The APEX-SZ cluster sample

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On behalf of the
APEX-SZ collaboration

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APEX Telescope

- 12 m on-axis ALMA prototype built by Vertex RSI
- Sited at the Atacama plateau, Chile, elevation 5100 m
- Submillimeter observatory
  - 18 μm surface accuracy
- 1′ resolution @ 150 GHz
- 0.4° field of view

Funded by:

Max-Planck-Institut für Radioastronomie

Onsala Rymdobservatorium – Chalmers Tekniska Högskola

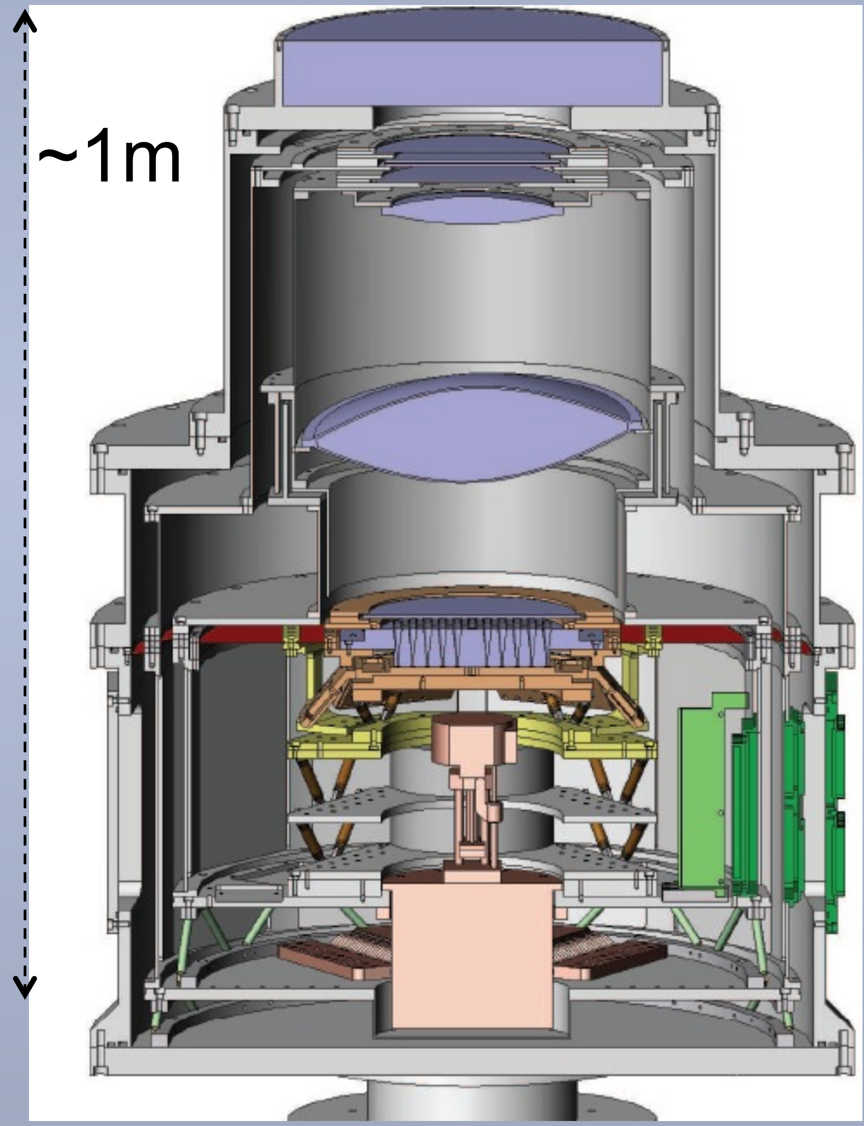
ESO

APEX-SZ Overview

- PI instrument on APEX
- First light: April 2007
- Decommissioned: December 2010
- 280 TES Bolometers @ 150 GHz (typically 170-180 live channels)
- From 2007 to 2010:

  Used ~ 1 month/year of which typically 2 weeks of good observing time
- New technologies (at the time), some used for SPT 1st generation:
  - TES bolometers
  - Frequency domain multiplexed readout
  - Pulse-tube cooler to eliminate liquid cryogens
- Powerful camera for targeted cluster observations
  - Overlaps with both northern and southern hemisphere multi-wavelength observations

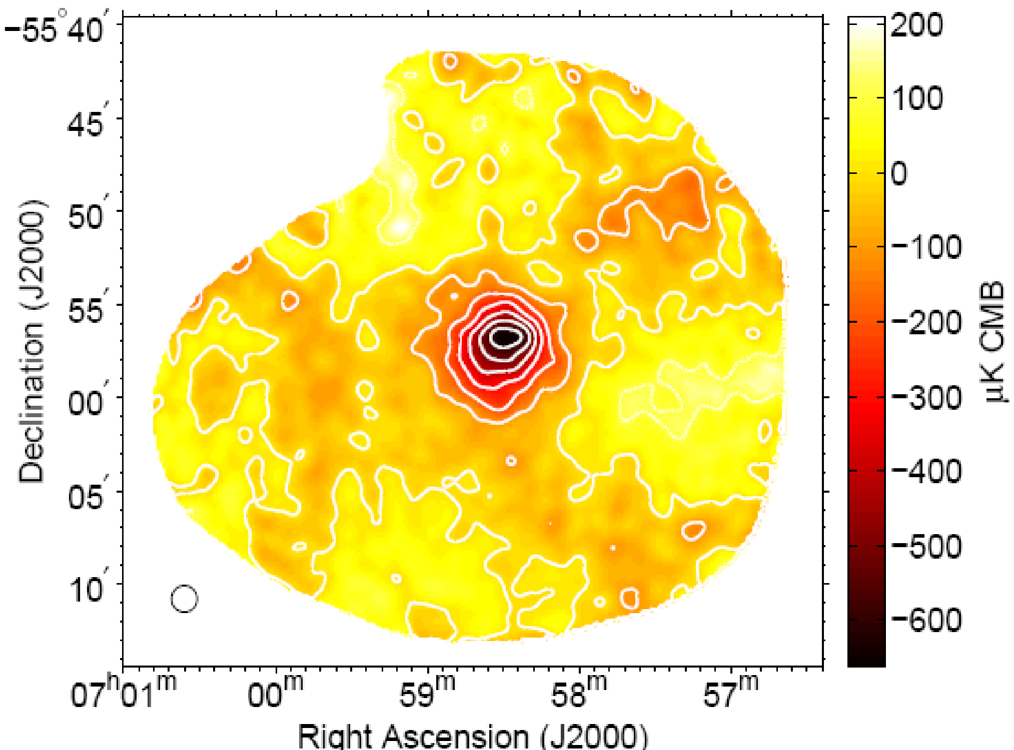
D. Schwan et al., 2011



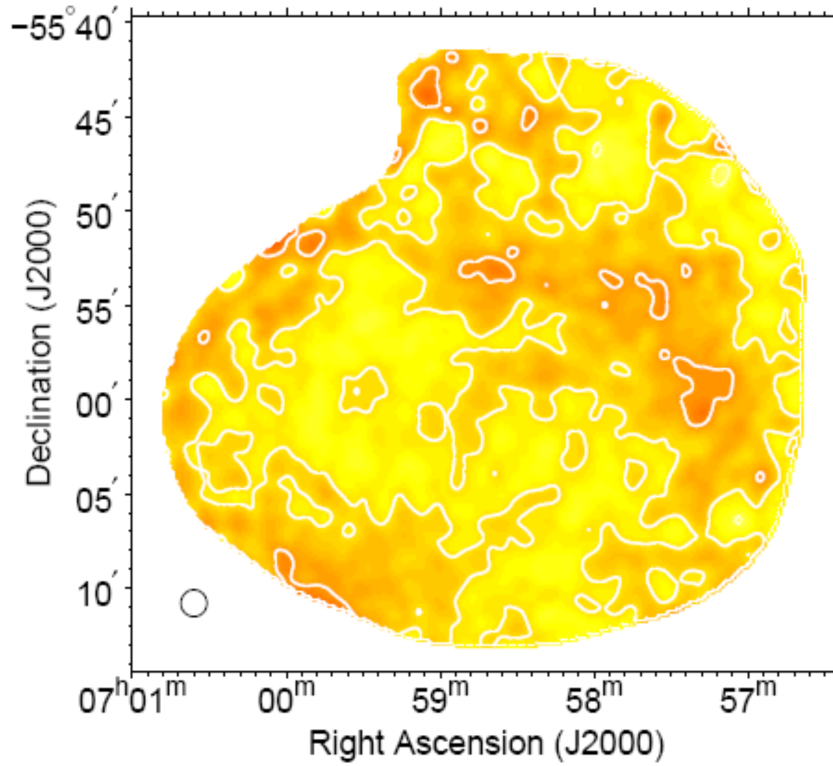
The Bullet Cluster

Halverson et al., 2009

Bullet Cluster (1E 0657-56)



Jackknife Noise Map



- 23 sigma detection
- no evidence for significant 150 GHz emission from 13.5 mJy @ 270 GHz point source reported by Aztec
- First science result released from a large array of multiplexed TES bollometers

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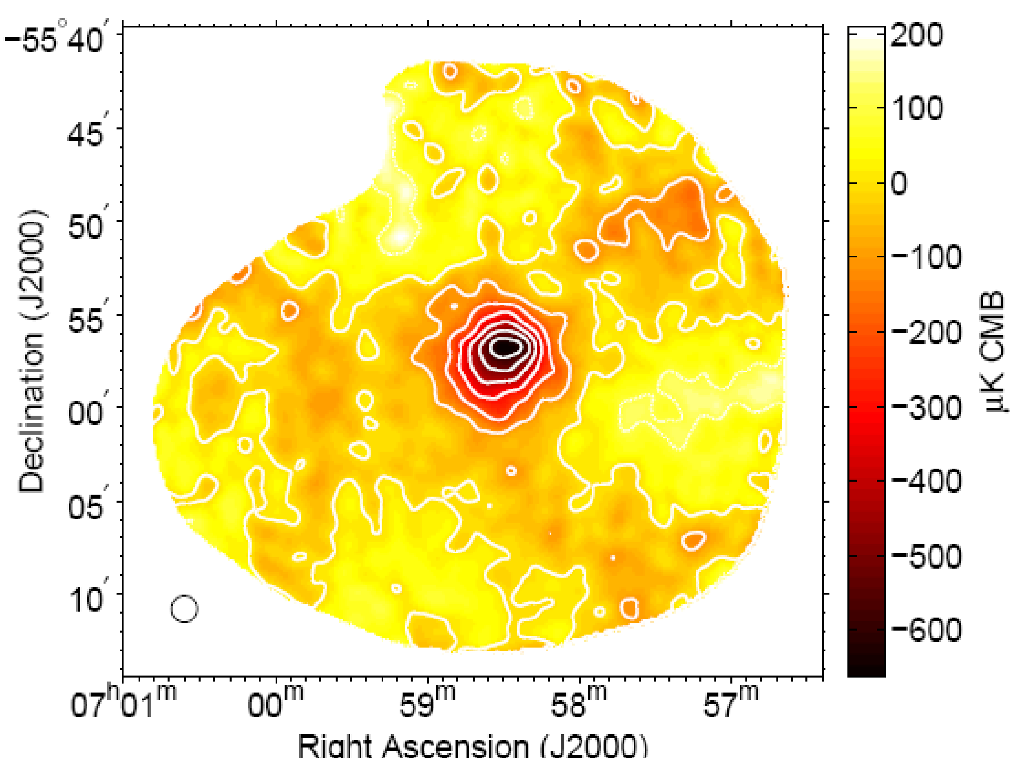

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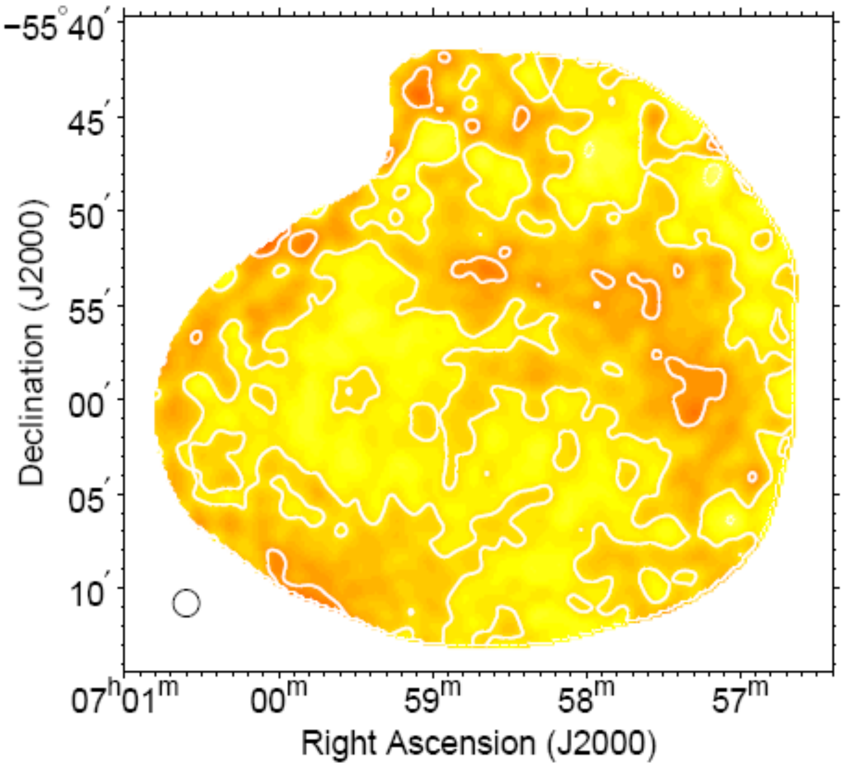

