Probing cosmic isotropy with galaxy clusters: a new challenge for ΛCDM?

Konstantinos Migkas

Cosmology from home

July 2022

Publications about this project

- **Migkas**, Schellenberger, Reiprich, Pacaud, Ramos-Ceja, Lovisari, **2020**, ***A&A*, 636, *A15***

- **Migkas**, Pacaud, Schellenberger, Erler, Nguygen, Reiprich, Ramos-Ceja, Lovisari, **2021**, ***A&A*, 649, *A151***

The Cosmological Principle

Cosmological Principle

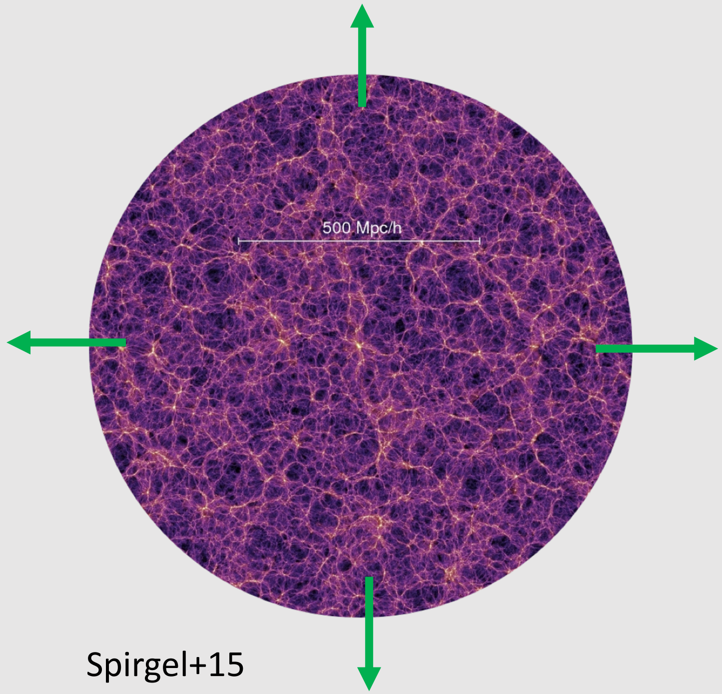
- Basis of standard Cosmology → Universe <u>isotropic & homogeneous</u>

Cosmological Principle

• Basis of standard Cosmology ⟹ Universe <u>isotropic & homogeneous</u>

Isotropy → Same cosmic properties in every sky direction on large scales

Same expansion rate H_0 towards every direction!



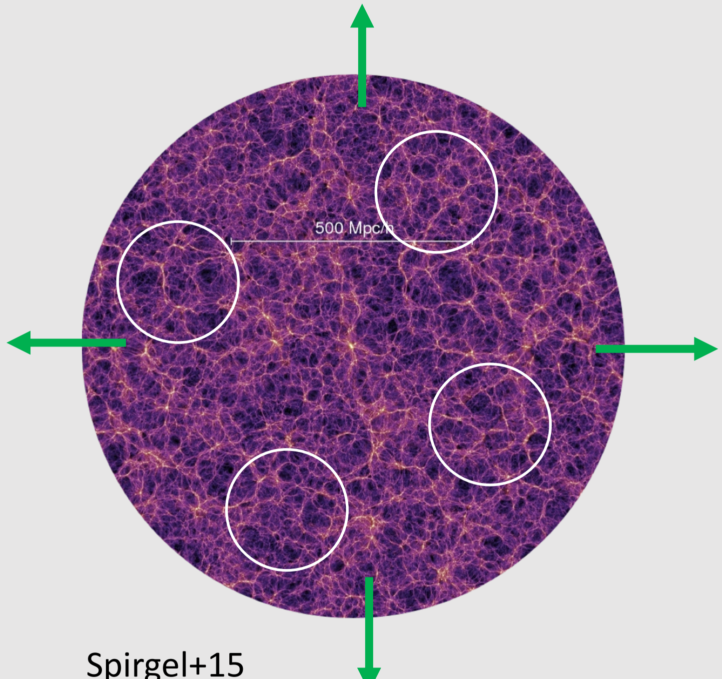
Spirgel+15

Cosmological Principle

- Basis of standard Cosmology → Universe <u>isotropic & homogeneous</u>

Homogeneity → Similar amount of matter averaged over large cosmic volumes

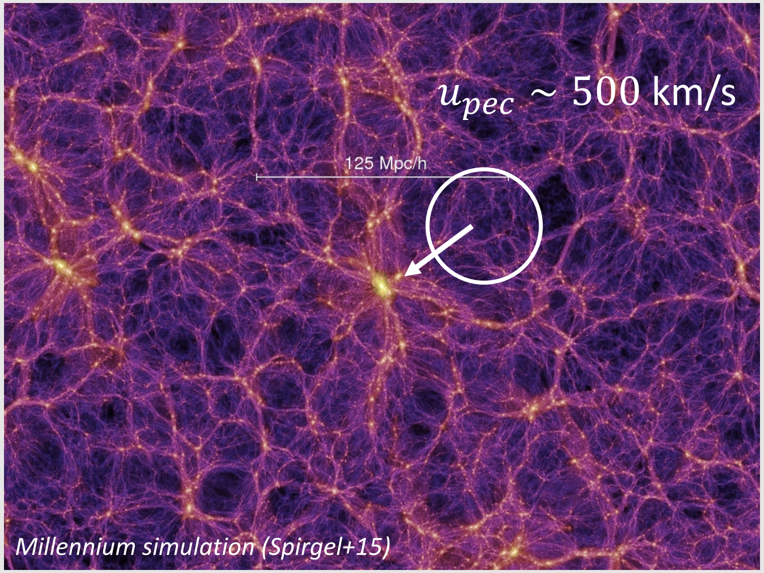
No major bulk flows at large scales!



Spirgel+15

Peculiar velocities & bulk flows

- Local matter inhomogeneties ➡ Stronger gravitational pull towards a direction

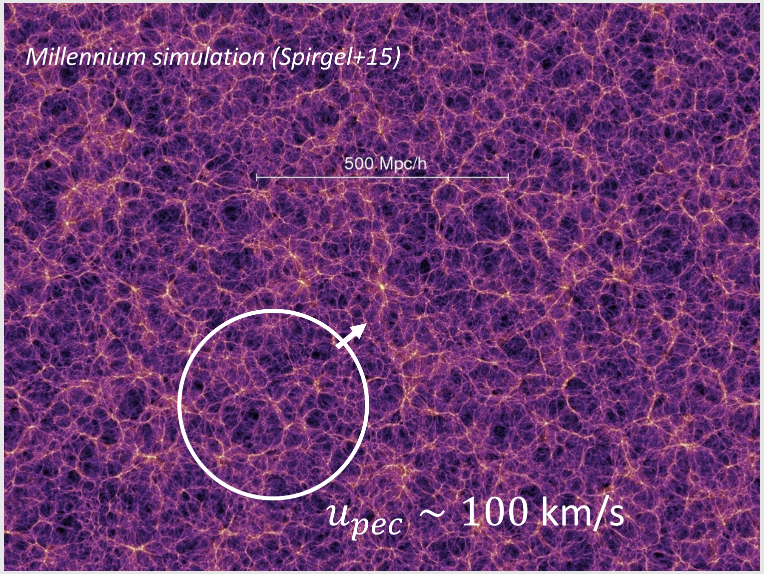


⬇

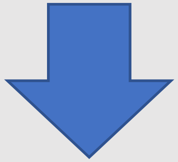
Local (peculiar) velocities!

Peculiar velocities & bulk flows

- Local matter inhomogeneties ➡ Stronger gravitational pull towards a direction



Large cosmic volume flows towards a direction



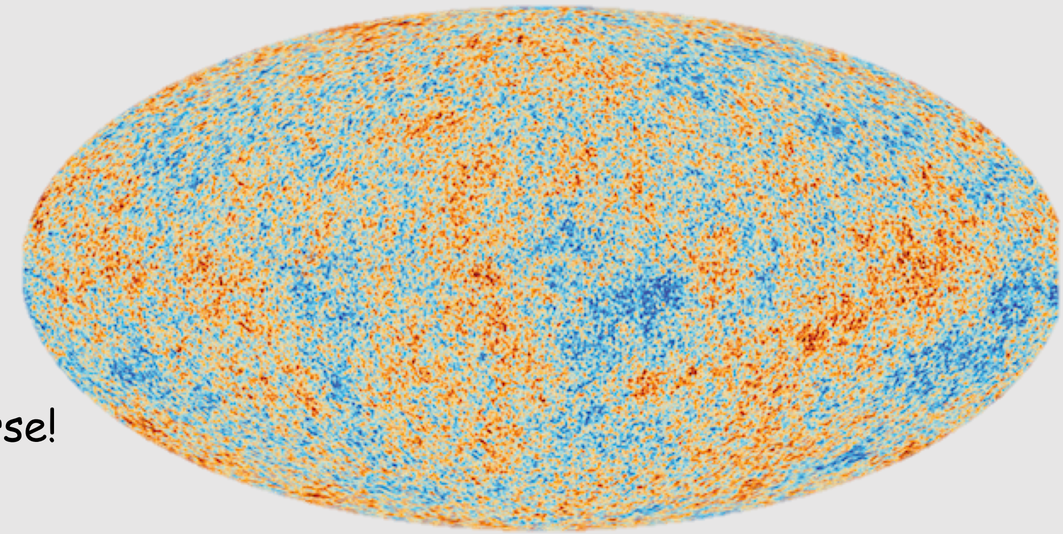
Bulk flow!

Doppler effect: $z_{\rm pec} \approx \dfrac{u_{\rm pec}}{c}$ → $z_{\rm meas} \approx z_{\rm cosm} + z_{\rm pec}$

Important: bulk flows bias the redshift-distance relation → Inferred cluster properties!

Cosmological Principle

Evidence for isotropy? Mostly Cosmic Microwave Background (CMB)



$\frac{\Delta T}{T} \sim 0.001\%$

Highly isotropic (..?)

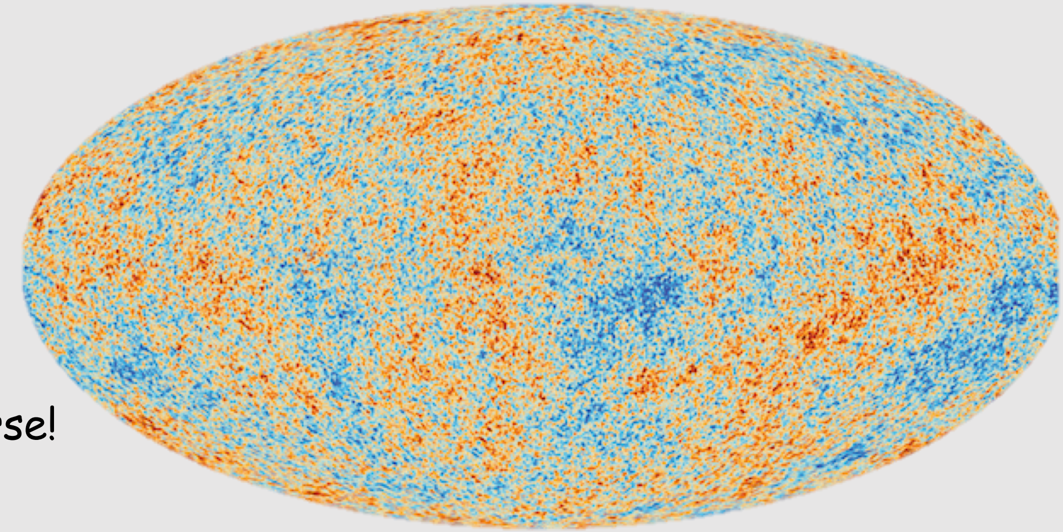
Very early Universe!

Planck Collaboration 2013

Cosmological Principle

Evidence for isotropy? Mostly Cosmic Microwave Background (CMB)

Very early Universe!



$\frac{\Delta T}{T} \sim 0.001\%$

Highly isotropic (..?)

Planck Collaboration 2013

Defines CMB (radiation) rest frame! Is it the cosmic (matter) rest frame..?

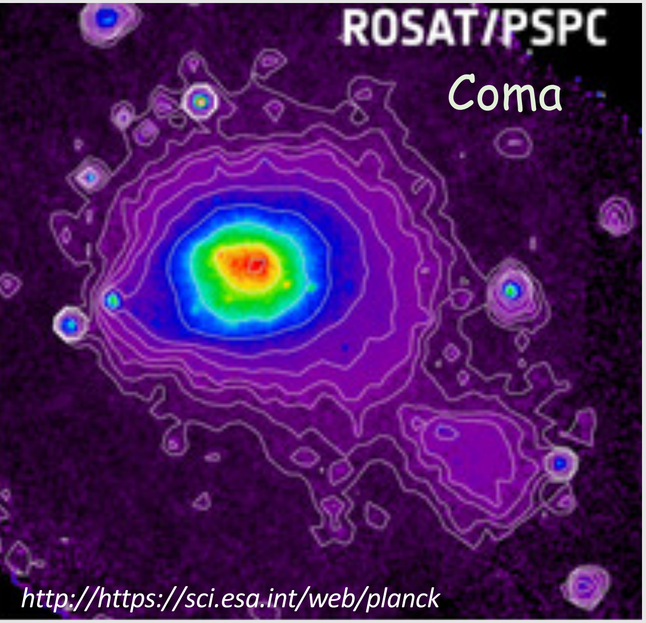
No late Universe probe has robustly shown isotropy

Galaxy Clusters

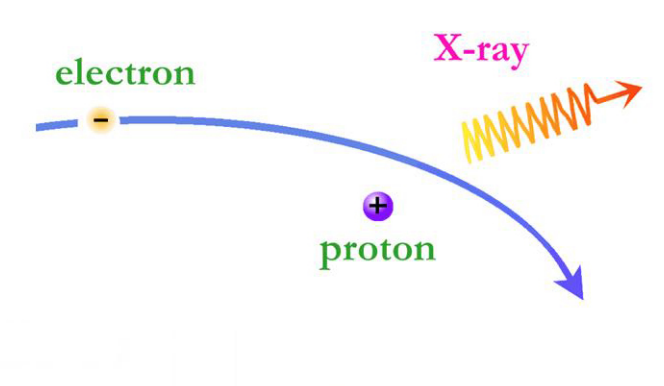
Galaxy clusters

- ~50-1000 galaxies (~3% of total mass)
- Dark matter (~85%)
- **Hot intra-cluster gas with $T \approx 10^7 - 10^8$ K (~12%)** → Mostly free electrons and protons
  - → Detected in **X-rays**
  - → Detected in **microwaves**

Galaxy clusters in X-rays

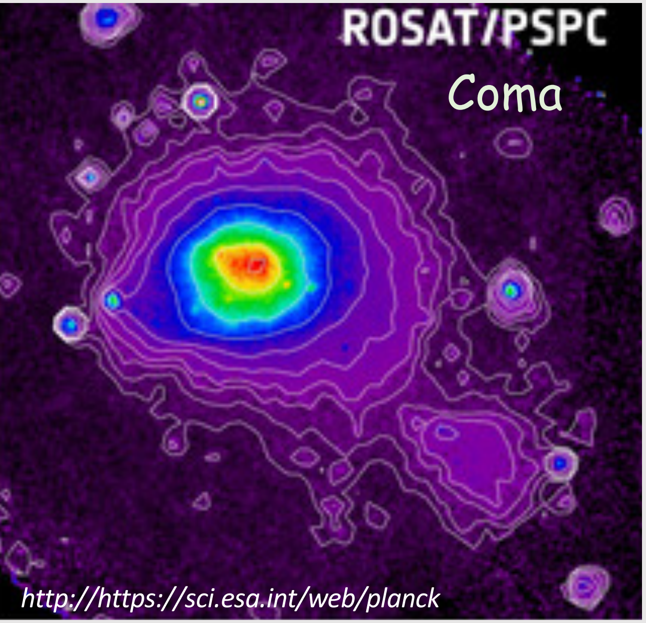


Bremsstrahlung emission →

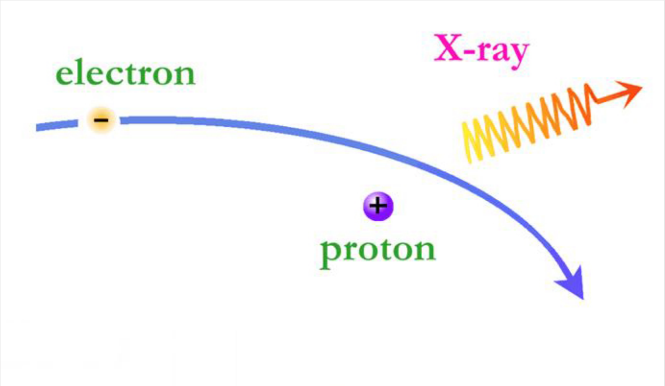


X-ray photons with $E \sim 0.1 - 10$ keV

Galaxy clusters in X-rays



Bremsstrahlung emission →



X-ray photons with $E \sim 0.1 - 10$ keV

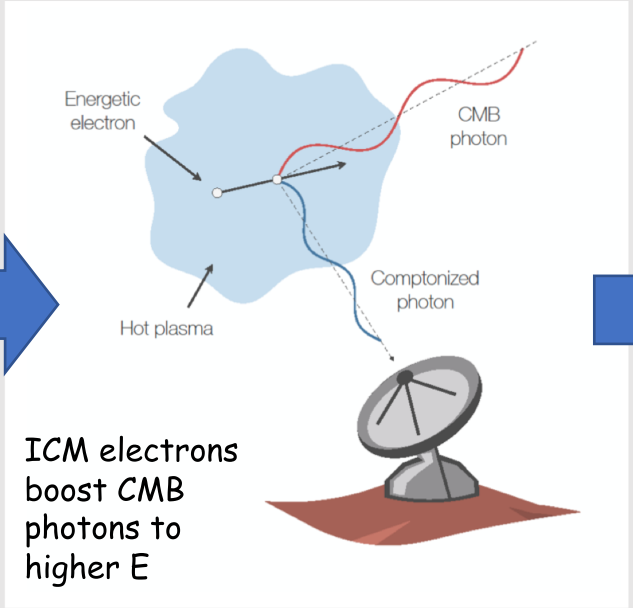
Flux + redshift → assume $\mathrm{H_0}$, etc. to get distance → **Get X-ray luminosity L_X**

Cosmology-dependent!

