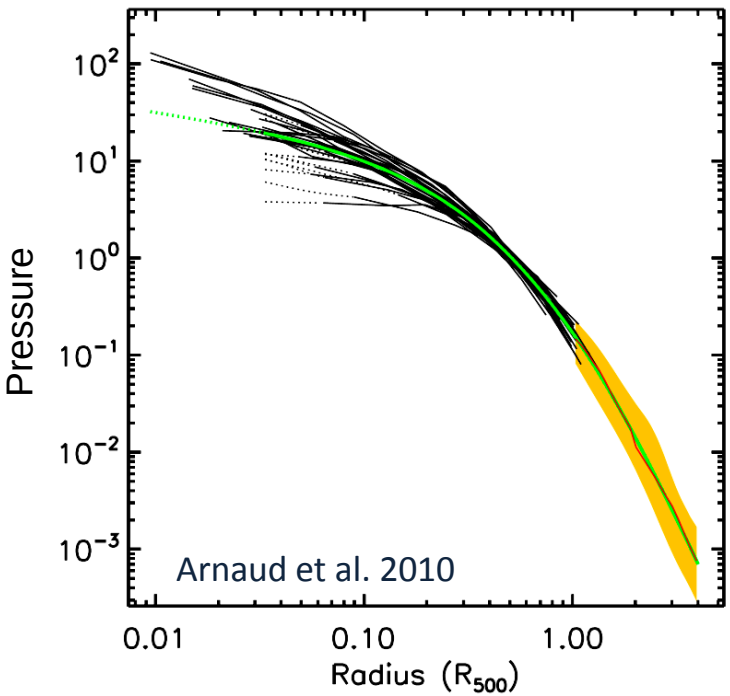


Observed Pressure profile

Arnaud et al. (2010): electron pressure profile,

- 33 local clusters: $z < 0.2$
- High mass clusters: $7 \times 10^{13} \lesssim M_{500}/h^{-1}\ \mathrm{M}_\odot \lesssim 6 \times 10^{14}$

$$P_{\mathrm{e}}(r) = 3.4\ h^2 \mathrm{eV\ cm}^{-3}\, E^{\frac{8}{3}}(z) \left[\frac{M_{500}}{(2 \times 10^{14}/h)\ \mathrm{M}_\odot}\right]^{\frac{2}{3}+0.12} p(r/r_{500}),$$

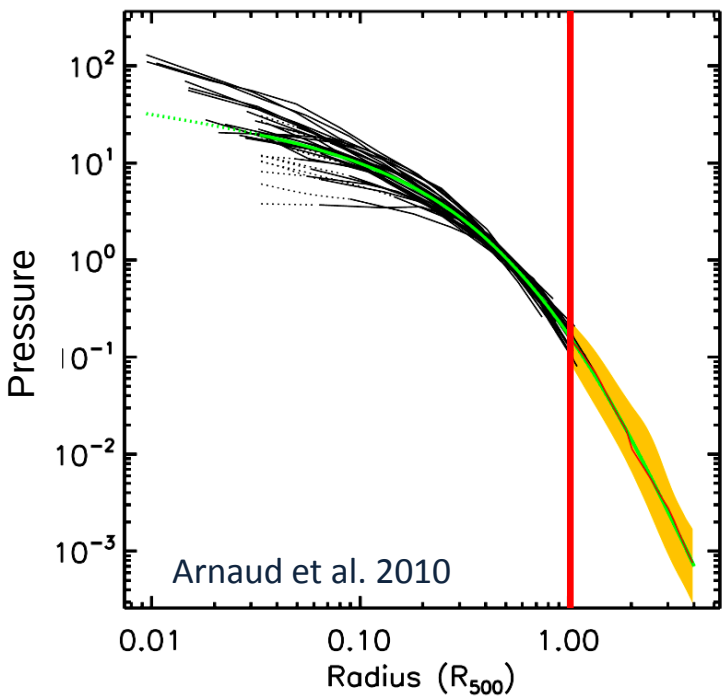


Observed Pressure profile

Arnaud et al. (2010): electron pressure profile,

- 33 local clusters: $z < 0.2$
- High mass clusters: $7 \times 10^{13} \lesssim M_{500}/h^{-1}\ \mathrm{M}_\odot \lesssim 6 \times 10^{14}$