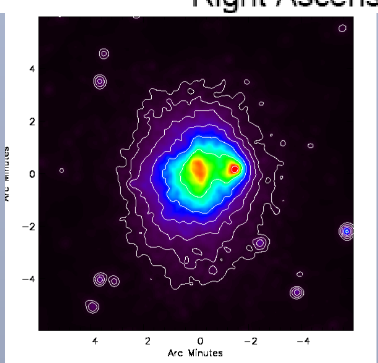

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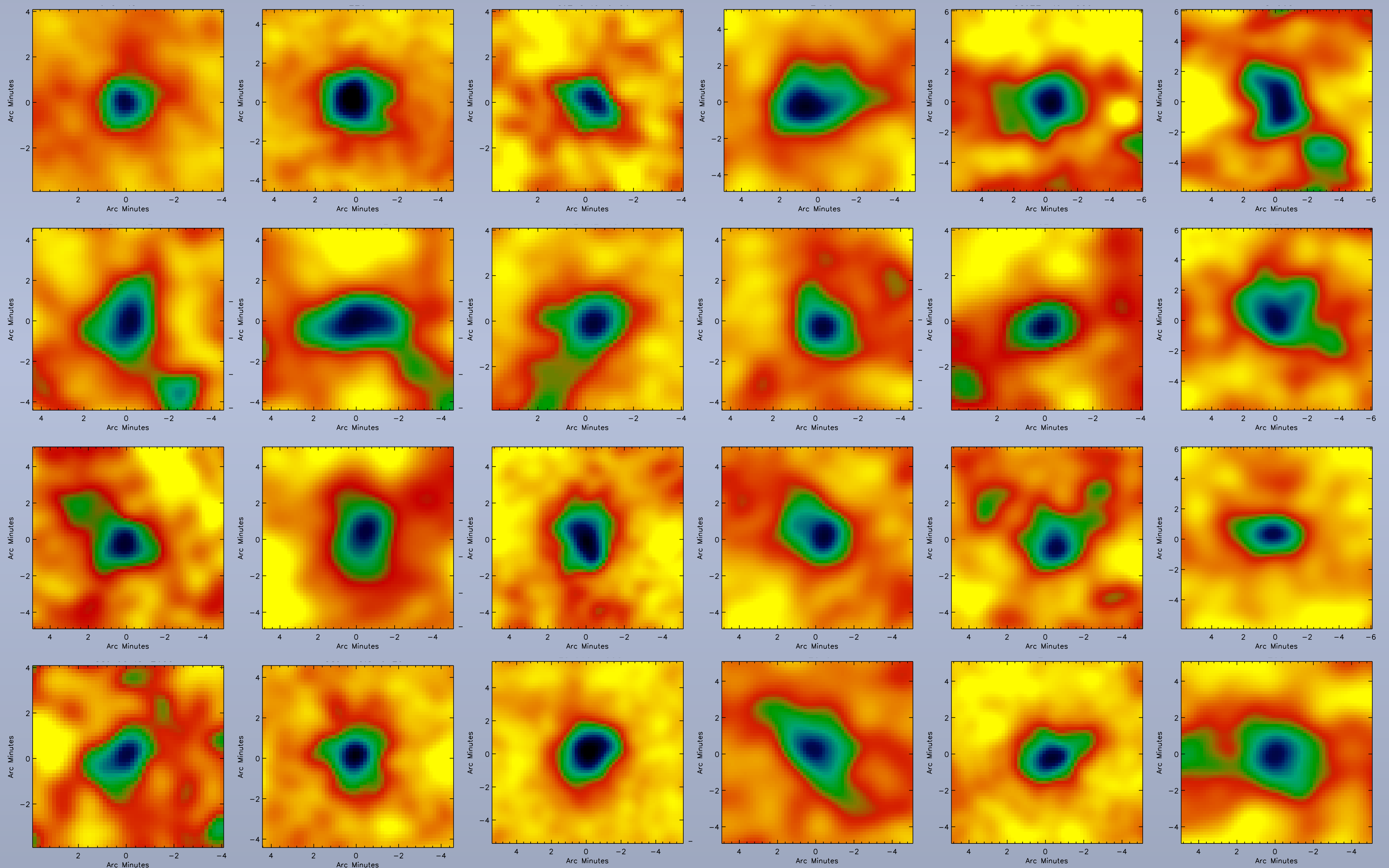
The APEX-SZ cluster sample

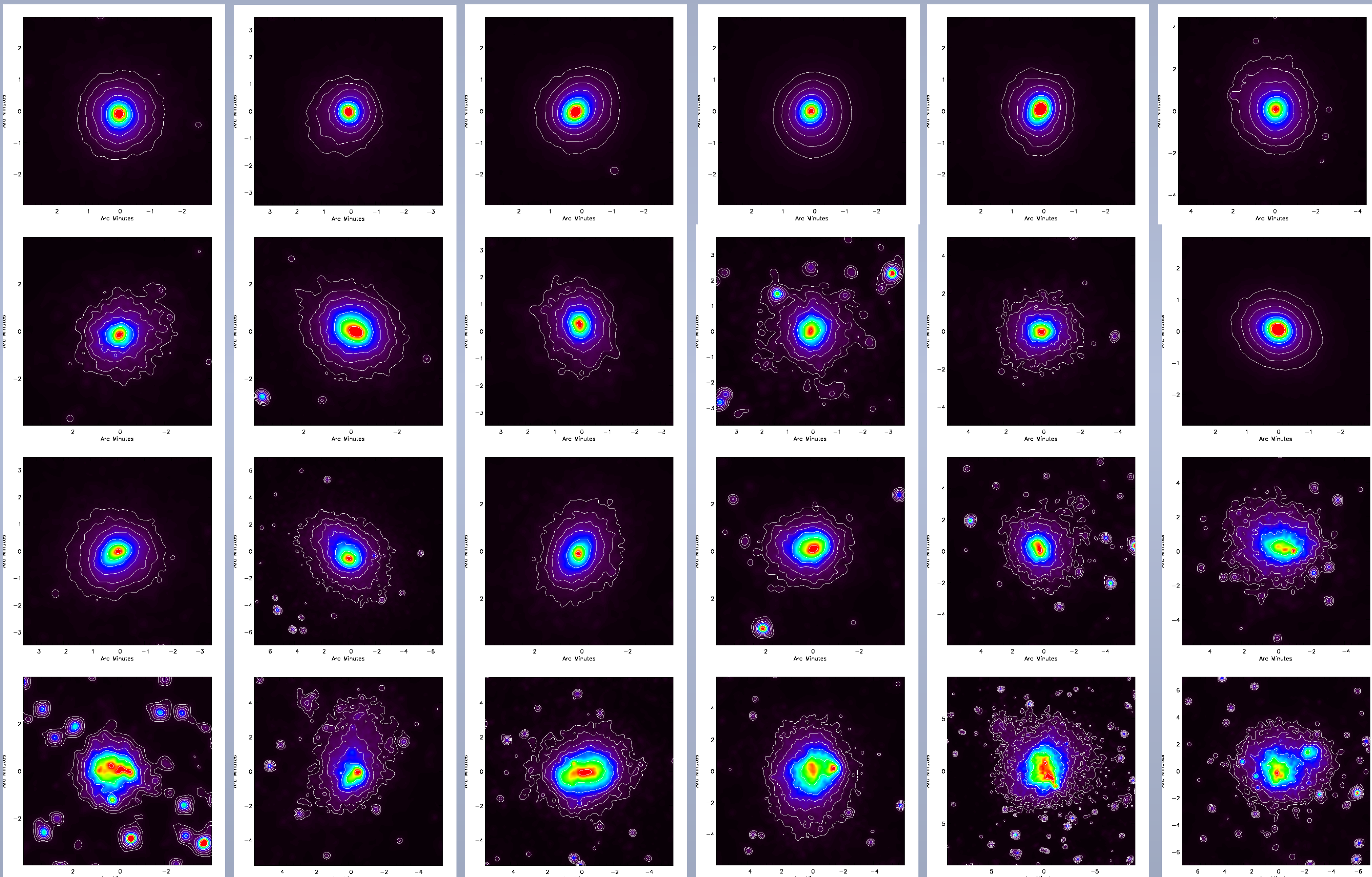
- Over the 4 year lifetime:
  - 49 clusters observed
  - 35 of them detected with $5<S/N<23$
  - Redshifts from $z=0.15$ to $z=0.8$
  - Resolved structures on angular scales $50'' < \theta < 10'$

- Extensive follow-up data:
  - XMM and/or Chandra data for 32/35
  - Weak lensing observations for all our detections with the Suprime-cam@Subaru and/or WFI@ESO/MPG2.2m