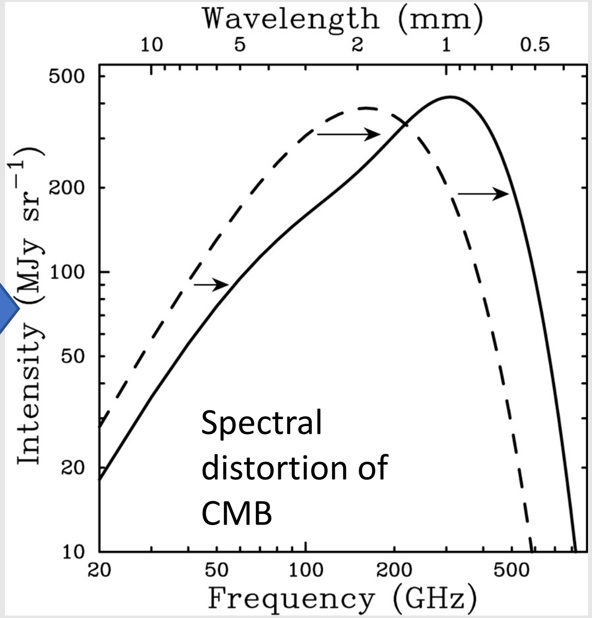
Galaxy clusters in microwaves

Sunyaev-Zeldovich

effect



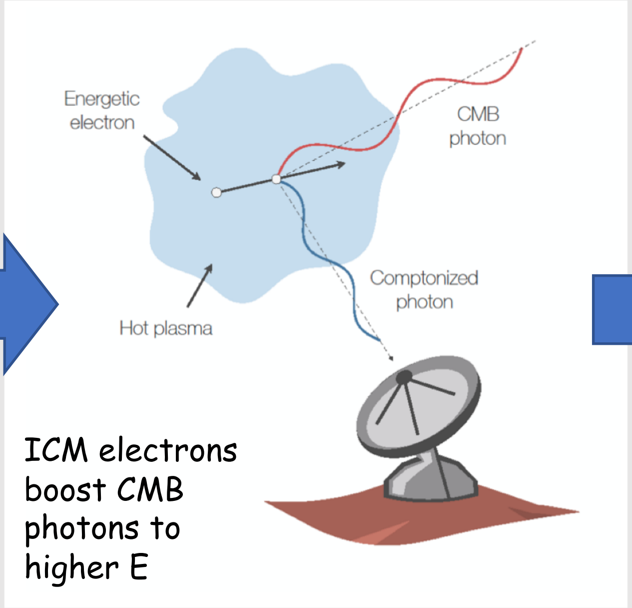
https://astro.uni-bonn.de/



*Carlstrom**+02***

Galaxy clusters in microwaves

Sunyaev-Zeldovich effect



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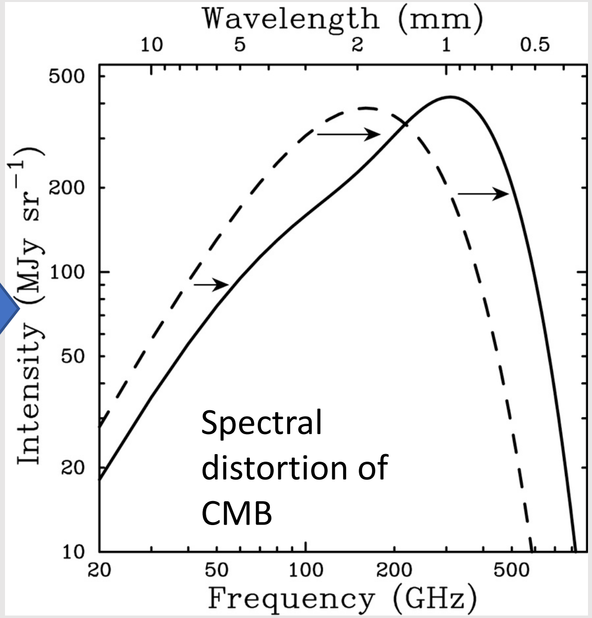


*Carlstrom**+02***

- Traces thermal state of ICM gas
- Total thermal energy Y_{SZ} depends on cluster's physical size
- Measure SZ distortion → assume $\mathrm{H_0}$, etc. to get distance → **Get Y_{SZ}**

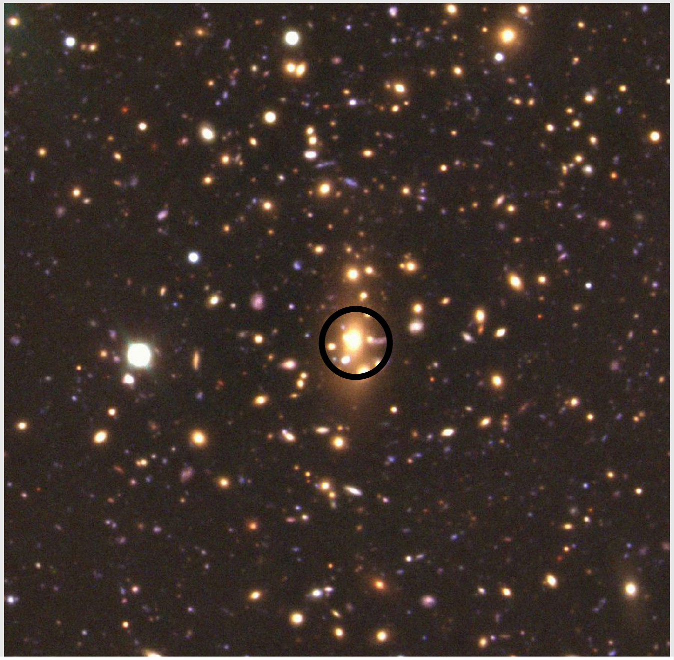
Cosmology-dependent!

Other cluster measurements

➢ **Brightest Cluster Galaxy (BCG)**

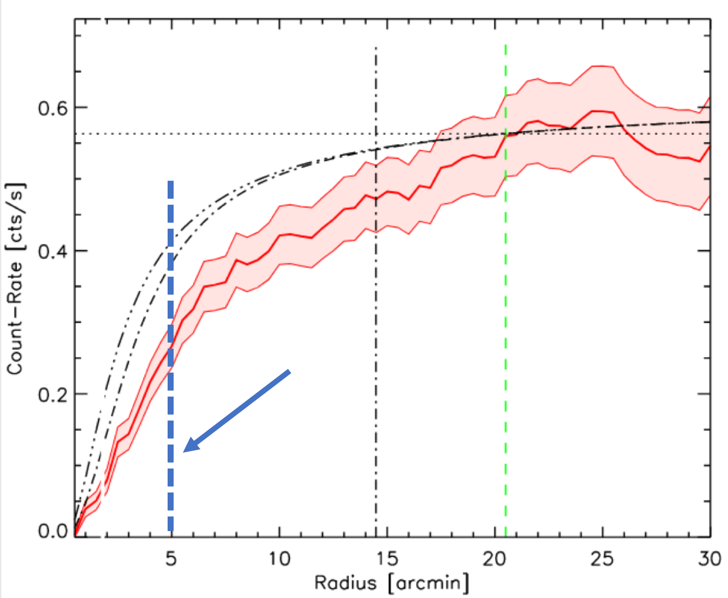
↓

Infrared luminosity L_{BCG} (cosmo-dependent)



➢ **X-ray effective radius**

Angular size + distance = physical size $R_{50\%}$



Cluster scaling relations

➢ Many cluster properties **scale with cluster mass** and thus **with each other**

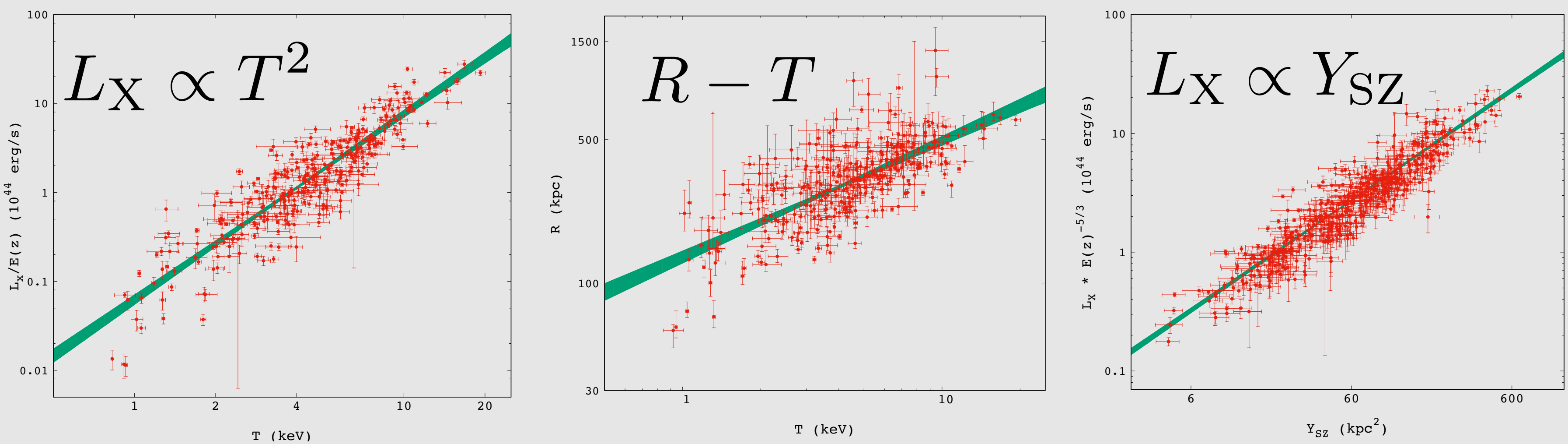
Higher mass

Larger radius R

Higher temperature T

Higher luminosity L_X

Theory+observations: Power laws relate physical quantities of clusters!

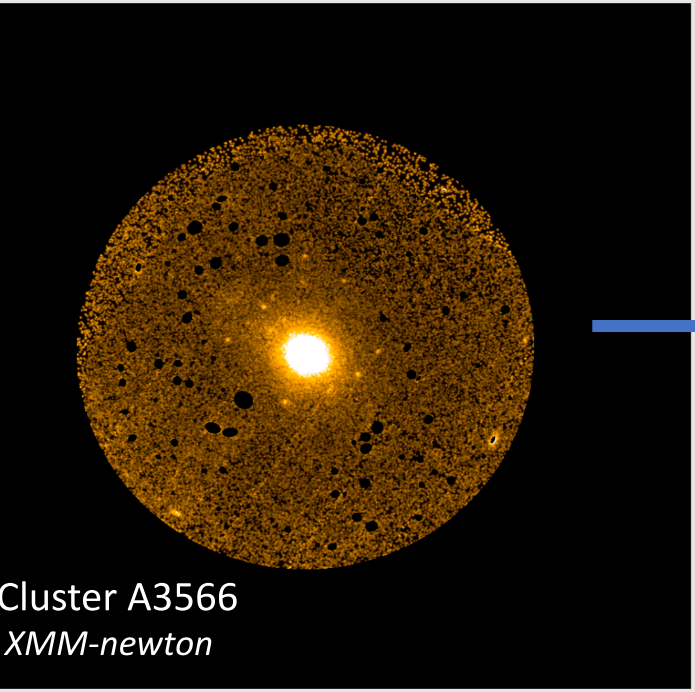


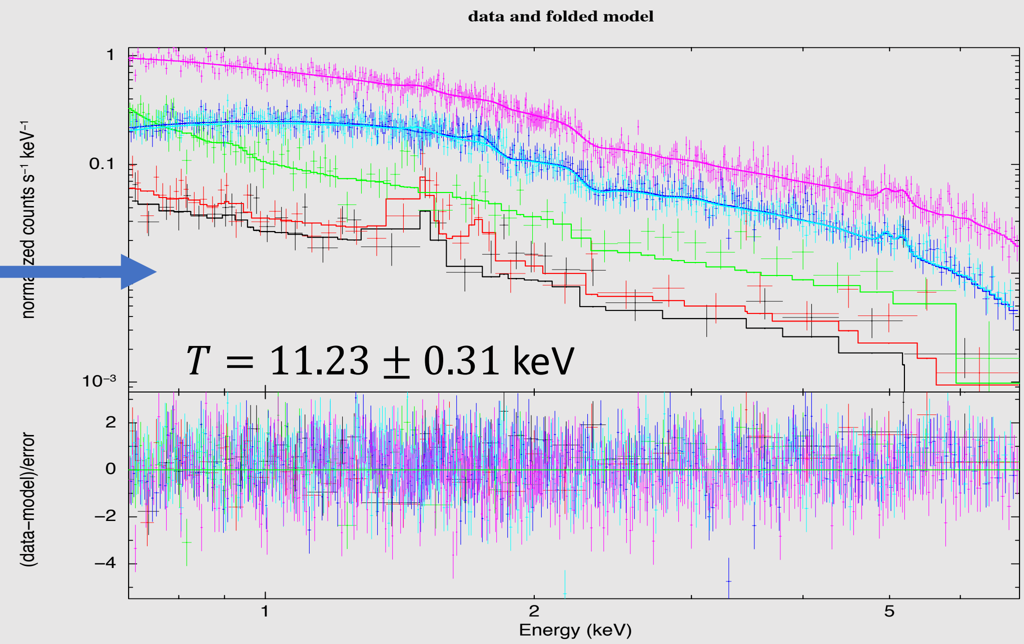
Cluster X-ray **temperature**

is the **key measurement**

for testing cosmic isotropy!