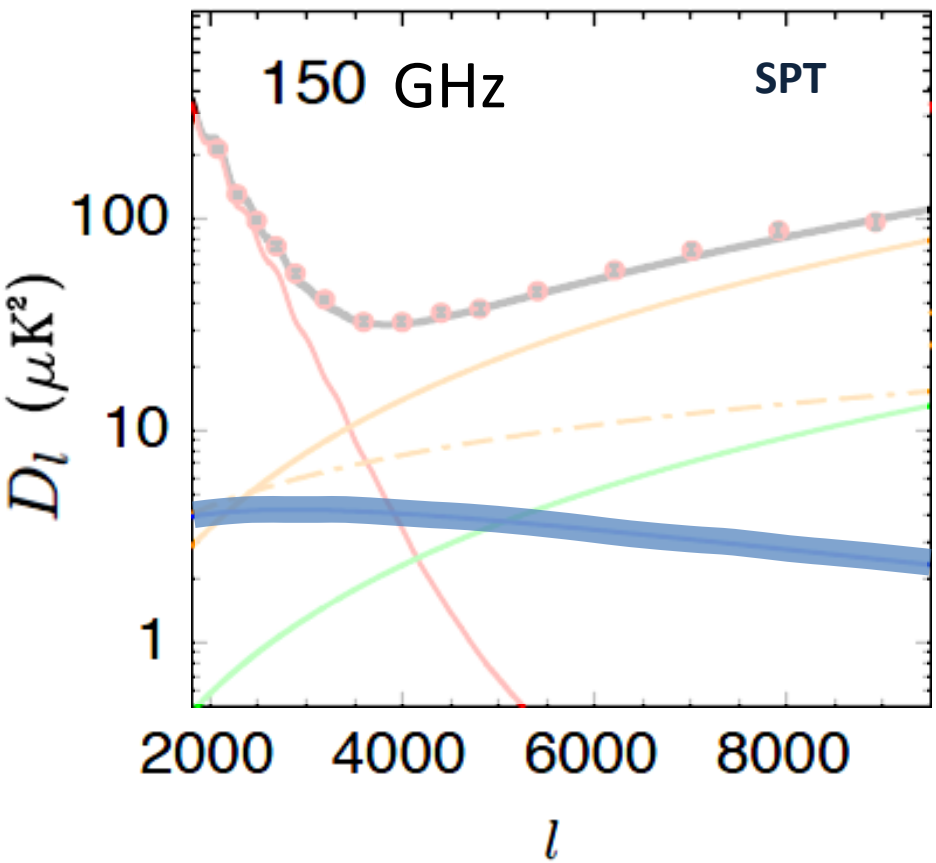
$$P_{\mathrm{e}}(r) = 3.4\ h^2 \mathrm{eV\ cm}^{-3}\ E^{\frac{8}{3}}(z) \left[\frac{M_{500}}{(2 \times 10^{14}/h)\ \mathrm{M}_\odot} \right]^{\frac{2}{3}+0.12} p(r/r_{500}),$$



→ Excellent agreement out to r_{500}

→ **Simulations to extrapolate at larger radii.**

SPT measurements: microwave sky



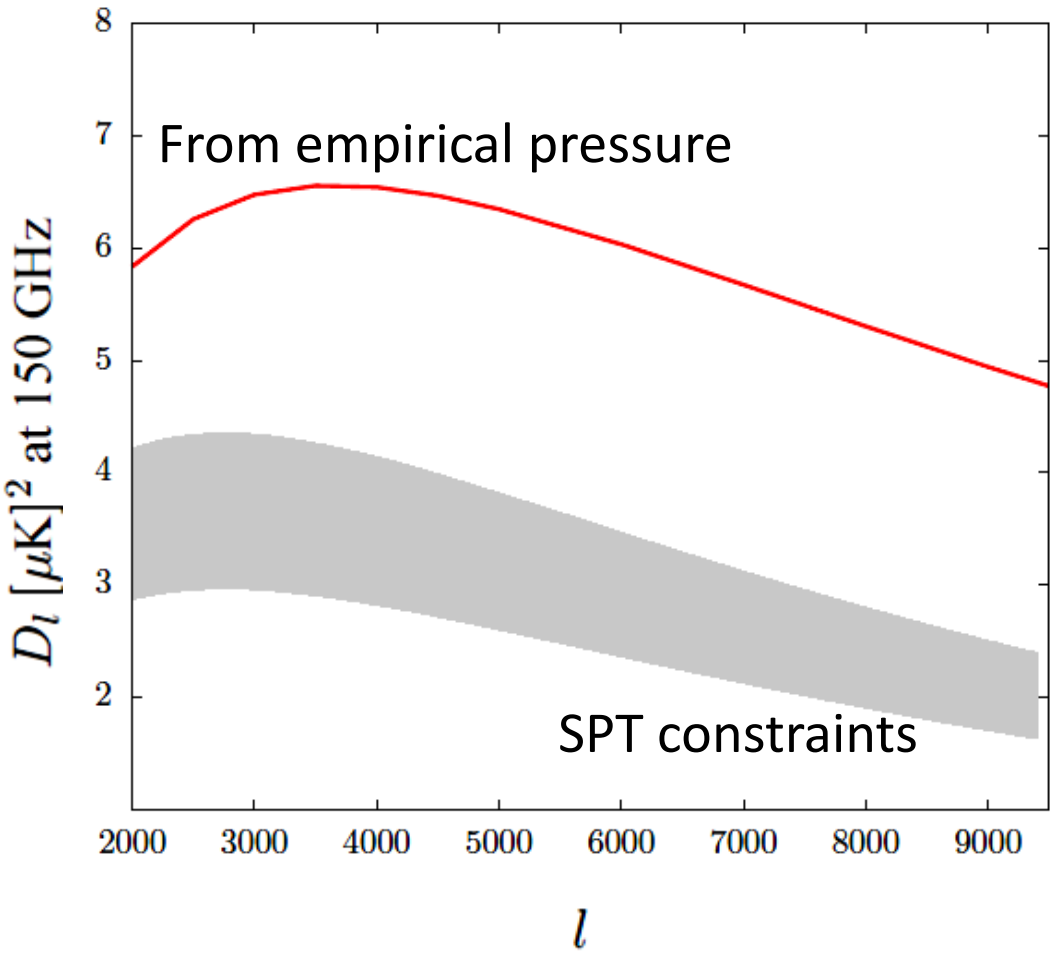
Reichardt et al. 2012

At l > 2500 the microwave sky is composed of:

1. Lensed CMB
2. **Thermal SZ signal**
3. Infrared galaxies:
   a. Clustered
   b. Poisson
4. Radio galaxies

tSZ power spectrum

tSZ power spectrum given by empirical pressure profile **significantly exceeds** the SPT constraints.