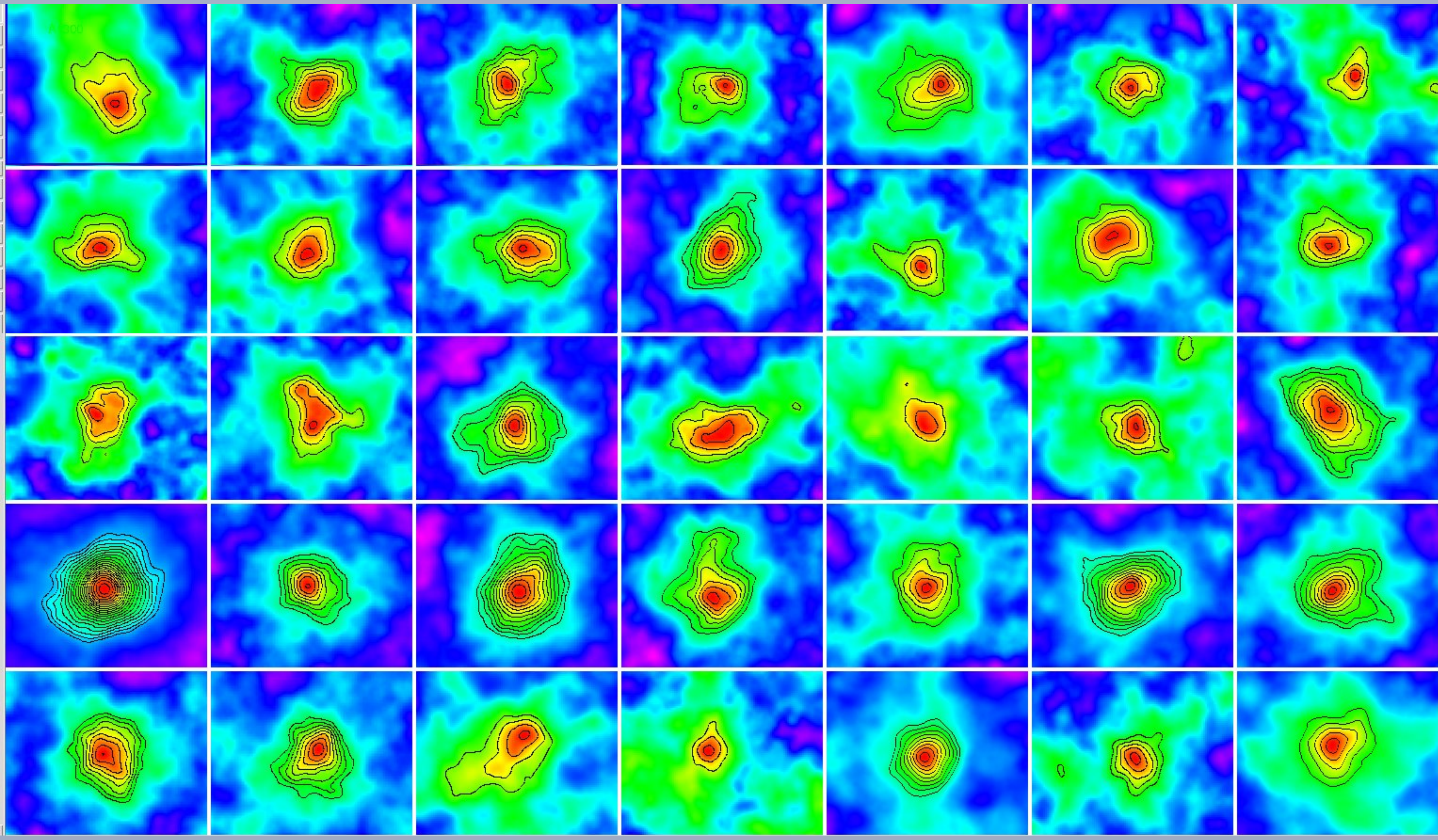
Some APEX-SZ signal maps



Some APEX-SZ X-ray maps



Some APEX-SZ mass maps

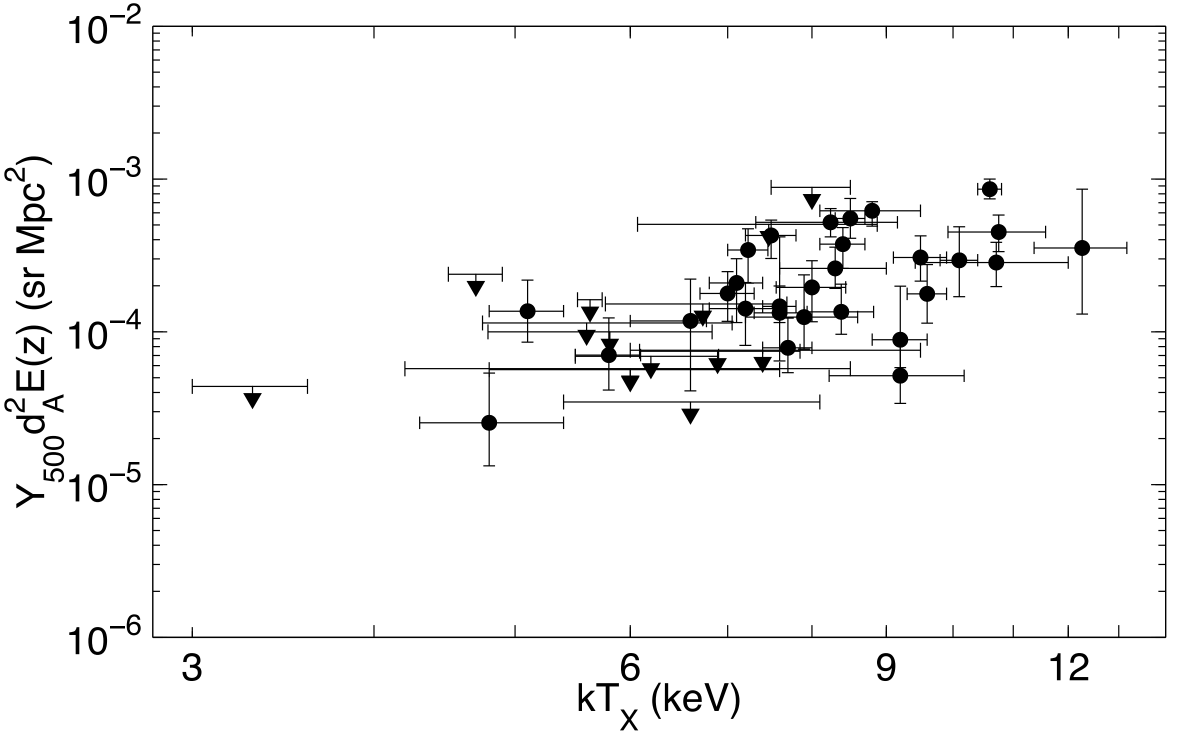


Scaling relations (1)

Homogeneous estimate of Y_{SZ} by profile Fitting (both GNFW and β-model)

First analysis of X-ray / SZ scaling laws with APEX-SZ

Preliminary !



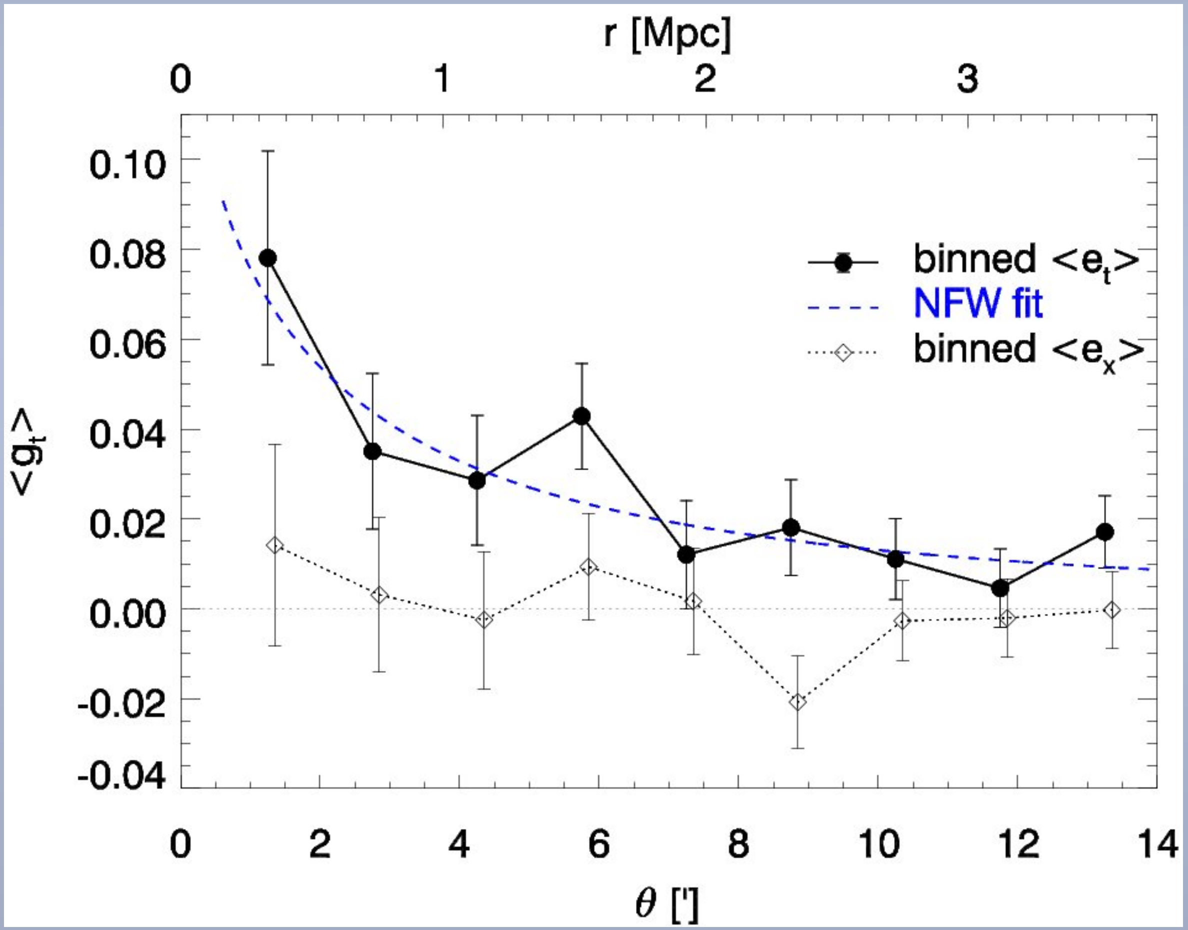
A. Bender et al. (in prep)

Scaling relations (2)

Lensing mass estimate using NFW fits to the tangential shear profiles

A1300

$$M_{200} = 9.3^{+2.4}_{-2.0} \times 10^{14} M_{sun}$$



Mass / SZ scaling laws with APEX-SZ

M. Klein et al. (in prep)

Combining thermal SZ and X-rays

Two probe of the same electron population

- SZ flux:

$$Y_{SZ} \propto \int \Delta T_{SZ} \, d\Omega \propto \frac{1}{D_A(z)^2} \int n_e T_e \, dV$$

- X-ray flux:

$$F_X = \frac{1}{4\pi D_L(z)^2} \int n_e^2 \Lambda_{ee} \, dV$$

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Fixed volume of constant n_e and T_e

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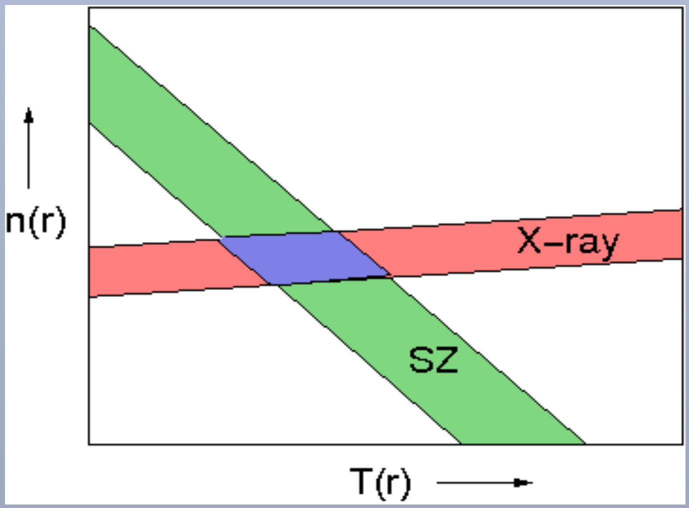
Combining thermal SZ and X-rays: Two applications

- **<u>Route 1 (e.g. Reese et al. 2002, Bonamente et al. 2006) :</u>**
  - Treat gas properties as nuisance parameters
  - Use SZ effect and X-ray spectroscopy to constrain both ICM and $D_A(z)$
  - Constrain H_0 (and possibly Ω_m, Ω_Λ) from the D_A-z diagram

- **<u>Route 2 (e.g. Laroque et al. 2006, Bonamente 2008) :</u>**
  - Consider cosmology fixed (and $D_A(z)$ known)
  - Use SZ effect and X-ray su rface brigthness to constrain gas thermodynamics
  - Most conveniently done using the X-ray soft band (Λ_{ee}~ Cst)
  - So far assuming parametric profiles



Combining thermal SZ and X-rays

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Fixed volume of constant n_e and T_e

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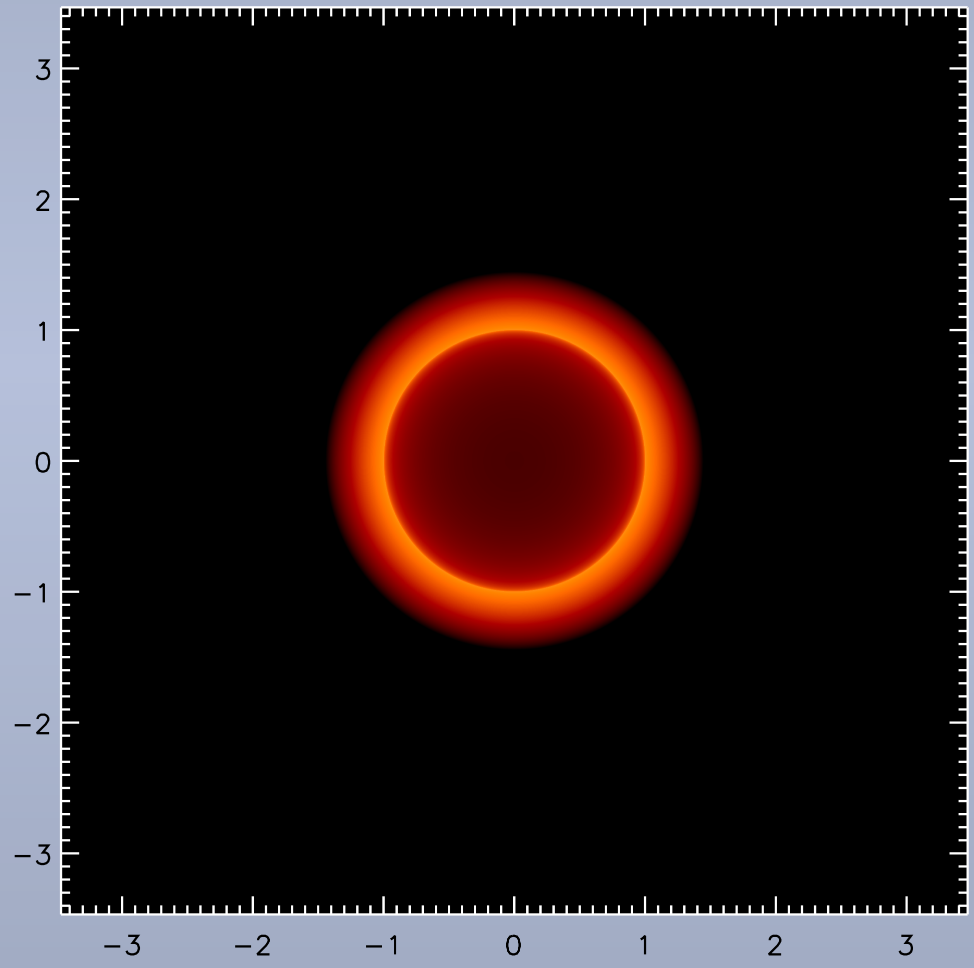
$$F_X = \frac{1}{4\pi D_L(z)^2} \int n_e^2 \Lambda_{ee} \, dV \propto \frac{n_e^2 \Lambda_{ee}}{D_A(z)^2}$$