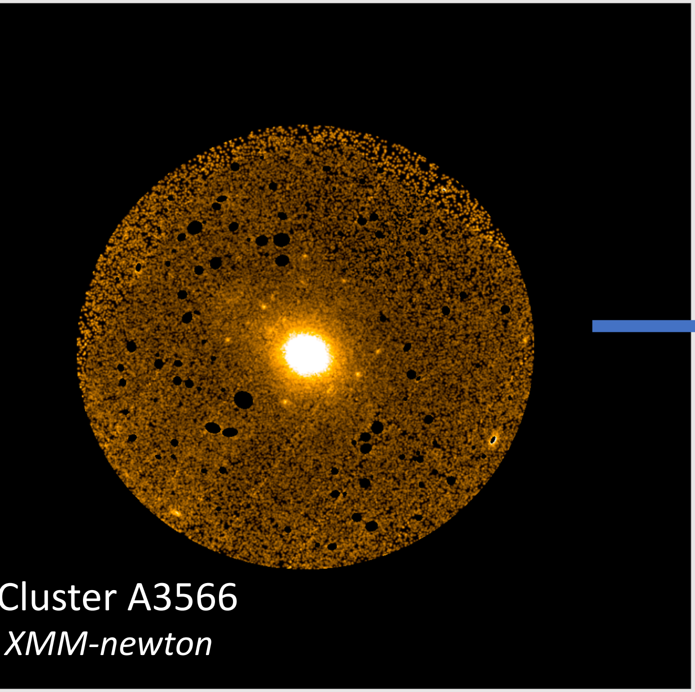
Galaxy clusters in X-rays

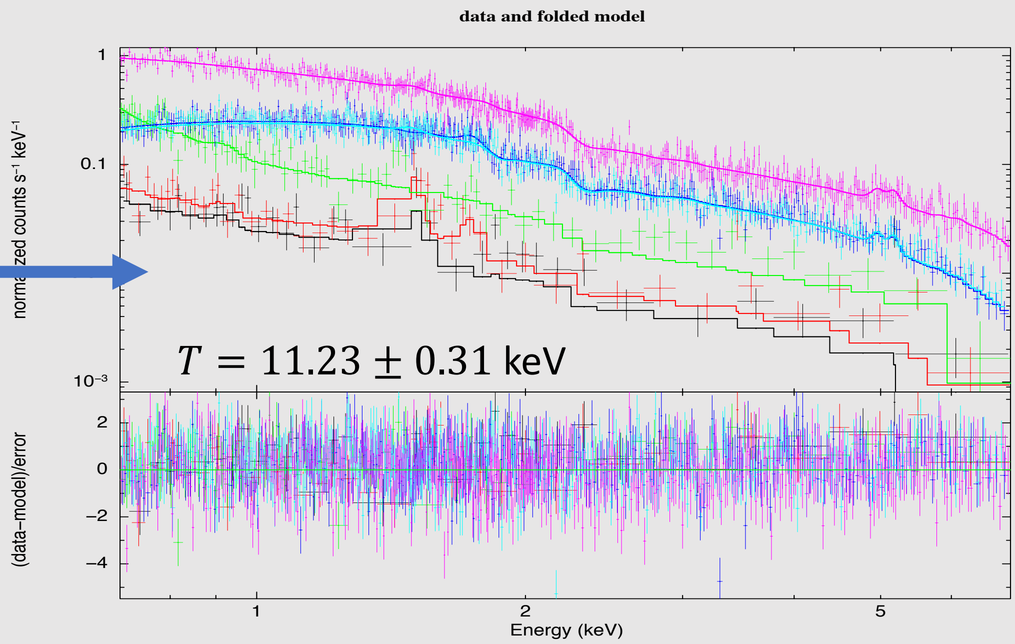


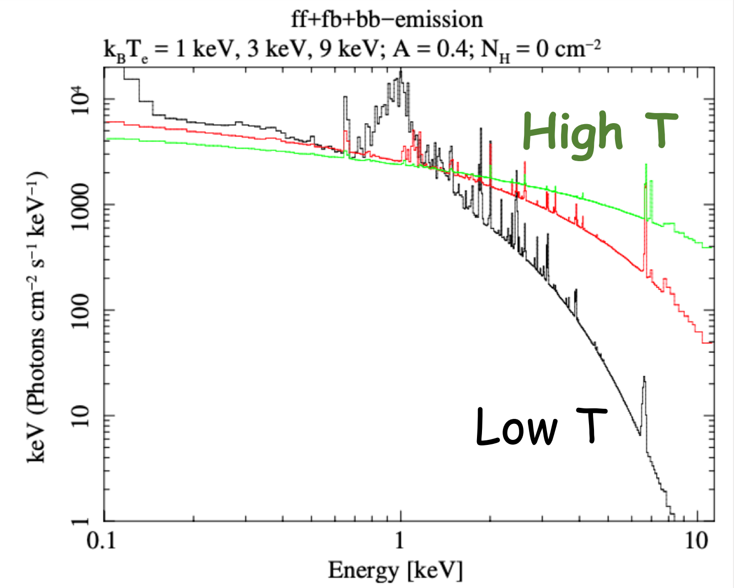


- ➢ Extract spectrum of cluster

Galaxy clusters in X-rays

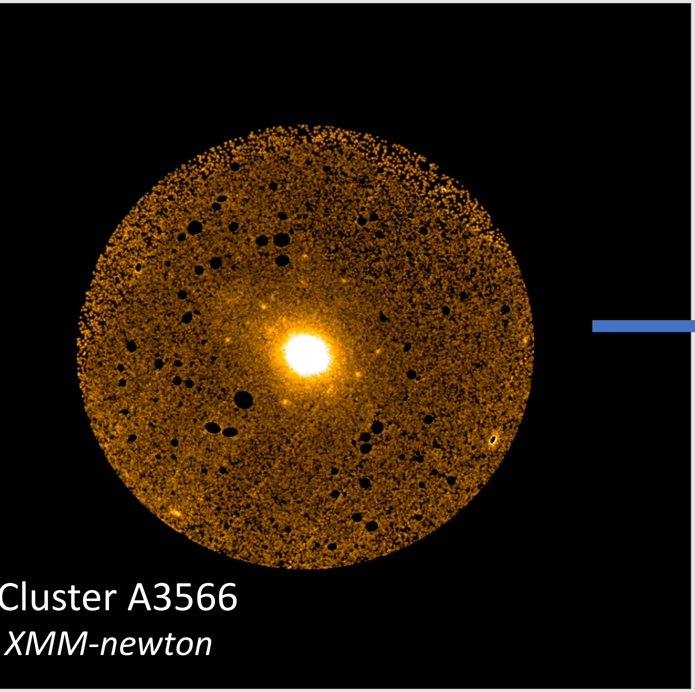


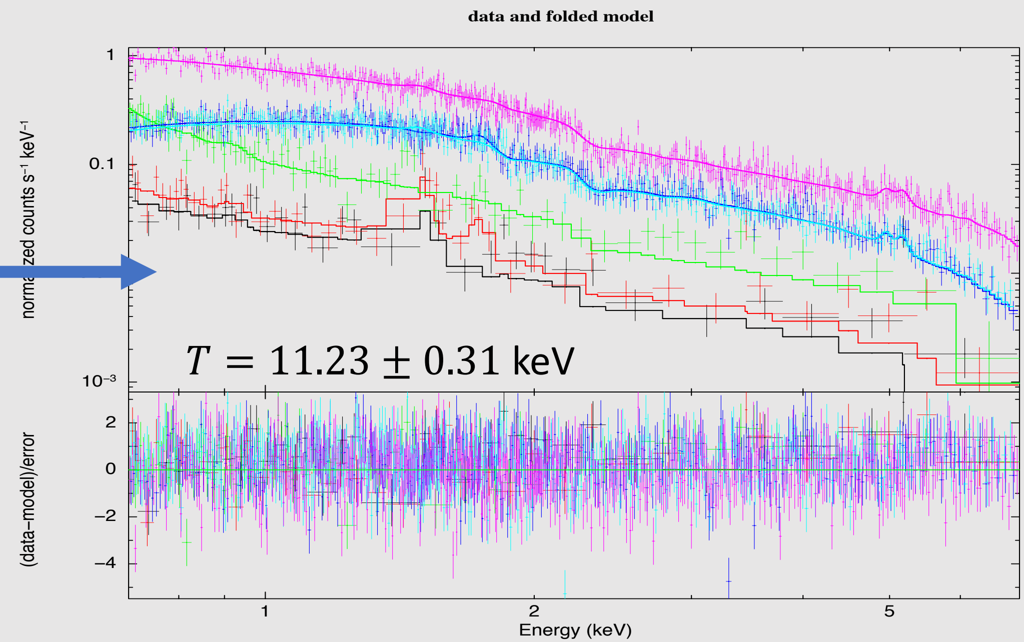




- Extract spectrum of cluster
- **Measure temperature** via fitted models

Galaxy clusters in X-rays





T **determination: cosmology-independent!**

Constrain isotropy with scaling relation

$$L_{\mathrm{X}} E(z)^{-1} \propto T^{B_{LT}}$$

$$Y_{\mathrm{SZ}} E(z) \propto T^{B_{YT}}$$

$$\propto \mathrm{distance}(H_0, z)^2$$

Strong cosmology and bulk flow dependence!

Measure T → Predict left part

cosmology-independent!

Constrain isotropy with scaling relation

$$L_{\mathrm{X}} E(z)^{-1} \propto T^{B_{LT}}$$

$$Y_{\mathrm{SZ}} E(z) \propto T^{B_{YT}}$$

cosmology!

no cosmology!

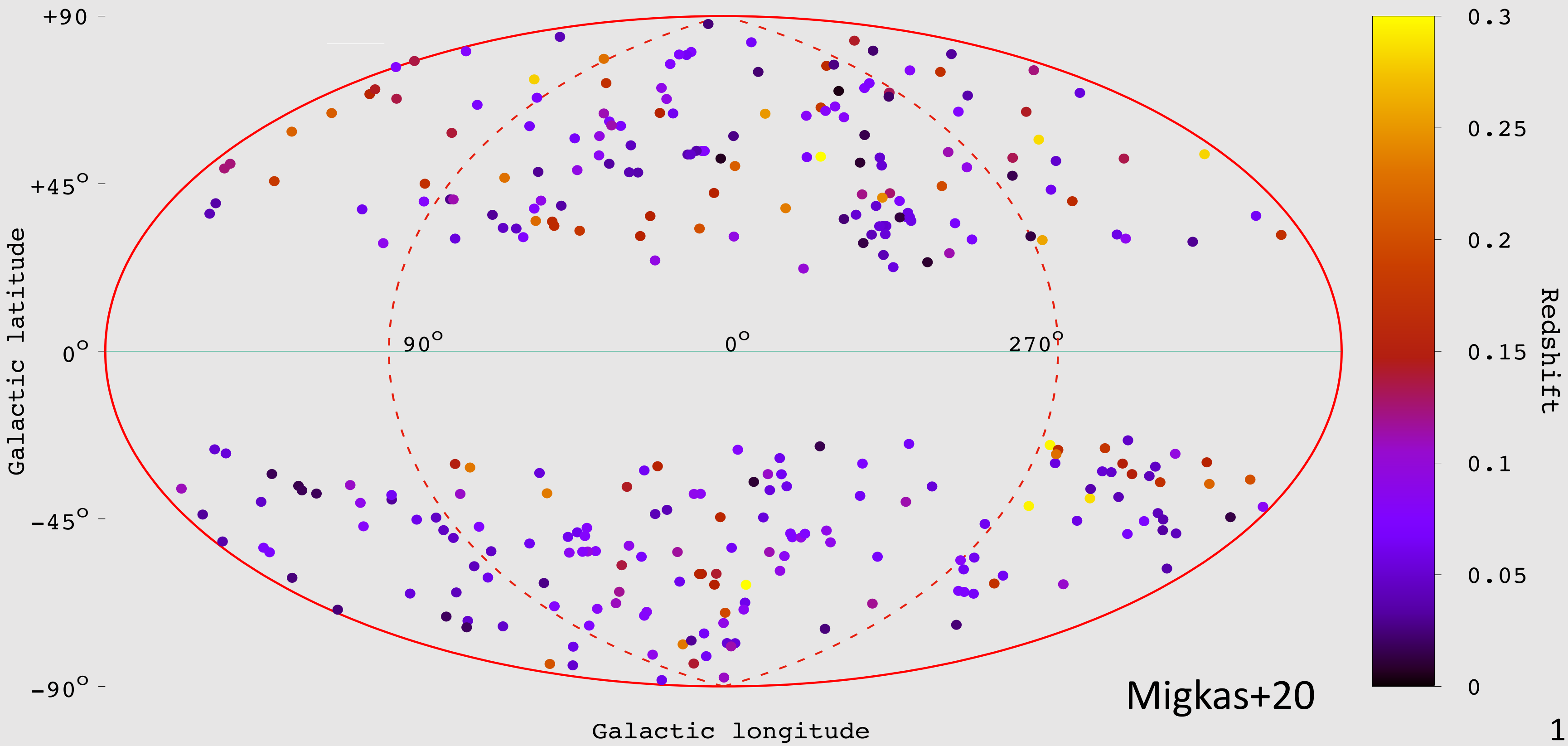
- Scan the sky with a $\pi/3$ cone ($\gtrsim$60 clusters), constrain relations for each cone separately → all-sky color map

- **Quantify apparent H_0 variation and bulk flows**

Our sample
&
the 10 scaling relations

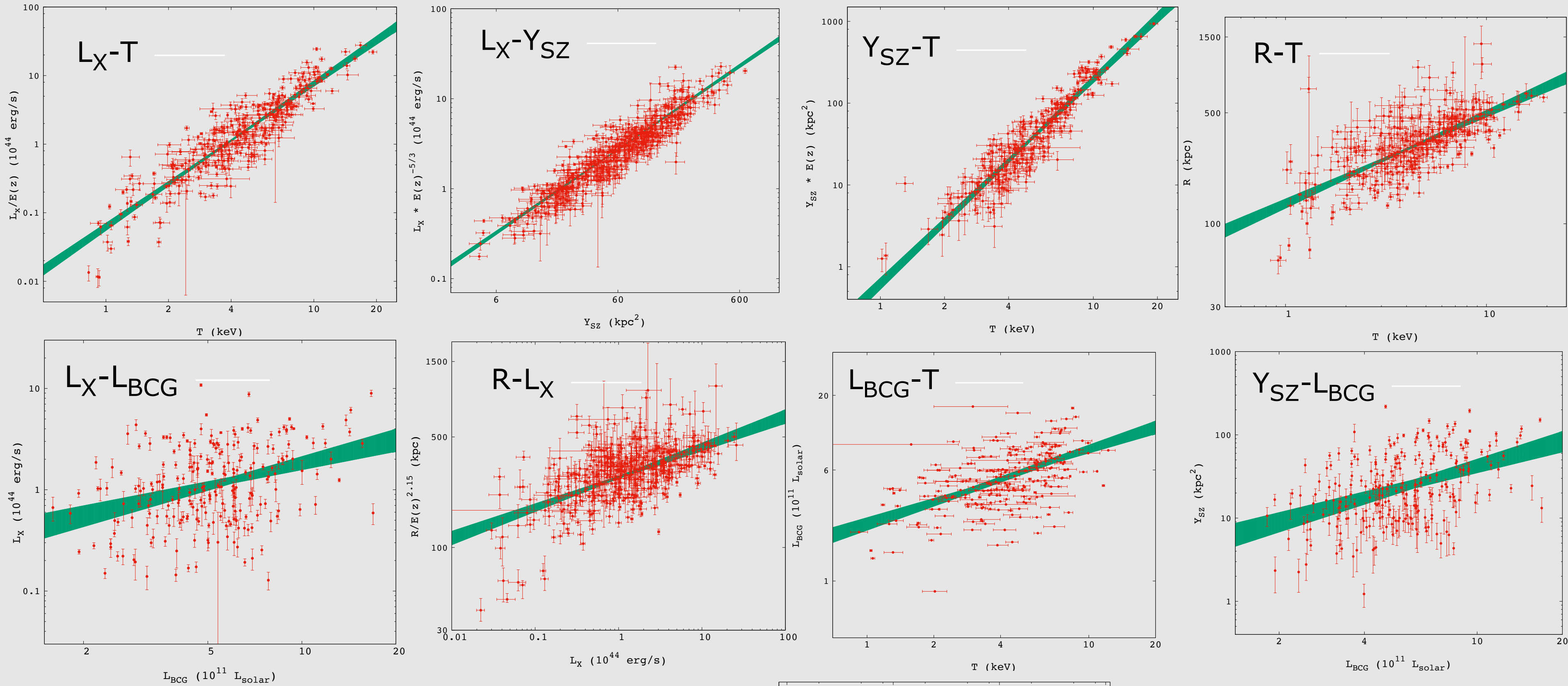
eeHIFLUGCS sample

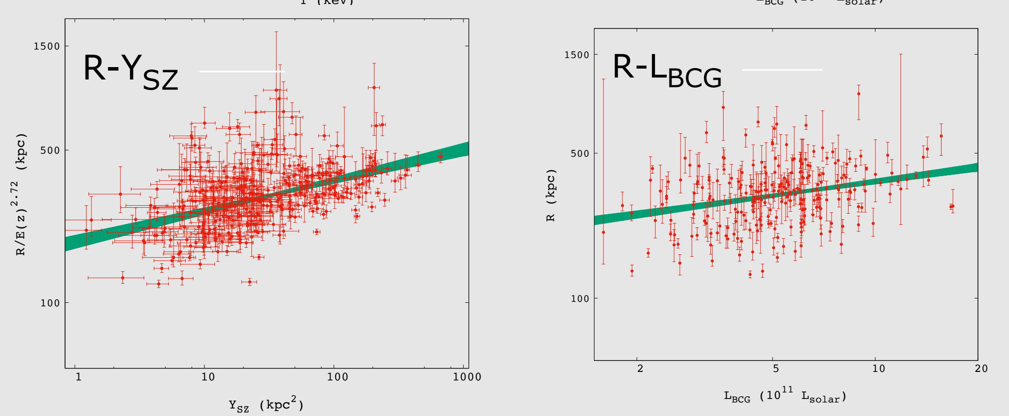
- Homogeneously selected, **~400** brightest **X-ray clusters**, mostly $z < 0.25$
- Measure **X-ray Lx**, **T** and $\mathbf{R_{50\%}}$
- Measure **microwave** $\mathbf{Y_{SZ}}$ and **infrared** $\mathbf{L_{BCG}}$



Migkas+20

10 multiwavelength cluster scaling relations!