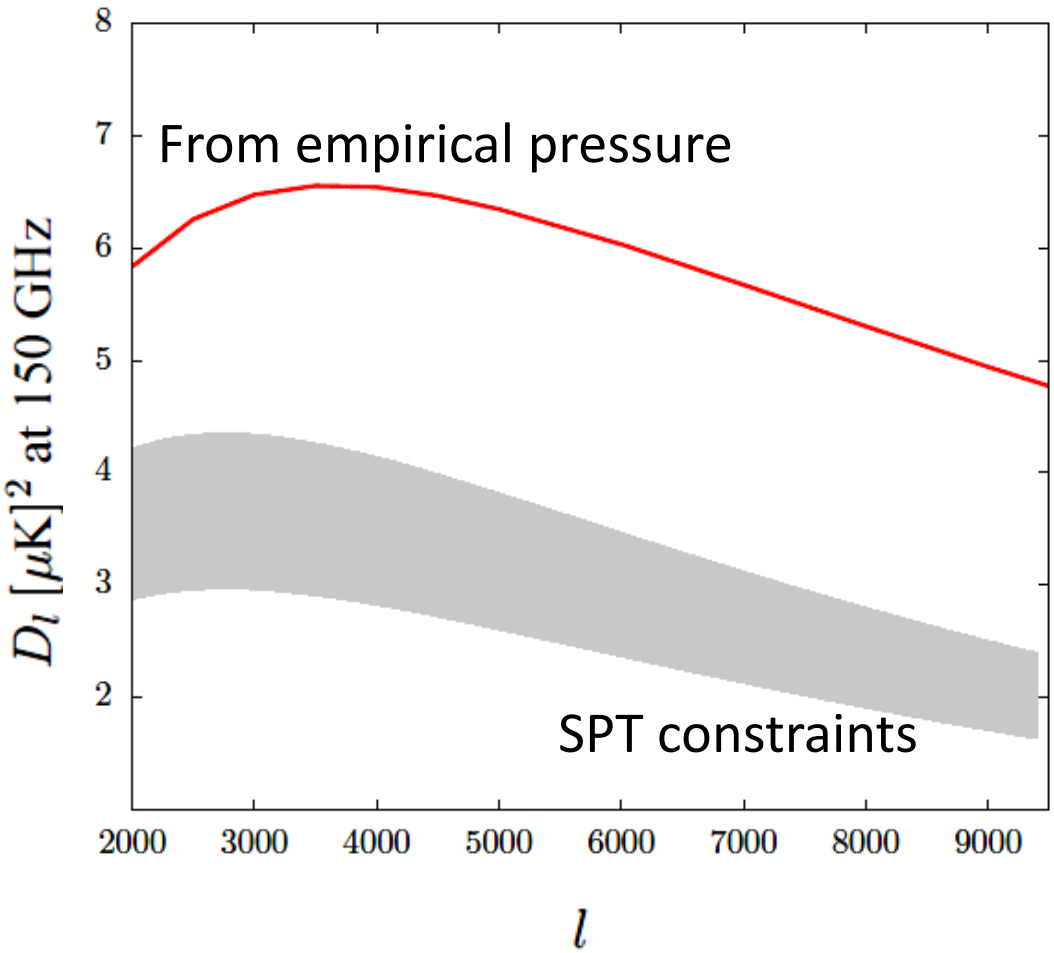


tSZ power spectrum

tSZ power spectrum given by empirical pressure profile **significantly exceeds** the SPT constraints.

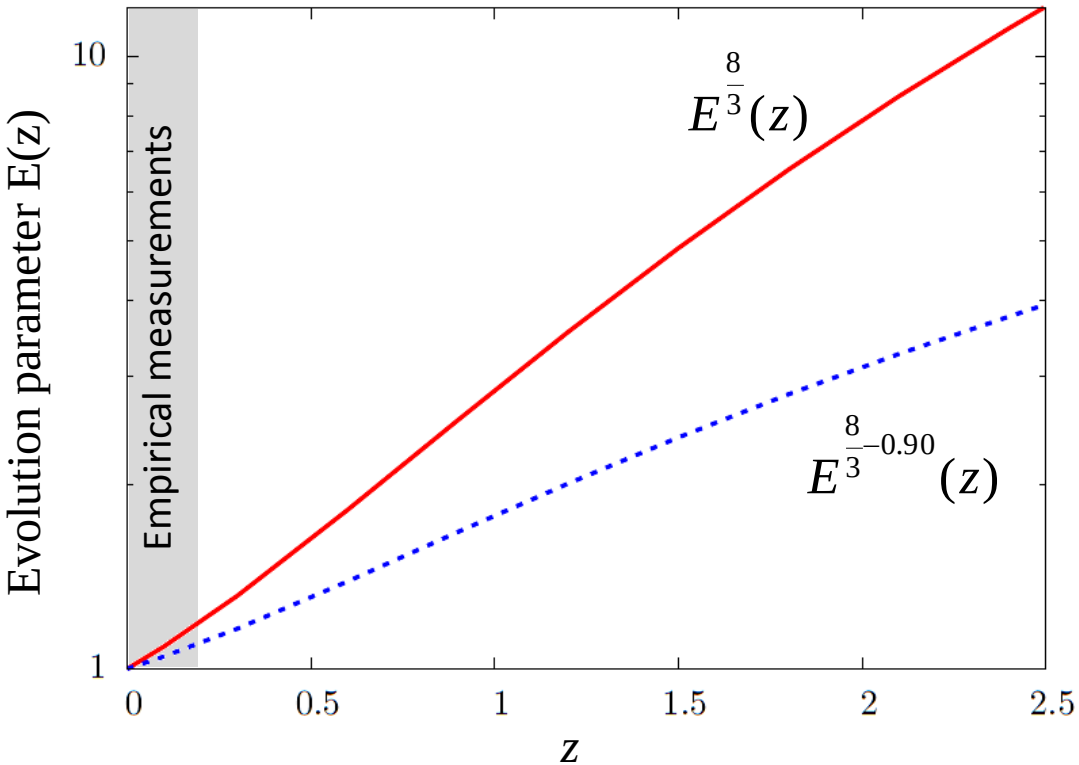
Possible explanation:

- Assumption of self-similar evolution.