Never happens

Assumption on geometry: concentric shells



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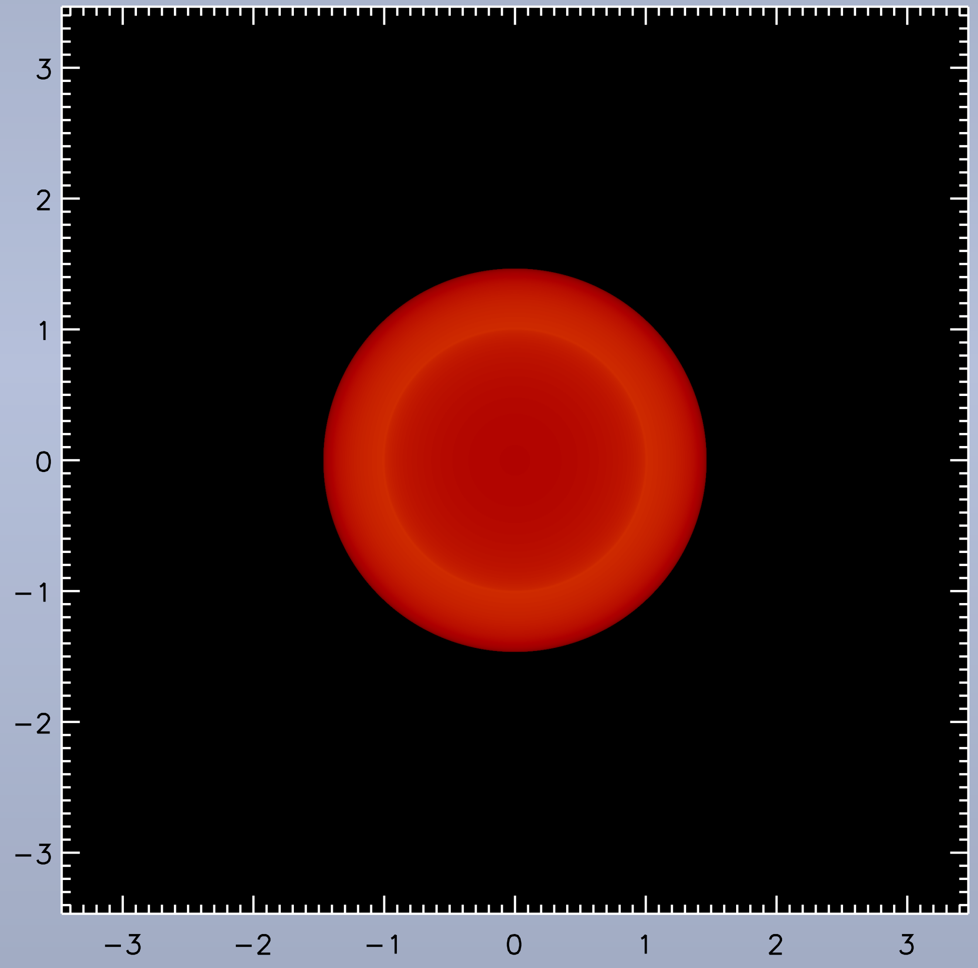
Log scale



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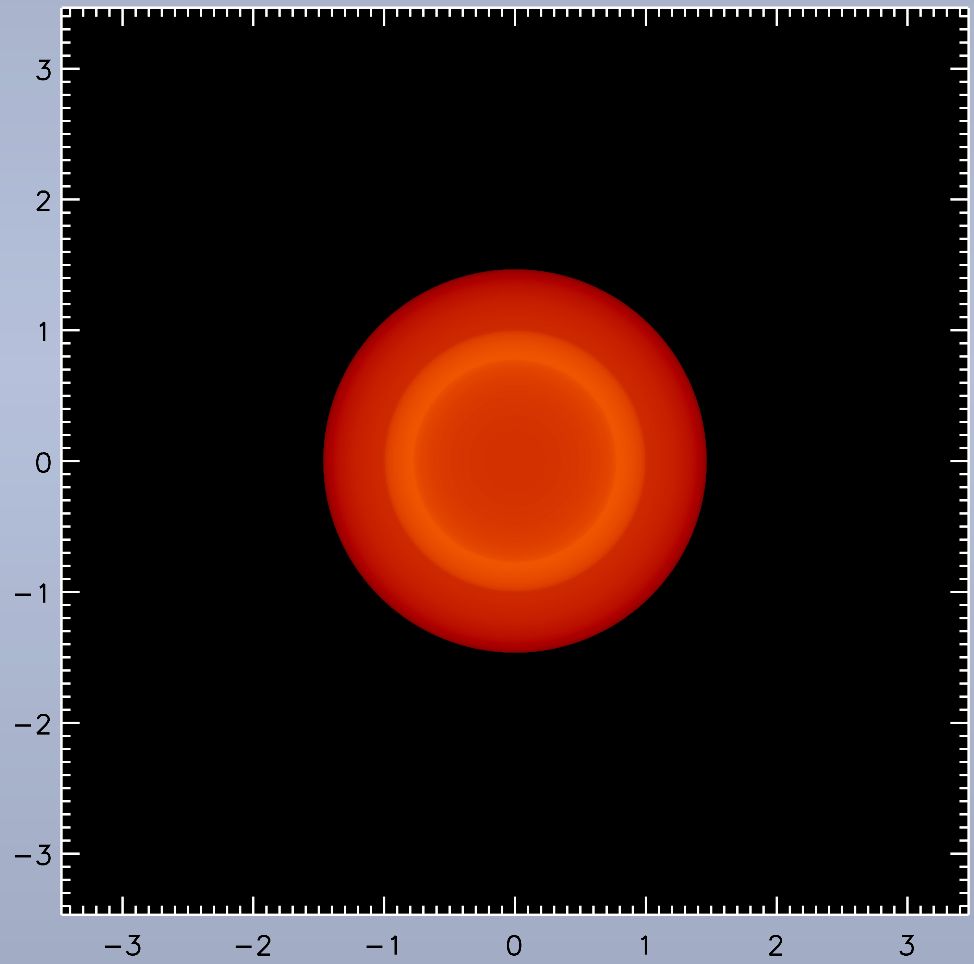

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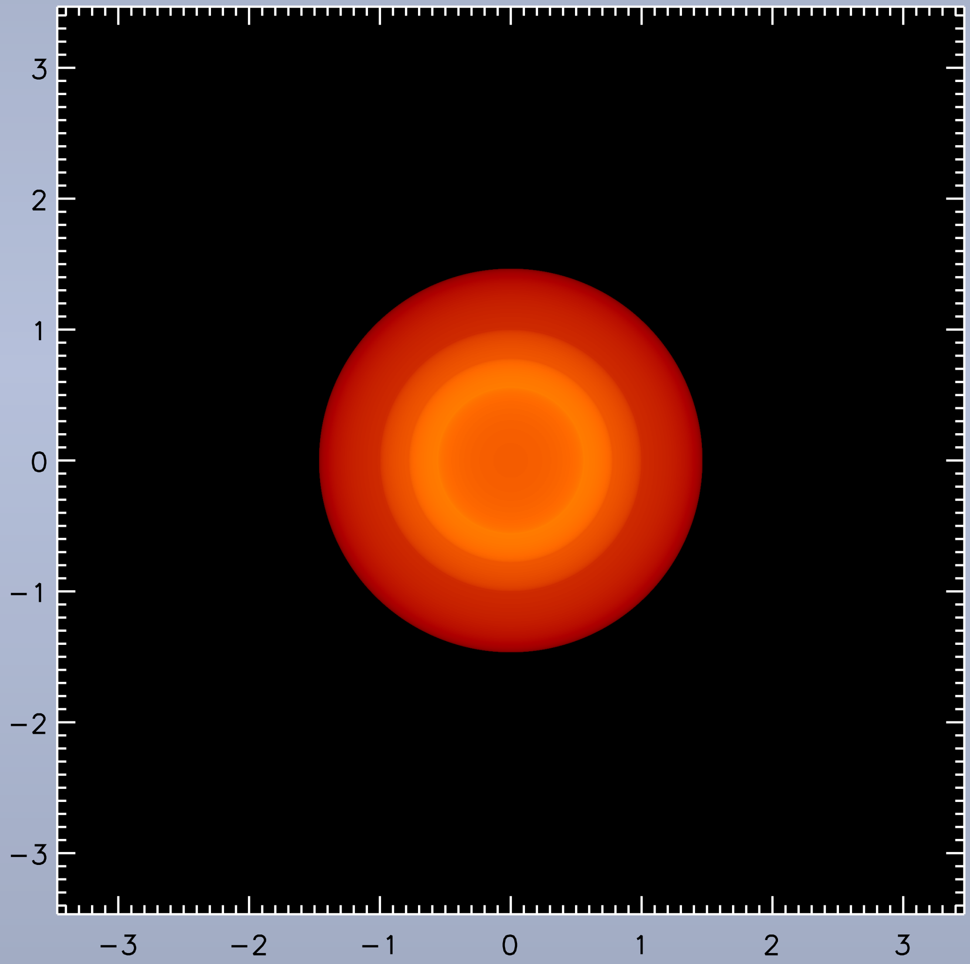

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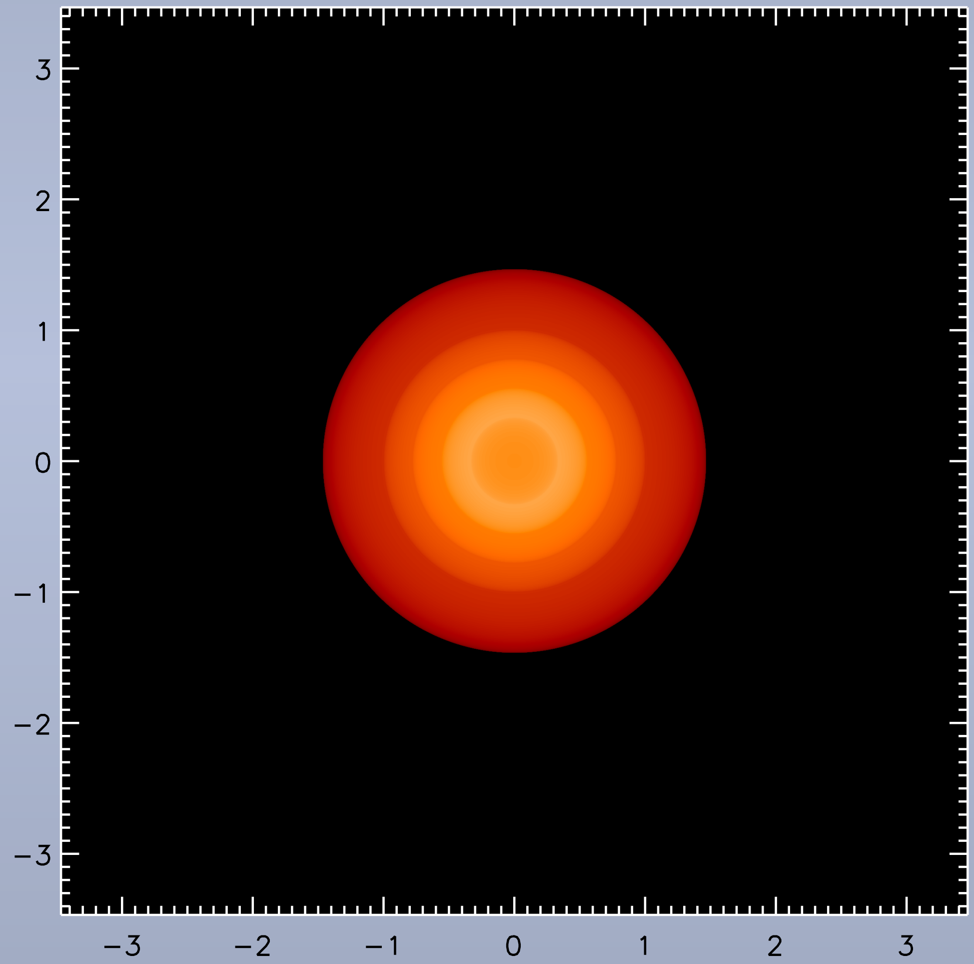

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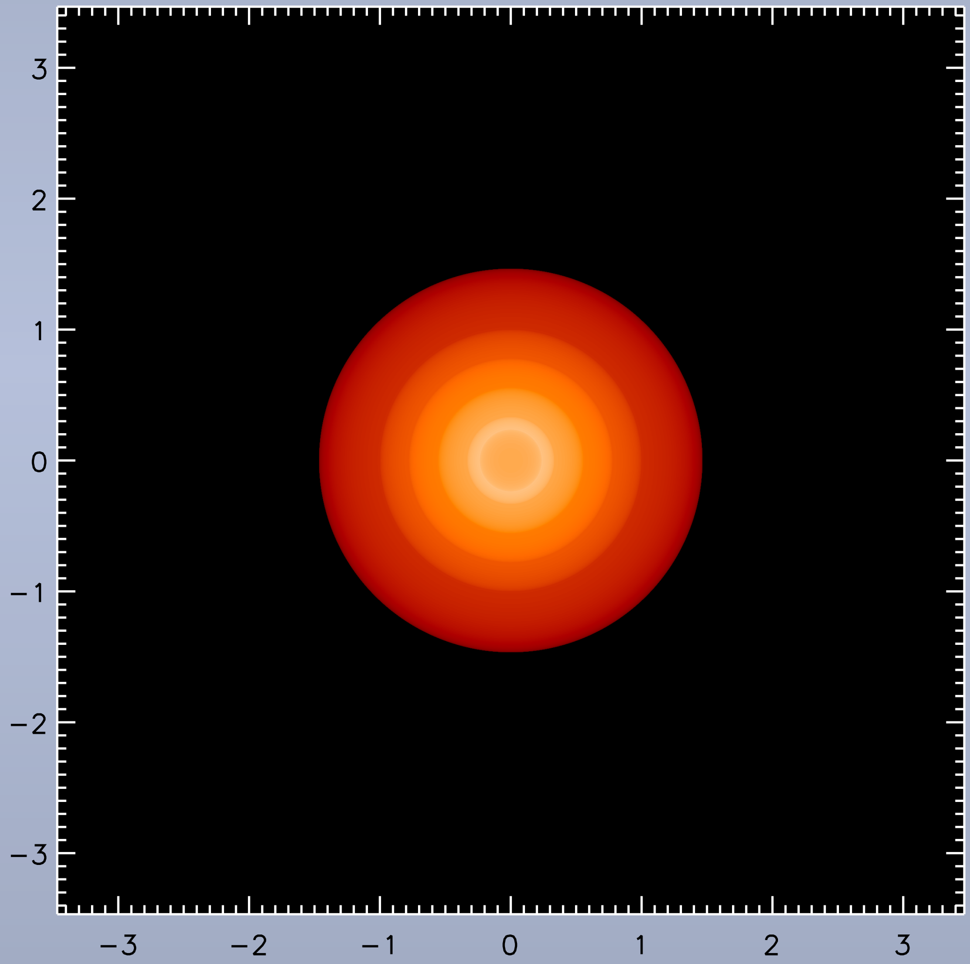

