Netherlands Institute for Space Research

Universiteit Leiden

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Probing H_0 isotropy and bulk flows with galaxy clusters and eROSITA

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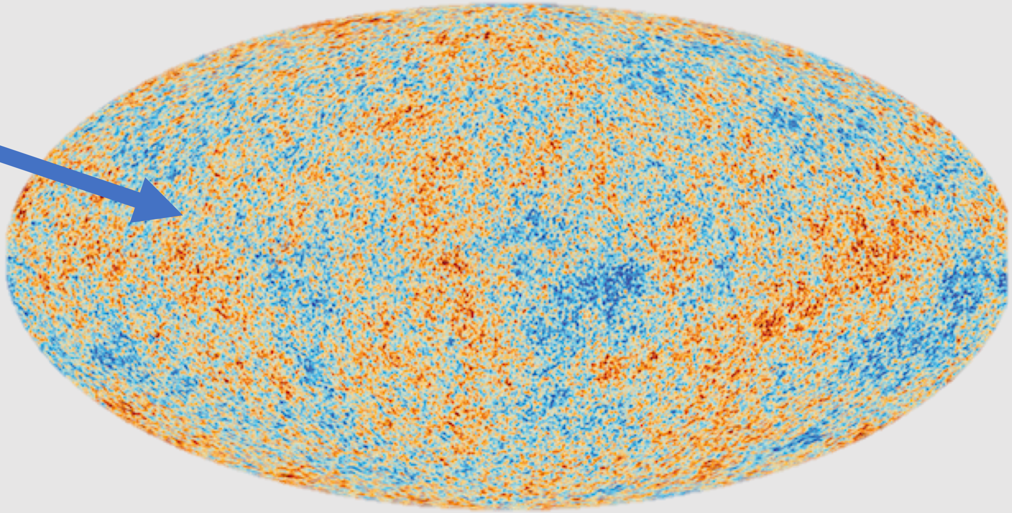
Oort fellow – Leiden University

Tensions in Cosmology – Corfu, Sept 2023

Cosmological Principle

Assumption: Universe is isotropic on large scales

High-z radiation rest frame



Planck Collaboration 2013

But how large..?

Cosmological Principle

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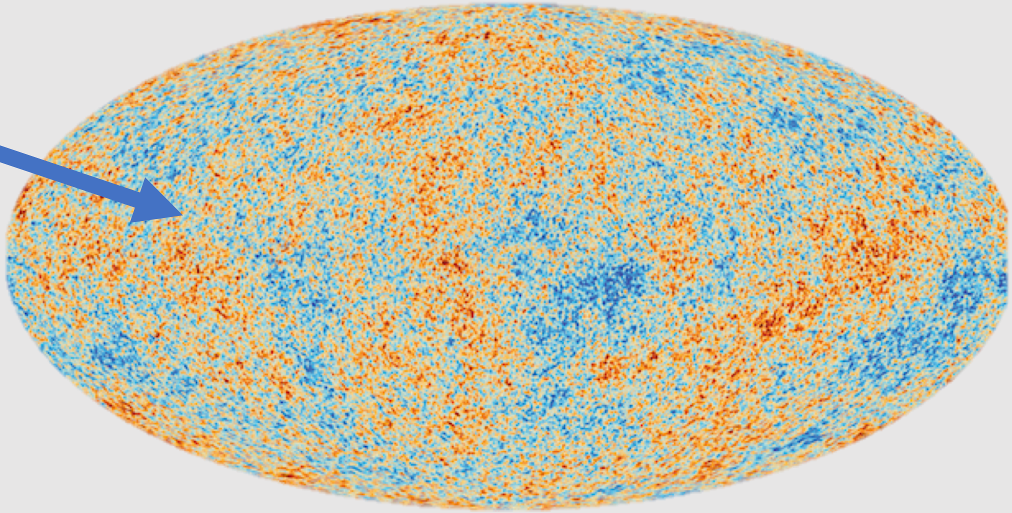
High-z radiation rest frame



Planck Collaboration 2013

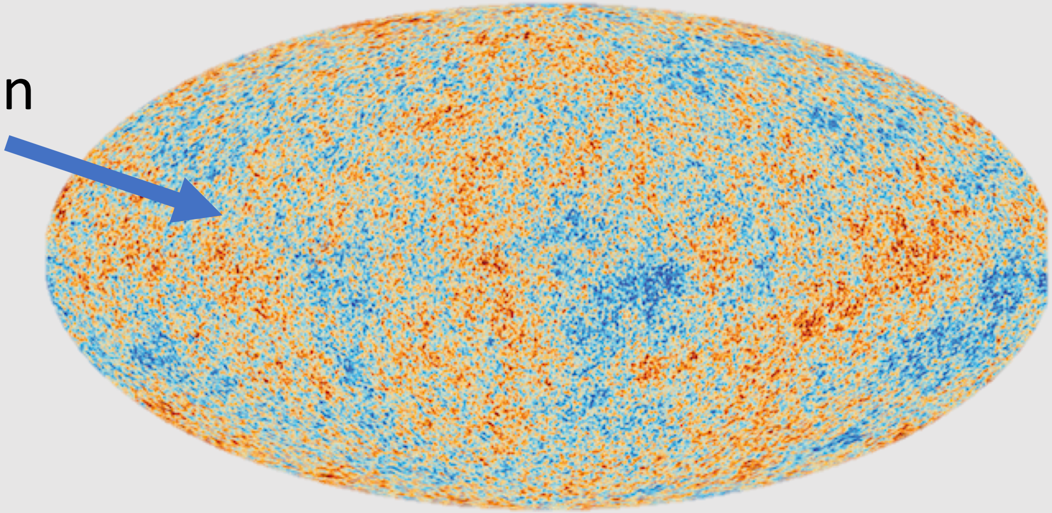
ΛCDM: matter should converge to isotropy

in CMB rest frame at $\gtrsim$ 150 Mpc

Cosmological Principle

Assumption: Universe is isotropic on large scales

High-z radiation rest frame



Planck Collaboration 2013

Crucial to test observationally!

Galaxy clusters can tell us if

- the Hubble constant the same in all directions

- bulk flows are consistent with ΛCDM

in the local ($z<0.3$) Universe

Cosmo-dependent cluster measurements

X-ray:

Luminosity: $L_{\mathrm{X}} \propto H_0^{-2}$

Gas mass: $M_{\mathrm{gas}} \propto H_0^{-5/2}$

Isophotal radius: $R_{50\%} \propto H_0^{-1}$

Microwave:

Total gas thermal energy: $Y_{\mathrm{SZ}} \propto H_0^{-2}$

Infrared:

Biggest galaxy luminosity: $L_{\mathrm{gal}} \propto H_0^{-2}$

Observable + redshift → assume H_0, etc. to get distance → **Cluster property**

Cosmology-dependent!

Cluster scaling relations

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

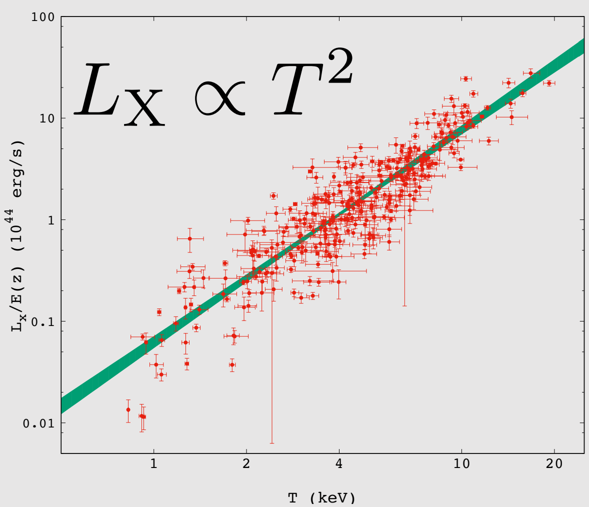
Higher mass

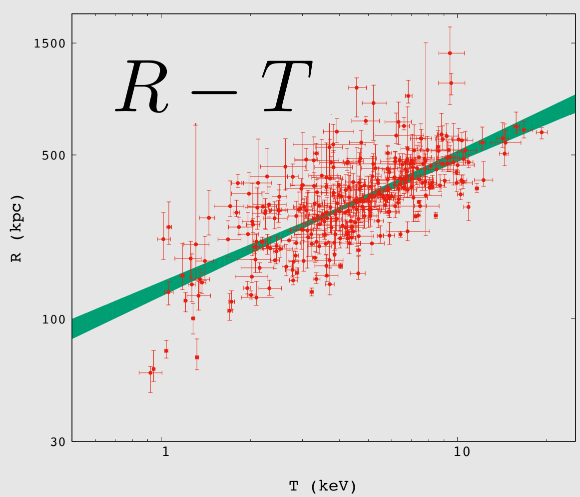
Larger radius *R*

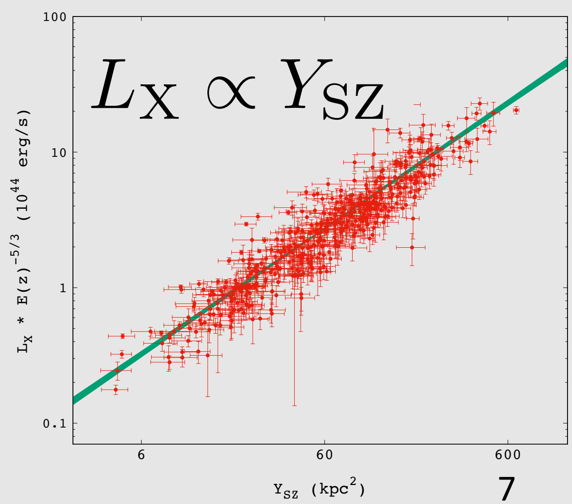
Higher temperature T

Higher luminosity L_X

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





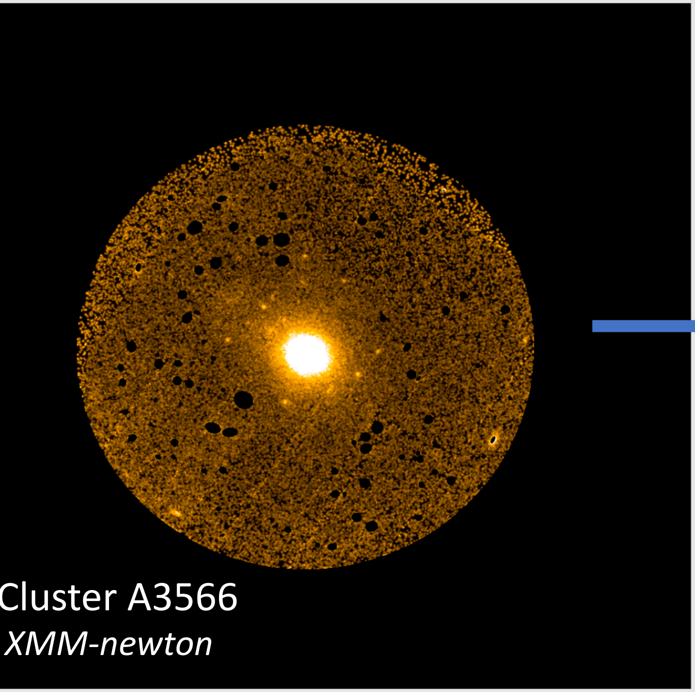


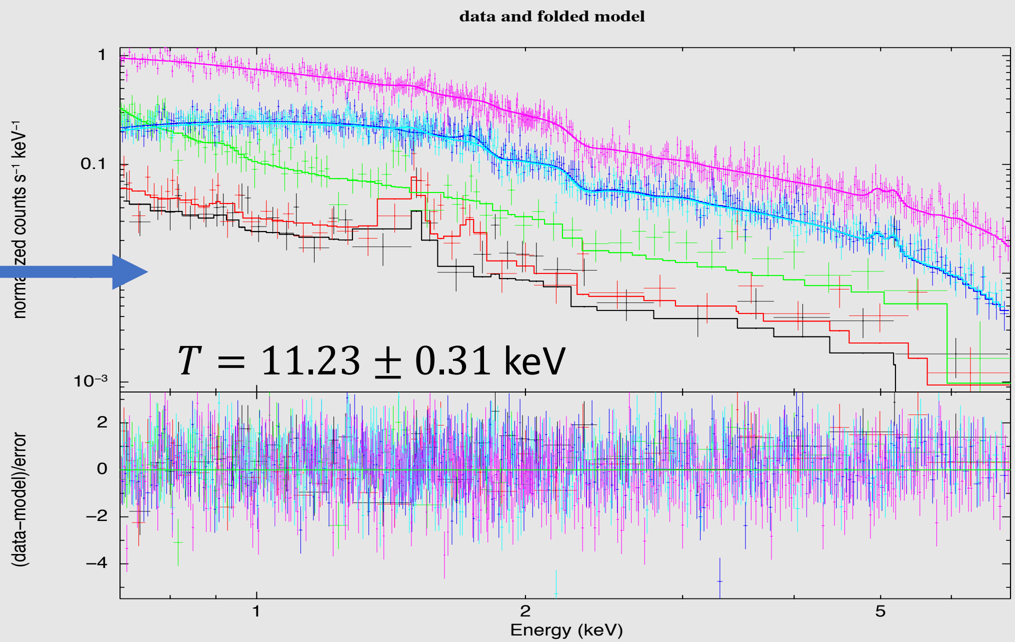
Cluster X-ray **temperature**

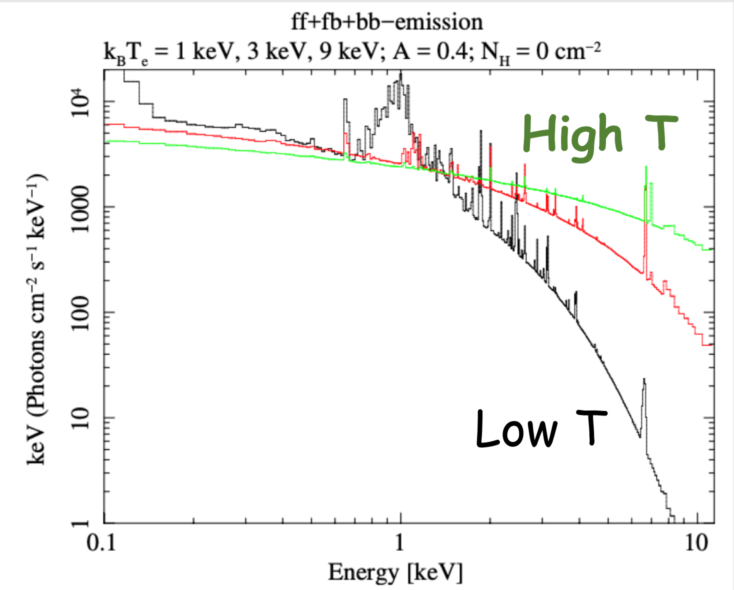
is the **key measurement**

for testing cosmic isotropy!

Galaxy clusters in X-rays

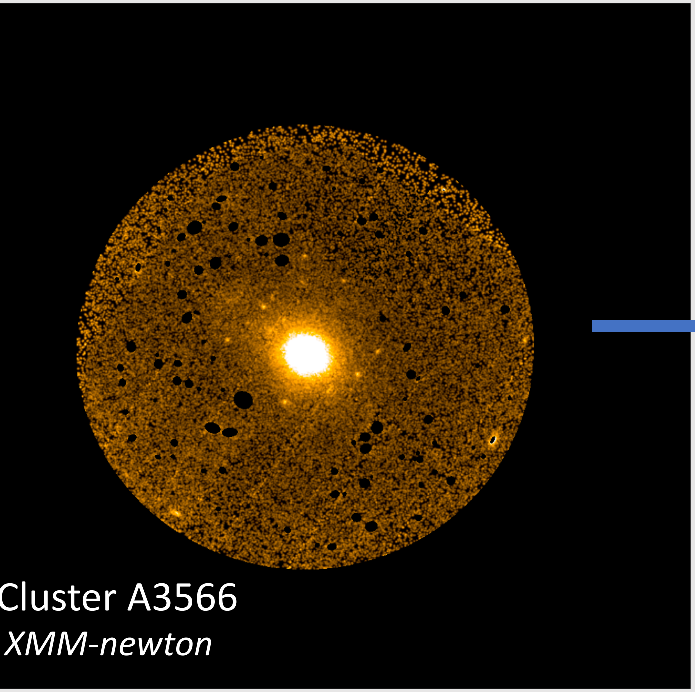


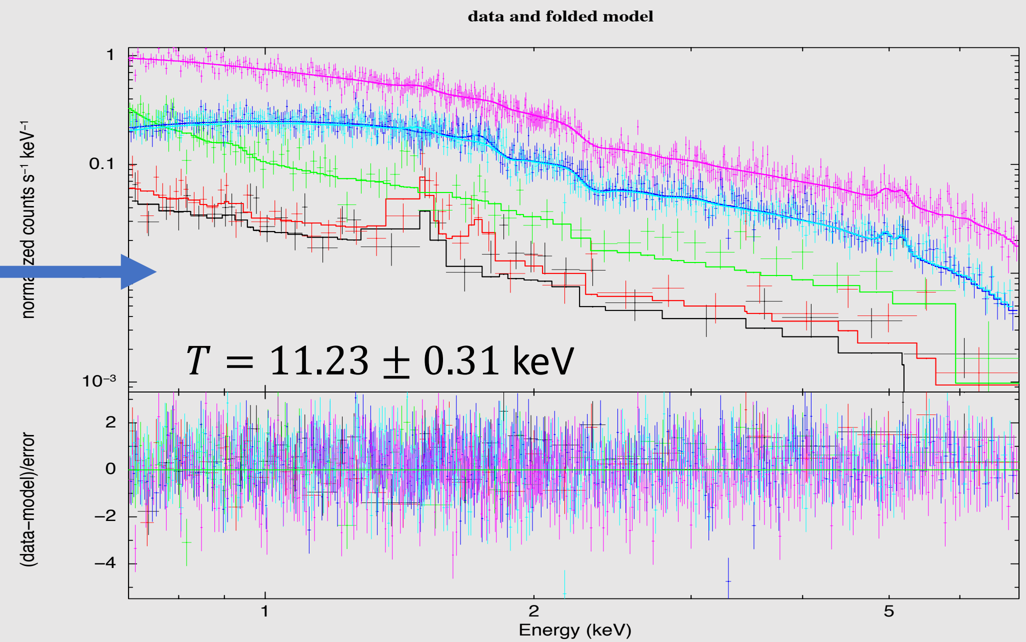




- Extract spectrum of cluster
- **Measure temperature** via fitted models

Galaxy clusters in X-rays





T determination: cosmology-independent!