Modifying the electron pressure profile

Redshift evolution: $P_e(r) \propto E^{\frac{8}{3}-\epsilon}(z) M_{500}^{\frac{2}{3}+0.12}$

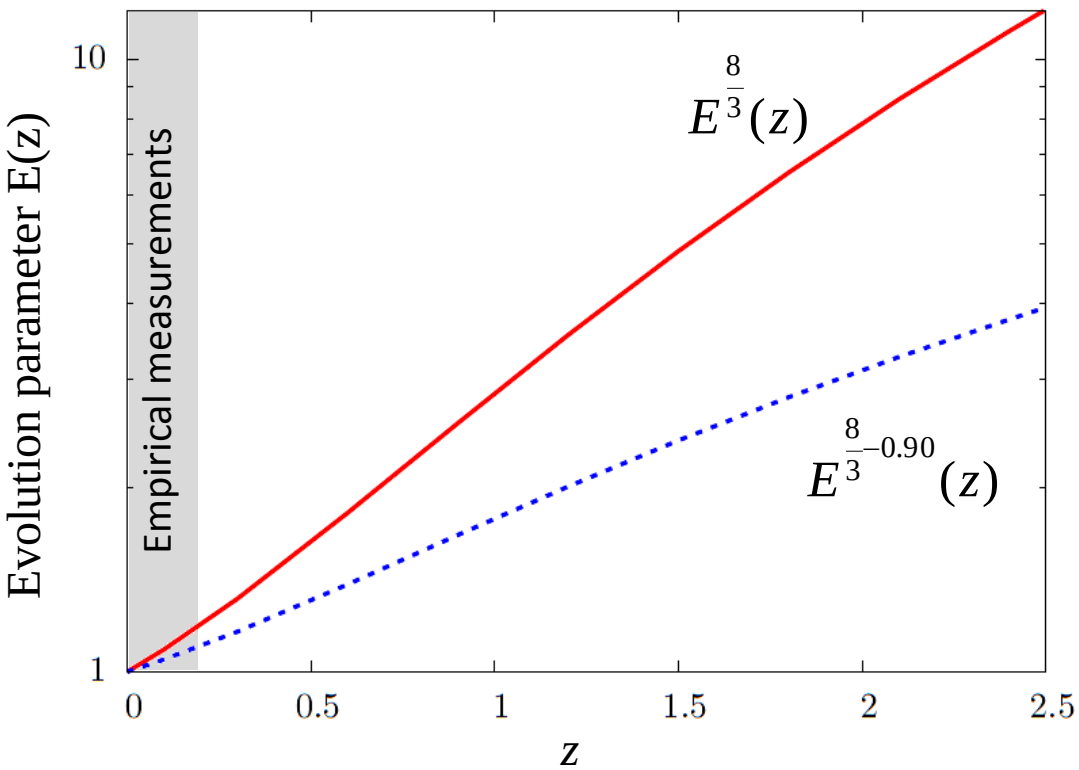


Unmodified pressure profile at **low redshift**.

Lower pressure profile amplitude at **high redshift**.

Modifying the electron pressure profile

Redshift evolution: $P_e(r) \propto E^{\frac{8}{3}-\epsilon}(z) M_{500}^{\frac{2}{3}+0.12} \longrightarrow \epsilon = 0.90 \pm 0.24$



Unmodified pressure profile at **low redshift**.