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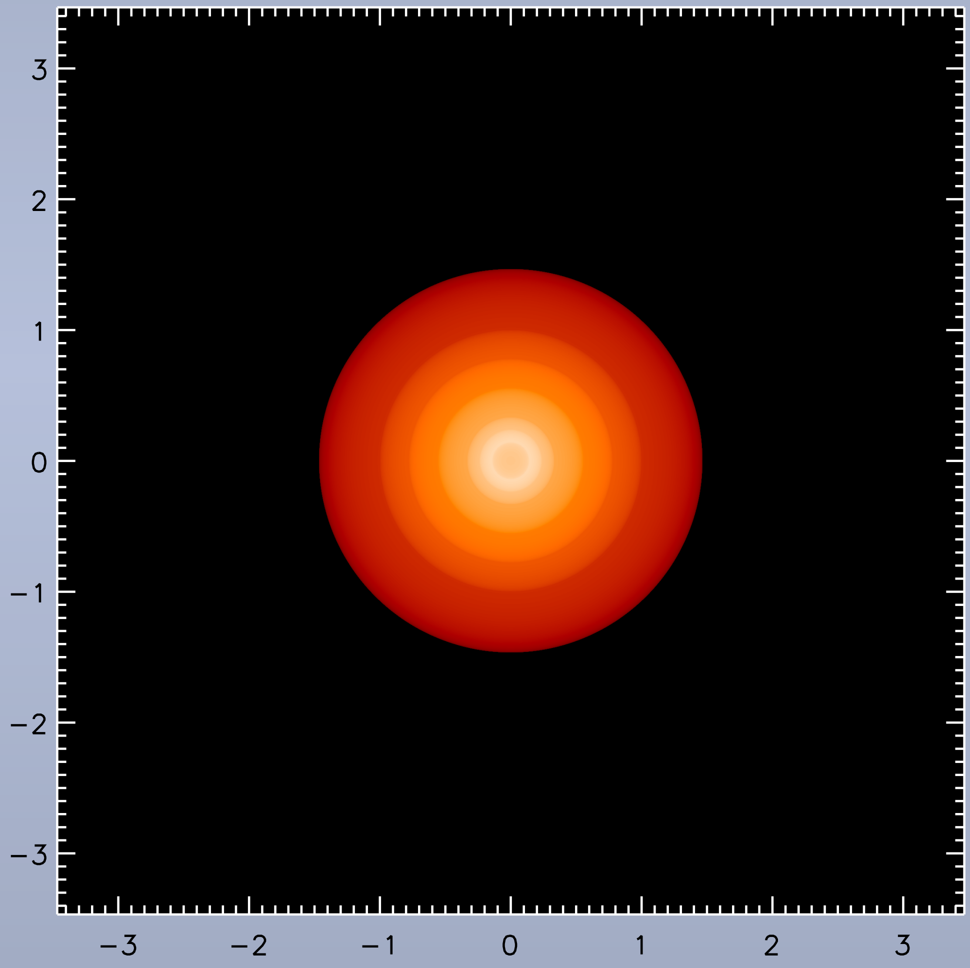

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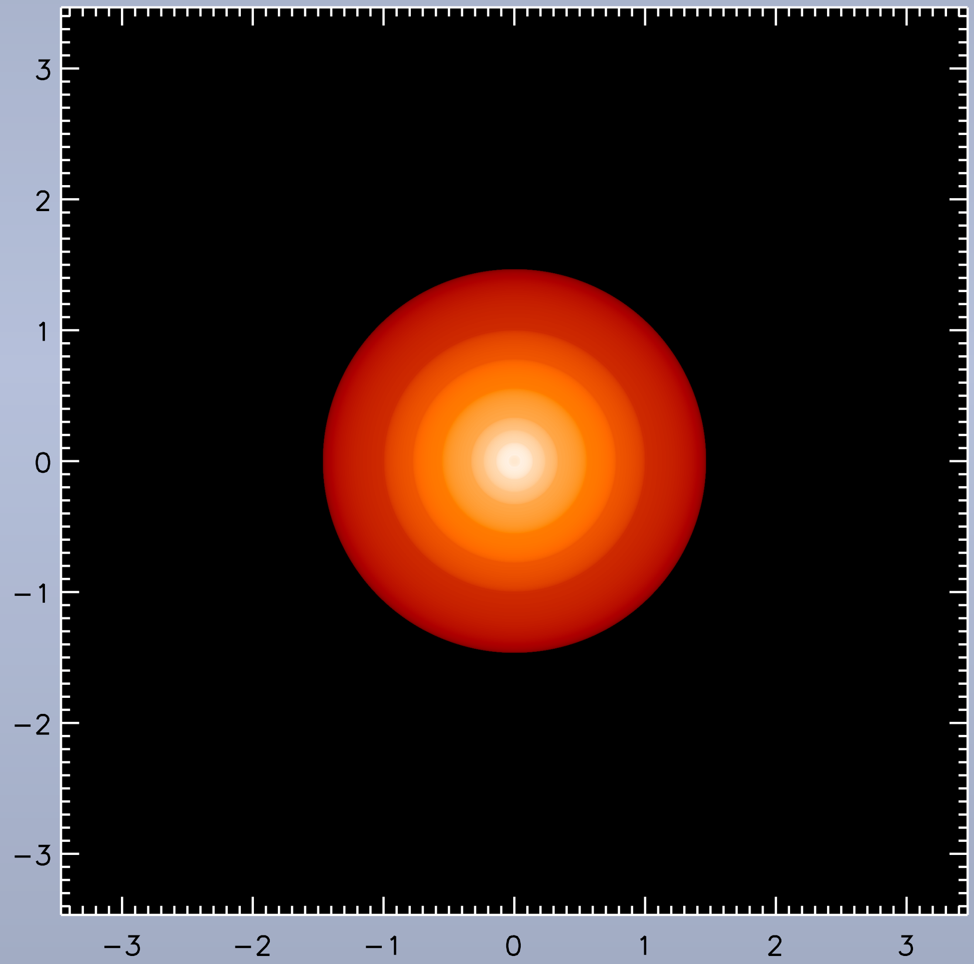

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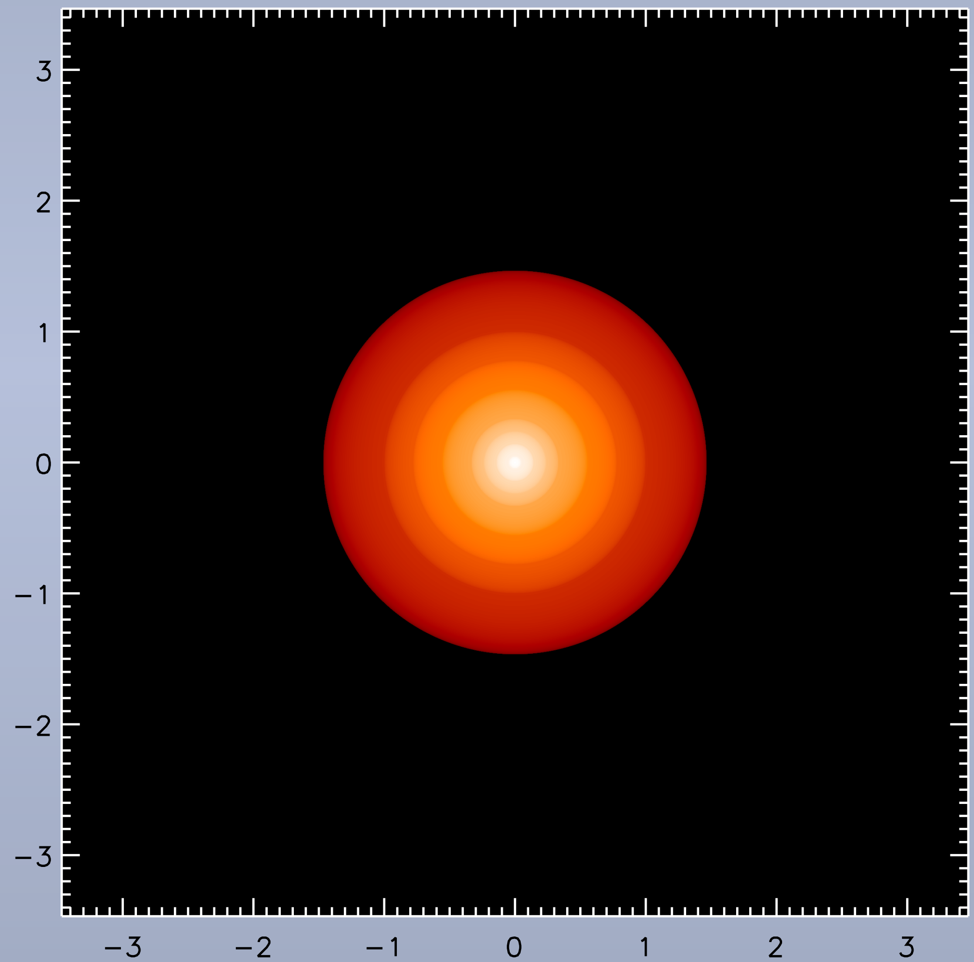
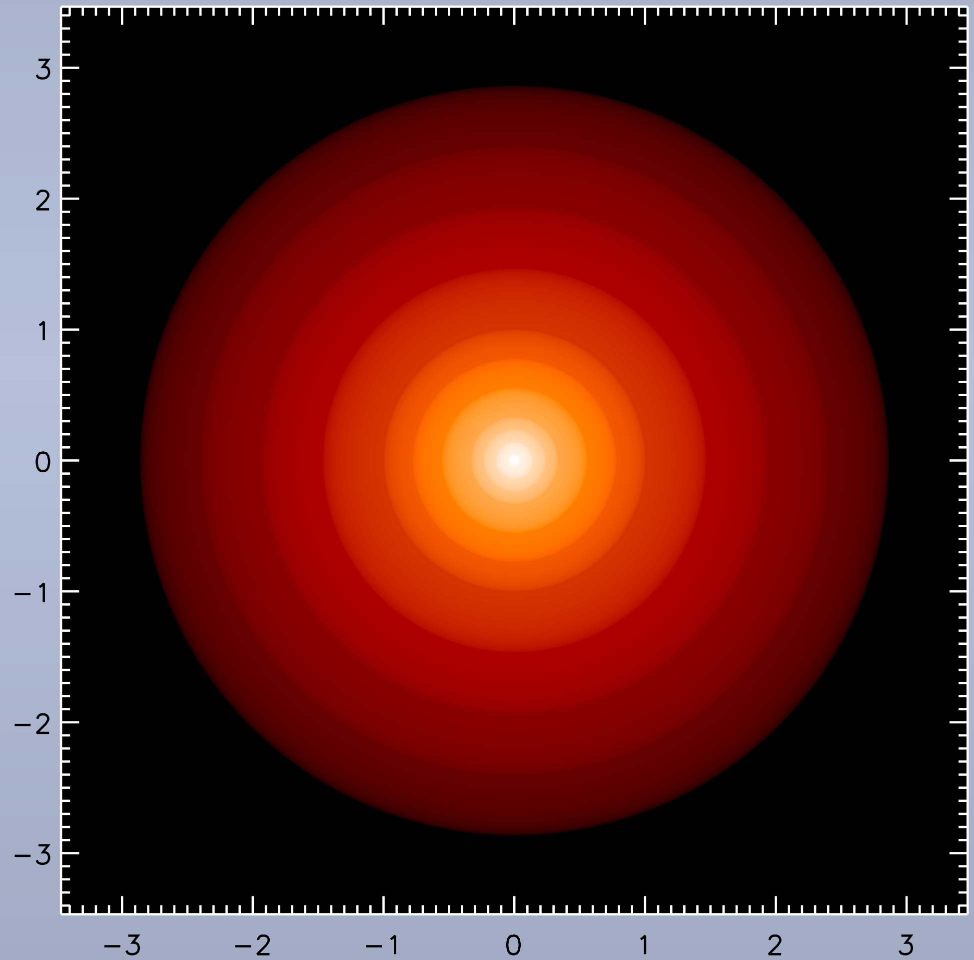


$n_e T_e$ normalization from GNFW profile Arnaud et al. (2010)