Constrain isotropy with scaling relations

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

$$2 \log H_0 + A_{LT} + G(\Omega_{\mathrm{m}}, w, z) = \log f_X - B \log T$$

Constrain isotropy with scaling relations

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

$$2\log H_0 + A_{LT} + G(\Omega_{\rm m}, w, z) = \log f_X - B\log T$$

Internal cluster property, same in all directions

Don't matter for local cluster sample (z<0.3)

Constrain isotropy with scaling relations

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

$$2\log H_0 + \cancel{A_{LT}} + G(\cancel{\Omega_{\mathrm{m}}}, \cancel{w}, z) = \log f_X - B \log T$$

Strong H_0 and bulk flow dependence!

Determine observationally!

Same for $Y_{\mathrm{SZ}} - T,\ M_{\mathrm{gas}} - T,\ R_{50\%} - T,\ M_{\mathrm{gas}} - L_{\mathrm{X}},\ \mathrm{etc}$

Constrain isotropy with scaling relations

$$2\log H_0 + G(\cancel{\Omega_{\rm m}}, \cancel{w}, z) = \log f_X - B\log T - A_{LT}$$

cosmology!

no cosmology!

- Scan the sky with a cone, constrain relations for each cone separately → all-sky color map
- **Quantify apparent H_0 variation and bulk flows**

Constrain isotropy with scaling relations

$$2\log H_0 + G(\Omega_\mathrm{m}, w, z) = \log f_X - B\log T - A_{LT}$$

cosmology!

no cosmology!

Important:

Done for every scaling relation ⇒ end up with several **independent** H_0/bulk flow constraints

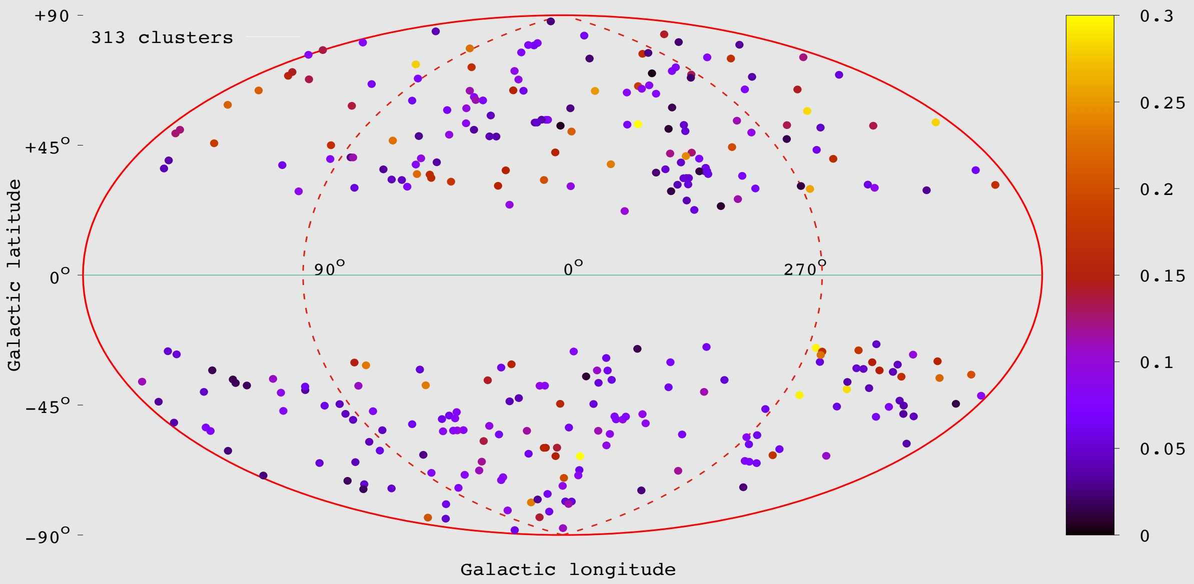
Our sample

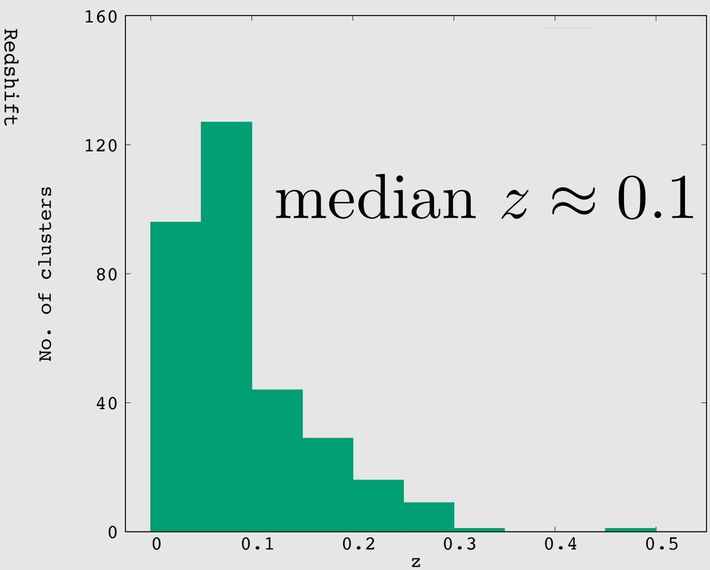
&

the 10 scaling relations

eeHIFLUGCS sample

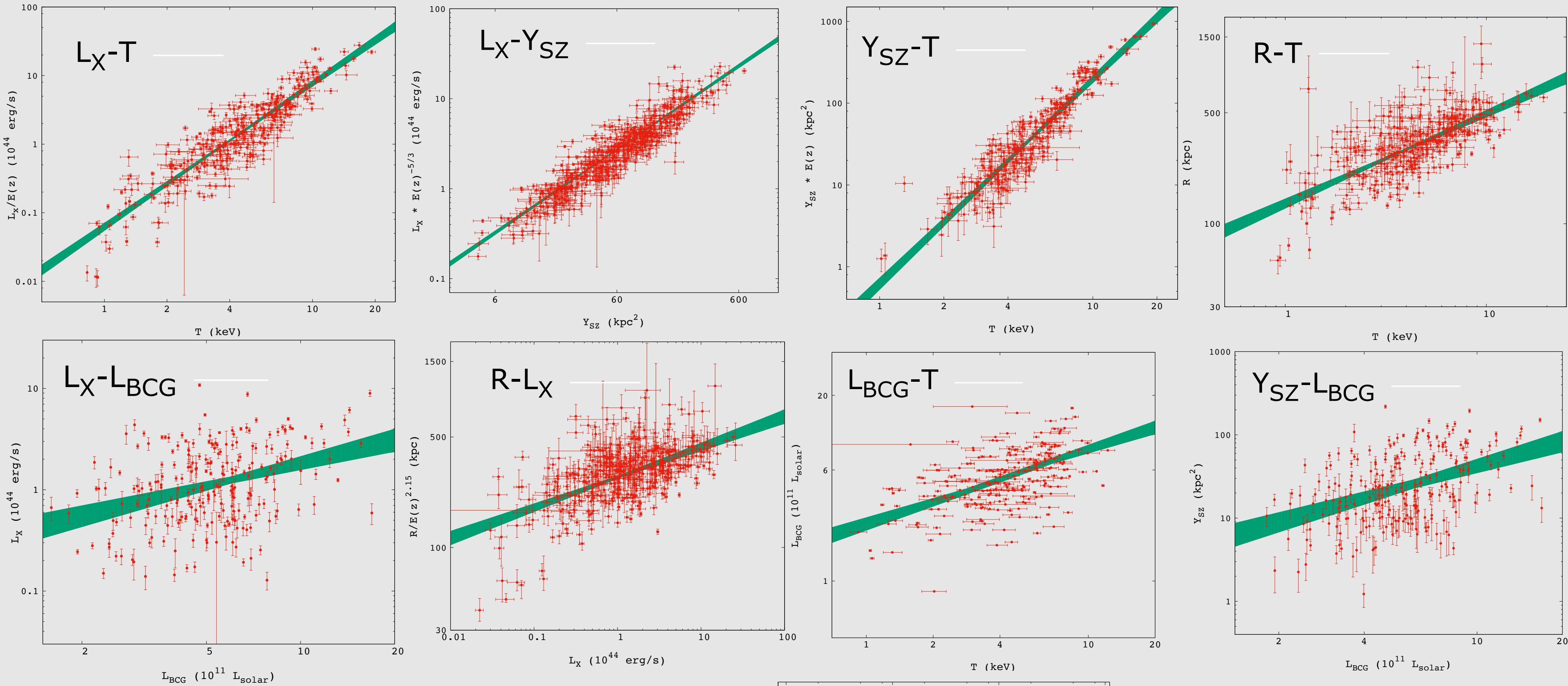
- Homogeneously selected, **~350** brightest **X-ray clusters**, mostly $z < 0.25$
- **X-ray L_X** and **$R_{50\%}$** (ROSAT), and **T** (XMM+Chandra)
- **Microwave Y_{SZ}** (Planck) and **infrared L_{BCG}** (2MASS)



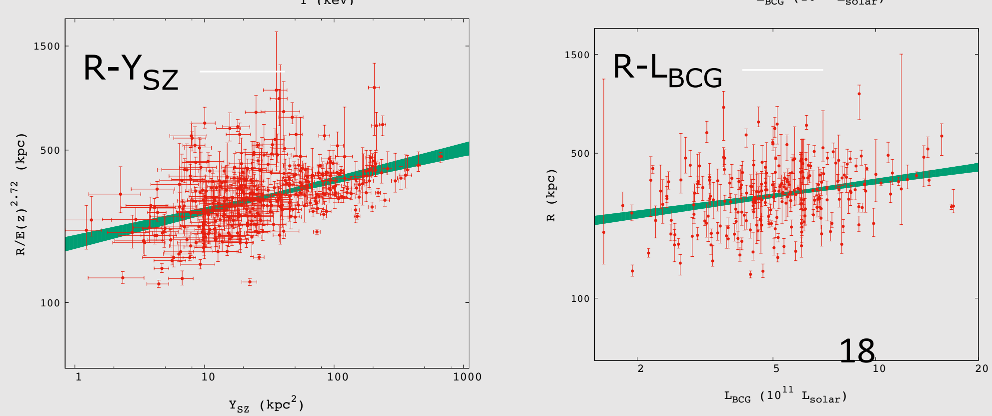


Migkas et al. 2020, A&A, 636,A15

10 multiwavelength cluster scaling relations!



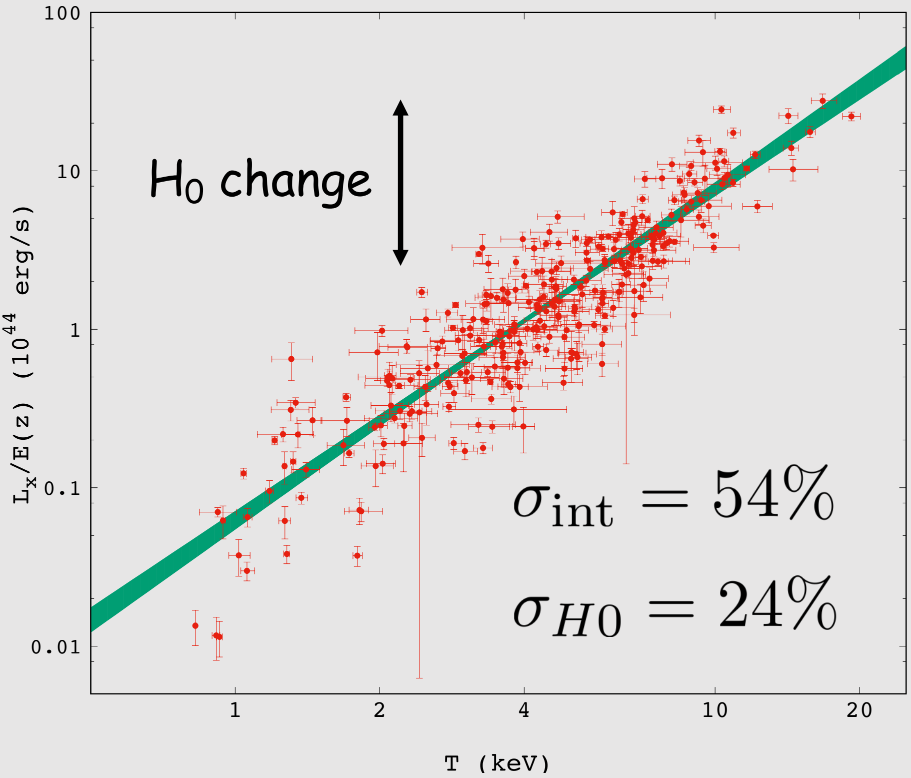
- Study anisotropy for all relations
- Obtain complementary information