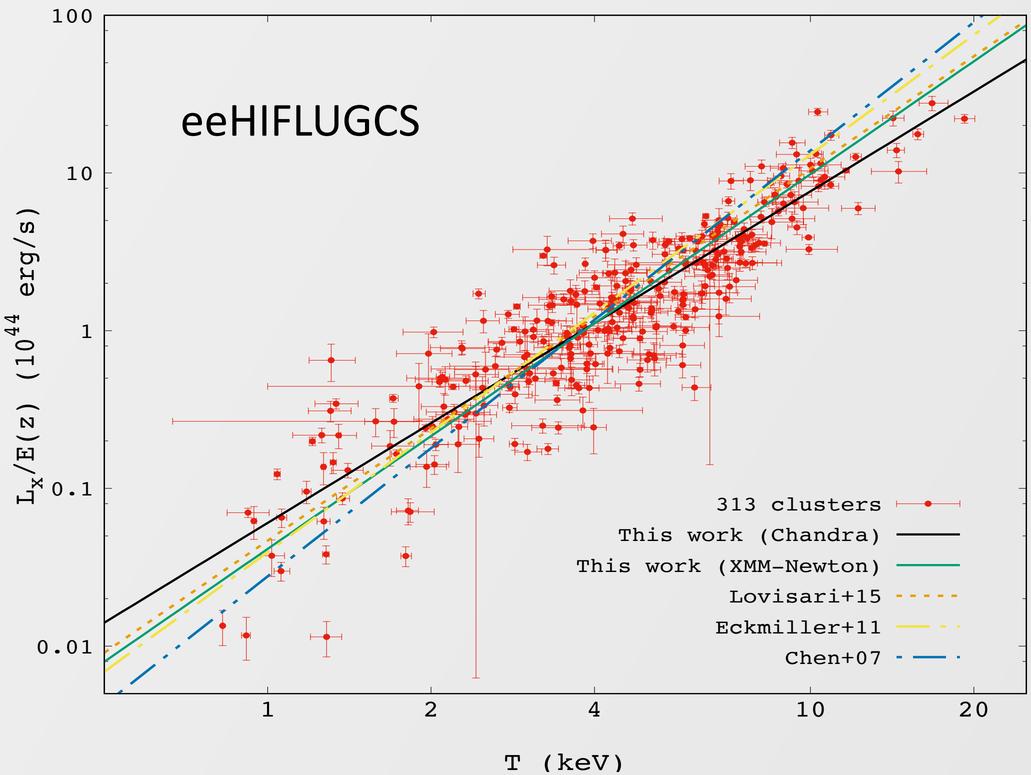




Migkas+21

Cosmological anisotropies

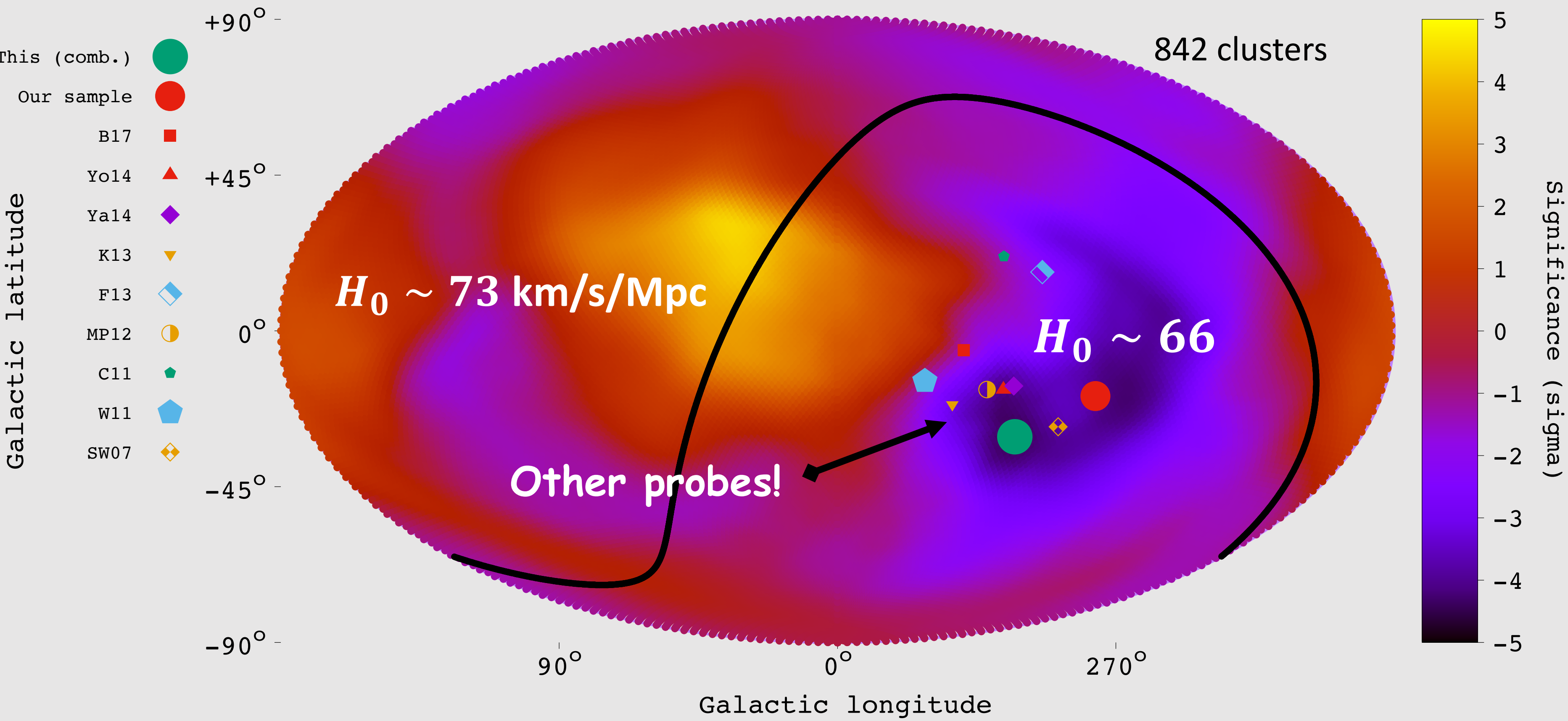
The $L_X - T$ relation



Question: will clusters behave isotropically?

eeHIFLUGCS + 2 other, independent, all-sky samples

Apparent H_0 anisotropy from $L_X - T$



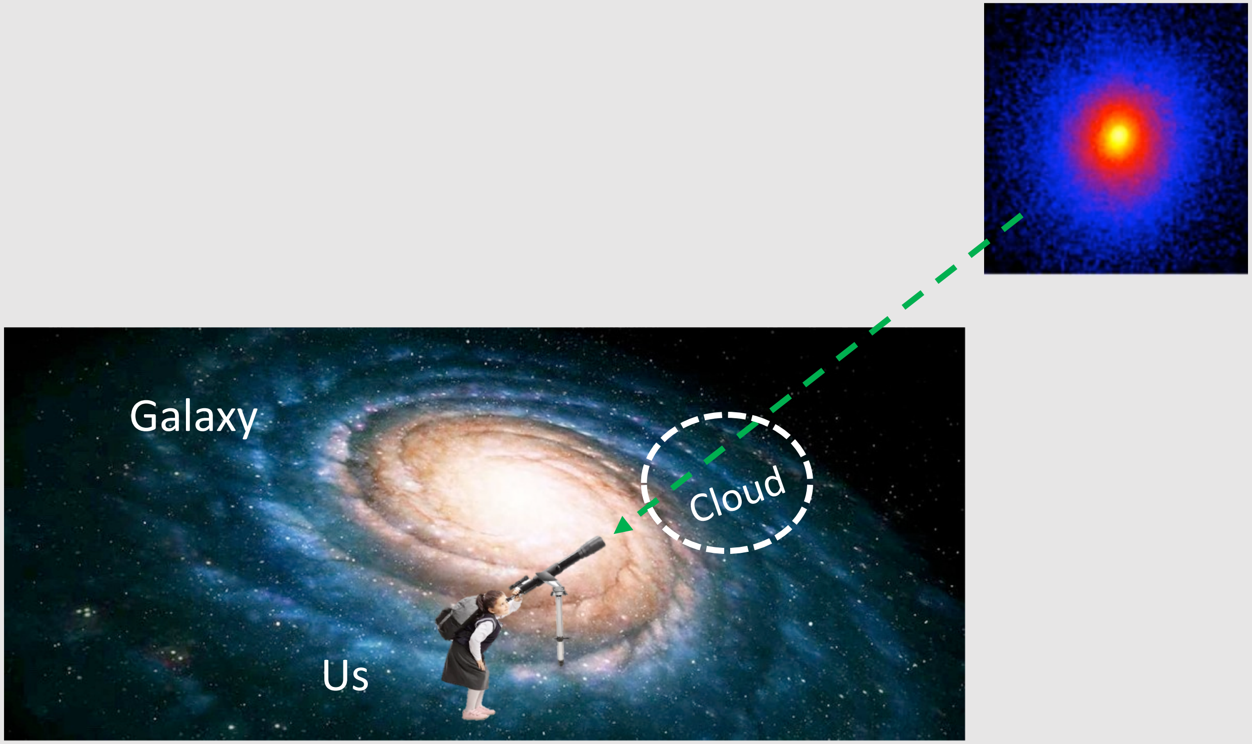
$\sim 4\sigma$ anisotropy!

Migkas et al. 2020, A&A, 636,A15

But what can cause the $L_X - T$ anisotropies…?

But what can cause the $L_X - T$ anisotropies…?

1. **Excess X-ray absorption:** previously undetected gas/dust masses (first tests say no)



But what can cause the $L_X - T$ anisotropies…?

1. **Excess X-ray absorption:** previously undetected gas/dust masses

2. **Bulk flows:** unexpectingly large velocity *and* volume

But what can cause the $L_X - T$ anisotropies…?

1. **Excess X-ray absorption:** previously undetected gas/dust masses

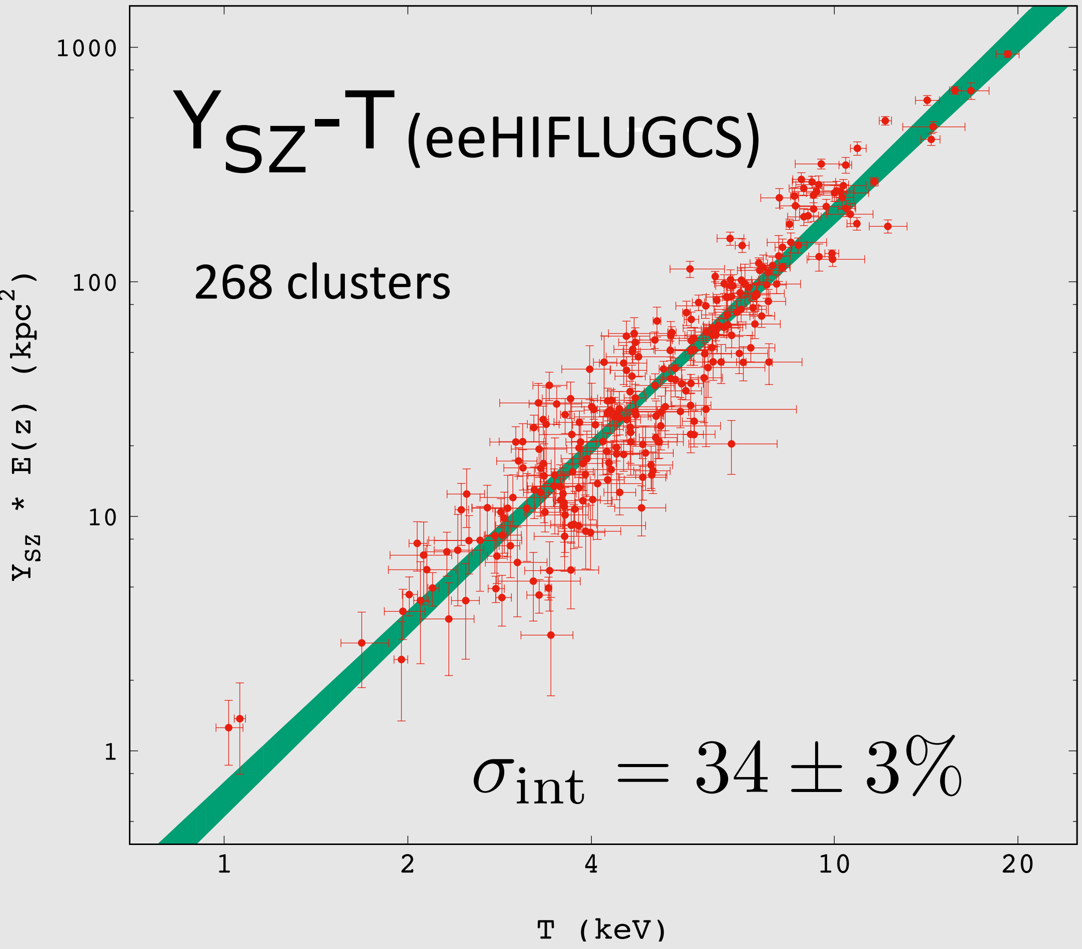
2. **Bulk flows:** unexpectingly large velocity *and* volume

3. $\boldsymbol{H(z)}$ **anisotropy**: at least up to ~ 800 Mpc

Most useful relation...

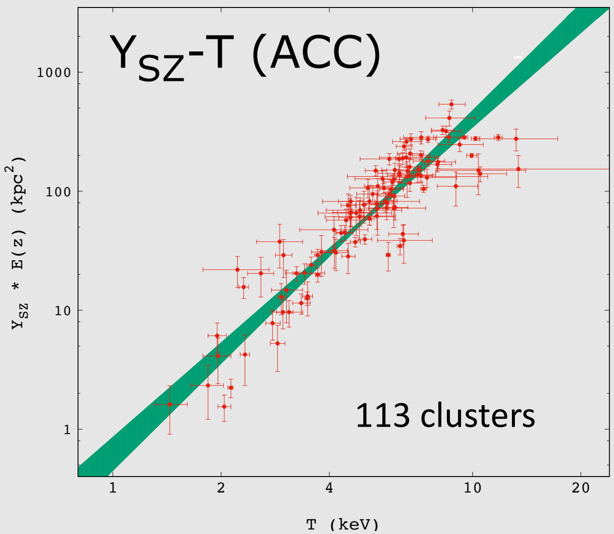
The $Y_{SZ} - T$ relation

The $Y_{SZ} - T$ relation



- **Lower scatter!**
- **Insensitive to absorption!**

$$\frac{Y_{\rm SZ}}{35\ {\rm kpc}^2} E(z) = (1.110 \pm 0.032) \left(\frac{T}{5\ {\rm keV}}\right)^{2.546 \pm 0.069}$$



Apparent H_0 anisotropies:

$Y_{\mathrm{SZ}} - T$ relation

Insensitive to absorption!