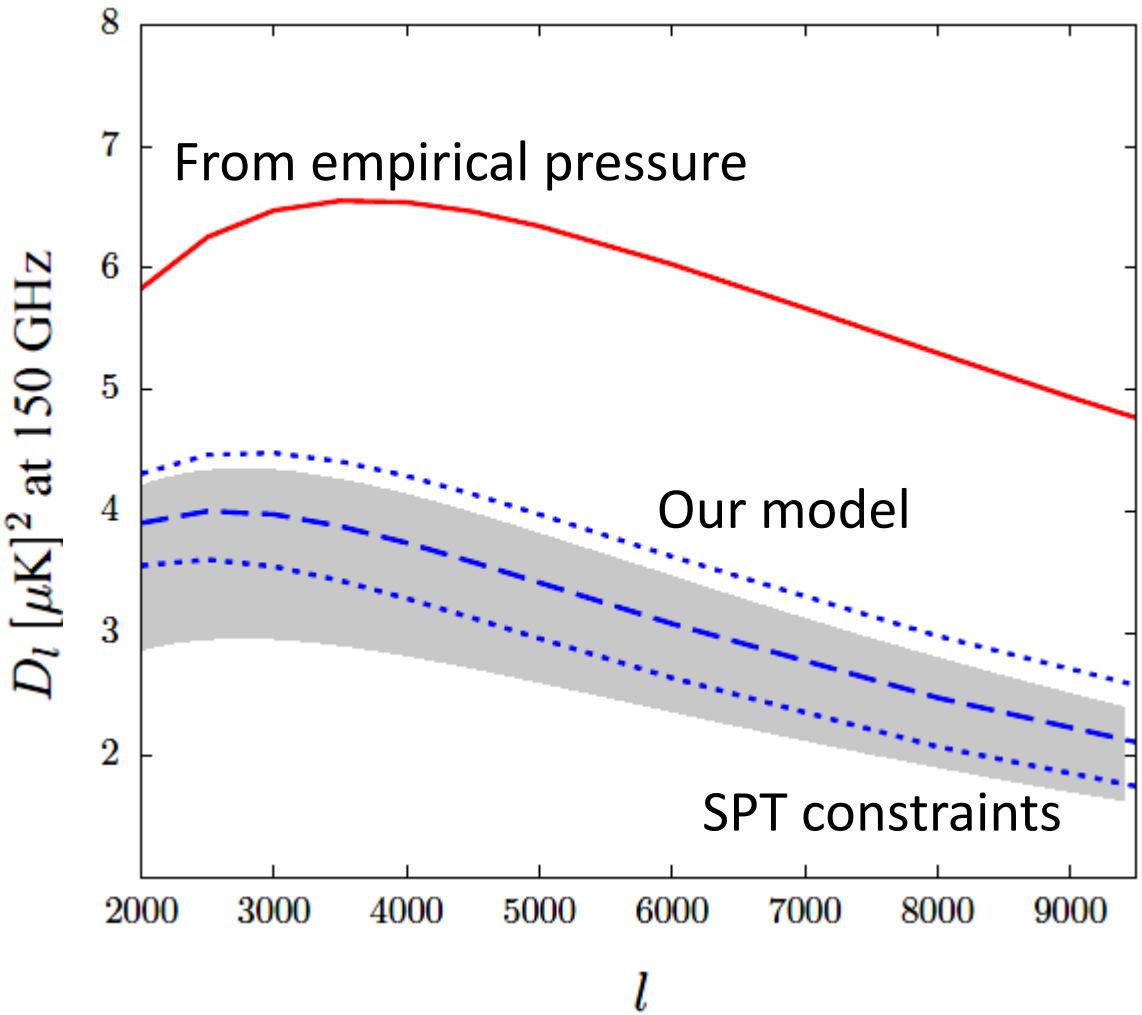
Lower pressure profile amplitude at **high redshift**.

Modifying the electron pressure profile

Lower the tSZ power spectrum and **reach** the SPT constraints.

↓

No observational counterpart for cross-checking our results



Non-self similar evolution from $f_{\rm gas}$

- Pressure profile:

$$P \propto f_{\rm gas} M^{\frac{2}{3}} E^{\frac{8}{3}}(z)$$

Non-self similar evolution from $f_{\rm gas}$

- Pressure profile:

$$P \propto f_{\rm gas} M^{\frac{2}{3}} E^{\frac{8}{3}}(z)$$

- Empirical pressure profile:

$$P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}}(z)$$

$\rightarrow$ Non-self similar evolution

due **gas mass fraction**:

$$f_{\rm gas} \propto M^{0.12}$$

Non-self similar evolution from $f_{\rm gas}$

- Pressure profile:

$$P \propto f_{\rm gas} M^{\frac{2}{3}} E^{\frac{8}{3}}(z)$$

- Empirical pressure profile:

$$P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}}(z)$$

$\rightarrow$ Non-self similar evolution due **gas mass fraction**:

$$f_{\rm gas} \propto M^{0.12}$$

$\rightarrow$ Observations show that $f_{\rm gas}$ has a mass dependence.

$\rightarrow$ Non-gravitational processes

- AGN feedback.
- Star formation.

Non-self similar evolution from $f_{\rm gas}$

- Pressure profile:

$$P \propto f_{\rm gas} M^{\frac{2}{3}} E^{\frac{8}{3}}(z)$$

- Empirical pressure profile:

$$P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}}(z)$$

$\rightarrow$ Non-self similar evolution due **gas mass fraction**:

$$f_{\rm gas} \propto M^{0.12}$$

- Our model:

$$P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}-(0.90\pm0.24)}(z)$$

$\rightarrow$ Gas mass fraction relation:

$$f_{\rm gas} \propto M^{0.12} E^{-(0.90\pm0.24)}(z).$$

Non-self similar evolution from $f_{\rm gas}$

- Pressure profile:

$$P \propto f_{\rm gas} M^{\frac{2}{3}} E^{\frac{8}{3}}(z)$$

- Empirical pressure profile:

$$P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}}(z)$$

$\rightarrow$ Non-self similar evolution due **gas mass fraction**:

$$f_{\rm gas} \propto M^{0.12}$$

- Our model:

$$P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}-(0.90\pm0.24)}(z)$$

$\rightarrow$ Gas mass fraction relation:

$$\boxed{f_{\rm gas} \propto M^{0.12} E^{-(0.90\pm0.24)}(z)}$$

Non-self similar evolution from $f_{\rm gas}$

- Pressure profile:

$$P \propto f_{\rm gas} M^{\frac{2}{3}} E^{\frac{8}{3}}(z)$$

- Empirical pressure profile:

$$P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}}(z)$$

$\rightarrow$ Non-self similar evolution due **gas mass fraction**:

$$f_{\rm gas} \propto M^{0.12}$$

- Our model:

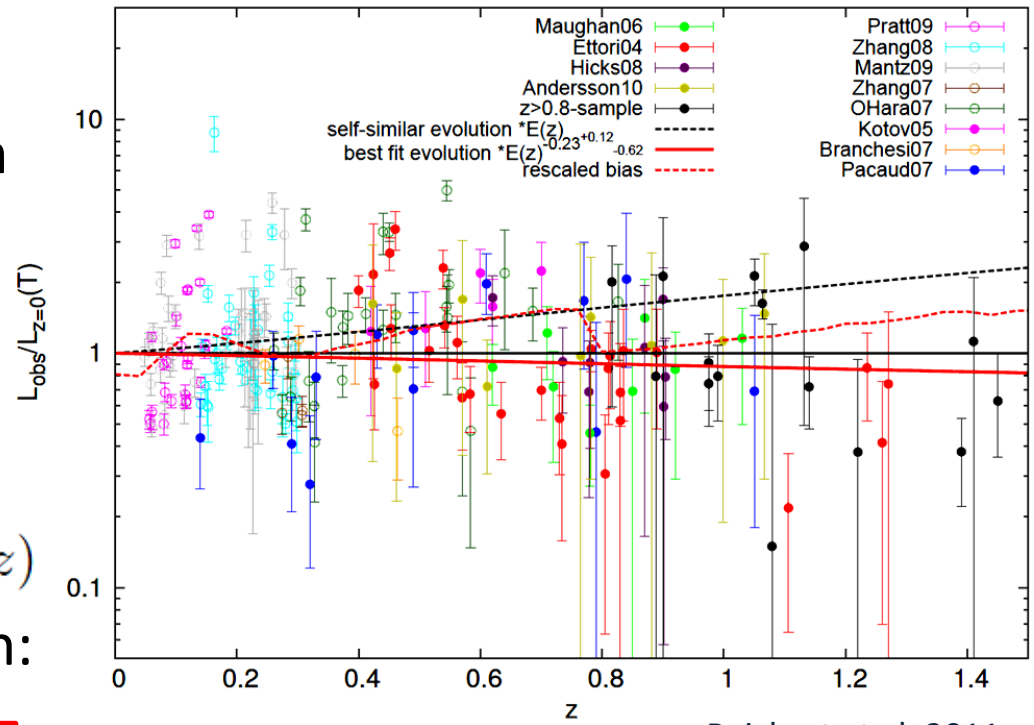
$$P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}-(0.90\pm0.24)}(z)$$

$\rightarrow$ Gas mass fraction relation:

$$f_{\rm gas} \propto M^{0.12} E^{-(0.90\pm0.24)}(z)$$

Luminosity-Temperature (L-T) relation:

$$L_{\rm bol} \propto f_{\rm gas}^2 T^2 E(z)$$



Reichert et al. 2011

Non-self similar evolution from $f_{\rm gas}$

- Pressure profile:

$$P \propto f_{\rm gas} M^{\frac{2}{3}} E^{\frac{8}{3}}(z)$$

- Empirical pressure profile:

$$P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}}(z)$$

$\rightarrow$ Non-self similar evolution due **gas mass fraction**:

$$f_{\rm gas} \propto M^{0.12}$$

- Our model:

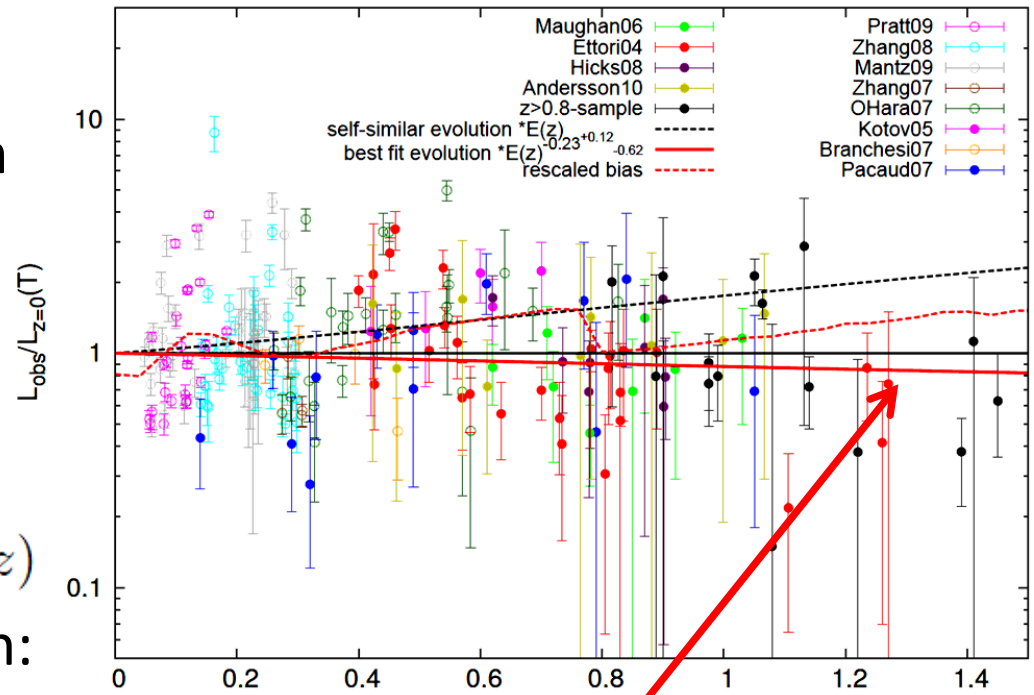
$$P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}-(0.90\pm0.24)}(z)$$