Assumption on geometry: concentric shells

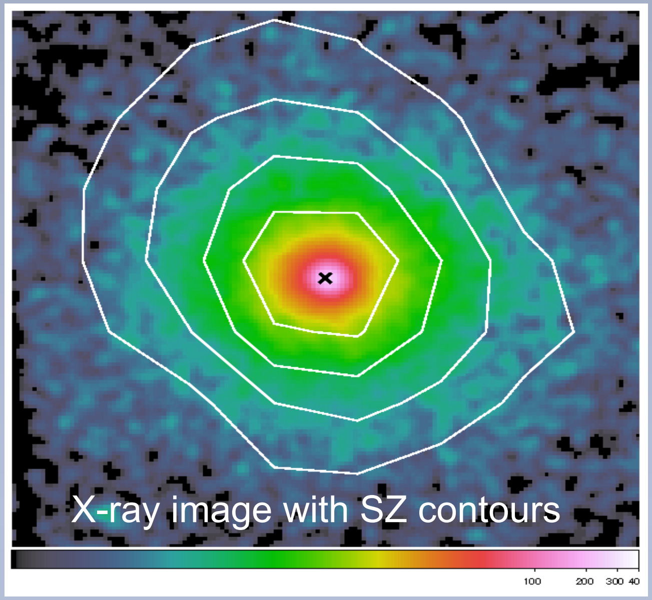
Extrapolation beyond R_{200} is not too problematic

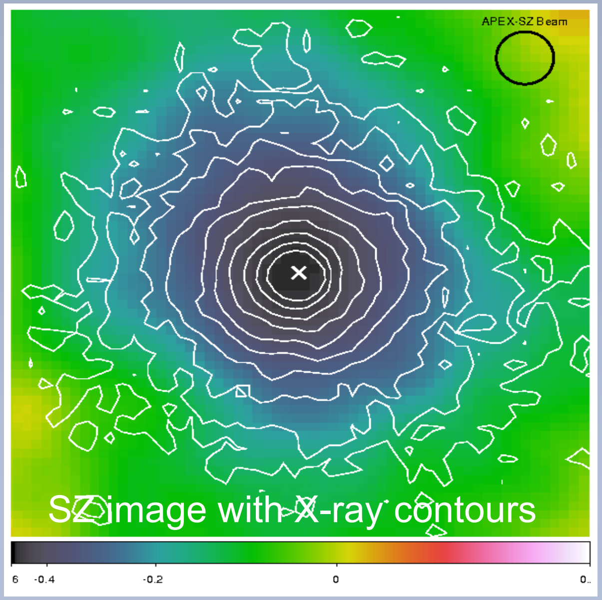


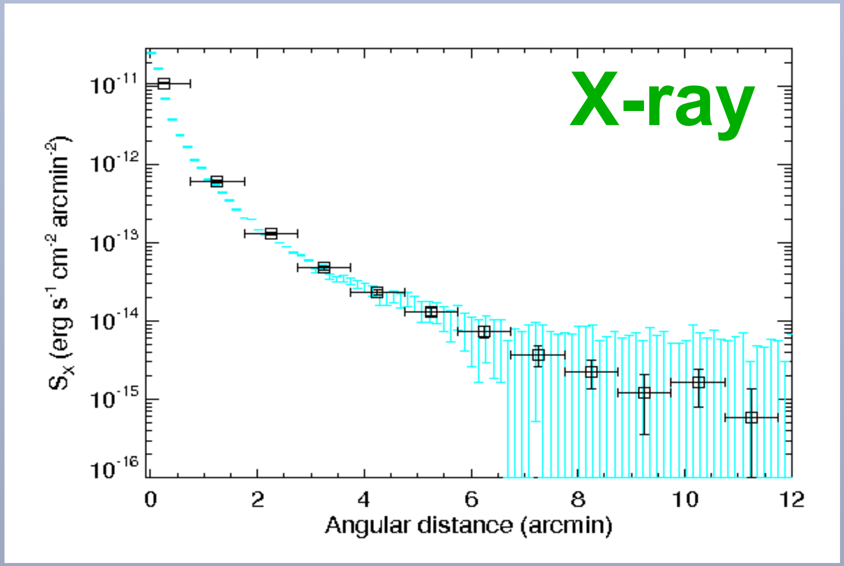
Investigating the structure of the ICM

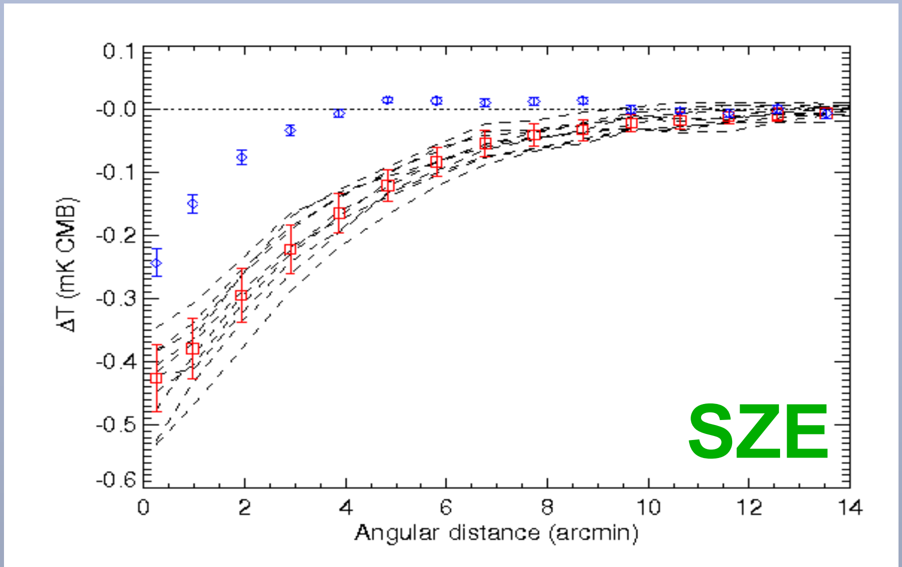
Abell 2204

Basu et al. 2010









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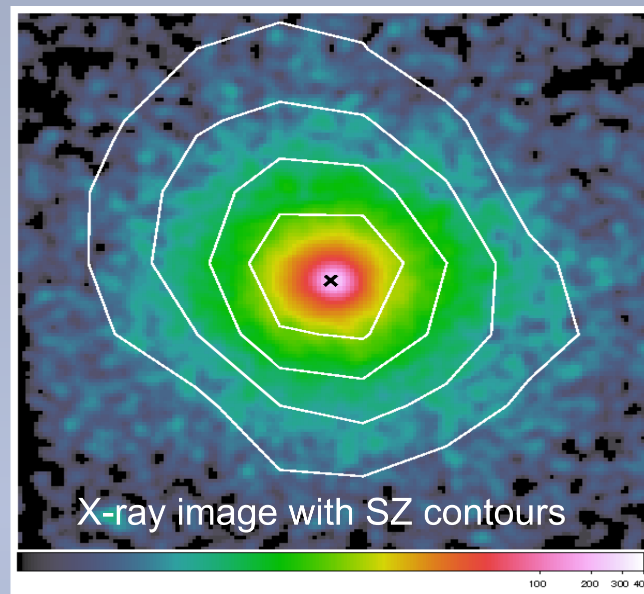
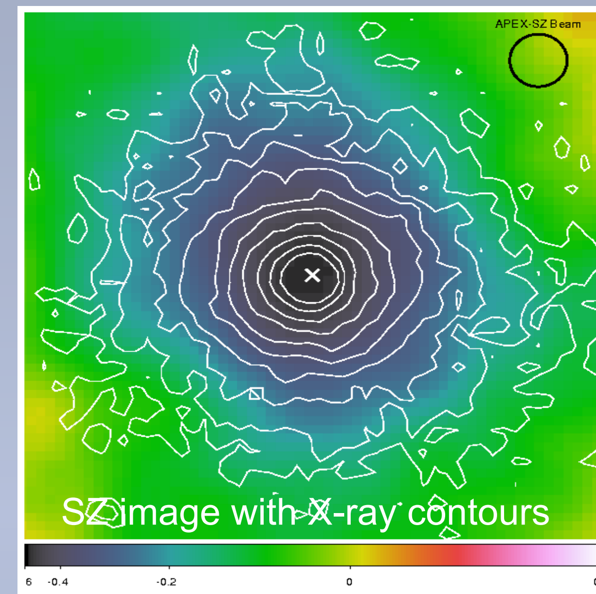
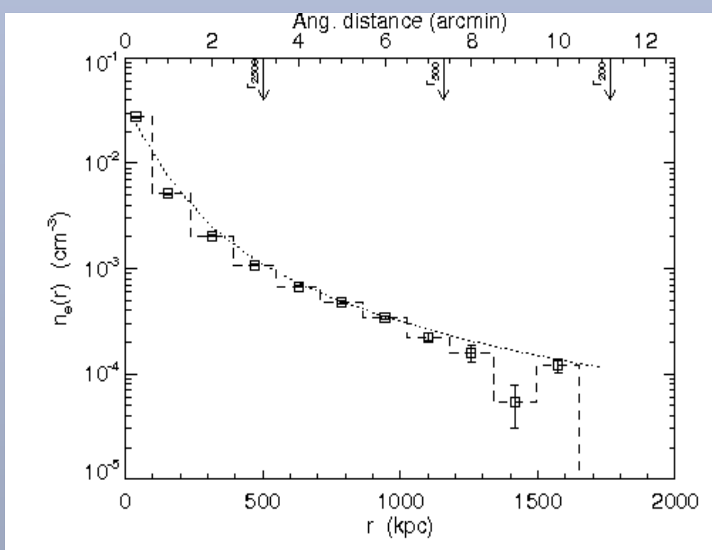
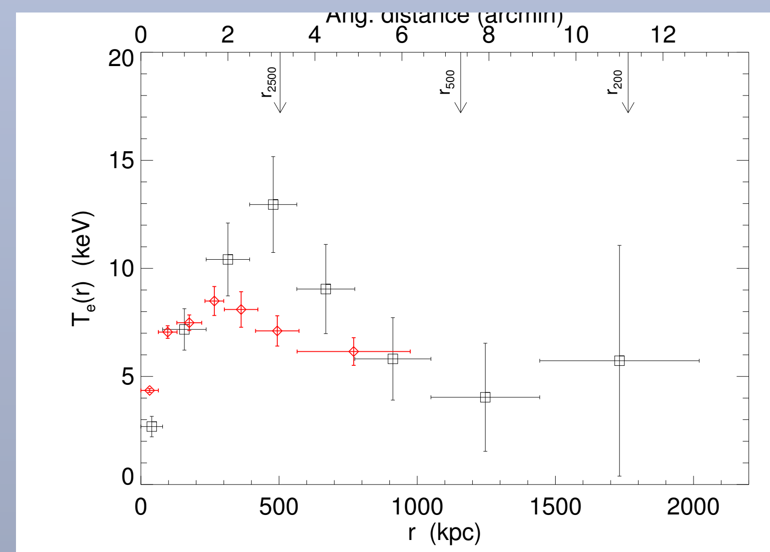