Similar anisotropies..? ⇒
cosmological origin or bulk flow

Anisotropies do not persist..? ⇒
Xray-related origin

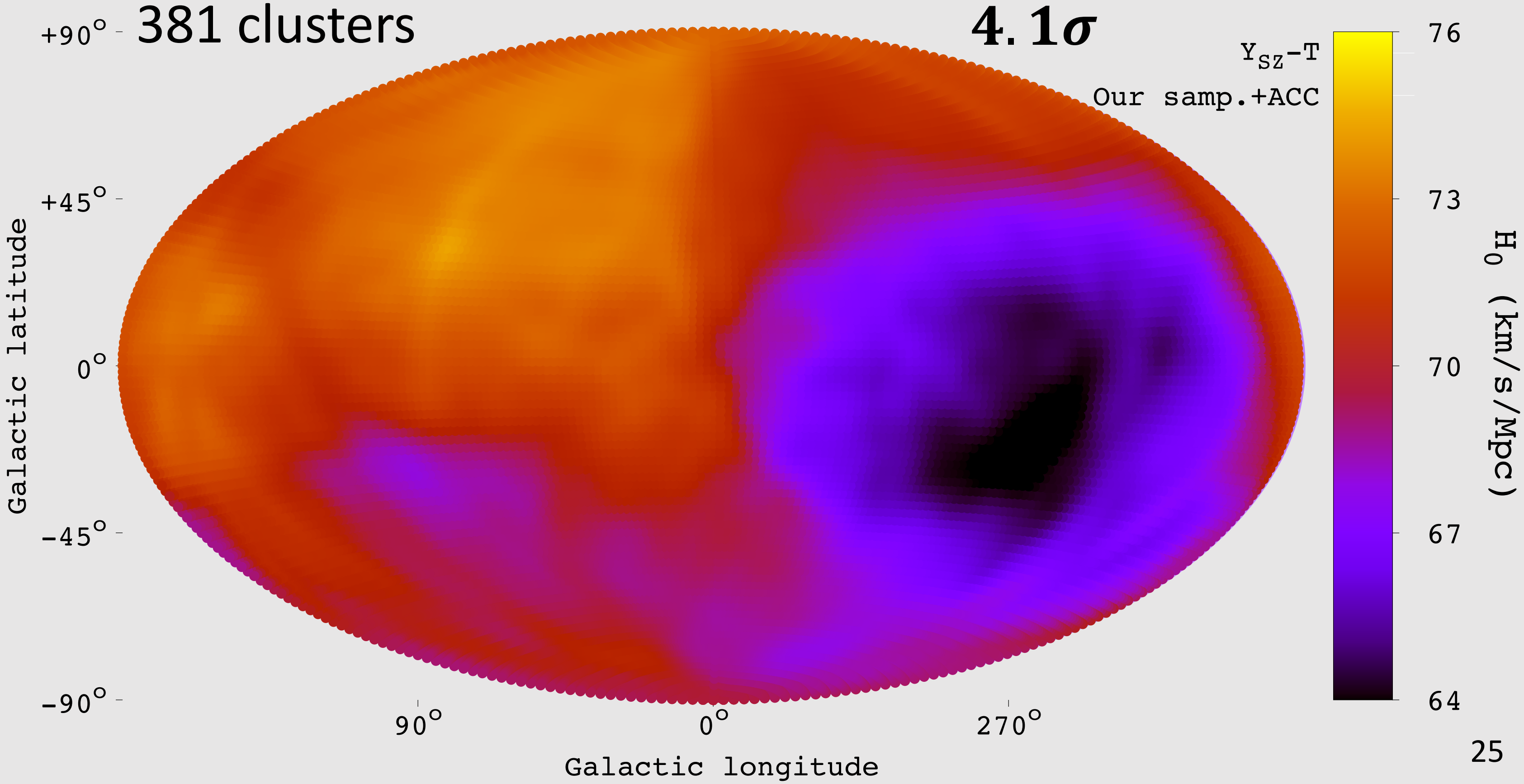
$Y_{SZ} - T$ anisotropies

Same H_0 variation!

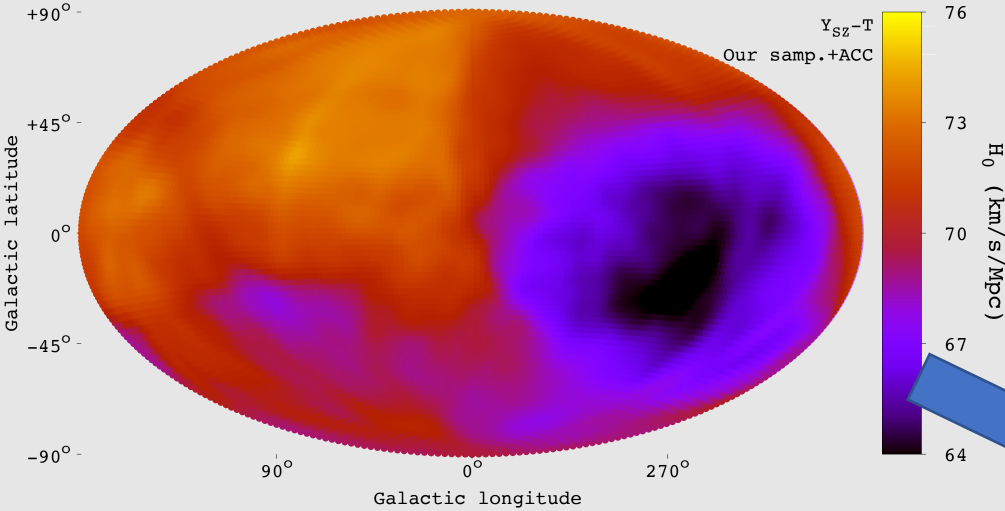
Reminder: no absorption origin!

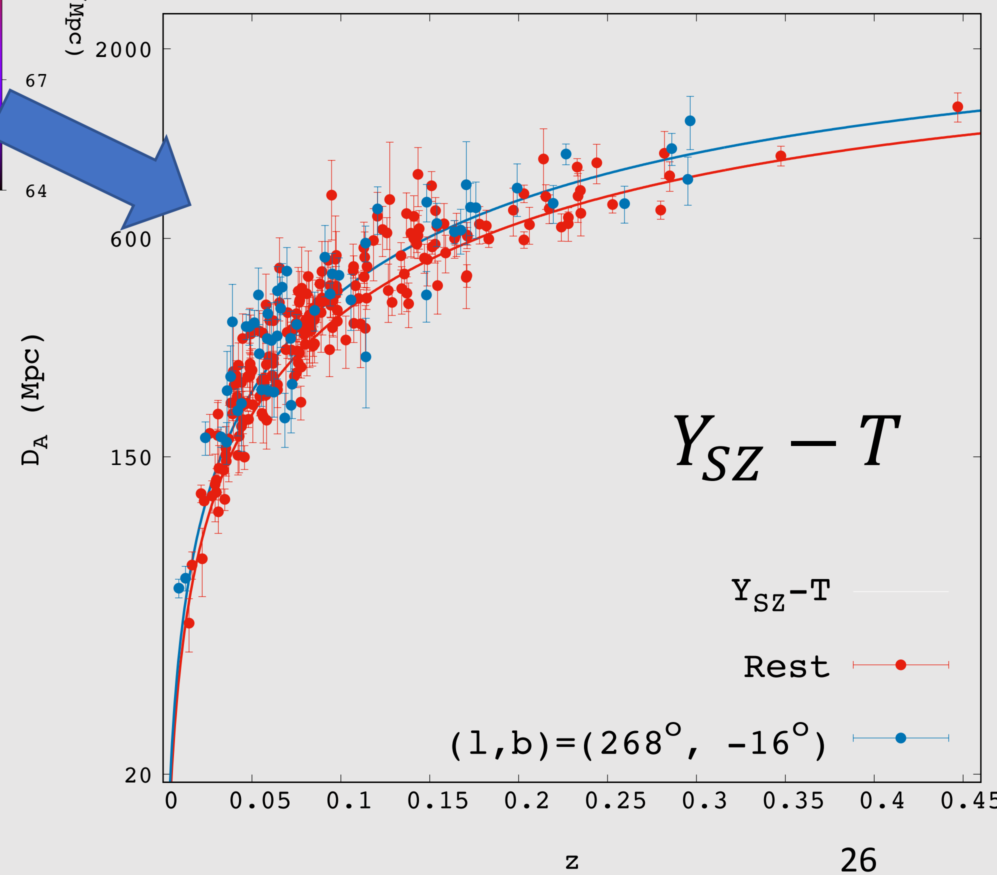
381 clusters

4.1σ



Hubble diagram of clusters!





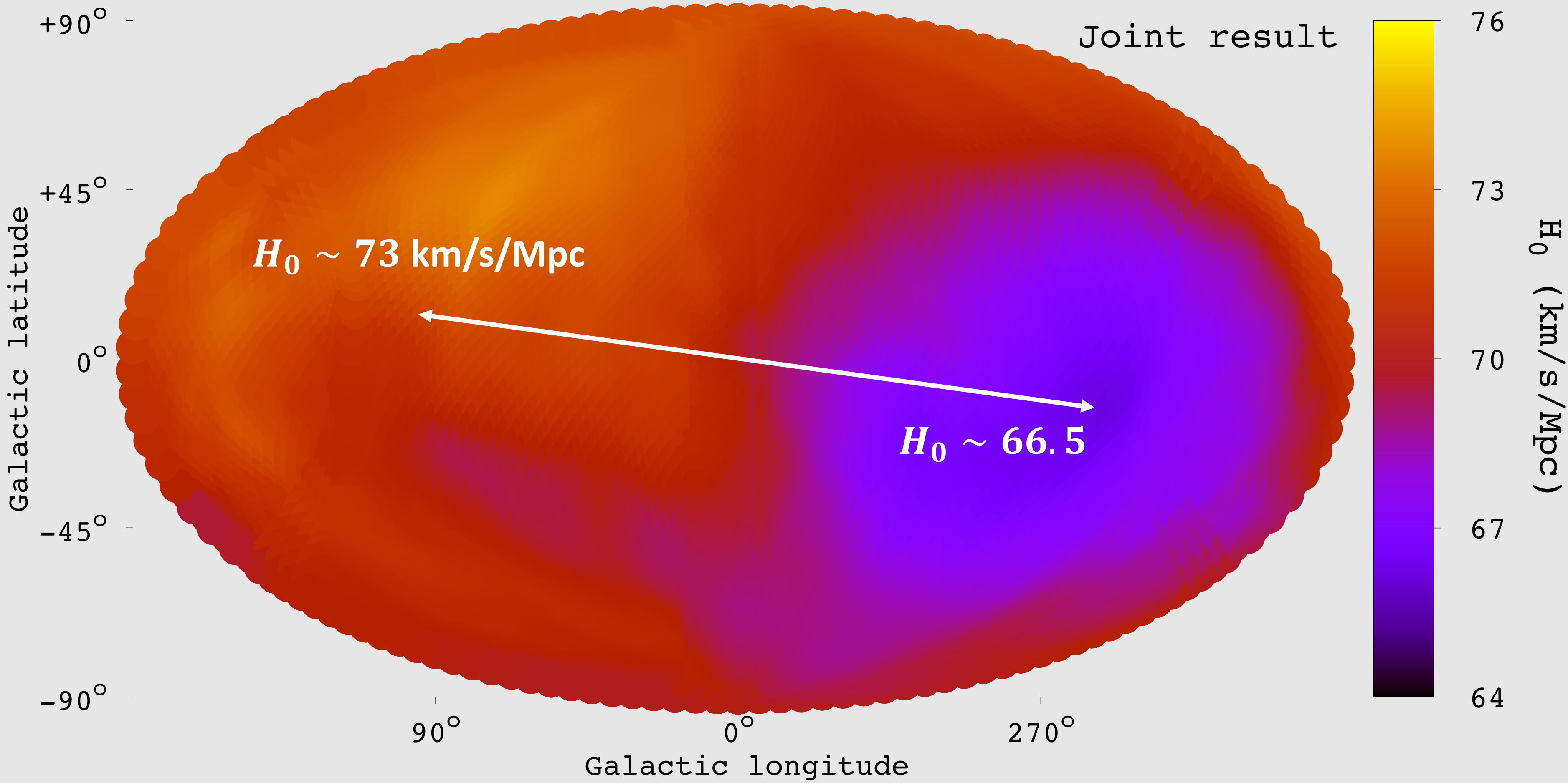
Blue: most anisotropic region

Red: rest

Combining all X-ray, microwave, and infrared cluster info with in-depth, exhaustive analysis…

First-ever multiwavelength H_0 anisotropy map!

Overall result: 5.9σ! (from Monte Carlo)

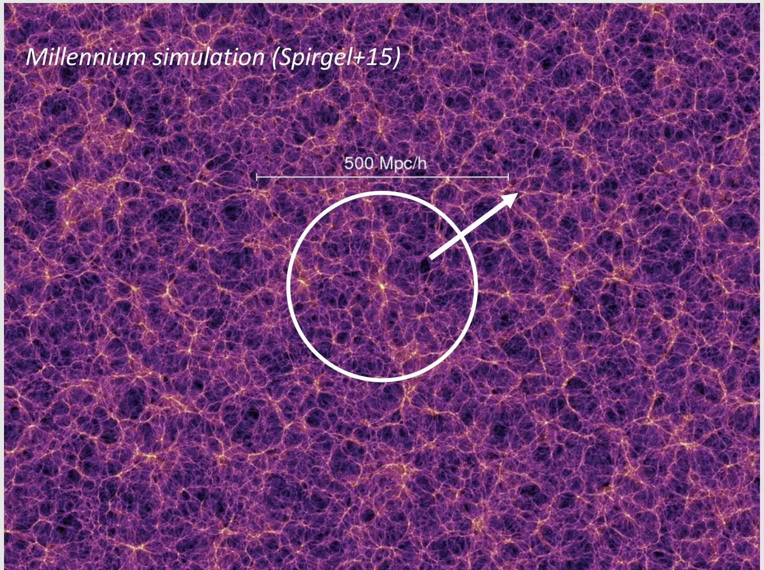


Most robust detection of late-Universe anisotropy ever!

$$(l, b) = (273^{\circ}{}^{+42^{\circ}}_{-38^{\circ}}, -11^{\circ}{}^{+27^{\circ}}_{-27^{\circ}})$$

What if true H_0 = isotropic?

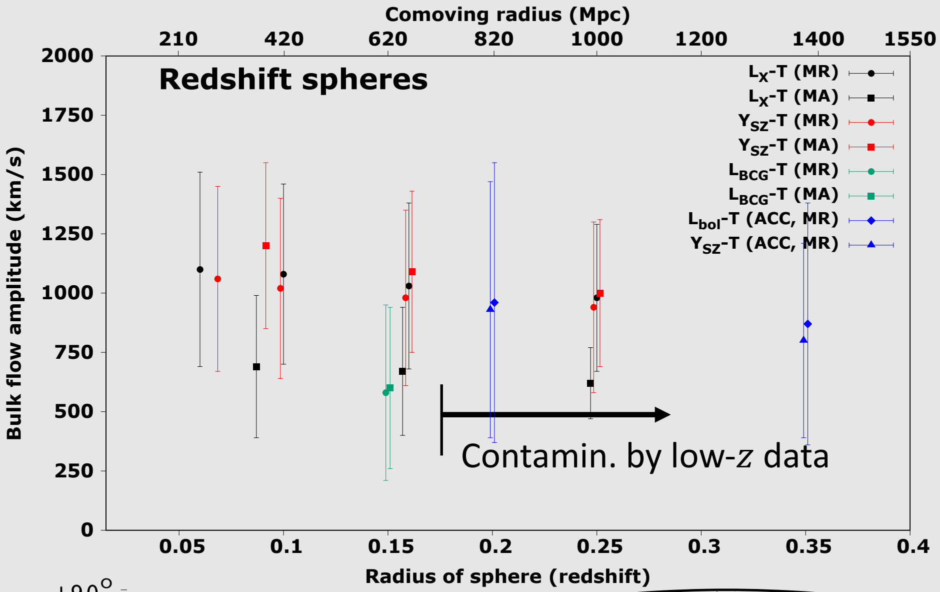
Then, we need a large bulk flow…

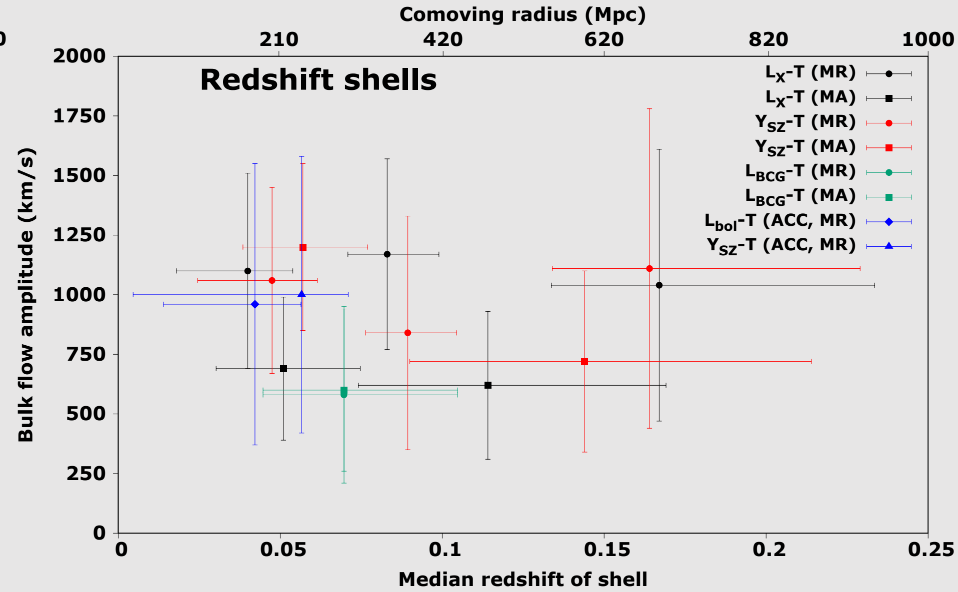


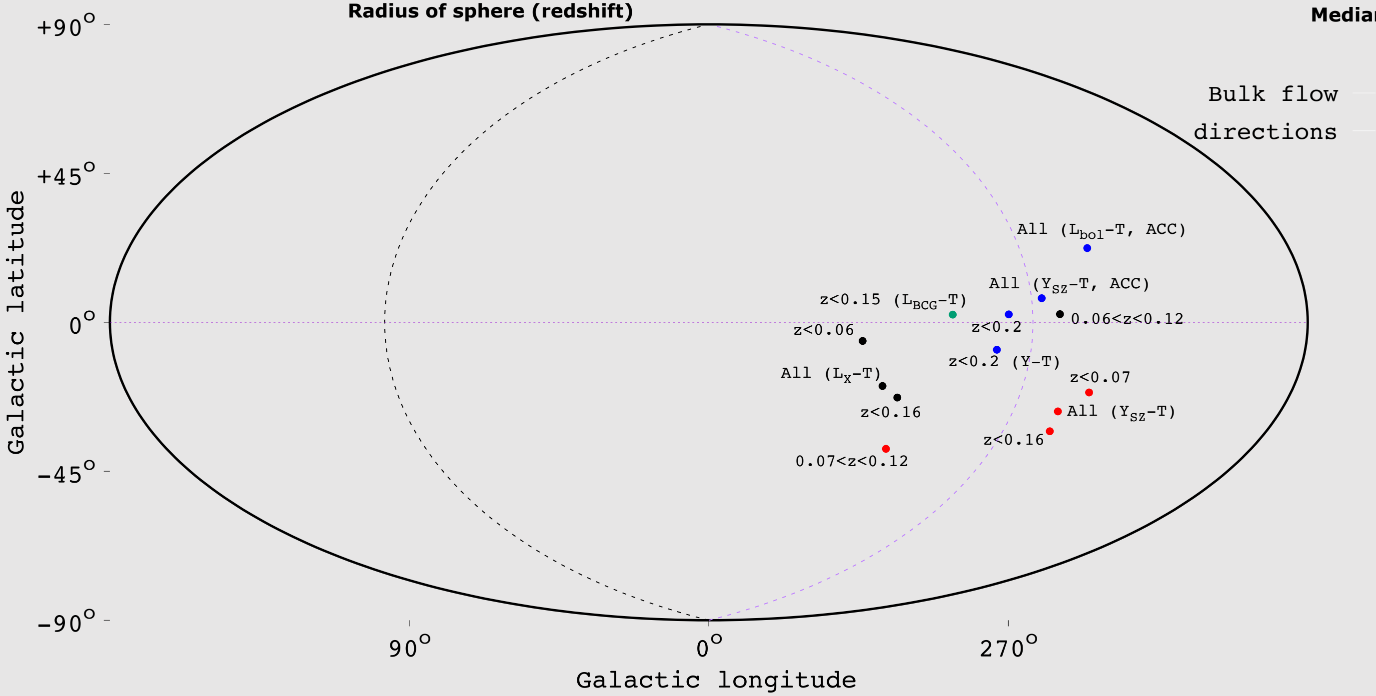
- But how fast and up to what scale..?