$\rightarrow$ Gas mass fraction relation:

$$f_{\rm gas} \propto M^{0.12} E^{-(0.90\pm0.24)}(z)$$

Luminosity-Temperature (L-T) relation:

$$L_{\rm bol} \propto f_{\rm gas}^2 T^2 E(z)$$



Non-self-similar evolution

Reichert et al. 2011

Non-self similar evolution from $f_{\rm gas}$

- Pressure profile:

$$P \propto f_{\rm gas} M^{\frac{2}{3}} E^{\frac{8}{3}}(z)$$

- Empirical pressure profile:

$$P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}}(z)$$

$\rightarrow$ Non-self similar evolution due **gas mass fraction**:

$$f_{\rm gas} \propto M^{0.12}$$

- Our model:

$$P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}-(0.90\pm0.24)}(z)$$

$\rightarrow$ Gas mass fraction relation:

$$\boxed{f_{\rm gas} \propto M^{0.12} E^{-(0.90\pm0.24)}(z)}$$

Luminosity-Temperature (L-T) relation:

$$L_{\rm bol} \propto f_{\rm gas}^2 T^2 E(z)$$

Hilton et al. (2012)

$$L_{\rm bol} \propto T^{3.18} E^{-1.2\pm0.5}(z)$$

Non-self similar evolution from $f_{\rm gas}$

- Pressure profile:

$$P \propto f_{\rm gas} M^{\frac{2}{3}} E^{\frac{8}{3}}(z)$$

- Empirical pressure profile:

$$P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}}(z)$$

$\rightarrow$ Non-self similar evolution due **gas mass fraction**:

$$f_{\rm gas} \propto M^{0.12}$$

- Our model:

$$P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}-(0.90\pm0.24)}(z)$$

$\rightarrow$ Gas mass fraction relation:

$$\boxed{f_{\rm gas} \propto M^{0.12} E^{-(0.90\pm0.24)}(z)}$$

Luminosity-Temperature (L-T) relation:

$$L_{\rm bol} \propto f_{\rm gas}^2 T^2 E(z)$$

Hilton et al. (2012)

$$L_{\rm bol} \propto T^{3.18} E^{-1.2\pm0.5}(z)$$

Combining results:

$$L_{\rm bol} \propto T^{2.36} E^{-1.04\pm0.48}(z)$$

Summary and Perspectives

- To match current observational constraint we must modify the self-similar evolution in the electron pressure.
- Try a different parametrization of the redshift evolution.
- Study the outer slope of the electron pressure profile and its effects on the tSZ power spectrum.
- Forecast tSZ power spectrum constraints for future experiments: CCAT.

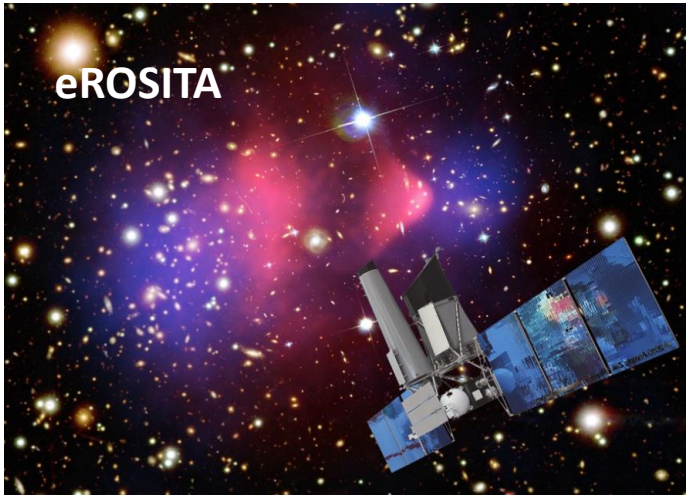
Summary and Perspectives

- To match current observational constraint we must modify the self-similar evolution in the electron pressure.
- Try a different parametrization of the redshift evolution.
- Study the outer slope of the electron pressure profile and its effects on the tSZ power spectrum.
- Forecast tSZ power spectrum constraints for future experiments: CCAT.

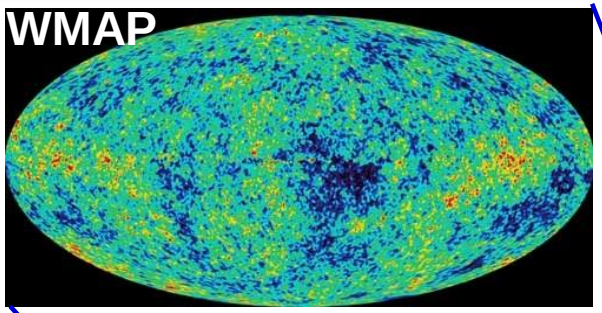
Thank you for your attention.