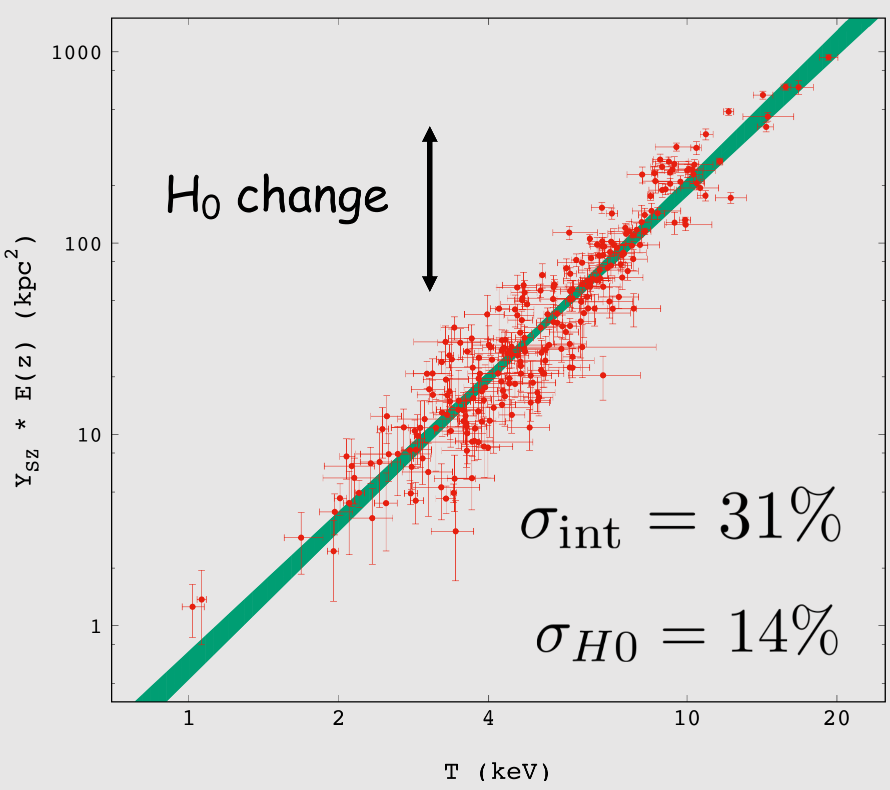
Migkas+21

Cosmological anisotropies

The $L_X - T$ relation

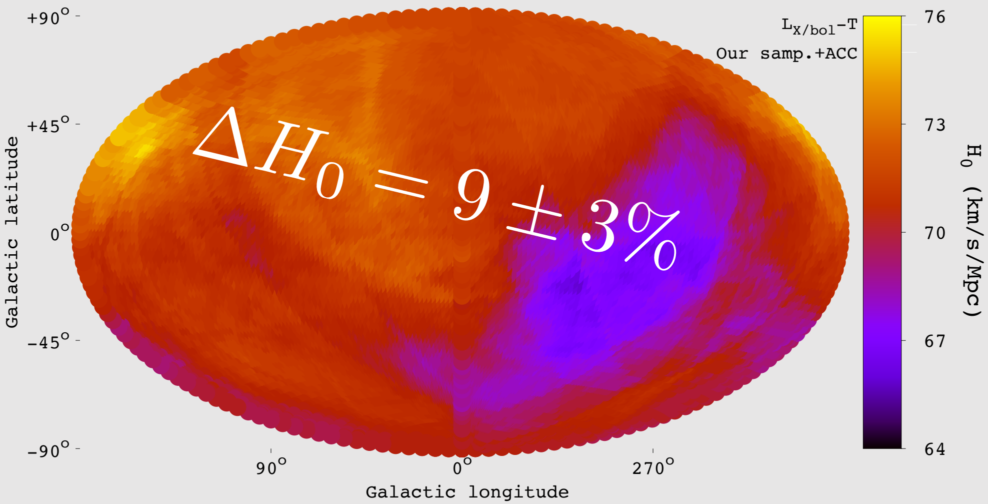


The $Y_{SZ} - T$ relation



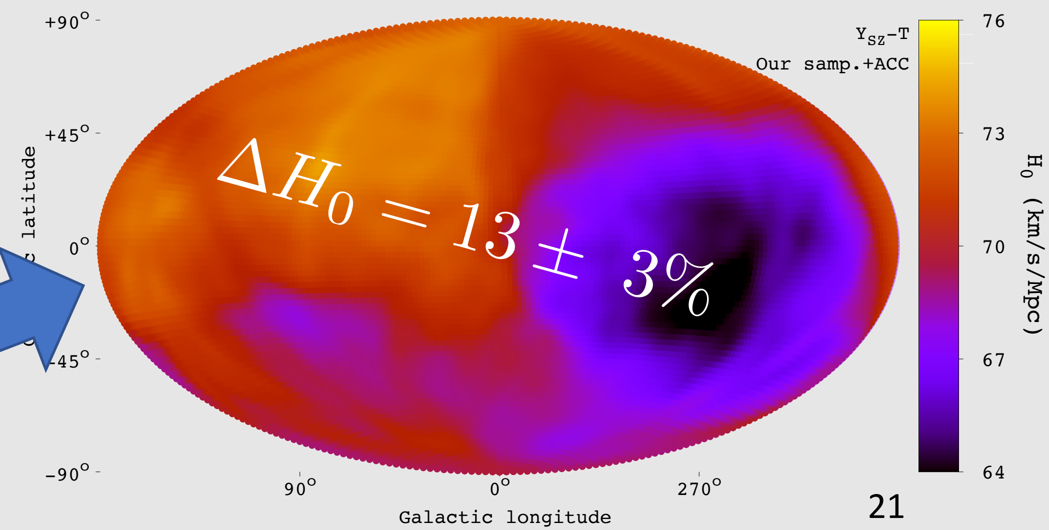
Apparent H_0 variation

$L_\mathrm{X} - T \quad 3\sigma$



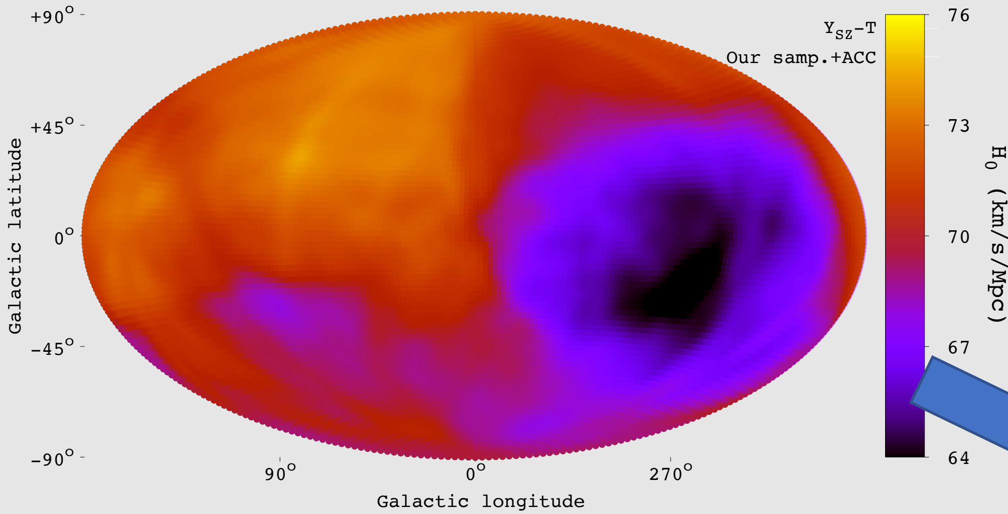
Nearly independent results..!

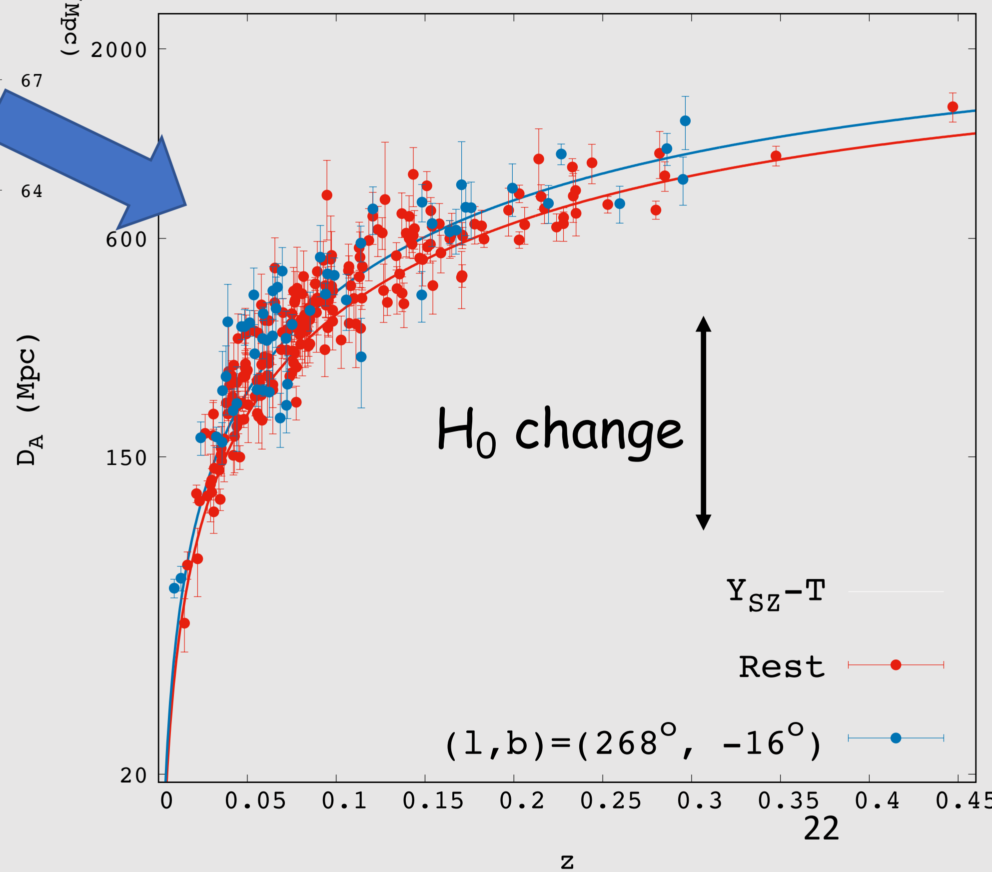
$Y_\mathrm{SZ} - T \quad 4.1\sigma$



Microwave ⇒ Insensitive to absorption!

Hubble diagram of clusters!





Blue: most anisotropic region

Red: rest

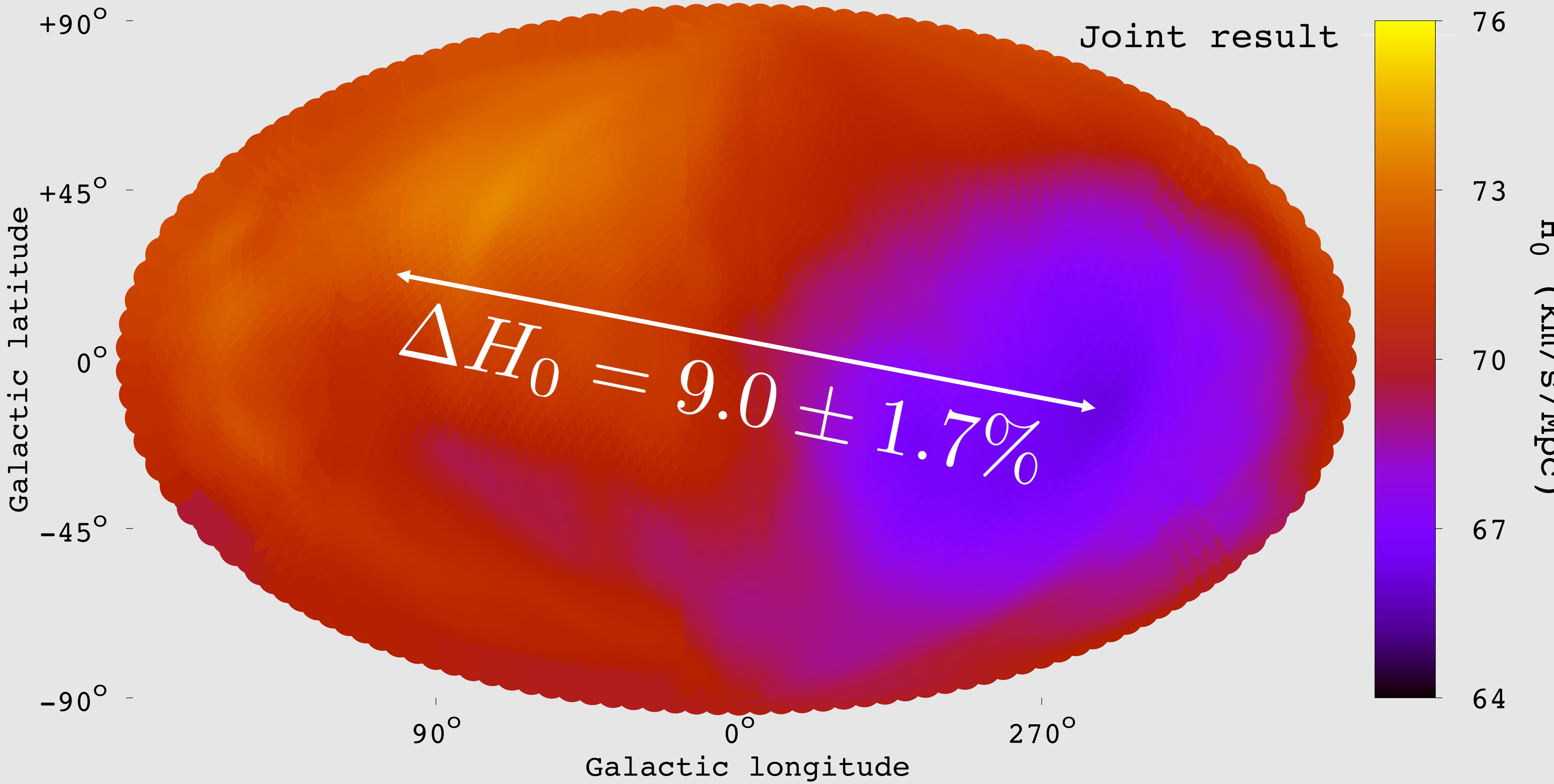
Combining all X-ray, microwave, and infrared cluster info with in-depth, exhaustive analysis…

…+other low-z independent cluster samples

First-ever multiwavelength H_0 anisotropy map!

Overall result: 5.4σ! (from Monte Carlo)

Migkas et al. (2021), A&A, 651, 151



Most robust detection of late-Universe anisotropy ever!

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

Exshaustive list of tested possible systematics

- 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!

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

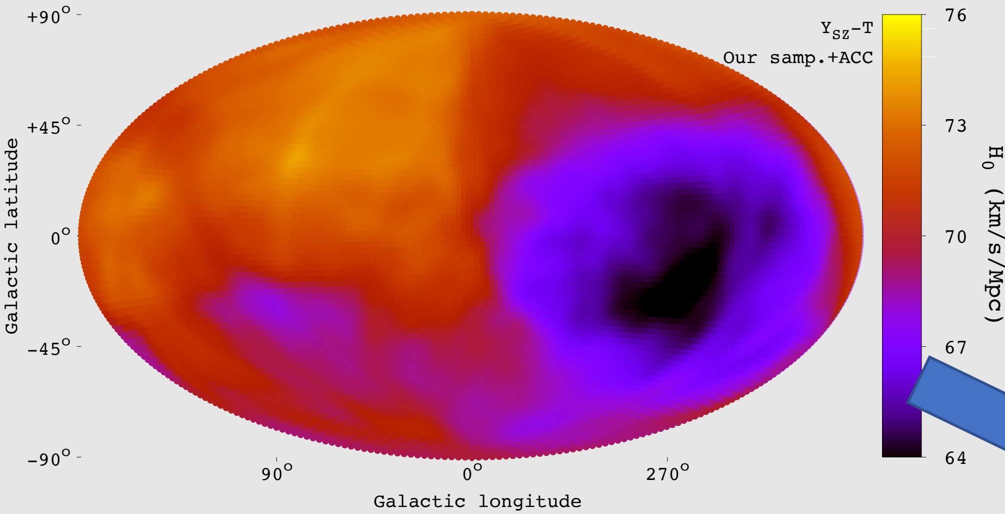
Migkas et al. (2021), A&A, 651, 151

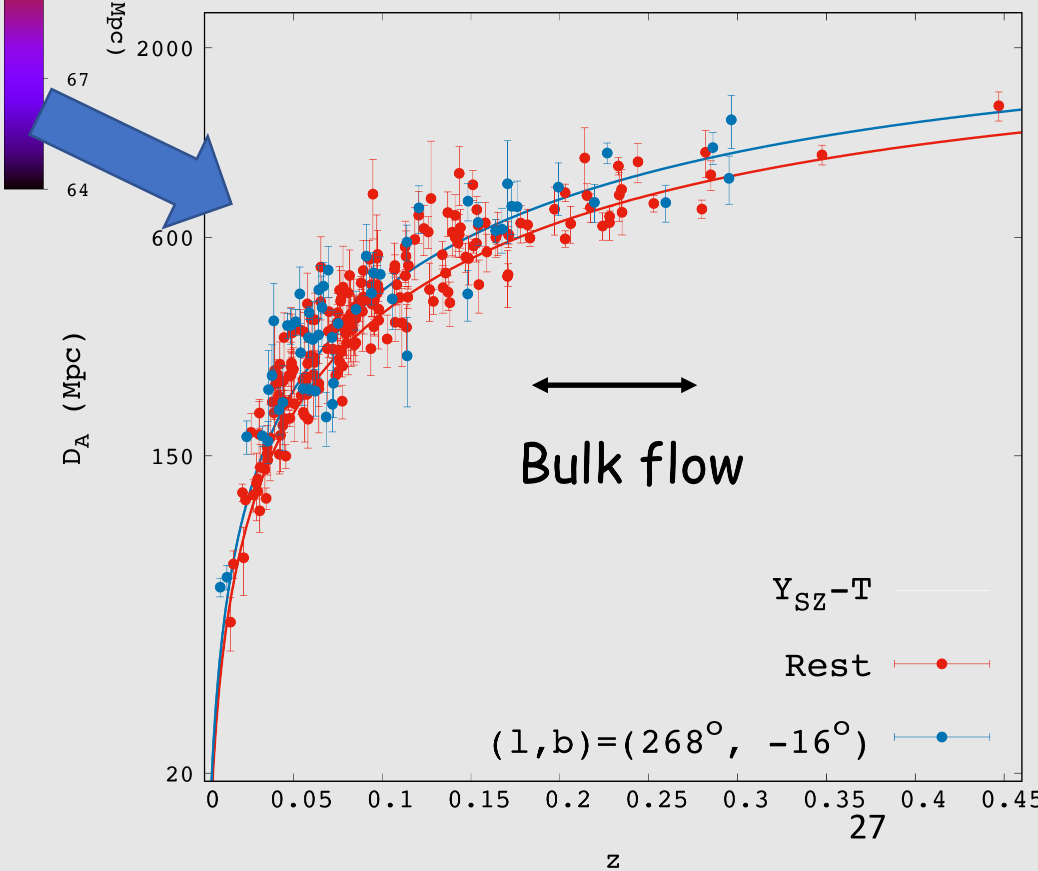
What if true $H_0 =$ isotropic?

Then, we need a large bulk flow...

First bulk flow constraints from cluster scaling relations

Hubble diagram of clusters!