- First-ever bulk flow constraints with cluster scaling relation

Cluster bulk flows





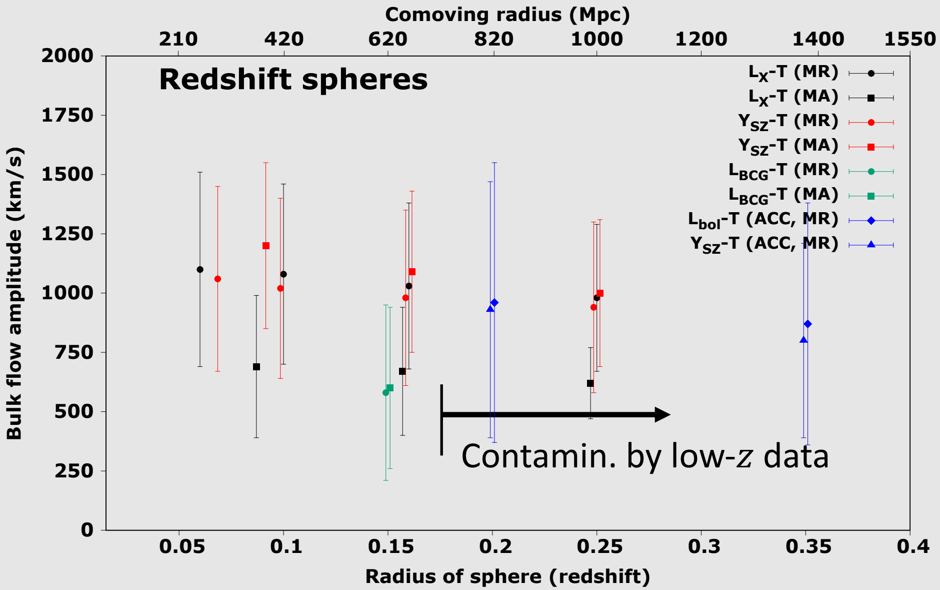


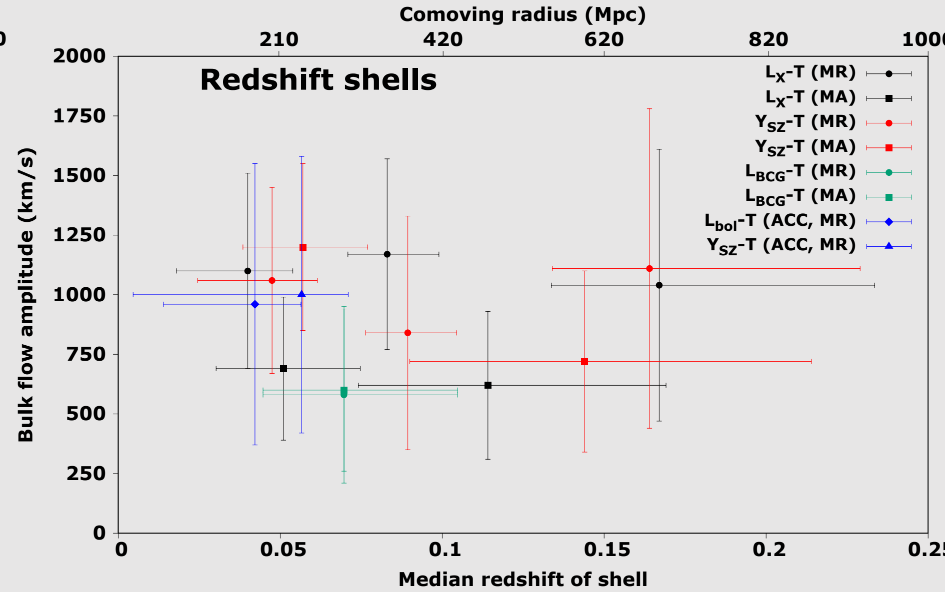
$\sim$ 900 km/s BF

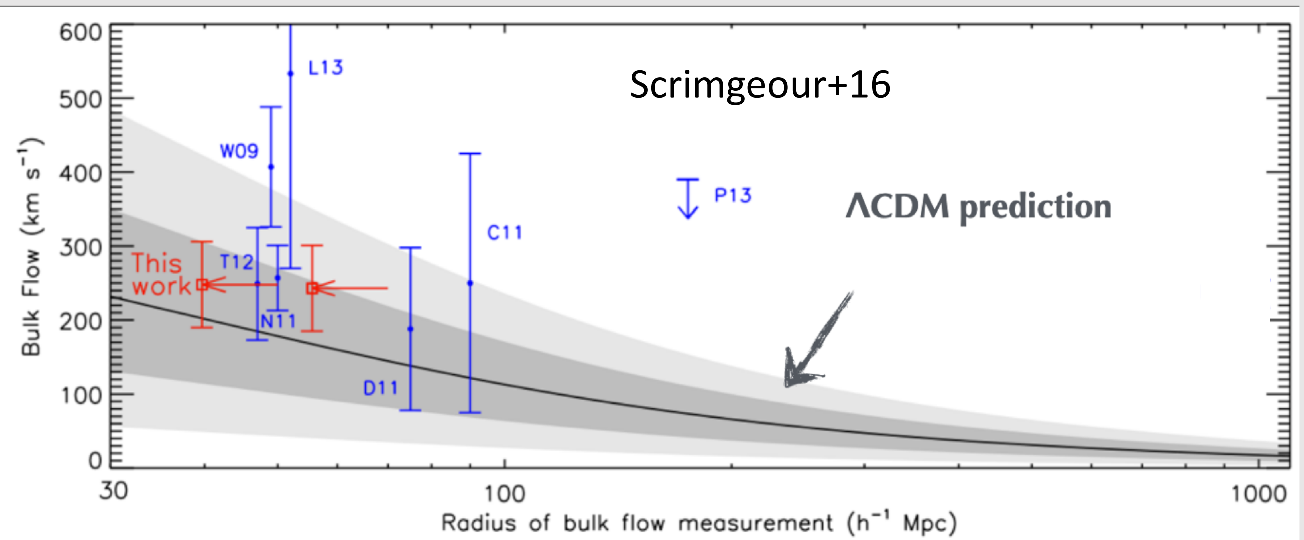
up to $\geq$ 500 Mpc

$(z \sim 0.12)$

Cluster bulk flows







Inconsistent with ΛCDM!

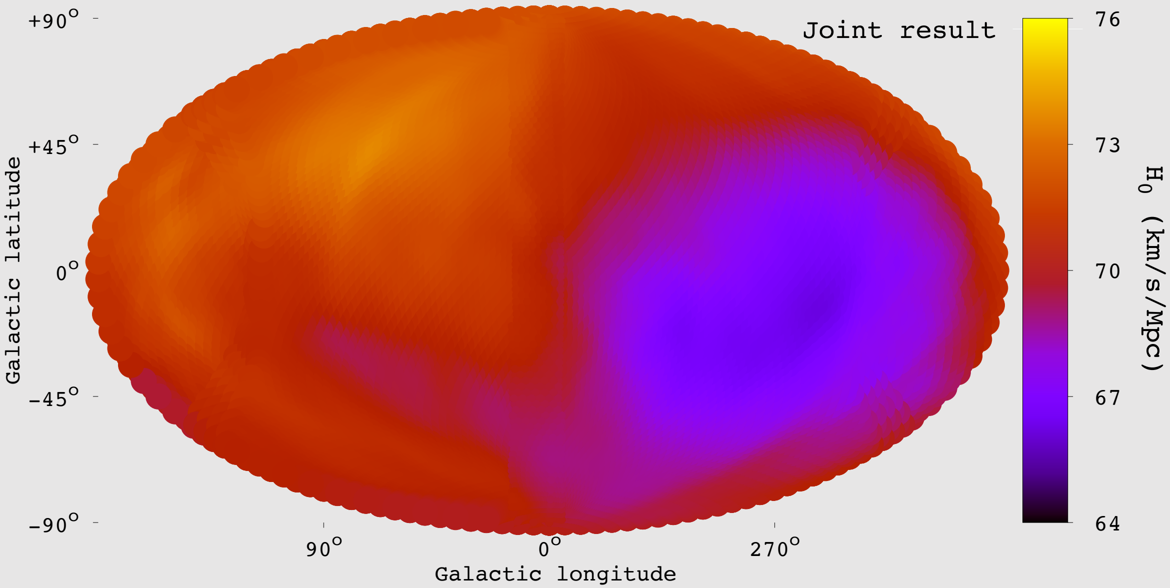
We kept searching for alternative explanations

Tested systematics (rejected)

- Cluster morphology effects
- Malmquist bias
- Zone of Avoidance bias
- Different selection cuts
- Scatter correlation of $L_{\mathrm{X}}, Y_{\mathrm{SZ}}$
- MCMC for any cluster properties correlation
- X-ray temperature calibration
- Redshift evolution
- Several other tests

No explanation for the anisotropies!

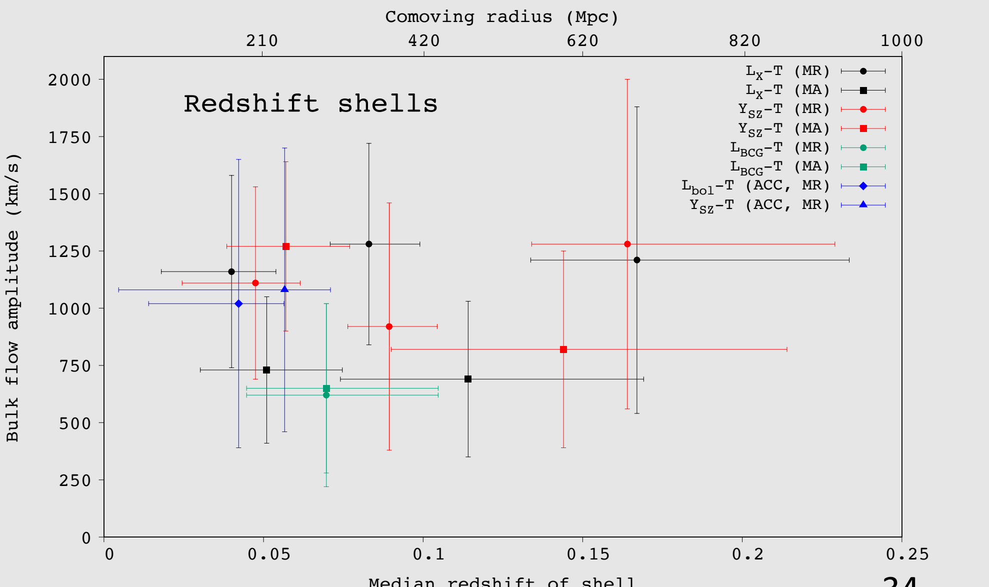
It looks like H_0 anisotropy or bulk flow…



Contradicts isotropy!

OR

Contradicts homogeneity!



Summary

- Developed powerful method to scrutinize cosmic isotropy with galaxy clusters
- Clusters show strong local anisotropies ($> 5\sigma$): local H_0 anisotropy or large bulk flow?
- Both contradicting concordance cosmology
- Keep pushing to improve data, statistics and methodology

Thank you!

Back up slides

Future prospects

Three main goals:

- Reducing the scatter of scaling relations with better modelling

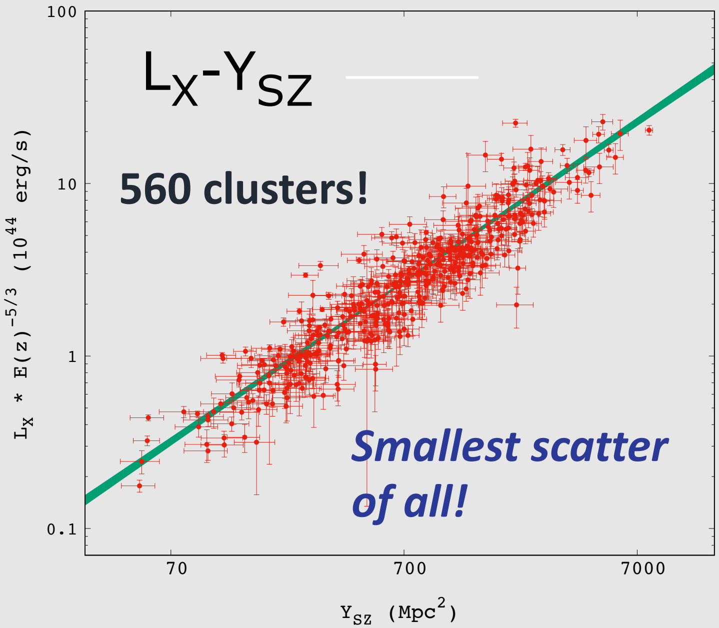
- New cluster samples and new cluster measurements (core-excised Lx and $R_{50\%}$, M_{gas}, etc...)

- More distant clusters to tell apart H_0 anisotropy and bulk flows

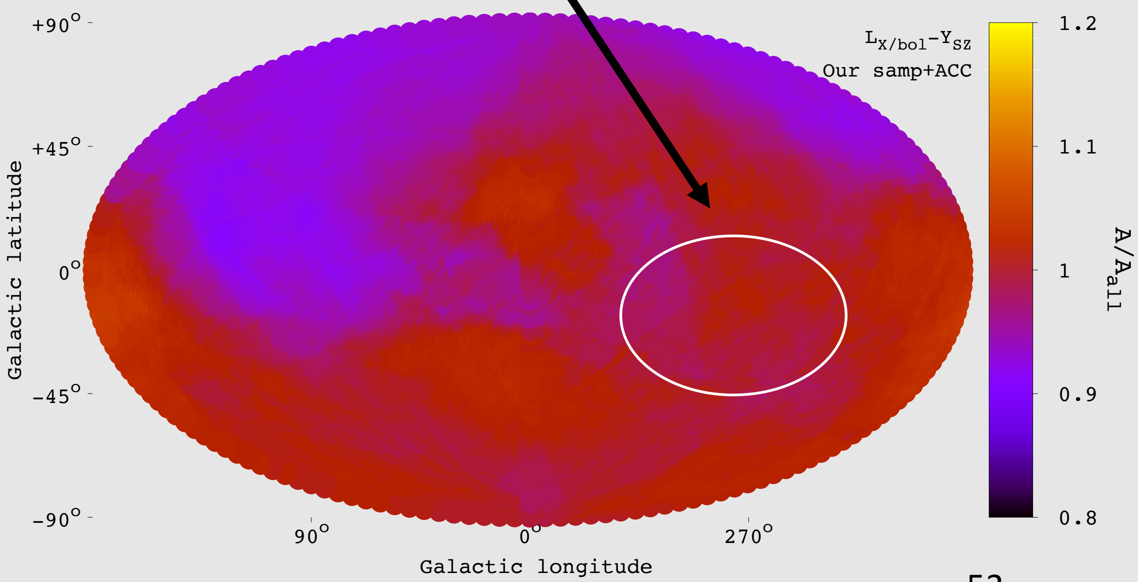
Undiscovered X-ray absorption..?