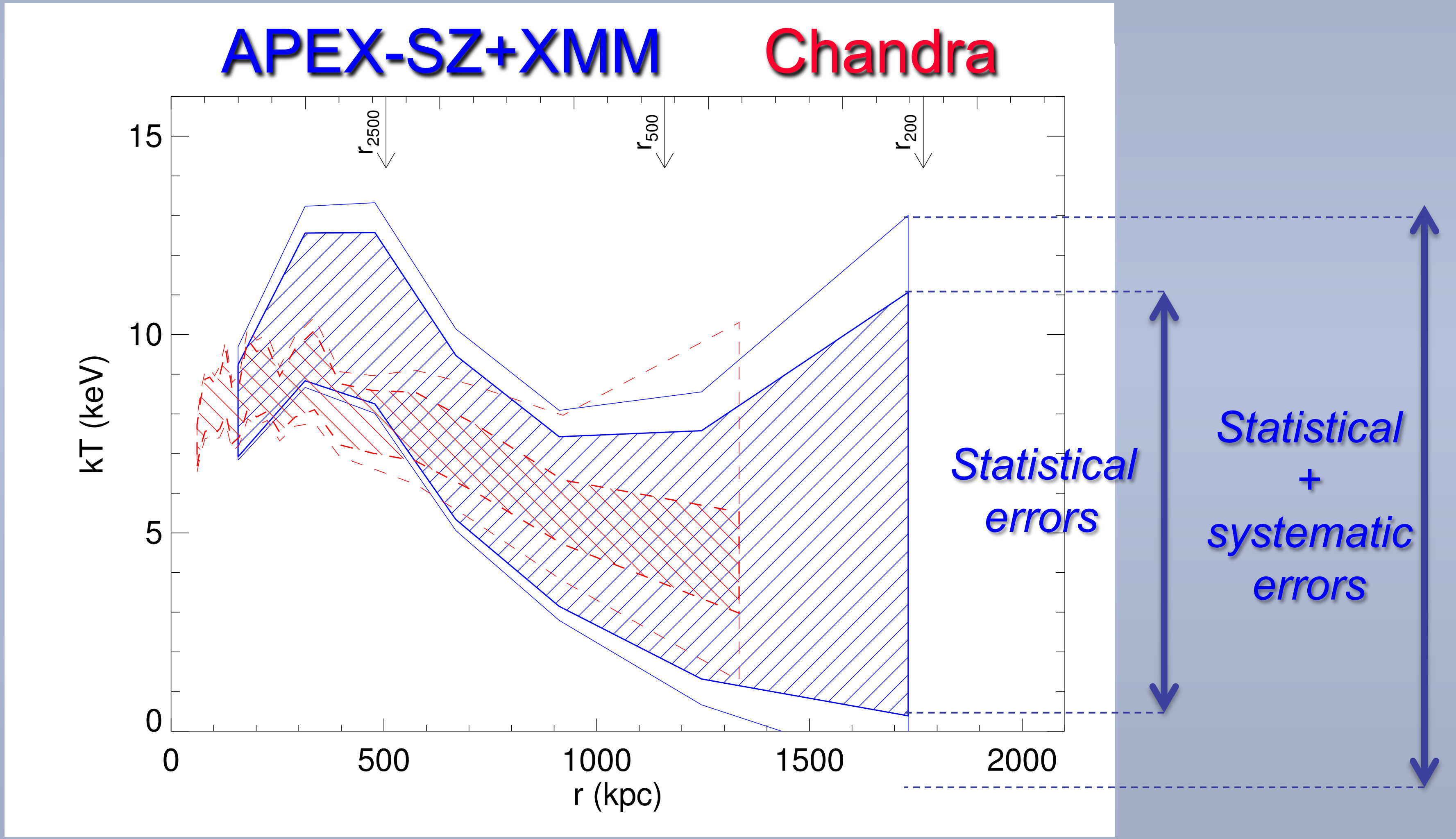


Non-Parametric deprojection



Comparison with the X-rays

Re-projected temperature profile



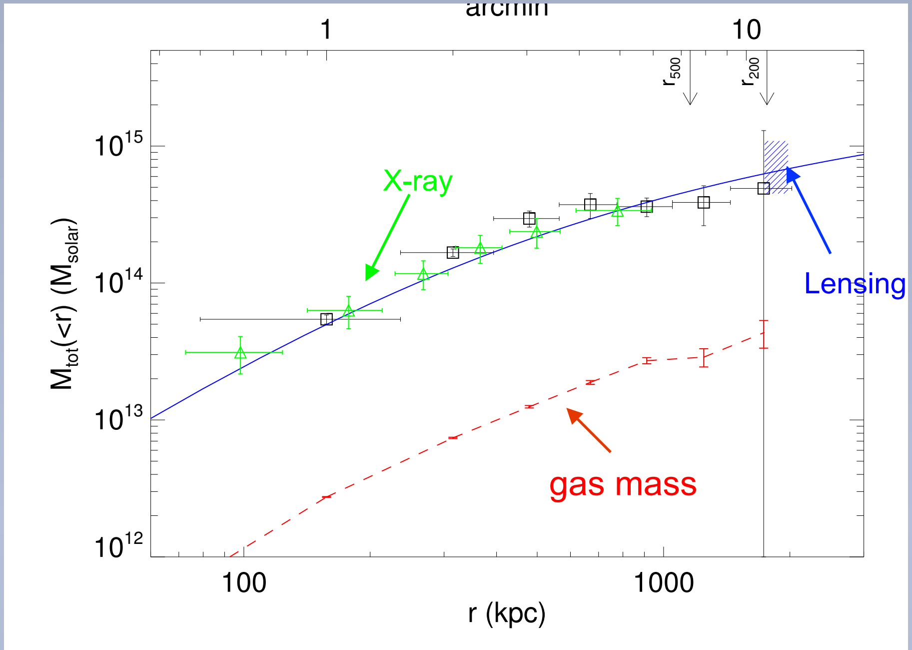
Basu et al. 2010

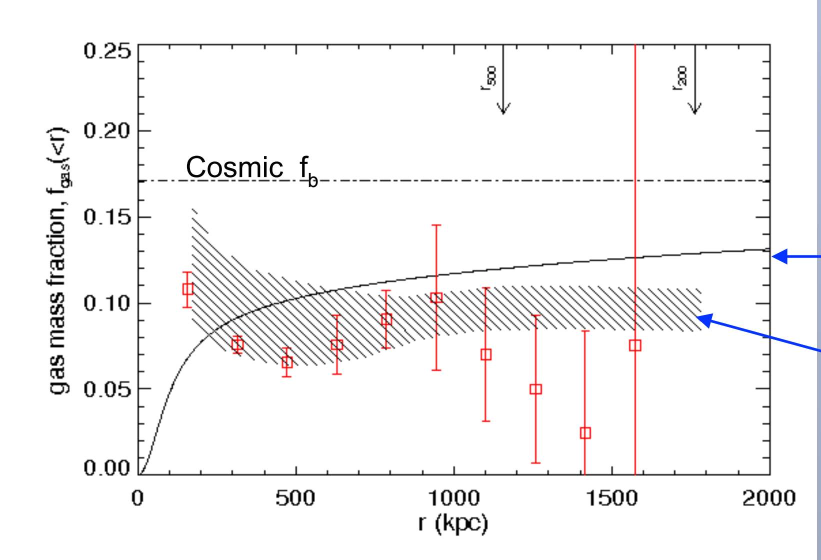
Mass estimate

Hydrostatic equilibrium inside the dark matter potential well

$$\frac{1}{\rho_g}\frac{dP}{dr} = -\frac{d\phi}{dr} = -\frac{GM(<r)}{r^2}$$

$$M_{tot}(<r) \propto -T_e(r)\left[\frac{d\ln n_e(r)}{d\ln r} + \frac{d\ln T_e(r)}{d\ln r}\right]$$

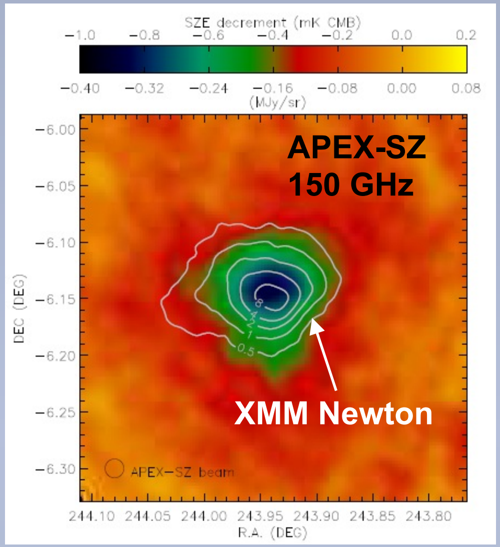


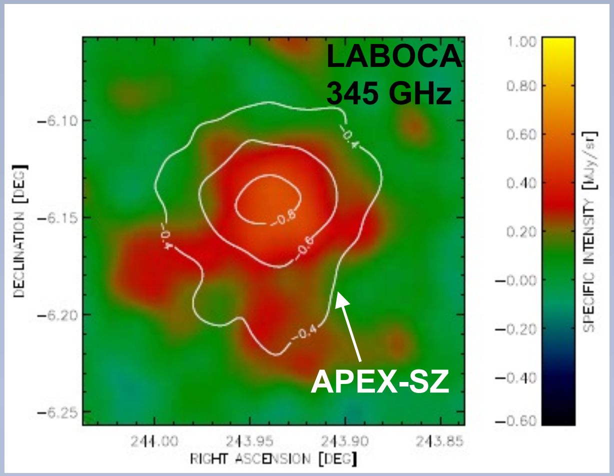


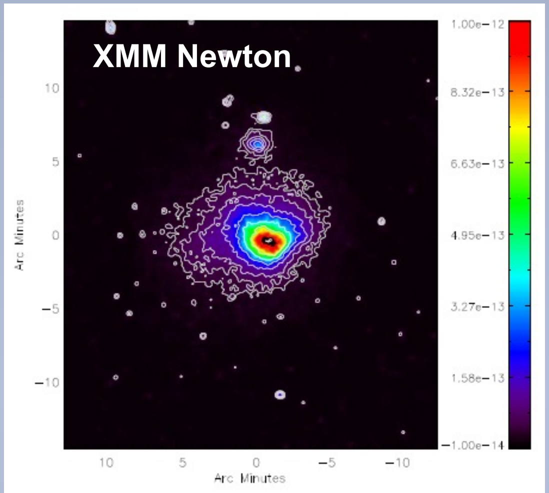
Free from clumping bias !
(only hydrostatic bias …)

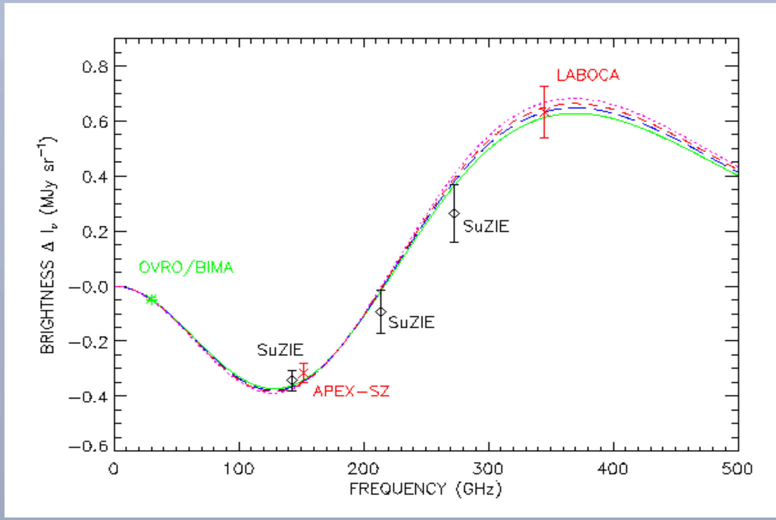
Basu et al. 2010

A2163 with APEX-SZ & LABOCA









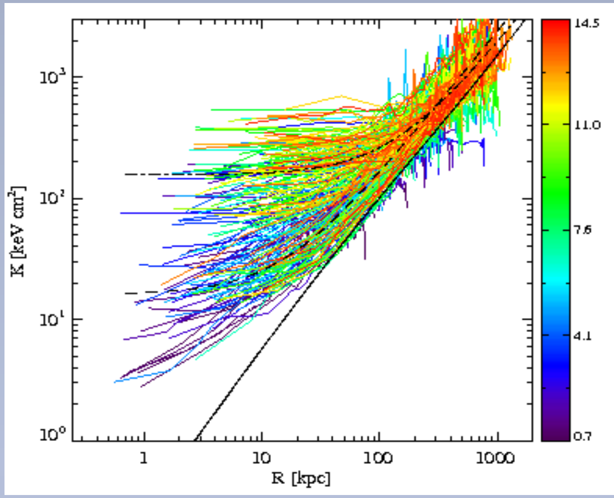
Nord, Basu, Pacaud, et al. (2009)

Entropy profiles

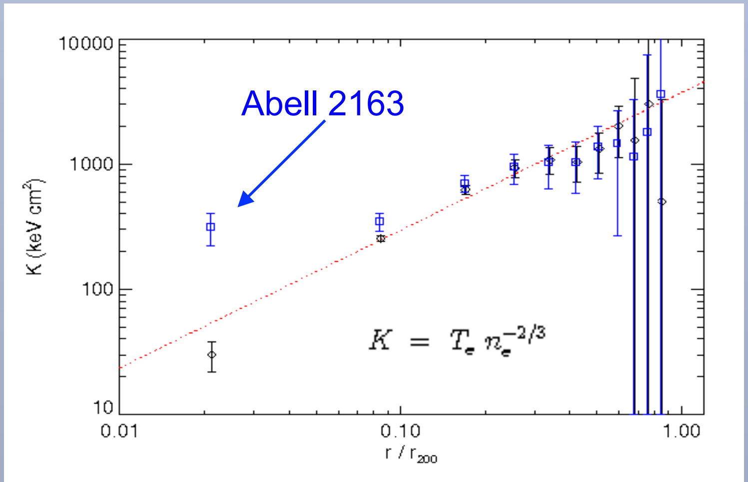
Entropy is a fundamental property of the ICM, describing its history of heating and cooling

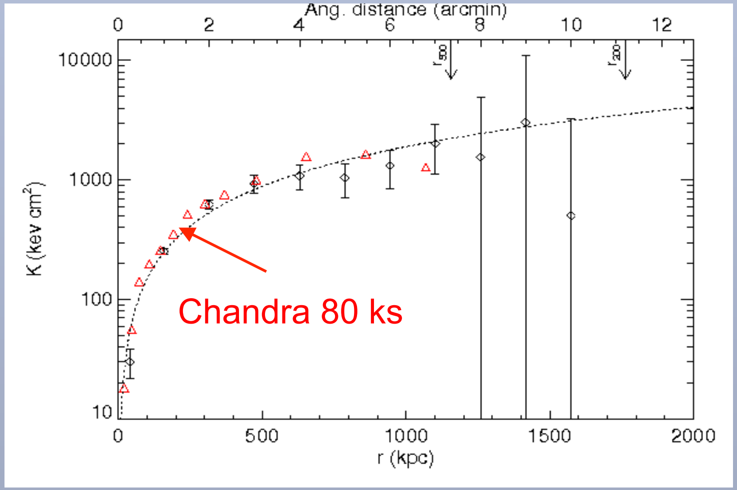
Slope of the entropy profile near the cluster center determines the extent of non-gravitational heating

Low entropy near the virial radius indicates missing baryons from the ICM!