Blue: most anisotropic region

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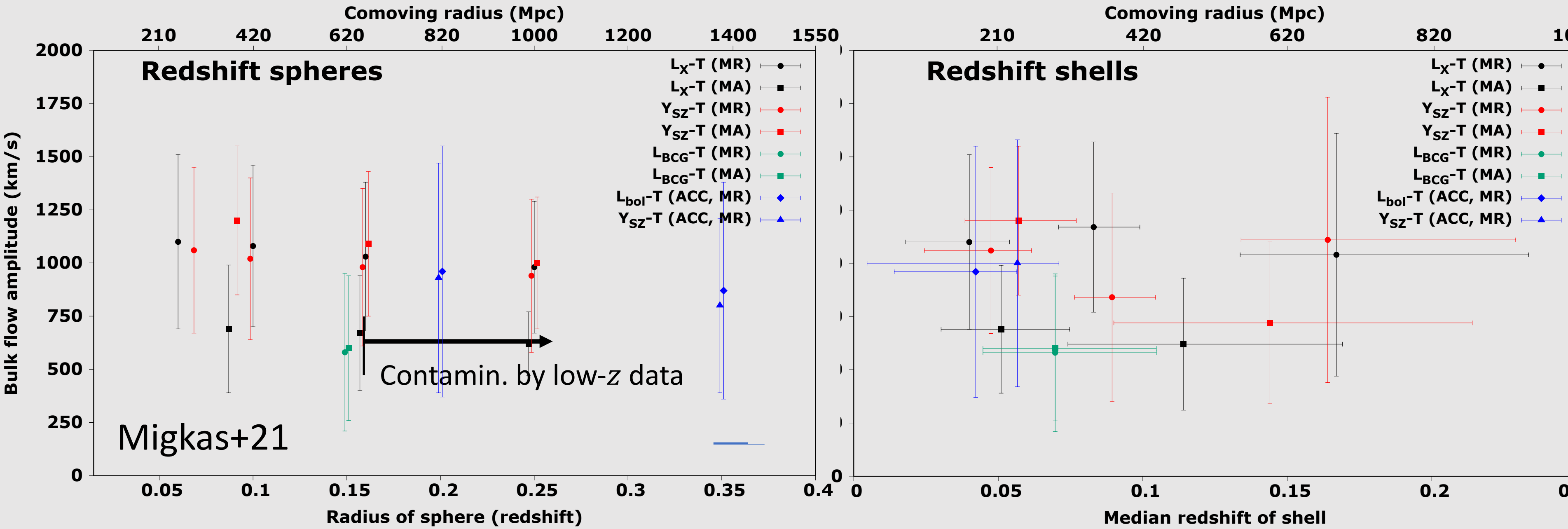
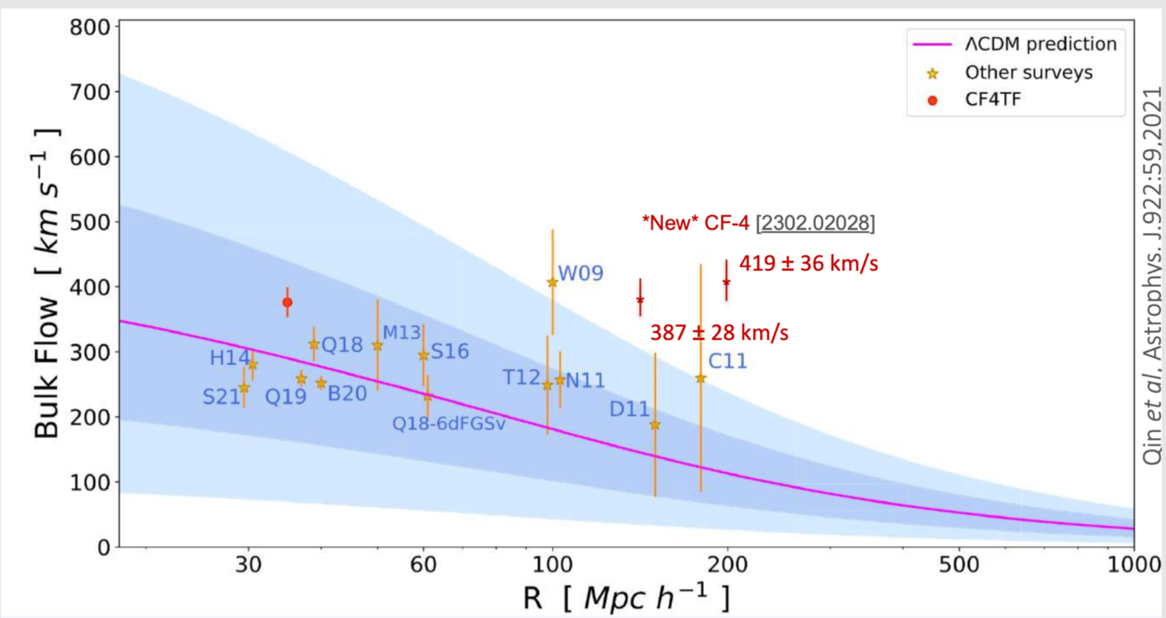
Cluster bulk flows



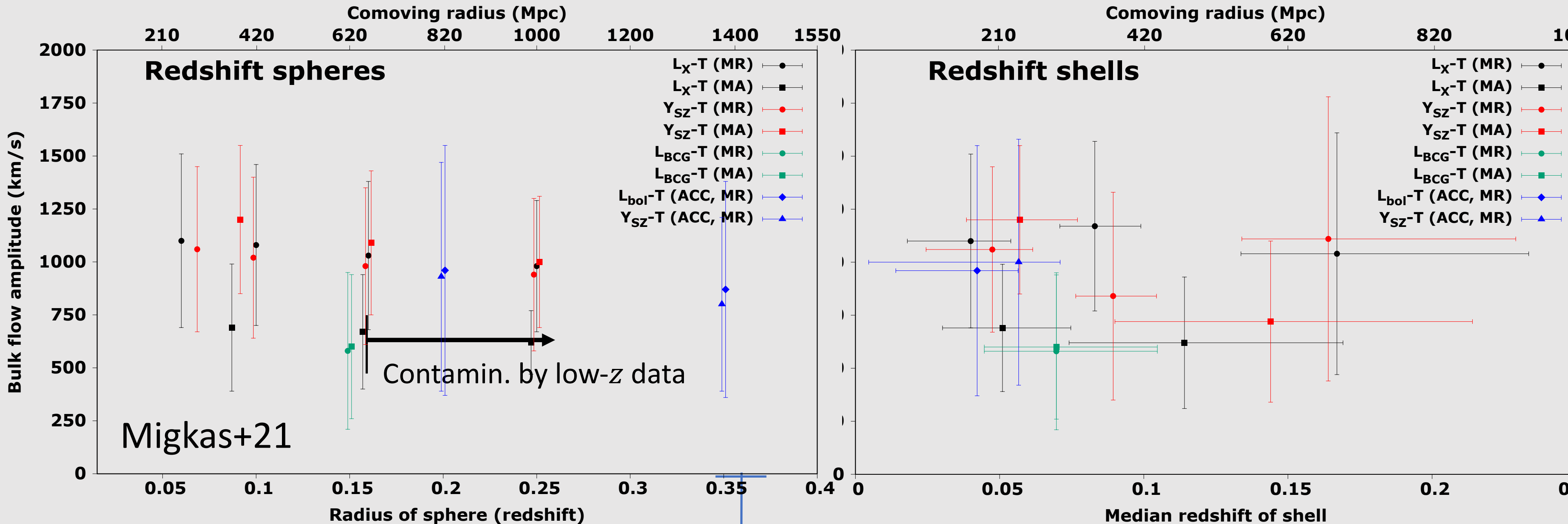


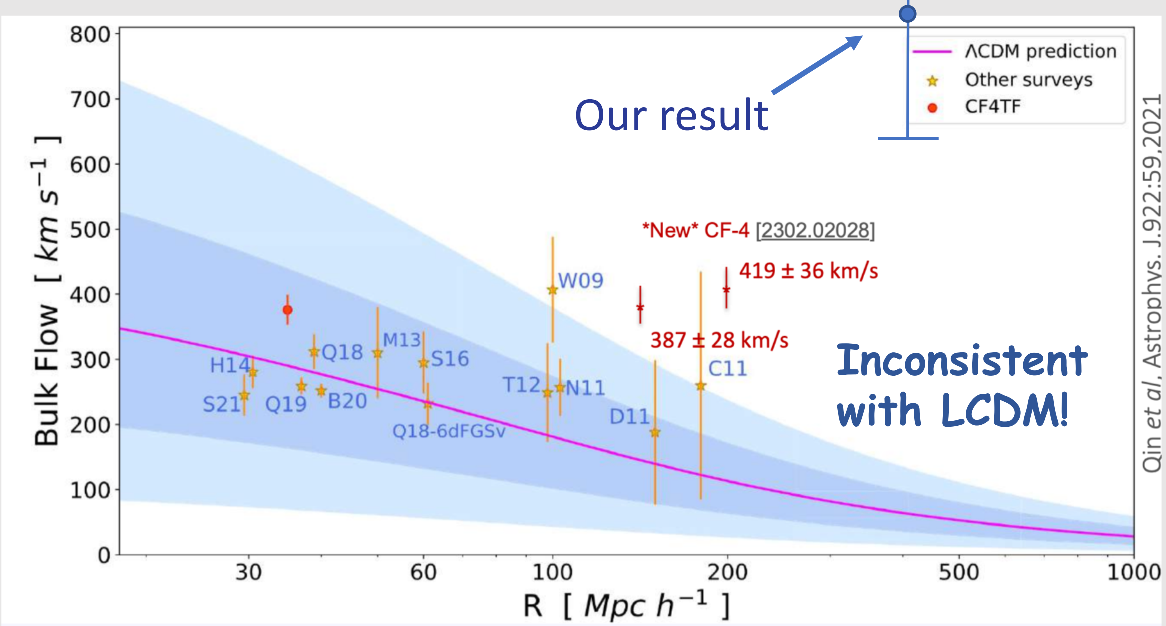
~ 900 km/s BF

up to 500 Mpc

$(z \sim 0.12)$

Cluster bulk flows





~ 900 km/s BF up to 500 Mpc ($z \sim 0.12$)

New, better results..!

Significant part of scatter comes from cluster core

(complicated baryonic physics)

- Use high-quality XMM-Newton data for 238 clusters
- Measure **core-excised** $\mathbf{L_X}$ and $\mathbf{R_{50\%}}$
- Measure total and **core-excised** cluster gas mass $\mathbf{M_{gas}}$

New, better results..!

Significant part of scatter comes from cluster core

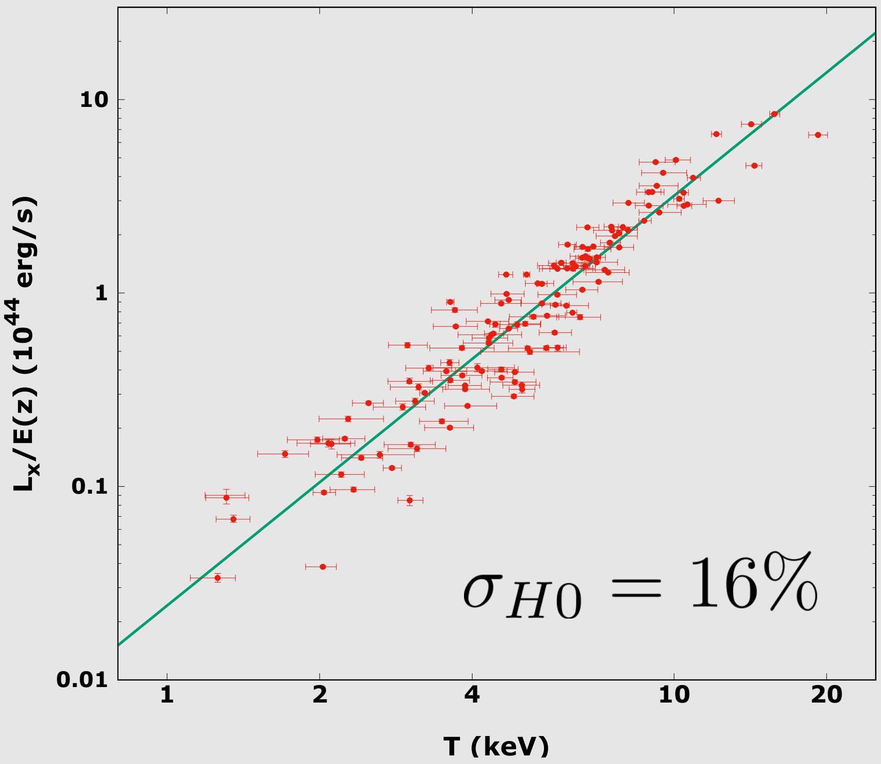
(complicated baryonic physics)

Reduced scatter & uncertainties, new scaling relations, better cosmological constraints..!

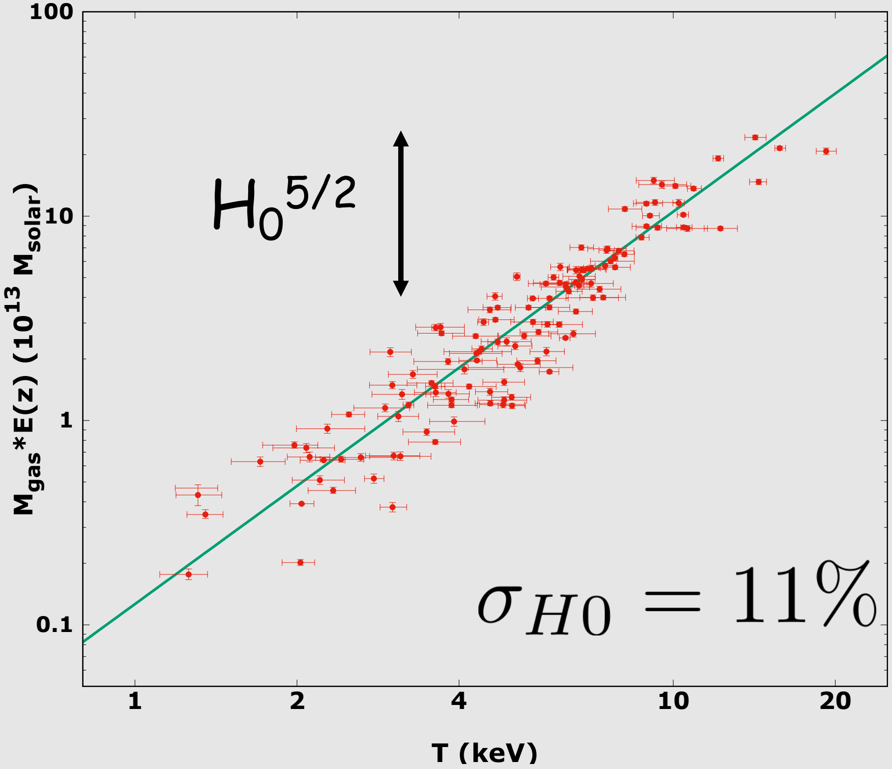
New scaling relation with reduced scatter

Migkas et al. (in prep.)

$L_{X,ce} - T$



$M_{gas} - T$

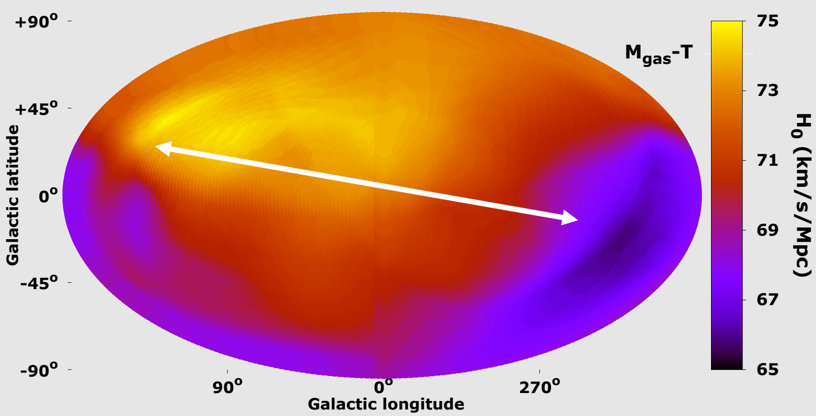


New results support detected anisotropy!