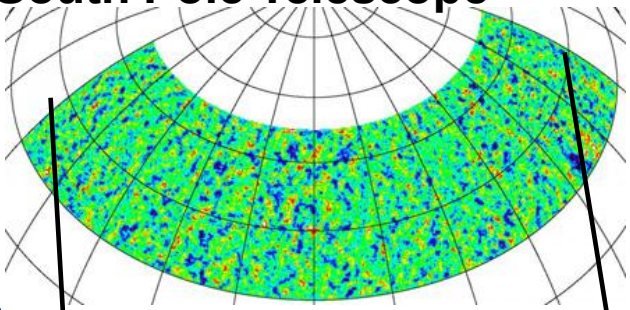
Perspective

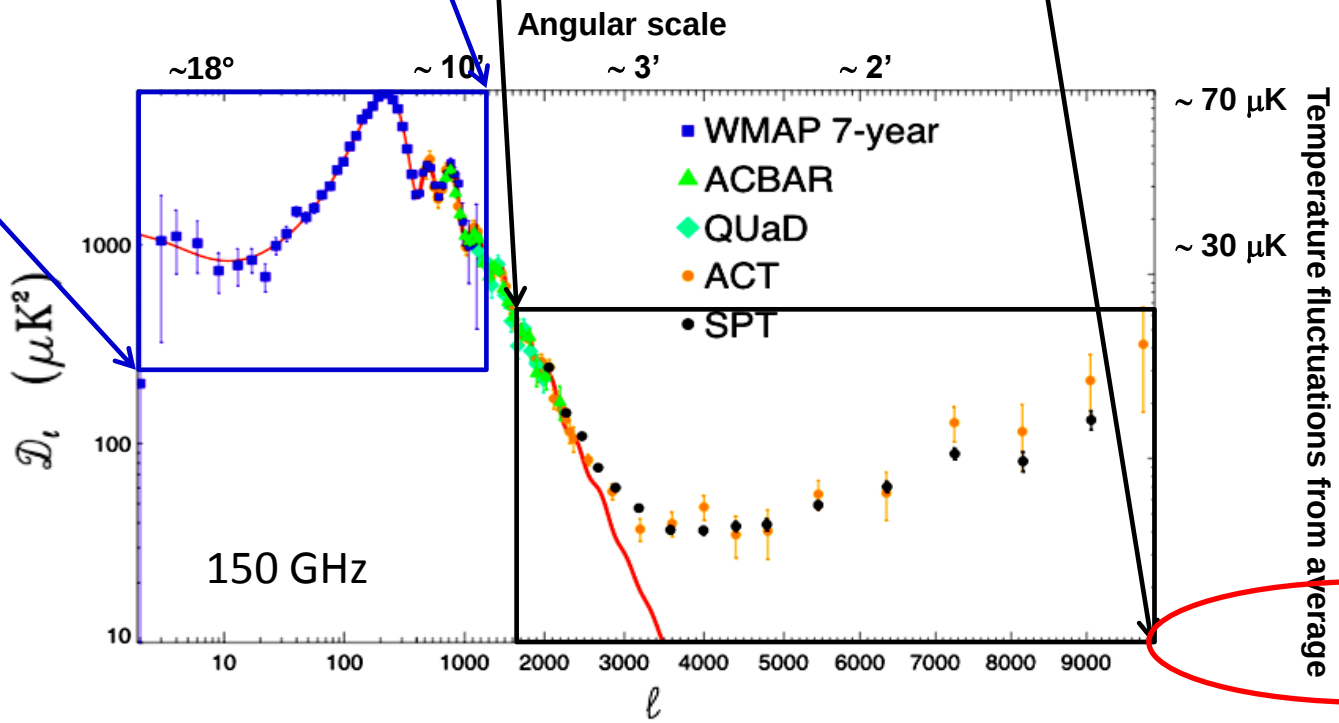
- Develop tools to study galaxy clusters:
  - X-rays:
    - With XXL survey as test bed for eROSITA.
  - tSZ power spectrum:
    - Have the tools to study future results



CMB power spectrum

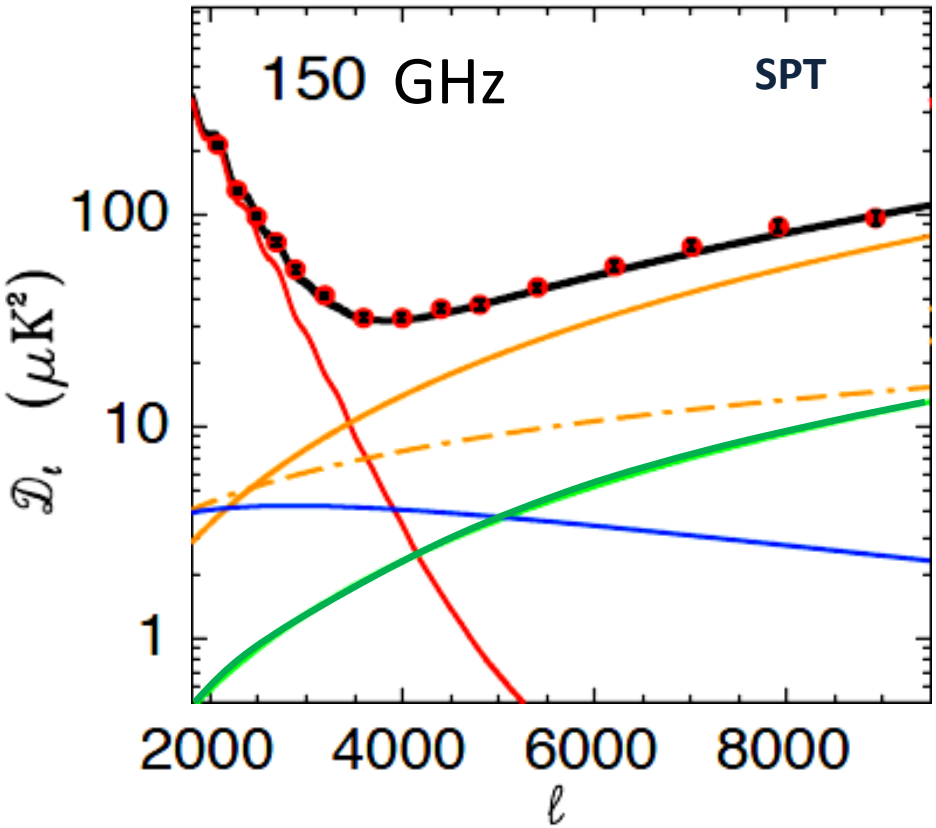






Shirokoff et al. 2011

SPT measurements: microwave sky



Reichardt et al. 2012

At l > 2500 the microwave sky is composed of:

1. Lensed CMB,
2. Thermal SZ signal,

} Secondary anisotropies

3. Infrared galaxies:
   a. Clustered,
   b. Poisson,
4. Radio galaxies.

} Galactic and extra-galactic emitters