Cavagnolo et al. 2009





Abell 2204, Basu et al. (2009)

Summary

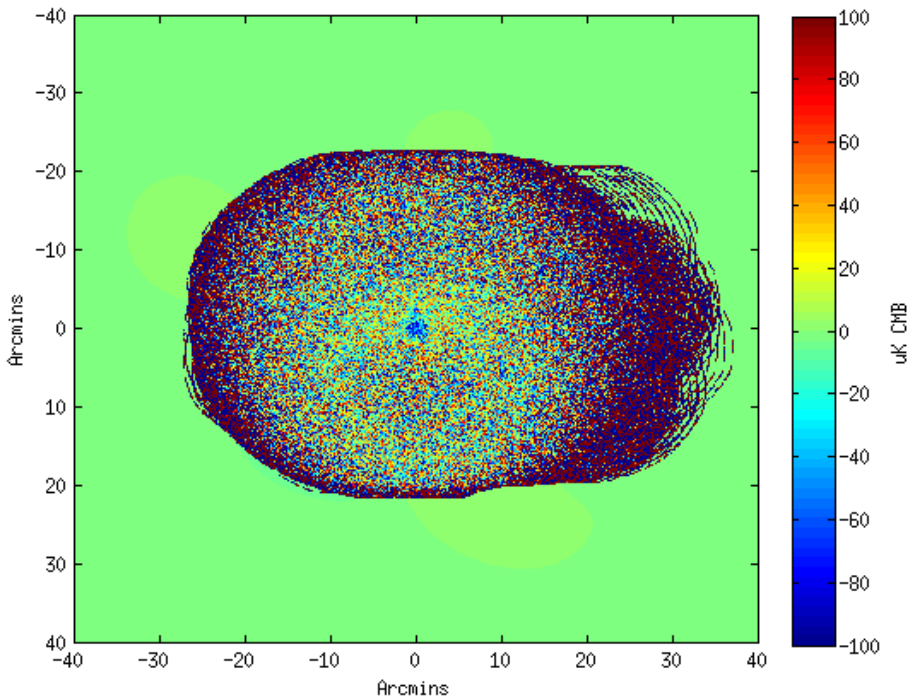
- APEX-SZ has detected 35 massive galaxy clusters
- X-ray/Lensing follow-up available for almost all
- Multi-wavelength scaling relations will come soon

- APEX-SZ data permit high resolution non-parametric analysis of our most significant detections
- This confirmed the potential of X-ray/SZ combination to overcome the drawbacks of X-ray spectroscopy (background systematics, sensitivity to clumping)

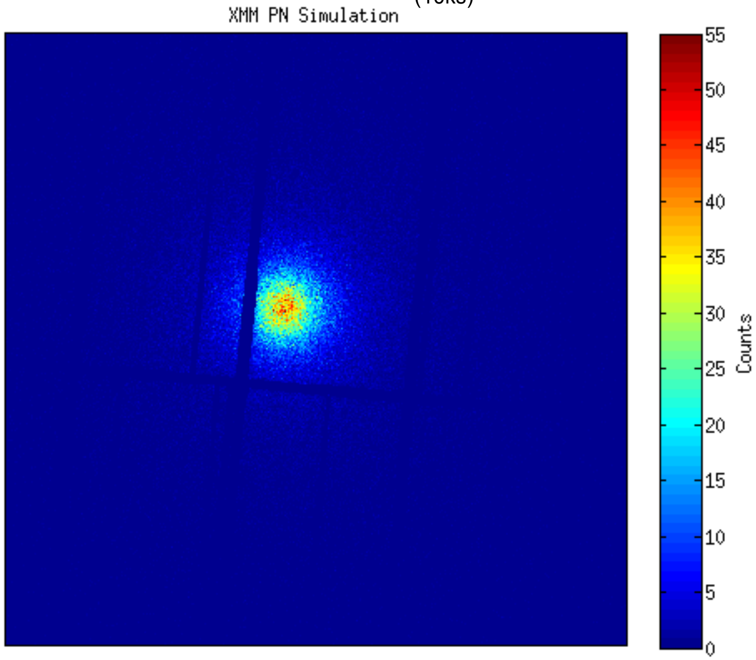
Taking route 2: $D_A(z)$

Test simulation:

- Isothermal b-model
- $z = 0.2$
- $T_e = 5$ keV
- $n_{e0} = 0.02\ cm^{-3}$

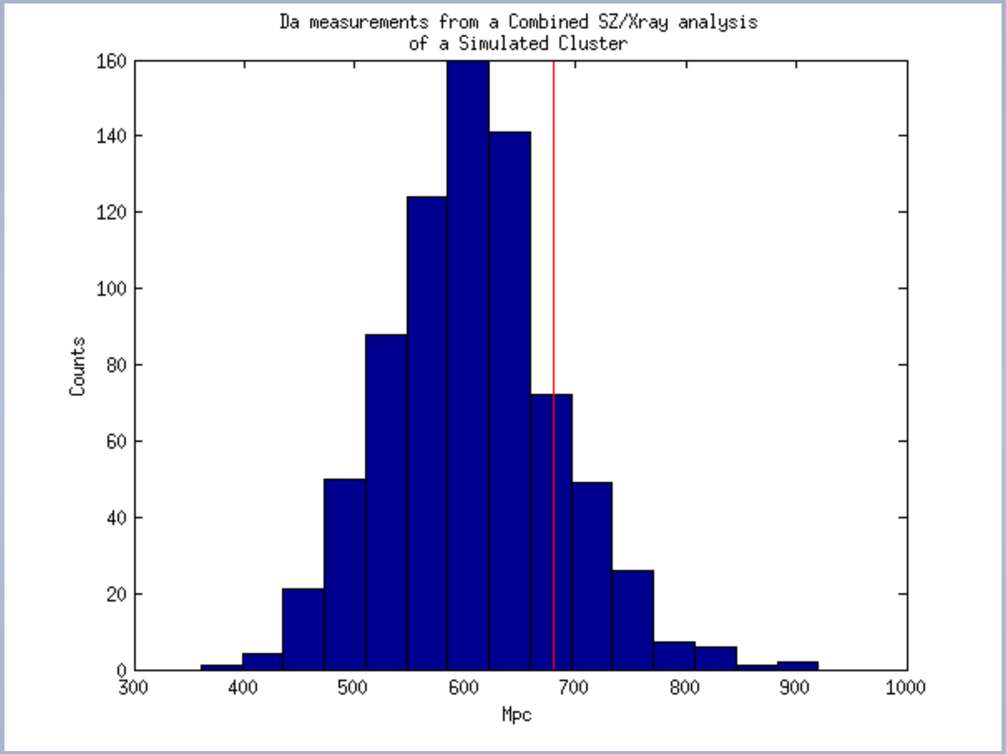


(10ks)



Kennedy et al. (in prep)

Taking route 2: $D_A(z)$



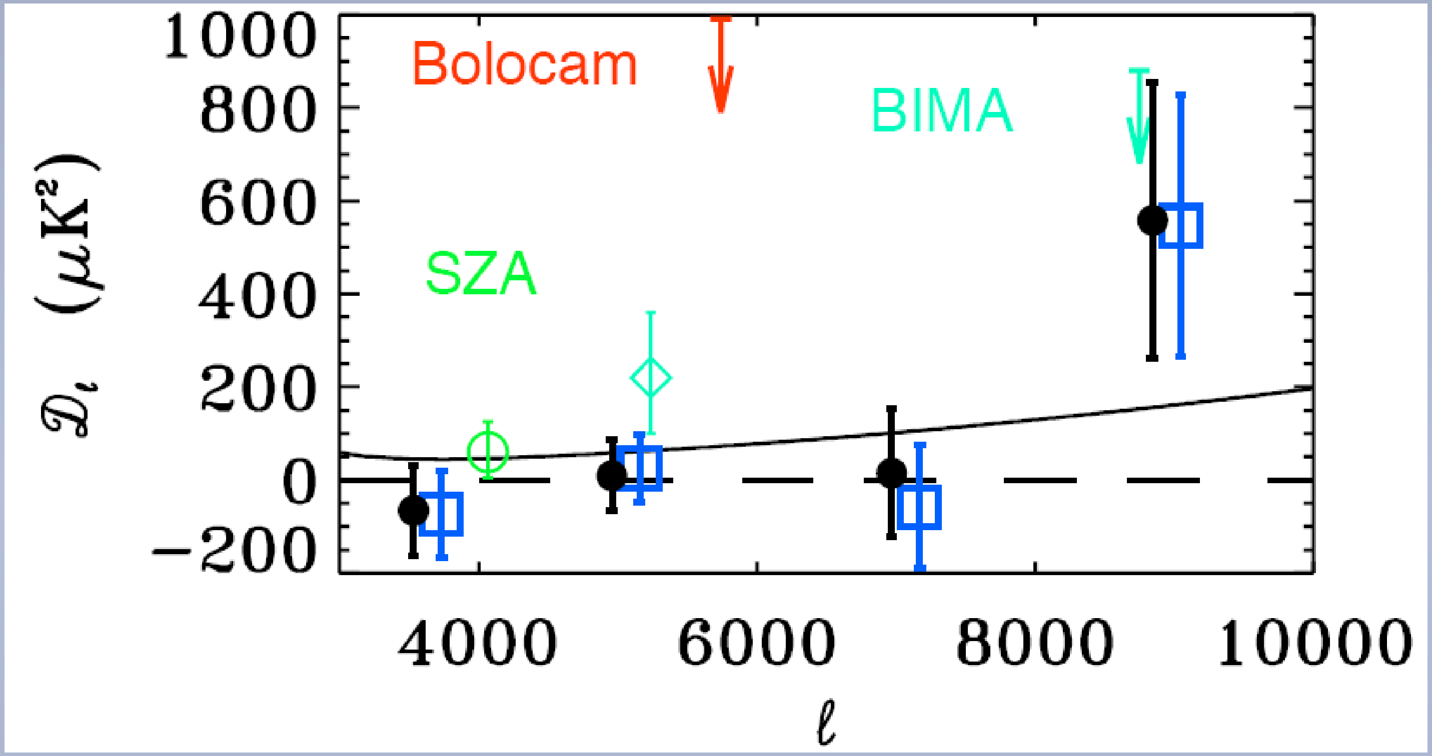
Results encouraging $\Delta D_A/D_A \sim 10\%$

Full spectroscopy with non-isothermal profile still missing

Kennedy et al. (in prep)

APEX 150 GHz Power Spectrum

Reichardt et al. (2009)



- 0.8 sq degrees at 150 GHz with 1' resolution
- 10 nights in Aug/Sept 2007, 2.9 k-bolo-hrs
- 12 μK_{RMS} per 1' pixel
- XMM LSS field, centered on XLSSU J022145.2-034614 (5 KeV x-ray cluster)

- Total Anisotropy < 105 μK^2 at 95%.
- $\sigma_8 < 1.18$ at 95%
  - Fitting for SZE & Poisson bright point source population
  - Properly accounting for non-Gaussian statistics (limit would be $\sigma_8 < 0.94$ assuming Gaussian noise only)

APEX 150 GHz Power Spectrum

Reichardt et al. (2009)

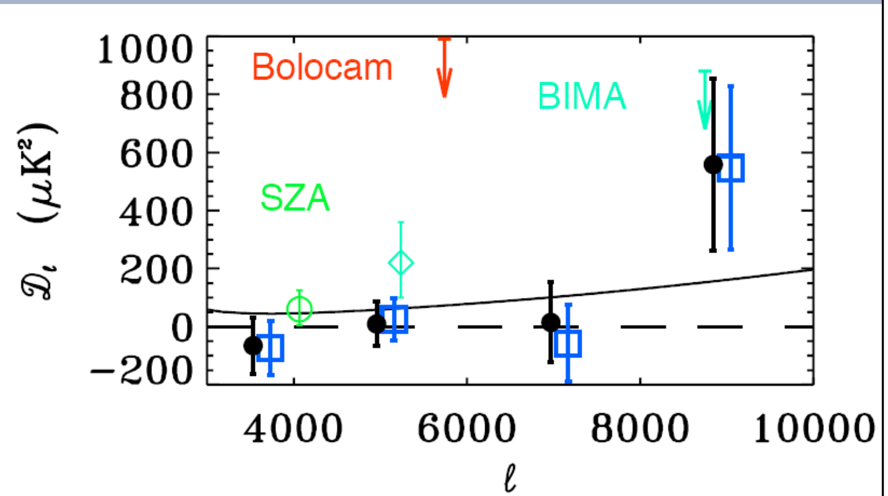


TABLE 2
POINT SOURCE POWER AND σ_8 CONSTRAINTS

	Cluster masked	Cluster + Sources masked
Zero SZE power: C_ℓ^{PS} (10^{-5} μK^2)	$1.0^{+0.9}_{-0.6}$	$1.2^{+1.0}_{-0.8}$
Fixed $\sigma_8 = 0.8$: C_ℓ^{PS} (10^{-5} μK^2)	$0.9^{+0.9}_{-0.6}$	$1.1^{+0.9}_{-0.8}$
Unconstrained σ_8: C_ℓ^{PS} (10^{-5} μK^2)	$0.9^{+0.9}_{-0.6}$	$1.1^{+0.9}_{-0.8}$
σ_8 (G) (95% CL)	0.94	0.94
σ_8 (NG) (95% CL)	1.18	1.18
Flat excess: (with $\ell_{center} = 4966$) D_ℓ (μK^2)	33^{+37}_{-24}	36^{+39}_{-26}
95% CL	97	105

Point Source Power

- At 150GHz, expect significant power from distant dusty galaxies
  - Expect 20x less power from radio sources
- Negrello *et al.* (2007) model predicts 1.1 x 10^{-5} μ K^2 in the absence of clustering.

- $C_l^{PS} \approx 1 \times 10^{-5}$ μK^2
  - Nearly independent of flux cut for masking point sources
- With BLAST 600 GHz data → spectral index $\alpha = 2.64^{+0.4}_{-0.2}$.
  - Agrees with MAMBO/SCUBA index, 2.65 Greve et al. (2004)
  - Knox et al., 2004.
- *Dusty galaxies account for most power in APEX-SZ maps.*