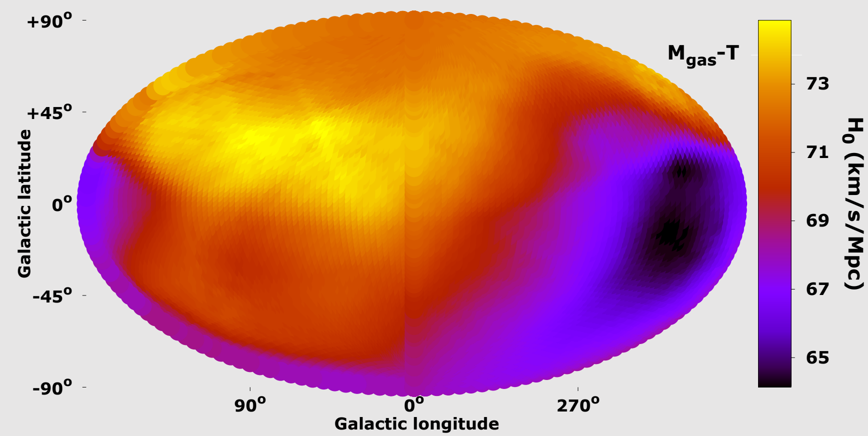
Migkas et al. (in prep.)

$$M_{\rm gas} - T$$

All



$z \leq 0.1$

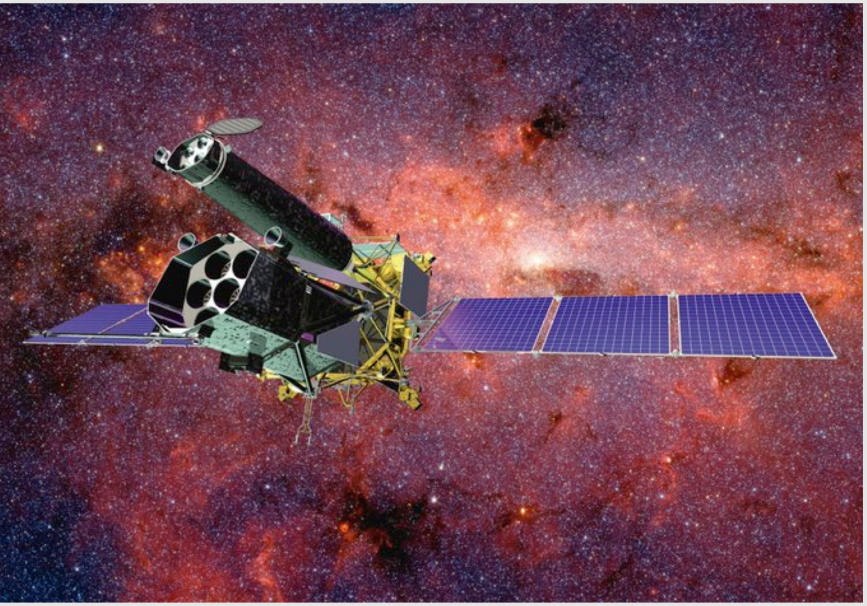


$3.6\sigma \qquad \Delta H_0 = 11 \pm 3\%$

$$(l, b) \approx (242^\circ, -25^\circ)$$

- 37° away from previous results, within uncertainties

eROSITA



Credit: MPE, Garching

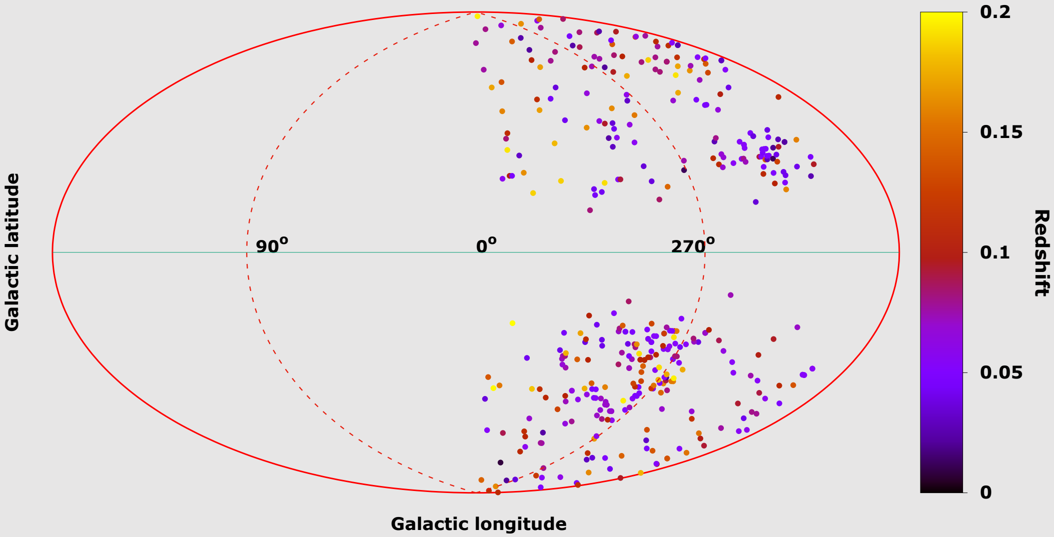
- First X-ray all-sky survey in 30 years
- 8 full-sky scans, one/6 months
- $\sim 10^4$ of new galaxy clusters eventually!
- One sky half for Germany, one for Russia
- eRASS1 data (after 1st scan) fully available

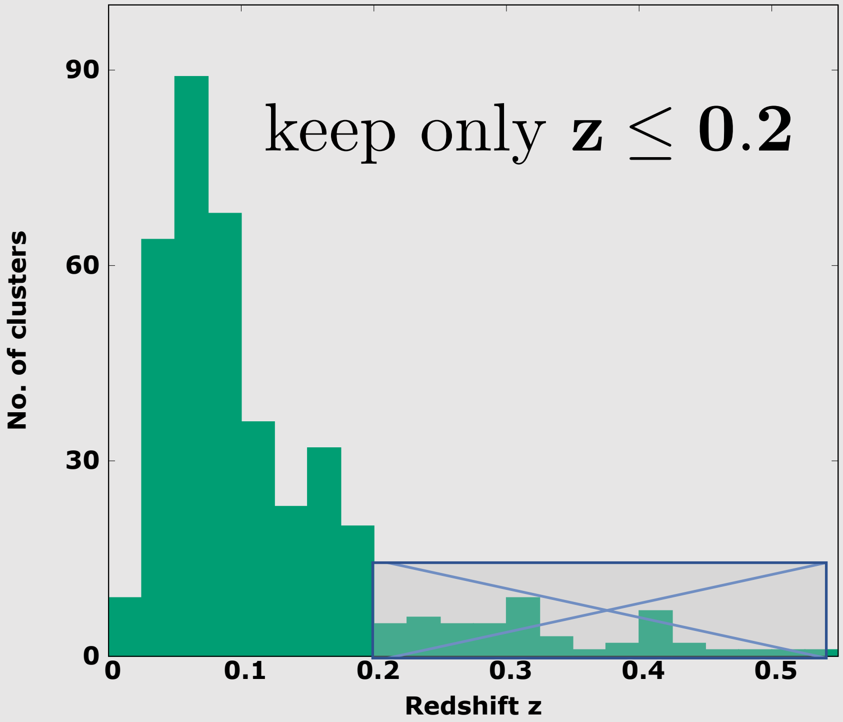
Merloni+12, Predehl+21

First results on isotropy from eROSITA...

eROSITA

- **309 clusters at z<0.2** with spec-z and reliable T

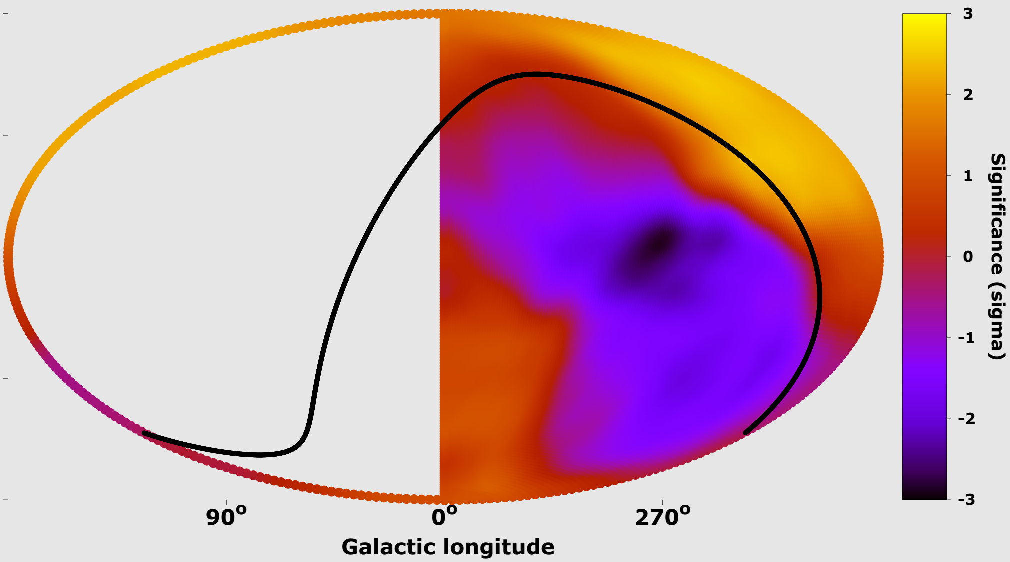




Nearly independent results to what you saw before…

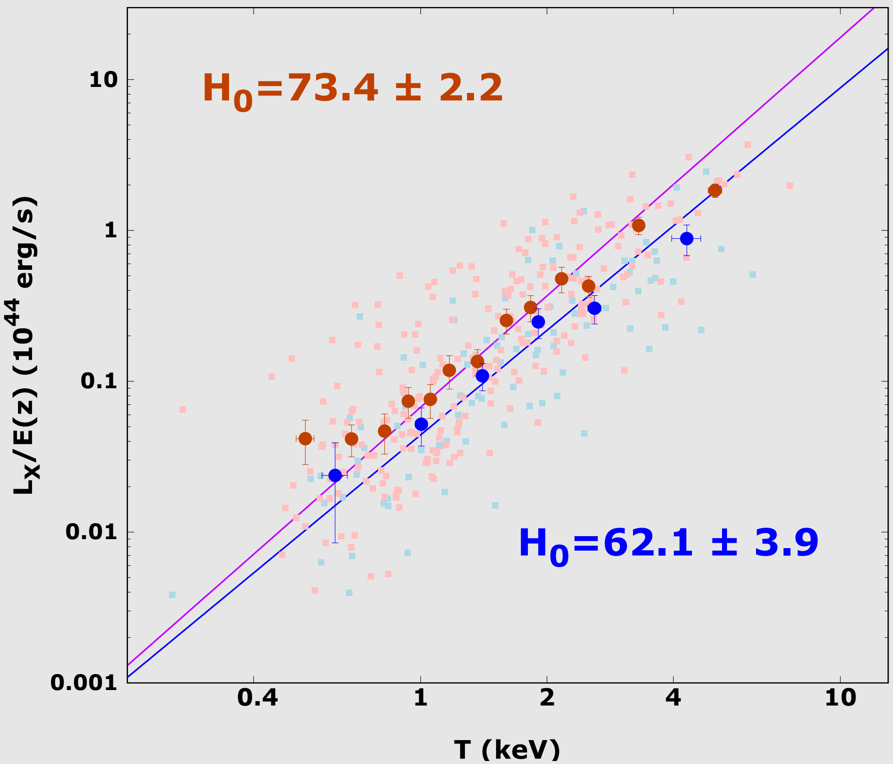
eROSITA: L_X-T

- Same anisotropy direction as in eeHIFLUGCS at z<0.2!
- Slightly stronger variation (16.1 ± 6.4% instead of 9.0 ± 1.7%)



$$2.5\sigma$$

$$(l, b) \sim (274°, +6°)$$



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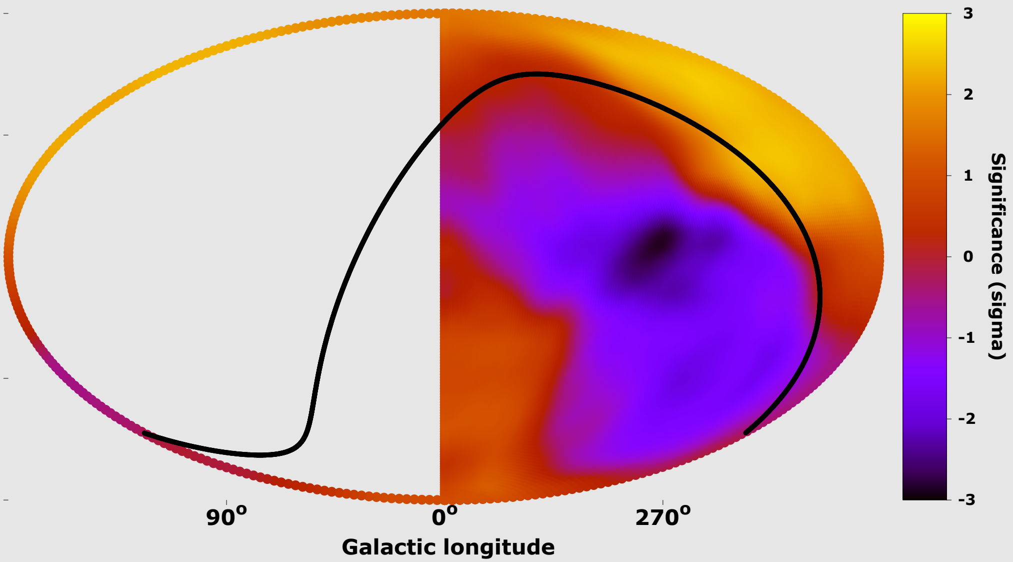


$$2.5\sigma$$

$$(l, b) \sim (274^\circ, +6^\circ)$$

Or, similar bulk flow as before!

$$1180 \pm 490 \text{ km/s}$$

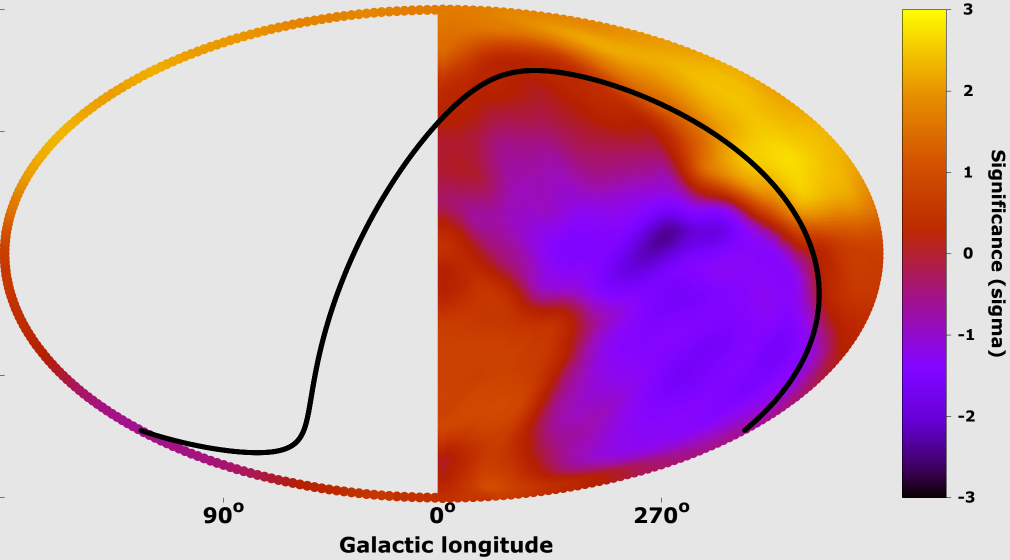
The $M_{\mathrm{gas}} - T$ relation

$H_0^{-\frac{5}{2}}$

no cosmology

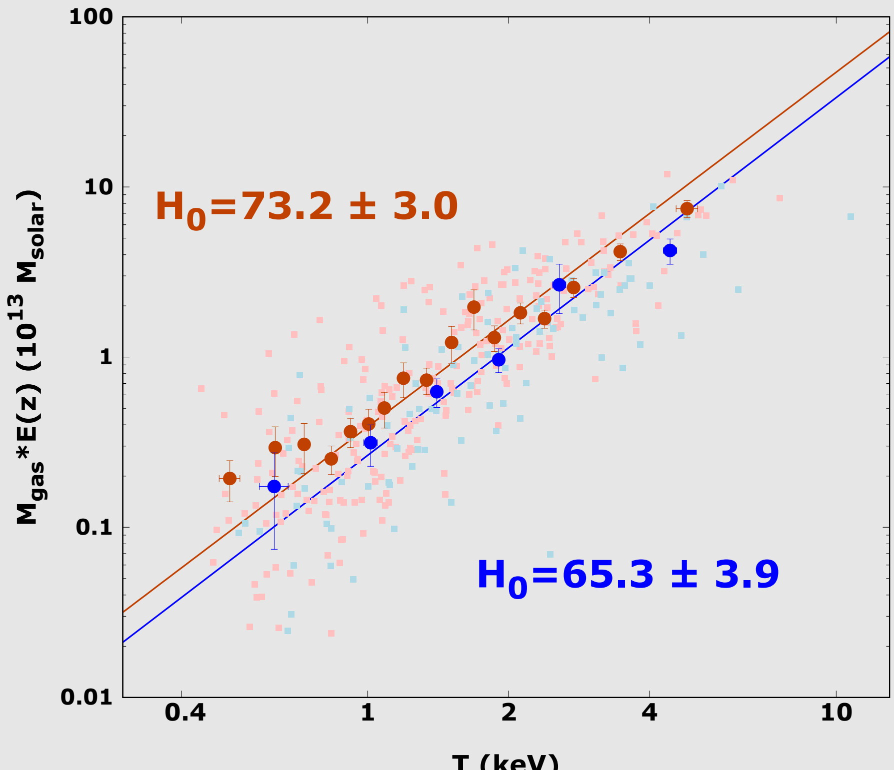
eROSITA: M_{gas}-T

- Same anisotropies again!
- H_0 variation = 11.2 ± 4.9% (instead of 9.0 ± 1.7% from eeHIFL)