$L_{\mathrm{X}} - Y_{\mathrm{SZ}}$ anisotropy:

Anisotropy only traces excess X-ray absorption and systematics!



No excess absorption there!

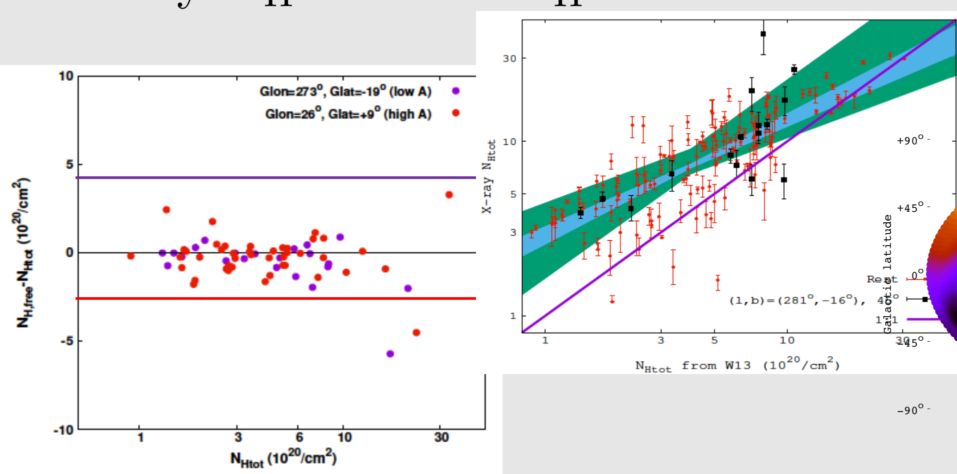


Undiscovered X-ray absorption..?

- 4 different tests for detecting previously unknown absorption

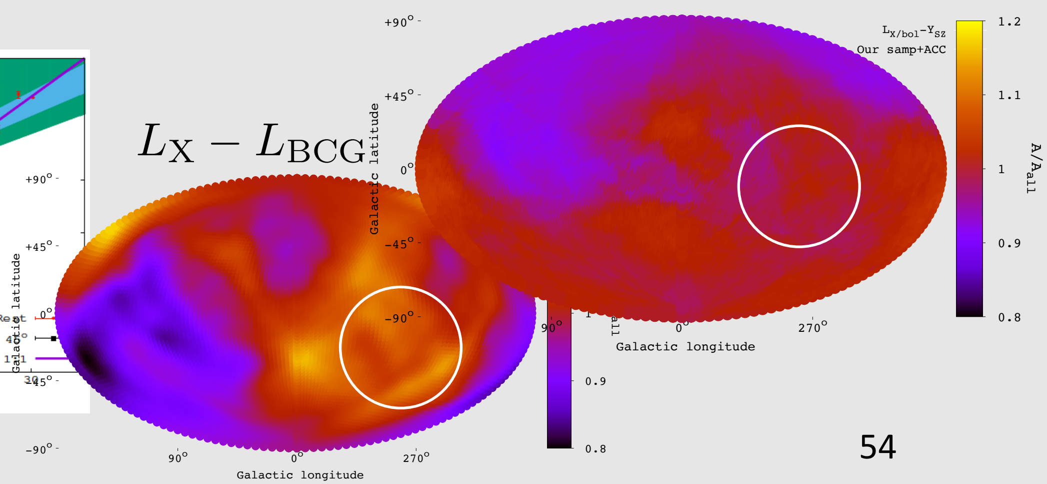
No excess X-ray absorption seen!

X-ray N_{H} – Radio N_{H}



$L_{\mathrm{X}} - L_{\mathrm{BCG}}$

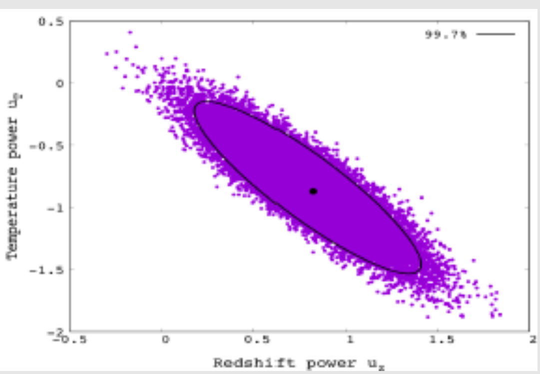
$L_{\mathrm{X}} - Y_{\mathrm{SZ}}$

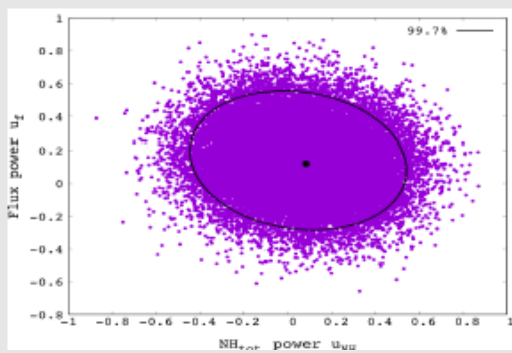


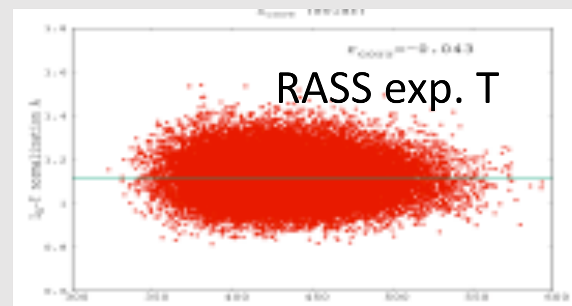
MCMC in 10-parameter space

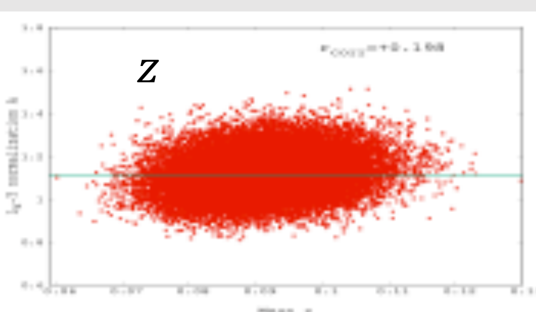
- **Predict expected behavior** from cosmology-independent **cluster propert**ies (z, T, N_H, σ_{int}, flux, metallicity, RASS exp. Time, Xray-BCG offset, etc.)

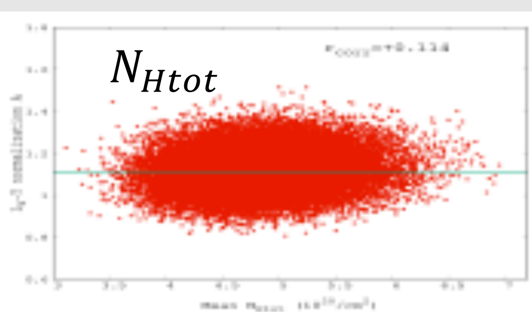
- **Anisotropic region** should behave the **same as rest**, average cluster properties!

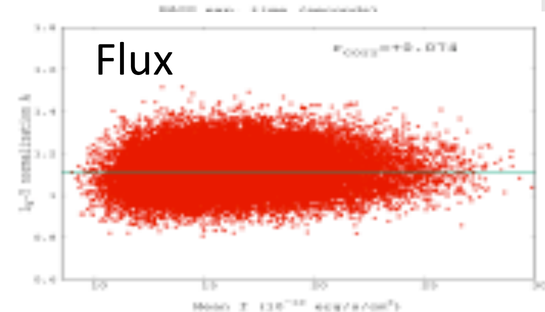




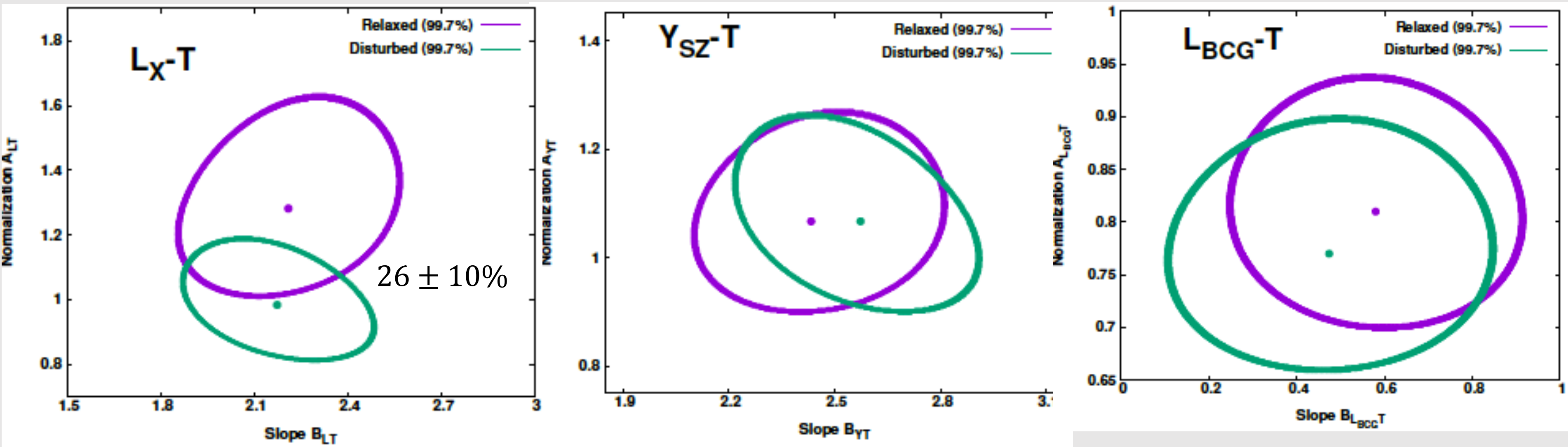






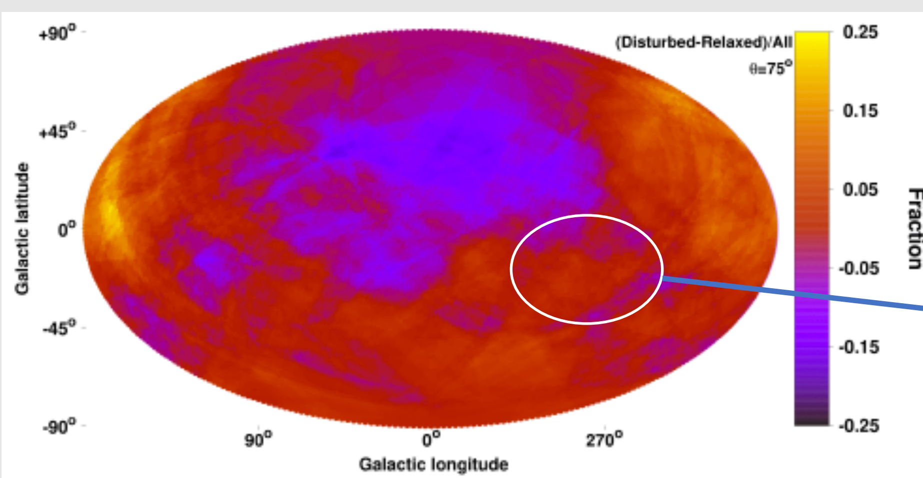


Relaxed vs disturbed clusters



Cluster dynamical state is irrelevant

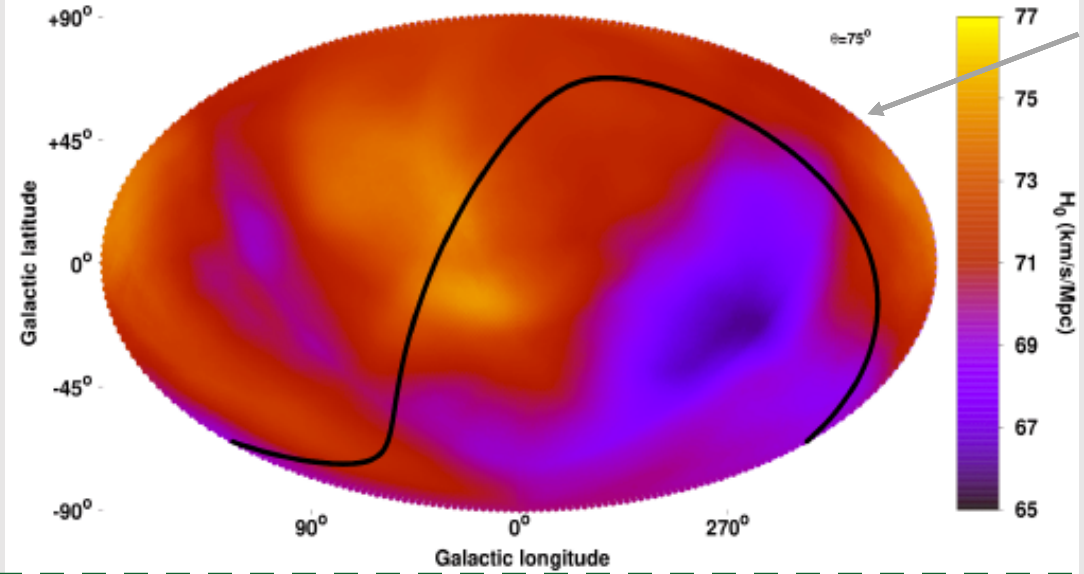
=more relaxed, =more disturbed



Average population!