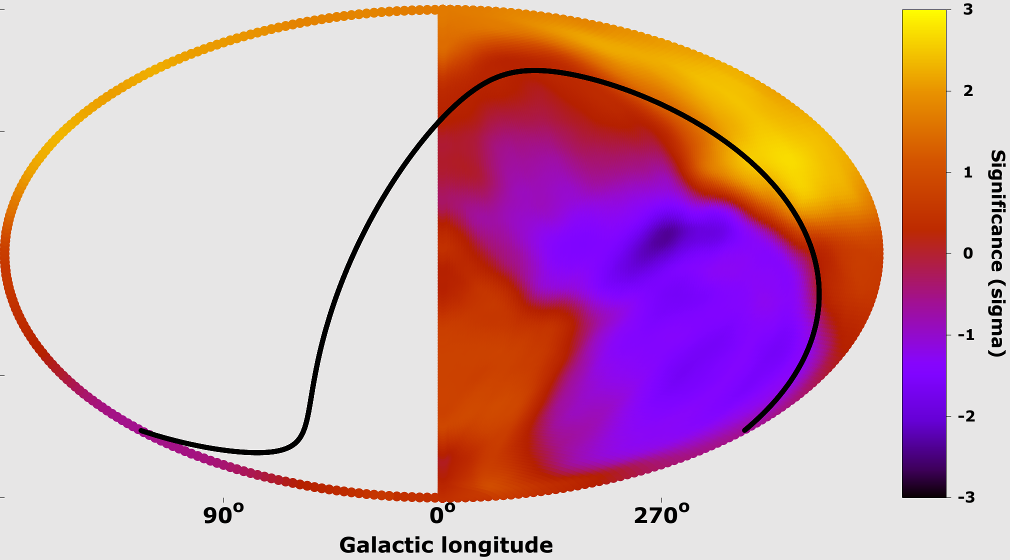
$$2.3\sigma$$

$$(l, b) \sim (271°, +7°)$$



eROSITA: M_{gas}-T

- Same anisotropies again!
- H_0 variation = 11.2 ± 4.9%   (instead of 9.0 ± 1.7% from eeHIFL)



$$2.3\sigma$$

$$(l,b) \sim (271^{\circ}, +7^{\circ})$$

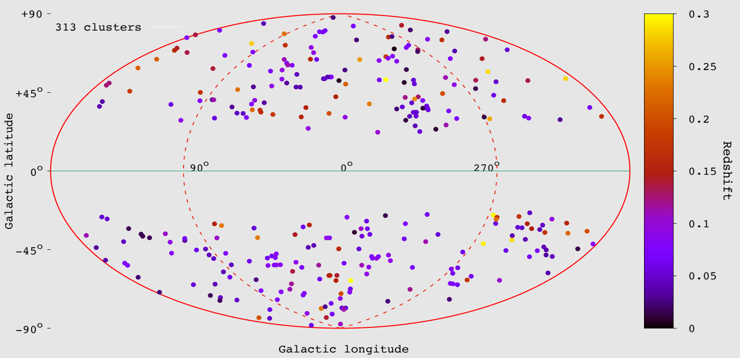
Or, similar bulk flow as before!

$$940 \pm 410 \text{ km/s}$$

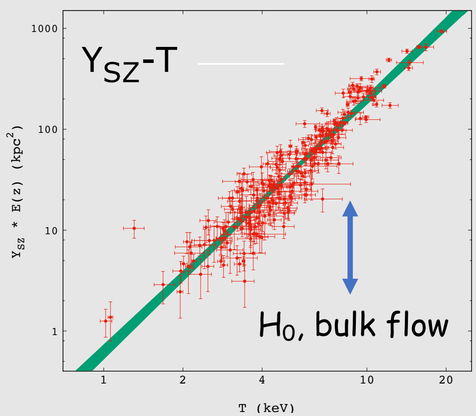
For now, we cannot tell apart bulk flows from an H_0 anisotropy

Summary

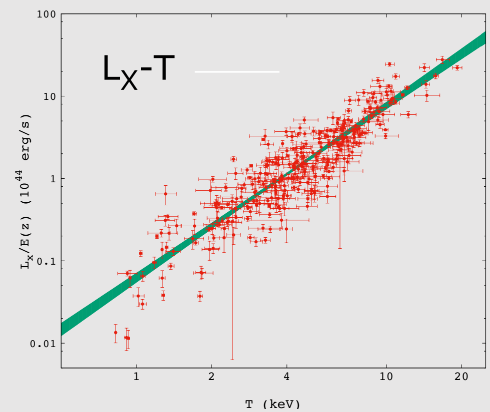
- **Galaxy clusters** provide a powerful, multiwavelength method to scrutinize **cosmic isotropy**



microwave

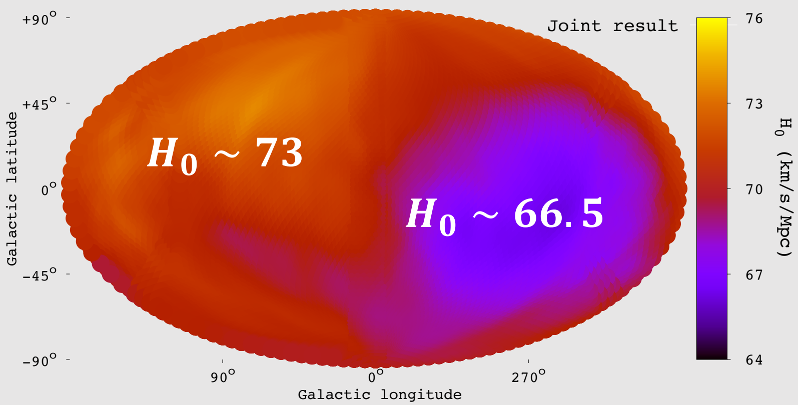


X-ray

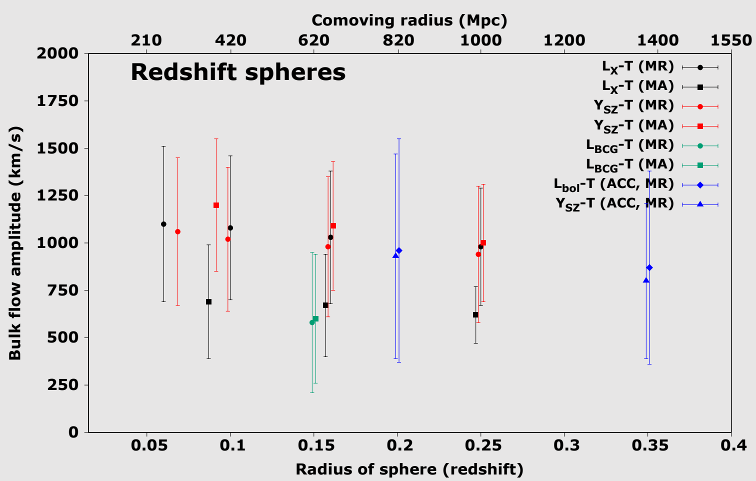


- Strong anisotropies at z<0.3: **9% H_0 anisotropy or 900 km/s bulk flow?**

5.4σ



or

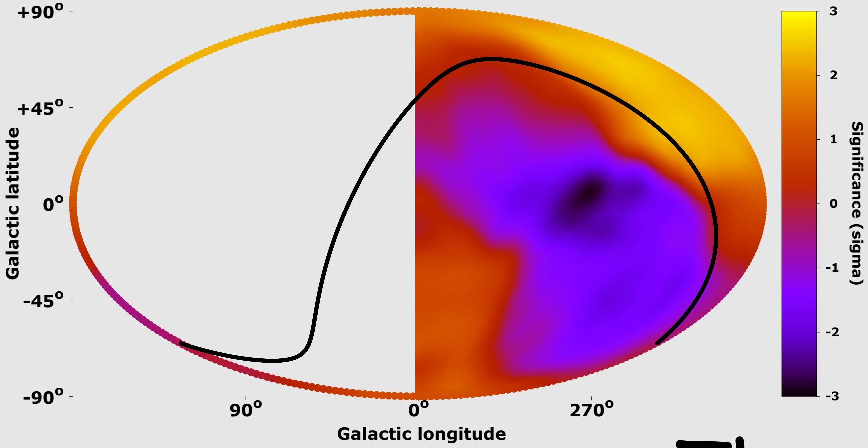


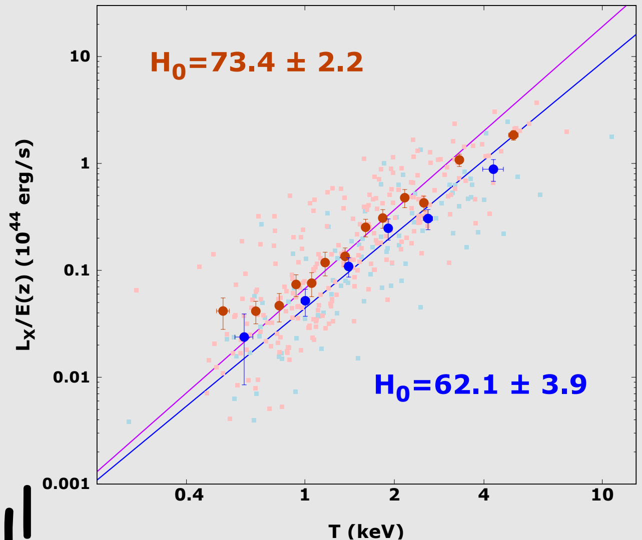
Summary

- **New results & lower-scatter scaling relations support initial findings**

$$M_{\rm gas} - T \;\Rightarrow\; \Delta H_0 = 11 \pm 3\% \;\Rightarrow\; 3.6\sigma$$

- **First eROSITA results** on cosmic isotropy! Independently **supports** previously detected **anisotropy in local Universe!**





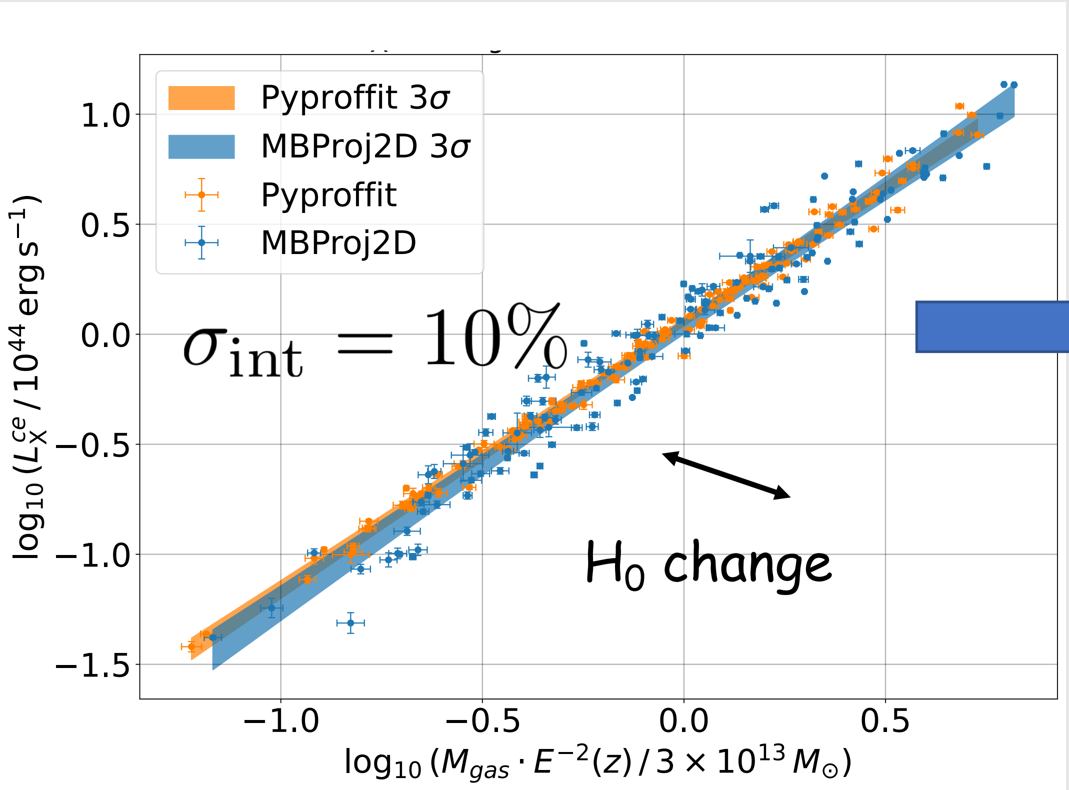
Thank you!

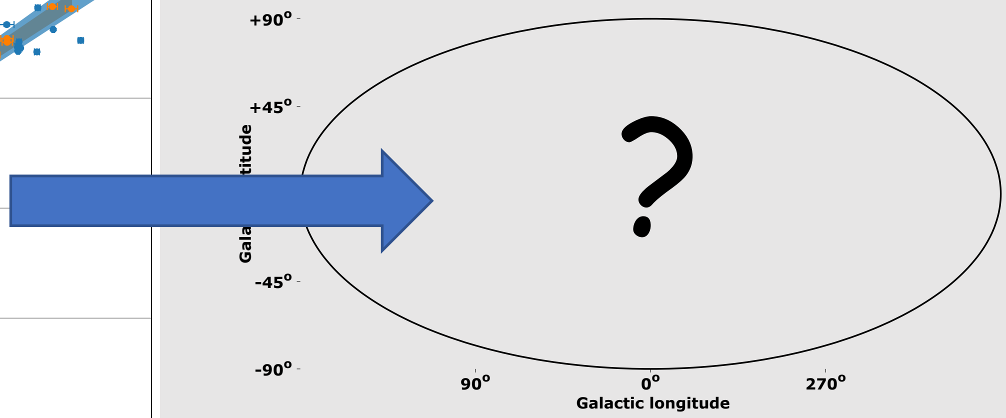
Back up slides

Future work with very low-scatter relations coming…

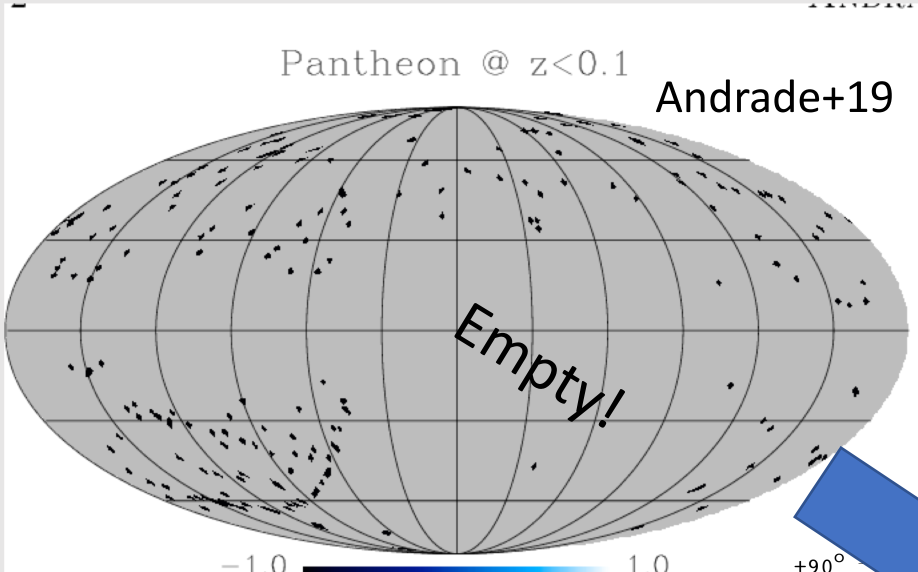
Migkas et al. (in prep.)