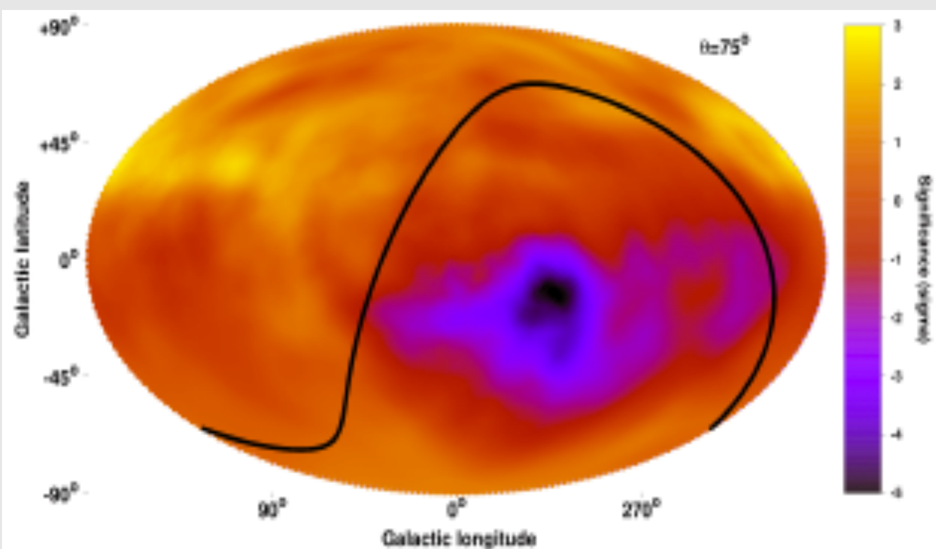
3 Independent samples

eeHIFLUGCS

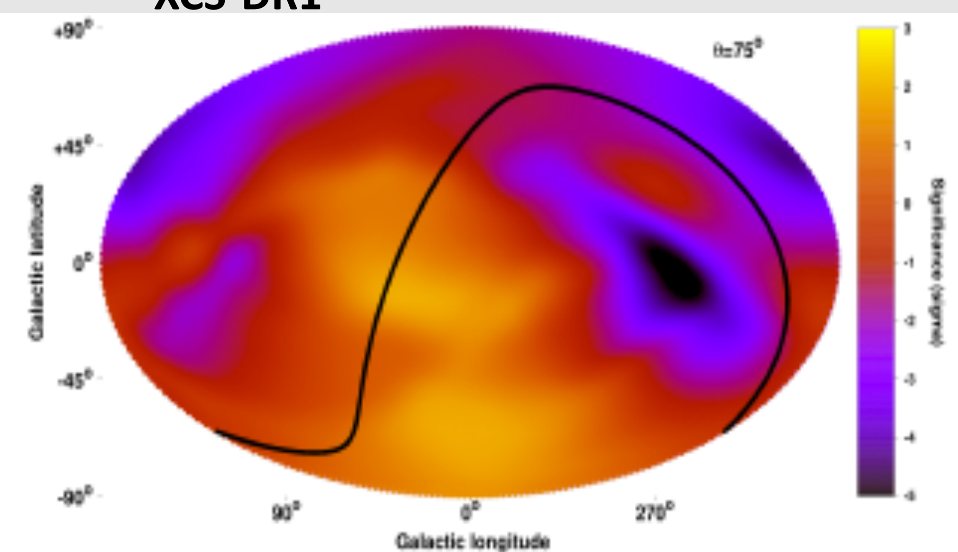


H_0 variation

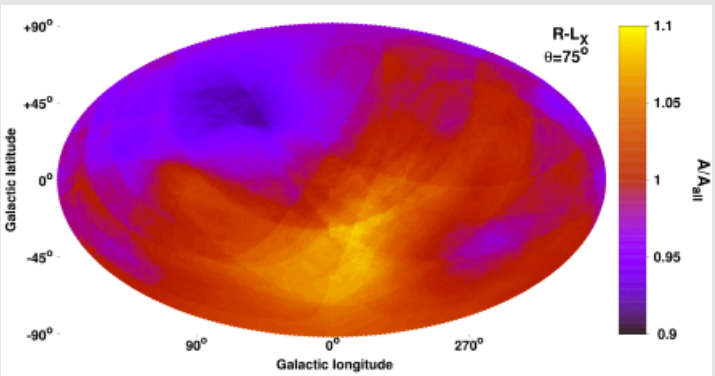
ACC

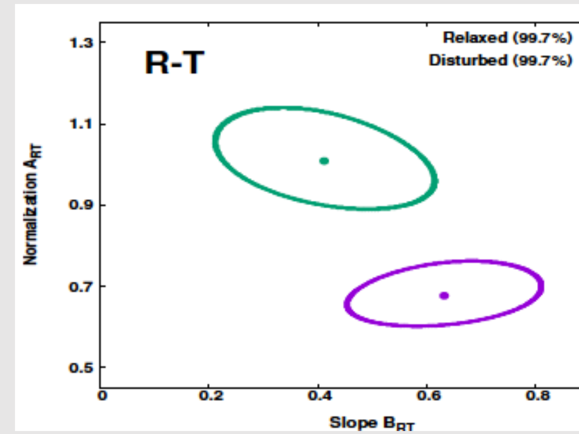


XCS-DR1



The $R_{50\%}$ scaling relations





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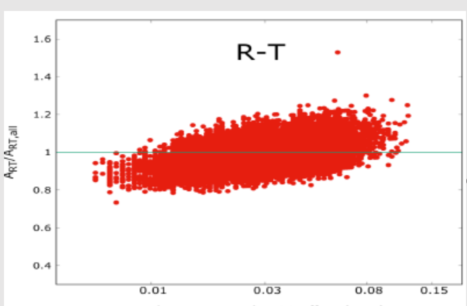

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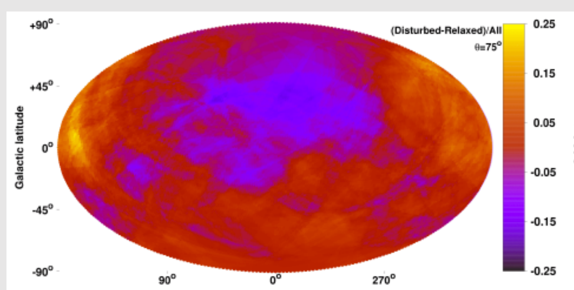

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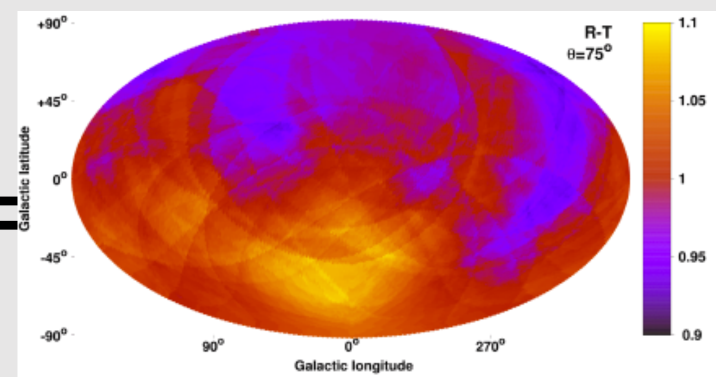
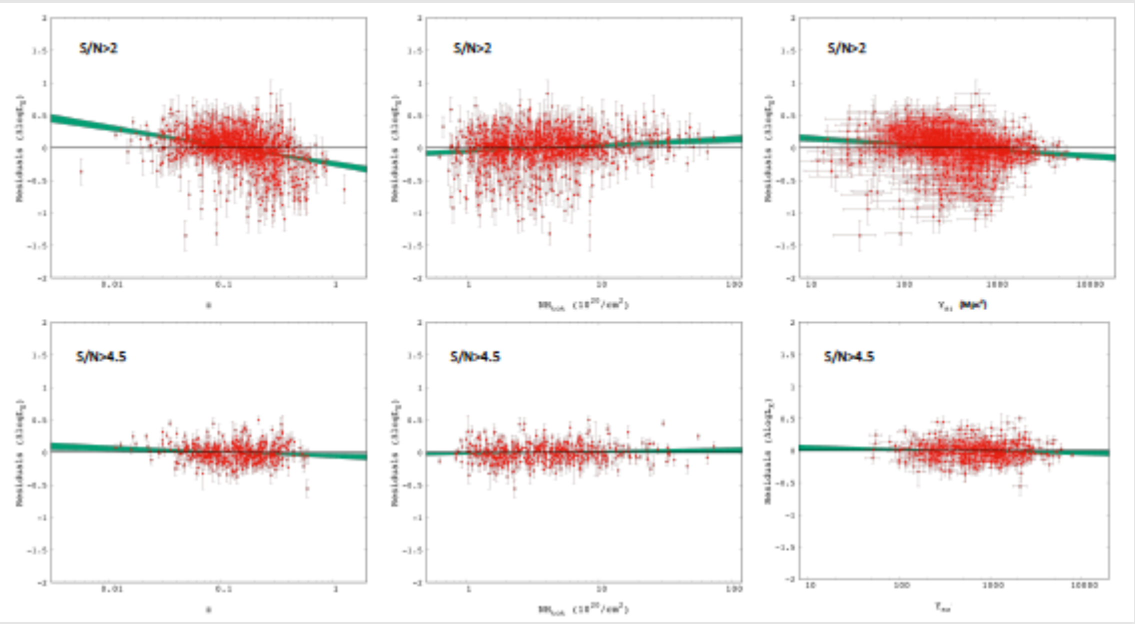
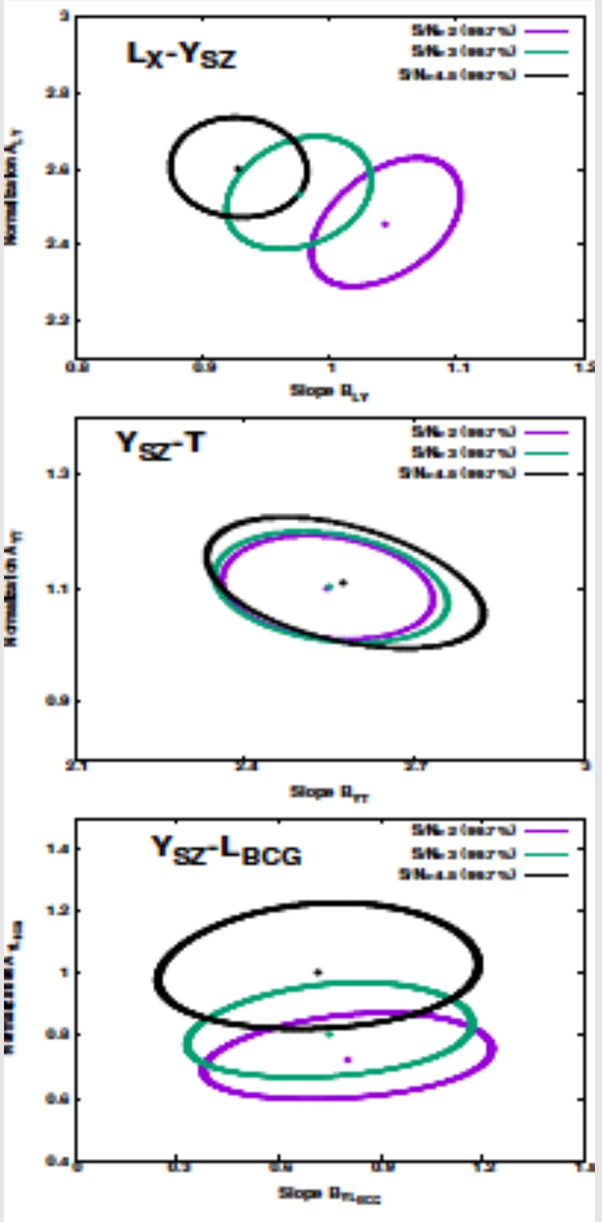


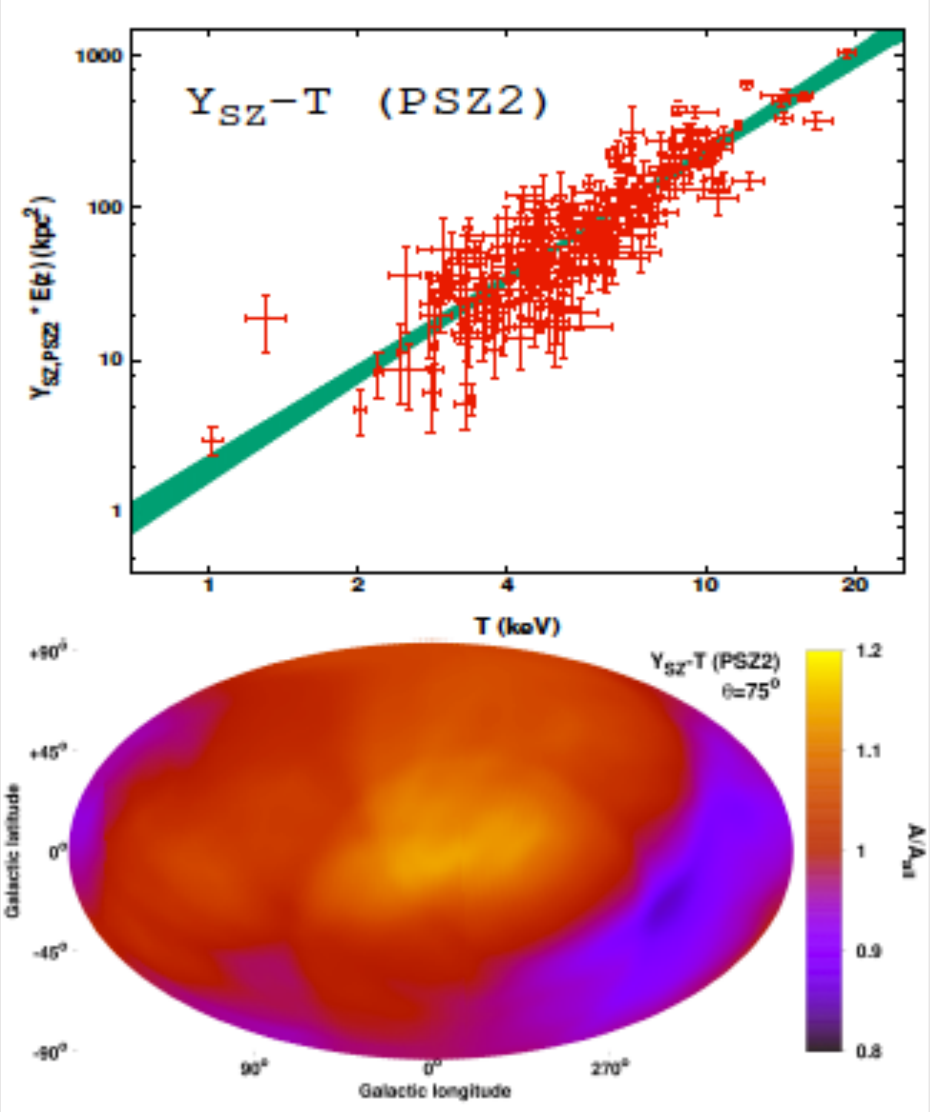
More tests- S/N cuts and residuals

$L_X - Y_{SZ}$ residuals



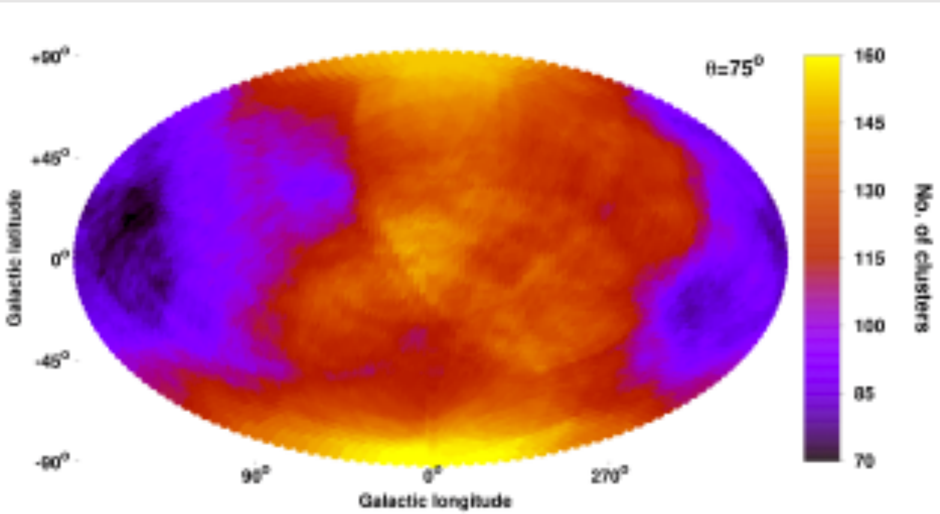


Ysz from PSZ2

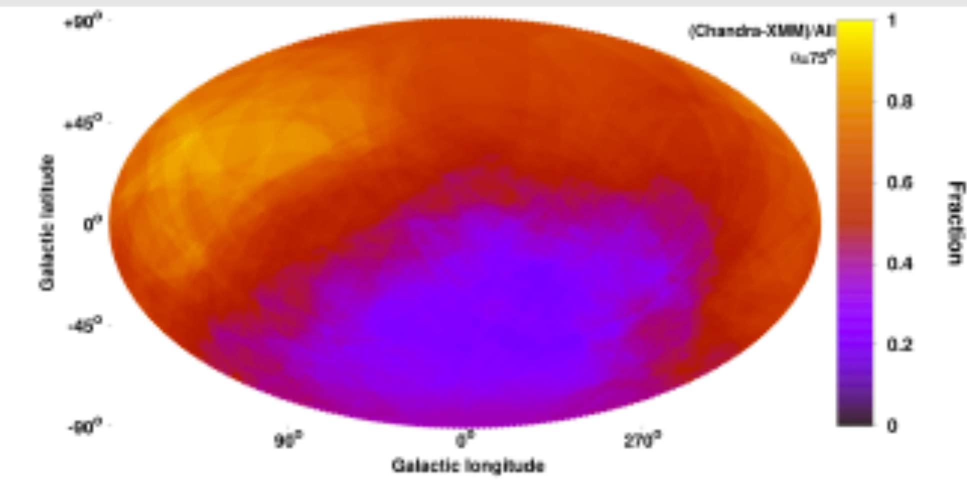


More tests

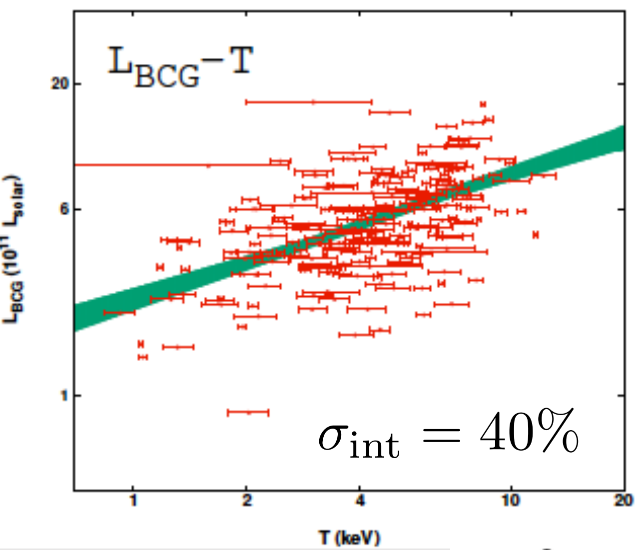
Number of clusters



Chandra/XMM clusters



$L_{BCG} - T$ anisotropies



Same pattern, low significance (1.9σ)