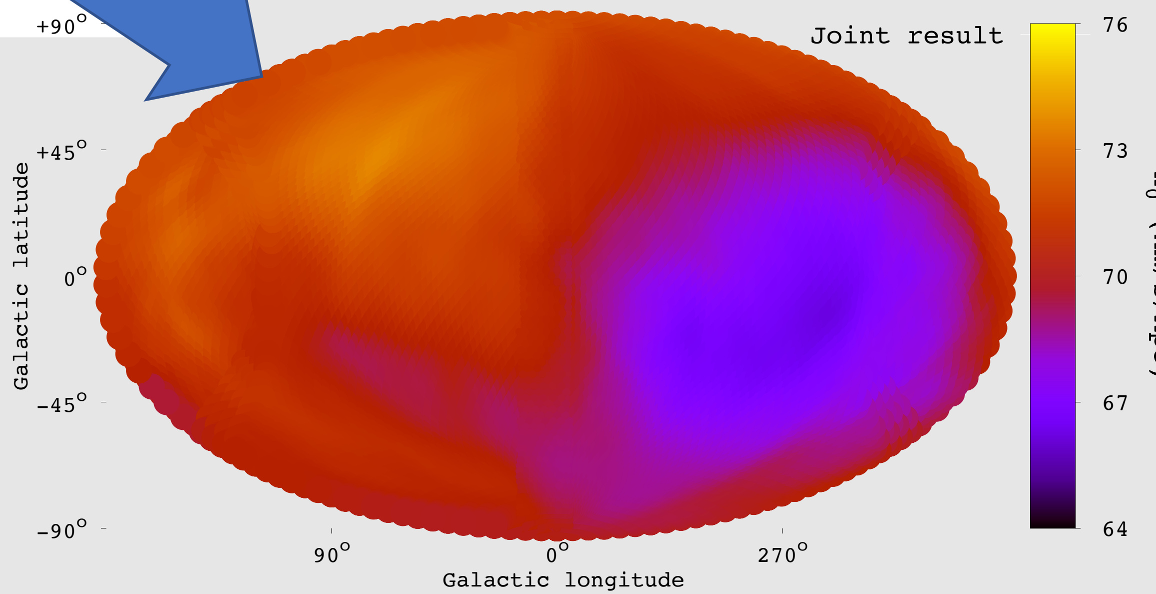
Core excised $L_X - M_{gas}$





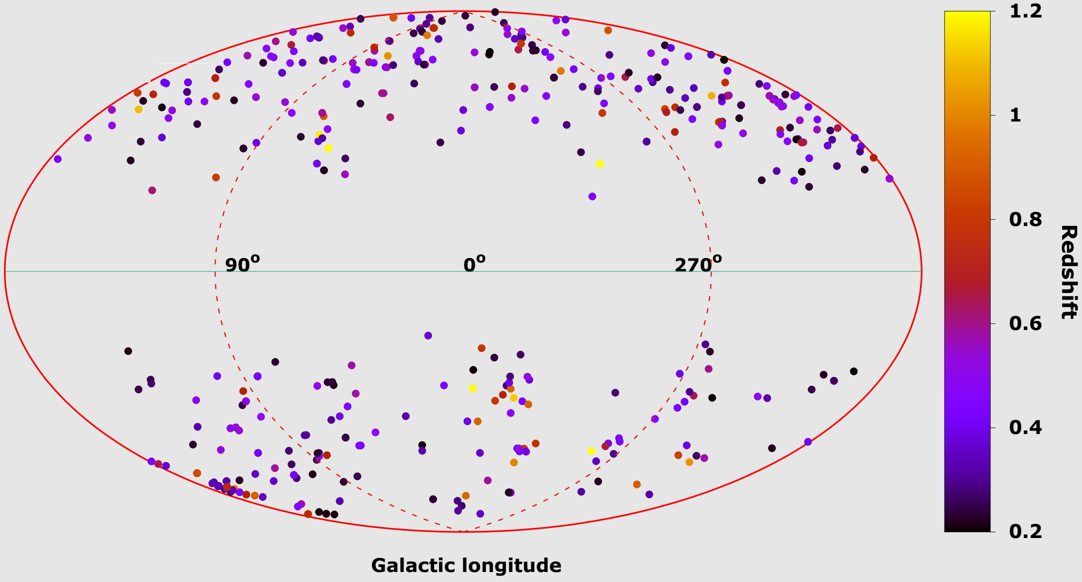
Non-uniform SNIa sky distribution

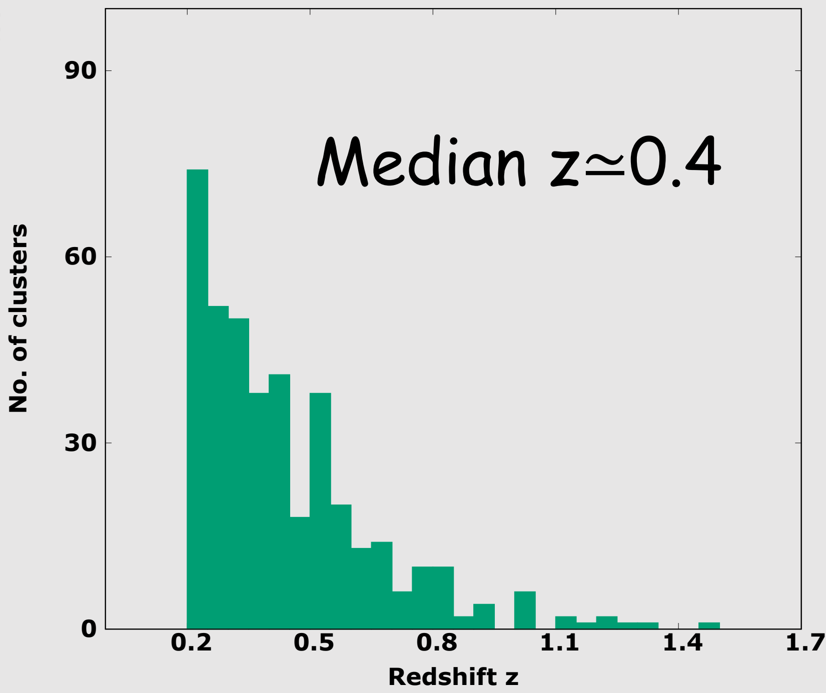




X-CLASS

- 1646 archival XMM-Newton cluster observations (Koulouridis+21)
- **404 clusters** at **z>0.2** with spec-z and reliable T

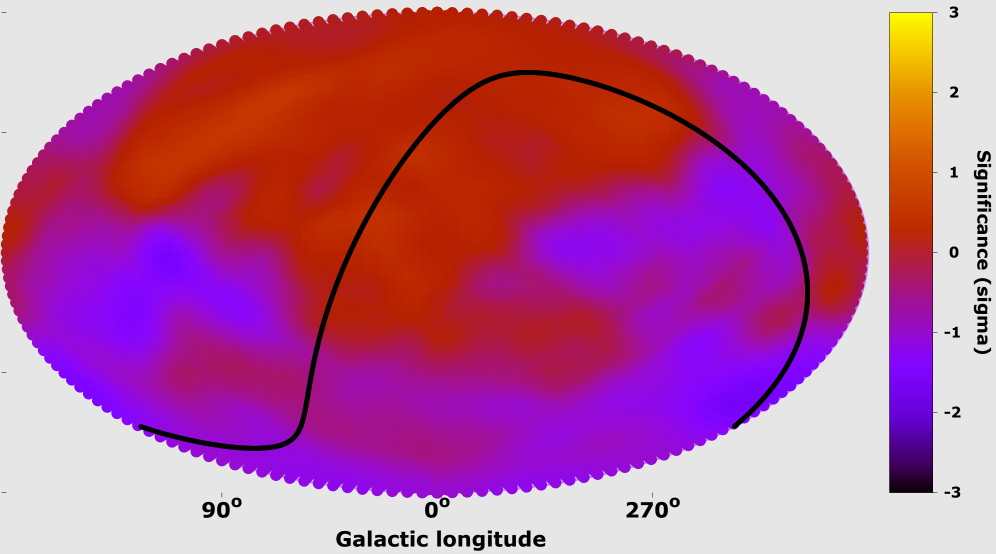


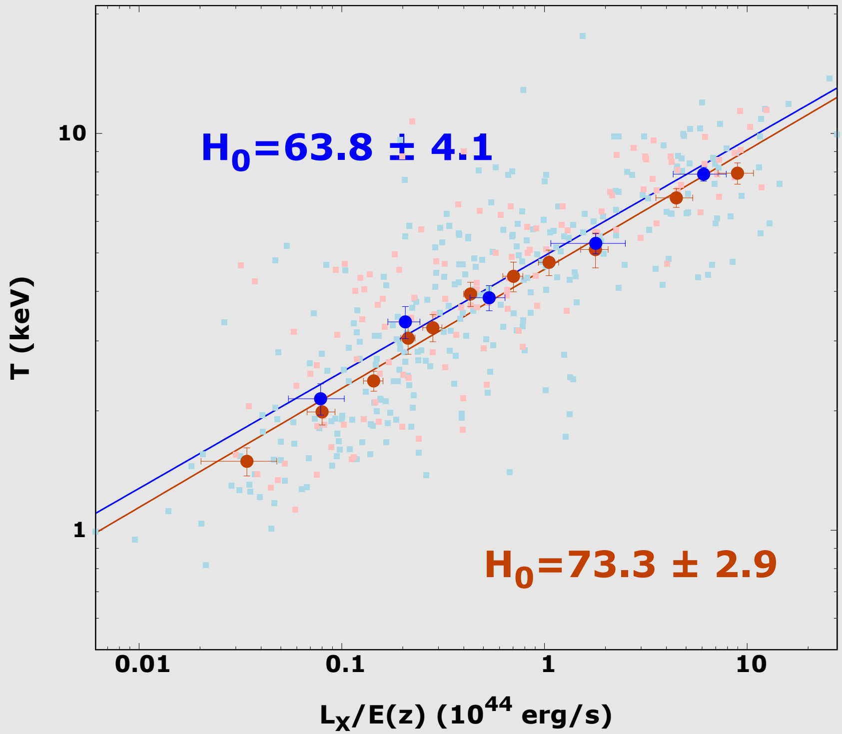


X-CLASS

- Does not see bulk flows (z~0.4)
- "Expected" H_0 variation ~ uncertainties (for now), very large scatter
- **Upper limit for cosmic H_0 anisotropy:** $\Delta H_0 \lesssim 11\%$

1.9σ

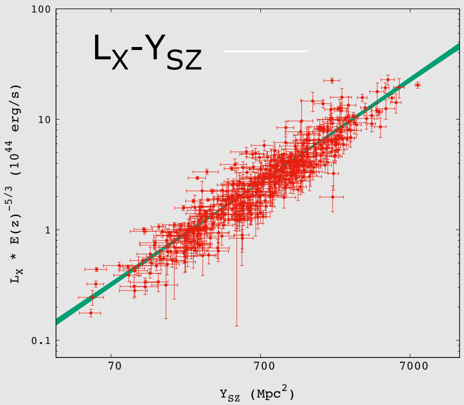




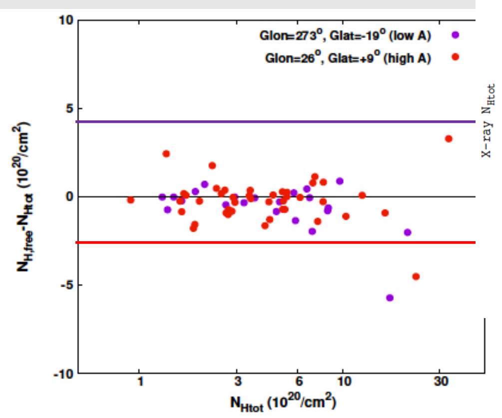
Undiscovered X-ray absorption..?

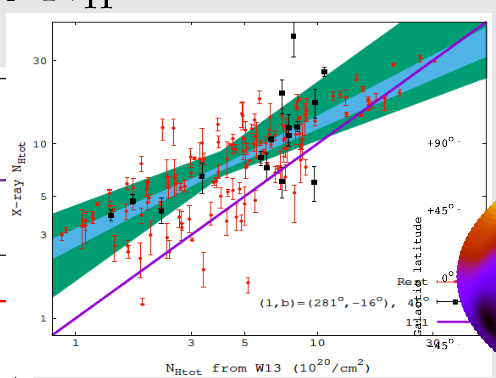
➢ 4 different tests for detecting previously unknown absorption

No excess X-ray absorption seen!

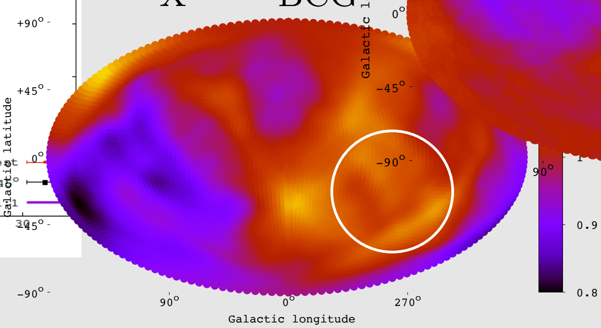


$\text{X-ray } N_{\text{H}} - \text{Radio } N_{\text{H}}$

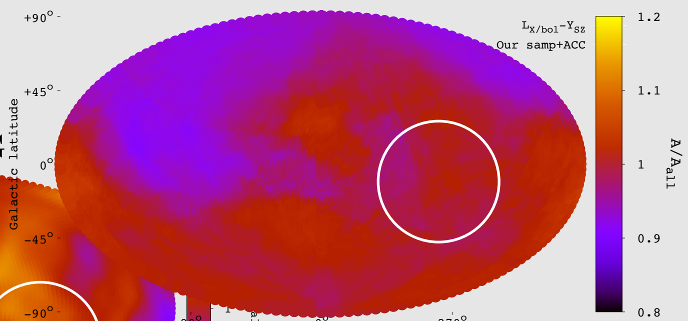




$L_{\text{X}} - L_{\text{BCG}}$



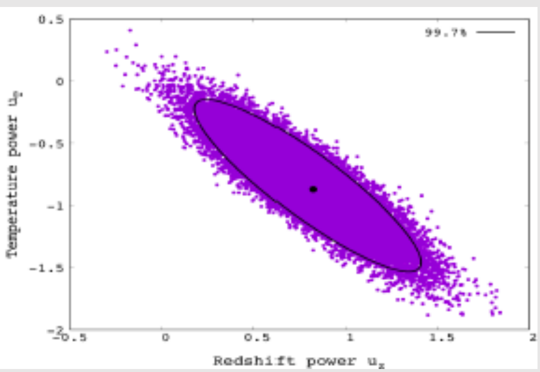
$L_{\text{X}} - Y_{\text{SZ}}$

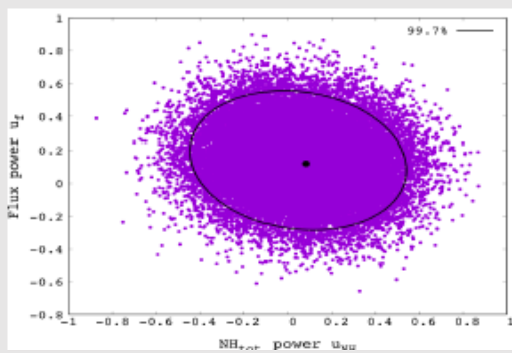


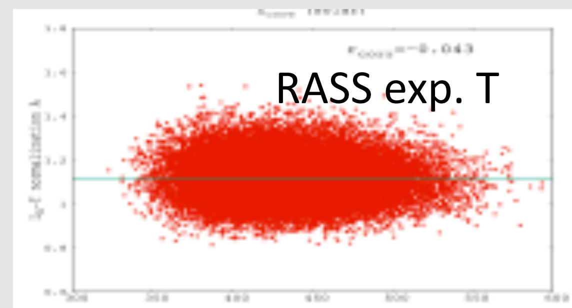
MCMC in 10-parameter space

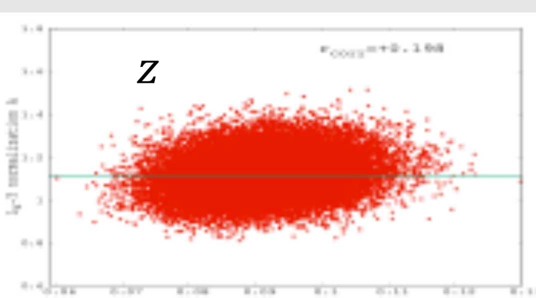
- **Predict expected behavior** from cosmology-independent **cluster propert**ies (z, T, N_H, σ_{int}, flux, metallicity, RASS exp. Time, Xray-BCG offset, etc.)

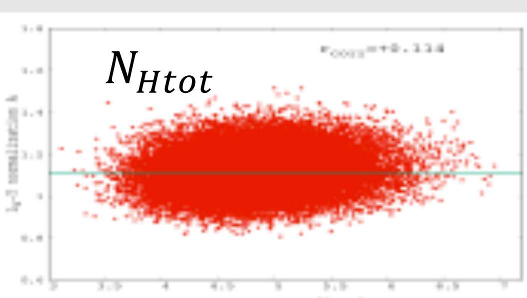
- **Anisotropic region** should behave the **same as rest**, average cluster properties!

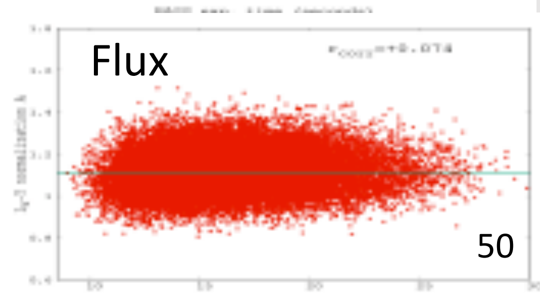




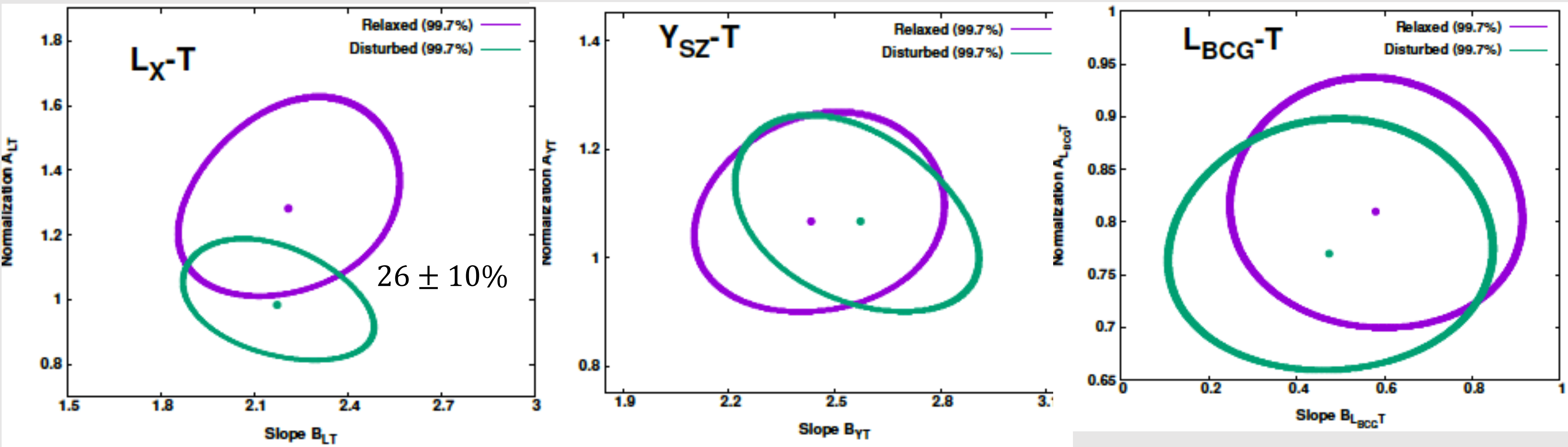






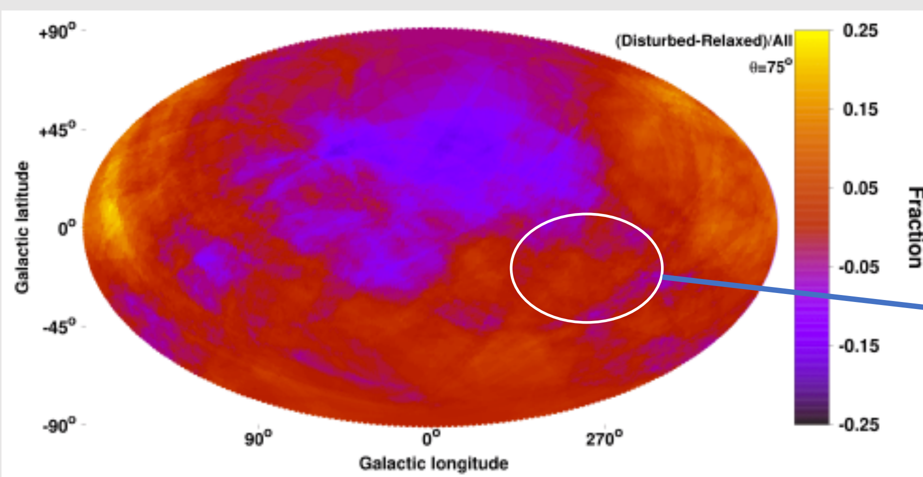


Relaxed vs disturbed clusters



Cluster dynamical state is irrelevant

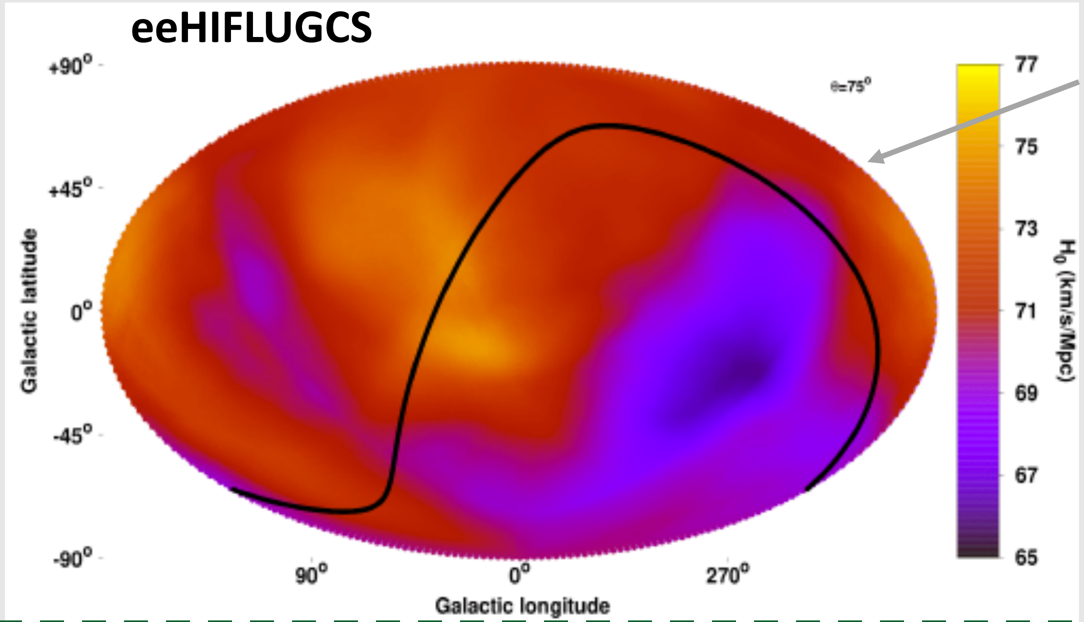
● =more relaxed, ● =more disturbed



Average population!

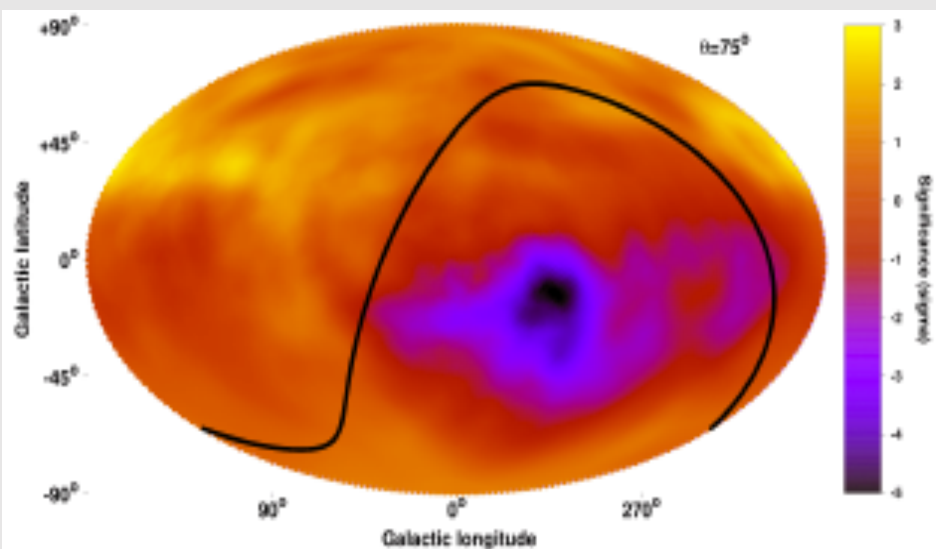
3 Independent samples

eeHIFLUGCS

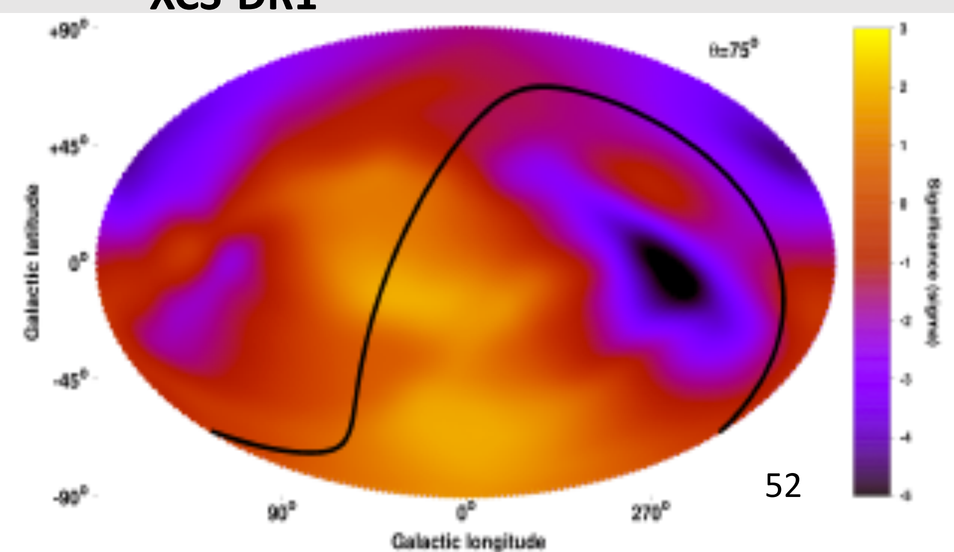


H_0 variation

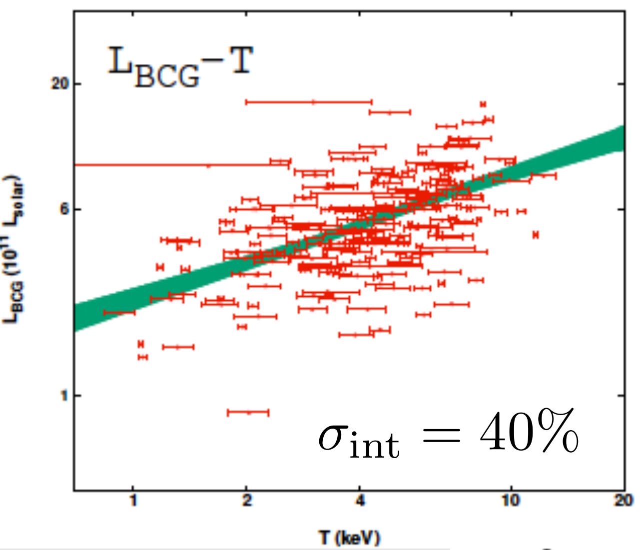
ACC



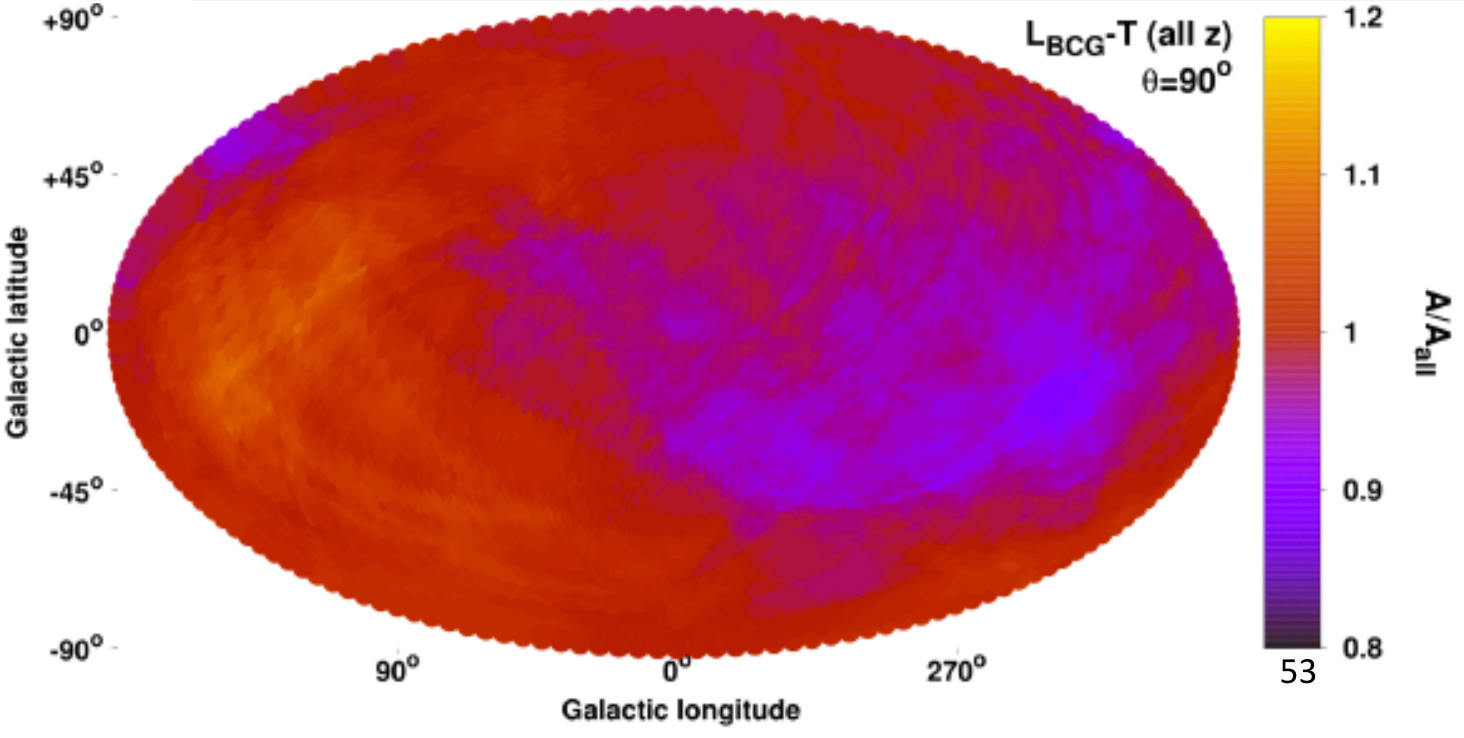
XCS-DR1



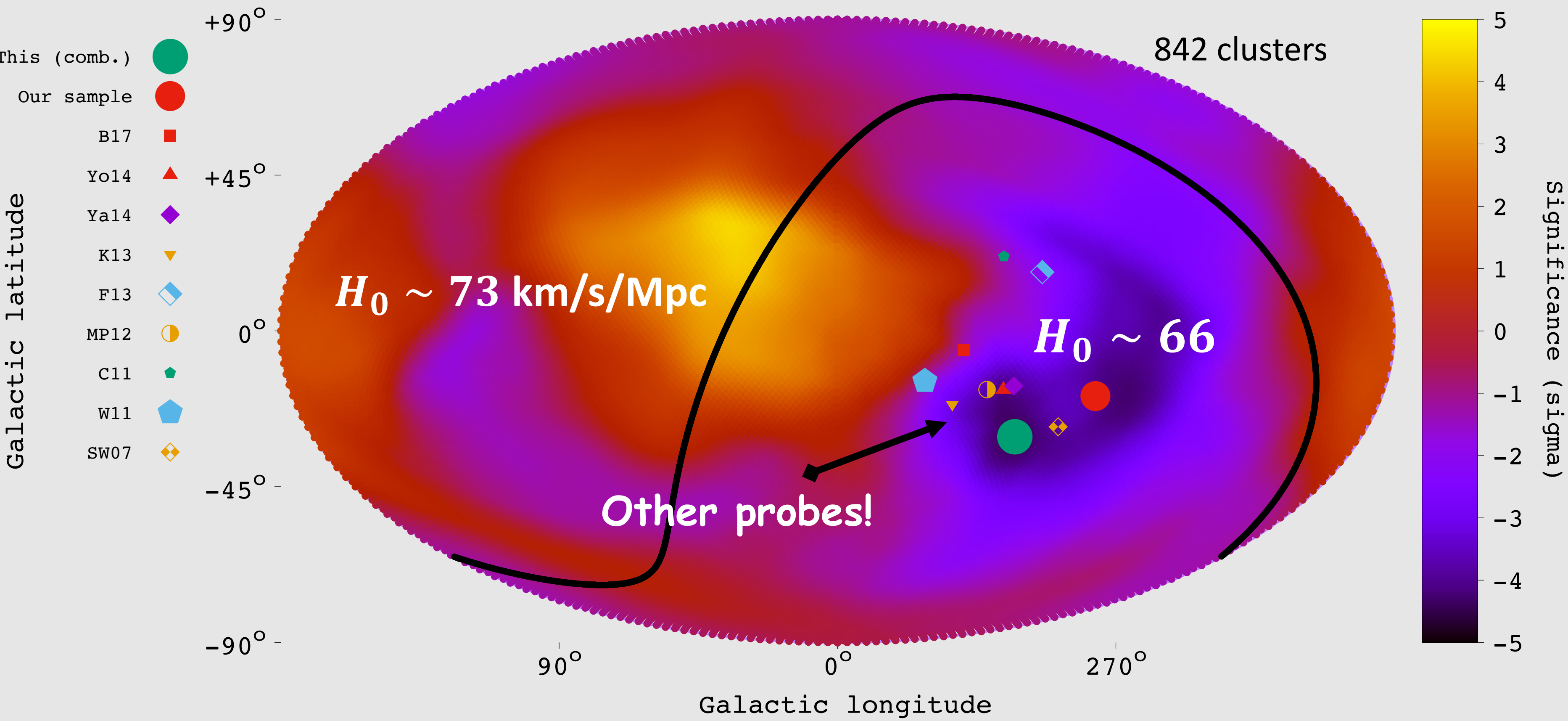
$L_{BCG} - T$ anisotropies



Same pattern, low significance (1.9σ)



Apparent H_0 anisotropy from $L_X - T$



$\sim 4\sigma$ **anisotropy!**

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